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A Brief Outline of the Dark Energy Cosmology

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Abstract. We review the basic aspects of the Dark Energy, pointing out the variety of the ideas proposed to explain it, and the connection with the Cosmological Constant Problem in physics. Within the Quintessence scalar field paradigm, we describe the main effects of the dark energy dynamics on the Cosmic Microwave Background anisotropies and structure formation, pointing out the capabilities of the next generation intruments probing the cosmic acceleration.

Key words. Cosmology – Theory

1. Parametrization of Mysteries

As we gain focus on the cosmological picture, our understanding fades. The structures appear to grow out of initially tiny and random fluctuations with almost equal power on all scales, around a nearly flat spatial geometry. The baryonic matter is a fraction $\Omega_b \simeq 5\%$ of the critical density, while for radiation Ω_R is of the order 10^{-5}. The remaining 95% is dark, observed only through its gravitational influence, constrained but not understood. This huge missing piece tells that our parametrization may finally converge, but we haven't yet a physical understanding of cosmology.
Almost 1/3 of the dark component should be made by non-relativistic particles, the Cold Dark Matter (CDM), playing a major role in the structure formation and interacting at most weakly with baryons (see Dodelson et al. 1996, and references therein). The remaining 2/3 is dark and non-interacting as the CDM, but gravitationally *repulsive* to accelerate the cosmic expansion, proposing a new fashion of the Cosmological Constant Problem in physics, as we'll see in the next Section. It was first detected by two independent teams observing Type Ia supernovae at cosmological distances Riess et al. (1998); Perlmutter et. al (1999), and it's now being confirmed by the Cosmic Microwave Background (CMB) and Large Scale Structure (LSS) data (see Bennett et al. 2003, and references therein).

2. Dark Energy

The success of the electro-weak unification indicates that physics acquires symmetry at increasing energies, possibly including all interactions at the Planck scale, 10^{19} GeV. The breaking of this symmetric state, occurring between the Planck scale and the highest probed so far, say 1 TeV, should leave a residual vacuum energy of the order of the breaking scale. The gigantic crash, known as the Cosmological Constant Problem, comes here. In general relativity, such relic is seen as a huge Cosmological Constant, making the cosmic expansion accelerating to the speed of light in a time scale ranging between 10^{-43} and 10^{-27} seconds. One could argue that there are two possible vacuum energy density terms in the Einstein equations:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu} + V g_{\mu\nu} \ . \qquad (1)$$

Λ is the purely geometric Cosmological Constant, introduced first by Einstein himself, while the V represents the contribution from particle physics, between $(1 \text{ TeV})^4$ and $(10^{19} \text{ GeV})^4$. We must invoque that the two terms cancel out not to exceed the cosmological critical density today, i.e. $|\Omega_{vacuum}| = |V - \Lambda|/3H_0^2 < 1$, where H_0 is the Hubble constant. Putting in the numbers, one realizes that $|V - \Lambda|$ gets an upper limit between 10^{-123} and 10^{-59} times the expectation mentioned above.

In front of these embarassing numbers, the most simple guess is that some unknown mechanism sets the vacuum energy to zero, exactly. That lasted until the evidence for cosmic acceleration, telling that $\Omega_{vacuum} = 0.7$ with a precision of about 5% bringing abruptly the Cosmological Constant Problem back at the center of the scene. In addition, the fact that matter and vacuum energy are comparable *now* raises a new problem, known as coincidence: the matter density decreases as the inverse of the volume expansion, while the vacuum one is constant: why are we observing them in the very special moment in which they are comparable? In absence of answers, the concept of vacuum energy in cosmology has been generalized; that is the Dark Energy, the dark cosmological component supposed to explain the cosmic acceleration, but *dynamical* in general.

3. New Theory

An impressive variety of ideas were proposed to explain the dark energy, although none fully successfull so far, expecially for what concern the coincidence; we mention here just a few of them (see Peebles and Ratra 2003; Padmanabhan 2003; Sahni and Starobinsky 2000; Carroll 2001, for reviews).

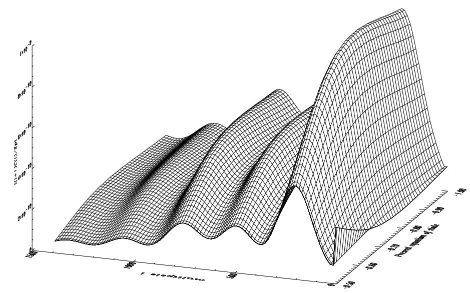

Fig. 1. CMB spectra in tracking inverse power law Quintessence cosmologies as a function of the present equation of state. The vertical axis represents the CMB anisotropy power at the angular scale given by $180/l$ degrees.

3.1. Gravity & Matter

It was argued that perturbations on very high wavelenght, corresponding to trans-Planckian scales, could be perceived as a non-zero vacuum energy Mersini et al. (2002). Another suggestion invoques a quantum spacetime capable to adjust in order to keep the vacuum energy density at the observed value Padmanabhan (2003). Moreover, physical extra-dimension could give a scale dependence to gravity (see Dvali et al. 2003, and references therein); at cosmological wavelenght the gravity weakens because of the graviton leakage off our four dimensional spacetime: in this way the vacuum energy level, seen as an infinite mode perturbation, can match the small observed value.

It is important to note that the dimming of Type Ia supernovae could not be due to cosmic acceleration or dark energy, but to the oscillations of photons in something else when traveling cosmological distances Csaki et al. (2002).

Finally, the dark energy has also been interpreted as the manifestation of exotic features of the cosmological constituents. Among other ideas, an anti-friction provided by CDM particles transferring energy to the vacuum Zimdahl et al. (2001), or a chaplygin gas possessing an equation of state progressively decreasing from zero to a negative value Dev et. al. (2003).

3.2. Quintessence and the Fifth Force

The dark energy is often associated to the concept of a new force. It can indeed conveniently described as a scalar field, the minimal theoretical generalization of a constant vacuum energy, known as Quintessence. The latter can be coherently described in the framework of the linear cosmological perturbation theory, admitting an umperturbed background evolution and spatial fluctuations.

The idea appeared well before the evidence for the dark energy Ratra and Peebles (1988); Wetterich (1988), and was recently revisited, with focus on the attractors in the trajectory space of the mean vacuum expectation value of the field, the tracking solutions Ferreira and Joyce (1998); Liddle and Scherrer (1999); Steinhardt et al. (1999). The latter aspect has the advantage not to require that the high energy processes in the very early universe provided a tiny residual vacuum energy as observed today; however, the Quintessence scenario does not explain why that tiny value is comparable to the cosmological critical density right today, missing the coincidence.

The Quintessemce could phenomenologically represent the residual supersymmetry breaking vacuum energy; these scenarios predict an inverse power law potential shape, also known as Ratra & Peebles (RP) potential Ratra and Peebles (1988); Masiero et al. (2000), possibly including super-gravity (SUGRA) corrections in an exponential form (see Brax and Martin 2000, and references therein). Cosine potential as in Pseudo Nambu-Goldstone scenarios have also been considered Dodelson et al. (2000).

In a generalized fashion the Quintessence Lagrangian can be modified, in its form and interactions with the other cosmological components. A generic kinetic term substantially changes the trajectory space Aramendariz-Picon et al. (2001); Malquarti et al. (2003); Caldwell (2002). The interaction with baryons is severely constrained Carroll (1998), while the case of dark energy/matter coupling Amendola (2000) is more accessible and intriguing: recently, the possibility that the Quintessence sets the dark matter mass has been revisited, and the basic equations for the non-linear clustering have been written Matarrese et al. (2003).

The Extended Quintessence theory links the field to gravity, through an explicit coupling in the fundamental Lagrangian. The first works Chiba (1999); Uzan (1999) investigated the trajectories of the unperturbed field vacuum expectation value, and demostrated that the tracking solutions are preserved in the case of a perturbative quadratic coupling. Scenarios involving a greater variation of the gravitational constant in the early universe have been considered Bartolo and Pietroni (2000). Non-trivial issues of scalar-tensor theories of gravity, such as the distinction between the Jordan and Einstein frames, and the necessary conditions for the onset of cosmic acceleration, have been solved Esposito-Farese and Polarski (2001); Faraoni (2000). A comprehensive work Baccigalupi (2000); Perrotta et. al. (2000) involving the linear perturbation theory in generalized cosmologies Hwang (1991) was carried out making accurate predictions on the most important cosmological observables. On this basis, it was demonstrated that the power injection due to the explicit coupling with gravity yield a sort of “gravitational dragging” transporting the Quintessence density fluctuations to non-linearity Perrotta and Baccigalupi

(2002). This intriguing phenomenology is further discussed in the next Section.

4. New Phenomenology

One of the most important features of the dark energy phenomenology is the equation of state w, since it affects geometry and perturation dynamics, and each proposed scenario predicts a specific dependence for it Corasaniti and Copeland (2003); Linder (2003). It is easy to see that the dark energy density as a function of the redshift z is

$$\rho_{DE} \propto \exp \int_0^z \frac{3[1+w(z)]dz}{1+z} \ , \qquad (2)$$

recovering the Cosmological Constant in the case $w = 1$. We give here a quick review of the known dark energy phenomenology.

4.1. Cosmic Microwave Background

The CMB anisotropy spectrum is affected mainly through the geometrical modification of the metric due to the onset of cosmic acceleration (see Baccigalupi et al. 2002, and references therein). First, for $w > -1$ the background density is higher in the past and the conformal distance to the CMB last scattering gets reduced; this causes a shift of all the features in the CMB anisotropy spectrum toward large angular scales. Second, the change in the equation of state enhances the dynamics to the gravitational potentials entering the horizon during acceleration, increasing the CMB power at large angular scales. These two effects are evident in figure 1, featuring a tracking RP Quintessence scenario. The signals have been computer by using a dark energy oriented version Perrotta and Baccigalupi (1999) of CMBfast Seljak and Zaldarriaga (1996). A third effect concerns the acoustic peak separation in models where the dark energy isn't subdominant at decoupling Doran et al. (2001).

Together with the degeneracy with the other cosmological parameters Efsthatiou (2002), the CMB efficiency in constraining dark energy is limited by the fact that the CMB photons integrate its effects along the line of sight.

4.2. Structure Formation

A general analysis of the linear perturbations perturbations behavior in terms of the equation of state and transport properties of the cosmological components has been carried out Hu (1998). The Quintessence field develops perturbation on horizon scales, yielding extra-power with respect to the Cosmological Constant; the latter aspect has been analysed only in models with a constant equation of state Ma et al. (1999); a more extensive study of this feature with respect to the different Quintessence scenarios is still lacking.

As we already mentioned, it was recently showed that in Extended Quintessence the power injection coming from the coupling with gravity can dominate the background and density perturbation dynamics of the Quintessence itself Perrotta and Baccigalupi (2002). Thus, if the gravitational fields are dominated by the contribution from pressureless dark matter, that forces the Quintessence to be also effectively pressureless, eventually becoming non-linear together with the dark matter. This is an entirely new phenomenology in Quintessence cosmology, and opens the possibility that the Quintessence may play a non-negligible role in dark haloes around galaxies and clusters.

The non-linear side of the perturbation spectrum in dark energy cosmology is a very recent and promising field of investigation. Semi-analytical estimates indicate that the concentration in clusters increases with the dark energy dynamics Bartelmann et al. (2002). The semi-analytical recipe describing the matter power spectrum in the non-linear regime has been extended to take into account the average dark energy equation of state Ma et al. (1999).

Only recently, the first results of N-body simulations in different Quintessence scenarios have been carried out, neglecting

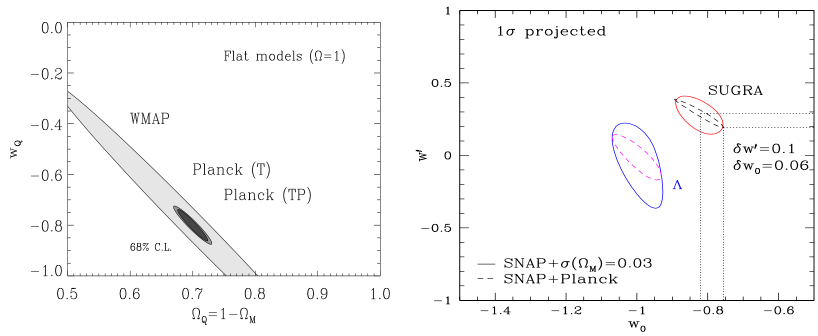

Fig. 2. Left: projected 1σ constraint on the effective dark energy equation of state w_Q from Planck. Right: projected 1σ constraints on the present value of the dark energy equation of state w_0 and its redshift derivative w' from SNAP, Linder (courtesy of Eric V. 2003), for a pure cosmological constant and SUGRA scenarios. The smaller contours represent the combination of Planck and SNAP data.

only the clustering of the dark energy itself Klypin et al. (2003); Linder and Jenkins (2003), making the first steps toward detailed predictions of the dark energy influence in realistic matter structures.
The best tool to detect these effects is the weak gravitational lensing, i.e. the shear pattern induced by forming structures on the background light. (see Mellier et al. 2002, and references therein). Optimized tools to extract the information relevant for the dark energy out of weak lensing data are under study (see Bartelmann et al. 2003; Hu and Haiman 2003, and references therein).

5. All About Future

We conclude this work with two plots, in figure 2, representative of the capabilities of the next dark energy probes. In the left panel, the projected sensitivity which we expect for Planck and WMAP Balbi et al. (2003), using only CMB data, and restricting to flat cosmological geometries, assuming a target model having an effective equation of state $w_Q \simeq -0.8$. On the right panel, the projected capability of SNAP[1] satellite (see Linder 2003, and references therein) to constrain the *time dependence* of the equation of state, for a Cosmological Constant and a SUGRA Quintessence model: that well represents the case in which the dark energy equation of state is close to the Cosmological Constant at present, but represents a completely different physics because of its marked dynamics.
This level of detail should be compared with the present one, where the average dark energy equation of state is constrained to stay at value less than -0.78 (see Bennett et al. 2003, and references therein).
That certainly means that we expect a great progress on our understanding the nature of the dark energy from the future probes. What is really important to keep in mind is that the dark energy manifests at low redshifts; this allows to test the impact which any given model of dark energy has *directly* on nearby processes probed with greater and greater accuracy in the near future.

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