ICTS

INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

ICTS ACTIVITY REPORT 2015 - 17

CONTENTS

DIRECTOR'S REPORT

"In our acquisition of knowledge of the universe (whether mathematical or otherwise) that which renovates the quest is nothing more or less than complete innocence ... It alone can unite humility with boldness so as to allow us to penetrate to the heart of things ..."

Alexander Grothendieck (From "*Reaping and Sowing*")

It has been a great privilege for me to helm ICTS these last two plus years, and to build on the strong foundations set by Spenta Wadia, the founding director. In this period, ICTS has grown from the close intimacy of our temporary garden home in IISc to something more akin to the expansive shade of a banyan tree in our new campus at Shivakote. Nevertheless, we continually strive to '*renovate the quest*', trying to retain the innocence of all new beginnings. In fact, it is hard to believe that we are now in the tenth year of our existence – ready to step into adolescence in the second decade of our explorations.

The last couple of years have seen ICTS grow in all the three components of its mission. In terms of our in–house research, we are thrilled to have some excellent faculty join ICTS. These include Vishal Vasan *(partial differential equations)* R. Loganayagam *(string theory, non–equilibrium quantum field theory),* Manas Kulkarni *(quantum statistical mechanics),* Rama Govindarajan *(fluid dynamics)* and Riddhipratim Basu *(probability theory)*. Shashi Thutupalli also joined as our joint faculty with NCBS. Chandan Dasgupta and Bala Iyer are our Simons Visiting Professors. The academic prowess of these and existing faculty have been recognized with various grants and awards, both national and international, as detailed later. ICTS researchers had a very significant role to play in the analysis of the gravitational waves discovered by LIGO. The ripples of that excitement continue to spread.

To prove that distinctions of theory and experiment are often artificial, Rama Govindarajan, Vishal Vasan and Shashi Thutupalli have set up small laboratories – the J. C. Bose and K. S. Krishnan labs. These also house labs for our master's level graduate students. Another new start has been the mathematics graduate program, now in its third year of student intake. As we make a determined push to grow in several areas of mathematics and theoretical computer science, we expect the student numbers here to grow as well.

A major challenge for our administration was to operationalise our many facilities, starting with the mundane ones of getting the water and electricity connections but also including setting up the IT infrastructure and audio–video connectivity, auditoria and seminar halls, office spaces, the guest house, cafetaria, health care centre, child care centre, sports and wellness centre, library, security, ATM, transport arrangements, among many others. I am happy to report that we have successfully been able to make this transition to a current stage of full functionality. This has allowed our researchers to work without hindrance at our campus and for us to conduct all our programs entirely on campus. I am very proud of how our entire administration under the steady guidance of Avinash Dhar (Dean, *Programs and Activities*) rose to the challenge of managing this nontrivial transition.

Our program cell ensured that we could seamlessly hold activities right from the get–go. We have had nearly fifty programs (including 22 discussion meetings) on campus since September 2015. Program organizers and participants (nearly three thousand of them including six hundred from abroad) have been giving high marks for the smooth running of the activities and appreciating the academic benefit. One can see this in terms of the high demand in the scientific community to organize programs at ICTS with proposals already for ones to be held in 2020. Academically, we have also

initiated programs in new areas like theoretical computer science. The Laser Plasma Acceleration program in early 2017 was an instance where ICTS actively worked to bring together researchers from the laser physics, plasma physics and high energy physics communities to give a new thrust direction in Indian science.

We have also not been idle on the third prong of our mandate, namely societal outreach through science popularization. We have been continuing, since the centenary of general relativity, with the novel Einstein lecture series wherein our researchers and visitors visit smaller colleges, often outside Bangalore as well. We have had a number of very popular public lectures on campus including by 2017's chemistry Nobel Laureate Joachim Frank. It was his first public lecture anywhere after the announcement of the Nobel Prize! In January 2018, we will have the inaugural C. V. Vishveshwara public lecture by Kip Thorne.

'*Kaapi with Kuriosity*' is just about a year old but is now seen as the flagship science outreach initiative of ICTS. It is a monthly lecture and discussion series for school and college students as well as the public of Bangalore by well–known scientists in Bangalore and visitors to ICTS programs. We have been very fortunate to have the enthusiastic partnership of the Jawaharlal Nehru Planetarium and other city institutions like Christ University in this venture. We now have an active Facebook and social media presence to help spread the word about these events which have also begun to be live–streamed. Our dedicated YouTube channel *ICTStalks* which archives all our talks, both for the public and for our programs, has now had more than a million views with over 10,000 subscribers.

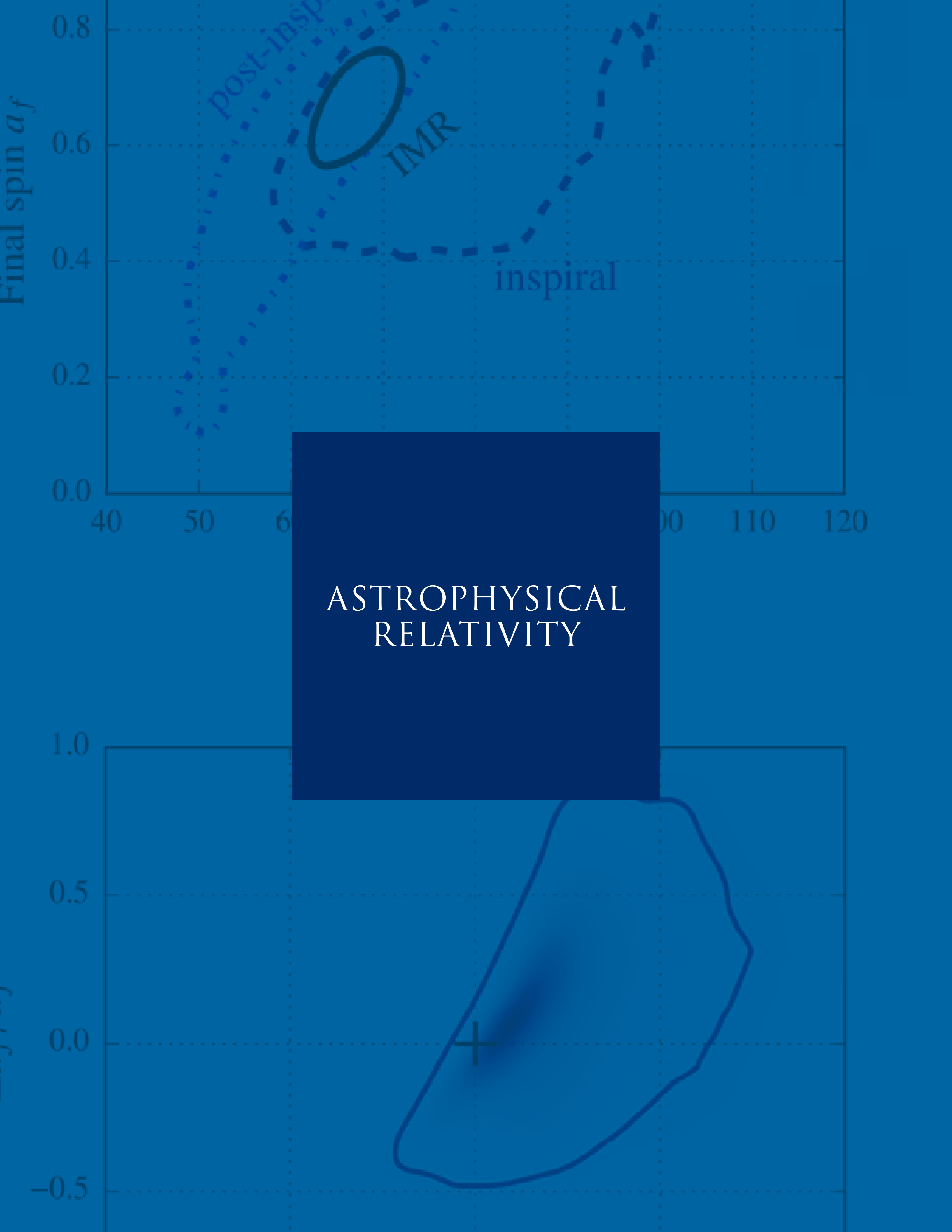
Our newly established Resource Development and Societal Engagement Wing (ResDev) aims to create more partnerships between ICTS and the broader society we are embedded in. In addition to the Simons and Airbus external grants, we have been fortunate to have the strong support of the Infosys Foundation through several grants. Our flagship lecture series have now become the Infosys–ICTS Chandrasekhar, Ramanujan and Turing Lecture series. Infosys is also supporting many of our international visitors for programs and collaborations as well as our researchers, through five year grants. To secure a strong foundation for ICTS' growth in its second decade, we are launching a tenth year endowment drive. This drive, which will be launched at the '*ICTS at Ten*' event in early Jan. 2018, is aiming to raise ₹20 Crores (or approx. $3 Million) in its first phase. I am optimistic that we can tap into the enormous national and international goodwill for ICTS and its unique mission and find the requisite support.

The events of the coming months starting with the '*ICTS at Ten*' are already building a sense of excitement. I am certain they will renew our vigor and repristinate our innocence for the next ten years. I can't wait to see the future unfold.

Rajesh Gopakumar
Bangalore, December 2017

RESEARCH REPORTS


Yourself
BATMAN



ASTROPHYSICAL RELATIVITY

Research of the **ASTROPHYSICAL RELATIVITY** group at ICTS is broadly concerned with the astrophysical applications of general relativity (GR). The recent detection of gravitational waves (GWs) by LIGO/Virgo not only confirms a century–old prediction of GR, but opens up a unique, new branch of gravitational wave astronomy. The ICTS group is interested in different aspects of gravitational wave physics and astronomy, including the modelling of the astrophysical sources of gravity waves using analytical and numerical relativity, gravity wave data analysis, probes of strong gravity using gravity wave observations, relativistic astrophysics, cosmology and high–performance computing.

Group members are actively involved in the LIGO Scientific Collaboration and the IndIGO collaboration, and have made direct contributions to enabling and deciphering the recent detection of GWs by LIGO/Virgo. The ICTS group played an active role in performing the first tests of GR using gravitational wave observations and in the estimation of astrophysical parameters from observed signals. The group operates a LIGO Tier–3 grid computing facility at ICTS.

FACULTY

Parameswaran Ajith

Bala Iyer

Simons Visiting Professor

POSTDOCTORAL FELLOWS

Rahul Kashyap

Sumit Kumar

Haris M K

Gayathri Raman

STUDENTS

Abhirup Ghosh

Ajit Kumar Mehta

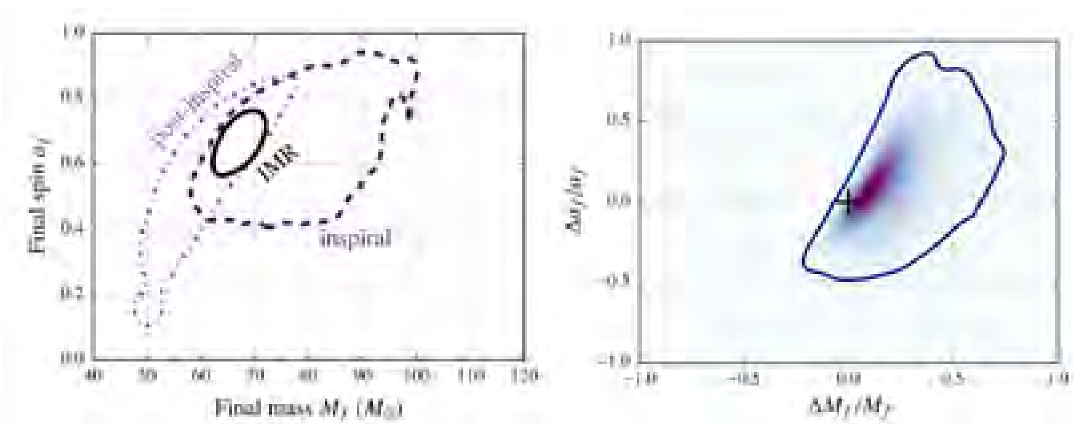
PARAMESWARAN AJITH

Parameswaran Ajith completed his PhD in Physics from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Germany, in 2007 under the supervision of Bernard F. Schutz. He went on to join postdoc positions at the Albert Einstein Institute and California Institute of Technology, before joining ICTS–TIFR. Ajith is the recipient of the CIFAR Azrieli Global Scholarship by the Canadian Institute for Advanced Research and the Ramanujan Fellowship from the Department of Science and Technology, India (2013–18). He heads the Max Planck Partner Group in Astrophysical Relativity and Gravitational–Wave Astronomy at ICTS–TIFR (2015–2018) and is the PI of the Indo–US Centre for the Exploration of Extreme Gravity funded by the IndoUS Science and Technology Forum (2016–18). His research spans different aspects of gravitational–wave (GW) physics and astronomy – modeling of GW sources by combining analytical and numerical relativity, GW data analysis, testing general relativity (GR) using GW observations, relativistic astrophysics and developing techniques for rejecting spurious instrumental triggers.

RESEARCH REPORT

The recent observations of GWs by LIGO and Virgo confirm a major prediction of Einstein's general theory of relativity (GR) and opens a fundamentally new observational window onto the Universe. **P. Ajith**'s research spans various aspects of GW physics and astronomy – theoretical modeling of expected GW signals by combining analytical and numerical relativity, tests of GR using GW observations, extraction of physics and astrophysics information from GW observations, etc. His research group at ICTS has directly contributed to deciphering the recent GW observations from merging black holes and neutron stars.

Ajith led the development of a phenomenological approach for constructing GW templates describing the coalescence of binary black holes through their orbital inspiral, merger and subsequent ringdown of the remnant black hole. Waveforms constructed using this method were used to extract the source parameters from the LIGO/Virgo observations and for testing the consistency of the observed signals with GR. Now that GW observations are becoming precision astronomical measurements, several sub–dominant effects in gravitational waveforms need to be taken into account. The group's recent work demonstrated that neglecting the sub–dominant modes of gravitational radiation will cause unacceptable loss of signal–to–noise ratio and systemic biases in the estimated parameters for binaries with large mass ratios. The most recent work by the group includes the construction of accurate theoretical waveforms for non–spinning black–hole binaries that include the effect of sub–dominant modes.



Left panel 90% credible regions in the joint posterior distributions for the mass M_f and dimensionless spin a_f of the final compact object as determined from the inspiral (dark violet, dashed curve) and post-inspiral (violet, dot-dashed curve) parts of the observed signal from the LIGO binary black hole event GW150914. The black curve shows the same determined from the full inspiral–merger–ringdown signal. Right panel: Posterior distributions for the parameters that describe the fractional difference in the estimates of the final mass and spin from inspiral and post-inspiral signals. The contour shows the 90% confidence region. The plus symbol indicates the expected GR value (0,0). [Phys. Rev. Lett. 116, 221101 (2016)]

The group formulated, developed and implemented a test of GR based on the consistency between the inspiral, merger and ringdown parts of observed GW signals from binary black holes. This was one of the first tests of GR performed in the highly relativistic regime, and was one among the handful of tests used to establish the consistency of the first LIGO event with a binary black hole system predicted by GR. This test has been performed on several massive binary black hole events detected by LIGO and Virgo. Their recent work demonstrates how multiple observations could be combined to produce stringent constraints on deviations from GR. Ajith was also involved in the tests of GR using the multimessenger (GW and electromagnetic) observations of the recently detected neutron star merger GW170817/GRB170817A.

The group also proposed and implemented a method to infer the mass and spin of the remnant black hole in a binary merger, making use of full inspiral, merger, ringdown waveforms and fitting formulas calibrated to numerical relativity simulations. This was used to infer the mass and spin of the remnant black hole in the LIGO binary black hole observations. These provide some of the best measurements of black–hole spin in astronomy. An extension of this idea was also used to infer the amount of radiated energy and peak GW luminosity from binary black hole mergers.

PUBLICATIONS

1. *Effectual gravitational–wave template banks for coalescing compact binaries using a hybrid placement algorithm,* S. Roy, A. S. Sengupta, P. Ajith. Submitted to Phys. Rev. D (2017). arXiv:1711.08743 [gr–qc]

2. *Accurate inspiral–merger–ringdown gravitational waveforms for non–spinning black–hole binaries including the effect of subdominant modes,* A. K. Mehta, C. K. Mishra, V. Varma, P. Ajith. To appear in Phys Rev D. (2017).

3. *Testing general relativity using gravitational wave signals from the inspiral, merger and ringdown of binary black holes,* Ab. Ghosh, N. K. Johnson–McDaniel, Ar. Ghosh, C. K. Mishra, P. Ajith, W. Del Pozzo, A. B. Nielsen, C. P. L. Berry, L. London. To appear in Class. Quantum Grav. (2017). arXiv:1704.06784 [gr–qc]

4. *GW170817: observation of gravitational waves from a binary neutron star inspiral*, B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations]. Phys. Rev. Lett. 119, 161101 (2017)

5. *Gravitational waves and gamma–rays from a binary neutron star merger: GW170817 and GRB 170817A,* B. P. Abbott et al. [LIGO, Virgo, Fermi GBM, and INTEGRAL Collaborations], Astrophys. J. Lett. 848, L13 (2017)

6. *Effects of non–quadrupole modes in the detection and parameter estimation of black hole binaries with nonprecessing spins,* V. Varma, P. Ajith. Submitted to Phys. Rev. D (2016). arXiv:1612.05608 [gr–qc].

7. *Observation of gravitational waves from a binary black hole merger,* B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations]. Phys. Rev. Lett. 116, 061102 (2016).

8. *Tests of general relativity with GW150914,* B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations]. Phys. Rev. Lett. 116, 221101 (2016)

9. *Properties of the binary black hole merger GW150914,* B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations].Phys. Rev. Lett. 116, 241102 (2016).

10. *Testing general relativity using golden black–hole binaries,* Ab. Ghosh, Ar. Ghosh,

N. K. Johnson–McDaniel, C. K. Mishra, P. Ajith, W. Del Pozzo, D. A. Nichols, Y. Chen, A. B. Nielsen, C. P. L. Berry, L. London. Phys. Rev. D 94, 021101 (R) (2016).

11. *Estimating effective higher order terms in the postNewtonian binding energy and gravitational–wave flux* – *Non–spinning compact binary inspiral,* S. J. Kapadia, N. K. Johnson–McDaniel and P. Ajith. Phys. Rev. D 93, 024006 (2016).
12. *Estimating parameters of binary black holes from gravitational–wave observations of their inspiral, merger and ringdown,* A. Ghosh, W. Del Pozzo and P. Ajith. Phys. Rev. D 94, 104070 (2016).
13. *Proposed search for the detection of gravitational waves from eccentric binary black holes,* V. Tiwari, S. Klimenko, N. Christensen, E. A. Huerta, S.R.P. Mohapatra, A. Gopakumar, M. Haney, P. Ajith, S.T. McWilliams, G. Vedovato, M. Drago, F. Salemi, G. A. Prodi, C. Lazzaro, S. Tiwari, G. Mitselmakher, and F. Da Silva. Phys. Rev. D 93, 043007 (2016).
14. *Template–space metric for searches for gravitational waves from the inspiral, merger and ringdown of binary black holes,* C. Kalaghatgi, P. Ajith and K. G. Arun, Phys. Rev. D 91, 124042 (2015).

BALA IYER

Bala Iyer completed his PhD from Bombay University in 1980 under Arvind Kumar. Before joining ICTS in 2015, he was a faculty member at the Raman Research Institute since 1982. He is a member of the International Society on General Relativity and Gravitation, International Astronomical Union (IAU), Indian Association of General Relativity and Gravitation (IAGRG), the Indian Physics Association Bangalore Chapter and the American Physical Society (APS), USA. Iyer is the Chair of the IndIGO Consortium and one of the principal leads of the LIGO–India project proposal. He is the Principal Investigator of IndIGO–LSC, the Indian participation in the LIGO Scientific Collaboration (LSC) and a member of the Gravitational Wave International Committee (GWIC). Iyer is also the chief editor and subject editor of Gravitational Waves for the Living Reviews in Relativity. His principal research interest relate to the computation of high accuracy gravitational waveforms for inspiralling compact binaries of neutron stars and black holes using a cocktail of multipolar post Minkowskian and post–Newtonian methods; development of tools to critically characterize template banks and quantify them; resummation techniques; tests of gravity using gravitational waves; and astrophysical, cosmological implications of higher harmonics.

RESEARCH REPORT

Bala Iyer's principal research relates to the computation of high accuracy gravitational–waveforms for inspiralling compact binaries of neutron stars and black holes using multipolar post Minkowskian and post–Newtonian methods. In particular, resummation techniques to extend domain of validity of post–Newtonian approximants; astrophysical and cosmological implications of higher harmonics and tests of gravity using gravitational–waves. More recently, he worked on extending the amplitude corrections to 3.5PN for the difficult modes corresponding to the (l=2) and (l=3) cases. This involved computations of non–linear multipole interactions in Gravitational–waves to third and a half post–Newtonian order. First, this required the control of all non–linear couplings between multipole moments up to order 3.5PN involving contributions of tails, tails–of–tails, and the non–linear memory effect. Second, it involved the computation of the mass octupole source moments of (nonspinning) compact binaries to order 3PN. This permits the computation of (3, 3) and (3, 1) modes of the Gravitational–waveform to 3.5PN order.

As the Principal Investigator, he has been leading the participation of the Indian Initiative in Gravitational–wave Observations (IndIGO) Consortium in the LIGO Scientific Collaboration (LSC). He also continues to be the Chair of the IndIGO Consortium (proposer of LIGO–India) and assist in building the broader community around GW research in the country. Forty scientists from 13 Indian institutions are part of the recent LIGO–Virgo discovery papers. The current Indian team in the LIGO–Virgo collaboration has made direct contributions to the extraction of the properties of the astronomical source from the data and to the first tests of Einstein's theory using these observations.

Iyer has mentored the GW group at ICTS in its manifold activities related to research in waveform modelling, outreach, organization of GW schools and other special events. Over weekends he lectures in the REAP program for physics undergraduate students at the Bangalore Planetarium. As Chief Editor of Living Reviews in Relativity, he was involved in putting together timely resources in emerging areas of research in general relativity and provide authoritative reviews from which graduate students and post–docs can enter emerging fields and researchers get updates on their areas related to their research.

PUBLICATIONS

1. *GW170608: Observation of a 19–solar–mass binary black hole coalescence,* The LIGO Scientific Collaboration, the Virgo Collaboration, Submitted to Astrophys. J. Lett. arXiv:1711.05578

2. *Search for post–merger Gravitational–waves from the remnant of the binary neutron star merger GW170817,* The LIGO Scientific Collaboration, the Virgo Collaboration, Accepted by Astrophys. J. Lett. arXiv:1710.09320

3. *Nobel for gravitational–waves,* P. Ajith and B.R. Iyer, Curr. Sc., 113, 1490 (2017).

4. *Search for high–energy neutrinos from binary neutron star merger GW170817*

with ANTARES, IceCube, and the Pierre Auger Observatory, The LIGO Scientific Collaboration, the Virgo Collaboration, Accepted by Astrophys. J. Lett. arXiv:1710.05839

5. *On the progenitor of binary neutron star merger GW170817,* The LIGO Scientific Collaboration, the Virgo Collaboration, Accepted by Astrophys. J. Lett. arXiv:1710.05838

6. *GW170817: Implications for the stochastic gravitational–wave background from compact binary coalescences,* The LIGO Scientific Collaboration, the Virgo Collaboration, Submitted to Phys. Rev. Lett. arXiv:1710.05837

7. *Estimating the contribution of dynamical ejecta in the kilonova associated with GW170817,* The LIGO Scientific Collaboration and The Virgo Collaboration. Accepted by Astrophys. J. Lett. arXiv:1710.05836

8. *A gravitational–wave standard siren measurement of the Hubble constant,* The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW–EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration, The MASTER Collaboration, Nature, 551, 85 (2017).

9. *Gravitational–waves and gamma–rays from a binary neutron star merger: GW170817 and GRB 170817A,* The LIGO Scientific Collaboration, Virgo Collaboration, Fermi GammaRay Burst Monitor, INTEGRAL, Ap. J. L. 848, L13 (2017). arXiv:1710.05834

10. *Multi–messenger observations of a binary neutron star merger,* The LIGO Scientific Collaboration, the Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The InsightHxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW–EM Collaboration, the DES Collaboration, The DLT40 Collaboration, GRAWITA: Gravitational–wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J–GEM, GROWTH, JAGWAR, Caltech– NRAO, TTU–NRAO, NuSTAR Collaborations, Pan–STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, et al. Ap. J. L. 848, L12 (2017). arXiv:1710.05833

11. *GW170817: Observation of gravitational–waves from a binary neutron star inspiral,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett. 119, 161101 (2017). arXiv:1710.05832

12. *First narrow–band search for continuous gravitational–waves from known*

pulsars in advanced detector data, The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1710.02327

13. *Effects of data quality vetoes on a search for compact binary coalescences in advanced LIGO's first observing run,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1710.02185

14. *First search for nontensorial gravitational–waves from known pulsars,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1709.09203

15. *GW170814: A three–detector observation of gravitational–waves from a binary black hole coalescence,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett. 119, 141101 (2017). arXiv:1709.09660

16. *LIGO–India – An unique adventure in Indian science,* T. Souradeep, S. Raja, Z. Khan, C.S. Unnikrishnan, B.R. Iyer, Curr. Sc. 113, 672 (2017)

17. *First low–frequency Einstein@Home all–sky search for continuous Gravitational–waves in Advanced LIGO data,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1707.02669

18. *All–sky Search for periodic gravitational–waves in the O1 LIGO Data,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 96, 062002 (2017).

19. *Upper limits on gravitational–waves from Scorpius X–1 from a model–based cross correlation search in advanced LIGO data,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1706.03119

20. *GW170104: Observation of a 50–solar–mass binary black hole coalescence at redshift 0.2,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett D 118, 221101 (2017). arXiv:1706.01812

21. *Search for intermediate mass black hole binaries in the first observing run of Advanced LIGO ,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 96, 022001 (2017). arXiv:1704.04628

22. *Search for gravitational–waves from Scorpius X–1 in the first Advanced LIGO observing run with a hidden Markov model,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 95, 122003 (2017). arXiv:1704.03719

23. *First search for gravitational–waves from known pulsars with Advanced LIGO,* The LIGO Scientific Collaboration, the Virgo Collaboration, Accepted arXiv:1701.07709

24. *Directional limits on persistent gravitational–waves from Advanced LIGO's first observing run,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett 118, 121102 (2017). arXiv:1612.02030

25. *Upper limits on the stochastic gravitational–wave background from Advanced*

LIGO's first observing run, The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett 118, 121101 (2017). arXiv:1612.02029

26. *Search for gravitational–waves associated with gamma–ray bursts during the first Advanced LIGO observing run and implications for the origin of GRB 150906B,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1611.07947

27. *Effects of waveform model systematics on the interpretation of GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Class. Quant. Grav. 34, 104002 (2017). arXiv:1611.07531

28. *All–sky search for short gravitational–wave bursts in the first advanced LIGO run,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 95, 042003 (2017). arXiv:1611.02972

29. *Exploring the sensitivity of next generation gravitational–wave detectors,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1607.08697

30. *Results of the deepest all–sky survey for continuous gravitational–waves on LIGO S6 data running on the Einstein@Home volunteer distributed computing project,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 94, 102002 (2016). arXiv:1606.09619

31. *GW151226: observation of gravitational–waves from a 22–solar–mass binary black hole coalescence,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett D 116, 241103 (2016). arXiv:1606.04855

32. *Search for transient gravitational–waves in coincidence with short duration radio transients during 2007–2013,* The LIGO Scientific Collaboration, the Virgo Collaboration, others Phys. Rev. D 93, 122008 (2016). arXiv:1605.01707

33. *The basic physics of the binary black hole merger GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Annalen. Phys. 529, 1600209 (2017).

34. *Upper limits on the rates of binary neutron star and neutron–star–black–hole mergers from Advanced LIGO's first observing run,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1607.07456

35. *Search for continuous gravitational–waves from neutron stars in globular cluster NGC 6544,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 95, 082005 (2017). arXiv:1607.02216

36. *Binary black hole mergers in the first Advanced LIGO observing run,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. X 6, 041015 (2016).

37. *Directly comparing GW150914 with numerical solutions of Einstein's equations for binary black hole coalescence,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 94, 064035 (2016). arXiv:1606.01262

38. *An improved analysis of GW150914 using a fully spin–precessing waveform model,*

The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. X 6, 041014 (2016).

39. *Comprehensive all–sky search for periodic gravitational–waves in the sixth science run LIGO data,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 94, 042002 (2016). arXiv:1605.03233

40. *A first targeted search for gravitational–wave bursts from core–collapse supernovae in data of first–generation laser interferometer detectors,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 94, 102001 (2016).

41. *Supplement: Localization and broadband follow–up of the gravitational–wave transient GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Ap. J. Supplement Series 225:8 (2016). arXiv:1604.07864

42. *Localization and broadband follow–up of the gravitational–wave transient GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Ap. J. L. 826, L13 (2016).

43. *High–energy neutrino follow–up search of gravitational–wave event GW150914 with ANTARES and IceCube,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 93, 122010 (2016). arXiv:1602.05411

44. *Tests of general relativity with GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett. 116, 221101 (2016). arXiv:1602.03841

45. *GW150914: Implications for the stochastic gravitational–wave background from binary black holes,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett D 116, 131102 (2016). arXiv:1602:03847

46. *Astrophysical Implications of the binary black–hole merger GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Ap. J. L 818, L22 (2016).

47. *Calibration of the Advanced LIGO detectors for the discovery of the binary black–hole merger GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, arXiv:1602.03845

48. *Characterization of transient noise in Advanced LIGO relevant to gravitational–wave signal GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Class. Quant. Grav. 33, 134001 (2016). arXiv:1602.03844

49. *Observing gravitational–wave transient GW150914 with minimal assumptions,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 93, 122004 (2016); Addendum Phys.Rev. D 94 069903 (2016) arXiv:1602.03843

50. *The rate of binary black hole mergers inferred from advanced LIGO observations surrounding GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Astrophys. J. 833 , 1 (2016). arXiv:1602.03842

51. *Properties of the binary black hole merger GW150914,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett. 116, 241102 (2016).

52. *GW150914: First results from the search for binary black hole coalescence with Advanced LIGO,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 93 , 122003 (2016). arXiv:1602.03839

53. *GW150914: The advanced LIGO detectors in the era of first discoveries,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett. D 116, 131103 (2016).

54. *Observation of gravitational–waves from a binary black hole merger,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. Lett. D 116, 061102 (2016).

55. *Advances in classical general relativity,* Curr. Sc., 109, 2230 (2015).

56. *An all–sky search for long–duration gravitational–wave transients with LIGO,* The LIGO Scientific Collaboration, the Virgo Collaboration, Phys. Rev. D 93, 042005 (2016),

57. *First low frequency all–sky search for continuous gravitational–wave signals,* The LIGO Scientific Collaboration, the Virgo Collaboration (2015), Phys. Rev. D 93, 042007 (2016), arXiv:1510.03621

58. *Search for the Orion spur for continuous gravitational–waves using a 'loosely coherent' algorithm on data from LIGO interferometers,* The LIGO Scientific Collaboration, the Virgo Collaboration (2015), Phys. Rev. D 93, 042006 (2016),

59. *The third post–Newtonian gravitational–waveforms for compact binary systems in general orbits: instantaneous terms,* Chandra Kant Mishra, K. G. Arun and Bala R Iyer, *Phys. Rev. D 91, 084040 (2015). arXiv: 1501.07096*

60. *Searches for continuous gravitational–waves from nine young supernova remnants,* The LIGO Scientific Collaboration, The Virgo Collaboration, Ap. J. 813, 39 (2015).

61. *Directed search for gravitational–waves from Scorpius X–1 with initial LIGO,* The LIGO Scientific Collaboration, The Virgo Collaboration, Phys. Rev. D 91, 062008 (2015).

62. *Advanced LIGO,* The LIGO Scientific Collaboration, Class. Quant. Grav, 32 074001 (2015). arXiv:1411.4547

63. *Narrow–band search for continuous gravitational–wave signals from Crab and Vela pulsars in Virgo VSR4 data,* The LIGO Scientific Collaboration, The Virgo Collaboration, Phys. Rev. D 91, 022004 (2015). arXiv:1410.8310

64. *Characterization of the LIGO detectors during their sixth science run, The LIGO Scientific Collaboration,* The Virgo Collaboration, Class. Quant. Gr 32, 115012 (2015).

65. *Searching for stochastic gravitational–waves using data from two co–located LIGO Hanford detectors,* The LIGO Scientific Collaboration, The Virgo Collaboration, Phys. Rev. D 91, 022003 (2015) arXiv:1410.6211

66. *Non–linear multipole interactions and gravitational–wave octupole modes for inspiralling compact binaries to third–and–a–half post–Newtonian order,* G. Faye, L. Blanchet and B. R. Iyer, Class. Quant. Gr., 32, 045016 (2015). arXiv:1409.3546

MATHEMATICS

The **MATHEMATICS** unit in ICTS aims to develop research that draws inspiration from and connects different mathematical disciplines and also encourages collaborations with scientists in areas such as physics, biology, social sciences, earth sciences, computer science, and many others, thus making it an integral part of the scientific ecosystem within ICTS. Current research areas include dynamical systems, probability, nonlinear partial differential equations, geometry and mathematical physics. It is one of the few mathematics research groups in the world with an experimental research laboratory – reflecting the highly interdisciplinary nature of the research in the math group. Building on this strength, members of the group are a part of the team of ICTS researchers working on mathematical models of the Indian summer monsoon.

FACULTY

Amit Apte
Riddhipratim Basu
Rukmini Dey
Vishal Vasan

POSTDOCTORAL FELLOWS

Suman Acharyya
Sajini Anand P S
Saibal Ganguli
Anish Mallick
Nachiketa Mishra
Adway Mitra
Varun Dilip Thakre
Shibi Vasudevan
Amit Chandra Vutha

STUDENTS

Anugu Sumith Reddy

AMIT APTE

Amit Apte received his PhD from the University of Texas, Austin, under the supervision of Phillip J. Morrison. His post doc affiliations include the Statistical and Applied Mathematical Sciences Institute (SAMSI), the University of North Carolina and the Mathematical Sciences Research Institute, Berkeley. Before joining ICTS–TIFR, he was a faculty member at the Centre for Applicable Mathematics, TIFR, Bangalore. Apte is an Editor for Nonlinear Processes in Geophysics. He is an applied mathematician, working on dynamical systems and their applications. The two main foci of his recent and future work are data assimilation in earth sciences, and modelling of monsoons and tropical dynamics.

RESEARCH REPORT

Amit Apte works on dynamical systems and their applications. The two main foci of his recent and future work are data assimilation in earth sciences, and modelling of monsoons and tropical dynamics.

In an ongoing collaboration with Marc Bocquet, Chris Jones, Alberto Carrassi, Colin Grudzien, and Karthik Gurumoorthy, Apte is working on devising an efficient particle filtering method that uses the dynamical information from the model. The main motivation is the series of papers on 'assimilation in unstable subspace' which works with the idea that generally in most assimilation schemes, the analysis covariance is low rank and spans only the unstable subspace. The main result in this work is the theorem for linear non–autonomous systems that essentially provides a solid mathematical foundation to the above idea.

Two primary challenges hindering sequential assimilation of data collected from Lagrangian instruments into ocean models are 1) the inherent nonlinearity of the Lagrangian paths and 2) the high–dimensionality of realistic ocean models. Apte and collaborators Laura Slivinski, Elaine Spiller, and Bjorn Sandstede, have proposed a hybrid particle–ensemble Kalman filter method that overcomes both of these challenges. They consider two specific aspects of the Lagrangian data assimilation problem, namely (i) low dimensionality of the highly nonlinear Lagrangian observations and (ii) less severe nonlinearity of the high dimensional Eulerian model of the velocity flow. These two aspects and the discussion of the complementary challenges tackled by the PF and EnKF motivate the primary idea behind their strategy which consists of using a particle filter in the low–dimensional, highly nonlinear Lagrangian coordinate variables and an ensemble Kalman filter in the high–dimensional, relatively linear flow variables. They show the efficacy of this method on a low dimensional problem of linear shallow water equation model and also on an intermediate size quasi–geostrophic flow.

Apte has contributed to laying down the mathematical foundations of a Bayesian approach to data assimilation and in illustrating its power through applications to highly nonlinear and high–dimensional systems. In particular, he has been one of the leaders in developing the Lagrangian data assimilation framework leading to an understanding of the role of nonlinearity in data assimilation problems.

PUBLICATIONS

1. *Degenerate Kalman filter error covariances and their convergence onto the unstable subspace,* M. Bocquet, K. S. Gurumoorthy, A. Apte, A. Carrassi, C. Grudzien and C. K. Jones, SIAM/ASA Journal on Uncertainty Quantification 5 No. 1, (2017) 304–333.

2. *Parameter estimation in the population dynamic model of Drosophila melanogaster: Application of Bayesian inference and the Markhov chain Monte Carlo method*, A. Ghosh, A. Apte, and S. Sinha. Submitted (2017).

3. *Rank deficiency of Kalman error covariance matrices in linear time–varying system with deterministic evolution,* K. S. Gurumoorthy, C. Grudzien, A. Apte, A. Carrassi and C. K. Jones. SIAM Journal on Control and Optimization 55 No. 2, (2017) 741–759.

4. *Markov random fields for spatio–temporal analysis of Indian monsoon,* R. Govindarajan, Vishal Vasan, A. Mitra, A. Apte and S. Vadlamani. Submitted (2017).

5. *Data assimilation in chaotic Chua circuit,* A. Apte, M. Ray and A. Amodkar, in Conference on Nonlinear Systems & Dynamics IISER Kolkata, vol. 16, p. 18. 2016

6. *A hybrid particle–ensemble Kalman filter for high dimensional Lagrangian data assimilation,* L. Slivinski, E. Spiller and A. Apte. Dynamic Data–Driven Environmental Systems Science, pp. 263–273. Springer, 2015.

7. *An introduction to data assimilation,* A. Apte. Applied Mathematics, pp. 31–42. Springer, 2015

8. *Observers for compressible Navier–Stokes equation,* A. Apte, D. Auroux and M. Ramaswamy, accepted for publication in SIAM J. Control and Optimization.

RIDDHIPRATIM BASU

Riddhipratim Basu has a PhD from the University of California, Berkeley. Before joining ICTS in 2017, he was the Szegö Assistant Professor of Mathematics at Stanford University. He received the Ramanujan Fellowship from the Department of Science and Technology, India (2017), the Simons Junior Faculty Fellowship from Simons Foundation (2017–2020), the AMS–Simons Travel Grant, from American Mathematical Society (2016–2018), Department citation in probability in recognition of an outstanding dissertation, Department of Statistics, University of California, Berkeley (2015), the UC Berkeley Graduate Fellowship, awarded by Graduate Division, University of California, Berkeley, (2013–2015) and the Loève Fellowship, awarded by the Department of Statistics, University of California, Berkeley, (2011–2013). His research interests are in probability theory and applications, with special focus in problems coming from statistical physics and theoretical computer science. Recent interests include first and last passage percolation, geometry of random interfaces, interacting particle systems, among other topics.

RESEARCH REPORT

In the last two years, the two major topics of **Riddhipratim Basu**'s research has been models of random growth and interacting particle systems, specifically focusing on planar models in KPZ universality class and particle systems believed to exhibit self–organized criticality.

Here is a brief report on some progress made on these subjects.

Kardar, Parisi and Zhang (1986) introduced the KPZ universality class to explain the asymptotic behaviour of a large class of strongly correlated models of random growth, where the limiting behaviour was predicted to be governed by the so–called KPZ equation, an ill–posed Stochastic PDE. KPZ prediction has been now verified for a number of exactly solvable growth models where powerful tools from algebra, combinatorics and random matrix theory were employed to perform some exact calculations. Despite this impressive progress, the understanding beyond the exactly solvable models remain rather limited. A major focus of his current research is to bring a geometric approach to studying these questions, which, can lead to results beyond the exactly solvable regime. Studying the geometry of polymers in these models they were able to obtain scaling exponents for the fluctuation of the Wulff shape in a problem of extremal isoperimetry in Poissonian last passage percolation (with Ganguly and Hammond). Using the connection between Exponential last passage percolation and Totally Asymmetric Simple Exclusion Process (TASEP), they also provided a proof for a conjectured characterization of invariant measures of TASEP with a slow bond, a model known to be not integrable (with Sarkar and Sly). In another direction, they also studied the geometry of polymers in large deviation regime in last passage percolation. Under mild conditions, and for a class much more general than the integrable models, they showed that the polymer is delocalized in the lower tail large deviation (with Ganguly and Sly).

Basu has also been investigating sandpile–like models with stochastic update rules that are of interest in non–equilibrium statistical mechanics. Due to the presence of non–local correlation, many of these models have resisted mathematical progress. They studied one model approximating the well–known Stochastic Sandpile Model that has turned out to be more tractable. Consider the interacting particle system Activated Random Walk (ARW) where particles do independent random walk and falls asleep at some rate $\lambda > 0$. On Z, started with an initial particle density μ (product measure) of active particles, it was known that the system exhibits absorbing state phase transition (i.e., if the particle density is sufficiently small the system reaches an absorbing state, remains active forever otherwise). This is an example of a general class of models that are believed to exhibit the phenomenon of self–organized criticality, when run with a carefully controlled mechanism in finite volume. In a joint work with Ganguly and Hoffman we showed that the critical density goes to 0 as λ goes to 0. In a more recent work, together with Ganguly, Hoffman and Richey, Basu established a parallel phase transition for ARW on a finite cycle.

PUBLICATIONS

1. *Lipschitz embeddings of random fields,* R. Basu, Vladas Sidoravicius and Allan Sly. To appear in Probability Theory and Related Fields, Accepted: 2017. Preprint. arXiv:1609.01273.
2. *Non–fixation for conservative stochastic dynamics on the line.* R. Basu, Shirshendu Ganguly and Christopher Hoffman. To appear in Comm. Math. Phys., Accepted: 2017. Preprint: arXiv:1508.05677.
3. *SO(N) Lattice Gauge Theory, planar and beyond,* R. Basu and Shirshendu Ganguly. To appear in Comm. Pure Appl. Math., Accepted: 2017. Preprint: arXiv:1608.04379.
4. *Limit theorems for longest monotone subsequences in random Mallows permutations.* R. Basu and Nayantara Bhatnagar. Annales de l'Institut Henri Poincare, Vol. 53, No. 4, 1934–1951, 2017.
5. *Characterization of cutoff for reversible Markov chains,* R. Basu, Jonathan Hermon and Yuval Peres. The Annals of Probability, Vol 45, No. 3, 1448–1487, 2017. Preprint: arXiv:1409.3250. Extended abstract in SODA 2015.
6. *Evolving voter model on dense random graphs,* R. Basu and Allan Sly. Annals of Applied Probability, Vol 27, No. 2, 1235–1288, 2017.
7. *Trapping games on random boards,* R. Basu, Alexander Holroyd, James Martin and Johan Wastlund. Annals of Applied Probability, Vol 26, No. 6, 3727–3753, 2016.

RUKMINI DEY

Rukmini Dey has a PhD from S.U.N.Y. at Stony Brook University. Her post doc positions were at the University of Texas, Austin, and the Indian Statistical Institute, Kolkata. Before joining ICTS, Rukmini was a faculty member at the Harish–Chandra Research Institute in Allahabad. She works on geometry and mathematical physics. Her research is currently centreed on geometric quantization of various moduli spaces of solutions of equations arising from physics as well as certain integrable systems.
She also works on some aspects of minimal surfaces in Euclidean 3–space, maximal surfaces in Lorentzian 3–space and Born Infeld solitons.

RESEARCH REPORT

Rukmini Dey, along with S. Ganguly, has worked on geometric quantization of finite Toda systems and coherent states. They used the coadjoint orbit description of the Toda system as given by Adler. With Saibal, she calculated the dimension of the Hilbert space of geometric quantization of vortices on a Riemann surface. Building on her previous work, she has given a possible way to the geometric quantization of the Hitchin System. With V. Thakre, she has worked on dimensional reduction of generalised Seiberg–Witten equations on a Riemann surface and its geometric quantization.

With I. Biswas, S. Chatterjee, she worked on the geometric prequantization on the path space of a prequantized manifold. She has worked with Pradip Kumar on a connection between minimal surfaces and Born Infeld solitons. She has shown that certain Ramanujan identities seem to be connected to minimal surfaces. With R.K. Singh, she has worked on certain aspects of Born–Infeld Solitions, maximal sufaces in Lorentz Minkowski space. They have shown that certain Ramanujan identities (and those of Weierstrass and Hadamard) seem to be relevant to the theory of maximal surfaces.

PUBLICATIONS

1. *Generalized Seiberg–Witten equations on Riemann surface,* R. Dey, V. Thakre. To appear in Journal of Geometry and Symmetry in Physics.
2. *Born–Infeld solitons, maximal surfaces, and Ramanujan's identities,* R. Dey and R. K. Singh, Archiv der Mathematik 108 No. 5, (2017) 527–538.
3. *Geometric quantization of finite Toda systems and coherent states,* R. Dey and S. Ganguli, Journal of Geometry and Symmetry in Physics 44 (2017) 21–38.
4. *The dimension of the Hilbert space of quantization of vortices on a Riemann surface,* R. Dey and S. Ganguli, International Journal of Geometric Methods in Modern Physics 14 No. 10, (2017) 1750144.
5. *Geometric quantization of the Hitchin system,* R. Dey, International Journal of Geometric Methods in Modern Physics, 14, No. 4, 1750064 (2017)
6. *Existence of maximal surface containing given curve and special singularity,* R. Dey, P. Kumar, and R. K. Singh, arXiv preprint arXiv:1612.06757 (2016)
7. *Ramanujan's identities, minimal surfaces and solitons,* R. Dey. Proceedings of Indian Mathematical Sciences 126 No. 3, (2016) 421–431.
8. *Geometric prequantization on the path space of a prequantized manifold,* I. Biswas, S. Chatterjee and R. Dey, International Journal of Geometric Methods in Mathematical Physics, Volume No.12, Issue No. 3, pp 1550030, (2015)

VISHAL VASAN

Vishal Vasan has a PhD from the University of Washington. Before joining ICTS, he was the S. Chowla Research Assistant Professor at the Pennsylvania State University. He is the recipient of the Boeing award for excellence in research from Department of Applied Mathematics, University of Washington. Vasan works in the area of partial differential equations with a focus on fluid mechanics in engineering and geophysical applications.
He employs a mixture of analytical, numerical and experimental techniques.

RESEARCH REPORT

Vishal Vasan's current research may be split into the following themes.

ANALYSIS OF PARTIAL DIFFERENTIAL EQUATIONS (PDES)

The Unified Transform Method (UTM) is an extension of Fourier analysis to boundary–value problems. Indeed UTM may be applied to problems where classical approaches based on separation of variables fails. Vasan is an active member of the UTM community and has been involved in a number of extensions of the method, in particular for PDEs with nonlocal character. In recent work he extended UTM to problems with nonlocality similar to that found in the incompressible fluid equations (with and without viscosity). In other work (with B. Deconinck, E. Shlizerman and Q. Guo), UTM was adapted to systems of PDEs. The important contribution of the work is that branches of the dispersion relation always appear as the arguments of symmetric functions. Currently, he is investigating the use of UTM in observer problems for PDEs.

INVERSE PROBLEMS

The reconstruction of the surface of the ocean from pressure measurements at the bottom bed is a problem of great practical import. Vasan and collaborators are pioneers in developing mathematical tools to construct wave profiles accurately. The successful reconstruction was proved under some idealised scenarios, but have since been tested experimentally in a wide range of situations far beyond the original framework. Simultaneously, the original theory has been advanced as well.

MATHEMATICS OF THE INDIAN MONSOON

Vasan is a member of the monsoon dynamics group at ICTS with interests in the understanding the fundamental physical processes of the Indian monsoon and their mathematical modeling. Vasan's interests are in the analysis of reduced order PDE models that describe waves in the equatorial atmosphere and their role in influencing the Indian monsoon. Currently, he is looking at rigorously establishing the existence of nonlinear propagating coherent structures in the equatorial atmosphere in the presence of moisture. Subsequently, questions of stability and their role in transporting moisture will be addressed.

EXPERIMENTAL FLUID MECHANICS

At the JC Bose Nonlinear Dynamics Lab, simple table–top fluid experiments are conducted to investigate waves and coherent structures in fluids. In earlier work, Vasan and Belmonte discovered many new patterns for circular hydraulic jumps in partially confined containers. In a first of its kind experiment, Vasan devised a set–up to investigate wave–vortex interactions in shallow–water flows using the resonant interaction between waves. This led to collaboration with S. Balasubramanian of IIT Bombay to investigate resonant interaction of parametrically excited internal gravity waves.

PUBLICATIONS

1. *A method to recover water–wave profiles from pressure measurements,* V. Vasan, K. Oliveras, D. Henderson, and B. Deconinck. Wave Motion 75 (2017) 25–35.
2. *Fokas's unified transform method for linear systems,* B. Deconinck, Q. Guo, E. Shlizerman, and V. Vasan. Quarterly of Applied Mathematics (2017).
3. *Water–wave profiles from pressure measurements: Extensions,* V. Vasan and K. L. Oliveras, Applied Mathematics Letters 68 (2017) 175–180.

STATISTICAL PHYSICS AND CONDENSED MATTER

The **STATISTICAL PHYSICS AND CONDENSED MATTER PHYSICS** group has many core interests. The focus of research in the condensed matter wing of this group is on the physics of quantum many–body system with emphasis on unconventional phases and phase transition in strongly correlated electronic systems with focus on the physics of quantum spin liquids, symmetry protected topological phases and interplay of spin–orbit coupling and electronic correlations. The focus of research in the statistical physics subgroup is on problems in non–equilibrium physics such as understanding anomalous transport in low–dimensional systems, developing theoretical approaches for understanding open quantum systems including driven dissipative systems and the dynamics of quantum systems subjected to measurements, dynamical critical phenomena, fluctuations and correlations in interacting many particle systems and various aspects of stochastic processes.

FACULTY

Subhro Bhattacharjee
Chandan Dasgupta
Simons Visiting Professor
Abhishek Dhar
Manas Kulkarni
Anupam Kundu

POSTDOCTORAL FELLOWS

Priyanka
Adhip Agarwala
Saurish Chakrabarty
Kusum Dhochak
Sambuddha Sanyal

STUDENTS

Avijit Das
Aritra Kundu
Animesh Nanda
Archak Purkayastha

SUBHRO BHATTACHARJEE

Subhro Bhattacharjee got his PhD from Indian Institute of Science under H.R. Krishnamurthy in 2010. He was a postdoctoral fellow at the University of Toronto and McMaster University (Canada). Before joining ICTS, he was a long–term guest scientist at the Max Planck Institute for the Physics of Complex Systems, Dresden, Germany. He was awarded the SERB early career research award, DST, Govt of India (2017–2020). He is also the head of the Max Planck Partner Group in strongly correlated electrons at ICTS–TIFR and an Associate of the Indian Academy of Sciences (2016–2019). Bhattacharjee works on quantum many–body physics with particular focus on frustrated magnets, quantum spin liquids, topological phases and interplay of strong spin–orbit coupling and electron correlations.

RESEARCH REPORT

In the last two years, **Subhro Bhattacharjee**'s research has primarily focussed on understanding quantum ordered phases which includes both topologically ordered phases (e.g. quantum spin liquids (QSL) as well as symmetry protected topological phases (SPT) (e.g. topological band insulators). These phases are important in understanding quantum many–body phases that lie beyond the conventional paradigm of description, i.e., spontaneous symmetry breaking. On the QSL side, he has been involved in understanding questions related to –

1– Experimental signatures of the physics of QSLs in context of candidate materials in two and three spatial dimensions. In particular, he has explored possible experimental signatures of emergent Majorana fermions of a Kitaev QSL in the honeycomb lattice candidate $RuCl_3$. Also, the nature of magneto–elastic coupling in the candidate QSL material, $Yb_2Ti_2O_7$ was studied to understand the nature of the low energy phase.

2– Investigation of the effect of disorder in the form of vacancies in three dimensional Kitaev QSL on a hyper–honeycomb lattice to get an insight into the emergence of new degrees of freedom near the vacancies.

3– Quantum Phase transition out of a two dimensional topologically ordered phase to a symmetry broken phase which forms outside the purview of Landau paradigm of order parameter based description of a phase transition.

4– Quantum phase transition between different QSLs driven by external electric fields resulting in different QSLs characterised by different projective representation of the symmetry group.

Regarding the SPT phases, he has focused on the effect of interaction on such phases, mainly the issue of new phases emerging exclusively because of interaction. To this end, he, along with his collaborators have been able to find a microscopic lattice Hamiltonian for interacting bosons that stabilises an integer quantum Hall effect of bosons and understand it from coupled wire construction. Furthermore, they have been interested in questions of understanding the underlying connections between the topologically order phases such as QSLs with SPTs through the concept of gauging of symmetries. Interestingly, such effects of gauging of symmetries is not confined to stable phases, but to quantum phase transitions, in particular to deconfined phase transitions. They studied how such gauging can lead to opening up of a deconfined phase.

More recently, he has been involved in understanding out–of equilibrium phenomena in classical and quantum systems such as issues related to–

1– Classical chaos in classical many–body spin systems.

2– Light–matter interactions inside an irradiated photon cavity.

PUBLICATIONS

1. *Anomalous dispersion of microcavity trion–polaritons,* S. Dhara, C. Chakraborty, K. Goodfellow, L. Qiu, T. O'Loughlin, G. Wicks, S. Bhattacharjee and A. Vamivakas. Nature Physics (2017) nphys4303.

2. *Electric field control of emergent electrodynamics in quantum spin ice,* E. Lantagne–Hurtubise, S. Bhattacharjee and R. Moessner, Physical Review B 96 No. 12, (2017) 125145.
3. *Acoustic signatures of the phases and phase transitions in $Yb_2Ti_2O_7$,* S. Bhattacharjee, S. Erfanifam, E. Green, M. Naumann, Z. Wang, S. Granovsky, M. Doerr, J. Wosnitza, A. Zvyagin, R. Moessner, et al. Physical Review B 93 No. 14, (2016) 144412
4. *Bridging coupled wires and lattice Hamiltonian for two–component Bosonic quantum hall states,* Y. Fuji, Y.–C. He, S. Bhattacharjee and F. Pollmann. Physical Review B 93 No. 19, (2016) 195143.
5. *Proximate Kitaev quantum spin liquid behaviour in a honeycomb magnet,* A. Banerjee, C. A. Bridges, J. Q. Yan, A. A. Aczel, L. Li, M. B. Stone, G. E. Granroth, M. D. Lumsden, Y Yiu, J. Knolle, D. L. Kovrizhin, Subhro Bhattacharjee, R. Moessner, D. A. Tennant, D. G. Mandrus, S. E. Nagler. Nature Materials 15, No. 7, pp 733-740 (2016)
6. *Vacancies in Kitaev quantum spin liquids on the three–dimensional hyperhoneycomb lattice,* G. Sreejith, S. Bhattacharjee and R. Moessner. Physical Review B 93 No. 6, (2016) 064433.
7. *Bosonic integer quantum hall effect in an interacting lattice model,* Y.–C. He, S. Bhattacharjee, R. Moessner and F. Pollmann. Physical review letters 115 No. 11, (2015) 116803.
8. *Kagome chiral spin liquid as a gauged U (1) symmetry protected topological phase,* Y.–C. He, S. Bhattacharjee, F. Pollmann and R. Moessner. Physical review letters 115 No. 26, (2015) 267209.
9. *Z 2 topological liquid of hard–core bosons on a Kagome lattice at 1/3 filling,* K. Roychowdhury, S. Bhattacharjee and F. Pollmann. Physical Review B 92 No. 7, (2015) 075141.
10. *Phases and phase transitions of a perturbed Kekule–Kitaev model,* E. Quinn, Subhro Bhattacharjee and R. Moessner. Phys. Rev. B 91, 134419 (2015)
11. *Ab initio Holography,* P. Lunts, Subhro Bhattacharjee, J. Miller, E. Schnetter, Y. B. Kim and S.–S. Lee. J. High Energy Phys. 107 (2015)

RESEARCH REPORT

During the period of his affiliation with ICTS, **Chandan Dasgupta** has carried out (in collaboration with Madan Rao and two graduate students) a numerical study of the effects of 'activity' (self–propulsion) on the dynamics of model glass–forming liquids near the structural glass transition. This work shows that the temperature at which a non–equilibrium glass transition in an active system occurs, decreases as the strength of the activity is increased and the transition disappears if the strength of the activity exceeds a critical value. The dependence of the glass transition temperature on the strength of activity can be understood in terms of an 'effective temperature' that approximately describes the effect of the presence of self–propulsion. Activity also changes the nature of the collective dynamics near the glass transition. The fragility

CHANDAN DASGUPTA

Chandan Dasgupta completed his PhD from the University of Pennsylvania in 1978. He has held postdoc positions at the University of California, San Diego, and at Harvard University. Before joining ICTS, he was a faculty member at the IISc, Bangalore, from 1987 to 2017. Dasgupta is a Fellow of the Indian Academy of Sciences, the Indian National Science Academy, the National Academy of Sciences, India, and The World Academy of Sciences (TWAS). He was awarded the J. C. Bose National Fellowship of the Department of Science and Technology (2006–present). He is on the editorial boards of Scientific Reports, Nature Publications (2015–present), EPJ–B: Condensed Matter and Complex Systems, Springer (2012–2014), Phase Transitions, Taylor & Francis (2010–present). His research interests are in statistical physics, including dense liquids near the structural glass transition, strongly confined liquids, glass transition in active systems, mechanical and thermal properties of nanomaterials, and non–equilibrium dynamics of complex fluids.

of the liquid, which describes the degree of deviation of the temperature dependence of the structural relaxation time from the simple Arrhenius form, is found to decrease with increasing activity. Also, activity leads to swirling motion with the formation of vortices whose scale increases as the non–equilibrium glass transition is approached. The route to the glass transition in athermal active systems with large persistence time of the self–propulsion force is found to be very different from that in thermal systems. The dynamics of the liquid is found to be ‘intermittent’ in this regime, with long quiescent periods during which the particles show very little movement, separated by short ‘bursts’ that represent large displacements of a small number of particles in spatially localized regions. The formulation of a theoretical description that provides explanations of some of the interesting effects observed in simulations is in progress.

Dasgupta has been working on another problem that involves a numerical study (in collaboration with Abhishek Dhar and two graduate students) of heat conduction in liquids near the glass transition and in the aging regime obtained by quenching a liquid from a high temperature to temperatures close to or below the glass transition temperature. Several interesting results about the dependence of the thermal conductivity on the temperature and the cooling rate and on the waiting time in the aging regime have been obtained from simulations. It is found that the thermal conductivity of the disordered solid obtained at low temperatures depends on the cooling rate with which it was prepared, with lower cooling rates leading to lower thermal conductivity. The thermal conductivity is also found to decrease with increasing age. This decrease of the thermal conductivity is a consequence of increased exploration of lower–energy local minima of the underlying potential energy landscape. The thermal conductivity for minima with lower energy is lower because most of the harmonic modes associated with minima with lower energy are more localized. This work provides a theoretical understanding of the behaviour of the thermal conductivity of glasses in terms of the properties of the potential energy landscape of the system.

PUBLICATIONS *(Since joining ICTS)*

1. *Block analysis for the calculation of dynamic and static length scales in glass-forming liquids,* S. Chakrabarty, I. Tah, S. Karmakar and C. Dasgupta. Phys. Rev. Lett. 119 (2017) 205502.

2. *Glassy swirls of active dumbbells,* R. Mandal, P.J. Bhuyan, P. Chaudhuri, M. Rao and C. Dasgupta, Phys. Rev. E 96 (2017) 042605.

3. *Role of pair correlation function in the dynamical transition predicted by the mode coupling theory,* M.K. Nandi, A. Banerjee, C. Dasgupta and S.M. Bhattacharyya, Phys. Rev. Lett. (in press).

RESEARCH REPORT

Abhishek Dhar and his collaborators compared the predictions of quantum master equation approaches, for a simple model example, with those from exact analytic and numerical results. It was shown that while the Redfield approach gives accurate results, the Lindblad completely fails in most parameter regimes. For a single site

ABHISHEK DHAR

Abhishek Dhar worked under Deepak Dhar for his PhD at the Tata Institute of Fundamental Research, Mumbai. His postdoc positions were at the Indian Institute of Science, the Raman Research Institute and the University of California, Santa Cruz. Before joining ICTS, he was a faculty member at the Raman Research Institute. He was awarded the ICTP prize (2008) and the S.S. Bhatnagar prize in physical sciences (2009). He is a Fellow of the Indian Academy of Sciences, an editorial board member at Pramana (2010–) and Journal of Statistical Physics (2010–2016). Dhar works on the theory and applications of statistical physics to understanding non–equilibrium problems such as classical and quantum transport, stochastic processes and large–deviations theory.

Bose-Hubbard model, exact results were obtained for quantities like steady state current and density. Transport properties of the so-called Aubry-André-Harper model, which describes non-interacting particles in a quasi-periodic potential, were investigated by studying equilibrium correlation functions as well as non-equilibrium steady state properties, obtained using exact methods. This model has a critical point and it was shown that transport is sub-diffusive at this point. For a generalization of this model it was shown that there is a line of critical points with sub-diffusive transport.

The stochastic single-particle dynamics of a model system widely used to model active matter was studied. The system consists of a single particle moving in one-dimension and driven by a Brownian noise and an 'active' (non-thermal) noise. Several exact results were obtained including evolution of the propagator, steady states, relaxation to the steady state and first passage properties.

A one-dimensional gas of interacting point particles was considered, where individual particle motion could be diffusive or ballistic or something inter-mediate. The displacement of a tagged particle in a given time was considered and the exact large deviation function for this quantity was computes and shown that to have a universal form, irrespective of the detailed nature of individual dynamics.

The theory of nonlinear fluctuating hydrodynamics was used to compute the exact cumulant generating function for energy current in a one-dimensional interacting gas. The system size scaling of the cumulants were computed and shown to be completely different for two known universality classes.

For a quantum integrable spin model, it was shown that the so-called eigenstate thermalization hypothesis remains valid but with some differences from non-integrable ones. In the classical integrable Toda system, it was shown that space-time correlation functions have scaling forms that are completely different from the non-integrable cases.

Two model systems which exhibit Anderson localization and many body localization were studied both numerically and analytically and it was shown that, in the steady state where the boundaries are kept at different temperatures, the temperature profile inside the system exhibited a jump whose average position and width scale as sqrt(L), where L is the system size.

Typically, non-equilibrium processes occurring in nature lead to positive production of entropy. An interesting question is as to how long one would have to wait to see a rare entropic fluctuation of a prescribed size? In a recent study we have asked this question and obtained several results for the waiting time, including the form of its distribution and connections to non-equilibrium fluctuation relations.

The question of first passage in quantum systems was investigated using the idea of successive projective measurements. It was shown that the time evolution consisting of a sequence of unitary evolutions and projective measurements can be described by an effective non-Hermitian Hamiltonian. Several explicit results for the arrival time distribution were obtained.

A one dimensional coulomb gas in a harmonic potential, in thermal equilibrium, was studied. The full distribution including large deviations, of the rightmost particle was exactly computed and found to be different from the Tracy-Widom distribution.

Exact results were obtained for the steady state velocity distribution in the driven Maxwell inelastic gas model, which is a mean-field-like model of inelastic gases where one ignores spatial correlations. An attempt was made to derive the effective Brownian dynamics of the so-called Szilard engine which is a version of the Maxwell demon and consists of a single particle interacting with a piston and a heat reservoir. The aim was to understand the detailed stochastic thermodynamics of this microscopic engine.

PUBLICATIONS

1. *Driven inelastic Maxwell gas in one dimension,* V. Prasad, S. Sabhapandit, A. Dhar and O. Narayan. Physical Review E 95 No. 2, (2017) 022115.

2. *Exact extremal statistics in the classical 1D Coulomb gas,* A. Dhar, A. Kundu, S. N. Majumdar, S. Sabhapandit and G. Schehr. Phys. Rev. Lett. 119 (2017) 060601.

3. *Step density profiles in localized chains, W. De Roeck,* A. Dhar, F. Huveneers and M. Schutz. Journal of Statistical Physics 167 No. 5, (2017) 1143–1163.

4. *Non-equilibrium phase diagram of a 1D quasiperiodic system with a single-particle mobility edge,* A. Purkayastha, A. Dhar and M. Kulkarni, Phys. Rev. B 96, (2017) 180204(R)

5. *Sub-diffusion and non-equilibrium probes of phases in Aubry-André-Harper model,* A. Purkayastha, S. Sanyal, A. Dhar and M. Kulkarni. arXiv preprint arXiv:1702.05228 (2017) .

6. *Unusual equilibration of a particle in a potential with a thermal wall,* D. Bhat, S. Sabhapandit, A. Kundu and A. Dhar, J. Stat. Mech. (2017) 113210

7. *Eigenstate Gibbs ensemble in integrable quantum systems,* S. Nandy, A. Sen, A. Das and A. Dhar. Physical Review B 94 No. 24, (2016) 245131.

8. *Equilibrium dynamical correlations in the toda chain and other integrable models*, A. Kundu and A. Dhar. Physical Review E 94 No. 6, (2016) 062130.

9. *Heat transport in harmonic systems.* In: *Lepri S. (eds)* Thermal transport in low dimensions. Lecture notes in Physics (Springer, Cham) A. Dhar and K. Saito. vol 921. Springer, Cham pp 39-105 (2016)

10. *Nonlinear transport in an out-of-equilibrium single-site bose-hubbard model: Scaling, rectification and time dynamics,* A. Purkayastha, A. Dhar and M. Kulkarni. Physical Review A 94 No. 5, (2016) 052134.

11. *Out-of-equilibrium open quantum systems: A comparison of approximate quantum master equation approaches with exact results,* A. Purkayastha, A. Dhar and M. Kulkarni. Physical Review A 93 No. 6, (2016) 062114.

12. *Waiting for rare entropic fluctuations,* K. Saito and A. Dhar. EPL (Europhysics Letters) 114 No. 5, (2016) 50004

13. *Exact Redfield description for open non-interacting quantum systems and failure of the Lindblad approach,* A. Purkayastha, M. Kulkarni and A. Dhar. Phys. Rev. A 93 (11, 2016) 062114.

14. *Detection of a quantum particle on a lattice under repeated projective measurements,* S. Dhar, S. Dasgupta, A. Dhar and D. Sen. Physical Review A 91 No. 6, (2015) 062115.

15. *Exact probability distribution for the two-tag displacement in single-file motion,* S. Sabhapandit and A. Dhar. Journal of Statistical Mechanics: Theory and Experiment 2015 No. 7, (2015) P07024.

16. *Heat transport and current fluctuations in harmonic crystals,* A. Dhar and R. Dandekar. Physica A: Statistical Mechanics and its Applications 418 (2015) 49–64.

17. *Pumping single-file colloids: Absence of current reversal,* D. Chaudhuri, A. Raju and A. Dhar. Physical Review E 91 No. 5, (2015) 050103.

18. *Quantum time of arrival distribution in a simple lattice model,* S. Dhar, S. Dasgupta and A. Dhar. Journal of Physics A: Mathematical and Theoretical 48 No. 11, (2015) 115304.

19. *Tagged particle diffusion in one-dimensional systems with Hamiltonian dynamics-II,* A. Roy, A. Dhar, O. Narayan and S. Sabhapandit. Journal of Statistical Physics 160 No. 1, (2015) 73–88.

MANAS KULKARNI

Manas Kulkarni has a PhD from Stony Brook University. His postdoc appointments were at the University of Toronto, Canada, and Princeton University, USA. Before joining ICTS, he was an assistant professor of physics at the City University of New York. Kulkarni was awarded the Ramanujan Fellowshio from the Department of Science and Technology (2016-2021). He was also elected an associate of the Indian Academy of Sciences. Kulkarni works on various aspects of Non-equilibrium Physics and Open Quantum Systems which sits at the interface of condensed matter and statistical physics. He also works on Integrable Models, Mathematical Physics and Nonlinear Hydrodynamics.

RESEARCH REPORT

MANAS KULKARNI's research during the period can be categorized as follows:

PERMANENT SPIN CURRENTS IN CAVITY–QUBIT SYSTEMS

This work is based on a recent remarkable experiment [P. Roushan et al, Nature Physics 13, 146–151 (2017)], where a spin current in an architecture of three superconducting qubits was produced during a few microseconds by creating a synthetic magnetic field. The current life–time was set by the typical dissipative mechanisms that occur in those systems. In this work, a scheme was proposed for the generation of permanent currents, even in the presence of such imperfections and scalable to larger system sizes.

PHASE DIAGRAM AND NON–EQUILIBRIUM PROPERTIES OF INCOMMENSURATE LATTICE MODELS IN LOW DIMENSIONS WITH AND WITHOUT MOBILITY EDGE

Properties of incommensurate lattice models in low dimensions were investigated. In particular, in the well–known Aubry–André–Harper (AAH) model, an interesting sub–diffusive scaling of non–equilibrium steady state current with system size at critical point was demonstrated. A novel approach was introduced for probing the phase diagram. A detailed study of certain closed system quantities was made and hints of the anomalous transport was found but there was no clear evidence of sub–diffusion seen in the open system. A generalized version of AAH (GAAH) which has a mobility edge was also investigated. Interesting phase diagram and a surprising and highly non–trivial correspondence between the eigenstates of GAAH model and those of AAH model were found. It was found that the co–existence of localized and delocalized phases in the presence of a mobility edge has a clear signature in the time evolution of particle density profiles and this universal feature has recently been experimentally seen in a 1D model with mobility edge.

QUANTUM DOT CIRCUIT–QED DIODES AND TRANSISTORS

It was demonstrated that Quantum Dot systems coupled to circuit–QED architecture (QD–cQED) can be an excellent platform to realize devices such as diodes and transistors. Elastic and inelastic currents (electronic and heat) through a voltage–biased double quantum dot system with strong and ultra–strong electron–photon interaction are investigated. By employing a diagrammatic Keldysh non–equilibrium Green's function approach, we found that the QD–cQED system displays remarkable charge and heat rectification effects which may provide a cutting–edge frontier for high performance thermoelectrics. The results demonstrate that QD c–QED systems can be a great candidate for novel quantum devices.

NON-LINEAR TRANSPORT IN AN OUT-OF-EQUILIBRIUM SINGLE–SITE BOSE HUBBARD MODEL – SCALING, RECTIFICATION AND TIME DYNAMICS

In the open quantum system generalization of the Bose Hubbard model, using Redfield equations in Born–Markov approximation, Kulkarni and his collaborators worked on non–equilibrium average particle number, energy and currents beyond linear response regime, both time–dynamics and steady state. The results are experimentally relevant not only to hybrid quantum systems, but also in other areas such as molecular junctions. These results are relevant in the context of quantum devices.

PHOTONIC PROPERTIES OF QUANTUM DOT CIRCUIT–QED SYSTEMS

They investigated gain in microwave photonic cavities coupled to voltage–biased N – double quantum dot systems with an arbitrary strong dot–lead coupling and with a Holstein–like light–matter interaction, by adapting the diagrammatic Keldysh non–equilibrium Green's function approach. By the careful engineering of these hybrid light–matter systems, one can achieve a significant amplification of the optical signal with the voltage–biased electronic system serving as a gain medium. These results show how recent advances in quantum electronics can be exploited to build hybrid light–matter systems that behave as single–atom amplifiers and photon source devices.

EMERGENCE OF CALOGERO FAMILY OF MODELS IN EXTERNAL POTENTIALS – DUALITY, SOLITONS AND HYDRODYNAMICS

In this work, a first–order formulation of the Calogero model in external potentials in terms of a generating function was presented. Solitons naturally appear in this formulation as particles of negative mass. Dual form of Calogero particles in external quartic, trigonometric and hyperbolic potentials were obtained. These were known to be integrable but had no known duality. They derived the corresponding soliton solutions, generalizing earlier results for the harmonic Calogero system and presented numerical results that demonstrate the integrable nature of the soliton motion.

PUBLICATIONS

1. *Non–equilibrium phase diagram of a 1D quasiperiodic system with a single–particle mobility edge,* A. Purkayastha, A. Dhar and M. Kulkarni, Phys. Rev. B 96, 180204, Rapid Communication (2017)

2. *Permanent spin currents in cavity–qubit systems,* M. Kulkarni, S. M. Hein, E. Kapit and C. Aron, arXiv:1709.04522 (2017).

3. *Emergence of Calogero family of models in external potentials: Duality, solitons and hydrodynamics,* M. Kulkarni and A. P. Polychronakos. J. Phys. A: Math. Theor. 50 455202 (2017).

4. *Sub–diffusion and non–equilibrium probes of phases in Aubry-André-Harper model,* A. Purkayastha, S. Sanyal, A. Dhar and M. Kulkarni, arXiv:1702.05228 (2017) .

5. *Nonlinear transport in an out–of–equilibrium single–site Bose–Hubbard model: Scaling, rectification and time dynamics,* A. Purkayastha, A. Dhar and M. Kulkarni. Physical Review A 94, 052134 (2016).

6. *Out–of–equilibrium open quantum systems: A comparison of approximate quantum master equation approaches with exact results,* A. Purkayastha, A. Dhar and M. Kulkarni. Physical Review A 93, 062114 (2016).

7. *Exact Redfield description for open non–interacting quantum systems and failure of the Lindblad approach.* A. Purkayastha, M. Kulkarni and A. Dhar. Phys. Rev. A 93, 062114 (2016).

RESEARCH REPORT

Anupam Kundu has been involved in the understanding the stationary as well as non–stationary properties of specific interacting multi–particle model systems in non–equilibrium. One simple example of such problems is understanding the motion of a driven particle traveling in a crowded environment which is ubiquitous

ANUPAM KUNDU

Anupam Kundu finished his PhD from Raman Research Institute under the supervision of Abhishek Dhar. Before joining ICTS, he was a Feinberg Research Fellow at the Weizmann Institute of Science, Israel. His other postdoc appointments have been with LPTMS, ESPCI and CEA, France. Kundu was awarded the CEFIPRA Project Award from the Indo-French Centre for the Promotion of Advanced Research (2016-2018) and the Early Research Career Award from the Science and Engineering Research Board, Government of India (2017-2019). He works on non-equilibrium interacting multi-particle systems, single file diffusion, anomalous energy transport and stochastic processes.

in physics, chemistry and biology. In collaboration with J. Cividini, S. N. Majumdar and D. Mukamel, Kundu has investigated the non–equilibrium properties of a specific interacting particle system in one dimension where particles perform random average process. They have shown that the non–equilibrium steady state (NESS) is in general not factorised and is characterized by long range correlation which have well defined scaling with respect to the ring size. Using both microscopic descriptions as well as fluctuating hydrodynamics, they have shown that similar long range correlations with appropriate scaling form also appear in the non–stationary state on infinite line. In absence the drive, they computed the distribution of the large deviation of the tagged particle displacement for arbitrary initial conditions.

Another way of taking a generic extended system out of equilibrium is to drive the system through its boundaries. Kundu, with O. Hirschberg and D. Mukamel, have looked at the deviation of the NESS from the Gaussianity and factorizability when the bulk dynamics conserves both total energy and momentum in a one dimensional lattice system with three particle interaction. They found that the heat transport in this model is diffusive. However, it has been observed that transport in low dimensional systems is in general anomalous. To understand this anomalous behaviour through closed system Green–Kubo formula, recently, a non–linear fluctuating hydrodynamic theory has been developed for isolated systems. But an experimental transport set up consists of two different thermal reservoirs attached at the two ends of an open system, thus implying a non–hamiltonian evolution of the degrees of freedom.

Applying this theory to an open stochastic linear system, Kundu and collaborators (J. Cividini, A. Miron, D. Mukamel) have shown that the usual Fourier's law gets modified and also computed temperature profiles theoretically for different boundary conditions. In a related mass transfer model he, with A. Das and P. Pradhan, has used the fluctuating hydrodynamic theory and have shown that even in non–equilibrium state one finds an equilibrium like Einstein relation.

Over the last few decades there has been great interest in the study of search problems that appear in various contexts from animal foraging, protein binding on DNA, internet search algorithms to locate one's misplaced keys. Kundu, A. Pal and M. R. Evans have investigated a simple stochastic intermittent search process where intermittency comes through resetting the search process randomly at some rate. In particular they have shown that considering time dependent resetting rate is more efficient than constant resetting rate.

PUBLICATIONS

1. *Exact extremal statistics in the classical 1D coulomb gas,* A. Dhar, A. Kundu, S. N. Majumdar, S. Sabhapandit and G. Schehr, Phys. Rev. Lett. 119 (2017) 060601.

2. *Einstein relation and hydrodynamics of nonequilibrium mass transport processes,* A. Das, A. Kundu and P. Pradhan. Phys. Rev. E 95 (2017) 062128.

3. *Tagged particle in single-file diffusion with arbitrary initial conditions,* J. Cividini and A. Kundu. Journal of Statistical Mechanics: Theory and Experiment 2017 No. 8, 083203.

4. *Temperature profile and boundary conditions in an anomalous heat transport 14 model,* J. Cividini, A. Kundu, A. Miron and D. Mukamel. Journal of Statistical Mechanics: Theory and Experiment 2017 No. 1, 013203.

5. *Unusual equilibration of a particle in a potential with a thermal wall,* A. Bhat, S. Sabhapandit, A. Kundu and A. Dhar, arXiv preprint arXiv:1707.00814 (2017) .

6. *Diffusion under time-dependent resetting,* A. Pal, A. Kundu and M. R. Evans, Journal of Physics A: Mathematical and Theoretical 49 No. 22, (2016) 225001.

7. *Equilibrium dynamical correlations in the Toda chain and other integrable models,* A. Kundu and A. Dhar, Physical Review E 94 No. 6, (2016) 062130

8. *Correlation and fluctuation in a random average process on an infinite line with a driven tracer,* J. Cividini, A. Kundu, S. N. Majumdar and D. Mukamel. Journal of Statistical Mechanics: Theory and Experiment 5 (2016) 053212.

9. *Exact correlations in a single-file system with a driven tracer,* A. Kundu and J. Cividini, EPL (Europhysics Letters) 115 No. 5, (2016) 54003.

10. *Exact gap statistics for the random average process on a ring with a tracer,* J. Cividini, A. Kundu, S. N. Majumdar and D. Mukamel. Journal of Physics A: Mathematical and Theoretical 49 No. 8, (2016) 085002

FLUID DYNAMICS AND TURBULENCE

The **FLUID DYNAMICS AND TURBULENCE** group at ICTS is interested in both fundamental and applied problems in fluid dynamics and turbulence. Current research is aimed at uncovering the fundamental mechanisms that underlie turbulence focuses on turbulent transport of finite-sized particles, Lagrangian measurements, and questions related to intermittency. The ICTS group also has a keen interest in understanding the still mysterious dynamics of cloud formation, and the interplay of this process with turbulence; how droplet growth in a cloud is accelerated by turbulence and how this microscale physics in turn affects large scale turbulence. The answer to this and other related questions is key to understanding the dynamics of the monsoon. One member of ICTS group is a co-PI in the project 'Coupled Physical Processes in the Bay of Bengal and Monsoon Air-Sea Interaction' funded by the Ministry of Earth Sciences.

FACULTY

Rama Govindarajan
Samriddhi Sankar Ray

POSTDOCTORAL FELLOWS

Priyanka Maity
Jason Ryan Picardo

STUDENTS

Sumit Kumar Birwa
Rahul Chajwa
Ganga Prasath
Mukesh Singh Raghav
Ritabrata Thakur

RESEARCH REPORT

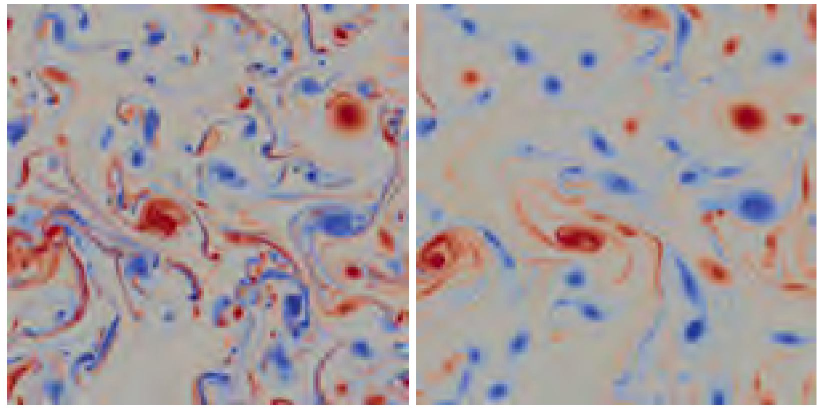
CLOUD FLOWS

There is an important open question in cloud evolution called the droplet growth bottleneck – microscopic cloud droplets, just before it rains, grow in about 15 minutes into raindrops. **Rama Govindarajan** and her group showed that caustics can form due to a single vortex and be an important reason for droplet growth.

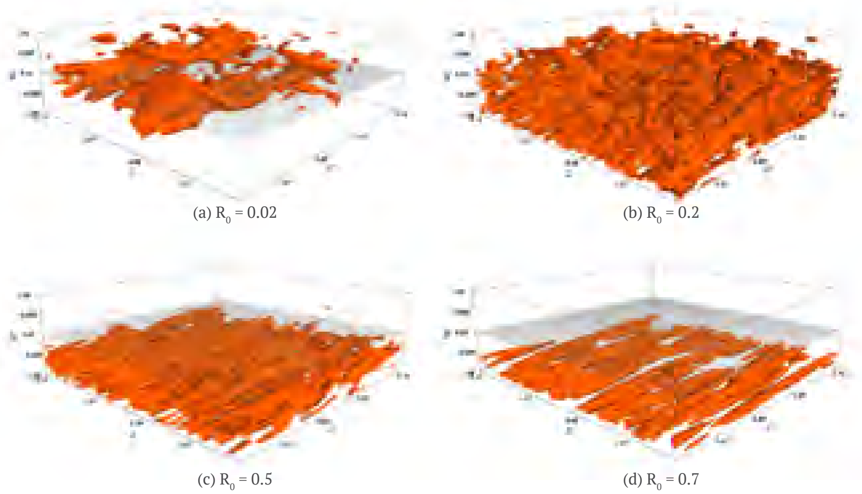
The group is greatly interested in the interplay of fluid dynamics and thermodynamics in clouds, and show how it leads to altered turbulent dynamics. The rapid evacuation of droplets in the vicinity of vortices means that these regions are devoid of cloud condensation nuclei. In the supersaturated environment of clouds, this results in preferential condensation outside vortical regions, and thus in inhomogeneous release of latent heat and thus inhomogeneous buoyancy. This can modify the turbulent flow significantly.

RAMA GOVINDARAJAN

Rama Govindarajan completed her PhD from the Indian Institute of Science. She then went to the California Institute of Technology for a postdoc. Before joining ICTS, she was a professor at the Tata Institute of Fundamental Research, Hyderabad, from 2012–2016 and a faculty member at the Jawaharlal Nehru Centre for Adv. Sci. Res. from 1998–2012. She is a fellow of the American Physical Society (Division of Fluid Dynamics). Govindarajan works on fluid mechanical problems, especially those of geophysical relevance, such as clouds, the ocean and the monsoon. Instabilities in stratified flows and fluid–structure interactions are related interests



Simulations of the Navier-Stokes and the temperature equations in two dimensions, including phase change and buoyancy effects. Left – no droplet inertia, right – including droplet inertia. Red stands for anticlockwise vorticity and blue for clockwise. Particle inertia, by orchestrating inhomogeneous phase change, results in a flow where there is much more energy in the small-scale turbulent structures than before. Given that the smallest flow structures are orders of magnitude larger than the largest droplets, what we show is that a dilute suspension of tiny droplets can alter the future of large structures. From Ravichandran and Govindarajan, J Fluid Mech., 2017.



Isocontours of vorticity at a typical level in channel flow at different levels of the rotation. Flow is highly turbulent at intermediate rotation levels (Ro=0.2). Structures are weaker, streaamwise oriented and localized close to one wall at higher rotation rates. This is a manifestation of the Taylor-Proudman effect. From Jose et al., Phys. Rev. Fluids, 2017.

INSTABILITIES IN ROTATING FLOWS

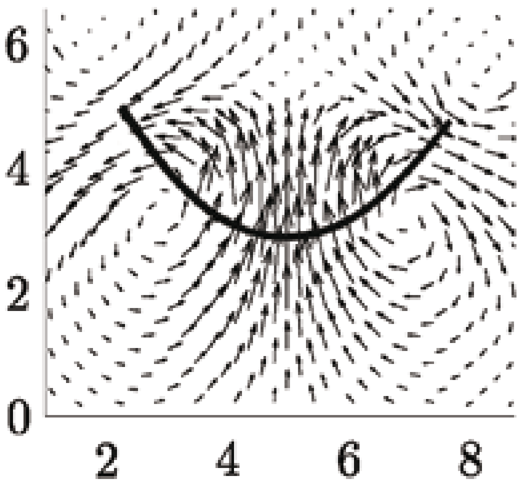
The group shows that rotation suppresses algebraic growth of instabilities in pressure-driven channel flow by suppressing the lift-up effect, in a manifestation of the Taylor-Proudman effect, and that flow structures depend strongly and nonmonotonically on rotation.

MIXING IN THE BAY OF BENGAL

In ongoing work done with Ritabrata Thakur, Jim Moum and Emily Shroyer, Govindarajan makes turbulence estimates for the first time in the Bay of Bengal by high frequency temperature measurements. They find a large quieting down of turbulence below the mixing layer at some times of year. They show that the stability of a shear layer can be affected by viscosity stratification.

FLUID–STRUCTURE INTERACTION

Working in the K.S. Krishnan lab, Govindarajan (with Sumit K Birwa, S Ganga Prasath, Rahul Chajwa, Narayanan Menon), is studying (a) collision dynamics of a solid sphere impacting on a solid plate through a viscous medium. Contrary to shallow–water theory they show by electrical means that contact does occur. (b) Flexible filaments on fluid interfaces. They showed that the nonlinear behaviour of an unbending filament on a fluid interface obeys a universal scaling. (c) Collective dynamics of non–spherical particles in Stokes flow.



Velocity field around an unbending filament, obtained from PIV images. From Prasath et al. Phys. Rev. Fluids, 2016.

INDIAN MONSOON

With Adway Mitra, Amit Apte, Vishal Vasan, Sreekar Vadlamani and Samriddhi Sankar Ray, who comprise the monsoon group, Govindarajan identifies coherent swathes of cloud and rainfall by describing observed data of rainfall and clouds by Markov Random. They are in the process of estimating their movement and the identification thereby of active and break phases of the monsoon in different regions.

PUBLICATIONS

1. *Algebraic disturbances and their consequences in rotating channel flow transition,* S. Jose, V. Kuzhimparampil, B. Pier and R. Govindarajan. Physical Review Fluids 2 No. 8, (2017) 083901.

2. *Caustics-induced coalescence of small droplets near a vortex,* P. Deepu, S. Ravichandran and R. Govindarajan. Physical Review Fluids 2 No. 2, (2017) 024305.

3. *Effects of viscosity and conductivity stratification on the linear stability and transient growth within compressible Couette flow,* B. Saikia, A. Ramachandran, K. Sinha and R. Govindarajan. Physics of Fluids 29 No. 2, (2017) 024105.

4. *Cloud microatlas,* R. Govindarajan and S. Ravichandran. Resonance 22 No. 3, (2017) 269–277.

5. *Lift-induced vortex dipole collapse,* S. Ravichandran, H. N. Dixit, and R. Govindarajan, Physical Review Fluids 2 No. 3, (2017) 034702.

6. *Non-modal stability of Jeffery-Hamel flow,* M. R. Jotkar and R. Govindarajan. Physics of Fluids 29 No. 6, (2017) 064107.

7. *Optimal energy growth in a stably stratified shear flow,* S. Jose, A. Roy, R. Bale, K. Iyer, and R. Govindarajan, accepted manuscript (in press) Fluid Dyn. Res. (2017).

8. *Two initially spherical bubbles rising in quiescent liquid,* M. K. Tripathi, A. Premlata, K. C. Sahu and R. Govindarajan. Physical Review Fluids 2 No. 7, (2017) 073601.

9. *Vortex-dipole collapse induced by droplet inertia and phase change,* S. Ravichandran and R. Govindarajan. Journal of Fluid Mechanics 832 (2017) 745–776.

10. *Attraction-induced jamming in the flow of foam through a channel,* K. Menon, R. Govindarajan and S. Tewari. Soft matter 12 No. 37, (2016) 7772–7781.

RESEARCH REPORT

Samriddhi Sankar Ray's interests lie in various aspects of turbulence and turbulent transport in its many 'avatars.'

In this period, he and his collaborators have made a significant advance in understanding the rather intriguing – and surprising – connection between intermittency in the incompressible Navier–Stokes equation and the effective degrees of freedom in the system by using the method of Fourier decimation. They were able to show that this feature is true for both Eulerian and Lagrangian measurements.

The results open up all sorts of questions related to the underlying connections between chaos, intermittency, and irreversibility – the ubiquitous fingerprints of turbulent flows – as well as the question of how non–equilibrium cascade solutions are related to thermalised ones which naturally emerge in finite–dimensional equations of hydrodynamics with no viscosity. They have addressed some aspects of these issues, including the onset of such thermalised states in finite–dimensional, inviscid equations of hydrodynamic.

They also explored the power and usefulness of reduced models of turbulence, namely the shell model, to investigate two different problems which would be hard to tackle by using the primitive equations of motion. One of these is related

SAMRIDDHI SANKAR RAY

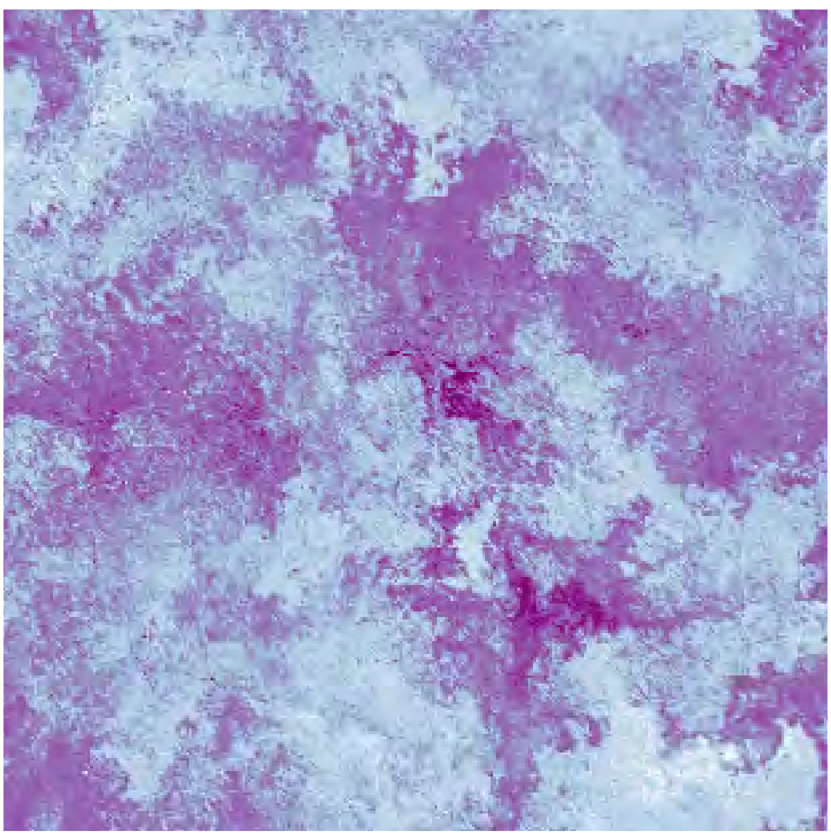
Samriddhi Sankar Ray completed his PhD from the Indian Institute of Science, Bangalore, in 2010 under the supervision of Rahul Pandit. His post doc appointment was with Laboratoire Lagrange, Observatoire de la Côte d'Azur, CNRS, Nice, France. He is the Principal Investigator (PI) of AIRBUS Group Corporate Foundation Chair in Mathematics of Complex Systems established in ICTS and Co-PI and member of the Indo-French Centre for Applied Mathematics (IFCAM). Ray works on various aspects of turbulence and turbulent transport problems. By borrowing tools from statistical mechanics, applied mathematics and computational fluid dynamics, he looks at fundamental and applied problems turbulence.

to characterising the two–point, time–dependent correlation functions in magnetohydrodynamic turbulence and fish out the relevant time–scales and the associated scaling exponents.

They carried out a systematic study of the transition to elastic turbulence, at low Reynolds numbers, in a fluid with polymer additives. Through extensive numerical simulations we extracted the chaotic behaviour and the transition to elastic turbulence as a function of both the concentration and the intrinsic time–scales of the polymer additives.

In the area of turbulent transport and inertial particles in turbulence, they studied both spherical, point particles as well as semi–flexible particles with internal degrees of freedom. For the latter, they were able to make precise analytical predictions and carry out numerical simulations in two and three dimensions to understand their bending statistics and typical configurations in turbulent and model flows. For spherical particles, they made rapid progress in how aggregates grow and the precise role of the advecting fluid in determining the rate the typical particle size increases through coalescence. They also looked at the typical velocities of colliding particles and their dependence on the diameters of the colliding pairs. Given the generality of our system, these results are applicable to problems ranging from the understanding the growth of protoplanets to rain drops in warm clouds.

They also combined ideas of turbulent transport with those from active systems.



Distance traveled by fluid elements in a 3D turbulent flow during one large-eddy turnover time. Long (white) and short (purple) distances, represented here as a function of the final position in a 2D slice, define an intricate landscape with fronts where particles coming from far apart meet.

Thus, they modified the popular Vicsek model to including self–driven organisms in a turbulent flow to show how flocking emerges and is inevitable if the sizes of the microorganisms are just right.

Within more traditional condensed matter systems, they applied ideas of multifractality to explain the nature of the universal conductance fluctuation in graphene. This result is special as its probably first work where multifractality has been observed and characterised, experimentally, in a quantum transport problem. These results also shed some light on the Anderson localisation problem for such systems.

PUBLICATIONS

1. *Non-intermittent turbulence:* Chaos and irreversibility, S. S. Ray. Under Review (2017).
2. *Revisiting the SABRA model: Statics and dynamics,* R. Tom and S. S. Ray. Under Review (2017).
3. *Light-cone spreading of perturbations and the butterfly effect in a classical spin chain,* A. Das, S. Chakrabarty, A. Dhar, A. Kundu, R. Moessner, S. S. Ray and S. Bhattacharjee. ArXiv: 1711:07505 (2017)
4. *Exotic multifractal conductance fluctuations in graphene,* K. R. Amin, Samriddhi Sankar Ray, N. Pal, R. Pandit and A. Bid. Communications Physics (Accepted) (2017).
5. *An overview of the statistical properties of two-dimensional turbulence in fluids with particles, conducting fluids, fluids with polymer additives, binary-fluid mixtures, and superfluids,* R. Pandit, D. Banerjee, A. Bhatnagar, M. Brachet, A. Gupta, D. Mitra, N. Pal, P. Perlekar, S. S. Ray, V. Shukla, et al. Physics of Fluids 29 No. 11, (2017) 111112.
6. *Enhanced droplet collision rates and impact velocities in turbulent flows: The effect of poly-dispersity and transient phases,* M. James and S. S. Ray. Scientific Reports 7 (2017) 12231.
7. *Abrupt growth of large aggregates by correlated coalescences in turbulent flow,* J. Bec, S. S. Ray, E. W. Saw and H. Homann. Physical Review E 93 No. 3, (2016) 031102.
8. *Dynamic multiscaling in magnetohydrodynamic turbulence,* S. S. Ray, G. Sahoo and R. Pandit. Physical Review E 94 No. 5, (2016) 053101.
9. *Elastic turbulence in a shell model of polymer solution,* S. S. Ray and D. Vincenzi. EPL (Europhysics Letters) 114 No. 4, (2016) 44001.
10. *Intermittency in fractal Fourier hydrodynamics: Lessons from the Burgers equation,* M. Buzzicotti, L. Biferale, U. Frisch and S. S. Ray. Physical Review E 93 No. 3, (2016) 033109.

11. *Lagrangian statistics for Navier–Stokes turbulence under Fourier-mode reduction: fractal and homogeneous decimations,* M. Buzzicotti, A. Bhatnagar, L. Biferale, A. S. Lanotte and S. S. Ray. New Journal of Physics 18 No. 11, (2016) 113047.

12. *Semiflexible particles in isotropic turbulence,* A. Ali, E. L. C. V. M. Plan, S. S. Ray and D. Vincenzi. Physical Review Fluids 1 No. 8, (2016) 082402.

13. *Effect of inertia on model flocks in a turbulent environment,* A. Choudhary, D. Venkataraman and S. S. Ray. EPL (Europhysics Letters) 112 No. 2, (2015) 24005.

14. *Thermalized solutions, statistical mechanics and turbulence: An overview of some recent results,* S. S. Ray. Pramana 84 No. 3, (2015) 395–407.

PHYSICAL BIOLOGY

The **PHYSICAL BIOLOGY** group at ICTS is interested in the physics of living systems at a broad level. Current research in this group focuses on the emergent active mechanochemical patterns in the actomyosin cortex of the cell and, at large scales, in tissues. A medium term research goal of this group is to understand how active mechanics and biochemistry combine with geometry leading to the emergence of the morphogenetic form and function in developing embryos

RESEARCH REPORT

Cell polarity establishment is a generic process seen in many developmental systems. In the zygotes of the C. elegans embryo, active mechanical flows drive the partitioning defective (PAR) proteins into anterior and posterior domains in response to external guiding cues. These cues ensure that the correct pattern forms at the right time and place, but how they control the processes of self-organization to steer pattern formation remains unknown. In a strongly interdisciplinary and collaborative study, **Vijay Kumar Krishnamurthy** and his collaborators have investigated PAR polarity establishment in C. elegans zygotes, by combining measurements of the spatial distribution of protein numbers and fluxes, with a physical theory. They have been successful in characterizing the handover from a pre-pattern to mechanochemical self-organization and found that guiding cues from the centrosome steer a patterning system comprised of PAR proteins and the actomyosin cortex to a transition point beyond which the patterned state becomes self-organized. This mechanism of controlled pattern formation integrates mechanical and molecular aspects of biological pattern formation with guiding cues.

Developmental patterns combine active mechanics and biochemistry to generate functional morphologies of embryos in a robust and reproducible manner. For a given

FACULTY

Vijay Kumar Krishnamurthy

Shashi Thutupalli
Joint faculty (with NCBS)

POSTDOCTORAL FELLOWS

Pritha Dolai

Debajit Goswami

Sankaran Nampoothiri

Pawan Nandakishore

Jemseena V.

VIJAY KUMAR KRISHNAMURTHY

Vijay Kumar Krishnamurthy completed his PhD at the Indian Institute of Science, Bangalore, under the supervision of Sriram Ramaswamy. His postdoc affiliations were with Yale University and Max Planck Institute, Dresden. He is partner with the Max Planck Partner Group in Biological Physics at ICTS–TIFR (2016- 2019) and was also awarded the Ramalingaswami Fellowship from the Department of Biotechnology, India (2016- 2020). Vijaykumar's interest is in the physics of living systems. Specifically, he is fascinated by developmental biology and is keen to understand the interplay between mechanics, geometry and biochemical signalling process in the emergence of morphogenetic patterns.

geometrical shape, pattern formation in cells and tissues has been extensively studied in the framework of reaction-diffusion systems which model diffusible biochemical signals. However, biochemical signalling alone cannot affect the geometry of embryos, since there are no mechanical stresses involved. Active mechanochemical patterns, on the other hand, combine biochemical signalling and mechanical stresses in an inseparable manner. A natural way to couple shape deformations and morphogen concentration fields would be to study mechanochemical pattern formation on deformable domains. The group is currently studying active mechanochemical patterns on two-dimensional curved surfaces, and plan to investigate the tight coupling between biochemical signalling, mechanics and the geometry of the underlying domain.

Active Brownian particles (ABPs) are minimalistic realizations of scalar active matter. ABPs display very non-trivial dynamics in their statistical properties and are relevant in the study of molecular motors. In a collaborative study, they have investigated the motion of a run-and-tumble particle (RTP) in one dimension and have found the exact probability distribution of the particle with and without diffusion on the infinite line, as well as in a finite interval. In the infinite domain, this probability distribution approaches a Gaussian form in the long-time limit, as in the case of a regular Brownian particle. At intermediate times, this distribution exhibits unexpected multi-modal forms. In a finite domain, the probability distribution reaches a steady state form with peaks at the boundaries, in contrast to a Brownian particle. They also studied the relaxation to the steady state analytically. Finally, they computed the survival probability of the RTP in a semi-infinite domain. In the finite interval, they computed the exit probability and the associated exit times. They have checked the analytical results with numerical verifications.

PUBLICATIONS

1. *Control of mechanochemical self-organization during cell polarization,* P. Gross, K. Vijay Kumar, N. Goehring, J. S. Bois, C. Hoege, F. Julicher, S. W. Grill. (under review, 2017).

2. *How active mechanics and regulatory biochemistry combine to form patterns in development,* P. Gross, K. Vijay Kumar, S. W. Grill. Annual Review of Biophysics (2017).

3. *Steady state, relaxation and first-passage properties of a run-and-tumble particle in one-dimension,* Kanaya Malakar, V. Jemseena, Anupam Kundu, K. Vijay Kumar, Sanjib Sabhapandit, Satya N. Majumdar, S. Redner, Abhishek Dhar. https://arxiv.org/abs/1711.08474

RESEARCH REPORT

Shashi Thutupalli and his group currently pursue two complementary lines of research–

(i) CONSTRUCTING DE NOVO, SYNTHETIC MIMICS OF LIVING MATTER TO STUDY THE MINIMAL INGREDIENTS FOR SELF- ASSEMBLY, REPLICATION, COMPUTATION AND FEEDBACK.
This serves as a kind of synthetic biology from a physical viewpoint and is likely to shed light on early evolution and the transitions therein. The focus is on understanding and duplicating, using synthetic inanimate components, the emergence of specific, quantifiable, and characteristic properties of living matter, rather than understanding how life itself emerges from its basic molecular building blocks. This is an important distinction from in vitro reconstitution approaches that have characterized many biophysical studies. The problem then naturally lends itself to the framework of statistical physics in which the key properties of the organization of living matter may be described.

Along these lines the group has created and studied synthetic soft objects (emulsion droplets) capable of self-propulsion and have demonstrated that their swimming motions couple via fluid-mediated long range interactions giving rise to generic and distinct collective organization reminiscent of that in many biological systems. These serve as a well-characterized experimental model to investigate emergent behavior in active matter systems.

SHASHI THUTUPALLI

Shashi Thutupalli has a PhD from the Max Planck Institute for Dynamics and Self-Organization, Göttingen. He was a postdoctoral fellow at the Max Planck Institute for Dynamics and Self-Organization and then an HFSP Cross-Disciplinary Fellow at Princeton University. At present he is a joint faculty member at the ICTS and the NCBS, Bangalore. Thutupalli is the Head of a Max Planck Partner Group with the MPI-DSO, Göttingen, at NCBS-TIFR and ICTS-TIFR (2017-2020). He is a recipient of the FOKOS Award for most striking discovery in complex systems (2014). Thutupalli is interested in the organization and function of living matter, with a focus on collective and emergent behavior. The investigations span phenomena at different scales - cells, organisms and ecologies - with an aim to uncover common organizational principles.

(ii) PROBING THE PHYSICAL BASIS OF ORGANIZATION IN BIOLOGICAL SYSTEMS. This represents a physical biology which will allow us to quantitatively identify the broadly universal features of biological systems. The approach is to make careful measurements on well-chosen biological phenomena and to use theories rooted in non-equilibrium statistical physics and dynamical systems to understand the data. Often, the experimental data requires the development of new theoretical ideas.

In one such study, Thutupalli and his group combined microbiological experiments, cutting-edge computer vision tracking and analysis with simulations of self-propelled particles to show that bacterial self-organization under stress is similar to a non-equilibrium phase separation process. The organization, namely a population level aggregation (into so-called fruiting bodies) under starvation stress, is driven by the underlying motility of individual bacterial cells and without the need for biochemical signaling mechanisms, condensed bacteria rich regions spontaneously phase separate from an initially uniform gas-like phase. The initial foundations of fruiting bodies are laid by these phase separated regions, the dynamics of which can be controlled by individual cells via the motility of individual cells. This type of phase transition has been studied in theoretical work, but our study is one of the first quantitative experimental demonstrations of a living organism that evolved to take advantage of this kind of active matter physics. They found quantitative agreement between their experiments and the very simple simulations, supporting the conclusion that simple physical principles rather than complex biochemistry ultimately govern the dynamics. The dynamics the group uncovered are likely to be relevant for diverse biological aggregation at vastly different length scales, underscoring the universality of the underlying physical mechanisms.

PUBLICATIONS

1. *Boundaries determine the collective dynamics of self-propelled particles,* S. Thutupalli, D. Geyer, R. Singh, R. Adhikari and H.A. Stone. Proc. Nat. Acad. Sci., In Revision

2. *A motility-induced phase transition drives Myxococcus xanthus aggregation,* G. Liu, A. Patch, F. Bahar, D. Yllanes, R.D. Welch, M.C. Marchetti, S. Thutupalli, J.W. Shaevitz. Proc. Nat. Acad. Sci., Under review

3. *Farming and public goods production in C. elegans populations,* Shashi Thutupalli, Sravanti Uppaluri, George Constable, Howard Stone, Simon Levin, Corina Tarnita, Clifford Brangwynne. Proc. Nat. Acad. Sci., 114 (9), 22892294 (2017)

4. *Intermittent chaotic chimeras in coupled rotators,* Simona Olmi, Erik Martens, Shashi Thutupalli, Alessandro Torcini. Phys. Rev. E (Rapid Communications), 92 (3), 030901 (2015)

5. *Orientational phase ordering at the onset of multicellular aggregation in Myxococcus xanthus,* Shashi Thutupalli, Mingzhai Sun, Filiz Bunyak, Kannappan Palaniappan, Joshua Shaevitz. Journal of the Royal Society Interface, 12 (109), 20150049, 2015

no gravity

Particle Theory

STRING THEORY AND QUANTUM GRAVITY

The **STRING THEORY AND QUANTUM GRAVITY** group at ICTS–TIFR investigates some of the most fundamental questions in theoretical physics. This group participates in the quest for the quantum theory of gravity. As part of this search, faculty members in this group strive for a deeper understanding of the most dramatic objects in our Universe – black holes, and also a better understanding of early Universe cosmology. The ICTS string group also uses the rich formalism developed for this purpose in order to study the underlying structure of quantum field theory and also to investigate applications in the study of strongly correlated systems, fluid dynamics, cosmology, and mathematics.

FACULTY

Pallab Basu

Avinash Dhar
Dean Emeritus and Visiting Professor

Rajesh Gopakumar

Loganayagam R.

Suvrat Raju

Spenta R. Wadia
Infosys Homi Bhabha Chair professor

POSTDOCTORAL FELLOWS

Victor Ivan Giraldo Rivera

Pinaki Banerjee

Bidisha Chakrabarty

Anosh Joseph

Prithvi Narayan

Alexandre Serantes

Junggi Yoon

STUDENTS

Soumyadeep Chaudhuri

Sudip Ghosh

Chandan Kumar Jana

Jaswin Kasi

Pushkal Shrivastava

PALLAB BASU

Pallab Basu received his PhD from the Tata Institute of Fundamental Research, under the supervision of Spenta R. Wadia. His postdoc appointments were at the University of British Columbia and University of Kentucky. Basu's research includes applications of the phases of large-N gauge theories and holography, QCD like systems in the context of string theory, condensed matter inspired systems in the context of string theory, non-integrability in the context of string theory and various properties of black holes.

RESEARCH REPORT

One central motto of **Pallab Basu**'s research is to have a deeper understanding, mostly using holography, of non–suerpsymmetric and dynamical questions in quantum field theories. This includes aspects of out of equilibrium dynamics including chaos and thermalization and static properties like phase transition of strongly coupled quantum field theories at finite density and temperature. Generally, studying dynamical properties at finite density and temperature is a hard question and most standard methods, both analytic and numerical, do not work well. They ask how can one use holography, i.e. stringy/gravitational dynamics in a holographic setup, to learn more about quantum field theories and vice versa. Some of his work, done in last couple of years was continuation of earlier work, described below.

Basu and his collaborators presented strong numerical evidence that a self–interacting probe scalar field in AdS, with only a few modes turned on initially, would undergo fast thermalization only if initial amplitude is above a certain energetic threshold. Below this threshold the energy stays close to constant in a few modes for ra very long time instead of cascading quickly. This indicates the existence of a Strong Stochasticity Threshold (SST) in holography. In the two time formalism, where they separate the fast and slow moving modes, they found out novel conserved charges which has also been observed in full gravitational settings.

A nonlinearly coupled scalar field in an asymptotically AdS black brane geometry behaves similar to a dissipative nonlinear system. When driven periodically, the transition to chaos proceeds through a series of period–doubling bifurcations. The presence of dissipation, crucial to this behavior, arises naturally in a black hole background from the ingoing conditions imposed at the horizon. AdS/CFT translates our solution to a chaotic response to the operator dual to the scalar field.

Phases of holographic black holes interacting with non–gravitational fields is an complex and interesting subject. Two massive, mutually interacting probe real scalar fields, in zero temperature holographic backgrounds leads to a second order quantum critical phase transition across which the one of the scalar field forms a condensate. Basu and collaborators have looked at the resulting phase diagram and numerically computed the condensate. They have also investigated our system in different backgrounds. A system with charged scalar and gauge field in an asymptotically Anti–de Sitter spacetime (AdS_4) in the grand canonical ensemble, for the conformally coupled scalar, has four phases – global AdS, boson star, Reissner–Nordstrom black hole and the hairy black hole. The nature of the phase diagram undergoes qualitative changes as the charge of the scalar is changed, which they discussed.

The eigenstate thermalization hypothesis (ETH) provides a way to understand how an isolated quantum mechanical system can be approximated by a thermal density matrix. Basu along with his collaborators find a class of operators in two dimensional conformal field theories, consisting of quasiprimaries of the identity module, which satisfy the hypothesis only at the leading order in large central charge. In the context of subsystem ETH, this plays a role in the deviation of the reduced density matrices, corresponding to a finite energy density eigenstate from its hypothesized thermal approximation. The universal deviation in terms of the square of the trace–square distance goes as the eighth power of the subsystem fraction and is suppressed by powers of inverse central charge (c). Furthermore, the nonuniversal deviations from subsystem ETH are found to be proportional to the heavy–light–heavy structure constants [1]

PUBLICATIONS

1. *Chaotic dynamics of strings in charged black hole backgrounds,* P. Basu, P. Chaturvedi and P. Samantray. Phys. Rev. D95 No. 6, (2017) 066014.

2. *Thermality of eigenstates in conformal field theories,* P. Basu, D. Das, S. Datta and S. Pal. Phys. Rev. E96 No. 2, (2017) 022149, arXiv:1705.03001 [hep–th].

3. *Phase transitions of a (super) quantum mechanical matrix model with a chemical potential,* T. Azuma, P. Basu and P. Samantray. JHEP 09 (2017) 071.

4. *Hairy black holes in a box,* P. Basu, C. Krishnan and P. N. B. Subramanian. JHEP 11 (2016) 041, arXiv:1609.01208 [hep–th].

5. *Phases of global AdS black holes,* P. Basu, C. Krishnan and P. N. Bala Subramanian. JHEP 06 (2016) 139, arXiv:1602.07211 [hep–th].

6. *A stochasticity threshold in holography and the instability of AdS,* P. Basu, C. Krishnan and A. Saurabh. Int. J. Mod. Phys. A30 No. 21, (2015) 1550128.

7. *AdS (in) stability: Lessons from the scalar field,* P. Basu, C. Krishnan and P. N. Bala Subramanian. Phys. Lett. B746 (2015) 261–265, arXiv:1501.07499 [hep–th].

8. *ε–expansions near three dimensions from conformal field theory,* P. Basu and C. Krishnan. JHEP 11 (2015) 040, arXiv:1506.06616 [hep–th].

RESEARCH REPORT

In his recent research, **Avinash Dhar** has worked on holographic models of strong interactions and a novel model with possible applications to physics beyond the standard model.

ASYMPTOTICALLY FREE 4–FERMI THEORY AND MASS GENERATION IN 4–DIMENSIONS

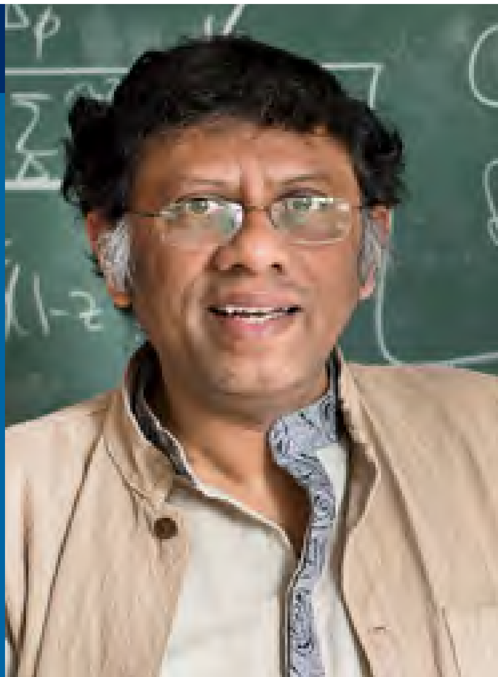
A fundamental problem of particle physics is the question of mass generation of elementary particles in (3+1) dimensions. In the SM, Higgs mechanism and Yukawa couplings take care of this. However, the SM has many problems and it is expected that this model will eventually get replaced by a more fundamental theory. If we are willing to tolerate a small violation of Lorentz invariance in the ultra–violet, then it is possible to have a renormalizable model involving a NJL type 4–fermi interaction in (3+1) dimensions. He showed (with G. Mandal and S. R. Wadia) that a model based on this idea is asymptotically free and has dynamical mass generation. Moreover,

AVINASH DHAR

Avinash Dhar completed his PhD under Virendra Gupta from the Tata Institute of Fundamental Research, Mumbai. He was a postdoc at the Stanford Linear Accelerator Centre (SLAC). Since joining ICTS in 2015, Dhar has served as the Dean of Programs and Activities. He has contributed actively to all aspects of setting up of the ICTS since its inception in 2007, including writing of the detailed project reports for the XI and XII plans, setting up of a transit campus in the IISc campus, processing of program proposals and other activities until Aug 2017, discussion of various academic activities of ICTS and its faculty induction and initial setting up of student and post-doctoral programs, setting up and initial upgradation of the ICTS website, hiring and training of administrative and technical personnel, supervising finance management and construction of new campus buildings at Hessaraghatta, etc. His research interests are in the areas of quantum field theory and string theory and their interconnections. His interests also include physics beyond the standard model.

he showed (with G. Mandal and P. Nag) that in an appropriate version, its infrared behaviour can be governed by an approximately Lorentz invariant theory. However, for realistic model building, one must find a concrete realization in which all particle excitations at low energies have the same 'maximum attainable' velocity. This is an open question.

CHIRAL SYMMETRY BREAKING IN HOLOGRAPHIC QCD
Holographic QCD models provide a laboratory in which to test our ideas about QCD in the strong coupling regime. One such example is the Sakai–Sugimoto model, which incorporates quark flavours and hence is suitable for studying chiral symmetry in QCD. He studied (with P. Nag) chiral symmetry breaking in this model in both the strong and weak coupling regimes. At strong coupling, a modified Sakai–Sugimoto model with the tachyon present has a classical solution in which the parameter corresponding to the non–normalizable mode of the tachyon gives rise to the quark mass, while the chiral condensate arises from the parameter corresponding to the normalizable solution. In this solution, chiral symmetry breaking coincides with tachyon condensation, pion mass is nonzero and satisfies the Gell–Mann–Oakes–Renner relation when a small quark mass is switched on. At weak coupling, a non–local NJL type short–range interaction emerges and chiral symmetry is broken only above a certain critical value of the (4)–dimensional 't Hooft coupling.



RAJESH GOPAKUMAR

Rajesh Gopakumar completed his PhD from Princeton University under the guidance of David Gross after his undergraduate degree from IIT Kanpur. He was a postdoc at Harvard University and a long-term visiting member at the Institute for Advanced Study, Princeton. Before joining ICTS, he was a faculty member at the Harish-Chandra Research Institute in Allahabad. He is currently the Director of ICTS. He is a member of the Editorial Board of Physical Review Letters *(DAE, Particles and Fields)* (2014-20) and Secretary of the Commission on Mathematical Physics (C18), International Union of Pure and Applied Physics (2017-20). In the past he has served on the council of the Indian National Science Academy and was a founding member (now alumnus) of Global Young Academy (GYA) in addition to being a fellow of the Indian Academy of Sciences and the National Academy of Sciences, India. Gopakumar is the recipient of the TWAS prize (2013), the G. D. Birla award (2013), the S.S. Bhatnagar Award (2009), the ICTP Prize (2006) and the B.M. Birla Science Prize (2004). He received the Swarnajayanti fellowship in 2006 and currently holds a J. C. Bose fellowship. Gopakumar's primary interests are in the areas of quantum field theory, string theory and the deep relation between the two exemplified by gauge-string dualities. Much of his research in recent years has been driven by the need to elucidate and even derive this relation from first principles.

RESEARCH REPORT

Rajesh Gopakumar's primary interests are in the areas of quantum field theory, string theory and the deep relation between the two exemplified by gauge–string dualities. Much of his research in recent years has been driven by the need to elucidate and even derive this relation from first principles.

His current research has had two major strands. The first has been to unravel aspects of gauge–string duality in one of the simplest, yet non–trivial such case, that of dualities between large N 2d conformal field theories (CFTs) and string theories (or theories of gravity) in three dimensional Anti–de Sitter (AdS) space. This work builds on developments originating from the proposal in 2010 of Gopakumar (with M. Gaberdiel) of duality between a class of large N coset CFTs in 2 and Vasiliev theories of gravity in AdS_3. This latter duality has been embedded by Gopakumar and Gaberdiel in the canonical string theory example of AdS_3/CFT_2. In particular, the higher spin symmetries of the Vasiliev theory are enlarged in the string theory.

This gives one of the first concrete examples of a large unbroken stringy symmetry. Moreover this symmetry algebra has a very interesting structure dubbed as the `*higher spin square*' which is fixed in terms of the conventional higher spin W_∞ algebra despite being much larger. The aim is to exploit this large underlying symmetry to constrain the structure of string theory and perhaps uniquely determine it.

The second strand of research, embarked on in the last couple of years (with Aninda Sinha and others), is a proposal for an alternative formulation of the idea of the conformal bootstrap for analytically understanding CFTs. There are two new ingredients here. The first is to work in a crossing symmetric basis for four point amplitudes which is built from the basic building blocks of the AdS/CFT correspondence, namely, the so–called Witten diagrams in AdS space. This revives an old idea of Polyakov. The second is to employ a Mellin space representation of the amplitude which turns out to be very natural for this problem. This has been applied to one of the simplest nontrivial CFTs – which underlies the 3d Ising model, namely the Wilson–Fisher fixed point – in an ε expansion. Remarkably this new approach yields both operator dimensions as well as, for the first time, three point functions (or OPE coefficients) up to order ε^3.

The current research strands have a natural development in terms of new questions to be addressed. Understanding the symmetries of string theory and exploiting their presence to understand the theory in the so–called Higgsed phase is a medium term goal. These symmetries will also hopefully shed light on why the structure of string theory is so rigid and effectively unique. In some sense these ideas also connect to the second strand which aims to give some kind of a general diagrammatic approach to CFTs. Perhaps CFTs are strongly constrained and isolated in the space of quantum field theories because they are secretly always string theories!

PUBLICATIONS

1. *BPS spectrum on* $AdS_3 \times S^3 \times S^3 \times S^1$, L. Eberhardt, M. R. Gaberdiel, R. Gopakumar and W. Li. JHEP 03 (2017) 124, arXiv:1701.03552 [hep–th].

2. *A Mellin space approach to the conformal bootstrap,* R. Gopakumar, A. Kaviraj, K. Sen and A. Sinha. JHEP 1705, 027 (2017), arXiv:1611.08407 [hep–th].

3. *Conformal bootstrap in Mellin space,* R. Gopakumar, A. Kaviraj, K. Sen and A. Sinha. Phys. Rev. Lett. 118 (Feb, 2017) 081601.

4. *Higher spins and Yangian symmetries,* M. R. Gaberdiel, R. Gopakumar, W. Li, and C. Peng. JHEP 04 (2017) 152, arXiv:1702.05100 [hep–th].

5. *Stringy* AdS_3 *from the worldsheet,* M. R. Gaberdiel, R. Gopakumar and C. Hull. JHEP 07 (2017) 090, arXiv:1704.08665 [hep–th].

6. *String theory as a higher spin theory,* M. R. Gaberdiel and R. Gopakumar. JHEP 09 (2016) 085, arXiv:1512.07237 [hep–th].

7. *Stringy Symmetries and the Higher Spin Square,* M.R. Gaberdiel and R. Gopakumar. J. Phys. A, 48, No. 18, 185402 (2015).

8. *String theory and the conundrums of quantum gravity,* R. Gopakumar. Curr. Sc. 109 No. 12, (2015) 2265–2270

RESEARCH REPORT

R. Loganayagam's primary interests are in string theory, black hole physics and quantum field theory with a focus on real–time, finite temperature quantum field theory. One of the major projects he has been involved in over the last two years is the question of formulating hydrodynamics as an effective field theory controlled by symmetries.

The most general non–equilibrium dynamics of a microscopic quantum field theory is described by Schwinger–Keldysh path integral which evolves the most general mixed state of the field theory under question. In this formalism, all microscopic fields (and their symmetries) are doubled and specific boundary conditions are imposed on the correlators of the two copies. On the other hand, the fundamental assumption implicit in all fluid dynamics is that, in an appropriate macroscopic regime, this doubled theory can be recast into dynamics of fluid fields.

However, the details of how this mapping or duality between these three descriptions work is ill–understood. For example, one may ask the following questions –

a) The conventional fluid dynamics by itself does not exhibit any doubling of fields. How does one reconcile this fact with the doubling structure present in the microscopic Schwinger Keldysh theory?

b) Fluid dynamics is strongly controlled by the presence of a local entropy current whose divergence is non–negative (second law of thermodynamics). How does this structure emerge from the doubled theory?

R. LOGANAYAGAM

R. Loganayagam completed his PhD from TIFR. He was a Junior Fellow at the Harvard Society of Fellows at Harvard University and a postdoc at the Institute for Advanced Study, Princeton. He was awarded the Ramanujan Fellowship from the Department of Science and Technology, India (2016). Loganayagam's primary interests are in string theory, black hole physics and quantum field theory with a focus on real time, finite temperature quantum field theory.

Motivated by these questions, Loganyagam, Mukund Rangamani and Felix Haehl have proposed an emergent abelian gauge symmetry/supersymmetry at long distances that gives a Wilsonian explanation for the emergence of entropy and second law within fluid dynamical path integrals.

A second set of questions involve open quantum field theories especially with regards to the structure of renormalization. While the notion of open quantum systems (i.e., quantum systems in contact with an environment) is itself old, many of the existing studies deal with quantum mechanical systems rather than quantum field theories. One of the most widely used models of open quantum systems is the quantum master equation approach by Gorini–Kossakowski–Sudarshan and Lindblad. In a recent work with his collaborators, Loganayagam tackled the issue of the emergence of such a Lindblad equation in open quantum field theories and its renormalization.

A third set of questions revolve around out of time ordered correlators (OTOCs) in a variety of systems, especially at finite temperature. In a sequence of papers, Loganayagam and his collaborators studied the general structure of path integrals which compute OTOCs and the generalized fluctuation–dissipation theorems for OTOCs. The aim was to describe general features of thermal correlation functions, in particular, the fluctuation–dissipation type relations implied by the KMS condition. These observations were then used to construct a natural causal basis for thermal n–point functions at generic frequencies in terms of fully nested commutators.

PUBLICATIONS

1. *Abelian tensor models on the lattice,* S. Chaudhuri, V. I. Giraldo–Rivera, A. Joseph, R. Loganayagam and J. Yoon. arXiv:1705.01930 [hep–th].

2. *Classification of out–of–time–order correlators,* F. M. Haehl, R. Loganayagam, P. Narayan and M. Rangamani. arXiv:1701.02820 [hep–th].

3. *Renormalization in open quantum field theory I: Scalar field theory,* Avinash, C. Jana, R. Loganayagam and A. Rudra. arXiv:1704.08335 [hep–th].

4. *Schwinger–Keldysh formalism. Part I: BRST symmetries and superspace,* F. M. Haehl, R. Loganayagam and M. Rangamani. JHEP 06 (2017) 069, arXiv:1610.01940.

5. *Schwinger–Keldysh formalism. Part II: Thermal equivariant cohomology,* F. M. Haehl, R. Loganayagam and M. Rangamani. JHEP 06 (2017) 070, arXiv:1610.01941.

6. *Thermal out–of–time–order correlators, KMS relations, and spectral functions,* F. M. Haehl, R. Loganayagam, P. Narayan, A. A. Nizami and M. Rangamani. arXiv:1706.08956 [hep–th].

7. *Towards a second law for Lovelock theories,* S. Bhattacharyya, F. M. Haehl, N. Kundu, R. Loganayagam and M. Rangamani. JHEP 03 (2017) 065, arXiv:1612.04024.

8. *Two roads to hydrodynamic effective actions – a comparison,* F. M. Haehl, R. Loganayagam and M. Rangamani. arXiv:1701.07896 [hep–th].

9. *Topological sigma models and dissipative hydrodynamics,* F. M. Haehl, R. Loganayagam and M. Rangamani. JHEP 04 (2016) 039, arXiv:1511.07809.

RESEARCH REPORT

In the past two years, **Suvrat Raju**'s work has primarily focused on understanding the information paradox, within the context of the AdS/CFT conjecture. This problem is closely related to the question of describing the black hole interior in AdS/CFT. These questions have proven to be intrinsically rich, and have led him and his collaborators to investigate several different topics as detailed below.

In earlier work, Raju and Kyriakos Papadodimas had proposed a construction of the black hole interior in AdS/CFT. This construction led to the suggestion that subtle non–local effects in gravity and a phenomenon called 'state–dependence' are important in the black–hole interior. They argued that a consideration of these effects also suggested a natural resolution of the information paradox.

Over the past two years, he has developed these themes further. First, with Kyriakos Papadodimas, he examined the implications of state–dependence in great detail and showed how this feature also appeared in a particularly simple model of AdS black holes, called the eternal Swarzschild black hole. They also showed how their construction of the interior was naturally related to the ER=EPR conjecture, that was advanced by Maldacena and Susskind in 2013.

In separate work, by means of some concrete calculations, Raju was able to resolve some puzzles about state–dependence that had been pointed out by Marolf and Polchinski. He was able to show that placing certain physical restrictions on the kind of observations that can be made in the black hole interior removes these puzzles.

He also examined the question of nonlocality in quantum gravity in greater detail. Together with Kyriakos Papadodimas, Souvik Banerjee and Jan–Willem Bryan, they showed, how even in the absence of black holes, degrees of freedom in gravity defy a local characterization; degrees of freedom in a local region of spacetime are not independent of degrees of freedom in other regions.

In the work described above, they found that nonlocal effects could be important at macroscopic scales if one examined the behaviour of 'very high point' correlators. To understand this issue better, with his student, Sudip Ghosh, he analyzed the behaviour of string perturbation theory in a novel limit – where the number of particles becomes large but the energy per particle remains small. Through analytical arguments, drawing on recent results in the mathematical literature, and extensive numerical analysis, they found that string perturbation theory breaks down in this limit. They showed that this phenomenon appeared in both bosonic string theory and also in superstring theory. They argued that this breakdown of perturbation theory is closely linked to the loss of locality thus lending support to the conclusion that they had derived from earlier work.

If nonlocal effects are important in gravity, then this means that commonly used measures of quantum information in local regions must be refined to account for this

SUVRAT RAJU

Suvrat Raju has a PhD from Harvard University. Before joining ICTS, he was a visiting fellow at the Harish-Chandra Research Institute, Allahabad, and then continued there as a Ramanujan Fellow of the Department of Science and Technology. Raju was awarded the Saraswathi Cowsik Medal, TIFR (2015), the INSA Young Scientist Medal (2013), the NASI-Young Scientist Platinum Jubilee Award (2013) and the Ramanujan Fellowship, Department of Science and Technology (2010–2015). He is also the recipient of the Swarnajayanti fellowship of the Department of Science and Technology. His primary interests are in string theory, quantum gravity, and quantum field theory. His work has focused on an exploration of these themes through the AdS/CFT duality. Most recently, he has examined the implications of this duality for black holes and their statistical and information-theoretic properties.

phenomenon. This is a problem that Raju has been working on, together with Sudip Ghosh and also Sandip Trivedi, Ronak Soni and M.V. Vishal at TIFR (Mumbai). At a technical level, extending commonly used information theoretic measures to theories of gravity requires one to examine these measures in settings where the set of accessible observables forms only a set and not analgebra. This is an interesting and relatively unexplored question on which they have made some progress by defining novel measures of quantum information.

PUBLICATIONS

1. *Breakdown of string perturbation theory for many external particles,* S. Ghosh and S. Raju. Phys. Rev. Lett. 118 No. 13, (2017) 131602, arXiv:1611.08003 [hep–th].

2. *Loss of locality in gravitational correlators with a large number of insertions,* S. Ghosh and S. Raju. Phys. Rev. D96 No. 6, (2017) 066033, arXiv:1706.07424.

3. *Smooth causal patches for AdS black holes*, S. Raju. Phys. Rev. D95 No. 12, (2017) 126002, arXiv:1604.03095 [hep–th].

4. *The sensitivity of black holes to low energy excitations,* S. Raju. arXiv:1703.10159.

5. *A toy model of black hole complementarity,* S. Banerjee, J.–W. Bryan, K. Papadodimas and S. Raju. JHEP 05 (2016) 004, arXiv:1603.02812 [hep–th].

6. *Remarks on the necessity and implications of state–dependence in the black hole interior*, K. Papadodimas and S. Raju. Phys. Rev. D93 No. 8, (2016) 084049.

7. *Local operators in the eternal black hole,* K. Papadodimas and S. Raju. Phys. Rev. Lett. 115 No. 21, (2015) 211601, arXiv:1502.06692 [hep–th]

RESEARCH REPORT

Spenta Wadia's research in the past two years can be classified as follows –

SACHDEV–YE–KITAEV (SYK) MODEL AND EMERGENCE OF QUANTUM GRAVITY IN 2D

Besides being a large N soluble model that provides a diagnostic of a black hole state, the SYK model also affords an opportunity to see if a dual quantum space–time emerges from the ingredients of the lower dimensional theory on its boundary. At large N and strong coupling the model has an emergent 1d reparametrisation symmetry in the infrared. He and his collaborators (G. Mandal and P. Nayak) recognised that quantizing the co–adjoint orbit of this symmetry group naturally leads to a theory in one higher space–time dimension, which is Polyakov's 2d quantum gravity (in a specific gauge). Once the arena of gravitational dynamics in 2d emerges it is natural to add a volume term with a cosmological constant to the Polyakov action. A negative value of the cosmological constant ensures that the (Euclidean) space–time is non–compact and has a boundary. In particular, AdS_2 space–time is a solution. It turns out that this model has no local degrees of freedom due to local diffeomorphism constraints and the dynamics is entirely described by the Schwarzian action of the residual large diffeomorphisms on the boundary of the 2d space–time. The quantum chaos exponent computed in this 2d gravity model agrees with the SYK model.

Wadia and his collaborators have also worked out an extension of the above for a SYK model with flavour and a chemical potential.

S–MATRIX OF 2+1 DIM CHERN–SIMONS THEORY COUPLED TO VECTOR MATTER : UNITARITY, CROSSING SYMMETRY AND FERMION–BOSON DUALITY:

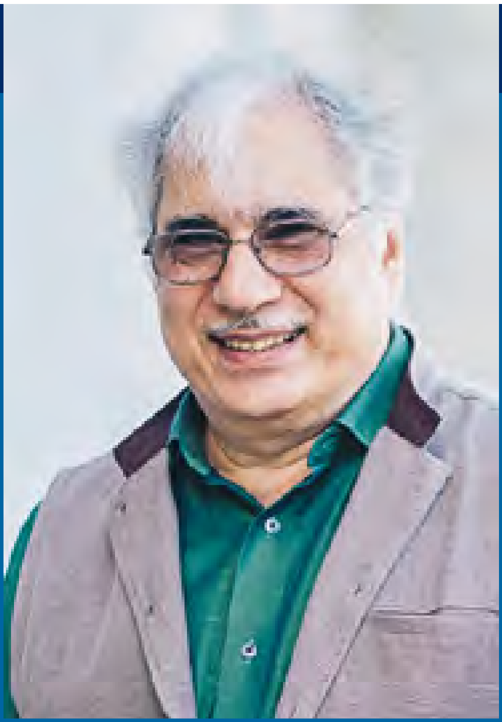
SU (N) Chern–Simons gauge theory coupled to fundamental matter is soluble in the large N limit and there is evidence that it is dual to Vasiliev's theory of higher spin gauge fields in AdS_4. Earlier results include – Fermion–Boson dualities in 2+1 dimensions. This highly non–trivial result reflects the level–rank duality of the topological Chern–Simons theory without matter.

The S–matrix in the presence of the Chern–Simons term has novel features. The S–matrix is not analytic due to the presence of anyons and standard rules of crossing symmetry need to be modified to ensure a unitary S–matrix.

RESULTS

The 2→2 S–matrix of critical bosons and fermions can be calculated exactly and unambiguously in the large N limit in the t and u channels. The answers are unitary and are consistent with fermion–boson duality. We proposed a s–channel S–matrix with modified crossing symmetry rules and a delta function for forward scattering that is unitary and consistent with gauge invariance and fermion–boson duality. They are currently trying to derive these new rules from first principles.

SPENTA R. WADIA



Spenta R. Wadia is the founding Director of ICTS and presently the Infosys Homi Bhabha Chair Professor at ICTS. He received his PhD from the City University of New York (1978) and was at University of Chicago till 1982, after which he joined the faculty of TIFR. His current research includes quantum field theory and their various applications, and quantum gravity and black holes. He has received the TWAS Prize (2004), the Steven Weinberg Prize of ICTP (1995), the J. C. Bose National Fellowship, Govt. of India (2006-2011; 2011-16), Distinguished Alumnus, St. Xavier's College, Bombay University (2009) and the TIFR Alumni Association Excellence Award (2016). He is a member of the – International Advisory Board, ICTS-TIFR, 2015-; IAC of the International Institute of Physics, Natal, Brazil, 2017- ; Science Council of APCTP, S. Korea, 2010-; Promotion and Assessment Committee, Indian Institute of Science, 2014-; Jury Panel, Infosys Science Foundation Prize for Physical Sciences, 2015-; Chair, Physics Committee, Indian National Science Academy, New Delhi, 2017-; Editor, Asian Journal of Mathematics, International Press, Boston, 2015-; Council service Indian Academy of Sciences, Bangalore, 2013-2015; Commission on Mathematical Physics (C-18), IUPAP, 1997-1999, 1999-2002; Editor, European Journal of Physics C, 2012-2015.

These results are of interest from the view point of applications to quantum Hall systems (the fractional quantum hall effect at filling fraction $\nu = 1/2$) in condensed matter physics and topological quantum computing.

FUTURE PLANS

1) In AdS/CFT correspondence, at strong coupling/small space–time curvatures, the $N \to \infty$ expansion corresponds to semi–classical gravity $G_N \to 0$. Many questions pertaining to loss of unitarity and black holes, could be elucidated and perhaps resolved quantitatively if we can understand the large N limit better. Wadia and his collaborators would like to explore–i) The operator content at large but finite N that distinguishes between mean field and micro–states in various known dualities including the plasma ball of 4d gauge theory and localised black hole in AdS_4. 2) They would like to work out from first principles the unusual rules for the S–matrix in SU(N) Chern–Simons plus matter theories for finite N.

PUBLICATIONS

1. *Coadjoint orbit action of virasoro group and two–dimensional quantum gravity dual to SYK/tensor models,* G. Mandal, P. Nayak and S. R. Wadia. JHEP 11 (2017) 046.

2. *Chern–Simons theories with fundamental matter: A brief review of large N results including Fermi–Bose duality and the S–matrix,* S. R. Wadia. International Journal of Modern Physics A 31 (2016).

3. *Unitarity, crossing symmetry and duality of the S–matrix in large N Chern–Simons theories with fundamental matter,* S. Jain, M. Mandlik, S. Minwalla, T. Takimi, S. R. Wadia and S. Yokoyama. JHEP 04 (2015) 129, arXiv:1404.6373 [hep–th].

ASSOCIATE FACULTY

ICTS has the privilege of being associated with several world–class scientists who are deeply involved with various activities of the Centre. They form the wide group of ICTS Associate Faculty.

Shivani Agarwal
University of Pennsylvania
Machine Learning and Learning Theory

K. G. Arun
CMI, Chennai
Gravitational–wave Physics and Astrophysics

Gyan Bhanot
Rutgers University, New Jersey, USA
Cancer Bioinformatics and Population Genetics

Sayantani Bhattacharyya
NISER, Bhubaneswar
String Theory, Fluid Mechanics

Debasish Chaudhuri
Insititute of Physics, Bhubaneswar
Biological Physics, Soft Condensed Matter Physics, Nonequilibrium Statistical Mechanics and Transport

Kedar Damle
TIFR, Mumbai
Condensed Matter Physics

Subinoy Das
IIA, Bangalore
Dark Matter, Dark Energy, Neutrino Cosmology

Justin David
IISc, Bangalore
String Theory

Nivedita Deo
University of Delhi, New Delhi
Theoretical Physics, Mathematical Physics, Condensed Matter Physics

Abhijit Gadde
TIFR, Mumbai
Theoretical Physics

Sidhartha Goyal
University of Toronto, Ontario, Canada
Biophysics and Evolutionary Dynamics

Karthik Gurumoorthy
Amazon Development Centre, Bangalore
Dynamical Systems and Data Assimilation

Shravan Hanasoge
TIFR, Mumbai
Astrophysics, Astronomy, Geology

Mark Hannam
Cardiff University, UK
Numerical Relativity and Gravitational–wave Astronomy

Sascha Husa
University of the Balearic Islands, Spain
Astrophysics, Computational Physics, Cosmology

Zubin Jacob
Purdue University, USA
Quantum Vacuum, Quantum Photonics, Energy, Thermal

Kavita Jain
JNCASR, Bangalore
Statistical Physics, Evolutionary Biology

Sanjay Jain
University of Delhi, New Delhi
Theoretical Biology

Dileep Jatkar
HRI, Allahabad
String Theory

Sandeep Krishna
NCBS–TIFR, Bangalore
Biophysics, Computational Physics, Animal Communications

Badri Krishnan
Max Planck Institute for Gravitational Physics (AEI) and Institute for Gravitational Physics of the Leibniz Universität Hannover
Mathematical Physics, Theoretical Physics, Astrophysics

Swapna Mahapatra
Utkal University, Bhubaneswar
String Theory, Particle Physics

Gautam Mandal
TIFR, Mumbai
String Theory, Black Holes, Gravity, Quantum Field Theory

Narayanan Menon
University of Massachusetts Amherst
Experimental Condensed Matter Physics, Statistical Mechanics

Tapan Mishra
IIT Guwahati
Condensed Matter Physics

Onuttom Narayan
University of California, Santa Cruz
Nonequilibrium Phenomena

Biman Nath
RRI, Bangalore
Cosmology

Shiroman Prakash
Dayalbagh Educational Institute, Agra
String Theory, Gauge Theories and Quantum Information

Surjeet Rajendran
University of California, Berkeley, USA
High Energy Physics

Sumathi Rao
HRI, Allahabad
Condensed Matter Physics

Madan Rao
RRI, Bangalore
Theoretical Condensed Matter, Biological Physics

Sanjib Sabhapandit
RRI, Bangalore
Statistical Physics

Tridib Sadhu
TIFR, Mumbai
Statistical Physics

Diptiman Sen
IISc, Bangalore
Condensed Matter Physics, Quantum Field Theory

Anand Sengupta
IIT Gandhinagar
Astrorelativity

Anirvan Sengupta
Rutgers, The State University of New Jersey
Systems Biology

Prajval Shastri
IIA, Bangalore
Astrophysics

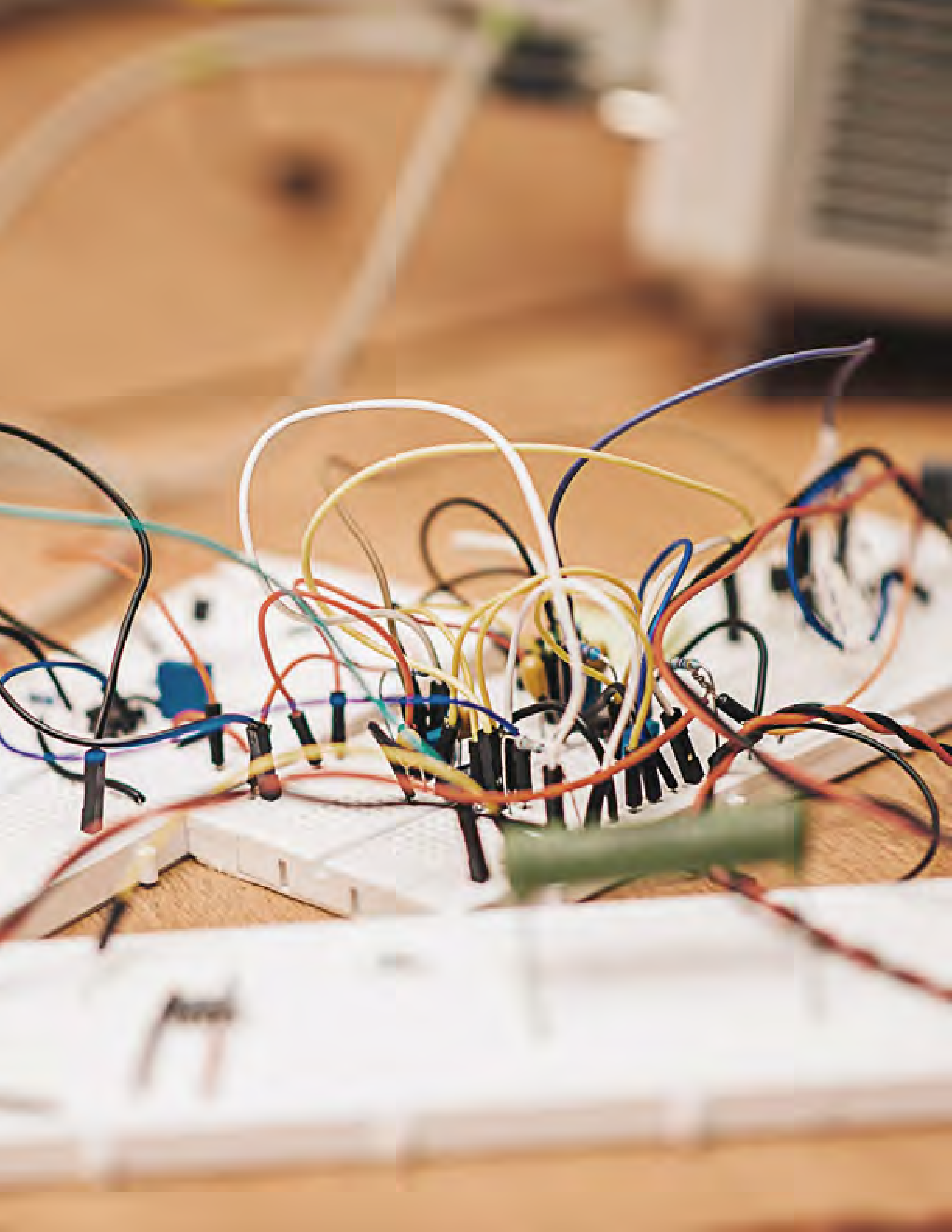
Ravi Sheth
International Centre for Theoretical Physics and The University of Pennsylvania
Cosmology

Aninda Sinha
IISc, Bangalore
String Theory

Piyush Srivastava
TIFR, Mumbai
Counting Complexity in Statistical Physics, Phase Trasitions And Correlation Decay, Mathematical Models of Evolution

Nisheeth Vishnoi
École polytechnique fédérale de Lausanne EPFL, Switzerland
Theoretical Computer Science

PROGRAM ACTIVITIES

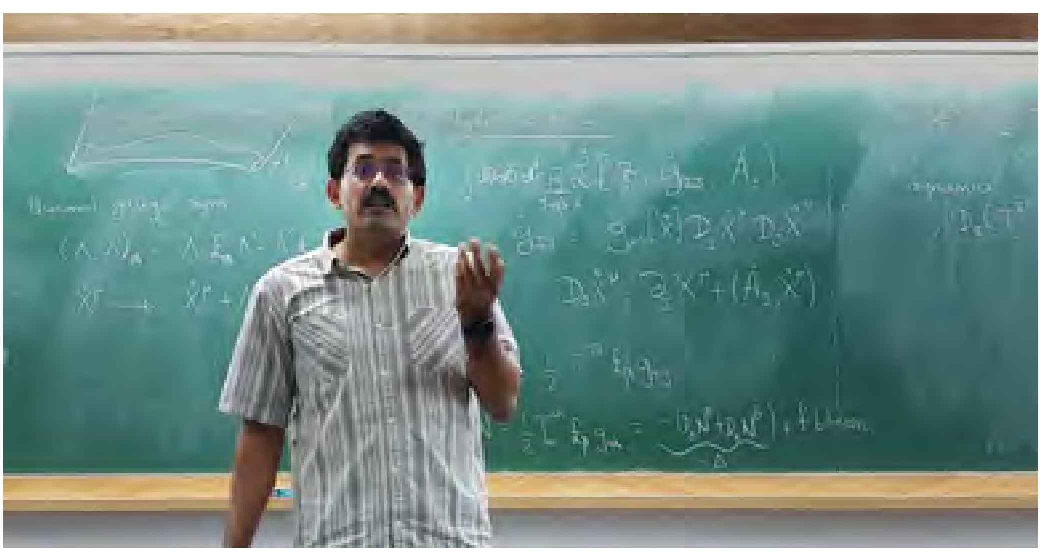


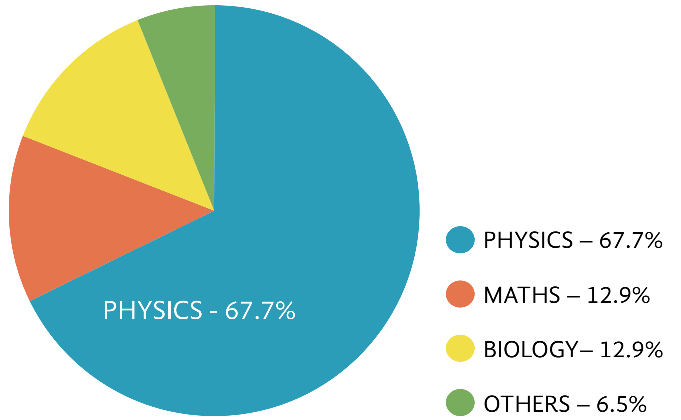
PROGRAMS AND DISCUSSION MEETINGS

Organizing high–quality visitor–driven PROGRAMS in the sciences and mathematics, combined with top–notch in–house research is one of the core mandates of ICTS. Programs are congregations of researchers, over varying and extended periods of time, with the aim of creating an interactive and participatory environment to catalyze transformations in scientific research, especially within the Indian scientific community. ICTS provides the platform and resources to bring together the best researchers in India and from around the world to interact and share expertise, collaborate and co–create knowledge. The aim is to make ICTS a science hub, with the national and international scientific community as its main users. Other goals of the programming activities are – (i) Fostering important research areas in which the effort in India needs to be enhanced, (ii) Incubating important new emerging areas of research and helping create new areas of research, (iii) Conducting academic training programs for transferring specialized knowledge to students and younger researchers and (iv) Fostering science education and human resource development. ICTS programming activities cover a wide spectrum over a broad canvas to cater to different needs of the scientific community. Programs can be long (6–12 weeks or longer), short (2 weeks or more, but less than 6 weeks) or mini (usually about 1–2 weeks in duration, but can be shorter depending on the topic and its timeliness). The DISCUSSION MEETINGS are shorter and can even be held over a day.

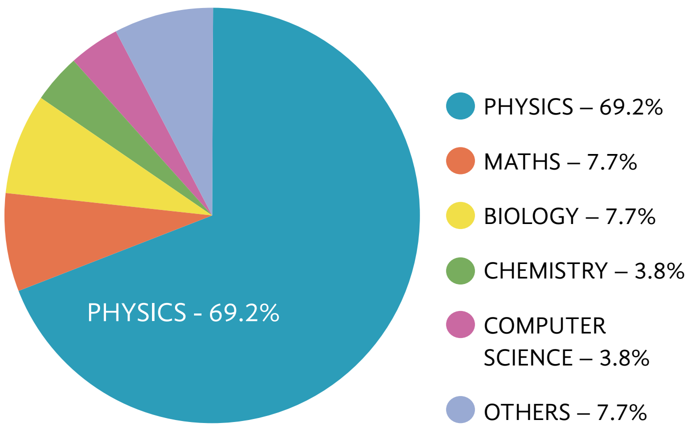
During 2015–2017, ICTS has hosted 31 programs and 26 discussion meetings, with a total of 3526 participants from all around the world.

ICTS also organizes lectures by eminent scientists on their work under three named LECTURE SERIES – (i) Infosys–ICTS Chandrasekhar Lectures (Physical Sciences), (ii) Infosys–ICTS Ramanujan Lectures (Mathematics) and (iii) Infosys–ICTS Alan Turing Lectures (Computer Science, Biological Sciences and Engineering Sciences). A set of three lectures are delivered under each of these series. The lectures are usually associated with either a discussion meeting or a program, around the theme of the lectures.

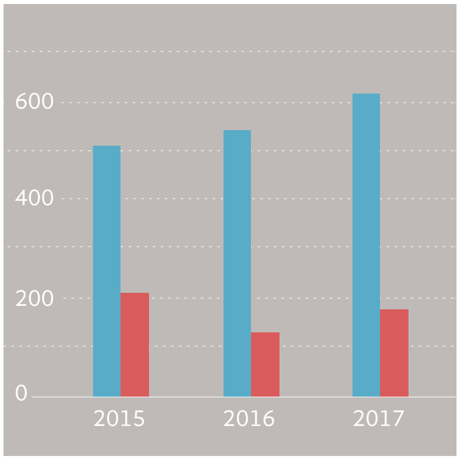




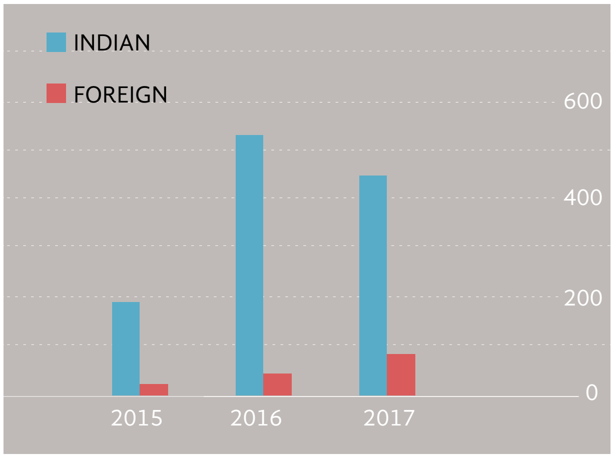
Subjectwise break up
PROGRAMS (2015-17)



Subjectwise break up
DISCUSSION MEETINGS (2015 – 17)



Indian and foreign participants
PROGRAMS (2015 – 2017)



Indian and foreign participants
DISCUSSION MEETINGS (2015 – 17)

PROGRAMS

J–Holomorphic Curves and Gromov–Witten Invariants
25 December 2017 – 4 January 2018 ♦ *Organisers* – Somnath Basu, Rukmini Dey and Ritwik Mukherjee

Winter School on Quantitative Systems Biology (QSB)
4 – 22 December 2017 ♦ *Organisers* – Sidhartha Goyal, Kavita Jain, Vijaykumar Krishnamurthy, Luca Peliti and Mukund Thattai

Geometry, Groups and Dynamics (GGD) – 2017
6–24 November 2017 ♦ *Organizers* – C. S. Aravinda, Shrikrishna Dani, Krishnendu Gongopadhyay and Athanase Papadopoulos

Large Deviation Theory in Statistical Physics – Recent Advances and Future Challenges
14 August–13 October 2017 ♦ *Organizers* – Arvind Ayyer, Frank den Hollander, Abhishek Dhar, Juan P. Garrahan, Christopher Jarzynski, Manjunath Krishnapur, Tony Lelievre, Sanjib Sabhapandit and Hugo Touchette

Open Quantum Systems
17 July–4 August 2017 ♦ *Organizers* – Abhishek Dhar, Manas Kulkarni, Jason Petta, Anatoli Polkovnikov, Sadiq Rangwala, Dibyendu Roy and Rajamani Vijayaraghavan

Summer School on Gravitational–Wave Astronomy
17–28 July 2017 ♦ *Organizers* – P. Ajith, K. G. Arun and Bala R. Iyer

Summer School and Discussion Meeting on Buoyancy–driven flows
12–20 June 2017 ♦ *Organizers* – Jaywant Arakeri, Anirban Guha, Pankaj Mishra, Jai Sukhatme, Vishal Vasanand Mahendra Verma

Correlation and Disorder in Classical and Quantum Systems
29 May–2 June 2017 ♦ *Organizers* – Aveek Bid, Pinaki Chaudhuri, Tanmoy Das, Smarajit Karmakar, Prabal Maiti, Subroto Mukerjee and Srikanth Sastry

Dynamics of Complex Systems – 2017
10 May–8 July 2017 ♦ *Organizers* – Amit Apte, Soumitro Banerjee, Pranay Goel, Partha Guha, Neelima Gupte, Amitabha Nandi, Ram Ramaswamy, G. Rangarajan and Somdatta Sinha

Time Series Analysis for Synoptic Surveys and Gravitational Wave Astronomy
20–23 March 2017 ♦ *Organizers* – P. Ajith, Jogesh Babu, Sujit Ghosh and Ashish Mahabal

Laser Plasma Accelerator
6–17 March 2017 ♦ *Organizers* – Amita Das, Srinivas Krishnagopal, M. Krishnamurthy, G. Ravindra Kumar and Pattathil Rajeev

US–India Advanced Studies Institute – Classical and Quantum Information
26 December 2016–07 January 2017 ♦ *Organizers* – Bulbul Chakraborty, Anupam Kundu and Albion Lawrence

Theoretical and Computational Aspects of the Birch and Swinnerton–Dyer Conjecture
12–22 December 2016 ♦ *Organizers* – Chandrakant Aribam, Somnath Jha, Narasimha Kumar and Sujatha R

ICTP–ICTS Winter School on Quantitative Systems Biology
5–16 December 2016 ♦ *Organizers* – Antonio Celani, Stefano Di Talia and Carl–Philipp Heisenberg

Fundamental Problems of Quantum Physics
21 November–10 December 2016 ♦ *Organizers* – Angelo Bassi, Sougato Bose, Saikat Ghosh, Tejinder Singh, Urbasi Sinha and Hendrik Ulbricht

Group Theory and Computational Methods
5–14 November 2016 ♦ *Organizers* – Manoj Kumar and N. S. N. Sastry

Summer School on Gravitational–Wave Astronomy
25 July–5 August 2016 ♦ *Organizers* – P. Ajith, K. G. Arun and Bala Iyer

Bangalore School on Statistical Physics – VII
1–15 July 2016 ♦ *Organizers* – Abhishek Dhar and Sanjib Sabhapandit

School on Current Frontiers in Condensed Matter Research
20–29 June 2016 ♦ *Organizers* – Subhro Bhattacharjee, Jainendra Jain, H. R. Krishnamurthy, Krishnendu Sengupta and Rajdeep Sensarma

Summer Research Program on Dynamics of Complex Systems
23 May–23 July 2016 ♦ *Organizers* – Amit Apte, Soumitro Banerjee, Pranay Goel, Partha Guha, Neelima Gupte, Govindan Rangarajan and Somdatta Sinha

Higgs Bundles
21 March–1 April 2016 ♦ *Organizers* – V. Balaji, I. Biswas and A. Parameswaran

Second Bangalore School on Population Genetics and Evolution
25 January–6 February 2016 ♦ *Organizers* – Deepa Agashe and Kavita Jain

Modern Finance and Macroeconomics – A Multidisciplinary Approach
22 December 2015–2 January 2016 ♦ *Organizers* – Vishwesha Guttal, Srikanth Iyer and Srinivas Raghavendra

Winter School on Quantitative Systems Biology 2015
5–19 December 2015 ♦ *Organizers* – Antonio Celani, Sanjay Jain, Sandeep Krishna, Vijaykumar Krishnamurthy, Pankaj Mehta and Matthew Scott

Algebraic Surfaces and Related Topics
21–30 November 2015 ♦ *Organizers* – Mario Chan, Jinwon Choi, R. V. Gurjar, DongSeon Hwang, JongHae Keum, Sagar Kolte and Ravi Rao

Non–equilibrium Statistical Physics
26 October–20 November 2015 ♦ *Organizers* – Cedric Bernardin, Abhishek Dhar, Joel Lebowitz, Stefano Olla, Sanjib Sabhapandit, Keiji Saito and Herbert Spohn

Extragalactic Relativistic Jets – Cause and Effect
12–20 October 2015 ♦ *Organizers* – C. H. Ishwara–Chandra, Ajit Kembhavi, Preeti Kharb (Convener), Dharam Vir Lal, Anthony Readhead and C. S. Stalin

Bangalore School on Statistical Physics – VI
2–18 July 2015 ♦ *Organizers* – Abhishek Dhar and Sanjib Sabhapandit

Summer School on Gravitational–Wave Astronomy
29 June–10 July 2015 ♦ *Organizers* – P. Ajith, K. G. Arun and Bala Iyer

Strings 2015
22–26 June 2015 ♦ *Organizers* – Pallab Basu, Justin David, Avinash Dhar, Rajesh Gopakumar, Chethan Krishnan, Shiraz Minwalla, Kumar S. Narain, Suvrat Raju, Aninda Sinha, Spenta R. Wadia

Advanced Strings School 2015
11–18 June 2015 ♦ *Organizers* – Justin David, Chethan Krishnan and Gautam Mandal

GdR Dynamo 2015
1–12 June 2015 ♦ *Organizers* – Emmanuel Dormy, Stephan Fauve, Samriddhi Sankar Ray, Binod Sreenivasan and Mahendra Verma

Mechanical Manipulations and Responses at the Scale of the Cell and Beyond
24 April–7 May 2015 ♦ *Organizers* – Aurnab Ghose, Darius Koester, Roop Mallik, Satyajit Mayor, Thomas Pucadyil and Pramod Pullarkat

DISCUSSION MEETINGS

Statistical Physics Methods in Machine Learning
26–30 December 2017 ♦ *Organizers* – Mikhail Belkin, Chandan Dasgupta, Partha Mitra and Rina Panigrahy

Surface Group Representations and Geometric Structures
27–30 November 2017 ♦ *Organizers* – Siddhartha Gadgil, Krishnendu Gongopadhyay, Subhojoy Gupta and Mahan Mj

Collective Dynamics of–, on– and around Filaments in Living Cells – Motors, MAPs, TIPs and Tracks
28 October–2 November 2017 ♦ *Organizers* – Tanweer Hussain, Ambarish Kunwar and Prabal K Maiti

Stochastic Thermodynamics, Active Matter and Driven Systems
7–11 August 2017 ♦ *Organizers* – Abhishek Dhar, Rajesh Ganapathy, Vijaykumar Krishnamurthy and Sriram Ramaswamy

Bangalore Area Strings Meeting – 2017
31 July–2 August 2017 ♦ *Organizers* – R. Loganayagam and Suvrat Raju

Airbus Day
28 July 2017 ♦ *Organizers* – CAM–TIFR and ICTS–TIFR

Candles of Darkness
5–9 June 2017 ♦ *Organizers* – Gautam Bhattacharyya, Amol Dighe, Sreerup Raychaudhuri and Seema Sharma

Complex Geometry
20–25 March 2017 ♦ *Organizers* – Indranil Biswas and A. J. Parameswaran

Remembering C. V. Vishveshwara
23 February 2017 ♦ *Organizers* – P. Ajith, Bala Iyer and Vijaykumar Krishnamurthy

Indian Statistical Physics Community Meeting 2017
17–19 February 2017 ♦ *Organizers* – Ranjini Bandyopadhyay, Abhishek Dhar, Kavita Jain, Rahul Pandit, Sanjib Sabhapandit, Samriddhi Sankar Ray and Prerna Sharma

Jets @ LHC
21–28 January 2017 to 28 January 2017 ♦ *Organizers* – Gobinda Majumder, Sreerup Raychaudhuri, Vikram Rentala, Tuhin S. Roy, Rishi Sharma and Seema Sharma

String Theory – Past and Present
11–13 January 2017 ♦ *Organizers* – Avinash Dhar, Rajesh Gopakumar, Gautam Mandal and Shiraz Minwalla

The Legacy of Emmy Noether
29–30 August 2016 ♦ *Organizers* – A. Adimurthi, Rukmini Dey and R. Loganayagam

Games, Epidemics and Behaviour
27 June – 01 July 2016 ♦ *Organizers* – Deeparnab Chakrabarty, Niloy Ganguly, Rajmohan Rajaraman and Ravi Sundaram

750 GeV Excess @LHC under scrutiny
5 May 2016 ♦ *Organizers* – Biplob Bhattacherjee, Fawzi Boudjema, Rohini Godbole and Sudhir Vempati

The Future of Gravitational–wave Astronomy
4–8 April 2016 ♦ *Organizers* – P. Ajith, K. G. Arun and Bala R. Iyer

Neighborhood Astronomy Meeting
28 March 2016 ♦ *Organizer* – P. Ajith

Indian Statistical Physics Community Meeting 2016
12–14 February 2016 to 14 February 2016 ♦ *Organizers* – Abhishek Dhar, Kavita Jain, Rahul Pandit, Samriddhi Sankar Ray and Sanjib Sabhapandit

Modern Trends in Electron Transfer Chemistry–From Molecular Electronics to Devices
28–29 January 2016 ♦ *Organizers* – Jyotishman Dasgupta and Ravindra Venkatramani

Airbus Day at ICTS–TIFR
11 January 2016 ♦ *Organizers* – Spenta Wadia

Information Processing in Biological Systems
4–7 January 2016 ♦ *Organizers* – Vijay Balasubramanian, Pallab Basu, Sandeep Krishna, Vijaykumar Krishnamurthy and Mukund Mukund

New Questions in Quantum Field Theory from Condensed Matter Theory
28 December 2015–05 January 2016 ♦ *Organizers* – Subhro Bhattacharjee, Rajesh Gopakumar, Subroto Mukerjee and Aninda Sinha

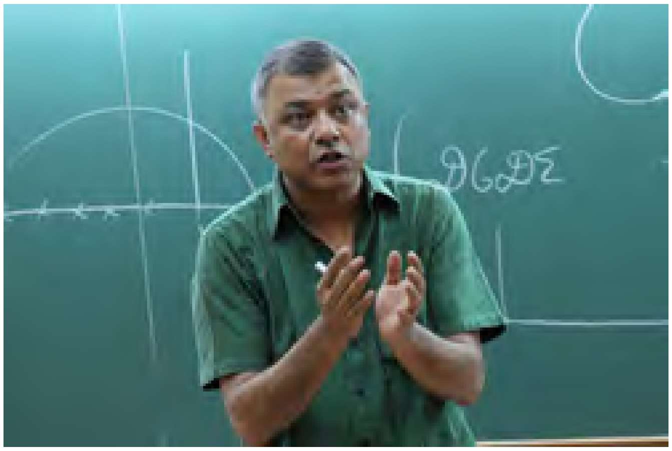
AEI–ICTS Joint Workshop on Gravitational–wave Astronomy
4–6 November 2015 ♦ *Organizers* – P. Ajith, Bala Iyer and Bruce Allen

Nonlinear Physics of Disordered Systems: From Amorphous Solids to Complex Flows
6–8 April 2015 ♦ *Organizers* – Samriddhi Sankar Ray

Bangalore Area String Meeting
16–20 February 2015 ♦ *Organizers* – Suvrat Raju

Indian Statistical Physics Community Meeting 2015
13–15 February 2015 ♦ *Organizers* – Abhishek Dhar, Kavita Jain, Rahul Pandit, Samriddhi Sankar Ray and Sanjib Sabhapandit

Quantum Entanglement in Macroscopic Matter
12–16 January 2015 ♦ *Organizers* – Kedar Damle and Subroto Mukerjee



LECTURE SERIES

CHANDRASEKHAR LECTURE SERIES

Fluctuations and Large Deviations in Nonequilibrium Systems
22, 23, 24 August 2017 ♦ *Speaker:* Bernard Derrida *(Laboratoire de Physique Statistique, Ecole Normale Supérieure, France)*

Microscopic Stochastic Heat Engines Using Nonequilibrium Bacterial Reservoirs
7, 8, 9 August 2017 ♦ *Speaker –* Ajay Sood *(IISc)* ♦ Infosys–ICTS Chandrasekhar lecture supported by Infosys Foundation

Models of Cosmological Inflation
5, 6, 7 June 2017 ♦ *Speaker –* John Ellis *(King's College, London, UK)* ♦ Infosys–ICTS Chandrasekhar lecture supported by Infosys Foundation

Random Matrix Theory and the Dynamics of Nonequilibrium Interfaces
27, 28, 29 October 2015 ♦ *Speaker –* Herbert Spohn *(Technical University, Munich)*

RAMANUJAN LECTURE SERIES

Understanding Non–equilibrium – Some Recent Advances and a Challenge for the Future
3, 4, 5 November 2015 ♦ *Speaker –* Giovanni Jona–Lasinio *(Sapienza University, Rome)*

TURING LECTURE SERIES

The Evolution of Individuality and Why Life is Hierarchically Structured
13, 14, 15 December 2017 ♦ *Speaker –* Paul B Rainey *(Department of Microbial Population Biology, Max Planck Institute for Evolutionary Biology, Plön, Germany; Laboratoire de Génétique de l'Evolution, ESPCI Paris, France & The New Zealand Institute for Advanced Study, Massey University, Auckland, New Zealand)* ♦ Infosys–ICTS Turing lecture supported by Infosys Foundation

Complexity, Phase Transitions, and Inference
28, 29, 30 June 2016 ♦ *Speaker –* Cristopher Moore *(Santa Fe Institute, USA)*

Alan Turing Lectures in Biology
4, 5, 6 January 2016 ♦ *Speaker –* William Bialek *(Princeton University, USA)*

ABDUS SALAM MEMORIAL LECTURE SERIES

The Early Indian Space Endeavour– An Anecdotal Account
17 March 2017 ♦ *Speaker –* K. Kasturirangan *(Chancellor of JNU, an Honorary Distinguished Advisor–ISRO, an Emeritus Professor at NIAS)*

Photochemical and Thermochemical Generation of Hydrogen by Water Splitting
30 December 2016 ♦ *Speaker –* C.N.R. Rao *(JNCASR)*

Brain Brawn and Behaviour
28 December 2015 ♦ *Speaker –* K. VijayRaghavan *(NCBS –TIFR and Secretary, DBT, Ministry of Science and Technology)*

DISTINGUISHED LECTURES

Geometry and Arithmetic of Calabi–Yau Manifolds
7 April 2017 ♦ *Speaker –* Philip Candelas FRS *(Rouse–Ball Professor of Mathematics, Mathematical Institute, University of Oxford, UK)*

What is Science?
28 December 2016 ♦ *Speaker –* Pierre Hohenberg *(New York University)*

Moduli of Vector Bundles on Compact Riemann Surfaces
20 December 2016 ♦ *Speaker –* M.S. Narasimhan *(NMI, Indian Institute of Science and TIFR–CAM, Bangalore)*

Special Session – 100 Years of General Relativity
26 June 2015 ♦ *Speakers –* François Bouchet, David Gross, Juan Maldacena, Peter Saulson and Edward Witten


BLACK

OUTREACH

PUBLIC LECTURES

Delivered by eminent visitors, the public lectures are an integral part of ICTS's outreach program. These lectures bring exciting new developments in science to the general public and play an important role in engaging students and civic society at large on issues of modern science.

Deciphering the Workings of Molecules, Building Blocks of Life, with the Electron Microscope
Speaker – Joachim Frank *(Columbia University, New York, USA)* ♦ 1 November 2017

What are We? Where do We Come From? Where are We Going?
Speaker – John Ellis *(King's College, London, UK)* ♦ 8 June 2017

Remarkable Lives and Legacy of Sofia Kovalevskaya and Emmy Noether
Speaker – Leon Takhtajan *(Stony Brook University, NY)* ♦ 10 January 2017

Whispers from Space – the Detection of Gravitational –waves from a Binary Black Hole Merger
Speaker – Stanley Whitcomb *(California Institute of Technology)* ♦ 7 April 2016

Scaling of Electronic Devices: From the Vacuum Tube to a Single–Molecule Diode
Speaker – Latha Venkataraman *(Columbia University)* ♦ 28 January 2016

Mathematics of Turbulent Flows: A Million Dollar Problem!
Speaker – Edriss S. Titi *(Texas A&M University and Weizmann Institute of Science)* ♦ 7 January 2016

Ramanujan: The Inspirational Story and a Glimpse of His Mathematics
Speaker – Ken Ono *(Emory University)* ♦ 17 December 2015

Time's Arrow and Entropy – Classical and Quantum
Speaker – Joel Lebowitz *(Rutgers University, USA)* ♦ 10 November 2015

Astronomy, Big Data and Human Capital Development

Speaker – Bernard Fanaroff *(South African Square Kilometre Array)* ♦ 16 October 2015 ♦

Particles, Gravity and Strings

Speakers – Nima Arkani–Hamed *(IAS, Princeton, USA)*, Ashoke Sen *(HRI, Allahabad)*, Nathan Seiberg *(IAS, Princeton, USA)*, Andrew Strominger *(Harvard University, USA)* and Cumrun Vafa *(Harvard University, USA)* ♦ 27 June 2015

Poetry, Drumming, and Mathematics

Speaker – Manjul Bhargava *(Princeton University)* ♦ 20 June 2015

EINSTEIN LECTURES

The Einstein lecture series was initiated in 2015, as part of the centenary celebration of Albert Einstein's General Theory of Relativity. Schools, colleges and other organizations can request to organize a lecture anywhere in India. Selected partner organizations work with the ICTS in selecting an appropriate speaker depending on the date and venue of the lecture, and the nature of the audience. Einstein lectures cover a wide spectrum of topics in physics and related areas. Speakers range from early–career scientists to international luminaries.

Engineering Exotic States of Light and Matter

Speaker – Manas Kulkarni *(ICTS–TIFR)* ♦ 8 September 2017 ♦ *Venue –* M S Ramaiah Institute of Technology, Bangalore

The Life History of a Raindrop

Speaker – Rama Govindarajan *(ICTS–TIFR)* ♦ 29 July 2017 ♦ *Venue –* School of Sciences, Jain University, Bangalore

Albert Einstein and the Zombie Stars: Exploring the Extremes of Physics with Gravitational–waves

Speaker – Nils Andersson *(University of Southampton, UK)* ♦ 28 July 2017 ♦ *Venue –* St. Joseph's College, Bangalore

Black Holes and the Reversibility of Time

Speaker – Suvrat Raju *(ICTS–TIFR)* ♦ 12 April 2017 ♦ *Venue –* National College, Bangalore

Undreamt by Einstein–The Discovery of Gravitational–waves

Speaker – P. Ajith *(ICTS–TIFR)* ♦ 28 February 2017 ♦ *Venue –* T K M College of Engineering, Kollam, Kerala

LIGO Detectors Observe the First Binary Black Hole Merger

Speaker – Archana Pai *(IISER, Trivandrum)* ♦ 17 February 2017 ♦ *Venue –* Rajiv Gandhi Institute of Technology (RIT), Kottayam, Kerala

The End of Space–time and Beyond

Speaker – Spenta R. Wadia *(ICTS–TIFR)* ♦ 2 December 2016 ♦ *Venue –* Christ University, Bangalore

Black Holes, Waves of Gravity, and other Warped Ideas of Dr. Einstein

Speaker – Clifford M. Will *(University of Florida, Gainesville and Institute of Astrophysics, Paris)* ♦ 29 July 2016 ♦ *Venue –* St. Joseph's College, Bangalore

When LIGO heard the Two Black Holes Talking

Speaker – Chandrakant Mishra *(ICTS–TIFR)* ♦ 1 April 2016 ♦ *Venue –* BITS – Hyderabad

Undreamt by Einstein – Discovery of Gravitational–waves

Speaker – P. Ajith *(ICTS–TIFR)* ♦ 19 February 2016 ♦ *Venue –* Providence Women's College, Calicut, Kerala

Gravitational–wave Astronomy: A new Window to the Universe

Speaker – P. Ajith *(ICTS–TIFR)* ♦ 18 February 2016 ♦ *Venue –* Regional Science Centre and Planetarium, Calicut, Kerala

Einstein's General Relativity – From Insight to Inspiration

Speaker – Bala Iyer *(ICTS–TIFR)* ♦ 3 February 2016 ♦ *Venue –*Sacred Heart College, Chalakudi, Kerala

LIGO–India: Beyond Gravitational Wave Detection to Gravitational Wave Astronomy

Speaker – Bala Iyer *(ICTS–TIFR)* ♦ 2 February 2016

♦ *Venue* – Mahatma Gandhi University, Kottayam, Kerala

General Relativity: Beyond Insight and Elegance to Observations and Astronomy
Speaker – Bala Iyer *(ICTS–TIFR)* ♦ 2 February 2016 ♦ *Venue* – Mahatma Gandhi University, Kottayam, Kerala

LIGO–India: Beyond Gravitational Wave Detection to Gravitational Wave Astronomy
Speaker – Bala Iyer *(ICTS–TIFR)* ♦ 1 February 2016 ♦ *Venue* – Cochin University of Science & Technology, Kerala

General Relativity: Beyond Insight and Elegance to Observations and Astronomy
Speaker – Bala Iyer *(ICTS–TIFR)* ♦ 1 February 2016 ♦ *Venue* – Cochin University of Science & Technology, Cochin

String Theory and the Search for Quantum Spacetime
Speaker – Rajesh Gopakumar *(ICTS–TIFR)* ♦ 7 January 2016 ♦ *Venue* – Jain College, Bangalore

LIGO–India: Beyond Gravitational Wave Detection to Gravitational Wave Astronomy
Speaker –Bala Iyer *(ICTS –TIFR)* ♦ 15 November 2015 ♦ *Venue* – Utkal University Auditorium

Einstein's General Relativity – From Insight to Inspiration
Speaker –Bala Iyer *(ICTS –TIFR)* ♦ 14 November 2015 ♦ *Venue* – Utkal University Auditorium

Einstein's Legacy, and the Search for Gravitational–waves
Speaker –Bruce Allen *(Max Planck Institute for Gravitational Physics)* ♦
6 November 2015 ♦ *Venue* –Faculty Hall, Indian Institute of Science, Bangalore

KAAPI WITH KURIOSITY

Kaapi with Kuriosity is a monthly public lecture series, held in collaboration with the Jawaharlal Nehru (J. N.) Planetarium and other educational institutions in Bangalore.
The aim of the lectures in this series is to stimulate the curiosity of the public towards the myriad aspects of science. The settings for these talks are informal with a lot of scope for open discussions. They are easily accessible to school/college students, families and working professionals interested in science.

Paleovirology: the Modern Legacy of Ancient Viruses
Speaker – Harmit Malik *(Fred Hutchinson Cancer Research Centre, Seattle, USA)* ♦ 10 December 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

Shapes and Geometry of Surfaces
Speaker – Mahan Mj *(TIFR, Mumbai)* ♦ 26 November 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

Great Triumphs and False Stories: A Brief History of Histories of Indic and European Science through the Ages
Speaker – Roddam Narasimha *(JNCASR, Bangalore)* ♦ 8 October 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

How Connected are You? An Introduction to Graph–theory and Network Science
Speaker – Hugo Touchette *(National Institute for Theoretical Physics, Stellenbosch)* ♦ 17 September 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

Fluids Everywhere – Flows on all Scales
Speaker – Julia Mary Yeomans *(St Hilda's College, University of Oxford, UK)* ♦ 6 August 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

The Arrow of Time in Quantum Measurement
Speaker – Kater Murch *(Washington University, St Louis)* ♦ 23 July 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

ASTROSAT– A Multiwavelength View of the Universe
Speaker – S. Seetha *(Programme Director at Space Science Program Office, ISRO – HQ)* ♦ 11 June 2017 ♦ *Venue* –Christ University, Bangalore

The Visions of Shamans and Saints – Dynamic Instabilities in Neuroscience
Speaker – Bard Ermentrout *(University of Pittsburgh, USA)* ♦ 14 May 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

Random Walks in Science
Speaker – Mustansir Barma *(TCIS, Hyderabad)* ♦ 9 April 2017 ♦ *Venue* – St. Joseph's College, Bangalore

Work, Progress and Prosperity in the Time of Exponential Technologies
Speaker – Vijay Chandru *(Centre for Biosystems Science and Engineering (BSSE), IISc, Bangalore)* ♦ 19 March 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

Footloose on a Tiled Trail – Exploring Repeating Patterns
Speaker – C S Aravinda *(TIFR – CAM, Bangalore)* ♦ 19 February 2017 ♦ *Venue* – J. N. Planetarium, Bangalore

My Life in Physics – From Quarks to Strings
Speaker – David Gross *(KITP, University of California, Santa Barbara, USA)* ♦ 14 January 2017 ♦ *Venue* – Christ University, Bangalore

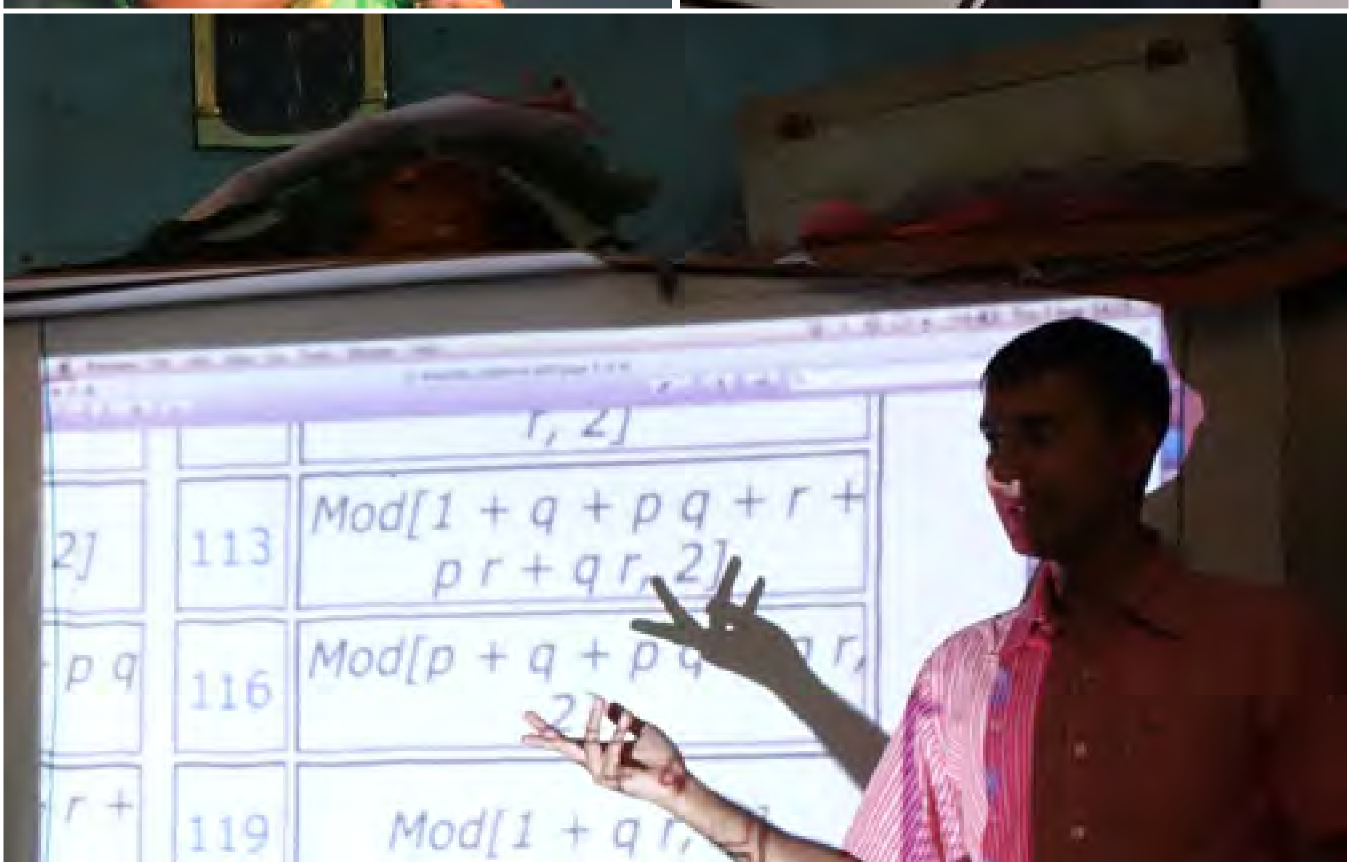
Insects as Architects – How insects engineer their ecosystems
Speaker – Sanjay Sane *(NCBS)* ♦ 11 December 2016 ♦ *Venue* – J. N. Planetarium, Bangalore

Vagaries of the Monsoon
Speaker – Sulochana Gadgil *(Centre for Atmospheric and Oceanic Sciences (CAOS), IISc, Bangalore)* ♦ 26 November 2016 ♦ *Venue* – Visvesvaraya Industrial & Technological Museum, Bangalore

The Universe – Big and Small
Speaker – Ashoke Sen *(HRI, Allahabad)* ♦ 23 October 2016 ♦ *Venue* – J. N. Planetarium, Bangalore

OTHER OUTREACH ACTIVITIES

- The students of the Jagadis Bose National Science Talent Search, Kolkata visited ICTS to attend lectures on biological physics, gravitational waves and partial differential equations.
- Around 50 students from the National Degree College, Bangalore, visited ICTS to learn all about gravitational wave detection from ICTS faculty member P. Ajith.
- The outreach members of ICTS, in collaboration with Agastya International Foundation, are making mathematical models with day to day materials to demonstrate ideas in mathematics. The aim is to make mathematics fun for children, especially middle and high school students.


113
Mod[1 + q + p q + r +
p r + q r, 2]
116
119


HARISH-CHANDRA
ACADEMIC BLOCK

GRADUATE PROGRAMS AND TRAINING

GRADUATE PROGRAMS

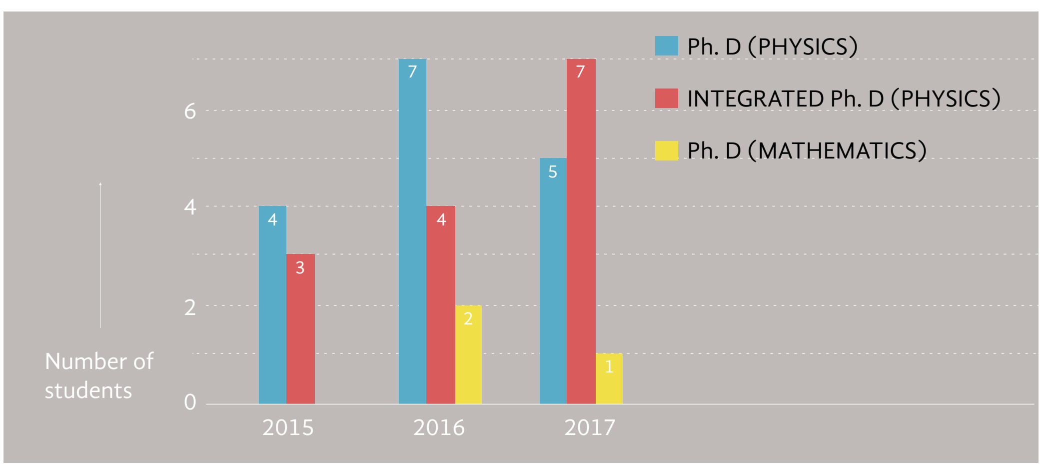
One of the core functions of ICTS-TIFR is to train graduate students and prepare them for years of research. The physics graduate program, which began in 2013, has quickly grown to a group of 40 students. The physics graduate students comprise both PhD students (who join after a masters degree) and integrated PhD students (who join directly after a bachelors degree). The mathematics graduate program started in 2016, and now has three students, all of whom have joined after a masters degree. We expect our first batch of PhD students to graduate next year (2018) and our first batch of integrated PhD students to graduate in 2020.

The graduate program at ICTS-TIFR functions within the framework set by the TIFR deemed university. Both the physics and mathematics programs coordinate their course structure and other decisions with their respective subject boards. Nevertheless, the program at ICTS is distinctive and has been designed keeping in mind the strengths and needs of the centre.

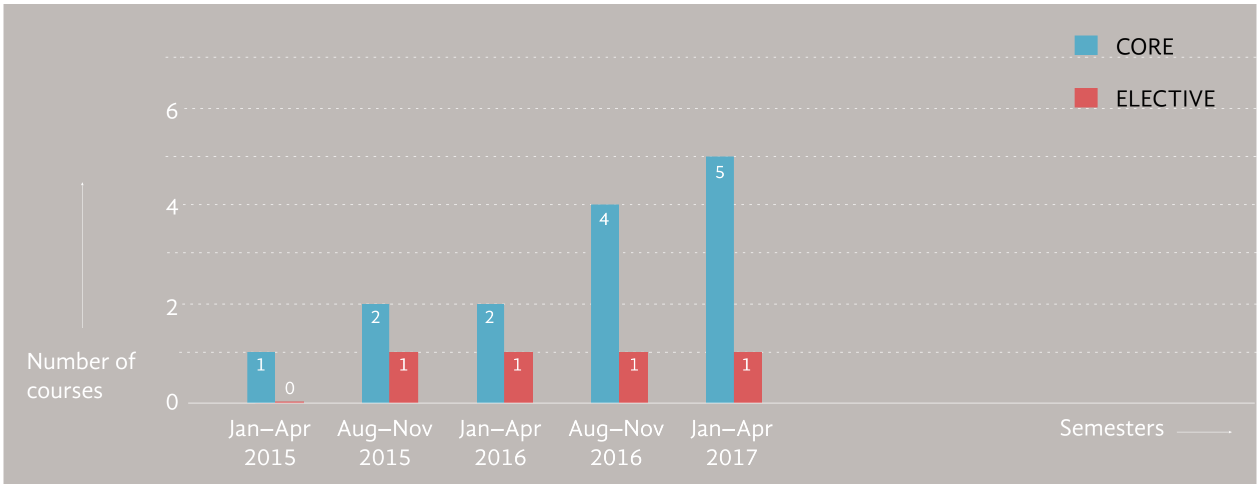
The ICTS graduate program also benefits from its close interactions with the IISc. ICTS students regularly complete their course-credits through courses taught at IISc, and conversely ICTS faculty have taught courses at IISc that have been credited by students both from ICTS and IISc.

The courses at ICTS comprise core courses, which constitute a common minimum that we expect all our students to learn and elective courses, which help students specialize in areas of their interest, as well as reading courses and research projects, which are highly specialized and help students explore potential thesis topics.

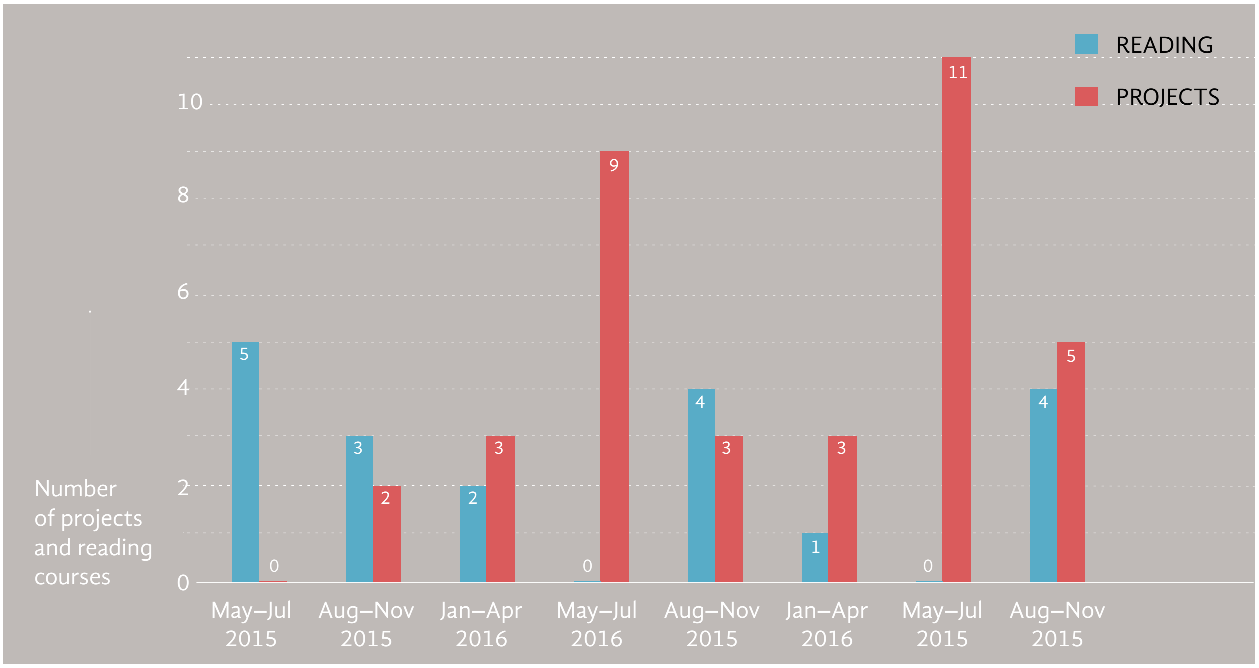
The number of students who joined the graduate courses during 2015-2017 is demonstrated in the graph below.



Faculty members at the centre are expected to teach at least one core or elective lecture course per year. This is in addition to the reading courses and research projects that they offer. The number of courses taught by the ICTS faculty has grown over the years. The graph below shows the number is of elective and core courses taught by ICTS faculty during 2015-2017.



Reading courses and research projects are taught on an individual basis, or to a small cohort of students. These are designed to introduce students to specialized topics and help them choose a PhD topic. The number of such courses taught by ICTS faculty has also increased over the past few years. The graph below shows the number of projects and reading courses taken up by the faculty members.

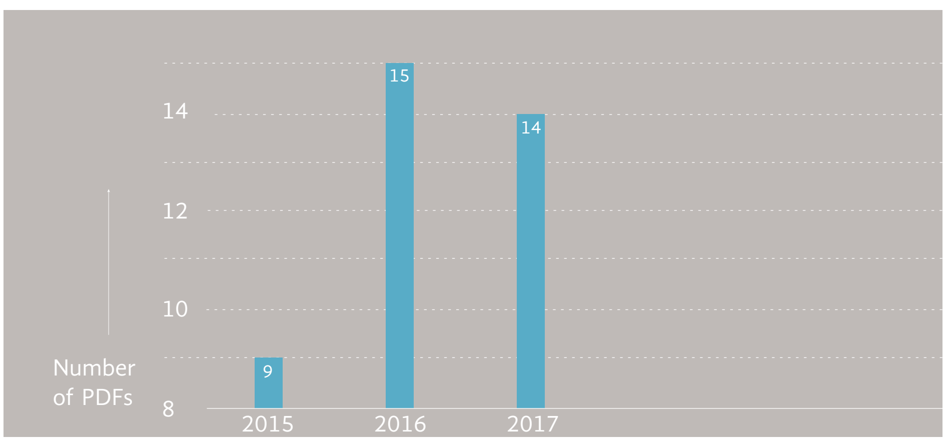


POST–DOCTORAL FELLOWSHIPS

The ICTS–TIFR has a very rich and vibrant post–doctoral fellowship program, which includes, apart from the usual institute post–doctoral fellows, special and highly–competitive prized positions, namely the Airbus and the Simons Postdoctoral Fellowships, and those supported through CEFIPRA and Max–Plank partner groups of individual faculty members. Post–doctoral fellows are offered a two–year position with a possible one–year extension, based on review.

We probably have the largest number of post–doctoral fellows among institutes in India. This large pool of excellent young scientists has played a vital role in furthering the excellence of research at the centre. Several of our post–doctoral fellows were involved in making a direct contribution to the LIGO discovery and were part of the team that was recognized by awards such as the Special Breakthrough Prize in Fundamental Physics. Many of our former post–doctoral fellows have now gone on to hold faculty positions in some of India's top institutes such as the IIT, IISER and the Institute of Chemical Technology (ICT).

At present there are 33 post–doctoral fellows working in ICTS. The graph below shows the number of post–doctoral fellows that have joined ICTS in the last two years.



VISITING STUDENTS PROGRAM

ICTS has a well–defined and established visiting students program which is divided into three main categories – (a) ICTS–S. N. Bhatt Memorial Excellence Fellowship Program (b) short–term visiting students program and (c) long–term visiting students program.

The **ICTS–S.N. Bhatt Memorial Excellence Fellowship Program** is organized every summer typically around the middle of May till the middle of July. This program offers a unique opportunity to academically bright and motivated undergraduate/ masters students of Science and Engineering to work with faculty and post–doctoral fellows of the centre and to participate in research at the frontiers of knowledge. This program was established in 2014 and since then it has been quite successful and is highly competitive. Every year ICTS receives around 700 –800 applications from all over the country, out of which around 10–20 students are finally selected after a very intensive screening. These selected students work closely with the faculty and post–doctoral members. Quite often they make substantial progress that often culminate in publications in international journals.

At present there are 18 students enrolled under this program. In 2016, 11 students joined, there were 11 students in 2015 also.

The **short term visiting program** offers opportunities to students to visit the centre for a short period (typically few weeks) to interact with the faculties and post–docs. This program is also an opportunity for those students who want to complete their unfinished projects that they might have started in their earlier visit to ICTS (for example, during the S.N. Bhatt Summer Program mentioned earlier). In 2017, 33 students have joined this program. In 2016 there were 31 students while in 2015 there were 23.

The **long–term visiting students program** mainly aims to provide opportunities to masters students of science and engineering to spend a longer period of time (3 months–1 year) to work in close collaboration with ICTS faculty members on concrete research projects. This program involves a streamlined application and selection procedure and is highly competitive. This year there are 13 long–term visiting students, in 2016 there were five and in 2015 there were 11.

The visiting students program also includes organizing summer courses geared towards undergraduates and masters students of science and engineering. This typically is synchronized with the S. N. Bhatt Memorial Excellence Fellowship Program to maximize benefit for students (for example, a summer course '*A Journey Through the Universe*' was given by a noted astrophysicist Prof. G Srinivasan from May 17 till 5th July 2017).


CADEMIC BLOCKS

STAFF

ADMINISTRATION

(as of December 31, 2017)

Jenny Burtan
Project Assistant *(Establishment)*

Raghu D. S.
Project Assistant *(Stores)*

Abhijit De
Administrative Officer *(Development Works)*

Abhishek Dhar
Dean *(Programs and Activities)*

Mukesh Dodain
Administrative Officer

Rajesh Gopakumar
Centre Director, ICTS

Rama Govindarajan
Dean *(Academics)*

Hamsa K.
Assistant Teacher *(Creche)*

Jeeva M.
Administrative Assistant *(Academic Dean's Office)*

Sini Mathew
Project Assistant *(Accounts)*

S. Meenaksi
Teacher/Co-ordinator *(Creche)*

Divya N.
Project Assistant *(Stores)*

Ashwini P.
Project Assistant *(Accounts)*

Basavaraj S. Patil
Project Assistant *(Front Desk)*

Suresh R.
Project Manager *(Services and Health Promotion Centre)*

Sunitha Ravikumar
Project Assistant *(Accounts)*

Nithya Seshadri
Project Assistant *(Accounts)*

Deepali Shewale
Project Administrative Officer

Renu Singh
Project Assistant *(General Administration)*

Madhulika Singh
Project Accounts Officer

K. P. Sowjanya
Project Assistant – Admin *(Academic Office)*

Rajalakshmi Swaminathan
Project Accountant *(Purchase)*

Arshitha Thomas C.
Project Assistant – Admin *(Academic Office)*

Mahindra V.
Project Manager *(Facilities and Services)*

SCIENTIFIC AND TECHNICAL ADMINISTRATION

Arun B.
Project Trainee *(AV)*

Ashwini Chandrashekhar
Intern *(HPC)*

Ananya Dasgupta
Consultant

Hemanta Kumar G.
Technical Support Engineer *(HPC)*

Anusha G. B.
Project Assistant *(IT)*

Anupam Ghosh
Project Coordinator *(Outreach)*

Mohan Gowda
Project Engineer *(Civil)*

Sreekanth H. V.
Project Engineer *(Civil)*

Mohammad Irshad
Project Assistant *(IT)*

Naveen Kumar L. C.
Technical Assistant *(AV)*

Gobinath M.
Project Assistant *(IT)*

Aruna Mahendarkar
Special Events Coordinator

Chitra Marickkani
Project Assistant *(Programs)*

Gayatri N.
Project Assistant *(Programs)*

Divya R.
Project Assistant *(Programs)*

Deepak R.
Project Assistant *(IT)*

Srinivasa R.
Scientific Officer *(IT)*

Muhammad Rayees
Project Scientific Assistant *(Lab)*

Parul Sehgal
Scientific Officer *(Resource Development and Societal Engagement Wing)*

Mayank Sharma
Scientific Officer *(IT)*

Manasi Shinde
Scientific Officer *(Programs)*

Amresh Kumar Singh
Engineer *(Electrical)*

Shantaraj S. K.
Technical Assistant *(AV)*

Gangadhara U.
Project Assistant *(IT)*

Prashanth Kumar V.
Technical Assistant *(IT)*

Juny K. Wilfred
Consultant

Veena S. Yeshawant
Project Librarian

CAMPUS

The ICTS–TIFR campus is located in Hesaraghatta, north Bangalore, and spread over 78,000 sq. m. The campus has been planned to be self–contained and includes academic, housing and recreational facilities for more than 150 academic members, including 75 visitors. The architectural design provides space for maximum academic interactions. It contains lecture halls with enough capacity for meetings with hundred plus participants, an auditorium, recreation spaces and comfortable living quarters for staff and visitors.

AUDITORIA AND MEETING ROOMS

The campus houses auditoria, lecture halls, seminar rooms, meeting and discussion rooms.

The auditorium is fully equipped with audio–visual systems for recording and broadcasting, air conditioning, wireless internet and steeply raked seating arrangement. The Chandrasekhar Auditorium is the largest space with a capacity of 300 persons. The Srinivasa Ramanujan and Madhava lecture halls are designed to hold smaller meetings and conferences. The Emmy Noether Seminar Room hosts most seminars, while the three meeting rooms are named after Amal Raychaudhuri, Obaid Siddiqi and S. N. Bose. The discussion rooms are named after Y. Nambu.

Apart from meeting rooms, the centre also has a 30–seater classroom with blackboard, projection facility and Wi–Fi. The e–conference facility of ICTS has facilitated scientists of other premiere institutes to participate in interactive meetings as well as to deliver lectures. The live telecast facility has allowed students and scientists from around the world to view the events organized in ICTS.

SCIENTIFIC INFORMATION RESOURCE CENTRE (SIRC)

SIRC is the most distinctive structure on campus with its interior spiral ramp leading to a dome that resembles the exterior of magnificent Guggenheim Museum in New York. The primary aim of the SIRC is to develop, organize, preserve and deliver

information and scholarly resources for the ICTS community. SIRC presently has a collection of more than 800 books covering subjects such as Astronomy and Astrophysics, Condensed Matter Physics, Mathematics, Particle Physics, Quantum Field Theory, String Theory and Physical Biology. It electronically subscribes to number of peer reviewed journals covering the above mentioned subject areas.

LABORATORIES

The two laboratories on the campus are named after Jagadish Chandra Bose and K.S. Krishnan.

At the **J. C. Bose Lab**, experiments like measurement of thermoelectric properties of metals & alloy, law of intermediate metals, electric and magnetic phase transitions, Van der Pauw arrangement for resistivity measuring techniques, relaxation experiments, Chua & Feigenbaum circuit to study the nonlinear dynamics, are carried out. Advance research experiments to measure Avogadro's constant – Jean Perrin's confirmation of Einstein's Brownian motion equation, wave phenomena in an acoustic resonance chamber, observation of topological phase by Berry phase of light using a modified Mach Zehnder Interferometer are conducted here.

There is an on–going effort to design and develop innovative experiments for graduate students.

The **K. S. Krishnan lab** table top experiments on problems that are at the interface of fluid mechanics and condensed matter are performed. The lab has three optical tables and appropriate opto–mechanics, three DSLR cameras, state of the art 3D printer and several sundry electronic and mechanical equipment.

A lab for doing experiments in fluid dynamics and non–linear dynamics is under development.

GUEST HOUSE

The guest house complex has three buildings named after the major rivers of North India that have housed some great ancient civilizations. While Brahmaputra and Sutlej blocks are three floors high and have 24 rooms each, Indus has four floors and has 23 rooms, 3 suites and a reception. ICTS guest house facility provides all the essential services at highly subsidised tariff.

There are special rooms under the Director's Discretionary Quota in Ajanta Guest house located slightly away from the main guest house complex.

HOUSING

The centre has three housing blocks named Cauvery, Narmada amd Godavari – three major rivers of South India. Due to unavailability of a hostel facility on campus for students, they are accommodated in the unoccupied portion of staff housing. With the growing activities and programmes, we also have had to rent housing outside the campus. About 15 apartments equipped with facilities have been rented outside campus to house students and post–doctoral fellows.

ELECTRICAL AND MECHANICAL FACILITY

ICTS is dedicated to following the green energy campus norms and sourcing a considerable portion of its energy requirement through renewable energy. ICTS has an installed capacity of solar energy at 22.5 KW, which can be extended up to 50 KW in future. ICTS also generates electricity at 3.5 KW through a conventional wind turbine installed at a height of 36 m. The solar generation and wind generation together generates 26 KW which is approximately 8% of current electricity consumption. ICTS also maintains a three–tier backup system to meet the critical load requirement during grid failure.

FIRST–AID CENTRE

The ICTS campus is equipped with a state of the art first–aid centre managed and maintained by M/S Columbia Asia Hospital. The first–aid centre functions as the primary health centre. Two doctors (day and night time) and a nurse staff the centre. The first–aid centre offers outpatient consultation services with a small pharmacy with general medicines are given against the doctor's advice.

The centre also conducts regular health talks and consultation by various specialists with the help of M/S Columbia Asia Hospital. The centre also offers confidential counselling service through an independent support group called *Parivartan* to all members. This is a free service.

CHILD CARE

The ICTS child care facility is a day–care centre for ICTS employees' children (infants, toddlers and school–going) as well as of all our visitors and caters to the age groups of six months to 12 years. Its pedagogical concept is based on the principles of Montessori to promote individual development of each child. The children are engaged in activities like poem recitation, story–telling and playing with educational toys.

CAFETERIA

The cafeteria is situated adjacent to the recreation block. The staff endeavors to cater to a diverse mix of palates and visitors can choose between a variety of ethnic and intercontinental cuisines at subsidized rates. This facility also caters to internal departmental meetings and events. Efficient and timely catering service is managed by professionals. With a seating capacity of more than 150, the cafeteria is shared by students, staff and faculty.

ICTS also has the Kaapi with Kuriosity corner which dispenses a range of beverages and snacks. Located in the lower ground floor of the academic block, it is a popular place for informal discussions.


ATM

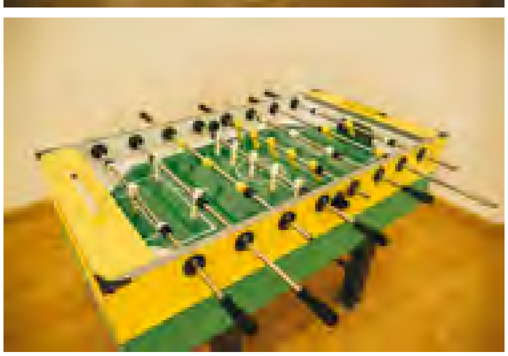
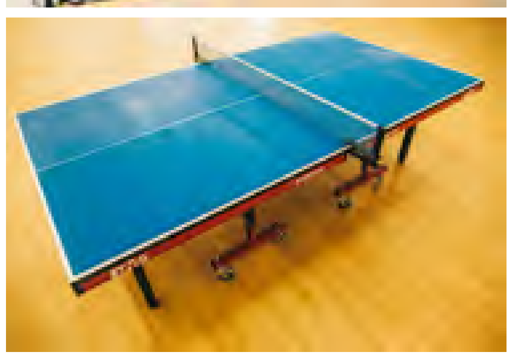
SPORTS AND WELLNESS FACILITY

There is a wide range of excellent sports facilities on campus. The sports complex includes a well–equipped gymnasium equipped with spacious locker rooms for men and women, as well as facilities for indoor sports such as badminton, squash, table tennis, foosball, carrom, chess along with provisions for outdoor sports including volleyball, basketball and cricket (nets). The swimming pool is the pride and joy of this campus, supervised by lifeguards and treated to maintain the very highest standards of cleanliness and safety.

TRANSPORT

ICTS offers a safe, reliable and convenient transit option between the campus and sister institutes located in the city. This service is operated on a subsidized and no–profit basis. The routes and schedules are approved by a committee with the needs of students and staff in mind. The routes and schedules are made available on the ICTS website. Any change in the schedule is alerted through emails. ICTS also provides on–demand transport service at nights and for emergencies.



IT INFRASTRUCTURE

The data centre at ICTS is named after Alan Turing. It is built in the area of 2500 sq. ft. It accommodates a minimum compute capacity of about 150 TFlops comprising about 10 racks of High Performance Computing IT hardware from day 1. Closed Loop Rack based cooling systems are used in ICTS's data centre to optimize airflow management and space utilization in the Data Centre. The racks are designed to accommodate 1000 cores per rack with a cooling output up to 30 KW per rack.

The ICTS data centre cooling solution is based on the concept of removing the heat at the source level. Closed Loop Rack based cooling systems are used in ICTS's data centre to optimize airflow management and space utilization. There is also a fire detection system, a fire suppression system, a water leakage system and a rodent repellent system installed in the data centre.

There is a 976 core cluster located in the ICTS data centre. It is called the Mowgli Cluster. Of the twenty six nodes, one is a head node and all others are execution nodes.

LIGO tier–3 grid computing centre

The latest addition to the ICTS HPC facility is the 512–cores Boston cluster. This cluster composed of 34 nodes, will be installed in the ICTS's new data centre.

In–house web hosting

ICTS websites and various campus services are hosted on inhouse 'Virtual Server Infrastructure.'

Network Infrastructure

The ICTS's network infrastructure is a vast web of cables, switches, and wireless access points that serve one purpose: to get the information and files you need to user computer as quickly as possible. ICTS's fiber backbone is designed on hybrid topology which includes star and ring topology. ICTS Campus network architecture is a converged architecture to carry voice, video and data. It is a hierarchical topology which segments the network into building blocks simplifying operation and increasing availability. This approach creates a flexible network on which new services can be easily added without major redesign. It also delivers separated traffic, balances load across devices and simplifies troubleshooting.

Wi–Fi services

The campus is completely Wi–Fi enabled and boasts of an extensive internet bandwidth. Registered students/faculty are given individual logins to access the campus internet services on any of their registered devices.

AWARDS AND HONORS

P. Ajith

- Awarded the Azrieli Global Scholar by the Canadian Institute for Advanced Research (CIFAR).
- Named PI of the 'Indo–U.S. Centre for the Exploration of Extreme Gravity' that is funded by the Indo–US Science and Technology Forum (US PI: B.S. Sathyaprakash, Penn State)
- Named head of the Max Planck Partner Group in Astrophysical Relativity and Gravitational–Wave Astronomy at ICTS–TIFR

The ICTS team, led by P. Ajith, and consisting of Abhirup Ghosh, Archisman Ghosh, Arunava Mukherjee, Chandrakant Mishra, Nathan Johnson–McDaniel and Bala Iyer, were part of the Special Breakthrough Prize 2016 awarded for the detection at the LIGO observatory of gravitational waves from a merger of two black holes a billion years ago.

Riddhipratim Basu

- Awarded the Ramanujan Fellowship by the Department of Science and Technology, Govt. of India.

Subhro Bhattacharjee

- Awarded the SERB Early Career Research award by the Department of Science and Technology, Govt. of India.
- Received junior associateship by Indian Academy of Sciences, Bangalore.
- Appointed head of a Max Planck partner group on physics of strongly correlated systems.

Abhishek Dhar

- Awarded the Indo–French CEFIPRA grant. The grant was jointly received with Anupam Kundu and Sanjib Sabhapandit of RRI.

Abhirup Ghosh

- Awarded Ramkrishna Cowsik Medal of TIFR

Rajesh Gopakumar

- Elected Fellow, The World Academy of Sciences (TWAS)
- Elected as Secretary, IUPAP Commission on Mathematical Physics (C18)
- Awarded J. C. Bose Fellowship of DST

Rama Govindarajan

- Awarded the Platinum Jubilee Award of the Aerospace department of IISc. This is awarded to the alumni of the department, who have made significant contributions in the field.

Bala Iyer

- Elected as chief editor of "*Living Reviews in Relativity*"

Vijay Kumar Krishnamurthy

- Awarded the DBT–Ramalingaswami re–entry fellowship, DBT, India.
- Received Max Planck Partner group award

Manas Kulkarni

- Awarded the Ramanujan Fellowship by the Department of Science and Technology, Govt. of India.
- Selected as an associate member of the Indian Academy of Sciences.

Anupam Kundu

- Awarded the Indo–French CEFIPRA grant. The grant was jointly received with Abhishek Dhar and Sanjib Sabhapandit of RRI.
- Awarded the SERB Early Career Research award by the Department of Science and Technology, Govt. of India.

R. Loganayagam

- Awarded the Ramanujan Fellowship by the Department of Science and Technology, Govt. of India.

Suvrat Raju

- Awarded the Swarnajayanti Fellowship of Department of Science and Technology, Govt. of India to advance the research on '*Information paradox*'.
- Awarded the Saraswathi Cowsik Medal of TIFR.

Samriddhi Sankar Ray

- Named PI of Airbus Group Corporate Foundation Chair in Mathematics of Complex Systems
- Named Co–PI and Member, Indo–French Centre for Applied Mathematics (IFCAM).
  Project – '*Theoretical and Numerical Studies of Turbulence in Fluids*'; Member, European Cooperation in Science and Technology (COST) on Flowing Matter – Cost Action (COST MP1305)

Shashi Thutupalli

- Named head of Max–Planck partner group with the MPI for dynamics and self organization.

Spenta R. Wadia

- Awarded the TIFR Alumni Association (TAA) Excellence Award 2016 for his distinguished contributions to science and for conceptualizing and founding the International Centre for Theoretical Sciences.
- Named ICTS Homi Bhabha Chair Professor of the Infosys Foundation.

MANAGEMENT

INTERNATIONAL ADVISORY BOARD

Nima Arkani-Hamed
Institute for Advanced Study, Princeton, USA
Elementary Particle Physics

Sanjeev Arora
Princeton University, USA
Theoretical Computer Science

Michael Atiyah
University of Edinburgh, UK
Mathematics

Manjul Bhargava
Princeton University, USA
Mathematics

William Bialek
Princeton University, USA

Roger Blandford
KIPAC, Stanford University, USA
Cosmology and Astrophysics

Jennifer Chayes
Microsoft Research New England
Theoretical Computer Science

Sankar Das Sarma
University of Maryland, USA
Condensed Matter Physics

Rajesh Gopakumar, Convenor
Centre Director, ICTS–TIFR
Quantum Field Theory and String Theory

Senapathy (Kris) Gopalakrishnan
Co-founder and former CEO of Infosys

Michael Green
Cambridge University, UK
String Theory

David Gross, Chair
KITP, University of California, Santa Barbara, USA
Elementary Particle Physics, String Theory

Juan Maldacena
Institute for Advanced Study, Princeton, USA
String Theory

Roddam Narasimha
JNCASR, Bangalore
Earth Sciences, Fluid Dynamics

Subir Sachdev
Harvard University, USA
Condensed Matter Physics

Ashoke Sen
HRI, Allahabad
String Theory

Boris Shraiman
KITP, University of California, Santa Barbara, USA
Systems Biology

Senthil Todadri
MIT, USA
Condensed Matter Physics

S. R. S. Varadhan
Courant Institute, New York University, USA
Mathematics

Spenta R. Wadia
ICTS–TIFR
String Theory, Quantum Gravity, Statistical Mechanics

MANAGEMENT BOARD

V. S. Borkar
IIT Bombay

Jayaram N. Chengalur
NCRA-TIFR

Abhishek Dhar
Dean (Program & Activities), ICTS - TIFR

Rajesh Gopakumar, Convenor
Centre Director, ICTS–TIFR

Rama Govindarajan
Dean (Academics), ICTS – TIFR

H. R. Krishnamurthy
IISc Bangalore

Satya Majumdar
CNRS, Universite Paris–Sud

Mahan Mj
TIFR, Mumbai

Shiraz N. Minwalla
TIFR, Mumbai

Sandip Trivedi, Chair
Director, TIFR, Mumbai

K. VijayRaghavan
NCBS–TIFR and
Secretary, DBT, Govt. of India

George Anthony
Registrar, TIFR, Mumbai

Joint Secretary *(R&D)*, DAE

Joint Secretary *(Finance)*, DAE

OTHER COMMITTEES

Academic committees

Graduate Cell
Visiting Students Committee
Postdoctoral Committee
Lectures & Visitors Committee
Computing Resources Committee
SIRC Committee
Outreach Committee
Program Cell

Non–academic committees

RTI Cell
Women's Cell
Childcare Cell
Cafeteria & Canteen Committee
Housing Cell
Standing Committee on Admin Role
Transport & Security Committee
Internal Purchase and Works Committee
Tender Opening Committee
Sports and Wellness Committee
Cultural Committee
Anti–Ragging Committee
Resource Development and Societal Engagement Wing
Cell for Prevention and Resolution of Sexual Harassment of Women at Workplace

International Centre for Theoretical Sciences (ICTS-TIFR)
Survey No. 151, Shivakote, Hesaraghatta Hobli, Bengaluru North 560 089
www.icts.res.in