# Research Interests

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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 research has been interdisciplinary: it has centered on the exploration of phenomena at the interface of cosmology, high energy physics and string phenomenology. I plan to continue the investigation of this rich arena. In the future I aim to look for new connections between cosmology and fundamental physics along the following directions of research:

• **Cosmological Smoking Guns**, where I plan to look for the signatures of new physics in answers to the cosmological puzzles. Some very promising examples are: *i) Using CMB as a probe of new physics near the scale of inflation.* The initial state of the Universe may be sensitive to new physics at high energies. If the inflaton couples to new degrees of freedom at a high scale, it may retain some memory of the initial state in the form of a small imprint in the CMB anisotropy. If close to the scales of inflation, the fundamental theory is well-approximated by a local quantum field theory coupled to gravity, the imprints of new physics may alter the spectrum of fluctuations. Such an imprint could be looked for by combining the information from scalar and tensor fluctuations from future experiments, by searching for the violations of the inflationary "consistency" conditions. It would be a strong indication of new physics at high energies. An observation of such an imprint, in addition to signaling new physics, would strongly support the existence of the large energy desert between the Standard Model and the scale of quantum gravity. Thus the possible reward may be great: a clear-cut evidence of new physics which may be inaccessible to observation in lab-based experiments. *ii) Devising new explanations for the dimming of Type Ia supernovae.* At present, observations of faint supernovae are the strongest evidence for cosmic acceleration. However if only a fraction of the photons departing supernovae reach us, the supernovae would appear fainter without cosmic acceleration. I have proposed such an explanation recently, invoking an axion-like particle with couplings to the photon. In the presence of extra-galactic magnetic fields, of order nano-Gauss, coherent over Mpc-sized domains, a photon can turn into an axion evading detection on the Earth. A supernova would then appear fainter even if the Universe is decelerating. This changes quite dramatically the nature of dark energy, avoiding the cosmological event horizon. The axion could also provide a source of ultrahigh-energy cosmic rays. Finally, some recent analysis indicate that the Universe may be expanding even faster than allowed with normal dark energy, suggesting the interpretation in terms of the so-called "phantom" field, which is a ghost with ill-defined Hamiltonian that is not bounded from below. It would lead to a future Big Rip singularity. In theories with the axion, this can be more naturally explained without any "phantoms", simply as a combined dimming effect coming from both the non-singular dark energy and the conversion of photons into axions. *iii) Explaining the unknown origin of the extra-galactic magnetic fields by combining inflation with the dynamics of extra dimensions.* Inflationary perturbations could squeeze the magnetic field into coherent states, which can be amplified by the extra-dimensional dynamics. In models where the extra dimensions are initially small, inflation is followed by an epoch of expansion of extra dimensions, during which the four-dimensional world shrinks, enhancing the primordial magnetic fields. This may provide a new window into the extra-dimensional physics.

• **High Energy Frontiers**, where I intend to pursue new ideas in high energy physics as a method of solving cosmological problems. Among the aims are: *i) Developing new models of inflation.* 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. *ii) Exploring modifications of gravity to attack the cosmological constant problem.* Cosmological constant problem is presently the greatest of all the unsolved problems in fundamental physics. Our best estimates of the cosmological vacuum energy density overshoot the observational bounds by at least 60 orders of magnitude. This clearly shows that our understanding of effective field theory coupled to gravity at very large scales is incomplete. A possible way around the cosmological constant problem, which I plan to pursue, is to modify gravity in the far infrared. This may account for the small cosmological acceleration by a weakening of the gravitational impact of a very homogeneous distribution of energy in the Universe. A model of this type has been proposed by Arkani-Hamed, Dvali, Dimopoulos and Gabadadze. However in its original form this interesting model is not consistent with the usual general covariance. This malady can be cured by additional modifications which involve higher powers of curvature and restore the symmetry of the model. It remains to determine the full series of such terms through an iterative procedure, which I am currently developing. Once this is in place, the consequences of modifications of gravity at large distances can be explored in detail.

• **Holography and Formal Theory**, where I am planning to continue to search for the implications of holography for low energy physics. At the moment, I am planning to pursue the following two directions: *i) Holography and cosmological initial conditions.* A remaining conundrum in the early universe cosmology is the problem of initial conditions. It seems to require the formulation of a complete theory of quantum gravity, which is still lacking. Currently string theory is the forerunner for the quantum theory of gravity unified with other forces, and so it is natural to hope that it may give new insights into the problem of initial conditions, and the origin of inflation. However at present we are only beginning the search for interesting cosmological backgrounds which are under control in string theory. In the absence of a precise formulation of string cosmology, it may be helpful to look for guidance from some of the principles believed to govern it, and this guidance may be provided by holography. The principle of holography posits that quantum gravity must respect unitarity. In cosmological applications, the holographic principle and the existence of the limit where the theory reduces to Einstein gravity point to the following properties of quantum gravity: 1) for systems whose total entropy approaches the covariant entropy bounds, the description based on the volume-distributed oscillator modes breaks down, and should be supplanted by the dual "screen" theory; and 2) at energies well below the Planck scale where the system is dilute enough, quantum gravity should quickly reduce to the description in terms a quantum field theory weakly coupled to Einstein's gravity. This suggests that a gravitating system has far fewer degrees of freedom than naively expected, which means there are fewer consistent initial conditions for gravity. Hence holography may help pick the initial conditions of the Universe, and develop a model where inflation naturally starts as the holographic phase ends. A successful model with this kind of behavior could simultaneously solve the problem of initial conditions for inflation and produce imprints of the holographic phase in density perturbations. *ii) Search for the bulk duals of Hawking radiation.* Here I aim to continue the investigation of the connection between classical brane-localized black holes and quantum-corrected black holes in CFT+gravity theory, which I have proposed recently. One interesting possibility is to study what happens when black holes are charged by both brane-localized and bulk charges, because in the dual CFT+gravity theory these objects should correspond to configurations with or without dilatonic secondary hair, respectively. The consideration of such black holes, which are relatively simple objects thanks to the bulk dynamics, may shed light on the structure of cross-couplings between the CFT and brane-localized matter fields.

These directions of research are very promising because they are synergistic at a very fundamental level, being firmly based on the intricate connection between cosmology and particle physics. This offers new opportunities for the searches for new phenomena, which is crucial at the time when cosmology is becoming a unique testing ground for fundamental physics beyond the TeV frontier.