

**DARK MATTER, DARK ENERGY, AND FUNDAMENTAL PHYSICS**

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More than sixty years ago Zwicky made the case that the great clusters of galaxies are held together by the gravitational force of unseen (dark) matter. Today, the case is stronger and more precise: Dark, nonbaryonic matter accounts for  $30\% \pm 7\%$  of the critical mass density, with baryons (most of which are dark) contributing only  $4.5\% \pm 0.5\%$  of the critical density. The large-scale structure that exists in the Universe indicates that the bulk of the nonbaryonic dark matter must be cold (slowly moving particles). The SuperKamioke detection of neutrino oscillations shows that particle dark matter exists, crossing an important threshold. Over the past few years a case has developed for a dark-energy problem. This dark component contributes about  $80\% \pm 20\%$  of the critical density and is characterized by very negative pressure ( $p_X < -0.6\rho_X$ ). Consistent with this picture of dark energy and dark matter are measurements of CMB anisotropy that indicate that total contribution of matter and energy is within 10% of the critical density. Fundamental physics beyond the standard model is implicated in both the dark matter and dark energy puzzles: new fundamental particles (e.g., axion or neutralino) and new forms of relativistic energy (e.g., vacuum energy or a light scalar field). A flood of observations will shed light on the dark side of the Universe over the next two decades; as it does it will advance our understanding of the Universe and the laws of physics that govern it.

**1 In the Beginning ...**

The simplest universe would contain just matter. Then, according to Einstein, its geometry and destiny would be linked: a high-density universe ( $\Omega_0 > 1$ ) is positively curved and eventually recollapses; a low-density universe is negatively curved and expands forever; and the critical universe ( $\Omega_0 = 1$ ) is spatially flat and expands forever, albeit at an ever decreasing rate.

As described by Sandage, such a universe is today characterized by two numbers: the expansion rate  $H_0 \equiv \dot{R}(t_0)/R(t_0)$  and the deceleration parameter  $q_0 \equiv -\ddot{R}(t_0)/H_0^2 R(t_0)$  where  $R(t)$  is the cosmic scale factor and  $t_0$  denotes the age of the Universe at the present epoch. Through Einstein's equations

the deceleration parameter and density parameter are related:  $q_0 = \Omega_0/2$ . There is a consensus that we are finally closing in on the expansion rate:  $H_0 = 65 \pm 5 \text{ km sec}^{-1} \text{ Mpc}^{-1}$  (or  $h = 0.65 \pm 0.05$ ).<sup>1</sup> Type Ia supernovae seem to have provided the first reliable measurement of the deceleration parameter<sup>2</sup> – and a surprise: the Universe is accelerating not decelerating. So much for a simple Universe.

We have known for thirty years our Universe is not as simple as two numbers; it is much more interesting! In 1964 Penzias and Wilson discovered the cosmic microwave background radiation (CMB). Today the CMB is a minor component,  $\Omega_{\text{CMB}} = 2.48h^{-2} \times 10^{-5}$  which modifies the relationship between the density parameter and deceleration parameter only slightly. However, the CMB changes the early history of the Universe in a profound way: Earlier than about 40,000 yrs the dynamics of the Universe are controlled by the energy density of the CMB (and a thermal bath of other relativistic particles) and not matter, with the temperature being the most important parameter for describing the events taking place.

Not only do we live in a very interesting Universe, but also fundamental physics is crucial to understanding its past, present and future. Figure 1, which summarizes the present make up of the Universe, makes the point well.<sup>3</sup> in units of the critical density CMB photons and relic relativistic neutrinos contribute about 0.01%; bright stars contribute about 0.5%; massive neutrinos contribute more than 0.3% (SuperK), but less than about 15% (structure formation); baryons (total) contribute  $4.5 \pm 0.5\%$ ; matter of all forms contributes  $35 \pm 7\%$ ; and dark energy contributes  $80 \pm 20\%$ . By matter I mean particles with negligible pressure (i.e., nonrelativistic, or in terms of a temperature,  $T \ll mc^2$ ); by dark energy I mean stuff with pressure whose magnitude is comparable to its energy density but negative.

While cosmology is much more than two numbers, the second of Sandage's two numbers is still very interesting and at the heart of much of what is most exciting today. Allowing for a Universe with more than just matter in it, the deceleration parameter becomes:

$$q_0 = \frac{\Omega_0}{2} + \frac{3}{2} \sum_i \Omega_i w_i \quad (1)$$

where  $\Omega_0 \equiv \sum_i \rho_i / \rho_{\text{CRIT}}$ ,  $\Omega_i$  is the fraction of critical density contributed by component  $i$  and  $p_i \equiv w_i \rho_i$  characterizes the pressure of component  $i$  (e.g., matter,  $w_i = 0$ , radiation,  $w_i = \frac{1}{3}$  and vacuum energy,  $w_i = -1$ ), and  $\rho_{\text{CRIT}} = 3H_0^2/8\pi G = 1.88h^2 \times 10^{-29} \text{ g cm}^{-3}$ . Note, the energy density in component  $i$  evolves as  $R^{-3(1+w)}$ :  $R^{-3}$  for matter,  $R^{-4}$  for radiation, and constant for vacuum energy.

## MATTER / ENERGY in the UNIVERSE

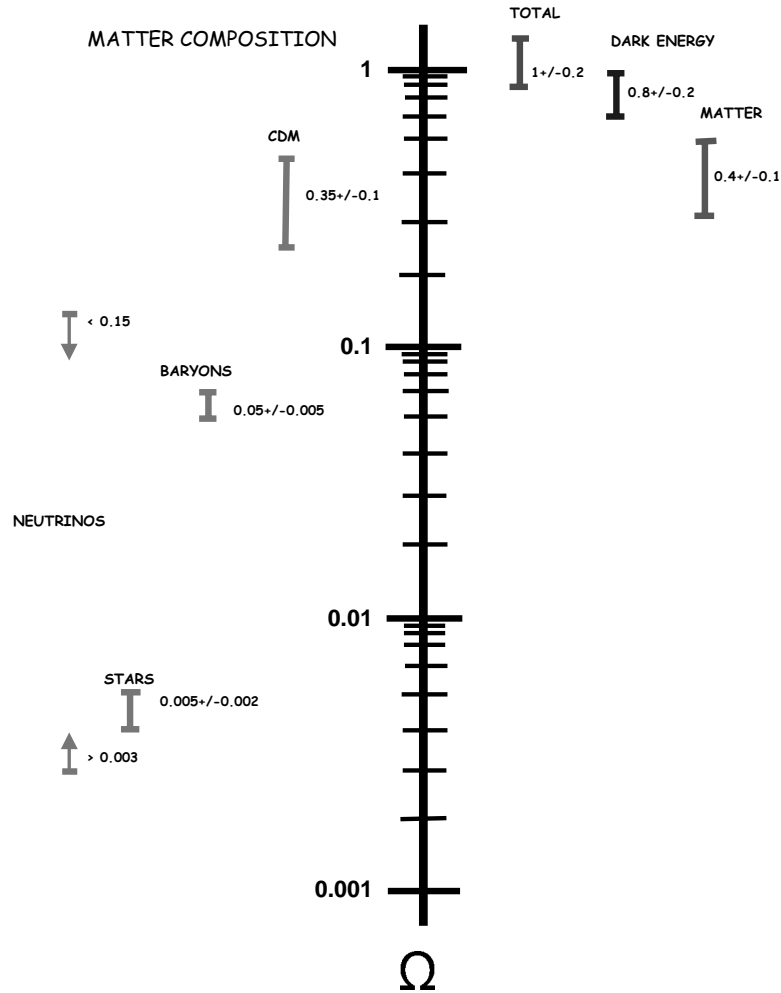


Figure 1: Summary of matter/energy in the Universe. The right side refers to an overall accounting of matter and energy; the left refers to the composition of the matter component. The contribution of relativistic particles, CBR photons and neutrinos,  $\Omega_{\text{rel}} h^2 = 4.170 \times 10^{-5}$ , is not shown. The upper limit to mass density contributed by neutrinos is based upon the failure of the hot dark matter model of structure formation, and the lower limit follows from the evidence for neutrino oscillations.  $H_0$  is taken to be  $65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

The density parameter  $\Omega_0$  determines the geometry of the Universe:

$$R_{\text{CURV}} = \frac{H_0^{-1}}{|\Omega_0 - 1|}, \quad (2)$$

but not necessarily its destiny. In particular, the simple connection between geometry and destiny mentioned earlier does not hold if there is a component to the energy density with  $w_i < -\frac{1}{3}$ .<sup>4</sup>

### 1.1 Dark matter past

The dark matter story begins with Zwicky in 1935. He observed that the velocities of galaxies within the great clusters of galaxies (e.g., Coma and Virgo) are too large for the gravity of the stars within the galaxies to hold the clusters together. In the 1970s Vera Rubin and others<sup>5</sup> measured galactic rotation curves (circular orbital velocity vs. radial distance from the galactic center) using stars and clouds of neutral hydrogen gas as test particles. The most conspicuous feature of these rotation curves is their flatness. According to Newtonian mechanics this implies an enclosed mass that rises linearly with galactocentric distance. However, the light falls off rapidly. Hence, the matter that holds ordinary spiral galaxies together must be “dark.”

In the early 1980s, a confluence of events spurred interest in the possibility that the dark matter is exotic (nonbaryonic). Those events included: the growing appreciation of the deep connections between particle physics and cosmology, a Russian experiment that indicated the electron neutrino had a mass of around 30 eV (the mass needed to close the Universe for  $h \sim 0.6$ ), and the growing case for gap between the dark matter density needed to hold the Universe together and what baryons can account for. While the Russian experiment proved to be wrong, the case for nonbaryonic dark matter grew and the inner space/outer space connection flourished.

### 1.2 Dark matter present

The case for nonbaryonic dark is now very solid and follows from the inequality,  $\Omega_M = 0.35 \pm 0.07 \gg \Omega_B = 0.0045 \pm 0.005$ . Briefly, here is where we stand. Big-bang nucleosynthesis provides the best accounting of the baryons. A precise determination of the primeval abundance of deuterium has allowed the baryon density to be very accurately pegged:  $\Omega_B = (0.019 \pm 0.001)h^{-2} \simeq 0.045 \pm 0.005$ .<sup>6</sup> From this follows the best determination of the total matter density.

The ratio of baryons to total mass in clusters has been determined from a sample of more than 40 clusters using x-ray and Sunyaev-Zel’dovich measurements:  $f = (0.075 \pm 0.002)h^{-3/2}$ .<sup>7</sup> (The fact that only about 15% of the

matter known to be in clusters can be accounted for as baryons is already strong evidence for nonbaryonic dark matter.) Making the assumption that clusters provide a fair sample of matter, a very reasonable assumption given their large size, one can equate  $f$  to  $\Omega_B/\Omega_M$  and use the BBN value for  $\Omega_B$  to infer:  $\Omega_M = 0.35 \pm 0.07$ .

There is plenty of supporting evidence for this value of the mean matter density.<sup>3</sup> It comes from studying the evolution of the abundance of clusters (with redshift), measurements of the power spectrum of large-scale structure, relating measured peculiar velocities to the observed distribution of matter, and observations of the outflow of material from voids. Further, every viable model for explaining the evolution of the observed structure in the Universe from density inhomogeneities of the size detected by COBE and other CMB anisotropy experiments requires nonbaryonic dark matter.

We have a very strong case that the bulk of the nonbaryonic dark matter is cold dark matter (slowly moving particles). This is based upon the many successes of the cold dark matter scenario for the formation of structure in the Universe, as well as the many failures of the hot dark matter scenario. We also have two very compelling – and highly testable – particle candidates: the axion and the neutralino.<sup>8</sup> A very light axion (mass  $\sim 10^{-6}$  eV –  $10^{-4}$  eV) is motivated by the use of Peccei-Quinn symmetry to solve the strong CP problem. A neutralino of mass 50 GeV to 500 GeV is motivated by low-energy supersymmetry.

On the experimental side, we now have the first evidence for the existence of particle dark matter. The SuperKamiokande Collaboration has presented a very strong case for neutrino oscillations based upon the direction dependent deficit of atmospheric muon neutrinos, which implies at least one of the neutrinos has a mass greater than about 0.1 eV.<sup>9</sup> This translates into a neutrino contribution to the critical density of greater than about 0.3% (about what stars contribute). *The issue is no longer the existence of particle dark matter, but the quantity of particle dark matter. An important threshold has been crossed.*

There are now experiments operating with sufficient sensitivity to directly detect particle dark matter in the halo of our own galaxy for the two most promising CDM candidates: axions and neutralinos.<sup>8</sup> The axion dark matter experiment at Livermore National Laboratory is slowly scanning the favored mass range; the DAMA experiment in Gran Sasso and the CDMS experiment in the Stanford Underground Facility (soon to be relocated in the Soudan Mine in Northern Minnesota) are now probing a part of neutralino parameter space that is favored by theory.

### 1.3 Baryonic dark matter and MACHOs

There are actually two dark-matter problems; the second being the discrepancy between the mass density contributed by bright stars (about 0.5% of the critical density) and the BBN-determined mass density of about 4.5% of the critical density. As this discussion will illustrate, a baryon inventory is much easier to do at 1 sec, when the baryons exist as a smooth soup of hadronic matter, than today, when they are dispersed in stars, stellar remnants, hot gas, cold gas, and so on.

At redshifts of around 3 to 4, most of the baryons were still in gas in the intergalactic medium (IGM). This is what numerical simulations of CDM say and what observations of the IGM at high redshift reveal. At this time, structure was just beginning to form and can be observed by studying the absorption of matter between us and distant quasars. The baryon accounting based upon these observations does indeed account for essentially all the baryons, though assumptions must be made and the uncertainties are not as small as at BBN.<sup>10</sup>

In clusters of galaxies today the accounting is complete: most of the baryons are in the hot, intracluster gas that glows in x-rays. The gas outweighs stars by about 10 to 1. However, only about 5% of galaxies are in the great clusters of galaxies, so this leaves the accounting very incomplete. Globally, only about 1/3 of the BBN baryon density can be accounted for, in the form of stars, cold gas, and warm gas within galaxies. The other 2/3 is *presumed* to be in hot intergalactic gas and/or warm gas associated with galaxies. One of the challenges for astrophysics is to complete the baryon accounting today by detecting this gas. Efforts will involve both x-ray and UV instruments looking for absorption or emission lines associated with the gas.

A dark horse possibility for the dark baryons is dark stars (low-mass objects that never lit their nuclear fuels or the end points of stellar evolution such as white dwarfs, neutron stars and black holes that have exhausted their nuclear fuels). Such objects in the halo of our own galaxy can be detected by microlensing. Microlensing of stars in the bulge of galaxy and in the Large and Small Magallenic Clouds by dark, foreground objects has been detected by the EROS, MACHO, DUO and OGLE groups. This is one of the exciting developments of the decade: These rare (one in a million or so stars is being lensed at any time) brightenings have provided a new probe of the dark side of the Universe. Already binary lenses, a black-hole candidate, planets and important information about the structure of the galaxy (strong evidence for a bar at the center) have been revealed, and one very intriguing mystery remains.

While the handful of events toward the SMC can be explained as “self

lensing,” foreground objects in the SMC lensing SMC stars, the more than twenty occurrences of microlensing of LMC stars are not so easily understood. Because the LMC is (thought to be) more compact, self lensing is less important. If one interprets the LMC lenses as a halo population of dark objects, they would account for about 50% of own halo. The mass inferred from the timescale of the brightenings (about  $0.5 M_{\odot}$ ) and the stringent limits to the number of main-sequence stars of this mass points to white dwarfs. (Recent HST observations give evidence for a handful of nearby, fast-moving white dwarfs, consistent with a halo population of white dwarfs.)

Beyond that, nothing else makes sense for this interpretation. Since white dwarf formation is very inefficient there should be 6 to 10 times as much gas left over as there are white dwarfs. This of course would exceed the total mass budget of the halo by a wide margin. The implied star formation rate exceeds the measured star formation rate in the Universe by more than an order of magnitude. And where are their siblings who are still on the main sequence?

Since microlensing only determines a line integral of the density of lenses toward the LMC, which is heavily weighed by the nearest 10 kpc or so, it gives little information about where the lenses are. Its limitations for probing the halo are significant: It cannot probe the halo at distances greater than the distance to the LMC (50 kpc), and as a practical matter it can only directly probe the innermost 15 kpc or so of the halo. Recall, the mass of the halo increases with radius and the halo extends at least as far as 200 kpc.

Alternative explanations for the LMC lenses have been suggested.<sup>11</sup> An unexpected component of the galaxy (e.g., a warped and flaring disk, a very thick disk component, a heavier than expected spheroid, or a piece of cannibalized satellite-galaxy between us and the LMC) which is comprised of conventional objects (white dwarfs or lower-main sequence stars); LMC self lensing (the LMC is being torn apart by the Milky Way and may be more extended than thought); or a halo comprised of  $0.5 M_{\odot}$  primordial black holes formed around the time of the quark/hadron transition (which also acts as the cold dark matter). For all but the last, very speculative explanation, the mass in lenses required is less than 10% of the halo.

Because the cold dark matter framework is so successful and a baryonic halo raises so many problems (in addition to those above, how to form large-scale structure), I am putting my money on a CDM halo. More data from microlensing is crucial to resolving this puzzle. The issue might also be settled by a dazzling discovery: direct detection of halo neutralinos or axions or the discovery of supersymmetry at the Tevatron or LHC.

## 2 Dark Energy

The discovery of accelerated expansion in 1998 by the two supernova teams (Supernova Cosmology Project and the High- $z$  Supernova Team) was the most well anticipated surprise of the century. It may also be one of the most important discoveries of the century. Instantly, it made even the most skeptical astronomers take inflation very seriously. As for the hard-core, true-believers like myself, it suffices to say that there was a lot of dancing in the streets.

### 2.1 Anticipation

In 1981 when Alan Guth put forth inflation most astronomers responded by saying it was an interesting idea, but that its prediction of a flat universe was at variance with cosmological fact. At that time astronomers argued that the astronomical evidence pointed toward  $\Omega_M \sim 0.05 - 0.10$  (even the existence of a gap between  $\Omega_B$  and  $\Omega_M$  was debatable). Inflationists took some comfort in the fact that the evidence was far from conclusive; it was largely based upon the mass-to-light ratios of galaxies and clusters of galaxies, and it did not sample sufficiently large volumes to reliably determine the mean density of matter. As techniques improved,  $\Omega_M$  rose. Especially encouraging (to inflationists) were the determinations of  $\Omega_M$  based upon peculiar velocity data (large-scale flows). They not only probed larger volumes and the mass more directly, but also by the early 1990s indicated that  $\Omega_M$  might well be as large as unity.

Even so, beginning in the mid 1980s, the Omega problem ( $\Omega_M \ll 1$ ) received much attention from theorists who emphasized that the inflationary prediction was a flat universe ( $\Omega_0 = 1$ ), and not  $\Omega_M = 1$  (though certainly the simplest possibility). A smooth, exotic component was suggested to close the gap between  $\Omega_M$  and 1 (smooth, so that it would not show up in the inventory of clustered mass). Possibilities discussed included a cosmological constant (vacuum energy), relativistic particles produced by the recent decay of a massive particle relic and a network of frustrated topological defects.<sup>12</sup>

By 1995 it seemed more and more unlikely that  $\Omega_M = 1$ ; especially damning was the determination of  $\Omega_M$  based upon the cluster baryon fraction discussed earlier. On the other hand, the CDM scenario was very successful, especially if  $\Omega_M h \sim 1/4$  (the shape of the power spectrum of density inhomogeneity today depends upon this product because it determines the epoch when the Universe becomes matter dominated). Add to that the tension between the age of the Universe and the Hubble constant, which is exacerbated for large values of  $\Omega_M$ .  $\Lambda$ CDM, the version of CDM with a cosmological constant ( $\Omega_M \sim 0.4$  and  $\Omega_\Lambda \sim 0.6$ ), was clearly the best fit CDM model (see Figure 2). And it has a smoking gun signature: accelerated expansion ( $q_0 = \frac{1}{2} - \frac{3}{2}\Omega_\Lambda$ ).



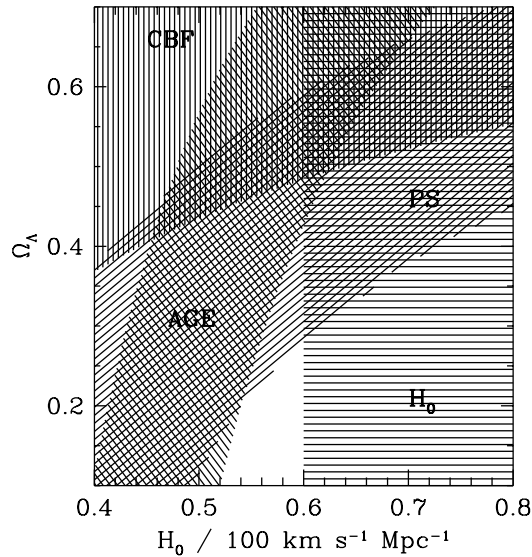


Figure 2: Constraints used to determine the best-fit CDM model: PS = large-scale structure + CBR anisotropy; AGE = age of the Universe; CBF = cluster-baryon fraction; and  $H_0$  = Hubble constant measurements. The best-fit model, indicated by the darkest region, has  $H_0 \simeq 60 - 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_\Lambda \simeq 0.55 - 0.65$ .

At the June 1996 Critical Dialogues in Cosmology meeting at Princeton, in the CDM beauty contest the only mark against  $\Lambda$ CDM was the early result from the Supernova Cosmology Project indicating that  $\Omega_\Lambda < 0.5$  (95%).<sup>14</sup>

After the Princeton meeting the case grew stronger as CMB anisotropy results began to define the first acoustic peak at around  $l = 200$ , as predicted in a flat Universe (the position of the first peak scales  $l = 200/\sqrt{\Omega_0}$ ). Today, the data imply  $\Omega_0 = 1 \pm 0.1$ <sup>13</sup> (see Figure 3). With results from the Boomerang Long-duration Balloon experiment expected in January, the DASI experiment at the South Pole next summer, and the launch of the MAP satellite in the Fall of 2000, we can expect a truly definitive determination of  $\Omega_0$  soon.

The smoking-gun confirmation came in early 1998 with the results from the two supernova groups indicating that the Universe is speeding up, not slowing down. Everything now fit together: inflation and the flat universe, the CMB determination that  $\Omega_0 \sim 1$  and the cluster measurement of  $\Omega_M \sim 0.4$ , and the successes of CDM, and  $\Lambda$ CDM in particular (see Figures 2-4). In the minds of theorists like me, the only surprise was that it took the cosmological constant to make everything work. Everything was pointing in that direction,

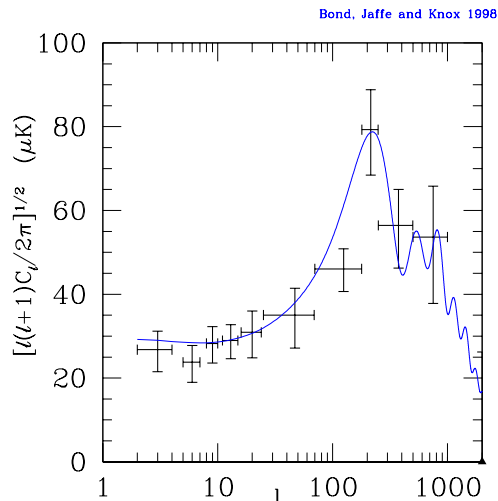


Figure 3: Summary of CMB anisotropy measurements, binned to reduce error bars. The theoretical curve is for the  $\Lambda$ CDM model with  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_M = 0.4$  (Figure courtesy of L. Knox).

and were it not to the checkered history of the cosmological constant, there would have been no surprise at all.

## 2.2 The dark-energy problem

At the moment, a crucial element in the case for accelerated expansion and dark energy is the “independent confirmation” based upon the otherwise discrepant numbers  $\Omega_0 \sim 1$  and  $\Omega_M \sim 0.4$ . Balancing the books requires a component that is smooth and contributes about 60% of the critical density. In order that it not interfere with the growth of structure, its energy density must evolve more slowly than matter so that there is a long matter-dominated era during which the observed structure today can grow from the density inhomogeneities measured by COBE and other CMB anisotropy experiments. Since  $\rho_X \propto R^{-3(1+w_X)}$ , this places an upper limit to  $w_X$ :<sup>15</sup>  $w_X < -\frac{1}{2}$ , and in turn, an upper limit to  $q_0$ :  $q_0 < \frac{1}{2} - \frac{3}{4}\Omega_X < 0$  for  $\Omega_X > \frac{2}{3}$  and a flat Universe.

Because of the checkered history of the cosmological constant – cosmologists are quick to invoke it to solve problems that later disappear and particle physicists have failed to compute it to an accuracy of better than a factor of  $10^{55}$  – there is an understandable reluctance to accept it without some skep-

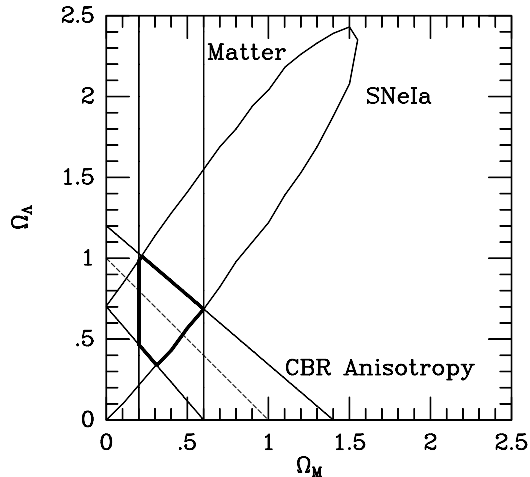


Figure 4: Two- $\sigma$  constraints to  $\Omega_M$  and  $\Omega_\Lambda$  from CBR anisotropy, SNe Ia, and measurements of clustered matter. Lines of constant  $\Omega_0$  are diagonal, with a flat Universe indicated by the broken line. The concordance region is shown in bold:  $\Omega_M \sim 1/3$ ,  $\Omega_\Lambda \sim 2/3$ , and  $\Omega_0 \sim 1$ .

ticism. To wit, other possibilities have been suggested: For example, a rolling scalar field (essentially a mini-episode of inflation),<sup>16</sup> or a frustrated network of very light topological defects (strings of walls).<sup>17</sup>

My preference is to characterize it as simply and most generally as possible, by its equation of state:  $p_X = w_X \rho_X$ , where  $w_X$  is  $-1$  for vacuum energy,  $-\frac{N}{3}$  for frustrated topological defects of dimension  $N$ , and time-varying and between  $-1$  and  $1$  for a rolling scalar field. The goal then is to determine  $w_X$  and test for its time variation.<sup>18</sup>

In determining the nature of dark energy, I believe that telescopes and not accelerators will play the leading role – even if there is a particle associated with it, it is likely to be extremely difficult to produce at an accelerator because of its gravitational or weaker interactions with ordinary matter. Specifically, I believe that type Ia supernovae will prove to be the most powerful probe. The reason is two fold: first, the dark energy has only recently come to be important; the ratio  $\rho_M/\rho_X = (\Omega_M/\Omega_X)(1+z)^{-3w_X}$  grows rapidly with redshift. Secondly, dark energy does not clump (or at least not significantly), so its presence can only be felt through its effects on the large-scale dynamics of the Universe. Type Ia supernovae have the potential of reconstructing the recent history of the evolution of the scale factor of the Universe and from it, to shed light on the nature of the dark energy. Figures 5 and 6 show the simulated

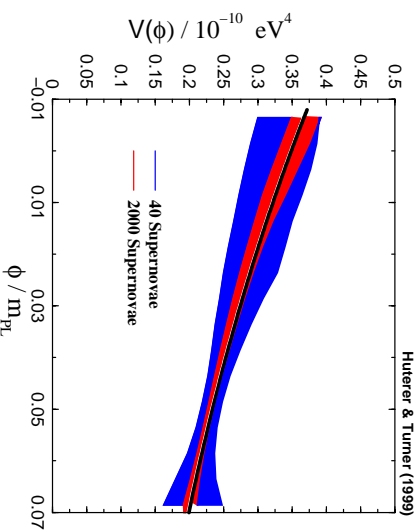


Figure 5: The 95% confidence bands for the simulated reconstruction of the scalar-field potential for a quintessence model; the solid curve is the original potential.

reconstruction of two dark-energy models: a quintessence model (scalar field rolling down a potential) by means of supernovae and a variable equation of state.

Once one is convinced with high confidence that there is dark energy out there (the next round of CMB anisotropy results will be crucial) and that type Ia supernovae are standardizable candles (more study of nearby supernovae), the next step is a dedicated assault, probably a satellite based telescope (which I like to call Dark-Energy eXplorer or D-REX) to collect 1000s of supernovae between redshift 0 and 1. By carefully culling the sample and doing good follow up and accurate photometry one will be able to address determine  $\Omega_X$ ,  $w_X$  and address the time variation of  $w_X$ .<sup>19</sup>

### 3 Looking Forward

The two dominant ideas in cosmology over the past 15 years have been inflation and cold dark matter. They have provided the field with a grand guiding paradigm which has spurred the observers and experimenters to put in place a remarkable program that keep the field of cosmology lively for at least two decades.

Over the past few years this paradigm has begun to be tested in a significant way, with many more important tests to come. The first tests have been encouraging. The first acoustic peak in the CMB power spectrum indicates a flat Universe and is consistent with the scale-invariant inflationary power spec-

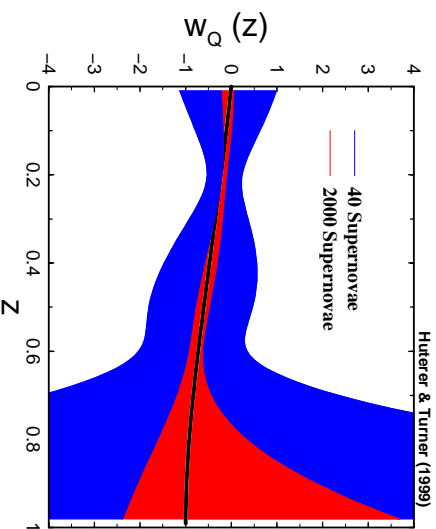


Figure 6: The 95% confidence bands for the simulated reconstruction of the equation of state,  $w(z)$ ; the solid curve is the input equation of state. Note, because dark energy becomes less important (relative to matter) at high redshift, it becomes more difficult to probe its properties.

trum which predicts a series of acoustic peaks. The discovery of accelerated expansion provided the evidence for the component that balanced the books: our flat universe = 40% dark matter + 60% dark energy. This is only the beginning of this great adventure.

Central to cosmology and the connection between cosmology and fundamental physics are the two dark problems: dark matter and dark energy. The dark matter problem is more than sixty years old and quick mature. We have divided the dark matter problem into two distinct problems, dark baryons and nonbaryonic dark matter, and narrowed the possibilities for each. The baryons are most likely in the form of diffuse, hot gas. The nonbaryonic dark matter is most likely slowly moving, essentially noninteracting particles (cold dark matter), with relic elementary particles from the earliest moments being the leading candidate. Foremost among them are the axion and neutralino.

We could still be in for some surprises: the CDM particles could be something more exotic (primordial black holes or superheavy particles produced in the reheating process at the end of inflation). Likewise, the simple and thus far very successful assumption that the only interactions of the CDM particles that are relevant today are gravitational, could be wrong. There are some hints otherwise: The halo profiles predicted for noninteracting CDM are too cuspy at the center.<sup>20</sup> The resolution could be astrophysical or it could involve fundamental physics. Perhaps, it is indicating that the CDM particles have

significant interactions today (scattering or annihilations) that round off the central cusps. It is intriguing to note that neither the axion nor the neutralino has such interactions.

By comparison, the dark-energy problem is in its infancy. The evidence for it, while solid, is not air tight. Unlike the dark-matter problem where sixty years of detective work have brought us to a couple of very specific suspects, the possibilities for the dark energy are wide open. But two things are clear: as with the dark-matter problem, the solution certainly involves fundamental physics, and telescopes will play a major role in clarifying the nature of the dark energy.

### Acknowledgments

This work was supported by the DoE (at Chicago and Fermilab) and by the NASA (through grant NAG 5-7092 at Fermilab).

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