Federico Piazza's Research

For many years advances in fundamental physics consisted in pushing the "high energy limit" of our knowledge higher and higher. The Standard Model of Particle Physics (SM) is perhaps the most notable example of that: theoretically suggested by UV-renormalizability, the experimental confirmation of the SM has involved – and is involving – scattering experiments at higher and higher energies. What I find most exciting nowadays is the new possibility that hints of fundamental physics may come from the *low-energy* side of the picture. During the last decade cosmology has been flooded with a wealth of data of increasing accuracy, yielding a more and more precise picture of our universe. Among other aspects, what is now calling for a deeper understanding are the two periods of accelerated expansion that our data strongly indicate:

- **Dark Energy:** One of the most puzzling discoveries in physics is that the expansion of the universe is currently accelerated. The most common description of this phenomenon involves a new "dark" component to be added to the total energy budget of the universe.
- **Inflation:** There is evidence for an epoch of acceleration also in the very early universe: *inflation*. Inflation is modeled e.g. with slowly rolling scalar field or with scalars with more general kinetic terms. This period has left very precise imprints in the Cosmic Microwave Background (CMB) and in the structures (galaxies, clusters etc...) that we see in the sky.

While inflation is an excellent "low energy window" on the highest energies, dark energy seems to insinuate that some new unraveled physics is effective already at unexpectedly low energies. In fact, as I argue in the review [24], the apparent acceleration of the universe, put together with other independent hits from the theory (such as the black hole information paradox and the cosmological constant problem), might be suggesting that the standard low-energy framework "gravity+matter fields" is just inadequate and needs to be modified.

During my career I have worked on a wide range of topics, always with the aim of grasping hints of fundamental new physics from low energy phenomenology/cosmology. In my undergraduate thesis program I worked out the perturbations and the quasi normal modes of a stringy black hole solution [2]. I did my PhD in Milan under the external supervision of Gabriele Veneziano. Among my best known papers are those on a string-inspired scenario (the "Runaway Dilaton") that I contributed to develop [3–6]. I studied its implications for dark energy, violations of the equivalence principle, cosmological variations of the Couplings. I have been working on several aspects of Dark Energy, not only within the above string-inspired scenario [3, 10], but also and from the point of view of effective descriptions and fitting with the data [11, 15, 16, 23] and by exploring substantial modifications of gravity at low energy [21–24]. I also worked on the Cold Dark Matter paradigm, especially in relation with its small scale problem [7–9] and with the axion as a viable CDM candidate in the presence of large extra dimensions [13]. Inflation and primordial non-gaussianities in Inflationary/Ekpyrotic scenarios are the subject of a recent paper [20]. In parallel with my research on cosmology, and only apparently detached from it, I studied a way to generalize the present framework for semiclassical gravity. The idea is to consider, in a quantum information fashion, regions of space as *quantum subsystems* rather than pieces of a manifold [12, 14, 24]. From there I considered the advantages of alternative localization schemes in QFT [17–19] and (in relation with dark energy) the intriguing possibility that the geometrical (-metric manifold) description of GR holds only as a small-scale approximation and breaks down in the infra-red. The variety of my research interests is also outlined in my webpage [1].

The different aspects of my ongoing and future research fit into one of the two main directions mentioned above: dark energy and inflation.

Dark Energy

(Fundamental, "top-down" approach) One of the most puzzling aspects of dark energy is the extremely tiny mass scale (typically, the energy density $\rho_0 \sim 10^{-3}$ eV) that looks inevitably related with it. In this respect, the models of modified gravity considered so far [28] do not change the basic pattern of dark energy models: there is still a tuned scale "hidden" in the theory (typically, the mass of the graviton $\sim H_0$) which becomes effective, by *coincidence*, when the Hubble parameter drops to about its value. In the last months I have worked intensively on the possibility of modifying gravity without introducing any new mass scale [21–24]. I took GR itself as an example: since curved space is approximately flat at small distances, GR can be considered as an infrared modification of flat-space/non-gravitational physics. The length scale of such a modification is not fixed by a parameter, but given by the curvature. Therefore, I proposed to modify GR by further subleading curvature-dependent terms. It emerges that the metric manifold GR-description might just be a small distance approximation. This directly relates with dark energy, because high redshift observations have the peculiar property of covering distances comparable to the average inverse curvature H_0^{-1}.

As a guiding principle for my modification, I attempted an "ultra-strong" version of the equivalence principle (USEP) [21, 22] that leave no free parameter in the theory. Such a simple assumption seems to alleviate some traditional difficulties of the low-energy effective framework for gravity [24] and gives interesting cosmological implications. By applying it to a scalar field on a Friedmann Robertson Walker spacetime, I worked out the corrections to GR, which go in the direction of an effective acceleration [22], but turn out to be too small to give full account for supernovae observations [23]. In [23] we also considered a more general class of modified models, still characterized by subleading curvature dependent corrections of the same type of [21, 22]. We found a region in the parameter space that fit supernovae data better than ΛCDM.

My idea opens up new exciting research directions. Hints for an exquisitely theoretical approach came from discussions with, among others, Burt Ovrut (Penn University), Sergio Cacciatori (University of Insubria) and Latham Boyle (CITA, Toronto): spectral geometry seems the natural instrument to put my model on a firmer mathematical basis. The properties of a metric manifold can be encoded by the spectra of the operators "living" therein. I expect that, by modifying the asymptotic behavior of the lowest eigenvalues, departures from the metric manifold structure in the IR can be considered. It would also be crucial to understand what types of deformations are implied, rather than by the a scalar field as in [22], by other types of fields. More generally, unorthodox approaches to dark energy look now very exciting in view of some emerging tensions between the ΛCDM paradigm and the data. Noteworthy examples include the lack of large-scale CMB correlations [29], the anomalously large integrated Sachs-Wolfe (ISW) cross-correlation [30], the growing evidence for abnormally large bulk flows on very large scales [31], and a (marginal) mismatch between angular diameter- and luminosity- distances at high redshift. Although I do not have a full general theory at my disposal yet, the implications of USEP to such aspects can be inferred with the same spirit of [22], i.e., by a formal Taylor expansion around GR.

(Effective "bottom-up" approach) Within the framework of GR, it is crucial to understand whether or not dark energy has any dynamical feature which makes it different from a cosmological constant. However, this problem is not even well posed until a precise set of priors in the dark energy models space is considered. Most parameterizations of dark energy do not reflect realistic underlying theoretical models. This problem has been address in [16], where, in collaboration with Robert Crittenden and Elisabetta Majerotto (ICG, Portsmouth), I developed a simple description of quintessence which is exact in the limit that the equation of state approaches that of a cosmological constant, with parameters living in the field space. I plan to extend the work [16] in such a way to gather different dark energy models into the fewest number of main branches that effectively behave in the same way and have similar priors. This should be done both at the level of the background evolution and at the level of the dynamical properties of the perturbations. In the long term, this will contribute to discriminate ΛCDM from alternative dark energy models on the basis of a definite Bayesian scheme.

Modifications of GR of the type considered in [21,22] (e.g. without new mass scales) can also be constrained with a more "bottom-up" phenomenological approach, like in [23]. I plan to consider the observational discrepancies that I mentioned earlier [**?**, 29–32] within some suitable general parametrized formalism (see e.g. [34]). It would be crucial to understand, by looking at effects at different cosmological epochs and on different scales, whether the discrepancies trace a fixed given length scale (as suggested by interacting scalars fields [3, 11] or by massive gravity [28, 33]) or they are better described by Hubble/curvature dependent subleading corrections, as implied by [21, 22].

(Relation with gravitational phenomenology) Crucially, if dark energy has some dynamical feature, it is expected to give rise to long range interactions and have implications on gravitational phenomenology. Variations of the coupling constants are also expected in some models [4, 5]. What seems to relate coupling variations to dark energy is also the apparent behavior in time of the fine-structure constant. By trusting the results of Webb et al. [35] on the one hand and the constraints of e.g. Damour and Dyson [36] on the other hand, it is apparent that the couplings have stabilized at about the same epoch when the Universe has started accelerating. Variations of the couplings and equivalence principle violations, when they apply, should also be included in the classifications that I intend to make and that I mentioned at the point above.

Intriguingly, not only dark energy but also dark matter can give rise to fifth forces! With Maxim Pospelov we have considered the phenomenology of a light scalar singlet coupled to the Higgs citemaxim by a simple super-renormalizable interaction, that is a dark matter candidate (non-thermal relic of axionic type) and that can mediate, according to its actual mass, forces in a range from sub-millimeter to few kilometers. This work opens two very interesting research directions: the first one, as I mentioned, is to investigate other models where dark matter fields, rather than dark energy, produce violations of the equivalence principle (EP). The second regards the general relation between composition dependent and composition independent EP violations. The models considered in [4,5] belong to a wide class of string inspired models where the coupling of ordinary matter originate from the dependence on the scalar field of the Lambda QCD scale. It is therefore a type of coupling mediated by the strong interactions. In [25] I considered a type of coupling that "goes throught the weak sector. It will be interesting to work out how the relation between composition dependent and composition independent effects changes in passing from the weak sector rather than the strong interactions.

Inflation

(Varying speed of sound, subluminal) A crucial feature of the observed primordial spectrum of perturbations is that its amplitude is very mildly dependent on the wavelength (scale-invariance). In the simplest (slow roll) inflationary models, this is the result of a primordial phase of quasi de-Sitter expansion. In collaboration with Justin Khoury [20], I explored a generalization of the above mechanism. In scalar field models where the Lagrangian is a generic function of the kinetic term and of the field itself [10], perturbations can travel at a velocity (the *speed of sound*) which can be much smaller than the velocity of light. We showed that an adiabatic scale invariant spectrum is produced even if the expansion is far from exponential, provided the speed of sound varies appropriately. We also found a class of contracting cosmologies where this mechanism can be applied and calculated in detail the three point function for both cases, expanding and contracting.

Most of the projects that I am currently working on are on inflation. I am interested in extending the mechanism that we found in [20] to theories as general as those reproduced by the effective field theory approach [37]. Alternatively, one can consider the *gelaton* mechanism [38] – instead of higher order kinetic terms – to get a varying speed of sound. Also, one of the features of our mechanism is that the amplitude of the three point function exhibits a strong running with the scale. Scale invariance is in fact protected only at the level of the two-point (and not higher-point) function. In the expanding case we find increasing non-Gaussianities at smaller (galactic) scales. Therefore, I would like to work on the same lines as e.g. [39, 40] and study the observable effects of such a scale-dependence on the cosmological structures.

(Varying speed of sound, superluminal) In [20] we considered the case of a subluminal speed of sound. Hovewer, in the formalism of bi-metric theories of gravity, also the superluminal option looks consistent [41]. In the superluminal case, the variation of the speed of sound can play a very relevant role, to the extent that the universe does not need to be accelerating [42]. The usual kinematics of the modes (exiting the horizon) during inflation can be replaced by the appropriate speed of sound- dependent quantities (modes exit the *sound*-horizon). By generalizing and extending [20], I am now considering [27] the implications of a close to infinite speed of sound for the three point function. Interestingly, the infinite speed of sound limit corresponds to the "cuscuton" model [43]. The analysis of such a limit suggests a novel type of expansion, to be done around the cuscuton instead of de Sitter, where deviations from scale invariance are given by the finiteness of the speed of sound and/or by appropriate modulations of the potential and of the kinetic function.

(Symmetries of a theory and scale invariance of the spectrum) By looking at several inflationary models, there seems to be a general relation between the symmetries inside the theory and the scale invariance of the produced primordial spectrum. In slow roll-inflation, the smallness of slow-roll parameters is just telling that the de Sitter/shift symmetry (the invariance of the action under the transformation $\phi \to \phi + \text{constant}$) is only slightly broken. I am already at work with Justin Khoury [26] on finding general relations between symmetries and scale invariance. Such a relation seems to be encoded in the (approximate) scaling symmetries of a theory: a transformation in the field space under which the action gets simply rescaled by a factor. I find this long term project is of great interest because the symmetries under study might be protected under radiative corrections. That would give a sort of naturalness – and protection – to the flat spectrum of perturbations that we see in the sky.

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