Dark Energy and the Preposterous Universe

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Abstract

A brief review is offered of the theoretical background concerning dark energy: what is required by observations, what sort of models are being considered, and how they fit into particle physics and gravitation. Contribution to the SNAP (SuperNova Acceleration Probe) Yellow Book.

1 The Preposterous Universe

Surprising experimental results are the most common driving force behind significant advances in scientific understanding. The recent discovery that the universe appears to be dominated by a component of "dark energy" qualifies as an extraordinarily surprising result; we have every reason to be optimistic that attempts to understand this phenomenon will lead to profound improvements in our pictures of gravitation, particle physics, and gravitation.

1.1 Dark energy

In general relativity, a homogeneous and isotropic universe is characterized by two quantities, the spatial curvature κ and scale factor $a(t)$. These are related to the energy density ρ by the Friedmann equation:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2} \ . \tag{1}$$

For any value of the Hubble expansion parameter H, there is a critical density which solves this equation for zero spatial curvature: $\rho_{\rm crit} = 3H^2/8\pi G$. The energy density is conveniently characterized by a density parameter constructed by normalizing with respect to the critical density: $\Omega = \rho/\rho_{\rm crit}$.

Observations of the dynamics of galaxies and clusters have shown that the amount of "matter" (slowly-moving particles that can fall into local gravitational potential wells) is $\Omega_{\rm M} = 0.3 \pm 0.1$, short of the critical density. At the same time, however, observations of temperature anisotropies in the cosmic microwave background (CMB) are consistent with nearly scale-free, gaussian, adiabatic primordial density perturbations (the kind predicted by the inflationary universe scenario) for a nearly spatially flat universe, $\Omega_{\rm total} \approx 1$. We therefore infer the existence of a dark energy component $\rho_{\rm dark}$ smoothly distributed through space (so that it does not influence the local motions of galaxies and clusters), with $\Omega_{\rm dark} \approx 0.7$. (See [1] for a recent overview and references.)

Meanwhile, measurements of the distance vs. redshift relation for Type Ia supernovae [2, 3] have provided evidence that the universe is accelerating — that $\ddot{a} > 0$. The significance of this disovery can be appreciated by rewriting the Friedmann equation (1) after multiplying by a^2:

$$\dot{a}^2 = \frac{8\pi G}{3}a^2\rho - \kappa \ . \tag{2}$$

The energy density in matter (non-relativistic particles) diminishes as the number density is diluted by expansion, so that $\rho_{\rm M} \propto a^{-3}$. If particles are relativistic, and thus classified as "radiation", they are both diluted in number density and have their individual energies redshift as a^{-1}, so that $\rho_{\rm R} \propto a^{-4}$. For either of these conventional sources of energy density, the right-hand side of (2) will be decreasing in an expanding universe (since $a^2\rho$ is decreasing, while κ is a constant), so that $\dot{a}$ will be decreasing. The supernova data therefore imply that, to make the universe accelerate, the dark energy must be varying slowly with time (roughly speaking, redshifting away more slowly than a^{-2}) as well as with space.

There is a straightforward candidate for a dark energy component that varies slowly in both space and time: vacuum energy, or the cosmological constant (for reviews see [1, 4, 5, 6, 7]). The distinguishing feature of vacuum energy is that it is a minimum amount of energy density in any region, strictly constant throughout spacetime. To match the data, we require a vacuum energy

$$\rho_{\rm vac} \approx (10^{-3}\ {\rm eV})^4 = 10^{-8}\ {\rm ergs/cm}^3\ . \tag{3}$$

(In units where $\hbar = c = 1$, energy density has units of $[\text{energy}]^4$.) The idea that the dark energy density is simply a constant inherent in the fabric of spacetime is in excellent agreement with the data, but raises two very difficult questions: first, why is the vacuum energy so much smaller than what we would think of as its natural value (the cosmological constant problem); and second, why are the matter and vacuum energy densities approximately equal today (the coincidence problem)? Of course the first question is important even if the dark energy is not a cosmological constant, although a nonzero value for the vacuum energy makes its smallness perhaps even more puzzling than if it were simply zero.

1.2 The cosmological constant problem

Let us turn first to the issue of why the vacuum energy is smaller than we might expect. Although the notion that empty space has a nonzero energy density can seem surprising at first, it is a very natural occurence in any generic pairing of general relativity with field theory (quantum or classical). We can consider for definiteness a simple model of a single real scalar field ϕ with a potential energy density $V(\phi)$. The total energy density is

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)\ , \tag{4}$$

where ∇ represents the spatial gradient. It is immediately clear that any solution in which the field takes on a constant value ϕ_0 throughout spacetime will have an energy density which is constant throughout spacetime, $\rho_\phi = V(\phi_0)$. The crucial point is that there is no principle or symmetry in such a theory which would prefer that $V(\phi_0)$ have the value zero rather than any other value. In richer theories there may be such principles, such as supersymmetry or conformal invariance; the observed world, however, shows no sign of such symmetries, so they must be severely broken if they exist at all. Hence, it requires fine-tuning to obtain a vanishing $\rho_{\rm vac}$.

We are unable to reliably calculate the expected vacuum energy in the real world, or even in some specific field theory such as the Standard Model of particle physics; at best we can offer order-of-magnitude estimates for the contributions from different sectors. In the Standard Model there are at least two important contributions, from nonvanishing condensates in the vacuum: the potential energy of the Higgs field, expected to be of the order $(100 \text{ GeV})^4 = (10^{11} \text{ eV})^4$, and a QCD energy density in the condensate of quark bilinears $\bar{q}q$ responsible for chiral symmetry breaking, expected to be of the order $(100 \text{ MeV})^4 = (10^8 \text{ eV})^4$. There is also a contribution from the quantum-mechanical zero-point vacuum fluctuations of each field in the model. This contribution actually diverges due to effects of very high-frequency modes; it is necessary to introduce a cutoff and hope that a more complete theory will eventually provide a physical justification for doing so. If this cutoff is at the Planck scale $M_{\rm Planck} = 1/\sqrt{8\pi G} = 10^{18}$ GeV, we obtain a vacuum energy of order $(10^{18} \text{ GeV})^4 = (10^{27} \text{ eV})^4$. Similarly, there is no reason to exclude a "bare" classical contribution to the cosmological constant at the Planck scale, $\rho_{\Lambda_0} \sim (10^{18} \text{ GeV})^4$. For any of these examples, we cannot even say with confidence whether the corresponding energy density is positive or negative; nevertheless, since there is no apparent relationship between the values of the disparate contributions, we expect the total vacuum energy to be of the same order as that of the largest components:

$$\rho_{\rm vac}^{\rm (theory)} \sim (10^{27} \text{ eV})^4 = 10^{112} \text{ ergs/cm}^3 \ . \tag{5}$$

There is clearly a mismatch between the theoretical prediction (5) and the observed value (3):

$$\rho_{\rm vac}^{\rm (theory)} \sim 10^{120} \rho_{\rm vac}^{\rm (obs)} \ . \tag{6}$$

This is the famous 120-orders-of-magnitude discrepancy that makes the cosmological constant problem such a glaring embarassment. Of course, it is somewhat unfair to emphasize the factor of 10^{120}, which depends on the fact that energy density has units of $[\text{energy}]^4$. If we express the vacuum energy in terms of a mass scale, $\rho_{\rm vac} = M_{\rm vac}^4$, the discrepancy becomes $M_{\rm vac}^{\rm (theory)} \sim 10^{30} M_{\rm vac}^{\rm (obs)}$; it is more accurate to think of the cosmological constant problem as a discrepancy of 30 orders of magnitude in energy scale. In fact, this problem can be ameliorated in theories where supersymmetry is spontaneously broken at a low scale, since the vacuum energy will then be given by the scale at which supersymmetry is broken (above that energy, for example, the zero-point contributions from fermions are exactly cancelled by equal and opposite contributions from bosonic superpartners). If supersymmetry is preserved down to just above the weak scale, so that $M_{\rm vac} \approx M_{\rm SUSY} \approx 10^3$ GeV, we would have $M_{\rm vac}^{\rm (SUSY)} = 10^{15} M_{\rm vac}^{\rm (obs)}$. In the most optimistic reading, therefore, we are left with a discrepancy of a mere fifteen orders of magnitude that we have no idea how to resolve; still, this qualifies as a problem worthy of our attention.

There have been a large number of suggested resolutions to the cosmological constant problem; see [1, 4, 6, 7] for reviews. To date none has seemed exceptionally compelling, and most researchers believe that the correct solution has yet to be found.

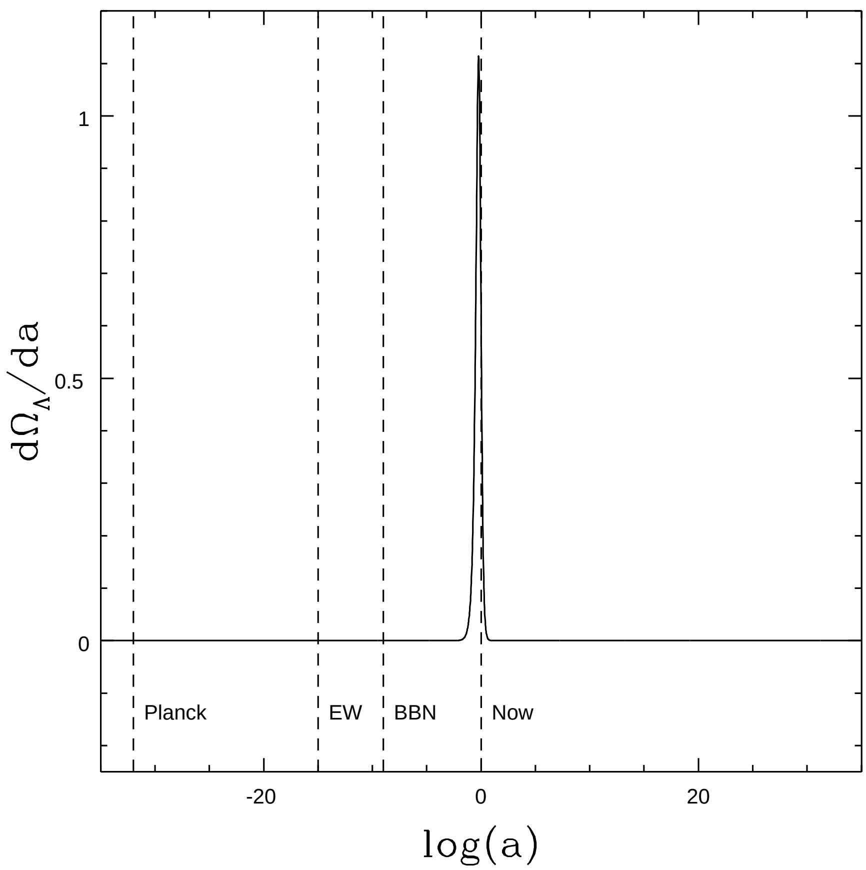

Figure 1: The rate of change of the vacuum energy density parameter, $d\Omega_\Lambda/da$, as a function of the scale factor a, in a universe with $\Omega_{\Lambda 0} = 0.7$, $\Omega_{M0} = 0.3$. Scale factors corresponding to the Planck era, electroweak symmetry breaking (EW), and Big Bang nucleosynthesis (BBN) are indicated, as well as the present day. The spike reflects the fact that, in such a universe, there is only a short period in which Ω_Λ is evolving noticeably with time.

1.3 The coincidence problem

The second issue mentioned above is the coincidence between the observed vacuum energy (3) and the current matter density. The "best-fit universe" model has $\Omega_{\Lambda 0} = 0.7$ and $\Omega_{M0} = 0.3$, but the relative balance of vacuum and matter changes rapidly as the universe expands:

$$\frac{\Omega_\Lambda}{\Omega_M} = \frac{\rho_\Lambda}{\rho_M} \propto a^3 \ . \tag{7}$$

As a consequence, at early times the vacuum energy was negligible in comparison to matter and radiation, while at late times matter and radiation are negligible. There is only a brief epoch of the universe's history during which it would be possible to witness the transition from domination by one type of component to another. This is illustrated in Figure 1, in which the rate of change of Ω_Λ is plotted as a function of the scale factor. At early times Ω_Λ is close to zero and changing very slowly, while at late times it is close to unity and changing very slowly. It seems remarkable that we live during the short transitional period between these two eras.

The approximate coincidence between matter and vacuum energies in the current universe is one of several puzzling features of the composition of the total energy density. Another great surprise is the comparable magnitudes of the baryon density ($\Omega_{\rm b} \approx 0.04$) and the density of cold non-baryonic dark matter ($\Omega_{\rm CDM} \approx 0.25$), and perhaps also that in massive neutrinos ($\Omega_\nu \leq 0.01$). In our current understanding, these components are relics of completely unrelated processes in the very early universe, and there seems to be no good reason why they should be of the same order of magnitude (although some specific models have been proposed). The real world seems to be a more rich and complex place than Occam's razor might have predicted. It is important to keep in mind, however, the crucial distinction between the coincidences relating the various matter components and that relating the matter and vacuum energy: the former are set once and for all by primordial processes and remain unchanged as the universe evolves, while the latter holds true only during a certain era. It is fruitless to try to explain the matter/vacuum coincidence by invoking mechanisms which make the dark energy density time-dependent in such a way as to *always* be proportional to that in matter; such a scenario would either imply that the dark energy would redshift away as $\rho_{\rm dark} \propto a^{-3}$, which from (2) would lead to a non-accelerating universe, or require dramatic departures from conventional general relativity, which would in turn make it difficult to recover the successes of conventional cosmology (Big Bang nucleosynthesis, CMB anisotropy, growth of structure, and the age of the universe, to name a few). Recent observations provide some evidence that the universe has only recently entered an era of acceleration out of a previous era of deceleration [8]; although the observational case is not airtight, the conclusion seems inescapable.

2 What might be going on?

It may seem misguided to put a great deal of energy into exploring models of a small nonzero dark energy density when we have very little idea why the vacuum energy is not as large as the Planck scale. On the other hand, the discovery of dark energy may provide an invaluable clue in our attempts to solve this long-lasting puzzle, giving us reason to redouble our efforts. Explanations of the current acceleration of the universe can be categorized into one of three types:

1. The dark energy is a true cosmological constant, strictly unchanging throughout space and time. The minimum-energy configuration of the universe may have a small but

nonvanishing energy density, or we may live in a false vacuum, almost degenerate with the true one but with a small nonzero additional energy.

2. The cosmological constant is zero, but a slowly-varying dynamical component is mimicking a nonzero vacuum energy.

3. Einstein was wrong, and the Friedmann equation does not describe the expansion of the universe.

We briefly examine each of these possibilities in turn.

2.1 An honest cosmological constant

The simplest interpretation of the dark energy is that we have discovered that the cosmological constant is not quite zero: we are in the lowest energy state possible (or, more properly, that the particles we observe are excitations of such a state) but that energy does not vanish. Although simple, this scenario is perhaps the hardest to analyze without an understanding of the complete cosmological constant problem, and there is correspondingly little to say about such a possibility. As targets to shoot for, various numerological coincidences have been pointed out, which may some day find homes as predictions of an actual theory. For example, the observed vacuum energy scale $M_{\rm vac} = 10^{-3}$ eV is related to the 1 TeV scale of low-energy supersymmetry breaking models by a "supergravity suppression factor":

$$M_{\rm vac} = \left(\frac{M_{\rm SUSY}}{M_{\rm Planck}}\right) M_{\rm SUSY} \ . \tag{8}$$

In other words, $M_{\rm SUSY}$ is the geometric mean of $M_{\rm vac}$ and $M_{\rm Planck}$. Unfortunately, nobody knows why this should be the case. In a similar spirit, the vacuum energy density is related to the Planck energy density by the kind of suppression factor familiar from instanton calculations in gauge theories:

$$M_{\rm vac}^4 = e^{-2/\alpha} M_{\rm Planck}^4 \ . \tag{9}$$

In other words, the natural log of 10^{120} is twice 137. Again, this is not a relation we have any right to expect to hold (although it has been suggested that nonperturbative effects in non-supersymmetric string theories could lead to such an answer [9]).

Theorists attempting to build models of a small nonzero vacuum energy must keep in mind the requirement of remaining compatible with some as-yet-undiscovered solution to the cosmological constant problem. In particular, it is certainly insufficient to describe a specific contribution to the vacuum energy which by itself is of the right magnitude; it is necessary at the same time for there to be some plausible reason why the well-known and large contributions from the Standard Model could be suppressed, while the new contribution is not. One way to avoid this problem is to imagine that an unknown mechanism sets the vacuum energy to zero in the state of lowest energy, but that we actually live in a distinct false vacuum state, almost but not quite degenerate in energy with the true vacuum [10, 11, 12]. From an observational point of view, false vacuum energy and true vacuum energy are utterly indistinguishable — they both appear as a strictly constant dark energy density. The issue with such models is why the splitting in energies between the true and false vacua should be so much smaller than all of the characteristic scales of the problem; model-building approaches generally invoke symmetries to suppress some but not all of the effects that could split these levels.

The only theory (if one can call it that) which leads a vacuum energy density of approximately the right order of magnitude without suspicious fine-tuning is the anthropic principle — the notion that intelligent observers will not witness the full range of conditions in the universe, but only those conditions which are compatible with the existence of such observers. Thus, we do not consider it unnatural that human beings evolved on the surface of the Earth rather than on that of the Sun, even though the surface area of the Sun is much larger, since the conditions are rather less hospitable there. If, then, there exist distinct parts of the universe (whether they be separate spatial regions or branches of a quantum wavefunction) in which the vacuum energy takes on different values, we would expect to observe a value which favored the appearance of life. Although most humans don't think of the vacuum energy as playing any role in their lives, a substantially larger value than we presently observe would either have led to a rapid recollapse of the universe (if $\rho_{\rm vac}$ were negative) or an inability to form galaxies (if $\rho_{\rm vac}$ were positive). Depending on the distribution of possible values of $\rho_{\rm vac}$, one can argue that the recently observed value is in excellent agreement with what we should expect [13, 14, 15, 16]. Many physicists find it unappealing to think that an apparent constant of nature would turn out to simply be a feature of our local environment that was chosen from an ensemble of possibilities, although we should perhaps not expect that the universe takes our feelings into account on these matters. More importantly, relying on the anthropic principle involves the invocation of a large collection of alternative possibilities for the vacuum energy, closely spaced in energy but not continuously connected to each other (since we do not observe the light scalar fields implied by such connected vacua). It is by no means an economical solution to the vacuum energy puzzle.

As an interesting sidelight to this issue, it has been claimed that a positive vacuum energy would be incompatible with our current understanding of string theory [17, 18, 19, 20]. At issue is the fact that such a universe eventually approaches a de Sitter solution (exponentially expanding), which implies future horizons which make it impossible to derive a gauge-invariant S-matrix. One possible resolution might involve a dynamical dark energy component such as those discussed in the next section. While few string theorists would be willing to concede that a definitive measurement that the vacuum energy is constant with time would rule out string theory as a description of nature, the possibility of saying something important about fundamental theory from cosmological observations presents an extremely exciting opportunity.

2.2 Dynamical dark energy

Although the observational evidence for dark energy implies a component which is unclustered in space as well as slowly-varying in time, we may still imagine that it is not perfectly constant. The simplest possibility along these lines involves the same kind of source typically invoked in models of inflation in the very early universe: a scalar field rolling slowly in a potential, sometimes known as "quintessence" [21, 22, 23]. There are also a number of more exotic possibilities, including tangled topological defects and variable-mass particles (see [1, 6] for references and discussion).

There are good reasons to consider dynamical dark energy as an alternative to an honest cosmological constant. First, a dynamical energy density can be evolving slowly to zero, allowing for a solution to the cosmological constant problem which makes the ultimate vacuum energy vanish exactly. Second, it poses an interesting and challenging observational problem to study the evolution of the dark energy, from which we might learn something about the underlying physical mechanism. Perhaps most intriguingly, allowing the dark energy to evolve opens the possibility of finding a dynamical solution to the coincidence problem, if the dynamics are such as to trigger a recent takeover by the dark energy (independently of, or at least for a wide range of, the parameters in the theory).

At the same time, introducing dynamics opens up the possibility of introducing new problems, the form and severity of which will depend on the specific kind of model being considered. The most popular quintessence models feature scalar fields ϕ with masses of order the current Hubble scale,

$$m_\phi \sim H_0 \sim 10^{-33} \text{ eV} . \tag{10}$$

(Fields with larger masses would typically have already rolled to the minimum of their potentials.) In quantum field theory, light scalar fields are unnatural; renormalization effects tend to drive scalar masses up to the scale of new physics. The well-known hierarchy problem of particle physics amounts to asking why the Higgs mass, thought to be of order 10^{11} eV, should be so much smaller than the grand unification/Planck scale, 10^{25}-10^{27} eV. Masses of 10^{-33} eV are correspondingly harder to understand. At the same time, such a low mass implies that ϕ gives rise to a long-range force; even if ϕ interacts with ordinary matter only through indirect gravitational-strength couplings, searches for fifth forces and time-dependence of coupling constants should have already enabled us to detect the quintessence field [24].

The need for delicate fine-tunings of masses and couplings in quintessence models is certainly a strike against them, but is not a sufficiently serious one that the idea is not worth pursuing; until we understand much more about the dark energy, it would be premature to rule out any idea on the basis of simple naturalness arguments. One promising route to gaining more understanding is to observationally characterize the time evolution of the dark energy density. In principle any behavior is possible, but it is sensible to choose a simple parameterization which would characterize dark energy evolution in the measurable regime of relatively nearby redshifts (order unity or less). For this purpose it is common to imagine that the dark energy evolves as a power law with the scale factor:

$$\rho_{\rm dark} \propto a^{-n} \ . \tag{11}$$

Even if $\rho_{\rm dark}$ is not strictly a power law, this ansatz can be a useful characterization of its effective behavior at low redshifts. It is common to define an equation-of-state parameter relating the energy density to the pressure,

$$p = w\rho \ . \tag{12}$$

Using the equation of energy-momentum conservation,

$$\dot\rho = -3(\rho + p)\frac{\dot a}{a} \ , \tag{13}$$

a constant exponent n of (11) implies a constant w with

$$n = 3(1 + w) \ . \tag{14}$$

As n varies from 3 (matter) to 0 (cosmological constant), w varies from 0 to -1. (Imposing mild energy conditions implies that $|w| \leq 1$ [25]; however, models with $w < -1$ are still worth considering [26].) Some limits from supernovae and large-scale structure from [27] are shown in Figure (2). These constraints apply to the $\Omega_{\rm M}$-w plane, under the assumption that the universe is flat ($\Omega_{\rm M} + \Omega_{\rm dark} = 1$). We see that the observationally favored region features $\Omega_{\rm M} \approx 0.35$ and an honest cosmological constant, $w = -1$. However, there is plenty of room for alternatives; one of the most important tasks of observational cosmology will be to reduce the error regions on plots such of these to pin down precise values of these parameters.

To date, many investigations have considered scalar fields with potentials that asymptote gradually to zero, of the form $e^{-\phi}$ or $1/\phi$. These can have cosmologically interesting properties, including "tracking" behavior that makes the current energy density largely independent of the initial conditions [28]; they can also be derived from particle-physics models, such as the dilaton or moduli of string theory. They do not, however, provide a solution to the coincidence problem, as the era in which the scalar field begins to dominate is still set by finely-tuned parameters in the theory. There have been two scalar-field models which come closer to being solutions: "k-essence", and oscillating dark energy. The k-essence idea

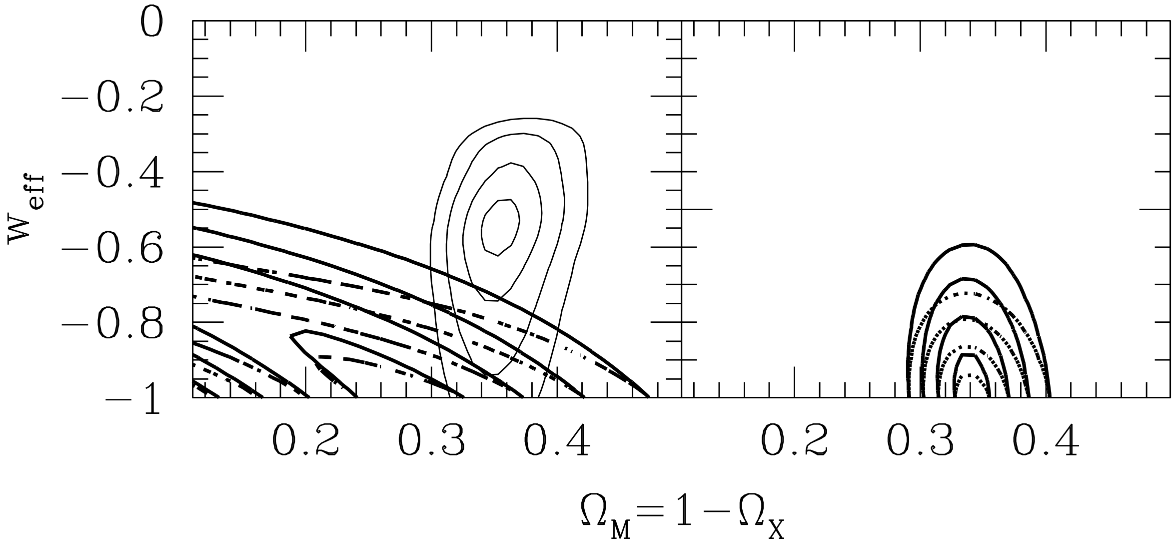

Figure 2: Limits on the equation-of-state parameter w in a flat universe, where $\Omega_M + \Omega_X = 1$. The left-hand panel shows limits from supernova data (lower left corner) and large-scale structure (ellipses); the right-hand panel shows combined constraints. From [27].

[29] does not put the field in a shallow potential, but rather modifies the form of the kinetic energy. We imagine that the Lagrange density is of the form

$$\mathcal{L} = f(\phi)g(X) \ , \tag{15}$$

where $X = \frac{1}{2}(\nabla_\mu \phi)^2$ is the conventional kinetic term. For certain choices of the functions $f(\phi)$ and $g(X)$, the k-essence field naturally tracks the evolution of the total radiation energy density during radiation domination, but switches to being almost constant once matter begins to dominate. In such a model the coincidence problem is explained by the fact that matter/radiation equality was a relatively recent occurence (at least on a logarithmic scale). The oscillating models [30] involve ordinary kinetic terms and potentials, but the potentials take the form of a decaying exponential with small perturbations superimposed:

$$V(\phi) = e^{-\phi}[1 + \alpha \cos(\phi)] \ . \tag{16}$$

On average, the dark energy in such a model will track that of the dominant matter/radiation component; however, there will be gradual oscillations from a negligible density to a dominant density and back, on a timescale set by the Hubble parameter. Consequently, in such models the acceleration of the universe is just something that happens from time to time. Unfortunately, in neither the k-essence models nor the oscillating models do we have a compelling particle-physics motivation for the chosen dynamics, and in both cases the behavior still depends sensitively on the precise form of parameters and interactions chosen. Nevertheless, these theories stand as interesting attempts to address the coincidence problem by dynamical means.

Rather than constructing models on the basis of cosmologically interesting dynamical properties, we may take the complementary route of considering which models would appear most sensible from a particle-physics point of view, and then exploring what cosmological properties they exhibit. An acceptable particle physics model of quintessence would be one in which the scalar mass was naturally small and its coupling to ordinary matter was naturally suppressed. These requirements are met by Pseudo-Nambu-Goldstone bosons (PNGB's) [22], which arise in models with approximate global symmetries of the form

$$\phi \to \phi + \text{constant}. \tag{17}$$

Clearly such a symmetry should not be exact, or the potential would be precisely flat; however, even an approximate symmetry can naturally suppress masses and couplings. PNGB's typically arise as the angular degrees of freedom in Mexican-hat potentials that are "tilted" by a small explicity symmetry breaking, and the PNGB potential takes on a sinusoidal form:

$$V(\phi) = \mu^4[1 + \cos(\phi)] \; . \tag{18}$$

As a consequence, there is no easily characterized tracking or attractor behavior; the equation of state parameter w will depend on both the potential and the initial conditions, and can take on any value from -1 to 0 (and in fact will change with time). We therefore find that the properties of models which are constructed by taking particle-physics requirements as our primary concern appear quite different from those motivated by cosmology alone. The lesson to observational cosmologists is that a wide variety of possible behaviors should be taken seriously, with data providing the ultimate guidance.

2.3 Was Einstein wrong?

Given the uncomfortable tension between observational evidence for dark energy on one hand and our intuition for what seems natural in the context of the standard cosmological model on the other, there is an irresistible temptation to contemplate the possibility that we are witnessing a breakdown of the Friedmann equation of conventional general relativity (GR) rather than merely a novel source of energy. Alternatives to GR are highly constrained by tests in the solar system and in binary pulsars; however, if we are contemplating the space of all conceivable alternatives rather than examining one specific proposal, we are free to imagine theories which deviate on cosmological scales while being indistinguishable from GR in small stellar systems. Speculations along these lines are also constrained by observations: any alternative must predict the right abundances of light elements from

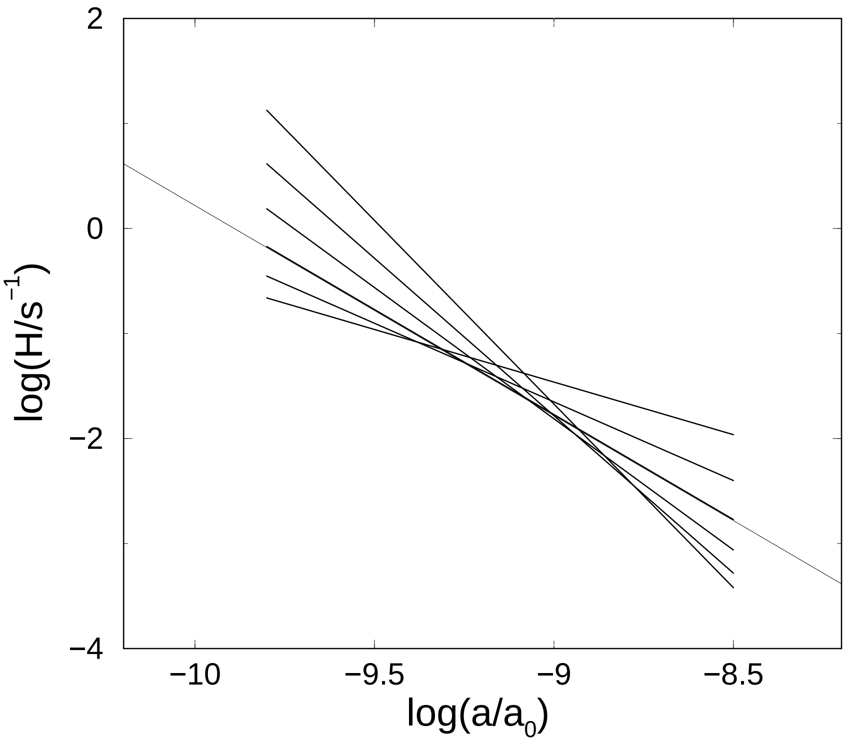

Figure 3: The range of allowed evolution histories during Big Bang nucleosynthesis (between temperatures of 1 MeV to 50 keV), expressed as the behavior of the Hubble parameter $H = \dot{a}/a$ as a function of a. Changes in the normalization of H can be compensated by a change in the slope while predicting the same abundances of ^{4}He, ^{2}D, and ^{7}Li. The extended thin line represents the standard radiation-dominated Friedmann universe model. From [31].

Big Bang nucleosynthesis (BBN), the correct evolution of a sensible spectrum of primordial density fluctutions into the observed spectrum of temperature anisotropies in the Cosmic Microwave Background and the power spectrum of large-scale structure, and that the age of the universe is approximately twelve billion years. Of these phenomena, the sharpest test of Friedmann behavior comes from BBN, since perturbation growth depends both on the scale factor and on the local gravitational interactions of the perturbations, while a large number of alternative expansion histories could in principle give the same age of the universe. As an example, Figure (3) provides a graphical representation of alternative expansion histories in the vicinity of BBN ($H_{\rm BBN} \sim 0.1\ {\rm sec}^{-1}$) which predict the same light element abundances as the standard picture [31]. The point of this figure is that expansion histories which are not among the family portrayed, due to differences either in the slope or the overall normalization, will not give the right abundances. So it is possible to find interesting nonstandard cosmologies which are consistent with the data, but they describe a small set in the space of all such alternatives.

Rather than imagining that gravity follows the predictions of standard GR in localized systems but deviates in cosmology, another approach would be to imagine that GR breaks down whenever the gravitational field becomes (in some sense) sufficiently weak. This would be unusual behavior, as we are used to thinking of effective field theories as breaking down at high energies and small length scales, but being completely reliable in the opposite regime. On the other hand, we might be ambitious enough to hope that an alternative theory of gravity could explain away not only the need for dark energy but also that for dark matter. It has been famously pointed out by Milgrom [32] that the observed dynamics of galaxies only requires the introduction of dark matter in regimes where the acceleration due to gravity (in the Newtonian sense) falls below a certain fixed value,

$$a/c \leq 10^{-18}\ \mathrm{sec}^{-1}\ . \tag{19}$$

Meanwhile, we seem to need to invoke dark energy when the Hubble parameter drops approximately to its current value,

$$H_0 \approx 10^{-18}\ \mathrm{sec}^{-1}\ . \tag{20}$$

A priori, there seems to be little reason to expect that these two phenomena should be characterized by timescales of the same order of magnitude; one involves the local dynamics of baryons and non-baryonic dark matter, while the other involves dark energy and the overall matter density (although see [33] for a suggested explanation). It is natural to wonder whether this is simply a numerical coincidence, or the reflection of some new underlying theory characterized by a single dimensionful parameter. To date, nobody has succeeded in inventing a theory which comes anything close to explaining away both the dark matter and dark energy in terms of modified gravitational dynamics. Given the manifold successes of the dark matter paradigm, from gravitational lensing to structure formation to CMB anisotropy, is seems a good bet to think that this numerical coincidence is simply an accident. Of course, given the incredible importance of finding a successful alternative theory, there seems to be little harm in keeping an open mind.

It was mentioned above, and bears repeating, that modified-gravity models do not hold any unique promise for solving the coincidence problem. At first glance we might hope that an alternative to the conventional Friedmann equation might lead to a naturally occuring acceleration at all times; but a moment's reflection reveals that perpetual acceleration is not consistent with the data, so we still require an explanation for why the acceleration began recently. In other words, the observations seem to be indicating the importance of a fixed scale at which the universe departs from ordinary matter domination; if we are fortunate we will explain this scale either in terms of combinations of other scales in our particle-physics model or as an outcome of dynamical processes, while if we are unfortunate it will have to be a new input parameter to our theory. In either case, finding the origin of this new scale is the task for theorists and experimenters in the near future.

3 Discussion

The discovery of dark energy has presented both observational and theoretical cosmologists with a win-win scenario. On the observational side, we will either verify to high precision the existence of a truly constant vacuum energy representing a new fundmental constant of nature and a potentially crucial clue to the reconcilation of gravity with quantum field theory, or we will detect variations in the dark energy density which indicate either a new dynamical component or an alteration of general relativity itself. On the theoretical side, we have been given invaluable insight into one of the most perplexing issues in theoretical physics (the cosmological constant problem), and we are now faced with a brand new issue (the coincidence problem) whose resolution will necessarily involve exciting new theoretical developments.

Nobody who took arguments of naturalness and fine-tuning seriously would have expected to discover a small but nonzero dark energy density. We should not conclude from this that such arguments have no value, but that we should always be prepared for surprises. One way of characterizing our current inventory of the universe is to divide it into ordinary baryonic matter, comprising 5% of the energy density of the universe, and a "dark sector" comprising the remaining 95%. In this classification, the role of the recent discoveries has been to reveal that the dark sector includes at least two distinct components, the dark matter and the dark energy. Who is to say that future experiments will not reveal further structure within this sector, perhaps including interesting interactions between components? It is safe to say that the future of dark physics looks very bright.

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