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Cosmology as the ultimate probe of fundamental physics

My research lies at the unique interface between fundamental particle physics and the cosmology of the large scale observable universe. The birth of the golden age of cosmology, with its burgeoning array of astrophysical observations of ever increasing precision, has both ignited and challenged the need to understand how our current picture of cosmology arises from fundamental theories. It is through our understanding of cosmic inflation that we understand how tiny quantum fluctuations can give rise to the *global structure of the Universe.* It is through cosmological observations that we are forced us to confront the greatest theoretical problem in our understanding of quantum gravity, the *cosmological constant problem*, and the nature of dark energy. These fascinating topics are precisely the target of my current research.

The Dark Energy Challenge

One of the most important observational discoveries in recent years has been that of the existence of dark energy. This energy component contributes to almost three quarters of the current energy density in the Universe, and its origin is currently unknown to us. This discovery has united astrophysicists, cosmologists and high energy theorists in an effort to understand its origin. The most pressing question to be addressed is 'can dark energy be entirely understood as a cosmological constant, or is it rather a dynamical energy indicating the presence of new light degrees of freedom (with masses comparable to the current Hubble scale) acting over cosmological scales?'.

The answer to this question will have a profound effect on how we understand the standard model of cosmology to arise within a more fundamental theory. If the data supports a pure cosmological constant, then it will represent a remarkable success for ΛCDM, but leave an unnerving theoretical puzzle which is the cosmological constant problem, the most significant hierarchy problem in theoretical physics. The precise statement of this problem is incorporated in the idea of technical naturalness, namely, that the observed cosmological constant is not stable against quantum contributions. Every particle in the standard model gives a contribution to the cosmological constant through vacuum effects which is many orders of magnitude larger than the true value. Although it has often been suggested that the vacuum may not contribute to the energy density of the Universe, such an assumption would violate the equivalence principle and indicate a significant departure from current understanding of fundamental physics.

More intriguing still is the possibility that the dark energy has dynamics, such as would be indicated by a departure of its equation of state from $w = -1$. In almost all such cases this dynamics implies the existence of new light degrees of freedom acting at cosmological length scales. These new degrees of freedom, may simply be scalars, of the type that typically arise in supergravity/string inspired models, they may be vector degrees of freedom, or more interesting still additional spin two fields mediating an additional force between matter particles. I am very interesting in understanding all the different classes of models, and their distinctive observational features. This is crucially important as it will give us the necessary clue to see how to connect the physics of dark energy with the current pictures of high energy physics, much as the paradigm of slow-roll inflation has driven recent progress in string phenomenology.

A. Is dark energy tied to the solution of the cosmological constant problem?

The nature of dark energy and the ever present cosmological constant problem are so inextricably linked that it is difficult to imagine a successful approach to the solution of one that would not incorporate the other. In recent years I have pursued two such approaches, and I hope to continue working on these and similarly physically motivated approaches in the future.

Modified Gravity Models

One intriguing idea that has emerged in recent years is the possibility that the force of gravity could be modified from the expectations of general relativity, either at small distances, less than a few microns which is the current experimental limit on Newton's law, or perhaps even more excitingly at large distances corresponding to cosmological scales today. In the latter case such infrared modifications of gravity arise if the graviton has a mass, or more precisely is a resonance. This possibility can be directly realized in the context of braneworld models, as first discussed by Dvali, Gabadadze and Poratti, where the resonance graviton is made out of Kaluza-Klein modes, that arise inevitably from having infinite extra dimensions.

Recently, with my collaborators, [1–3] we have developed a braneworld model which could induce infrared modifications that can screen the effect of a cosmological constant. This idea, termed *degravitation* by Dvali, Hofmann and Khoury, based on early work by Arkani-Hamed, Dimopoulos, Dvali and Gabadadze, could possibly provide the basis of a dynamical solution to the cosmological constant problem, since any large cosmological constant initially present would over the course of time degravitate away. Nevertheless, the development of a consistent effective field theory that allows for an infrared modification of gravity has proven to be notoriously challenging and considerable work needs to be done before a truly consistent framework realising this idea is found.

This is only the beginning of this promising direction, and there are many exciting questions to be addressed. As an example, even considering the perturbatively ghost free setups that we have constructed [1–3], one should still demonstrate if these are nonperturbatively stable. In order to establish if these models exhibit degravitation it is necessary to understand their cosmological evolution, and this is particularly technically challenging, even to obtain the effective Friedman equation. These models have the generic feature that they predict the existence of new scalar degrees of freedom which are strongly coupled in the presence of dense gravitational sources. Whilst this strong coupling phenomenon allows for consistency with the usual light scalar field constraints, the full cosmological and astrophysical implications of such scalar fields have yet to be determined. These are the aspects that I am currently studying and I look forward to pursuing them further in future research.

Technically natural approaches

Intriguingly, the nature of the cosmological constant can change in the context of higher dimensional theories. In recent years I have worked on a number of ideas such as the Supersymmetric Large Extra Dimensions proposal (SLED) [4–8]. This is an attempt to provide a technically naturally solution to the cosmological constant problem, by relating the scale of the cosmological constant to the scale of the Kaluza-Klein modes, and using bulk supersymmetry to suppress the most dangerous corrections to the cosmological constant. My own work on this has been tackled the key issue of the stability of these setups and understanding the cosmological effects of matter on the branes. The validity of this proposal rests on understanding the detailed picture of supersymmetry mediation between the brane and bulk, and whether this can truly suppress the loop corrections to the cosmological constant. I have also worked on more novel scenarios in which the nature of the cosmological constant problem can be reinterpreted in the context of large extra dimensions [9], and I believe that there is still much to be learned from proposals of this type that I intend to explore in future work. For instance it is crucial to understand how the light degrees of freedom in these models can play the role of quintessence, while remaining stable under quantum corrections.

B. Phenomenological approaches: How can we observe the dark energy degrees of freedom?

The most obvious approach to probing dark energy is to detect its direct influence on the expansion history of the Universe, i.e. by getting a picture of its equation of state as a function of redshift. Direct probes of this come from the now celebrated Type IA Supernovae luminosity distance measurements, and this is in turn complemented by the angular distance scale measurements of the Baryon Acoustic Oscillations and of course the influence on the CMB density perturbations. In the future many other probes such as galaxy cluster counts and gravitational lensing may be brought to bear on the cosmic expansion history which will serve to further elucidate the behaviour of dark energy.

However, these measurements alone do not allow us to completely distinguish between different models. If dark energy does indeed give rise to new degrees of freedom which are light, it is necessary to understand why we have not already directly observed them, since their presence would naively seem to modify many fundamental tenets of modern cosmology or even solar system physics. The resolution is that these degrees of freedom must couple effectively very weakly to matter fields, so that processes in which these new particles can be created are suppressed, and that in most instances the additional gravitational forces mediated by them are negligible at say solar system scales. There are at present three types of mechanisms by which this can occur.

a) Quintessence/k-essence: In typical quintessence models (including there non-minimal kinetic generalization of k-essense) matter is minimally coupled, or at least sufficiently weakly coupled, to the quintessence field, so that effectively no additional gravitational force is propagated.

b) Potential chameleon: In the chameleon effect, the additional scalars are coupled to matter and in principle mediate a fifth force. However in the presence of large energy densities, these additional scalars can become sufficiently massive to kill off this fifth force contribution.

c) Kinetic chameleon/Vainshtein effect: In the types of modified gravity theories described earlier, a new possibility has opened where, similar to the chameleon mechanism, the additional scalars get frozen in the presence of dense sources. However the effect is quite different, rather than simply becoming massive, here the additional scalar becomes strongly coupled via its own derivative interactions. It is in this sense a kinetic analogue of the chameleon effect.

Each of these three types of models behave differently with regard to the evolution and growth of both linear and non-linear perturbations, and so it is the direct influence of these effects on the growth of structure in the Universe that can give an independent probe of these differing dark energy models. In particular the latter two cases are distinguished by the fact that the additional scalars will propagate at low densities and large scales, but not at high densities. These additional scalar degrees of freedom will contribute to the anisotropic stress which can affect the observed CMB fluctuations, for instance in the Sachs-Wolfe and Integrated Sachs-Wolfe effects. The full implications of these types of models have still to be explored, in particular in the case of the modified gravity frameworks discussed earlier, more theoretical progress needs to be made to connect with phenomenology. I hope to continue exploring these exciting proposals in the future as a means of uncovering the true nature of dark energy.

Early Universe

Non-gaussianities as a probe of fundamental physics

As our observational data on the cosmic microwave background (CMB) continues to improve through ground based and satellite experiments, the bar is continually being raised on the extent to which we can learn about the cosmology of the early Universe. The next great challenges that experiments such as the future *Planck satellite* can face are the possible indirect observation of tensor modes through B-mode polarization, and potential departures from non-gaussianity. In the past few years there has been a great deal of progress in constraining primordial non-gaussianity, largely via the *Wilkinson Microwave Anisotropy Probe* (WMAP), our currently most detailed probe of the CMB. However there has also been considerable interest in other measures of non-gaussianity. In a recent paper [10] with Dr. Niayesh Afshordi we argued that the statistics of collapsed objects and auto- and cross-correlation of galaxy surveys with the Integrated Sachs-Wolfe in the CMB could be use to constrain primordial non-gaussianity at a level which could be competitive with the CMB probes. I believe these ideas will play a significant role in future developments.

In recent years there has been a great deal of interest in understanding to what extend the CMB can probe new high energy physics, and possibly even the transplanckian regime. With Prof. Rich Holman [11], we have considered the possible effects of high energy physics, specifically in the context of starting inflation in an excited (non Bunch-Davies vacuum) state, for non-gaussianities. We have found that the CMB three and higher point functions could be a more accurate probe of high energy physics than the usual two-point function or power spectrum, precisely because they probe the interactions of the inflaton more strongly. Intriguingly these initial state effects have a characteristic momentum space signature that could make them easy to distinguish in future data such as those expected from the *Planck* satellite.

Non-gaussianities, whilst observationally challenging, can contain a wealth of information. We have been extending this work to understand to what extent there are theoretical limits on the initial non-gaussianities from backreaction [12]. Surprisingly, these are not as tightly constrained as the power spectrum, and for models in which the number of e-folds of inflation is relatively modest (∼60-70) there could be interesting observable effects of the initial state in any observed departures from gaussianity. In the future, I am interested in exploring the information on primordial fluctuations and non-gaussianity that could come from 21cm physics, our only window into the cosmological dark ages between recombination and reionization, which with the advent of many new experiments being developed to detect it, has the potential of providing a wealth of cosmological information that goes well beyond that provided by the already spectacularly successful CMB experiments.

Inflationary Model Building

With Dr. Mark Wyman [13, 14], I have turned to the initial conditions problem in the context of DBI inflation. This is a fascinating version of the inflationary paradigm, that can be naturally embedded into string theory, having many similarities with k-inflation. The framework we have used is the stochastic inflation picture which we have generalized beyond previous studies in order to accommodate the different features of DBI models in an elegant formalism. There are significant challenges in understanding this class of inflationary models and much more work needs to be done. More recently we have been considering intriguing models [15] in which relatively standard multiple field inflationary theories can exhibit all of the nontrivial features of non-minimal kinetic term inflatons.

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