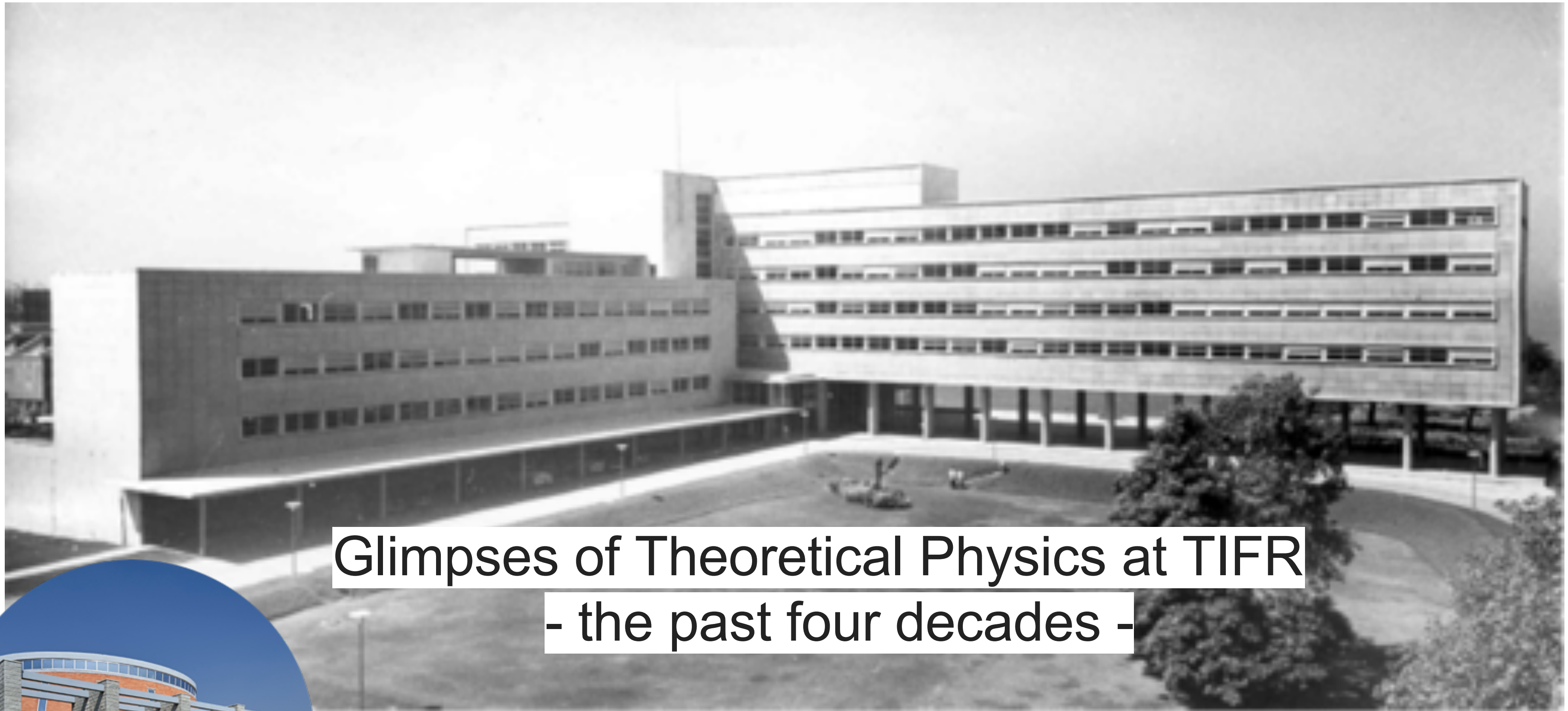

Glimpses of Theoretical Physics at TIFR
- the past four decades -

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Tata Institute of Fundamental Research, Bangalore

Plan of talk

- The Beginning: H.J. Bhabha
- Early leadership: B. M. Udgaonkar, K. S. Singhvi, Virendra Singh, Sudhanshu Jha
- Main areas: High Energy and Nuclear Physics, Statistical and Condensed Matter Physics, String Theory and Mathematical Physics
- Summer/Winter Schools and Major Conferences
- ICTS
- Future

The Beginning

Quotes from `Tata Institute of Fundamental Research 1945-1970'

"Interest in Theoretical Physics at the TIFR is as old as the Institute itself. Dr. Bhabha, in his letter dated 12th March 1944 to Sir Sorab Saklatvala, of the Sir Dorabji Tata Trust, proposing the setting up of the institute, had stated, "**the subjects on which research and advanced teaching would be done would be theoretical physics, especially on fundamental problems and with special reference to cosmic rays and nuclear physics**…." The importance of developing a strong school of modern Theoretical Phyšics, where the principal concern would be with the basic theoretical understanding of physical phenomena, and one of whose tasks would also be to provide theoretical assistance and guidance to experimental programmes, was thus realised from the beginning. During the fifties, this group provided the core of the Reactor Theory Group for the country's atomic energy programme in its initial stages".

Dr. Homi J. Bhabha

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The Beginning..contd 1

Early Work:

"Research activity during the first period was almost entirely dominated by the personal work of Dr. Bhabha, and was principally in the field of Elementary Particles.

Around the year 1945, one of the burning questions in particle physics concerned the nature of the meson, which had been postulated by Yukawa in 1935 as the mediator of nuclear force, but had yet to be discovered experimentally. Bhabha's earlier work on penetrating cosmic ray showers, using the cascade theory developed by him in collaboration with Heitler, had also led him to see the necessity of assuming that a particle of intermediate mass existed in these showers, and in fact the name meson was suggested by him.

It was therefore natural that during the early years, Dr. Bhabha in collaboration with a few associates, actively pursued the theory of cosmic ray showers, meson production, and nuclear forces".

The Beginning..contd 2

"He also attacked the question of appropriate relativistic quantum mechanical description of mesons and nucleons. In some of this work, he was assisted by half a dozen young students, who were thus initiated into theoretical research, and some of whom were to take a lead in the later development of the group.

The principal contributions during this period were Bhabha's extension of the Fermi Theory of meson production in high energy collisions, and his ambitious attempt to develop a postulational basis for the theory of elementary particles. In the course of this work he investigated a class of relativistic linear wave equations, which were capable of describing a particle having states with different masses and spins. Such equations have also been reinvestigated in recent years, following the discovery of large numbers of particles ad resonances during the last decade".

The Beginning..contd 3

Educational programmes:

As the group grew in strength, it was natural for it to make a contribution to the development of various educational programmes. In earlier years, when the Institute was small, it could not offer many formal courses to its Ph.D. students, though there were always a few courses every year, some given by its own members, and some by visiting foreign scientists. Thus courses by distinguished visiting scientists like Alfven, Dirac, Pauli, Rosenfeld, Serber, Wentzel filled part of the gap with regard to graduate courses. Since 1964, however, a regular graduate course programme has been gradually evolved at the Institute, aimed at making the Ph.D. training more and more systematic and broad-based.

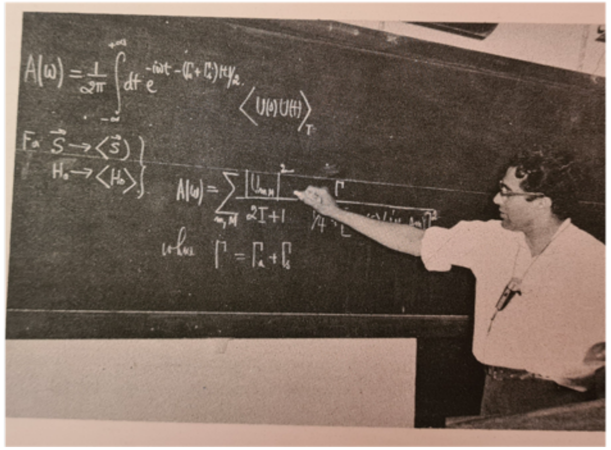
The theoretical physics group has taken a leading part in developing this programme. Members of the group have also been actively involved in developing various educational programmes at the University of Bombay. These include participation in lectures to the M.Sc. students, modernization of the M.Sc. syllabus, discussion groups for college teachers and bright undergraduates, etc. Many of them have also given courses at summer schools and refresher programmes organised elsewhere in the country".

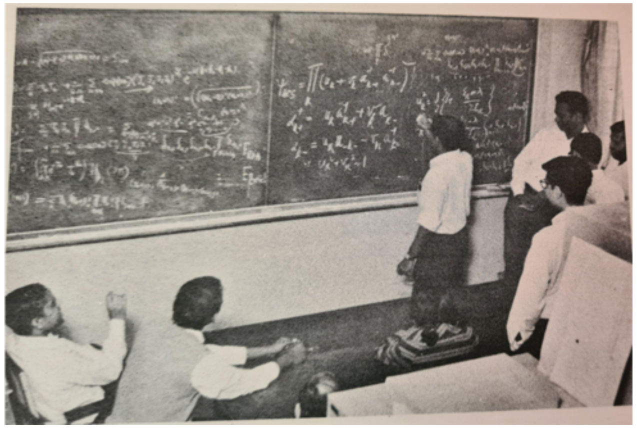
Early History

B.M. Udgaonkar and K. S. Singhvi set up the Theoretical Physics Group.

B. M. Udgaonkar - was a polymath with important contributions to particle physics and in later years to physics education.

K. S. Singhvi was a condensed matter physicist.





Early History...contd.

Prof. V. Singh, Chair DTP (1976-1987); Director TIFR (1987-1997); High Energy Physics: S-Matrix theory, High energy theorems, Foundations of Quantum mechanics.

Prof. S.S Jha, Chair DTP (1988-92); Director TIFR (1997-2002); Condensed Matter Physics: Nonlinear optics, Surface enhanced Raman scattering, Superconductivity, Semiconductors.

Mustansir Barma, Deepak Dhar, SRW joined approximately at the same time four decades ago.

In the following I will give you a survey of the work done in Theoretical Physics at TIFR in the past four decades.

I would like to thank M. Barma, A. Dighe, S. Raychaudhuri, N. Mathur, S. Majumdar, A. Dhar, R. Govindarajan, P. Ajith and all the string theorists at TIFR Mumbai and Bangalore for their assistance to prepare this talk. I would like to acknowledge the assistance of P. Sehgal in preparing this presentation.

Statistical and Condensed Matter Physics

Self organized criticality and the Sandpile model

Self-organized criticality is a property of dynamical systems that has an attractor which is a critical point that arises without the tuning of parameters of the system. It is a paradigm for the explanation of many natural phenomena like the magnitudes of earthquakes and frequency of aftershocks, fluctuations in the financial market, forest fires etc. The subject and the sand pile model was introduced in a seminal paper by Bak, Tang and Wiesenfeld in 1987.

Abelian Sandpile Model of Self-organized Criticality: In 1990 D. Dhar in an important contribution elucidated its mathematical solution by recognising the abelian nature of the sand pile dynamics, and presented an exact solution of the directed version that has led to a deeper understanding of this subject including proportionate growth models (D. Dhar and T. Sadhu, 2013).

Random Spanning Trees and the Sandpile Model: An exact connection was established between the equilibrium random spanning tree problem and the non-equilibrium abelian sandpile model in all dimensions. It allowed exponents for the 2D sandpile model to be computed exactly. (D. Dhar, S. N. Majumdar 1992)

Driven systems & Phase ordering, Exact solutions

Disordered Driven Systems: Quenched randomness in transport rates has important consequences for current-carrying systems which reach non-equilibrium steady states, including transitions to phase-separated states (M. Barma and collaborators, 1997).

Fluctuation-dominated phase ordering: This is a state in which long-range order coexists with macroscopically large fluctuations. It replaces the normal critical state as the separatrix of ordered and disordered states in several equilibrium and non-equilibrium systems (M. Barma and collaborators, 2000).

Enumeration of directed branched polymers: The exact solution of the problem of enumeration directed branched polymers in general dimensions and its relation to the edge singularity problem is notable for being one of the few exact results in exactly soluble nontrivial models in higher than two dimensions (D. Dhar, 1983).

Integrability of the 1D Hubbard Model: The quantum integrability of the 1-d Hubbard model was established by showing that it has an infinite number of mutually commuting conservation laws. It allowed the computation of the explicit form of the S-matrix of the underlying Yang-Baxter equations for this system (B. S. Shastry, 1983).

Superconductivity

Superconductivity in Layered Materials: A layer representation of single-particle states enabled the characterization of effective pairing interaction for spin-singlet superconductivity in layered superconductors, and allowed the determination of T_c and the order parameter. (S. S. Jha and collaborators, 1992)

Variational wavefunction study of high-temperature superconductors: This comprehensive study showed that much of the physics of the high Tc superconducting phase itself could be captured by a projective construction of the many-body wavefunction starting from a Fermi sea (M. Randeria, N. Trivedi and A. Paramekanti, 2000).

Single-electron gaps across disorder-induced superconductor-insulator transitions: This study showed that local superconductivity and concomitant gaps in the single particle spectrum persist even when the superconductivity gives way to insulating behavior due to disorder effects (Nandini Trivedi and collaborators, 2001).

Low-energy Higgs mode in disordered superconductors: This study showed that disorder effects couple phase and amplitude (Higgs) modes in superconductors, and identified signatures of the Higgs physics in this coupled spectrum (Rajdeep Sensarma, Nandini Trivedi and collaborators, 2018).

Real space condensation, Entanglement entropy

Real-space Condensation in Non-equilibrium Processes: A phenomenon similar to Bose-Einstein condensation, but in real space, with macroscopic occupancy of a single site, was found in non-equilibrium models of mass transport, a paradigm for later identifications of real-space condensates. (S. N. Majumdar, M. Barma and collaborators, 1998)

Keldysh field theory for entanglement entropy and dynamics of correlated systems: This body of work developed a new field-theoretical formalism which allows for the calculation of entanglement entropy. A closely related formalism also allows for the study of real time dynamics of strongly correlated systems starting from arbitrary initial conditions (Rajdeep Sensarma and collaborators, 2016).

Conditional large deviations in nonequilibrium dynamics: Conditional large deviations of the local density were found exactly in an interacting stochastic system (the exclusion process). (Tridib Sadhu and collaborators, 2019, 2022)

Subsystem thermalization in integrable field theories

Theorems about subsystem thermalization in integrable field theories were established on the asymptotic equality between post-quench reduced density matrices of 1+1 dimensional conformal field theory and those in the generalized Gibbs ensemble.
(Mandal, Sinha and Sorokhaibam, 2015)

High Energy Physics

Early Work in Electroweak Theory

- Possible e-μ non universality was studied in the context of kaon decays by G. Rajasekaran and K.V.L. Sarma (1970). *This topic has again come into prominence after half a century*.
- Calculation of loop effects in muon decay in the electroweak model was done by G. Rajasekaran (1972) and it was shown that divergences cancel.
- Deep inelastic neutrino scattering was studied by G. Rajasekaran and K.V.L. Sarma (1975, 1978) in an attempt to measure the neutral current coupling.
- Charm and charmonium were studied by L.K. Pandit, K.V.L. Sarma and J. Pasupathy (1975).
- L.K. Pandit built a model of fermions with U(3) horizontal symmetry (1976)
- H.S. Mani, V. Raval and P. Roy studied anomaly cancellation in EW theory (1977).
- Left-right symmetries were studied by V. Gupta and P. Roy (1978).
- Proton decay in GUTs was investigated by K.V.L. Sarma and V. Singh (1981).
- An early guess of Z^0 discovery was made by V. Gupta, K.V.L. Sarma (1984).

Collider and Beyond Standard Model Physics

- Searches strategies for the top quark were initiated by D.P. Roy (1982), and continued with collaborators like R.M. Godbole and S. Pakvasa (1983). They suggested the 'isolated lepton' signal which became the means of discovering the top in 1994.
- Search methods for a charged Higgs boson were pioneered by D.P. Roy, with D. Choudhury, S. Raychaudhuri (1994-1996) and M. Guchait (2007).
- Low-energy SUSY signals were studied by D.P. Roy and several others, including R.M. Godbole, D. Choudhury, S. Raychaudhuri, D.K. Ghosh, S. Roy, P. Poulose, etc. over a period spanning three decades.
- P. Roy studied GUTs and no-scale SUSY models with A. Joshipura, A. Raychaudhuri, A. Mukherjee, U. Sarkar, P. Majumdar (1980s).
- Oblique electroweak corrections were studied by P. Roy with S. Banerjee, G. Bhattacharyya, D. Choudhury, R. Sinha, A. Kundu et al (1990s).
- Heavy quarks decaying through flavor-changing neutral currents were studied by D.P. Roy and B. Mukhopadhyaya (1992).
- S. Raychaudhuri, B Bhattacherjee et al studied the LHC 'inverse problem'.
- Dark matter constraints on SUSY models were studied by D.P. Roy with collaborators from 2006 – 2017.
- T.S. Roy has been studying jet grooming and non-jet hadronic signals at LHC in novel ways, creating some new paradigms in this area.

BSM and flavor physics at colliders

- S. Raychaudhuri studied CP violating Higgs bosons, triple gauge boson vertices, and a light RS radion in the context of collider signals (2012, 2017-2018).
- Combined SUSY studies of flavor and collider experiments were done by B. Bhattacharjee, A. Dighe, S. Raychaudhuri et al (2011, 2013).
- Signals for extra dimensions were studied by K. Sridhar, S. Raychaudhuri, P. Mathews, P. Poulose, et al.
- A. K. Alok, A. Dighe, D. Ghosh et al performed a comprehensive analysis of allowed Lorentz structures of new physics in $b \to s \ell\ell$ (2008-2012).
- T.S. Roy, S. Chakraborty et al discussed a solution to the μ problem using new 'supersoft' operators and classified all the operators of this type.
- T.S. Roy, R. Khatri et al (2018) discussed the interplay between 'dark neutrinos' and gravitational waves, and suggested a solution to the Hubble tension.
- N. Desai and collaborators have been studying long lived particles (LLP) at colliders.
- D. Bhatia, S. Chakraborty, A. Dighe, N. Desai et al proposed a class of U(1) models that satisfies flavour anomalies as well as neutrino mixing (2017, 2022).

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Neutrino Physics and Astrophysics

- Fourth generation neutrinos were studied by P. Roy et al (1992-95).
- D. P. Roy et al performed some of the first global fits to the solar neutrino data, that led to the Large Mixing Angle solution being confirmed as the solution to the solar neutrino problem (2001-2004)
- A. Dighe, S. Ray, P. Roy et al calculated the changes in neutrino mixing parameters due to the renormalization group evolution of these parameters at the high scale, in seesaw models (2006-2009)
- A. Bandyopadhyay, D. S. Chattopadhyay, A. Dighe, S. Ray et al calculated signals of new physics, like sterile neutrinos, CPT violation, neutrino decay, long-range forces, etc., at neutrino experiments (2006-2022)
- B. Dasgupta, A. Banerjee, A. Dighe et al clarified the nonlinear "collective" effects due to neutrino-neutrino interactions inside a supernova core and predicted unique signatures of "multiple spectral splits" on neutrino spectra (2006-2009).
- A. Dighe led the Physics Analysis group of the India-based Neutrino Observatory which performed extensive detector simulations to determine the physics potential of the proposed ICAL detector by observing atmospheric neutrinos (2009-2022)
- S. Bhattacharyya, B. Dasgupta, M. Sen et al clarified many features of the "fast collective oscillations" that may take place deep inside the core if certain angular symmetries are broken (2017-2022)

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QCD

Renormalization scheme-invariant perturbation theory: A complete solution to the problem of the renormalization scheme dependence of perturbative approximants to physical quantities is presented. An equation is derived which determines any physical quantity implicitly as a function of only scheme independent variables.
(A. Dhar, 1983)

Nambu-Jona-Lasinio type phenomenological model for SU(N) Quantum Chromodynamics at large N and low energies: Based on the fact that QCD has a mass gap. It contains a derivation of the Wess-Zumino-Witten (WZW) model of low energy pion dynamics including current algebra anomalies. The WZW term is derived here as a `Berry phase'. (This work directly lead us to a model of string theory in space dim = 1).

(A. Dhar, R. Shankar and S.R. Wadia, 1983-1985).

Lattice Gauge Theory-A non-perturbative formulation with exact gauge invariance but no Lorentz invariance.

Nonperturbative investigation of energy spectra and structures of subatomic particles including exotic hadrons, for example high precision prediction of the energy spectra of a large number of hadrons with charm and bottom quark contents, some of which have been observed afterwards. Prediction of the existence of tetraquarks and dibaryons, some of which even with very large binding energies. One of the predicted tetraquarks has recently been observed.
Nilmani Mathur and collaborators

Nonperturbative investigation of static and dynamic properties of strongly interacting matter at high temperatures; e.g., calculation of transport coefficients related to the thermalization of heavy (charm and bottom) quarks in the deconfined quark-gluon plasma; investigation of a heavy quark-antiquark pair as a probe of the plasma, in particular, calculation of the interaction potential between the pair in various color configurations in the deconfined plasma. Saumen Datta and collaborators

Deep inelastic scattering: modelling nucleon structure: Developed a very successful statistical model of the polarized and unpolarized parton distribution functions.

Ultra relativistic heavy-ion collisions: Quark-gluon plasma. One of the earliest works that showed incomplete equilibration of QGP fluid; Proposed new data analysis methods based on Lee-Yang zeroes, Principal Component Analysis, etc.; Proposed a number of new multiparticle correlation observables for RHIC/LHC.

Relativistic second-order dissipative fluid dynamics: Developed new methods to derive second-order hydrodynamics from kinetic theory; Simulated complete evolution of the strongly interacting matter. Rajeev Bhalerao and collaborators

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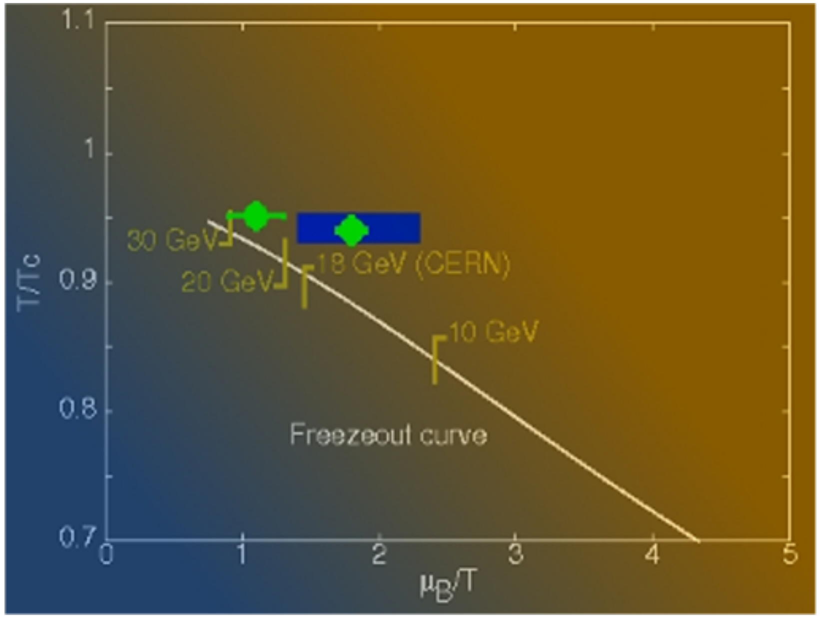
The phase diagram of QCD-1

- A critical point was seen for the first time in computations
- RHIC collider program was broadened to verify this prediction
- First results presented in 2005. Then improved in 2008. (R. Gavai and S. Gupta, 2005, 2008-)



2014: Now seen in experiments?

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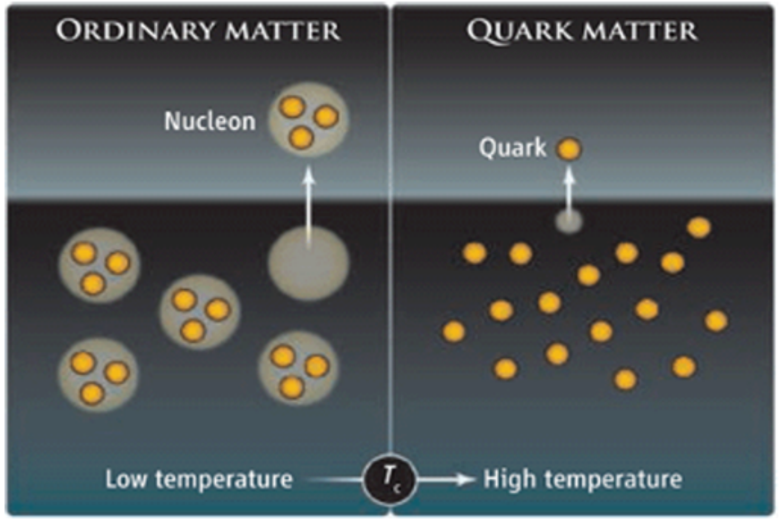
The phase diagram of QCD-2



A Scale for the Phase Diagram of QCD by Sourendu Gupta (TIFR, India), Xiao-Feng Luo (Wuhan, PRC), Bedangadas Mohanty (VECC, India), Hans-Georg Ritter (Berkeley, USA), Nu Xu (Berkeley, USA) in Science 332 (2011) 1525.

- Predictions for fluctuations in terms of a single free parameter: the crossover temperature Tc.
- Exptl data on fluctuations in good agreement with computations when Tc is 175 MeV, ie, **2 trillion Celsius**
- Consistency check: correct value of Avogadro's number

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Entanglement Entropy in Lattice Gauge Theory

Entanglement is a defining property of Quantum Mechanics. The definition of Von Neumann entropy which is a measure of entanglement between various `parts' of a quantum system for a gauge theory is not trivial due to Gauss' law and a definition was provided in the work of (S. Trivedi, R. Soni and S. Ghosh, 2015)

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String Theory and Mathematical Physics

String Theory and Mathematical Physics

- When we began working in the newly ushered area of String theory in 1984, we worked within the umbrella of the High Energy Physics unit in the theory group.
- The number of String theorists in DTP grew mainly due to the support and encouragement of Prof V. Singh who recognised the importance of the questions string theory attempts to answer.
- In the early 1990s, Prof S.S. Jha, Chair of the Department of Theoretical Physics created a new unit in DTP: String theory and Mathematical physics.
- This enabled the group to grow and invite some of the best people in the subject worldwide to join the department…to become one of top string theory groups in the world!

Why String theory?

String theory a theory in making has its origins in the high energy physics of strongly interacting particles. It is a new paradigm of physics in which the laws of physics are formulated in terms of extended objects rather than point particles. Historically the extended object was a one dimensional string…hence the name which is bit of a misnomer.

The work in TIFR (both Mumbai and Bangalore) has explored and contributed to various important physics questions since 1984:

1. What is string theory and what is its mathematical structure?
2. Can string theory resolve the conundrums presented by the fact that black holes radiate?
3. Can string theory provide a basis for the Cosmology of an expanding universe?
4. Can string theory provide a basis and a language to discuss questions like the origin of the universe or the multiverse?

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String theory: Early works are about classical solutions of ST

Strings propagating on a group manifold: The 2-dim WZW model coupled to 2-dim gravity is a model of a String propagating on a group manifold (S. Jain, R. Shankar, S.R. Wadia 1984).

This paper was in time to join the String revolution ushered by Green and Schwarz in the summer of 1984. Hitherto string theory was a model of strongly interacting particles. After 1984 string theory would have the potential to describe all of particle physics and gravity.

General technique to compute quantum corrections to non-linear sigma models to all orders using **the geometric background field method** (Sunil Mukhi 1986).

Program initiated to classify **Rational Conformal Field Theories in 2d**. This has now become a mainstream subject within the pure mathematics literature on Modular Forms and Vertex Operator Algebras, and very recently a part of the program has been taken to completion (Mathur-Mukhi-Sen 1988-89).

S-duality in String theory

Perturbation theory provides a way to carry out systematic study of weakly coupled quantum field theories and string theory.

What about strongly coupled theories?
S-duality is a conjecture that for certain quantum field theories and string theory, a weakly coupled theory is equivalent to a strongly coupled theory
– difficult to test / prove due to our inability to systematically study strongly coupled theory.

For certain supersymmetric theories, a systematic procedure for testing such conjectures was developed by studying the spectrum of supersymmetric states
(A. Sen, 1994). This procedure was later used by others for conjecturing new relations between different theories and testing these conjectures
– eventually led to the realization that apparently different string theories are all different descriptions of a single underlying theory.

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Matrix models and String theory in low dimensions

Bosonization of the non-relativistic fermion representation of the c=1 matrix model in terms of fluctuations of the fermi surface played a key role in low dimensional string theory (A.M. Sengupta and S.R. Wadia, 1990). Exact bosonization needs tools from geometric quantization (A. Dhar, G. Mandal and S. R. Wadia, 1992-93)

Discovery of a topological matrix model that computes amplitudes of non-critical string theory (Imbimbo-Mukhi 1995).

String theory is a theory of gravity: Black Holes-1

Black hole in 2-dim string theory: An explicit exact black hole solution was constructed in 2-dim string theory (G. Mandal, A. M. Sengupta and S.R. Wadia, 1991). The special significance of this was that 2-dim string theory in a linear dilaton background is a non-critical string theory that is equivalent to a 1-dim matrix model (S. R. Das, S. Naik and S. R. Wadia, 1988; A. M. Sengupta and S. R. Wadia, 1990; S. R. Das and A. Jevicki, 1990). This raised for the first time the important question whether the degrees of freedom of the 2-dim black hole reside in a matrix theory which is unitary and in one lower dimension…a precursor to the AdS/CFT correspondence.

Extremal black holes and elementary string states: The entropy of elementary BPS string states was shown to be equal to that of an extremal black hole up to a constant that was subsequently calculated to show an exact agreement. This provided a first indication of the statistical origin of black hole entropy (A. Sen, 1995).

Black Holes - 2

Quantum corrections to black hole entropy: If String theory is a complete theory of quantum gravity it should account not only for the leading Bekenstein-Hawking formula but also for quantum corrections. It was shown that the exact entropy of two-charge supersymmetric black holes in N=4 string theories can be computed to all orders (Dabholkar, 2005)

The attractor mechanism for non-supersymmetric black holes was used to argue that one can compare macroscopic results for entropy computed at strong coupling with the microscopic entropy computed at weak coupling. It was also shown that this comparison needs to be done for small but non-zero temperature. Below that temperature the black hole horizon will be destroyed by stringy or quantum corrections and in the microscopic theory the effect of lifting of ground state degeneracy by quantum corrections becomes important, making both sides ill defined. (Dabholkar, Sen and Trivedi, 2006)

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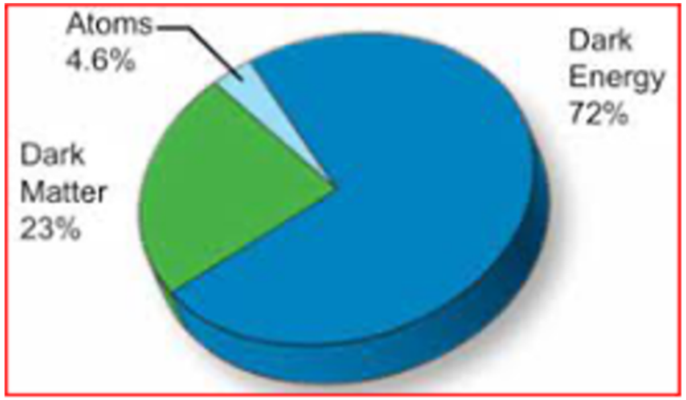
Black Holes-3

The Information paradox arose from the work of Stephen Hawking in 1974. In his treatment of quantized matter interacting with a classical black hole Hawking demonstrated that black holes radiate thermally. This is in conflict with unitary evolution in quantum mechanics. In attempts to resolve it physicists beginning with Strominger and Vafa discovered that a BH is just like any dynamical system which obeys the laws of quantum statistical mechanics. Maldacena in 1996 discovered that gravity in an anti-de Sitter spacetime has a holographic quantum field theory representation on its boundary. Hence BH degrees of freedom are residing in the boundary theory

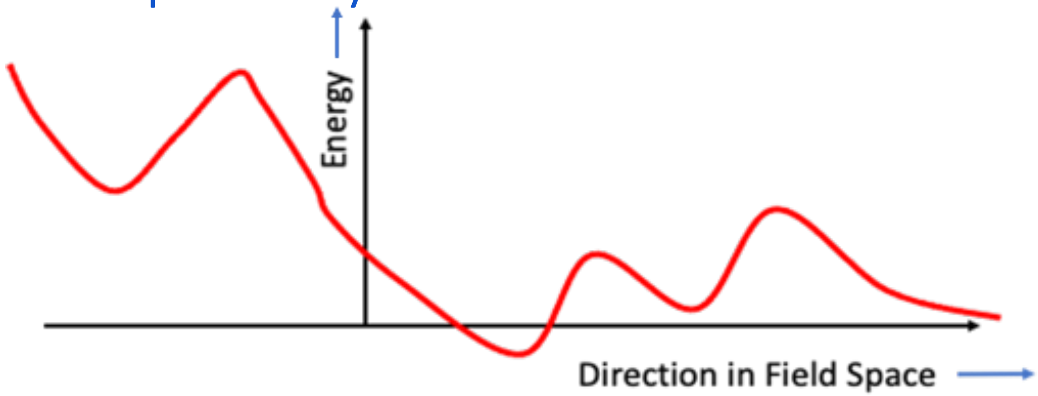
Hawking radiation and String theory: Strominger and Vafa modeled of a class of extremal supersymmetric black holes as a bound state of a collection of D-branes and calculated the Bekenstein-Hawking entropy using Boltzmann's formula (1996). A. Dhar, G. Mandal and S. Wadia (1996) and (a bit later) S. Das and S. Mathur took the first step towards a string theory calculation of Hawking radiation using quantum statistical mechanics. The more precise calculation of Hawking's formulas used the AdS/CFT correspondence (J. David, G. Mandal and S. R. Wadia 2000).

String theory is a theory of gravity: Cosmology-Dark Energy

It is an experimental fact that in the present epoch of our universe the cosmological constant which is a measure of the energy density of the universe (dark energy) is tiny and positive:10^{-8} ergs/cm^3. Kachru, Kallosh Linde, Trivedi (KKLT) 2002 proposed a scenario in string theory that realizes this possibility.



Energy budget of universe (YY Mao)



String Theory has a complicated Landscape of many vacua

Actually about 100 directions. Estimate: 10^{500} Vacua.

Some with positive ground state energy, can account for observed dark energy. Model is subject of current active

M and F- theory Dualities, Integrability in AdS, Giant gravitons,

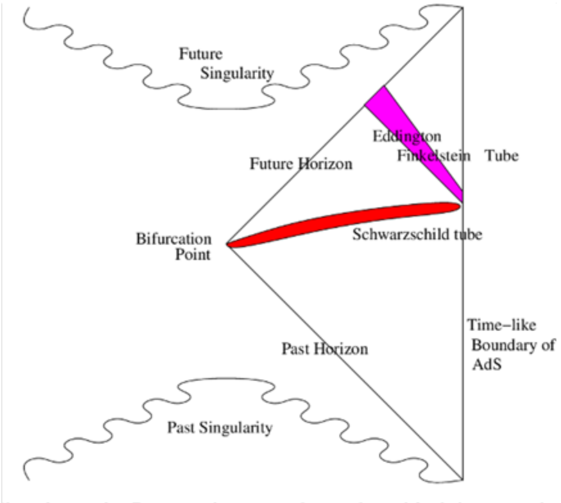
New dualities were discovered in non-perturbative formulations of string theory called M-theory and F-theory (Dasgupta-Mukhi 1995-96, 1998 Gopakumar-Mukhi 1996).

The discovery of **integrability of world sheet string theory** in anti de Sitter spacetimes (generalized to supersymmetric theories by Polchinski et al), and the subsequent discovery of integrability in the dual super Yang Mills theory paved the way for nonperturbative exploration of gauge-gravity equivalence. (G.Mandal, N.Suryanarayana and S.R.Wadia, 2002)

Supersymmetric solitons in string theory called **giant gravitons** provided a window to derive AdS/CFT duality in a subsector with high supersymmetry. The geometric quantization of supergravity in the half-BPS sector allowed one to rewrite the theory in terms of the corresponding sector of super Yang Mills theory. (G.Mandal, 2005)

A long-standing problem to find the **world-volume field theory and dualities of membranes in M-theory** was addressed, with a key role being played by a novel Higgs mechanism in 3d (Mukhi-Papageorgakis 2008).

Fluid Gravity Correspondence: Dissipation and Horizons



A surprising and precise connection was established between two of the best studied partial differential equations in theoretical physics, namely Einstein's equations of general relativity and the Navier Stokes equations. In particular it was demonstrated that Einstein's equations with a negative cosmological constant in D dimensions, reduce to relativistic generalizations of the Navier Stokes equations in D-1 dimensions. This so called fluid gravity map has had many applications. It has led to the discovery of new terms in the equations of fluid dynamics of charged fluids in theories that violate parity. It has also set in motion a stream of still ongoing work that has greatly improved our understanding of the nature and structure of the equations of fluid dynamics and their generalizations. (S. Minwalla, S. Bhattacharya, R. Loganayagam and Collaborators 2008-)

Chern Simons Matter Theories

Quantum field theories with no massless particles come in two varieties: those that reduce at low energies to a completely trivial theory, and those that reduce at low energies to a topological field theory. Dynamics in theories of the second sort is much less understood than in the first sort. A particular example of such theories – **SU(N)_k Chern-Simons theories coupled to massive fundamental matter in the limit that N and k are both large with their ratio held fixed – are exactly soluble.** (S. Minwalla, S. Jain, N. Prabhakar, S. Trivedi, S. R. Wadia, I. Haldar, S. Yokoyama, A. Mishra, C. Patel…] (2011-2022)

The exact solutions to these theories has revealed many surprises. **First,** it was understood that fermions coupled to a Chern-Simons theory are dual to bosons coupled to a level rank dual Chern Simons theories. **Second,** it was realized that the fundamental excitations of these theories carry fractional spin, and obey rules of statistics that are a one parameter generalization of the famous rules of Bose Einstein and Fermi Dirac Statistics. **Finally,** it was shown that the rules for crossing symmetry of such theories are a q deformation of the familiar standard rules for crossing symmetry.

The S-Matrix

Assuming the Regge bound on the growth of **tree level S-Matrix for gravitons** implies strong constraints on them and leads to a sharp conjecture that the only allowed four graviton scattering matrices are those that come from Einstein gravity, Type IIB string theory and Heterotic string theory. (Abhijit Gadde, Shiraz Minwalla and collaborators, 2019)

A new **“S-matrix'' type local observable in Anti-de Sitter space** was proposed together with Feynman-like rules to compute it. It turns out to be intimately tied to the so called Mellin transform of the boundary CFT correlation functions. (Abhijit Gadde and T. Sharma, 2022)

Cosmology and Astroparticle Physics

Cosmology and Astroparticle (CAP) -1…since 2010

The full phase-space of Dark Matter in the Milky Way from galactic centre to the galaxy boundary from observations: (Subha Majumdar +) TIFR has the best observationally constrained model of both density and velocities of DM in the Milky Way – the crucial input to ALL direct or indirect detection DM experiments.

Collective Neutrino Oscillations: (Basudeb Dasgupta +) Dense neutrinos inside supernovae, merging neutron stars, and in the early Universe, can exhibit new types of flavor oscillations. This has practical relevance for stellar explosions and formation of heavy elements. TIFR has made Internationally-noted contributions to the theory of "collective instabilities" of neutrino oscillations.

Discovery of a new class of non-thermal relativistic spectral distortions of the CMB: (Rishi Khatri +) Produced before recombination upending existing wisdom which assumed that all energy injected before recommendation would thermalize. TIFR remains world leader in CMB spectral distortions.

The largest ever radiative transfer simulations of cosmological reionization: (Girish Kulkarni +) TIFR possesses the most detailed and complex full hydro+radiative transfer cosmological simulation in the world for 21cm, Lyman alpha, reionization studies.

Cosmology and Astroparticle (CAP) -2

The CAP group is part of many international cosmology collaborations:

Current -(LSST) Rubin Observatory's Large Survey of Space and Time

- ➔ largest photometric survey in the world
- ➔ Basudeb Dasgupta, Rishi Khatri, Girish Kulkarni & Subha Majumdar are PI's in LSST.

(DESI) Dark Energy Spectroscopic Instrument

- ➔ largest spectroscopic survey in the world, Shadab Alam is a lead scientist.

(SKA) Square Kilometer Array

- ➔ largest 21cm survey in the world, Girish Kulkarni & Subha Majumdar

SQR-30 and **REACH** project

- ➔ SQR-30 is the largest observational program on VLT for probing the 1-billion year of our Universe
- ➔ REACH are two telescopes in South Africa dedicated for detecting of global 21cm signal, Girish Kulkarni

CMB-Bharath ISRO proposal

- ➔ proposal to measure CMB polarization and spectral distortions with CMB satellite launched by ISRO
- ➔ Rishi Khatri & Subha Majumdar

Past –

(RCS) Red-Sequence Cluster Surveys

- ➔ first large optical cluster survey Subha Majumdar, Subha Majumdar

THEIA Microarcsecond astrometry observatory

- ➔ proposal for medium size ESA mission to map the Milky Way and surrounding dark matter
- ➔ Subha Majumdar

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Monographs and Conferences

Monographs:

1. *Bombay Lectures on Highest Weight Representations of Infinite Dimensional Lie Algebras* (V.G. Kac and A.K. Raina, 1986)[World Scientific]
2. *Theory and Phenomenology of Sparticles* (M. Drees, R. Godbole, P. Roy) [World Scientific]
3. *Particle Physics of Brane Worlds and Extra Dimensions* (S. Raychaudhuri, K. Sridhar) [CUP]

Conference/Proceedings:

1. *Modern Quantum Field Theory I and II* (S.R. Das, G. Mandal, S. Mukhi, S.R. Wadia) 1990, 1994 [WS]
2. *Supersymmetry and Supergravity Nonperturbative QCD* (1984) (Ed. Probir Roy and Virendra Singh) [Springer-Verlag]
3. *Exactly Solvable Problems in Condensed Matter and Relativistic Field Theory* (Ed. B.S. Shastry, S.S. Jha and V.Singh) (1985) [Springer-Verlag]
4. Proceedings of Strings 2001 at TIFR-Mumbai (A. Dabholkar, S. Mukhi, S.R. Wadia) [AMS]
5. Strings 2015 at ICTS-TIFR + all other ICTS Conferences

TIFR-Hyderabad: Statistical & Condensed Matter Physics

- **Origin of rigidity of solids:** Pioneering work on affine and non-affine fluctuations addressing the origin of rigidity and yielding in crystalline solids. (Surajit Sengupta)
- **Effect of random pinning on yielding of amorphous solids:** Demonstrating spatial localisation of plastic activity due to inclusions of randomly pinned articles. (Smarajit Karmakar)
- **Glassy dynamics in confluent cells**: Adapting statistical mechanics models for characterising glassy behaviour of confluent epithelial cells. Applications: Dynamics of asthmatic and cancer cells. (Saroj K. Nandi)
- **Theoretical characterization of athermal materials:** Determination of displacement fields away from the crystalline state as a response to microscopic disorder. (Kabir Ramola)
- **Turbulence in active matter:** Characterising collective behaviour of polar active flocks in a bulk fluid medium. (Prasad Perlekar)

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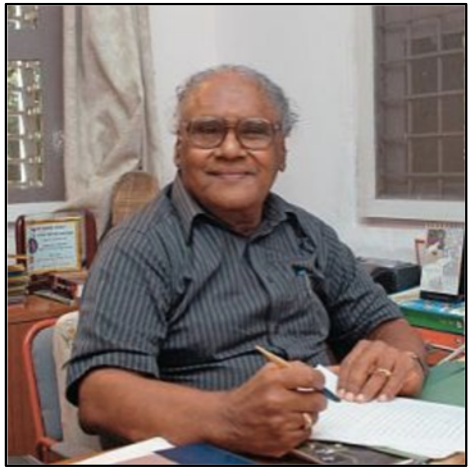
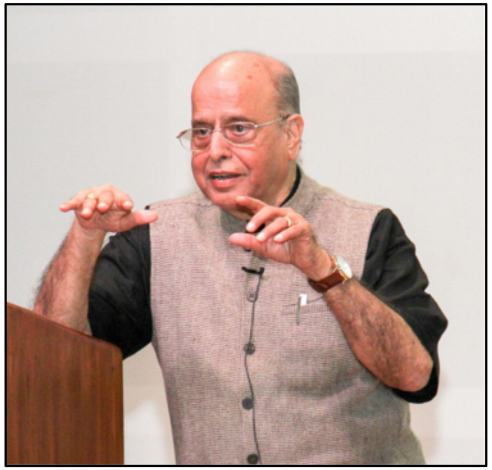
ICTS-TIFR

The ICTS concept

- The idea to create a Centre such as the ICTS was born in 2001, after the success of the Strings 2001 and a visit to the Infosys Campus in Bangalore.
- The former boosted our confidence based on our achievement in fundamental physics and the latter assured us that institutional infrastructure and management of the highest international quality was possible in India.
- This combination of highest quality science within a modern state of the art campus, managed along modern thoughts, inspired the idea of the ICTS. Our memory of the creation of the Tata Institute by Bhabha, in the 1950s, was also an inspiration.
- **ICTS is unique in India as *an international science hub that would transform the ways of doing scientific research and science education. Established in August 2007.***

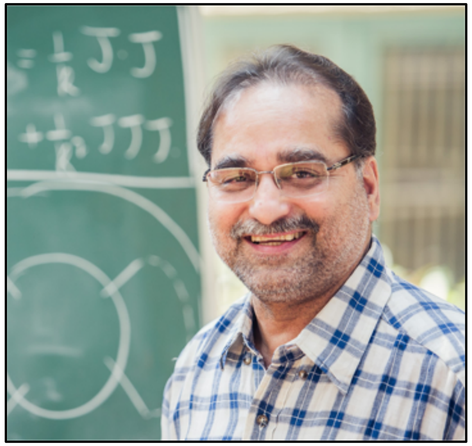


CNR Rao



K Kasturirangan

David Gross



Avinash Dhar

Mukesh Dodain

Uma Mahadevan

The creation of ICTS was a huge collective effort by people from TIFR, DAE and the international community....

Key achievements of ICTS: 2007-2022

ICTS has excelled in its programs, research and public outreach and has an accomplished faculty.

Research
ICTS faculty has made widely recognised contributions.

International Science Hub - Huge Impact on Indian Science

ICTS has hosted more than 300 programs with over 25,000 participants (18000 from India and 7000 from abroad)

Science Outreach and Popularization

Our outreach has become a fixture for science enthusiasts in India with over 250 outreach activities and over 80000 participants.

311 Programs

250 Outreach Activities

>7000 Talks on ICTStalks

>50K Subscribers on YouTube

>3M Views on YouTube

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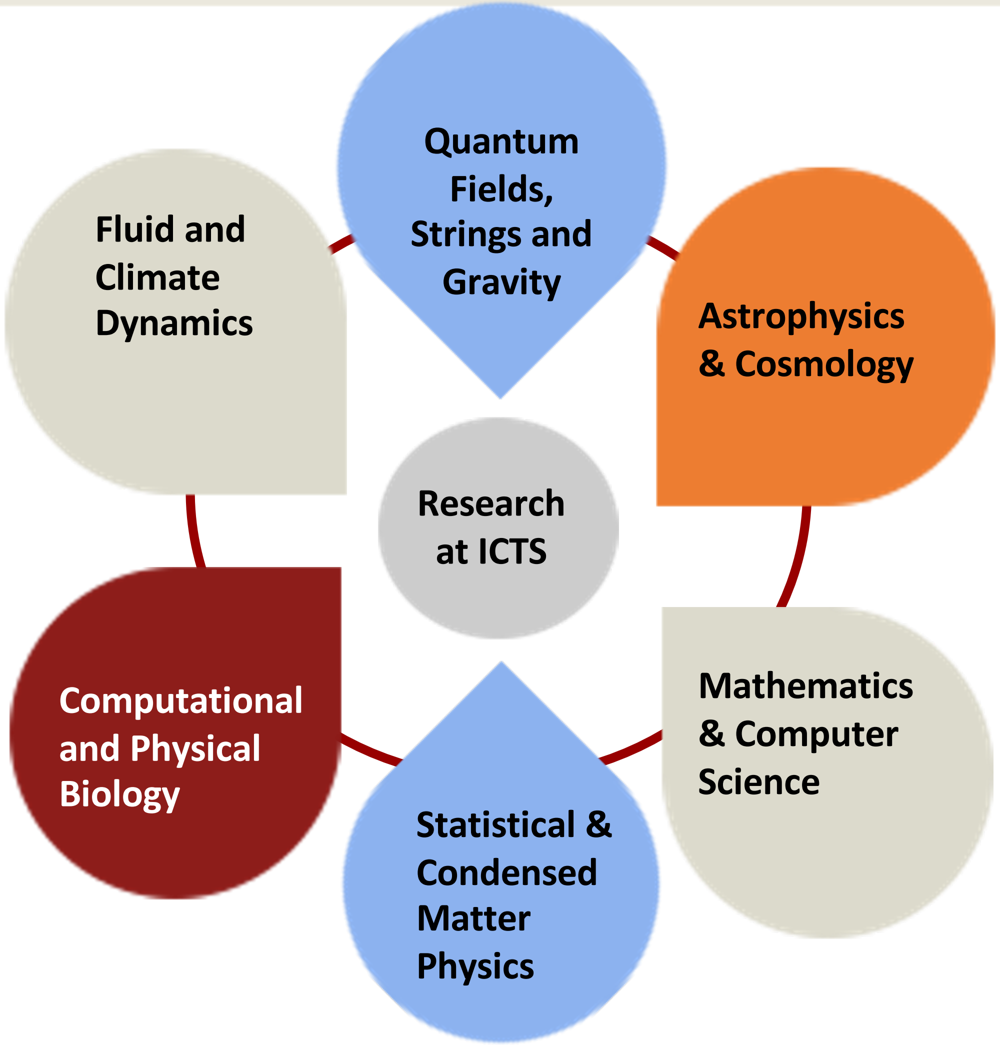
Areas of research at ICTS



Faculty at ICTS

Parameswaran Ajith
Amit Apte
Siva Athreya
Anirban Basak
Riddhipratim Basu
Pallavi Bhat
Subhro Bhattacharjee

Chandan Dasgupta
Bala Iyer
Rajaram Nityananda
Mythily Ramaswamy
Sumathi Rao
Joseph Samuel
Ashoke Sen
Spenta R. Wadia (Founding Director)

Rukmini Dey
Abhishek Dhar
Rajesh Gopakumar (Centre Director)
Rama Govindarajan
Vijay Kumar Krishnamurthy
Manas Kulkarni
Prayush Kumar

Anupam Kundu
Pranav Pandit
Loganayagam R
Jaikumar Radhakrishnan
Suvrat Raju

Sthitadhi Roy
Samriddhi Sankar Ray
Jim Thomas- - Joint Fac.
Shashi Thutupalli - Joint Fac.
Vishal Vasan

ICTS in pictures






ICTS-Statistical and Condensed Matter Physics-1

Exact results for trapped gases with long-range interactions: Trapped systems of interacting particles are now routinely studied in cold atom setups and an interesting question is the process of thermalization. A novel field theoretic approach has been developed by ICTS researchers that enables one to compute exactly the equilibrium particle density profile for a large class of systems with strong long-range interactions. This includes important cases such as the coulomb gas, the plasma gas, the log-gas and the Calogero-Moser system. Analytic results were also obtained for correlation functions and distributions of individual tagged particles.
[A. Dhar, A. Kundu, M. Kulkarni, S. Agarwal, S. Santra, J. Kethepalli, S. Sabhapandit, S. M Majumdar, G. Schehr, D. Mukamel].

Anomalous transport in one-dimensional systems refers to the observation of superdiffusive transport of energy, particle and spin in one-dimensional interacting particle systems. Over the last ten years this has been understood within the framework of nonlinear fluctuating hydrodynamics. ICTS researchers have played a leading role in establishing this framework. This includes extensive numerical work which established the validity of the hydrodynamic framework in a wide range of models such as the Fermi-Pasta-Ulam chain, Heisenberg spin chains, the nonlinear Schrodinger equation and various stochastic models. ICTS researchers also were part of two independent collaborations that have attempted the first microscopic derivations of fluctuating hydrodynamics.
[A. Dhar, A. Kundu, M. Kulkarni, A.Das, S. Das, K. Damle, D. Huse, H. Spohn, C. B. Mendl, K. Saito, S. Sasa, M. Hongo, D. Mukamel, A Miron, J Cividini]

2017-2022

ICTS-SPCMT-2

Looking for quantum spin liquids: Quantum spin liquids are special states formed by strongly interacting quantum matter where one finds absence of ordering even at absolute zero and that are characterized by strong entanglement. These phases are predicted to have exotic emergent properties and unconventional excitations with properties distinct from the underlying electrons. The theory of spin-liquids is well-developed but experimental observation of the spin liquid phase has been a challenge.

ICTS faculty Subhro Bhattacharjee has been involved in two important international theory-experiment collaborations that have reported some of the few experimental signatures of quantum spin liquids in (i) a family of hexagonal ruthenium-based materials (2016) and (ii) in a pyrochlore compound (2022).

Chaos propagation in many-body systems: how does chaos propagate in a system of interacting particles and how does it affect transport properties? Motivated by studies of the so-called Out-of-Time-Ordered-Correlator that is used to quantify quantum chaos,

ICTS researchers have studied their classical analogues in a variety of models including Heisenberg spin chains, Kagome lattices, Navier Stokes fluids and dissipative nonlinear lattices. Several important discoveries have been made such as: (i) an unexpected connection to the Kardar Parisi Zhang model of surface growth (ii) relations have been established between the Lyapunov exponent, the butterfly speed and the diffusion constant and their temperature dependence understood.

[S. Bhattacharjee, A. Dhar, M. Kulkarni, A. Kundu, S.S Ray, A. Das, S. Chakrabarty, A. K Chatterjee, D. Huse, R. Moessner, T. Bilitewski]

2014-2022

Biophysics at ICTS

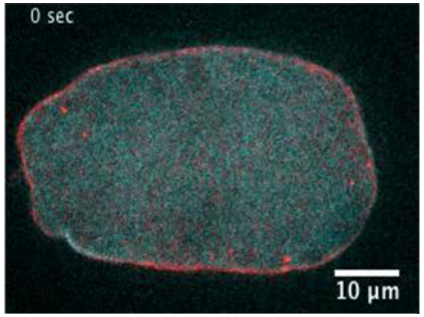
Statistical Physics of Living Systems

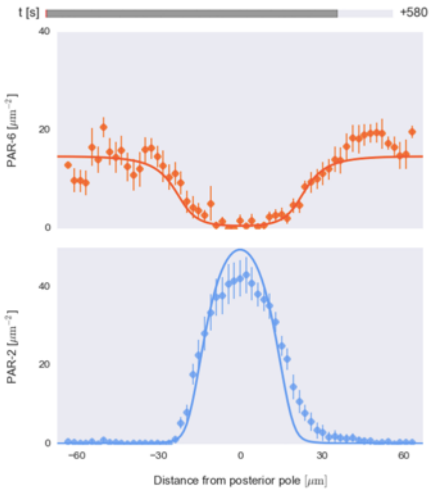
What are the emergent physical principles of self-organisation in cells and tissues?

Tight coupling between biochemical signalling (information processing), mechanochemical stresses (active matter), and the emergent functional shapes (geometry) of cells & tissues.

Cell polarity

- emergent mechanochemical pattern
- establishes the primary head-tail axes





ICTP-ICTS Winter Schools on Quantitative Systems Biology

Experimental Collaborations

Shashi Thutupalli (NCBS-TIFR)
[Active particles, Infection patterns in bacterial colonies]

Maithreyi Narasimha (DBS-TIFR)
[Drosophila: Germband retraction, Dorsal closure]

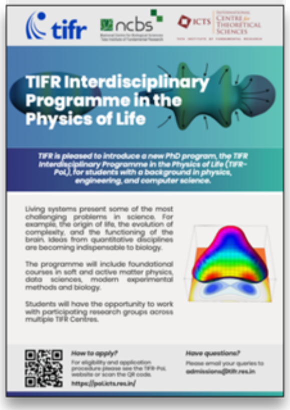
Ramray Bhat (IISc)
[Aggregation patterns in D. Discoideum and Cancer cells]

Vaishnavi Ananthanarayanan (UNSW)
[Kinetics of molecular motors and cargo]

Masatoshi Nishikawa (Univ Hosei)
[Asymmetries in cell division]

Stephan Grill (MPICBG)
[Cell polarity, morphogenesis]

New PhD program "Physics of Life"



Theory Collaborations

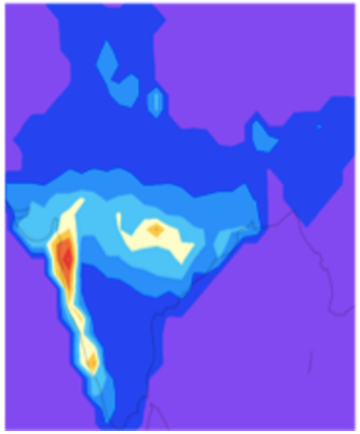
Vishal Vasan (ICTS-TIFR)
[Size regulation in actively growing tissues]

Sriram Ramaswamy (IISc)
[Active polar patterns on curved manifolds]

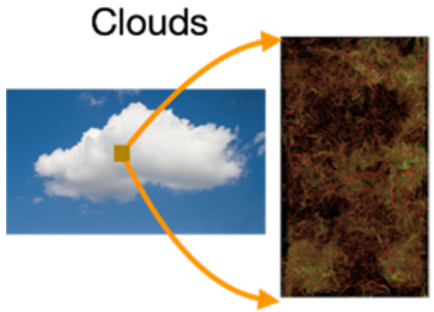
Climate and Weather initiative at ICTS

Some findings of the groups of Amit Apte, Vishal Vasan, Samriddhi Sankar Ray, Rama Govindarajan

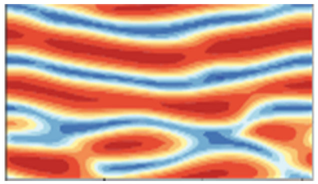
Indian monsoon



Treating rainfall as a probabilistic manifestation of underlying dynamics, they showed that most monsoon days of the past 110 years can be described by one out of 10 patterns, such as this one above.

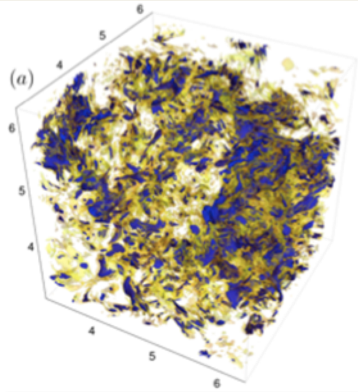


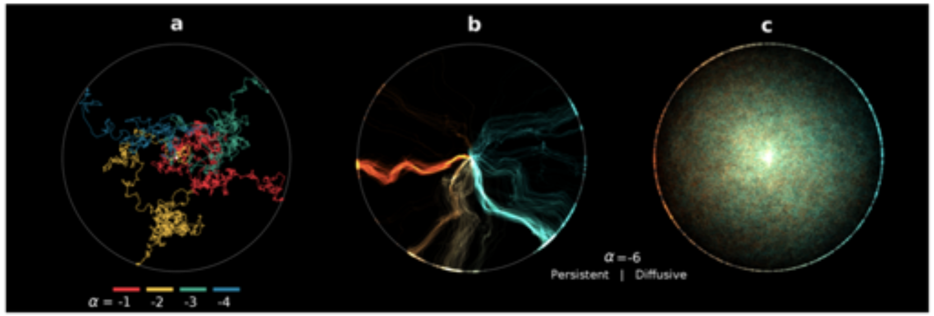
Turbulence in clouds is shown to accelerate raindrop descent and their early-stage growth, and reorient ice crystals



Shear flows undergo a transition to turbulence even when the laminar flow is stable to small perturbations, because algebraic growth of instabilities can happen here. We show how variations of viscosity change the answer fundamentally

Data assimilation, nonlinear dynamics, fluids, turbulence





Regions of intense dissipation in turbulence.

Classical bound on many-body chaos through decorrelators

Emergence of anomalous diffusion mediated by Levy walks in highly active bacterial suspensions

Some research directions:

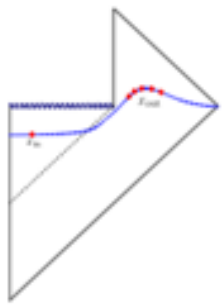
Role of dynamical instabilities in data assimilation; Nonlinear filter stability for deterministic dynamics; Particle filtering methods for deterministic systems; Small-noise limits for data assimilation, using theory of large deviations; Asking if different initial conditions converge to the same distribution…

Gravitational wave physics and astronomy

- **Tests of GR using GWs:** Developed a test of GR based on the consistency between different parts of observed GW signals from BBHs. This was among the handful of tests used to establish the consistency of the first LIGO event with a BBH system predicted by GR, and was one of the first observational tests of GR in the strong-field regime. [P. Ajith and collaborators 2016, 2018].
- **BH spin measurement:** Developed and implemented a method to infer the mass and spin of the remnant black hole in a binary merger, making use of fitting formulas calibrated to numerical-relativity simulations. This enabled some of the best measurements of black-hole spin from any astronomical observations. [P. Ajith and collaborators 2016].
- **Gravitational lensing of GWs:** Significant body of work on the gravitational lensing of GWs. Developed methods that are currently employed to search for strongly lensed GW signals, performed the first searches for lensed GW signals. Obtained constrained on primordial BHs from the non-detection of microlensing effects in the observed GW signals by LIGO and Virgo. [P. Ajith and collaborators 2022].

Black holes and the information puzzle

Unusual localization of information in gravity



- In the context of the information-paradox, it was argued that degrees of freedom in the black-hole interior can be represented as complicated combinations of degrees of freedom in the exterior.

$$\phi(x_{\mathrm{in}}) = \mathcal{P}\left[\phi(x_{\mathrm{out},1}) \ldots \phi(x_{\mathrm{out},n})\right]$$

[Papadodimas, S.R., 2012–15]

- Later, it was argued that this feature arises as a consequence of gravitational constraints on the quantum-mechanical state.

- This sheds light on why gravitational theories are holographic and indicates how holography should work beyond AdS.

[Laddha,Prabhu, S.R., Shrivastava, Godet, Papadoulaki, Chowdhury, 2019–22]

Deriving the AdS/CFT correspondence

- **Proposal of a novel tensionless limit of string theory dual to free 2d CFT** - leading to a derivation of the AdS/CFT correspondence in a nontrivial example.
- Progress in the **string theory dual to super Yang Mills theory**.
- Realizations of a **broad program to systematically derive gauge-string duality**.

(R. Gopakumar, M. Gaberdiel and collaborators, 2019-22).

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Conformal bootstrap and critical phenomena

A new and powerful approach to the **conformal bootstrap** was developed that involves expanding in a new crossing symmetric basis (of Witten diagrams in AdS) and using a Mellin space representation. Resulted in new results in the expansion of Wilson-Fisher fixed point for structure constants.

(R. Gopakumar, A. Kaviraj, K. Sen and A. Sinha, 2017-21)

Schwinger-Keldysh method: Effective action for fluid dynamics and Langevin equation

Effective action for fluid dynamics and Schwinger-Keldysh formalism: Fluid dynamics is a description of a system in terms of conserved or anomalous currents with an additional constraint that is imposed by the second law of thermodynamics. Understanding this dissipative system in the framework of Wilsonian effective theory and an action principle is an important open problem towards which important progress was made. Working in the Schwinger-Keldysh formulation the emergence of the entropy current and its positivity places constraints that require the introduction of a U(1) gauge field conjugate to the entropy current, and a pair of emergent BRST symmetries related to the KMS conditions. This formalism also accommodates fluids charged under anomalous flavour symmetries (R. Loganayagam and collaborators).

Nonlinear Langevin equation: The effective action of the Brownian particle in a generalised Caldeira-Leggett model was computed by generalizing the Schwinger-Keldysh method with 2-time folds and results in a generalization of the Langevin equation with a non-Gaussian noise probability distribution with a cubic term. This is the first time a precise connection between a non-linear quantum open system and Langevin dynamics has been established, including new fluctuation-dissipation and Onsager relations (R. Loganayagam and collaborators).

BH formation and evaporation in 2-dim gravity

Using the duality of the Sachdev-Ye-Kitaev model of random interacting fermions with 2-dim gravity, an explicit time dependent calculation of BH formation and evaporation was performed. In the study of BH formation the final state of the BH exhibits Choptuik like scaling. **For the evaporation process when coupled to a bath the evaporating asymptotic state exhibits large fluctuations of the metric.**

(A. Dhar, L. Joshi, A. Gaikwad, G. Mandal, A. Kaushal and S.R. Wadia, 2018-2022)

The Future - new areas

Theoretical Physics at TIFR grew over the years to include cutting edge subjects.

High Energy Physics

HEP, Condensed Matter

HEP, CMT, Statistical Physics

HEP, CMT, SP, String Theory

HEP, CMT, SP, ST

HEP, CMT, SP, ST, Cosmology

HEP, CMT, SP, ST, Cosmology, Gravitational Waves, Climate dynamics, Biological physics

It would be important to grow in the areas of **Quantum information and Quantum science.**

Make a concerted effort to interact and work with experimentalists in this area.

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The Future - administration and infrastructure

The Department of Theoretical Physics (and other departments too) could try to achieve greater administrative and financial autonomy at TIFR-Mumbai.

It could do better with an Advisory Board especially if it would like to explore new areas of research.

It could try to improve infrastructure and this will surely enhance the academic environment.

Join the movement to bring about `Ease of doing Science' in India.

Thank you

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