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Physics Reports 333–334 (2000) 619–635

PHYSICS REPORTS

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The dark side of the universe: from Zwicky to accelerated expansion

Michael S. Turner[a,b,*]

[a]*Departments of Astronomy & Astrophysics and of Physics, Enrico Fermi Institute, The University of Chicago, 5640 So. Ellis Avenue, Chicago, IL 60637-1433, USA*

[b]*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Box 500, Batavia, IL 60510-0500, USA*

Abstract

More than 60 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 $4.5 \pm 1\%$ 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 SuperKamiokande detection of neutrino oscillations shows that particle dark matter, in the form of massive neutrinos, actually exists and accounts for as much mass as bright stars. *An important threshold has been crossed*; *particle dark matter is no longer hypothetical.* Over the past few years a case has developed for dark energy. This dark, relativistic 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 matter and energy together account for the critical density (within 10%). 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). Dark matter and dark energy are central issues in both cosmology and particle physics. Over the next two decades a flood of precision cosmological observations and laboratory experiments will shed light on the dark side of the universe. As they do they will advance our understanding of both the universe and the laws of physics that govern it. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 9.80.Cq; 95.30.Cq; 98.80. −k

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[*] Correspondence address: Departments of Astronomy & Astrophysics and of Physics, Enrico Fermi Institute, The University of Chicago, 5640 So. Ellis Avenue, Chicago, IL 60637-1433, USA.

E-mail address: mturner@oddjob.uchicago.edu (M.S. Turner).

PII: S0370-1573(00)00040-5

1. David Schramm and cosmology

I divide cosmology in the 20th century into three eras: discovery of the big bang; establishing the standard cosmology; and inner space/outer space. The first era began with Einstein's introduction of general relativity and Hubble's discovery of the expansion of the universe. It ended with the triumph of the big-bang theory over the steady-state theory in the early 1960s.

The discovery of the cosmic microwave background (CMB) in 1964 began the second era. The successful prediction of the light-element abundances by big-bang nucleosynthesis (BBN), the development of the gravitational instability picture of structure formation, and the black-body spectrum of the CMB led to the emergence of the hot big-bang model as the standard cosmology in the late 1970s.

The inner space/outer space era began in the early 1980s with the realization that the standard cosmology left important questions unanswered (origin of the asymmetry between matter and antimatter, nature of the dark matter, and origin of the large-scale isotropy and homogeneity and small-scale inhomogeneity) which might be explained by events that took place during the earliest moments when the universe was a hot soup of elementary particles. The success of gauge theories (standard model of particle physics and grand unified theories) and their direct applicability to the hot plasma that existed during the earliest moments allowed easy and well motivated speculation about the events of the earliest moments. From these speculations came baryogenesis, particle dark matter, cosmological phase transitions, and inflation. Inflation, coupled with baryogenesis and particle dark matter, became the dominant theoretical idea in cosmology, defining the direction of the field for the past 20 years.

David Schramm played key roles both in establishing the standard cosmology and in pioneering the connections between elementary particle physics and cosmology that are central to the inner space/outer space era. David's work on big-bang nucleosynthesis with his students, postdocs and other collaborators (sometimes known as the Chicago Mafia) honed BBN into the precise test of the hot big-bang cosmology that it is today. Big-bang nucleosynthesis is earliest probe of the standard cosmology and tests validity a fraction of a second after the big-bang beginning.

BBN is the gateway to the early universe and helped to jump start the inner space/outer space connection. The BBN limit to the number of light neutrino species served as an example of the power of cosmology to probe particle physics. In 1977 when Steigman et al. [1] published their first limit, $N_\nu < 7$, the laboratory limit to N_ν (based upon Kaon decays) was around 5000! The BBN limit proved to be a very significant constraint in constructing grand unified theories and caught the attention of particle physicists who could understand and appreciate the solid, underlying physics. The laboratory verification of the BBN neutrino bound by experiments at SLAC and CERN in 1989 remains today as one of the triumphs of inner space/outer space.

Just as important, and even more relevant for this article, is the BBN concordance range for the baryon density. For almost two decades it stood at: $0.01 < \Omega_B < 0.1$. Within this interval, the predicted light-element abundances are consistent with their inferred primordial abundances. The upper limit to baryon density is based upon the big-bang production of deuterium and a simple, but powerful argument due to Schramm [2]: in the contemporary universe deuterium is destroyed and hence the big bang must produce at least what is seen today. The lower limit is based upon another Schramm argument: the sum of D + ^{3}He has not changed significantly by astrophysical processes.

These limits to the baryon density established two dark-matter problems: since the fraction of critical density contributed by stars is less than 1%, the lower limit to the baryon density implies that most of the baryons are (optically) dark. The upper limit to the baryon density is less than dynamical measurements of total mass density, making it the linchpin in the case for nonbaryonic dark matter. David was one of the early advocates of particle dark matter, especially neutrinos, and his influential essay, *A neutrino-dominated universe*, won the Gravitational Research Foundation's Essay Competition in 1980.

Dark matter has been and continues to be one of the most important and pervasive themes in the inner space/outer space era. It illustrates the boldness of the enterprise: not only are we not at the center of the universe, we are not made of the primary stuff of the cosmos!

Beyond his scientific contributions David played a critical role as senior spokesman, advocate and spiritual leader for inner space/outer space. He mentored students, postdocs, and young faculty, both at Chicago and around the world. He pressed for recognition for this new discipline from the astronomy and physics establishments as well as the funding agencies. He lobbied astronomers to take seriously the predictions that came from the study of the early universe, and with equal vigor he urged the new cosmologists to make testable predictions. In fact, he invented a new intellectual razor for cosmology: given two new ideas of equal attractiveness, pursue the one that is more testable – Schramm's razor.

David died just as the Golden Age in Cosmology that he prophesied and helped to make possible became reality. Just months before his death, David saw the primeval deuterium abundance determined by David Tytler and Scott Burles, and with it, his dream to use deuterium as a "baryometer" to determine the baryon density to high precision. David's last paper talked about the precision era of BBN this measurement ushered in [3]. Three weeks after his death Saul Perlmutter's group made their startling announcement: the universe is speeding up, not slowing down. With it came the first complete accounting of matter and energy in the universe, the first strong evidence for inflation, and a new puzzle, the nature of the mysterious dark energy that is causing the universe to accelerate. I can picture David's child-like excitement over this discovery, had he lived to hear about it.

David was scheduled to debate P.J.E. Peebles in April 1998 (Great Debate III in Washington, DC) on the value of Ω_0; he was to argue for a flat universe ($\Omega_0 = 1$). He was worried, and had good reason to be. Even some diehard inflationists were starting to talk about an open universe. In the Fall of 1997, on an almost daily basis, David would come into my office to ask if there any new results he could use to defend a flat universe. He was especially anxious to hear the results from Perlmutter's group for their sample of 42 supernovae; their early results based upon the first seven SNe Ia indicated $\Omega_M \sim 1 \pm 0.5$, one of the few measurements that supported a flat universe.

Little did David know how much would transpire by April 1998, when the issue would no longer be deemed worthy of a great debate. By then, the position of the Doppler peak in the CMB power spectrum indicated $\Omega_0 = 1$; the BBN value for Ω_B together with the cluster baryon fraction put Ω_M at $\frac{1}{3}$; and the acceleration of the expansion (seen by both Perlmutter's group and Kirshner's group) implied the existence of a dark-energy component that contributes $\frac{2}{3}$'s of the critical density. Every school child knows that $\frac{1}{3} + \frac{2}{3} = 1$! When the debate, dedicated to David's memory, did take place in October 1998 with me filling in for him, the question was changed to cosmology solved?, reflecting the rapid turn of events.

Six months after David's death, SuperKamiokande announced their evidence for neutrino oscillation and mass, based upon the zenith angle dependence of the ratio of muon to electron atmospheric neutrinos. Particle dark matter was no longer speculation; it was fact. It is fitting that the first particle dark matter discovered was David's beloved hot dark matter. I am certain that the fact that hot dark matter turned out to be just a spice in the cosmic mix would not have bothered David in the least.

This mini review of the dark side of the universe is close to what David could have presented at Great Debate III, and I dedicate it to his memory.

2. Not simple, but interesting

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 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 linked: $q_0 = \Omega_0/2$. There is a consensus that we are finally closing in on the expansion rate: $H_0 = 65 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (or $h = 0.65 \pm 0.05$) [4]. Type Ia supernovae seem to have provided the first reliable measurement of the deceleration parameter [5] – and a surprise: the universe is accelerating not decelerating. So much for a simple universe.

Actually, we have known for 30 years that 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. Today the CMB is a minor component of the energy density, $\Omega_{\mathrm{CMB}} = 2.48h^{-2} \times 10^{-5}$, and modifies the relationship between the density parameter and deceleration parameter only slightly. But, the CMB changes the early history of the universe in a most profound way: earlier than about 40,000 yr 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. Because inhomogeneities in the matter cannot grow when the universe is radiation dominated, the growth of structure is postponed until the universe becomes matter dominated, some 40,000 yr after the beginning.

Not only do we live in a very interesting universe, but fundamental physics is crucial to understanding its past, present and future. Fig. 1, which summarizes the present make up of the universe, makes the point well [6]: 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 $4.5 \pm 1\%$; 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 its temperature, $T \ll mc^2$); by dark energy I mean stuff with pressure whose magnitude is comparable to its energy density but negative.

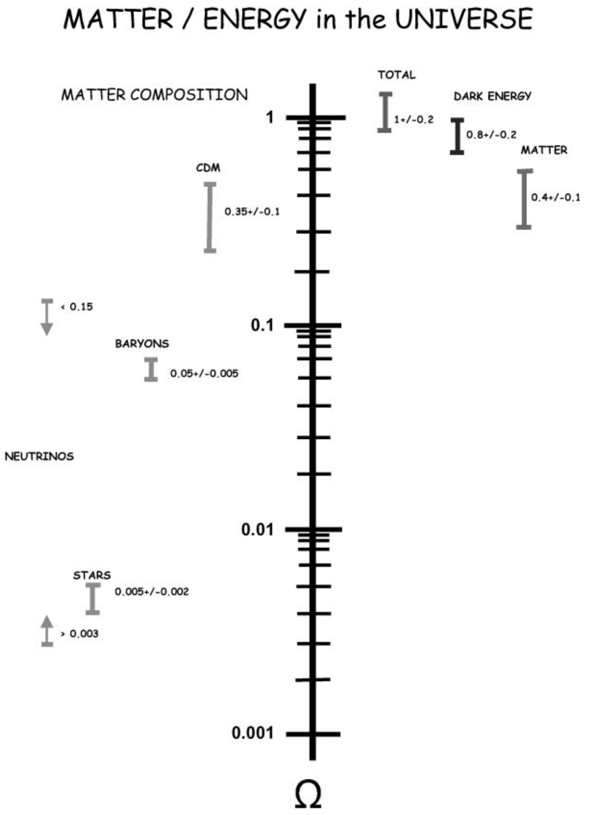


Fig. 1. Summary of matter/energy in the universe. The right-hand side refers to an overall accounting of matter and energy; the left refers to the composition of the matter component. The contribution of relativistic particles, CMB photons and neutrinos, $\Omega_{\rm rel}h^2 = 4.170 \times 10^{-5}$, is not shown. The upper limit to mass density contributed by neutrinos is based upon the failure of the hot dark matter model to account for the structure that exists in the universe today; the lower limit follows from the evidence for neutrino oscillations from the SuperKamiokande experiment; where necessary, H_0 is taken to be $65\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

While cosmology today 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 is given by

$$q_0 = \frac{\Omega_0}{2} + \frac{3}{2}\sum_i \Omega_i w_i \ , \tag{1}$$

where $\Omega_0 \equiv \sum_i \rho_i/\rho_{\rm CRIT}$, Ω_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 $\rho_{\rm CRIT} = 3H_0^2/8\pi G = 1.88h^2 \times 10^{-29}\,{\rm g\,cm^{-3}}$. 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.

Even if the universe is not simple, the density parameter Ω_0 still determines the geometry of the universe: the curvature radius:

$$R_{\mathrm{CURV}} = H_0^{-1}/\sqrt{|\Omega_0 - 1|}\ , \tag{2}$$

where $\Omega_0 = 1$ corresponds to flat spatial geometry, $\Omega_0 < 1$ to open geometry, and $\Omega_0 > 1$ to closed geometry. However, Ω_0 does not necessarily determine 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 $w_i < -\frac{1}{3}$: for example, a flat universe with negative vacuum energy can recollapse, and a closed universe with positive vacuum energy can expand forever [7].

3. Dark matter

3.1. The dark 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 [8] 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 (see Fig. 2). According to Newtonian

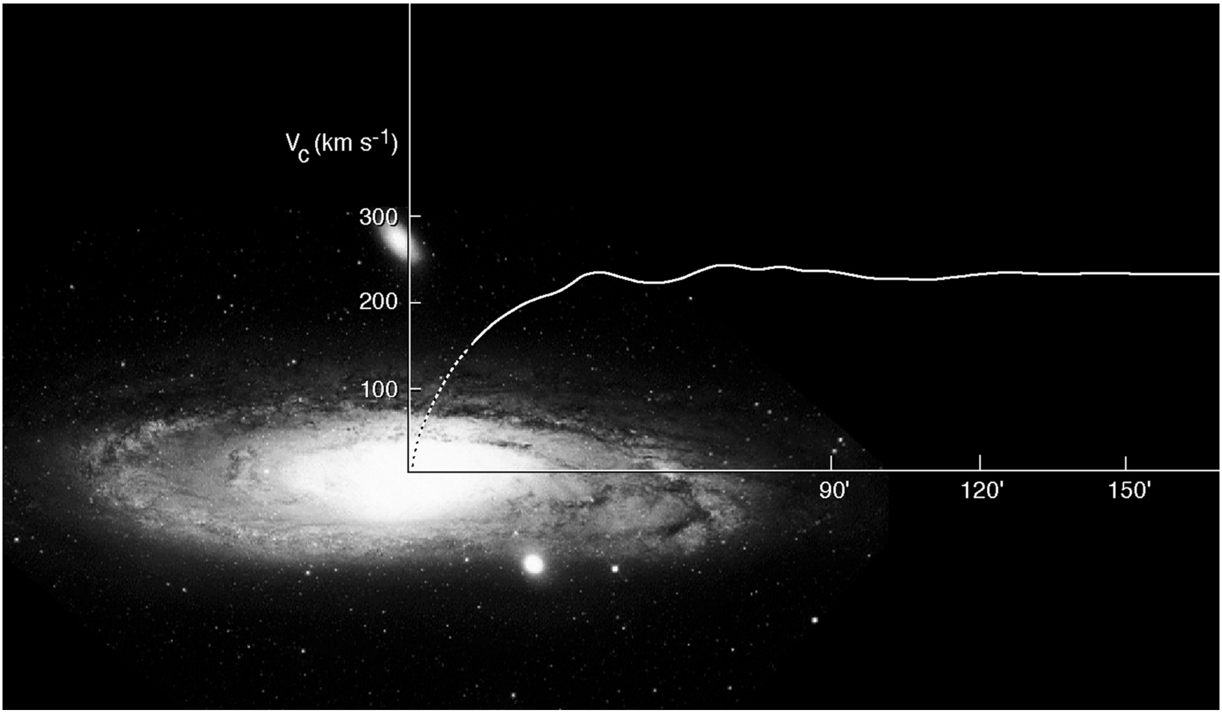


Fig. 2. Image of the Andromeda galaxy (M31) with rotation curve superimposed (courtesy of M. Roberts).

mechanics this implies an enclosed mass that rises linearly with galactocentric distance. However, the light falls off more 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 gap between the amount of dark matter needed to hold the universe together and what baryons can account for. While the experiment proved to be wrong, the case for nonbaryonic dark matter has been growing ever since.

David Schramm was one of the first advocates for particle dark matter. In his prize-winning essay in 1980, he made the case for a neutrino-dominated universe [9]. Although a few months before he died he was won over to cold dark matter, David was a long-time advocate of hot dark matter, through good times and bad. It seems fitting that the first evidence for particle dark matter came with massive neutrinos.

3.2. Dark matter present

The case today for nonbaryonic dark is very solid and follows from the inequality

$$\Omega_M = 0.35 \pm 0.07 \gg \Omega_B = 0.045 \pm 0.01 \ . \tag{3}$$

I will now briefly describe how firmly we stand on both sides of the inequality.

David Schramm was one of the first to realize the importance of the three light elements made in much smaller amounts during BBN, D, ^{3}He and ^{7}Li. As he put it, ^{4}He is the go/no-go element; the other elements have more probative power. In particular, he realized that deuterium was the "baryometer" because its production is very dependent upon the baryon density and its post big-bang evolution is so simple (astrophysical processes are always net destroyers of deuterium [2]).

Big-bang nucleosynthesis provides the best accounting of the baryons because the universe was simpler at an age of 1 s than it is now. Today, baryons are found in bright stars, dark stars, dust grains, hot gas, warm gas and cold gas. An accounting nightmare! For more than a decade the four light elements made in the big bang defined a concordance region for the baryon density, where the predicted and measured abundances of all four light elements were consistent, $0.007 < \Omega_B h^2 < 0.022$ [10]. While the range for Ω_B was about a factor of 10 when the Hubble constant uncertainty was a factor of two, the BBN determination still stood as the best measure of the baryon density for two decades.

When Tytler and Burles determined the primeval deuterium abundance in 1998 [11], the situation changed dramatically and David's dream was realized (see Fig. 3). Their 10% deuterium measurement pegged the baryon density very precisely: $\Omega_B = (0.019 \pm 0.001)h^{-2} \simeq 0.045 \pm 0.01$ [12]. The factor of 10 concordance interval became a 5% measurement (about 20% for Ω_B when the present Hubble constant uncertainty is included).

Moreover, the BBN baryon density and a clever accounting argument allows the total matter density to be accurately determined. The ratio of baryons to total mass in clusters has been determined from a sample of 45 clusters using X-ray measurements [13] and from a sample of more

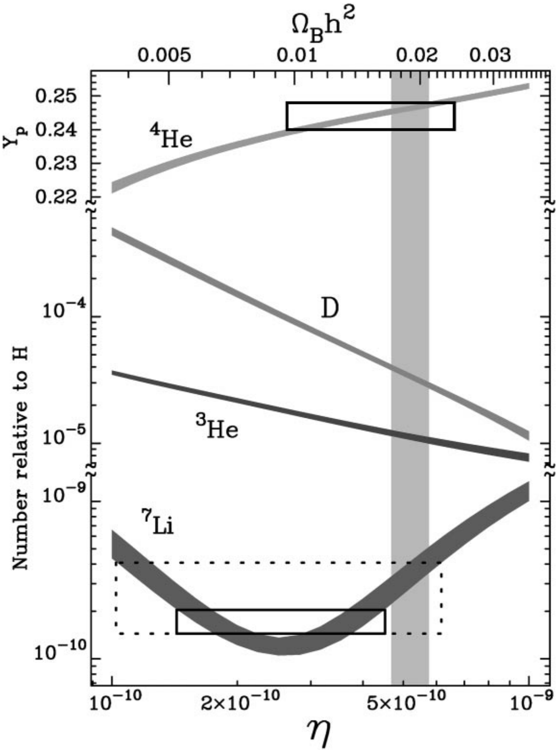


Fig. 3. Predicted light-element abundances as a function of the baryon-to-photon ratio η (the mean baryon density $\rho_B = 3.76\times10^{-31}\,(\Omega_B h^2/0.02)\,\mathrm{g\,cm^{-3}}$). Vertical band indicates the baryon density indicated by the primeval deuterium abundance; boxes show baryon densities consistent with measurements of the primordial abundances of ^{4}He and ^{7}Li (all at 95%). Broken box for ^{7}Li allows for a factor of two depletion in old pop II stars.

than 20 clusters using Sunyaev–Zel'dovich measurements [14]:

$$f = (0.075 \pm 0.002)h^{-3/2} \quad \text{(X-ray)}, \qquad (0.079 \pm 0.01)h^{-1} \quad \text{(S–Z)}\,.$$

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 in the universe, a very reasonable assumption given their large size, one can equate f to Ω_B/Ω_M and use the BBN value for Ω_B to infer

$$\begin{aligned}\Omega_M &= (0.25 \pm 0.02)h^{-1/2} \quad \text{(X-ray)}, \qquad (0.24 \pm 0.03)h^{-1} \quad \text{(S–Z)}\\ &= 0.35 \pm 0.07 \quad \text{(my conservative error bar)}\,. \qquad (4)\end{aligned}$$

There is plenty of supporting evidence for this value of the mean matter density [6]. 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.

The cluster sampling argument is a strong one: only the US Congress does not acknowledge the accuracy of scientific sampling. However, because clusters only account for around 5% of the matter in the universe, it begs the question as to where all the dark matter is. Very significant progress has been made toward answering this question recently. Using Sloan Digital Sky Survey data of the weak-gravitational lensing of distant galaxies by the halos of closer foreground galaxies, the size and mass of the halos of typical galaxies has been revised upward by a factor of several [15]. This brings the estimated mass associated with bright galaxies close to the 35% of critical density inferred from the cluster baryon fraction method. The Sloan result also changes dramatically our view of the universe: halos are so large that they overlap; the universe is a web of dark matter decorated by luminous matter.

3.3. Cold dark matter

As described above, we have a very strong case that the bulk of the dark matter is nonbaryonic. 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 can infer that the bulk of the nonbaryonic dark matter is cold (slowly moving particles) and for essentially all purposes today only interacts gravitationally with itself and the baryons. [In a sentence, observations show that structure formed from the bottom up (galaxies first, followed by clusters and superclusters) as predicted by CDM and not top down as predicted by hot dark matter (fast moving particles like neutrinos).]

We also have two very compelling – and highly testable – particle candidates: the axion and the neutralino [16]. A very light axion (mass $\sim 10^{-6}$–10^{-4} eV) is motivated by the use of Peccei–Quinn symmetry to solve the strong CP problem. A neutralino of mass 50–500 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. Their results implies at least one of the neutrinos has a mass greater than about 0.1 eV [17]. This translates into a neutrino contribution to the critical density of greater than about 0.3% (about what stars contribute). *An important threshold has been crossed*: *The issue is no longer the existence of particle dark matter, but the quantity of particle dark matter.*

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 [16]. 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.

3.4. Baryonic dark matter

There is a second dark-matter problem: the factor of ten discrepancy between the mass density contributed by bright stars, $\Omega_{\mathrm{LUM}} = (0.003 \pm 0.001)h^{-1} \simeq 0.5\%$, and the BBN-determined baryon density (about 4.5% of the critical density). As this discussion will illustrate, a baryon inventory is much easier to do at 1 s, when the baryons existed 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 3–4, most of the baryons were still in a gaseous state 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 by 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 for BBN [18].

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 overall accounting incomplete. Globally, about $\frac{1}{3}$ of the BBN baryon density can be accounted for as stars, cold gas, and warm gas within galaxies [19]. The other $\frac{2}{3}$ 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.

3.5. MACHOS ?

A dark horse possibility for the dark baryons is dark stars (low-mass objects that never ignited 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 gravitational microlensing. Microlensing of stars in the bulge of galaxy and in the large and small magellanic 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 past decade: these rare (one in a million or so stars is being lensed at any time) brightenings provide 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 (e.g., strong evidence for a bar at the center) have been revealed. 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 20 or so occurrences of microlensing of LMC stars are not so easily explained. 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 20% of own halo. The lens mass inferred from the timescale of the brightenings (about $0.5M_{\odot}$) 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 [20].

Beyond that, nothing else makes sense for the halo MACHO interpretation! Since white dwarf formation is very inefficient there should be 6–10 times as much gas left over as there are white dwarfs (a point made in one of the last papers David Schramm authored [21].) 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 farther than 200 kpc.

Alternative explanations for the LMC lenses have been suggested [22]: 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 $0.5M_\odot$ 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 a tiny fraction 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 in a baryons only universe), I am putting my money on a CDM halo and a surprise about the structure of the galaxy. 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.

4. Dark energy

The discovery of accelerated expansion in 1998 by the two supernova teams (Supernova Cosmology Project and the High-z Supernova Search Team) may have been the most well anticipated surprise of the century. It is certainly 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. Moreover, it has presented us with a puzzle that is at least as exciting as dark matter and is also tied to fundamental physics.

4.1. 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 $\Omega_M \sim 0.10$ (even the existence of a gap between Ω_B and Ω_M was debatable). It is interesting to note that the most comprehensive analysis at around this time was the very influential 1974 paper of Gott et al. [23], which pointed to an ever expanding universe with $\Omega_B \sim \Omega_0 \sim 1$. David would soon change his views on both accounts!

Inflationists took some comfort in the fact that the evidence for an open universe 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, Ω_M rose. Especially encouraging (to inflationists) were the determinations of Ω_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 Ω_M might well be as large as unity [24].

Even so, beginning in the mid 1980s, "the Omega problem" ($\Omega_M < 1$) 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 Ω_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 [25].

By 1995 it seemed more and more unlikely that $\Omega_M = 1$; especially damning was the determination of Ω_M based upon the cluster baryon fraction discussed earlier [26]. On the other hand, the CDM scenario was very successful, especially if $\Omega_M h \sim \frac{1}{4}$ (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 Ω_M. ΛCDM, the version of CDM with

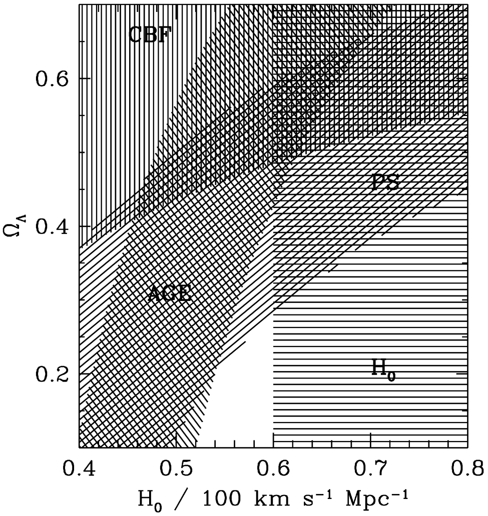


Fig. 4. Constraints used to determine the best-fit CDM model: PS = large-scale structure + CBR anisotropy; AGE = age of the universe; CBF = cluster-baryon fraction; and H_0 = Hubble constant measurements. The best-fit model, indicated by the darkest region, has $H_0 \simeq 60$–65 km s^{-1} Mpc^{-1} and $\Omega_\Lambda \simeq 0.55$–0.65.

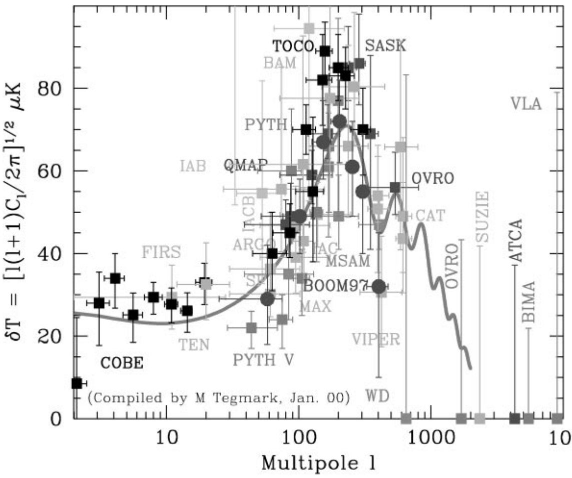


Fig. 5. Summary of all CMB anisotropy measurements. WOW! The theoretical curve is for the ΛCDM model with $H_0 = 65$ km s^{-1} Mpc^{-1} and $\Omega_M = 0.4$ (figure courtesy of M. Tegmark).

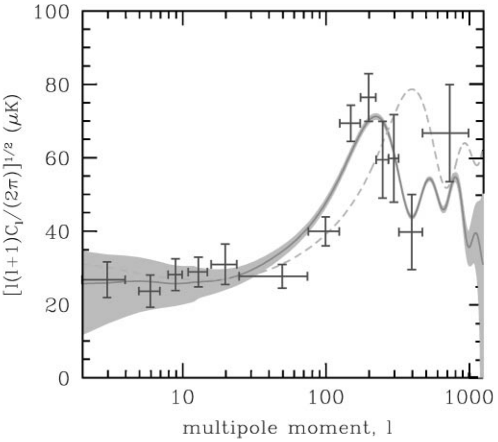
a cosmological constant ($\Omega_M \sim 0.4$ and $\Omega_\Lambda \sim 0.6$), was clearly the best-fit CDM model (see Fig. 4). And it has a smoking gun signature: accelerated expansion ($q_0 = \frac{1}{2} - \frac{3}{2}\Omega_\Lambda \approx -\frac{1}{2}$). At the June 1996 Critical Dialogues in Cosmology meeting at Princeton [27], in the CDM beauty contest the only mark against ΛCDM was the early result from the Supernova Cosmology Project indicating that $\Omega_\Lambda < 0.5$ (95%) [28].

After the Princeton meeting the case for ΛCDM grew stronger. 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 as $l \sim 200/\sqrt{\Omega_0}$). Today, the data imply $\Omega_0 = 1 \pm 0.1$ [29] (see Figs. 5 and 6). With results from the Boomerang long-duration balloon experiment expected soon, 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 definitive determination of Ω_0 before long.

The smoking-gun confirmation of ΛCDM came in early 1998 with the results from the two supernova groups indicating that the universe is speeding up, not slowing down ($q_0 < 0$). Everything now fit together: inflation and the flat universe; the CMB evidence for $\Omega_0 \sim 1$ and the cluster baryon fraction argument indicating $\Omega_M \sim 0.4$, and the successes of ΛCDM (see Figs. 4–7). In the minds of theorists like myself, the only surprise was that it took the cosmological constant to make everything work. Everything was pointing in that direction, and were it not to the checkered history of the cosmological constant, there would have been no surprise at all.

4.2. 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 $\Omega_M \sim 0.4$.



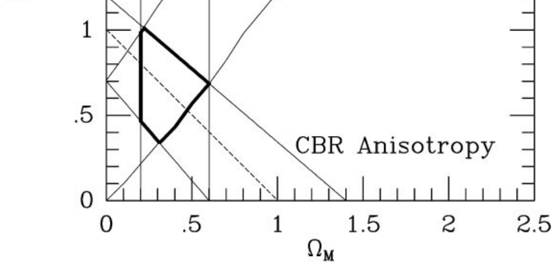


Fig. 6. Summary of CMB anisotropy measurements, binned to reduce error bars. The theoretical curves are for the ΛCDM model with $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (solid) and $\Omega_M = 0.3$ (broken). The width of the ΛCDM curve indicates the error bars expected from MAP (with multipoles summed in 10% logarithmic bins) (figure courtesy of L. Knox).

Fig. 7. Two-σ constraints to Ω_M and Ω_Λ from CBR anisotropy, SNe Ia, and measurements of clustered matter. Lines of constant Ω_0 are diagonal, with a flat universe indicated by the broken line. The concordance region is shown in bold: $\Omega_M \sim \frac{1}{3}$, $\Omega_\Lambda \sim \frac{2}{3}$, and $\Omega_0 \sim 1$.

Balancing the energy 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 $\rho_{\rm M}/\rho_X \propto R^{3w_X}$, this places an upper limit to w_X [30]: $w_X < -\frac{1}{2}$, 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.

The energy of the quantum vacuum (the modern description of the cosmological constant) has $w \equiv p/\rho = -1$. Perfect! However, it also has a very checkered history – 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 great skepticism. To wit, other possibilities have been suggested: for example, a rolling scalar field (essentially a mini-episode of inflation also called quintessence) [31], or a frustrated network of very light topological defects (strings of walls) [32].

That leaves us with what I call the dark-energy problem: what is the nature of the smooth, negative energy component that contributes about 60% of the present energy budget of the universe and is causing the expansion to speed up. I call it dark energy as opposed to dark matter because this dark component is intrinsically relativistic ($|p| \sim \rho$) and does not clump like matter. My preference is to characterize it by its equation of state: $p_X = w_X \rho_X$, where w_X is -1 for vacuum energy, $-N/3$ for a network of frustrated topological defects of dimension N, and time varying and between -1 and 1 for a rolling scalar field. The immediate goal is to determine w_X and test for its time variation [33].

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. (However, it might show itself by the presence of new weaker than gravity, long-range forces [34].) Specifically, I believe that type Ia supernovae will prove to be the most powerful probe. The reason is twofold: first, the dark energy has only recently come to be important; the ratio $\rho_{\rm M}/\rho_X = (\Omega_{\rm M}/\Omega_X)(1+z)^{-3w_X}$ grows rapidly with redshift, as it must if the universe is to have a long, matter-dominated era to grow structure. 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.

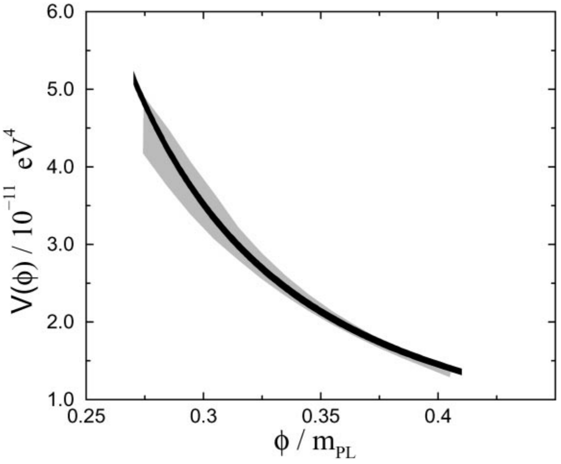
Supernova observations can map out luminosity distance as a function of redshift. In a flat universe, the luminosity distance, $d_{\rm L}(z) \equiv (1+z)r(z)$, is related to the comoving distance to an object at redshift z by

$$r(z) = \int_0^z \frac{{\rm d}x}{H(x)} , \tag{5}$$

$$H^2 = 8\pi(\rho_{\rm M} + \rho_X)/3 . \tag{6}$$

Using the equation of motion for the dark-energy, ${\rm d}\ln\rho_X = -3(1+w_X)\,{\rm d}\ln R$, this equation can be solved for $w_X(z)$:

$$1 + w_X(z) = \frac{1+z}{3} \frac{3H_0^2\Omega_{\rm M}(1+z)^2 + 2({\rm d}^2r/{\rm d}z^2)/({\rm d}r/{\rm d}z)^3}{H_0^2\Omega_{\rm M}(1+z)^3 - ({\rm d}r/{\rm d}z)^{-2}} . \tag{7}$$



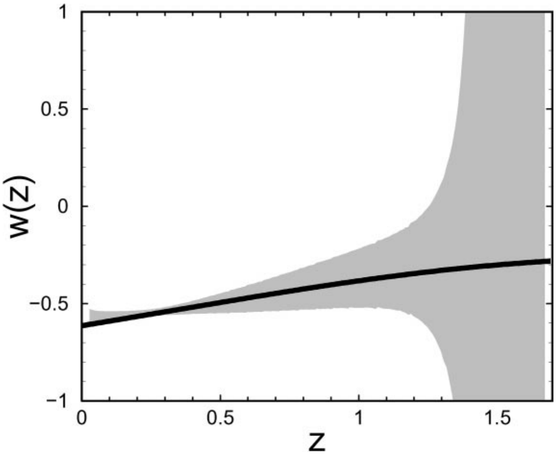


Fig. 8. The 95% confidence bands for the simulated reconstruction of the scalar-field potential for a quintessence model with exponential potential; the solid curve is the original potential. The Monte Carlo data consisted of 2100 SNe with redshifts from $z = 0$ to 1.5 with 7% luminosity distance errors (from Huterer and Turner).

Fig. 9. 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; the same is true at low redshift, where the expansion obeys Hubble's law independent of the composition of the universe. Same Monte Carlo technique as previous figure (from Huterer and Turner).

A similar equation can be obtained for the scalar-field potential in a rolling scalar field model [35]. Figs. 8 and 9 show the simulated reconstruction of two dark-energy models from supernova measurements: a quintessence model (scalar field rolling down a potential) 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 can do that) and that Type Ia supernovae are standardizable candles (further study of nearby supernovae is crucial), 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 redshift between 0 and 1.5. By carefully culling the sample and doing good follow up one will able to determine Ω_X, w_X and probe the time variation of w_X [35].

5. Looking forward

The two dominant ideas in cosmology over the past 20 years have been particle dark matter and inflation. They have provided the field with a guiding paradigm which has spurred the observers and experimenters to put in place a remarkable program that will keep the field of cosmology lively for at least another two decades with a flood of precision cosmological data.

Over the past few years both ideas have begun to be tested in a significant way, with more decisive tests to come. The early results 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 spectrum 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 as we begin the 21st century are the two dark problems – dark matter and dark energy – whose solutions almost certainly involve fundamental physics. The dark matter problem is more than 60 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, particle relics from the earliest moments. At the top of the list of particle candidates are the axion and the 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 of this: the halo profiles predicted for noninteracting CDM appear to rise more rapidly at the center than observations indicate [36]. 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 annihilation) to limit the central halo density. 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 yet air tight. Unlike the dark-matter problem where 60 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. David would be happy to hear this.

Acknowledgements

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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