# TIFR Annual Report (2012-13) - Department of Theoretical Physics

## String Theory and Mathematical Physics

### Gauge Theories

The thermal partition function of level $k$ $U(N)$ Chern-Simons theories on $S^2$, interacting with matter in the fundamental representation, was studied in the 't Hooft limit, $N, k \to \infty$, with $\lambda = N/k$ and $T^2$ $V_2$ $N$ held fixed ($T$ is the temperature and $V_2$ the volume of the sphere). The partition function was shown to be related to the expectation value of a potential function of the $S^1$ holonomy in pure Chern-Simons theory, which was computed in several examples as a function of $\lambda$. Level rank duality of pure Chern-Simons theory was used to demonstrate the equality of thermal partition functions of previously conjectured dual pairs of theories as a function of the temperature. The summation over flux sectors quantizes the eigenvalues of the holonomy matrix in units of $2\pi k$, while the eigenvalue density of the holonomy matrix is bounded from above by $1/(2\pi\lambda)$. The corresponding matrix integrals generically undergo two phase transitions as a function of temperature. For several Chern-Simons-matter theories it is possible to exactly solve the relevant matrix models in the low temperature phase, and determine the phase transition temperature as a function of $\lambda$. At low temperatures the partition function smoothly matches onto the $N$ and $\lambda$ independent free energy of a gas of non renormalized multi trace operators. Finally, as a simple illustration, an exact solution was found to a simple toy matrix model, namely the large N Gross-Witten-Wadia matrix integral, subject to an upper bound on eigenvalue density. [Sachin Jain, Shiraz Minwalla, Tarun Sharma, Tomohisa Takimi, Spenta R. Wadia, Shuichi Yokoyama]

Thermal $\mathcal{N} = 2$ Supersymmetric Chern-Simons theory was studied in the large $N$ limit using a generalization of the standard Huddard-Stratanovich technique for arbitrary polynomial interactions within the functional integral approach. [Sachin Jain, Sandip P. Trivedi, Spenta R. Wadia, Shuichi Yokoyama]

A study was carried out of $SU(N)$ level $k$ Chern-Simons theories coupling to a fundamental fermion with chemical potential for $U(1)$ flavor symmetry. Determination of various quantities such as the exact propagator and grand-canonical potential was made in the 't Hooft limit. The system was shown to effectively

behave as free fermion system, which is consistent with the fact that this system preserves higher spin symmetry in the 't Hooft limit. [Shuichi Yokoyama]

A simple non-perturbative formulation was provided for non-commutative four-dimensional $\mathcal{N} = 2$ supersymmetric Yang-Mills theories. The formulation was constructed by a combination of deconstruction (orbifold projection), momentum cut-off and matrix model techniques. A moduli xing term was proposed that preserves lattice supersymmetry on the deconstruction formulation. Although the analogous formulation for four-dimensional $\mathcal{N} = 2$ supersymmetric Yang-Mills theories has been proposed earlier, the action in this work was simpler and better suited for computer simulations. Beyond the non-commutative theories, this formulation also has a potential to be a non-perturbative tool for the commutative four-dimensional $\mathcal{N} = 2$ supersymmetric Yang-Mills theories. [Tomohisa Takimi]

**Fluid Dynamics**

The thermal partition function of quantum field theories on arbitrary stationary background spacetime, and with arbitrary stationary background gauge fields, was studied in the long wavelength expansion. It was found that the equations of relativistic hydrodynamics are significantly constrained by the requirement of consistency with any partition function. Examples at low orders in the derivative expansion demonstrated that these constraints coincide precisely with the equalities between hydrodynamical transport coefficients that follow from the local form of the second law of thermodynamics. In particular the results of Son and Surowka were recovered on the chiral magnetic and chiral vorticity flows, starting from a local partition function that manifestly reproduces the field theory anomaly, without making any reference to an entropy current. It is conjectured that the relations between transport coefficients that follow from the second law of thermodynamics agree to all orders in the derivative expansion with the constraints described in this paper. [Sachin Jain, Shiraz Minwalla and Tarun Sharma, with Nabamita Banerjeea (Utrecht), Jyotirmoy Bhattacharya (IPMU), Sayantani Bhattacharyya (HRI)].

Following up on the above work in the context of ordinary fluids, the equilibrium partition function of a 3+1 dimensional superfluid was studied on an arbitrary stationary background spacetime, and with arbitrary stationary background gauge fields, in the long wavelength expansion. It was argued that this partition function is generated by a 3 dimensional Euclidean effective action for the massless Goldstone field. The general form of this action at first order in the derivative expansion was parametrized. It was found that the constitutive relations of relativistic superfluid hydrodynamics are significantly constrained by the requirement of consistency with such an effective action. At first order in the derivative expansion it was found that the resultant constraints on constitutive relations coincide precisely with the equalities between hydrodynamic [Sachin Jain, Shiraz Minwalla and Tarun Sharma, with Sayantani Bhattacharyya (HRI)].

**Cosmology**

The consequences of conformal invariance were explored for correlation functions of perturbations produced during inflation. It was shown that conformal invariance fixes the form of a particular three point function involving two scalars and one tensor perturbation completely. [Sandip Trivedi and Ishan Mata, with Suvrat Raju (ICTS)]

**Non-equilibrium Dynamics**

Quantum quench dynamics was considered in a one dimensional unitary matrix model with a single trace potential. This model is integrable and has been studied in the context of non-critical string theory. This work studied dynamical phase transitions, and the role of the quantum critical point in a quantum quench. In course of the time evolution, evidence was found of selective equilibration for a certain class of observables. The equilibrium is governed by the Generalized Gibbs Ensemble (GGE) and differs from the standard Gibbs ensemble. It was found that the equilibration amounts to the production of entropy which is O(N) for large N matrices. An important feature of the equilibration is the appearance of an energy cascade, reminiscent of the Richardson cascade in turbulence, where energy flows from initial long wavelength modes to progressively shorter wavelength excitations. Possible implications were discussed of the equilibration and of GGE in string theories and higher spin theories. In another related study, time evolutions were discussed in a double trace unitary matrix model, which arises as an effective theory of D2 branes in IIA string theory in the confinement phase. Equilibrations and dynamical transitions in this matrix model were found, in close similarity with the single trace model discussed above. The dynamical transitions are related to Gregory-Laflamme transitions in string theory and are potentially connected with the issue of appearance of naked singularities [G. Mandal, with T. Morita (KEK)].

Nonequilibrium dynamics in various isolated systems was studied. Such studies have recently attracted a lot of attention. Besides a renewed interest in understanding relaxation and approach to equilibrium in macroscopic isolated systems, an added motivation is to apply these ideas to strongly coupled theories using the AdS/CFT conjecture. The hope (in string theory community) is that such studies will shed some light on the question of thermalization in the context of black hole formation. [A. Dhar]

**Gauge-gravity duality**

**From higher spin gravity to Strings**

It was shown that a supersymmetric and parity violating version of Vasilievs higher spin gauge theory in AdS4 admits boundary conditions that preserve $\mathcal{N}$ = 0, 1, 2, 3, 4 or 6 supersymmetries. In particular, it was argued that the Vasiliev theory with $U(M)$ Chan-Paton and $\mathcal{N} = 6$ boundary condition is holographically dual to the 2+1 dimensional $U(N)_k \times U(M)_k$ ABJ theory in the limit of large $N, k$ and finite $M$. In this system, all bulk higher spin fields transform in the adjoint of the $U(M)$ gauge group, whose bulk 't Hooft coupling is

$M/N$. Analysis of boundary conditions in Vasiliev theory allows determination of exact relations between the parity breaking phase of Vasiliev theory and the coefficients of two and three point functions in Chern-Simons vector models at large N. This picture suggests that the supersymmetric Vasiliev theory can be obtained as a limit of type IIA string theory in $AdS_4 \times CP^3$, and that the non-Abelian Vasiliev theory at strong bulk 't Hooft coupling smoothly turns into a string field theory. The fundamental string is a singlet bound state of Vasilievs higher spin particles held together by $U(M)$ gauge interactions. This was illustrated by the thermal partition function of free ABJ theory on a two sphere at large M and N, in the analytically tractable free limit. In this system, the traces or strings of the low temperature phase break up into their Vasiliev particulate constituents at a U(M) deconfinement phase transition of order unity. At a higher temperature, of order $T = \sqrt{N/M}$, Vasiliev's higher spin fields themselves break up into more elementary constituents at a U(N) deconfinement temperature, in a process described in the bulk as black hole nucleation. [Shiraz Minwalla and Tarun Sharma, with Chi-Ming Chang (Harvard), and Xi Yin (Harvard)]

**Applications to Condensed Matter Theory**

Einstein-Maxwell theory coupled to a dilaton is known to give rise to extremal solutions with hyperscaling violation. A study was carried out of the behaviour of these solutions in the presence of a small magnetic field. It was found that in a region of parameter space the magnetic field is relevant in the infra-red and completely changes the behaviour of the solution which now flows to an $AdS_2 \times R^2$ attractor. As a result there is an extensive ground state entropy and the entanglement entropy of a sufficiently big region on the boundary grows like the volume. In particular, this happens for values of parameters at which the purely electric theory has an entanglement entropy growing with the area, $A$, like $A \log(A)$ which is believed to be a characteristic feature of a Fermi surface. Some other thermodynamic properties were also analysed and a more detailed characterisation of the entanglement entropy was also carried out in the presence of a magnetic field. It was also shown that there are other regions of the parameter space which are not described by the $AdS_2 \times R^2$ end point. [Nilay Kundu, Prithvi Narayan, Nilanjan Sircar, Sandip P. Trivedi]

Classifying the zero-temperature ground states of quantum field theories with finite charge density is an interesting problem, which can be mapped, via holography, to the classification of extremal charged black brane geometries with anti-de Sitter asymptotics. In this context, it had been proposed to use a classification of gravity duals based on Bianchi classification of the extremal near-horizon geometries in five dimensions, in the case where they are homogeneous but, in general, anisotropic. In this project, this study was extended in two directions: it was shown that Bianchi attractors can lead to new phases, and the classification of homogeneous phases was generalized in a way suggested by holography. In the first direction, it was shown that hyperscaling violation can naturally be incorporated into the Bianchi horizons. Analytical examples of

"striped" horizons were found. In the second direction, a more complete classification of homogeneous horizon geometries was proposed, where the natural mathematics involves real four-algebras with three dimensional sub-algebras. This gives rise to a richer set of possible near-horizon geometries, where the holographic radial direction is non-trivially intertwined with field theory spatial coordinates. Examples were found of several of the new types in systems consisting of reasonably simple matter sectors coupled to gravity, while arguing that others are forbidden by the Null Energy Condition. Extremal horizons in four dimensions governed by three-algebras or four-algebras were also analyzed. [Nilay Kundu, Nilanjan Sircar, Sandip P. Trivedi, with Prithvi Narayan (Weizmann Inst.), Norihiro Iizuka (CERN), Shamit Kachru (Stanford U.,ITP,SLAC), and Huajia Wang (Stanford U.,ITP,SLAC)]

**Applications to Particle Physics Phenomenology**

A critical discussion was presented of the possibility that the 125 GeV boson recently discovered at the LHC is the holographic techni-dilaton. Studying a variety of holographic models, it was found that the value of the decay constant for the holographic techni-dilaton is remarkably universal. Furthermore, a statistical analysis of the ATLAS, CMS, and Tevatron measurements was made, concluding that these models are consistent with current experimental data. [Daniel Elander, with M. Piai (Swansea University)]

Work was continued on the model of a light scalar from walking solutions in gauge-string duality. The model had been constructed by considering a system of wrapped D5 branes, and found to exhibit walking dynamics, in the sense that a suitably defined gauge coupling stayed constant over a sizeable intermediate range of energies. The new computation, involving more rigorously derived boundary conditions for the fluctuations, confirmed the existence of a light scalar in the spectrum, as well as two towers of states, and is in qualitative agreement with the results of the older paper. [Daniel Elander, with M. Piai (Swansea University)]

A study of scenarios of physics beyond the standard model was initiated involving strong coupling dynamics, using the AdS/CFT correspondence. The interest in these studies is that generic features of such scenarios can allow model independent predictions, which can be tested at LHC. [A. Dhar]