# Academic Report (2022-23)


Harish - Chandra Research Institute
Chhatnag Road, Jhunsi
Prayagraj - 211019, India

# Contents

# About The Institute

## History

The Harish-Chandra Research Institute is one of the premier research institutes in the country. It is an autonomous institution fully funded by the Department of Atomic Energy (DAE), Government of India. The Institute was founded as the Mehta Research Institute of Mathematics and Mathematical Physics (MRI). On 10th Oct 2000 the Institute was renamed as Harish-Chandra Research Institute (HRI) after the acclaimed mathematician, the late Prof Harish-Chandra. MRI started with the efforts of Dr. B. N. Prasad, a mathematician at the University of Allahabad, with initial support from the B. S. Mehta Trust, Kolkata. Dr. Prasad was succeeded in January 1966 by Dr. S. R. Sinha, also of Allahabad University. He was followed by Prof. P. L. Bhatnagar as the first formal Director. After an interim period, in January 1983 Prof. S. S. Shrikhande joined as the next Director of the Institute. During his tenure the dialogue with the DAE entered into decisive stage and a review committee was constituted by the DAE to examine the Institute's future. In 1985 Shri N. D. Tiwari, the then Chief Minister of Uttar Pradesh, agreed to provide sufficient land for the Institute and the DAE promised financial support for meeting both the recurring and non-recurring expenditure. In January 1990, about 66 acres of land was acquired in Jhunsi, Allahabad, and the Institute came up at this site.

Prof. Shrikhande was followed by Prof. H. S. Mani who took over as the Director in January 1992. With his joining, and the shift to the new campus at Jhunsi in 1996, the Institute's activities picked up pace. After a distinguished tenure of about nine years Prof. Mani retired in August 2001 and the charge was taken over by Prof. R.S. Kulkarni. After Prof. Kulkarni's tenure, Prof. Amitava Raychaudhuri was the Director from July 19, 2005 to May 15, 2011. After him Prof. Sumathi Rao officiated as Acting Director till April 28, 2012. Prof. Jayanta Kumar Bhattacharjee was the next Director and continued till April 9, 2017. Prof. Pinaki Majumdar, the current Director, took over on April 10, 2017.

The Institute has a residential campus in Jhunsi, Allahabad, with a library, state of the art computational facility and fast internet link to the outside world. There is an active Ph.D program, an M.Sc program in Physics that started in 2017, and a large traffic of visiting scientists and students.

## Research

The Institute continues to be devoted to fundamental research in diverse areas of mathematics and theoretical physics. Research is carried out by faculty members, visiting scientists, post-doctoral fellows and Ph.D. students.

The mathematics group at HRI carries out research in several areas. In algebra, work is done on algebraic groups and related structures, the theory of groups and group rings, representation theory, and infinite-dimensional Lie algebras. Work in analysis is in the field of harmonic analysis of Lie groups. Activity in geometry includes discontinuous groups and Riemann surfaces, algebraic topology, variation all problems on manifolds, Chow groups of rational surfaces, and moduli of vector bun-

dles. The number theory group works on algebraic, analytic and combinatorial number theory, automorphic forms and cryptography.

The areas of research in physics are astrophysics, condensed matter physics, quantum information and computing, high energy phenomenology and string theory. In astrophysics, work is done on the cosmic microwave background, large scale structure formation, and galaxy evolution. Main areas of activity in condensed matter physics are strongly correlated systems, study of energy materials, and the study of clusters and nanomaterials. In string theory, perturbative and non-perturbative aspects of string theory and quantum field theory are being actively investigated. Research in neutrino physics, strong interactions, lattice gauge theory, super symmetry and various aspects of physics beyond the standard model is done in high-energy phenomenology. The Institute is a member of the India-based Neutrino Observatory (INO) collaboration.

## Recognition

Since 1992 the Institute has attracted worldwide attention, as is evident from the recognition received by many of its members. Several members of the Institute have been recognised for their scientific contribution. Prof. Ashoke Sen, Prof. B. Mukhopadhyaya, Prof. Pinaki Majumdar and Prof. Rajesh Gopakumar have been awarded the Shanti Swarup Bhatnagar prize and in 2018 Prof. Aditi Sen De became the first woman scientist in India to be awarded the Bhatnagar prize in Physical Sciences. The outstanding contribution of Prof. Ashoke Sen has been recognised by a Fellowship of the Royal Society, the award of Padmashri and Padmabhushan and the award of one of the first Fundamental Physics Prize (2012) from the Yuri Milner Foundation. He was the only recipient of the prize from all of Asia. In 2017 the Institute was recognized as being among the top 10 research centers in India by the Nature journal.

# Director's Report

By April 2022 we were essentially out of the covid emergency phase. All activities were back to the physical mode. Classes were offline and the number of visitors and visiting students went back to the pre covid levels. I give the highlights for the one year period, April 2022 to March 2023, below.

1. Student admissions and teaching program: We admitted 14 M.Sc. students in Physics and 7 students in Ph.D Physics and 5 in Ph.D Math in 2022. Five M.Sc students graduated in 2022 (one of the earlier small batches). The M.Sc graduating number for 2023 is 18. Eight students finished their Ph.D, four respectively in Math and Physics. The Physics M.Sc program has stabilised in terms of student numbers and teaching. The Math group at HRI has prepared a proposal for starting a M.Sc program from 2024, this will be put up to the Governing Council.

2. Academic events: By April 2022 most travel restrictions had been lifted and physical meetings restarted. Among these we had String Seminar Days (21 to 23 Dec 2022), the Young Quantum Conference (15 to 18 Feb 2023), and the International Conference on Recent Advances in Renewable Energy (CARE-2023), from 2 to 4 Feb 2023, in collaboration with TIFR Hyderabad. In Math we had an NCM workshop on Elliptic Curves, Elliptic functions and Transcendence (24 Nov to 3 Dec 2022), an Infosys Lecture Series by Prof. M. Ram Murty (10 to 19 Dec 2022), a Conference on Algebraic Geometry (12 to 16 Dec 2022), and an Infosys Lecture Series by Prof. Jean-Marc Deshouillers (22 to 25 Feb 2023).

3. Programs related to Azadi ka Amrit Mahotsav: 2022 was the 75th anniversary year of Indian independence and all institutions celebrated the occasion as part of the Azadi ka Amrit Mahotsav. At HRI the focus was on involving school and college students in scientific activities. On 22 Aug we had a Open Day and Quiz for Class IX-X Students, on Aug 23 and 24 there were Essay Competitions, on Aug 25-26 HRI faculty, students and postdocs gave talks at Colleges in the city, on 27 Aug there was a Open Day & Quiz for Class XI and XII Students, and finally on 28 Aug there was an Open Day & Quiz for BSc Students. In addition to these activities during the focus week we had a year long colloquium program on the History of Indian Mathematics.

4. Faculty appointments: Our appointments had been stalled for a few years due to administrative reasons. Once that hurdle was lifted two years back we tried to build back our faculty numbers by recruiting promising young physicists and mathematicians. During 2022-23 this also coincided with the recruitment drive of the Government of India. Two Physics faculty members joined during the period - Dr. Sayan Choudhury who works on nonequilibrium quantum systems, and Dr. Bhupendra Mishra who works on general relativistic magnetohydrodynamic simulations. Four members joined in Maths: Dr. Jishnu Ray, who works on Iwasawa theory, Dr. B. Sreedhar who works on algebraic geometry, and Dr. Tuhin Ghosh and Dr. Amrita Ghosh, who work on partial differential equations.

5. Changes in the administration: We are in the process of recruiting a new registrar and an accounts officer. At a junior level, we have made six appointments during this period. This includes an Administrative Officer, an assistant for the Physics laboratory, and personnel for the library and general administration. We are also in the midst of

a cadre restructuring process to make the manpower deployment more suited to HRI needs and also consistent with the DAE cadre norms.

6. Infrastructure activities: The major works of our three year infrastructure apex project are complete. This includes re-carpeting of internal roads, the outer repainting of all buildings in campus, renovation of games facilities in the community centre, and the enhancement of lighting on the jungle pathway that encircles the campus. We have freed up three rooms for classroom and discussion use. We are moving to more energy efficient lighting.

7. Recognition: Dr. Aditi Sen De has been elected a Fellow of the Indian National Science Academy (INSA), and Dr. Sudip Chakraborty has received the DST Solar Challenge Award from the Department of Science and Technology (as part of one of only three teams selected from all over India).

8. Harish-Chandra centenary: 2023 is the centenary year of the birth of Prof. Harish-Chandra. A major international conference on Representation Theory has been planned in Oct 2023. This will be preceded by an NCM School on the same topic to prepare junior Indian participants for the conference. The Math conference will be succeeded by a small Physics gathering. The organisational work is in full sway.

Pinaki Majumdar

Director

# List of Governing Council Members (2022 - 23)

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|---|---|
| 1. **Shri K.N. Vyas**<br>(Chairman) | Chairman, Atomic Energy<br>Commission (AEC) & Secretary,<br>Department of Atomic Energy, Govt. of India,<br>Anushakti Bhawan,<br>Chhatrapati Shivaji Maharaj Marg,<br>Mumbai – 400 001 |
| 2. **Smt. Sushma Taishete** | Joint Secretary (R & D)<br>Deptt. of Atomic Energy, Govt. of India,<br>Anushakti Bhavan,<br>Chhatrapati Shivaji Maharaj Marg,<br>Mumbai – 400 001 |
| 3. **Mrs. Richa Bagla** | Joint Secretary (Finance)<br>Deptt. of Atomic Energy, Govt. of India,<br>Anushakti Bhavan,<br>Chhatrapati Shivaji Maharaj Marg,<br>Mumbai – 400 001 |
| 4. **Prof. V. Srinivas** | Senior Professor TIFR & Chairman<br>NBHM, School of Mathematics,<br>Tata Institute of Fundamental Research,<br>Homi Bhabha Road, Colaba,<br>Mumbai – 400 005 |
| 5. **Prof. V. Arvind** | Director<br>Institute of Mathematical Sciences,<br>CIT Campus, Taramani,<br>Chennai – 600 113 |
| 6. **Prof. Sanghamitra Bandopadhyay** | Director<br>Indian Statistical Institute,<br>203, B.T. Road,<br>Kolkata – 700 108 |
| 7. **Prof. Mustansir Barma**<br>(w.e.f. March 2021 vice<br>Prof. S.M. Chitre) | Professor Emeritus,<br>Tata Institute of Fundamental Research,<br>36/P Gopanpally Village,<br>Serilingampally Madal,<br>Hyderabad – 500 046 |

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| 8. Director, Higher Education (Ex-officio) | Higher Education Department, U.P.<br>Near G.P.O., Civil Lines,<br>Allahabad – 211 001 |
| 9. **Shri S. L. Mehta** | 4, Clive Row,<br>Kolkata – 700 001 |
| 10. **Shri Avnish Mehta** | 4, Penn Road,<br>Kolkata – 700 027 |
| 11. **Shri Rajnish Mehta** | 4, Penn Road,<br>Kolkata – 700 027 |
| 12. **Prof. Pinaki Majumdar** (Ex-Officio) | Director<br>Harish-Chandra Research Institute,<br>Chhatnag Road, Jhunsi,<br>Allahabad – 211 019 |
| **Prof. D. Surya Ramana** | Acting Registrar, HRI was the Non-Member Secretary of the Governing Council. |

# Academic Report - Mathematics

# Punita Batra

## Research Summary:

In a joint work with Santanu Tantubay and Priyanshu Chakraborty, I have classified twisted Hamiltonian EALA and classified its irreducible, integrable modules with finite dimensional weight spaces, when the center is acting non-trivially on the modules.

## Publications:

1. (With Santanu Tantubay) Irreducible integrable modules for the full toroidal Lie algebras coordinated by rational quantum torus, 527-545, **J. of Algebra, 610, 2022.**

2. (With Priyanshu Chakraborty) A Class of irreducible modules for loop-Virasoro algebras, **J. of Algebra and its Applications, Vol 22, No. 07, 2350156, 2023.**

3. (With Santanu Tantubay) Classification of irreducible integrable modules for the extended affine Lie algebras with center acting trivially, **Accepted to appear in J. of Lie Theory.**

## Preprints:

1. (With Santanu Tantubay, Priyanshu Chakraborty) Simple modules for twisted Hamiltonian extended affine Lie algebras, **arxiv:2304.07749, Submitted**.

## Invited Lectures/Seminars:

1. Gave an online invited seminar on National Mathematics Day, December 22, 2022 in the Department of Mathematics, Aligarh Muslim University, Aligarh on "Ramanujan's Contributions to Mathematics".

## Other Activities:

1. Serving as "Dean of Students' Affairs" at HRI since April 2022.

2. Organised SPIM (Summer Programme in Mathematics 2022) at HRI during June 27- July 16, 2022 and gave 6 lectures on "Galois Theory" in this programme.

3. Gave a graduate course "Algebra-I" to first year Ph.D students at HRI during August-December 2022.

4. My student Priyanshu Chakraborty defended his Ph.D thesis " Irreducible modules for Loop of Lie Algebras" in November 2022 at HRI.

5. Organised various outreach activities at HRI:

1.) International Yoga day for Harsha School kids (June 21, 2022),

2.) Azadi ka Amrit Mahotsava- Nibandh Pratiyogita ( August 2022),

3.) Children's Day Programme (November 13, 2022),

4.) (Along with Prof. Aditi Sen De) Women in Science (February 26, 2023).

6. Served in the Outreach Committee, The Rajbhasha Committee, The Sports and Entertainment Committee and Women's Grievance Cell during April 2022-March 2023.

# Chandan Singh Dalawat

## Conference/Workshops Attended:

1. Conference on Algebraic Geometry, Harish-Chandra Research Institue, Allahabad, 12–16 December 2022.

## Visits to other Institutes:

1. Indian Institute of Technology, Gandhinagar, 2–5 January, 2023.
2. Azim Premji University, Bangalore, 11–14 January, 2023.
3. The Institute of Mathematics Sciences, 15–21 January, 2023.
4. Indian Statistical Institute, Bangalore, 22–29 January, 2023.
5. Indian Institute of Technology, Benares, 13–14 March, 2023.

## Invited Lectures/Seminars:

1. *Other worlds are possible*, Malaviya National Institute of Technology, Jaipur, 18 October 2022 ; Ahmedabad University, Ahmedabad, 19 October 2022 ; Indian Institute of Technology, Jodhpur, 21 October 2022 ; Allahabad University, Allahabad, 4 November 2022 ; Manipur University, Imphal, 29 November 2022.
2. *Galois's Last Theorem*, Allahabad University, Allahabad, 10 November 2022 ; Indian Institute of Information Technology, Allahabad, 14 November 2022.
3. *Primitive $p$-extensions of $p$-fields*, Indian Institute of Technology, Gandhinagar, 2 January 2023 ; Instiute of Mathematical Sciences, Madras, 20 January 2023.
4. *The oldest problem*, Indian Institute of Technology, Gandhinagar, 4 January 2023 ; Instiute of Mathematical Sciences, Madras, 18 January 2023 ; Indian Statistical Institute, Bangalore, 24 January 2023 ; Indian Institute of Science Education and Research, Mohali, 9 February 2023 ; Indian Institute of Technology, Benares, 13 March 2023.

## Other Activities:

A major effort was made to recruit the best available young people, as soon as it became possible for us to do so. As a result, and over a very short period of time, the mathematics group at HRI has emerged as one of the best centres in the country in algebraic number theory, algebraic geometry, and partial differential equations.

# Umesh V Dubey

## Research Summary:

In this academic year with Gopinath Sahoo, we applied the result of the classification of compactly generated tensor t-structure to the classification of tensor w-structurer on $\mathcal{D}(X)$ the derived category of the Noetherian scheme $X$. We introduce the notion of tensor w-structure and prove that there is a bijection between tensor t-structure and tensor w-structure with decreasing Thomason filtration $\Phi$. We also observe the asymmetry between bounded t-structure and bounded w-structure on the bounded derived category of the projective line. More precisely, we prove that there are no non-trivial bounded tensor w-structure on the projective line but there are lots of bounded t-structure on it given by specialisation closed subsets.

In joint work with Parul Keshari, we introduce the notion of the quiver Tannakian category and observe that we can develop the theory of essentially finite quiver bundles. We also explicitly classify some finite quiver bundles in some very specific cases of loop quivers. Here we also study the tensor structure of Simpson and get the group scheme using rigidity. We also studied the Chevalley property for some quiver representation categories.

In ongoing joint work with Sreedhar Bhamidi, we have studied the derived matrix factorization category $DMF(\mathcal{X}, W)$ for some classes of algebraic stacks $\mathcal{X}$ and their tensor subcategories in terms of some (pseudo-) tensor structures.

We continued the study of the Atiyah-Segal-Vistoli type formula in tensor triangular geometry with Vivek Mallick for some particular examples of tt-categories.

We also continued the study of the analog of the Hopf-Galois extension in the non-commutative setup with Parul Keshari and N. Raghavendra.

## Publications:

1. Umesh V Dubey and Gopinath Sahoo, *Compactly generated tensor t-structures on the derived categories of Noetherian schemes,* Math. Z. **303 , no. 4**, Paper No. 100, 22 pp, (2023).

2. Sanjay Amrutiya and Umesh V Dubey, *Moduli of parabolic sheaves and filtered Kronecker modules* , Kyoto J. Math. **63, no. 2**, 241-269, (2023).

3. Umesh V Dubey and Gopinath Sahoo, *Tensor weight structures and t-structures on derived categories*, C. R. Math. Acad. Sci. Paris (Accepted) (2022).

## Preprints:

1. Pradeep Das, Umesh V Dubey and N Raghavendra, *Tensor product of representations of Quivers*, arXiv:2305.09159 [math.AG] (under review).

2. Umesh V Dubey and Subham Sarkar, *On Perverse sheaves of a Coxeter hyperplane arrangement of type* $\mathcal{A}_n$, arXiv:2211.09525 [math.AG] (under review).

3. Umesh V Dubey and Parul Keshari, *On quiver Nori fundamental monoid scheme*, (In preperation).

## Conference/Workshops Attended:

1. *Conference on Algebraic cycles, motives and K-theory*, Tifr, Mumbai, March 13 - 17, 2023.
2. *Conference on Commutative Algebra and Algebraic Geometry*, IIT, Hyderabad, February 10 - 11, 2023.
3. *Vector bundles in Chennai*, IIT Madras, Chennai, February 6 - 9, 2023.
4. *Conference on Algebraic Geometry*, HRI, Prayagraj, December 12 - 16, 2022.
5. *(Online) Vector Bundles and Algebraic Curves (VBAC) Webinars*, ICMAT, Spain, January 23, March 27, 2023.
6. *(Online) Vector Bundles and Algebraic Curves (VBAC) Webinars*, ICMAT, Spain, May 16, September 26, November 21, 2022.
7. *(Online) VBAC 2022: Moduli Spaces and Vector Bundles' New Trends "On the occasion of Peter Newstead's 80th birthday"*, July 25 - 29, 2022.
8. *(Online) International Congress of Mathematicians*, July 6 - 14, 2022.

## Visits to other Institutes:

1. Indian Institute of Technology Bombay, Mumbai, October, 10 - 14, 2022.

## Invited Lectures/Seminars:

1. *Tensor w-structure on the derived category of schemes*, Conference on Commutative Algebra and Algebraic Geometry, IIT, Hyderabad, February 11, 2023.
2. *A functorial construction of moduli of parabolic sheaves*, IIT Bombay, Mumbai, October 11, 2022.

## Other Activities:

1. Graduate Course on Topology - II, HRI, January – May, 2023.
2. Supervising one research scholar and thesis submitted for Mr. Gopinath Sahoo under HBNI.
3. RAC member of two students from IISER Tirupati and IISER Pune.
4. Involved in refereeing manuscripts for some journals.
5. Convenor of Sports and Entertainment Committee and member of Mathematics Graduate Programme Committee and Outreach committee.

# Saikatul Haque

## Research Summary:

In recent years, I have been working on well-posedness and ill-posedness of nonlinear dispersive and parabolic partial differential equations, namely the Schrödinger equation, wave equation, Benjamin–Bona–Mahony (BBM) equation and heat equation. These equations have several applications in physical, biological and chemical sciences. Below I am describing the research done in the academic year 2022-2023 at HRI on these problems:

- **Heat equation:** (under review) We (with D G Bhimani, IISER-Pune) studied inhomogeneous heat equation with inverse square potential, namely,

$$u_t + \mathcal{L}_a u = \pm \frac{|u|^\sigma}{|x|^b} u \text{ in } \mathbb{R} \times \mathbb{R}^d, \quad u(0,\cdot) = u_0 \text{ on } \mathbb{R}^d,$$

  where $\mathcal{L}_a = -\Delta + a|x|^{-2}$, $b > 0$. This equation is referred as Hardy parabolic equation. In arXiv:2210.09910, (2022), we established some fixed-time decay estimate for the semigroup $\{e^{-t\mathcal{L}_a}\}_{t\geq 0}$ associated with inhomogeneous nonlinearity $|\cdot|^{-b}$ in Lebesgue spaces. We then develop local theory in $L^q-$ scaling critical and super-critical regime and small data global well-posedness in critical Lebegue spaces. We further studied asymptotic behaviour of global solutions by using self-similar solutions, provided the initial data satisfies certain bounds. This generalizes the work of Slimene-Tayachi-Weissler (Nonlinear Anal., 152 (2017), pp. 116–148) where they considered the classical case, i.e. $a = 0$.

- **Hénon parabolic equation:** (on going) The above heat equation is also referred as Hénon parabolic equation in the case $b < 0$. In an ongoing work with D G Bhimani and M Ikeda (Riken AIP & Keio University, Japan), we are investigating well-posedness and long time behaviour of global solution for this equation in weighted Lebesgue spaces.

- **Hartree equation:** (submitted) Jointly with D G Bhimani and H Hichem (California State University, Los Angeles, USA), we considered the mixed fractional NLS with Hartree-type nonlinearity:

$$i\partial_t u + (-\Delta)^{s_1} u + (-\Delta)^{s_2} u = (\frac{\lambda}{|\cdot|^\gamma} * |u|^2)u \text{ in } \mathbb{R} \times \mathbb{R}^d, \quad u(0,\cdot) = u_0 \text{ on } \mathbb{R}^d.$$

  The classical case $s_1 = s_2 = 1$ is referred as Hartree equation. We established local and global well-posedness in Fourier amalgam and modulation spaces by establishing new trilinear estimates and known Strichartz estimates for mixed fractional NLS (arXiv:2302.10683, 2023). It extends the work in Communi- cations in Partial Differential Equations, 45 (2020), pp. 1088–1117, Annales Henri Poincaré, 24 (2023), pp. 1005–1049.

- **Strichartz estimate:** (on going) With Prof P K Ratnakumar (HRI, Allahabad) we are interested in finding all possible inhomogeneous Strichartz estimate in clas-

sical situation i.e. finding all $(q, r), (\tilde{q}, \tilde{r})$ for which

$$\left\| \int_0^t e^{i(t-\tau)\Delta} g(\tau) d\tau \right\|_{L_t^q L_x^r} \leq C \|g\|_{L_t^{\tilde{q}'} L_x^{\tilde{r}'}}, \quad \forall g \in L_t^{\tilde{q}'} L_x^{\tilde{r}'}$$

is satisfied. Only partial results are known in this direction see work of Strichartz (Duke Math J 44, no 3, 705–714, 1977), Vilela (Trans Amer Math Soc 359, no. 5, 2123–2136, 2007) etc.

## Publications:

1. D. G. Bhimani and S. Haque, *Norm inflation with infinite loss of regularity at general initial data for nonlinear wave equations in Wiener amalgam and Fourier amalgam spaces*, Nonlinear Analysis, 223 (2022), 113076.

2. D. G. Bhimani, H. Hajaiej, S. Haque and T. Luo, *A sharp Gagliardo-Nirenberg inequality and its application to fractional problems with inhomogeneous nonlinearity*, Evolution Equation and Control Theory, 12 (2023), No. 1, pp. 362–390.

## Preprints:

1. D. G. Bhimani, S. Haque and M. Ikeda, *Well-posedness of the Hardy-Hénon parabolic equation with an inverse square potential*, (under preparation).

2. D. G. Bhimani, H. Hajaiej and S. Haque, *The mixed fractional Hartree equations in Fourier amalgam and modulation spaces*, arXiv:2302.10683 (submitted).

3. D. G. Bhimani, S. Haque, *On the inhomogeneous heat equation with inverse square potential*, arXiv:2210.09910, (under review).

## Conference/Workshops Attended:

1.

## Visits to other Institutes:

1.

## Invited Lectures/Seminars:

1. *Well and ill-posedness of nonlinear evolution equations*, Extension talk, Harish-Chandra Research Institute, Allahabad (Prayagraj), India, January 2023.

## Other Activities:

1. Selected as Inspire faculty fellow by DST, India.

2. Nominated as Fulbright-Nehru postdoctoral research fellow by Fulbright-India.

# Muna Naik

## Research Summary:

1. Let $X$ be a rank one Riemannian symmetric space of non-compact type and $\mu$ be a radial measure on X. We characterize eigenfunctions of the Laplace–Beltrami operator $\Delta$ from the convolution equation $f * \mu = f$, which generalizes the classical question: "Is a $\mu$-harmonic function harmonic?" Two original sources of this question are perhaps Furstenberg's characterization of harmonic functions and Delsarte's two radius theorem.

2. Let $X = G/K$ be a symmetric space of non-compact type. We characterize joint eigenfunctions of G-invariant differential operators on X through an asymptotic generalized mean value property.

## Preprints:

1. M. Naik, R. P. Sarkar: *Furstenberg's characterization of harmonic functions and Delsarte's two radius theorem, some generalization for eigenfunctions* , Preparation.

2. M. Naik, R. P. Sarkar: *Asymptotic mean value property for joint eigenfunctions of G-invariant differential operator"*, Preparation.

## Invited Lectures/Seminars:

1. Delivered five lectures at AIS (Lie groups and Lie algebras) at Indian Institute of Science, Bangalore (19 Jun, 2023– 8 Jul, 2023).

# Aprameyo Pal

## Research Summary:

The role of the multi-variable $(\varphi, \Gamma)$–modules is at the center stage of $p$-adic Langlands correspondence of higher rank reductive groups (e.g. $GL_n$) after the recent progress in the conjectural categorical $p$-adic Lnglands programme by Emerton-Gee and Breuil, Schraen et al. We have already extended the classical results of Cherbonnier-Colmez about the multi-variable $(\varphi, \Gamma)$–modules being overconvergent. This has now also been proved by Carter-kedlaya-Zabradi via geometric methods using Drinfeld's lemma for diamonds. The multi-variable $(\varphi, \Gamma)$–modules then becomes connected with the emerging picture in $p$-adic geometry as multi-variable $(\varphi, \Gamma)$–modules can be thought as equivariant vector bundles on the product of Fargues-Fontaine curves. Now, Brinon-Chiarellotto-Mazzari have used our results and defined the multivariable de-Rham rings generalizing Fontaine. Along with Gergely Zabradi, we are using (analytic) Iwasawa cohomology to define Bloch-Kato exponential map in the multi-variable setup.

The Bloch-Kato exponential map is an important ingredient that has a lot of applications in Iwasawa theory including the construction of $p$-adic $L$-functions, reciprocity laws, and $\epsilon$-conjectures. Along with Matthias Flach, we have initiated a study to redefine the Bloch-Kato exponential map using recently developed Prismatic cohomology by Bhatt-Scholze. The idea is that using the integral refinement we should get finer information in Bloch-Kato exponential maps, eventually Iwasawa theory.

Integral refinements are at the heart of the Iwasawa theoretic treatments of motives over number fields and function fields. Even though, over function fields, there are certain results, they break down in the complicated $\ell = p$ case. This is precisely due to the absence of a good integral $p$-adic cohomology theory. Rigid cohomology is a nice (Weil) cohomology theory, which is a good candidate. Unfortunately, the cohomology uses rational coefficients which are not enough for Iwasawa theoretic applications. Along with Tomoyuki Abe, we have initiated a study to overcome this problem.

## Preprints:

1. Multivariable $(\varphi, \Gamma)$-modules and Iwasawa theory, *(with Gergely Zabradi*), Preprint.

## Conference/Workshops Attended:

1. ICTS workshop on "Elliptic curves and Special values of $L$-Functions" , 8-19th August, 2022, at ICTS Bangalore.
2. NCM workshop on "Elliptic Curves, Elliptic Functions and Trancendence", 24th November to 3rd December, 2022 at HRI, Prayagraj.
3. 37th Annual Ramanujan Mathematical Society Conference (RMS 2022), 6-8th December, 2022, at Department of Mathematics, Sri Sivasubramaniya Nadar College of Engineering, Chennai.

## Visits to other Institutes:

1. Visit to ICTS, 8-19th August, 2022.
2. Visit to IPMU, Tokyo to visit Prof. Tomoyuki Abe, from 25th July to 5th August, 2022.
3. Visit to Caltech, Pasadena to visit Prof. Matthias Flach and MSRI, Berkely (Special semester on "Euler systems"), from 1st February to 7th March, 2023.

## Invited Lectures/Seminars:

1. Number theory seminar, Tokyo Technological University, 3rd August, 2022.
2. ICTS workshop on "Elliptic curves and Special values of $L$-Functions", 15th August, 2022.
3. 37th Annual Ramanujan Mathematical Society Conference (RMS 2022), 8th December, 2022.
4. Mathematics colloqium at IIT Kanpur, 12th January, 2023.
5. Number theory seminar, University California Los Angeles, 13th february, 2023.
6. Number theory seminar, Caltech, pasadena, 23rd February, 2023.

## Other Activities:

1. Organized a discussion meeting on "North Indian number theory meeting ($p$-adic aspects)", at HRI, Prayagraj from 23rd - 25th September, 2022.
2. Organized a NCM workshop on "Elliptic Curves, Elliptic Functions and Trancendence", 24th November to 3rd December, 2022 at HRI, Prayagraj with Prof. R. Thangadurai.
3. Gave a course in "Differential Manifolds" for 1st year Ph.D. students from August-December, 2022.
4. Organized an ongoing reading seminar on "Condensed mathematics" with S. Bhamidi and R. Gupta.
5. Participated in some committees involved in administrative duties.

# Gyan Prakash

## Research Summary:

Let $A$ denotes the set consisting of natural numbers $n$ such that $n = x_1^3 + x_2^3 + x_3^3$ for some natural numbers $x_1, x_2, x_3$. The properties of $A$ is not well understood. For an instance one expects that the density of $A$ is positive, but this is unknown and is considered a very difficult problem to prove this. In order to predict the properties of $A$, one tries to define a probabilistic model in which the set consisting of **"pseudo-cubes"** behaves like cubes and one study the properties of those natural numbers which can be written as a sum of three pseudo-cubes. Since the pseudo-cubes behaves like cubes then one conjectures that the cubes will have similar properties. In other words, the probabilistic model provides a heuristic understanding of the properties of $A$. One such probabilistic model is due to Erdös and Renyi. However this model has a defect that it does not account for certain congruence conditions and as a result predicts certain results which we know are false. To remedy this defect a different probabilistic model has been developed by Jean-Marc Deshouillers along with François Hennecart and Bernard Landreau. In this model in a joint work with Jean-Marc Deshouillers, François Hennecart and Bernard Landreau we proved the following result. Given any integer $H \geq 1$, there exists an interval $[n, n + H]$ of length $H$ such that every integer $m \in [n, n + H]$ such that $m$ is not congruent to $\pm 4$ modulo $9$ can be written as a sum of three "**pseudo-cubes**".

## Preprints:

1. Jean-Marc Deshouillers, François Hennecart, Bernard Landreau and Gyan Prakash *Cluster of sum of three pseudo-cubes* (in preparation).

## Other Activities:

1. Taught Analysis 2 course during August-December 2022
2. Taught Complex Analysis in "Summer Programme in Mathematics" (**SPIM**) held at HRI during 27th June 2022-16th July 2022.

# N. Raghavendra

## Research Summary:

I have continued my work on type theory and formalisation. I have also been involved in discussions about quiver principal bundles with some other members of the algebraic geometry group.

## Other Activities:

1. Taught the graduate course "Topology II" from August to December, 2022.

# D. Surya Ramana

## Research Summary:

My research activity for several years has been on investigating if large but otherwise arbitrary subsets of "interesting subsets" of the natural numbers retain certain properties of these interesting sets. This theme is a mix of combinatorics linked to Ramsey theory and additive representation problems in analytic number theory.

## Invited Lectures/Seminars:

1. Three lectures (online) on "Introduction to Sieves" in a programme of NISER, Bhubaneswar, 20 to 23 February, 2023.

## Other Activities:

1. Taught Algebra - II (August - December 2022), which is largely basic commutative algebra, and is a part of the graduate teaching programme in mathematics of the institute.

2. Supervised project work, as a part of course work, of Ms. Bina Jha and Mr. Swapnil Sanap.

3. Serving as Dean (Administration), HRI from 30 August 2019 and as Acting Registrar, HRI from 1 July 2022. Also served on a number of academic and administrative committees of HRI including the Mathematics Faculty Appointments Committee (as member).

4. Member, Board of the School of Mathematics, Statistics and Computational, Central University of Rajasthan.

5. Member and Co-convenor, Board of Studies in Mathematical Sciences, HBNI.

6. Member, Library Committee, National Board for Higher Mathematics (NBHM).

## Jishnu Ray

## Research Summary:

Algebraic Number Theory began by finding integer solutions to algebraic equations; perhaps its most famous problem is Fermat's Last Theorem, the problem of showing there are no non-zero integers $x, y, z, n$ satisfying $x^n + y^n = z^n$ if $n \geq 3$. It has long been understood that it is necessary to also examine the solutions where $x, y, z$ range over number systems beyond the natural numbers, and eventually the focus turned to the number systems themselves. A key tool in the study of algebraic number fields is Iwasawa algebras, originally constructed by Iwasawa in the 1960s to study the "class groups" of those fields, but since appearing in varied settings such as a Lazard's work on $p$-adic Lie groups and Fontaine's work on local Galois representations. Iwasawa algebras come up naturally in Iwasawa theory which are used to study the arithmetic of elliptic curves over any number field and its Selmer group. There are various versions of the Iwasawa Main Conjecture over appropriate arithmetic towers connecting some variant of the Selmer group on the arithmetic side to some $p$-adic $L$-function on the analytic side. Therefore, it is a bridge between arithmetic and analysis. The Iwasawa $\lambda$- and $\mu$-invariants describe the algebraic nature of the Selmer group.

Jointly with Aranya Lahiri, we generalized my earlier results on explicit presentation of Iwasawa algebras. Using Lazard's techniques and the theory of $p$-saturated compact $p$-adic Lie groups we found an explicit presentation of the Iwasawa algebra for the pro-$p$ Iwahori subgroup of any general split reductive group over $\mathbb{Z}_p$. Earlier I have shown such a result for $SL(n)$ (Forum Mathematicum, 32(2):319–338, 2020) but then an explicit description of a $p$-ordered basis was missing for general groups which prevented me to generalize for reductive groups other than $SL(n)$. In the preprint with Lahiri, we address this problem and give a more conceptual proof using root datum and techniques from Lie theory.

Jointly with Filippo Nuccio and Tadashi Ochiai we constructed a formal model for Coleman families of non-ordinary modular forms with finite slope and applied it to generalize a result of Somnath Jha and Sujatha Ramdorai. We have shown that the triviality of the $\mu$-invariant of the dual fine Selmer group stays the same for all classical modular forms in a Coleman family. Under the assumption that the $\mu$-invariant is zero, the $\lambda$-invariants stay constant for all but finitely many classical modular forms in a given (branch of a) Coleman family.

For supersingular abelian varieties over $\mathbb{Q}$, under certain hypothesis, using the theory of Coleman maps of Buyukboduk—Lei, I defined the signed Mordell-Weil group and the signed Tate-Shafarevich group; these generalize the plus and minus variants of the Mordell-Weil group and the plus and minus Tate-Shafarevich group defined by Antonio Lei. These groups can be used to study the signed Selmer groups. Furthermore, I have computed the asymptotic growth of these newly defined groups along the cyclotomic tower of $\mathbb{Q}$ and compared it with the existing growth results for the classical Mordell-Weil group and the classical Tate-Shafarevich group.

## Publications:

1. Filippo Alberto Edoardo Nuccio Mortarino Majno Di Capriglio, Tadashi Ochiai, Jishnu Ray, *A formal model of Coleman families and applications to Iwasawa invariants*, to appear in Annales mathématiques du Québec, arxiv: 2303.14940.

## Preprints:

1. Aranya Lahiri and Jishnu Ray, *Presentation of an Iwasawa algebra: The pro-$p$ Iwahori of reductive groups*, arxiv: 2301.00458.

2. Jishnu Ray, *Asymptotic growth of the signed Tate-Shafarevich groups for supersingular abelian varieties*, arxiv: 2304.13452.

## Visits to other Institutes:

1. TCG CREST, Kolkata, India, January 2023.

## Other Activities:

1. Present in HRI colloquiums and FGC-HRI-IPM Number Theory Seminar (virtual), 2023.

2. Refereed papers in Transactions of American Mathematical Society, Israel Journal of Mathematics.

3. Currently mentoring Debojyoti Hatui for Project II (2nd semester) at HRI.

4. Served as a member of the postdoc selection meeting held on 22nd March 2023 at HRI.

5. Served as a member of the Oral General Comprehensive Examination for math students at HRI during the 27th and 28th of March 2023.

# Hemangi Madhusudan Shah

## Research Summary:

H. Shah and S. Verma, *An isoperimetric inequality for the harmonic mean of Steklov eigenvalues in rank one symmetric spaces*, arXiv:2302.05854 [math.DG]. : In this note, an isoperimetric inequality for the harmonic mean of lower order Steklov eigenvalues is proved on bounded domains in noncompact rank-1 symmetric spaces. This work extends earlier results proved for bounded domains in Euclidean space and Hyperbolic space, respectively.

A. Sahu, R. Gangopadhyay, H. Shah and B. Tiwari, *The Isoperimetric Problem In Randers Poincaré Disc*, arXiv:2204.00760 [math.DG]. : It is known that a simply connected Riemann surface satisfies the isoperimetric equality if and only if it has constant Gaussian curvature. In this article, we show that Randers Poincaré disc satisfies isoperimetric equality with respect to different volume forms. These metric do not necessarily have constant (negative) flag curvature. Thus we show that the Riemannian result could not be extended to the corresponding Finslerian case.

A. Bhattacharya, P. Ghosh, P. Naeem and H. Shah,*Some solitons on homogeneous almost $\alpha$- cosymplectic 3-manifolds and harmonic manifolds*,
submitted, arxiv:2301.02430v1[math.GM]. : In this paper, we investigate the nature of Einstein solitons, whether it is steady, shrinking or expanding on almost $\alpha$-cosymplectic 3-manifolds. We also prove that a simply connected homogeneous almost $\alpha$-cosymplectic 3-manifold, admitting a contact Einstein soliton, is an unimodular semidirect product Lie group. Finally, we show that a harmonic manifold admits a non-trivial Ricci soliton if and only if it is flat. Thus we show that rank one symmetric spaces of compact as well as non-compact type are stable under a Ricci soliton. In particular, we obtain a strengthening of Theorem 1 and Theorem 2 of R. Balmer.

## Publications:

1. Hemangi Shah and Ebstam Taha, *Busemann functions in asymptotically harmonic Finsler manifold*, J. Math. Phys. Anal. Geom. **18** (2022), 546–561.

2. Randip Gangopadhyay, Ashok Kumar, Hemangi Madhusudan Shah, Bankteshwar Tiwari, *On minimal surfaces of rotations immersed in deformed hyperbolic Kropina space*, Results Math. **77** (2022), Paper No. 202, 18 pages.

## Preprints: Submitted

1. A. Sahu, R. Gangopadhyay, H. Shah and B. Tiwari, *The Isoperimetric Problem In Randers Planes*, arxiv2204.00760[math DG].

2. A. Bhattacharya, P. Ghosh, P. Naeem and H. Shah,*Some solitons on homogeneous almost $\alpha$- cosymplectic 3-manifolds and harmonic manifolds*, submitted, arxiv:2301.02430v1[math.GM

3. A. Kumar, H. Shah and B. Tiwari, *Isometric models of the Funk disc and the Busemann function*.

4. A. Sahu, R. Gangopadhyay, H. Shah and B. Tiwari, *The Isoperimetric Problem In Randers Poincaré Disc*, arXiv:2204.00760 [math.DG].

5. P. Ghosh, H. Shah and A. Bhattacharya, *Nature of Some Solitons on Almost coKähler Manifolds and Asymptotically Harmonic Manifolds*, arXiv:2305.06597[math.DG].

6. H. Shah and S. Verma, An isoperimetric inequality for the harmonic mean of Steklov eigenvalues in rank one symmetric spaces, arXiv:2302.05854 [math.DG].

## Conference/Workshops Attended:

1. Trends in Calculus of Variation and PDES, Virtual Conference, May 2022, UK.

## Visits to other Institutes:

1. Dec 11 2022 - Dec 15 2022, Visit to Jadavpur University, Calcutta.

## Visit to HRI

1. Ashok Kumar, Ph. D. Student from Banaras Hindu University, visited at HRI from September 2022 - April 2023 for his Thesis work. I am his coguide.

## HONOURS

1. Invited to Refer a manuscript for Kyungpook Mathematical Journal, March 2023.

2. Invited to Refer a manuscript for Proceedings of Mathematical Sciences, March 2023.

## MEMBERSHIP

- Member of Calcutta Mathematical Society, March 2023.
- Nominated for the membership of Asian - Oceanian Women in Mathematics, July 2022.
- Member of American Mathematical Society since 2018.
- Member of Indian Mathematical Society since 2018.
- Member of Homi Bhabha National Institute since 2013.

## Invited Lectures/Seminars:

1. **Invited to speak at conference on Einstein and Harmonic manifolds at Sungkyunkwan University, Suwon, Korea, January,** 2023**.**
2. **Invited virtual seminar on geometry with symmetries organised by the Dartmouth College, US, the University of Queensland, Brisbane, Australia, and University of Bahia Blanca, Argentina, March** 8**-**2023.
3. **Invited speaker at Indian Women and Mathematics Annual Conference** $2022-2023$ **held at IISER, Pune during December** $27-29, 2022$**.**
4. **Invited speaker at the international CIMPA school on Geometric Structures on Surfaces, Moduli Spaces and Dynamics during** $12-22$ **December** 2022**, BHU, Varanasi**.
5. **Invited Suddhodan Ghosh Memorial Talk in the International Conference on Modern Trends in Mathematical Modelling, Analysis and Algebra,** $8-10$**, December 2022, Calcutta Mathematical Society.**

## DOCTORAL MENTORSHIP

1. Ashok Kumar, Ph. D. Student from Banaras Hindu University, Co-supervisor of his Thesis. **He will be submitting his Thesis by December 2023**.
2. Arti Sahu, Ph. D. Student from Banaras Hindu University, Co-supervisor of her Thesis.
3. M. Aquib, Supervising his Thesis from 2022, HRI.
4. Arkadeepta Roy, Research Project from 2022, HRI.
5. Shubham Yadav, Research Project from 2023, HRI.
6. Paritosh Ghosh, Ph. D. Student from Jadhavpur University, Kolkatta, Co-supervisor of his Thesis from 2021.

## POST-DOCTORAL MENTORSHIP

1. Kiran Meena, post-doctoral at HRI from 2023.
2. P. Naeem, post-doc at Jadavpur University, Calcutta working on soliton geometry, 2022−.
3. Ranadip Gangopadhyay, post-doc at IISER Mohali, woring on isoperimetric problems in Finsler Geometry, 2021−.

## MEMBERSHIP

1. Member of Calcutta Mathematical Society, March 2023.

2. Nominated for the membership of Asian - Oceanian Women in Mathematics, July 2022.
3. Member of American Mathematical Society since 2018.
4. Member of Indian Mathematical Society since 2018.

## Other Activities: Published Mathematical reviews for Mathscinet

1. MR4424263, MR4430589, MR4415734,
2. MR4362904, MR4385782, MR4354982,
3. MR4310114, MR4323331, MR4249875,
4. MR4478476, MR4472956, MR4504627,

## COMMITTEES AT HRI

1. Member of the syllabus review committee of the courses on Topology and Differential manifolds, $2022 - 2023$.

2. Member of the Foreign Travel Committee, $2020$-present.

## Teaching At Harish-Chandra Research Institute, Allahabad, India

1. Topology I (Graduate), August - December $2022$.

2. Delivered a seminar on, *Participation in Scientific Activities*, HRI, Graduate Students, 16th May 2022, Research Methodology Course Module C.

# Ravindranathan Thangadurai

## Research Summary:

In 1919, G. Polya proved that the given algebraic number $\alpha$ is an algebraic integer if and only if $Tr(\alpha^n) \in \mathbb{Z}$. Then Lame posed a question that if a non-zero algebraic number $\alpha$ satisfies $Tr(\alpha^m) \in \mathbb{Z}\backslash\{0\}$ for infinitely many natural numbers $m$, is it true that $\alpha$ is an algebraic integer?. This question was solved by Corvaja and Zannier in 2004 and generalized by Philippon and Rath in 2021. We looked into the following problem. *Let $\alpha_1, \ldots, \alpha_n, \lambda_1, \ldots, \lambda_n$ be non-zero algebraic numbers. Does $Tr(\lambda_1\alpha_1^m + \cdots + \lambda_n\alpha_n^m) \in \mathbb{Z}\backslash\{0\}$ for infinitely many natural number $m$ imply that each $\alpha_i$ is an algebraic integer?* One can obtain a counter-example to this question. Thus, we needed to understand that if the linear recurrence sequence $\lambda_1\alpha_1^m + \cdots + \lambda_n\alpha_n^m$ are algebraic integers for infinitely many natural numbers $m$, then what kind of exhaustive cases arises. Precisely we found what cases arises and we obtain many results in this directions. We also could prove a finite version in the spirit of De Smit when $n = 2$. This is a joint work with A. Bharatwaj, A. Pal and V. Kumar.

In another work, along with A. Tripathi, we are studying the $\mathbb{Q}$-linearly independence of the following values of the infinite series. More generally, we are exploring the $\mathbb{Q}$-linearly independence of

$$1, \sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mq+1]}, \sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mq+2]}, \ldots, \sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mq]}$$

where $q$ is a prime number and $[1, 2, \ldots, n]$ denotes the least common multiple of the numbers $1, 2, \ldots, n$?. We have solved this question when $q = 2$ and $q = 3$. Moreover, we have also proved that the value of the series

$$\sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mn+r]}$$

is an irrational number for any natural number $n$ and $r \in \{0, 1, 2, \ldots, n-1\}$. We are looking at the possibility of proving their transcendence nature.

## Publications:


1. V. Kumar and R. Thangadurai, *On simultaneous approximation of algebraic numbers*, Mathematika **68** (2022), no. 4, 1153-1175.

2. M. Makeshwari, V. P. Ramesh and R. Thangadurai, *A necessary and sufficient condition for 2 to be a primitive root of $2p+1$*, Math. Student **89** (2020), no. 3-4, 171-176.


## Preprints:


1. A. Bharadwaj, A. Pal, V. Kumar and R. Thangadurai, *Sufficient conditions for classifying algebraic integers*, Preprint, (2022).

2. A. Tripathi and R. Thangadurai, *On the irrationality of certain infinite series*, In preparation, (2023).

## Conference/Workshops Attended:

1. Discussion Meeting DiMBS - 2022, HBNI, BARC, Mumbai, 6-8, April 2022
2. IISER TVM Frontier Symposium-Mathematics 2022, IISER Thiruvananthapuram, 8-10, April 2022.
3. NCM Workshop on "Elliptic curves, Elliptic functions and Transcendence" at HRI, Prayagraj, 24 November - 03 December 2022.
4. Workshop and a conference on Number Theory at NISER, Bhubaneswar during 20-25, February 2023.
5. Diophantine Day at Indian Statistical Institute, Delhi on 09 March 2023.

## Visits to other Institutes:

1. HBNI, BARC, Mumbai 6-8, April 2022.
2. IISER Thiruvananthapuram, 8-10, April 2022.
3. RKMVERI, Kolkata, 14-20, October 2022.
4. IIT Delhi, Delhi, 17-27, January 2023.
5. NISER, Bhubaneswar, 12-26, February 2023.
6. Indian Statistical Institute, Delhi, 7-13, March 2023.

## Invited Lectures/Seminars:

1. Delivered a Mathematics Colloquium on "the trace of powers of algebraic numbers" at Indian Statistical Institute, Delhi on 27th April 2022.
2. Delivered a talk on "Challenges in Number Theory" AKAM, HBNI, Mumbai on 23rd August, 2022.
3. Delivered a short course on "Introduction to Modular forms and Rational approximation" in NCM Workshop on "Elliptic curves, Elliptic functions and Transcendence" at HRI, Prayagraj during 24-27, November 2022.
4. Delivered a talk on National Mathematics Day at IIT Jammu, 22nd December 2022.
5. Delivered a 9-lecture course on Transcendental Number Theory at IIT Delhi during 17-27, January 2023.
6. Delivered a talk on "Primitive Element Theorem" at NISER, Bhubaneswar on 18th February 2023.
7. Delivered a talk on "Trace of Powers of Algebraic Numbers" at ISI Delhi on 9th March 2023.

## Other Activities:

1. Guided a master thesis student, Ms. Sanskruti Karnawat, CBS Mumbai on Elliptic Curves during August 2021 - July 2022.

2. Guided a master thesis student, Mr. Vaibhav Gupta, NIT Surat on "Hilbert Irreducibility Theorem" during December 2022 - April 2023.

3. Co-guide of a Ph.D student, Mr. Debashish Karmakar, HRI during August 2015-December 2022.

4. Organized a one-day meet on "Algebra and Number Theory" at HRI, Prayagraj on 10th September 2022.

5. Organized NCM Workshop on 'Elliptic Curves, Elliptic Functions and Transcendence" at HRI, Prayagraj during 24, November - 03, December 2022.

6. Served as a Nodal Officer at HRI for HBNI during this academic year.

# Manoj Kumar

## Research Summary:

An algebraic structure $(E, +, \circ)$ is said to be a skew left brace if $(E, +)$ and $(E, \circ)$ are groups and, for all $a, b, c \in E$, the following compatibility condition holds:

$$a \circ (b + c) = (a \circ b) - a + (a \circ c).$$

A skew left brace is called a left brace if $(E, +)$ is an abelian group. This concept was introduced by Guarnieri and Vendramin in connection with set theoretic solutions of the quantum Yang-Baxter equation. During the period under consideration, I, along with my student Arpan Kanrar, studies several fundamental research papers on solutions of the Yang-Baxter equation, skew braces and their connections. As a result, Arpan got some results, which he will mention in his report.

## Publications:

1. Valeriy G. Bardakov, Mikhail V. Neshchadim and Manoj K. Yadav, *Symmetric skew braces and brace systems*, Forum Mathematicum **35**, 713-738, (2023).
2. Rahul Kaushik and Manoj K. Yadav, *Commutators in groups of order $p^7$*, J. Algebra Appl. **22**, 2350158, 24 pp., (2023).

## Conference/Workshops Attended:

1. *The algebra of the Yang-Baxter equation*, Poland (Virtual), July, 2022.
2. *Annual Conference of the Ramanujan Maths. Soc.*, India, Dec, 2022.
3. *Conference on group theory and related topics*, India, February - March, 2023.
4. *Knots, Algebra and Geometry*, Russia (Virtual), March, 2023.
5. *International Conference on Mathematical Sciences and Applications*, India, March, 2023.

## Visits to other Institutes:

1. IISER, Pune, India, October, 2022.
2. I.M.Sc., Chennai, India, December, 2022.

## Invited Lectures/Seminars:

1. *Construction of skew braces*, Mathematics Seminar, IISER, Pune, October, 2022.
2. *Skew braces and solutions of the Yang-Baxter equation*, Workshop on group theory and related areas, IIIT, Prayagraj, Virtual, November, 2022.
3. *Skew left braces and solutions of Yang-Baxter equation*, 37th annual conference of the RMS, SSN College of Engineering , Chennai, December, 2022.

4. *Construction of skew braces*, Mathematics Seminar, IMSc, Chennai, December, 2022.

5. *Solutions of YBE and related algebraic structures*, Conference on group theory and related topics, NISER, Bhubaneshwar, February - March, 2023 (delivered two lectures).

6. *Skew braces*, Knots, Algebra and Geometry, Sobolev Institute of Mathematics, Novosibirsk, Virtual, March, 2023.

7. *Skew braces and set-solutions of the Yang-Baxter equation*, International Conference on Mathematical Science and Application, BR Ambedkar University, Agra, March, 2023

8. *Skew braces and set-solutions of the Yang-Baxter equation*, International webinar on advances in mathematical sciences, West Bengal State University, Kolkata, Virtual, March, 2023.

## Other Activities:

1. Taught Algebra II course at HRI during January - May 2023.

2. Served as an editorial board member of Proc. Math. Soc., IASc.

3. Refereed research papers for national and international journals.

4. Instructed Susanta Mondal for his first and second semester graduate Project Course at HRI.

5. Served HRI on several committees.

6. Served as Dean Academic, HRI.

7. Chaired sessions in 'International conference on evaluation in pure and applied mathematics' held at AKAL Univ. Bathinda, November 2022, and in 'International webinar on advances in mathematical sciences' held at West Bengal State University, Kolkata, March 2023.

# Rahul Gupta

## Research Summary:

I joined Harish-Chandra Institute on January 10, 2023. For January–March 2023, I was working on my research project "$p$-Duality over local fields". This is a joint project with Prof. Amalendu Krishna who visited me at HRI for the period from February 20 until February 25, 2023. This project is about finding the dual of the abelianized étale fundamental group $\pi_1^{\mathrm{ab}}(X)/p^m$ for a quasi-projective smooth variety over a local field $k$. We made significant progress in the project during the said period.

The above project is the subproject of a much bigger project "ramified class field theory over higher local fields" that is a joint project with Prof. Amalendu Krishna and Jitendra Rathore. Significant progress in this project was made during the visit of J. Rathore for the period from March 19 until April 1, 2023.

## Other Activities:

1. I arranged visits and seminars of Prof. Amalendu Krishna from February 20 until February 25, 2023, and that of Jitendra Rathore from March 19 until April 1, 2023.

2. I co-organized the seminar series "Arithmetic and Algebraic Geometry Seminar" that started on February 22, 2023.

# Ratnadeep Acharya

## Research Summary:

Suppose $f$ is a fixed holomorphic cusp form of weight $k$ for the full modular group $SL(2,\mathbb{Z})$ and $\lambda_f(n)$ denote its 'normalized' $n$-th Fourier coefficient. We further assume that $f$ is a Hecke eigenform. Then under the above normalization, the Ramanujan Conjecture predicts that $\lambda_f(p) \in [-2,2]$ for all prime $p$, which is known due to the works of Deligne. Moreover, the Sato - Tate Conjecture, which is now a theorem of Clozel, Harris, Shepherd-Barron and Taylor, governs the statistical behaviour of the sequence $\{\lambda_f(n) : n \in \mathbb{N}\}$ for a newform $f$ which is not of CM type. It implies that if $I \subset [-2,2]$ of positive Lebesgue measure, then $\mathbb{P}_{f,I} := \{p \in \mathbb{P} : \lambda_f(p) \in I\}$ has positive natural density. More precisely, for such an $I$, there exists an absolute constant $c(I) > 0$ such that

$$\#\{p \leq N; p \in \mathbb{P}_{f,I}\} = c(I)\pi(N) + E_f(N,I), \quad \text{where } E_f(N,I) = o(\pi(N)). \tag{1}$$

Consequently, $\mathbb{P}_{f,I}$ is an infinite subset of primes. We now recall a classical problem in Number Theory and mention its developments briefly. Next, motivated by the Sato-Tate Conjecture and its consequences, we discuss an analogue of this problem, I have studied during my tenure at HRI.

Let $p_n$ denote the $n$-th prime in ascending order. Goldston, Pintz and Yildrim (G-P-Y) introduced a new method for counting tuple of primes and eventually proved that

$$\liminf_n \frac{p_{n+1} - p_n}{\log p_n} = 0.$$

Later Zhang was successful in exhibiting bounded gaps between consecutive primes. Precisely, he proved

$$\liminf_n (p_{n+1} - p_n) \leq 70000000. \tag{2}$$

Maynard refined the approach of G-P-Y and improved the above result. He established

$$\liminf_n (p_{n+1} - p_n) \leq 600. \tag{3}$$

Recently, due to a more accurate numerical method applied by the Polymath Project, the best known unconditional result in this direction is $\liminf_n (p_{n+1} - p_n) \leq 246$. We observe that Maynard's idea can be extended to answer above type of question for any subset $\mathbb{P}'$ of primes of positive natural density, if $\mathbb{P}'$ is equidistributed over reduced residue classes modulo $q > 1$ in the sense of classical Bombieri-Vinogradov Theorem. Suppose $\mathbb{P}' = \{q_1, q_2, q_3, \cdots\}$ with $q_{n+1} > q_n$ for $n \geq 1$. We define $G(\mathbb{P}') = \liminf(q_{n+1} - q_n)$. We establish finiteness of $G(\mathbb{P}')$ for some $\mathbb{P}'$ of particular interest.

Let us consider $\mathbb{P}' = \mathbb{P}_{f,I}$ for the aforementioned purpose. Wong has studied above type of question for $I = [-2,0) \cup (0,2]$, which is of full Lebesgue measure and consequently, $\mathbb{P}_f(I) = \{p : \lambda_f(p) \neq 0\}$ has natural density 1. He exhibited the existence of a positive absolute constant $C$, independent of the form $f$, such that there exists infinitely many pairs $(p,q)$ of distinct primes satisfying

$$|p - q| \leq C \text{ and } \lambda_f(p)\lambda_f(q) \neq 0. \tag{4}$$

Subject to the Lehmer's Conjecture, which tells us that $\lambda_f(p) \neq 0$ for all prime $p$, (4) follows immediately from (2) or (3). We now state our main result. We have $G(\mathbb{P}_{f,I}) < \infty$ and explicitly computable in terms of $I$, whenever $I \subset [-2,2]$ lies in any of the following classes:

1. $(\alpha, 2]$ for $\alpha < 1/2$,
2. $[-2, \alpha)$, for $\alpha > -1/2$,
3. $(-\alpha, \alpha)$ for $|\alpha| > 1$ and
4. $[-2, -\alpha) \cup (\alpha, 2]$ for $|\alpha| < 1$.

One might wonder why $I \subset [-2,2]$ is required to lie in the restricted class listed above. The reason behind such restriction lies in our approach that requires the equidistribution of the sequences $\{\lambda_f(p^j) : p \text{ prime}\}$ over arithmetic progressions for $j \leq 2$. Analogous results for all $j > 2$, which is unknown till date, would remove the restrictions in the aforementioned result. However, one can adopt another method to circumvent this difficulty by producing a reasonable estimate for the error term of the Sato - Tate Conjecture over arithmetic progressions.

## Publications:

1. R. Acharya, S. Drappeau, S. Ganguly & O. Ramare : A Modular Analogue of a Problem of Vinogradov, to appear in The Ramanujan J.

## Preprints:

1. R. Acharya : *On the interface of Sato-Tate Conjecture and small gaps between primes*.
2. R. Acharya : *Rational approximation and certain exponential sums involving Hecke eigenvalues of cusp forms*.
3. R. Acharya & L. Vaishya : *Oscillation of Hecke eigenvalues at integers represented by binary quadratic forms*.

## Conference/Workshops Attended:

1. Discussion meeting "L-functions, Circle-Method and Applications (HYBRID)" (ICTS Bengaluru, June 27– July 01, 2022).
2. Conference in Analytic Number Theory (ISI Kolkata, July 04–05, 2022).

## Visits to other Institutes:

1. IIT Kanpur, November 2022
2. ISI Kolkata, February 2023

## Invited Lectures/Seminars:

1. Title: A modular analogue of a problem of Vinogradov; Discussion meeting "L-functions, Circle-Method and Applications (HYBRID)" (ICTS Bengaluru, June 27– July 01, 2022).

2. Title: On the interface of Sato-Tate Conjecture and small gaps between primes; Conference in Analytic Number Theory (ISI Kolkata, July 04–05, 2022).

3. Title: Maynard's work on small gaps between primes; lecture series delivered at Harish-Chandra Research Institute (May 25–June 01 2023).

# Bappa Bisai

## Research Summary:

Over the past year, my research has primarily focused on the study of operator theory in two popular domains: the symmetrized polydisc $\mathbb{G}_n$ and the tetrablock $\mathbb{E}$, which are defined as follows:

$$\mathbb{G}_n = \left\{ \left( \sum_{1\leq i\leq n} z_i, \sum_{1\leq i<j\leq n} z_i z_j, \ldots, \prod_{i=1}^{n} z_i \right) : |z_i| < 1, i = 1, \ldots, n \right\},$$
$$\mathbb{E} = \left\{ (x_1, x_2, x_3) \in \mathbb{C}^3 \ : \ 1 - zx_1 - wx_2 + zwx_3 \neq 0 \quad \forall z, w \in \overline{\mathbb{D}} \right\}.$$

There exists a direct relationship between the symmetrized polydisc, the tetrablock, and the $\mu$-synthesis problem. The $\mu$-synthesis is a crucial component of robust control theory, which addresses systems consisting of interconnected electronic devices whose outputs are linearly dependent on the inputs.

*A commuting $n$-tuple of operators $(S_1, \ldots, S_{n-1}, P)$ for which the closed symmetrized polydisc $\Gamma_n$ $(= \overline{\mathbb{G}_n})$ is a spectral set is called a $\Gamma_n$-contraction. Similarly, a commuting triple of operators $(A, B, P)$ for which $\overline{\mathbb{E}}$ is a spectral set is called an $\mathbb{E}$-contraction.*

For every $\Gamma_n$-contraction $(S_1, \ldots, S_{n-1}, P)$ there is a unique operator tuple $(A_1, \ldots, A_{n-1})$ on $\mathcal{D}_P$, called the *fundamental operator tuple* or $\mathcal{F}_O$-tuple of $(S_1, \ldots, S_{n-1}, P)$, such that

$$S_i - S_{n-i}^* P = D_P A_i D_P, \quad i = 1, \ldots, n-1,$$

where $D_P = (I - P^*P)^{1/2}$ and $\mathcal{D}_P = \overline{\text{Ran}} D_P$. Also it is known that for every $\mathbb{E}$-contraction $(A, B, P)$ there is a unique operator pair $(F_1,\ F_2)$ on $\mathcal{D}_P$, called the *fundamental operator pair* or $\mathcal{F}_O$-pair of $(A, B, P)$, such that

$$A - B^*P = D_P F_1 D_P, \quad B - A^*P = D_P F_2 D_P.$$

The fundamental operator tuple for a $\Gamma_n$-contraction or the fundamental operator pair for an $\mathbb{E}$-contraction plays a central role in the existing operator theoretic literature on these two domains. Thus, such a tuple or pair is named the fundamental operator tuple or fundamental operator pair, respectively. The task at hand is to determine the specific type of operator tuples that can serve as the $\mathcal{F}_O$-tuples of a $\Gamma_n$-contraction and its adjoint. I have independently resolved this matter by providing necessary and sufficient conditions for both the $\Gamma_n$-contraction and $\mathbb{E}$-contraction cases.

In another project with S. Barik, our focus was on studying dilation theory for a special class of non-commuting tuples called q-commuting operators, which we defined as follows:
*Suppose $q : \{1, \ldots, n\} \times \{1, \ldots, n\} \to \mathbb{T}$ is a function such that $q(i, i) = 1$ and $q(i, j) = \overline{q(j, i)}$ for all $i, j = 1, \ldots, n$. An $n$-tuple of operators $(T_1, \ldots, T_n)$ on a Hilbert space $\mathcal{H}$ is said to be $q$-commuting if $T_iT_j = q(i, j)T_jT_i$ for all $i, j = 1, \ldots, n$. In particular, if $q(i, j) = -1$ for all $i, j = 1, \ldots, n$ and $i \neq j$, we call the tuple as anti-commuting tuple.*

In recent years, the usefulness of operator tuples of this kind in quantum theory has drawn the attention of many researchers. It is worth noting that every $n$-tuple of commuting operators is trivially a $q$-commuting operator tuple, where $q(i,j) = 1$ for all $i, j = 1, \ldots, n$.

Recently, Mallick and Sumesh extended the celebrated result of Ando for pairs of Q-commuting contractions, where Q is a unitary. Their definition of a pair of Q-commuting contractions is as follows:
*Given $Q \in \mathcal{B}(\mathcal{H})$, a pair of bounded operators $(T_1, T_2)$ on $\mathcal{H}$ is said to be $Q$-commuting if one of the following conditions holds:*

$$T_1T_2 = QT_2T_1 \text{ or } T_1T_2 = T_2QT_1 \text{ or } T_1T_2 = T_2T_1Q.$$

They demonstrated that if $(T_1, T_2)$ denotes a pair of contractions on a Hilbert space $\mathcal{H}$ that satisfy the $Q$-commuting relation $T_1T_2 = QT_2T_1$ (or $T_1T_2 = T_2T_1Q$), then there exists a pair of isometries $(V_1, V_2)$ on a larger Hilbert space $\mathcal{K}$, where $V_1V_2 = \widetilde{Q}V_2V_1$ (or $V_1V_2 = V_2V_1\widetilde{Q}$) for some unitary $\widetilde{Q}$ that extends $Q$, and $T_1^{n_1}T_2^{n_2} = P_{\mathcal{H}}V_1^{n_1}V_2^{n_2}|_{\mathcal{H}}$ for all $n_1, n_2 \geq 0$. However, it remains unknown whether a $\widetilde{Q}$-commuting isometric dilation exists for the other case, where $T_1T_2 = T_2QT_1$. Additionally, there is currently no explicit construction of isometric dilations available for a pair of $Q$-commuting contractions in existing literature.

Recently, we have proved by an explicit construction that any pair of $Q$-commuting contractions can always be dilated to a pair of $\widetilde{Q}$-commuting isometries and further into a pair of $\widetilde{Q}$-commuting unitaries. We have extended our work to include a class of $n$-tuples of $q$-commuting contractions, which generalizes the class studied by Brehmer for the commutative setup. We have also determined the isometric dilations of these $n$-tuples and provided an explicit construction. Furthermore, we have demonstrated that the dilating $n$-tuples also belong to the same class. In certain specific cases, our dilation result generalizes the isometric dilation result for a class of commuting tuples that was explored by Curto and Vasilescu.

## Publications:


1. B. Bisai, S. Pal and P. Sahasrabuddhe, *On $q$-commuting co-extensions and $q$-commutant lifting*, Linear Algebra Appl. 658 (2023), 186–205.


## Preprints:


1. S. Barik and B. Bisai, A generalization of Ando's dilation, and isometric dilations for a class of tuples of $q$-commuting contractions, *https://arxiv.org/abs/2210.10617*.

2. B. Bisai, Admissible fundamental operators associated with two domains related to $\mu$-synthesis, *https://arxiv.org/abs/2208.06170*.

## Invited Lectures/Seminars:

1. HRI PDF joining talk. (May 19, 2022)
   **Tittle:** Operator theory on two domains related to $\mu$-synthesis.

# Tarun Dalal

## Research Summary:

**Drinfeld Modular Forms:** In the theory of classical modular forms, the existence of a canonical basis for the space of weakly holomorphic modular forms is well known. In many cases, we know the generating function satisfied by the basis elements. On the other hand, the existence of a canonical basis for the space of weakly holomorphic Drinfeld modular forms is known only for the case $\mathrm{GL}_2(A)$. In Preprint 1, we explicitly constructed a canonical basis for the space of certain weakly holomorphic Drinfeld modular forms for $\Gamma_0(T)$ (resp., for $\Gamma_0^+(T)$) and computed the generating function satisfied by the basis elements. We also gave an explicit expression for the action of the $\Theta$-operator, which depends on the divisor of meromorphic Drinfeld modular forms.

**Rational Points on Modular Curves:** Let $C$ be a non singular smooth curve of genus $g_C > 1$ defined over a number field $K$. A point $P \in C$ is said to be a point of degree $d$ over $K$ if $[K(P) : K] = d$. We consider the set of all points of degree $d$ on $C$ by $\Gamma'_d(C, K) = \cup_{[L:K]=d} C(L)$, where $L \subseteq \overline{K}$ runs over the finite extensions of $K$ and $C(L)$ denotes the set of all $L$-rational points on $C$ (here we fix once and for all $\overline{K}$, an algebraic closure of $K$). We say the curve $C$ has infinitely many points of degree $d$ over $K$ if and only if the set $\Gamma'_d(C, K)$ is infinite. By Falting's theorem, we know that the set $\Gamma'_1(C, L) = C(L)$ is finite for any number field $L$. Now it is natural to ask for a given curve $C$ and $d \geq 2$, whether the set $\Gamma'_d(C, K)$ is finite or not. In Preprint 2, we computed all intermediate modular curves $X_\Delta(N)$ such that the set $\Gamma'_3(X_\Delta(N), \mathbb{Q})$ is infinite.

## Preprints:

1. Tarun Dalal, *A Basis for the space of weakly holomorphic Drinfeld modular forms of level T*, `arXiv:2303.14383`.

2. Tarun Dalal, *Intermediate modular curves with infinitely many cubic points over* $\mathbb{Q}$, `arXiv:2305.07794`.

## Conference/Workshops Attended:

1. *"Elliptic Curves"*, IISER Thiruvananthapuram, India, 3rd April - 15th April, 2023.

# Shamik Das

## Research Summary:

A positive integer $n$ is a congruent number if the rank of the Mordell-Weil group of the *congruent number elliptic curve* $E_n : y^2 = x^3 - n^2x$ is positive. Notably, congruent numbers were first documented in an anonymous manuscript written in Arabic in the 10th century and have since been studied by several mathematicians including Fibonacci, Fermat and Euler.

The problem of providing a complete classification, which is know as congruent number problem, still remains elusive. Due to the difficult nature of finding a complete solution to the congruent number problem, various mathematicians have been interested in constructing infinite family of congruent or non-congruent numbers with prime factors that satisfy certain congruence conditions.

In the twentieth century, an association between congruent numbers and elliptic curves was established. This association led Tunnell to prove a simple criterion for determining whether or not a given positive integer is a congruent number under the assumption of the Birch and Swinnerton-Dyer (BSD) Conjecture. It is natural to ask whether we can associate the property of an integer $n$ being congruent to the class number of some associated quadratic number field or to the continued fraction of certain associated quadratic irrationals.

## A Brief Outline of Work

- We prove a necessary condition for $2p$ to be a congruent number, where $p$ is a prime of the form $8k+1$. We show that a prime $p$ of the form $16k+9$ cannot be a congruent number. Moreover, by employing 2-descent on the congruent number elliptic curve $E_n$, we produce certain divisibility results for the class number of the imaginary quadratic field $\mathbb{Q}(\sqrt{-p})$ and $\mathbb{Q}(\sqrt{-2p})$ when $p$ is a congruent prime. Our results have been accepted for publication in *Journal of Pure and Applied Algebra*, 2022.

- Tunnell and Kazalicki investigated the 2-part of class number of an quadratic imaginary field $\mathbb{Q}(\sqrt{-p})$ where $p$ is congruent prime number equivalent to $1$ modulo $8$ by studying congruence between certain half-integral weight modular forms. Motivated by their work,

    1. we establish a congruence relation modulo $16$ between 2-part of class numbers for both real and complex quadratic field $\mathbb{Q}(\sqrt{\pm pq})$, where $p, q$ are distinct primes satisfying $p \equiv q \equiv 5 \pmod 8$. Our result is based on certain assumption on the 2-part of Shafarevich-Tate group of the $E_{pq}$. The assumption holds if the Selmer Conjecure or the Parity Conjecture is valid for $E_{pq}$. These results have been published in *Research in Number Theory*, 2022)
    2. we prove a divisibility result for the class number of $\mathbb{Q}(\sqrt{-pq})$, where $p$ and $q$ are distinct primes satisfying $(p, q) \equiv (5, 7) \pmod 8$ and $pq$ is a congruent number. Rather than modular forms of half-integral weight, we exploit the method of complete 2-descent. Unlike the previous result mentioned above, our proof does not rely on any assumption. (communicated).

- Steuding and Komatsu considered the continued fraction expansion of some special type of irrational number (such as $\sqrt{n^2+1}$ or $\sqrt{n^2+2}$), whose limit is related to rational right triangles of area close to some positive number. Keeping that perspective in mind, we have studied the period of the regular continued fraction of certain quadratic irrationals $\sqrt{n}$ though we have not yet been able to link our findings to the question of $n$ being congruent or not. We have obtained results concerning the period of the regular continued fraction of $\sqrt{pq}$ where $p<q$ are two primes congruent to $3$ modulo $4$. We prove that the length of the period is divisible by $4$ when $q$ is a quadratic non-residue modulo $p$ and is of the form $4k+2$ when $q$ is a quadratic residue modulo $p$. We further examine the parity of the the central term in the palindromic part of the period of $\sqrt{pq}$ (published in *Acta Arithmetica, 2020*).

- The notion of $\theta$-congruent number is a generalization of congruent number, where one considers the area of a triangle with all possible angles $\theta$ such that $\cos\theta$ is rational rather than just $\theta=\frac{\pi}{2}$. Inspired by the work of Tomasz over some real number field, we prove a criterion for a natural number to be a $\theta$-congruent number over certain classes of real number fields (published in *Bulletin of Australian Mathematical Society, 2021*).

- We have constructed infinite families of odd non-congruent numbers with arbitrarily many pairs of prime factors satisfying certain congruence conditions by employing the method of complete $2$-decent (published in *Integers, 2020*). We have also constructed families of non-congruent highly composite numbers, each containing infinitely many non-congruent numbers with arbitrary many pairs (Published in *Rocky Mountain Journal of Mathematics*, 2022)and triples of prime factors (accepted in *Kyushu Journal of Mathematics*, 2023) by considering Monsky's matrices. (Published in *Rocky Mountain Journal of Mathematics*, 2022).

- Apart from my thesis work under Prof. A. Saikia, I have also collaborated on a research problem concerning $\tau$-congruent numbers. A $\tau$-congruent number, another generalization of classical congruent number, is a natural number that appears as the area of Heron triangle. For a given prime $p \not\equiv 1 \pmod 8$ such that $p^2+1=2q$ for a prime $q$, we look into the possibility of the existence of the triangles with rational sides with $p$ as the area and $\frac{1}{p}$ as $\tau=\tan\frac{\theta}{2}$ for one of the angles $\theta$ (accepted in *Periodica Mathematica Hungarica*, 2022).

- I am also working independently on a few projects to examine the $2$-part of class number of $\mathbb{Q}(\sqrt{\pm n})$, where $n$ is a square-free congruent number having at most three prime factors under certain restrictions. I am currently focusing on the following cases:

  1. $n=pq$, where $(p,q)\equiv(1,3) \pmod 8$ with $p$ is a quadratic residue modulo $q$ and $n$ is a congruent number (preprint).
  2. $n=pq$ or $2pq$, where $p\equiv q\equiv 1 \pmod 8$ and $n$ is a congruent number (preprint).

## Publications:

1. Das, S. and Saikia, A.: *A Necessary Condition for $p$ and $2p$ to be congruent for a prime $p \equiv 1 \pmod 8$*, **Journal of Pure and Applied Algebra**, 2022.
2. Das, S. and Saikia, A.: *On the 2-part of the class number of $\mathbb{Q}(\sqrt{\pm D})$ for a congruent number $D$*, **Research in Number Theory**, volume 8, page 78, 2022.
3. Das, S. and Saikia, A.: *Families of highly composite non-congruent numbers*, accepted in **Kyushu Journal of Mathematics**.

## Preprints:

1. Shamik Das, *Necessary Condition for a Congruent Number of the form $pq$, where $p \equiv 1, q \equiv 3 \pmod 8$ are primes*, preprint.
2. Shamik Das, *Sufficient Condition for a Non-congruent Number of the form $pq$, where $p \equiv q \equiv 1 \pmod 8$* are primes, preprint.
3. Das, S., Chakraborty D. and Saikia, A.: *On the continued fraction of $\sqrt{2p}$*, preprint.

## Conference/Workshops Attended:

1. Elliptic Curves, NCMW, IISER Trivandrum, 2023;
2. Number Theory Meet, IIT Kanpur, 2023;
3. Jacobi form, NCMW, IIT Guwahati, 2022;
4. RMS Meet, SSNCE, Chennai, 2022;
5. Elliptic Curves, Elliptic Functions and Trancendence, HRI, 2022;
6. Elliptic curves and the special values of L-functions (HYBRID), ICTS, 2022;
7. Leuca2022 Celebrating Claude Levesque's, Damien Roy's and Michel Waldschmidt's birthdays, Italy, 2022.

## Invited Lectures/Seminars:

1. RMS Meet, SSNCE, Chennai, 2022;
2. Leuca2022 Celebrating Claude Levesque's, Damien Roy's, and Michel Waldschmidt's birthdays, Italy, 2022.

## Other Activities:

1. Mathscinet Review

# Amrendra Singh Gill

## Research Summary:

We worked on inducing a new ordering on Virtual knot invariants based on some local operations. For the same, we found some skein relations that can act as potential candidates for relating the original singular diagrams with simpler knot diagrams of less complexity. Using these relations, we defined an invariant to be of order $n$ if its value vanishes for a diagram with more than $n$-singular points computed using the particular relation. We are in the process of characterizing the equivalence among diagrams via the local moves in terms of ordering defined on invariants, i.e., two diagrams are related by moves iff invariants of a particular order agree for the two diagrams.

## Preprints:

1. A. Gill, An ordering induced on Virtual Knot Invariants by local moves.(under preparation)

## Conference/Workshops Attended:

1. 'International conference on knot theory and applications' at Regional Scientific and Educational Mathematical Centre in Tomsk, Russia(online mode) from June 29-July 5, 2022.

2. 'Tangled in Knot Theory' at ICERM Providence RI, USA from May 22-25, 2023.(Virtual Participation)

## Invited Lectures/Seminars:

1. Talk titled 'Variation in Writhes of Virtual knots' delivered in the conference 'Tangled in Knot Theory' organized at ICERM Providence RI, USA from May 22-25, 2023.

# Sohan Ghosh

## Research Summary:

In the late 1950s, Iwasawa formulated an intriguing conjecture about the growth of the $p$-primary part of the ideal class group in the cyclotomic tower of certain number fields. This conjecture is widely referred to as the "Iwasawa's $\mu = 0$ conjecture". Although Ferrero, Washington in 1979 and later Sinnot in 1984 proved this conjecture for abelian number fields, it is open for general number fields.

In 2005, Coates and Sujatha found a surprising connection between Iwasawa's $\mu$ invariant vanishing conjecture and a certain subgroup of the classical Selmer group of an elliptic curve, which they called the "fine Selmer group" of an elliptic curve. In fact, the $p^\infty$-fine Selmer group of an elliptic curve $E$ defined over a number field $F$ has been studied, under various names, throughout in Iwasawa theory and is closely related to the 1st and 2nd Iwasawa cohomology groups.

Our research aims to investigate the properties of the $p^\infty$-fine Selmer group of an elliptic curve over certain compact $p$-adic Lie extensions of global fields. In particular, we investigate the properties of the $p^\infty$-fine Selmer group of an elliptic curve $E$ over function fields of characteristic $p$. In this setting of function fields, we have examined the pseudonullity of $p^\infty$-firne Selmer groups over various $p$-adic Lie extensions of the function field.

## Preprints:

1. Some cases in pseudonullity of fine Selmer groups, https://arxiv.org/abs/2304.00499

## Conference/Workshops Attended:

1. Elliptic curves and the special values OF L-functions (HYBRID), from 08 August 2022 to 19 August 2022 at ICTS, Bangalore.
2. Elliptic Curves, Elliptic Functions and Transcendence, from 24 Nov 2022 to 3 Dec 2022 at HRI.
3. Non-Archimedean Geometry and Eigenvarities, from March 06 2023 to March 17th, 2023 at the University of Heidelberg, Germany.

## Invited Lectures/Seminars:

1. Elliptic Curves, Elliptic Functions and Transcendence, from 24 Nov 2022 to 3 Dec 2022 at HRI. (Topic: Complex Multiplication).

## Samir Kumar Hazra

## Research Summary:

The deformation of O-operators has already been introduced and studied in the setting of Hom-Lie algebras and Hom-Associative algebras. In this context, the Rota-Baxter operators have been deformed while keeping the original product structure as it is. Motivated by this work, the purpose of our work was to study the deformations of relative Rota-Baxter Hom-Lie algebras which are Hom-Lie algebras with a relative Rota-Baxter operator given on it. In this way, we have studied both, the deformations of the algebra structure as well as the Rota-Baxter operator, simultaneously. This has been accomplished by developing a suitable cohomology theory for the relative Rota-Baxter Hom-Lie algebras which turns out to be the correct cohomology which governs the deformations. Such cohomologies are called deformation cohomologies in the literature. Note that the similar deformation cohomology for associative algebras and Lie algebras happened to be the usual Hochschild cohomology and Chevalley-Eilenberg cohomology, respectively. Likewise, for Hom-associative and Hom-Lie algebras, a deformation cohomology theory (generalising Hochschild cohomology and Chevalley-Eilenberg cohomology) had been developed in previous works.

In order to measure the capability of quantum gates, we take various classes of separable states, referred to as "k-separable states", as the input states. For example, in the case of three parties, a set of 3-separable states represent fully separable states, having vanishing genuine and bipartite entanglement while biseparable states which possess bipartite entanglement in some bipartitions are the 2-separable ones. Secondly, the maximum genuine multipartite entanglement (GME) as measured by the generalised geometric measure (GGM) of the resulting states produced by the action of the unitary operator on k-separable states is employed to determine the entangling power of a unitary operator. We refer to it as genuine multipartite entangling capability of a quantum gate. Note that unlike in a bipartite scenario where input states are also considered to be entangled, all the k-separable input states possess vanishing GME and hence nonvanishing GGM in the outputs after the action of quantum gate ensures the creation of entanglement via that operator. Apart from identifying unitary operators which can create a high amount of GME state, we also classify the unitary operators based on input separable states according to their capability to generate GGM. We determine unitary operators such as diagonal, permutation and Haar uniformly generated unitary operators which indeed provide the benefit of initial entanglement.

## Publications:

1. Satyendra Kumar Mishra, Apurba Das, Samir Kumar Hazra, *Non-abelian extensions of Rota-Baxter Lie algebras and Inducibility of Automorphisms*, Linear Algebra Appl., Vol. 669 (2023), 147–174.

## Preprints:

1. Samir Kumar Hazra, and Aditi Sen(De), *Hierarchies among Genuine Multipartite Entangling Capabilities of Quantum Gates*, arXiv:2302.06574.

## Other Activities:

1. Participated in the outreach program to visit ECC and CMP college on occasion of Azadi Ka Amrit Mahotsav.

2. Delivered a talk on "Fun with numbers" to the students on the occasion of Childrens' Day celebration at HRI.

# Arijit Jana

## Research Summary:

My research interest in the last several years centered around supercongruence problems for truncated hypergeometric series. Motivated by some supercongruence conjectures of Guo, we obtained two closed hypergeometric formulas in $2021$. In the academic year$(2022-23)$, we give new interesting proof of those two results. We establish our first results using the powerful WZ-method designed by Wilf and Zeilberger. The method is based on finding a Wilf-Zeilberger pair (WZ pair) for which one needs to have a preliminary human guess. We establish our second result using the Zeilberger Algorithm.

## Preprints:

1. A. Jana, *Another proof of two results for sums involving certain rising factorials*, Submitted.

## Other Activities:

1. Reviewed one article of Journal of Mathematical Analysis and Applications.

# Kiran Meena

## Research Summary:

During the period of 27 February 2023 to 31 March 2023, we define Clairaut semi-invariant Riemannian map (CSIRM) from a Riemannian manifold to a Kähler manifold with a non-trivial example. We obtain necessary and sufficient conditions for a semi-invariant Riemannian map to be CSIRM. We also find necessary and sufficient condition for such map to be totally geodesic.

## Preprints:

1. Murat Polat and Kiran Meena, *Clairaut semi-invariant Riemannian maps to Kähler manifolds*, arXiv:2303.08108

# Saikat Panja

## Research Summary:

I am interested in Algebra and topology. Here I will describe a few of them point-wise.

1. By a word we mean an element $w = w(x_1, ..., x_d)$ of the free group $F_d$ on the free generators $x_1, ..., x_d$. Given a word $w$ and a group $G$, we consider the *word map*

$$w = w_G : G^d = \underbrace{G \times G \times \cdots \times G}_{d \text{ times}} \to G, \quad (g_1, ..., g_d) \mapsto w(g_1, ..., g_d).$$

   The famous Ore's conjecture (1951) asks whether every element of a non-abelian finite simple group is a commutator. This was solved by A. Shalev et al where the authors prove that if $G$ is any quasisimple classical group over a finite field, then every element of $G$ is a commutator, using character-theoretic results due to Frobenius. We are currently focusing on finding the proportions of elements in several classical groups, which admit an $M$-th root for an integer $M \geq 2$. The approach is via generating functions.

2. Let $F_n$ denotes the free group on $n$ symbols $x_1, x_2, \cdots, x_n$ and $K$ be an algebraically closed field. The elements of the group ring $K[F_n]$ will be called as *polynomials in non-commutative variables*. Given an algebra $\mathcal{A}$ over $K$ and $p \in K[F_n]$, consider the following map

$$\Phi_p : \mathcal{A}^n \longrightarrow \mathcal{A}, \quad (a_1, a_2, \cdots, a_n) \mapsto p(a_1, a_2, \cdots, a_n).$$

   These are known as polynomial maps on $\mathcal{A}$. The famous Kaplansky-Lvov conjecture states that the image set of $M_n(k)$ under a multilinear polynomial map, is either $\{0\}$, $\{aI : a \in k\}$, $\mathfrak{sl}_n(k)$ or $M_n(k)$, where $\mathfrak{sl}_n(k)$ denotes the set of all trace $0$ matrices in $M_n(k)$. We are interested in finding images of polynomials on different associative algebras.

3. Let $K$ and $F$ be two fields. Assume $K/F$ is a finite separable field extension. An $F$-Hopf algebra $\mathcal{H}$, with an action on $K$ such that $K$ is an $H$-module algebra and the action makes $K$ into an $\mathcal{H}$-Galois extension, will be called a *Hopf-Galois structure* on $K/F$. This has a connection with the theory of skew braces, which are set-theoretic solutions to Yang-Baxter equations. Via the theory of Byott' s translation, we know that this is equivalent to finding pair of groups $(G, N)$ of same order such that $G$ can be embedded inside $\mathrm{Hol}(N) = N \rtimes \mathrm{Aut}(N)$. We are interested in finding for which pair of groups of the same order, there exists a Hopf-Galois structure.

4. V. G. Drinfeld suggested the study of the set-theoretic solution to the quantum Yang-Baxter equation (QYBE). A *set-theoretic solution to the QYBE* is an ordered pair $(X, R)$, where $X$ is a set and $R : X \times X \longrightarrow X \times X$ is a map, satisfying

$$R^{12}R^{13}R^{23} = R^{23}R^{13}R^{12},$$

   with $R^{ij} : X \times X \times X \longrightarrow X \times X \times X$ being the map acting on the $(i, j)$-th position by $R$. This has been an important research topic for the last two decades after the

breakthrough by P. Etingof, T. Schedler and A. Soloviev. Although such solutions were constructed by A. D. Weinstein and P. Xu and by J. H. Lu, M. Yan and Y. C. Zhu independently, the paper by Etingof *et. al.* further studies solutions with additional conditions of *nondegeneracy* of $R$ (i.e. if $R(x,y) = (g_x(y), f_y(x))$ then $g_x, f_y$ are bijective for all $x, y \in X$) and $R$ being involutive (i.e. $R^2 = \mathrm{Id}_{X\times X}$) and derive powerful consequences. We are interested in finding and counting new such solutions to Yang-Baxter equations.

5. A *graph* is an ordered pair $G = (V, E)$, where $V$ is called the set of vertices and $E$ is called the set of edges. The set $E$ consists of 2-element subsets of $V$. The subject topological combinatorics is consist of the study of homotopy invariants of certain cell complexes constructed using the graph to obtain combinatorial information about the graph $G$. The first example of this is the Lovász celebrated proof of the Kneser conjecture. The neighbourhood complex $\mathcal{N}(G)$ of a graph $G$ is an abstract simplicial complex whose simplices are subsets of the vertex set $V$ having common neighbours. Lovász uses the connectivity of neighbourhood complex $\mathcal{N}(G)$ to compute a lower bound on the chromatic number of the corresponding graph. Lovász stated a similar conjecture that the lower bound on the chromatic number of a graph $G$ can be given in terms of the connectivity of certain cell complexes associated with the cycle graph and $G$. These complexes are known as *hom complexes*. Babson and Kozlov proved Lovász conjecture, where they relate these hom complexes to the *independence complexes*. These are also partially motivated by some combinatorial questions in statistical physics, namely the properties of the Witten index in the so-called hard squares. We are interested in the computational aspects of the independence complex and the deduction of other properties (e.g. shellability) of graphs.

## Publications:

1. Namrata Arvind, **Saikat Panja**, *Hopf-Galois realizability of $\mathbb{Z}_n \rtimes \mathbb{Z}_2$*, Journal of Pure and Applied Algebra, Volume 227, Issue 4, April 2023, 107261

2. Namrata Arvind, **Saikat Panja**, *Unit group of some finite semisimple algebras*, Journal of the Egyptian Mathematical Society volume 30, Article number: 17 (2022)

3. **Saikat Panja**, *Acceptability of classical groups in non-zero characteristic*, Linear Algebra and its Applications, Volume 669, 15 July 2023, Pages 118-124

## Preprints:

1. Navnath Daundkar, Saikat Panja, Sachchidanand Prasad, *Independence complexes of wedge of graphs*, arXiv:2303.08798

2. Arpan Kanrar, Saikat Panja, *Cycle matrices: A combinatorial approach to the set-theoretic solutions of the Quantum Yang-Baxter Equation*, arXiv:2303.09398

3. Anupam Singh, Saikat Panja, *Powers in finite unitary groups*, arXiv:2304.13735

## Conference/Workshops Attended:

1. Workshop on Group Theory, 2023 (IISER Pune)
2. Conference on group theory and related topics, 2023 (NISER Bhubaneswar)

## Invited Lectures/Seminars:

1. (Course) Topology module 3 at AFS 1, IIT Jodhpur, December 2022
2. (Talk) Images of Word Maps on Groups: Old and New. (WGT23), Januray 2023

## Other Activities:

1. Algebra tutor (all modules), AFS 1, IIT Jodhpur, December 2022

# Amit Patra

## Research plan:

Since I have joined as a PDF on 22/02/2023. So I don't have enough research work between 22/02/23 - 31/03/23. I have attached my research plan. My research revolves mostly around the study the minimum number of generators of derivation modules for some affine algebra. I am trying to research generators of the module of derivations of rings of invariants and obtain bounds on their minimum number of generators. I am trying to prove Krämer's conjecture. I will try to extend some result on derivation modules for one dimensional local case. I am very interested to study some homological properties of the derivation modules for some cetain rings.

Andrzej Nowicki had studied the derivations of the polynomial algebra over a field of characteristic zero. I am studying the derivations of the polynomial algebra over a field of characteristic zero. I will try to extend many results from Andrzej Nowicki's polynomial derivations and their rings of constants. I will study linear derivation, simple derivation of polynomial rings.

I am preparing for some results on integer-valued polynomial rings.

# Prashant Tiwari

## Research Summary:

In the published paper, we prove a quantitative result for the number of sign changes of the Fourier coefficients of a Hermitian cusp form of degree 2. In addition, we prove a quantitative result for the number of sign changes of the primitive Fourier coefficients. We give an explicit upper bound for the first sign change of the Fourier coefficients of a Hermitian cusp form of degree 2 over certain imaginary quadratic extensions.

In the second submitted article, let $\{x_n\}_{n\geq 0}$ be the balancing-like sequence defined by $x_{n+1} = Ax_n - x_{n-1}$ with initial terms $x_0 = 0, x_1 = 1$ for $A \geq 3$. In this study, we demonstrate how to find all the solutions of the Diophantine equation, $\sum_{i=1}^{3} C_i x_{n_i} = \sum_{i=4}^{6} C_i x_{n_i}$ in fixed integers $A \geq 3$, $n_1 > n_2 > n_3 \geq 0, n_4 > n_5 > n_6 \geq 0$, and $C_1 x_{n_1} \neq C_4 x_{n_4}$, where $C_i; 1 \leq i \leq 6$ are given integers satisfying $C_1 C_2 C_3 \neq 0$.

In the third ongoing project, let $F$ be a non-zero Hecke eigenform in $S_k(Sp_2(\mathbb{Z}))$, the space of Siegel cusp forms of weight $k$, degree two for $Sp_2(\mathbb{Z})$. The long standing problem was to prove that the first Fourier-Jacobi coefficient of $F$ is non-zero. Only very recently in 2021, this problem solved by M. Manickam. In particular, he proved that the first Fourier-Jacobi coefficient of a non-zero Hecke eigenform in $S_k(Sp_2(\mathbb{Z}))$ is not identically zero. The first natural extension of this problem is, to look for the non-vanishing of the first Fourier-Jacobi coefficient in the case of congruence subgroups and the second is, what happened if the degree is greater than two. In this project, first we are considering the problem for congruence subgroups. This is an ongoing project with M. K. Pandey.

## Publications:

1. R. Nandi, S. K. Singh and P. Tiwari, *On sign changes of Fourier coefficients of Hermitian cusp forms of degree two*, https://doi.org/10.1007/s11139-023-00716-2 (Published in The Ramanujan Journal, 2023).

## Preprints:

1. B. K. Patel and P. Tiwari, ***Diophantine equation with balancing-like sequences associated to the Pillai-Tijdeman-type problem***, arxiv.org/abs/2105.15127 (the final revision is submitted, 2023).

## Conference/Workshops Attended:

1. Workshop on Number Theory, NISER, Bhubaneswar, India (20 - 25 February 2023).

2. NCM Workshop on Jacobi forms, IIT Guwahati, India (12 Dec 2022 to 24 Dec 2022).

3. NCM Workshop on Elliptic Curves, Elliptic Functions and Transcendence, HRI Prayagraj, India (24 Nov 2022 to 3 Dec 2022).

4. L-functions, Circle-Method and Applications (HYBRID); ICTS Bangalore, India (27 June 2022 to 01 July 2022).

## Visits to other Institutes:

1. SRM University AP, Andhra Pradesh, India, February 2023

## Invited Lectures/Seminars:

1. On sign changes of primitive Fourier coefficients of Siegel cusp forms, Workshop on Number Theory at NISER, Bhubaneswar, India, February 2023

## Other Activities:

1. Took tutorial in Jacobi Forms (NCM Workshop), IIT Guwahati, India (2022).

2. Took tutorial in Elliptic Curves, Elliptic Functions and Trancendence (NCM Workshop), HRI Prayagraj, India (2022).

# Mohammad Aqib

## Research Summary:

One of the important open problems in the Riemannian geometry asked by A. L. Besse is: "Does there exists a compact Einstein warped product space with non-constant warping function?" Kim and Kim provided the negative partial answer of the open problem.

The concept of Riemannian warped product can be naturally extended to the Finslerian settings. And also The notion of Finsler manifolds of Einstein type have been studied extensively. In Finsler manifold of Einstein type the Ricci curvatures are scalar functions on manifolds unlike the Riemannian settings.

In case when $\lambda$ is a constant function on manifold, then the aforementioned Kim and Kim result was extended to the Finslerian settings when the base manifold is a Riemannian manifold and the fiber space is a Berwald manifold. That is also generalized further recently by Hemangi Shah and et al., when the base manifold is Riemannian of finite volume and the fibre space is Berwald Finsler manifold. We are trying to generalize the Kim and Kim result to a more general Finslerian settings. When the Ricci curvature of base manifold is a nonpositive function, and the base manifold is compact Riemannian or Berwald and the fiber space is Berwald, then we will try to show that the warping function is a constant function.

## Conference/Workshops Attended:

1. CIMPA School On Geometric Structures On Surfaces, Moduli Spaces And Dynamics Banaras Hindu University, Varanasi-221005, INDIA December 12-22, 2022

# Kushal Bhowmick

## Research Summary:

In the academic year(2022-23), my primary focus was to study the content of the two papers titled " The Size of Selmer Groups for the Congruent Number Problem " by D.R.Heath-Brown and " The Rank of 2-Selmer Group Associated to $\theta$-Congruent Numbers " by Tao Wei and Xuejan Guo. The brief summary of the first paper is as follows:
The oldest problem in the theory of elliptic curves to determine which positive integers D can be common difference of a three term arithmetic progression of squares of rational numbers. Such integers D are known as congruent numbers. Equivalently one may ask which elliptic curves

$$E_D : y^2 = x^3 - D^2x$$

have positive rank. Clearly one may, and we shall, restrict attention to square-free numbers D. At present there is no known algorithm for deciding whether or not a given integer is a congruent number. However the conjecture of Birch and Swinnerton-Dyer, if true, would provide such a procedure. One defines

$$L_D(s) = \prod_{p \nmid 2D} (1 - a_p p^{-s} + p^{1-2s})^{-1}, \qquad a_p = p + 1 - N_p$$

where $N_p$ is the number of solutions of the congruence $y^2 \equiv x^3 - D^2x \pmod{p}$. Then $L_D(s)$ has an analytic continuation as an entire function on the complex plane. The conjecture of Birch and Swinnerton-Dyer then states, in particular, that the rank $r(D)$ of $E_D$ is equal to the order $R(D)$ of $L_D(s)$ at $s = 1$, this being the so-called analytic rank. While we can not at present find $R(D)$ in all cases, we can atleast determine whether or not $L_D(1) = 0$, and hence, conjecturally, whether or not $r(D) = 0$. Moreover one has a functional equation for $L_D(s)$ which relates its values at $s$ and $2 - s$, via a sign change $\epsilon_D = \pm 1$. One may deduce that $(-1)^{R(D)} = \epsilon_D$. It would then follow from the conjecture of Birch and Swinnerton-Dyer that the rank is positive whenever $\epsilon_D = -1$. According to the calculations of Birch and Stephens one has

$$\epsilon_D = \begin{cases} +1, & D \equiv 1, 2, 3 \pmod{8} \\ -1, & D \equiv 5, 6, 7 \pmod{8} \end{cases}$$

which would imply that D is congruent whenever $D \equiv 5, 6 \text{ or } 7 \pmod{8}$. We know from the work of Coates and Wiles, Gross and Zagier, and Rubin that, for our curves, $r(D) = R(D)$ whenever $R(D) = 0 \text{ or } 1$, but little can be said when $R(D) \geq 2$.

A straightforward approach to these questions is provided by the use of descents. We shall be concerned with the "full 2-descents", which can be done over $\mathbb{Q}$ for our curves. However what is of interest is that the number of 2-descents is the order of the Selmer group $S^{(2)}$. This is a power of 2, and will be a multiple of 4, on account of the rational points of order 2 on $E_D$. We shall therefore write $\#S^{(2)} = 2^{2+s(D)}$. The exponent $s(D)$ has sometimes been refered to as the 'Selmer rank' of the curve $E_D$. According to the Selmer conjecture, $s(D)$ and $r(D)$ should have the same parity.

It therefore seems likely, in view of the conjecture of Birch and Swinnerton-Dyer, that $s(D)$ and $R(D)$ always have the same parity. The purpose of the paper is to investigate $s(D)$ on average. D.R.Heath-Brown has proved the following theorem.

**Theorem 1** *For any odd integer h let*

$$S(X,h) = \{D \equiv h \pmod 8 \ : \ 1 \leq D \leq X, \ D\, squarefree\}.$$

*Then*

$$\sum_{D \in S(X,h)} 2^{s(D)} = 3\#S(X,h) + O(X(\log X)^{-\frac{1}{4}}(\log\log X)^8).$$

Of course $\#S(X,h)$ is of order X, so that we have an asymptotic formula, with a relative saving of $O(X(\log X)^{-\frac{1}{4}}(\log\log X)^8)$. We can immediately deduce the following.

$$\sum_{D \in S(X,h)} 2^{r(D)} \leq 3\#S(X,h) + O(X(\log X)^{-\frac{1}{4}}(\log\log X)^8).$$

The main purpose of the second paper is to understand the parity of the 2-Selmer rank of the elliptic curve associated to $\frac{\pi}{3}$ (resp. $\frac{2\pi}{3}$) - congruent number problem. Fujiwara introduced a general definition : a positive integer n is called a $\theta$-congruent number if there exists a rational $\theta$-triangle with area $n\sqrt{r^2 - s^2}$, where $\theta$ be a real number with $0 < \theta < \pi$, $\cos\theta = \frac{s}{r}$ is rational and $r, s \in \mathbb{Z}$, $\gcd(r,s) = 1$, a rational $\theta$-triangle is a triangle with rational sides and an angle $\theta$. Note that congruent number can be seen as $\frac{\pi}{2}$-congruent number. The elliptic curves associated to $\theta$-congruent number problem is defined by

$$E_{n,\theta} : y^2 = x(x + n(r+s))(x - n(r-s))$$

where $\cos\theta = \frac{s}{r}$, $r, s \in \mathbb{Z}$, $\gcd(r,s) = 1$ and $n \in \mathbb{N}$. There are some important criteria for $\theta$-congruent numbers by Fujiwara.

**Theorem 2** *Let n be any square free natural number,* $0 < \theta < \pi$. *Then*

*1) n is $\theta$-congruent if and only if $E_{n,\theta}$ has a rational point of order greater than 2.*

*2) For $n \nmid 6$, n is $\theta$-congruent if and only if the Mordell-Weil group $E_{n,\theta}(\mathbb{Q})$ has a positive rank.*

In the last section of the paper they have showed that for $n = pq \equiv 5(resp.11) \pmod{24}$ the density of non $\frac{\pi}{3}$ (resp. $\frac{2\pi}{3}$) -congruent numbers is at least $75\%$, where $p, q$ are primes.

My aim is to investigate the 2-Selmer rank of elliptic curves $E_{n,\frac{\pi}{3}}$ (resp. $E_{n,\frac{2\pi}{3}}$) on average. I would be trying to prove an analogue of **Theorem 1** for $E_{n,\frac{\pi}{3}}$ (resp. $E_{n,\frac{2\pi}{3}}$).

## Conference/Workshops Attended:

1. ICTS Workshop on " Elliptic Curves and Special Values of $L$-Functions " August, 08-19, 2022.

2. NCM Workshop on " Elliptic Curves and Iwasawa Theory ", IISER Thiruvananthapuram, April 03-15, 2023.

# Srijonee Shabnam Chaudhury

## Research Summary:

Currently I am working on 'Sums of squares of integer-multiple of an integral element on real bi-quadratic fields'. In my current project I have tried to show for any given positive integer $m$ we construct certain totally positive algebraic integers $\alpha$ of a real bi-quadratic field $K$ and obtain some necessary conditions for which $m\alpha$ can not be represented as sum of integral squares. We show this for integers lie in quadratic subfields of $K$ and for integers which are in $K$ but not in any quadratic subfield of $K$. We provide examples in tabular form for each cases to corroborate the results.

## Preprints:

1. Some cases in pseudonullity of fine Selmer groups, https://arxiv.org/abs/2304.00499

## Conference/Workshops Attended:

1. International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2018, HRI
2. International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2019, HRI
3. Workshop on Additive Combinatorics – 2020, ICTS, Bangalore
4. IIT Guwahati , for AIS ( Advanced Instructional School) on Modular Form, May,2019 .
5. International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2021, KSOM
6. Recent Advances in Mathematics and Related Areas (April 21, 2022 - April 24, 2022), KSOM (Hybrid Conference)
7. International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2022, KSOM
8. XXIII International Workshop for Young Mathematicians "Number Thoery" - 2022, Jagiellonian University, Krakow, Poland. (hybrid conference)

## Visits to other Institutes:

1. Kerala School of Mathematics (KSOM) Kozhikode, Kerala, India (October 20,2021 - November 30, 2021).

## Invited Lectures/Seminars:

1. Sum of Integral Squares in non-totally Real Fields and Beyond, International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2021, KSOM, Kozhikode, Kerala, India.

   Date of my talk- 24th October, 2021

2. XXIII International Workshop for Young Mathematicians ”Number Thoery” - 2022, Jagiellonian University, Krakow, Poland. (hybrid conference)

   Date of my talk - 19th September, 2022 (online)

# Arpan Das

## Research Summary:

Let $\omega_{Sp_{2n}}$ be the Weil representation of the finite symplectic group $Sp_{2n}(\mathbb{F}_q)$ with $q$ odd (constructed by P. Gerardin in 1977). We call a pair of subgroups $(G, G')$ of $Sp_{2n}(\mathbb{F}_q)$ a *reductive dual pair* if they centralize each other. The Weil representation then restricts to a representation of $G \times G'$ and this is denoted as $\omega_{G,G'}$. The decomposition of this restricted representation and its character, both denoted $\omega_{G,G'}$ by abuse of notation, was studied by B. Srinivasan (1979) for the pairs $(Sp_{2m}(\mathbb{F}_q), SO^{\epsilon}_{2m'}(\mathbb{F}_q))$ ($q$ odd and $\epsilon = \pm$), $(GL_m(\mathbb{F}_q), GL_{m'}(\mathbb{F}_q))$ and $(U_m(\mathbb{F}_q), U_{m'}(\mathbb{F}_q))$ where $n = mm'$. Based on this J.Adams and A.Moy (1993) and A.M.Aubert et al. (1996,2016) studied certain aspects of the finite theta correspondence for the above three dual pairs. Later S.Y. Pan (2016) obtained a decomposition along the lines of the work of Srinivasan for the symplectic-odd orthogonal dual pair. We would like to understand to what extent the works of Adams-Moy and Aubert et al. can be generalized for the symplectic-odd orthogonal pair.

## Conference/Workshops Attended:

1. NCM Workshop: *Elliptic Curves, Elliptic Functions and Trancendence.* HRI, Prayagraj, India, Nov - Dec 2022.

## Other Activities:

1. Five lectures on *Homotopy Theory and Fundamental Groups*, Summer Program in Mathematics, HRI, July, 2022.

# Bhargab Das

## Research Summary:

Suppose $\rho$ and $\rho'$ are two Galois Representations. Then $L$-functions attached to them have an intrinsic property called Artin Formalism, which says that $L(\rho \oplus \rho', s) = L(\rho, s)L(\rho', s)$ for suitable complex number $s$. The analogous property attached to $p$-adic avatar of $L$-functions is called $p$-adic Artin Formalism. There are some known examples of $p$-adic Artin Formalism along with their algebraic counterparts Compatible with the Iwasawa Main Conjecture.
The first of them was given by B. Gross in 1980 for a direct sum of two characters and later S. Dasgupta showed (2016) the same property for the product of two elliptic curves. The algebraic counterparts are proved by R. Greenberg (1982) and B. Palvannan (2018) respectively. We are trying to generalize the work of Palvannan for the product of three elliptic curves.

## Conference/Workshops Attended:

1. Advanced Instructional School: *Geometric Group Theory.* (Online), May - June, 2022.
2. *Elliptic Curves and The Special Values of L-functions.* International Centre for Theoritical Sciences. Bangalore, India, August 2022.
3. NCM Workshop: *Elliptic Curves, Elliptic Functions and Trancendence.* HRI, Prayagraj, India, Nov - Dec 2022.

## Other Activities:

1. Two lectures on *Homotopy Theory and Fundamental Groups*, Summer Program in Mathematics, HRI, July, 2022.
2. Teaching Assitant for the course *Differentiable Manifolds* (Instuctor: Dr. Aprameyo Pal), HRI, Aug - Dec, 2022.

# Shubham Gupta

## Research Summary:

Let $\mathbb{Z}[\sqrt{d}]$ be a quadratic ring of integers. Assume that $d \equiv 2 \pmod 4$ such that the equations $x^2 - dy^2 = -1$ and $x^2 - dy^2 = 6$ are solvable in rational integers. In a joint work with Prof. K. Chakraborty and Dr. A. Hoque, we proved that there exist infinitely many Diophantine quadruples in $\mathbb{Z}[\sqrt{d}]$ with the property $D(n)$ for $n = 4m + 4k\sqrt{d}$ with $m, k \in \mathbb{Z}$ satisfying $(m, k) \not\equiv (5, 3), (11, 3) \pmod{(12, 6)}$, where $(a, b) \equiv (c, d) \pmod{(f, g)}$ denotes $a \equiv c \pmod f$ and $b \equiv d \pmod g$. Also, we proved a similar result for $n = (4m + 2) + 4k\sqrt{d}$, where $(m, k) \not\equiv (9, 3), (0, 0) \pmod{(12, 6)}$.

I have done another work in collaboration with Prof. K. Chakraborty and K. Krishnamoorthy, which is as follows. Under some mild hypotheses, we proved that for every Diophantine $m$-tuple $\{t_1, t_2, \ldots, t_m\}$ with the property $D(n)$ for some $n$, there exist integral ideals $\mathfrak{t}_1, \mathfrak{t}_2, \ldots, \mathfrak{t}_m$ of $\mathbb{Q}(\sqrt{n})$ and $c \in \{1, 2\}$, such that $t_i = c\mathcal{N}(\mathfrak{t}_i)$ for $i = 1, 2, \ldots, m$, where $\mathcal{N}(\cdot)$ denotes the norm map from $\mathbb{Q}(\sqrt{n})$ to $\mathbb{Q}$. Moreover, if $\mathfrak{t}_1$ and $\mathfrak{t}_2$ are principal ideals with generators $\alpha_1$ and $\alpha_2$, respectively, then we obtained equivalent conditions on $\alpha_1$ and $\alpha_2$, so that $\{\mathcal{N}(\alpha_1), \mathcal{N}(\alpha_2)\}$ is a Diophantine pair with the property $D(n)$.

## Publications:

1. Shubham Gupta, *$D(-1)$ tuples in imaginary quadratic fields*, Acta Math. Hungar., **164** (2021), 556-569.

2. Kalyan Chakraborty, Shubham Gupta, and Azizul Hoque, *On a conjecture of Franušić and Jadrijević: counter-examples*, Results Math., **78** (2023), Paper No. 18, 14pp.

3. Kalyan Chakraborty, Shubham Gupta, and Azizul Hoque, *Diophantine triples with the property $D(n)$ for distinct $n$'s*, Mediterr. J. Math., **20** (2023), Paper No. 31, 13pp.

## Preprints:

1. Kalyan Chakraborty, Shubham Gupta, and Azizul Hoque, *Diophantine $D(n)$-quadruples in $\mathbb{Z}[\sqrt{4k+2}]$*, (communicated).

2. Kalyan Chakraborty, Shubham Gupta, and Krishnarjun Krishnamoorthy, *Diophantine tuples and quadratic extensions of $\mathbb{Q}$*, (communicated).

3. Shubham Gupta, *A survey on some recent works on generalized Diophantine $m$-tuples*, (in preparation).

## Conference/Workshops Attended:

1. *Workshop on Elliptic Curves* (2023), IISER Thiruvananthapuram, Thiruvananthapuram, Kerala, India, April 3-15, 2023.

2. *Diophantine Day @ ISI Delhi*, ISI Delhi, Delhi, India, March 9, 2023.

3. *International Conference on Class Groups of Number Fields and Related Topics*-2022 (*ICCGNFRT*), Kerala School of Mathematics, Kerala, India, November 21-24, 2022.

4. *Recent Advances in Mathematics and Related Areas*-2022, Kerala School of Mathematics, Kerala, India, April 21-24, 2022.

# Arpan Kanrar

## Research Summary:

A bijective set map $r : X^2 \to X^2$ (we usually write $r(x, y) = (g_x(y), f_y(x))$) is called a non-degenerate involutive set theoretic solution (later we will call it "solution" only) of quantum Yang-Baxter equation on $X$, if it satisfies
1. $r_1r_2r_1 = r_2r_1r_2$, where $r_1, r_2 : X^3 \to X^3$ set maps defined by $r_1(x, y, z) = (r(x, y), z)$ and $r_2(x, y, z) = (x, r(y, z))$ respectively;
2. $r^2 = id_{X^2}$;
3. for $x \in X$, $f_x$ and $g_x$ are permutations on $X$.
The group $\mathcal{G}$ generated by these $f_x$ is called the permutation group of the solution. If $\mathcal{G}$ acts on $X$ transitively (under the usual action) then the solution $(X, r)$ is called indecomposable otherwise decomposable. I explored some properties of decomposable and indecomposable solutions. Under the guidance of my supervisor Prof. Manoj Yadav, I have read some papers on it and found some interesting results. In 2021, L. Vendramin conjecture that for a finite solution $(X, r)$, if there is a $f_x \neq 1$ and a prime $p$, divides the order of $f_x$ such that $\gcd(p, |X|) = 1$, then the solution is decomposable. I gave an affirmative answer to this conjecture in the case of $\mathcal{G}$ is nilpotent. Then I studied cycle set and concentrated on techniques to find new solutions. In joint work with Saikat Panja, we found some recipes to find an infinite collection of solutions, and also for a given $r$ we constructed a multipermutation solution of level $r$. Parallelly, I have been reading combinatorial group theory and geometric group theory.

## Preprints:

1. A. Kanrar, S. Panja, *Cycle matrices: A combinatorial approach to the set-theoretic solutions of the Quantum Yang-Baxter Equation*, submitted.

2. A. Kanrar, *(In)Decomposability of finite solutions of Yang-Baxter equation*, submitted.

## Conference/Workshops Attended:

1. The algebra of the Yang-Baxter equation, Bedlewo, Poland, July 11-15, 2022 (Online Mode).

2. Group theory and related topics, 27 Feb - 04 Mar 2023, National Institute of Science Education and Research, Bhubaneswar.

# Parul Keshari

## Research Summary:

In 1892, Madhav V Nori proved that the category of essentially finite quiver bundle over a complete connected reduced scheme X over a field is a neutral tannakian category and hence gave the notion of Nori fundamental group of X. Motivated by this we asked a similar question for a diagram of vector bundles. More explicitly, we studied the category of quiver representation in the category of quiver bundles and tried to speculate the appropriate conditions for the objects and the morphism so that we can get an object which would replace the group scheme obtained in the classical case.

In this direction, we have generalized the results of Amir Jafari and Mostafa Einollahzadeh, who have proved that a category with a fiber functor taking values in more general rings is also equivalent to the representations of a group scheme over the ring.

## Preprints:

1. Parul Keshari and Anoop Singh, *A Remark on the Moduli Space of Lie Algebroid $\lambda$-Connections*, submitted (2023).

## Conference/Workshops Attended:

1. Discussion meeting on Bundles 2023, 27 March-31 March 2023 at TIFR Mumbai, India.
2. Conference on Algebraic Geometry, 12-16 December 2022 at HRI, India.
3. International Conference on Evolution in Pure and Applied Mathematics(ICEPAM-2022) (Online Mode), organized by the Department of Mathematics, Akal University, Talwandi Sabo India, 16-18 November 2022

## Invited Lectures/Seminars:

1. *Tannaka duality and Quiver Bundle*, Conference on Algebraic Geometry, HRI, on 15 December 2022
2. *A remark on the Hodge moduli space of Lie Algebroid Connections*(online), ICEPAM-2022, Department of Mathematics, Akal University, Talwandi Sabo, India, on 18 November 2022.
3. *A remark on the Hodge moduli space of Lie Algebroid Connections*, one day meet on Algebra and Number Theory, HRI, India, on 10 September 2022.

## Other Activities:

1. Tutored in SPIM 2023 for algebra course.
2. Gave two lectures in Rajbhasha Programme.
3. Volunteer in Talent Search Exam and NBHM exam.

# Uday Sureshbhai Patel

## Research Summary:

In this academic year, I have been learning the basics of Euclidean Harmonic Analysis. Particularly, I have covered the preliminaries of Fourier Analysis and Distribution Theory from Folland's Real Analysis book, and simultaneously attended the online course on Singular Integrals given by Prof. P.K. Ratnakumar, based on Elias Stein's book on Singular Integrals and Differentiability Properties of Functions. I have also meticulously gone through the paper "Estimates For Translation Invariant Operators in $L^p$ spaces" by L. Hörmander, for familiarity with preliminaries for my future research work, planned in the area of Fourier multipliers. With my guide, we have been learning "Oscillatory Fourier multipliers". Precisely, we are trying to understand the function $e^{iP}$ (where $P$ is a polynomial) in the sense that whether it defines an $L^p - L^q$ multiplier.

## Other Activities:

1. Tutored for the Measure Theory course in SPIM at HRI, Prayagraj during June 2022.

2. Tutored for the Complex Analysis course in SPIM at HRI, Prayagraj during June 2022.

3. Tutored for the Analysis-I course in the first year coursework at HRI, Prayagraj during August-December, 2022.

# Santanu Tantubay

## Research Summary:

In the academic year 2022-2023, I characterized simple smooth modules over some classes of Lie algebras. I classified all simple integrable modules with finite dimensional weight spaces.

## Preprints:

1. CHARACTERIZATION OF SIMPLE SMOOTH MODULES, YAO MA, KHOA NGUYEN, SANTANU TANTUBAY, AND KAIMING ZHAO, (Submitted to a Journal)

2. Simple Modules For Twisted Hamiltonian Extended Affine Lie Algebras, Santanu Tantubay, Priyanshu Chakraborty, Punita Batra, https://arxiv.org/abs/2304.07749

## Visits to other Institutes:

1. Visited Uppsala University, Sweden (01/03/2023-31/03/2023)

## Invited Lectures/Seminars:

1. Presented a talk titled "Integrable representations of full toroidal Lie algebras " at UPPSALA ALGEBRA SEMINAR, Department of Mathematics, Uppsala University, 21/03/2023.

# Aparna Tripathi

## Research Summary:

In this academic year, I have been learning basic Algebraic Number Theory and Transcendental Number Theory. I have read papers related to 'Schanuel's Conjecture' and 'Certain classification of Real Numbers and to generate transcendental fields from them and their properties'. Also, with my guide, we are trying to explore the $\mathbb{Q}$-linearly independence of some infinte series. Precisely, we have proved that the value of the series

$$\sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mn + r]}$$

is an irrational number for any natural number $n$ and $r \in \{0, 1, 2, \ldots, n-1\}$. We are exploring the $\mathbb{Q}$-linearly independence of

$$1, \sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mq + 1]}, \sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mq + 2]}, \ldots, \sum_{m=1}^{\infty} \frac{1}{[1, 2, \ldots, mq]}$$

where $q$ is a prime number and $[1, 2, \ldots, n]$ denotes the least common multiple of the numbers $1, 2, \ldots, n$. We could prove this when $q = 2$ and $q = 3$.
I would be continuing exploring and learning transcendental techniques along with reading basics of Number Theory related topics.

## Preprints:

1. A. Tripathi and R. Thangadurai, *On the irrationality of certain infinite series*, In preparation, (2023).

## Conference/Workshops Attended:

1. NCM Workshop on "Elliptic curves, Elliptic functions and Transcendence" at HRI, Prayagraj, 24 November - 03 December 2022.
2. Infosys lecture series by Prof. M. Ram Murty on "Probability and Number Theory" at HRI, Prayagraj, 10-19, December 2022.
3. Workshop and a conference on Number Theory at NISER, Bhubaneswar during 20-25, February 2023.

## Visits to other Institutes:

1. IIT Delhi, Delhi, 17-27, January 2023.
2. NISER, Bhubaneswar, 12-26, February 2023.

## Other Activities:

1. Tutored for Topology course in SPIM at HRI, Prayagraj during June 2022.

# Academic Report - Physics

# Anirban Basu

## Research Summary:

Elliptic modular graphs arise in the asymptotic expansion of two loop string amplitudes around the non–separating node on the moduli space of genus two Riemann surfaces. I have obtained eigenvalue equations satisfied by various elliptic modular graphs with five links where two of the vertices are unintegrated over the toroidal worldsheet, generalizing results for graphs with lesser number of links. Solving them leads to several non–trivial algebraic identities between these graphs. I have also considered certain families of elliptic modular graphs, each of which is denoted by an arbitrary integer which parametrizes the number of links. Solving the eigenvalue equations they satisfy, I have obtained an algebraic relation between these families of graphs. On identifying the two vertices at fixed locations, this automatically leads to an algebraic relation between families of modular graphs where all the vertices are integrated over the worldsheet.

## Preprints:

1. Anirban Basu, *Elliptic Modular Graphs, Eigenvalue Equations and Algebraic Identities*, e-Print: 2210.00648

2. Anirban Basu, *An algebraic identity between families of (elliptic) modular graphs*, e-Print: 2212.13464

## Other Activities:

1. Taught Quantum Field Theory I (August–December 2022)

# Sudip Chakraborty

## Research Summary:

We have continued our materials modelling research based on electronic structure theory for renewable energy, mostly focused on solar cells and fundamentals behind different catalytic reaction for efficient hydrogen generation and carbon emission. We envisage possible implications of Rashba phenomena particularly for non-centrosymmetric and heavy element containing nano-structured systems. Our work would shed light on the application paradigm of these exciting phenomena in the field of light matter interactions through a case study of photocatalytic water splitting. We are also trying to explore ion-migration mechanism to be constructively implemented in neuromorphic computing through tuning the memristive properties of novel materials. The experimental realization along with the theoretical prediction of vivid materials phenomena in the emerging energy materials family opens up a new direction for modulating the charge carrier recombination probability of the excited electrons and the holes. The influence of external parameters, such as pressure, uniaxial and biaxial strain, and electric field, has been addressed explicitly to change the Rashba splitting factor, which essentially suppresses the recombination rate. Our work would provide a possible roadmap of materials design and the effect of external stimuli on the plethora of perovskite materials for extensive energy scavenging with the focus on catalytic reaction mechanism. As a case study, we have observed a significant Rashba splitting in a halide and nitride perovskite systems. We have employed Density Functional Theory(DFT) based first-principles electronic structure calculations along with Spin-Orbit-Coupling(SOC) to envisage the spin-splitting qualitatively and quantitatively from the bandstructure and spin-texture. To understand the trend in the splitting parameter, an extensive study of compressive strain up to within the experimental limit would be perceived, which provides evidence for the tunability of spin-splitting. The Rashba-enabled system could be possibly emerged to be a potential candidate for bi-functional catalytic reactions HER and OER. Hence with applied compressive strain, the catalytic behavior of the material will be systematically investigated to see such promise. Here we will try to establish a cooperative trend between Rashba splitting and bi-functional catalytic reaction mechanism. All these efforts successfully culminated into twenty-one published articles in last academic year, while there are twelve more works, which are either in the review process or at submission stage. The published articles are not only on pure theoretical investigations, but some of them are also the reflection of successful feedback between experimental investigations and our theoretical prediction based on the electronic structure analysis.

## Publications:


1. Manasa G. B., Sudip Chakraborty*, *Rationalization of Double Perovskite Oxides as Energy Materials: A Theoretical Insight from Electronic and Optical Properties*, ACS Materials Au, **2**, 655 (2022). (Invited Perspective Article for Rising Stars in ACS Materials Au)

2. H. Banerjee, J. Kaur, M. K. Nazeeruddin*, Sudip Chakraborty*, *Tuning Paradigm*

*of External Stimuli Driven Electronic, Optical and Magnetic Properties in Hybrid Perovskites and Metal Organic Complexes*, Materials Today, **60**, 183 (2022). [Impact Factor: 26.9]

3. A. Kar, R. Sarkar, A. Manal, R. Kumar, Sudip Chakraborty*, R. Ahuja, R. Srivastava*, *Unveiling and Understanding the Remarkable Enhancement in the Catalytic Activity by the Defect Creation in UIO-66 during the Catalytic Transfer Hydrodeoxygenation of Vanillin with Isopropanol*, Applied Catalysis B, **325**, 122385(2022). [Impact Factor: 24.3]

4. K. Sakhatskyi, R. John, A. Guerrero, S. Tsarev, S. Sabisch, Tisita Das, G. Matt, S.Yakunin, I.Cherniukh, M.Kotyrba, Y. Berezovska, M. Bodnarchuk, Sudip Chakraborty, J. Bisquert, Maksym Kovalenko, *Assessing the Drawbacks and Benefits of Ion migration in Lead Halide Perovskites*, ACS Energy Letters, **7**, 3401 (2022). [Impact Factor: 24.0]

5. S. Kaur, M. Kumar, D. Gupta, P. P. Mohanty, T. Das, Sudip Chakraborty, R. Ahuja, T. Nagaiah, *Efficient CO2 utilization and sustainable energy conversion via aqueous Zn-$CO_2$ batteries*, Nano Energy, **109**, 108242(2023). [Impact Factor: 19.1]

6. R. Belgamwar, R. Verma, T. Das, Sudip Chakraborty, P. Sarawade, V. Polshettiwar, *Defects Tune the Strong Metal-Support Interactions in Copper Supported on Defected Titanium Dioxide Catalyst for $CO_2$ Reduction*, Journal of the American Chemical Society (JACS), **145**, 8634 (2023). [Impact Factor: 16.4]

7. D. Gupta, A. Kafle, S. Kaur, P. P. Mohanty, T. Das, Sudip Chakraborty, R. Ahuja, T. Nagaiah, *High yield selective electrochemical conversion of $N_2$ to $NH_3$ via morphology controlled silver phosphate under ambient conditions*, Journal of Materials Chemistry A, **10**, 20616 (2022). [Impact Factor: 14.5]

8. X. Guan, M. Fawaz, R. Sarkar, C. Lin, Z. Li, Z. Lei, N. Dharmarajan, P. Kumar, X. Zhang, J. Yang, L. Hu, T. Wu, Sudip Chakraborty, J. Yi, A. Vinu,*S-doped $C_3N_5$ derived from thiadiazole for efficient photocatalytic hydrogen evolution*, Journal of Materials Chemistry A, in press (doi: 10.1039/D3TA00318C) (2022). [Impact Factor: 14.5]

9. S. Bhowmick, A. Sarangi, C. Moi, Sudip Chakraborty, M. Qureshi, *Diffusion mediated morphological transformation in bifunctional complex for enhanced electrochemical water splitting*, ACS Applied Materials Interfaces, **14**, 52204 (2022). [Impact Factor: 10.4]

10. N. Kitchamsetti, M. Samtham, P. Didwal, D. Kumar, D. Singh, S. Bimli, P. Chikatea, D. Bashaa, S. Kumar, C. Park; Sudip Chakraborty*, R. Devan*, *Theory abide experimental investigations on morphology driven enhancement of electrochemical energy storage performance for manganese titanate perovskites electrodes* Journal Power Sources, **538**, 231525 (2022). [Impact Factor: 9.8]

11. S. Gratious, A. Karmakar, D. Kumar, S. Kundu, Sudip Chakraborty, S. Mandal, *Incorporating Au-11 Nanocluster on $MoS_2$ Nanosheet Edges for Promoting Hydrogen Evolution Reaction at the Interface* Nanoscale, **14**, 7919 (2022). [Impact Factor: 8.3]

12. T. Sheikh, G. Anilkumar, T. Das, A. Rahman, Sudip Chakraborty*, A. Nag*, *Combining $\pi$-Conjugation and Cation-$\pi$ Interaction for Water Stable and Photoconductive One-Dimensional Hybrid Lead Bromide*, Journal of Physical Chemistry Letters, **114**, 1870 (2023). [Impact Factor: 6.9]

13. S. Tomar, P. Sen, Sudip Chakraborty*, *Single Atom Functionalization in Vanadium Dichalcogenide Monolayers: Towards Enhanced Electrocatalytic Activity* Sustainable Energy Fuels, **6**, 5337 (2022). [Impact Factor: 6.8]

14. T. Das, Sudip Chakraborty, P. Sen, *Complementary Effect of Functionalization, Vacancy Defects and Strain Engineering in activating the basal plane of monolayer $FePS_3$ for HER*, Sustainable Energy & Fuels, **6**, 5621 (2022) [Impact Factor: 6.8]

15. S. Kumaravel, D. Kumar, S. Sankar, A. Karmakar, R. Madhu, K. Bera, H. Dhandapani, S. Nagappan, Sudip Chakraborty*, S. Kundu*, *Vacancy Fused Multiple Layers of Copper Sulfoselenide Superstructures: A Propitious HER Electrocatalyst in Acid,*, Catalysis Science & Technology, **13**, 694 (2023). [Impact Factor: 6.2]

16. R. Wadhwa, A. Kumar, R. Sarkar, P. P. Mohanty, D. Kumar, S. Deswal, P. Kumar, R. Ahuja, Sudip Chakraborty, M Kumar, *Pt nanoparticles sensitized vertical aligned large area $MoS_2$ flakes for enhanced and selective H2 sensing at room temperature*, ACS Applied Nano Materials, **6**, 2527 (2023). [Impact Factor: 6.1]

17. A. Karmakar, T. Das, K. Karthick, S. Kumaravel, S. Sankar, R. Madhu, Sudip Chakraborty*, S. Kundu, *Tuning the electronic structure of Ni vacancy enriched AuNi spherical nanoalloy via electrochemical etching for water oxidation study in alkaline and neutral medium*, Inorganic Chemistry, **21**, 8570 (2022). [Impact Factor: 5.4]

18. S. Singh, A. Neveu, K. Jayanthi, Tisita Das, Sudip Chakraborty, A. Navrotsky, V. Pralong, P. Barpanda, *Facile Synthesis and Phase Stability of Cu-based $Na_2Cu(SO_4)_2.xH_2O$ (x=0-2) Sulfate Minerals as Conversion type Battery Electrodes*, Dalton Transactions, **51**, 11169 (2022). [Impact Factor: 4.6]

19. N Sethulakshmi, S. Nellaiappan, Ponnappa K.P., T. Das, S. Irusta,, Sudip Chakraborty*, S. Sharma*, *Nanocoral Architecture for Enhanced Hydrazine Assisted Water Oxidation: Insight from Experiment and Theory*, Journal of Electroanalytical Chemistry, **922**, 116776 (2022). [Impact Factor: 4.6]

20. P. Elango, S. Kabir, Ponnappa K. P., M. Low, M. Yang, Sudip Chakraborty, S. Walia, S. Sriram, M. Bhaskaran, *Vanadium Dioxide-based Miniaturised Thermal Sensors: Humidity Effects on Phase Change and Sensitivity*, ACS Applied Electronic Materials **4**, 5456 (2022). [Impact Factor: 4.5]

21. P. P. Mohanty, R. Ahuja, Sudip Chakraborty*, *Progress and Challenges in Layered Two-dimensional Hybrid Perovskites*, Nanotechnology, **33**, 292501 (2022) (Invited Perspective Article [Impact Factor: 3.9]

## Preprints:

1. Manasa G. B., Sudip Chakraborty*, *Tuning Optoelectronic Properties of KBaTeBiO6 through Cationic Interplay of Bismuth-Antimony in Composition Space* (Under Revision).

2. S. H. Mir, Sudip Chakraborty*, *Pressure Driven Optical Transitions in Non-toxic Double Perovskite with a Columnar-ordered B-Site Cation: Piezochromism without Phase Transformation* (Under Revision).

3. D. Kumar, Sudip Chakraborty*, *Augmenting Bi-functional Catalytic Efficiency in Vanadium based Pseudo-monolayer: Chemical Paradigm of Functionalization* (Under Revision).

4. S. Tomar, Sudip Chakraborty*, *Chalcogen Composition Driven Enhancement of Catalytic Efficiency in Zirconium based Monolayers: Insight from Reaction Coordinate* (Under Revision).

5. D. Gupta, A. Kafle, P. P. Mohanty, T. Das, Sudip Chakraborty, R. Ahuja, T. Nagaiah, *Self-powered NH3 synthesis by trifunctional $Co_2B$ based high power density Zn-air batteries* (Under Revision).

6. A. Kulkarni, R. Sarkar, S. Akel, M. Haeser, B. Klingebiel, M. Wuttig, Sudip Chakraborty*, M. Saliba*, T. Kirchartz*, *A Universal Strategy of Perovskite Ink-Substrate Interaction to Overcome the Poor Wettability of a Self-Assembled Monolayer for Reproducible Perovskite Solar Cells* (Under Revision).

7. S. H. Mir, Sudip Chakraborty*, *Spin Texture Evolution of Rashba Splitting under Pressure: A Case Study of Inorganic Nitride Perovskite* (Under Review).

8. S. H. Mir, Sudip Chakraborty*, *Pressure Driven Band Gap Narrowing in $Rb_2AgPdCl_5$: Towards Shockley–Queisser limit of Lead Free Double Perovskite* (Under Review).

9. D. Nilegave, A. Sarangi, S. Rondiya, G. Shaikh, M. Nasane, S. Jathar, S. Barma, K. Kore, S. V. Ghaisas, Sudip Chakraborty*, A. Funde*, *Tuning Band-edge Alignment in $Cu_2NiSnS_4$-CdS hetero-interface for Enhanced Water Splitting Activity: Experiment meets Electronic Structure* (Under Review).

10. A. Ajayakumar, C. Muthu, Manasa G. B., A. Dev, Sudip Chakraborty*, A. Saeki, L.Dou, C. Vijayakumar*, *Zero-dimensional Tin Halide Perovskite with Anisotropic Photoconductivity andHigh Charge Carrier Lifetime for Selective Deep-UV Photodetection* (Under Review).

11. Y. Alishan, Anitha B, A. Joseph, Aparna R., R. Sarkar, Sudip Chakraborty*, S. Mandal*, M. Namboothiry* *Interface engineering using metal nanoclusters for enhanced charge extraction and photovoltaic performance in organic solar cells* (Under Review).

12. P. Mishra, R. Kumar, Sudip Chakraborty*, *Theoretical Investigation of electrocatalytic activity in niboium based chalcogenide monolayers under the influence of functionalization and vacancy defect* (Under Review).

## Conference/Workshops Attended:

1. HBNI Interaction Meeting on Condensed Matter Physics (HBNI-im-CMP), SINP, Kolkata June 23-24, 2022.
2. QMAT-2022(Quantum Condensed Matter), IIT Kanpur, September 18-22, 2022.
3. YIMQCMT-2022, NISER, Bhubaneswar, October 29 - November 1, 2022.
4. Designing Catalysts on Computer(DCC - 2022), IACS, Kolkata, December 2-3, 2022.
5. International Workshop on Materials Under Extreme Conditions, CTFM, IIT Madras, December 5-6, 2022.
6. International School of CMSMEE, JNCASR Bangalore, December 12-14, 2022.
7. DAE-SSPS Conference, 2022, December 18 -22, 2022.
8. Indo-German Joint International Conference (PDC-IT), IIT Madras, March 8-11, 2023.
9. Indo-German Joint International Conference (DEEPT-23), SRM University, March 12-15, 2023.

## Invited Lectures/Seminars:

1. HBNI Interaction Meeting on Condensed Matter Physics (HBNI-im-CMP), SINP, Kolkata to represent HRI CMP Research, June 23-24, 2022.
2. Invited Talk in QMAT-2022(Quantum Condensed Matter), IIT Kanpur, September 18-22, 2022.
3. Resource Person for Refresher Course (Online Inivited Talk), Faculty Development Programme, University of Hyderabad, October 22, 2022.
4. Invited Talk in YIMQCMT-2022, NISER, Bhubaneswar, October 29 - November 1, 2022.
5. Invited Talk in Research Institute for Sustainable Energy (RISE), TCG-CREST, Kolkata, December 1, 2022.
6. Invited Talk in Designing Catalysts on Computer(DCC - 2022), IACS, Kolkata, December 2-3, 2022.
7. Invited Talk in International Workshop on Materials Under Extreme Conditions, CTFM, IIT Madras, December 5-6, 2022.
8. Invited Talk in International School of CMSMEE, JNCASR Bangalore, December 12-14, 2022.
9. Invited Talk in DAE-SSPS Conference, 2022, December 18 -22, 2022.

10. Invited Talk in Indo-German Joint International Conference (PDC-IT), IIT Madras, March 8-11, 2023.
11. Invited Talk in Indo-German Joint International Conference (DEEPT-23), SRM University, March 12-15, 2023.

## Academic recognition/Awards:

1. DST Solar Challenge Award, 2022.
2. Phase-II Funding for Centre of Excellence, CTFM.
3. Invited to be Editorial Board Member, Energy Advances, Royal Society of Chemistry(RSC), February, 2023.
4. Invited to be Editorial Board Member, Chemistry of Inorganic Materials, Elsevier, August, 2022.
5. Invited to be Editorial Board Member, Graphene and 2D Materials, Springer-Nature, August, 2022.
6. Visiting Professorship in GICAN, University of Newcastle, NSW, Australia, June, 2022.

## Other Activities:

1. Teaching course: Numerical Methods and Projects for M.Sc and Ph.D students (Republic Term: January 2023 to May 2023)
2. Supervision: 6 Ph.D, 3 Postdocs and 3 Masters Students
3. Reviewer of External Funding: Ministry of New and Renewable Energy (MNRE), Govt. of India
4. Reviewer Ph.D Thesis: University of Pune (SPPU), India
5. Organizing Activity: International Conference on Advances in Renewable Energy (CARE-23), organised by HRI and TIFR-Hyderabad, February 2-4, 2023.
6. Editorial Activity:
   Editorial Board Member of (i) Energy Advances (Royal Society of Chemistry), (ii) Chemistry of Inorganic Materials (Elsevier) and (iii) Graphene and 2D Materials (Springer-Nature).
7. Reviewer Activity: Nano Letters, ACS Energy Letters, JACS, Nano Energy, Chemistry of Materials, ACS Applied Energy Materials
8. Administrative Activity: Convener of Institute Colloquium Committee. Committee Member of Computing Cluster, Academic Infrastructure and Outreach Activity. I also manage HRI Social Media. I am one of the Founding Members of Perovskite Society of India.

# Tapas K Das

## Research Summary:

My broad areas of research are astrophysics, general relativity, and dynamical systems. For last one year, I have been working on black hole accretion, emergent gravity phenomena, theory of traversable wormholes, and application of the theory of dynamical systems in large scale fluid flow under strong gravity. With one of my Ph.D. students and external collaborators, I have started exploring the emergence of nonlinearity and chaotic traits of the dynamics of axially symmetric flow around black holes, and its signatures as revealed in the observed spectra.

I, along with my Ph.D. students and my post doctoral fellows, made two important contributions through our works published in the last one year, which are as follows:

In a set of two papers published in the Physical Review D Letters (Erstwhile Physical Review D Rapid Communication) and Physical Review D, we have demonstrated that an emergent space time can be obtained through nonlinear perturbation of arbitrary order of a transonic flow. As of now, every single work in the literature (on analogue gravity phenomena) constructs the black hole like analogue space time within flowing fluid by linearly perturbing the flow. We have explicitly demonstrated that such analogue space time can be produced even for nonlinear perturbation of higher orders. This proves that the emergent gravity phenomena is not an artifact of the linear perturbation process, rather it has a much deeper physical significance compared to what had been believed in the literature before our works. Our works in this direction have attracted attention in the community and has been highlighted by Nature (journal). One can go through the article published in Nature highlighting our works, the corresponding article, titled 'Model shows how to create a black hole in a lab', was published as a Nature highlights in the journal Nature on $29^{\text{th}}$ of August, 2022. The corresponding URL of the article is

https://www.nature.com/articles/d44151-022-00093-7

In another series of published works, we have demonstrated, for the first time in the literature as we believe, how identify and classify the horizons in the emergent space time using the analogue Carter-Penrose diagrams. For the first time the construction of the compactified Causal structures have been used for study of analog spacetime embedded within a natural large scale fluid flow under the influence of strong gravity. Such works will be helpful in future to understand the natures of the analogue black hole horizons in various emergent gravity systems, as we believe.

In addition to the aforementioned works, we have devised an elegant technique which enables one to estimate, completely analytically (without any numerical computation) the multi transonic properties and the nature of related bifurcation phenomena for matter flow in accretion disc around non-spinning black holes.

We have also started working on astrophysical jets in connection to certain type of AGNs, and on traversable acoustic wormholes, which will be reported in the next academic report.

## Publications:

1. Mitra, Arpan Krishna., Chakraborty, Aishee., Tarafder, Pratik., & Das, Tapas K., *Multi-criticality and related bifurcation in accretion discs around non-rotating black holes – an analytical study*, General Relativity and Gravitation, **Volume 54, Issue 11, article id.149**, November, (**2022**).

2. Maity, Susovan.,Shaikh, Md. Arif., Tarafdar, Pratik., & Das, Tapas K., *Carter-Penrose diagrams for emergent spacetime in axisymmetrically accreting black hole systems*, Physical Review D, **Volume 106, Issue 4, article id.044062**, August, (**2022**).

3. Fernandes, Karan., Maity, Susovan., & Das, Tapas K., *Dynamical spacetimes from nonlinear perturbations*, Physical Review D Letters, **Volume 106, Issue 2, article id.L021701**, July, (**2022**).

4. Fernandes, Karan., Maity, Susovan., & Das, Tapas K., *Dynamical analogue spacetimes in non-relativistic flows*, Physical Review D, **Volume 106, Issue 2, article id.025020**, July, (**2022**).

## Preprints:

1. Maity, Susovan.,Shaikh, Md. Arif., Tarafdar, Pratik., Ghose, Souvik, & Das, Tapas K., *Influence of the flow thickness on acoustic surface gravity for accreting black holes*, Physical Review D, **Under Review**, Manuscript Number DC13575, (**Submitted on 27$^{\text{th}}$ of March, 2022**)

## Conference/Workshops Attended:

1. *Exploring The Cosmos 2023: A National Seminar on Relativistic Universe*, organized by, and at took place at High Energy & Cosmic Ray Research Centre University of North Bengal, during the period

## Visits to other Institutes:

1. Surendranath College, University of Calcutta, September 2022.
2. Bhairab Ganguly College, West Bengal State University, January, 2023.
3. Lady Brabourne College, University of Calcutta, February, 2023.
4. High Energy & Cosmic Ray Research Centre, University of North Bengal, February, 2023.
5. Visva-bharati University, Santiniketan, March 2023.
6. Physics and Applied Mathematics Unit, Indian Statistical Institute, Kolkata (several times).
7. Ramakrishna Mission Vivekananda Centenary College, Kolkata (several times).
8. St. Xavier's College, Kolkata (several times).

## Invited Lectures/Seminars:

1. *Black Holes*, a popular lecture for the college and the university students on the occasion of the Department of Atomic Energy Azadi Ki Amrit Mahotsav iconic week held at HRI, Prayagraj in September 2023.

2. *Supermassive Black Holes in Astrophysics*, public lecture delivered at University of North Bengal, February, 2003.

3. *Massive Black Holes at the centres of the galaxies*, Colloquium presented at Visva-bharati University, Santiniketan, in March 2023.

4. As a part of the public outreach programme, I am involved in advocating the idea of the persuasion of higher education in mother tongue. I use to deliver lectures on popular topics in astrophysics in general, in Bengali language, at several schools and colleges in West Bengal upon invitation. Following is a list such talks I delivered at various undergraduate colleges in last one year. The duration for all such public lectures in Bengal were two hours, including an extensive discussion and question answer sessions:

   (a) Public lecture in Bengali on the connection of the study of astronomy with various other branches of knowledge, i.e., philosophy and history of sciences, fine arts (classical European paintings), and literature, at Surendranath College, Kolkata , in September 2023.

   (b) On the history of the discovery of giant black holes in the universe, a public lecture in Bengali at the Lady Brabourne College, University of Calcutta, in February, 2023.

   (c) On general overview of astrophysical black holes, at Bhairab Ganguly College, West Bengal State University, January, 2023.

## Other Activities:

1. **Interview in Television:**

   I have been interviewed by Doordorshan (DD1) to discuss about the state of the art research on black hole astrophysics. The programme has been telecast in two episodes, with duration of thirty minutes for each episode. The YouTube links for the programmes are available at:

   (a) https://youtu.be/7gk_80Vd8H0

   (b) https://youtu.be/2oVmkPrzTVA

2. I served as the thesis examiner of a Ph.D. candidates which thesis was submitted in Jadavpur University. The works presented in the aforementioned thesis was on nonlinear dynamics.

3. Taught Mathematical Methods and Dynamical systems, two one semester courses at the M.Sc. course as conducted by HRI.

4. Supervised several visiting students (VSRP) and supervised one student for his six month's masters thesis programme.

5. Several M.Sc. students and Ph.D. candidates from HRI worked under my supervision for various projects.

6. Served as the member of the medical committe and the foreign travel committee of HRI.

7. Wrote post editorial articles in various noted Bengali Newspapers, in **Anandabazar Patrika**, for example, on different topics releted to higher education and its social impact.

# Aditi Sen De

## Research Summary:

During 2022-23, my works on quantum information science include designing efficient quantum devices in implementable mediums, characterization of resources required to build quantum technologies, understanding dynamical states of quantum many-body systems with the help of the concepts from quantum information theory, and quantum communication networks and their possible implementations via quantum optical systems.

In the last few decades, the rapidly emerging field of quantum thermodynamics has offered the prospect of unravelling fundamental laws of miniaturized quantum systems, including thermal devices such as quantum batteries, quantum thermal transistors, diodes and quantum refrigerators. On one hand, we propose a design of a quantum refrigerator by using quantum spin systems with nearest-neighbour interactions, namely the quantum XYZ and the bilinear-biquadratic (BB) models and we introduce a definition of local temperature for a spin-j system that uses the minimum distance between the time-evolved state of the system and a canonical thermal state to quantify the performance of the refrigerator. On the other hand, we go beyond finite dimensional systems to provide an architecture of a multimode quantum battery by using continuous variable (CV) systems. Moreover, a quantum refrigerator with an arbitrary number of qubits in a one-dimensional array that interacts through variable-range XY interactions is designed based on repeated evolution followed by a measurement of the single accessible qubit.

Another important avenue is to quantify quantum resources which are responsible for obtaining advantages in quantum technologies. We investigate the overall pattern in entanglement transformation via local operations and classical communication obtained from typical pairs of states and catalysts. We also develop a resource theory of a set of non-absolutely separable states where absolutely separable states which are free states cannot be made entangled via global unitary operations.

Since it is not possible to control all the qubits in the current generation of quantum hardware, thereby lacking scalability, identifying systems having a finite number of pairing interactions which can generate entanglement-like systems with long-range interaction is important. In one of our works in 2022-23, we report such systems in one dimension. We also explore the dynamical states of a non-Hermitian model which is effectively a Hermitian system undergoing decoherence.

Photons are one of the important platforms for implementing quantum communication protocols in which entanglement is the key ingredient. We propose a design of a quantum dense coding network with an arbitrary number of senders and a single receiver using continuous variable systems which can be realized in currently available technologies. Moreover, we provide a deterministic gate-based method to create multipartite entanglement which is also shown to be robust against imperfections during gate implementations.

## Publications:

1. T.K. Konar, S. Ghosh, A.K. Pal, and A. Sen(De), *Beyond Qubits: Building Quantum Refrigerators in Higher Dimensions*, **Phys. Rev. A 107,** 032602 (2023) (arXiv:2107.11668).

2. L.G. C. Lakkaraju, S. Ghosh, D. Sadhukhan and A. Sen(De), *Can a finite range Hamiltonian mimic quantum correlation of a long-range Hamiltonian?*, **Phys. Rev. A 106,** 052425 (2022) (arXiv:2206.09199).

3. A. Patra, R. Gupta, S. Roy, T. Das, and A. Sen(De), *Quantum Dense Coding Network using Multimode Squeezed States of Light*, **Phys. Rev. A 106,** 052607 (2022) (arXiv:2203.06684).

4. P. Haldar, R. Banerjee, S. Mal and A. Sen(De), *Limits of network nonlocality probed by time-like separated observers*, **Phys. Rev. A 106,** 052413 (2022) (arXiv:2203.05353).

5. R. Gupta, A. Maity, S. Mal and A. Sen(De), *Statistics of Entanglement Transformation with Hierarchies among Catalysts*, **Phys. Rev. A 106**, 052402 (2022) (arXiv:2202.01540).

6. T.K. Konar, S. Ghosh, and A. Sen(De), *Refrigeration via purification through repeated measurements*, **Phys. Rev. A 106**, 022616 (2022) (arXiv:arXiv:2206.00633).

7. T. K. Konar, L.G.C.Lakkaraju S. Ghosh, and A. Sen(De), *Quantum Battery with Ultracold Atoms: Bosons vs. Fermions*, **Phys. Rev. A 106**, 022618 (2022) (arXiv:2109.06816).

8. P. Haldar, R. Banerjee, S. Ghosh, A.K. Pal, and A. Sen (De), *Circulating Genuine Multiparty Entanglement in Quantum Network*, **Phys. Rev. A 106**, 032604 (2022) (arXiv:2112.10122).

9. A. Patra, R. Gupta, S. Roy and A. Sen(De), *Significance of fidelity deviation in continuous variable teleportation*, **Phys. Rev. A 106** , 022433 (2022) (arXiv:2203.06684).

10. R. Banerjee, A.K. Pal and A. Sen(De), *Hierarchies of localizable entanglement due to spatial distribution of local noise*, **Phys. Rev. Research 4**, 023035 (2022) (arXiv:2003.02175).

## Preprints:

1. T Anuradha, A. Patra, R. Gupta, A. Rai, A. Sen(De), *Production of genuine multimode entanglement in circular waveguides with long-range interactions*, arXiv:2303.15137.

2. P. Halder, R. Banerjee, S. Roy, and A. Sen(De), *Hybrid nonlocality via atom photon interactions with and without impurities*, arXiv:2302.11513.

3. A. I. Singh, A. Sen(De), and U. Sen, *Polynomial representation for multipartite entanglement of resonating valence bond ladders*, arXiv:2302.09383.

4. S.K. Hazra, and A. Sen(De), *Hierarchies among Genuine Multipartite Entangling Capabilities of Quantum Gates*, arXiv:2302.06574.

5. L.G.C. Lakkaraju, S. K. Halder, and A. Sen(De), *Predicting Topological Quantum Phase Transition via Multipartite Entanglement from Dynamics*, arXiv:2212.13252.

6. K. Das Agarwal, T.K. Konar, L.G.C. Lakkaraju, and A. Sen(De), *Detecting Exceptional Point through Dynamics in Non-Hermitian Systems*, arXiv:2212.12403.

7. A. Patra, A. Maity, and A. Sen(De), *Resource Theory of Non-absolute Separability*, arXiv:2212.11105.

8. A. Muhuri, R. Gupta, S. Ghosh, A. Sen(De), *Superiority in dense coding through non-Markovian stochasticity*, arXiv:2211.13057.

9. T.K. Konar, A. Patra, R. Gupta, S. Ghosh, and A. Sen(De), *Multimode advantage in continuous variable quantum battery*, arXiv:2210.16528.

10. T.K. Konar, A. Maity, and A. Sen(De), *Classical correlations for Generic States are Fragile under Decoherence*, arXiv:2209.03334.

11. P. Halder, R. Banerjee, S. Mal, and A. Sen(De), *Manifestation of Rank-Tuned Weak Measurements Towards Featured State Generation*, arXiv:2208.09317.

## Conference/Workshops Attended:

1. Research Scholars' Days UGC-DAE Consortium for Scientific Research, Indore 5-6 Jan, 2023.

2. Young Quantum-2023, HRI, 15-18 February, 2023.

## Visits to other Institutes:

1. Visited IIIT Hyderabad, Jan 2023 (Presented a talk on Quantumm Networks).

## Invited Lectures/Seminars:

1. *Technologies in a Quantum World*, DAE's Iconic Week in Azadi ka Amrut Mahotsav (AKAM), HRI outreach program for Class XI and Class XII students, 27 August, 2022.

2. *Quantum technologies*, Research Scholars' Days UGC-DAE Consortium for Scientific Research, Indore 5-6 Jan, 2023.

## Academic recognition/Awards:

1. Selected as a Fellow of Indian National Science Academy.

## Other Activities:

1. Serving as a Member of the Gender in Physics Working Group of Indian Physics Association.
2. Taught qunatum mechanics course during Aug-Dec semester. Taught quantum information and computation -I and II courses.
3. Serving as the convenors of the medical committee, Internal complaint committee (ICC) and women's grievances at HRI.
4. Serving as referees in national and international journals.
5. Serving as members of the physics graduate committee, and Guest House / Pantry / Student Mess/housing committee.
6. Serving as editorial board members of J. Phys A and Pramana.
7. Mentors of master thesis of Monika (IISER Berhampur), several MSc, visiting and PhD students at HRI.
8. Served as a member of the Advisory Committee, YouQu-2023.

## AseshKrishna Datta

## Research Summary:

During the past year, the focus of my research was in trying to understand the implications of experimental results from the collider (the LHC) and the cosmology (dark matter and gravitational waves (GWs)) fronts. Primarily, these aim at understanding the prospects of the LHC in its search for Supersymmetry (SUSY), an appraisal of the viability of a strong first order electroweak phase transition in the early Universe (which is a prerequisite to Electroweak Baryogenesis (EWBG) that can explain the observed baryon asymmetry in the Universe), getting a sense of what these all mean to detection of GWs at future experiments, all in a connected way, in various SUSY frameworks.

In a recently published work (in collaboration with a faculty member from an Indian institute and two postdoctoral fellows from two different institutes) we had explored the nontrivial dependencies of the bottom and the tau Yukawa couplings on the parameters of a SUSY scenario like the Non-Holomorphic SUSY Standard Model (NHSSM) and their implications for the LHC. These are over and above their well-known dependencies on a parameter like $\tan\beta$ and are mostly driven by the nonholomorphic soft trilinear parameters like $A'_{b,\tau}$.

In another work which had recently been communicated, with my graduate student and others from another Institute, we had studied an enhanced LHC-sensitivity in the searches for the lighter electroweakinos when those arise in the cascade decays of the top squarks in a rather popular SUSY scenario like the $Z_3$-symmetric NMSSM. Novel signatures arise as further cascades of the electroweakinos now might involve relatively light singlet-like scalars which are rather characteristic of the NMSSM. Both conventional cut-based approach and machine learning techniques had been employed for a comparative study. Given that relatively light top squarks and electroweakinos constitute scenarios that are highly theoretically motivated on the 'naturalness' ground but, at the same time, receiving stringent lower bounds on their masses from the LHC experiments, exploiting their interplay and collective contributions had been found to constitute an interesting approach to sniff out the characteristic excitations of the scenario in one go or, in the absence of a signal, to push up the lower bounds on the masses of some of them in such a scenario.

In a different collaboration which involves my graduate student, one of my colleagues from a University abroad and her graduate student, we had been studying the prospects of EWBG in a $CP$-violating N2HDM. The project had taken a concrete shape and the preliminary results were being critically studied.

## Publications:


1. AseshKrishna Datta, with Utpal Chattopadhyay, Samadrita Mukherjee and Abhaya Kumar Swain, *Associated production of heavy Higgs bosons with a $b\bar{b}$ pair in the Nonholomorphic MSSM and LHC searches*, JHEP **08**, 113, (2022).

## Preprints:

1. AseshKrishna Datta, Monoranjan Guchait, Arnab Roy, Subhojit Roy, *Hunting electroweakinos and a light singlet scalar of the Z3-NMSSM in top squark decays at the LHC,* arXiv:2211.05905 [hep-ph].

## Conference/Workshops Attended:

1. "Workshop on BSM Physics", Institute of Physics, Bhubaneswar, India, August, 2022.
2. "International Meeting on High Energy Physics (IMHEP II)", Institute of Physics, Bhubaneswar, India, February, 2023.
3. "Frontiers in Particle Physics 2023", IISc., Bengaluru, India, March, 2023.
4. "Workshop on Particle Physics, Astrophysics and Cosmology", Shiv Nadar University, Delhi NCR, India, March, 2023.

## Visits to other Institutes:

1. Department of Physics, Shiv Nadar University, Delhi NCR, March, 2023.

## Invited Lectures/Seminars:

1. None. Had to decline a few invited talks as I had been busy dealing with some unpleasant circumstances at my workplace.

## Other Activities:

1. Had been supervising one graduate students towards his Ph.D. theses.
2. Had been serving the doctoral committees of several graduate students.
3. Served as a member of the Outreach Programme Committee and the Sports and Entertainment Committees at HRI.
4. Served as an examiner of a Ph.D. thesis from a reputed institution in India.
5. Could not commit to another request that I received for examining a Ph.D. thesis from another Institute of much repute for reasons mentioned earlier (see under "Invited Lectures/Seminars").
6. Had been in the panel of referees of various international journals.
7. Was not able to take part in several activities at the Institute for reasons mentioned earlier (see under "Invited Lectures/Seminars").

# Raj Gandhi

## Research Summary:

My work over the past academic year has focussed on understanding and interpreting the LSND, MiniBooNE , muon g-2 and the CDF W-mass measurements as signals originating in common new physics.

The strong statistical significance of an observed electron-like event excess in the MiniBooNE (MB) experiment, along with an earlier similar excess seen in the Liquid Scintillator Neutrino Detector (LSND), when interpreted in conjunction with recent MicroBooNE results may have brought us to the cusp of new physics discoveries. This has led to many attempts to understand these observations, both for each experiment individually and in conjunction, via physics beyond the Standard Model (SM). The possibility that the same new, non-oscillation physics explains both anomalies leads to new restrictions and requirements. An important class of such common solutions, consists of a heavy (MeVsub-GeV) sterile neutral fermion produced in the detectors, (via up-scattering of the incoming muon neutrinos), and subsequently decaying to photons or e+e pairs which mimic the observed signals. Such solutions are subject to strong demands from a) cross section requirements which would yield a sufficient number of total events in both LSND and MB, b) requirements imposed by the measured energy and angular distributions in both experiments and finally, c) consistency and compatibility of the new physics model and its particle content with other bounds from a diverse swathe of particle physics experiments. We found that these criteria often pull proposed solutions in different directions, and stringently limit the viable set of proposals which could resolve both anomalies. Our conclusions are relevant for both the general search for new physics and for the ongoing observations and analyses of the MicroBooNE experiment.

Additionally, in recent times, several experiments have observed results that are in significant conflict with the predictions of the Standard Model (SM). Both the Brookhaven and the Fermi- lab muon g  2 collaborations have measured values of this parameter which, while consistent with each other, are in conflict with the SM. Recently, the CDF II collaboration has reported a precision measurement of the W -boson mass that is in strong conflict with the SM prediction. It is worthwhile to seek new physics which may underly all four anomalies. In such a quest, the neutrino experiments could play a crucial role, because once a common solution to these anomalies is sought, LSND and MB, due to their highly restrictive requirements and observed final states, help to greatly narrow the multiplicity of new physics possibilities that are otherwise open to the W mass and muon g  2 discrepancies. Pursuant to this, earlier work has shown that LSND, MB and the muon g  2 results can be understood in the context of a scalar extension of the SM which incorporates a second Higgs doublet and a dark sector singlet. We showed that the same model leads to a contribution to the W mass which is consistent with the recent CDF II measurement. While the LSND, MB fits and the muon g  2 results help determine the masses of the light scalars in the model, the calculation of the oblique parameters S and T determines the allowed mass ranges of the heavier pseudo-scalar and the charged Higgs bosons as well as the effective Weinberg angle and its new range.

## Publications:

1. S. Roy, W. Abdallah and R. Gandhi, *"MiniBooNE Excess with a Light $Z'$ and a Second Higgs Doublet," Springer Proc. Phys.* **277**, *611-615 (2022) doi:10.1007/978-981-19-2354-8_111*

2. *W. Abdallah, R. Gandhi and S. Roy, "LSND and MiniBooNE as guideposts to understanding the muon $g-2$ results and the CDF II W mass measurement," Phys. Lett. B* ***840***, *137841 (2023) doi:10.1016/j.physletb.2023.137841 [arXiv:2208.02264 [hep-ph]].*

3. *W. Abdallah, R. Gandhi and S. Roy, 'A simple solution to the LSND, MiniBooNE and muon $g-2$ anomalies," PoS* ***EPS-HEP2021***, *193 (2022) doi:10.22323/1.398.0193*

4. *W. Abdallah, R. Gandhi and S. Roy, "Requirements on common solutions to the LSND and MiniBooNE excesses: a post-MicroBooNE study," JHEP* ***06***, *160 (2022) doi:10.1007/JHEP06(2022) [arXiv:2202.09373 [hep-ph]].*

## Collaboration Publications:

1. A. Abed Abud *et al.* [DUNE], *"Highly-parallelized simulation of a pixelated LArTPC on a GPU," JINST* ***18***, *no.04, P04034 (2023) doi:10.1088/1748-0221/18/04/P04034 [arXiv:2212.09807 [physics.comp-ph]].*

2. *A. Abed Abud et al. [DUNE], "Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a convolutional neural network," Eur. Phys. J. C* ***82***, *no.10, 903 (2022) doi:10.1140/epjc/s10052-022-10791-2 [arXiv:2203.17053 [physics.ins-det]].*

## Conference/Workshops Attended:

1. *International Meeting on HIGH ENERGY PHYSICS "(IMHEP 23)", 16th-22th February, 2023, Institute of Physics, Bhubaneshwar,*

2. *Royal Society Yusuf Hamied Workshop for India and theUK , Virtual event, 23-24 February 2023*

%endenumerate

## Invited Lectures/Seminars:

1. Invited Plenary talk, **"BSM Physics at Neutrino Detectors: Motivations and Examples"**, *International Meeting on HIGH ENERGY PHYSICS "(IMHEP 23)"*, 16th-22th February, 2023.

2. Opening Plenary talk, **'Overview of particle physics and importance of neutrinos'.**, Royal Society Yusuf Hamied Workshop for India and the UK , Virtual event, 23-24 February 2023.

## Other Activities:

1. Member, DUNE International Collaboration, Fermilab.
2. Member, Institutional Board, DUNE International Collaboration, Fermilab.

# Tathagata Ghosh

## Research Summary:

My main research focus in the past year has been on gravitational waves from a phase transition in the early Universe and searching for beyond the standard model physics at the upcoming Electron-Ion Collider (EIC). A brief description of the research carried out on these topics is given below.

In **arXiv: 2211.15640 [hep-ph]**, we study the prospect of simultaneous explanation of tiny neutrino masses, dark matter (DM), and the observed baryon asymmetry of the Universe in a $Z_3$-symmetric complex singlet scalar extended type-II seesaw model. The complex singlet scalar plays the role of DM. Analyzing the thermal history of the model, we identify the region of the parameter space that can generate a first-order electroweak phase transition (FOEWPT) in the early Universe, and the resulting stochastic gravitational waves (GW) can be detected at future space/ground-based GW experiments. First, we find that light triplet scalars do favor an FOEWPT. In our study, we choose the type-II seesaw part of the parameter space in such a way that light triplet scalars, especially the doubly charged ones, evade the strong bounds from their canonical searches at the Large Hadron Collider (LHC). However, the relevant part of the parameter space, where FOEWPT can happen only due to strong SM doublet-triplet interactions, is in tension with the SM-like Higgs decay to a pair of photons, which has already excluded the bulk of this parameter space. On the other hand, the latest spin-independent DM direct detection constraints from XENON-1T and PANDA-4T eliminate a significant amount of parameter space relevant for the dark sector assisted FOEWPT scenarios, and it is only possible when the complex scalar DM is significantly underabundant. In short, we conclude from our analysis that the absence of new physics at the HL-LHC and/or various DM experiments in the near future will severely limit the prospects of detecting a stochastic GW at future GW experiments and will exclude the possibility of electroweak baryogenesis within this model.

On the other hand, the future EIC at Brookhaven National Laboratory, along with its primary capacity to elucidate the nuclear structure, will offer new opportunities to probe physics beyond the Standard Model coupled to the electroweak sector. Among the best motivated examples of such new physics are new heavy neutral leptons (HNLs), which are likely to play a key role in neutrino mass generation and lepton number violation. In **JHEP 03 (2023) 020 [arXiv: 2210.09287 [hep-ph]]**, we study the capability of the EIC to search for HNLs, which can be produced in electron-proton collisions through charged current interactions as a consequence of their mixing with light neutrinos. We find that, with the EIC design energy and integrated luminosity, one is able to probe HNLs in the mass range of $1-100$ GeV with mixing angles down to the order of $10^{-4}-10^{-3}$ through the prompt decay signatures, and in the mass range of $1-10$ GeV with $|U_e|^2 \sim 10^{-6}-10^{-4}$ via the displaced decay signatures. We also consider the invisible mode where an HNL is undetected or decaying to dark sector particles. One could potentially probe heavy HNLs for mixing angles in the window $10^{-3}-10^{-2}$, provided SM background systematics can be brought under control. These searches

are complementary to other probes of HNLs, such as neutrino-less double-$\beta$ decay, meson decay, fixed-target, and high-energy collider experiments.

**ArXiv: 2209.13128 [hep-ph]** is a community report of physics beyond the Standard Model at present and future energy frontier experiments. In this report, our above work on HNL search at the EIC is included and highlighted in Section 10.1.1 and Figure 15.

## Publications:

1. **Heavy neutral leptons at the Electron-Ion Collider**
   B. Batell, T. Ghosh, T. Han, K. Xie;
   JHEP 03 (2023) 020 [arXiv: 2210.09287 [hep-ph]]

## Preprints:

1. **Report of the Topical Group on Physics Beyond the Standard Model at Energy Frontier for Snowmass 2021**
   T. Bose *et. al.*
   arXiv: 2209.13128 [hep-ph]

2. **Interplay among gravitational waves, dark matter and collider signals in the singlet scalar extended type-II seesaw model**
   P. Ghosh, T. Ghosh, S. Roy
   arXiv: 2211.15640 [hep-ph]

## Conference/Workshops Attended:

1. **Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-based Quantum Sensors for HEP/NP**
   International Centre of Theoretical Sciences, Bengaluru, Karnataka, India,
   November 14-16, 2022

2. **A collaborative discussion on aspects of high energy collider physics**
   Indian Institute of Science Education & Research (Kolkata), Haringhata, West Bengal, India,
   November 17-18, 2022

3. **International Meeting on HIGH ENERGY PHYSICS (IMHEP II)**
   Institute of Physics, Bhubaneswar, Odisha, India,
   February 16-22, 2023

4. **Frontiers in Particle Physics 2023**
   Indian Institute of Science, Bengaluru, Karnataka, India,
   March 10-12, 2023

5. **Less Travelled Path to the Dark Universe**
   International Centre of Theoretical Sciences, Bengaluru, Karnataka, India,
   March 13-20, 2023

6. **Workshop on Particle physics, Astrophysics and Cosmology (WPAC2023)**
   Shiv Nadar University, Greater Noida, Delhi, India,
   March 21, 2023

## Visits to other Institutes:

1. Tata Institute of Fundamental Research, Mumbai, Maharashtra, India,
   February 5-10, 2023
2. Indian Institute of Science Education & Research (Pune), Pune, Maharashtra, India,
   February 12-15, 2023

## Invited Lectures/Seminars:

1. **[Invited Talk (Workshop)]** "Heavy Neutral Leptons at the Electron-Ion Collider"
   *A collaborative discussion on aspects of high energy collider physics*,
   Indian Institute of Science Education & Research (Kolkata), Haringhata, WB, India,
   November 17, 2022
2. **[Invited Seminar]** "Heavy Neutral Leptons at the Electron-Ion Collider"
   *Special Free Meson Seminar*,
   Tata Institute of Fundamental Research, Mumbai, Maharashtra, India,
   February 10, 2023
3. **[Invited Seminar]** "Heavy Neutral Leptons at the Electron-Ion Collider"
   Indian Institute of Science Education & Research (Pune), Pune, Maharashtra, India,
   February 14, 2023
4. **[Invited Talk (Conference)]** "Heavy Neutral Leptons at the Electron-Ion Collider"
   *Frontiers in Particle Physics 2023*,
   Indian Institute of Science, Bengaluru, Karnataka, India,
   March 10, 2023
5. **[Invited Talk (Conference)]** "Di-Higgs Blind Spots in Gravitational Wave Signals"
   *Less Travelled Path to the Dark Universe*,
   International Centre of Theoretical Sciences, Bengaluru, Karnataka, India,
   March 15, 2023
6. **[Invited Talk (Conference)]** "Di-Higgs Blind Spots in Gravitational Wave Signals"
   *Workshop on Particle physics, Astrophysics and Cosmology (WPAC2023)*,
   Shiv Nadar University, Greater Noida, Delhi, India,
   March 21, 2023

## Other Activities:

1. *Organized Talent Search Examination for both Mathematics and Physics (Class IX-X and XI-XII level)*
   Member of the HRI organizing committee
   Harish-Chandra Research Institute, Jhunsi, Uttar Pradesh, India,
   December 11, 2022

## Dileep Jatkar

### Research Summary:

For last few years, I have been woking on scattering amplitudes. We recently worked on the BCFW relations in N=2* theory. We are now generalising these results to loop computations in the N=4 theory at an arbitraary point in the Coulomb branch.

I also worked on the DBI counterterms showed that they have wider applications than demonstrated earlier.

### Publications:

1. Scattering Amplitudes and BCFW in N=2* Theory *Md. Abhishek, Subramanya Hegde, Dileep P. Jatkar, Arnab Priya Saha* Published in: SciPost Phys. 13 (2022) 008, e-Print: 2202.12204

### Preprints:

1. DBI Counter-Term and Black Hole Thermodynamics, *Dileep P. Jatkar, Upamanyu Moitra* e-Print: 2212.12545

### Conference/Workshops Attended:

1. *String Theory, Gravity and Cosmology* (SGC 2022) South Korea, Online June 22-24, 2022.

### Visits to other Institutes:

1. Visited SINP (August 22-25, 2022)
2. Visited ICTP (Sept 1–Oct 15, 2022)
3. Visited IMSc (Nov 8-30, 2022)

### Invited Lectures/Seminars:

1. BCFW in N=2* theory, *String Theory, Gravity and Cosmology* (SGC 2022) South Korea, Online June 22-24, 2022.

# Anshuman Maharana

## Research Summary:

I have worked on string phenomenology and cosmology. My major results have been the following. We have developed an understanding of the joint statistics of the cosmological constant and the SUSY breaking scale in the IIB landscape. We have obtained novel flux vacua with approximately flat directions. We have studied the effect of light massive relics on structure formation. We have also studied the possibility to search for light primordial blackholes by making use of ultra-high-frequency gravitational waves.

## Publications:

1. M. Cicoli, M. Licheri, A. Maharana, K. Singh and K. Sinha,
   *Joint statistics of cosmological constant and SUSY breaking in flux vacua with nilpotent Goldstino* JHEP **01** (2023), 013

2. M. Cicoli, M. Licheri, R. Mahanta and A. Maharana,
   *Flux vacua with approximate flat directions* JHEP **10** (2022), 086

3. G. Franciolini, A. Maharana and F. Muia,
   *The Hunt for Light Primordial Black Hole Dark Matter with Ultra-High-Frequency Gravitational Waves*
   Phys.Rev.D 106 (2022) 10, 103520

4. A. Banerjee, S. Das, A. Maharana and R. Kumar Sharma,
   *Signatures of Light Massive Relics on nonlinear structure formation*
   Mon.Not.Roy.Astron.Soc. 516 (2022) 2, 2038-2049

5. S. Das, A. Maharana and F. Muia
   *A faster growth of perturbations in an early matter dominated epoch: primordial black holes and gravitational waves*
   Mon. Not. Roy. Astron. Soc. **515** (2022) no.1, 13-21

6. I. Broeckel, M. Cicoli, A. Maharana, K. Singh and K. Sinha
   *On the Search for Low $W_0$*
   Progress of Physics 70 (2022) 6

## Preprints:

1. M. Cicoli, J. P. Conlon, A. Maharana, S. Parameswaran, F. Quevedo and I Zavala;
   *String cosmology: from the early universe to today*;
   Invited review submitted to Physics Reports, arXiv:2303.04819

2. S. Bhattacharya, K. Dutta, M. R. Gangopadhyay and A. Maharana, $\alpha$-attractor inflation: Models and Predictions arXiv:2212.13363 astro-ph.CO.

## Conference/Workshops Attended:

1. Discussion Meeting on Basic Science, HBNI Mumbai (April 2022)

## Visits to other Institutes:

1. Tata Institute of Fundamental Research, Mumbai (November 2022)

## Invited Lectures/Seminars:

1. Tata Institute of Fundamental Research, Mumbai (November 2022)
2. DST JSPS Online String Seminar Series (October 2022)
3. Discussion Meeting on Basic Science, HBNI Mumbai (April 2022)

## Other Activities:

1. Organised " String Seminar Days " @ HRI (Dec 21 - Dec 23, 2022)
2. Member, HBNI Board of Studies for Physical Sciences
3. Chief Vigilance Officer, HRI
4. Chief Patent Officer, HRI

# Pinaki Majumdar

## Research Summary:

The work by me and my students has been on (i) pump-probe dynamics in correlated systems, (ii) magnetism in the kagome Mott insulator, and (iii) dense polaron physics in strong coupling electron-phonon systems. Our pump-probe studies have been based on a factorised equation of motion approach that can access large spatial scales and long times. Our main discoveries include a 'suppression-revival' dynamics in charge ordered systems, and the emergence of 'hidden order' in frustrated Mott insulators. On the kagome problem we have found that while the $\sqrt{3} \times \sqrt{3}$ correlations well known in the Heisenberg limit survive in the intermediate coupling Hubbard model near the insulator-metal transition, the dynamical signatures are quite different. We no longer have a three peaked 'spin wave like' spectrum at a given momentum but a broader two peak spectrum, comparing better with the experiments. We are also studying strong coupling electron-phonon systems to infer multipolaron dynamics and the onset of charge order, using a dynamical scheme that handles the strong coupling as well as thermal effects. We have a detailed map of the low temperature behaviour in terms of changing density in one dimension and are working on the thermal effects as well as higher dimensions.

## Publications:

1. Nyayabanta Swain, Madhuparna Karmakar, and Pinaki Majumdar, *Spin-orbital liquids and insulator-metal transitions on the pyrochlore lattice*, Phys. Rev. B 106, 245114 (2022).

## Invited Lectures/Seminars:

1. *Correlated insulators out of equilibrium*, at QMAT 2022, at at I.I.T Kanpur in Nov 2022.

2. *Nonequilibrium dynamics in correlated quantum systems*, at SymPhy 2023 at I.I.T Bombay in Jan 2023.

## Other Activities:

1. Taught the courses on Statistical Mechanics and Condensed Matter Physics.

2. Participated in a review of the National Institute of Science Education and Research (NISER), Bhubaneswar.

# Santosh Kumar Rai

## Research Summary:

My research over the last year has continued to focus on aspects of non-observation of any distinct and clear signatures of models beyond the Standard Model (SM) of particle physics. The common and hopeful perception in the particle physics community was that the Large Hadron Collider (LHC) would be able to observe new phenomena very early and give us hints of BSM physics. Although the experiment has proved to be a huge success, quickly establishing the SM by observing the Higgs boson as early as in 2012, it has been unable to detect any signals which may be inconsistent with SM predictions or hint towards any of the new physics proposals one would have expected to see. We proposed and studied new BSM models which are consistent with SM predictions and still provide solutions to the unresolved problems in SM but can remain effectively hidden in experimental searches. The proposed models encompass additional discrete symmetries and/or extensions of the SM symmetry group structure. We studied the phenomenology of the new proposed models and propose ways to observe its feeble signatures at LHC and future linear colliders.

We also looked at signatures of vector like fermions in BSM models with additional discrete symmetry where one finds a dark sector that may provide new signatures of BSM physics and in the process also render experimental studies on some popular BSM exotics to be much weakly constrained by existing data. Such possibilities were considered in models with $S_3$ symmetries as well as left-right symmetric models. A detailed analysis was done to consistently search for parameter regions of the new models that could accommodate a dark matter candidate.

In another separate study we showed how one could distinguish signatures of different models having DM candidates in the final state and similar visible SM particles with limited kinematic characteristics separating the identity of the individual models. We proposed the use of beam polarisations at future linear electron-positron colliders that will be allow one to distinguish the models in a clear and robust way, even in the same final states.

We also propose a LHC analysis using fat jets to look for signatures of a universal seesaw model embedded in the left-right symmetry extension of the SM. These signatures are much more exotic and rich than the typical left-right models that give rise to neutrino mass via Type-I seesaw.

## Publications:


1. Nivedita Ghosh, Santosh Kumar Rai, Tousik Samui, *Collider Signatures of a Scalar Leptoquark and Vector-like Lepton in Light of Muon Anomaly*, Physical Review **D 107**, no.3, 035028 (2023).

2. Anjan Kumar Barik, Rafiqul Rahaman, Santosh Kumar Rai, *Distinguishing non-standard scalar and fermionic charged particles at future $e^+e^-$ collider* Physical Review **D 107**, no.3, 035002 (2023)

3. Waleed Abdallah, Anjan Kumar Barik, Santosh Kumar Rai, Tousik Samui, *Emergent new symmetry from the Higgs shadow*
Physical Review **D 107**, no.1, 015026 (2023).

4. Syamashis Dey, Purusottam Ghosh, Santosh Kumar Rai, *Confronting dark fermion with a doubly charged Higgs in the left–right symmetric model* European Physics Journal **C 82**, no.10, 876 (2022)

5. Indrani Chakraborty, Dilip K. Ghosh, Nivedita Ghosh, Santosh Kumar Rai, **"Signals for vector-like leptons in an $S_3$-symmetric 2HDM at ILC"** European Physics Journal **C 82**, no.6, 538 (2022)

## Preprints:

1. Atri Dey, Rafiqul Rahaman, Santosh Kumar Rai, *Fatjet signatures of heavy neutrinos and heavy leptons in a left-right model with universal seesaw at the HL-LHC*, [arXiv:2207.06857 [hep-ph]]

## Conference/Workshops Attended:

1. *Celebrating a decade of the Higgs (online)*, June 2022, TIFR Mumbai, India.

2. *Collaborative Discussion on Aspects of High Energy Physics*, November 2022, IISER Kolkata, India.

3. *Particle Physics - Phenomena, Puzzles, Promises*, November 2022, ICTS-TIFR Bengaluru, India.

4. *XXV DAE-BRNS HEP Symposium*, December 2022,, IISER Mohali, Punjab, India.

5. *IMHEP 2023:* Institute of Physics (IOP), Bhubaneswar, India, February, 2023.

6. *Frontiers in Particle Physics*, CHEP, IISc., Bengaluru, India, March, 2023.

## Invited Lectures/Seminars:

1. "Can Machine Learning give hints on the Inverse Problem?"; November 2022, IISER Kolkata, India.

2. *Summary of BSM Working Group Activity*, December 2022, XXV DAE-BRNS HEP Symposium, IISER Mohali, Punjab, India.

3. *Collider signals for a Universal Seesaw Model*; February 2023, Institute of Physics, Bhubaneswar, India (Plenary Session).

## Other Activities:

1. Taught M.Sc. course titled *Particle Physics*, Jan-May, 2022 (shared).
2. Teaching M.Sc. course titled *Particle Physics*, Jan-May, 2023.
3. Supervising Ph.d. of Mr. Anjan Kr. Barik and Mr. Shyamashish Dey.
4. Stand-in Supervisor of Ph.d. student Mr. Deepak Raikwal.
5. Member - NOC and BSM WG convener, December 2022, XXV DAE-BRNS HEP Symposium, IISER Mohali, Punjab, India.
6. External Referee, Ph.d. Thesis by Mr. Vishal Singh Ngairangbam, Physics Research Laboratory (PRL), Ahmedabad, India (2022).
7. External member in the Doctoral Committee of Mr. Rameswar Sahu, Institute of Physics (IOP), Bhubaneswar.
8. Invited external reviewer for PDF selection at IISER, Kolkata; March 2023. (online)
9. Invited Session Chair for *Frontiers in Particle Physics 2023*, CHEP, IISc. Bengaluru, March 2023.
10. Referee for journals Physical Review D, EPJC.
11. Co-ordinator, Regional Centre for Accelerator-based Particle Physics (RECAPP).
12. Member, Computer Committee, Faculty Appointment Committee.
13. Convener, Security Committee, HPC Cluster.

## Debraj Rakshit

## Research Summary:

I worked in the interface of quantum information and quantum many-body physics. The major themes were ultracold simulators, open quantum systems and quantum metrology. For example, we proposed a ultracold simulatior for understanding the exotic strongly correlated phenomena, such as flat-band induced superconductivity in magic-angle twisted bilayer structures, via the coupling between atomic sublevels, where the twist is achieved by a spatial modulation of this coupling. In another work we analyzed the quantum resource generation of capacitively-coupled multi-level transmon circuits surrounded by bosonic baths, within the Markovian limit. In a work related to quantum sensing we showed that the delocalization-localization transition in a quantum-many body (QMB) system is a compelling quantum resource for achieving quantum-enhanced sensitivity in parameter estimation.In a work related to quantum sensing we showed that the delocalization-localization transition in a quantum-many body (QMB) system is a compelling quantum resource for achieving quantum-enhanced sensitivity in parameter estimation. This was explicitly demonstrated by considering a Fermi lattice under quasi-periodic modulation that supports an energy-independent delocalization-localization transition.This was explicitly demonstrated by considering a Fermi lattice under quasi-periodic modulation that supports an energy-independent delocalization-localization transition.

## Publications:

1. T. Salamon, B. Irsigler, D. Rakshit, M. Lewenstein, T. Grass and R. Chhajlany, *Flat-band-induced superconductivity in synthetic bilayer optical lattices*, Physical Review B **106**, 174503 (2022).

## Preprints:

1. T. Ray, A. Ghoshal, D. Rakshit and U Sen, *Optimal quantum resource generation in coupled transmons immersed in Markovian baths*, arXiv:2303.16136.

2. A. Sahoo, U. Mishra and D. Rakshit, *Localization Driven Quantum Sensing*, arXiv:2305.02315.

## Conference/Workshops Attended:

1. "Quantum Information and Quantum Technology (QIQT-2023)", IISER Kolkata, Kolkata.

2. "Meeting On Statistical Physics and Complex Systems (MeetStatPhysIndia-2023), IIT Kharagpur, Kharagpur.

## Visits to other Institutes:

1. IIT Kharagpur, Kharagpur.

## Invited Lectures/Seminars:

1. "Ultracold quantum simulator", IISER Kolkata, Kolkata.
2. "Ultracold quantum simulator with focus on twistronics", IIT Kharagpur.

## Other Activities:

1. Organized conference: "Young Quantum (YouQu-2023)", Harish-Chandra Research Institute, Prayagraj.

# Prasenjit Sen

## Research Summary:

We continued with our research of materials for alternative, renewable energy; and understanding and design of magnetic materials. In collaboration with our experimental colleagues in TIFR Hyderabad, we studied how addition of polysaccharides to a carbon electrode enhances performance of Li-air batteries.

We have been exploring ways of activating the basal planes of the layered ternary tri-chalcogenide materials towards HER via DFT calculations.

We used materials data available from publicly available databases to train a series of Machine Learning models. Using a toolkit consisting of these models, we showed that the vast materials space can be explored very efficiently at a much less computational cost than performing DFT calculations on all possible materials. As an example, we undertook the exercise of identifying rare earth free permanent magnets. We identified 21 candidate materials, and discussed the possibility of their experimental synthesis.

We are developing a generative Machine Learning model which can 'inverse design' materials with desired target properties.

## Publications:


1. *Enhancing efficiency of the ternary tri-chalcogenide $MnPSe_3$ towards hydrogen evolution reaction by activating its basal plane*, Megha and P. Sen, Int. J Hyd. Energy, (https://doi.org/10.1016/j.ijhydene.2023.03.044).

2. *Polysaccharides Modified Cathodes for High-Capacity Rechargeable Non-Aqueous Li-$O_2$ Batteries*, P. Thakur, K. Alam, P. Sen and T. N. Narayanan, J Phys. Chem. Lett. **14**, 437 (2023).

3. *Complementary Effects of Functionalization, Vacancy Defects and Strain Engineering in Activating the Basal Plane of Monolayer $FePS_3$ for HER*, T. Das, S. Chakraborty and P. Sen, Sustainable Energy & Fuels **6**, 5621 (2022).

4. *Single Atom Functionalization in Vanadium Dichalcogenide Monolayers: Towards Enhanced Electrocatalytic Activity*, S. Tomar, P. Sen and S. Chakraborty, Sustainable Energy and Fuels **6**, 5337 (2022), (https://doi.org/10.1039/D2SE00985D).

5. *Role of Water Structure in Alkaline Water Electrolysis*, A. Guha, M. Sahoo, K. Alam, D. K. Rao, P. Sen and T. N. Narayanan, iScience **25**, 104835 (2022).

6. *Ionization Energies and Ground State Structures of Neutral $La_n$ ($n = 2 - 14$) Clusters: A Combined Experimental and Theoretical Investigations*, S. Bhattacharyya, D. Bandyopadhyay, S. Mukund, P. Sen and S. Nakhate, J Phys. Chem. A **126**, 3135 (2022).

## Preprints:

1. *A first-principles study on enhancing efficiency of the basal plane of $FePSe_3$ monolayer towards hydrogen evolution reaction*, Megha and P. Sen. (Submitted).

2. *Rational Design of Two-Dimensional Buckled-Hexagonal $Nb_2S_2$ Monolayer as an Efficient Anode Material for Ca-ion Batteries: A First-Principles Study*, S. Chowdhury, P. Mukherjee, P. Sen and B. C. Gupta (submitted).

3. *Leveraging available data for efficient exploration of materials space using Machine Learning: A case study for identifying rare earth-free permanent magnets*, S. Mal and P. Sen (Submitted).

4. *Establishing stability of the novel layered ternary tri-chalogenide materials: Emergence of a new generation of earth abundant HER catalysts*, K. Alam and P. Sen (Submitted).

## Conference/Workshops Attended:

1. *5th Annual Meeting of the Indian National Academy of Engineers (INAE) and National Academy of Engineers of Korea (NAEK)* in Kolkata, August, 2022.

2. Annual Conference on Quantum Condensed Matter (*QMAT 2022*) at Indian Institute of Technology, Kanpur, September 2022.

3. *Bridging the gap between Experiments and Atomistic Modeling*, theme meeting at BARC Mumbai, November, 2022.

4. *APCTP-IACS-SNBNCBS Workshop* at S. N. Bose National Centre for Basic Sciences on Computational Methods for Emergent Quantum Matter, November 2022.

## Visits to other Institutes:

1. IISER Kolkata, May 2022.

2. IIT Kanpur, September 2022.

3. S. N. Bose National Centre for Basic Sciences, Kolkata, November 2022.

4. BARC Mumbai, November 2022.

5. BARC Mumbai, December 2022.

## Invited Lectures/Seminars:

1. "Machine Learning assisted hierarchical screening Finding new magnetic materials", *5th INAE-NAEK Annual Meeting*, Kolkata, August 25-26, 2022.

2. "Hierarchical Filtering by Machine Learning: A route to identify new strong and hard magnets", Annual Conference on Quantum Condensed Matter (*QMAT 2022*), Indian Institute of Technology, Kanpur, September 2022.

3. "Materials for alternative energy: Synergy between atomistic modeling and experiments", *Bridging the gap between Experiments and Atomistic Modeling'*, theme meeting at BARC, November 4, 2022.

4. "DFT and beyond for materials design and discovery", perspective talk at the *APCTP-IACS-SNBNCBS Workshop on Computational Methods for Emergent Quantum Matter*, November 2022.

## Other Activities:

1. Organized International Conference on Advances in Renewable Energy (*CARE-2023*) in HRI during February 2-4, 2023.

2. Editorial Board Member of *Physica Scripta*.

3. Member Cluster Committee, Library Committee.

4. Teaching courses: Quantum Mechanics 3.

# Ujjwal Sen

## Research Summary:

In the previous academic year, I have been working on the general aspects of quantum information and computation, and its interface with other sciences. In particular, we have found a connection between quantum incompatibility and local quantum state discrimination. We have shown that incompatibility of local measurements provide advantage in local quantum state discrimination. In another work, we have proceeded towards finding a local version of the second law of thermodynamics within the quantum regime. We have identified a multiparty Spohn's theorem for mixed local Markovian and non-Markovian quantum dynamics.

We have recently started to work in the technologically important area of quantum metrology. We found instances of disorder-induced enhancement of precision in quantum metrology.

In another work, we have tried to assess the efficiency of quantum batteries in realistic noisy setups.

Further works by our group include recycled detection of genuine multiparty entanglement of unlimitedly stretched array of parties and arbitrarily long series of sequential observers, sequential detection of genuine multipartite entanglement is unbounded for entire hierarchy of number of qubits recycled, preservation of entanglement in local noisy channels, estimating phase transition of perturbed J1-J2 Heisenberg quantum chain in mixtures of ground and first excited states, quantum switch and nonclassicality in teleportation, restoring metrological quantum advantage of measurement precision in noisy scenario, polynomial representation for multipartite entanglement of resonating valence bond ladders, improved refrigeration in presence of non-Markovian spin-environment, fundamental speed limits on entanglement dynamics of bipartite quantum systems, and optimal quantum resource generation for coupled transmons immersed in Markovian baths.

## Publications:


1. Mahasweta Pandit, Chirag Srivastava, Ujjwal Sen, *Recycled entanglement detection by arbitrarily many sequential and independent pairs of observers*, Phys. Rev. A **106**, 032419 (2022).

2. Sheikh Parvez Mandal, Ahana Ghoshal, Chirag Srivastava, Ujjwal Sen, *Invariance of success probability in Grover's quantum search under local noise with memory*, Phys. Rev. A **107**, 022427 (2023).

3. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Correlation between resource-generating capacities of quantum gates*, Phys. Rev. A **107**, 032406 (2023).

4. Chirag Srivastava, Mahasweta Pandit, Ujjwal Sen, *Entanglement witnessing by arbitrarily many independent observers recycling a local quantum shared state*, Phys. Rev. A **105**, 062413 (2022).

5. Sohail, Ujjwal Sen, *Convolution algebra of superoperators and nonseparability witnesses for quantum operations*, J. Phys. A: Math. Theor. **55**, 295301 (2022).

6. Saronath Halder, Ujjwal Sen, *Separability and entanglement in superpositions of quantum states*, Phys. Rev. A **107**, 022413 (2023).

7. Saronath Halder, Ujjwal Sen, *Unextendible entangled bases and more nonlocality with less entanglement*, Phys. Rev. A **105**, L030401 (2022).

8. Ahana Ghoshal, Ujjwal Sen, *Heat current and entropy production rate in local non-Markovian quantum dynamics of global Markovian evolution*, Phys. Rev. A **105**, 022424 (2022).

9. Asmita Kumari, Ujjwal Sen, *Local preservation of no-signaling in multiparty PT-symmetric evolutions*, J. Phys. A: Math. Theor. **55** 185302 (2022).

10. Tanaya Ray, Ahana Ghoshal, Arun Kumar Pati, Ujjwal Sen, *Estimating quantum coherence by noncommutativity of any observable and its incoherent part*, Phys. Rev. A **105**, 062423 (2022).

11. Saubhik Sarkar, Ujjwal Sen, *Glassy disorder-induced effects in noisy dynamics of Bose-Hubbard and Fermi-Hubbard systems*, J. Phys. B: At. Mol. Opt. Phys. **55**, 205502 (2022).

## Preprints:

1. Tanaya Ray, Ahana Ghoshal, Debraj Rakshit, Ujjwal Sen, *Optimal quantum resource generation in coupled transmons immersed in Markovian baths*, arXiv:2303.16136.

2. Vivek Pandey, Swapnil Bhowmick, Brij Mohan, Sohail, Ujjwal Sen, *Fundamental speed limits on entanglement dynamics of bipartite quantum systems*, arXiv:2303.07415.

3. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Improved refrigeration in presence of non-Markovian spin-environment*, arXiv:2303.06712.

4. Ajit Iqbal Singh, Aditi Sen De, Ujjwal Sen, *Polynomial representation for multipartite entanglement of resonating valence bond ladders*, arXiv:2302.09383.

5. Kornikar Sen, Ujjwal Sen, *Noisy quantum batteries*, arXiv:2302.07166.

6. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Disorder-induced enhancement of precision in quantum metrology*, arXiv:2212.08523.

7. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Restoring metrological quantum advantage of measurement precision in noisy scenario*, arXiv:2211.05537.

8. Kornikar Sen, Adithi Ajith, Saronath Halder, Ujjwal Sen, *To share and not share a singlet: quantum switch and nonclassicality in teleportation*, arXiv:2211.02921.

9. Sayan Mondal, George Biswas, Ahana Ghoshal, Anindya Biswas, Ujjwal Sen, *Estimating phase transition of perturbed J1-J2 Heisenberg quantum chain in mixtures of ground and first excited states*, arXiv:2211.00623.

10. Priya Ghosh, Kornikar Sen, Ujjwal Sen, *Preservation of entanglement in local noisy channels*, arXiv:2209.04422.

11. Ahana Ghoshal, Ujjwal Sen, *Multiparty Spohn's theorem for mixed local Markovian and non-Markovian quantum dynamics*, arXiv:2208.13026.

12. Chirag Srivastava, Mahasweta Pandit, Ujjwal Sen, *Sequential detection of genuine multipartite entanglement is unbounded for entire hierarchy of number of qubits recycled*, arXiv:2208.08435.

13. Chirag Srivastava, Mahasweta Pandit, Ujjwal Sen, *Recycled detection of genuine multiparty entanglement of unlimitedly stretched array of parties and arbitrarily long series of sequential observers*, arXiv:2205.02695.

14. Ujjwal Sen, *Quantum entanglement and anthropology*, arXiv:2205.00843.

15. Kornikar Sen, Saronath Halder, Ujjwal Sen, *Incompatibility of local measurements provide advantage in local quantum state discrimination*, arXiv:2204.10948.

## Conference/Workshops Attended:

1. *Young Quantum - 2023 at HRI Prayagraj/Allahabad*, India, February 2023.

## Visits to other Institutes:

1. Indian Institute of Technology Palakkad, India, May 2022.

2. National Institute of Technology Sikkim, Ravangla, India, March 2023.

## Invited Lectures/Seminars:

1. *Towards a local version of the second law of thermodynamics*, `Seminar`, Indian Institute of Technology Palakkad, India, May 2023.

2. *Noisy quantum batteries*, `Seminar`, National Institute of Technology Sikkim, Ravangla, India, March 2023.

## Other Activities:

1. Supervised/-ing masters theses of Soubhadra Maiti (IISER Pune), Sheikh Parvez Mondal (IISER Pune), Soham Sau (Central Uni of Rajasthan), Pratha Dongre (IISER Mohali), Piyush Galav (IISER Pune), Soumyajit Pal (IISER Berhampur).

2. Mentored/-ing the visiting students, Samannay Bhuyan (IISER Mohali), Indrasen Ghosh (IIT Kharagpur), Arshid Lone (NIT Srinagar), Soumik Mahanti (IISER Kolkata), Priyankar Banerjee (IIT Guwahati), Subhra Priyadarshini (NIT Bhopal), Sangita Bera (Presidency Uni), Amrita Mandal (IIT Kharagpur), Vimlesh Vimal

(IIT Kanpur), Prabhat, Sudheer Kumar (IISER Pune), Parveen Kumar (Weizmann Institute of Science, Rehovot), Ayushi Dubal (BITS Pilani, Goa), Shivam Sawarn (Delhi Uni), Aziz Lokhandwala (Pandit Deendayal Energy Uni, Gandhinagar), Vipul Rai (NIT Mangalore), Mahasweta Pandit (Uni Gdańsk), Rakesh Kumar Saini (Macquarie University, Sydney), Pratha Dongre (IISER Mohali), Archi Gupta (NIT Nagpur), Rohit Shukla (IIT Varanasi), Abhyuidai S S (NIT Patna).

3. Courses given: Quantum Mechanics 2, Quantum Information and Computation 1, Quantum Information and Computation 2, Mathematical Methods 2.

4. Mentored final year projects of several HRI Masters and students and coursework projects of several HRI PhD students.

5. Mentored numerical analysis projects of several HRI Masters and PhD students.

6. Convener of computer committee, HRI; Member of Faculty Appointment committee, HRI.

7. Editorial boards/committees of Quantum, J. Phys. B, IOP SciNotes, Frontiers of Physics.

8. PI of QuEST project of DST, GoI.

# Subinay Dasgupta

## Research Summary:

In a previous paper, we have reported that the quantum phase transition occurring at zero temperature is reflected in the bahaviour of a measurable quantity at a high temperature. This quantity is the long-time limit of a rate function related to quantum fidelity. Recently, we have extended our work to cover XY chain, 1D Su-Schrieffer-Heeger model, the general case of Kitaev model on honeycomb chain, and topological nodal line semimetal. The amount of discontinuity for the first two case were derived analytically. We are now woking on the behaviour of a generic type of topological nodal line semimetal.

## Preprints:

1. P. Nandi, S. Bhattacharyya, and S. Dasgupta, Signature of quantum phase transition manifested in quantum fidelity at zero and finite temperatures, arXiv:2302.01795

## Other Activities:

1. One abstract has been accepted for oral presentation at the 28th International Conference on Statistical Physics (Statphys28) to be held in August 2023.
2. July 2022 to December 2022: Took a course on Mathematical Methods 1 for M.Sc First Semester students
3. January 2023 to May 20223: Took a course on Advanced Statistical Mechanics for M.Sc and PhD students

# Shyam Lal Gupta

## Research Summary:

Working in reseach collaboration with Dr. Diwaker (Dept. Higher Education, HP) and Dr. Karan Singh Vinayak (DAV College, Chandigarh) exploring Heusler alloys.

Further, use of AI in biomedical applications is being explored in collaboration with Dr. Manish Kumar Bajpai of IIITDM Jabalpur.

I am also a co-supervisor along with Dr. Vinayak to a PhD candidate registered at Punjab University Chandigarh.

## Publications:

1. Sumit Kumar, Diwaker, Shyam Lal Gupta, and Karan Singh Vinayak,*Ab initio study of the newly proposed full Heusler alloy Co2CuAl : Insights from DFT*, Materialstoday: Proceedings, in press [DOI:10.1016/j.matpr.2023.03.105]

2. Sumit Kumar, Diwaker, Shyam L. Gupta, Deepak Kumar, Karan Singh Vinayak, *Structural properties of novel potential spintronic material and Full-Heusler alloy Co2NbGe: First Principles investigation*, Materialstoday: Proceedings, in press [DOI:10.1016/j.matpr.2022.1

3. Sumit Kumar, Shyam L. Gupta, Diwaker, Karan Singh Vinayak *Structural properties of novel potential spintronics material and half Heusler alloy CoNbGe: First principle investigation* poster in National Conference on Natural Sciences-Exploration through Innovation (NCNSEI), May 27-28, 2022.

## Other Activities:

1. **Teaching:**

| M.Sc. Batch | Courses Taught |
|---|---|
| 2022-2024 | Lab I, Lab II, Electronics Theory |
| 2021-2023 | Lab I (backlog), Lab II, Electronics Theory, Lab III |
| 2020-2022 | Evaluation of Lab I and Lab II (backlog), Lab III |

2. **Academic events:**

   a) Hosted the lab visit of students visiting HRI during Aazadi Ka Amrit Mahotsav celebration week (Aug. 22 - 28, 2022)

   b) Demonstration of few Physics experiments in an event entitled ”Physics Learning through fun” for Harsha school children on Nov. 13, 2022.

3. **Administrative and Others:**

   a) Member of Institute’s Academic and Lab infra committee

   b) Member of Institute’s different Technical Evaluation Committees

   c) Member of Institute’s Transport committee

   d) Represented DAE in Swadeshi Shilp Mahotsav Prayagraj during Oct. 01st - 03rd, 2022 to showcase different research outcomes of DAE in the fields of Agriculture, Defence, Biomedical Applications, Water treatment and Waste management.

# Jayanta Dutta

## Research Summary:

During the last few months we have developed a semi-analytical model that includes the radiative feedback along with the Bondi-Hoyle accretion in order to understand the dynamics of the primordial protostars. The model can predict the upper bound on the mass of the accreting protostars within their parent gas clumps that are rotating with different strength. We have prepared the manuscript for re-submission in Astronomy and Astrophysocs. A second manuscript is on the way for submission.

In addition, for one year we are also working on a 3D simulation of rotating collapsing gas clumps using a modified version of Gadget-2 SPH code. This Numerical experiment is a challenging task to investigate the survival possibility of primordial stars. A Postdoc and three more students are working together on the survival probability of Pop III stars using a semi-analytical method.

## Publications:

1. Shubham P. Raghuvanshi and Jayanta Dutta
   The Astrophysical Journal, Volume 944, Number 1, Published 2023 February 14, 2023.
   https://iopscience.iop.org/article/10.3847/1538-4357/acac30

## Preprints:

1. Ref. : AA/2022/45489,
   2nd report is on 08/03/2023, First report on 10/12/2022
   Title: Effects of radiative feedback in Bondi-Hoyle accretion of primordial protostars within rotating collapsed gas clumps,
   Authors: S. Kundu, J. Dutta, S. Sur, J.S. Bagla

2. Radiative Feedback During Primordial Star Formation on Survival of Population III Stars Till Present Day,
   Authors: Yash Mehta, Jasjeet Singh Bagla, Jayanta Dutta, Sharanya Sur Submitted to the Journal of Astrophysics and Astronomy

3. Effect on Rotation on Survival rate of Pop III stars
   Jayanta Dutta and Shubham Raghuvanshi. Rejected from Astronomy and Astrophysics LETTER, with recommendation in publishing in Astronomy and Astrophysocs Journal, modifying/working on it.

## Visits to other Institutes:

1. MNNIT seminar: Feb 23
2. NISER seminar: March 10-13
3. SNBOSE visit : May 22-25

## Invited Lectures/Seminars:

1. SNBOSE invited talk: April 20-24
2. BIT Mesra talk: March 6-7

## Other Activities:

1. **New Collaboration/Ongoing work:** Discussing early generation of stars within the Globular cluster with Nishikanta Khandai at NISER. We had a long time discussion on implementing his idea into my code as the topic is very relevant to my work on primordial star formation.
2. Probable collaborator in Presidency is Prof. Saumyadip Samui, with whom I am work on the end stage of the primordial star.
3. Collaboration with Jasjeet Singh Bagla, Sharanya Sur, Sukalpa, Shubham, and Yash (new student) continues.

# Amrita Mandal

## Research Summary:

We are investigating the effect of disorder on the ballistic phenomena of discrete-time quantum walks. We are studying in detail how the ballistic spreading of quantum walks are hindered due to the presence of glassy disorder.

## Publications:

1. Amrita Mandal, Rohit Shrama Sarkar and Bibhas Adhikari, Localization of two-dimensional quantum walks defined by generalized Grover coins, Journal of Physics A: Mathematical and Theoretical **56**, 025303, (2023).

## Conference/Workshops Attended:

1. Young Quantum 2023, HRI.

# Arghya Maity

## Research Summary:

In the previous year, my research was primarily focused on two fields: quantum information theory and quantum thermodynamics. Besides that, my research work also include topics from soft-condensed matter physics. In quantum information theory, my research work specifically emphasizes the resource theory and characterization of quantum and classical correlations. On the other hand, in quantum thermodynamics, I have worked on quantum engine.

We develop a resource theory for non-absolutely separable states (non-AS) in which absolutely separable states (AS) that cannot be entangled by any global unitaries are recognised as free states and any convex mixture of global unitary operations can be performed without incurring any costs. We employ two approaches to quantify non-absolute separability (NAS) – one based on distance measures and the other one through the use of a witness operator. We prove that both the NAS measures obey all the conditions which should be followed by a "good" NAS measure. We demonstrate that NAS content is equal and maximal in all pure states for a fixed dimension. We then establish a connection between the distance-based NAS measure and the entanglement quantifier. We illustrate our results with a class of non-AS states, namely Werner states.

Quantum correlations typically decrease with increasing noise, although classical correlators (CCors) may rise for a particular class of states with noise. To analyse the behavior of classical correlation (CC) in the presence of local noise, we scrutinize the set of classical correlators, axiomatic CC measures like classical discord, and local work for Haar uniformly generated states. Like quantum correlation measures, we illustrate that when noise levels rise, the average value of the CC measures for noisy output states obtained from random input states decreases for most of the channels. We also demonstrate a connection between the CCors of the noise-affected multipartite states that are produced and the CCors of the initial states that exhibit exponential, polynomial, and constant behavior as the noise level changes. Moreover, based on CCors of the generalised N-qubit W state as input, we determine a method to discriminate between the quantum channels, namely phase damping, depolarizing, and amplitude damping channels. We also relate classical, quantum, and total correlation measures that exhibit a comparable reaction to decoherence for generic states.

A four-stroke quantum Otto engine can outperform when conducted between two thermal reservoirs, one at a positive spin temperature and the other one at an effective negative spin temperature. Along with a magnetic field in the (x,y)-plane, we introduce an additional magnetic field in the z-direction. We demonstrate that the efficiency increases with the increase in the strength of the additional magnetic field although the impact is not monotonic. Specifically, we report a threshold value of the magnetic field, depending on the driving time which exhibits a gain in efficiency. We argue that this benefit may result from the system being more coherent with driving time, which we assess using the $l_1$-norm coherence measure. Moreover, we find that

the increment obtained in efficiency with an additional magnetic field endures even in presence of disorder in parameter space.

Additionally I did some work on soft condensed matter, specifically on thermodynamic properties of DNA molecule.

Recent advances in operating and manipulating DNA have provided unique experimental possibilities in many fields of DNA research, especially in gene therapy. Researchers have deployed many techniques, experimental and theoretical, to study the DNA structure changes due to external perturbation. It is crucial to understand the structural and dynamical changes in the DNA molecules in a confined state to understand and control the self-assembly of DNA confined in a chamber or nano-channel for various applications. In the current manuscript, we extend the work study the effect of confinement on the thermal stability and the structural properties of duplex DNA. The present work is an extension of our previous research works (Maity et al., 2019; 2020). For our study, we have considered a 1 BNA chain that is confined in a cylindrical geometry. How the geometry of the confinement affects the opening and other structural parameters of DNA molecule is the objective of this manuscript. We have used a statistical model(PBD model) and molecular dynamics simulations for our purpose.

## Publications:

1. R. Gupta, Arghya Maity, S. Mal, Aditi Sen De; "Statistics of Entanglement Transformation with Hierarchies among Catalysts", Phys. Rev. A 106, 052402 (2022).

2. Arghya Maity, N. Mathur, Petra Imhof, Navin Singh ; "Structural Analysis of DNA molecule in a confined shell", Physica A: Statistical Mechanics and its Applications 609(128382), 0378-4371 (2023)

3. **Review Article**
   A. Singh, Arghya Maity, N. Singh ; "Review: Structure and dynamics of dsDNA in cell mimicking environments", Entropy, 24(11),1587 (2022)

4. **Book Chapters**
   N. Mathur, Arghya Maity, N. Singh, Booktitle : "Advances in Computational Modeling and Simulation", Publisher : "Springer Nature Singapore", Chapter Title : "DNA Molecule Confined in a Cylindrical Shell: Effect of Partial Confinement", isbn="978-981-16-7857-8" (2022)

## Preprints:

1. T. K. Konar, Arghya Maity, Aditi Sen De; "Classical correlations for Generic States are Fragile under Decoherence", arXiv:2209.03334 (2022).

2. A. Patra, Arghya Maity, Aditi Sen De; "Resource Theory of Non-absolute Separability", arXiv:2212.11105 (2022).

3. Arghya Maity, Aditi Sen De; "Enhanced efficiency in quantum Otto engine via additional magnetic field and effective negative temperature", arXiv:2304.10420 (2023).

## Conference/Workshops Attended:

1. Young Quantum - 2023 (YouQu-2023), organized by the Quantum Information and Computation group(QIP) of Harish-Chandra Research Institute (HRI), Prayagraj (Allahabad), 15-18 Feb, 2023. Presented a talk on "Resource Theory of Non-absolute Separability" (in person) and I was one of the members of the organizing committee.

# Deepti Sharma

## Research Summary:

We study the time evolution of spin squeezing in Fully Connected Ising model subject to a sudden quantum quench of a transverse mag- netic field. The initial state is selected from the initial spin coherent state which is also ground state of the model, consisting of ferro and paramagnetic phases sepa- rated by a critical value of the transverse field. We identify a nonanalyticity in the long-time average of the spin-squeezing parameter when quenching to the dynamical and equilibrium quantum critical point. This suggests that the ferro- and param- agnetic phases also define distinct phases for how the transverse field redistributes quantum fluctuations among the spin components away from equilibrium. We have also studied the results for disordered case. (work in continuation)

## Publications:

1. Deepti Sharma, Priyankar Banerjee, Aranya B. Bhattacherjee, *Enhanced photon squeezing in two-photon Dicke model, Physics Letter A.*

## Conference/Workshops Attended:

1. *Young Quantum Conference (YouQ-2023)*, Organised by QIC group, HRI-HBNI, 15-18 February-2023

## Other Activities:

1. Internal arxiv flashbacks arranged on weekly basis.

## Najimuddin Khan

### Research Summary:

The primary focus of my research is the study of various aspects of the dark matter, neutrino and collider phenomenology of physics beyond the Standard Model. We have worked on various supersymmetric and non-supersymmetric extensions of the Standard Model. I have also developed a few computer codes in Mathematica and C++, which were used to investigate the research problems. We also have plans to develop new computer codes to make our phenomenological studies more realistic.

### Publications:

1. Pritam Das, and **Najimuddin Khan**, "Origin of Neutrino Mass, Dark Matter, Leptogenesis and Inflation in Seesaw Model with Triplets", Phys. Rev. D **107**, no.7, 075008 (2023) [arXiv:2207.01238 [hep-ph]].

2. **Najimuddin Khan**, "The stability analysis of the extended singlet scalar model with two high scale minima", Nucl. Phys. B 985, 116015 (2022) [arXiv:2206.13113 [hep-ph]].

3. Pritam Das, Mrinal K. Das and **Najimuddin Khan**, "Leptogenesis in a Multi-Higgs Doublet Model", XXIV DAE-BRNS High Energy Physics Symposium 2020 at National Institute of Science Education and Research, Jatni, India, Springer Proc. Phys. **277**, 599-604 (2022).

### Preprints:

1. Marco A Arroyo-Ureña, Amit Chakraborty, J. Lorenzo Díaz-Cruz, Dilip Kumar Ghosh, **Najimuddin Khan**, Stefano Moretti, "Higgs Pair Production at the LHC through the Flavon," [arXiv:2205.12641 [hep-ph]].

### Conference/Workshops Attended:

1. XXV DAE-BRNS High Energy Physics Symposium-2022, Indian Institute of Science Education and Research, Mohali, India, December 12-16, 2022.

2. 2nd International Meeting on High Energy Physics (IMHEP 2023), Institute of Physics, Bhubaneswar India, February 16-22, 2023.

### Visits to other Institutes:

1. Participated in collaborative discussions on aspects of high energy collider physics at Indian Institute of Science Education and Research Kolkata (IISER-K), November 17-21, 2022.

## Invited Lectures/Seminars:

1. "Phenomenology in the Extended Scalar Sector", 2nd International Meeting on High Energy Physics (IMHEP 2023), Institute of Physics, Bhubaneswar India, February 21, 2023.

2. "Phenomenology in the Extended Singlet Dark Matter Model", presented at Jamia Millia Islamia, Delhi, India, on $8^{th}$ February 2023.

3. "Phenomenology in the Extended Singlet Dark Matter Model", presented at Sri Guru Tegh Bahadur Khalsa College, University of Delhi, Delhi, India, on $10^{th}$ February 2023.

4. "Dark matter within the framework of minimal extended seesaw", presented (poster) at XXV DAE-BRNS High Energy Physics Symposium-2022, Indian Institute of Science Education and Research, Mohali, India, on $14^{th}$ December 2022.

5. "A minimal dark matter model with vector like fermions", presented (poster) at XXV DAE-BRNS High Energy Physics Symposium-2022, Indian Institute of Science Education and Research, Mohali, India, on $15^{th}$ December 2022.

# Tisita Das

## Research Summary:

During the period from $1^{st}$ April 2022 to $31^{st}$ March 2023, I have worked on a number of projects in catalytic materials, battery and hybrid perovskite systems. Firstly, I have explored a few transition metal based tri-chalcogenide monolayers to investigate bifunctional oxygen evolution and oxygen reduction reaction activity that could be used for rechargable metal air batteries. I have been also involved in the investigation of solid-liquid interface to explore the explicit effect of solvent in any electro or photo-catalytic mechanism. Apart from pure theoretical works I have also worked on a few other projects in collabaoration with experimental groups where using first-principles DFT calculations I have validated the experimental outcomes along with a more profound understand- ing at the electronic level. These projects not only include exploring catalytic acitivity and catalytic pathway in different 2D or quassi 2D materials but also involves determination of ion migration in battery and perovskite materials to study their stability as well as efficiency for sustainble energy production.

## Publications:


1. Tisita Das, S. Chakraborty and P. Sen, *Complementary Effects of External Strain, Functionalization and Vacancy Defects Towards Enhanced HER Activity in Transition Metal Phosphorous based Tri-chalcogenide Monolayers*, Sustainable Energy and Fuel **6**, 5621-5630 (2022).

2. R. Belgamwar, R. Verma, Tisita Das, S. Chakraborty, P. Sarawade, V. Polshettiwar, *Defects Tune the Strong Metal-Support Interactions in Copper Supported on Defected Titanium Dioxide Catalyst for $CO_2$ Reduction*, JACS **145**, 8634 (2023).

3. T. Sheikh, G. M. A., Tisita Das, A. Rahman, S. Chakraborty and A. Nag, *Combining $\pi$-Conjugation and Cation $\pi$-Interaction for Water-Stable and Photoconductive Hybrid Lead Bromide*, JPC Lett. **14**, 1870-1876 (2023).

4. A. Karmakar, Tisita Das, K. Karthick, S. Kumaravel, S. Sankar, R. Madhu, S. Chakraborty, S. Kundu, *Ni Vacancy Enriched AuNi Nanoalloy via Electrochemical Etching: Electronic Structure Modulation for Water Oxidation Reaction*, Inorganic Chemistry **21** 8570 (2022).

5. K. Sakhatskyi, R. A. John, A. Guerrero, S. Tsarev, S. Sabisch, Tisita Das, G. J. Matt, S. Yakunin, I. Cherniukh, M. Kotyrba, Y. Berezovska, M. I. BodnarchukS. Chakraborty, J. Bisquert, M. V Kovalenko, *Assessing the Drawbacks and Benefits of Ion Migration in Lead Halide Perovskites*, ACS Energy Letters **7**, 3401 (2022).

6. S. Kaur, M. Kumar, D. Gupta, Prajna P. Mohanty, Tisita Das, S. Chakraborty, R. Ahuja, T. Nagaiah, *Efficient $CO_2$ utilization and sustainable energy conversion via aqueous Zn-CO batteries*, Nano Energy **109**, 108242 (2023).

7. D. Gupta, A. Kafle, S. Kaur, P. P. Mohanty, Tisita Das, S. Chakraborty, R. Ahuja and T. C. Nagaiah, *High Yield Selective electrochemical conversion of $N_2$ to $NH_3$ via morphology controlled silver phosphate under ambient conditions*, Journal of Materials Chemistry A **10**, 20616, (2022).

8. N. Sethulakshmi, S. Nellaiappan, P. Prasanna, Tisita Das, S. Irusta, S. Chakraborty, S. Sharma *Electrocatalytic Splitting of Hydrazine Using Hydrothermally Synthesized $CuCo_2S_4$ Nanocatalyst*, Journal of Electroanalytical Chemistry **922**, 116776 (2022).

9. S. Singh, A. Neveu, K. Jayanthi, Tisita Das. S. Chakraborty, A. Navrotsky, V. Pralong, P. Barpanda, *Facile Synthesis and Phase Stability of Cu-based $Na_2Cu(SO_4)_2.xH_2O(x=0$-$2)$ Sulfate Minerals as Conversion type Battery Electrodes*, Dalton Transactions **51**, 11169 (2022).

10. D. Gupta, A. Kafle, S. Kaur, P. P. Mohanty, Tisita Das, S. Chakraborty, R. Ahuja, T. Nagaiah, *Self-powered $NH_3$ synthesis by trifunctional $Co_2B$ based high power density Zn-air batteries*, JMCA, Accepted, (2023).

## Preprints:

1. Tisita Das and P. Sen, *Developing $FePSe_3$ based bifunctional OER/ORR catalyst for rechargeable Zn-Air battery*, (in preparation).

2. Y. Luo, J. V. Handy, Tisita Das, J. D. Ponis, R. Albers, M. Pharr, S. Chakraborty and S. Banerjee, *Effect of Pre-Intercalation on Li-Ion Diffusion Mapped by Topochemical Single-Crystal Transformation and Operando Investigation*, (in preparation).

3. N. Livaskas, S. Toso, Tisita Das, S. Chakraborty, L. Manna, *Anion Exchange on $CsPbCl_3$ towards $CsPbI_3$ Colloidal Nanocrystals*, (in preparation).

## Conference/Workshops Attended:

1. Oral Presentation in *Annual Conference on Quantum Condensed Matter (QMAT) 2022*, IIT Kanpur, September 2022.

2. Invited poster presentation on in *International Conference– Designing Catalysts on Computers (DCC22)* IACS Kolkata, December 2022.

3. Attended school on *Computational Modeling and Simulations of Materials for Energy and Environment*, JNCASR Bangalore, December 2022.

4. Attended *Conference on Advances in Renewable Energy (CARE-2023)*, HRI Allahabad, February 2023.

## Invited Lectures/Seminars:

1. Invited talk delivered in Two-day workshop*Advanced Ceramics under Extreme Conditions*, IIT Madras, December 2022.

2. Invited talk delivered in *PDC-IT workshop under the aegis of Indo-German Science and Technology Centre (IGSTC) organized jointly by University of Bayreuth, Germany and IIT Madras*, IIT Madras, March 2023.

## Academic recognition/Awards :

1. Awarded DST INSPIRE Faculty Fellowship, 2022 (Result declared in February 2023).

# Pratim Roy

## Research Summary:

Recently, a method of regularising black hole spacetimes was put forward by Simpson and Visser. We have attempted to analyse the consequences of generalising this method to spacetimes containing a naked singularity. Two naked singularity spacetimes, namely the Janis-Newman-Winicour (JNW) and the Joshi-Malafarina-Narayan (JMN) metrics have been regularised. The first metric is the solution of the Einstein equations coupled with a scalar field and the second one represents the equilibrium configuraion of a collapsing star. It has been shown that, depending on parameter values, the result of the regularisation procedure on the JNW metric is either a traversable wormhole or a naked singularity. On the other hand, the procedure applied on the JMN metric always results in a wormhole.

The resulting regularised geometries are analysed from the point of view of particle motion to investigate possible observational aspects. Finally, stability of these systems are analysed by introducing a scalar field perturbation and studying the response. This is characterised by quasinormal modes, which are the complex frequencies of propagation of the perturbation in spacetime. A negative component of the quasinormal mode implies that the perturbation is damped over time and that the spacetime is stable. It has been shown that the wormhole geometries are stable for a range of parameter values.

Other ongoing work includes investigating Krylov complexity for long-range quantum systems. Physical systems which incorporate long-range interactions typically exhibit interesting properties like scrambling and chaotic behaviour. Hence, these systems become interesting from the point of view of quantum information theory. Krylov complexity might give further insights into the behaviour of these systems from an information theoretic point of view.

## Publications:

1. Regularizing the JNW and JMN naked singularities, Kunal Pal, Kuntal Pal, Pratim Roy and Tapobrata Sarkar, (European Physical Journal C, 83 (2023) 5, 397)

# Rajiv Kumar

## Research Summary:

I joined as PDF on 1st March 2023. So I have just started to work here in the last financial year (2022-2023) with my new projects and continuing some previous works. We have initiated work on a study of 2D inflowoutflow solutions around black holes using self-similar solutions of the second kind for solving partial differential equations (PDEs). In this study, we have considered two new things or improvements from all previous this kind of 2D studies. One is using self-similar solutions of the second kind (Kumar & Gu 2019) instead of the self-similar solution of the first kind (Narayan & Yi 1994). Since, a self-similar solution of the second kind is providing a better representation of the hot accretion disk in the two-zone model theory than the first-kind solutions. And the second improvement is using two viscous stress tensor components in the fluid equations of motion. So with these improvements, we are expecting that this study can give us a better understanding of the outflows generation and variation of it with changing size of the hot accretion disk in the two-zone disk model theory.

I am also continuing my previous work on the 2D simulation study of accretion disk structures with changing outer boundary conditions (OBCs). This work will be communicated soon in the Astrophysical Journal (ApJ).

# Preprints:

1. Rajiv Kumar and Ye-Fei Yuan, A new prospect for jet origin and spectral state transitions with three hybrid accretion flows around black holes, arXiv:2210.00683, received positive referee report and revised version will be submitted soon.

2. Rajiv Kumar and Seong-Jae Lee, Simulations of accretion disk structures around black holes with various outer boundary conditions, in preparation.

# Ravindra Pankaj

## Research Summary:

Laser pump-probe experiments have emerged as a powerful tool for investigating the ultrafast dynamics and electronic properties of complex materials as well as providing an opportunity to study non-equilibrium physics. Ultrafast photoexcitation of oxides such as cuprates and manganites derives them out-of-equilibrium and leads to exotic phenomena like enhancement of the charge-density-wave state, the occurrence of the hidden states and melting of the symmetry-broken phases etc.

To study the ultrafast photoexcitation dynamics of the manganites, we consider a model Hamiltonian involving terms such as the tight-binding term and the cooperative Jahn-Teller interaction for the $e_g$ sector whereas the core spins in the $t_{2g}$ sector are treated classically. The spins of the $e_g$ sector interact with the on-site core $t_{2g}$ spins via Hund coupling while the core $t_{2g}$ spins interact with the other nearest neighbour core $t_{2g}$ spins. Taking inspiration from a newly developed method (arXiv:2205.14710) to study ultrafast dynamics in electron-phonon systems, we derive coupled differential equations for the expectation values of displacement and density operators for the manganites. Furthermore, the fourth-order Runge-Kutta method needs to be employed to solve the coupled differential equations. A computer program will be developed to solve the coupled differential equations using the fourth-order Runge-Kutta method. Obtained solutions will be studied to understand ultrafast dynamics in manganites and the results will be compared to the experimental data.

## Invited Lectures/Seminars:

1. *Non-equilibrium phenomena induced in oxides via ultrafast photoexcitation*, CMP seminar at HRI in January 2023.

2. *Enhanced Charge Density Wave Coherence in a Light-quenched, High-temperature Superconductor*, CMP seminar at HRI in February 2023.

# Shalini Tomar

## Research Summary:

Since June 29, 2021, I have been employed as a Research Associate under the supervision of Dr. Sudip Chakraborty for the DST-NSM project. My primary research objective involves the theoretical prediction of Layered Materials for hydrogen production.

Specifically, my focus has been on studying transition metal dichalcogenides, particularly layered materials such as $VX_2$ and $ZrX_2$ structures. Utilizing a Density Functional Theory-based code, I have conducted theoretical investigations on the catalytic properties of both pristine and doped layered structures. In addition to my research on layered materials for hydrogen production, I have also conducted investigations into the type-II band alignment in heterostructures involving $CdS/NiI_2$ and $ZnS/NiI_2$ monolayers. This research was carried out with the aim of exploring their potential applications in photocatalysis.

## Publications:

1. S. Tomar, S. Chakraborty, "Insight into electronic and optical essence of $ZnS/NiI_2$ and $CdS/NiI_2$ heterostructure as a novel visible-light photocatalyst for hydrogen production", Journal of Materials Chemistry C.( In preparation)

2. S. Tomar, S. Chakraborty, "Chalcogen Composition Driven Enhancement of Catalytic Efficiency in Zirconium based Monolayers: Insight from Reaction Coordinate Mapping", accepted in Sustainable Energy Fuels, 31 May, 2023.

3. S. Tomar, P. Sen, S. Chakraborty, "Single atom functionalization in vanadium dichalcogenide monolayers: towards enhanced electrocatalytic activity", Sustainable Energy Fuels, 6, 5337-5344, 2022.

# Shilendra Kumar Sharma

## Research Summary:

Electronic structure calculations of CuO decorated fullerene ($C_{60}$) sheet for supercapacitor energy storage and Li-ion battery applications have been studied. In this project we are looking the effect of CuO decoration on interstitial sites of $C_{60}$ sheet. Decoration of CuO originates the defect states of Cu and O in the band gap region of $C_{60}$ sheet resulting decrement in the band gap which will enhance conductivity of $C_{60}$ sheet. Conductivity enhancement decreases charge transfer registance during catalytic reaction on electrode surface for supercapacitor energy storage which enhances overall performance of energy storage device. Further Li intercalation at the possible interstial sites in the CuO decorated $C_{60}$ sheet has been studied for Li-ion battery applications. In addition charge transfer analysis has been performed by caclulating charge density difference and bader charge calculatios to study the effect of CuO decoration on $C_{60}$ fullerene sheet during charge storage mechanism.

## Other Activities:

1. Involvement in colloborative research projects with other institutes. Research work has been started.

# Souvik Ghose

## Research Summary:

**Theory of Relativity**
Article: A quest for the origin of the Sagnac effect Together with my collaborators Arunabha Bhadra from the University of North Bengal and Biplab Raychaudhury, we worked on a fundamental issue related to the Sagnac Effect in the Special Theory of Relativity. Despite its well-known status, the origin of the relativistic Sagnac effect remains a topic of debate in the literature, particularly with regards to the perspective of a rotating observer. Recent experiments have also raised doubts about the significance of the platform's rotation in the Sagnac effect. In this context, we proposed a thought experiment on the linear Sagnac effect and examined an earlier proposal to demonstrate that the origin of the Sagnac effect is not influenced by the rotation of the frame affecting clock synchronization, nor by the relative motion between the source and observer. Instead, we found that the Sagnac effect arises solely from the observer's asymmetric position with respect to the light paths. This conclusion was substantiated by analyzing a hypothetical Sagnac experiment that involves no rotation.

Our work has been published in Eur. Phys. J. C.

**Cosmology**
I have continued my works in Cosmology and worked on holographic dark energy models in different frameworks.

(1) Article: Interacting and Non-interacting Reńyi Holographic Dark Energy Models in DGP Braneworld In this project, my collaborators from the University of North Bengal and I investigated interacting and non-interacting Rényi Holographic Dark Energy (RHDE) models in the DGP brane world framework. Our goal was to obtain realistic cosmological models by studying the cosmological parameters and their evolutions.

We found that the RHDE models were able to accurately fit the observed dark energy density and the present accelerating phase of expansion. Additionally, we examined the classical stability of the cosmological models and used the Om-diagnostic to test their suitability.

Our work has been made available as a pre-print on arXiv and has been accepted for publication in Mod. Phys. Lett. A. (2)Article: Barrow Holographic Dark Energy in Brane World Cosmology. I have been collaborating with Arpan Krishna Mitra, a former post-doctoral researcher (current at the time of pre-print publication) in my current astrophysics group at HRI, and other collaborators from the University of North Bengal on a project related to Barrow Holographic Dark Energy in Brane World Cosmology. Our work has resulted in a pre-print publication on the arXiv, and we are currently working on some additional details before submitting our manuscript to a journal.

**Astrophysics** I am currently working with my mentor Prof. Tapas Das, and Susovan Maity, a Ph.D. student at HRI, along with other collaborators on a study related to accretion and analogue gravity. Specifically, we are investigating how the thickness of the flow affects the acoustic surface gravity of accreting black holes.

Our study focuses on the acoustic geometry of axially symmetric accretion in hydrostatic equilibrium along the vertical direction. We are examining how the charac-

teristics of the geometry are influenced by the Kerr metric and the thickness of the matter flow. To achieve this, we are locating the sonic points and stationary shocks, and then perturbing the flow to determine the corresponding metric elements.

Our findings indicate that the sonic points and shocks correspond to black-holetype and white-hole-type horizons, respectively. We are also calculating the acoustic surface gravity as a function of the black hole's spin angular momentum for three different flow thicknesses. However, we have discovered that for some flow models, the acoustic geometry cannot be constructed beyond a certain truncation radius due to the expression of the thickness function. (Communicated: Phys. Rev. D)

## Publications

1. Bhadra, A., Ghose, S. and Raychaudhuri, B. A quest for the origin of the Sagnac effect. Eur. Phys. J. C 82, 649 (2022). https://doi.org/10.1140/epjc/s10052022-10620-6

2. arXiv:2202.06813 [gr-qc] (To Appear in Mod. Phys. Lett. A)

## Pre-prints

1. arXiv:2209.05749 [gr-qc] https://doi.org/10.48550/arXiv.2209.05749

## Articles under communication

1. Phys. Rev. D (Manuscript No. DC13575)

## Conference/Workshops Attended:

1. "Exploring The Cosmos 2023: A National Seminar on Relativistic Universe", February 15, 2023 at High Energy and Cosmic Ray Research Centre, University of North Bengal (NBU). (Oral Presentation: Brane World Cosmology with Barrow Holographic Dark Energy)

## Visits to other Institutes

- High Energy and Cosmic Ray Research Centre, University of North Bengal.

## Invited Lectures/Seminars:

1. Seminar Talk: Brane World Cosmology with Barrow Holographic Dark Energy. (Exploring The Cosmos 2023: A National Seminar on Relativistic Universe)

2. On the origin of the relativistic Sagnac effect (Talk given at NBU during a visit.)

## Other Activities:

1. Worked as a reviewer for Class. Quant. Grav.

2. Partially supervised project students (M.Sc.) of Prof. Tapas Das: 1. Saikat Bera (HRI) 2. Snehashish (HRI) 3. Souvik Chatterjee (Sister Nivedita University, Kolkata)

# Suchetana Goswami

## Research Summary:

In the period of past few months, I have worked on two main directions of quantum information theory. One is related to the problem of entanglement detection and the other is about secret information sharing using entanglement.

In the first part, we find a positive but non-completely positive map that is able to detect entanglement beyond the $2 \otimes 2$ or $2 \otimes 3$ dimensions. Considering the Lindblad master equation, we give a new prescription to construct a linear positive that is useful for detecting entanglement. We show that two famous positive maps viz. transposition and Choi map can be obtained as a special case of a class of positive maps having Lindblad structure. Generalizing the transposition map to a one parameter family we have used it to detect genuine multipartite entanglement. We define the action of the map first on tripartite qubit system and show that this can be seen as a one-parameter generalisation of transposition map. The W and GHZ states can be detected by larger family of maps arising from Lindblad structure compared to the previous results. Finally being motivated by the negativity of entanglement, we have defined a similar measure for genuine multipartite entanglement. We prove that this measure gives zero for all bi-separable states, monotonic under local operation and classical communication (LOCC) and convex, making it a valid entanglement measure.

In the other work, we consider an information distribution protocol using orthogonal states for $m \geq 3$ spatially separated parties such that even if any $k \leq (m-1)$ parties collaborate still the information cannot be revealed completely. Such a protocol is useful to understand up to what extent the encoded information remains locked. However, if required, the parties can share entanglement and extract the information completely by LOCC. To make the process resource efficient, it should consume less number of entangled states. We show that though the set of states, which are locally indistinguishable across every bipartition, are sufficient for the above protocol, they may consume higher number of entangled states when aiming for complete information extraction. We establish this by constructing a class of locally indistinguishable sets of orthogonal states which can be employed to accomplish the above protocol and these sets consume less number of entangled states, compared to the former sets, for complete information extraction. In fact, this difference in the number of required entangled states for complete information extraction grows linearly with the number of parties. This study sheds light on suitable use of local indistinguishability property of quantum states as resource and thus, we demonstrate an efficient way of information distribution.

## Publications:


1. Moein Naseri, Tulja Varun Kondra, **Suchetana Goswami**, Marco Fellous-Asiani, and Alexander Streltsov, *Entanglement and coherence in the Bernstein-Vazirani algorithm*, Phys. Rev. A **106**, 062429 (2022).

## Preprints:

1. Vaibhav Chimalgi, Bihalan Bhattacharya, **Suchetana Goswami**, Samyadeb Bhattacharya, *Detecting entanglement harnessing Lindblad structure*, arXiv:2210.17204v1.

2. **Suchetana Goswami**, Saronath Halder, *Efficient information distribution*, arXiv:2301.02287v2.

## Conference/Workshops Attended:

1. Young Quantum, India, February, 2023.

## Invited Lectures/Seminars:

1. *Entanglement and coherence in the Bernstein-Vazirani algorithm*, Young Quantum 2023, Harish Chandra Research Institute, India, February, 2023.

## Other Activities:

1. Reviewed three papers for the journal "Quantum Information Processing".

## Sujoy Mahato

## Research Summary:

After joining HRI at the end of September 2022, I have mostly focused on studies of supersymmetric gauge theories and its coupling to a non-trivial gravitational background which is a continuation of my last published work. To be more specific we look at special class of $\mathcal{N} = 2$ four dimensional SUSY theories called the Kaluza Klein theories, and study their gravitational couplings by placing the theory on the so called $\Omega$-background parametrized by $(\epsilon_1, \epsilon_2)$. The Log of partition function $Z$ has the following expansion in these parameters,

$$\epsilon_1\epsilon_2 \log Z = -F + (\epsilon_1 + \epsilon_2)H + \epsilon_1\epsilon_2 \log A + \frac{\epsilon_1^2 + \epsilon_2^2}{3} \log B + ... \tag{5}$$

The sub-sub leading terms i.e. $\log A$ and $\log B$ are the quantities of interest which captures the gravitational couplings. What makes these quantities even more important is the fact that they are directly related to the central charges of SCFT that we are considering.

We extract the exact form of both $\log A$ and $\log B$ using two methods : Localization and Seiberg-Witten Curves. We mainly focus on $U(N)$ gauge theories with explicit answers for low lying $N$ and some general comment for any $N$.

## Preprints:

1. Effective Gravitational Couplings of Kaluza-Klein Gauge Theories (*In preparation*)

# Rafiqul Rahaman

## Research Summary:

During the academic year 2022-2023, encompassing the period from April 1, 2022, to March 31, 2023, I actively participated in a range of notable projects that served as significant milestones in my research and academic journey. These projects were characterized by in-depth investigation, meticulous analysis, and fruitful collaborations with esteemed colleagues who specialize in diverse fields. The following projects represent the key highlights of my academic pursuits during this period:

We have successfully completed and published our work on "Distinguishing non-standard scalar and fermionic charged particles at future $e^+e^-$ colliders" in collaboration with Dr. Santosh Kumar Rai and Anjan Kumar Barik. In this study, we focused on two well-motivated BSM models: the inert doublet model (IDM) and the minimal supersymmetric standard model (MSSM), which serve as examples of new physics models featuring scalar and fermionic exotic charged particles, respectively.

The signal in our analysis consists of a charged lepton, two jets, and significant missing energy. In the Standard Model (SM), the final state originates from $W^+W^-$ production, where one $W$ boson decays leptonically while the other decays into a pair of jets. However, in the IDM and MSSM scenarios, the signal arises from the pair production of exotic charged particles, either fermionic or bosonic in nature. These exotic charged particles then decay into a weakly charged boson, the $W$ boson, and a lightest neutral stable particle that escapes detection, leading to missing energy. This decay process closely resembles the SM background from $W$ boson decays.

To distinguish between the spin-0 and spin-1 dark matter (DM) models in the $l^{\pm}jj+MET$ final state, we utilize the potential of beam polarization, both longitudinal and transverse, at the International Linear Collider (ILC). By exploiting these polarization options, we can effectively differentiate between the two types of DM models.

I have completed and published my work titled "On two-body and three-body spin correlations in leptonic $t\bar{t}Z$ production and anomalous couplings at the LHC". In this study, I investigated anomalous couplings in the production of leptonic $t\bar{t}Z$ events at the Large Hadron Collider (LHC). I specifically focused on utilizing the polarizations of top quarks and $Z$ bosons, as well as studying two-body and three-body spin correlations.

One key aspect of my research was analyzing the impact of reconstructing two neutrinos at the detector level on the angular distributions related to polarizations and spin correlations, in comparison to the parton level distributions. I further explored the sensitivity of the couplings to polarizations and spin correlations by evaluating the $\chi^2$ values for a set of luminosity. By progressively incorporating the polarization and spin correlation asymmetries, I examined the improvements in the limits on the couplings over the cross section with added effects of systematic uncertainty.

I have successfully completed and published our work titled "Exploring the dark $Z_d$-boson in the future Large Hadron-electron collider" in collaboration with Prof. Ashok Kumar Goyal, Dr. Mukesh Kumar, and Dr. Satendra Kumar. In this study, we delve into the Lorentz structure and magnitude of parity violation associated with the dark-$Z$ coupling to standard model (SM) fermions.

As the $Z_d$ boson couples to SM particles through interactions, its production in an $e^-p$ collider occurs via charged (neutral (NC)) currents (CC): $e^-p \to \nu_e(e^-)Z_d, j$. We uti-

lize this process to explore the mass range of $Z_d$ as a function of $\epsilon$ in our experimental setup. To achieve this, we employ cross-section measurements and asymmetries derived from polarization observables of $Z_d$, obtained through its subsequent decay into $\ell^+\ell^-$.

Our investigation provides valuable insights into the properties and behavior of the dark $Z_d$ boson within the context of the future Large Hadron-electron collider. By examining the coupling to SM fermions, as well as the associated parity violation, we contribute to the understanding of the potential presence and characteristics of this dark boson.

I have collaborated with Dr. Ritesh K. Singh and Dr. Soubhik Kumar on the project titled "Measuring Electroweak Quantum Numbers of Color Sextet Resonances at the LHC." Our study focuses on investigating the feasibility of determining the electroweak quantum numbers of color sextet particles beyond the Standard Model (SM) that decay into same-sign top quark pairs.

In particular, we examine two types of color sextet particles: color sextet scalars, which generate top quarks with the same chirality, and color sextet vectors, which yield top quarks with opposite chirality. This distinction is reflected in the angular distributions of the bottom quarks and leptons stemming from the decays of the top quarks. By utilizing these angular distributions, along with the energy distributions of the final-state jets and leptons, we aim to differentiate among the three potential color sextet resonances. Our analysis takes into account various SM background processes.

We have compiled our findings into a manuscript, which has been submitted to PRD (Physical Review D) for publication.

I collaborated with Dr. Santosh Kumar Rai and Dr. Tathagata Ghosh on a project that focuses on the search for multi-lepton signatures, including four same-sign charged leptons, associated with a lepto-phobic triplet scalar in a left-right symmetric extension of the Standard Model (LRSM).

In this study, our objective was to identify the signal in the final state resulting from the pair production of a doubly charged Higgs with non-leptonic interactions within a left-right symmetric model featuring two triplets, a bi-doublet, and two doublet scalars. Notably, we generated right-handed neutrino masses using a dimension-$5$ lepton-number violating operator, rather than relying on left-handed triplet interactions with leptons as required by the seesaw mechanism for generating light neutrino masses.

Our investigation revealed that distinct signatures, including four-lepton, six-lepton, and SS4L (same-sign four-lepton) events, can be observed at the high-luminosity phase of the Large Hadron Collider (HL-LHC) with minimal background, particularly within the mass range of $150$-$500$ GeV for the right-handed doubly charged Higgs. The manuscript of this work is almost prepared, and we hope to communicate this work very soon.

I am also involved in a project titled "Exploring new physics in $tW$ production using polarization and spin correlations at the LHC," in collaboration with Amir Subba. This study focuses on investigating the production of a single top quark in association with a $W$ boson at the LHC, aiming to probe anomalous chromo-magnetic and chromo-electric moments. We achieve this through the utilization of polarization and spin correlation observables in the leptonic final state.

To measure the polarization and spin correlation asymmetries of the top quark and the $W$ boson, we employ the $M_{T2}$ assisted on-shell (MAOS) reconstruction method,

which allows for the reconstruction of the two neutrinos in the final state. Through detector-level simulations, considering various backgrounds and systematic uncertainties, we estimate the limits on the anomalous moments. Remarkably, these limits are found to be comparable to existing experimental limits obtained from the $t\bar{t}$ process.

## Publications:

1. **R. Rahaman** and R. K. Singh, " Breaking down the entire spectrum of spin correlations of a pair of particles involving fermions and gauge bosons", *Nuclear Physics B* **948** (2022) 115984, arXiv:2109.09345 [hep-ph].

2. **R. Rahaman**, " On two-body and three-body spin correlations in leptonic $t\bar{t}Z$ production and anomalous couplings at the LHC", *JHEP* **02** (2023) 077, arXiv:2204.12152 [hep-ph].

3. A. K. Barik, **R. Rahaman**, and S. K. Rai, " Distinguishing nonstandard scalar and fermionic charged particles at future $e^+e^-$ collider", *Phys. Rev. D* **107** no. 3, (2023) 035002, arXiv:2206.11560 [hep-ph].

4. A. K. Goyal, M. Kumar, S. Kumar, and **R. Rahaman**, " Exploring dark $Z_d$-boson in future Large Hadron-electron collider", *Eur. Phys. J. C* **83** no. 2, (2023) 132, arXiv:2209.03240 [hep-ph].

## Preprints:

1. S. Kumar, **R. Rahaman**, and R. K. Singh, "Measuring Electroweak Quantum Numbers of Color Sextet Resonances at the LHC", arXiv:2302.11355 [hep-ph], under review in PRD.

2. T. Ghosh, **R. Rahaman**, and S. K. Rai, "Multi-lepton collider signatures of leptophobic doubly charged scalar", manuscript under preparation.

3. **R. Rahaman** and Amir Subba, " Exploring new physics in $tW$ production using polarization and spin correlations at the LHC", manuscript under preparation.

## Conference/Workshops Attended:

1. **Seminar presented on** "Search for a leptophobic doubly charged Higgs in same-sign-four-lepton and six-lepton signatures in a left-right symmetric model" in the "International Meeting on High Energy Physics - 2023" held at IOP Bhubaneswar, India during 17-22 February 2023.

# Swapnil Sanjay Deshpande

## Research Summary:

I, Dr Swapnil Deshpande, am a recent graduate (15/12/2022) of Savitribai Phule Pune University (SPPU), Pune, Maharashtra, India. Prof. Mrinalini D. Deshpande, Dept. of Physics, H. P. T. Arts and R. Y. K. Science College, Nashik, was my Ph. D. advisor. In the academic year 2022-2023, we have calculated the electronic structures of pure and 3d-transition metal atom doped carbon nitride monolayers ($C_3N_6$ MLs). We investigated their broad domain of potential applications in sensing small gas molecules. Subsequently, collaborated to explore the adsorption mechanism of different toxic gases onto pristine $BNC_2$ and Al-doped $BNC_2$ MLs.

I joined HRI as a Research Associate (CoE-CTFM) on 26/04/2023, in Computational Condensed Matter Physics, MATEs lab, HRI which is led by Dr. Sudip Chakraborty. I am jointly working with ICSR, IIT Madras as a Postdoctoral Researcher with Prof. Ravi Kumar N V, Head, Department of Metallurgical and Materials Engineering, IIT Madras. Prior to joining HRI, I joined the ICSR project on 15/03/2023. We are currently designing and conducting detailed theoretical studies on various functionalized ternary BNC sheets could be used in a variety of technological applications. Our main objective is to explore the electronic structure, magnetic properties, and optical properties of functional materials and utilize them for global sustainable development goals

## Publications:

1. Poonam Chalase, **Swapnil Deshpande**, Sandip Kumavat and Mrinalini Deshpande, Adsorption mechanism of different toxic gases onto pristine $BNC_2$ and Al-doped $BNC_2$ monolayers, *Phys. Chem. Chem. Phys.*, Advance Article, 2023.

2. **Swapnil Deshpande**, Mrinalini Deshpande, Rajeev Ahuja, and Tanveer Hussain, Tuning the electronic, magnetic, and sensing properties of a single atom embedded microporous $C_3N_6$ monolayer towards $XO_2$ (X = C, N, S) gases, *New J. Chem.*, 46, 13752-13765, 2022.

## Conference/Workshops Attended: NIL

1. Participated in the "INUP-i2i 2022 Online Familiarization Workshop on 2D Semiconductor Nanodevices and Simulations" organized at the Centre for Nanotechnology, Indian Institute of Technology, Guwahati, on December 8-10, 2022.

2. Participated in the national conference on "Challenges and Opportunities in Chemistry Research "(COCR-2022)" and poster presentation "First-principles study of pristine and Al-doped $BNC_2$ monolayers as an Adsorbent for Small gas molecules" held at Dept. of Chemistry, H. P. T. Arts and R. Y. K. Science, College, Nasik from September 18-19, 2022.

## Other Activities:

1. Attending the HRI Physics Colloquia.
2. Participating in a weekly group discussions and CMP Seminar Series.
3. "Business Analysis Foundations Course" completed on February 03, 2023 Endorsed by Linkedin Learning, PMI, and IIBA.

# Abhay Srivastav

## Research Summary:

In the last academic year, I worked on the concept of masking of quantum information in the Heisenberg picture. The notion of masking was generalised from states to that of the observables and a corresponding no-go theorem was proved in arbitrary dimensions. This shows that the physical attributes of a system such as the energy, spin, etc., cannot be made blind to the system itself. Furthermore, it was shown that the famous unconditional no bit-commitment result follows from the no-masking theorem for observables. This results will have important applications in thermalisation of observables, information scrambling etc.
I also worked on quantum speed limit which provides a fundamental bound on how fast a quantum system can evolve between the initial and the final states under any physical operation. A new quantum speed limit was derived using the tighter uncertainty relations for pure as well as mixed quantum states undergoing arbitrary unitary evolution. Finally, I also studied the usefulness of entanglement in information theory specifically the role it plays as resource in local state discrimination problems.

## Preprints:

1. Swapnil Bhowmick, Abhay Srivastav, Arun Kumar Pati, *No-Masking Theorem for Observables and No-Bit Commitment*, **arxiv: 2209.12261**

2. Shrobona Bagchi, Abhay Srivastav, Arun Kumar Pati, *Quantum Speed Limit From Tighter Uncertainty Relation*, **arxiv: 2211.14561**

## Conference/Workshops Attended:

1. *Young Quantum*, Harish-Chandra Research Institute, Feb 15-18, 2023.

# Abhishek Muhuri

## Research Summary:

In the previous year, I investigated the effect of noise in the very well-known paradigmatic information-sharing protocol of quantum dense coding. Our most significant finding is that the channel's randomness, which is in general present in a real-life noise model, can compensate for the detrimental effects of non-Markovian depolarizing channels in the dense coding protocol.

This work is a thorough study of the distributed dense coding protocol, involving many senders and single or two receivers in a noisy environment where the environment effect is considered to be dephasing and depolarizing by nature. The work can be divided into two parts: in the first part, we have shown that high nonMarkovianity of a dephasing channel can counteract the negative effects of the noisy channel on the dense coding protocol for some classes of states. This constructive effect, however, is not observed in the case of a depolarizing channel. The second part of our work introduces realistic models of paradigmatic channels like depolarizing and dephasing channels. The models are stochastic and have inherent randomness as we replaced the Pauli matrices with random unitaries. We illustrated this randomness to be beneficial for the dense coding protocol. Interestingly, we reported that the detrimental effect of non-Markovian depolarising channels in the protocol could be eliminated when randomness was added to the channel.

## Preprints:

1. Abhishek Muhuri, Rivu Gupta, Srijon Ghosh, Aditi Sen(De), Superiority in dense coding through non-Markovian stochasticity, arXiv:2211.13057

## Conference/Workshops Attended:

1. Organizing committee member, Young Quantum 2023, HRI Prayagraj India, February 2023

## Visits to other Institutes:

1. International Institute of Information Technology Hyderabad, 31st December 2022 - 3rd January 2023

# Md. Abhishek

## Research Summary:

During the academic year 2022-2023, in collaboration with Subramanya Hegde, Dileep P. Jatkar, Arnab Priya Saha, and Amit Suthar, I have been studying how to compute scattering amplitudes at loop level using on-shell methods. Our current focus is to compute $\mathcal{N} = 4$ Coulomb branch loop amplitudes using generalised unitarity.

With Subramanya Hegde, Alok Laddha, and Arnab Priya Saha, we are trying to realise associahedron geometry in $4$-dimensions, consistent with Gram determinant conditions.

In another project with Arindam Bhattacharjee, we are studying the scattering of particles coupled to $3$-dimensional gravity in the Chern-Simons formulation. We want to see non-trivial asymptotic symmetries of this $3$-dimensional theory and find some analog of the gravitational memory effect.

With Sachin Grover, Dileep P. Jatkar, and Kajal Singh, we are addressing some problems related to the $2$-dimensional rational conformal field theories (2d RCFTs) and $4$-dimensional superconformal theories (SCFTs).

## Publications:

1. Md. Abhishek, S. Hegde, D. P. Jatkar, and A. P. Saha, *Scattering Amplitudes and BCFW in $\mathcal{N} = 2^*$ Theory*, SciPost Phys. **13**, 008, (2022). arXiv: 2202.12204.

## Preprints:

1. Md. Abhishek, and B. P. Mandal, *Effect of minimal length on Landau diamagnetism and de Haas–van Alphen effect*, arXiv: 2206.04407.

## Conference/Workshops Attended:

1. *Student Talks on Trending Topics in Theory ($ST^4$) 2022*, IIT-Indore, Indore, India, 4–15 July, 2022.
2. *Amplitudes 2022 and Summer School*, Charles University, Prague, Czech Republic, 1-12 August 2022.
3. *Regional Strings Meet - Bhopal Chapter*, IISER-Bhopal, Bhopal, India, 17–19 November, 2022.
4. *String Seminar Days*, HRI, Allahabad, India, 21–23 December, 2022.
5. *Chennai Strings Meeting*, IMSc, Chennai, India, 21-24 February 2023.

## Visits to other Institutes:

1. International Centre for Theoretical Sciences, Bangalore, India, 22 August-9 September 2022.
2. Chennai Mathematical Institute, Chennai, India, 10-20 September 2022.
3. Indian Institute of Science Education and Research - Bhopal, Bhopal, India, 10-20 November 2022.
4. Chennai Mathematical Institute, Chennai, India, 20 February-2 March 2023.
5. The Institute of Mathematical Sciences, Chennai, India, 3-20 March 2023.

## Invited Lectures/Seminars:

1. *Scattering Amplitudes and BCFW Recursion in $\mathcal{N} = 2^*$ Theory* (Gong show talk and Poster presentation), Amplitudes 2022 and Summer School, Charles University, Prague, Czech Republic, August 2022.
2. *Scattering Amplitudes and BCFW Recursion in $\mathcal{N} = 2^*$ Theory* (Invited talk), IISc, Bangalore, India, 26 August 2022.
3. *Scattering Amplitudes and BCFW Recursion in $\mathcal{N} = 2^*$ Theory* (Invited talk), ICTS-TIFR, Bangalore, India, 30 August 2022.
4. *Scattering Amplitudes and BCFW Recursion in $\mathcal{N} = 2^*$ Theory* (Invited talk), CMI, Chennai, India, 15 September 2022.
5. *Scattering Amplitudes and BCFW Recursion in $\mathcal{N} = 2^*$ Theory* (Invited talk), IMSc, Chennai, India, 16 September 2022.
6. *Scattering Amplitudes and BCFW Recursion in $\mathcal{N} = 2^*$ Theory* (Invited talk), Regional Strings Meet - Bhopal Chapter, IISER-Bhopal, Bhopal, India, 17 November, 2022.

## Academic recognition/Awards:

- Infosys Foundation Fellowship, 2022-2023.

## Other Activities:

1. Attended **Infosys Lecture Series (Online)** on *Double-Copy Bootstrap* by Prof. Henriette Elvang (University of Michigan), HRI, Allahabad, India, July, 2022.

# Ahana Ghoshal

## Research Summary:

My research work is in the general area of quantum information and computation under the guidance of Prof. Ujjwal Sen. In the previous academic year, I have worked on different aspects of quantum information, like correlation between quantum entanglement and coherence, Grover quantum search algorithm, weak measurements, quantum thermodynamics, response to disorder in few- and many-body quantum spin systems, quantum metrology, quantum refrigerators, resource generation in coupled transmons, and local quantum state discrimination etc.

In the first work, We analyze the optimal basis for generating the maximum relative entropy of quantum coherence by an arbitrary gate on a two-qubit system. The optimal basis is not unique, and the high quantum coherence generating gates are also typically high entanglement generating ones and vice versa. However, the profile of the relative frequencies of Haar random unitaries generating different amounts of entanglement for a fixed amount of quantum coherence is different from the one in which the roles of entanglement and quantum coherence are reversed, although both follow the beta distribution.

In the work related to Grover's search algorithm, we analyze the robustness of the algorithm performed by a quantum register under a possibly time-correlated noise acting locally on the qubits. We model the noise as originating from an arbitrary but fixed unitary evolution, $U$, of some noisy qubits. The noise can occur with some probability in the interval between any pair of consecutive noiseless Grover evolutions. Although each run of the algorithm is a unitary process, the noise model leads to decoherence when all possible runs are considered. We derive a set of unitary $U$'s, called the 'good noises,' for which the success probability of the algorithm at any given time remains unchanged with varying the non-trivial total number ($m$) of noisy qubits in the register. The result holds irrespective of the presence of any time-correlations in the noise. We further show that the positions of the noisy sites are irrelevant in case of any of the Pauli noises. The results are illustrated in the cases of time-correlated and time-correlation-less noise. We find that the former case leads to a better performance of the noisy algorithm. We also discuss physical scenarios where our chosen noise model is of relevance.

The so-called quantum Cheshire cat is a phenomenon in which an object, identified with a "cat", is dissociated from a property of the object, identified with the "grin" of the cat. In our work, we propose a thought experiment, similar to this phenomenon, with an interferometric setup, where a property (a component of polarization) of an object (photon) can be separated from the object itself and can simultaneously be amplified when it is already decoupled from its object. We further show that this setup can be used to dissociate two complementary properties, e.g., two orthogonal components of polarization of a photon and identified with the grin and the snarl of a cat, from each other and one of them can be amplified while being detached from the other. Moreover, we extend the work to a noisy scenario, effected by a spin-orbit-coupling - like additional interaction term in the Hamiltonian for the measurement process, with the object in this scenario being identified with a so-called confused Cheshire cat. We

devise a gedanken experiment in which such a "confusion" can be successfully dissociated from the system, and we find that the dissociation helps in the amplification of signals.

In quantum thermodynamics, we obtain the Gorini-Kossakowski-Sudarshan-Lindblad master equation for two or more quantum systems connected locally to a combination of Markovian and non-Markovian heat baths. We analyze the thermodynamic quantities for such a mixed set of local environments, and derive a modified form of the Spohn's theorem for that setup. The modification of the theorem naturally leads to a witness as well as an easily computable quantifier of non-Markovianity. Furthermore, we find that for multiparty situations, where a combination of Markovian and non-Markovian heat baths are active, the response in thermodynamic system characteristics due to non-Markovian baths is prominent at times close to the initial time of evolution, whereas the long-time behavior is predominantly controlled by the Markovian ones.

In another direction, we show that the nearest neighbour entanglement in a mixture of ground and first excited states - the subjacent state - of the $J_1 - J_2$ Heisenberg quantum spin chain can be used as an order parameter to detect the phase transition of the chain from a gapless spin fluid to a gapped dimer phase. We study the effectiveness of the order parameter for varying relative mixing probabilities between the ground and first excited states in the subjacent state for different system sizes, and extrapolate the results to the thermodynamic limit. We observe that the nearest neighbour concurrence can play a role of a good order parameter even if the system is in the ground state, but with a small probability of leaking into the first excited state. Moreover, we apply the order parameter of the subjacent state to investigate the response to introduction of anisotropy and of glassy disorder on the phase diagram of the model, and analyse the corresponding finite-size scale exponents and the emergent tricritical point.

In quantum metrology, we show that in presence of a dephasing noise, quantum advantage can be obtained in the Fisher information-based lower bound of the minimum uncertainty in estimating parameters of the system Hamiltonian. The quantum advantage refers here to the benefit of initiating with a maximally entangled state instead of a product one. This quantum advantage was known to vanish in the same noisy scenario for a frequency estimation protocol. Restoration of the better precision in frequency estimation with maximally entangled probes can be attained via an Ising interaction between system particles or a magnetic field applied in the transverse direction or both. A quantum advantage can also be obtained while estimating the strength of the introduced magnetic field along the transverse direction, whereas for the instances considered, no quantum advantage is achieved in measuring the coupling parameter of the Ising interaction. We also investigate the dependence of measurement precision on the entanglement content, which is not necessarily maximal, of the initial states. The precision in estimation of frequency and of transverse field strength increases monotonically with the increase of entanglement content of the initial state, while the same of coupling parameter of the Ising interaction, shows a non-monotonic behavior. Also, we find that insertion of glassy disorder, accidental or engineered, can lead to enhancement of metrological precision in estimating an unknown parameter of a quantum system. We compare the Fisher information-based lower bound of the minimum standard deviation of an estimated parameter, in pres-

ence of glassy disorder in the system, with the same of an ideal, viz. disorder-free, situation. We find instances where the disorder-averaged error in estimation outperforms the same for a disorder-less scenario for uncorrelated as well as copies of two-qubit maximally entangled probes. The advantage in the accuracy of measurement obtained in a disordered situation over the ideal one is often greater than the corresponding dispersion of the disorder-induced error distribution, and in such cases, we refer to the effect as an example of "order from disorder". Moreover, disorder insertion can reduce the requirement of entanglement content of the initial probes, which are copies of two-qubit states, along with providing a disorder-induced enhancement.

In quantum refrigerators, we explore a small quantum refrigerator consisting of three qubits each of which are kept in contact with an environment. We consider two settings: one is when there is necessarily transient cooling and the other is when both steady-state and transient cooling prevail. We show that there can be significant advantages than the Markovian environments case for both these settings in the transient regime and also in equilibrium if we replace the bath attached to the cold qubit by a non-Markovian reservoir. We also consider refrigeration with more than one non-Markovian bath of the three-qubit refrigerating device. Curiously, a steady temperature is reached only if there are at least two Markovian environments, although there are distinct envelopes of the temperature oscillations in all cases. We compare the device connected to one or more non-Markovian reservoirs with the case of all Markovian environs, as also with two- and single-qubit self-sustained devices connected to one or more non-Markovian baths. We propose a measure to quantify the amount of non-Markovianity in the systems. Finally, the refrigerator models are studied in presence of Markovian noise, and we analyse the response on the refrigeration of the noise strength. In particular, we find the noise strength until which refrigeration remains possible.

In coupled transmon system, we analyze the quantum resource generation of capacitively-coupled multilevel transmon circuits surrounded by bosonic baths, within the Markovian limit. In practice, the superconducting circuit elements are usually part of a larger circuit, constructed with many other linear circuit elements, which along with their environment is assumed to be mimicked by the baths. We study the response to variation of the coupling strength of resource generation for thee system prepared in zero-resource initial states. We focus, in particular, on entanglement and quantum coherence as resources. We quantify the entanglement generation power of coupled transmon qutrits, taking into account the maximum entanglement the system can generate and the time-scale over which the system can sustain a significant entanglement. We identify the optimal initial separable states leading to maximum entanglement generating power.

In another direction, we find that the $m$-separability and $k$-partite entanglement of a multipartite quantum system is correlated with quantum coherence of the same with respect to complete orthonormal bases, distinguishable under local operations and classical communication in certain partitions. In particular, we show that the geometric measure of $m$-inseparable entanglement of a multipartite quantum state is equal to the square of minimum fidelity-based quantum coherence of the state with respect to complete orthonormal bases, that are locally distinguishable in a partition into $m$-parties.

## Publications:

1. A. Bhattacharyya, A. Ghoshal, U. Sen, *Correlation between resource-generating capacities of quantum gates*, Phys. Rev. A **107**, 032406 (2023).

2. S. P. Mandal, A. Ghoshal, C. Srivastava, U. Sen, *Invariance of success probability in Grover quantum search under local noise with memory*, Phys. Rev. A **107**, 022427 (2023).

3. A. Ghoshal, S. Sau, D. Das, U. Sen, *Isolating noise and amplifying signal with quantum Cheshire cat*, Phys. Rev. A **107**, 052214 (2023).

## Preprints:

1. A. Ghoshal, U. Sen, *Multiparty Spohn's theorem for mixed local Markovian and non-Markovian quantum dynamics*, arXiv:2208.13026.

2. S. Mondal, G. Biswas, A. Ghoshal, A. Biswas, U. Sen, *Estimating phase transition of perturbed $J_1 - J_2$ Heisenberg quantum chain in mixtures of ground and first excited states*, arXiv:2211.00623.

3. A. Bhattacharyya, A. Ghoshal, U. Sen, *Restoring metrological quantum advantage of measurement precision in noisy scenario*, arXiv:2211.05537.

4. A. Bhattacharyya, A. Ghoshal, U. Sen, *Disorder-induced enhancement of precision in quantum metrology*, arXiv:2212.08523.

5. A. Bhattacharyya, A. Ghoshal, U. Sen, *Improved refrigeration in presence of non-Markovian spin-environment*, arXiv:2303.06712.

6. T. Ray, A. Ghoshal, D. Rakshit, U. Sen, *Optimal quantum resource generation in coupled transmons immersed in Markovian baths*, arXiv:2303.16136.

7. A. Ghoshal, S. Choudhary, U. Sen, *All multipartite entanglements are quantum coherences in locally distinguishable bases*, arXiv:2304.05249.

## Conference/Workshops Attended:

1. Young Quantum 2023, Harish-Chandra Research Institute, Allahabad, India, 15-18 Feb, 2023. Presented a talk on "*Towards a local version of the second law of thermodynamics*".

## Visits to other Institutes:

1. Université libre de Bruxelles in Belgium from 5th March to 7th March 2023.

2. Atominstitut at Vienna in Austria from 8th March to 10th March 2023.

3. University of Warsaw in Poland from 13th March to 14th March 2023.

4. University of Gdańsk in Poland from 15th March to 17th March 2023.
5. Heinrich-Heine-Universität Düsseldorf in Germany on 20th March 2023.
6. University of Siegen in Germany from 21st March to 27th March 2023.
7. ICFO - The Institute of Photonic Sciences in Barcelona from 29th March to 31st March 2023.

# Aman Chauhan

## Research Summary:

During mid and late 2022, I have done three projects on supersymmerty, string theory-II and string flux compactifications. In addition, I familiarized myself with the algebraic and differential geometry methods for physicist. Since February-2023, in the collaboration with Anshuman Maharana, Michele Cicoli and Pellegrino Piantadosi, we have been working on the search of low superpotenial, $|W_0|$, for general tadpole condition with $12$ independent fluxes in flux compactification of type II-B string theory on Calabi-Yau manifold $\mathbb{CP}^4_{[1,1,1,6,9]}$.

## Conference/Workshops Attended:

1. String Seminar Days, H.R.I Prayagraj, India, December 2022.

# Anjan Kumar Barik

## Research Summary:

In this academic year, I worked on two projects under the supervision of Prof. Santosh Kumar Rai . The first project "Emergent new symmetry from the Higgs shadow", I did with Dr. Waleed Abdallah, Prof. Santosh Kumar Rai and Dr. Tousik Samui.

The second project was named "Determining the spin of exotic charged particles at future $e^+$ $e^-$ collider", I did with Dr. Rafiqul Rahaman and Prof. Santosh Kumar Rai.

## Publications:

1. Waleed Abdallah, Anjan Kumar Barik, Santosh Kumar Rai and Tousik Samui *Emergent new symmetry from the Higgs shadow,* ***Phys.Rev.D 107.015026 (2023)*** , ***arXiv: 2109.07980 [hep-ph]***.

2. *Anjan Kumar Barik, Rafiqul Rahaman and Santosh Kumar Rai Distinguishing non-standard scalar and fermionic charged particles at a future e+e- collider,* ***Phys.Rev.D 107.035002 (2023)*** , ***arXiv: 2206.11560 [hep-ph]***

## Conference/Workshops Attended:

1. *Data and Machine Learning at the Large Hadron Collider, IIT Hyderabad, 22nd to 28th August, 2022.*

2. *Participated in collaborative discussions on aspects of high energy collider physics, IISER Kolkata, November 17-21, 2022.*

3. *DAE-BRNS High Energy Physics Symposium 2022, IISER Mohali, 12-16 December, 2022.*

4. *2nd International Meeting on High Energy Physics (IMHEP 2023), IOP Bhubaneswar, 16th to 22nd February, 2023.*

## Invited Lectures/Seminars:

1. I presented two posters, *Emergent new symmetry from the Higgs shadow and Distinguishing nonstandard scalar and fermionic charged particles at a future e+e- collider in* ***DAE-BRNS High Energy Physics Symposium 2022*** *at IISER Mohali on 13th and 15th December, 2022.*

2. *I gave a talk, Emergent new symmetry from the Higgs shadow in* ***2nd International Meeting on High Energy Physics (IMHEP 2023)*** *at IOP Bhubaneswar on 21st February, 2023.*

# Aparajita Bhattacharyya

## Research Summary:

Quantum information and computation constitutes a broad area of research at the interface of physics, computer science, and engineering. Important applications of quantum information include secure cryptography and efficient integer factorisation. At the fundamental level, it provides a perhaps better understanding of the quantum world. Moreover, the area has tantalizing connections with other fields of science, such as cooperative phenomena and information paradox near event horizons.

It is interesting and important to understand and probe the resources necessary for obtaining advantage in the different quantum information processing tasks over their classical counterparts, and this was one of the areas of my research in quantum metrology. I have also worked on the effects of disorder in quantum metrological precision enhancement. I have also worked on the resource generating capacities of non-local unitaries in the separated laboratories paradigm. Further, I have also worked on quantum thermodynamics, particularly in quantum refrigerators.

The formulation of resource theory, within quantum information science, was initiated by the theory of entanglement. Since then, quantifying entanglement for pure and mixed states, with and without auxiliary systems, and the generation of maximal entanglement using global unitaries have been extensively studied in literature. Similarly, various aspects of the quantum theory of coherence have also been uncovered. In one of my previous work, I have analyzed the optimal product basis for generating the maximum relative entropy of quantum coherence by an arbitrary gate on a two-qubit system. The optimal basis is not unique, and the high quantum coherence generating gates are also typically high entanglement generating ones and vice versa. However, the profile of the relative frequencies of Haar random unitaries generating different amounts of entanglement for a fixed amount of quantum coherence is different from the one in which the roles of entanglement and quantum coherence are reversed, although both follow the beta distribution.

In a separate work, I considered frequency estimation protocols using quantum measurements. It was familiar from previous studies that in absence of noise, one can overcome the shot-noise limit by using a maximally entangled initial state instead of the uncorrelated ones. But this quantum advantage can be lost if we apply a noise to the system, say a dephasing one. In my work, I have emphasized that the benefit of using maximally entangled probes in quantum metrology, which disappears for frequency estimation in a noisy case, can be restored in presence of a transverse field and/or two-qubit interactions, like the Ising one, incorporated in the system particles. I subsequently considered the estimation of the field and interaction strengths, for different system Hamiltonians, and found that while the maximally entangled probe can provide advantage in certain situations, there are also instances where the same advantage is absent. Finally, I have investigated the role of the amount of entanglement of the probe states in quantum parameter estimation. I found that while a monotonic behavior of the uncertainty of estimation with respect to initial entanglement in the probes is present in some cases, non-monotonic behavior also crops up in other instances.

In another paper, I have examined the effect of glassy disorders present in the sys-

tem, on the precision in estimation of system parameters. I consider copies of uncorrelated as well as two-qubit maximally entangled initial probes and identify instances where relative advantages in the efficiency of estimations are obtained in presence of glassy disorder in the system over the ideal cases. In looking for disorder-induced enhancement, I compare the disorder-averaged minimum Fisher information-based error with the corresponding quantity in the ideal, i.e., disorder-free limit. However, I also check whether the difference between the disorder-averaged and ideal cases is higher than the disorder-induced fluctuations in the disorder-average. I also find cases where a glassy disorder, present in the system, reduces the requirement of initial quantum correlation, entanglement, for attaining better precision in the estimation of a parameter over an ideal - disorder free - situation.

In another paper, I have considered a few-qubit refrigerator where each qubit is connected with a local reservoir, and look at the effect of substituting each Markovian reservoir by a non-Markovian one. I have found that quantum absorption refrigerators, in the presence of mixed Markovian and non-Markovian environments, are sometimes advantageous over the ideal Markovian setting, where all the environments are Markovian. In particular, I have considered spin-baths as non-Markovian environments. Moreover, I have compared the three-qubit quantum refrigerator connected to spin-baths, with single- and two-qubit self-sustaining devices connected to spin-baths, and depicted the significance of using the three-qubit refrigerator model.

## Publications:

1.Correlation between resource-generating capacities of quantum gates, Aparajita Bhattacharyya, Ahana Ghoshal and Ujjwal Sen, Phys. Rev. A 107, 032406 (2023).

## Preprints:

1. Restoring metrological quantum advantage of measurement precision in noisy scenario, Aparajita Bhattacharyya, Ahana Ghoshal and Ujjwal Sen, arXiv:2211.05537.

2. Disorder-induced enhancement of precision in quantum metrology, Aparajita Bhattacharyya, Ahana Ghoshal and Ujjwal Sen, arXiv:2212.08523.

3. Improved refrigeration in presence of non-Markovian spin-environment, Aparajita Bhattacharyya, Ahana Ghoshal and Ujjwal Sen, arXiv:2303.06712.

## Conference/Workshops Attended:

1. Young Quantum, Harish Chandra Research Institute, India, February 2023.

Who's afraid of disorder? (poster), Young quantum, Harish Chandra Research Institute, February 2023.

## Other Activities:

1. Teaching Assistantship, Mathematical Methods, Harish Chandra Research Institute, 2022.

# Arijeet Sarangi

## Research Summary:

Solar cells are one promising avenue in order to perceive the sustainable and green environment as they can convert readily available visible and ultraviolet photon flux into usable electricity. In particular, perovskite materials sandwiched between other substrates have demonstrated impressive power conversion efficiencies. One can achieve desirable type of band alignment through these combinations, which could not only beneficial for solar cells, but also could be envisaged for light emitting diodes and photocatalysts. There is a plethora of materials, which can be used for such quest of optimum and desirable band alignment. In this investigation, we have consciously chosen a member of MXene family and a promising member of inorganic halide perovskites family. The reason behind this particular combination is the inorganic halide perovskites are inherently more stable as compared to the organic-inorganic hybrid perovskites, however the corresponding photo-conversion efficiency is lower. Therefore, we would like to envisage whether two-dimensional(2D) titanium-carbide MXene support layers could improve perovskite solar cell performance without compromising the stability. Application of MXene materials in perovskite solar cells (PSCs) has attracted considerable attention owing to their supreme electrical conductivity, excellent carrier mobility, adjustable surface functional groups, excellent transparency and superior mechanical properties. Density functional theory (DFT) based electronic structure calculations show that the addition of one such Mxene to halide perovskite could tune the work function of the perovskite absorber. Moreover, the dipole could be used to change the band alignment between these layers. The combined action of work function tuning and interface engineering can lead to substantial performance improvements in MXene- modified perovskite solar cells. Going forward, we believe, apart from the experimental work reported so far, profound theoretical understanding through first-principle calculations via density functional theory (DFT) formalism would provide more insight into charge transport and work function of new MXene compositions, MXene/perovskite interfaces. In this work, we have performed rigorous theoretical analysis for the impact of MXene surface modifications, various termination groups, work functions modifications and energy level alignment.

## Publications:

1. S. Bhowmick, Arijeet Sarangi, C. Moi, Sudip Chakraborty, M. Qureshi, *Diffusion mediated morphological transformation in bifunctional Mn2O3/CuO-(VO)3(PO4)2.6H2O for enhanced electrochemical water splitting*, ACS Applied Materials Interfaces, 14, 52204, (2022)

## Preprints:

1. Arijeet Sarangi, S. Rondiya, G. Shaikh, M. Nasane, S. Jathar, S. Barma, K. Kore, S. V. Ghaisas, Sudip Chakraborty, A. Funde *Tuning Band-edge Alignment in Cu2NiSnS4-*

*CdS hetero-interface for Enhanced Water Splitting Activity: Experiment meets Electronic Structure* (in submission)

2. Arijeet Sarangi and Sudip Chakraborty *Theoretical Investigations of Interfacial phenomena for Perovskite- Mxene based Heterostructures* (in preparation)

## Conference/Workshops Attended:

1. *International conference on Evolution of Electronic Structure Theory and Experimental Realization*, India, January, 2023

2. *International conference on recent advances in renewable energy*, India, February, 2023

# Ayan Patra

## Research Summary:

In academic year $2022-23$, I have mainly worked on two directions – $(1)$ Characterization and quantification of resources in discrete quantum system and their generation in continuous variable (CV) regime; $(2)$ design of quantum technologies in CV frameworks and quantifying their performances. Let us briefly discuss them.

We provide a framework for a continuous variable (CV) system-based multimode dense coding network with several senders and a single receiver. The protocol is adaptable to any number of modes, with displacements serving as the encoding method and the decoding involves homodyne measurements of the modes after they are combined in a pairwise manner by a sequence of beam splitters. This shows the protocol's viability for use in laboratories using currently available resources. For the scenarios of two and three senders, when sharing of three- and four-mode states is involved, we compute the closed form expression of the dense coding capacity. The dense coding capacity is calculated with the constraint of fixed average energy transmission when the modes of the sender are transferred to the receiver after the encoding operation. We use paradigmatic classes of three- and four-mode states in both instances to illustrate the quantum advantage of the protocol. The quantum advantage grows as the amount of energy permitted to be transmitted from the senders to the receiver rises.

In another project, we create a multimode quantum battery (QB) using the foundation provided by CV systems. Using a generic class of multimode initial states that can have their parameters tweaked to yield both separable and entangled, and that may be charged locally as well as globally by Gaussian unitary operations. We investigate the battery's performance by using the figures of merit as the second moments of the change in energy, and we demonstrate that a separable state is just as favorable as an entangled one. We then provide a scaling analysis by demonstrating that for a multimode separable initial Gaussian state, fluctuations diminish as the number of modes grows.

We also shed light on how to generate genuine multimode entanglement (GME), quantified via the generalized geometric measure (GGM), in CV systems. We show how introducing disorder can help to achieve a steady production of GME.

In discrete quantum system, we investigate the possibility that, when we restrict our quantum operations to a mixture of global unitary operations, non-absolute separability (NAS) might be viewed as a resource. We then develop the resource theory of NAS by constructing monotone functions based on distance measures and witness operators. We also establish a link between the resource theory entanglement and the NAS resource theory.

## Publications:


1. Ayan Patra, Rivu Gupta, Saptarshi Roy, Tamoghna Das, and Aditi Sen(De), *Quantum dense coding network using multimode squeezed states of light*, Phys. Rev. A 106, 052607 (2022)

## Preprints:

1. Tanoy Kanti Konar, Ayan Patra, Rivu Gupta, Srijon Ghosh, Aditi Sen De, *Multimode advantage in continuous variable quantum battery,* arXiv:2210.16528v1 (2022).

2. Ayan Patra, Arghya Maity, Aditi Sen De, *Resource Theory of Non-absolute Separability,* arXiv:2212.11105v1 (2022).

3. T Anuradha, Ayan Patra, Rivu Gupta, Amit Rai, Aditi Sen De, *Production of genuine multimode entanglement in circular waveguides with long-range interactions,* arXiv:2303.15137 (2023).

## Conference/Workshops Attended:

1. Young Quantum - 2023 (YouQu-2023), QIC group at Harish-Chandra Research Institute, Prayagrag, UP, India, 15th February- 19th February, 2023-*Poster presentation: NOISE-AUGMENTED DENSE CODING NETWORK AND ITS OPTICAL IMPLEMENTATION.*

## Other Activities:

1. Member of the organising committee of Young quantum-23 conference at HRI.

2. Served as TA in Mathematical methods in Physics-II in Independence term.

# Ayan Sahoo

## Research Summary:

In 2022, I did a project on the interface of quantum information and many-body physics. In this, I studied the quantum phase transition of the Ising model on a spin chain and estimated its critical points. In the later part of 2022 and early 2023, I did a project on Quantum Sensing.

## Preprints:

1. Ayan Sahoo, Utkarsh Mishra, Debraj Rakshit, *Localization Driven Quantum Sensing*, arXiv:2305.02315

## Conference/Workshops Attended:

1. *Young Quantum 2023*, HRI Prayagraj, India, February 2023.

# Debraj Bose

## Research Summary:

We calculate the retarded electronic Green's function in the Holstein model in the background of slow phonon dynamics using a trajectory based method. We compare our result with the existing "exact" results at dilute filling and zero temperature. We then investigate the effects of increasing electron density and temperature on the spectral features, all the way from weak to strong electron-phonon coupling.

## Other Activities:

Tutor for Advance Statistical Mechanics, Jan-May 2023

# Deepak Raikwal

## Research Summary:

Neutrinos play a crucial role in the Standard Model (SM) of particle physics. Initially, the SM considered neutrinos to be massless particles. However, experiments such as Super-Kamiokande (SK), Sudbury Neutrino Observatory (SNO), and Tokai to Kamioka (T2K) have demonstrated that neutrinos have mass through a phenomenon called neutrino oscillation.

Neutrinos exist in three different flavor states, denoted as $\nu_\alpha$, corresponding to the three lepton families. However, these flavor states are the combinations of three mass eigenstates of neutrinos, denoted as $\nu_i$. Neutrinos undergo oscillation as they travel, which means they change from one flavor state to another. The probability of a neutrino tranforming to a particular flavor state is determined by quantum mechanics.

The masses of the three neutrino mass eigenstates can have two possible orderings: Normal Ordering (NO), where $m_1$ is the lightest, followed by $m_2$ and $m_3$ in increasing order, or Inverted Ordering (IO), where $m_3$ is the lightest, followed by $m_1$ and $m_2$. Determining the mass ordering of neutrinos is an important goal in neutrino physics.

In my research, I focused on understanding the mass ordering of neutrinos and investigating the impact of the squared mass difference $\Delta m^2_{31}$ on the sensitivity of measuring the mass ordering in experiments such as ICAL, JUNO, and T2HK. By combining the data from these experiments, I demonstrated that it is possible to achieve a sensitivity of more than $7\sigma$ for determining the mass ordering, regardless of the specific values of the oscillation parameters.

Additionally, I utilized the neutrino oscillation method to probe beyond the Standard Model (BSM) physics in the neutrino sector. One area of interest is Lorentz violation, which arises from BSM theories like string theory and quantum gravity. According to string theory, Lorentz symmetry is not an exact symmetry but can be spontaneously broken at plank temprature, resulting in a non-zero vacuum expectation value (vev). The presence of a non-zero vacuum expectation value (VEV) gives rise to a background field that pervades our universe. This background field may exhibit directional properties or display isotropy. While the Lorentz symmetry remains invariant in the observer frame, it is broken in the particle frame.

Through a study of neutrino oscillations, I investigated the impact of Lorentz violation on the probabilities of neutrino oscillations. Specifically, I examined the sensitivity of Lorentz invariance violation (LIV) in experiments such as ICAL, DUNE, and T2HK.

## Publications:

1. Deepak Raikwal, Sandhya Choubey, Monojit Ghosh, **Neutrino Mass Ordering – Circumventing the Challenges using Synergy between T2HK and JUNO**, Phys. Rev. D 106, 115013

2. Deepak Raikwal, Sandhya Choubey, Monojit Ghosh **Determining Neutrino Mass Ordering with ICAL, JUNO and T2HK**, Eur. Phys. J. Plus 138, 110 (2023)

3. Deepak Raikwal, Sandhya Choubey, Monojit Ghosh, **Comprehensive study of**

**Lorentz invariance violation in atmospheric and long-baseline experiments**, Phys.Rev.D 107 (2023) 11, 115032

## Conference/Workshops Attended:

1. Deepak Raikwal, Sandhya Choubey, Monojit Ghosh, **Neutrino Mass Ordering Using Synergy between ICAL, T2HK, and JUNO**, LHEP 2023 (2023) 376
2. **Determining Neutrino Mass Ordering with INO, JUNO and T2HK**, Neutrino-2022 At: Virtual Seoul, DOI: 10.5281/zenodo.6757794
3. **Neutrino Mass Ordering with Atmospheric, long baseline and reactor experiments**, XXV DAE-BRNS high energy physics symposium, 12-16 December 2022, IISER Mohali
4. **Comprehensive study of LIV in atmospheric and long-baseline experiments**, Workshop on Particle physics, Astrophysics and Cosmology - 2023, Shiv Nadar Institute.
5. Workshop attended on **1st National Workshop on GEANT4 and its Application to High-Energy Physics and Astrophysics** , 5-9 Dec 2022, IUCAA, Pune

# Dhirendra Kumar

## Research Summary:

The crisis of energy is increasing as the population is increasing over the world. And fossil fuels are limited and harmful. We have many alternate resources to generate and store energy like, wind energy, perovskite solar cell, hydrogen energy, batteries, supercapacitors, *etc*. Out of these resources for energy, solar cell and hydrogen energy is the most environment friendly to be used with negligible pollution. There are many ways to produce hydrogen energy. The water splitting is one of the most favorable techniques for the production of hydrogen. There are two methods, electrocatalysis and photocatalysis to split the water. The most important work is to find perfect materials for the procedure of water splitting. In the last few decades, lots of nanomaterials have been experimentally synthesized and theoretically predicted for energy applications. I work on the theoretical and computational characterization of nanomaterials for electrocatalysis and other various applications based on their electronic and mechanical properties. I have done work on two-dimensional (2D) transition metal tri-chalcogenide material (TMD) **VS3** monolayer. In this work, I investigated the hydrogen evolution reaction and oxygen evolution reaction catalytic activity of VS3 monolayer for the production of hydrogen and oxygen. I use first-principle density functional theory (DFT) methods to investigate the electronic structure and mechanical properties of materials.

## Publications:

1. Dhirendra Kumar; Jagjit Kaur; Prajna Parimita Mohanty; Rajeev Ahuja; and Sudip Chakraborty; *Recent Advancements in Nontoxic Halide Perovskites: Beyon Divalent Composition Space* **ACS Omega 2021**, 6, 33240-33252

## Conference/Workshops Attended:

1. International school and conference on Evolution of Electronic Structure Theory and Experimental Realization (EESTER), SRM Institute + IIT Madras, INDIA, January 2023 Chennai.

2. International Conference on recent advances in renewable energy (CARE), Harish-Chandra Research Institute, India, February 2023

# Divyansh Shrimali

## Research Summary:

The topic of study was information theoretic counterpart of specific heat capacity which we term as capacity of entanglement. We studied its rate for general bipartite Hamiltonians and self-inverse Hamiltonians, where the later had some interesting insights owing to its mathematical structure. We further evaluated a bound on the rate of entanglement and its speed limit was evaluated while further extending the definition for mixed state case in our published work. Further effort is being made to study this quantity in driven open quantum systems, PT symmetric and beyond. In an another finished and submitted project, we studied dynamics of several correlations like negativity, involved in driven bipartite quantum systems.

Others works which are undergoing involve composite quantum systems with aim of extracting subsystems closest possible local observables. A basis independent approach is contemplated which is based on convex optimization on space of operators. This method also gives a witness for the presence of non locality in the observable. In one ongoing work, behaviour of capacity of entanglement is studied in case of sudden death of entanglement in a double jaynes-cummings model. In yet another project, relation between non-commutativity and coherence is studied where further speed limit of what we term as quantumness generation, is related to non-commutativity of observables and relevant examples are worked out.

protocol was proposed for a general interacting composite system with the aim of extracting subsystems closest possible local Hamiltonian. The protocol is based on optimization on a Hilbert Schmidt space of operators and further through this technique a witness for the presence of nonlocal term of any bipartite Hamiltonian is also proposed.

for information as a no go result with a quantum machine learning ansatz. It was proposed that the reason why scrambling for unitary operator involved in quantum process, under any cost function ansatz, will ultimately end up in a plateau, establishing a need for exponential increase of required training data needed with respect to the parameters involved. This was further verified by utilizing loshmidt echo as a viable ansatz and realizing its analogous nature to OTOC(Out of Time ordered Correlator), the rate of spread of scrambling was also studied.

of thermodynamic specific heat capacity which we term as Entanglement capacity. Study of rate of capacity for general two qubit hamiltonian and arbitrary dimensional self Inverse Hamiltonian was studied. Further more, through Entanglement capacity, a bound on rate of entanglement and its speed limit was evaluated. The definition of capacity for pure state was further generalized to mixed state case. Finally speed limit for various quantum correlations in bipartite quantum systems were also evaluated.

## Publications

1. Divyansh Shrimali, Vivek Pandey, Swapnil Bhowmick and Arun Kumar Pati, *Capacity of Entanglement for Non-Local Hamiltonians, Phys. Rev. A 106, 042419 – Published 14 October 2022*

2. Vivek Pandey, Divyansh Shrimali, et.al., *Speed limits on correlations in bipartite quantum systems, Phys. Rev. A 107, 052419 - Published 25 May 2023*

## Preprints:

1. Divyansh Shrimali, Sohail, Ujjwal Sen and Arun Kumar Pati, *Witnessing Non-Local Hamiltonians* (In preparation)
2. Divyansh Shrimali, Brij Mohan and Arun Kumar Pati, *Fundamental limitation on Quantumness of Observables* (In preparation)
3. Divyansh Shrimali, Arun Kumar Pati, *Capacity of Entanglement for multipartite systems* (In preparation)

## Conference/Workshops Attended:

1. *International Conference on Complex Quantum systems (ICCQS)-2023*, Organised by Board of Research in Nuclear Studies, Bhabha Atomic Research Center, Mumbai, India, 18-21 January-2023.
2. *Young Quantum Conference (YouQ-2023)*, Organised by QIC group, HRI-HBNI, 15-18 February-2023
3. Summer School on *Quantum Information and Quantum Technology (QIQT -2023)* IISER Kolkata

## Visits to other Institutes:

1. Visited CQST group, IIIT-Hyderabad from 10 May - 30 July 2023.

## Invited Lectures/Seminars:

1. Invited for a talk on Entanglement dynamics and capacity at QIQT-2023, IISER-Kolkata (online mode)

## Other Activities:

1. Tutor of Classical Mechanics course, October-22 to January-23.
2. Volunteer in Talent Search Exam.
3. Member of the organizing committee of YouQu-2023.
4. Internal arxiv flashbacks arranged on weekly basis.

# Faruk Abdulla

## Research Summary:

Currently, my research focuses on the categorization and topological characteristics of topological semimetals. Among these semimetals, the Weyl semimetals and nodal line semimetals hold significant importance, having well-established gapless topological phases supported by both theoretical models and experimental evidence.
My work revolves around several key areas:

- Investigating the impact of magnetic field couplings on Weyl semimetals, with a particular focus on studying the annihilation of topological Weyl nodes beyond the linear dispersion regime in the Hofstadter regime.
- Exploring the magneto-transport properties when two Weyl when two Weyl semimetals, twisted relative to each other, form an interface. This study aims to uncover localized Fermi arc states at the interface.
- Engaging in the classification of three-dimensional topological nodal line semimetals and two-dimensional Weyl semimetals within the chiral classes.

In summary, my research delves into the properties and behaviors of topological semimetals, with a specific focus on magnetic field couplings, interface phenomena, and classification aspects for both Weyl and nodal line semimetals.

## Preprints:

1. Faruk Abdulla, Ankur Das and Ganpathy Murthy, *Topological nodal line semimetal in the chiral class* (in preparation).
2. Nirnoy Basak, Sumathi Rao, and Faruk Abdulla, *Magneto-transport through an interface of twisted Weyl semimetals* (in preparation).
3. Faruk Abdulla, *Annihilation of Weyl nodes by external magnetic fields in the Hofstadter regime* (in preparation).

## Presentation in School/Conferences:

1. Oral presentation in "*Annual Conference on QuantumCondensed Matter(Q-MAT:2022)*", Indian Institute of Technology (IIT), Kanpur, India, Sep 2022
2. Oral presentation in "*ICTS In-House Meeting*", ICTS, Bangalore, 2023.

## Other Activities:

1. Attended an online course *"Computational condensed matter physics"* by Stitadhi Roy and Arnab Sen
2. Co-supervised (with Sumathi Rao) Durga Naga Hareesh (IISC) for his Master thesis.
3. Visited ICTS from May 2022 to June 2023.

# Jagjit Kaur

## Research Summary:

Energy demand has led to the over dependence on the non-renewable resources of energy. So, it is important to focus more on renewable energy like solar energy. Silicon solar cells are bulky and are expensive. Perovskites are a rapidly growing material for the solar cell application. Our main focus is to tune the perovskites to make them more efficient for optoelectronics applications. We have focused on non toxic double halide perovskites and hybrid halide perovskites for electronic, optical and magnetic properties.

## Publications:

1. Jagjit Kaur, Sudip Chakraborty, Tuning Spin Texture and Spectroscopic Limited Maximum Efficiency through Chemical Composition Space in Double Halide Perovskites, ACS Applied Energy Materials 20225 (5), 5579-5588 DOI: 10.1021/acsaem.1c03824

2. Dhirendra Kumar, Jagjit Kaur, Prajna Parimita Mohanty, Rajeev Ahuja, and Sudip Chakraborty, Recent Advancements in Nontoxic Halide Perovskites: Beyond Divalent Composition Space, ACS Omega 20216 (49), 33240-33252 DOI: 10.1021/acsomega.1c05333

3. Hrishit Banerjee, Jagjit Kaur, M.K. Nazeeruddin, Sudip Chakraborty, Tuning paradigm of external stimuli driven electronic, optical and magnetic properties in hybrid perovskites and metal organic complexes, Materials Today, Volume 60, 2022, Pages 183-200, ISSN 1369-7021

## Conference/Workshops Attended:

1. Conference on recent advances in renewable energy (CARE), India, February, 2023

## Other Activities:

1. Poster presentation on the title ”Tuning Spin Texture and Spectroscopic Limited Maximum Efficiency through Chemical Composition Space in Double Halide Perovskites” in the Conference on recent advances in renewable energy (CARE), India, February, 2023.

# Kajal Singh

## Research Summary:

During the academic year 2020-2021, I collaborated with Michele Cicoli, Matteo Licheri, Kuver Sinha, and Anshuman Maharana to investigate the interplay between Kahler moduli stabilisation and the joint statistics of the cosmological constant and supersymmetry breaking scale in the string landscape. Our research focused on two different scenarios of moduli stabilisation, and we observed that in both cases, the distributions favored lower scales of supersymmetry breaking.

Alongside Chandramouli Chowdhury, I studied the analytic structure of loop-level Witten diagrams for conformally coupled scalars. We provided an analysis of the wave function coefficients for conformally coupled scalars in general cosmologies. Specifically, we focused on the evaluation of these coefficients at the leading order in the coupling constant, considering both one and two-loop levels in momentum space. To regularize the loop integrals, we employed the hard-cutoff regularization technique. Additionally, we discussed the renormalization of these loop integrals in detail.

I am also exploring dualities between 4-dimensional Super Conformal Field Theories (SCFTs) and 2-dimensional Rational Conformal Field Theories (RCFTs) in collaboration with Dileep Jatkar, Md. Abhishek and Sachin Grover.

## Publications:

1. Matteo Licheri, Michele Cicoli, Anshuman Maharana, Kajal Singh, Kuver Sinha, *Joint statistics of cosmological constant and SUSY breaking in flux vacua with nilpotent Goldstino,* JHEP **01**, 013, (2023).

## Conference/Workshops Attended:

1. *The 17th Kavli Asian Winter School on Strings, Particles and Cosmology*, Institute for Basic Science, Daejeon, South Korea, January 2023
2. *Student Talks on Trending Topics in Theory (st4)*, IIT Indore, India, July 2022.

## Visits to other Institutes:

1. National Institute for Nuclear Physics (INFN), Bologna, Italy, October, 2022.
2. University of Heidelberg, Heidelberg, Germany, October, 2022.
3. Max Planck Institute for Physics, Munich, Germany, October, 2022
4. International Centre for Theoretical Physics (ICTP), Trieste, Italy, November, 2022.
5. International Centre for Theoretical Sciences (ICTS), Bengaluru, India, March, 2023.

## Invited Lectures/Seminars:

1. *Joint Statistics of Cosmological Constant and SUSY Breaking Scale in Flux Vacua with Nilpotent Goldstino*, String Seminar, International Centre for Theoretical Sciences (ICTS), Bengaluru, March, 2023.

2. *Joint Distribution of Cosmological Constant and Gravitino Mass*, Gong Show, 17th Kavli Asian Winter School, IBS Daejeon, South Korea, January, 2023.

3. *Moduli Stabilisation and Statistics of Low Energy Physics in String Landscape*, Conference Talk, XXV DAE-BNRS HER Symposium IISER Mohali, India, December, 2022.

4. *Moduli Stabilisation and Statistics of Low Energy Physics in String Landscape*, HEP Seminar, Swansea University, United Kingdom, November, 2022.

5. *Cosmological Constant and Gravitino Mass: Statistical Correlations from the Nilpotent Goldstino Formalism*, HEP Seminar, The University of Wisconsin-Madison, USA, November, 2022.

6. *Cosmological Constant and Gravitino Mass: Statistical Correlations from the Nilpotent Goldstino Formalism,* HEP Seminar*, Max Planck Institute for Physics Munich, Germany, November, 2022.*

7. *Moduli Stabilisation and Statistics of Low Energy Physics in String Landscape,* HEP Seminar*, The University of Liverpool, United Kingdom, November, 2022.*

8. *Cosmological Constant and Gravitino Mass: Statistical Correlations from the Nilpotent Goldstino Formalism,* ITP Seminar*, University of Heidelberg, Germany, October, 2022.*

9. *Moduli Stabilisation and Statistics of Low Energy Physics in String Landscape,* HEP Seminar*, INFN and University of Bologna, Italy, October, 2022.*

10. *Landscape in String Theory,* Lectures*, Student Talks on Trending Topics in Theory (st4), IIT Indore, India, July, 2022.*

## Academic recognition/Awards:

1. Infosis Fellowship, 2022.

# Kalyanbrata Pal

## Research Summary:

Title: Quasi Periodic Oscillations in GRHD simulations

Motivation: The observed data from black hole X-ray binaries show oscillations at certain frequencies. These oscillations are not very well understood in theory. In order to address it further we are simulating a plasma flow in the vicinity of the black hole to understand the role of general relativistic effects of gravity on fluid oscillations.

Title: On spherical Bondi flow and beyond

Motivation: Accretion on compact objects such as black hole or neutron star demands general relativistic treatment, more so in the vicinity of the accretor. However, a complete general relativistic treatment often becomes computationally demanding, if not unsolvable. Thus pseudo potentials have surfaced in the literature which are often motivated from a particular solution of general relativity at the same time allowing us to use the Newtonian framework. Although these modified potentials can never mimic all the features of the general relativity, different potentials can mimic some features of the general relativity sufficiently well without having to deal with the hustle of the complete general relativistic treatment, thus saving valuablecomputational resourses. A class of velocity dependent, modified Newtonian potential has recently been proposed in the literature which achieves this feat. While these potentials have been shown to mimic features like bending of light, precession of orbits, etc. extremely well, whether they can be used to explore accretion phenomena is yet to be explored. We are working on the simplest case of spherical accretion with one such potential proposed by Tejeda et. al.(MNRAS, Volume 433, Issue 3, 11 August 2013, Pages 1930–1940) as a toy model. Once a satisfactory scheme is developed, we further plan to explore more realistic framework such as accretion disks.

## Conference/Workshops Attended:

1. Astronomical Society of India(ASI) meeting IIT Indore, 1-5th March, 2023.

## Other Activities:

1. TA for General relativity course, August-December, 2022.

# Keshav Das Agarwal

## Research Summary:

In the last year, I have worked on the properties of the non-Hermitian quantum spin models, and the role of their equilibrium properties in the dynamics.

Non-Hermitian models with certain anti-unitary symmetries have enriching physics and topology, which may not be present in their Hermitian counterparts. They arise from the effective description of the open quantum systems. We look at the $\mathcal{RT}$-symmetric models, namely the $iXY$ model ($XY$ model with the imaginary anisotropy parameter) in the magnetic field, with and without the KSEA interaction. These systems have unbroken phase (complete real eigenspectrum) and broken phase. The loci of parameters separating these two phases are called the exceptional points.

We first look at the $iXY$ model in the magnetic field, and the effect of quenching the ground state. The system is prepared as the ground state of the unbroken phase, i.e., the eigenvector with the lowest eigenvalue. The evolution is performed by suddenly changing a parameter, which is the magnetic field strength in this case. Changing the magnetic field strength brings non-trivial dynamics in the systems as the initial and the final Hamiltonians do not commute. We look at the Loschmidt echo, which is the amplitude of the fidelity (distance) between the initial and the final state. We also look at the corresponding rate function, which in Hermitian systems, have been shown to have dynamical quantum phase transitions (DQPT). We show analytically for the $iXY$ model and numerically for the $iXYZ$ model that the long time average of the Loschmidt echo and the rate function shows non-analyticity at the exceptional points, thereby capturing the equilibrium phase transition of the initial model.

In the second work, we look at the $iXY$ model with KSEA interactions in the magnetic field, and find that the systems posses richer phase diagram than the $iXY$ model. The system is completely unbroken for all magnetic field strengths, if the magnitude of the imaginary anisotropy parameter is less than KSEA interaction strength. We also look at the entanglement in this parameter space, and show that the exceptional point in the non-Hermitian case corresponds to the factorization point in the Hermitian model (where the ground state is completely separable). We show that this is a direct consequence of the similarity transformation of the Hermitian $XY$ model with KSEA interaction. We also show that there is a critical line when the magnetic field strength is unity which is perfectly captured by the entanglement dynamics of the quenching.

Our studies reveal intriguing properties of the $\mathcal{RT}$ symmetric models, and demonstarte that the dynamical state can capture the equilibrium critical lines and the exceptional lines.

## Preprints:


1. Keshav Das Agarwal, Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Aditi Sen (De), *Detecting Exceptional Point through Dynamics in Non-Hermitian Systems,* arXiv:2212.12403.

2. Keshav Das Agarwal, Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju,

Aditi Sen (De), *Recognizing critical lines via entanglement in non-Hermitian systems*, arXiv:2305.08374.

## Conference/Workshops Attended:

1. *Young Quantum 2023*, Harish Chandra Research Institute, (February 15-18), 2023. (Presented a poster: *Non-Hermitian dynamics and Quantum Battery*)

## Invited talks:

1. Detecting Exceptional Point through Dynamics in Non-Hermitian Systems, *Center for Quantum Science and Technology, Center for Security Theory Algorithmic Research*, IIIT Hyderabad (31 December, 2022 - 4 January, 2023)

## Other Activities:

1. Teaching assistant for the course on Numerical Methods (January-present 2023) Instructor: Prof. Sudip Chakraborty

2. Member of the organizing committee - *Young Quantum 2023*, Harish Chandra Research Institute, (February 15-18), 2023.

# Kornikar Sen

## Research Summary:

A pack of quantum measurements that cannot be measured simultaneously is said to form a set of incompatible measurements. Every set of incompatible measurements has an advantage over the compatible ones in a quantum state discrimination task where one prepares a state from an ensemble and sends it to another party, and the latter tries to detect the state using available measurements. We have considered the local quantum state discrimination task, where a sender prepares a bipartite state and sends the subsystems to two receivers. The receivers try to detect the sent state using locally incompatible measurements. We have analysed the ratio between the probability of successfully guessing the state using incompatible measurements and the maximum probability of successfully guessing the state using compatible measurements. We have found that this ratio is upper bounded by a simple function of robustnesses of the incompatibilities of the local measurements. Interestingly, for every pair of sets of incompatible measurements, there exists at least one local state discrimination task where this bound can be achieved. We have argued that the optimal local quantum state discrimination task does not present any "nonlocality", where the term has been used in the sense of a difference between the ratios of probabilities of successful detection via incompatible and compatible measurements, in global and local state discriminations. The results can be generalised to the regime of multipartite local quantum state distinguishing tasks.

The superposition principle provides us with the opportunity to unfold many surprising facts. One such fact leads to the generation of entanglement, which may allow one to teleport an unknown quantum state from one location to another. While all pure entangled states can provide nonclassical fidelity for quantum teleportation, perfect teleportation comes at the cost of having a maximally entangled state shared between the sender and the receiver. We have considered a situation where the sender and the receiver are in a superposed situation of sharing a maximally entangled state and not sharing anything, controlled by a quantum switch. We have considered two distinct protocols: in the first case, the sender and the receiver do nothing when there is no shared entanglement, and in the second case, they use classical communication in the absence of entanglement. In each of the protocols, we have followed two different paths. In the first path, after the protocol is completed, we simply throw away the switch. In the second path, after accomplishing the protocol, we have operated a Hadamard gate on the switch, measured the switch's state, and considered the outcome corresponding to a particular state of the switch. We have compared the two paths with the maximum fidelity achievable through random guessing or utilising classical resources only. In particular, we have provided conditions to achieve nonclassical fidelity in teleportation by applying the quantum switch. We have commented on whether the difference between the two paths can be expressed in terms of the quantum coherence present in the switch's state.

In realistic situations, physical systems cannot be completely isolated from their environment. Its inevitable interaction with the environment can influence the working process of the device. We have considered two-qubit quantum batteries where one qubit of the battery is interacting successively with the spins present in the surround-

ing environment. We have examined the effect of the interaction on the maximum amount of energy that can be extracted from the battery using unitaries. In particular, we have analysed the behaviour of the amount of globally extractable work from the noisy battery, initially prepared in a locally passive or generic pure state with a fixed initial entanglement, with the number of interactions the qubit has gone through. We have also examined the amount of locally extractable work from the noisy battery. We have realised that though the amount of extractable energy, be it global or local, would decrease with the number of spins of the environment it interacted with, if we increased the time interval of the interaction with each spin, after a cut-off value of the interval, the short-time behaviour showed a peculiarity, viz., the extractable energy within a single interaction started to increase with time. The cut-off time indicated the Markovian-to-non-Markovian transition of the interaction within the current perspective. We have also obtained upper and lower bounds on the entanglement content of the initial noiseless shared two-qubit battery state, depending on the extractable energies.

## Preprints:

1. Kornikar Sen, Ujjwal Sen, *Incompatibility of local measurements provide advantage in local quantum state discrimination*, arXiv:2204.10948.
2. Priya Ghosh, Kornikar Sen, Ujjwal Sen, *Preservation of entanglement in local noisy channels*, arXiv:2209.04422.
3. Kornikar Sen, Adithi Ajith, Saronath Halder, Ujjwal Sen, *To share and not share a singlet: quantum switch and nonclassicality in teleportation*, arXiv:2211.02921.
4. Kornikar Sen, Ujjwal Sen, *Noisy quantum batteries*, arXiv:2302.07166.

## Conference/Workshops Attended:

1. *Young Quantum (YouQu)*, India, February 2023: Presented poster.

## Visits to other Institutes:

1. University of Turku, Turku, Finland, March, 2023.
2. Centre of New Technologies, University of Warsaw, Warsaw, Poland, March, 2023.
3. Institute for Quantum Optics and Quantum Information, Vienna, Austria, March, 2023.
4. Technical University of Munich, Munich, Germany, March, 2023.
5. French National Centre for Scientific Research, Grenoble, France, March, 2023.
6. University College London, London, UK, March, 2023.
7. University of Bristol, Bristol, UK, March, 2023.

# Leela Ganesh Chandra Lakkaraju

## Research Summary:

In the past year, my research focused on two main areas: (1) Investigating the ability of a connected system with a finite interaction range to replicate quantum correlations found in fully connected systems. (2) Exploring dynamical quantum phase transitions in Hermitian topological systems and non-Hermitian spin systems.

In the first direction, we considered long-range extended Ising model. We discovered that a finite-range model can reproduce the entanglement pattern observed in a long-range model when the interaction strength is moderate. However, for strong interactions, the entanglement distribution in the long-range model differs from that of a model with only a few interactions. We also found that the monogamy score of entanglement aligns with the behavior of pairwise entanglement, saturating when the finite-range Hamiltonian behaves similarly to the long-range model, and decaying algebraically otherwise.

In the second direction, we studied a solvable Kitaev model on a two-dimensional square lattice. We observed a topological quantum phase transition that is distinct from the symmetry-breaking transition at zero temperature. By quenching different initial states to a pure Kitaev model, we demonstrated that the dynamics of the system, including the Loschmidt echo and time-averaged multipartite entanglement, can determine whether the initial state belongs to the topological phase or not. Additionally, we showed that derivatives of these quantifiers can accurately identify the topological quantum phase transition.

Finally, we investigated non-Hermitian spin models with rotation-time reversal (RT) symmetry. These models exhibit two phases: an unbroken phase with a real spectrum and a broken phase with complex eigenspectra indicating an exceptional point. We found that dynamical quantities such as the short and long-time average of the Loschmidt echo, as well as the rate function, can predict the exceptional point in the equilibrium scenario. Specifically, we analytically demonstrated that the rate function and average Loschmidt echo can distinguish between quenches occurring in the broken or unbroken phase for certain models, such as the nearest-neighbor XY model with uniform and alternating magnetic fields. We also showed that these quantities are capable of identifying the exceptional point even in models like the non-Hermitian XYZ model with a magnetic field, which require numerical solutions.

## Publications:


1. Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen(De), *Quantum battery with ultracold atoms: Bosons versus fermions,* Physical Review A 106, 022618 (2022).

2. Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Debasis Sadhukhan, Aditi Sen(De), *Mimicking quantum correlation of a long-range Hamiltonian by finite-range interactions,* Physical Review A 106, 052425 (2022).

## Preprints:

1. Leela Ganesh Chandra Lakkaraju, Sudip Kumar Haldar, Aditi Sen(De), *Predicting Topological Quantum Phase Transition via Multipartite Entanglement from Dynamics* , arXiv:2212.13252.

2. Keshav Das Agarwal, Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Aditi Sen(De), *Detecting Exceptional Point through Dynamics in Non-Hermitian Systems*, arXiv:2212.12403.

## Conference/Workshops Attended:

1. QMAT 2022 - Annual Conference on Quantum Condensed Matter at Indian Institute of Technology, Kanpur, *September 18-22 (2022)*, Presented a poster on "Detection of unbroken phase of non-Hermitian system via Hermitian factorization surface".

2. YouQu 2023 - Young Quantum 2023 at Harish-Chandra Research Institute, Prayagraj, *February 15-18 (2023)*, Presented a poster on two papers - (1) "Detecting Exceptional Point through Dynamics in Non-Hermitian Systems" and (2) "Quantum Battery with Non-Hermitian Charging".

## Other Activities:

1. Member of the organising committee of Young Quantum 2023 conference at HRI.

2. Developed the website for Young Quantum Conference 2023 and the corresponding URL is https://www.hri.res.in/ confqic/youqu23/.

# Manasa G. B.

## Research Summary:

I have been working on tuning optoelectronic properties of double oxide perovskites for photovoltaic applications. Under this study I have carried out two projects. In the first project I have studied varying optical and electronic properties in $KBaTeBi_{(1-x)}Sb_{(x)}O_6$ by substituting Sb in place of Bi. I observed substantial reduction in bandgap along with increase in spectroscopic limited maximum efficiency for the substituted system. This work is in revision stage. In the second work, I have extended the idea of imposing external stimuli for tuning bandgap in $KBaTeSbO_6$ material. I have used external pressure as the stimuli. In this work, I have observed the system undergoing closure of bandgap with imposing pressure. However, on further increasing pressure the bandgap opens up. Interestingly, all these tuning occurring while the system retains the original phase of the system. This work is now under the manuscript preparation. Along with these works, I have written a review paper on Rationalization of Double Perovskite Oxides as Energy Materials which has been published.

## Publications:

1. Manasa G. Basavarajappa and Sudip Chakraborty, *Rationalization of Double Perovskite Oxides as Energy Materials: A Theoretical Insight from Electronic and Optical Properties*, ACS Materials Au 2022, 2, 6, 655–664, (2022)

## Preprints:

1. Manasa G. Basavarajappa and Sudip Chakraborty, *Tuning Optoelectronic Properties of $KBaTeBiO_6$ through Cationic Interplay of Bismuth-Antimony in Composition Space* (in revision)

2. Manasa G. Basavarajappa, Diwakar Singh and Sudip Chakraborty, *Pressure Induced Band-gap Variation in $KBaTeSbO_6$: Towards Transparent Solar Cell* (in preparation)

## Conference/Workshops Attended:

1. *International conference on Evolution of Electronic Structure Theory and Experimental Realization*, India, January, 2023

2. *International conference on recent advances in renewable energy*, India, February, 2023

# Nirnoy Basak

## Research Summary:

In the time period 1st April,2022 to 31st March, 2023 I have worked on the various aspects of the transport properties of a three dimensional material named Weyl-semimetal(WSM). The defining properties of WSM consist of the even number of points in the bulk Brillouin zone where the valence band touches the conduction band and near these points, namely Weyl nodes, the electrons are governed by the massless Weyl equation. The consequence of the existence of the Weyl nodes can be observed in the surface Brilloin zone of a finite sample known as Fermi arcs.

In my first work, done with Ruchi Saxena, Pritam Chatterjee, Sumathi Rao and Arijit Saha, I investigated various implications of the thermal transport in an inversion symmetry broken WSM and a Weyl superconductor heterostructure where we have to take account of the Andreev reflection process to calculate the thermal conductivity of the heterostructure. We have investigated the characteristic features of thermal conductance, thermal power and figure of merit under different sets of parameter values. In addition, We have also investigated the effect of a thin insulating barrier on the thermal conductance and thermal power. We also looked for the effect of the superconducting gap and of the Weyl node on the Lorentz number given by the Weidemann-Franz law for metals. This paper is published.

In the next work, which I am currently doing with Ritajit Kundu, Rohit Mukherjee, Sumathi Rao and Arijit Kundu, we tried to investigate the effect of the Fermi arcs on the conduction of electrons. For that matter we took a thin sample of WSM which has large surface to bulk ratio in order to have the Fermi arcs dominant mode of transport. Here we calculate the electrical conductivity using the Kubo formula in presence of disorder. The disorder density is considered to be weak and therefore we restrict ourshelves within the first Born approximation to calculate the finite lifetime of scattering. We investigate the scaling behaviour of the conductivity with different disorder strength. We also look at the dependence of the scattering rate on the Fermi arc lengths and look for the universal behaviour. This work is in the finishing stage and we hope to finish this in coming month.

I am doing another work with Faruk Abdulla, Sumathi Rao and Durga Naga Hareesh Nendraganti regarding the Fermi arc reconstruction at the interface of two slabs of WSM with a relative twist. We try to investigate on the effect of the reconstruction of the Fermi arc states on the electrical conductance.

## Publications:

1. Ruchi Saxena, Nirnoy Basak, Pritam Chatterjee, Sumathi Rao, Arijit Saha, *Thermoelectric properties of inversion symmetry broken Weyl semimetal–Weyl superconductor hybrid junctions*, Phys.Rev.B 107 (2023) 19, 195426

## Conference/Workshops Attended:

1. Annual Conference on Quantum Condensed Matter, IIT Kanpur, India, September, 2022.

## Visits to other Institutes:

1. IIT Kanpur, September, 2022

# Paranjoy Chaki

## Research Summary:

Loopholes present in an experimental set-up can significantly affect the reliability of entanglement detection. We discuss two methods for detection of entanglement: one is by using the positive partial transposition criterion after quantum state tomography and the other by estimating the second and third moments of partial transposition of the quantum state through random classical snapshots. We examine the impact of inaccuracies in these detection methods by considering presence of spurious clicks or suppression of valid clicks in the detectors. By comparing the two methods, we observe that the condition based on partial transposition moments is more robust to missing counts than the positive partial transposition criteria. Moreover, we realize that in the presence of additional counts, none of the criteria misinterpret any separable state as entangled. But in such a scenario, the condition based on the moments can not guarantee any state as entangled, unless the additional event efficiency is about 0.9 or higher.

## Preprints:

1. Paranjoy Chaki, Kornikar Sen, and Ujjwal Sen, Effects of detection loophole on rival entanglement attestation techniques, arXiv:2305.00488.

## Conference/Workshops Attended:

1. Young Quantum 2023, HRI Prayagraj, India, February 2023.

# Ponnappa Kechanda Prasanna

## Research Summary:

Energy is one of the resources for any development that makes our life easier. There is a great need to find an alternative energy carrier that can act as a clean and sustainable alternative to fossil fuels. Hydrogen (H2) is one of the ideal energy carriers, has zero carbon emission and recyclability, which makes it environmentally friendly, and has a high energy density. In my work I mainly consider Hydrogen production by electrocatalyis. Along side with this I have also worked on Vanadium Dioxide surface which can be used for detecting the humidity Effects and another work on Hydrazine Assisted Water Oxidation. In all of these work we have used first principle Density Functional Theory as an theoretical framework.

## Publications:

1. Soumi Mondal; Shreya Sarkar; Debabrata Bagchi; Tisita Das; Risov Das; Ashutosh Kumar Singh; Ponnappa Kechanda Prasanna; CP Vinod; Sudip Chakraborty; Sebastian C Pete, Morphology-Tuned Pt3Ge Accelerates Water Dissociation to Industrial-Standard Hydrogen Production over a wide $pH$ Range, Advanced Materials 34, 2202294, (2022)

2. Narayanan Sethulakshmi; Subramanian Nellaiappan; Ponnappa Kechanda Prasanna; Tisita Das; Silvia Irusta; Sudip Chakraborty; Sudhanshu Sharma, Nanocoral Architecture for Enhanced Hydrazine Assisted Water Oxidation: Insight from Experiment and Theory, Journal of Electroanalytical Chemistry 922, 116776, (2022)

3. Peter Francis Mathew Elango; Sumaiya Kabir; Ponnappa Kechanda Prasanna; Mei Xian Low; Mingjie Yang; Sudip Chakraborty; Sumeet Walia; Sharath Sriram; Madhu Bhaskaran, Vanadium Dioxide-Based Miniaturized Thermal Sensors: Humidity Effects on Phase Change and Sensitivity, ACS Applied Electronic Materials 4, 5456-5467, (2022)

## Conference/Workshops Attended:

1. International Conference on recent advances in renewable energy (CARE), Harish-Chandra Research Institute, India, February 2023

## Other Activities:

1. Presented Poster in CARE Conference- Enhancing the Catalytic Activity of Zirconium Tri-sulfides by Functionalization, Vacancy Defect and Strain Engineering, February 2023

# Priya Ghosh

## Research Summary:

Entanglement subject to noise can not be shielded against decaying. But, in case of many noisy channels, the degradation can be partially prevented by using local unitary operations. We consider the effect of local noise on shared quantum states and evaluate the amount of entanglement that can be preserved from deterioration. The amount of saved entanglement not only depends on the strength of the channel but also on the type of the channel, and in particular, it always vanishes for the depolarizing channel. The main motive of this work is to analyze the reason behind this dependency of saved entanglement by inspecting properties of the corresponding channels. In this context, we quantify and explore the biasnesses of channels towards the different states on which they act. We postulate that all biasness measures must vanish for depolarizing channels, and subsequently introduce a few measures of biasness. We also consider the entanglement capacities of channels. We observe that the joint behaviour of the biasness quantifiers and the entanglement capacity explains the nature of saved entanglement. Furthermore, we find a pair of upper bounds on saved entanglement which are noticed to imitate the graphical nature of the latter.

Coherences in mutually unbiased bases of states of an isolated quantum system follow a complementarity relation. The nonlocal advantage of quantum coherence (NAQC), defined in a bipartite scenario, is a situation in which the average quantum coherences of the ensembles of one subsystem, effected by a measurement performed on the other subsystem, violates the complementarity relation. We analyze two criteria to detect NAQC for bipartite quantum states. We construct a more generalized version of the criterion to detect NAQC that is better than the standard criterion as it can capture more states exhibiting NAQC. We prove the local unitary invariance of these NAQC criteria. Further on, we focus on investigating the monogamy properties of NAQC in the tripartite scenario. We check for monogamy of NAQC from two perspectives, differentiated by whether or not the nodal observer in the monogamy relation performs the measurement for the nonlocal advantage. We find in particular that in the case where the nodal observer does not perform the measurement, a strong monogamy relation - an exclusion principle - is exhibited by NAQC.

We question the role of entanglement in masking quantum information contained in a set of mixed quantum states. We first show that a masker that can mask any two single-qubit pure states, can mask the entire set of mixed states comprising of the classical mixtures of those two pure qubit states as well. We then try to find the part played by entanglement in masking two different sets: One, a set of mixed states formed by the classical mixtures of two single-qubit pure commuting states, and another, a set of mixed states obtained by mixing two single-qubit pure non-commuting states. For both cases, we show that the masked states remain entangled unless the input state is an equal mixture of the two pure states. This in turn reveals that entanglement is necessary as well as sufficient for masking an arbitrary set of two single qubit states, regardless of their mixednesses and mutual commutativity.

## Preprints:

1. Priya Ghosh, Kornikar Sen, Ujjwal Sen, Preservation of entanglement in local noisy channels, arXiv:2209.04422.

2. Priya Ghosh, Mahasweta Pandit, Chirag Srivastava, Ujjwal Sen, Exclusion principle for nonlocal advantage of quantum coherence, arXiv:2304.07154.

3. Debarupa Saha, Priya Ghosh, Ujjwal Sen, Entanglement is indispensable for masking arbitrary set of quantum states, arXiv:2305.02999.

## Conference/Workshops Attended:

1. Young Quantum - 2023, India, February 2023. Presented a poster titled "Who's afraid of disorder?"

## Other Activities:

1. Tutorship in Quantum Mechanics I, August-December 2022.

# Ratul Banerjee

## Research Summary:

Quantum technological developments require generalization and realization of different communication protocols in a multipartite domain involving sev- eral parties situated in distant locations, thereby building a quantum commu- nication network. In this direction, we explored the importance of different measurement schemes in detecting network nonlocality.

We propose that an unsharp measurement-based process to generate gen- uine multipartite entanglement from an entangled initial state with a fewer number of qubits can be classified in two ways – biased and unbiased inflation protocols. In the biased case, genuine multipartite entanglement (GME) of the resulting state obtained after a single measurement outcome is optimized, thereby creating a possibility of states with high GME while in the unbiased case, average GME is optimized over all possible outcomes. Interestingly, we showed that the set of two-qubit unsharp measurements can generate multi- partite states having different features according to GME measure, general- ized geometric measure, the monogamy-based entanglement measure, tangle and robustness against particle loss quantified via persistency depending on the rank of the unsharp measurement operators.

To obtain Bell statistics from hybrid states composed of finite- and infinite- dimensional systems, we propose a hybrid measurement scheme, in which the continuous mode is measured using the generalized pseudospin oper- ators, while the finite (two)-dimensional system is measured in the usual Pauli basis. Maximizing the Bell expression with these measurements leads to the violations of local realism which is referred to as hybrid nonlocality. We demonstrate the utility of our strategy in a realistic setting of cavity quantum electrodynamics, where an atom interacts with a single mode of an electromagnetic field under the Jaynes-Cummings Hamiltonian. We dynami- cally compute the quenched averaged value of hybrid nonlocality in imperfect situations by incorporating disorder in the atom-cavity coupling strength. In the disordered case, we introduce two kinds of measurement scenarios to de- termine the Bell statistics – in one situation, experimentalists can tune the optimal settings according to the interaction strength while such controlled power is absent in the other case. In contrast to the oscillatory behavior observed in the ordered case, the quenched averaged violation saturates to a finite value in some parameter regimes in the former case, thereby highlighting an advantage of disordered systems. We also examine the connection between Wigner negativity and hybrid nonlocality.

## Publications:

1. Sudipta Das, Pritam Halder, Ratul Banerjee, Aditi Sen De, *Sequential Reattempt of Telecloning*, *Phys. Rev. A 107, 042414, (2023).*

## Preprints:

1. Pritam Halder, Ratul Banerjee, Shiladitya Mal, Aditi Sen(De), *Manifestation of Rank-Tuned Weak Measurements Towards Featured State Generation, arXiv:2208.09317v1.*

2. *Pritam Halder, Ratul Banerjee, Saptarshi Roy, Aditi Sen(De), Hybrid nonlocality via atom photon interactions with and without impurities, arXiv:2302.11513v1.*

## Rivu Gupta

## Research Summary:

In the previous year, my research was mainly focussed on quantum information theory within the continuous variable paradigm. I worked on designing a quantum battery using continuous variable states of light, and showed how it can offer advantage when multiple modes are employed in constructing the same. I also worked towards devising a method to generate and quantify genuine multimode entanglement in photonic quantum states using optical waveguides as the medium. Furthermore, I investigated the effect of noise on the quantum dense coding protocol, involving multiple senders and receivers and demonstrated how deviation from paradigmatic noise models can enhance the performance of the scheme in transmitting classical information.

In my first work, my collaborators and I provided an architecture for a multimode quantum battery based on the framework of continuous variable systems. We examined the performance of the battery by using a generic class of multimode initial states whose parameters could be tuned to produce separable as well as entangled states and that could be charged locally as well as globally by Gaussian unitary operations. Analytical calculations showed that a separable state was equally advantageous as an entangled one for two- and three-mode batteries when taking the figures of merit as the second moments of the change in energy. In order to produce a stable quantum battery consisting of an arbitrary number of modes, we derived compact analytical forms of the energy fluctuations and proved that for a multimode separable Gaussian initial state, fluctuations decreased as the number of modes was increased, thereby obtaining a scaling analysis. Moreover, we demonstrated that local displacement as a charger was better to minimize the fluctuations in energy than that involving the squeezing unitary operation.

My second work consisted of studying the distributed dense coding protocol, involving multiple senders and a single or two receivers under the influence of non-Markovian noise, acting on the encoded qubits transmitted from senders to the receiver(s). We compared the effects of non-Markovianity on the protocol both for the dephasing and depolarising channels. In the case of dephasing channels, we illustrated that for some classes of states, high non-Markovian strength can eradicate the negative influence of noisy channels which is not observed for depolarizing noise. Furthermore, we incorporated randomness into the noise models by replacing the Pauli matrices with random unitaries and demonstrated the constructive impact of stochastic noise models on the quenched averaged dense coding capacity. Interestingly, we reported that the detrimental effect of non-Markovian depolarising channels in the protocol could be eliminated when randomness was added to the channel.

My last work of the academic year comprised the theoretical proposal for the production of genuine multimode entanglement. Starting with a product initial state, squeezed (coherent squeezed) state in one of the modes, and vacuum in the rest, we reported that a circular waveguide comprising modes coupled with varying coupling strength is capable of producing genuine multimode entanglement, quantified via the generalized geometric measure (GGM). We demonstrated that for a fixed coupling and squeezing strength, the entanglement content of the resulting state increased as the range of couplings between the waveguides was increased, although the GGM

collapsed and revived with the variation of coupling strength and time. To illustrate the advantage of long-range couplings, we proposed a quantity, called accumulated GGM, measuring the area under the GGM curve, which clearly illustrated the growing trends with the increasing range of couplings. We analytically determined the exact expression of GGM for systems involving an arbitrary number of modes, when all the modes interacted with each other equally. We manifested the constructive effect of disorder in the coupling parameter, which promised a steady production of genuine entanglement, independent of the coupling strength.

## Publications:

1. Rivu Gupta, Arghya Maity, Shiladitya Mal, and Aditi Sen(De), *Statistics of entanglement transformation with hierarchies among catalysts*
   Physical Review A **106**, 052402 (2022)

2. Ayan Patra, Rivu Gupta, Saptarshi Roy, Tamoghna Das, and Aditi Sen(De), *Quantum dense coding network using multimode squeezed states of light*
   Physical Review A **106**, 052607 (2022)

3. Rivu Gupta, Saptarshi Roy, Shiladitya Mal, Aditi Sen(De), *Emergence of Monogamy under Static and Dynamic Scenarios*
   (accepted for publication in Physical Review A)

## Preprints:

1. Tanoy Kanti Konar, Ayan Patra, Rivu Gupta, Srijon Ghosh, Aditi Sen(De), *Multimode advantage in continuous variable quantum battery*
   arXiv:2210.16528

2. Abhishek Muhuri, Rivu Gupta, Srijon Ghosh, Aditi Sen(De), *Superiority in dense coding through non-Markovian stochasticity*
   arXiv:2211.13057

3. T Anuradha, Ayan Patra, Rivu Gupta, Amit Rai, Aditi Sen(De), *Production of genuine multimode entanglement in circular waveguides with long-range interactions*
   arXiv:2303.15137

## Conference/Workshops Attended:

1. *Young Quantum 2023*, Harish Chandra Research Institute, (February 15-18), 2023. (Presented a poster: *Noise-augmented Dense-coding network and its optical implementation*)

## Visits to other Institutes:

1. IIIT Hyderabad, *Center for Quantum Science and Technology, Center for Security Theory Algorithmic Research* (31 January, 2022 - 4 February, 2023)

## Other Activities:

1. Teaching assistant for the course on Electrodynamics (August-December 2023) Instructor: Prof. Tathagata Ghosh

2. Member of the organizing committee - *Young Quantum 2023*, Harish Chandra Research Institute, (February 15-18), 2023.

## Sachin Grover

## Research Summary:

Our main focus during the past year has been on non-invertible defect lines or symmetries in two-dimensional meromorphic conformal field theories (CFTs) with a current algebra at level 1 and a low central charge, $c \leq 24$. This study aims to classify defects in meromorphic CFTs with $c \leq 24$. Subramanya Hegde, Dileep Jatkar and I hope to present our results next month.

In addition to the previous theme, we continue our investigations to establish connections between non-unitary fractional level two-dimensional, two-character CFTs with unitary CFTs at integrable levels under character exchange. This approach is valuable to classify the four-dimensional unitary $\mathcal{N} = 2$ superconformal field theories or SCFTs. This work is in collaboration with Md. Abhishek, Dileep Jatkar and Kajal Singh. We hope to present the results of our work soon.

The third theme is the study of $\mathcal{PT}$-symmetric quantum field theories (QFTs). Collaborating with Arindam Bhattacharya and Dileep Jatkar, we are studying $\mathcal{PT}$-symmetric quantum mechanics and QFTs to employ their salient features of taming instabilities, such as negative Dirac norms and unstable ground states in quantum field theories to the quantum mechanics of the Kodama wavefunction. This work is also near conclusion.

## Preprints:

1. Sachin Grover, *Quasi-characters in $\widehat{su(2)}$ current algebra at fractional levels*, arXiv: 2208.09037.

## Conference/Workshops Attended:

1. **XXV DAE-BNRS HEP Symposium**, IISER Mohali, India, December 2022 .
2. **Student Talks on Trending Topics in Theory** (ST$^4$), IIT Indore, India, July 2022.

## Visits to other Institutes:

1. Institute of Mathematical Science (IMSc), Chennai, India, November 2022.

## Invited Lectures/Seminars:

1. Invited talk on **Quasi-characters in $\widehat{su(2)}$ current algebra at fractional levels**, Institute of Mathematical Science (IMSc), Chennai, India, November 2022.
2. Poster presentation on **Quasi-characters in $\widehat{su(2)}$ current algebra at fractional levels** at **XXV DAE-BRNS HEP Symposium**, IISER Mohali, India, December 2022.

## Academic Awards

1. **HRI - Infosys Award** for excellence in research (2022).

## Sankha Subhra Bakshi

## Research Summary:

The behavior of strongly correlated systems in nonequilibrium setups is indeed a challenging problem in condensed matter physics. While their properties in equilibrium are relatively well understood, understanding their dynamics and behavior out of equilibrium requires a proper treatment of the system's temporal and spatial correlations.

When excess energy is added to a correlated system, the expectation is that it will eventually reach a thermal state. However, determining how an isolated system reaches a thermal state and the timescale for internal thermalization can be difficult to answer in many cases.

In the specific scenario of pumping excess energy into gapped correlated systems, it becomes necessary to consider temporal and spatial correlations seriously. The dynamics of such systems cannot be easily captured using traditional approximations valid in equilibrium.

One approach to studying these nonequilibrium dynamics is through the use of equation of motion schemes. These schemes, which would lead to mean field theory in equilibrium, capture the nonlinear spatio-temporal dynamics of the system when it is out of equilibrium.

We applied this method in two cases of gapped system that can host degenerate broken symmetry ground states. In the case of the Holstein model, which describes the interaction between electrons and lattice vibrations, laser pumping can lead to the emergence of charge order. The nonequilibrium dynamics in this case exhibit a "suppression-revival" behavior of the order parameter at intermediate pumping strengths. As the loss of order is approached, the revival timescale diverges. This behavior is not present in equilibrium and highlights the unique features of nonequilibrium dynamics.

In the case of the half-filled Hubbard model on a triangular lattice, laser pumping can result in the appearance of reduced moment ordered states that have no equivalent in equilibrium. These states with reduced magnetic order emerge due to the interplay of strong correlations and the nonequilibrium electron population.

To explain these intriguing features, we construct energy landscapes that take into account the nonequilibrium electron population. The highly excited electron population cannot equilibrate their energy to the slow degrees of freedom as the gap develops. This results in a distorted effective low-energy landscape.

Overall, studying nonequilibrium dynamics in strongly correlated systems requires methods that go beyond traditional approximations used in equilibrium. By considering temporal and spatial correlations, and employing techniques like equation of motion schemes and energy landscape analysis, we can gain a better understanding of the rich behavior exhibited by these systems when driven out of equilibrium.

## Preprints:

1. Sankha Subhra Bakshi, Debraj Bose, Arijit Dutta, Pinaki Majumdar, "Nonequilibrium dynamics of suppression, revival, and loss of charge order in a laser pumped electron-phonon system", arXiv:2205.14710 [cond-mat.str-el]

## Conference/Workshops Attended:

1. "Annual Conference on QUANTUM CONDENSED MATTER", Indian Institute of Technology, Kanpur, India, 18th - 22nd September 2022

## Invited Lectures/Seminars:

1. "Gluon students' talk", IISER Kolkata, Mohanpur, West Bengal, 13 March, 2023.

# Sayan Mondal

## Research Summary:

In 2022, I did a project on the interface of quantum information and many-body physics. In this, I studied the quantum phase transition of the $J_1 - J_2$ model on a spin chain and estimated its critical points. In the later part of 2022 and early 2023, I studied the theory of open quantum systems and quantum thermodynamics.

## Preprints:

1. Sayan Mondal, George Biswas, Ahana Ghoshal, Anindya Biswas, Ujjwal Sen *Estimating phase transition of perturbed $J_1 - J_2$ Heisenberg quantum chain in mixtures of ground and first excited states*, arXiv:2211.00623

## Conference/Workshops Attended:

1. *Young Quantum 2023*, HRI Prayagraj, India, February 2023.

## Shyamashish Dey

## Research Summary:

Several new project started and in progress, ”Universal seesaw in Trinification model” with S.K.Rai and S.Bhattacharyya. ”Scalar triplet dark matter in LRSM model” with S.K. Rai, P.Ghosh. ”Dark matter in Standard Model with S3 extension” with D.Das, A.Barik, S.K.Rai. ”Fermionic triplet dark matter in LRSM model with Z2 extension” with N.Khan. S.k.Rai .

## Conference/Workshops Attended:

1. XXV DAE-BRNS HEP Symposium 2022, IISER Mohali, Dec 2022
2. IMHEP-2, IOP Bhubaneswar, Feb 2023

# Sohail

## Research Summary:

In the academic year 2022-2023, I have worked on Uncertainty Relations in Pre-and Post-Selected Systems, Teleportation of Quantum Coherence and Fundamental speed limits on entanglement dynamics of bipartite quantum systems. In the following paragraphs these works are presented briefly.

**Uncertainty Relations in Pre-and Post-Selected Systems:** In this work, we derive Robertson-Heisenberg like uncertainty relation for two incompatible observables in a pre- and post-selected (PPS) system. The newly defined standard deviation and the uncertainty relation in the PPS system have physical meanings which we present here. We demonstrate two unusual properties in the PPS system using our uncertainty relation. First, for commuting observables, the lower bound of the uncertainty relation in the PPS system does not become zero even if the initially prepared state i.e., pre- selection is the eigenstate of both the observables when specific post-selections are considered. This implies that for such case, two commuting observables can disturb each other's measurement results which is in fully contrast with the Robertson-Heisenberg uncertainty relation. Secondly, unlike the standard quantum system, the PPS system makes it feasible to prepare sharply a quantum state (pre- selection) for non-commuting observables. Some applications of uncertainty and uncertainty relation in the PPS system are provided: (i) detection of mixedness of an unknown state, (ii) stronger uncertainty relation in the standard quantum system, (iii) "purely quantum uncertainty relation" that is, the uncertainty relation which is not affected (i.e., neither increasing nor decreasing) under the classical mixing of quantum states, (iv) state dependent tighter uncertainty relation in the standard quantum system, and (v) tighter upper bound for the out-of-time-order correlation function.

**Teleportation of Quantum Coherence:** We investigate whether it is possible to teleport the coherence of an unknown quantum state from Alice to Bob by communicating lesser number of classical bits in comparison to what is required in teleporting an unknown quantum state. We find that we cannot do perfect teleportation of coherence with one bit of classical communication for an arbitrary qubit. However, we find that if the qubit is chosen from equatorial and polar circles, then teleportation of coherence will be possible with transfer of one cbit of information if we have maximally entangled states as a shared resource. In the case of resource being a non maximally entangled state, we can teleport quantum coherence with a certain probability of success. In a general teleportation protocol for coherence, we derive a compact formula for the final state at Bob's lab in terms of composition of the completely positive maps corresponding to the shared resource state and joint POVM performed by Alice on her qubit and the unknown state. With the help of this formula, we investigate the amount of coherence teleported when the resource shared state is the maximally entangled mixed state and Werner state for the unknown pure as well as mixed states state at Alice's lab. In particular, we show that when the Werner state becomes separable then also the amount of teleported coherence is non-zero, implying the possibility of teleportation of coherence without entanglement. We have also shown that teleportation of coherence of an arbitrary state with real matrix elements is exactly possible

with the help of maximally entangled state as a resource.

**Fundamental speed limits on entanglement dynamics of bipartite quantum systems:** The speed limits on entanglement are defined as the maximal rate at which entanglement can be generated or degraded in a physical process. We derive the speed limits on entanglement, using the relative entropy of entanglement, for unitary and arbitrary CPTP dynamics, where we assume that the dynamics of the closest separable state can be approximately described by the closest separable dynamics of the actual dynamics of the system. For unitary dynamics of closed bipartite systems which are described by pure states, the rate of entanglement production is bounded by the product of fluctuations of the system's driving Hamiltonian and the surprisal operator, with a additional term reflecting the time-dependent nature of the closest separable state. Removing restrictions on the purity of the input and on the unitarity of the evolution, the two terms in the bound get suitably factorized. We demonstrate the tightness of our speed limits on entanglement by considering quantum processes of practical interest. Moreover, we provide a method to find the closest separable map of a given map.

## Preprints:

1. Sahil, Sohail, Sibasish Ghosh, *Uncertainty Relations in Pre-and Post-Selected Systems,* arXiv:2207.07687.

2. Sohail, Arun K Pati, Vijeth Aradhya, Indranil Chakrabarty, Subhasree Patro, *Teleportation of Quantum Coherence,* arXiv:2302.11499.

3. Vivek Pandey, Swapnil Bhowmick, Brij Mohan, Sohail, Ujjwal Sen, *Fundamental speed limits on entanglement dynamics of bipartite quantum systems,* arXiv:2303.07415.

## Conference/Workshops Attended:

1. Young Quantum - 2023, Feb 15 to Feb 18, 2023

## Visits to other Institutes:

1. IIIT, Hyderabad from 8th March 2023 to 10th May 2023.

# Sourav Mal

## Research Summary:

In this academic year I worked on the problem of designing new materials for rare earth free permanent magnets. Machine learning models are trained on the data from novomag and Novamag databases to predict thermodynamic stability, and magnetic properties of materials. Performance of these models are tested thoroughly and are found satisfactory. These models are subsequently used to interpolate within the above databases, and to extrapolate to parts of the materials composition and structure space not covered in these databases, to identify stable, magnetic materials that have large saturation magnetization and large easy-axis anisotropy. Screening 1136 materials via the trained models, and subsequently performing first principles calculations, 21 new candidate materials for rare earth free permanent magnets are identified. Some of these materials have anisotropy constants as large as 5 and 6 MJ $m^{-3}$, larger than that of the most widely used permanent magnet $Nd_2Fe_{14}B$.

Another problem that I have studied is about the layer dependent magnetic properties of van der Waals layered ferromagnet $CrGeTe_3$(CGT) using density functional theory. Magnetic anisotropy energy, the essential property to sustain ferromagnetism in 2D limit, is reduced significantly from bulk to monolayer. Whether both the magneto-crystalline and dipolar anisotropy are out-of-plane in bulk CGT, in bilayer and monolayer CGT, magneto-crystalline anisotropy is out-of-plane with much reduced value, but dipolar anisotropy is in-plane, which reduces the net anisotropy in bilayer and monolayer. Reduction in anisotropy energy significantly affect the magnetic properties of CGT from bulk to 2D limit.

Currently, I am working on inverse designing of materials with desired properties using constrained variational autoencoders (cVAE), a class of deep generative models based on convolutional neural networks.

## Preprints:

1. Sourav Mal, Prasenjit Sen, Leveraging available data for efficient exploration of materials space using Machine Learning : A case study for identifying rare earth-free permanent magnets (in preparation).

## Conference/Workshops Attended:

1. APCTP-IACS-SNBNCBS Workshop on Computational Methods for Emergent Quantum Matter : From Theoretical Concepts to Experimental Realization, Kolkata, India, November 17-25, 2022

2. International Conference on Advances in Renewable Energy, CARE-2023, HRI, Prayagraj, India, February 2-4, 2023

## Visits to other Institutes:

1. Indian Institute of Technology, Kanpur, India, February 11-18, 2023
2. National Institute of Science, Education and Research (NISER), Bhubaneswar, India, March 26 - April 1, 2023

## Invited Lectures/Seminars:

1. Machine Learning in Materials Designing, Ewing Christian College, Prayagraj, India, August 25, 2023

## Other Activities:

1. Tutor of QFT-1 in the August-December Semester, 2022

# Srijon Ghosh

## Research Summary:

In the last one year, my reserach work was mainly focused on application based quantum thermodynamics, precisley on the quantum thermal devices. In the last few years, the breakneck modernization of technology has created several essential and pertinent directions in the field of quantum thermodynamics. Rapid developments also demand designing quantum devices which perform more efficiently than the existing ones and can be built by using currently available technologies. In all discovered thermal machines, such as quantum batteries, quantum transistors, diodes, and quantum refrigerators, significant enhancements can be shown to be achieved in the quantum domain compared to classically available devices.

In the first part, we provide an architecture for a multimode quantum battery (QB) based on the framework of continuous variable (CV) systems. We examine the performance of the battery by using a generic class of multimode initial states whose parameters can be tuned to produce separable as well as entangled states and that can be charged locally as well as globally by Gaussian unitary operations. Analytical calculations show that a separable state is equally advantageous as an entangled one for two- and three-mode batteries when taking the figures of merit as the second moments of the change in energy. In order to produce a stable quantum battery consisting of an arbitrary number of modes, we derive compact analytical forms of the energy fluctuations and prove that for a multimode separable Gaussian initial state, fluctuations decrease as the number of modes increases, thereby obtaining a scaling analysis. Moreover, we demonstrate that local displacement as a charger is better to minimize the fluctuations in energy than that involving the squeezing unitary operation.

Secondly, we design a measurement-based quantum refrigerator with an arbitrary number of qubits situated in a one-dimensional array that interact through variable-range XY interactions. The method proposed is based on repeated evolution followed by a measurement on the single accessible qubit, which has the potential to reduce the temperature in the rest of the subsystems, thereby demonstrating cooling in the device. The performance of the refrigerator is quantified by the fidelity of each local subsystem with the ground state of the local Hamiltonian and the corresponding probability of success. We identify system parameters, which include the interaction strength, range of interactions, initial temperature of each qubit, and the position of the measured qubit, so that the fidelities of all the unmeasured qubits approach unity with a nonvanishing probability. We observe that although strong interactions during evolution are required to achieve cooling, the long-range interactions typically deteriorate the performance of the refrigerator, which indicates that interactions are not ubiquitous. We report the scalability and the saturation property of the success probability with respect to the system size, which turns out to be independent of the involved system parameters and the number of repeated measurements. Furthermore,

we show that the number of subsystems which can be cooled changes depending on the odd or even number of sites in the refrigerator. We argue that the distribution of entanglement between unmeasured qubits can give a possible explanation of the dependence of cooling process on the measured and unmeasured sites.

Moreover I have also worked on long-range quantum spin Hamiltonian and report that the pattern obtained from the entanglement between any two arbitrary sites of the long-range model can be mimicked by the model having a finite range of interactions provided the interaction strength is moderate.

## Publications:

1. Tanoy Kanti Konar, **Srijon Ghosh**, Aditi Sen De, *Refrigeration via purification through repeated measurements*, Phys. Rev. A **106**, 022616 (2022)

2. Leela Ganesh Chandra Lakkaraju, **Srijon Ghosh**, Debasis Sadhukan, Aditi Sen De, *Mimicking quantum correlation of a long-range Hamiltonian by finite-range interactions*, Phys. Rev. A **106**, 052425 (2022)

3. Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, **Srijon Ghosh**, Aditi Sen De, *Quantum battery with ultracold atoms: Bosons versus fermions*, Phys. Rev. A **106**, 022618 (2022)

4. Pritam Halder, Ratul Banerjee, **Srijon Ghosh**, Amit Kumar Pal, and Aditi Sen(De), *Circulating genuine multiparty entanglement in a quantum network*, Phys. Rev. A **106**, 032604 (2022)

## Preprints:

1. Tanoy Kanti Konar, Ayan Patra, Rivu Gupta, **Srijon Ghosh**, Aditi Sen De, *Multimode advantage in continuous variable quantum battery*, arXiv:2210.16528

2. Abhishek Muhuri, Rivu Gupta, **Srijon Ghosh**, Aditi Sen De, *Superiority in dense coding through non-Markovian stochasticity*, arXiv:2211.13057

## Conference/Workshops Attended:

1. "Quantum Dynamics: From Electrons to Qbits", The Abdus Salam International Centre for Theoretical Physics, Italy, August 2022.

2. "Young Quantum", Harish-Chandra Research Institute, India, February 2023.

## Visits to other Institutes:

1. Technical University of Vienna, Austria, September 2022
2. Saarland University, Germany, September 2022
3. University of Gdansk, Poland, September 2022

## Invited Lectures/Seminars:

1. "Designing quantum refrigerator beyond convention", Young Quantum, Harish Chandra Research Institute, February, 2023
2. "Quantum thermal machine", Technical University of Vienna, Austria, September 2022
3. "Desinging quantum battery in many body systems", Saarland University, Germany, September 2022
4. "Environmental effect on the modelling of thermal devices", University of Gdansk, Poland, September 2022

## Other Activities:

1. Teacher assistance (TA) in statistical mechanics course.
2. Member of the organizing committee of YouQu-2023.

# Subhojit Roy

## Research Summary:

During the academic year 2022-'23, I have circulated three research paper on the arXiv and one project from last year with Arindam Chatterjee and AseshKrishna Datta has been published in JHEP.

In a project (arXiv:2211.05905) with AseshKrishna Datta, Monoranjan Guchait and Arnab Roy, we explore a possible signal of the presence of relatively light electroweakinos (ewinos) and a singlet-like scalar ($a_s$) of the $Z_3$-symmetric Next-to-Minimal Supersymmetric Standard Model ($Z_3$-NMSSM) in the cascade decays of not so heavy top squarks ($m_{\tilde{t}_1} \lesssim 1.5$ TeV) that may be produced in pairs at the Large Hadron Collider LHC. We work in a scenario where the lightest (next-to-lightest) SUSY particle is bino (singlino)-like with its mass below 100 GeV and is mildly tempered with higgsino and singlino admixtures. The singlet-like scalar provides an annihilation funnel for the bino-like states such that the latter could act as a viable dark matter candidate, unlike what is now highly constrained in the MSSM. We consider a pair of immediately heavier neutralinos and the lighter chargino which all are higgsino-like with masses in the range $\sim$ 0.5–1 TeV and are still compatible with all experimental constraints. While these states may not be accessible in their direct searches at the LHC in our present scenario, such ewinos could still be traced in the decays of the top squarks of the above-mentioned kind. We consider the signal final state $1\ell\,(e,\mu) + (\geq 1)\; a_s\,(b\bar{b}) + (\geq 1)\; h_{\rm SM}\,(b\bar{b}) + \geq 4$ jets $+ \not{E}_T$ at the LHC. We find that while a usual cut-based analysis (CBA) of LHC data worth 300 fb$^{-1}$ would be unable to discover such excitations, a multivariate analysis (MVA) can be reasonably sensitive to higgsino-like ewinos having masses $\gtrsim 650$ GeV when $m_{\tilde{t}_1} \gtrsim 1$ TeV. On the other hand, with 3000 fb$^{-1}$ of data, these masses become accessible in a CBA while even an MVA on such a data set is unlikely to find these ewinos with masses around 1 TeV when $m_{\tilde{t}_1}$ hits $\sim 1.5$ TeV.

In an another work (arXiv:2211.15640) with Purusottam Ghosh and Tathagata Ghosh, we study the prospect of simultaneous explanation of tiny neutrino masses, dark matter (DM), and the observed baryon asymmetry of the Universe in a $Z_3$-symmetric complex singlet scalar extended type-II seesaw model. The complex singlet scalar plays the role of DM. Analyzing the thermal history of the model, we identify the region of the parameter space that can generate a first-order electroweak phase transition (FOEWPT) in the early Universe, and the resulting stochastic gravitational waves (GW) can be detected at future space/ground-based GW experiments. First, we find that light triplet scalars do favor an FOEWPT. In our study, we choose the type-II seesaw part of the parameter space in such a way that light triplet scalars, especially the doubly charged ones, evade the strong bounds from their canonical searches at the LHC. However, the relevant part of the parameter space, where FOEWPT can happen only due to strong SM doublet-triplet interactions, is in tension with the SM-like Higgs decay to a pair of photons, which has already excluded the bulk of this parameter space. On the other hand, the latest spin-independent DM direct detection constraints from XENON-1T and PANDA-4T eliminate a significant amount of parameter space

relevant for the dark sector assisted FOEWPT scenarios, and it is only possible when the complex scalar DM is significantly underabundant. In short, we conclude from our analysis that the absence of new physics at the HL-LHC and/or various DM experiments in the near future will severely limit the prospects of detecting a stochastic GW at future GW experiments and will exclude the possibility of electroweak baryogenesis within this model.

In a seperate project (arXiv:2212.11230), I investigate the effect of a FOEWPT, which is one of the prerequisites for electroweak baryogenesis, on the thermal relic abundance of the DM that freezes out before the occurrence phase transition in the complex singlet scalar extended $Z_3$-invariant type-II seesaw model that can simultaneously provide a DM candidate, explain the non-vanishing neutrino masses and the baryon asymmetry of the Universe. Such a phase transition around the electroweak scale leaves an impact on the relic density due to the release of entropy, particularly for a TeV-scale DM. I concentrate on the region of parameter space of the said model, which favors an FOEWPT in the early Universe and for which the DM is heavy such that its freeze-out temperature turns out to be larger than the phase transition temperature. I further study the dependencies of the dilution factor of the DM relic density on the model parameters, the nucleation temperature, the strength and the duration of the phase transition. Such a dilution might retrieve some of the regions of parameter space that were previously ruled out by the measured value of the DM relic density and/or the latest constraints from the DM direct-detection experiments. Furthermore, a direct connection is drawn between the dilution factor and the generation of stochastic GW as a result of an FOEWPT.

In a different collaboration with AseshKrishna Datta, Lisa Bierman, Margarete Muehlleitner, we are studying the prospect of electroweak barryogenesis in a $CP$-violating singlet extended 2HDM scenario in view of current searches at the LHC and various DM experiments.

## Publications:

1. Subhojit Roy with Arindam Chatterjee, AseshKrishna Datta, *Electroweak Phase Transition in the $Z_3$- NMSSM: Implications of LHC and Dark matter searches and prospects of detecting the gravitational waves,* arXiv:2202.12476; JHEP 06 (2022) 108.

## Preprints:

1. Subhojit Roy with Purusottam Ghosh and Tathagata Ghosh, *Interplay among gravitational waves, dark matter and collider signals in the singlet scalar extended type-II seesaw model,* arXiv:2211.15640 [hep-ph].

2. Subhojit Roy, *Dilution of Dark Matter Relic abundance due to First Order Electroweak Phase Transition in the singlet scalar extended type-II seesaw model,* arXiv:2212.11230[hep-ph].

3. Subhojit Roy with AseshKrishna Datta, Lisa Bierman, Margarete Muehlleitner *Electroweak baryogenesis in view of recent LHC and DM searches in CN2HDM,* (in preparation)

## Conference proceedings:

1. Subhojit Roy with Arindam Chatterjee, AseshKrishna Datta, *Prospects of a Strong first-order Electroweak Phase Transition in the $Z_3$-NMSSM,* arXiv:2212.10732; PoS ICHEP2022 (2022) 138.

## Conference/Workshops Attended:

1. *International Meeting on HIGH ENERGY PHYSICS "(IMHEP II)" Institute of Physics (IoP) Bhubaneswar, India, February, 2023.*
2. *Gravitational Wave Probes of Physics Beyond Standard Model 2, Europe/Warsaw (online) November 2022.*
3. *Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-based Quantum Sensors for HEP/NP, ICTS Bangalore, India November 2022.*
4. *Particle Physics: Phenomena, Puzzles, Promises, ICTS, Bangalore, India, November, 2022.*
5. *AUGUST meeting on BSM physics@IOP at institute of physics, Bhubaneswar, India, August, 2022.*
6. *LHC Machine Learning workshop at Indian Institute of Technology, Hyderabad, India, August 2022.*
7. *ICHEP, Bologna, Italy, July 2022.*
8. *SUSY 2022, University of Ioannina, Greece (online) June–July 2021.*

## Visits to other Institutes:

1. A two-week visit (July-2022) to Prof. Margarete Muhlleitner at Karlsruhe Institute of Technology, Karlsruhe, Germany

## Invited Lectures/Seminars:

1. *Some aspects of DM, EWPT, LHC searches and prospects of detecting the gravitational waves in $Z_3$-NMSSM*, Invited-Talk, IIT-Hyderabad, India (online), September, 2022.
2. *Some aspects of DM, EWPT, LHC searches and prospects of detecting the gravitational waves in $Z_3$-NMSSM*, IInvited-Talk , IOP, Bhubaneswar, India, August, 2022.
3. *Some aspects of DM, EWPT, LHC searches and prospects of detecting the gravitational waves in $Z_3$-NMSSM*, ICHEP, Bologna, Italy, July, 2022.

# Sudip Manna

## Research Summary:

In the last academic year 2022-2023, I had mainly done two projects with my Ph.D. supervisor Dr. Tathagata Ghosh.

- **The expansion of the universe and Cosmic Microwave Background (CMB) anisotropy**
  In the first part of this project we had done calculations related to propagation of photons in a clumpy universe, perturbed conservation equations for a pressureless fluid and large-scale solutions of Einstein equations during the Matter era.
  In the 2nd part we studied the Einstein equation for a co-moving fluid for the flat Robertson-Walker metric, basic properties of CMB, recombination and decoupling, Sachs-Wolfe effect, and gravitational waves (GW) in linearized gravity approximation. Eventually, we evaluated the temperature anisotropy in the CMB power spectrum from both gravitational potentials and GW.

- **Simulation techniques pertaining to collider physics**
  Here using **FeynRules** we constructed a simple extension of Standard Model (SM) by adding a singlet right-handed neutrino in the SM and using **MadGraph** we simulated the production channel of this right-handed neutrino in electron-ion collider.

My primary research interest lies in early universe cosmology especially the generation of primordial Gravitational Waves (GW) from the strong first- order phase transitions in the early universe and how we can detect these primordial GW in our ground-based and space-based future detectors. I am also interested how we can detect the heavy particles which comes form the construction of models in future collider experiments.
Currently I am learning **Cosmotransitions** software for calculating critical temperature, nucleation temperature etc. for different kind of models at finite temperature.

## Conference/Workshops Attended:

1. 2nd International Meeting on High Energy Physics (IMHEP 2022) [16–22 Feb 2023 Institute of Physics, Bhubaneswar, India]

# Suman Jyoti De

## Research Summary:

The research work that I have done during the academic year "2022-2023", is given below.

The first part of my research is dedicated to the study of quantum Hall effect in monolayer graphene system. Monolayer graphene at charge neutrality in a quantizing magnetic field is a quantum Hall ferromagnet. Due to the spin and valley (near) degeneracies, there is a plethora of possible ground states. Previous theoretical work, based on a stringent ultra short-range assumption on the symmetry-allowed interactions, predicts a phase diagram with distinct regions of spin-polarized, canted antiferromagnetic, inter-valley coherent, and charge density wave order. While early experiments suggested that the system was in the canted antiferromagnetic phase at a perpendicular field, recent scanning tunneling studies universally find Kekule bond order, and sometimes also charge density wave order. Recently, it was found that if one relaxes the stringent assumption mentioned above, a phase with coexisting canted antiferromagnetic and Kekule order exists in the region of the phase diagram believed to correspond to real samples. In this work, starting from the conitinuum limit appropriate for experiments, we present the complete phase diagram of $\nu = 0$ graphene in the Hartree-Fock approximation, using generic symmetry-allowed interactions, assuming translation invariant ground states up to an intervalley coher- ence. Allowing for a sublattice potential (valley Zeeman coupling), we find numerous phases with different types of coexisting order. We conclude with a discussion of the physical signatures of the various states.

The second part of my research work is related to the effect of interaction induced superconductivity on the edge of a 2D quantum spin Hall insulator(QSHI). Here we investigate the effects of introducing a boost (a Zeeman field parallel to the spin quantization axis) at the proximitized helical edge of a two-dimensional (2D) QSHI. Our self-consistent analysis finds that a Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superconducting phase may emerge at the edge when the boost is larger than a critical value tied to the induced pairing gap. A non-trivial consequence of retaining the 2D bulk in the model is that this boundary FFLO state supports a finite magnetization as well as finite current (flowing along the edge). This has implications for a proper treatment of the ultra-violet cutoff in analyses employing the effective one-dimensional (1D) helical edge model. Our results may be contrasted with previous studies of such 1D models, which found that the FFLO phase either does not appear for any value of the boost (in non-self-consistent calculations), or that it self-consistently appears even for infinitesimal boost, but carries no current and magnetization.

Currently I am involved in another project related to magnon scattering calculation in graphene quantum Hall systems. In this setting, we want to find out the effects of external fields on the magnon transmission amplitude for the $\nu = 1/-1/1$ junction and see whether it can be used as an experimental probe to determine the values of symmetry allowed anisotropic interactions.

## Publications:

1. Suman Jyoti De, Ankur Das, Sumathi Rao, Ribhu K. Kaul, and Ganpathy Murthy, *Global phase diagram of charge-neutral graphene in the quantum Hall regime for generic interactions, Phys. Rev. B 107, 125422 ,(2023).*

## Preprints:

1. Suman Jyoti De, Udit Khanna, Sumathi Rao, and Sourin Das, *Boost driven transition in the superconductivity proximitized edge of a quantum spin Hall insulator, arXiv:2305.17229 (2023).*

2. *Suman Jyoti De, Sumathi Rao, and Ganpathy Murthy, Magnon transmission across* $\nu = 1/-1/1$ *graphene quantum Hall junction, (In preparation).(In preparation)*

## Conference/Workshops Attended:

1. Participated in *QMAT 2022*, IIT Kanpur, Kanpur, India, September 2022.

2. Participated in *EPVWH 2023*, TIFR, Mumbai, India, January 2023.

## Visits to other Institutes:

1. Visited ICTS Bangalore from January 2023 to June 2023.

# Susovan Maity

## Research Summary:

I am currently working with my Ph.D. Prof. Tapas K. Das, and Souvik Ghose, a post-doctoral fellow at HRI, along with other collaborators on a study related to accretion and analogue gravity. Specifically, we have investigated how different formulations of the thickness of the flow affects the acoustic surface gravity of accreting black holes.

Our study focuses on the acoustic geometry embedded in axially symmetric accretion in hydrostatic equilibrium along the vertical direction. We are examining how the characteristics of the geometry are influenced by the spin parameter of Kerr metric and the thickness of the accretion disc. To achieve this, we perturbed the flow and established that the saddle type critical points in the phase portrait of the flow and stationary shocks, correspond to black-hole-type and white-hole-type acoustic horizons, respectively.

We also calculated the acoustic surface gravity as a function of the black hole's spin angular momentum for three different flow thicknesses. However, we have discovered that for some flow models, the acoustic geometry cannot be constructed beyond a certain truncation radius due to the expression of the thickness function. (Communicated: Phys. Rev. D)

## Preprints:

1. Susovan Maity, Pratik Tarafdar, Md Arif Shaikh, Tapas K. Das, *Influence of the flow thickness on acoustic surface gravity for accreting black holes*, Submission ID: DC13575 in Physical Rev. D.

## Conference/Workshops Attended:

1. *32nd meeting of Indian Association for General Relativity and Gravitation (IAGRG32)*, India, December, 2022

## Invited Lectures/Seminars:

1. *Opportunities of Having Research Experience(PhD & More)*, Public outreach talk for "Azadi Ka Amrit Mahotsav", C.M.P Degree College, Allahabad, August, 2022.

2. *Research in Astrophysics and Opportunities of Having Research Experience(PhD & More)*, Public outreach talk for "Azadi Ka Amrit Mahotsav", Ewing Christian College, Allahabad, August, 2022.

## Other Activities:

1. Partially supervised project students (M.Sc.) of Prof. Tapas Das: 1. Saikat Bera (HRI) 2. Snehashish (HRI) 3. Souvik Chatterjee (Sister Nivedita University, Kolkata)

# Swapnil Bhowmick

## Research Summary:

My work so far has been in two broad areas. First is the no masking theorem. Specifically, we consider the possibility of masking observables, and prove that it is not possible. We also derive as an implication of our theorem, the impossibility of no bit commitment. The second area is the speed limits of quantum correlations where we derive a bound on the rate of change of entanglement entropy for unitary evolution of pure states using the capacity of entanglement. We also derive a bound on the amount of entanglement generated or degraded for arbitrary CPTP evolution using the nearest separable evolution.

## Publications:

1. Divyansh Shrimali, et.al., *Capacity of entanglement for non-local Hamiltonians*, **PhysRevA.106.042419**

## Preprints:

1. Vivek Pandey, Swapnil Bhowmick, Brij Mohan, Sohail , Ujjwal Sen, *Fundamental speed limits on entanglement dynamics of bipartite quantum systems* , **arxiv: 2303.07415**

2. Swapnil Bhowmick, Abhay Shrivastava, Arun Kumar Pati, *No-Masking Theorem for Observables and No-Bit Commitment* , **arXiv.2209.12261**

## Conference/Workshops Attended:

1. Young Quantum 2023

## Visits to other Institutes:

1. Dr. Alok Pan, IIT Hyderabad

# Tanaya Ray

## Research Summary:

I have been working in the field of Quantum Information & Quantum Computation, under the guidance of Prof. Ujjwal Sen. The general area of my research has been focused into two sub-classes of this fast developing field: (i) quantum foundations and theory, and (ii) open quantum systems and quantum thermodynamics.

In quantum foundations, my research has been on the relation of the two important aspects of any quantum system: quantum coherence and incompatibility of canonically conjugate quantum observables. We have established an inequality involving the quantum coherence of an arbitrary mixed quantum state in arbitrary dimension and a noncommutativity estimator of an arbitrary observable in the mentioned state. The noncommutativity estimator uses the commutator of the observable and its incoherent i.e. classical part. The relation provides a direct method of obtaining an estimate of the quantum coherence of an arbitrary quantum state. This can have potentially useful applications, because neither for providing the quantitative estimate nor for the qualitative witnessing do we require the usual methods of quantum state tomography or resort to the existing witness operators. We believe that the relation can be easily tested and put to use with existing experimental quantum information set-ups.

I am currently working on open quantum system involving superconducting quantum systems. Transmon arrays have turn out to be a promising candidate for building quantum computers in recent years, outperforming its predecessors like cold atom systems and ion traps. We have recently concluded a work (soon to be arxived) on coupled transmons in bosonic baths. We have studied the dynamics of quantum resources in the mentioned system, and found out interesting resource generating property of this system. We have also come across potential increase of the decoherence time of the coupled transmon system in presence of Markovian baths. We believe that the results of our work will be particularly useful in practical applications in pursuit of building quantum computers with improved coherence times. This work also highlights the resource generating power of such quantum systems, which is believed to be a very useful aspect for practical implementation of quantum protocols. I am now interested in studying the properties of various quantum correlations in superconducting quantum systems, and their prospective applications.

## Publication

1. T. Ray, A. Ghoshal, A. K. Pati and U. Sen, Estimating quantum coherence by noncommutativity of any observable and its incoherent part, Phys. Rev. A 105, 062423.

## Preprints:

1. T. Ray, A. Ghoshal, D. Rakshit and U. Sen, Optimal quantum resource generation in coupled transmons immersed in Markovian baths, arXiv:2303.16136.

## Conference/Workshops Attended:

1. YouQu 2023, India, February, 2023.

## Invited Lectures/Seminars:

1. Seminar on ”Optimal quantum resource generation by coupled transmons immersed in Markovian baths” in QIQT, organised by Indian Institute of Science Education and Research, Kolkata.

## Academic recognition/Awards:

1. ’Infosys scholarship for senior students (HRI)’ , February’22 - January’23.

# Tanmoy Mondal

## Research Summary:

**Magnetic dynamics near the Mott transition on the Kagome lattice:** The classical Heisenberg model on the kagome lattice reveals a spin liquid ground state with $\sqrt{3} \times \sqrt{3}$ correlations and long-lived spin wave excitation. I have benchmarked the large $U$ Hubbard model with this behavior of the Heisenberg model and investigated the effects of variation of $t/U$ and temperature on the magnetic dynamics. The static structure factor shows a Iakening of $\sqrt{3} \times \sqrt{3}$ correlations as $t/U$ increases, with a shorter correlation length. Near the Mott transition, the three-peak magnetic spectrum observed in the Heisenberg limit transforms into a two-peak signature. I quantify the dynamical structure factor, identifying key modes and their energy, lifetime, and Iight. Constructing a dynamical "phase diagram" reveals significant differences betIen the magnetic dynamics near the Mott transition and the Heisenberg limit. These findings hold relevance for understanding Kagome Mott materials and shed light on the interplay betIen strong correlations and geometric frustration.

I want to explore a simplified model that can somewhat capture the above mentioned dynamical changes at lower coupling strengths.

**Electron localisation in a correlated magnetic background:** The behavior of electronic density in a background of a spin system undergoing a paramagnetic to ferromagnetic transition at temperature Tc is temperature dependent. At temperatures above Tc, low electron density leads to localized electron characteristics, while at temperatures below Tc, extended characteristics emerge. The transition range relies on the electron-spin coupling strength (g). For high g values, where electron impact on magnetic ordering is minimal, I determine the localized-extended boundary via electron problem diagonalization on Monte Carlo configurations. As g increases, electron influence grows, and I address the coupled problem at finite temperature using exact diagonalization-based Langevin dynamics. This analysis clarifies the role of magnetic polarons as self-trapped electrons and establishes electronic regimes by varying density, temperature, and coupling g.

I am planning to look into the effect of disorder and external field on this localization effect.

## Conference/Workshops Attended:

1. QMAT 2022 conferance IITK

## Other Activities:

1. Tutorship of ASM course

# Tanoy Kanti Konar

## Research Summary:

During last year, I have mainly worked in two directions –(1) implementation of quantum batteries by ultra-cold atom in optical lattices, (2) design of quantum refrigerator in higher dimensional quantum systems. Let us discuss them in detail.

We design a quantum battery made up of bosons or fermions in an ultracold-atom setup, described by *Fermi-Hubbard* and *Bose-Hubbard* models, respectively. We compare the performance of bosons and fermions to determine which can function as a quantum battery more effectively given a particular on-site interaction and initial state temperature. The performance of a quantum battery is quantified by the maximum energy stored per unit time over the evolution under an on-site charging Hamiltonian. We report that when the initial battery state is in the ground state, fermions outperform bosons in a certain configuration over a large range of on-site interactions which are shown analytically for a smaller number of lattice sites and numerically for a considerable number of sites. Bosons take the lead when the temperature is comparatively high in the initial state for a longer range of on-site interaction. We study a number of up and down fermions as well as the number of bosons per site to find the optimal filling factor for maximizing the average power of the battery. We also introduce disorder in both on-site and hopping parameters and demonstrate that the maximum average power is robust against impurities. Moreover, we identify a range of tuning parameters in the fermionic and bosonic systems where the disorder-enhanced power is observed.

We design quantum refrigerators based on spin-$j$ quantum $XYZ$ and bilinear-biquadratic models with individual spins attached to bosonic thermal baths. We illustrate an enhancement in the performance of the refrigerators with an increase in the spin dimension irrespective of the choice of the spin models. To assess the performance of the refrigerators, we introduce a distance-based measure to quantify the local temperature of a particle with arbitrary spin quantum number $j$. Interestingly, we find that the local temperature quantifier, defined via minimizing the distance between a spin-$j$ thermal state and the evolved state of the spin-$j$ particle in the steady state, coincides with the population-based definition of local temperature known in the literature for spin-$\frac{1}{2}$ particles. Moreover, we demonstrate that the qualitative behavior of the distance-based local temperature is independent of the choice of the distance measure by comparing the trace distance, Uhlmann's fidelity and relative entropy distance. We further observe by computing local master equation that the quantum refrigerator consisting of a spin-$1/2$ and a spin-$j$ particle can lead to a lower local temperature compared to a refrigerator with two identical spin-$j$ particles following the $XYZ$ interactions.

## Publications:


1. Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen(De) *Quantum battery with ultracold atoms: Bosons versus fermions,* Phys. Rev. A 106, 022618 (2022)

2. Tanoy Kanti Konar, Srijon Ghosh, and Aditi Sen(De) *Refrigeration via purification through repeated measurements,* Phys. Rev. A 106, 022616 (2022)

3. Tanoy Kanti Konar, Srijon Ghosh, Amit Kumar Pal, Aditi Sen(De) *Designing refrigerators in higher dimensions using quantum spin models,* Phys. Rev. A 107, 032602 (2023)

## Preprints:

1. Tanoy Kanti Konar, Arghya Maity, Aditi Sen (De), *Classical correlations for Generic States are Fragile under Decoherence,* arXiv:2209.03334.

2. Tanoy Kanti Konar, Ayan Patra, Rivu Gupta, Srijon Ghosh, Aditi Sen (De), *Multimode advantage in continuous variable quantum battery,* arXiv:2210.16528.

3. Keshav Das Agarwal, Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Aditi Sen (De), *Detecting Exceptional Point through Dynamics in Non-Hermitian Systems,* arXiv:2212.12403.

4. Keshav Das Agarwal, Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Aditi Sen (De), *Recognizing critical lines via entanglement in non-Hermitian systems,* arXiv:2305.08374.

## Conference/Workshops Attended:

1. Quantum Thermodynamics Conference 2022, Quantum Technology group at Queen's University Belfast, UK, 27th June- 1st July, 2022-*Poster presentation: DESIGNING ROBUST QUANTUM REFRIGERATORS IN DISORDERED SPIN MODEL* .

2. Young Quantum - 2023 (YouQu-2023), QIC group at Harish-Chandra Research Institute, Prayagrag, UP, India, 15th February- 19th February, 2023-*Poster presentation: NON-EQUILIBRIUM NON-HERMITIAN SYSTEMS AND ITS APPLICATIONS.*

## Other Activities:

1. Member of the organising committee of Young quantum-23 conference at HRI.

2. Served as TA in Quantum Mechanics-3 in Indepence term and Numerical Methods in Republic term.

# Vivek Pandey

## Research Summary:

In the last academic year 2022-2023, I have studied speed limit on quantum correlations, quantification and detection of quantum entanglement. Along with this, I am also working on entropy of quantum channels, decoherence, and recovery map.

## Publications:

1. Divyansh Shrimali, Swapnil Bhowmick, Vivek Pandey, Arun Kumar Pati, *Capacity of entanglement for a nonlocal Hamiltonian*, **Phys.Rev.A 106 (2022) 4, 042419.**
2. Vivek Pandey, Divyansh Shrimali, Brij Mohan, Siddhartha Das, Arun Kumar Pati, *Speed limits on correlations in bipartite quantum systems* **Phys.Rev.A 107 (2023) 5, 052419**
3. Som Kanjilal, Vivek Pandey, Arun Kumar Pati, *Entanglement meter: estimation of entanglement with single copy in interferometer*, **New J.Phys. 25 (2023) 4, 043026**
4. Vivek Pandey, Swapnil Bhowmick, Brij Mohan, Sohail , Ujjwal Sen, *Fundamental speed limits on entanglement dynamics of bipartite quantum systems* , **arxiv: 2303.07415**

## Conference/Workshops Attended:

1. *You-Qu 2023*, Harish Chandra Research Institute, India, 15-18 February.

## Other Activities:

1. Tutor Classical Mechanics course, October-January, 2023.

# Mathematics Conferences/Workshops

1. *NCM Workshop on Elliptic Curves, Elliptic functions and Transcendence*, November 24 - December 03, 2022.

2. *Conference on Algebraic Geometry*, December 12-16, 2022.

# Physics Conferences/Workshops

1. *International Conference on recent advances in renewable energy (CARE-23)*, HRI-HBNI, 2-4 February-2023.
2. *Young Quantum Conference (YouQ-2023)*, Organised by QIC group, HRI-HBNI, 15-18 February-2023.

# Recent Graduates

## Mathematics

1. **Lalit Vaishya**
   *Some problems on sign change and shifted convolution sums of Fourier coefficients of certain automorphic forms.*

2. **Souvik Pal**
   *On level zero Integrable modules over extensions of Lie tori.*

3. **Mohit Mishra**
   *Structure of the class groups of totally real number fields.*

4. **Rishabh Agnihotri**
   *Arithmetical properties of Fourier coefficients of Hilbert modular forms.*

# Physics

1. **Sauri Bhattacharyya**
   *Finite temperature dynamics in strongly correlated systems.*

2. **Arpita Sen**
   *First-principles studies of Electronic and Magnetic properties of atomic clusters and surfaces of polar oxides.*

3. **Arijit Dutta**
   *Nonequilibrium response and dynamics in the Mott insulator.*

4. **Arpan Kar**
   *Indirect search for dark matter in current and upcoming radio observations.*

5. **Avirup Ghosh**
   *Phenomenology of feebly coupled dark sectors.*

6. **Ratul Mahanta**
   *Topics in Conformal Field Theory and String Theory.*

7. **Saptarshi Roy**
   *Implementation of quantum information protocols in physical Systems.*

## MSc Physics

1. Aman Chauhan
2. Ayan Sahoo
3. Harshit Rajgadia
4. Kaustubh Singhi
5. Sayan Mondal
6. Sukalpa Kundu
7. Manojit Das

# Publications

## Publications (Mathematics)

1. B. Bisai, S. Pal and P. Sahasrabuddhe, *On $q$-commuting co-extensions and $q$-commutant lifting*, Linear Algebra Appl., 658 (2023), 186–205.

2. Hemangi Shah and Ebstam Taha, *Busemann functions in asymptotically harmonic Finsler manifold*, J. Math. Phys. Anal. Geom., 18 (2022), 546–561.

3. Randip Gangopadhyay, Ashok Kumar, Hemangi Madhusudan Shah, Bankteshwar Tiwari, *On minimal surfaces of rotations immersed in deformed hyperbolic Kropina space*, Results Math., 77, (2022), Paper No. 202, 18 pages.

4. Filippo Alberto Edoardo Nuccio Mortarino Majno Di Capriglio, Tadashi Ochiai, Jishnu Ray, *A formal model of Coleman families and applications to Iwasawa invariants*, to appear in Annales mathématiques du Québec, arxiv: 2303.14940.

5. Valeriy G. Bardakov, Mikhail V. Neshchadim and Manoj K. Yadav, *Symmetric skew braces and brace systems,* Forum Mathematicum, 35, 713-738, (2023).

6. Rahul Kaushik and Manoj K. Yadav, *Commutators in groups of order $p^7$*, J. Algebra Appl., 22, 2350158, 24 pp., (2023).

7. Tantubay, Santanu , Batra, Punita, *Irreducible integrable modules for the full toroidal Lie algebras coordinated by rational quantum torus*, J. Algebra, 610 (2022), 527–545.

8. Chakraborty, Priyanshu; Batra, Punita, *A class of irreducible modules for loop-Virasoro algebras*, J. Algebra Appl., 22 (2023), no. 7, Paper No. 2350156, 13 pp.

9. Santanu Tantubay, Punita Batra, *Classification of irreducible integrable modules for the extended affine Lie algebras with center acting trivially*, Accepted to appear in J. of Lie Theory.

10. Arup Kumar Maity, P. K. Ratnakumar, *On $L^p \to L^q$ boundedness of the twisted convolution operators*. J. Anal., 31 (2023), no. 2, 945–950.

11. R. Acharya, S. Drappeau, S. Ganguly, O. Ramare, *A Modular Analogue of a Problem of Vinogradov*, to appear in The Ramanujan J.

12. D. G. Bhimani and S. Haque, *Norm inflation with infinite loss of regularity at general initial data for nonlinear wave equations in Wiener amalgam and Fourier amalgam spaces*, Nonlinear Analysis, 223 (2022), 113076.

13. D. G. Bhimani, H. Hajaiej, S. Haque and T. Luo, *A sharp Gagliardo-Nirenberg inequality and its application to fractional problems with inhomogeneous nonlinearity*, Evolution Equation and Control Theory, 12 (2023), No. 1, pp. 362–390.

14. Satyendra Kumar Mishra, Apurba Das, Samir Kumar Hazra, *Non-abelian extensions of Rota-Baxter Lie algebras and Inducibility of Automorphisms*, Linear Algebra Appl., Vol. 669 (2023), 147–174.

15. Kalyan Chakraborty, Shubham Gupta, and Azizul Hoque, *On a conjecture of Franušić and Jadrijević: counter-examples*, Results Math., 78, (2023), Paper No. 18, 14pp.

16. Kalyan Chakraborty, Shubham Gupta, and Azizul Hoque, *Diophantine triples with the property $D(n)$ for distinct $n$'s*, Mediterr. J. Math., 20, (2023), Paper No. 31, 13pp.

17. Namrata Arvind, Saikat Panja, *Hopf-Galois realizability of $\mathbb{Z}_n \rtimes \mathbb{Z}_2$*, Journal of Pure and Applied Algebra, Volume 227, Issue 4, April 2023, 107261

18. Namrata Arvind, Saikat Panja, *Unit group of some finite semisimple algebras*, Journal of the Egyptian Mathematical Society, volume 30, Article number: 17 (2022).

19. Saikat Panja, *Acceptability of classical groups in non-zero characteristic*, Linear Algebra and its Applications, Volume 669, 15 July 2023, Pages 118-124.

20. Dongwook Choa, Bumsig Kim, Bhamidi Sreedhar, *Riemann-Roch for stacky matrix factorizations*, Forum of Mathematics, Sigma, Volume 10, (2022).

21. V. Kumar and R. Thangadurai, *On simultaneous approximation of algebraic numbers*, Mathematika, 68, (2022), no. 4, 1153-1175.

22. M. Makeshwari, V. P. Ramesh and R. Thangadurai, *A necessary and sufficient condition for $2$ to be a primitive root of $2p+1$*, Math. Student, 89, (2020), no. 3-4, 171-176.

23. Umesh V Dubey and Gopinath Sahoo, *Compactly generated tensor t-structures on the derived categories of Noetherian schemes,* Math. Z., 303, no. 4, Paper No. 100, 22 pp, (2023).

24. Sanjay Amrutiya and Umesh V Dubey, *Moduli of parabolic sheaves and filtered Kronecker modules* , Kyoto J. Math., 63, no. 2, 241-269, (2023).

25. Umesh V Dubey and Gopinath Sahoo, *Tensor weight structures and t-structures on derived categories*, C. R. Math. Acad. Sci. Paris (Accepted) (2022).

26. Arpan Kanrar, *Wolstenholme's theorem revisited*, Elem. Math., 78 (2023), no. 1, 35–36.

27. Sahil Gehlawat, Aakanksha Jain, Amar Deep Sarkar, *The reduced Bergman kernel and its properties*. Internat. J. Math. 34 (2023), no. 3, Paper No. 2350015, 23 pp. 30H20 (30C40 46E22)

28. Kiran Meena, Akhilesh Yadav, *Conformal submersions whose total manifolds admit a Ricci soliton*, Mediterr. J. Math, 20 (2023), no. 3, Paper No. 168, 26 pp.

29. Abhash Kumar Jha, Lalit Vaishya, *Estimates for the shifted convolution sum involving Fourier coefficients of cusp forms of half-integral weight*, Funct. Approx. Comment. Math., 68 (2023), no. 1, 7–18.

30. Bhimani, Divyang G., Haque, Saikatul *The Hartree and Hartree-Fock equations in Lebesgue Lp and Fourier-Lebesgue $L^p$ spaces*, Ann. Henri Poincaré, 24 (2023), no. 3, 1005–1049.

31. Karmakar, Debasish, Patil, Bhuwanesh Rao, *Multiplicative patterns in syndetic sets*, Arch. Math., (Basel) 120 (2023), no. 1, 35–45.

32. Bag, Nilanjan, Shparlinski, Igor E. *Bounds on bilinear sums of Kloosterman sums*, J. Number Theory 242 (2023), 102–111.

33. R. Nandi, S. K. Singh and P. Tiwari, *On sign changes of Fourier coefficients of Hermitian cusp forms of degree two*, https://doi.org/10.1007/s11139-023-00716-2 (Published in The Ramanujan Journal, 2023).

34. Agnihotri, Rishabh; Chakraborty, Kalyan; Krishnamoorthy, Krishnarjun, *Sign changes in restricted coefficients of Hilbert modular forms*, Ramanujan J., 59 (2022), no. 4, 1225–1243.

35. Das, Shamik, Saikia, Anupam, *On the 2-part of the class number of $Q(\sqrt{\pm D})$ for a congruent number $D$*, Res. Number Theory, 8 (2022), no. 4, Paper No. 78, 9 pp.

36. Chakraborty, Kalyan; Krishnamoorthy, Krishnarjun, *On some symmetries of the base n expansion of 1/m: the class number connection*, Pacific J. Math., 319 (2022), no. 1, 39–53.

37. Jana, Arijit; Kalita, Gautam, *Supercongruences motivated by some generalized Van-Hamme type supercongruences*, Res. Number Theory, 8 (2022), no. 3, Paper No. 54, 11 pp.

38. Naik, Muna; Sarkar, Rudra P., *Asymptotic mean value property for eigenfunctions of the Laplace-Beltrami operator on Damek-Ricci spaces*, Ann. Mat. Pura Appl., (4) 201 (2022), no. 4, 1583–1605.

39. Bhimani, Divyang G.; Haque, Saikatul, *Norm inflation with infinite loss of regularity at general initial data for nonlinear wave equations in Wiener amalgam and Fourier amalgam spaces*, Nonlinear Anal., 223 (2022), Paper No. 113076, 14 pp.

40. Agnihotri, Rishabh, Lambert series associated to Hilbert modular form, Int. J. Number Theory, 18 (2022), no. 6, 1335–1349.

41. Chakraborty, Kalyan; Krishnamoorthy, Krishnarjun, *On moments of non-normal number fields*, J. Number Theory, 238 (2022), 183–196.

42. Hennecart, François; Prakash, Gyan; Pramod, *Eyyunni On thin sum-product bases*,Combinatorica 42 (2022), no. 2, 165–202.

43. Manna, Ramesh; Ratnakumar, P. K., *Global Fourier integral operators in the plane and the square function*, J. Fourier Anal. Appl., 28 (2022), no. 2, Paper No. 25, 28 pp.

44. S. Das, A. Saikia, *A Necessary Condition for $p$ and $2p$ to be congruent for a prime $p \equiv 1 \pmod 8$*, Journal of Pure and Applied Algebra, 2022.

## Publications (Physics)

1. Mahasweta Pandit, Chirag Srivastava, Ujjwal Sen, *Recycled entanglement detection by arbitrarily many sequential and independent pairs of observers*, Phys. Rev. A **106**, 032419 (2022).

2. Sheikh Parvez Mandal, Ahana Ghoshal, Chirag Srivastava, Ujjwal Sen, *Invariance of success probability in Grover's quantum search under local noise with memory*, Phys. Rev. A **107**, 022427 (2023).

3. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Correlation between resource-generating capacities of quantum gates*, Phys. Rev. A **107**, 032406 (2023).

4. Chirag Srivastava, Mahasweta Pandit, Ujjwal Sen, *Entanglement witnessing by arbitrarily many independent observers recycling a local quantum shared state*, Phys. Rev. A **105**, 062413 (2022).

5. Sohail, Ujjwal Sen, *Convolution algebra of superoperators and nonseparability witnesses for quantum operations*, J. Phys. A: Math. Theor. **55**, 295301 (2022).

6. Saronath Halder, Ujjwal Sen, *Separability and entanglement in superpositions of quantum states*, Phys. Rev. A **107**, 022413 (2023).

7. Saronath Halder, Ujjwal Sen, *Unextendible entangled bases and more nonlocality with less entanglement*, Phys. Rev. A **105**, L030401 (2022).

8. Ahana Ghoshal, Ujjwal Sen, *Heat current and entropy production rate in local non-Markovian quantum dynamics of global Markovian evolution*, Phys. Rev. A **105**, 022424 (2022).

9. A. Ghoshal, S. Sau, D. Das, U. Sen, *Isolating noise and amplifying signal with quantum Cheshire cat*, Phys. Rev. A **107**, 052214 (2023).

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