TIFR Annual Technical Report (2016-17)

Department of Theoretical Physics

1. **School / Centre / Department / Group**
   Department of Theoretical Physics

2. **Highlights**

A. Cosmology and Astroparticle Physics

- The scale of homogeneity in the cosmological distribution of galaxies, galaxy clusters and AGNs was probed using multiple tracers from the Sloan Digital Sky Survey data to show that the Universe becomes homogeneous for each tracers on cosmological scales.
- A novel analytic model was constructed of the X-ray AGN-halo occupation distribution and prospects of constraining the AGN-halo connection with upcoming eROSITA satellite was demonstrated.
- Using a select sample of clusters observed in both XRays and SZ, the non-gravitational energy injection to the cluster, its dependencies on various cluster formation, dynamics, and cosmological physics was explored.
- The idea of pre-heating of cluster gas was conclusively ruled out for the first time.
- It was shown that a self-interacting neutrino gas can spontaneously acquire a non-stationary pulsating component in its flavor content, with a frequency that can exactly cancel the "multi-angle" refractive effects of dense matter.
- It was shown that photon jets can be distinguished from isolated photons by exploiting the fact that a large fraction of photons pair-convert inside the inner detector. This distinguishing power was quantified in the context of a diphoton-like signal.
- The sterile neutrinos with secret interactions was studied and their viability in the light of constraints from observations of the microwave background and large scale structure was investigated. It was shown that two interesting regimes remained marginally viable.

B. Condensed Matter and Statistical Physics

- The generalization of the three arcsine laws of Brownian motion was obtained for the fractional Brownian motion with arbitrary Hurst index H. The results were derived by an exact calculation and verified with extensive numerical simulation.
- Computational methods were developed for the sign-problem-free simulation of a class of frustrated antiferromagnets, and for the efficient study of transverse field Ising models in frus-

trated geometries.

- The physics of an interesting vacancy-induced crossover in the density of state of Graphene was elucidated.
- An interesting regime of spin liquid behaviour was identified in frustrated honeycomb lattice antiferromagnets.
- A novel superconductor driven by resonant tunneling was predicted in the Ionic Hubbard model.
- It was found that strong disorder kills superconductivity in strongly interacting systems by creating Mott insulating patches in them.
- A Mott-insulator to metal like transition was seen and explained in the depinning of a vortex lattice in a superconducting film with a periodic array of holes.
- Experimental data on possible quantum Hall ferromagnetism in trilayer graphene was explained through strong correlation effects.

C. High Energy Physics

- A class of lepton flavour violating models was constructed in a bottom-up approach, to simultaneously account for the neutrino mixing pattern as well as anomalies in the flavour physics data.
- Using lattice QCD, the ground state masses of the B^*_c meson and triply bottom baryon (Ω_{bbb}) were predicted which are yet to be discovered. Their masses are found to be 6331^{+5}_{-4} MeV and 14362^{+6}_{-5} MeV respectively. This prediction will help for the discovery of these subatomic particles.
- Topological excitations, such as instantons, were found to continue to dominate across the chiral phase transition at finite isospin chemical potential in quantum chromodynamics (QCD).
- Location of QCD critical point at finite baryon density was shown to be insensitive to lattice cut-off.
- Equation of state for QCD at nonzero baryon density was obtained.
- A thorough analysis was made of flavour-changing neutral current decays of the top quark, mainly in the context of supersymmetric models, and the conditions for obtaining observable signals were clearly laid out.
- Extra scalars in the broken R-symmetric minimal supersymmetric Standard Model were studied in the specific context of the erstwhile 750 GeV diphoton resonance at CERN. Though the signal has disappeared. much of the analysis is of general relevance.

- Introduced a new observable ξ, which involves counting charged tracks in an event that are not part of any reconstructed objects. Binned in transverse momenta, ξ was found to be the single most effective variable in the search of models with compressed spectra at the LHC in the monojet channel.
- It was shown that the use of many grooming jets coupled with cuts on particle multiplicities in jets give rise of unexpected scales even for QCD events. In fact, the bump at 1.8 TeV reported by the ATLAS collaboration at LHC, in their search for diboson resonances, was shown most likely to be the manifestation of these effects, rather than hint for new physics.
- A new tool, namely Qtrimming, was introduced in jet substructure physics, that brings the advantages of stochastic clustering algorithms (namely, Qjets) in the context of grooming jets using trimming. Examples where the use of Qtrimming allows one to discover new particles using only a quarter of data compared to trimming were also given.
- Calculation of the dynamic structure factor of a strongly correlated Fermi superfluid within a density functional theory approach was done.
- A Proposal for measuring Anisotropic Shear Viscosity in Unitary Fermi Gases was put forward.
- Calculation of the shear viscosity of two-flavor crystalline color superconducting quark matter was performed.

D. String Theory and Mathematical Physics

- Classical 4pt graviton scattering with an infinite tower of (linear) massive higher-spin particles was studied.
- The classical dynamics of black holes was investigated in the limit of black holes propagating in an infinite number of dimensions. It was demonstrated that the reduction of black hole dynamics to the dynamics of an effective event horizon `membrane' - demonstrated at leading order in earlier work at TIFR – persists to all orders. The stress tensor and charge current of the black hole membrane were computed and radiation formulae for this membrane developed at infinite *D*.
- Matter Chern Simons theories interacting with regular bosons and critical fermions were studied. The beta functions of these theories (w.r.t. their classically massless parameters) were computed at leading nontrivial order to all orders in the t'Hooft coupling. Based on the results of this computation it was demonstrated that each of these theories have three conformal fixed points (atleast at large *N*). It was conjectured that the corresponding bosonic and fixed points are dual to each other.
- Flat limits of various AdS_3 asymptotic symmetries were studied.

- The large-N limit of a (0+1) dimensional quantum theory of gauged complex fermionic fields transforming under fundamental representation of SO(N) was considered, which coincides with the SYK-like model at large-N. Specifically, the mass deformation of the theory was studied. It was analyzed how the dynamics of gauge holonomies dominate the free energy at certain low temperature regime.
- Quantum quench dynamics is studied in some one dimensional models. Thermalization is proved and relaxation rates are computed exactly.
- Dynamical entanglement entropy in a finite box is computed and explained from a gravity dual. Long time behaviour is shown to be non-thermal and explained in suitable limits in terms of ballistic propagation and reflection of quasiparticles.
- The holographic renormalization prescription in AdS/CFT is revisited and refined, allowing one to distinguish between cut-off dependence in a conformal field theory (i) at a fixed point, (ii) in the presence of double trace couplings and (iii) in presence of contact counter terms.
- A holographic dual of Sachdev-Ye-Kitaev model is proposed, based on a two-dimensional gravity action in asymptotically AdS spaces. The low energy effective action is given in terms of a universal"Schwarzian" term and agrees with the SYK result.

3. Text

- **Cosmology and Astroparticle Physics**

Temporal Instabilities of Supernova Neutrinos

We performed a detailed study of a model where neutrinos are assumed to be emitted in a two-dimensional plane from an infinite line that acts as a neutrino antenna. We considered several examples with varying matter and neutrino densities and find that temporal instabilities with various frequencies are excited in a cascade. We compared the numerical calculations of the flavor evolution with the predictions of linearized stability analysis of the equations of motion. The results obtained with these two approaches are in good agreement in the linear regime, while a dramatic speed-up of the flavor conversions occurs in the non-linear regime due to the interactions among the different pulsating modes. We showed that large flavor conversions can take place if some of the temporal modes are unstable for long enough, and that this can happen even if the matter and neutrino densities are changing, as long as they vary slowly. [F. Capozzi (INFN, Italy), B. Dasgupta and A. Mirizzi (INFN, Italy)].

Fast Flavor Conversions in Supernovae

It had been recently pointed out that neutrino fluxes from a supernova can show substantial flavor conversions almost immediately above the core. We performed a detailed study of these fast conversions, focussing on the region just above the supernova core where flux ratios and angular asymmetries produce a crossing between the zenith-angle spectra of electron neutrinos and electron antineutrinos. Using fluxes and angular distributions predicted by supernova simulations, we found that fast conversions can occur within tens of nanoseconds, only a few meters away from the putative neutrinospheres. If these fast flavor conversions indeed take place, they would have important implications for the supernova explosion mechanism and nucleosynthesis. [B. Dasgupta, A. Mirizzi (INFN, Italy), and M. Sen].

Selection Rule for Sommerfeld Enhancement

We pointed out a selection rule for enhancement (suppression) of odd (even) partial waves of dark matter co/annihilation using Sommerfeld effect. Using this, the usually velocity-suppressed p-wave annihilation can dominate the annihilation signals in the present Universe. The selection mechanism is a manifestation of an exchange symmetry, and generic for multi-state DM with off-diagonal long-range interactions. As a consequence, the relic and late-time annihilation rates are parametrically different and a distinctive phenomenology, with large but strongly velocity-dependent annihilation rates, was predicted. [A. Das and B. Dasgupta].

Measuring the scale of homogeneity using multiple tracers from SDSS

Multifractal analyses of multiple tracers namely the main galaxy sample, the LRG sample and the quasar sample from the SDSS were carried out to test the assumption of cosmic homogeneity and identify the scale of transition to homogeneity, if any. The behaviour of the scaled number counts and the scaling relations of different moments of the galaxy number counts in spheres of varying radius *R* to calculate the spectrum of the Minkowski-Bouligand general dimension Dq (R) for $-4 \leq q \leq 4$ were considered. The analysis provided the opportunity to study the spectrum of the generalized dimension Dq(R) for multiple tracers of the cosmic density field over a wide range of length scales and allowed us to confidently test the validity of the assumption of cosmic homogeneity. Our analysis indicated that the SDSS main galaxy sample is homogeneous on a length scales of $80\,h^{-1}$ Mpc and beyond whereas the SDSS quasar sample and the SDSS LRG sample show transition to homogeneity on an even larger length scales at $150\,h^{-1}$ Mpc and $230\,h^{-1}$ Mpc respectively. These differences in the scale of homogeneity were shown to arise due to the effective mass and redshift scales probed by the different tracers in a Universe where structures form hierarchically. Our results reaffirmed the validity of cosmic homogeneity on large scales irrespective of the tracers used and strengthened the foundations of the Standard Model of Cosmology. [Subhabrata Majumdar with Prakash Sarkar (NIT, Jamshedpur), Biswajit Pandey (Visva-Bharati University), Atul Kedia (IIT Bombay) and Suman Sarkar (Visva-Bharati University)]

Little evidence for entropy and energy excess beyond r500 - an end to ICM pre-heating?

Non-gravitational feedback affects the nature of the intracluster medium (ICM). X-ray cooling of the ICM and in situ energy feedback from active galactic nuclei (AGNs) and supernovae as well as pre-heating of the gas at epochs preceding the formation of clusters are proposed mechanisms for such feedback. While cooling and AGN feedbacks are dominant in cluster cores, the signatures of a pre-heated ICM are expected to be present even at large radii. To estimate the degree of pre-heating, with minimum confusion from AGN feedback/cooling, we studied the excess entropy and non-gravitational energy profiles up to r200 for a sample of 17 galaxy clusters using joint data sets of Planck Sunyaev-Zeldovich pressure and ROSAT/Position Sensitive Proportional Counter gas density profiles. The canonical value of pre-heating entropy floor of >300 keV cm^2, needed in order to match cluster scalings, was ruled out at $\approx 3\sigma$. We also showed that the feedback energy of 1 keV particle-1 is ruled out at 5.2σ beyond r500. Our analysis took both non-thermal pressure and clumping into account which can be important in outer regions. This work based on the direct probe of the ICM in the outermost regions did not support any significant pre-heating. [Subhabrata Majumdar with Asif Iqbal (Kashmir University), Biman B Nath (RRI, Bangalore), Stefano Ettori (INFN Bologna), Dominique Eckert (University of Geneva) and Manzoor A. Malik (Kashmir University)].

Constraining the X-ray AGN halo occupation distribution: implications for eROSITA

The X-ray emission from active galactic nucleus (AGN) is a major component of extragalactic X-ray sky. The X-ray luminosity function (XLF) and halo occupation distribution (HOD) formalism was used to construct a halo model for the X-ray emission from AGNs. Verifying that the two inputs (XLF and HOD) are in agreement with each other, the auto-correlation power spectrum in the soft X-ray band (0.5-2 keV) was computed due to the AGNs potentially resolved by eROSITA (extended ROentgen Survey with an Imaging Telescope Array) mission and the redshift and mass dependence of the power spectrum were explored. Studying the relative contribution of the Poisson and the clustering terms to the total power, it was found that at multipoles $l \lesssim 1000$ (i.e. large scales), the clustering term is larger than the Poisson term. The potential of X-ray auto-correlation power spectrum and X-ray-lensing cross-correlation power spectrum using eROSITA and eROSITA-LSST (Large Synoptic Survey Telescope) surveys, respectively, to constrain the HOD parameters and their redshift evolution were also forecasted. In addition, the power spectrum of the AGNs lying below the flux resolution limit of eROSITA was computed, which is essential to understand in order to extract the X-ray signal from the hot diffuse gas present in galaxies and clusters. [Subhabrata Majumdar with Priyanka Singh (RRI), Alexandre Refrefier (ETH Zurich) and Biman B. Nath (RRI)]

Excess entropy and energy feedback from within cluster cores up to r_{200}

The non-gravitational entropy injection profiles and resulting non-gravitational energy feedback profiles of the intracluster medium for a sample of 17 clusters were estimated using the joint data sets of Planck SZ and ROSAT X-Ray observations, spanning a large radial range from 0.2 x r500 up to r200. We included that non-thermal pressure and clumping in our analysis since they become important at larger radii. The inclusion of non-thermal pressure and clumping resulted in changing the estimates for r500 and r200 by 10%-20%. We showed that neglect of clumping leads to an under-estimation of extra entropy by approximately 300 keV cm-squared at r500 and approximately 1100 keV cm-squared at r200. We conclusively showed that for the sample as a whole, an entropy floor excess of 300 keV cm-squared is ruled out at around 3-sigma throughout the entire radial range and hence strongly constraining all ICM pre-heating scenarios. For the estimated feedback energy profiles, we found that the neglect of clumping leads to an under- estimation of energy per particle of 1 keV at r500 and ≈ 1.5 keV at r200. Similarly, neglect of the non-thermal pressure results in an over-estimation of the non-gravitational energy of 0.5 keV at r500 and under-estimation of 0.25 keV at r200. We found that the average feedback energy per particle to be approximately 1 keV is also ruled out at more than 3-sigma beyond r500. We also demonstrated the robustness of our results w.r.t sample selection, X-Ray analysis procedures, non-radiative entropy modelling. [Subhabrata Majumdar with Asif Iqbal (Kashmir University), Biman B. Nath (RRI, Bangalore), Stefano Ettori (INFN Bologna), Dominique Eckert (University of Geneva) & Manzoor A. Malik (Kashmir University)]

Can Dark matter be an artifact of extended theories of gravity?

In this work, we propose different background models of extended theories of gravity, which are minimally coupled to the SM fields, to explain the possibility of genesis of dark matter without affecting the SM particle sector. We modify the gravity sector by allowing quantum corrections motivated from (1) f(R) gravity and (2) non-minimally coupled gravity with SM sector and dilaton field. We also show that an effective theory constructed from these extended theories of gravity and SM sector looks exactly the same. Using the relic constraint observed by Planck 2015, we constrain the scale of the effective field theory as well as the dark matter mass. We consider two cases- (1) light dark matter and (2) heavy dark matter, and deduce upper bounds on thermally averaged cross section of dark matter annihilating to SM particles. Further we show that our model naturally incorporates self interactions of dark matter. Using these self interactions, we derive the constraints on the parameters of the (1) f(R) gravity and (2) non-minimally coupled gravity from dark matter self interaction. Finally, we propose some different UV complete models, which can give rise to the same effective theory that we have deduced from extended theories of gravity. [S. Choudhury, M. Sen and S. Sadhukhan]

Bell violation in the Sky

In this paper, we have worked on the possibility of setting up an Bell's inequality violating experiment in the context of primordial cosmology following the fundamental principles of quantum mechanics. To set up this proposal we have introduced a model independent theoretical framework using which we have studied the creation of new massive particles for the scalar fluctuations in the presence of additional time dependent mass parameter. Next we explicitly computed the one point and two point correlation functions from this setup. Then we comment on the measurement techniques of isospin breaking interactions of newly introduced massive particles and its further prospects. After that, we give an example of string theory originated axion monodromy model in this context. Finally, we provide a bound on the heavy particle mass parameter for any arbitrary spin field. [S. Choudhury, S. Panda and R. Singh]

- **Condensed Matter and Statistical Physics**

Superconductivity from Doublon Condensation in Ionic Hubbard Model

In the ionic Hubbard model, the onsite repulsion U, which drives a Mott insulator and the ionic potential V, which drives a band insulator, compete with each other to open up a window of charge fluctuations when $U \sim V$. We studied this model on square and cubic lattices in the limit of large U and V, with $V \sim U$. Using an effective Hamiltonian and a slave boson approach with both doublons and holes, it was found that the system undergoes a phase transition as a function of V from an antiferromagnetic Mott insulator to a paramagnetic insulator with strong singlet correlations, which is driven by a condensate of "neutral" doublon-hole pairs. On further increasing V, the system undergoes another phase transition to a superconducting phase driven by condensate of "charged" doublons and holes. The superfluid phase, characterized by presence of coherent (but gapped) fermionic quasiparticle, and hc/e flux quantization, has a high $Tc \sim t$ which shows a dome shaped behaviour as a function of V. The paramagnetic insulator phase has a deconfined U(1) gauge field and associated gapless photon excitations.
[R. Sensarma, with A. Samanta]

From Immunity to Sudden Death: Strong Disorder in Strongly Correlated Superconductors

The effect of strong disorder on a system with strong electronic repulsion was investigated in this work. In absence of disorder, the system has a d-wave superconducting ground-state with strong non-BCS features due to its proximity to a Mott insulator. While strong correlations make superconductivity in this system immune to weak disorder, superconductivity is destroyed efficiently when disorder strength is comparable to the effective bandwidth. The suppression of charge motion in regions of strong potential fluctuation leads to formation of Mott insulating patches, which anchor a larger non-superconducting region around them. The system thus breaks into islands of Mott insulating and superconducting regions, with Anderson insulating regions occurring along the boundary of these regions. Thus, electronic correlation and disorder, when both are strong, aid each other in destroying superconductivity, in contrast to their competition at weak disorder. Our results shed light on why Zinc impurities are efficient in destroying superconductivity in cuprates, even though it is robust to weaker impurities. [R. Sensarma, with D. Chakraborty (IISER Kolkata) and A. Ghosal (IISER Kolkata)]

Dynamic transition of vortex lattice in Superconducting film with periodic arrays

It was shown that under an ac magnetic field excitation the vortex lattice in a superconductor with a periodic array of holes can undergo a transition from a Mott-like state where each vortex is localized in a hole, to a metal-like state where the vortices get delocalized. The vortex dynamics was studied through the magnetic shielding response which is measured using a low-frequency two-coil mutual inductance technique on a disordered superconducting NbN film having a periodic array of holes. It was observed that the shielding response of the vortex state is strongly dependent on the amplitude of the ac magnetic excitation. At low amplitude the shielding response varied smoothly with the excitation amplitude, corresponding to the elastic deformation of the vortex lattice. However, above a threshold value of excitation the response showed a series of sharp jumps, signaling the onset of the Mott-to-metal transition. A quantitative analysis revealed that this is a collective phenomenon which depends on the filling fraction of vortices in the antidot lattice. [R. Sensarma, with I. Roy, P. Chauhan, H. Singh, S. Kumar, J. Jesudasan, P. Parab, S. Bose and P. Raichaudhuri, TIFR]

Quantum Hall Effect in Trilayer Graphene

Experimental data obtained in Mandar Deshmukh’s lab in TIFR on quantum Hall effect in trilayer graphene showed interesting overlapping Landau fan diagram, evidence of broken symmetry states at very low magnetic fields and hysteretic behavior indicating the presence of quantum Hall ferromagnetism. A theory of quantum Hall effect, which included disorder in self-consistent Born approximation and Coulomb interactions within a static screened exchange approximation, was constructed, which explained the experimental data and showed that Landau level crossings was related to the oberlapping fan diagram, while Coulomb interactions are crucial in obtaining the broken symmetry states. [R. Sensarma, with S. Dey, A. Samanta, B. Datta, A. Borah, K. Watanabe (NIMS Japan), T. Taniguchi (NIMS Japan) and M. M. Deshmukh, TIFR]

Cluster algorithms for efficient and ergodic Monte Carlo simulations of frustrated Ising models

Two dual worm constructions were employed to develop cluster algorithms for efficient and ergodic Monte Carlo simulations of frustrated Ising models with arbitrary two-spin interactions that extend up to third-neighbours on the triangular lattice. One of these algorithms generalizes readily to other frustrated systems, such as Ising antiferromagnets on the Kagome lattice with further neighbour couplings. The performance of both these algorithms was analyzed in a challenging regime with power-law correlations at finite wavevector. [K. Damle and G. Rakala]

Physics of the "trimon",

A theoretical scheme was developed to model the physics of the "trimon", a multi-mode superconducting circuit implementing three qubits with all-to-all longitudinal coupling, developed in the group of R. Vijay. The theoretical approach was found to provide an excellent account of the key characteristics of the device, namely the self-Kerr and the cross-Kerr coeficients, and the harmonic mode frequencies. The procedure was also used to model generalizations of the trimon, currently under development in the group of R. Vijay. [K. Damle, Tanay Roy, Suman Kundu, Madhavi Chand, Sumeru Hazra, N. Nehra, R. Cosmic, A. Ranadive, Meghan P. Patankar, and R. Vijay]

Low-field magnetoresponse of strongly disordered two-dimensional superconductors

Strongly-disordered superconductors often exhibit a colossal positive magnetoresistance when subjected to small magnetic fields of the order of a tesla, with the resistance increasing by as much as four decades. To understand this mystery, we studied the role of weak magnetic fields in such systems through their twofold effect of diamagnetic orbital shrinking and geometric (Aharanov-Bohm) phase frustration. We analyzed the relative importance of these effects for thin films in physical regimes dominated by Coulomb blockade, thermal phase fluctuations and phase frustration respectively, using phenomenological and replica field theory approaches. We obtained the field dependences of superfluid stiffness and resistance. Our predicted low-field magnetoresistance is in quantitative agreement with experiment. [V. Tripathi and S. Sankar]

Disordered BKT transition and finite-temperature insulators

Strongly-disordered superconductor thin films under certain conditions have been recently reported to undergo a finite temperature transition to a state of apparent infinite resistivity following either the Berezinskii-Kosterlitz-Thouless (BKT) or an even more singular Vogel-Fulcher-Tammann (VFT) temperature dependence in the critical region. In this work, the authors constructed a 2D Josephson-junction model taking into account the effect of residual random dipole moments of the superconducting grains and showed, for weak Josephson coupling, it is equivalent to a Coulomb gas with logarithmically correlated disorder. They found that strong disorder results in a nonergodic regime which is associated with VFT instead of the usual BKT criticality, and propose that the experimentally observed VFT criticality corresponds to transition to a nonergodic insulator phase.
[V. Tripathi, S. Sankar and V. Vinokur (Argonne)]

Generalized arcsine law for fractional Brownian motion

The three arcsine laws for the standard Brownian motion are a cornerstone of extreme value statistics. For a Brownian motion starting from the origin, and evolving during time T, one can consider the following three observables: (i) the time the process is positive, (ii) the last time the process visits the origin, and (iii) the time it takes its maximum (or minimum). All three observables have the same cumulative probability distribution expressed as an arcsine function. We asked how these laws change for the fractional Brownian motion, which is a non-Markovian Gaussian process, indexed by the Hurst index H. It generalizes the standard Brownian motion (corresponding to H=1/2). Using a series expansion in $\alpha=H-1/2$, we obtained the corrections of the arcsine laws. We found that, for general H, all three probabilities are different and this distinction can only be made at the second order in α and beyond. Using extensive numerical simulations at different values of H, we measured precisely the probability, confirming our theoretical results. [Tridib Sadhu with Kay J Weise (ENS, Paris), submitted to Phys. Rev. Lett.]

- **High Energy Physics**

Neutrino mixing and R_K anomaly in $U(1)_X$ models: a bottom-up approach

A class of $U(1)_X$ models which can explain the R_K anomaly and the neutrino mixing pattern was identified by using a bottom-up approach. The different X-charges of lepton generations accounted for the lepton universality violation required to explain R_K. In addition to the three right-handed neutrinos needed for the Type-I seesaw mechanism, these minimal models only introduced an additional doublet Higgs and a singlet scalar. While the former helped in reproducing the quark mixing structure, the latter gave masses to neutrinos and the new gauge boson Z′. The bottom-up approach determined the X-charges of all particles using theoretical consistency and experimental constraints. The parameter space allowed by the constraints from neutral meson mixing, rare b→s decays and direct collider searches for Z′ were identified. Such a Z′ may be observable at the ongoing run of the Large Hadron Collider. [Disha Bhatia, Sabyasachi Chakraborty, and Amol Dighe]

Supersymmetric extension of the standard model with U(1)R

In this paper we proposed a supersymmetric extension of the Standard Model (SM) with a continuous global U(1)R symmetry. The R-charges of the SM fields are identified with that of their lepton numbers. As a consequence, a bi-linear "R-parity violating" term emerges at the superpotential. However, R-symmetry is not an exact symmetry as it is broken by supergravity effects. In such a limit, neutrino masses and mixing can be explained at the tree level itself. Moreover, the gravitino mass turns out to be the order parameter of R-breaking and directly related to the neutrino mass. To have thermal production of gravitinos, we require the gravitino mass to be >200 keV. We showed that such a gravitino is an excellent dark matter candidate and is safe from all constraints. Finally, we found that the model has interesting collider implications. [Sabyasachi Chakraborty, Joydeep Chakrabortty of IIT Kanpur]

Probing the nature of phases at finite isospin chemical potential

The baryon density-temperature (μ_B-T) phase diagram of quantum chromodynamics (QCD) has received a lot of attention in the recent past. The presence of a sign (phase) problem adds an extra layer of uncertainty in these results. On the other hand, no such problem exists for the isospin density-temperature (μ_I-T) case. Employing dynamical configurations on $24^3\times 6$ lattices, generated with a Symanzik improved action with 2 stout steps and for a quark mass tuned to have the physical pion mass, the the eigenvalue spectra of the Overlap Dirac operator was investigated both below and above the isospin breaking phase transition at a μ^c_I (= $m_{pi}/2$). Very small changes in the number of zero modes and low lying modes were found between μ_I/μ^c_I =0.5 and 1.5 which is in stark contrast with the corresponding finite temperature phases (with μ_I=0) where one sees a sharp drop across the phase transition. Further quantitative investigations in pinning down the changes in these modes may help in efforts to understand the difference in T and μ_I directions, if any. [G. S. Bali of University of Regensburg, R. Gavai, G. Endrodi of University of Regensburg and N. Mathur]

Quark number susceptibilities and equation of state at finite chemical potential

Investigation of quark number susceptibilities (QNS) has acquired huge importance since the early work of TIFR group on this subject. QNS are crucial ingredients in the determination of the phase diagram of QCD as well as the equation of state (EOS) of strongly interacting matter. They are also of interest in experimental studies of event-to-event fluctuations of conserved quantities as well. The temperature dependence of QNS was determined from simulations of QCD with two flavours of light dynamical staggered quarks at finite temperature on 8×32^3 lattices. From the radius of convergence of the Taylor expansion of the baryon number susceptibility, the critical end point was determined and found to be completely consistent with earlier result on a coarser lattice (N_t=6), suggesting the lattice spacing artifacts to be under reasonable control. A Pade approximant was employed to resum the series expansion and compute the equation of state at finite chemical potential, namely the baryon number density, its contribution to the pressure and the isothermal compressibility of QCD matter at finite baryon density. Finally, the freezeout conditions in heavy ion experiments were explored for measure of fluctuations and some sources of systematic and statistical errors in all of these measurements were examined. [Saumen Datta, Rajiv Gavai, and Sourendu Gupta]

Bayesian priors and nuisance parameters

Bayesian techniques are widely used to obtain spectral functions from correlators. We suggested a method to rid the results of nuisance parameters, ie, parameters which are needed for the regularization but cannot be determined from data. We gave examples where the method works, including a pion mass extraction with two flavours of staggered quarks at a lattice spacing of about 0.07 fm. We also gave an example where the method does not work. [Sourendu Gupta, Anirban Lahiri (currently in Univ. of Bielefeld, Germany)]

Statistical tweaks and flow scale from masses

We compared lattice scales determined from the vector meson mass and the Wilson flow scale in QCD with two-flavours of staggered quarks for a wide range of lattice spacing and quark mass. We find that the distributions of meson correlation functions are non-Gaussian. We modify the statistical analysis to take care of the non-Gaussianity. Current day improvements in the statistical quality of data on hadron correlations further allow us to simplify certain aspects of the analysis of masses. We examine these changes through the analysis of pions and apply them to the vector meson. We compare the flow scale determined using the rho mass with that using Λ_{QCD}. [Saumen Datta, Sourendu Gupta, Anirban Lahiri (currently in Univ. of Bielefeld, Germany) and Pushan Majumdar (of IACS, Kolkata)]

Probing Higgs-radion mixing in warped models through complementary searches at the LHC and the ILC

We considered the Higgs-radion mixing in the context of warped space extra dimensional models with custodial symmetry and investigate the prospects of detecting the mixed radion. Custodial symmetries allow the Kaluza-Klein excitations to be lighter, and protect $Zb\bar{b}$ to be in agreement with experimental constraints. We perform a complementary study of discovery reaches of the Higgs- radion mixed state at the 13 and 14 TeV LHC and at the 500 and 1000 GeV ILC. We carry out a comprehensive analysis of the most significant production and decay modes of the mixed radion in the 80 GeV − 1 TeV mass range, and indicate the parameter space that can be probed at the LHC and the ILC. There exists a region of the parameter space which can be probed, at the LHC, through the diphoton channel even for a relatively low luminosity of 50 fb inverse . [Mariana Frank of Concordia U., Katri Huitu of Helsinki U., Ushoshi Maitra, Monalisa Patra of Boskovic Inst.]

A Higgs in the Warped Bulk and LHC Signals

Warped models with the Higgs in the bulk can generate light Kaluza-Klein (KK) Higgs modes consistent with the electroweak precision analysis. The first KK mode of the Higgs (h1) could lie in the 1-2 TeV range in the models with a bulk custodial symmetry. We found that the h1 is gaugephobic and decays dominantly into a $t\bar{t}$ pair. We also discuss the search strategy for h1 decaying to $t\bar{t}$ at the Large Hadron Collider. We used substructure tools to suppress the large QCD background associated with this channel. We found that h1 can be probed at the LHC run-2 with an integrated luminosity of 300 fb inverse.
[F. Mahmoudi of Univ Lyon, U. Maitra, N. Manglani Mumbai U., K. Sridhar]

Dissecting new physics models through kinematic edges

In this work we proposed a scenario wherein these edges could be utilised in discriminating between different classes of models. To this effect, we consider the resonant production of a heavy Higgs like resonance (H1) as a case study. In the event of a discovery, it is essential to identify the true nature of the underlying theory. In this work we propose a channel, H1 → t2 t, where t2 is a vector-like gauge singlet top-partner that decays into W b, Zt, ht. Invariant mass distributions constructed out of these final states are characterized by the presence of kinematic edges, which are unique to the topology under consideration. The absence of these edge like features, in the specific invariant mass distributions considered here, in minimal versions of supersymmetric models (MSSM) also serves as a harbinger of such non MSSM-like scenarios. [Abhishek Iyer, Ushoshi Maitra]

Mixed Higgs-Radion States at the LHC – A detailed Study

Light radions constitute one of the few surviving possibilities for observable new particle states at the sub-TeV level which arise in models with extra spacetime dimensions. It is already known that the 125 GeV state discovered at CERN is unlikely to be a pure radion state, since its decays resemble those of the Standard Model Higgs boson too closely. However, due to experimental errors in the measured decay widths, the possibility still remains that it could be a mixture of the radion with one (or more) Higgs states. We use the existing LHC data at 8 and 13 TeV to make a thorough investigation of this possibility. We then make a detailed study of the so-called ‘conformal point’, where this heavy state practically decouples from (most of) the Standard Model fields. Some projections for the future are also included. [Amit Chakraborty, Ushoshi Maitra, Sreerup Raychaudhuri, Toushik Samui]

Charmed-bottom hadrons from lattice QCD

We calculated ground state spectra of mesons containing a charm and a bottom quark. For the charm quark we used overlap valence quarks while a non-relativistic formulation was utilized for the bottom quark on a background of 2+1+1 flavors HISQ gauge configurations generated by the MILC collaboration. The hyperfine splitting between 1S states of B_c mesons was found to be 56^{+5}_{-4} MeV. The prediction for the B^*_c meson and the triply bottom baryon (Ω_{bbb}), which are yet to be discovered, are 6331^{+5}_{-4} MeV and 14362^{+6}_{-5} MeV respectively. We also studied the baryons containing only charm and bottom quarks and predicted their ground state masses. [N. Mathur, M. Padmanath of Regensburg U., Randy Lewis of York U., Canada.]

Flavour-changing neutral currents

If the LHC fails to find direct signals for new particles, the only way to look for them would be to study rare processes where the Standard Model contribution is heavily suppressed and heavy new particles make considerable contributions to one-loop induced processes. The most promising among these for discovery at the LHC are top quark decays through flavour-changing neutral currents (FCNC). A thorough investigation of these was carried out and it was found that observable signals require three suppression mechanisms of the Standard Model to be violated by any new physics model. This conclusion was validated by studying supersymmetric model with and without R-parity conservation. In the process, the current constraints on R-parity-violating constraints were also updated using current LHC sparticle bounds. This work sets up a useful framework to discuss one-loop induced FCNC processes involving the top quark. [Debjyoti Bardhan, Gautam Bhattacharyya of SINP, Diptimoy Ghosh of Weizmann Institute of Science, Monalisa Patra of Boskovic Inst., and Sreerup Raychaudhuri]

On the R-symmetric minimal supersymmetric Standard Model

The R-symmetric minimal supersymmetric Standard Model gives a natural explanation for the feature that the scalar partners of the top quark can be light – as demanded by the Higgs mass constraint – in spite of the gluinos being very heavy. However, to avoid having observably light charginos, one requires to add two scalar doublets to the theory, which would have distinctive signatures. It was shown that the model parameters could be easily tuned to explain the erstwhile 750 GeV diphoton resonance at CERN. Though the signal has disappeared, much of the analysis can be carried over to a more general analysis of the phenomenology of this interesting variant of supersymmetry. [Amit Chakraborty, Sabyasachi Chakraborty, and Sreerup Raychaudhuri]

Cautionary tale of mismeasured tails from q/g bias

Jet substructure techniques such as subjet p_T-asymmetry, mass-drop, and grooming have become powerful and widely used tools in experimental searches at the LHC. While these tools provide much-desired handles to separate signal from background, they can introduce unexpected mass scales into the analysis. These scales may be misinterpreted as excesses if these are not correctly incorporated into background modeling. As an example, we studied the ATLAS hadronic di-W/Z resonance search. There, we found that the substructure analysis—in particular the combination of a subjet asymmetry cut with the requirement on the number of tracks within a jet—induces a mass scale where the dominant partonic subprocess in the background changes from $pp\to g+q/\bar{q}$ to $pp\to q+\bar{q}$. In light of this scale, we showed that modeling the QCD background using a simple smooth function with monotonically decreasing slope (as was done by the experimental collaboration) was insufficient. [Adam Martin of Notre Dame U. and Tuhin S. Roy]

Chasing New Physics in Stacks of Soft Tracks

In this paper, we introduced a new variable ξ, namely, the number of tracks associated with the primary vertex, which are not parts of reconstructed objects such as jets, isolated leptons, etc. We demonstrated its usefulness in the context of new physics searches with compressed spectrum in the channel monojet+missing transverse momentum (MET). In models such as in compressed supersymmetry, events are often characterized by a rather large number of soft partons from the cascade decays, none of which results in reconstructed objects. We found that ξ, binned in p_T, can discriminate these new physics events from events due to Z+jets, that is, the main background in the channel monojet+MET (see Figure 1). Further, we reported that the information contained in soft tracks to be largely uncorrelated with traditional variables such as the effective mass, MET, p_T of the jet, etc., and, therefore, can be combined with these to increase the discovery potential by more than 300% (depending on the spectra, of course). In fact we found that simple cuts on $\xi(p_T)$, when combined with cuts on the effective mass, outperforms sophisticated optimized Multivariate Data Analysis using all conventional variables. Additional virtues of using $\xi(p_T)$ as a new observable are: (i) one can model the background distribution of $\xi(p_T)$ in an entirely data-driven way, and (ii) these could be made robust against pileup by identifying the primary vertex. [Amit Chakraborty, Sabyasachi Chakraborty, and Tuhin S. Roy]

Augmenting Collider Searches and Enhancing Discovery Potentials through Stochastic Jet Grooming

The jet trimming procedure has been demonstrated to greatly improve event reconstruction in hadron collisions by mitigating contamination due initial state radiation, multiple interactions, and event pileup. Meanwhile, Qjets—a nondeterministic approach to tree-based jet substructure—has been shown to be a powerful technique in decreasing random statistical fluctuations, yielding significant effective luminosity improvements. This manifests through an improvement in the significance $S/\delta B$, relative to conventional methods. Qjets also provides novel observables in many cases, like mass-volatility, that could be used to further discriminate between signal and background events. The statistical robustness and volatility observables, for tagging, are obtained simultaneously. We explored a combination of the two techniques, and demonstrated that significant enhancements in discovery potentials may be obtained in nontrivial ways. We illustrated this by considering a diboson resonance analysis as a case study, which enabled us to interpolate between scenarios where the gains are purely due to statistical robustness and scenarios where the gains are due to the use of volatility variable discriminants. The former, for instance, is applicable to digluon/diquark resonances, while the latter will be of relevance for di-$W_{\pm}$/di-Z resonances, where the boosted vector bosons are decaying hadronically and have an intrinsic mass scale attached to them. We argue that one can enhance signal significance and discovery potentials markedly through stochastic grooming, and help augment studies at the Large Hadron Collider and future hadron colliders. [Tuhin S. Roy and Arun M. Thalapillil of Rutgers U., Piscataway & IISER, Pune]

Calculation of the dynamic structure factor of a strongly correlated Fermi superfluid

within a density functional theory approach

We theoretically investigated the dynamic structure factor of a strongly interacting Fermi gas at the crossover from Bardeen–Cooper–Schrieffer superfluids to Bose–Einstein condensates, by developing an improved random phase approximation within the framework of a density functional theory (DFT)—the so-called superfluid local density approximation. Compared with the previous random-phase-approximation studies based on the standard Bogoliubov–de Gennes equations, the use of the DFT greatly improves the accuracy of the equation of state at the crossover, and leads to a better description of both collective Bogoliubov-Anderson-Goldstone phonon mode and single-particle fermionic excitations at small transferred momentum. Near unitarity, where the s-wave scattering length diverges, we showed that the single-particle excitations start to significantly contribute to the spectrum of dynamic structure factor once the frequency is above a threshold of the energy gap at 2Delta. The sharp rise in the spectrum at this threshold can be utilized to measure the pairing gap Delta. Together with the sound velocity determined from the phonon branch, the dynamic structure factor provides us some key information of the crossover Fermi superfluid. Our predictions could be examined in experiments with (6)Li or (40)K atoms using Bragg spectroscopy. [Peng Zou of Centre for Quantum and Optical Science, Melbourne, Franco Dalfovo of Università di Trento, Rishi Sharma, Xia-Ji Liu of Centre for Quantum and Optical Science, Melbourne, Hui Hu of Centre for Quantum and Optical Science, Melbourne]

A Proposal for measuring Anisotropic Shear Viscosity in Unitary Fermi Gases

We presented a proposal to measure anisotropic shear viscosity in a strongly interacting, ultra-cold, unitary Fermi gas confined in a harmonic trap. We introduced anisotropy in this setup by strongly confining the gas in one of the directions with relatively weak confinement in the remaining directions. This system has a close resemblance to anisotropic strongly coupled field theories studied recently in the context of gauge-gravity duality. Computations in such theories (which have gravity duals) revealed that some of the viscosity components of the anisotropic shear viscosity tensor can be made much smaller than the entropy density, thus parametrically violating the famous bound proposed by Kovtun, Son and Starinets (KSS). We performed a Boltzmann analysis in a system of weakly interacting particles in a linear potential also shows that components of the viscosity tensor can be reduced. Motivated by these exciting results, we proposed two hydrodynamic modes in the unitary Fermi gas whose damping is governed by the component of shear viscosity expected to violate the KSS bound. One of these modes is the well known scissor mode. We estimated trap parameters for which the reduction in the shear viscosity is of order unity and find that the trap geometry, the damping timescales, and mode amplitudes are within the range of existing experimental setups on ultra-cold Fermi gases. [Rickmoy Samanta of TIFR and Bar Ilan U., Rishi Sharma, Sandip P. Trivedi]

Calculation of the shear viscosity of two-flavor crystalline color superconducting quark matter

We performed the first calculation of the shear viscosity for two-flavor plane wave (FF) color superconducting quark matter. This is a member of the family of crystalline color superconducting phases of dense quark matter that may be present in the cores of neutron stars. The paired quarks in the FF phase feature gapless excitations on surfaces of crescent shaped blocking regions in momentum space and participate in transport. We calculated their contribution to the shear viscosity. We noted that they also lead to dynamic screening of transverse t1, t2, t3 gluons which are undamped in the 2SC phase. The exchange of these gluons is the most important mechanism of the scattering of the paired quarks. We found that the shear viscosity of the paired quarks is roughly a factor of 100 smaller compared to the shear viscosity of unpaired quark matter. Our results may have implications for the damping of r−modes in rapidly rotating, cold neutron stars. [Sreemoyee Sarkar of TIFR and Mumbai U. and Rishi Sharma]

Collider probes of the Inert Doublet Model

An interesting extension of the electroweak symmetry-breaking sector is the Inert Doublet Model (IDM) which is a two-higgs doublet model appended with a discrete symmetry so that one of the Higgs doublet fields does not have any direct interaction with the matter particles of the Standard Model and couples only to the gauge sector. The dijet + missing transverse energy channel at the Large Hadron Collider was proposed as an effective way of searching for the scalar particles of the IDM. This channel receives contributions from gauge boson fusion, and t−t−channel production, along with contributions from H+H+ associated production. For $\sqrt{s}$=13TeV with moderate luminosity, this channel has the potential to probe the IDM in the mass range of up to about 150 GeV, complementing other leptonic channel searches. [K. Sridhar]

Light Higgs KK modes in warped extra dimensions

Models of warped extra dimensions with the Standard Model fields in the bulk are consistent with constraints from electroweak precision if a bulk custodial symmetry is invoked. In these models, it is interesting to consider the Higgs in the bulk. We have shown that the

Higgs KK mode can be quite light (lighter than the corresponding gauge KK mode) in some regions of the parameter space. For the Higgs KK mode of such a mass, we suggest strategies that will help pin down the search for this resonance at the Large Hadron Collider. [K. Sridhar]

- **String Theory and Mathematical Physics**

Long distance Thermal behaviour of the Klebanov-Witten-Gurav SYK model

The Klebanov-Witten-Gurav model – whose dynamics reduces to that of the SYK model at large N – was studied. It was demonstrated the effective action for thermal physics in this model includes a sigma model for the group symmetry $U(N)^{q-1}$ in addition to the Schwarzian action for diffeomorphisms previously uncovered in the SYK model. These modes dominate the four point functions of operators over an intermediate time period whose duration goes to infiinty in the strict large *N* limit. It is also demonstrated that a mass deformed version of the Klebanov-Witten-Gurav model has a spectrum whose growth with energy is faster than Hagedorn. [R. Poojary, S. Minwalla, I. Haldar, L. Janagal, A. Dey, S. Choudhury, S. Mazumdar]

Gauge/gravity dualty

(a) Gravity dual to SYK models:

The Sachdev-Ye-Kitaev model has emerged as a possible, simple workable model of AdS/CFT. The model describes a large number of fermionic particles with a random coupling. It has been found that at strong coupling it exhibits approximate one-dimensional reparametrization invariance, and that the correlators show chaotic behaviour with a maximum Liapunov exponent characterstic of gravity. In this work a gravity dual in two-dimensional anti de Sitter space is proposed, which correctly reproduces these two features. It is found that the low energy physics is described by pseudo Nambu-Godstone modes governed by a universal action in the form of a Schwarzian. (Gautam Mandal, Pranjal Nayak and Spenta R. Wadia)

(b) Revisiting AdS/CFT at a finite radial cut-off:

The AdS/CFT prescription, which relates properties of a CFT to those of an anti de Sitter space, requires the use of a radial cut-off since geometrical quantities typically diverge when the radial coordinate goes to infinity. Finite CFT correlators are obtained from bulk calculations after suitable applications of holographic counterterms. In the present work, it is shown that at finite cut-off the holographic renormalization techniques need certain careful refinements without which correlators and beta-functions get spurious contributions involving contact terms and double trace operators. (Gautam Mandal, Pranjal Nayak)

<u>Thermalization</u>

Finite size effect on dynamical entanglement entropy: CFT and holography

Time-dependent entanglement entropy (EE) is computed for a single interval in two-dimensional conformal theories from a quenched initial state in the presence of spatial boundaries. The EE is found to be periodic in time with periodicity equal to the system size L. For large enough L, the EE shows a rise to a thermal value (characterized by a temperature determined by the initial state), followed by periodic returns to the original value. This works irrespective of whether the conformal field theory (CFT) is rational or irrational. For conformal field theories with a holographic dual, the large central charge limit plays an essential role in ensuring that the EE computed from the CFT is universal (independent of the details of the CFT and of boundary conditions) and is exactly matched by the holographic EE. The dual geometry is computed and it interpolates between a BTZ black hole at large L and global AdS at low temperature. Gautam Mandal, Ritam Sinha, and Tomonori Ugajin (Santa Barbara))

<u>Review article on Wilson's contributions (in *Resonance*})</u>

The Wilsonian revolution in statistical mechanics and quantum field theory:

It is described how Wilson's concept of the renormalization group revolutionized our understanding of the physics of phase transitions, and of quantum field theory in general. The article underlines the key ideas of Wilso, based on earlier ideas of Landau, Ginzburg, Kadanoff and many others, which led to an insight into the observed universality of diverse physical phenomena, and the remarkable efficacy of a few simple models to describe them (Gautam Mandal).

<u>The Charged Black Hole Membrane paradigm</u>

The effective dynamics of black hole horizons in Einstein-Maxwell theory is studied in a large number of spacetime dimensions D. It is demonstrated that horizon dynamics may be recast as a well posed initial value problem for the motion of a codimension one non gravitational membrane moving in flat space. The dynamical degrees of freedom of this membrane are its shape, charge density and a divergence free velocity field. The equations that govern membrane dynamics are determine at leading order in the large D expansion. Our derivation of the membrane equations assumes that the solution preserves an SO(D - p - 2) isometry with p held fixed as D is taken to infinity. The final membrane equations are cast into a completely geometric form that makes no reference to this symmetry algebra. (Shiraz Minwalla with

Sayantani Bhattacharyya (Indian Inst. Tech., Kanpur), Mangesh Mandlik and Somyadip Thakur).

The Black Hole Membrane paradigm at higher order in 1/D

In the large D limit, and under certain circumstances, it has recently been demonstrated that black hole dynamics in asymptotically flat spacetime reduces to the dynamics of a non gravitational membrane propagating in flat D dimensional spacetime. In this work it is demonstrated that this correspondence extends to all orders in a 1 /D expansion and outline a systematic method for deriving the corrected membrane equation in a power series expansion in 1 /D. As an illustration of our method the first subleading corrections to the membrane equations of motion are determined. A qualitatively new effect at this order is that the divergence of the membrane velocity is nonzero and proportional to the square of the shear tensor reminiscent of the entropy current of hydrodynamics. As a test, the modified membrane equations are used to compute the corrections to frequencies of light quasinormal modes about the Schwarzschild black hole and perfect match with earlier computations is found. (Shiraz Minwalla with Yogesh Dandekar, Anandita De (IISER, Pune), Subhajit Mazumdar and Arunabha Saha.).

Black branes from Membranes

It has recently been demonstrated that the dynamics of black holes at large D can be recast as a set of non gravitational membrane equations. These membrane equations admit a simple static solution with shape S D- p-2× R p,1. In this note the equations for small fluctuations about this solution are studieed in a limit in which amplitude and length scale of the fluctuations are simultaneously scaled to zero as D is taken to infinity. It is demonstrated that the resultant nonlinear equations, which capture the Gregory-Laflamme instability and its end point, exactly agree with the effective dynamical `black brane' equations of Emparan Suzuki and Tanabe. Our results thus identify the `black brane' equations as a special limit of the membrane equations and so unify these approaches to large D black hole dynamics (Shiraz Minwalla with Yogesh Dandekar, Subhajit Mazumdar and Arunabha Saha).

Currents and Raduiations from the large D black hole membrane

It has recently been demonstrated that black hole dynamics in a large number of dimensions D reduces to the dynamics of a codimension one membrane propagating in flat space. In this paper a stress tensor and charge current on this membrane are defined and explicitly computed at low orders in the expansion in 1/D. It is demonstrated that dynamical membrane equations of motion derived in earlier work are simply conservation equations for our stress tensor and charge current. Through the paper attention is focussed on solutions of the membrane equations which vary on a time scale of order unity. Even though the charge current and stress tensor are not parametrically small in such solutions, we show that the radiation sourced by the corresponding membrane currents is generically of order $1/D^D$. In this regime it follows that the `near horizon' membrane degrees of freedom are decoupled from asymptotic flat space at every perturbative order in the 1/D expansion. An entropy current on the membrane is also defined and the Hawking area theorem is used to demonstrate that the divergence of the entropy current is point wise non negative. This result is a local form of the second law of thermodynamics for membrane motion. (Shiraz Minwalla with Anup Kumar Mandal (Indian Inst. Tech., Kanpur), Mangesh Mandlik, Umang Mehta (Indian Inst. Tech., Mumbai), Utkarsh Sharma (Indian Inst. Tech., Mumbai) and Somyadip Thakur).

Ward identities for scale and special conformal transformations in inflation

The general Ward identities for scale and special conformal transformations in theories of single field inflation are derived. This analysis is model independent and based on symmetry considerations alone. The identities obtained are valid to all orders in the slow roll expansion. For special conformal transformations, the Ward identities included a term which was non-linear in the fields that arose due to a compensating spatial reparametrization. Some observational consequences were also discussed. (Sandip Trivedi with N. Kundu and A. Shukla).

Aspects of entanglement entropy for gauge theories

A definition for the entanglement entropy in a gauge theory was given recently. Working on a spatial lattice, it involved embedding the physical state in an extended Hilbert space obtained by taking the tensor product of the Hilbert space of states on each link of the lattice. The extended Hilbert space admits a tensor product decomposition by definition and allowed a density matrix and entanglement entropy for the set of links of interest defined. The study of the extended Hilbert space definition is continued with particular emphasis on the case of Non-Abelian gauge theories.

The electric centre definition of Casini, Huerta and Rosabal is extended to the Non-Abelian case and it is found that it differs in an important term. It is also found that the entanglement entropy does not agree with the maximum number of Bell pairs that can be extracted by the processes of entanglement distillation or dilution, and gave protocols which achieved the maximum bound. Finally, the topological entanglement entropy that follows from the extended Hilbert space definition is computed and it is shown that it correctly reproduces the total quantum dimension in a class of Toric code models based on Non-Abelian discrete groups. (Sandip Trivedi with R. Soni)

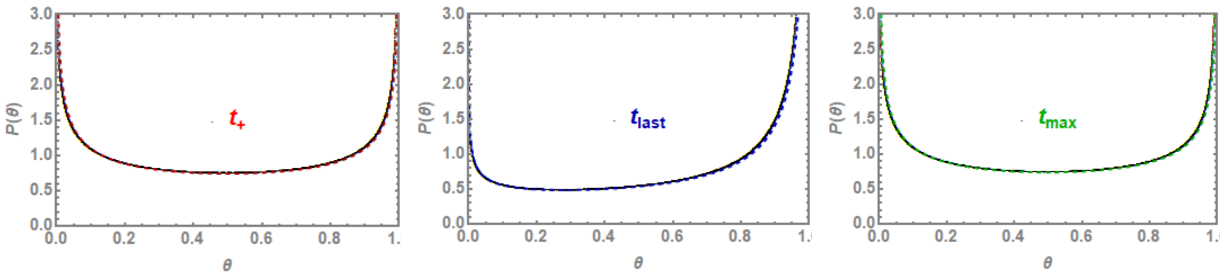
Symmetry contraints in inflation, α-vacua, and the three point function

The Ward identities for conformal symmetries in single field models of inflation are studied in more detail in momentum space. For a class of generalized single field models, where the inflation action contains arbitrary powers of the scalar and its first derivative, it is shown that the Ward identities are valid. A one-parameter family of vacua, called α-vacua, which preserve conformal invariance in de Sitter space, is studied. It is demonstrated that the Ward identities, upto contact terms, are obeyed for the three point function of a scalar field in the probe approximation in these vacua. Interestingly, the corresponding non-Gaussian term in the wave function does not satisfied the operator product expansion. For scalar perturbations in inflation, in the α-vacua, it is found that the Ward identities are not satisfied. It is argued that this is a consequence of the back-reaction on the metric of the full quantum stress tensor not being accounted for. Drawing on techniques from the AdS/CFT correspondence, a calculation for the for the three point function of scalar perturbations in inflation in the Bunch-Davis vacuum is also presented (Sandip Trivedi with A. Shukla and V. Vishal)

Entanglement entropy in (3+1)-d free U(1) gauge theory

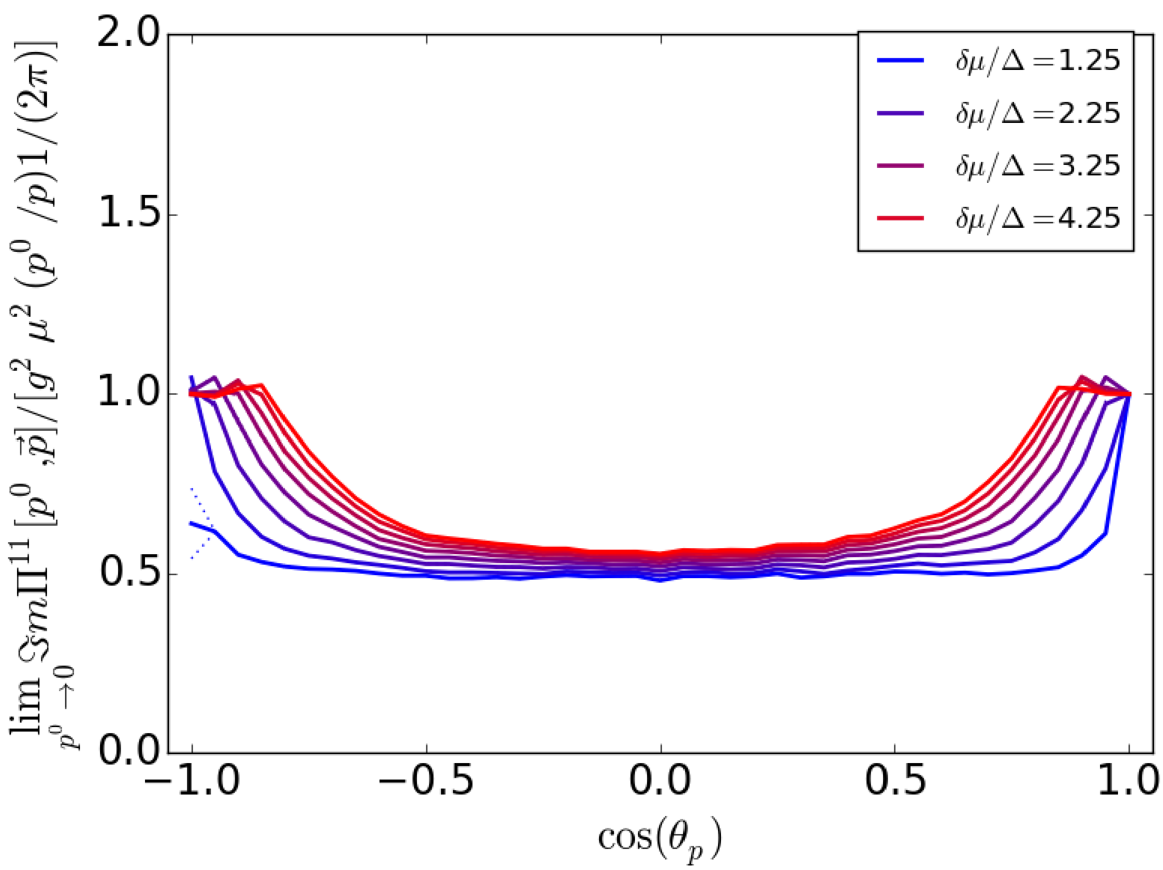
The entanglement entropy for a free U(1) theory in 3 + 1 dimensions in the extended Hilbert space definition is considered. By taking the continuum limit carefully, a replica trick path integral which calculates the entanglement entropy is obtained. The path integral is gauge invariant, with a gauge fixing delta function accompanied by a Faddeev-Popov determinant. For a spherical region it follows that the result for the logarithmic term in the entanglement, which is universal, is given by the a anomaly coefficient. The extractable part of the entanglement, which corresponds to the number of Bell pairs which can be obtained from entanglement distillation or dilution, is also considered. For a spherical region it is shown that the coefficient of the logarithmic term for the extractable part is different from the extended Hilbert space result. It is argued that the two results will differ in general, and this difference is accounted for by a massless scalar living on the boundary of the region of interest (Sandip Trivedi with R. Soni).

4. **Figure/Photograph Captions**



Caption: The figures show a comparison of our theoretical result of the three probabilities with their numerical simulation result: (a) for time spent on the positive half, (b) time of last visit to the origin, (c) time when the process attained maximum.

(Page 12 "Generalized arcsine law for fractional Brownian motion")



Caption: Damping coefficient of the transverse polarization components in the FF phase for the t^1, t^2, t^3 gluons as a function of the cosine of the angle between the momentum direction and the z axis. From:https://doi.org/10.1140/epja/i2017-12249-x

(Page 20 "Calculation of the shear viscosity of two-flavor crystalline color superconducting quark matter")