Frontiers of Elementary Particle Physics, the Standard Model and Beyond

Cosmic Acceleration, Dark Energy, and Fundamental Physics

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A web of interlocking observations has established that the expansion of the Universe is speeding up and not slowing, revealing the presence of some form of repulsive gravity. Within the context of general relativity the cause of cosmic acceleration is a highly elastic ($p \sim -\rho$), very smooth form of energy called "dark energy" accounting for about 75% of the Universe. The "simplest" explanation for dark energy is the zero-point energy density associated with the quantum vacuum; however, all estimates for its value are many orders-of-magnitude too large. Other ideas for dark energy include a very light scalar field or a tangled network of topological defects. An alternate explanation invokes gravitational physics beyond general relativity. Observations and experiments underway and more precise cosmological measurements and laboratory experiments planned for the next decade will test whether or not dark energy is the quantum energy of the vacuum or something more exotic, and whether or not general relativity can self consistently explain cosmic acceleration. Dark energy is the most conspicuous example of physics beyond the standard model and perhaps the most profound mystery in all of science.

1. Quarks and the Cosmos

The final 25 years of the 20th century saw the rise of two highly successful mathematical models that describe the Universe at its two extremes, the very big and the very small. The standard model of particle physics (detailed in this volume) provides a fundamental description of almost all phenomena in the microscopic world. The standard hot big bang model describes in detail the evolution of the Universe from a fraction of a second after the beginning, when it was just a hot soup of elementary particles, to the present some 13.7 billion years later when it is filled with stars, planets, galaxies, clusters of galaxies and us.[1] Both standard models are consistent with an enormous body of precision data, gathered from high-energy particle accelerators, telescopes and laboratory experiments. The standard model of particle physics and the hot big bang cosmology surely rank among the most important achievements of 20th century science (see Fig. 1).

Both models raise profound questions. Moreover, the "big questions" about the very small and the very large are connected, both in their asking and ultimately in their answering. This suggests that the deeper understanding that lies ahead will reveal even more profound connections between the quarks and the cosmos. The big questions include

- How are the forces and particles of nature unified?
- What is the origin of space, time and the Universe?
- How are quantum mechanics and general relativity reconciled?
- How did the baryonic matter arise in the Universe?
- What is the destiny of the Universe?
- What is the nature of the dark matter that holds the

Universe together and of the dark energy that is causing the expansion of the Universe to speed up?

The last question illustrates the richness of the connections between quarks and the cosmos: 96% of the matter and energy that comprises the Universe is still of unknown form, is crucial to its existence, and determines its destiny. Dark matter and dark energy are also the most concrete and possibly most important evidence for new physics beyond the standard model of particle physics.

The solution to the dark matter problem seems within reach: we have a compelling hypothesis, namely that it exists in the form of stable elementary particles left over from the big bang; we know that a small amount of dark matter exists in the form of massive neutrinos; we have two good candidates for the rest of it (the axion and neutralino) and an experimental program to test the particle dark matter hypothesis.[2]

The situation with cosmic acceleration and dark energy is very different. While we have compelling evidence that the expansion of the Universe is speeding up, we are far from a working hypothesis or any significant understanding of cosmic acceleration. The solution to this profound mystery could be around the corner or very far away.

2. Evidence for Cosmic Acceleration

2.1 Cosmology basics

For mathematical simplicity Einstein assumed that the Universe is isotropic and homogeneous; today, we have good evidence that this is the case on scales greater than 100 Mpc (from the distribution of galaxies in the Universe) and that it was at early times on all scales (from the uniformity of the cosmic microwave background). Under this assumption, the expansion is merely a rescaling and is described by a single function, the cosmic scale factor, $R(t)$. (By convention, the value of the scale factor today is set equal to 1.) The wavelengths of photons moving through the Universe scale

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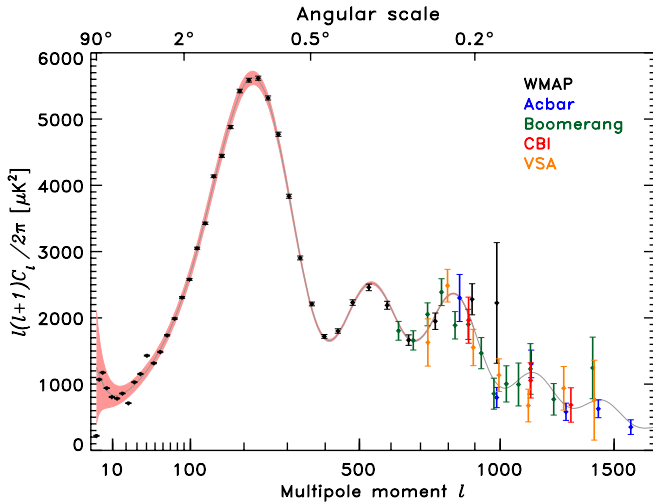†E-mail: dhuterer@kicp.uchicago.edu

Fig. 1. (Color online) Multipole power spectrum of the CMB temperature fluctuations from WMAP and other CMB anisotropy experiments. Position of the first peak at $l \simeq 200$ indicates the flatness of the Universe; height of the first peak determines the matter density, and the ratio of the first to second peaks determines the baryon density. Together with SDSS large-scale structure data, the CMB measurements have determined the shape and composition of the Universe: $\Omega_{\rm TOT} = 1.003 \pm 0.010$, $\Omega_{\rm M} = 0.24 \pm 0.02$, $\Omega_{\rm B} = 0.042 \pm 0.002$, and $\Omega_{\Lambda} = 0.76 \pm 0.02$.[18] The curve is the theoretical prediction of the "concordance cosmology", with a band that indicates cosmic variance. Figure adopted from ref. 19.

with $R(t)$, and the redshift that light from a distant object suffers, $1 + z = \lambda_{\rm rcvd}/\lambda_{\rm emit}$, directly reveals the size of the Universe when that light was emitted: $1 + z = 1/R(t_{\rm emit})$.

The key equations of cosmology are

$$H^2 \equiv (\dot{R}/R)^2 = \frac{8\pi G \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \qquad (1)$$

$$\ddot{R}/R = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \qquad (2)$$

$$w_i \equiv \frac{p_i}{\rho_i} \qquad \rho_i \propto (1+z)^{3(1+w_i)} \qquad (3)$$

$$q(z) \equiv -\frac{\ddot{R}}{RH^2} = \frac{1}{2}(1 + 3w), \qquad (4)$$

where ρ is the total energy density of the Universe (sum of matter, radiation, dark energy) and p is the total pressure. For each component the ratio of pressure to energy density is the equation-of-state w_i which, through the conservation of energy, $d(R^3 \rho) = -p dR^3$, determines how the energy density evolves. For constant w, $\rho \propto (1+z)^{3(1+w)}$: For matter ($w = 0$) $\rho_{\rm M} \propto (1+z)^3$ and for radiation ($w = 1/3$) $\rho_R \propto (1+z)^4$. The first of these equations, known as the Friedmann equation, is the master equation of cosmology.

The quantity k is the 3-curvature of the Universe and $R_{\rm curv} \equiv R/\sqrt{|k|}$ is the curvature radius; $k = 0$ corresponds to a spatially flat Universe, $k > 0$ a positively curved Universe and $k < 0$ a negatively curved Universe. Because of the evidence from the cosmic microwave background that the Universe is spatially flat (see Fig. 1), unless otherwise noted we shall assume $k = 0$.

Λ is Einstein's infamous cosmological constant; it is equivalent to a constant energy density, $\rho_\Lambda = \Lambda/8\pi G$, with pressure $p_\Lambda = -\rho_\Lambda$ ($w = -1$). The quantity $q(z)$ is the deceleration parameter, defined with a minus sign so that $q > 0$ corresponds to decelerating expansion.

The energy density of a flat Universe ($k = 0$), $\rho_{\rm C} \equiv 3H^2/8\pi G$, is known as the critical density. For a positively curved Universe, $\Omega_{\rm TOT} \equiv \rho/\rho_{\rm C} > 1$ and for a negatively curved Universe $\Omega_{\rm TOT} < 1$. Provided the total pressure is greater than $-1/3$ times the total energy density, gravity slows the expansion rate, i.e., $\ddot{R} < 0$ and $q > 0$. Because of the $(\rho + 3p)$ term in the $\ddot{R}$ equation (Newtonian gravity would only have ρ), the gravity of a sufficiently elastic form of energy ($p < -\rho/3$) is repulsive and causes the expansion of the Universe to accelerate. In Einstein's static solution ($H = 0$, $q = 0$) the repulsive gravity of Λ is balanced against the attractive gravity of matter, with $\rho_\Lambda = \rho_{\rm M}/2$ and $R_{\rm curv} = 1/\sqrt{8\pi G \rho_{\rm M}}$. A cosmological constant that is larger than this results in accelerated expansion ($q < 0$); the observed acceleration requires $\rho_\Lambda \simeq (2-3)\rho_{\rm M}$.

For an object of known intrinsic luminosity L, the measured energy flux F defines the luminosity distance $d_{\rm L}$ to the object (i.e., the distance inferred from the inverse square law). The luminosity distance is related to the cosmological model via

$$d_{\rm L}(z) \equiv \sqrt{L/4\pi F} = (1+z) \int_0^z \frac{dz'}{H(z')}. \qquad (5)$$

Astronomers determine the luminosity distance from the difference between the apparent magnitude m of the object (proportional to the log of the flux) and the absolute magnitude M (proportional to the log of the intrinsic luminosity), $m - M = 5 \log_{10}(d_{\rm L}/10\,{\rm pc})$ (where 5 astronomical magnitudes correspond to a factor of 100 in flux or a factor of 10 in luminosity distance).

The use of "standard candles" (objects of known intrinsic luminosity L) and measurements of the energy flux F constrain the cosmological model through this equation. In particular, the Hubble diagram (or magnitude-redshift diagram) is the simplest route to probing the expansion history. In terms of the deceleration parameter the equation is deceptively simple:

$$H_0 d_{\rm L} = z + \frac{1}{2}(1 - q_0)z^2 + \cdots \qquad (6)$$

where the subscript "0" denotes the value today. While this Taylor expansion of eq. (5), valid for $z \ll 1$, is of historical significance and utility, it is not useful today since objects as distant as redshift $z \sim 2$ have been used to probe the expansion history. However, it does illustrate the general principle: the first term on the r.h.s. represents the linear Hubble expansion, and the deviation from a linear relation reveals the deceleration (or acceleration).

2.2 Λ's checkered history

Before discussing the evidence for cosmic acceleration, we will recount some of the history of the cosmological constant. Realizing that there was nothing to forbid such a term and that it could be used to obtain an interesting solution (a static and finite Universe), Einstein introduced the cosmological constant in 1917. While his static solution was consistent with astronomical observations at that time, Hubble's discovery of the expansion of the Universe in 1929 led Einstein to discard the cosmological constant in favor of expanding models without one, calling the cosmological constant "my greatest blunder".

In 1948, Bondi, Gold, and Hoyle put forth the "steady state cosmology", with $\rho_\Lambda > 0$ and $\rho_M \simeq 0$. The model was motivated by the aesthetics of an unchanging universe and a serious age problem (the measured value of the Hubble constant at the time, around $500\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ implied an expansion age of only 2 Gyr, less than the age of Earth). The redshift distribution of radio galaxies, the absence of quasars nearby and the discovery of the cosmic microwave background radiation in 1960s all indicated that we do not live in an unchanging Universe and ended this revival of a cosmological constant.

The cosmological constant was briefly resurrected in the late 1960s by Petrosian *et al.*[3] to explain the preponderance of quasars at redshifts around $z \sim 2$ (as it turns out, this is a real effect: quasar activity peaks around $z \sim 2$). In 1975 weak evidence for a cosmological constant from a Hubble diagram of elliptical galaxies extending to redshifts of $z \sim 0.5$ was presented.[4] Significant concerns about whether or not elliptical galaxies were good standard candles led to the demise of Λ once again. Shortly thereafter came the rise of the standard cosmology with $\Lambda = 0$.

The current attempt at introducing a cosmological constant (or something similar), which is backed up by multiple lines of independent evidence, traces its roots to the inflationary universe scenario and its prediction of a spatially flat Universe. In the early 1980s when inflation was introduced, the best estimate of the average mass density fell short of the critical density by almost a factor of 10 ($\Omega_M \sim 0.1$); the saving grace for inflation was the large uncertainty associated with measuring the mean matter density. From 1980 to the mid 1990s, as measurement techniques took better account of dark matter, Ω_M rose to of order 0.5 or so. However, as the uncertainties got smaller, Ω_M began converging on a value of around 1/3, not 1. Moreover, the predictions of the cold dark matter scenario of structure formation matched observations if Ω_M was around 1/3, not 1.

Starting in 1984 and continuing to just before the discovery of cosmic acceleration, a number of papers suggested the solution to inflation's "Ω problem"[1] was a cosmological constant.[5] Owing to its checkered history, there was not much enthusiasm for this suggestion at first. However, with time the indirect evidence for Λ grew,[6–8] and in 1998 when the supernova evidence for accelerated expansion was presented the cosmological constant was quickly embraced — this time, it was the missing piece of the puzzle that made everything work.

2.3 Discovery and confirmation

Two breakthroughs enabled the discovery that the Universe is speeding up and not slowing down. The first was the demonstration that type Ia supernovae (SNe Ia), the brightest of the supernovae and the ones believed to be associated with the thermonuclear explosions of 1.4 $M_\odot$ white-dwarf stars pushed over the Chandrasekhar mass limit by accretion, are (nearly) standard candles.[10] The second breakthrough involved the use of large (of order 100 megapixel) CCD cameras to search big regions of the sky containing thousands of galaxies for these rare events (the SN Ia rate in a typical galaxy is of the order of one per 100 to 200 years). By comparing images of thousands of galaxies
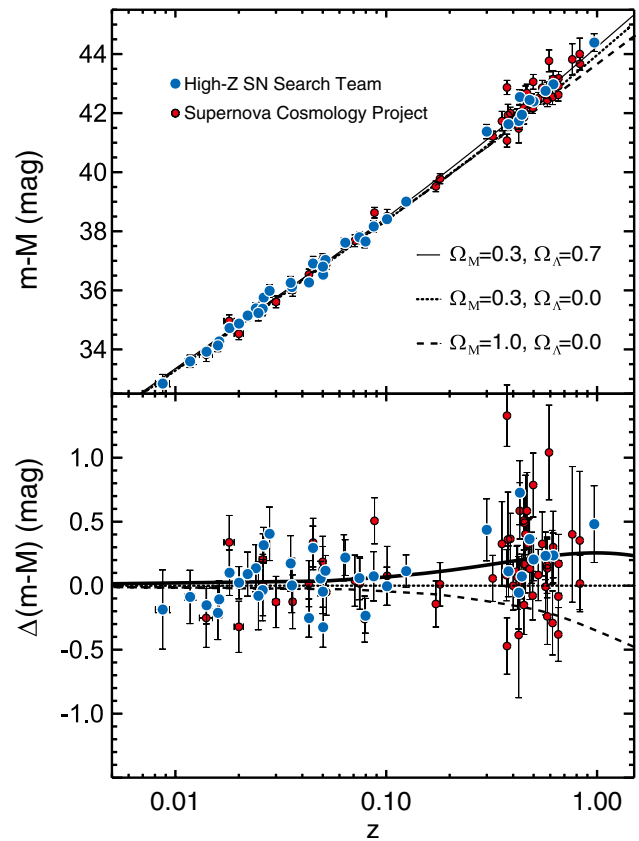

Fig. 2. (Color online) Discovery data: Hubble diagram of SNe Ia measured by the Supernova Cosmology Project and High-z Supernova Team. Bottom panel shows magnitudes relative to a universe with $\Omega_{TOT} = \Omega_M = 0.3$. Figure adopted from ref. 9.

taken weeks apart the discovery of SNe could be reliably "scheduled" on a statistical basis.

Two teams working independently in the mid- to late-1990s took advantage of these breakthroughs to determine the expansion history of the Universe. They both found that distant SNe are dimmer than they would be in a decelerating Universe, indicating that the expansion has actually been speeding up for the past 5 Gyr;[11,12] see Fig. 2. Analyzed for a Universe with matter and cosmological constant, their results provide evidence for $\Omega_\Lambda > 0$ at greater than 99% confidence; see Fig. 3.

Since this work, the two teams have discovered and studied more SNe, as have other groups.[13–16] Not only has the new data confirmed the discovery, but it has also allowed measurements of the equation-of-state of dark energy $w = p/\rho$ (assuming constant w), and even constrains the time variation of w, with the parametrization $w = w_0 + w_a(1 - R)$.

Especially important in this regard are SNe with redshifts $z > 1$ which indicate that the universe was decelerating at earlier times (see Fig. 4), and hence that dark energy started its domination over the dark matter only recently, at redshift $z = (\Omega_M/\Omega_{DE})^{1/3w} - 1 \approx 0.5$. This finding is an important reality check: without a long, matter-dominated, slowing phase, the Universe could not have formed the structure we see today.

Evidence for dark energy comes from several other independent probes. Measurements of the fraction of X-ray emitting gas to total mass in galaxy clusters, f_{gas}, also
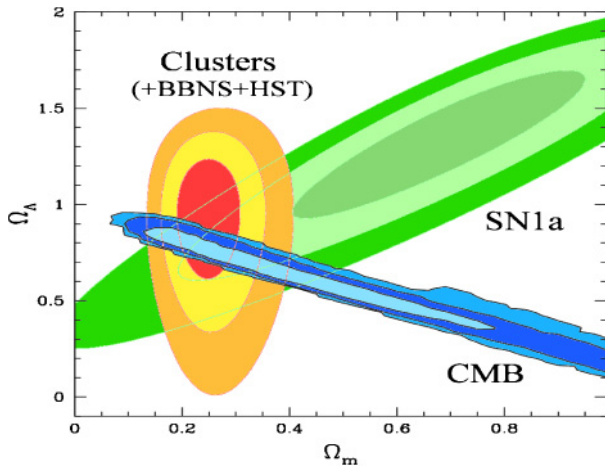
Fig. 3. (Color online) Three independent lines of evidence for cosmic acceleration: galaxy clusters, CMB anisotropy, and SNe. Flatness is not assumed, but $w = -1$. Note the concordance of the independent methods; evidence for $\Omega_\Lambda > 0$ is greater 99.9% C.L. Figure adopted from ref. 17.
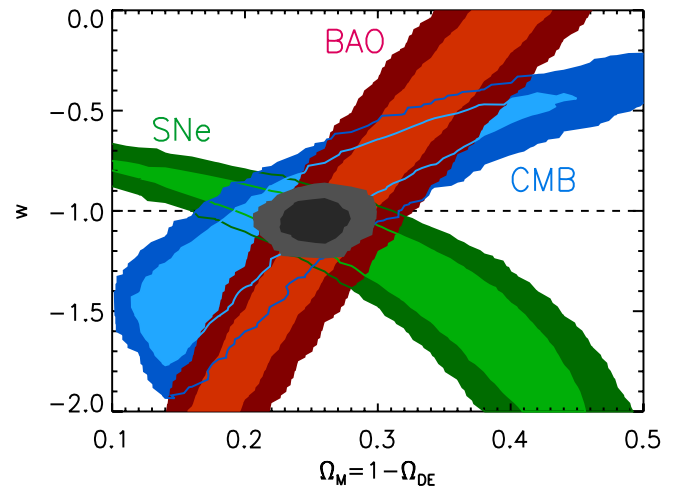

Fig. 5. (Color online) 68 and 95% C.L. constraints on the matter density Ω_M and dark energy equation-of-state w, assuming a flat Universe. Constraints come from the Supernova Legacy Survey,[15] WMAP,[27] and SDSS detection of BAO.[22] The combined constraint is shown by the central dark contours.
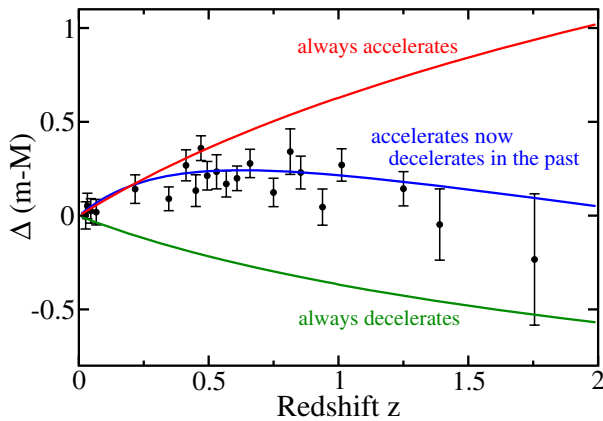

Fig. 4. (Color online) Evidence for transition from recent acceleration to deceleration in the past. The Hubble diagram with measured distances to SNe Ia is not fitted well by either a purely accelerating or purely decelerating cosmological model, but rather one with early deceleration and recent acceleration. SN data are binned in redshift and come from ref. 14.

indicates the presence of dark energy. Because galaxy clusters are the largest collapsed objects in the universe, the gas fraction in them is presumed to be constant and equal to the overall baryon fraction in the universe, Ω_B/Ω_M (most of the baryons in clusters reside in the gas). Measurements of the gas fraction f_{gas} depend not only on the observed X-ray flux, but also on the distance to the cluster; therefore, only the correct cosmology will produce distances which make the apparent f_{gas} constant in redshift. Using data from the Chandra X-ray Observatory, Allen *et al.*[17] have determined Ω_Λ to an accuracy of about ±0.2; see Fig. 3.

Cosmic microwave background (CMB) anisotropies provide a record of the Universe at simpler time, before structure had developed and when photons were decoupling from baryons, $z \approx 1100$.[20] The multipole power spectrum is dominated by the acoustic peaks that arise from gravitationally driven photon–baryon oscillations (see Fig. 1). The positions and amplitudes of the acoustic peaks encode much information about the Universe, today and at earlier times. In

particular, they indicate that the Universe is spatially flat, with a matter density that accounts for only about a quarter of the critical density. However, the presence of a uniformly distributed energy density with large negative pressure which accounts for three-quarters of the critical density brings everything into good agreement, both with CMB data and the large-scale distribution of galaxies in the Universe. The CMB data of WMAP together with large-scale structure data of the Sloan Digital Sky Survey (SDSS) provides the following cosmic census:[18] $\Omega_{TOT} = 1.003 \pm 0.010$, $\Omega_M = 0.24 \pm 0.02$, $\Omega_B = 0.042 \pm 0.002$, and $\Omega_\Lambda = 0.76 \pm 0.02$.

The presence of dark energy also affects the large-angle anisotropy of the CMB (the low multipoles) and leads to the prediction of a small correlation between the galaxy distribution and the CMB anisotropy. This subtle effect has been observed;[21] while not detected at a level of significance that could be called independent confirmation, its presence is a reassuring cross check.

Baryon acoustic oscillations (BAO), so prominent in the CMB anisotropy (see Fig. 1), leave a smaller characteristic signature in the clustering of galaxies that can be measured today and provide an independent geometric probe of dark energy. Measurements of the BAO signature in the correlation function of SDSS galaxies constrains the distance to redshift $z = 0.35$ to a precision of 5%.[22] While this alone does not establish the existence of dark energy, it serves as a significant complement to other probes, cf. Fig. 5.

Weak gravitational lensing[23] — slight distortions of galaxy shapes due to gravitational lensing by intervening large-scale structure — is a powerful technique for mapping dark matter and its clustering. Currently, weak lensing sheds light on dark energy by pinning down the combination $\sigma_8(\Omega_M/0.25)^{0.6} \approx 0.85 \pm 0.07$, where σ_8 is the amplitude of mass fluctuations on the 8 Mpc scale.[25] Since other measurements put σ_8 at ~ 0.9, this implies that $\Omega_M \simeq 0.25$, consistent with a flat Universe whose mass/energy density is dominated by dark energy. In the future, weak lensing will also be very useful in probing the equation-of-state of dark energy;[24] see §4.
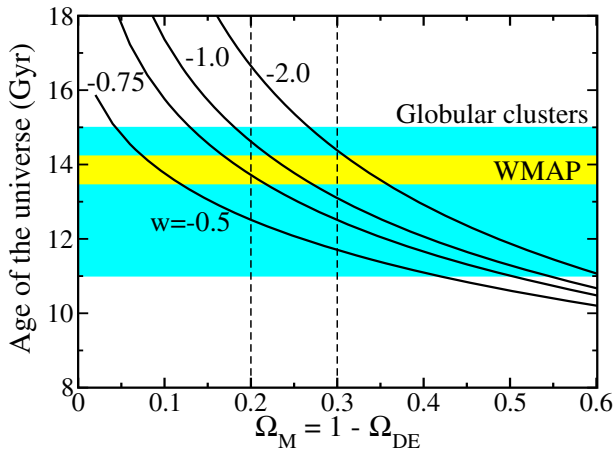
Fig. 6. (Color online) Age of the universe as a function of the matter energy density, assuming a flat universe and four different values of the dark energy equation-of-state. Also shown are constraints from globular clusters[26] and from WMAP[27] and the range of Ω_M favored by measurements of the matter density. Age consistency holds for $-2 \lesssim w \lesssim -0.75$.

Finally, because the time back to the big bang, $t_0 = \int dz/(1 + z)H(z)$, depends upon the expansion history, the comparison of this age with other independent age estimates can be used to probe dark energy. The ages of the oldest stars in globular clusters constrain the age of the Universe: $11 \lesssim t_0 \lesssim 15$ Gyr.[26] CMB anisotropy is very sensitive to the expansion age, and WMAP data determine it accurately: $t_0 = 13.84^{+0.39}_{-0.36}$ Gyr.[27] Figure 6 shows that a consistent age is possible if $-2 \lesssim w \lesssim -0.75$. Agreement on the age of the Universe provides an important consistency check as well as confirmation of a key feature of dark energy, its large negative pressure.

3. Understanding Cosmic Acceleration

Sir Arthur Eddington is quoted as saying, "It is (also) a good rule not to put too much confidence in observational results until they are confirmed by theory". While this may seem a bit paradoxical (or worse yet, an example of blatant theoretical arrogance), the point is well taken: science is not just a collection of facts, it is also understanding; if the understanding does not eventually follow new facts, perhaps there is something wrong with the facts.

Cosmic acceleration meets the Eddington criterion and at the same time presents a stunning opportunity for theorists: General relativity (GR) can accommodate accelerated expansion, but GR has yet to provide a deeper understanding of the phenomenon.

Within GR, a very elastic fluid has repulsive gravity, and, if present in sufficient quantity, can lead to the observed accelerated expansion. This then is the definition of dark energy: the mysterious, elastic and very smooth form of energy which is responsible for cosmic acceleration and is characterized by an equation-of-state $w = p/\rho \sim -1$.[8]

Vacuum energy is a concrete example of dark energy. General covariance requires that the stress energy associated with the vacuum take the form of a constant times the metric tensor. This implies that it has a pressure equal to minus its energy density, is constant both in space and time, and is mathematically equivalent to a cosmological constant.

The stress energy associated with a homogeneous scalar field ϕ can also behave like dark energy. It takes the form of a perfect fluid with

$$\begin{aligned} \rho &= \dot{\phi}^2/2 + V(\phi) \\ p &= \dot{\phi}^2/2 - V(\phi), \end{aligned} \tag{7}$$

where $V(\phi)$ is the potential energy of the scalar field, dot denotes time derivative, and the evolution of the field ϕ is governed by

$$\ddot{\phi} + 3H\phi + V'(\phi) = 0. \tag{8}$$

If the scalar field evolves slowly, that is $\dot{\phi}^2 \ll V$, then $p \simeq -\rho$ and the scalar field behaves like a slowly varying vacuum energy.

While cosmic acceleration can be accommodated within the GR framework, the fundamental explanation could be new gravitational physics. With this as a prelude, we now briefly review the present theoretical situation.

(a) *Vacuum energy.* Vacuum energy is both the most plausible explanation and the most puzzling possibility. For almost 80 years we have known that there should in principle be an energy associated with the zero-point fluctuations of all quantum fields. Moreover, $p_{VAC} = -\rho_{VAC}$. However, all attempts to compute the value of the vacuum energy lead to divergent results. The so-called cosmological constant problem was finally articulated about thirty years ago.[28] However, because of the success of the standard hot big bang model (where $\Lambda = 0$) and the absence of good (or any) ideas, the problem was largely ignored. With the discovery of cosmic acceleration, the cosmological constant problem is now front and center and can no longer be ignored.

To be more quantitative, the energy density required to explain the accelerated expansion is about three quarters of the critical density or about 4×10^{-47} GeV$^4 \approx (3 \times 10^{-3}$ eV$)^4$. This is tiny compared to energy scales in particle physics (with the exception of neutrino mass differences). Such a small energy precludes solving the problem by simply cutting off the divergent zero-point energy integral at some energy beyond which physics is not yet known. For example, a cutoff of 100 GeV would leave a 54 orders-of-magnitude discrepancy. If supersymmetry were an unbroken symmetry, fermionic and bosonic zero-point contributions would cancel. However, if supersymmetry is broken at a scale of order M, one would expect that imperfect cancellations leave a finite vacuum energy of the order M^4, which for the favored value of $M \sim 100$ GeV to 1 TeV, would leave a discrepancy of 50 or 60 orders-of-magnitude.

One approach to the cosmological constant problem involves the idea that the value of the vacuum energy is a random variable which can take on different values in different disconnected pieces of the Universe. Because a value much larger than needed to explain the observed cosmic acceleration would preclude the formation of galaxies, we could not find ourselves in such a region.[29] This very anthropic approach finds a home in the landscape version of string theory.[30]

(b) *Scalar fields, etc.* While introducing a new dynamical degree of freedom can also provide a very elastic form of energy density, it does not solve the cosmological constant problem. In order to roll slowly enough the mass

of the scalar field must be very light, $m \lesssim H_0 \sim 10^{-42}$ GeV, and its coupling to matter must be very weak to be consistent with searches for new long-range forces.[31] Unlike vacuum energy, scalar-field energy clusters gravitationally, but only on the largest scales and with a very small amplitude.[32]

The equation-of-state w for a scalar field can take on any value between -1 and 1 and in general varies with time. (It is also possible to have $w < -1$, though at the expense of ghosts, by changing the sign of the kinetic energy term in the Lagrangian.) Scalar field models also raise new questions and possibilities: Is cosmic acceleration related to inflation? Is dark energy related to dark matter or neutrino mass? No firm or compelling connections have been made to either, although interesting possibilities have been suggested.

Scalar fields in a very different form can also explain cosmic acceleration. The topological solitons that arise in broken gauge theories, e.g., strings, walls, and textures, are very elastic, and tangled networks of such defects can on large scales behave like an elastic medium with $w = -N/3$, where N is the dimensionality of the network ($N = 1$ for strings, 2 for walls, and 3 for textures). In this case w is a fixed, rational number.

(c) *Modified gravity.* A very different approach holds that cosmic acceleration is a manifestation of new gravitational physics and not of dark energy. Assuming that our 4-d spacetime can still be described by a metric, the operational changes are twofold: (1) a new version of the Friedmann equation governing the evolution of the background spacetime; (2) modifications to the equations that govern the growth of the small matter perturbations that evolve into the structure seen in the Universe today. A number of ideas have been explored, from models motivated by higher-dimensional theories and string theory[33,34] to generic modifications of the usual gravitational action.[35]

An aside: One might be concerned that when the assumption of general relativity is dropped the evidence for accelerated expansion might disappear. This is not the case; using the deceleration $q(z)$ as a kinematic description of the expansion, the SNe data still provide strong evidence for a period of accelerated expansion.[36]

Changes to the Friedmann equation are easier to derive, discuss, and analyze. In order not to spoil the success of the standard cosmology at early times (from big-bang nucleosynthesis to the CMB anisotropy to the formation of structure), the Friedmann equation must reduce to the GR form for $z \gg 1$. Because the matter term scales as $(1 + z)^3$ and the radiation term as $(1 + z)^4$, to be safe any modifications should decrease with redshift more slowly than this. As a specific example, consider the DGP model, which arises from a five-dimensional gravity theory,[33] and has a 4-d Friedmann equation,

$$H^2 = \frac{8\pi G\rho_M}{3} + \frac{H}{r_c}, \qquad (9)$$

where r_c is an undetermined scale and ρ_M is the matter enegy density. As $\rho_M \to 0$, there is a (self) accelerating solution, with $H = 1/r_c$. The additional term in the Friedmann equation, H/r_c, behaves just like dark energy with an equation-of-state that evolves from $w = -1/2$ (for $z \gg 1$) to $w = -1$ in the distant future.

4. Prospects for Revealing the Nature of Dark Energy

We divide the probes of dark energy into three broad categories: kinematical and dynamical cosmological probes, and laboratory/astrophysical probes. Kinematical tests rely on the measurement of cosmological distances and volumes to constrain the evolution of the scale factor and thus the background cosmological model. Specific techniques include SNe Ia, CMB, and baryon acoustic oscillations.

The dynamical tests probe the effect of dark energy on perturbations of the cosmological model, including the evolution of the small inhomogeneities in the matter density that give rise to structure in the Universe. Specific techniques include the use of gravitational lensing to directly determine the evolution of structure in the dark matter and the study of the growth of the abundance of galaxy clusters to indirectly probe the growth of structure. A potential probe of dark energy, which at the present seems beyond reach, is to study the clustering of dark energy itself. Since vacuum energy does not cluster, detection of such would rule out vacuum energy as the explanation for cosmic acceleration.

In general relativity, for both kinematical and dynamical cosmological probes, the primary effect of dark energy enters through the Friedmann equation, cf. eq. (1),

$$
\begin{aligned}
H(z)^2 &= \frac{8\pi G}{3}\big[\rho_M + \rho_{DE}\big] \\
&= H_0^2\big[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)}\big], \quad (10)
\end{aligned}
$$

where a flat Universe and constant w have been assumed. In turn, the expansion rate affects the luminosity distance, $d_L = (1 + z) \int dz/H(z)$, the number of objects seen on the sky, $d^2N/(d\Omega\, dz) = n(z)d_L^2/[(1 + z)^2 H(z)]$ (n is the comoving density of objects), and the evolution of cosmic structure via the growth of small density perturbations. In GR the growth of small density perturbations in the matter, and on subhorizon scales, is governed by

$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho_M\delta_k = 0, \qquad (11)$$

where density perturbations in the cold dark matter have been decomposed into their Fourier modes of wavenumber k. Dark energy affects the growth through "the drag term", $2H\dot{\delta}_k$. The equations governing dark energy perturbations depend upon the specific dark energy model.

The kinematical and dynamical tests probe complementary aspects of the effect of dark energy on the Universe: the overall expansion of the Universe (kinematical) and the evolution of perturbations (dynamical). Together, they can test the consistency of the underlying gravity theory. In particular, different values of the dark energy equation-of-state obtained by the two methods would indicate an inconsistency of the underlying gravity theory.

The kinematical tests are easier to frame because they only depend upon knowing the effect of dark energy on the background cosmological model. Further, cosmological variables (such as q) can even be formulated without reference to a particular theory of gravity. The dynamical tests are both harder to frame — they require detailed knowledge of how dark energy clusters and affects the growth of density perturbations — and also harder to implement — they rely upon the details of describing and measuring the distribution of matter in the Universe. Both the

kinematical and dynamical tests have their greatest probative power at redshifts between about $z = 0.2$ and $z = 2$, for the simple reason that at higher redshifts dark energy becomes increasingly less important, $\rho_{DE}/\rho_M \propto (1+z)^{3w}$.[37]

While the primary probes of dark energy are cosmological, laboratory experiments may be able to get at the underlying physics. If dark energy couples to matter there will be long-range forces that are in principle detectable; if it couples to electromagnetism, polarized light from distant astrophysical sources should suffer rotation.[31] It is also possible that accelerator-based experiments will have something to say about dark energy. For example, if evidence for supersymmetry is found at the Large Hadron Collider, understanding how supersymmetry is broken could shed light on the vacuum energy puzzle.

Observations to date have established the existence of dark energy and have begun to probe its nature; e.g., by constraining $w \approx -1 \pm 0.1$. Future experiments will focus on testing whether or not it is vacuum energy and the consistency of GR to accommodate dark energy. The Supernova/Acceleration Probe (SNAP),[38] a proposed space-based telescope to collect several thousand SNe out to $z \approx 2$, would significantly reduce uncertainties (both statistical and systematic) on dark-energy parameters. SNAP, together with the planned wide-field surveys from the ground, the Dark Energy Survey (DES)[39] and the Large Synoptic Survey Telescope (LSST),[40] would map the weak lensing signal from one arcminute out to the largest observable scales on the sky and accurately determine the effect of dark energy on the growth of structure. Large BAO surveys are also planned, both from the ground and space. The just-completed South Pole Telescope (SPT)[41] and the Atacama Cosmology Telescope (ACT)[42] will soon begin studying dark energy by determining the evolution of the abundance of galaxy clusters. In 2008, ESA's Planck Surveyor CMB satellite[43] will be launched and will extend precision measurements of CMB anisotropy to $l \sim 3000$ (i.e., down to angular scales of about 5 arcmin), more accurately pinning down the matter density and providing an important prior constraint for other dark energy measurements.[44] Theoretical forecasts for future constraints on the parameters (w_0, w_a) are shown in Fig. 7.

5. Dark Energy and Destiny

One of the first things one learns in cosmology is that geometry is destiny: a closed (positively curved) Universe eventually recollapses and an open (flat or negatively curved) Universe expands forever. Provided that the Universe only contains matter and $\Lambda = 0$, this follows directly from eq. (1). If $k > 0$, the Universe achieves a maximum size when H^2 is driven to zero by the inevitable cancellation of ρ_M and k/R^2. If $k = 0$, R always grows as $t^{2/3}$ and $q = 1/2$. For $k < 0$, the Universe ultimately reaches a coasting phase where R grows as t and $q = 0$. Adding radiation only changes the story at early times (see Fig. 8): because the radiation density increases as $(1+z)^4$, for $z \gg 3 \times 10^3$ the Universe is radiation dominated and during this epoch, $R \propto t^{1/2}$ and $q = 1$ [this is a manifestation of the fact that gravity is sourced by $\rho + 3p = 2\rho$ for radiation, cf. eqs. (2) and (4)]. It is only during the matter-dominated phase that small density inhomogeneities are able to grow and form bound structures.
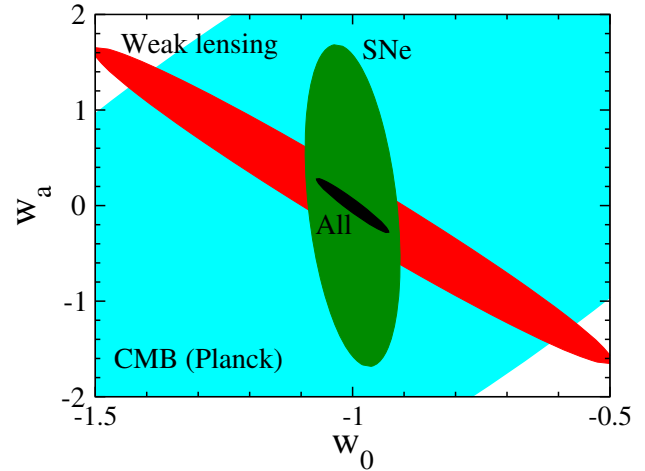

Fig. 7. (Color online) Forecasts of future constraints to the dark energy equation-of-state and its time evolution using SNe Ia, weak gravitational lensing, and CMB anisotropy (measured by Planck). Future SNe Ia and weak lensing estimates are both modeled on the SNAP experiment. The large improvement in combining the various data sets is due to breaking of the parameter degeneracies in the full (eight-dimensional) parameter space.
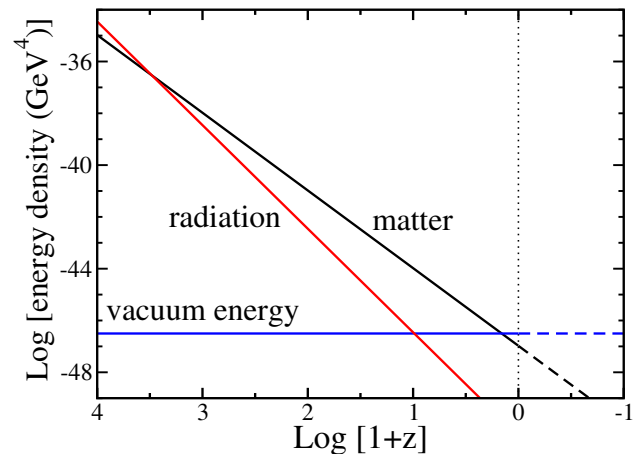

Fig. 8. (Color online) Evolution of dark matter, dark energy, and radiation. Earlier than $z \sim 3000$ radiation dominates the mass/energy density of the Universe; between $z \sim 3000$ and $z \sim 0.5$ dark matter dominates, and thereafter dark energy dominates and the expansion accelerates. Structure only grows during the matter dominated epoch.

Dark energy provides a new twist: because the dark energy density varies slowly if at all, it eventually becomes the dominant form of matter/energy (around $z \sim 0.5$); see Fig. 8. After that, the expansion accelerates and structure formation ceases, leaving in place all the structure that has formed. The future beyond the present epoch of accelerated expansion is uncertain and depends upon understanding dark energy.

In particular, if dark energy is vacuum energy, acceleration will continue and the expansion will become exponential, leading inevitably to a dark Universe. (In a hundred billion years, the light from all but a few hundred nearby galaxies will be too redshifted to detect.) On the other hand, if dark energy is explained by a scalar field, then eventually the field relaxes to the minimum of its potential. If the minimum of the potential energy is zero, the Universe again

becomes matter dominated and returns to decelerated expansion. If the minimum of the scalar potential has negative energy density, the energy of dark matter and of scalar field energy will eventually cancel, leading to a recollapse. Finally, if the potential energy at the minimum is positive, no matter how small, accelerated expansion eventually ensues again.

Absent dark energy geometry and destiny are linked. The presence of dark energy severs this relation[7] and links instead destiny to an understanding of dark energy.

6. Summary

We end our brief review with our list of the ten most important facts about cosmic acceleration

1. Independent of general relativity and based solely upon the SN Hubble diagram, there is very strong evidence that the expansion of the Universe has accelerated recently.[36]

2. Within the context of general relativity, cosmic acceleration cannot be explained by any known form of matter or energy, but can be accommodated by a nearly smooth and very elastic ($p \sim -\rho$) form of energy ("dark energy") that accounts for about 75% of the mass/energy content of the Universe.

3. Taken together, current data (SNe, galaxy clustering, CMB and galaxy clusters) provide strong evidence for the existence of dark energy and constrain the fraction of critical density contributed by dark energy to be $71 \pm 5\%$ and the equation-of-state to be $w \approx -1 \pm 0.1$ (stat) ± 0.1 (sys), with no evidence for variation in w. This implies that the Universe decelerated until $z \sim 0.5$ and age $\sim 10\,\mathrm{Gyr}$, when it began accelerating.

4. The simplest explanation for dark energy is the zero-point energy of the quantum vacuum, mathematically equivalent to a cosmological constant. In this case, w is precisely -1, exactly uniformly distributed and constant in time. All extant data are consistent with a cosmological constant; however, all attempts to compute the energy of the quantum vacuum yield a result that is many orders-of-magnitude too large (or is infinite).

5. There is no compelling model for dark energy. However there are many intriguing ideas including a new light scalar field, a tangled network of topological defects, or the influence of additional spatial dimensions. It has also been suggested that dark energy is related to cosmic inflation, dark matter and neutrino mass.

6. Cosmic acceleration could be a manifestation of gravitational physics beyond general relativity rather than dark energy. While there are intriguing ideas about corrections to the usual gravitational action or modifications to the Friedmann equation that can give rise to the observed accelerated expansion, there is no compelling, self-consistent model for the new gravitational physics that explains cosmic acceleration.

7. Even assuming the Universe has precisely the critical density and is spatially flat, the destiny of the Universe depends crucially upon the nature of the dark energy. All three fates — recollapse or continued expansion with and without slowing — are possible.

8. Cosmic acceleration is arguably the most profound puzzle in physics. Its solution could shed light on or be central to unraveling other important puzzles, including the cause of cosmic inflation, the vacuum-energy problem, supersymmetry and superstrings, neutrino mass, new gravitational physics, and dark matter.

9. Today, the two most pressing questions about dark energy and cosmic acceleration are: Is dark energy something other than vacuum energy? Does general relativity self consistently describe cosmic acceleration? Establishing that $w \neq -1$ or that it varies with time would rule out vacuum energy; establishing that the values of w determined by the kinematical and dynamical methods are not equal would indicate that GR cannot self consistently accommodate accelerated expansion.

10. Dark energy affects the expansion rate of the Universe, which in turn affects the growth of structure and the distances to objects. (In gravity theories other than GR, dark energy may have more direct effects on the growth of structure.) Upcoming ground- and space-based experiments should probe w at the percent level and its variation at the ten percent level. These measurements should dramatically improve our ability to discriminate between vacuum energy and something more exotic as well as testing the self consistency of general relativity. Laboratory- and accelerator-based experiments could also shed light on dark energy.

Because of its brevity, this review could not do justice to the extensive literature that now exists; for readers interested in a more thorough treatment of dark energy and/or a more extensive review, we refer them to ref. 45.

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