A Brief Description of Recent and Current Research

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We are now entering a golden era of cosmology, which is rapidly becoming a data-driven field, acquiring a wealth of new information about the global origins of our universe and the fundamental microphysics which shaped it. It is thus crucial to find out how the cosmological observations can push the frontiers of our knowledge of gravity and particle physics in new and original ways. There are many outstanding cosmological mysteries which beg for answers. At the moment we know that more than 90% of the contents of our Universe is in the form of mysterious dark energy and dark matter. Our best theory for explaining the origin of our Universe is inflation, a sudden burst of extremely rapid expansion, which made it so large and homogeneous. Yet we do not know how to drive inflation with the familiar forces and particles. We do not even know what are the fundamental energy scales which control the strengths of forces between particles, such as gravity and electromagnetism. Our experimental tests of these forces have established the Standard Model, which is very successful at energies below the TeV scale. However it does not provide a consistent framework for describing gravity, because of the proliferation of ultraviolet divergences which obstruct the quantization of General Relativity. Further its parameters must be fine-tuned to maintain its consistency, as exemplified by the gauge hierarchy problem. The extensions of the Standard Model to energies above TeV generically predict new forces and new particles. String theory, which has emerged as the best candidate for quantizing gravity and unifying it with other forces in Nature, even predicts new dimensions of space. However, string theory does not yet provide clear insights into the wonders of cosmic acceleration, which is supported by current observations in cosmology. It is therefore crucial to seek phenomena which are sensitive to physics beyond the Standard Model in order to advance our knowledge. The quest for physics beyond the Standard Model in lab-based experiments such as colliders and proton decay searches is one avenue of investigation while cosmology provides for another, complementary, direction. The interface of cosmology and elementary particle physics has already become a very fruitful area, and will continue to be an especially important source of information about microphysics if there really exist fundamental scales in Nature which are much higher than TeV, because this physics shapes the universe.

My work has been interdisciplinary, focusing on the exploration of phenomena at the interface of cosmology, high energy physics and string phenomenology. It has benefited greatly both from the recent formal developments like AdS/CFT and string inflationary model building, on one side, and the achievements of precision cosmology leading to more accurate information about the universe which can be used to reveal intricacies of fundamental microphysics that shaped it. Below is a summary of recently completed work and a description of currently ongoing projects.

Recently Completed Work

How (not) to Palatini

Working with Iglesias, Padilla, and Park, I have revisited the problem of defining non-minimal gravity in the first order formalism. Specializing to scalar-tensor theories, which may be disguised as 'higher-derivative' models with the gravitational Lagrangians that depend only on the Ricci scalar, it was shown how to *correctly* recast these theories as Palatini-like gravities. This formulation utilizes the Lagrange multiplier method, which preserves the canonical structure of the theory, and yields the conventional metric scalar-tensor gravity. This explains the discrepancies between the naïve Palatini and the Lagrange multiplier approach, showing that the naïve Palatini approach really swaps the theory for another. Having identified the correct decoupling limits and the strong coupling regimes, this work showed that the so-called 'Modified Source Gravity' models suffer from strong coupling problems at very low scales, and hence cannot be a realistic approximation of our universe. Comments were made about a method to decouple the extra scalar using the chameleon mechanism.

A new perspective on DGP gravity

In collaboration with Gregory, Myers, and Padilla, I have continued exploring brane induced gravity on codimension-1 branes. They have identified new pathologies in this theory, noting that in Schwarzschild bulks the brane hits a pressure singularity at finite radius when bulk masses are large. Further, on the self-accelerating branch, the five-dimensional energy is unbounded from below, providing the states of arbitrarlly low negative energy which that the self-accelerating backgrounds can access via the ghost instability. Even in an empty Minkowski bulk, using the standard Euclidean techniques these authors showed that the spontaneous nucleation of self-accelerating branes is unsuppressed. Altogether these pathologies present a serious challenge that any proposed UV completion of the DGP model must overcome.

Challenging the cosmological constant

I have suggested a new dynamical dark energy scenario whose signatures may be simultaneously tested by astronomical observations and laboratory experiments. The dark energy is a field with slightly sub-gravitational couplings to matter, a logarithmic self-interaction potential with a scale tuned to $\sim 10^{-3}$eV, as is usual in quintessence models, and an effective mass m_ϕ influenced by the environmental energy density. After inflation and reheating, the field is relativistic, and attains a Planckian expectation value before Hubble friction freezes it. This can make gravity in space slightly stronger than on Earth. During the matter era, interactions with nonrelativistic matter dig a minimum close to the Planck scale. However, due to its sub-gravitational matter couplings the field will linger away from this minimum until the matter energy density dips below $\sim 10^{-12}\text{eV}^4$. Then it starts to roll to the minimum, driving a period of cosmic acceleration. Among the signatures of this scenario may be dark energy equation of state $w \neq -1$, stronger gravity in dilute mediums, that may influence

BBN and appear as an excess of dark matter, and since it is a chameleon, sub-millimeter corrections to Newton's law, close to the present laboratory limits.

How black holes form in high energy collisions

Working with Terning, I have elucidated how black holes form in trans-Planckian collisions. In the rest frame of one of the incident particles, the gravitational field of the other, which is rapidly moving, looks like a gravitational shock wave. The shock wave focuses the target particle down to a much smaller impact parameter. In turn, the gravitational field of the target particle captures the projectile when the resultant impact parameter is smaller than its own Schwarzschild radius, forming a black hole. One can deduce this by referring to the original argument of escape velocities exceeding the speed of light, which Michell and Laplace used to discover the existence of black holes.

Charting the landscape of modified gravity

In the work with my student Kiley, I discovered a large diversity of possible solutions in codimension-2 brane induced gravity controlled by the axion flux, as governed by its boundary conditions. Hence brane induced gravity models really give rise to a *landscape* of vacua, at least semiclassically. For sub-critical tensions, the vacuum energy problem is different in brane induced gravity: instead of tuning the 4D curvature, generically one must tune the crossover scale. On the other hand, in the near-critical limit, branes live inside very deep throats which efficiently compactify the angular dimension. In there, 4D gravity first changes to $5D$, and only later to $6D$. The crossover scale saturates at the gravitational see-saw scale, independent of the tension. Using the fields of static loops on a wrapped brane, they found that in sub-critical cases the scalars are strongly coupled already at the crossover scale even in the vacuum, because the brane bending is turned on by the axion flux. Near the critical limit, linearized perturbation theory remains under control below the crossover scale, and linearized gravity around the vacuum looks like a scalar-tensor theory.

A new dimension hidden in the shadow of a wall

I have proposed a new way to hide the fifth dimension, and to modify gravity in the far infra-red. A gravitating tensional membrane in five dimensions folds the transverse space into a truncated cone, stoppered by the membrane. For near-critical tension, the conical opening is tiny, and the space becomes a very narrow conical sliver. A very long section, of length comparable to the membrane radius divided by the remaining conical angle, of this sliver is well approximated by a narrow cylinder ending on the membrane. Inside this cylindrical throat we can reduce the theory on the circle. At distances between the circle radius and the length of the cylinder, the theory looks 4D, with a Brans-Dicke-like gravity, and a preferred direction, while at larger distances the cone opens up and the theory turns 5D. The gravitational light scalar in the throat can get an effective local mass term from the interplay of matter interactions and quantum effective potentials on the cone, which may suppress its long range effects.

Evaporation of a black hole off of a tense brane

In collaboration with Dai, Starkman and Stojkovic, I have calculated the gray-body factors for scalar, vector and graviton fields in the background of an exact black hole localized on a tensional 3-brane in a world with two large extra dimensions. Finite brane tension modifies the standard results for the case with of a black hole on a brane with negligible tension. For a black hole of a fixed mass, the power carried away into the bulk diminishes as the tension increases, because the effective Planck constant, and therefore entropy of a fixed mass black hole, increase. In this limit, the semiclassical description of black hole decay becomes more reliable.

On cosmological perturbations and string gases

In collaboration with Kofman, Linde, and Mukhanov, I have investigated the recent proposal for a non-inflationary mechanism of generation of scale-free cosmological perturbations of metric by Brandenberger, Nayeri, and Vafa in the context of the string gas cosmology. Various problems of this model were elucidated, and an argument was given that the cosmological perturbations of metric produced in this model have blue spectrum with a spectral index n = 5, which strongly disagrees with observations.

Low energy bounds on Poincare violation in causal set theory

Working with Mattingly, I have investigated the causal set approach to quantum gravity. We considered bounds on the rate of momentum space diffusion coming from astrophysical molecular clouds, nuclear stability and cosmological neutrino background, and found that the strongest limits come from relic neutrinos. This constrains the momentum space diffusion constant by $k < 10^{-61}\text{GeV}^3$ for neutrinos with masses $m_\nu > 0.01\text{eV}$, improving the previously quoted bounds by roughly 17 orders of magnitude.

Currently Ongoing Projects

Exploring modifications of gravity to attack the cosmological constant problem

A possible approach to the cosmological constant problem may be to change gravity in the far infrared. If gravity is weakened at such large scales, this weakening of the gravitational impact of a very homogeneous distribution of energy in the Universe may lead to cosmic acceleration. However it is not clear how such models stack up against observational tests and constraints, because of the difficulties with instabilities, strong couplings etc. To help with these issues, I have recently initiated a very powerful new approach for the exploration of modified theories of gravity by means of gravitational shock waves, which provide a clear and controllable arena for testing the consistency of a modified theory of gravity and its phenomenological implications. With my student Kiley, I have explored higher codimension brane induced gravity models, finding cases where ghosts are avoided. Furthermore, this work has revealed that the nature of the vacuum energy problem in these models is completely different than in the standard $4D$ theory. Instead of generating large curvature, in this case the vacuum energy controls the length scale where gravity changes from $4D$ to higher-dimensional. I plan to explore the details of this mechanism further, in the attempt to see if the self-tuning mechanism can be utilized to help with the cosmological constant problem.

Exploring string cosmology

With the advent of the String Landscape paradigm it becomes very interesting to reopen some of the questions about cosmological evolution in string theory. Issues concerning initial conditions, singularity resolution and generation of initial perturbations are particularly interesting. With Kofman, Mukhanov and Linde, I have investigated the potential of string and brane gas cosmology for generation of initial spectrum of scale invariant perturbations. This scenario is very similar to the pre-Big Bang model, which I have studied extensively in the past. The conclusion was that this scenario is not a viable model for explaining the origin of cosmic structures. However, additional issues arose in the attempt to understand how different phases of string gases connect to each other. Currently, I am exploring the dynamics of these models in more detail, in collaboration with Scott Watson (Michigan). These questions may have implications for the cosmology of string landscape.

Inflationary model building

I plan to investigate several new directions for constructing models of inflation in string theory. While inflation is the best framework for explaining the origin of the Universe, it is still unclear how it should be implemented in fundamental theory. Inflation requires the existence of light degrees of freedom with very flat potentials and positive vacuum energy, which are hard to obtain from first principles. A new direction to pursue is to incorporate inflation in new models with non-minimal couplings to gravity and matter, such as brane-motivated constructions where moduli can be inflatons. At the moment, I am working in collaboration with Sorbo (UMass) and Yokoyama (Tokyo) on the development of two novel models of inflation. One is an idea based on two-stage inflation, where the fist is driven by a Dirac-Born-Infeld brane motion, at some high scale, while the other is a stage of N-flation, driven by a large number of axionic fields, whose initial conditions are prepared by the earlier stage. The other model uses radiative corrections to actually assist inflation. Such scenarios may emerge in induced gravity models which have several different sectors, that generate an inflaton-dependent effective Planck mass. This then may flatten the effective potential of the inflation, allowing inflation to take place.

Signatures of dark energy

I intend to continue the search for the signatures of new physics in the answers to cosmological puzzles. In recent work, I have proposed a model of quintessence which may have observable signatures accessible to terrestrial searches for new forces below a millimeter. This is because the quintessence forces are suppressed by environmental effects, as the field picks up large environmental corrections to the mass. This chameleon-like mimicry reduces the amount of mass of an object that has long range interactions to only the outer layers of mass distributions, of thickness $1/m_\phi$. The implications of this mechanism for observations are numerous. Among the signatures of this scenario may be dark energy equation of state $w \neq -1$, stronger gravity in dilute mediums, that may influence BBN and appear as an excess of dark matter, and sub-millimeter corrections to Newton's law, close to the present laboratory limits. Currently I am collaborating with Copeland and Padilla (Nottingham) in working out the precise signatures of such theories.