# Theory challenges of the accelerating Universe

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# Theory challenges of the accelerating Universe

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**Abstract**
The accelerating expansion of the Universe presents an exciting, fundamental challenge to the standard models of particle physics and cosmology. I highlight some of the outstanding challenges in both developing theoretical models and interpreting without bias the observational results from precision cosmology experiments in the next decade that will return data to help reveal the nature of the new physics. Examples given focus on distinguishing a new component of energy from a new law of gravity, and the effect of early dark energy on baryon acoustic oscillations.

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(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Acceleration of the expansion of the Universe is an implicit possibility within Einstein's equations of motion, achievable through a component of the energy density with sufficiently negative pressure. One example is the cosmological constant, which has close ties to quantum field theory and the nature of the spacetime vacuum. Acceleration also occurs during the epoch of inflation in the first tiny fraction of the age of the Universe, but here is believed to arise from a dynamical field connected with high energy physics.

With the discovery of the recent acceleration of the cosmic expansion a fundamental question is whether we are seeing physics from a cosmological constant (whose magnitude we are far from understanding) or a new, dynamical field—or completely novel physics such as an expanded theory of gravity. We can hope that by studying this modern acceleration epoch we can probe uncharted areas of physics, learning about quantum and gravitational physics, and perhaps even approach a unification of the two.

In this paper I consider some broad theoretical avenues for understanding the accelerating Universe and how to interpret the data in the next decade to reveal the nature of the new physics in a clean and robust manner. In section 2 I discuss some general, model independent

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conclusions we might draw about the dark physics. Section 3 examines the prospects for distinguishing between a new physical component of energy density in the Universe and a new physical law for gravitation, and the necessity of making such a distinction. The search for cosmological methods of probing cleanly the nature of the acceleration is investigated from a theory perspective in section 4, cautioning against implicitly assuming an answer that we are trying to find.

## 2. Which ideas?

A huge variety of theoretical ideas exist that attempt to explain the acceleration of our Universe. For one recent survey, see [1], as well as these proceedings. While some of the initial ideas have fallen out of favour under the pressure of observations, to a large extent the current data sets are insufficient to decide on a particular physical origin. This has led to ambitious and detailed plans for future experiments to guide us in our exploration.

Here I attempt only to make some general points that might aid our understanding. First, on the surface at least, dark energy (modern acceleration) and inflation (early Universe acceleration) appear very different and we should not expect perhaps to apply the same methods of analysis to each. I will be bold enough to posit that dark energy may be a harder problem to solve than inflation. Unlike inflation, dark energy is likely not a slow roll phenomenon (or not exclusively slow roll) and it does not currently completely dominate the Universe.

In fact, dark energy faces us with a Goldilocks problem, after the folk tale where from a landscape of possibilities the character Goldilocks found some components (e.g. porridge, in the tale) were too hot, some were too cold, and one was just right. Dark energy is neither dynamically fully dominant nor negligible, but at an intermediate stage 'just right'—the dimensionless energy density $\Omega_{\rm DE} \sim 0.7$—to allow dark energy and matter cosmological observations (whereas a factor of four ago in expansion factor the dark energy was undetectable and a factor of four in the future there will be relatively few large matter structures within the visible Universe).

Similarly, the expansion is accelerating—dark energy equation of state $w \lesssim -0.8$—but one needs either a period of fast roll in the field or else fine tuning of initial conditions. Inflation, by contrast, is simpler to treat because during inflation the field's energy density is completely dominant and the field is slowly rolling. In this sense, measurements of inflation lend themselves to more straightforward interpretation in terms of the underlying physics.

One question I will not address is the bedrock issue of the cosmological constant $\Lambda$; while observations can tell us whether the physics is distinct from the cosmological constant, they cannot declare definitely that the answer is the cosmological constant if the physics looks nearly like the cosmological constant. Moreover, if the physics is not that of the cosmological constant we still must figure out what happened to the cosmological constant—why is it zero?

Beyond $\Lambda$, perhaps the simplest physics is that of a canonical scalar field. While a wide variety of different potentials have been suggested for such a field, there are common elements and physics among them. From the Klein–Gordon equation of motion,

$$\ddot{\phi} = -3H\dot{\phi} - {\rm d}V/{\rm d}\phi, \tag{1}$$

we see that the field evolution is driven by the steepness of the potential $V(\phi)$ and dragged by the Hubble expansion $H = \dot{a}/a$. By the time the dark energy causes acceleration of the Universe, one or the other of these terms will dominate. Either the field starts frozen by the early, high Hubble drag and then is released to roll as $H$ decreases in the expansion—we say such fields are 'leaving $\Lambda$' or 'thawing'—or the field starts by rolling down a steep potential but

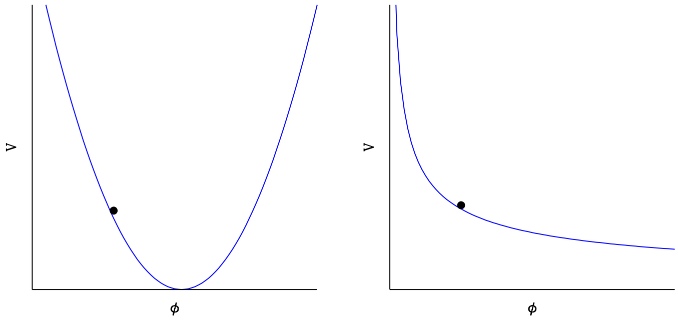

**Figure 1.** Cartoons of thawing and freezing potentials with the scalar field rolling down. The left panel represents a thawing potential where the Hubble drag dominates early but diminishes with age so the field is released to roll. The right panel represents a freezing potential where the steepness drives the early evolution but at late times the Hubble drag dominates.

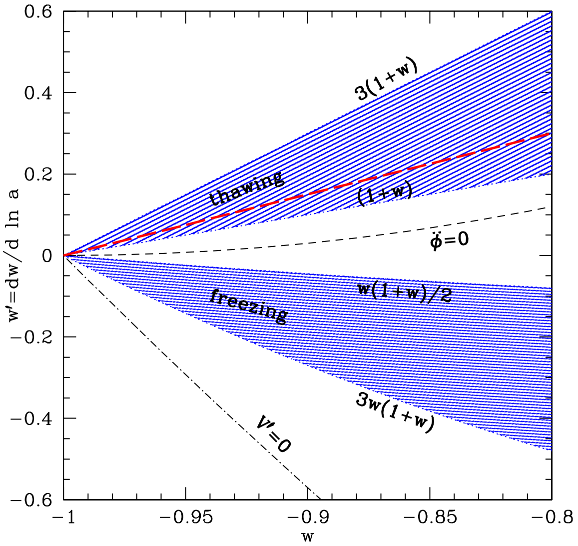

**Figure 2.** The phase space $w'$–$w$ possesses distinct regions corresponding to thawing and freezing behaviour. In between, the field evolution would need to be finely tuned to coast, $\ddot{\phi} \approx 0$, neither accelerating nor decelerating. The long-dashed (orange) line shows the degeneracy surface of observations that can measure only the averaged or assumed constant equation of state. (Adapted from [2].)

slows to a crawl as it comes into a flatter section of the potential—such fields are 'approaching $\Lambda$' or 'freezing'. See figure 1 for illustration of the two cases.

This bimodal classification of canonical scalar field behaviour [2] has proved quite successful. The phase space behaviour of such fields giving rise to a current epoch of acceleration falls into one of two distinct regions, separated by a distance $\sigma(w') \approx 2(1 + w)$, where $1 + w$ is the 'tilt' of the equation of state away from the cosmological constant value of $w = -1$, and $w' = \mathrm{d}w/\mathrm{d}\ln a$ is the running. As we see from figure 2, the reason there is a separation between the thawing and freezing behaviours is that for a field to live in the phase space in between, it must be fine tuned so the driving and dragging terms balance nearly exactly to yield $\ddot{\phi} = 0$—over many dynamical Hubble times.

Another lesson from figure 2 is that cosmological observations, which possess inherent degeneracies between parameters, do not zero in on a specific point in the phase space but rather an elongated region following the degeneracy. The long-dashed line shows the degeneracy direction (virtually all types of observations have roughly the same degeneracy direction in the $w'$–$w$ phase space; see, e.g., [3]). In particular, any experiment that lacks the redshift reach and accuracy to be sensitive specifically to the time variation (such as all current and near term experiments), seeing only an averaged equation of state or constant $w$, will not be able to distinguish points along or near the long-dashed line.

This implies that a result consistent with the cosmological constant is also consistent with almost the entire half of the populated phase space that represents the thawing models. So near term experiments that might deliver a measurement of dark energy in terms of constant $w$ to 5%, say $\langle w\rangle = -1 \pm 0.05$, would not in fact lead us to the conclusion that the answer is the cosmological constant. A new generation of experiments specifically designed to be sensitive to time variation $w'$ is required to gain insight into the physics of the acceleration: cosmological constant or not, thawing or freezing.

The characteristics of approaching or leaving $\Lambda$, and the cosmological physics defining boundaries for the associated freezing or thawing behaviours, are general enough that they apply to many other explanations of acceleration besides canonical scalar fields [4]. An effective equation of state can be defined for any Friedmann expansion equation, even if the modification arises from alteration of the gravity theory rather than a physical component. An example of this is the braneworld theory [5, 6], which follows a freezing track in the effective phase space. It is awe inspiring to think that next generation cosmological measurements can put precision limits on something as exotic and fundamental as the five-dimensional Planck mass, yet the Supernova/Acceleration Probe (SNAP: [7]) could determine $M_5\big/\big(H_0 M_{\mathrm{Pl}}^2\big)^{1/3}$ to 0.2%.

## 3. Which reality?

While the expansion history, or equivalently the effective dark energy equation of state phase space, description can treat a physical component such as a scalar field or a physics modification such as an extended theory of gravity equally, we of course also want to know which is the true physical origin of the cosmic acceleration. This requires experimental data giving both the expansion history and the growth history of mass density fluctuations.

In general relativity, the two histories are tied together; one can write the growth purely in terms of the expansion. For other theories of gravity, however, the growth behaviour is governed both by the expansion and by the specifics of the gravity theory. Therefore, measurements showing a tension between the results from the expansion history and the results from the growth history can guide us to modifications of general relativity and answer the question of whether the acceleration comes from a new physical component or new physical laws.

To see down to the deeper levels of the reality of dark energy we need to simultaneously fit the data for the expansion characteristics and the gravity theory. Assuming one of these to be fixed can yield precise *but incorrect* results for both. An illustration of this ‘gravity’s bias’ appears in figure 1 of [8]. For mapping expansion and growth together we simulate the combination of the supernova (SN) distance-redshift relation and the weak gravitational lensing (WL) shear power spectrum (correlations between background galaxy shape distortions caused by light deflection by intervening mass structures, as a function of redshift), along with cosmic microwave background (CMB) data to break further degeneracies.

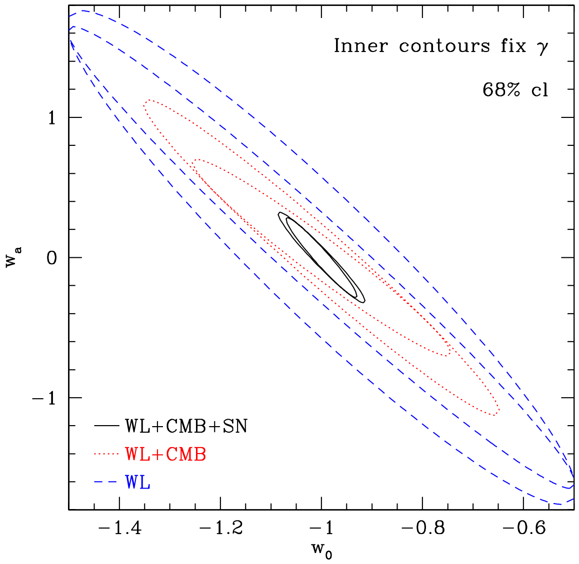

**Figure 3.** Simultaneously fitting the cosmological expansion and the gravity gives robust characterization of the accelerating physics. The combination of weak lensing, supernovae, and cosmic microwave background measurements has the power to constrain the deviation from Einstein gravity (parameterized by $\gamma$)—rather than assuming its value—without degrading estimation of the expansion history parameters $w_0$, $w_a$ by more than 15–25%.

Carrying out the analysis within the fixed gravity framework of general relativity can bias the result from the true answer. However, allowing for the possibility of deviations in gravity (through the gravitational growth index $\gamma$ described in [9]), i.e. simultaneously fitting the expansion and the gravity, gives the correct result, with only a slight increase in the size of the confidence contours. Figure 3 shows that with the combination of WL+SN+CMB we can indeed successfully carry out such a program seeking the origin of the new physics.

Furthermore, for the minimal modified gravity considered here, where the deviation from Einstein gravity is described by a single parameter, that deviation can be measured to 8% precision. So we do not want to ignore new gravity (hence biasing the results), or marginalize over it (hence learning little about it), but allow and fit for it. Future work will be needed to address more generally the issue of simultaneously constraining the expansion characteristics and the gravity framework—how wide a class of gravitational modifications can be described with how many parameters in a model independent manner? As well, specific, well motivated gravity theories should be compared with simulated future data to explore how to achieve robust, unbiased fits and to estimate how well the new gravity can be recognized. Of course not only the gravitational modifications enter the predictions but all the other influences on the growth history, such as neutrino mass (included in figure 3), running spectral index of the mass fluctuations, etc. Experiments need to cover a wide range of spatial scales, i.e. high resolution and large area, precisely and accurately, and interpretation of the data must be well enough understood, to have confidence in any new physics.

## 4. Ideas versus reality

In the previous two sections we saw there exist avenues for theoretical and experimental progress in revealing the new physics behind cosmic acceleration. For the data, the limiting factor will be systematic uncertainties in the measurements, calibration and astrophysical effects. Similarly, theoretical systematics exist in the interpretation of the data to reach the fundamental physics. We saw a hint of this with ‘gravity’s bias’.

In pursuing the question of whether the acceleration is caused by a physical component or a new physical law, we can gain perspective by looking historically. In the 18th century, discrepancies with Newtonian gravity were identified in the orbits of the outer planets of our solar system: was the origin a new component or a new law? The answer, of course, turned out to be a new component—Neptune. In the 19th century, discrepancies were measured in the orbit of the inner planet Mercury. Here the answer was a new physical law—Einstein gravity. In the 20th century, galaxy rotation curves gave unexpected results. We are still waiting for the definitive resolution but a new physical component—dark matter—seems likely. So for such a mysterious effect as dark energy we should not assume we know its nature ahead of time; we must guard against theoretical analysis that depends on assuming characteristics of the thing we are exploring.

Some examples of theoretical systematic uncertainties are (see [10] for a somewhat different approach):

- Physical fluids need not be fully described by the equation of state. Perturbations in the field must exist at some level (unless it is a true cosmological constant), described by the sound speed $c_s$ and anisotropic stress $\pi_s$ (see, e.g., [11, 12]). If the scalar field is canonical then $c_s = 1$ and $\pi_s = 0$.
- Gravitational effects (growth of density fluctuations, deflection law for light, etc) need not be fully described by a single Newton–Poisson potential $\Phi$. Two potentials, $\Phi$ and $\Psi$, enter the metric and can include anisotropic stress $\pi_s$, as can changes to the action, also leading to scale and time dependence of the gravitational coupling, $G(k, t)$. (See, e.g., the review by [13] and references therein.)
- Dark energy need not be fully dark. Coupling of it to dark matter or other species could affect the matter evolution and growth, e.g. $\dot{\rho}_m = -3H\rho_m + \Gamma$ (see, for example, [14]).

Given these possibilities, for which we do not possess a rigourous measure of their ‘unnaturalness’, what could go wrong—purely from fundamental theory systematics—in our interpretation of various types of cosmological probes? In particular, let us concentrate on geometric probes which do not involve issues of (nonlinear) mass growth or gas hydrodynamics.

The supernova distance–redshift relation comes from the Friedmann–Robertson–Walker metric. That’s all. Issues of dark energy sound speed, anisotropic stress, matter growth, etc do not affect this probe.

Weak lensing geometric probes need to separate out the mass power spectrum aspects of the measurements [15, 16], which may be complicated by allowing for alterations to gravity, but may be feasible. Otherwise they depend on the light deflection law, which will depend on the gravity theory [17, 18], specifically $\Phi - \Psi$ of the metric potentials mentioned above.

Baryon acoustic oscillations (BAO) as a distance probe have been analysed to date within the standard cold dark matter paradigm. The assumptions are that BAO in the matter power spectrum scale according to the standard model, to standard gravity, and blind to the dark energy (other than through the geometry). Theoretical adjustments could arise from each of these, i.e. the metric potentials $\Phi$ and $\Psi$ (see, for example, [19] for difficulties in the braneworld case), new density perturbations due to $c_s$ (see, e.g., [20]) and altered fluctuations due to coupling $\Gamma$ (see, e.g., [14, 21]). Substantial and exciting theoretical work lies ahead to bring this method to its rich fruition.

**Table 1.** Theory systematics can impose floors on the precision with which cosmological probes can usefully constrain the nature of the acceleration physics. Here we consider geometric probes, the cleanest astrophysically, and summarize the dominant and the potential theory systematics (see the text for details).

| Probe | Theory systematic (dominant) | Theory systematic (potential) |
|---|---|---|
| SN Ia | – | – |
| WL | $\Phi - \Psi$ | $c_s, \pi_s, G(k, t)$ |
| BAO | $\Phi, \Psi, c_s, \Gamma$ | $\pi_s, G(k, t)$ |

Table 1 summarizes these putative theoretical pitfalls.

As one specific example, misunderstanding of the calibration required for the BAO method—the sound horizon at decoupling—can impose a theory systematics floor on precision, or bias the result. Due to excellent CMB measurements, the sound horizon is rather robust to many theory uncertainties [22] but a loophole (as identified by [22]) lies in the predecoupling expansion history. This can be upset by couplings such as in scalar–tensor theory or early epochs of acceleration such as in stochastic dark energy models. Perhaps the simplest mechanism is a nonnegligible early dark energy density, as predicted by dilatation symmetry solutions to the cosmological constant problem [23, 24]. In terms of early dark energy density $\Omega_e$, [25] found a shift in the sound horizon by a factor $(1-\Omega_e)^{1/2}$. By itself such a shift can be precisely measured through CMB observations, but it would not be recognized if the distance to the last scattering surface were shifted as well. Here we take into account both effects[1] and see what the consequences are if BAO are miscalibrated.

We consider a mocker model [4] of dark energy with low redshift behaviour of $w_0 = -0.95$ and high redshift dark energy density of $\Omega_e = 0.03$, and compare this to a constant $w$ model with the same low redshift behaviour and negligible early dark energy density. (The results are similar if we use the early dark energy model of [26] instead of a mocker model.) The CMB acoustic peaks are essentially indistinguishable for the two models—the acoustic multipoles agree within 0.02%. However the unrecognized shift in the sound horizon causes an offset in the BAO scale that varies as a function of redshift, mimicking a false cosmology. The uncertainty in calibration imposes a theory induced systematic of order 1%.

Figure 4 illustrates the bias in cosmology parameter estimation caused by such sound horizon miscalibration. The expansion history for the late Universe, as probed by SN, does not rely on an early Universe calibration and so is unbiased; the best fit value shown by the black $x$ reproduces the distance relation for $z = 0$–1.7 to 0.2%, or 0.004 mag. BAO, though, suffer a shift in their scale and so are biased to an incorrect cosmology by several statistical deviations (shown by the red triangle). Obtaining BAO measurements more precisely than the 1% theory systematics level, i.e. shrinking the contour in figure 4, simply exacerbates the bias.

To some extent, the strength of BAO becomes its weakness. BAO assumes that to extract the key scale from the pattern of density fluctuations, modes are modes are modes. This allows huge statistical gains by measuring huge volumes. However, if modes evolve anomalously with redshift, e.g. because of the very dark energy properties we are trying to test, we will not know it. This contrasts with SN where its weakness turns into its strength: if SN properties change with redshift, we have a rich array of measurements to reveal this—SN *are* distinguishable—and so because change is testable we can guard against such bias.

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[1] There is another issue, regarding the effect on the gravitational potentials: depending on the clustering properties of dark energy, the CMB may see $(\Omega_m + \Omega_e)h^2$ driving the potentials, while BAO, in the more recent Universe, see $\Omega_m h^2$ (cf [22]).

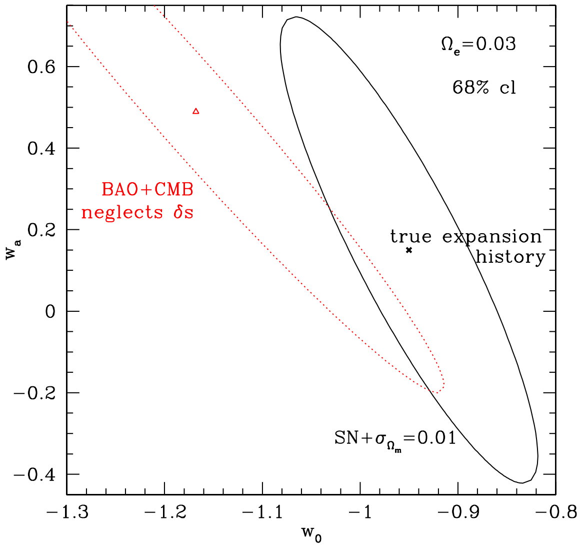

**Figure 4.** Theory systematics can bias constraints on the expansion history of the Universe, shown here in terms of the dark energy equation of state parameters $w_0 = w(0)$, $w_a = -[\mathrm{d}w/\mathrm{d}a](z = 1)$. Miscalibration of the sound horizon $s$ due to not recognizing early dark energy can affect the baryon acoustic oscillation scale at the 1% level, without leaving an appreciable signature in the CMB. The black x shows the true late Universe expansion history, accurately mapped by supernovae. The best fit from BAO+CMB (red triangle) is biased due to unrecognized miscalibration $\delta s$.

## 5. Conclusions

Theory challenges need not be theory pitfalls or insurmountable obstacles to understanding the acceleration of the Universe. We should remember Feynman's insightful quote that 'Yesterday's sensation is today's calibration and tomorrow's background.' In the initial steps toward understanding the accelerating Universe that we will take with the next generation of experiments we should include a super clean method like supernovae, substantially free of theory systematics so we obtain clear and direct interpretation in terms of fundamental physics. Otherwise we run the risk of assuming the answer we are seeking to find.

For further future experiments we will want more complicated—rich—dependences so once the expansion history is well mapped we can probe deeper, from an established foundation, into the microphysical quantities like the sound speed and coupling and the gravitational deviations like the metric potentials and varying gravitational strength. Baryon acoustic oscillations hold promise then to look at microphysical effects from both the dark matter and dark energy sectors. The combination of all available probes will meet the theory challenges, giving a robust understanding of the accelerating Universe.

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