

Dark Matter and Dark Energy in the Universe

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Abstract.

For the first time, we have a plausible, complete accounting of matter and energy in the Universe. Expressed a fraction of the critical density it goes like this: neutrinos, between 0.3% and 15%; stars, 0.5%; baryons (total), 5%; matter (total), 40%; smooth, dark energy, 60%; adding up to the critical density (summarized in Fig. 1). This accounting is consistent with the inflationary prediction of a flat Universe and defines three dark-matter problems: Where are the dark baryons? What is the non-baryonic dark matter? What is the nature of the dark energy? The leading candidate for the (optically) dark baryons is diffuse hot gas; the leading candidates for the nonbaryonic dark matter are slowly moving elementary particles left over from the earliest moments (cold dark matter), such as axions or neutralinos; the leading candidates for the dark energy involve fundamental physics and include a cosmological constant (vacuum energy), a rolling scalar field (quintessence), and light, frustrated topological defects.

1. Introduction

The quantity and composition of matter and energy in the Universe is a fundamental and important issue in cosmology. The fraction of the critical energy density contributed by matter and energy today,

$$\Omega_0 \equiv \frac{\rho_{\text{tot}}}{\rho_{\text{crit}}} = \sum_i \Omega_i, \quad (1)$$

determines the geometry of the Universe:

$$R_{\text{curv}}^2 = \frac{H_0^{-2}}{\Omega_0 - 1}. \quad (2)$$

Here, $\rho_{\text{crit}} = 3H_0^2/8\pi G \simeq 1.88h^2 \times 10^{-29} \text{ g cm}^{-3}$, Ω_i is the fraction of critical density contributed by component i today (e.g., baryons, photons, stars, etc) and $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$.

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MATTER / ENERGY in the UNIVERSE

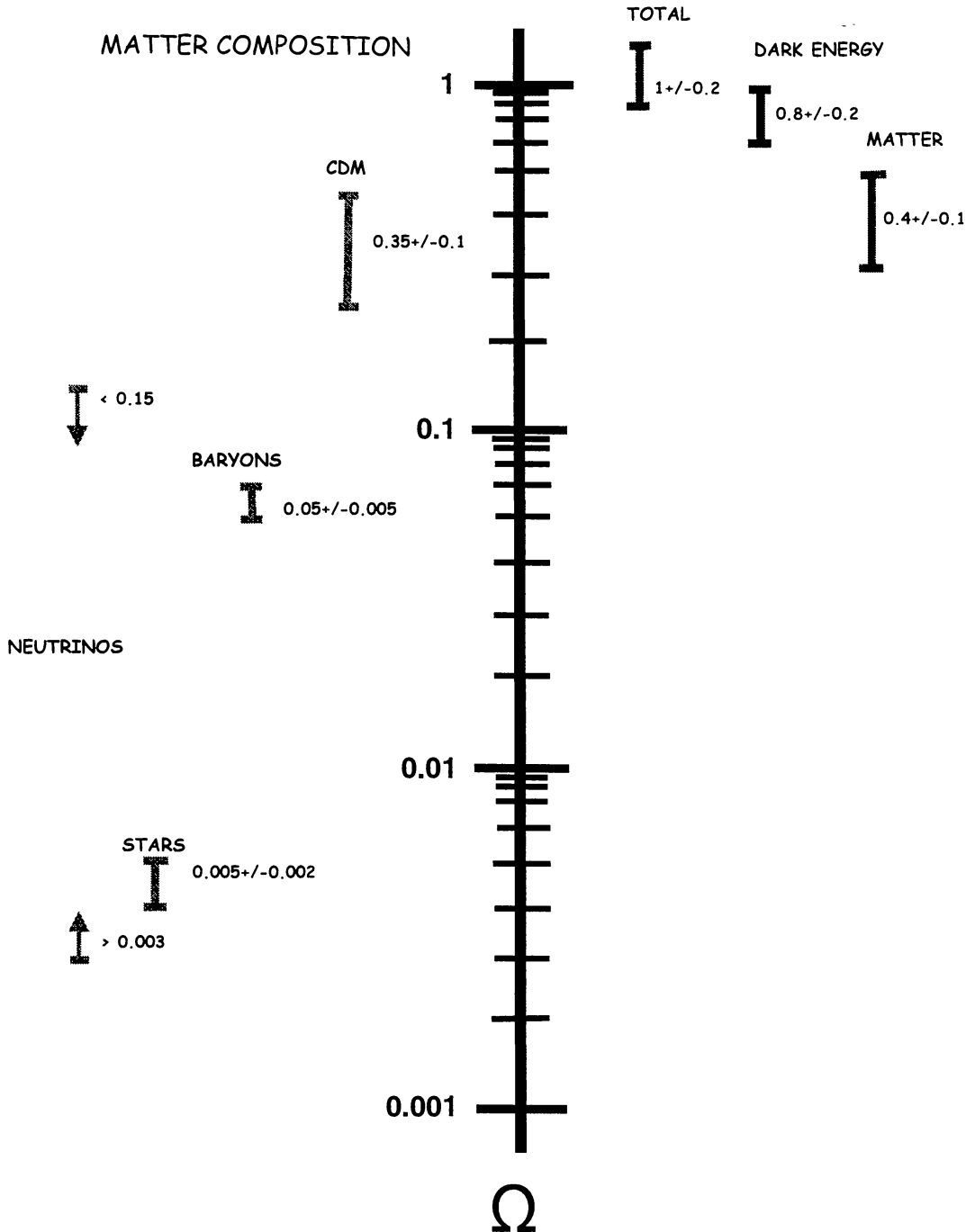


Figure 1. Summary of matter/energy in the Universe. The right side refers to an overall accounting of matter and energy; the left refers to the composition of the matter component. The contribution of relativistic particles, CBR photons and neutrinos, $\Omega_{\text{rel}}h^2 = 4.170 \times 10^{-5}$, 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 (Fukuda et al, 1998). Here H_0 is taken to be $65 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Supplemented by the equation of state for matter and energy in the Universe, Ω_0 determines the present rate of deceleration (or acceleration as the case may be) of the expansion

$$q_0 \equiv \frac{(\ddot{R}/R)_0}{H_0^2} = \frac{1}{2}\Omega_0 + \frac{3}{2} \sum_i \Omega_i w_i, \quad (3)$$

where the pressure of component i , $p_i \equiv w_i \rho_i$ (e.g., for baryons $w_i = 0$, for radiation $w_i = 1/3$, and for vacuum energy $w_i = -1$).

The fate of the Universe – expansion forever or recollapse – is not directly determined by H_0 , Ω_0 and q_0 . It also depends upon knowing the composition of *all* components of matter and energy for all times in the future. Recollapse occurs only if there is a future turning point, that is a future epoch when the expansion rate,

$$H^2 = \frac{8\pi G}{3} \sum_i \rho_i - \frac{1}{R_{\text{curv}}^2}, \quad (4)$$

becomes zero and $\ddot{R} < 0$. In a universe comprised of matter alone, only a positively curved universe eventually recollapses. Exotic components can complicate matters: a positively curved universe with positive vacuum energy can expand forever, and a negatively curved universe with negative vacuum energy can recollapse.

The quantity and composition of matter and energy in the Universe is crucial for understanding the past as well as the future. It determines the present age of the Universe, when the Universe ended its early radiation dominated era, the growth of small inhomogeneities in the matter and ultimately how large-scale structure formed in the Universe, as well as the formation and evolution of individual galaxies.

Measuring the quantity and composition of matter and energy in the Universe is a challenging task. Not just because the scale of inhomogeneity is so large, around 10 Mpc; but also, because there may be components that remain exactly or relatively smooth (e.g., vacuum energy or relativistic particles) which only reveal themselves by their influence of the evolution of the Universe itself.

Because it is known to be black-body radiation to very high precision (better than 0.005%) and its temperature is known to four significant figures, $T_0 = 2.7277 \pm 0.002$ K, the contribution of the cosmic background radiation (CBR) is very precisely known, $\Omega_\gamma h^2 = 2.480 \times 10^{-5}$. If neutrinos are massless or very light, $m_\nu \ll 10^{-4}$ eV, their energy density is equally well known because it is directly related to that of the photons, $\Omega_\nu = \frac{7}{8}(4/11)^{4/3}\Omega_\gamma$ (per species) (actually, there is a 1% positive correction to this number; see Dodelson & Turner, 1992).

The matter component (denoted by Ω_M), i.e., particles that have negligible pressure, is the easiest to determine because matter clumps and its gravitational effects are thereby enhanced (e.g., in rich clusters the matter density typically exceeds the mean density by a factor of 1000 or more). With all of this in mind, I will decompose the present matter/energy density into two components, matter and vacuum energy,

$$\Omega_0 = \Omega_M + \Omega_\Lambda. \quad (5)$$

I will not again mention the contribution of the CBR and ultrarelativistic neutrinos and will use vacuum energy as a stand in for any smooth component (more later). Vacuum energy and a cosmological constant are indistinguishable: a cosmological constant corresponds to a uniform energy density of magnitude $\rho_{\text{vac}} = \Lambda/8\pi G$.

2. A Complete Inventory of Matter and Energy

2.1. Curvature

There is a growing consensus that the anisotropy of the CBR offers the best means of determining Ω_0 and the curvature of the Universe. This is because the method is geometric – standard ruler on the last-scattering surface – and involves straightforward physics at a simpler time (see e.g., Kamionkowski et al, 1994).

At last scattering baryons were still tightly coupled to photons; as they fell into the dark-matter potential wells the pressure of photons acted as a restoring force, and gravity-driven acoustic oscillations resulted. These oscillations can be decomposed into their Fourier modes; Fourier modes with $k \sim lH_0/2$ determine the multipole amplitudes a_{lm} of CBR anisotropy. Last scattering occurs over a short time, and thus the CBR is a snapshot of the Universe at $t_{\text{ls}} \sim 300,000$ yrs. Different Fourier modes are captured at different phases of their oscillation. (Note, for the density perturbations predicted by inflation, all modes have same initial phase because all are growing-mode perturbations.) Modes caught at maximum compression or rarefaction lead to the largest anisotropy; this results in a series of acoustic peaks beginning at $l \sim 200$ (see Fig. 2). The wavelength of the lowest frequency acoustic mode that has reached maximum compression, $\lambda_{\text{max}} \sim v_s t_{\text{ls}}$, is the standard ruler on the last-scattering surface. Both λ_{max} and the distance to the last-scattering surface depend upon Ω_0 , and the position of the first peak $l \simeq 200/\sqrt{\Omega_0}$. This relationship is insensitive to the composition of matter and energy in the Universe.

CBR anisotropy measurements, shown in Figs. 2 and 3, now cover three orders of magnitude in multipole number and come from more than twenty experiments. COBE is the most precise and covers multipoles $l = 2 - 20$; the other measurements come from balloon-borne, Antarctica-based and ground-based experiments using both low-frequency ($f < 100$ GHz) HEMT receivers and high-frequency ($f > 100$ GHz) bolometers. Taken together, all the measurements are beginning to define the position of the first acoustic peak, at a value that is consistent with a flat Universe. Various analyses of the extant data have been carried out, indicating $\Omega_0 \sim 1 \pm 0.2$ (see e.g., Lineweaver, 1998). It is certainly too early to draw definite conclusions or put too much weight in the error estimate. However, a strong case is developing for a flat Universe and more data is on the way (Maxima, Boomerang, MAT, Python V, DASI, and others). Ultimately, the issue will be settled by NASA's MAP (launch late 2000) and ESA's Planck (launch 2007) satellites which will map the entire CBR sky with 30 times the resolution of COBE (around 0.1°).

2.2. Matter

Baryons For more than twenty years big-bang nucleosynthesis (BBN) has provided a key test of the hot big-bang cosmology as well as the most precise determination of the baryon density. Careful comparison of the primeval abundances of D, ^3He , ^4He and ^7Li with their big-bang predictions defined a concordance interval, $\Omega_B h^2 = 0.007 - 0.024$ (see e.g., Copi et al, 1995).

Of the four light elements produced in the big bang, deuterium is the most powerful “baryometer” – its primeval abundance depends strongly on the baryon density ($\propto 1/\rho_B^{1.7}$) – and its the evolution of its abundance since the big bang is simple – astrophysical processes only destroy deuterium. Until recently deuterium could not be exploited as a baryometer because its abundance was only known locally, where roughly half of the material has been through stars with a similar amount of the primordial deuterium destroyed. In 1998, the situation changed dramatically.

Over the past four years there have been many claims for upper limits, lower limits, and determinations of the primeval deuterium abundance, ranging from $(\text{D}/\text{H}) = 10^{-5}$ to $(\text{D}/\text{H}) = 3 \times 10^{-4}$. Within the past year Burles and Tytler have clarified the situation and established a strong case for $(\text{D}/\text{H})_P = (3.4 \pm 0.3) \times 10^{-5}$. Their case is based upon the deuterium abundance measured in four high-redshift hydrogen clouds seen in absorption against distant QSOs, and the remeasurement and reanalysis of other putative deuterium systems. In this important enterprise, the Keck I and its HiRes Echelle Spectrograph have played the crucial role. The primordial deuterium measurement turns the previous factor of three concordance range for the baryon density into a 10% determination of the baryon density, $\rho_B = (3.8 \pm 0.4) \times 10^{-31} \text{ g cm}^{-3}$ or $\Omega_B h^2 = 0.02 \pm 0.002$ (see Fig. 4).

It is nice to see that this very precise determination of the baryon density, based upon the early Universe physics of BBN, is consistent with two other measures of the baryon density, based upon entirely different physics. By comparing measurements of the opacity of the Lyman- α forest toward high-redshift quasars with high-resolution, hydrodynamical simulations of structure formation, several groups (Meiksin & Madau, 1993; Rauch et al, 1997; Weinberg et al, 1997) have inferred a lower limit to the baryon density, $\Omega_B h^2 > 0.015$ (it is a lower limit because it depends upon the baryon density squared divided by the intensity of the ionizing radiation field). The second test involves the height of the first acoustic peak: it rises with the baryon density (the higher the baryon density, the stronger the gravitational force driving the acoustic oscillations). Current CBR measurements are consistent with the Burles – Tytler baryon density; the MAP and Planck satellites should ultimately provide a 5% or better determination of the baryon density, based upon the physics of gravity-driven acoustic oscillations when the Universe was 300,000 yrs old. This will be an important cross check of the BBN determination.

It's dark! Based upon the mass-to-light ratios of the bright, inner regions of galaxies and the luminosity density of the Universe, the fraction of critical density in stars has been determined,

$$\Omega_* = (M/L)_* \mathcal{L} / \rho_{\text{crit}} = (M/L)_* / 1200h \simeq (0.003 \pm 0.001) h^{-1}. \quad (6)$$

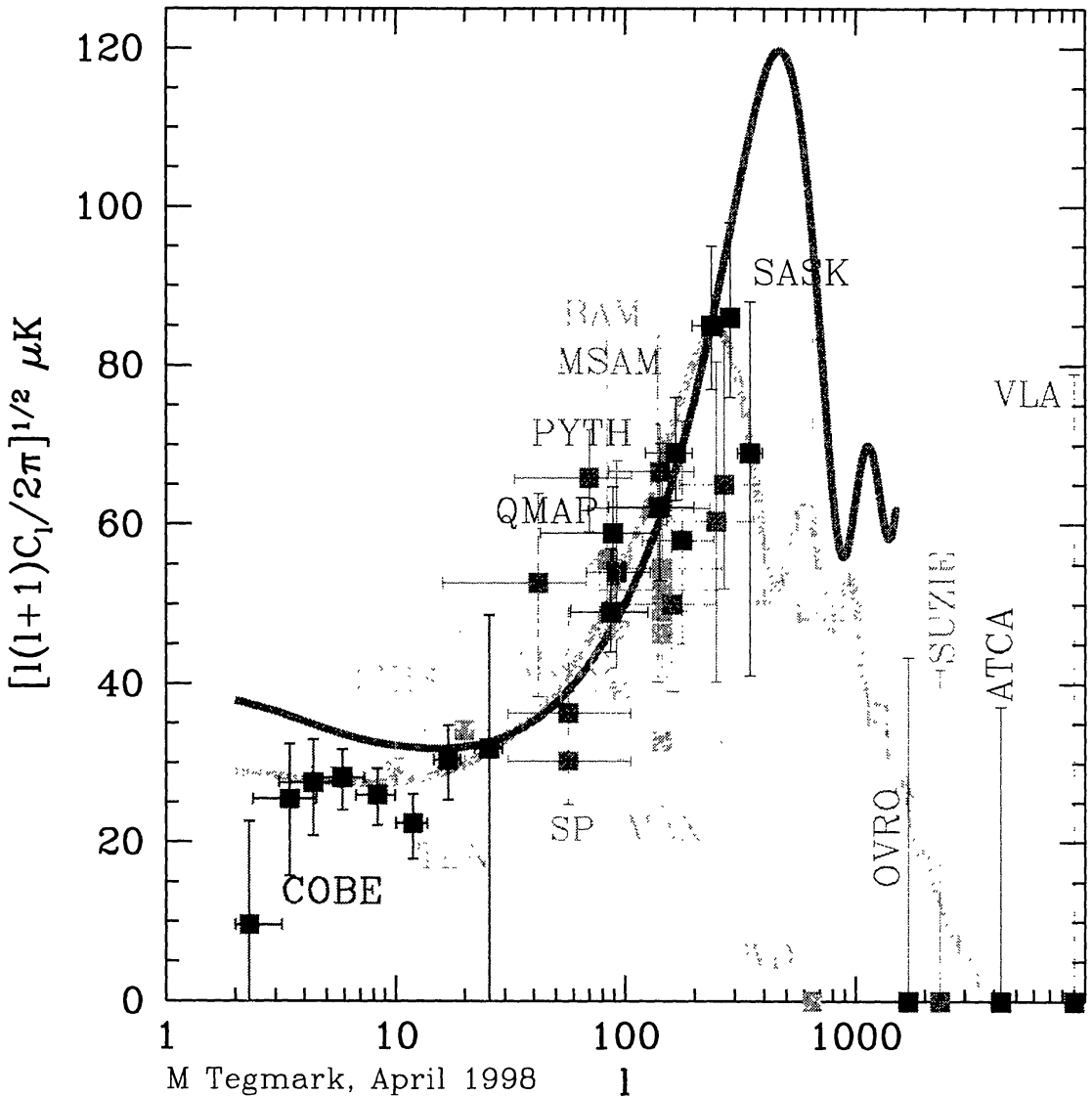


Figure 2. Summary of all CBR anisotropy measurements, where the temperature variations across the sky have been expanded in spherical harmonics, $\delta T(\theta, \phi) = \sum_i a_{lm} Y_{lm}$ and $C_l \equiv \langle |a_{lm}|^2 \rangle$. In plain language, this plot shows the size of the temperature variation between two points on the sky separated by angle θ (ordinate) vs. multipole number $l = 200^\circ/\theta$ ($l = 2$ corresponds to 100° , $l = 200$ corresponds to $\theta = 1^\circ$, and so on). The curves illustrate the predictions of CDM models with $\Omega_0 = 1$ (curve with lower peak) and $\Omega_0 = 0.3$ (darker curve). Note: the preference of the data for a flat Universe, and the evidence for the first of a series of “acoustic peaks.” The presence of these acoustic peaks is a key signature of the density perturbations of quantum origin predicted by inflation (Figure courtesy of M. Tegmark).

Bond, Jaffe and Knox 1998

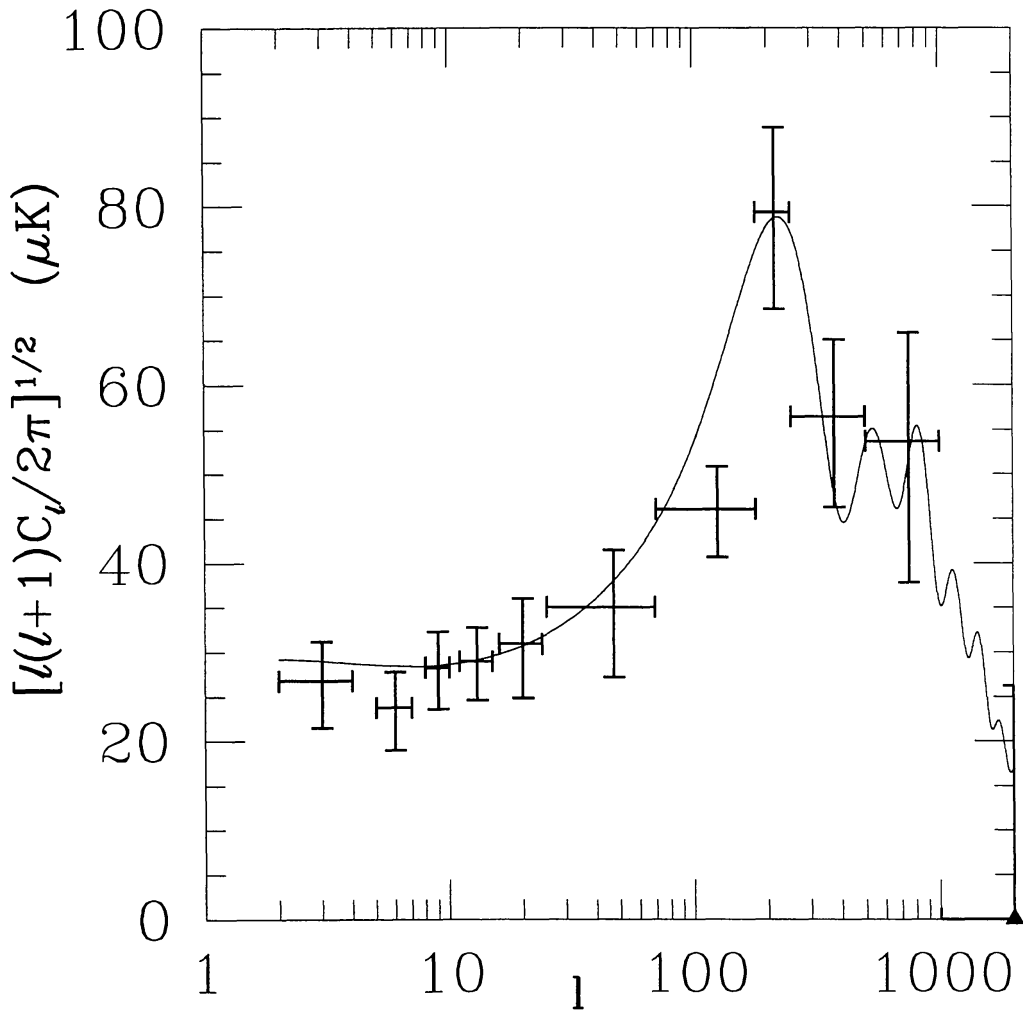


Figure 3. The same data as in Fig. 2, but averaged and binned to reduce error bars and visual confusion. The theoretical curve is for the Λ CDM model with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_M = 0.4$ (Figure courtesy of L. Knox).

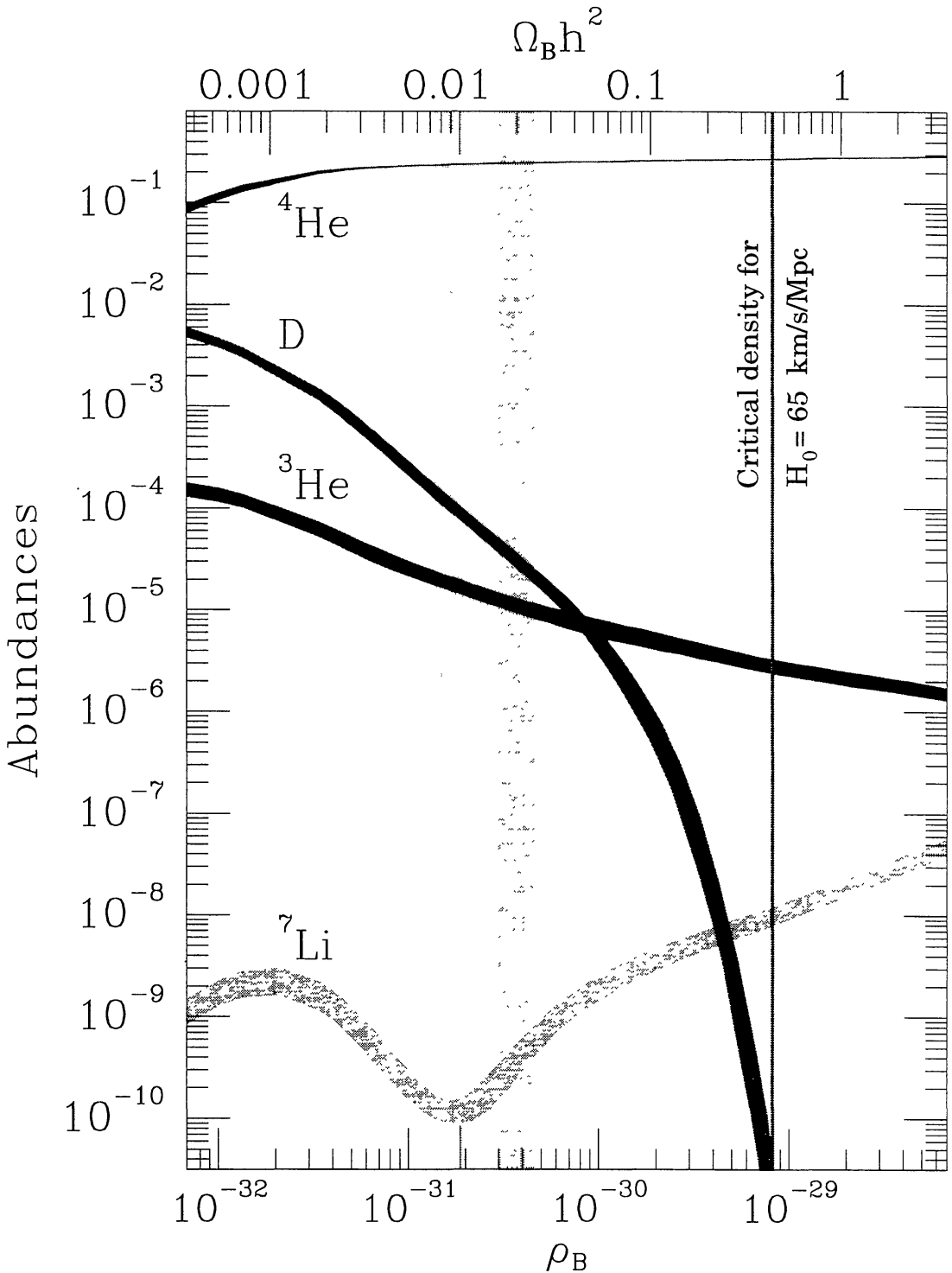


Figure 4. Predicted abundances of ^4He , D, ^3He , and ^7Li (relative to hydrogen) as a function of the density of ordinary matter (baryons); the width of the curves indicate the “ 2σ ” theoretical uncertainty. The full vertical band denotes the concordance interval based upon all four light elements that dates back to 1995 (Copi et al, 1995). The darker portion highlights the determination of the baryon density based upon the recent measurement of the primordial abundance of deuterium (Burles & Tytler, 1998a,b), which implies $\Omega_B h^2 = 0.02 \pm 0.002$.

Since the pioneering work of Fritz Zwicky and Vera Rubin, it has been known that this is far too little material to hold galaxies and clusters together, and thus, that most of the matter in the Universe is dark. Determining the total amount of dark matter has been the challenge. At present, I believe that clusters seem to provide the most reliable estimate of the matter density.

Total density of matter Rich clusters formed from density perturbations of size around 10 Mpc; in so doing they gather a sample of matter from a very large region, large enough to provide a “fair sample” of matter in the Universe. Using clusters as such, the precise BBN baryon density can be used to infer the total matter density (White et al, 1993). (Note, the baryons and dark matter need not be well mixed, provided that the baryon and total mass are determined over a large enough region of the cluster.)

Most of the baryons in clusters reside in the hot, x-ray emitting intracluster gas and not in the galaxies themselves, and so the problem reduces to determining the gas-to-total mass ratio. The gas mass can be determined by two methods: 1) measuring the x-ray flux from the intracluster gas and 2) mapping the Sunyaev - Zel’dovich CBR decrement caused by CBR photons scattering off hot electrons in the intracluster gas. The total cluster mass can be determined three independent ways: 1) using the motion of the galaxies and the virial theorem; 2) assuming that the gas is in hydrostatic equilibrium and using the virial theorem for the gas; and 3) mapping the cluster mass by gravitational lensing. Within their uncertainties and where comparisons can be made, the three methods for determining the total mass agree; likewise, the two methods for determining the gas mass are consistent.

Mohr et al (1998) have compiled the gas to total mass ratios determined from x-ray measurements for a sample of 45 clusters; they find $f_{\text{gas}} = (0.07 \pm 0.002)h^{-3/2}$. Carlstrom (1999), using his S-Z gas measurements and x-ray measurements for the total mass for 27 clusters, finds $f_{\text{gas}} = (0.06 \pm 0.006)h^{-1}$. (The agreement of these two numbers means that clumping of the gas, which could lead to an overestimate of the gas fraction based upon the x-ray flux, is not a problem.) Using the fair sample assumption, the mean matter density in the Universe can be inferred:

$$\begin{aligned}\Omega_M = \Omega_B / f_g &= (0.3 \pm 0.05)h^{-1/2} \text{ (Xray)} \\ &= (0.25 \pm 0.04)h^{-1} \text{ (S - Z)} \\ &= 0.4 \pm 0.1 \text{ (my summary)}. \end{aligned} \tag{7}$$

At present, I believe this to be the most reliable and precise determination of the matter density. It involves few assumptions, and most of them have now been tested (clumping, hydrostatic equilibrium, variation of gas fraction with cluster mass).

Supporting evidence for $\Omega_M = 0.4 \pm 0.1$ This result is consistent with a variety of other methods, that involve very different physics. For example, based upon the evolution of the abundance of rich clusters with redshift, Henry (1998) finds $\Omega_M = 0.45 \pm 0.1$ (also see, Bahcall & Fan, 1998). Dekel and Rees (1994) place a low limit $\Omega_M > 0.3$ (95% cl) derived from the outflow of material from voids (a void effectively acts as a negative mass proportional to the mean matter density).

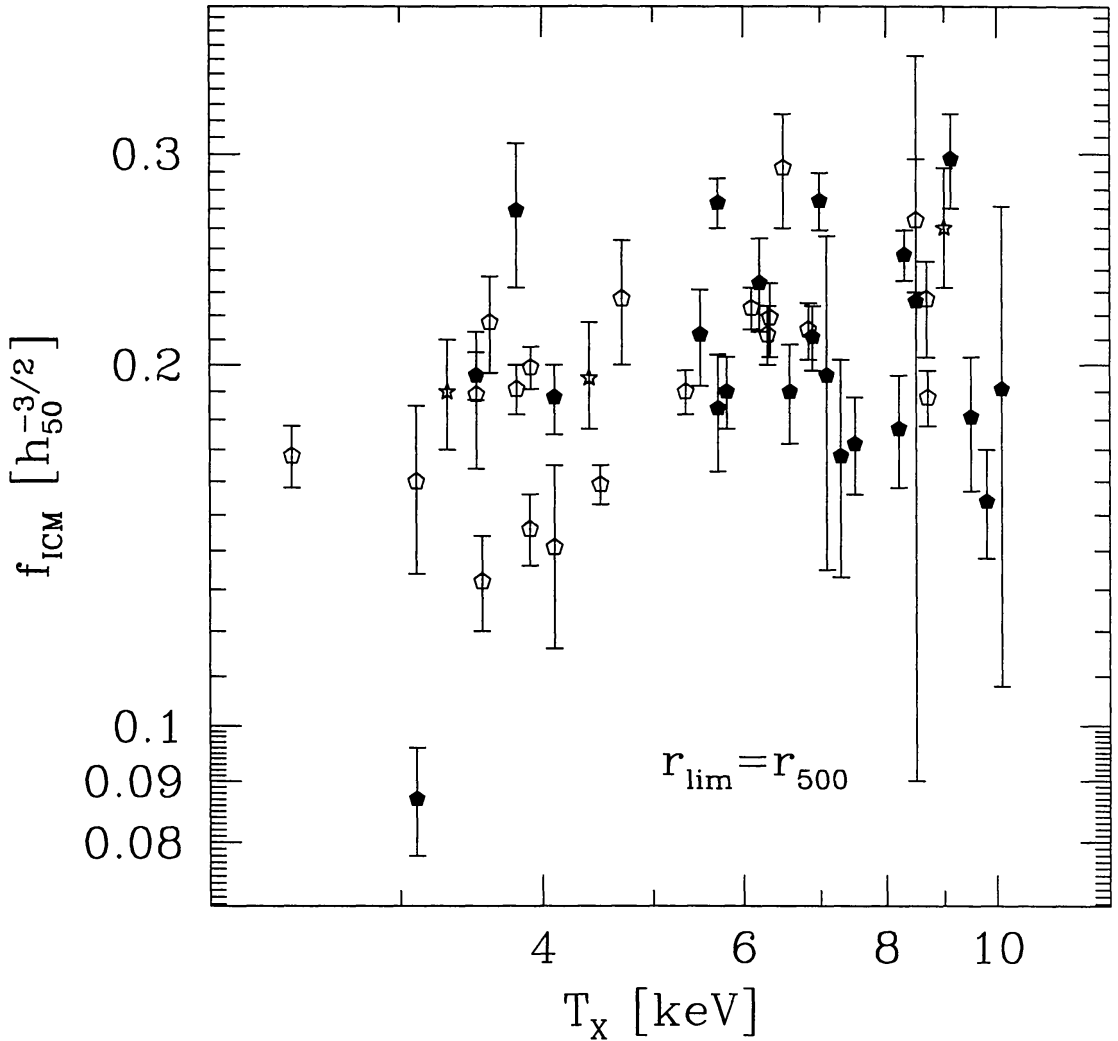


Figure 5. Cluster gas fraction as a function of cluster gas temperature for a sample of 45 galaxy clusters (Mohr et al, 1998). While there is some indication that the gas fraction decreases with temperature for $T < 5$ keV, perhaps because these lower-mass clusters lose some of their hot gas, the data indicate that the gas fraction reaches a plateau at high temperatures, $f_{\text{gas}} = 0.075 \pm 0.002$.

The analysis of the peculiar velocities of galaxies provides an important probe of the mass density averaged over very large scales (of order several 100 Mpc). By comparing measured peculiar velocities with those predicted from the distribution of matter determined by redshift surveys such as the IRAS survey of infrared galaxies, one can infer the quantity $\beta = \Omega_M^{0.6}/b_I$ where b_I is the linear bias factor that relates the inhomogeneity in the distribution of IRAS galaxies to that in the distribution of matter (in general, the bias factor is expected to be in the range 0.7 to 1.5; IRAS galaxies are expected to be less biased.). Recent work by Willick & Strauss (1998) finds $\beta = 0.5 \pm 0.05$, while Sigad et al (1998) find $\beta = 0.9 \pm 0.1$. The apparent inconsistency of these two results and the ambiguity introduced by bias preclude a definitive determination of Ω_M by this method. However, Dekel (1994) quotes a 95% confidence lower bound, $\Omega_M > 0.3$, and the work of Willick & Strauss seems to strongly indicate that Ω_M is much less than 1.

Finally, there is strong, but circumstantial, evidence from structure formation that Ω_M is around 0.4 and significantly greater than Ω_B . Since the demise of Peebles' isocurvature baryon model (Peebles, 1987) some five years ago due to its prediction of excessive CBR anisotropy on small angular scales, there has been no model for structure formation without nonbaryonic dark matter. The basic reason is simple: in a baryons only model, density perturbations only grow from decoupling, $z \sim 1000$, until the Universe becomes curvature dominated, $z \sim \Omega_B^{-1} \sim 20$; this is simply not enough growth to produce all the structure seen today with the size of density perturbations inferred from CBR anisotropy. With nonbaryonic dark matter, dark matter perturbations begin growing much earlier and grow until the present epoch, or nearly so.

In addition, the transition from radiation domination at early times to matter domination determines the shape of the present power spectrum of density perturbations, with the redshift of matter – radiation equality depending upon $\Omega_M h^2$. Measurements of the shape of the present power spectrum based upon redshift surveys indicate that the shape parameter, $\Gamma = \Omega_M h \sim 0.25 \pm 0.05$ (see e.g., Peacock & Dodds, 1994). For $h \sim 2/3$, this implies $\Omega_M \sim 0.4$. (If there are relativistic particles beyond the CBR photons and relic neutrinos, the formula for the shape parameter changes and $\Omega_M \sim 1$ can be accommodated; see Dodelson et al, 1996).

2.3. Mass-to-light ratios: the glass is half full!

The most mature approach to estimating the matter density involves the use of mass-to-light ratios, the measured luminosity density, and the simple equality

$$\langle \rho_M \rangle = \langle M/L \rangle \mathcal{L}, \quad (8)$$

where $\mathcal{L} = 2.4h \times 10^8 L_{B\odot} \text{ Mpc}^{-3}$ is the luminosity density of the Universe. Once the average mass-to-light ratio for the Universe is determined, Ω_M follows by dividing it by the critical mass-to-light ratio, $(M/L)_{\text{crit}} = 1200h$ (in solar units). Though it is tantalizingly simple – and it is far too easy to take any measured mass-to-light ratio and divide it by $1200h$ – this method does not provide an easy and reliable method of determining Ω_M .

The CNOC group (Carlberg et al, 1996, 1997) have done a very careful job of determining a mean cluster mass-to-light ratio, $(M/L)_{\text{cluster}} = 240 \pm 50$,

which translates to an estimate of the mean matter density, $\Omega_{\text{cluster}} = 0.20 \pm 0.04$. Because clusters contain thousands of galaxies and cluster galaxies do not seem *radically* different from field galaxies, one is tempted to take this estimate of the mean matter density very seriously. However, it is significantly smaller than the value I advocated earlier, $\Omega_M = 0.4 \pm 0.1$. Which estimate is right?

I believe the higher number, based upon the cluster baryon fraction, is correct and that we should be surprised that the CNOC number is so close, closer than we had any right to expect! After all, only a small fraction of galaxies are found in clusters and the luminosity density \mathcal{L} itself evolves strongly with redshift and corrections for this effect are large and uncertain. (We are on the tail end of star formation in the Universe: 80% of star formation took place at a redshift greater than unity.)

Even if mass-to-light ratios were measured in the red (they typically are not), where the starlight is dominated by low-mass stars and reflects the integrated history of star formation rather than the present rate as blue light does, one would still require the fraction of baryons converted into stars in clusters to be identical to that in the field to have agreement between the CNOC estimate and that based upon the cluster baryon fraction. Apparently, the fraction of baryons converted into stars in the field and in clusters is similar, but not identical.

To put this in perspective and to emphasize the shortcomings of the mass-to-light technique, had one used the cluster mass-to-x-ray ratio and the x-ray luminosity density, one would have inferred $\Omega_M \sim 0.05$. A factor of two discrepancy based upon this method is not so bad. Enough said.

2.4. Missing energy found!

The results $\Omega_0 = 1 \pm 0.2$ and $\Omega_M = 0.4 \pm 0.1$ are in apparent conflict. However, prompted by a strong belief in a flat Universe, theorists have explored the logical possibility a dark, exotic form of energy that is smoothly distributed and contributes 60% of the critical density to explain this discrepancy (Turner et al, 1984; Peebles, 1984). To avoid interfering with structure formation, this energy density must be less important in the past than it is today (development of the structure observed today from density perturbations of the size inferred from measurements of the anisotropy of the CBR requires that the Universe be matter dominated from the epoch of matter – radiation equality until very recently). If the effective equation of state for this component is parameterized as $w_x = p_X/\rho_X$, its energy density evolves as $\rho_X \propto R^{-n}$ where $n = 3(1 + w_x)$. To be less important in the past than matter, n must be less than 3 or $w_X < 0$; the more negative w_X is, the faster this component gets out of the way. Another added benefit of negative pressure is an older Universe for a given Hubble constant: $H_0 t_0$ increases with decreasing w_X . The simplest example of an exotic smooth component is vacuum energy, which is characterized $w_X = -1$.

The “smoking-gun” signature of such a smooth component is accelerated expansion (due to negative pressure); for a cosmological constant, $q_0 = \frac{1}{2}\Omega_M - \Omega_\Lambda \sim -0.4$. This year, evidence for this smoking gun was presented in the form of the magnitude – redshift (Hubble) diagram for fifty-some SNeIa out to redshifts of nearly 1 (Riess et al, 1998; Perlmutter et al, 1998). These two groups, working independently both found evidence for accelerated expansion.

Perlmutter et al (1998) summarize their results as

$$\Omega_\Lambda = \frac{4}{3}\Omega_M + \frac{1}{3} \pm \frac{1}{6}, \quad (9)$$

which for $\Omega_M \sim 0.4 \pm 0.1$ implies $\Omega_\Lambda = 0.85 \pm 0.2$, or just what is needed to explain the missing energy! (see Fig. 6).

(To explain their startling result in simple terms: If the distances and velocities to distant galaxies were all measured at the present, they would obey a perfect Hubble law, $v = H_0 d$, because the expansion of the Universe is just a (conformal) scaling up of all distances. However, we see distant galaxies at an earlier time and so if the expansion is slowing, their velocities should fall above the Hubble-law prediction; these two groups found the opposite, implying that the expansion rate is speeding up.)

The statistical errors reported by the two groups are smaller than possible systematic errors. Thus, the believability of the SNeIa result turn on the reliability of SNeIa as one-parameter standard candles. SNeIa are thought to be associated with the nuclear detonation of Chandrasekhar mass white dwarfs. The one parameter is the rate of decline of the light curve: The brighter ones decline more slowly (the so-called Phillips relation). The lack of a good theoretical understanding of this (e.g., what is the physical parameter?) is offset by strong empirical evidence for the relationship between peak brightness and rate of decline, based upon a sample of thirty-some nearby SNeIa. It is reassuring that in all respects studied, the distant sample of SNeIa appear to be similar to the nearby sample. For example, distribution of decline rates and dispersion about the Phillips relationship. Further, the local sample spans a wide range of metallicity, both suggesting that metallicity is not an important second parameter and most likely spanning the range of metallicities of the distant sample. At this point, it seems fair to say that if there is a problem with SNeIa as standard candles, it must be subtle.

Riess et al (1998) and Perlmutter et al (1998) have presented a strong case for accelerated expansion: their data are impressive and both groups have been very careful and self-critical. Cosmologists are even more inclined to believe the SNeIa results because of the preexisting evidence for a “missing-energy component,” which predicted accelerated expansion.

2.5. Cosmic concordance

The reason for my enthusiasm about the SNeIa results is that for the first time we have a complete, self-consistent accounting of mass and energy in the Universe, as well as a self-consistent picture for structure formation. The consistency of the matter/energy accounting is illustrated in Fig. 6. Let me explain this very exciting figure in words. The SNeIa results are sensitive to the acceleration (or deceleration) of the expansion, and the results constrain the combination $\frac{4}{3}\Omega_M - \Omega_\Lambda$. (Note, $q_0 = \frac{1}{2}\Omega_M - \Omega_\Lambda$; $\frac{4}{3}\Omega_M - \Omega_\Lambda$ corresponds to the deceleration parameter at redshift $z \sim 0.4$, the median redshift of these samples). The (approximately) orthogonal combination, $\Omega_0 = \Omega_M + \Omega_\Lambda$ is constrained by CBR anisotropy. Together, they define a concordance region around $\Omega_0 \sim 1$, $\Omega_M \sim 1/3$, and $\Omega_\Lambda \sim 2/3$. The constraint to the matter density alone, $\Omega_M = 0.4 \pm 0.1$, provides a cross check, and it is consistent with the previous numbers. Cosmic concordance!

But there is more. The Λ CDM model, that is the cold dark matter model with $\Omega_B \sim 0.05$, $\Omega_{\text{CDM}} \sim 0.35$ and $\Omega_\Lambda \sim 0.6$, is a very good fit to all cosmological constraints: large-scale structure, CBR anisotropy, age of the Universe, Hubble constant and the constraints to the matter density and cosmological constant; see Fig. 7 (Krauss & Turner, 1995; Ostriker & Steinhardt, 1995; Turner, 1997). Further, as can be seen in Figs. 2 and 3, CBR anisotropy measurements are beginning to show evidence for the acoustic peaks characteristic of the Gaussian, curvature perturbations predicted by inflation. Until recently, Λ CDM's only major flaw was the absence of evidence for accelerated expansion. Not now.

3. Three Dark Matter Problems

While stars are very interesting and pretty to look at – and without them, astronomy wouldn't be astronomy and we won't exist – they represent a tiny fraction of the cosmic mass budget, only about 0.5% of the critical density. As we have known for several decades at least – the bulk of the matter and energy in the Universe is dark. The present accounting defines clearly three dark matter/energy problems; none is presently fully addressed.

3.1. Dark Baryons

By a ten to one margin, the bulk of the baryons do not exist in the form of bright stars. With the exception of clusters, where the dark baryons exist in the form of hot, x-ray emitting intracluster gas, the nature of the dark baryons is not known. Clusters of course only account for around 10% or so of the matter in the Universe and the (optically) dark baryons elsewhere could take on a different form.

The two most promising possibilities for the dark baryons are diffuse hot gas and “dark stars” (white dwarfs, neutron stars, black holes or objects of mass around or below the hydrogen-burning limit). The former possibility is favored by me for a number of reasons. First, that's where the dark baryons in clusters are. Second, the cluster baryon fraction argument can be turned around to infer Ω_{gas} at the time clusters formed, redshifts $z \sim 0 - 1$,

$$\Omega_{\text{gas}} h^2 = f_{\text{gas}} \Omega_M h^2 = 0.023 (\Omega_M / 0.4) (h / 0.65)^{1/2}. \quad (10)$$

That is, at the time clusters formed, the mean gas density was essentially equal to the baryon density (unless $\Omega_M h^{1/2}$ is very small), thereby accounting for the bulk of baryons in gaseous form. Third, numerical simulations suggest that most of the baryons should still be in gaseous form today (Rauch et al, 1997).

I should mention that there are two arguments for dark stars as the baryonic dark matter. First, the gaseous baryons not associated with clusters have not been detected. Second, the results of the microlensing surveys (see Alcock, 1999) toward the LMC and SMC are consistent with about one-third of our halo being in the form of half-solar mass white dwarfs.

I find neither argument compelling; gas outside clusters will be much cooler ($T \sim 10^5 - 10^6$ K) and very difficult to detect, either in absorption or emission. There are equally attractive explanations for the Magellanic Cloud microlensing events (e.g., self lensing by the Magellanic Clouds, lensing by stars in the

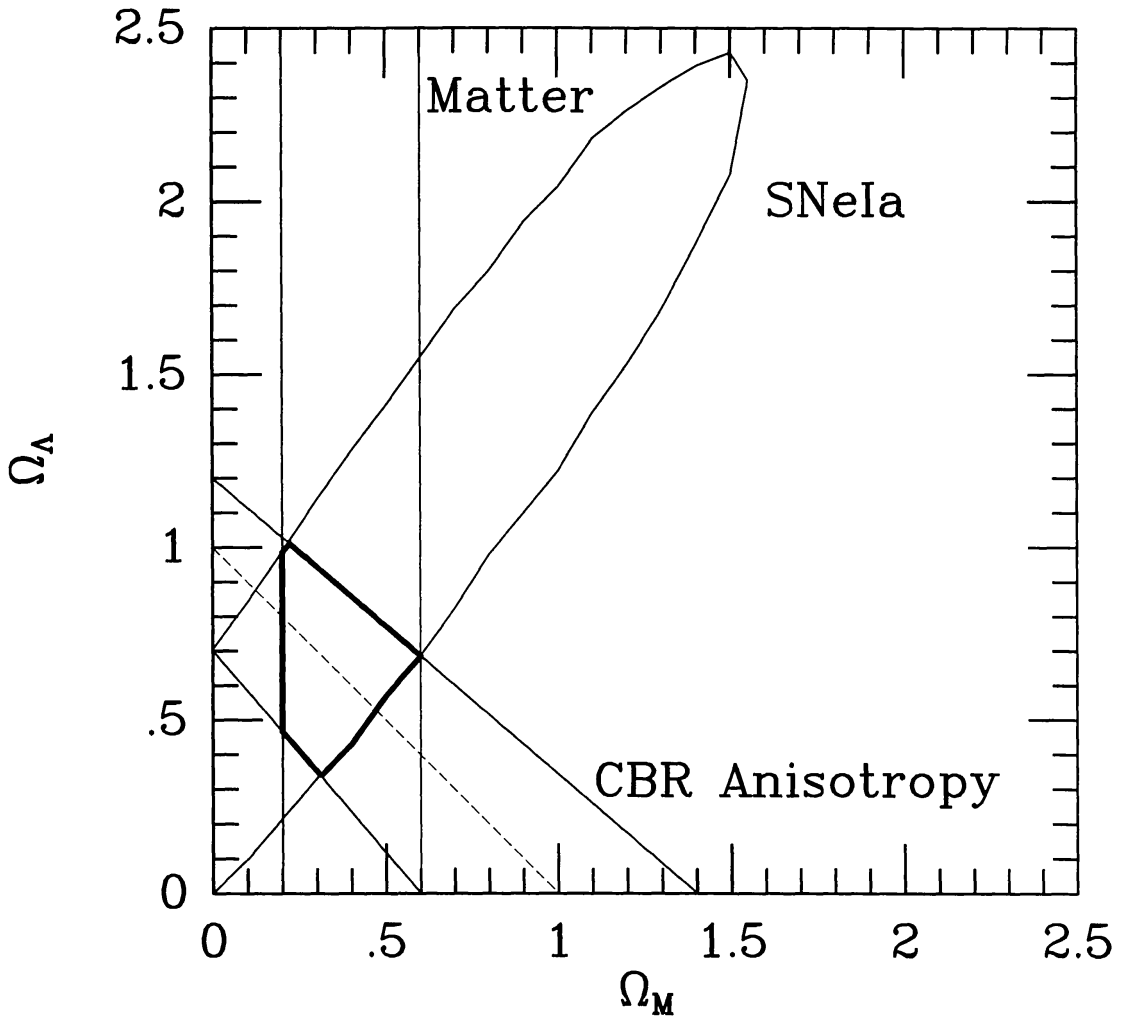


Figure 6. Constraints to Ω_M and Ω_Λ from CBR anisotropy, SNeIa, and measurements of clustered matter. Lines of constant Ω_0 are diagonal, with a flat Universe shown by the broken line. The concordance region is shown in bold: $\Omega_M \sim 1/3$, $\Omega_\Lambda \sim 2/3$, and $\Omega_0 \sim 1$. (Particle physicists who rotate the figure by 90° will recognize the similarity to the convergence of the gauge coupling constants.)

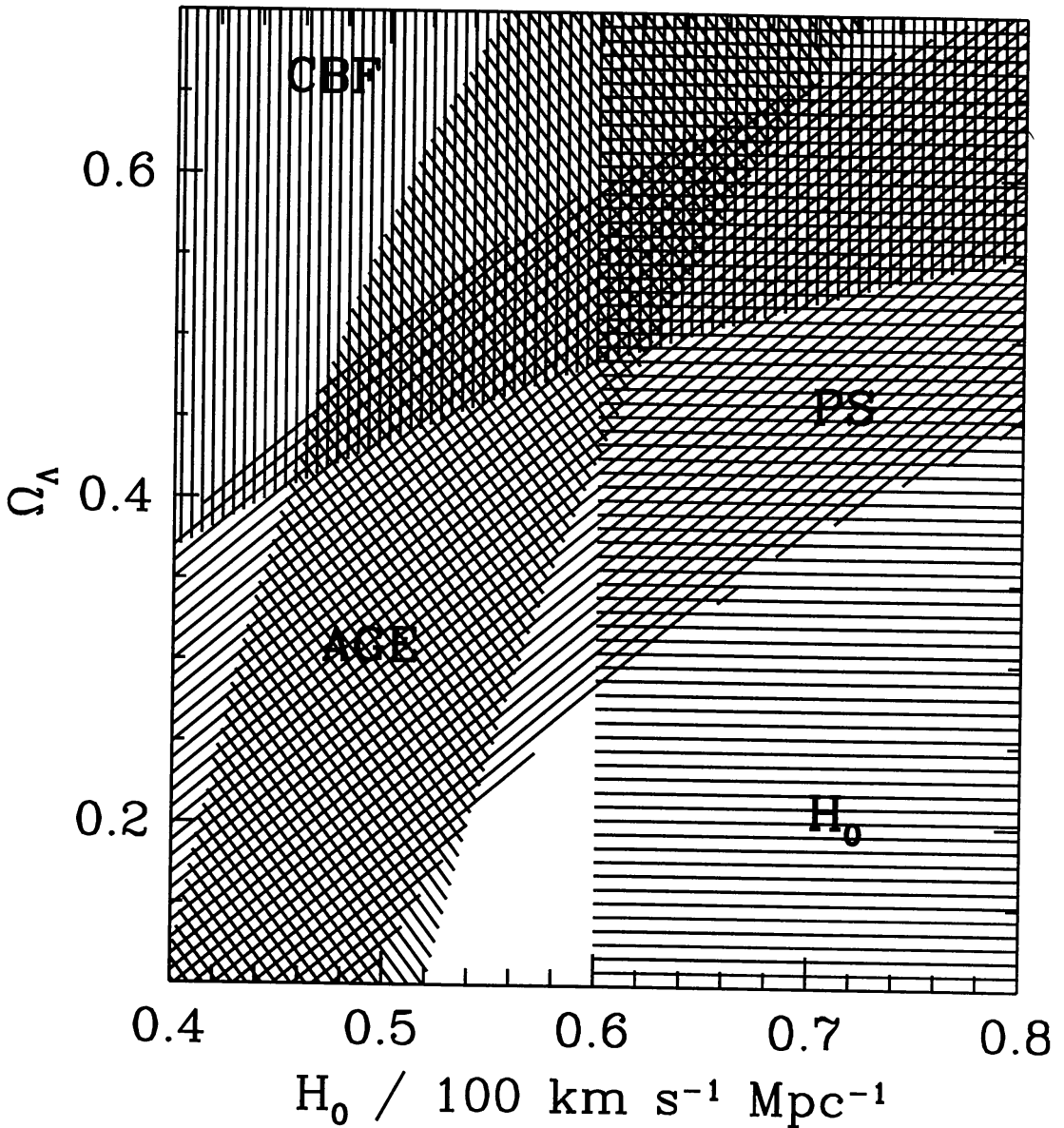


Figure 7. Constraints used to determine the best-fit CDM model: PS = large-scale structure + CBR anisotropy; AGE = age of the Universe; CBF = cluster-baryon fraction; and H_0 = Hubble constant measurements. The best-fit model, indicated by the darkest region, has $H_0 \simeq 60 - 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_\Lambda \simeq 0.55 - 0.65$. Evidence for its smoking gun signature – an accelerating expansion – was presented in 1998 by Perlmutter et al and Riess et al.

spheroid, or lensing due to disk material that, due to flaring and warping of the disk, falls along the line of sight to the LMC; see Sahu, 1994; Evans et al, 1998; Gates et al, 1998; Zaritsky & Lin, 1997; Zhao, 1998). The white-dwarf interpretation for the halo has a host of troubles: Why haven't the white dwarfs been seen (Graff et al, 1998)? The star formation rate required to produce these white dwarfs – close to $100 \text{ yr}^{-1} \text{ Mpc}^{-3}$ – far exceeds that measured for other parts of the Universe. Where are the lower-main-sequence stars associated with this stellar population and the gas (expected to be 6 to 10 times that of the white dwarfs) that didn't form into stars (Fields et al, 1997)? Finally, there is evidence that the lenses for both SMC events are stars within the SMC (Alcock et al, 1998; EROS Collaboration, 1998a,b) and at least one of the LMC events is explained by an LMC lens.

3.2. Cold Dark Matter

The second dark-matter problem follows from the inequality $\Omega_M \simeq 0.4 \gg \Omega_B \simeq 0.05$: There is much more matter than there are baryons, and thus, nonbaryonic dark matter is the required, dominant form of matter. The evidence for this very profound conclusion has been mounting for almost two decades. This year, the Burles – Tytler deuterium measurement anchored the baryon density and allowed the cleanest determination of the matter density.

Particle physics provides an attractive solution to the nonbaryonic dark matter problem: relic elementary particles left over from the big bang. Long-lived or stable particles with very weak interactions can remain from the earliest moments of particle democracy in sufficient numbers to account for a significant fraction of critical density (very weak interactions are needed so that their annihilations cease before their numbers are too small). The three most promising candidates are a neutrino(s) of mass 30 eV or so, an axion of mass $10^{-5 \pm 1} \text{ eV}$, and a neutralino of mass between 50 GeV and 500 GeV. All three are motivated by particle physics theories that attempt to unify the forces and particles of Nature. The fact that such particles can also account for the nonbaryonic dark matter is either a big coincidence or a big hint. Further, the fact that these particles interact with each other and ordinary very weakly, provides a simple and natural explanation for dark matter being more diffusely distributed.

At the moment, there is significant circumstantial evidence against neutrinos as the bulk of the dark matter. Because they behave as hot dark matter, structure forms from the top down, with superclusters fragmenting into clusters and galaxies (White, Frenk & Davis, 1983), in stark contrast to the observational evidence that indicates structure formed from the bottom up. (Hot + cold dark matter is still an outside possibility, with $\Omega_\nu \sim 0.15$; see Gawiser & Silk, 1998.) Second, the evidence for neutrino mass based upon the atmospheric and solar-neutrino data suggests a neutrino mass pattern with the tau neutrino at 0.1 eV, the muon neutrino at 0.001 eV to 0.01 eV and the electron neutrino with an even smaller mass. In particular, the factor-of-two deficit of atmospheric muons neutrinos with its dependence upon zenith angle is very strong evidence for a neutrino mass difference squared between two of the neutrinos of around 10^{-2} eV^2 (Fukuda et al, 1998). In turn, this sets a lower bound to neutrino mass of about 0.1 eV, implying neutrinos contribute at least as much mass as bright stars. WOW!

Both the axion and neutralino behave as cold dark matter; the success of the cold dark matter model of structure formation makes them the leading particle dark-matter candidates. Because they behave as cold dark matter, they are expected to be the dark matter in our own halo – in fact, there is nothing that can keep them out (Gates & Turner, 1994). As discussed above, 2/3 of the dark matter in our halo – and probably all the halo dark matter – cannot be explained by baryons in any form. The local density of halo material is estimated to be $10^{-24} \text{ g cm}^{-3}$, with an uncertainty of slightly less than a factor of 2 (Gates et al, 1995). This makes the halo of our galaxy an ideal place to look for cold dark matter particles! An experiment at Livermore National Laboratory with sufficient sensitivity to detect halo axions is currently taking data (van Bibber et al, 1998) and experiments at several laboratories around the world are beginning to search for halo neutralinos with sufficient sensitivity to detect them (Sadoulet, 1999). The particle dark matter hypothesis is a very bold one, and it is now being tested.

3.3. Dark Energy

I and others have often used the term exotic to refer to particle dark matter. That term will now have to be reserved for the dark energy that is causing the accelerated expansion of the Universe – by any standard, it is more exotic and more poorly understood.

Here is what we do know: it contributes about 60% of the critical density and has pressure more negative than $-\rho/3$ (i.e., effective equation of state $w \equiv p/\rho < -\frac{1}{3}$). It does not clump (otherwise it would have contributed to estimates of the mass density). The simplest possibility is that it is the energy associated with the virtual particles that populate the quantum vacuum (which has equation of state $w = -1$ and is absolutely spatially uniform).

This simple interpretation has its difficulties. Einstein “invented” the cosmological constant to make a static model of the Universe and then he discarded it; we now know that the concept is not optional. The cosmological constant corresponds to the energy associated with the vacuum. However, there is no sensible calculation of that energy (see e.g., Weinberg, 1989), with estimates ranging from 10^{122} to 10^{55} times the critical density. Some particle physicists believe that when the problem is understood, the answer will be zero. Spurred in part by the possibility that cosmologists may have actually weighed the vacuum (!), particle theorists are taking a fresh look at the problem (see e.g., Harvey, 1998; Sundrum, 1997). Sundrum’s proposal, that the energy of the vacuum is close to the present critical density because the graviton is a composite particle with size of order 1 cm, is indicative of the profound consequences that a cosmological constant has for fundamental physics.

Because of the theoretical problems mentioned above, as well as the checkered history of the cosmological constant, theorists have explored other possibilities for a smooth, component to the dark energy (see e.g., Turner & White, 1997). Wilczek and I pointed out that even if the energy of the true vacuum is zero, as the Universe as cooled and went through a series of phase transitions, it could have become hung up in a metastable vacuum with nonzero vacuum energy (Turner & Wilczek, 1982). In the context of string theory, where there are a very large number of energy-equivalent vacua this becomes a more interesting

possibility: perhaps the degeneracy of vacuum states is broken by very small effects, so small that we were not steered into the lowest energy vacuum during the earliest moments.

Vilenkin (1984) has suggested a tangled network of very light cosmic strings (also see, Spergel & Pen, 1997) produced at the electroweak phase transition; networks of other frustrated defects (e.g., walls) are also possible. In general, the bulk equation-of-state of frustrated defects is characterized by $w = -N/3$ where N is the dimension of the defect ($N = 1$ for strings, $= 2$ for walls, etc.). The SNeIa data almost exclude strings, but still allow walls.

An alternative that has received a lot of attention is the idea of a “decaying cosmological constant”, a term coined by the Soviet cosmologist Matvei Petrovich Bronstein in 1933 (Bronstein, 1933). (Bronstein was executed on Stalin’s orders in 1938, for reasons not directly related to the cosmological constant.) The term is, of course, an oxymoron; what people have in mind is making vacuum energy dynamical. The simplest realization is an evolving scalar field. If it is spatially homogeneous, then its energy density and pressure are given by

$$\begin{aligned}\rho &= \frac{1}{2}\dot{\phi}^2 + V(\phi) \\ p &= \frac{1}{2}\dot{\phi}^2 - V(\phi)\end{aligned}\tag{11}$$

and its equation of motion by (see e.g., Turner, 1983)

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0\tag{12}$$

The basic idea is that energy of the true vacuum is zero, but not all fields have evolved to their state of minimum energy. This is qualitatively different from that of a metastable vacuum, which is a local minimum of the potential and is classically stable. Here, the field is classically unstable and is rolling toward its lowest energy state.

Two features of the “rolling-scalar-field scenario” are worth noting. First, the effective equation of state, $w = (\frac{1}{2}\dot{\phi}^2 - V)/(\frac{1}{2}\dot{\phi}^2 + V)$, can take on any value from 1 to -1 . Second, w can vary with time. These are key features that allow it to be distinguished from the other possibilities.

The rolling scalar field scenario (aka mini-inflation or quintessence) has received a lot of attention over the past decade (Freese et al, 1987; Ozer & Taha, 1987; Ratra & Peebles, 1988; Frieman et al, 1995; Coble et al, 1996; Turner & White, 1997; Caldwell et al, 1998). It is an interesting idea, but not without its own difficulties. First, in this scenario one must *assume* that the energy of the true vacuum state (ϕ at the minimum of its potential) is zero; i.e., it does not address the cosmological constant problem. Second, as Carroll (1998) has emphasized, the scalar field ϕ is very light and can mediate long-range forces. This places very stringent constraints on it. Finally, with the possible exception of one model, none of the scalar-field models address how ϕ fits into the grander scheme of things and why it is so light ($m \sim 10^{-33}$ eV).

4. Concluding Remarks

1998 was a very good year for cosmology. We have for the first time a plausible, complete accounting of matter and energy in the Universe, in Λ CDM a model for structure formation that is consistent with all the data at hand, and the first evidence for the key tenets of a bold and expansive paradigm that extends the standard hot big-bang model (Inflation + Cold Dark Matter). One normally conservative cosmologist has gone out on a limb by saying that 1998 may be a turning point in cosmology as important as 1964, when the CBR was discovered (Turner, 1999)!

We still have important questions to address: Where are the dark baryons? What is the dark matter? What is the nature of the dark energy? What is the explanation for the complicated pattern of mass and energy: neutrinos (0.3%), baryons (5%), cold dark matter particles (35%) and dark energy (60%)? Especially puzzling is the ratio of dark energy to dark matter: because they evolve differently, the ratio of dark matter to dark energy was higher in the past and will be smaller in the future; only today are they comparable. WHY NOW?

While we have many urgent questions, we can see a flood of precision cosmological and laboratory data coming that will help to answer these questions: High-resolution maps of CBR anisotropy (MAP and Planck); large redshift surveys (SDSS and 2dF); more SNeIa data; experiments to directly detect halo axions and neutralinos; more microlensing data (MACHO, EROSII, OGLE, AGAPE, and superMACHO); accelerator experiments at Fermilab and CERN searching for the neutralino and its supersymmetric friends and further evidence for neutrino mass; and nonaccelerator experiments that will shed further light on neutrino masses, particle dark matter, new forces, and the nature of gravity.

These are exciting times in cosmology!

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