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Why is the Universe Accelerating?

SEAN M. CARROLL
Enrico Fermi Institute, Department of Physics, and Center for Cosmological Physics, University of Chicago
Kavli Institute for Theoretical Physics, University of California, Santa Barbara

Abstract

The universe appears to be accelerating, but the reason why is a complete mystery. The simplest explanation, a small vacuum energy (cosmological constant), raises three difficult issues: why the vacuum energy is so small, why it is not quite zero, and why it is comparable to the matter density today. I discuss these mysteries, some of their possible resolutions, and some issues confronting future observations.

1.1 Introduction

Recent astronomical observations have provided strong evidence that we live in an accelerating universe. By itself, acceleration is easy to understand in the context of general relativity and quantum field theory; however, the very small but nonzero energy scale seemingly implied by the observations is completely perplexing. In trying to understand the universe in which we apparently live, we are faced with a problem, a puzzle, and a scandal:

- The *cosmological constant problem:* why is the energy of the vacuum so much smaller than we estimate it should be?
- The *dark energy** *puzzle:* what is the nature of the smoothly distributed, persistent energy density that appears to dominate the universe?
- The *coincidence scandal:* why is the dark energy density approximately equal to the matter density today?

Any one of these issues would represent a serious challenge to physicists and astronomers; taken together, they serve to remind us how far away we are from understanding one of the most basic features of the universe.

The goal of this article is to present a pedagogical (and necessarily superficial) introduction to the physics issues underlying these questions, rather than a comprehensive review; for more details and different points of view see Sahni & Starobinski (2000), Carroll (2001), or Peebles & Ratra (2003). After a short discussion of the issues just mentioned, we will turn to mechanisms that might address any or all of them; we will pay special attention to

* “Dark energy” is not, strictly speaking, the most descriptive name for this substance; lots of things are dark, and everything has energy. The feature that distinguishes dark energy from ordinary matter is not the energy but the pressure, so “dark pressure” would be a better term. However, it is not the existence of the pressure, but the fact that it is negative—tension rather than ordinary pressure—that drives the acceleration of the universe, so “dark tension” would be better yet. And we would have detected it long ago if it had collected into potential wells rather than being smoothly distributed, so “smooth tension” would be the best term of all, not to mention sexier. I thank Evalyn Gates, John Beacom, and Timothy Ferris for conversations on this important point.

the dark energy puzzle, only because there is more to say about that issue than the others. We will close with an idiosyncratic discussion of issues confronting observers studying dark energy.

1.2 The Mysteries

1.2.1 Classical Vacuum Energy

Let us turn first to the issue of why the vacuum energy is smaller than we might expect. When Einstein proposed general relativity, his field equation was

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu} \ , \tag{1.1}$$

where the left-hand side characterizes the geometry of spacetime and the right-hand side the energy sources; $g_{\mu\nu}$ is the spacetime metric, $R_{\mu\nu}$ is the Ricci tensor, R is the curvature scalar, and $T_{\mu\nu}$ is the energy-momentum tensor. (I use conventions in which $c = \hbar = 1$.) If the energy sources are a combination of matter and radiation, there are no solutions to (1.1) describing a static, homogeneous universe. Since astronomers at the time believed the universe was static, Einstein suggested modifying the left-hand side of his equation to obtain

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \ , \tag{1.2}$$

where Λ is a new free parameter, the cosmological constant. This new equation admits a static, homogeneous solution for which Λ, the matter density, and the spatial curvature are all positive: the "Einstein static universe." The need for such a universe was soon swept away by improved astronomical observations, and the cosmological constant acquired a somewhat compromised reputation.

Later, particle physicists began to contemplate the possibility of an energy density inherent in the vacuum (defined as the state of lowest attainable energy). If the vacuum is to look Lorentz-invariant to a local observer, its energy-momentum tensor must take on the unique form

$$T^{\rm vac}_{\mu\nu} = -\rho_{\rm vac} g_{\mu\nu} \ , \tag{1.3}$$

where $\rho_{\rm vac}$ is a constant vacuum energy density. Such an energy is associated with an isotropic pressure

$$p_{\rm vac} = -\rho_{\rm vac} \ . \tag{1.4}$$

Comparing this kind of energy-momentum tensor to the appearance of the cosmological constant in (1.2), we find that they are formally equivalent, as can be seen by moving the $\Lambda g_{\mu\nu}$ term in (1.2) to the right-hand side and setting

$$\rho_{\rm vac} = \rho_\Lambda \equiv \frac{\Lambda}{8\pi G} \ . \tag{1.5}$$

This equivalence is the origin of the identification of the cosmological constant with the energy of the vacuum.

From either side of Einstein's equation, the cosmological constant Λ is a completely free parameter. It has dimensions of $[\rm length]^{-2}$ (while the energy density ρ_Λ has units [energy/volume]), and hence defines a scale, while general relativity is otherwise scale-free.

Indeed, from purely classical considerations, we cannot even say whether a specific value of Λ is "large" or "small"; it is simply a constant of nature we should go out and determine through experiment.

1.2.2 Quantum Zeropoint Energy

The introduction of quantum mechanics changes this story somewhat. For one thing, Planck's constant allows us to define a gravitational length scale, the reduced Planck length

$$L_{\rm P} = (8\pi G)^{1/2} \sim 10^{-32}\ {\rm cm}\ , \tag{1.6}$$

as well as the reduced Planck mass

$$M_{\rm P} = \left(\frac{1}{8\pi G}\right)^{1/2} \sim 10^{18}\ {\rm GeV}\ , \tag{1.7}$$

where "reduced" means that we have included the 8π's where they really should be. (Note that, with $\hbar = 1$ and $c = 1$, we have $L = T = M^{-1} = E^{-1}$, where L represents a length scale, T a time interval, M a mass scale, and E an energy.) Hence, there is a natural expectation for the scale of the cosmological constant, namely

$$\Lambda^{\rm (guess)} \sim L_{\rm P}^{-2}\ , \tag{1.8}$$

or, phrased as an energy density,

$$\rho_{\rm vac}^{\rm (guess)} \sim M_{\rm P}^4 \sim (10^{18}\ {\rm GeV})^4 \sim 10^{112}\ {\rm erg\ cm^{-3}}\ . \tag{1.9}$$

We can partially justify this guess by thinking about quantum fluctuations in the vacuum. At all energies probed by experiment to date, the world is accurately described as a set of quantum fields (at higher energies it may become strings or something else). If we take the Fourier transform of a free quantum field, each mode of fixed wavelength behaves like a simple harmonic oscillator. ("Free" means "noninteracting"; for our purposes this is a very good approximation.) As we know from elementary quantum mechanics, the ground-state or zeropoint energy of an harmonic oscillator with potential $V(x) = \frac{1}{2}\omega^2 x^2$ is $E_0 = \frac{1}{2}\hbar\omega$. Thus, each mode of a quantum field contributes to the vacuum energy, and the net result should be an integral over all of the modes. Unfortunately this integral diverges, so the vacuum energy appears to be infinite. However, the infinity arises from the contribution of modes with very small wavelengths; perhaps it was a mistake to include such modes, since we do not really know what might happen at such scales. To account for our ignorance, we could introduce a cutoff energy, above which we ignore any potential contributions, and hope that a more complete theory will eventually provide a physical justification for doing so. If this cutoff is at the Planck scale, we recover the estimate (1.9).

The strategy of decomposing a free field into individual modes and assigning a zeropoint energy to each one really only makes sense in a flat spacetime background. In curved spacetime we can still "renormalize" the vacuum energy, relating the classical parameter to the quantum value by an infinite constant. After renormalization, the vacuum energy is completely arbitrary, just as it was in the original classical theory. But when we use general relativity we are really using an effective field theory to describe a certain limit of quantum gravity. In the context of effective field theory, if a parameter has dimensions $[{\rm mass}]^n$, we expect the corresponding mass parameter to be driven up to the scale at which the effective description breaks down. Hence, if we believe classical general relativity up to the Planck scale, we would expect the vacuum energy to be given by our original guess (1.9).

However, we believe we have now measured the vacuum energy through a combination of Type Ia supernovae (Riess et al. 1998; Perlmutter et al. 1999; Knop et al. 2003; Tonry et al. 2003), microwave background anisotropies (Spergel et al. 2003), and dynamical matter measurements (Verde et al. 2002), to reveal

$$\rho_{\rm vac}^{\rm (obs)} \sim 10^{-8}\ {\rm erg\ cm^{-3}} \sim (10^{-3}\ {\rm eV})^4\ , \tag{1.10}$$

or

$$\rho_{\rm vac}^{\rm (obs)} \sim 10^{-120} \rho_{\rm vac}^{\rm (guess)}\ . \tag{1.11}$$

For reviews, see Sahni & Starobinski (2000), Carroll (2001), or Peebles & Ratra (2003).

Clearly, our guess was not very good. This is the famous 120-orders-of-magnitude discrepancy that makes the cosmological constant problem such a glaring embarrassment. Of course, it is somewhat unfair to emphasize the factor of 10^{120}, which depends on the fact that energy density has units of $[\text{energy}]^4$. We can express the vacuum energy in terms of a mass scale,

$$\rho_{\rm vac} = M_{\rm vac}^4\ , \tag{1.12}$$

so our observational result is

$$M_{\rm vac}^{\rm (obs)} \sim 10^{-3}\ {\rm eV}\ . \tag{1.13}$$

The discrepancy is thus

$$M_{\rm vac}^{\rm (obs)} \sim 10^{-30} M_{\rm vac}^{\rm (guess)}\ . \tag{1.14}$$

We should think of the cosmological constant problem as a discrepancy of 30 orders of magnitude in energy scale.

1.2.3 The Coincidence Scandal

The third issue mentioned above is the coincidence between the observed vacuum energy (1.11) and the current matter density. To understand this, we briefly review the dynamics of an expanding Robertson-Walker spacetime. The evolution of a homogeneous and isotropic universe is governed by the Friedmann equation,

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2}\ , \tag{1.15}$$

where $a(t)$ is the scale factor, $H = \dot{a}/a$ is the Hubble parameter, ρ is the energy density, and κ is the spatial curvature parameter. The energy density is a sum of different components, $\rho = \sum_i \rho_i$, which will in general evolve differently as the universe expands. For matter (nonrelativistic particles) the energy density goes as $\rho_{\rm M} \propto a^{-3}$, as the number density is diluted with the expansion of the universe. For radiation the energy density goes as $\rho_{\rm R} \propto a^{-4}$, since each particle loses energy as it redshifts in addition to the decrease in number density. Vacuum energy, meanwhile, is constant throughout spacetime, so that $\rho_\Lambda \propto a^0$.

It is convenient to characterize the energy density of each component by its density parameter

$$\Omega_i = \frac{\rho_i}{\rho_c} , \tag{1.16}$$

where the critical density

$$\rho_c = \frac{3H^2}{8\pi G} \tag{1.17}$$

is that required to make the spatial geometry of the universe be flat ($\kappa = 0$). The "best-fit universe" or "concordance" model implied by numerous observations includes radiation, matter, and vacuum energy, with

$$\begin{aligned} \Omega_{\rm R0} &\approx 5 \times 10^{-5} \\ \Omega_{\rm M0} &\approx 0.3 \\ \Omega_{\Lambda 0} &\approx 0.7 , \end{aligned} \tag{1.18}$$

together implying a flat universe. We see that the densities in matter and vacuum are of the same order of magnitude.* But the ratio of these quantities changes rapidly as the universe expands:

$$\frac{\Omega_\Lambda}{\Omega_{\rm M}} = \frac{\rho_\Lambda}{\rho_{\rm M}} \propto a^3 . \tag{1.19}$$

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 1.1, in which the various density parameters Ω_i are plotted as a function of the scale factor. At early times $\Omega_{\rm R}$ is close to unity; the matter-radiation transition happens relatively gradually, while the matter-vacuum transition happens quite rapidly.

How finely tuned is it that we exist in the era when vacuum and matter are comparable? Between the Planck time and now, the universe has expanded by a factor of approximately 10^{32}. To be fair, we should consider an interval of logarithmic expansion that is centered around the present time; this would describe a total expansion by a factor of 10^{64}. If we take the transitional period between matter and vacuum to include the time from $\Omega_\Lambda/\Omega_{\rm M} = 0.1$ to $\Omega_\Lambda/\Omega_{\rm M} = 10$, the universe expands by a factor of $100^{1/3} \approx 10^{0.67}$. Thus, there is an approximately 1% chance that an observer living in a randomly selected logarithmic expansion interval in the history of our universe would be lucky enough to have $\Omega_{\rm M}$ and Ω_Λ be the same order of magnitude. Everyone will have his own favorite way of quantifying such unnaturalness, but the calculation here gives some idea of the fine-tuning involved; it is substantial, but not completely ridiculous.

As we will discuss below, there is room to imagine that we are actually not observing the effects of an ordinary cosmological constant, but perhaps a dark energy source that varies gradually as the universe expands, or even a breakdown of general relativity on large scales. By itself, however, making dark energy dynamical does not offer a solution to the coincidence scandal; purely on the basis of observations, it seems clear that the universe has begun to accelerate recently, which implies a scale at which something new is kicking in. In particular, it is fruitless to try to explain the matter/dark energy coincidence by invoking

* Of course, the "matter" contribution consists both of ordinary baryonic matter and nonbaryonic dark matter, with $\Omega_{\rm b} \approx 0.04$ and $\Omega_{\rm DM} \approx 0.25$. The similarity between these apparently independent quantities is another coincidence problem, but at least one that is independent of time; we have nothing to say about it here.

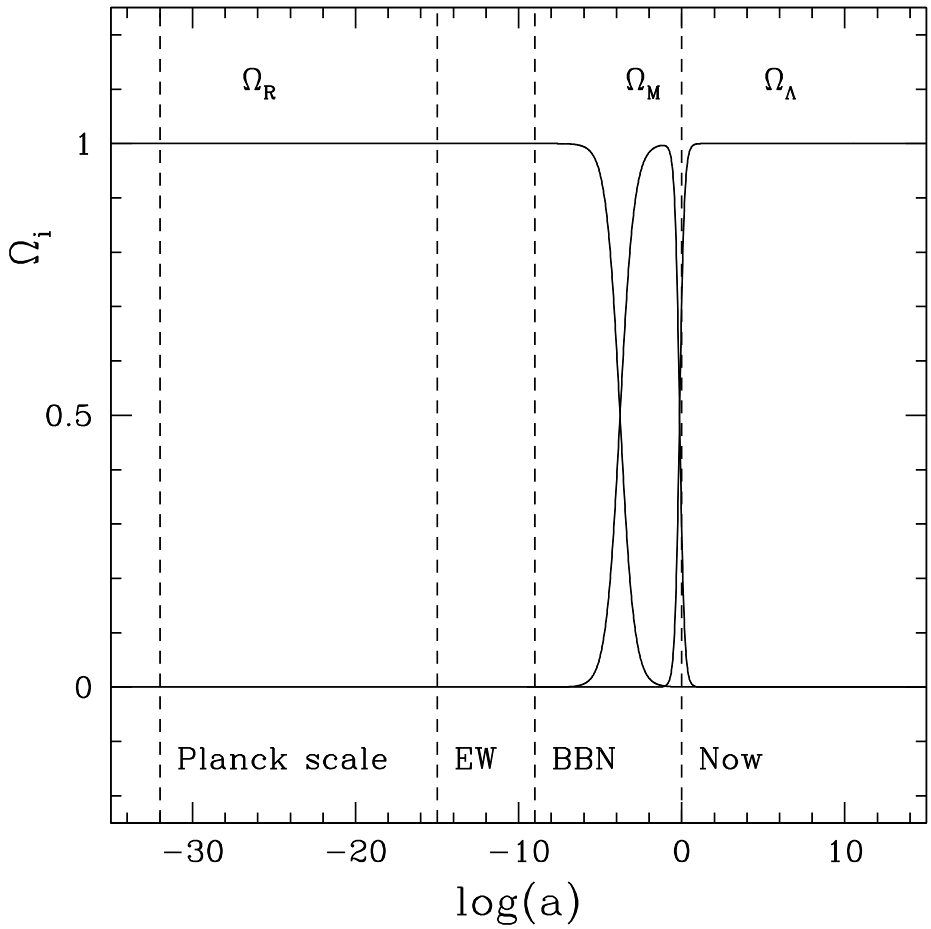

Fig. 1.1. Density parameters Ω_i for radiation (R), matter (M), and vacuum (Λ), as a function of the scale factor a, in a universe with $\Omega_{\Lambda 0} = 0.7$, $\Omega_{M0} = 0.3$, $\Omega_{R0} = 5 \times 10^{-5}$. Scale factors corresponding to the Planck era, electroweak symmetry breaking (EW), and Big Bang nucleosynthesis (BBN) are indicated, as well as the present day.

mechanisms that 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 (1.15) would lead to a nonaccelerating universe, or require departures from conventional general relativity of the type that (as discussed below) are excluded by other measurements.

1.3 What Might be Going on?

Observations have led us to a picture of the universe that differs dramatically from what we might have expected. In this section we discuss possible ways to come to terms with this situation; the approaches we consider include both attempts to explain a small but

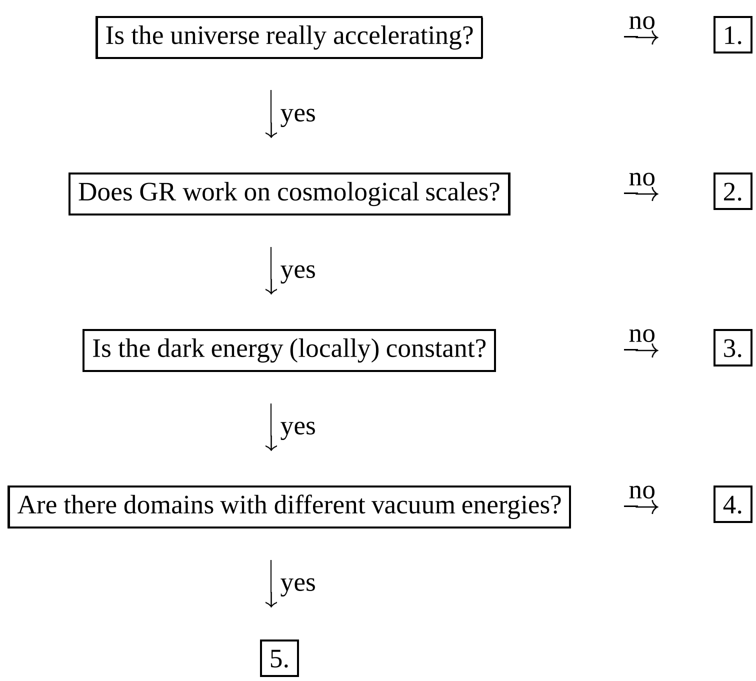

Fig. 1.2. A flowchart classifying reasons why the universe might be accelerating. The possibilities include: 1. misinterpretation of the data; 2. breakdown of general relativity; 3. dynamical dark energy; 4. unique vacuum energy; 5. environmental selection.

nonzero vacuum energy, and more dramatic ideas that move beyond a simple cosmological constant. We certainly are not close to settling on a favored explanation, neither for the low value of the vacuum energy nor the recent onset of universal acceleration, but we can try to categorize the different types of conceivable scenarios.

The flowchart portrayed in Figure 1.2 represents a classification of scenarios to explain our observations. Depending on the answers to various questions, we have the following possibilities to explain why the universe appears to be accelerating:

(1) Misinterpretation of the data.
(2) Breakdown of general relativity.
(3) Dynamical dark energy.
(4) Unique vacuum energy.
(5) Environmental selection.

Let us examine each possibility in turn.

1.3.1 Are We Misinterpreting the Data?

After the original supernova results (Riess et al. 1998; Perlmutter et al. 1999) were announced in 1998, cosmologists converted rather quickly from skepticism about universal acceleration to a tentative acceptance, which has grown substantially stronger with time. The primary reason for this sudden conversion has been the convergence of several complementary lines of evidence in favor of a concordance model; foremost among the relevant observations are the anisotropy spectrum of the cosmic microwave background (Spergel et al. 2003) and the power spectrum of large-scale structure (Verde et al. 2002), but a number of other methods have yielded consistent answers.

Nevertheless, it remains conceivable that we have dramatically misinterpreted the data, and the apparent agreement of an $\Omega_\Lambda = 0.7$, $\Omega_\mathrm{M} = 0.3$ cosmology with a variety of observations is masking the true situation. For example, the supernova observations rely on the nature of Type Ia supernovae as "standardizable candles," an empirical fact about low-redshift supernovae that could somehow fail at high redshifts (although numerous consistency checks have confirmed basic similarities between supernovae at all redshifts). Given the many other observations, this failure would not be enough to invalidate our belief in an accelerating universe; however, we could further imagine that these other methods are conspiring to point to the wrong conclusion. This point of view has been taken by Blanchard et al. (2004), who argue that a flat matter-dominated ($\Omega_\mathrm{M} = 1$) universe remains consistent with the data. To maintain this idea, it is necessary to discard the supernova results, to imagine that the Hubble constant is approximately 46 km s^{-1} Mpc^{-1} (in contrast to the Key Project determination of 70 ± 7 km s^{-1} Mpc^{-1}; Freedman et al. 2001), to interpret data on clusters and large-scale structure in a way consistent with $\Omega_\mathrm{M} = 1$, to relax the conventional assumption that the power spectrum of density fluctuations can be modeled as a single power law, and to introduce some source beyond ordinary cold dark matter (such as massive neutrinos) to suppress power on small scales. To most workers in the field this conspiracy of effects seems (even) more unlikely than an accelerating universe.

A yet more drastic route is to imagine that our interpretation of the observations has been skewed by the usual assumption of an isotropic universe. It has been argued (Linde, Linde, & Mezhlumian 1995) that some versions of the anthropic principle in an eternally inflating universe lead to a prediction that most galaxies on a spacelike hypersurface are actually at the center of spherically symmetric domains with radially dependent density distributions; such a configuration could skew the distance-redshift relation at large distances even without dark energy. This picture relies heavily on a choice of measure in determining what "most" galaxies are like, an issue for which there is no obvious correct choice.

The lengths to which it seems necessary to go in order to avoid concluding that the universe is accelerating is a strong argument in favor of the concordance model.

1.3.2 Is General Relativity Breaking Down?

If we believe that we live in a universe that is homogeneous, isotropic, and accelerating, general relativity (GR) is unambiguous about the need for some sort of dark energy source. GR has been fantastically successful in passing classic experimental tests in the solar system, as well as at predicting the amount of gravitational radiation emitted from the binary pulsar (Will 2001). Nevertheless, the possibility remains open that gravitation might deviate from conventional GR on scales corresponding to the radius of the entire universe. For our present purposes, such deviations may either be relevant to the cosmological constant problem, or to the dark energy puzzle.

The idea behind modifying gravity to address the cosmological constant problem is to somehow allow for the vacuum energy to be large, but yet not lead to an appreciable spacetime curvature (as manifested in a rapidly expanding universe). Of course, we still need to allow ordinary matter to warp spacetime, so there has to be something special about vacuum energy. One special thing is that vacuum energy comes with a negative pressure $p_\mathrm{vac} = -\rho_\mathrm{vac}$, as in (1.4). We might therefore imagine a theory that gave rise to a modified version of the Friedmann equation, of the form

$$H^2 \sim \rho + p \, . \tag{1.20}$$

With such an equation, ordinary matter (for which p vanishes) leads to conventional expansion, while vacuum energy decouples entirely. Such a theory has been studied (Carroll & Mersini 2001), and may even arise in "self-tuning" models of extra dimensions (Arkani-Hamed et al. 2000; Kachru, Schulz, & Silverstein 2000). Unfortunately, close examination of self-tuning models reveals that there is a hidden fine-tuning, expressed as a boundary condition chosen at a naked singularity in the extra dimension. Furthermore, any alternative to the conventional Friedmann equation is also constrained by observations: any alternative must predict the right abundances of light elements from Big Bang nucleosynthesis (BBN; see Burles, Nollett, & Turner 2001), the correct evolution of a sensible spectrum of primordial density fluctuations into the observed spectrum of temperature anisotropies in the cosmic microwave background (CMB) and the power spectrum of large-scale structure (Tegmark 2002; Lue, Scoccimarro, & Starkman 2003; Zahn & Zaldarriaga 2003), and that the age of the universe is approximately 13 billion years. The most straightforward test comes from BBN (Carroll & Kaplinghat 2002; Masso & Rota 2003), since the light-element abundances depend on the expansion rate during a relatively brief period (rather than on the behavior of perturbations, or an integral of the expansion rate over a long period). Studies of BBN in alternate cosmologies indicate that it is possible for modifications of GR to remain consistent with observations, but only for a very narrow set of possibilities. It seems likely that the success of conventional BBN, including its agreement with the baryon density as determined by CMB fluctuations (Spergel et al. 2003), is not a misleading accident, but rather an indication that GR provides an accurate description of cosmology when the universe was of the order of one minute old. The idea of modifying GR to solve the cosmological constant problem is not completely dead, but is evidently not promising.

Rather than trying to solve the cosmological constant problem, we can put aside the issue of why the magnitude of the vacuum energy is small and focus instead on whether the current period of acceleration can be traced to a modification of GR. A necessary feature of any such attempt is to include a new scale in the theory, since acceleration has only begun relatively recently.* From a purely phenomenological point of view we can imagine modifying the Friedmann equation (1.15) so that acceleration kicks in when either the energy density approaches a certain value ρ_*,

$$H^2 = \frac{8\pi G}{3}\left[\rho + \left(\frac{\rho}{\rho_*}\right)^{\alpha}\right] \, , \tag{1.21}$$

* One way of characterizing this scale is in terms of the Hubble parameter when the universe starts accelerating, $H_0 \sim 10^{-18}\ \mathrm{s}^{-1}$. It is interesting in this context to recall the coincidence pointed out by Milgrom (1983), that dark *matter* only becomes important in galaxies when the acceleration due to gravity dips below a fixed value, $a_0/c \leq 10^{-18}\ \mathrm{s}^{-1}$. Milgrom himself has suggested that the explanation for this feature of galactic dynamics can be explained by replacing dark matter by a modified dynamics, and it is irresistible to speculate that both dark matter and dark energy could be replaced by a single (as yet undiscovered) modified theory of gravity. However, hope for this possibility seems to be gradually becoming more difficult to maintain, as different methods indicate the existence of gravitational forces that point in directions other than where ordinary matter is (Van Waerbeke et al. 2000; Dalal & Kochanek 2002; Kneib et al. 2003)—a phenomenon that is easy to explain with dark matter, but difficult with modified gravity—and explanations are offered for $a_0/c \sim H_0$ within conventional cold dark matter (Scott et al. 2001; Kaplinghat & Turner 2002).

or when the Hubble parameter approaches a certain value H_*,

$$H^2 + \left(\frac{H}{H_*}\right)^\beta = \frac{8\pi G}{3}\rho \ . \tag{1.22}$$

The former idea has been suggested by Freese & Lewis (2002), the latter by Dvali & Turner (2003); in both cases we can fit the data for appropriate choices of the new parameters. It is possible that equations of this type arise in brane-world models with large extra spatial dimensions; it is less clear whether the appropriate parameters can be derived. An even more dramatic mechanism also takes advantage of extra dimensions, but allows for separate gravitational dynamics on and off of our brane; in this case gravity can be four-dimensional *below* a certain length scale (which would obviously have to be very large), and appear higher-dimensional at large distances (Dvali, Gabadadze, & Porrati 2000; Arkani-Hamed et al. 2002; Deffayet, Dvali, & Gabadadze 2002). These scenarios can also make the universe accelerate at late times, and may even lead to testable deviations from GR in the solar system (Dvali, Gruzinov, & Zaldarriaga 2003).

As an alternative to extra dimensions, we may look for an ordinary four-dimensional modification of GR. 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. Nevertheless, it is worth exploring whether a simple phenomenological model can easily accommodate the data. Einstein's equation can be derived by minimizing an action given by the spacetime integral of the curvature scalar R,

$$S = \int d^4x \sqrt{|g|}\, R \ . \tag{1.23}$$

A simple way to modify the theory when the curvature becomes very small (at late times in the universe) is to simply add a piece proportional to $1/R$,

$$S = \int d^4x \sqrt{|g|}\, \left(R - \frac{\mu^4}{R}\right) \ , \tag{1.24}$$

where μ is a parameter with dimensions of mass (Carroll et al. 2003a). It is straightforward to show that this theory admits accelerating solutions; unfortunately, it also brings to life a new scalar degree of freedom, which ruins the success of GR in the solar system (Chiba 2003). Investigations are still ongoing to see whether a simple modification of this idea could explain the acceleration of the universe while remaining consistent with experimental tests; in the meantime, the difficulty in finding a simple extension of GR that does away with the cosmological constant provides yet more support for the standard scenario.

1.3.3 Is Dark Energy Dynamical?

If general relativity is correct, cosmic acceleration implies there must be a dark energy density that diminishes relatively slowly as the universe expands. This can be seen directly from the Friedmann equation (1.15), which implies

$$\dot{a}^2 \propto a^2\rho + \text{constant} \ . \tag{1.25}$$

From this relation, it is clear that the only way to get acceleration ($\dot{a}$ increasing) in an expanding universe is if ρ falls off more slowly than a^{-2}; neither matter ($\rho_M \propto a^{-3}$) nor radiation

($\rho_R \propto a^{-4}$) will do the trick. Vacuum energy is, of course, strictly constant; but the data are consistent with smoothly distributed sources of dark energy that vary slowly with time.

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 that 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). To date this hope has not quite been met, but dynamical mechanisms at least allow for the possibility (unlike a true cosmological 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 ϕ rolling slowly in a potential, sometimes known as "quintessence" (Frieman, Hill, & Watkins 1992; Frieman et al. 1995; Caldwell, Dave, & Steinhardt 1998; Peebles & Ratra 1998; Ratra & Peebles 1998; Wetterich 1998; Huey et al. 1999). The energy density of a scalar field is a sum of kinetic, gradient, and potential energies,

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi) \ . \tag{1.26}$$

For a homogeneous field ($\nabla\phi \approx 0$), the equation of motion in an expanding universe is

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0 \ . \tag{1.27}$$

If the slope of the potential V is quite flat, we will have solutions for which ϕ is nearly constant throughout space and only evolving very gradually with time; the energy density in such a configuration is

$$\rho_\phi \approx V(\phi) \approx \text{constant} \ . \tag{1.28}$$

Thus, a slowly rolling scalar field is an appropriate candidate for dark energy.

However, 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. Most quintessence models feature scalar fields ϕ with masses of order the current Hubble scale,

$$m_\phi \sim H_0 \sim 10^{-33}\ \text{eV} \ . \tag{1.29}$$

(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.

Nevertheless, this apparent fine-tuning might be worth the price, if we were somehow able to explain the coincidence problem. To date, many investigations have considered scalar fields with potentials that asymptote gradually to zero, of the form $e^{1/\phi}$ or $1/\phi$. These can have cosmologically interesting properties, including "tracking" behavior that makes the current energy density largely independent of the initial conditions (Zlatev, Wang, & Steinhardt 1999). 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. One way to address the coincidence problem is to take advantage of the fact that matter/radiation equality was a relatively recent occurrence (at least on a logarithmic scale); if a scalar field has dynamics that are sensitive to the difference between matter- and radiation-dominated universes, we might hope that its energy density becomes constant only after matter/radiation equality. An approach that takes this route is *k*-essence (Armendariz-Picon, Mukhanov, & Steinhardt 2000), which modifies the form of the kinetic energy for the scalar field. Instead of a conventional kinetic energy $K = \frac{1}{2}(\dot{\phi})^2$, in *k*-essence we posit a form

$$K = f(\phi)g(\dot{\phi}^2) \, , \tag{1.30}$$

where f and g are functions specified by the model. For certain choices of these functions, 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. Unfortunately, it seems necessary to choose a finely tuned kinetic term to get the desired behavior (Malquarti, Copeland, & Liddle 2003).

An alternative possibility is that there is nothing special about the present era; rather, acceleration is just something that happens from time to time. This can be accomplished by oscillating dark energy (Dodelson, Kaplinghat, & Stewart 2000). In these models the potential takes the form of a decaying exponential (which by itself would give scaling behavior, so that the dark energy remained proportional to the background density) with small perturbations superimposed:

$$V(\phi) = e^{-\phi}[1+\alpha\cos(\phi)] \, . \tag{1.31}$$

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 time scale set by the Hubble parameter, leading to occasional periods of acceleration. In the previous section we mentioned the success of the conventional picture in describing primordial nucleosynthesis (when the scale factor was $a_{\rm BBN} \sim 10^{-9}$) and temperature fluctuations imprinted on the CMB at recombination ($a_{\rm CMB} \sim 10^{-3}$), which implies that the oscillating scalar must have had a negligible density during those periods; but explicit models are able to accommodate this constraint. 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.

1.3.4 Did We Just Get Lucky?

By far the most straightforward explanation for the observed acceleration of the universe is an absolutely constant vacuum energy, or cosmological constant. Even in this case we can distinguish between two very different scenarios: one in which the vacuum energy is some fixed number that as yet we simply do not know how to calculate, and an alternative in which there are many distinct domains in the universe, with different values of the vacuum energy in each. In this section we concentrate on the first possibility. Note that such a scenario requires that we essentially give up on finding a dynamical resolution to the coincidence scandal; instead, the vacuum energy is fixed once and for all, and we are simply fortunate that it takes on a sufficiently gentle value that life has enough time and space to exist.

To date, there are not any especially promising approaches to calculating the vacuum energy and getting the right answer; it is nevertheless instructive to consider the example of supersymmetry, which relates to the cosmological constant problem in an interesting way. Supersymmetry posits that for each fermionic degree of freedom there is a matching bosonic degree of freedom, and *vice versa*. By "matching" we mean, for example, that the spin-1/2 electron must be accompanied by a spin-0 "selectron" with the same mass and charge. The good news is that, while bosonic fields contribute a positive vacuum energy, for fermions the contribution is negative. Hence, if degrees of freedom exactly match, the net vacuum energy sums to zero. Supersymmetry is thus an example of a theory, other than gravity, where the absolute zeropoint of energy is a meaningful concept. (This can be traced to the fact that supersymmetry is a spacetime symmetry, relating particles of different spins.)

We do not, however, live in a supersymmetric state; there is no selectron with the same mass and charge as an electron, or we would have noticed it long ago. If supersymmetry exists in nature, it must be broken at some scale $M_{\rm SUSY}$. In a theory with broken supersymmetry, the vacuum energy is not expected to vanish, but to be of order

$$M_{\rm vac} \sim M_{\rm SUSY} \ , \qquad \text{(theory)} \tag{1.32}$$

with $\rho_{\rm vac} = M_{\rm vac}^4$. What should $M_{\rm SUSY}$ be? One nice feature of supersymmetry is that it helps us understand the hierarchy problem—why the scale of electroweak symmetry breaking is so much smaller than the scales of quantum gravity or grand unification. For supersymmetry to be relevant to the hierarchy problem, we need the supersymmetry-breaking scale to be just above the electroweak scale, or

$$M_{\rm SUSY} \sim 10^3 \ {\rm GeV} \ . \tag{1.33}$$

In fact, this is very close to the experimental bound, and there is good reason to believe that supersymmetry will be discovered soon at Fermilab or CERN, if it is connected to electroweak physics.

Unfortunately, we are left with a sizable discrepancy between theory and observation:

$$M_{\rm vac}^{\rm (obs)} \sim 10^{-15} M_{\rm SUSY} \ . \qquad \text{(experiment)} \tag{1.34}$$

Compared to (1.14), we find that supersymmetry has, in some sense, solved the problem halfway (on a logarithmic scale). This is encouraging, as it at least represents a step in the right direction. Unfortunately, it is ultimately discouraging, since (1.14) was simply a guess, while (1.34) is actually a reliable result in this context; supersymmetry renders the vacuum energy finite and calculable, but the answer is still far away from what we need. (Subtleties in supergravity and string theory allow us to add a negative contribution to the vacuum energy, with which we could conceivably tune the answer to zero or some other small number; but there is no reason for this tuning to actually happen.)

But perhaps there is something deep about supersymmetry that we do not understand, and our estimate $M_{\rm vac} \sim M_{\rm SUSY}$ is simply incorrect. What if instead the correct formula were

$$M_{\rm vac} \sim \left(\frac{M_{\rm SUSY}}{M_{\rm P}}\right) M_{\rm SUSY}\ ? \tag{1.35}$$

In other words, we are guessing that the supersymmetry-breaking scale is actually the geometric mean of the vacuum scale and the Planck scale. Because $M_{\rm P}$ is 15 orders of magnitude larger than $M_{\rm SUSY}$, and $M_{\rm SUSY}$ is 15 orders of magnitude larger than $M_{\rm vac}$, this guess gives us the correct answer! Unfortunately this is simply optimistic numerology; there is no theory that actually yields this answer (although there are speculations in this direction; Banks 2003). Still, the simplicity with which we can write down the formula allows us to dream that an improved understanding of supersymmetry might eventually yield the correct result.

Besides supersymmetry, we do know of other phenomena that may in principle affect our understanding of vacuum energy. One example is the idea of large extra dimensions of space, which become possible if the particles of the Standard Model are confined to a three-dimensional brane (Arkani-Hamed, Dimopoulos, & Dvali 1998; Randall & Sundrum 1999). In this case gravity is not simply described by four-dimensional general relativity, as alluded to in the previous section. Furthermore, current experimental bounds on simple extra-dimensional models limit the scale characterizing the extra dimensions to less than 10^{-2} cm, which corresponds to an energy of approximately 10^{-3} eV; this is coincidentally the same as the vacuum-energy scale (1.10). As before, nobody has a solid reason why these two scales should be related, but it is worth searching for one. The fact that we are forced to take such slim hopes seriously is a measure of how difficult the cosmological constant problem really is.

1.3.5 Are We Witnessing Environmental Selection?

If the vacuum energy can in principle be calculated in terms of other measurable quantities, then we clearly do not yet know how to calculate it. Alternatively, however, it may be that the vacuum energy is not a fundamental quantity, but simply a feature of our local environment. We do not turn to fundamental theory for an explanation of the average temperature of the Earth's atmosphere, nor are we surprised that this temperature is noticeably larger than in most places in the universe; perhaps the cosmological constant is on the same footing.

To make this idea work, we need to imagine that there are many different regions of the universe in which the vacuum energy takes on different values; then we would expect to find ourselves in a region that was hospitable to our own existence. Although most humans do not 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 observed value is in excellent agreement with what we should expect (Efstathiou 1995; Vilenkin 1995; Martel, Shapiro, & Weinberg 1998; Garriga & Vilenkin 2000, 2003).

The idea of understanding the vacuum energy as a consequence of environmental selection often goes under the name of the "anthropic principle," and has an unsavory reputation in some circles. There are many bad reasons to be skeptical of this approach, and at least one good reason. The bad reasons generally center around the idea that it is somehow an abrogation of our scientific responsibilities to give up on calculating something as fundamental as the vacuum energy, or that the existence of many unseen domains in the universe is a metaphysical construct without any testable consequences, and hence unscientific. The problem with these objections is that they say nothing about whether environmental selection actually happens; they are only declarations that we hope it does not happen, or it would be difficult for us to prove once and for all that it does. The good reason to be skeptical is that environmental selection only works under certain special circumstances, and we are far from understanding whether those conditions hold in our universe. In particular, we need to show that there can be a huge number of different domains with slightly different values of the vacuum energy, and that the domains can be big enough that our entire observable universe is a single domain, and that the possible variation of other physical quantities from domain to domain is consistent with what we observe in ours.*

Recent work in string theory has lent some support to the idea that there are a wide variety of possible vacuum states rather than a unique one (Bousso & Polchinski 2000; Giddings, Kachru, & Polchinski 2002; Kachru et al. 2003; Susskind 2003). String theorists have been investigating novel ways to compactify extra dimensions, in which crucial roles are played by branes and gauge fields. By taking different combinations of extra-dimensional geometries, brane configurations, and gauge-field fluxes, it seems plausible that a wide variety of states may be constructed, with different local values of the vacuum energy and other physical parameters. (The set of configurations is sometimes known as the "landscape," and the discrete set of vacuum configurations is unfortunately known as the "discretuum.") An obstacle to understanding these purported solutions is the role of supersymmetry, which is an important part of string theory but needs to be broken to obtain a realistic universe. From the point of view of a four-dimensional observer, the compactifications that have small values of the cosmological constant would appear to be exactly the states alluded to in the previous section, where one begins with a supersymmetric state with a negative vacuum energy, to which supersymmetry breaking adds just the right amount of positive vacuum energy to give a small overall value. The necessary fine-tuning is accomplished simply by imagining that there are many (more than 10^{100}) such states, so that even very unlikely things will sometimes occur. We still have a long way to go before we understand this possibility; in particular, it is not clear that the many states obtained have all the desired properties (Banks, Dine, & Motl 2001; Banks, Dine, & Gorbatov 2003), or even if they are stable enough to last for the age of the universe (Hertog, Horowitz, & Maeda 2003).

Even if such states are allowed, it is necessary to imagine a universe in which a large number of them actually exist in local regions widely separated from each other. As is well known, inflation works to take a small region of space and expand it to a size larger than the observable universe; it is not much of a stretch to imagine that a multitude of different domains may be separately inflated, each with different vacuum energies. Indeed, models of inflation generally tend to be eternal, in the sense that the universe continues to inflate in some regions even after inflation has ended in others (Vilenkin 1983; Linde 1985; Goncharov, Linde, & Mukhanov 1987). Thus, our observable universe may be separated by inflating regions from other "universes" that have landed in different vacuum states; this is precisely what is needed to empower the idea of environmental selection.

Nevertheless, it seems extravagant to imagine a fantastic number of separate regions of the universe, outside the boundary of what we can ever possibly observe, just so that we may understand the value of the vacuum energy in our region. But again, this does not mean it is

* For example, if we have a theory that allows for any possible value of the vacuum energy, but insists that the vacuum energy scale be equal to the supersymmetry breaking scale, we have not solved any problems.

not true. To decide once and for all will be extremely difficult, and will at the least require a much better understanding of how both string theory (or some alternative) and inflation operate—an understanding that we will undoubtedly require a great deal of experimental input to achieve.

1.4 Observational Issues

From the above discussion, it is clear that theorists are in desperate need of further input from experiment—in particular, we need to know if the dark energy is constant or dynamical, and if it is dynamical what form it takes. The observational program to test these ideas has been discussed in detail elsewhere (Sahni & Starobinski 2000; Carroll 2001; Peebles & Ratra 2003); here we briefly draw attention to a couple of theoretical issues that can affect the observational strategies.

1.4.1 Equation-of-state Parameter

Given that the universe is accelerating, the next immediate question is whether the acceleration is caused by a strictly constant vacuum energy or something else; the obvious place to look is for some time dependence to the dark energy density. In principle any behavior is possible, but it is sensible to choose a simple parameterization that 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:

$$\rho_{\rm dark} \propto a^{-n} \ . \tag{1.36}$$

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. We can then define an equation-of-state parameter relating the energy density to the pressure,

$$p = w\rho \ . \tag{1.37}$$

Using the equation of energy-momentum conservation,

$$\dot{\rho} = -3(\rho + p)\frac{\dot{a}}{a} \ , \tag{1.38}$$

a constant exponent n of (1.36) implies a constant w with

$$n = 3(1+w) \ . \tag{1.39}$$

As n varies from 3 (matter) to 0 (cosmological constant), w varies from 0 to -1. Some limits from supernovae and large-scale structure from Melchiorri et al. (2003) are shown in Figure 1.3; see Spergel et al (2003) for limits from *WMAP* observations of the cosmic microwave background, and Tonry et al. (2003) and Knop et al. (2003) for more recent supernova limits. 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 $\Omega_{\rm M} \approx 0.3$ and an honest cosmological constant, $w = -1$. However, there is room for alternatives; one of the most important tasks of observational cosmology will be to reduce the error regions on plots such as this to pin down precise values of these parameters.

It is clear that $w = -1$ is a special value; for $w > -1$ the dark energy density slowly decreases as the universe expands, while for $w < -1$ it would actually be *increasing*. In

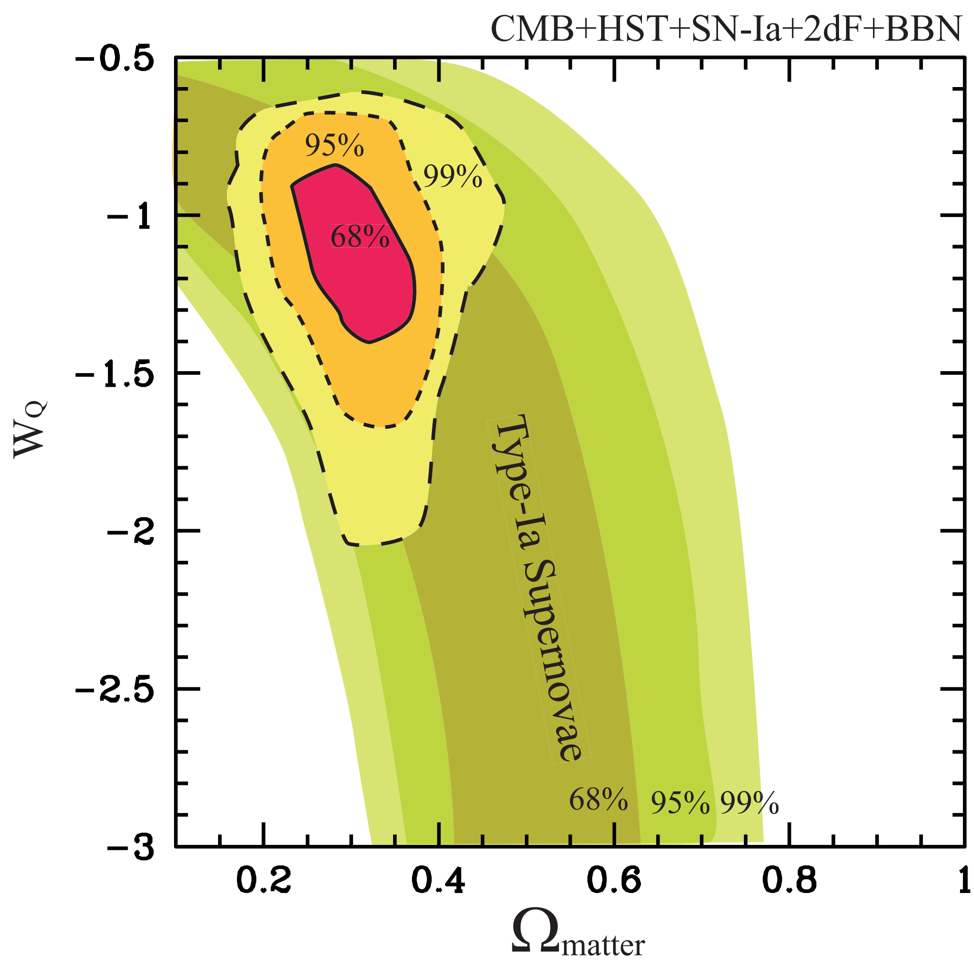

Fig. 1.3. Limits on the equation-of-state parameter w in a flat universe, where $\Omega_{\rm M} + \Omega_X = 1$. (Adapted from Melchiorri et al. 2003.)

most conventional models, unsurprisingly, we have $w \geq -1$; this is also required (for sources with positive energy densities) by the energy conditions of general relativity (Garnavich et al. 1998). Nevertheless, it is interesting to ask whether we should bother to consider $w < -1$ (Parker & Raval 1999; Sahni & Starobinski 2000; Caldwell 2002; Carroll, Hoffman, & Trodden 2003b). If w is constant in such a model, the universe will expand ever faster until a future singularity is reached, the "Big Rip" (Caldwell, Kamionkowski, & Weinberg 2003); but such behavior is by no means necessary. An explicit model is given by so-called phantom fields (Caldwell 2002), scalar fields with negative kinetic and gradient energy,

$$\rho_\phi = -\frac{1}{2}\dot{\phi}^2 - \frac{1}{2}(\nabla\phi)^2 + V(\phi)\,, \tag{1.40}$$

in contrast with the conventional expression (1.26). (A phantom may be thought of as a physical realization of the "ghost" fields used in some calculations in quantum field theory.)

A phantom field rolls to the maximum of its potential, rather than the minimum; if there is a maximum with positive potential energy, we will have $w < -1$ while the field is rolling, but it will settle into a state with $w = -1$.

However, such fields are very dangerous in particle physics; the excitations of the phantom will be negative-mass particles, and therefore allow for the decay of empty space into a collection of positive-energy ordinary particles and negative-energy phantoms. Naively the decay rate is infinite, because there is no boundary to the allowed phase space; if we impose a cutoff by hand by disallowing momenta greater than 10^{-3} eV, the vacuum can be stable for the age of the universe (Carroll et al. 2003b). Of course, there may be other ways to get $w < -1$ other than a simple phantom field (Parker & Raval 1999; Dvali & Turner 2003), and there is a lurking danger that a rapidly time-varying equation of state might trick you into thinking that $w < -1$ (Maor et al. 2002). The moral of the story should be that theorists proposing models with $w < -1$ should be very careful to check that their theories are sufficiently stable, while observers should be open-minded and include $w < -1$ in the parameter space they constrain. To say the least, a convincing measurement that the effective value of w were less than -1 would be an important discovery, the possibility of which one would not want to exclude *a priori*.

1.4.2 Direct Detection of Dark Energy

If dark energy is dynamical rather than simply a constant, it is able to interact with other fields, including those of the Standard Model of particle physics. For the particular example of an ultra-light scalar field, interactions introduce the possibility of two observable phenomena: long-range "fifth forces" and time dependence of the constants of nature. Even if a dark energy scalar ϕ interacts with ordinary matter only through indirect gravitational-strength couplings, searches for these phenomena should have already enabled us to detect the quintessence field (Carroll 1998; Dvali & Zaldarriaga 2002); to avoid detection, we need to introduce dimensionless suppression factors of order 10^{-5} or less in the coupling constants. On the other hand, there has been some evidence from quasar absorption spectra that the fine-structure constant α was slightly smaller ($\Delta\alpha/\alpha \approx -10^{-5}$) at redshifts $z \approx 0.5-3$ (Murphy et al. 2001). On the most optimistic reading, this apparent shift might be direct evidence of a quintessence field; this would place strong constraints on the quintessence potential (Chiba & Kohri 2002). Before such an interpretation is accepted, however, it will be necessary to be certain that all possible sources of systematic error in the quasar measurements are understood, and that models can be constructed that fit the quasar data while remaining consistent with other experimental bounds (Uzan 2003).

More likely, we should work to construct particle physics models of quintessence in which both the mass and the interactions of the scalar field with ordinary matter are naturally suppressed. These requirements are met by Pseudo-Nambu-Goldstone bosons (PNGBs) (Frieman et al. 1992, 1995), which arise in models with approximate global symmetries of the form

$$\phi \to \phi + \text{constant}. \tag{1.41}$$

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. PNGBs typically arise as the angular degrees of freedom in Mexican-hat potentials that are "tilted" by a small explicitly symmetry breaking, and the PNGB potential takes on a sinusoidal form:

$$V(\phi) = \mu^4[1+\cos(\phi)] \ . \tag{1.42}$$

Fields of this type are ubiquitous in string theory, and it is possible that one of them may have the right properties to be the dark energy (Choi 2000; Kim 2000; Kim & Nilles 2003). Interestingly, while the symmetry (1.41) suppresses most possible interactions with ordinary matter, it leaves open one possibility—a pseudoscalar electromagnetic interaction in which ϕ couples to $\mathbf{E}\cdot\mathbf{B}$. The effect of such an interaction would be to gradually rotate the plane of polarization of light from distant sources (Carroll 1998; Lue, Wang, & Kamionkowski 1999); current limits on such a rotation are not quite sensitive enough to tightly constrain this coupling. It is therefore very plausible that a pseudoscalar quintessence field will be directly detected by improved polarization measurements in the near future.

Even if we manage to avoid detectable interactions between dark energy and ordinary matter, we may still consider the possibility of nontrivial interactions between dark matter and dark energy. Numerous models along these lines have been proposed (Casas, Garcia-Bellido, & Quiros 1992; Wetterich 1995; Anderson & Carroll 1998; Amendola 2000; Bean 2001; for recent work and further references, see Farrar & Peebles 2003; Hoffman 2003). If these two dark components constitute 95% of the universe, the idea that they are separate and noninteracting may simply be a useful starting point. Investigations thus far seem to indicate that some sorts of interactions are possible, but constraints imposed by the cosmic microwave background and large-scale structure are actually able to exclude a wide range of possibilities. It may be that the richness of interaction we observe in the ordinary-matter sector is an exception rather than the rule.

1.5 Conclusions

The acceleration of the universe presents us with mysteries and opportunities. The fact that this behavior is so puzzling is a sign that there is something fundamental we do not understand. We do not even know whether our misunderstanding originates with gravity as described by general relativity, with some source of dynamical or constant dark energy, or with the structure of the universe on ultra-large scales. Regardless of what the answer is, we seem poised to discover something profound about how the universe works.

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