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Cosmology and Dark Energy: Theory

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We present a very brief and incomplete overview of the on-going theoretical activity aiming at providing an explanation for the (at least apparent) acceleration of the universe. We discuss the issue of the cosmological constant amplitude, describe some inhomogeneous cosmology models, present some quintessence and other dark energy models, and say a few words on non-minimal gravity. We mention the difficulty to distinguish between dark energy and non-minimal gravity models, and summarize the reasons for which a detailed measurement of the evolution of metric perturbations in the recent universe may offer the best smoking gun in favor of one particular model.

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1. The problem

We all know that explaining the apparent acceleration of the universe raises one of the biggest fine-tuning issues of modern physics. Observations of Supernovae luminosity, of Cosmic Microwave Background anisotropies, of the Large Scale Structure of the Universe, etc., suggest that we need to add a constant energy density of the order of $(10^{-3}\mathrm{eV})^4$ to the Friedmann equation

$$3m_P^2(H^2 \pm a^2/k) = \rho \ ,$$

where m_p is the reduced Planck mass ($m_p^{-2} = 8\pi\mathscr{G}$). However, particle physics tends to predict much larger values. From radiative corrections to the vacuum energy, one would expect contributions of the order of the fourth power of the cut-off of the theory (at most, $\rho_{\mathrm{vacuum}} \sim m_P^4 \sim (10^{28} eV)^4$ for a cut-off at the Planck scale; possibly less, e.g. m_{susy}^4 if we assume supersymmetry; but not smaller than $m_{\mathrm{EW}}^4 \sim (10^{11}\ eV)^4$ even if we make the extreme assumption that there is no new physics above the electroweak scale). Besides, within our understanding of phase transitions, we expect the vacuum energy to drop several times by some amounts $\Delta\rho_{vacuum}$ always much larger than ρ_{vacuum} today (e.g. by $(10^{11}\mathrm{eV})^4$ during EW symmetry breaking, or $(10^8 eV)^4$ during the QCD transition). This is summarized in the sketchy plot of Figure 1. The upper dashed curve corresponds to

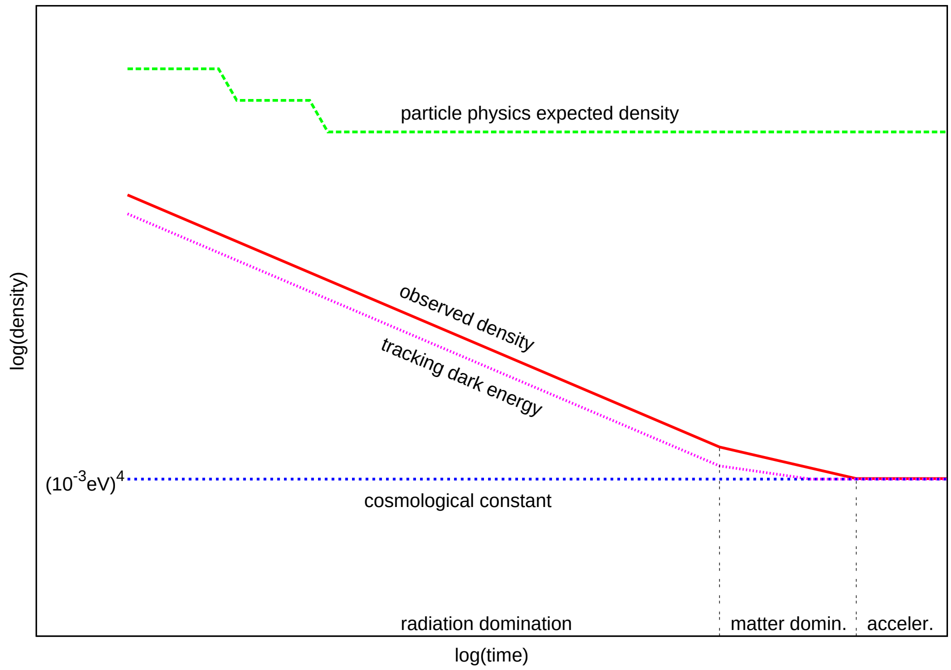

Figure 1: A sketchy view of the evolution of total density in our universe, and of the vacuum density according to various assumptions/expectations.

what we would expect from particle physics: a huge contribution from vacuum energy to the total density, with jumps corresponding to phase transitions; but in fact, what we see, or more precisely what contributes to the Friedmann equation is the solid line, scaling first like radiation, then like matter, and finally, in order to fit observations, like a nearly constant term. We don't know whether the term responsible for the acceleration was actually constant in the past, but we have anyway two problems: the "old problem" (why is the huge contribution to the vacuum energy expected from particle physics suppressed?) and the "recent problem" (why is there a small but non-zero contribution?).

Some people believe that this problem can be alleviated by assuming a "tracking dark energy model" instead of a static cosmological constant. Indeed, there exist simple dark energy models in which the energy density remains a fixed fraction of the main component in the past, until some point at which it starts to be constant and dominate. This is represented schematically by the thin dotted line in Figure 1. But in this category of models, some strong fine-tuning is usually still needed in order to explain why dark energy leaves its tracking solution at very recent times (we will however mention some possible exceptions in section 4). In general, this fine-tuning is roughly equivalent to that of initial conditions in non-tracking scenarios. In other words, the "why so small" issue is often replaced by a "why now" issue, which is essentially identical.

We should stress that, generally speaking, it is very difficult to build a predictive model for dark energy. Indeed, the purpose of a given dark energy model is to explain a single phenomenon. Moreover, this single phenomenon – the apparent acceleration of the universe – corresponds to a single measured number (at least, at the current level of experimental precision), which is the value of the apparent cosmological constant Λ (or, equivalently, its density ρ_Λ or its fractional density Ω_Λ). It is very difficult to discriminate between models as long as we only have a single observable. Of course, if we hesitate between several models able to explain the universe acceleration, we can still invoke the Occam razor argument, and retain the model with the smallest number of parameter. But how can we be sure that nature is not described by a model with more free parameters?

After these pessimistic comments, we should notice that:

- in principle, it will be possible to measure more than one observable in the future: for instance, we could detect a time-variation of the density of dark energy (which could be parametrized through a dark energy equation of state parameter w different from minus one and possibly depending on time/redshift, while a pure comsological constant has $w = -1$); in that case, some models could be ruled out, while other ones would appear as more predictive; but it is not guaranteed that we will ever detect anything beyond Λ.

- it is also possible to construct theories leading to independent predictions, which could be tested in the laboratory or in astrophysics; but who knows? The true explanation for the acceleration of the universe might have absolutely no connection with any other testable sector: in that case, science would remain in an ever-lasting frustrating situation.

2. Cosmological constant and beyond

From the point of view of Occam's razor, the cosmological constant is the most economical model on the market, since it contains only one parameter. But of course, setting Λ in order to fit observations today is not satisfactory, given the fine-tuning issues mentioned above. How could Λ be tuned in the early universe "in advance", i.e. in such a way that today, after a given number of phase transitions dramatically affecting the value of $\rho_{\rm vacuum}$, the total $(\rho_\Lambda + \rho_{\rm vacuum})$ would reach a tiny non-zero value?

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The case for a simple cosmological constant may sound better when approached with some anthropic reasoning. Within the "eternal inflation" and/or "string landscape" paradigm, we could imagine that many observable patches of universe are generated on much larger scales than our own observable universe. Each patch would have its own value of Λ (or of the vacuum energy: in the rest of this discussion we will consider ρ_Λ and $\rho_{\rm vacuum}$ as standing for the same quantity), because the theory might have many different vaccua corresponding to different values of Λ, and the dynamics leading to one vacuum or another could be complicated and random. In any patch in which Λ is significantly bigger than what we observe in our universe, matter domination could not last long enough for structures to form, stars to be turned on, and life to appear. Hence, we could consider that it is natural to live in a patch where Λ is of the same order of magnitude as the upper bound above which life is impossible.

I am not against this way of thinking, and would even find it very reasonable, if the argument was not spoiled by the fact that there is no lower anthropic bound on Λ. Indeed, supporters of the anthropic argument consider that all values of Ω_Λ are equiprobable between 0 and the antropic upper bound $\Omega_{\Lambda\ \rm max}$, which is of order one. Then, $\Omega_\Lambda \sim 0.7$ is not an unreasonable value. But how do we know that all values of Ω_Λ are equiprobable? Why shouldn't we assume instead a flat prior on the energy scale of Λ (i.e. on $\Omega_\Lambda^{1/4}$), or even on the order of magnitude of the energy scale (i.e. on $\ln[\Omega_\Lambda]$)? With the latter assumption, the value that we observe is extremely close to saturating the upper bound, and so again the situation appears as very special and fine-tuned. We see that the antropic argument would be much more convincing if for some reason, it would be impossible to live in a universe with an arbitrarily low cosmological constant.

The solution to the cosmological constant / vacuum energy problem will hopefully come from particle physics. A better understanding of fundamental theories may provide us with a new way to compute the vacuum energy at a given time, that will reconcile particle physics with cosmological observations. While aiming at such a fundamental solution to the problem, we can also check whether some explanation can be provided within our current understanding of particle physics and quantum field theory. The attitude adopted by many researchers in theoretical comsology consists in assuming that some yet unknown symmetry drives the vacuum energy to exactly zero, and in trying to explain the acceleration of the universe without touching this vacuum energy.

In the rest of this contribution, we will stick to this point of view. If we do not touch quantum field theory / high energy physics, the theories or assumptions that we can question are:

- Einstein gravity
- the assumption of a homogeneous universe
- the assumption that our universe only contains ordinary matter today (non-relativistic baryons, pressureless dark matter, and a tiny fraction of radiation).

3. Inhomogeneous cosmology

Many different ideas are hidden behind the terms "inhomogeneous cosmology". What they have in common is the assumption that Einstein gravity is correct, that the only matter components playing a role today are baryons and dark matter, but that the Friedmann model does not provide an appropriate framework, at least for describing the recent universe.

In standard cosmology, density and metric fluctuations are small (and well captured by linear perturbation theory) at early times and on large scales. At late time and on small scales, perturbations remain small at the level of the metric tensor (because even in galaxies and clusters, the gravitational potential is at most of the order of $\phi \sim (v/c)^2 \leq 10^{-5}$, excepted in the vicinity of black holes), but become large at the level of the Einstein tensor (depending on second derivatives of metric fluctuations) and of the energy-momentum tensor. It is usually assumed that the Friedmann equation remains applicable for describing the average expansion even when $T_{\mu\nu}$ becomes strongly non-linear on small wavelengths. Some people (e.g. [1, 2]) questioned this assumption and tried to calculate the back-reaction of non-linearities in the Friedmann equation. Explaining the apparent acceleration of the universe with back-reaction effects would provide a very economic solution to the problem, since it would involve no deviations from Einstein gravity, nor from homogeneity on intermediate and large scales, and no ad hoc fluid. It would also solve the "why now" problem, since the stage of apparent acceleration would naturally follow the stage of non-linear structure formation during matter domination. Unfortunately, most recent studies of back-reaction terms (which are extremely difficult to compute in a general relativity framework) indicate that they should be extremely small, at least if we stick to the idea that the Universe can be described by the Friedmann model till the beginning of structure formation (e.g. [3]).

One can then investigate more radical deviations from the Friedmann model, caused not just by local inhomogeneities on small scales, but by possible non-linear overdensities or voids on intermediate or large scales, on which the standard cosmological model would predict only small linear perturbations. The geodescis of photons crossing such structures might be strongly deviated, and images of object might be focused in such a way to change the angular diameter distance and luminosity distance as a function of redshift, mimicking an accelerating universe.

Essentially two classes of models have been investigated. In the first class of models, one relaxes the assumption of homogeneity in the Friedmann model, but keeps that of isotropy. It is then assumed that we live close to the centre of a big non-linear void. This is not conceptually very nice, because one is led to give up the Copernician principle, and assume that we live in a special place in the universe. But such models could in principle mimic an accelerated universe (e.g. [4, 5]). The other class of models relies on the assumption that many non-linear bubbles and/or matter shells are scattered throughout the universe; after crossing many such bubbles, photon geodesics are focused in such a way to mimic dark energy. Several groups have been studying toy models obtained by taking the Friedmann metric, and gluing to it inside several spherical patches the Tolman-Bondi metric (e.g. [6, 7]),

These models still need more investigation, but they experience generic problems which can be summarized as follows. Enough non-linear structures need to be introduced in order to observe a significant modification of the luminosity distance relation, and agree with supernovae observations. But at the same time, these inhomogeneities should not be too strong, in order not to distort the spectrum of primary CMB anisotropies with lensing effects, and not to generate an excess of secondary anisotropies through the integrated Sachs-Wolfe effect. It is very difficult to reconcile the two, and most (if not all) toy models investigated so far conclude that observational tests cannot be passed without reintroducing a cosmological constant (e.g. [8, 9, 10]). Moreover, in these

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models, it is very difficult to compute the evolution of cosmological perturbations, and people did not investigate yet the constraints coming from the matter power spectrum. Another problem of these models is the need for a theory which could explain the formation of such non-linear structures. This is possible in principle e.g. with phase transitions, but then the models start to be really complicated.

If these models (and in particular, the first ones, with a big spherical bubble nearly centered on us) survive to the calculation of the matter power spectrum and of the CMB anisotropy spectrum, it will be difficult to distinguish them from the standard cosmological model. A direction of research in observational cosmology consists in studying the evolution of a few cosmological observables as a function of time. If we perform the same observations at a few years of distance and start to see an evolution (thanks to extremely precise instruments), we will be able to compare the properties of the universe along two 3-dimensional cuts, corresponding to two distinct past-light-cones. Such measurements would provide a way to remove the degeneracy between a homogeneous accelerating universe, and an inhomogeneous, isotropic, non-accelerating one.

4. Dark energy

Let us now discuss the possibility of introducing a specific fluid or component (generically called “dark energy”) in order to explain the acceleration of the Universe. We will start from the well-known quintessence paradigm, in which dark energy is assumed to be a classical, nearly homogeneous scalar field (for a review, see [11]). Most theorists never took quintessence models too seriously, because they just replace one fine-tuning by another one, as we shall see below. Still, these models are very popular, first, because they are easy to calculate, and second, because they have a lot of freedom. So, the common belief is that by studying only quitessence, one covers all possible signatures of dark energy models. We will see later that this is not even true, because quintessence models can mimic arbitrary dark energy models (not violating the weak energy principle) at the level of the background evolution, but not at the level of cosmological perturbations.

A major problem with quintessence is that in order to get acceleration today, the scalar field must fullfill the well-known “slow-roll conditions”, like the inflaton during inflation. This implies that the effective mass of the field today should be smaller than the current Hubble rate, i.e. than 10^{-33}eV. This is very unnatural for two reasons:

- first, because such a light boson should a priori trigger fifith forces if it was coupled with other species. There are very strong constrains on such extra forces, especially in the solar system. To avoid this fifth-force issue, one should assume that the couplings between the quintessence field and matter fields are unaturally supressed.

- second, because such a small mass should be completely instable against radiative corrections. So, one should invoke special symmetries such that if the symmetry was unbroken, the quintessence mass would vanish. This symmetry should be slightly broken in order to obtain a tiny non-zero mass protected from radiative corrections. At the end of the day, this machinery is usually as fine-tuned as a plain cosmological constant.

One view on these issues is that fine-tuning problems appear only when one tries to write the Lagrangian of the scalar field in the perturbation theory way, i.e. when expanding the scalar potential $V(\phi)$ in a mass term and higher powers of the fields. But suppose that the field has a run-away potential, that cannot be captured by a Taylor expansion around its minimum. In that case, the field rolls away to infinity, its effective mass $m_{\text{eff}}^2 \equiv \frac{1}{2}\frac{\partial^2 V}{\partial \phi^2}$ decreases forever, and sooner or later it will reach the very small value that we need. But why would it reach such a small value in our era, i.e. not so long after the time of equality between radiation and matter? This issue can be adressed with the famous tracking potentials [12]. These classes of potentials lead to an attractor solution in which the energy density of the field adjusts itself to a fixed fraction of the total energy density of the universe. There is a simple run-away potential leading to perfect tracking, namely the Ratra-Peebles potential [13]

$$V(\phi) = \lambda m_p^4 e^{-\alpha\phi} ,$$

in which no parameters need to be fine-tuned in order to get a tracking behavior till today (λ and α don't need to be very small). But since this potential leads to a perfect tracking solution, the field will never get out of the tracking regime, and will never dominate the expansion of the universe. We would need instead imperfect tracking, i.e. a potential such that at some time, the field stops tracking the total density, enters in a slow-roll regime, and accelerates the universe expansion. This can easily be achieved with inverse power-law potentials of the form [12]

$$V(\phi) = \lambda (\phi/m_p)^{-\alpha} ,$$

but then, in order to get out of tracking only recently, one needs to fine-tune the normalization parameter λ of this potential, coming back to the initial fine-tuning problem.

Another approach to the quintessence mass problem consists in considering non-canonical kinetic terms, like in the so-called k-essence model [14]. In that case, the field can lead to accelerated expansion without satisfying the usual slow-roll relations, and without tiny parameters in the scalar field potential. However, fine-tuning issues usually strike back in the choice of initial conditions [15].

There are other approaches to the small mass and fifth force problems, like the chameleon mechanism [16, 17]. If we assume that quintessence gets its mass not from its own potential, but from couplings with other matter fields, this mass becomes a varying quantity, depending on the background energy density at a given time and place. We could be in a situation in which the effective mass relevant for cosmology and the one controlling fifth forces on astrophysical scales are completely different. Indeed, for cosmological applications, one would infer the mass after averaging the background density over very large distances; this could give a very small effective mass, and a quintessence-like behavior. Instead, for studying the behavior of the field on astrophysical scales, one would need to take into account the fact that in the vicinity of dense compact objects, the mass of the field would be locally much larger. This mechanism can result in a screening of astrophysical objects against the fifth force. This idea is elegant, but in order to pass all tests of gravity, chameleon models still need to be rather complicated and fine-tuned.

In usual quintessence models, couplings with other fields are set to zero (usually without any good reason) in order to avoid a fifth force, while in the chameleon model one introduces special couplings leading to a screening of the fifth-force. A third approach to the coupling issue consists in assuming that for some particular reason, quintessence couples only to a specific sector. This sector can then be used to explain some energy scale in the quintessence sector, or to trigger some

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event. Such theories can be predictive, because they relate the quintessence sector to another sector of particle physics. For instance, in the mass-varying neutrino (MaVaN) scenario, one assumes that quintessence couples only with neutrinos, in such way that neutrino masses depend on the local value of the quintessence field, and also that the dynamics of quintessence changes radically when neutrinos become non-relativistic. It is then possible to assign to quintessence a Ratra-Peebles potential, which has the advantage of avoiding any fine-tuned parameters. Quintessence will depart from its tracking behavior as a result of the non-relativistic transition of neutrinos. This is an example of a scenario where the energy scale of the effective cosmological constant is related to another scale in particle physics, namely that of neutrino masses today, which have the correct order of magnitude. In principle, this model is predictive, because the variation of the neutrino mass as a function of time and space could be tested with better experiments; however, since the coupling between neutrinos and the scalar field is not supressed, neutrinos do feel a fifth force. As a result, just after their non-relativistic transition, they tend to collapse inside some big neutrino clumps. This argument was sufficient for ruling out the original MaVaN model of Ref. [18]. There is still another category of models which may survive, studied by the group of Wetterich (see e.g. [19]). In that case, neutrino clumps do form, but only on very large scales and with a rather small density. So, it is not clear that they are incompatible with observations. This is still an open question, and a rather difficult one, since it relies on strongly non-linear clustering processes.

There are many other dark energy models not even involving any classical scalar field. It is of course impossible to list them in this short review. For instance, we can mention that some particles (e.g. dark matter) could undergo Bose condensation at some point in the history of the universe, due to some microscopic phenomenon; they would then start to behave like dark energy [20]. But no precise model of this kind has ever been constructed. People have also thought of using thermodynamical effects: the dark energy behavior might emerge not from some specific terms in the Lagrangian, but from some collective behavior of particles. Following this logic, and adopting a phenomenological rather than fundamental approach, one could postulate that dark energy is a fluid with some non-trivial equation of state. For instance, the Chaplygin gas equation of state (e.g. [21]) allows a gas to mimic first dark matter, and then dark energy. However, this models suffers from unstable cosmological perturbations. One could also assume that the dark energy fluid is imperfect and features bulk viscosity, which could mimic the negative pressure of dark energy. This has been proposed (with again a phenomenological approach) in e.g. [22, 23]: in these works, the authors postulate some relation between the bulk viscosity coefficient and the fluid density.

Recently, in [25], we revisited this last issue, taking advantage of the fact that bulk viscosity has been computed from first principles for a gas of spin-zero bosons with a quartic self-coupling [24]. This gas can be assumed to be decoupled from the rest of the plasma (since some arbitrary time), but to remain self-coupled thanks to the $\lambda\phi^4$ interaction. At some point, due to the dilution of the fluid, the self-interaction becomes too weak for maintaing the equilibrium pressure, and the bulk viscosity becomes important, leading to acceleration. This model passes observational tests for reasonable values of the boson mass and coupling parameters. However, further work is needed in order to check that the expression of bulk viscosity derived in a different context in Ref. [24] (using quantum field theory at finite temperature) can really be extrapolated to this regime, and that bulk viscosity can really lead to a negative pressure.

5. Non-minimal gravity

Non-minimal gravity (i.e. modified Einstein gravity) is a vast topic, that we do not intend to review here. Most recent developments are summarized in the review of Clifton et al. [26]. The different possibilities can be classified as:

- theories with extra scalar fields (scalar-tensor gravity, aether theories, bimetric gravity, massive gravity, tensor-vector-scalar gravity, ...)
- theories with higher derivatives and/or non-local terms ($f(R)$ gravity, Horava-Lifshitz gravity, Galileon theories, gravity braiding, ...)
- theories with extra dimensions (DGP, degravitation, Einstein-Gauss-Bonnet gravity...)

All these models lead to very technical issues, complicated assumptions and challenging computations. We can identify recurrent problems, like the existence of extra light scalar fields with universal coupling to all matter fields, leading to a fifth force and clashing with solar system tests; the presence of ghosts (fields with the wrong sign in the kinetic term) signaling instabilities; the breaking of causality; etc. These problems can be addressed at the expense of rendering the theories considerably more complicated than General Relativity. In summary, this field will require more work in the future (e.g. for computing the evolution of cosmological perturbations and checking that they are compatible with observations), and does not offer yet any simple and compelling paradigm leading to an accelerating universe.

6. Equivalence between dark energy and non-minimal gravity; perturbations as a smoking gun

Note that there is a formal equivalence between non-minimal gravity models and dark energy models. Any modification can be placed arbitrarily on the left-hand side of the Einstein equation (non-minimal gravity) or on the right-hand side (extra matter). But in the future, if we can observe a manifestation of what is happening in the recent universe other than just a constant (or nearly constant) background energy, the explanation might appear as more natural when formulated in gravity terms rather than in dark energy terms, or vice-versa. We should enter in few more details in order to justify this point of view.

Let us assume for simplicity that our universe if flat, homogeneous and isotropic, and contains only linear perturbations. However, we don't assume that gravity is described exactly by General Relativity, and we allow for the presence of some dark energy fluid. At the level of the background, the geometry of such a universe can be described by a single function of time (the scale factor $a(t)$ or the Hubble rate $H(t)$), and at the level of perturbations, by two metric perturbations, i.e. two functions of time and space (for instance, the so-called Bardeen potentials $\phi(t,\mathbf{x})$ and $\psi(t,\mathbf{x})$). All these functions can be measured independently: $H(t)$ with all methods sensitive to the expansion history (e.g. supernovae); the generalized Newtonian potential ψ by measuring the growth of structure (e.g. with galaxy redshift surveys); and the sum $(\phi+\psi)$ with weak lensing techniques (e.g. with galaxy shear surveys).

In the standard cosmological model (with baryons, Cold Dark Matter and a cosmological constant), we expect the two metric fluctuations ϕ and ψ to be equal to each other, because the Einstein equations tell us that $(\phi - \psi)$ is related to the anisotropic pressure of total matter, which vanishes in the case of nearly pressureless components like baryons and Cold Dark Matter. Also, in the same standard model, the Einstein equations predict a simple relation between ψ and the density fluctuation of baryons $\delta\rho_B$ and of Cold Dark Matter $\delta\rho_{CDM}$ (the Poisson equation).

Hence, any non-trivial effect at the level of perturbations would consists in $(\phi - \psi)$ being non-zero, and/or in a violation of the relation between ψ and $(\delta\rho_B + \delta\rho_{CDM})$. These are the smoking guns that future experiments will try to detect. If such a signal was observed, we could in principle choose between:

- sticking to just pressureless baryons and CDM in the matter sector, and validating a theory of gravity such that $(\phi - \psi)$ is not just given by anisotropic pressure, and ψ by density perturbations;
- sticking to Einstein equations, and postulating an extra fluid with the appropriate anisotropic pressure and extra density fluctuations needed to match observations.

It could well be that no simple modification of General Relativity could match such observations; or that no consistent fluid formulation would lead to the needed extra contributions. In that case, there would be some hope to discriminate between non-minimal gravity and dark energy on the basis of simplicity criteria. As long as a non-trivial behavior of cosmological perturbations is undetected, such a discrimination sounds unlikely. Measuring the recent evolution of ϕ and ψ on various scales and with exquisite precision is the target of many planned experiments, such as the ESA satellite Euclid.

This reasoning also shows that quintessence models cannot mimic any other dark energy model. Quintessence always have a sound speed equal to zero, implying negligible perturbations, a standard relation between ψ and $(\delta\rho_B + \delta\rho_{CDM})$, no anisotropic pressure at leading order, and $\phi = \psi$. An experiment like Euclid could in principle rule out all quintessence models.

7. Conclusions

The future of this field is completely uncertain. We don't know whether we will see anything more than the value of Λ, but there is still a chance to detect a time variation of the dark energy background density, or some non-trivial effect at the level of perturbations. Depending on the results of future observational campaigns, dark energy might be understood (leading to one of the biggest success of modern physics), or remain forever ambiguous (showing one of its biggest limitations).

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