Gauge Fields, Cosmology and Mathematical String Theory (09w5130)

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for the organizers
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1 Overview

This 5-day workshop finds string theory at a crossroads of its development. For the past twenty five years it has been perhaps the most vigorously investigated subject in theoretical physics and has spilled over into adjacent fields of theoretical cosmology and to mathematics, particularly the fields of topology and algebraic geometry. At this time, it retains a significant amount of the momentum which most recently received impetus from the string duality revolution of the 1990's. The fruits of that revolution are still finding their way to the kitchen table of the working theoretical physicist and will continue to do so for some time.

After undergoing considerable formal development, string theory is now poised on another frontier, of finding applications to the description of physical phenomena. These will be found in three main places, cosmology, elementary particle physics and the description of strongly interacting quantum systems using the duality between gauge fields and strings.

The duality revolution of the 1990's was a new understanding of string theory as a dynamical system. All known mathematically consistent string theories were recognized to simply be corners of the moduli space of a bigger theory called M-theory. M-theory also has a limit where it is 11-dimensional supergravity. This made it clear that, as a dynamical system, string theory is remarkably rich. Its many limits contain quantum mechanical and classical dynamical systems which are already familiar to physicists and mathematicians as well as a host of new structures.

A byproduct of the duality revolution was the realization that, in the context of string theory, there is a simple concrete example of the long expected duality between quantized Yang-Mills gauge field theories and string theories in the form of the "Maldacena conjecture" – the conjectured exact duality between maximally supersymmetric $\mathcal{N} = 8$ Yang-Mills theory defined on flat four-dimensional Minkowski spacetime and the type IIB supersymmetric string theory on an $AdS_5 \times S^5$ background space-time. Although this duality is still a conjecture, there are a large number of nontrivial quantitative checks of it and it agrees in every instance.

On the face of it, this correspondence between a gauge theory and a string theory is remarkable. It is a one-to-one mapping of all of the quantum states and all of the observables from a non-trivial four dimensional quantum field theory, a close relative of the field theories which are used to describe elementary particle physics, and a ten dimensional string theory. It literally states that one set of observers, who are equipped with particle accelerators for instance, would see the world as four space-time dimensional and being composed of elementary building, particles, which are the quanta of the Yang-Mills theory, propagating scalar, spinor and vector fields. Another set of observers, equipped differently, would see the same world as being ten space-time dimensional with the elementary building blocks being fundamental strings. What is more, the duality is informative and useful in a technical sense as it relates the weakly coupled limit of one theory to the strongly coupled limit of the other theory, and mixes the classical and quantum limits of both theories. For example, it allows one to relate solutions of the classical nonlinear partial differential equations of classical type IIB supergravity – ordinary classical multivariate functions – to the very strong coupling limit of Yang-Mills theory, which is also the deep quantum limit where all variables are random variables and quantum fluctuations rule the day. That one could learn anything about this limit of a quantum field theory is remarkable by any measure. Moreover, in many instances, the AdS/CFT correspondence is the only way to obtain strong coupling information about one or the other of the theories.

The gauge-theory - string theory duality also can be viewed as giving a precise definition of the type IIB string theory. In spite of some decades of intense effort, string theory as a dynamical system still has a less precise formulation than classical or quantum field theory. Given the duality, the string theory can be given a technical definition which is at least as sound as the gauge theory.

One development in the AdS/CFT correspondence is the observation, originally due to Minahan and Zarembo (who were both speakers at this workshop) that the problem of finding the spectrum of $\mathcal{N} = 4$ supersymmetric Yang Mills theory is equivalent to that of solving a quantum integrable model, which is usually done using the Bethe Ansatz. This gives the as yet unrealized hope that the entire spectrum could be constructed and spawned a large amount of activity.

At the same time as it is a crossroads of string theory, this is the golden age of cosmology. Once regarded as a science that was starved for data, cosmology has burgeoned as ground and space-based astronomical observations supply a wealth of precise cosmological measurements. In the present epoch, after many years on the speculative side of the scientific spectrum, cosmological theory is now being confronted by cosmological fact. Questions that were until recently the stuff of speculation can now be analyzed in the context of rigorous, predictive theoretical frameworks whose viability is determined by observational data. The most surprising and exciting feature of cosmology's entrance into the realm of data-driven science is its deep reliance on theoretical developments in elementary particle physics. At the energy scales characteristic of the universe's earliest moments, one can no longer approximate matter and energy using an ideal gas formulation; instead, one must use quantum field theory, and at the highest of energies, one must invoke a theory of quantum gravity, such as string theory. Cosmology is thus the pre-eminent arena in which our theories of the ultra-small will flex their muscles as we trace their role in the evolution of the universe. As such, it give perhaps the most promising approach to confirming whether string theory is the correct theoretical model for planck scale physics. One avenue to doing this which has seen much discussion recently is through string models of inflation, the phase of rapid, exponential expansion of the early universe, whose existence seems to be confirmed by current data. The idea is that inflation stretches distance scales so drastically that even physics which occurs on distance scales as minute as the size of strings gets blown up to astronomical size and there is the hope that the physics which determines the structure at that scale is blown up with it and carries hints about its origin. This exciting possibility as well as some others are what occupy the present day string cosmologists.

The relationship between the highly mathematical subject of string theory and cosmology, which has traditionally been more phenomenological, is rapidly evolving. One of the main motivations for string theory is to find a framework capable of dealing with the singularities which arise in classical general relativity, most notably the cosmological singularity of the big bang. Moreover, according to present cosmological models, physics on scales close to the singularity, i.e., close to the Planck energy scale) is responsible for producing the structure we observe today in the Universe. Thus, the largely unexplored interface between cosmology and string theory is enormously rich and promising terrain.

Years of research have shown that cosmology requires input from new developments in fundamental physics in order to make significant progress. For example, such input is needed to provide a consistent basis for inflationary cosmology (or for alternatives such as the the pre-big-bang or ekpyrotic scenarios), to provide insight into the formation of structure, to provide possible solutions to the dark matter problem, to provide a mechanism for the apparent acceleration of the Universe, and to explain other observational facts which are still a mystery in the current models of cosmology. On the other hand, since it is unlikely that string theory will ever be directly tested through accelerator experiments, cosmological observations may well be the most promising way of confirming this approach to quantum gravity. Thus, sharpening string cosmology is both crucial for further breakthroughs in cosmology and to provide a means to one day test string theory itself.

This time of great progress in cosmology coincides with another important event, the startup of the Large Hadron Collider particle physics experiment. This is the first particle physics experiment in almost three decades where there is a reasonable expectation of seeing truly new physics, and could well be the most important one in the life-time of currently active particle physicists. Some of this physics is related to cosmology. For example, supersymmetric extensions of the standard model – which could very well be the new physics – have particles which are candidates for dark matter. Finally, mathematics has made significant progress in unraveling the nature of string theory. It is clear that its understanding at the most fundamental level will require sophisticated, most likely new mathematics. Some of this new mathematics is already there and bringing it into contact with physics is particularly timely.

Over the years there have been many fruitful interactions between string theory and various fields of mathematics. Subjects like algebraic geometry and representation theory have been stimulated by new concepts such as mirror symmetry, quantum cohomology and conformal field theory.

2 String cosmology

There were six speakers in the string cosmology section covering a spectrum from the phenomenology of inflation to the appearance of cosmological structures in solvable string models of toy cosmologies.

- Alexander Westphal discussed his recent work on monodromy in the cosmic microwave background. He presented a simple mechanism for obtaining large-field inflation, and hence a gravitational wave signature, from string theory compactified on twisted tori. For Nil manifolds, he obtained a leading inflationary potential proportional to $\phi^{2/3}$ in terms of the canonically normalized field phi, yielding predictions for the tilt of the power spectrum and the tensor-to-scalar ratio, $n_s \approx 0.98$ and $r \approx 0.04$ with 60 e-foldings of inflation; he noted the possibility of a variant with a candidate inflaton potential proportional to $\phi^{2/5}$. The basic mechanism involved in extending the field range – monodromy in D-branes as they move in circles on the manifold – arises in a more general class of compactifications, though his methods for controlling the corrections to the slow-roll parameters require additional symmetries.

- Robert Brandenberger reviewed the current status of string gas cosmology. String gas cosmology is a string theory-based approach to early universe cosmology which is based on making use of robust features of string theory such as the existence of new states and new symmetries. A first goal of string gas cosmology is to understand how string theory can effect the earliest moments of cosmology before the effective field theory approach which underlies standard and inflationary cosmology becomes valid. String gas cosmology may also provide an alternative to the current standard paradigm of cosmology, the inflationary universe scenario.

- Nemanja Kaloper discussed the relationship between quintessence and the string landscape. He argued that quintessence may reside in certain corners of the string landscape. It could arise as a linear combination of internal space components of higher rank forms, which are axion-like at low energies, and may mix with 4-forms after compactification of the Chern-Simons terms to four dimensions due to internal space fluxes. The mixing induces an effective mass term, with an action which preserves the axion shift symmetry. The symmetry is then broken spontaneously by background selection. With several axions, several 4-forms, and a low string scale, as in one of the setups already invoked for dynamically explaining a tiny residual vacuum energy in string theory, the 4D mass matrix generated by random fluxes may have ultra-light eigen-modes over the landscape, which are quintessence. He illustrated how this works in simplest cases, and outlined how to get the lightest mass to be comparable to the Hubble scale now, $H_0 \sim 10^{-33}$eV. The shift symmetry protects the smallest mass from perturbative corrections in field theory. If the ultra-light eigen-mode does not couple directly to any sector strongly coupled at a high scale, the non-perturbative field theory corrections to its potential will also be suppressed. Finally, if the compactification length is larger than the string length by more than an order of magnitude, the gravitational corrections may remain small too, even when the field value approaches M_{Pl}.

- Matt Kleban spoke about his recent work entitles "Watching Worlds Collide". He showed how to extend their previous work on the cosmology of Coleman-de Luccia bubble collisions. Within a set of approximations he showed how to calculate the effects on the cosmic microwave background (CMB) as seen from inside a bubble which has undergone such a collision. He showed that that the effects are always qualitatively similar–an anisotropy that depends only on the angle to the collision direction–but can produce a cold or hot spot of varying size, as well as power asymmetries along the axis determined by the collision. With other parameters held fixed the effects weaken as the amount of inflation which took place inside our bubble grows, but generically survive order 10 efolds past what is required to solve the horizon and flatness problems. In some regions of parameter space the effects can survive arbitrarily long inflation.

- Joanna Karczmarek talked about her work on matrix model cosmology. She reviewed the idea that the leading classical low-energy effective actions for two-dimensional string theories have solutions describing the gravitational collapse of shells of matter into a black hole. She reviewed the argument that string loop corrections can be made arbitrarily small up to the horizon, but α' corrections cannot. She used the matrix model to show that typical collapsing shells do not form black holes in the full string theory. Rather, they backscatter out to infinity just before the horizon forms. The matrix model was also used to show that the naively expected particle production induced by the collapsing shell vanishes to leading order. This agrees with the string theory computation. From the point of view of the effective low energy field theory this result is surprising and involves a delicate cancellation between various terms.

- Washington Taylor spoke about his recent work on inflationary constraints on type IIA string theory. He discussed how to prove that inflation is forbidden in the most well understood class of semi-realistic type IIA string compactifications: Calabi-Yau compactifications with only standard NS-NS 3-form flux, R-R fluxes, D6-branes and O6-planes at large volume and small string coupling. With these ingredients, the first slow-roll parameter satisfies epsilon ¿= 27/13 whenever V ¿ 0, ruling out both inflation (including brane/anti-brane inflation) and de Sitter vacua in this limit. His proof is based on the dependence of the 4-dimensional potential on the volume and dilaton moduli in the presence of fluxes and branes. He also described broader classes of IIA models which may include cosmologies with inflation and/or de Sitter vacua. The inclusion of extra ingredients, such as NS 5-branes and geometric or non-geometric NS-NS fluxes, evades the assumptions used in deriving the no-go theorem. He focused on NS 5-branes and outlined how such ingredients may prove fruitful for cosmology.

3 Mathematical String Theory

The presentations which could be classified as Mathematical string theory. They were centered around issues in supersymmetry and duality.

- Simeon Hellerman discussed his recent proof that every unitary two-dimensional conformal field theory (with no extended chiral algebra, and with central charges c_L, c_R ¿ 1) contains a primary operator with dimension Delta$_1$ that satisfies 0 ¡ Delta$_1$ ¡ $(c_L + c_R)/12 + 0.473695$. Translated into gravitational language using the AdS$_3$ /CFT$_2$ dictionary, this result proves rigorously that the lightest massive excitation in any theory of 3D gravity with cosmological constant Lambda ¡ 0 can be no heavier than $1/(4\ G_N)$ + o(—Lambda—$\hat{(}$1/2)). In the flat-space approximation, this limiting mass is twice that of the lightest BTZ black hole. The derivation of the bound applies at finite central charge for the CFT, and does not rely on an asymptotic expansion at large central charge. Neither does the proof rely on any special property of the CFT such as supersymmetry or holomorphic factorization, nor on any bulk interpretation in terms of string theory or semiclassical gravity. The only assumptions are unitarity and modular invariance of the dual CFT. The proof demonstrates for the first time that there exists a universal center-of-mass energy beyond which a theory of "pure" quantum gravity can never consistently be extended.

- Charles Doran spoke about the recent work on the classification scheme of so-called adinkraic off-shell supermultiplets of N-extended worldline supersymmetry without central charges. He showed how, with collaborators, he was recently able to complete the constructive proof that all of these trillions or more of supermultiplets have a superfield representation. While different as superfields and supermultiplets, these are still super-differentially related to a much more modest number of minimal supermultiplets. He discussed how they were constructed.

- Keshav Dasgupta spoke about he derivation of a novel deformation of the warped resolved conifold background with supersymmetry breaking ISD (1,2) fluxes by adding D7-branes to this type IIB theory. He showed that they allow spontaneous supersymmetry breaking without generating a bulk cosmological constant. In the compactified form, the background will no longer be a Calabi-Yau manifold as it allows a non-vanishing first Chern class. In the presence of D7-branes the (1,2) fluxes can give rise to non-trivial D-terms. He reviewed the study the Ouyang embedding of D7-branes in detail and showed that in this case the D-terms are indeed non-zero. He also showed that, in the limit approaching the singular conifold, the D-terms vanish for Ouyang's embedding, although supersymmetry appears to be broken. He also discussed constructing the F-theory lift of their background and demonstrated how these IIB (1,2) fluxes lift to non-primitive (2,2) flux on the fourfold. The seven branes correspond to normalisable harmonic forms. he briefly sketched a possible way to attain an inflaton potential in this background once extra D3-branes are introduced and point out some possibilities of restoring supersymmetry in our background that could in principle be used as the end point of the inflationary set-up.

- Sunil Mukhi spoke about how to obtain the complete set of constraints on the moduli of N=4 superstring compactifications that permit "rare" marginal decays of 1/4-BPS dyons to take place. The constraints are analysed in some special cases. The analysis extends in a straightforward way to multi-particle decays. He discussed the possible relation between general multi-particle decays and multi-centred black holes.

4 String theory Gauge theory duality

Gauge theory - string theory duality was the largest category of presentations. The topics centered around the formal structure of duality, including the conjectured integrability of the planar limit of the gauge theory and the classical limit of string theory as well as applications to the study of strongly interacting gauge theories and to gravity.

- Mark van Raamsdonk spoke about his work which attempts to provide some insights into the structure of non-perturbative descriptions of quantum gravity using known examples of gauge-theory / gravity duality. He argued that in familiar examples, a quantum description of space-time can be associated with a manifold-like structure in which particular patches of spacetime are associated with states or density matrices in specific quantum systems. He also argued that quantum entanglement between microscopic degrees of freedom plays an essential role in the emergence of a dual spacetime from the nonperturbative degrees of freedom. In particular, in at least some cases, classically connected spacetimes may be understood as particular quantum superpositions of disconnected spacetimes.

- Joe Minahan, Konstantin Zarembo, These speakers reviewed the status of integrability of the planar limit of $\mathcal{N} = 4$ supersymmetric Yang-Mills theory and its dual, the classical limit of IIB superstring theory. They also discussed new results about the two-loop anomalous dimensions for fermionic operators in the ABJM model and the ABJ model. They discussed the appropriate Hamiltonian and reviewed the argument that it is consistent with a previously predicted Bethe ansatz for the ABJM model. The difference between the ABJ and ABJM models is invisible at the two-loop level by cancelation of parity violating diagrams. They showed how to construct a Hamiltonian for the full two-loop OSp(6—4) spin chain by first constructing the Hamiltonian for an SL(2—1) subgroup, and then showed the lift to OSp(6—4). They showed that this Hamiltonian is consistent with the Hamiltonian found for the fermionic operators.

- Alex Buchel discussed the use of the AdS/CFT correspondence to study first-order relativistic viscous magneto-hydrodynamics of (2+1) dimensional conformal magnetic fluids. He showed that the first order magneto-hydrodynamics constructed following Landau and Lifshitz from the positivity of the entropy production is inconsistent.

He proposed additional contributions to the entropy motivated dissipative current and, correspondingly, new dissipative transport coefficients. He used the strongly coupled M2-brane plasma in external magnetic field to show that the new magneto-hydrodynamics leads to self-consistent results in the shear and sound wave channels.

- Troels Harmark, Gianluca Grignani, Marta Orselli each gave one of a series of talks which reviewed aspects of their recent interesting work on the string dual of the recently constructed $N = 6$ superconformal Chern-Simons theory of Aharony, Bergman, Jafferis and Maldacena (ABJM theory). They focused in particular on the $SU(2) \times SU(2)$ sector. They showed how to find a sigma-model limit in which the resulting sigma-model is two Landau-Lifshitz models added together. They considerd a Penrose limit for which they can approach the $SU(2) \times SU(2)$ sector. Finally, they showed how to find a new Giant Magnon solution in the $SU(2) \times SU(2)$ sector corresponding to one magnon in each $SU(2)$. Putting these results together, they found the full magnon dispersion relation and they compared this to recently found results for ABJM theory at weak coupling.

- Xi Yin reviewed study spin chain operators in the N=6 Chern-Simons-matter theory recently proposed by Aharony, Bergman, Jafferis and Maldacena to be dual to type IIA string theory in AdS4xCP3. He discussed the two-loop dilatation operator in the gauge theory, and compared to the Penrose limit on the string theory side.

- Pallab Basu, Anindya Mukerjee, each gave one of a series of two seminars where they reviewed their work on the large N SU(N) gauge theories on a compact manifold S^3 X R (with possible inclusion of adjoint matter) which is known to show first order deconfinement transition at the deconfinement temperature. This includes the familiar example of pure YM theory and N=4 SYM theory. They discussed the effect of introduction of N_f fundamental matter fields in the phase diagram of the above mentioned gauge theories at small coupling and in the limit of large N and finite N_f/N. They found some interesting features like the termination of the line of first order deconfinement phase transition at a critical point as the ratio N_f/N is increased and absence of deconfinement transition thereafter (there is only a smooth crossover). The results have implications for QCD, which unlike a pure gauge theory does not show a first order deconfinement transition and only displays a smooth crossover at the transition temperature.

- Hong Liu reviewed recent work where they showed that, for a class of conformal field theories (CFT) with Gauss-Bonnet gravity dual, the shear viscosity to entropy density ratio, η/s, could violate the conjectured Kovtun-Starinets-Son viscosity bound, $\eta/s \geq 1/4\pi$. He argued, in the context of the same model, that tuning η/s below $(16/25)(1/4\pi)$ induces microcausality violation in the CFT, rendering the theory inconsistent. This is a concrete example in which inconsistency of a theory and a lower bound on viscosity are correlated, supporting the idea of a possible universal lower bound on η/s for all consistent theories.

- David Kutasov reviewed his work on Seiberg duality in the context of AdS/ cft duality. He argued that N=2 supersymmetric Chern-Simons theories exhibit a strong-weak coupling Seiberg-type duality. He also discussed supersymmetry breaking in these theories.

- Jaume Gomis discussed his recent work on maximally supersymmetric 2+1-dimensional gauge theory. He discussed adding a supersymmetric Faddeev-Popov ghost sector to the recently constructed Bagger-Lambert theory based on a Lorentzian three algebra and obtained an action with a BRST symmetry that can be used to demonstrate the absence of negative norm states in the physical Hilbert space. He showed that the combined theory, expanded about its trivial vacuum, is BRST equivalent to a trivial theory, while the theory with a vev for one of the scalars associated with a null direction in the three-algebra is equivalent to a reformulation of maximally supersymmetric 2+1 dimensional Yang-Mills theory in which there a formal SO(8) superconformal invariance.

- Martin Kruczenski reviewed a computation of the 1-loop correction to the effective action for the string solution in AdS_5 x S^5 dual to the circular Wilson loop. More generically, the method he used can be applied whenever the two dimensional spectral problem factorizes, to regularize and define the fluctuation determinants in terms of solutions of one-dimensional differential equations. A such it can be applied to non-homogeneous solutions both for open and closed strings and to various boundary conditions. In the case of the circular Wilson loop, he obtained, for the 1-loop partition function a result which up to a factor of two matches the expectation from the exact gauge theory computation. The discrepancy can be attributed to an overall constant in the string partition function coming from the normalization of zero modes, which have not been fixed.

- Takuya Okuda and Diego Trancanelli each gave talks which discussed Wilson loop correlators at strong coupling. They reviewed the computation at strong coupling the large N correlation functions of supersymmetric Wilson loops in large representations of the gauge group with local operators of N=4 super Yang-Mills. The gauge theory computation of these correlators is performed using matrix model techniques. They showed that the strong coupling correlator of the Wilson loop with the stress tensor computed using the matrix model exactly matches the semiclassical computation of the correlator of the 't Hooft loop with the stress tensor, providing a non-trivial quantitative test of electric-magnetic duality of N=4 super Yang-Mills. They then perform these calculations using the dual bulk gravitational picture, where the Wilson loop is described by a "bubbling" geometry. By applying holographic methods to these backgrounds they calculate the Wilson loop correlation functions, finding perfect agreement with our gauge theory results.

5 String theory and particle physics

- Savdeep Sethi and Katrin Becker each gave seminars discussing their work on torsional heterotic geometries. They discussed the construction of new examples of torsional heterotic backgrounds using duality with orientifold flux compactifications. They explained how duality provides a perturbative solution to the type I/heterotic string Bianchi identity. The choice of connection used in the Bianchi identity plays an important role in the construction. They proposed the existence of a much larger landscape of compact torsional geometries using string duality. They also presented some quantum exact metrics that correspond to NS5-branes placed on an elliptic space. These metrics describe how torus isometries are broken by NS flux.

- Melanie Becker spoke about her work on new heterotic non-Kahler geometries. New heterotic torsional geometries are constructed as orbifolds of T^2 bundles over K3. The discrete symmetries considered can be freely-acting or have fixed points and/or fixed curves. She gave explicit constructions when the base K3 is Kummer or algebraic. The orbifold geometries can preserve N=1,2 supersymmetry in four dimensions or be non-supersymmetric.

- Herman Verlinde discussed his work on a holographic perspective on D-brane model building for elementary particle physics. He spoke about geometric aspects of extensions of the supersymmetric standard model that exhibit a periodic duality cascade. In the spirit of the holographic correspondence, the growth of the gauge group rank towards the UV is interpreted as a gradual decompactification transition. He showed that this class of models typically develop a duality wall in the UV, and presented an efficient method for estimating the hierarchy between the on-set of the cascade and the formation of the wall. As an illustrative example, he studied the model introduced by Cascales, Saad and Uranga which has an known geometric realization in terms of D-branes on an SPP/Z_3 singularity.

- Arkady Vainshtein spoke about his work on Dyon dynamics near marginal stability and non-BPS states. He showed how to derive the general form of the moduli-space effective action for the long-range interaction of two BPS dyons in N=2 gauge theories. This action determines the bound state structure of various BPS and non-BPS states near marginal stability curves, and he utilized it to compute the leading correction to the BPS-mass of zero-torsion non-BPS bound states close to marginal stability.

6 Participants

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