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Big-Bang Nucleosynthesis Enters the Precision Era

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ABSTRACT

The last parameter of big-bang nucleosynthesis, the baryon density, is being pinned down by measurements of the deuterium abundance in high-redshift hydrogen clouds. When it is determined, it will fix the primeval light-element abundances. D, ^{3}He and ^{7}Li will become "tracers" for the study of Galactic and stellar chemical evolution, and big-bang nucleosynthesis will become an even sharper probe of particle physics, e.g., the bound to the number of light neutrino species will be tightened significantly. Two key tests of the consistency of the standard theory are on the horizon: an independent, high-precision determination of the baryon density from anisotropy of the cosmic background radiation and a precision determination of the primeval ^{4}He abundance.

1 From Gamow to Keck

Over the last two decades big-bang nucleosynthesis (BBN) has emerged as one of the cornerstones of the big bang, joining the Hubble expansion and the Cosmic microwave Background Radiation (CBR) in this role. Of the three, big-bang nucleosynthesis probes the Universe to the earliest times, from a fraction of a second to hundreds of seconds. Since BBN involves events that occurred at temperatures of order 1 MeV, it naturally played a key role in forging the connection between cosmology and nuclear and particle physics that has blossomed during the past fifteen years.

It is the basic consistency of the predictions for the abundances of the four light-elements D, ^{3}He, ^{4}He and ^{7}Li with their measured abundances, which span more than nine orders of magnitude, that moved BBN to the cosmological centerstage. In its success, BBN has led to the most accurate determination of the mass density of ordinary matter: Consistency holds only if the fraction of critical density contributed by baryons ($\equiv \Omega_B$) is between $0.007h^{-2}$ to $0.024h^{-2}$. This "measurement" has three important implications for cosmology: baryons cannot close the Universe; most of the baryons are dark; and most of the matter is nonbaryonic. (The Hubble constant $H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ enters because it fixes the critical density; recent measurements seem to be converging on a value $h = 0.65 \pm 0.1$.)

Currently, there is great excitement because we are on the verge of determining the baryon density to a precision of 20% or better from measurements of the primeval deuterium abundance. When this occurs, BBN will enter a qualitatively new phase – an era of high precision. The consequences for cosmology are clear – pinning down the baryon density and completing the story of BBN. The implications for astrophysics are just as important – fixing the baryon density fixes the primeval abundances of the light elements and allows them to be used as tracers in the study of the chemical evolution of the Galaxy and aspects of stellar evolution. Finally, important limits to particle properties, such as the limit to the number of light neutrino species, can be further sharpened.

The BBN story [1] begins with Gamow and his collaborators, Alpher and Herman, who viewed the early Universe as a nuclear furnace that could "cook the periodic table." Their speculations, while not correct in all details, led to the prediction of the CBR. Key refinements include those made by Hayashi recognized the role of neutron-proton equilibration, and by Turkevich and Fermi pointed out that lack of stable nuclei of mass 5 and 8 precludes light nucleosynthesis beyond the lightest elements. The framework for the calculations themselves dates back to the work of Alpher, Follin and Herman and of Taylor and Hoyle, preceding the discovery of the 3K background, of Peebles and of Wagoner, Fowler and Hoyle, immediately following the discovery, and the more recent work of our group of collaborators [2] and of other groups around the world [3].

The basic calculation, a nuclear reaction network in an expanding box, has changed very little. The most up to date predictions are shown in Fig. 1. The predictions of BBN are robust because essentially all input microphysics is well determined: The relevant energies, 0.1 to 1 MeV, are explored in nuclear-physics laboratories and the experimental uncertainties are minimal, though not unimportant (see Fig. 1).

Over the last twenty-five years the focus has been on understanding the evolution of the light-element abundances from the big bang to the present in order to test the BBN predictions for the *primeval* abundances. (Astronomers refer to the evolution of the elemental abundances due to nuclear transmutations as "chemical evolution.") In the 1960s, the main focus was ^{4}He, which is very insensitive to the baryon density. The agreement between the BBN prediction – lots of ^{4}He production – and observations/chemical evolution – observed ^{4}He abundance, 25% to 30%, is much greater than what stars can make, a few percent – gave strong support to the big-bang model but gave no significant constraint to the baryon density.

During the 1960s, there was little cosmological interest in the other light isotopes, which are, in principle, capable of giving information about the baryon density, because they were assumed to have been made during the T-Tauri phase of stellar evolution [4]. That changed in the 1970s and primordial nucleosynthesis developed into an important probe of the Universe. In part, this was stimulated by Ryter et al [5] who showed that the T-Tauri mechanism for light-element synthesis failed. Furthermore, knowledge of the deuterium abundance improved significantly with solar-wind and meteoritic measurements [6, 7] and the interstellar medium (ISM) measurements made by the Copernicus satellite [8].

Reeves, Audouze, Fowler and Schramm [9] argued for a cosmological origin for deuterium. By exploiting the rapid decline in deuterium production with baryon density ($\mathrm{D/H} \propto 1/\rho_B^{1.7}$) they were able to place an upper limit to the baryon density which excluded a Universe closed by baryons. This was the beginning of the use of deuterium as a cosmic baryometer, which will soon culminate in an accurate determination of the baryon density. Their argument was strengthened when Epstein, Lattimer and Schramm [10] showed conclusively that no realistic astrophysical process other than the big bang could produce significant deuterium (most astrophysical processes destroy deuterium because it is so weakly bound), and thus, the contemporary abundance leads to a firm upper limit to the baryon density.

In the late 1970s, attention turned to ^{3}He. In part, this was to exploit the steep dependence of deuterium production upon the baryon density to constrain it from below by using the fact that deuterium is burned to ^{3}He. In particular, it was argued that ^{3}He, unlike D, is made in stars: during the pre-main-sequence stage by burning deuterium and in low-mass stars during the main sequence stage. Thus the sum D+^{3}He should increase with time or at least stay constant [11]. Unfortunately, this simple argument is not correct in detail. A recent measurement of ^{3}He in the local ISM [12] has shown that D+^{3}He has been constant for the last 5 Gyr, contradicting a significant increase due to ^{3}He production by low-mass stars, and further, the ^{3}He abundance within the Galaxy shows great variation. The chemical evolution of ^{3}He is not fully understood; however, because the only stars that efficiently destroy ^{3}He are massive and also make metals, metal production provides an upper limit to the amount by which D+^{3}He can decrease and thus a lower bound to the baryon density [13].

The abundances of D, ^{3}He and to a lesser extent ^{4}He led to the prediction that the primeval ^{7}Li abundance should be near its minimum, $^7(\mathrm{Li/H}) \sim 10^{-10}$. This was verified by Spite and Spite [14], who measured the ^{7}Li abundance in the atmospheres of the oldest (pop II) stars in the halo of our galaxy. Their work was confirmed and extended by Hobbs, Thorburn, and others [15]. An important question still remains – could the ^{7}Li abundance in these stars have been reduced by nuclear burning over the past 10 Gyr or so?

The status of BBN was reviewed and summarized in 1995 by Copi et al [16] who concluded: Within the uncertainties – chemical evolution for ^{3}He and D, stellar depletion for ^{7}Li and systematic error for ^{4}He – the abundances of the four light elements produced in the big bang are consistent with their BBN predictions provided that the fraction of critical density contributed by baryons is between $0.007h^{-2}$ and $0.024h^{-2}$ and the equivalent number of light neutrino species is less than 3.7. This is an impressive achievement; it will be eclipsed when the full potential of deuterium as the cosmic baryometer is realized.

2 Keck: The Great Leap Forward

As discussed above, it took a while to recognize the cosmic importance of deuterium and its role as the baryometer. Measuring the primeval deuterium abundance has take even longer and required the advent of the 10 meter W.M. Keck Telescope and its HiRes spectrograph. However, it was worth the wait.

In 1976 Adams [17] outlined how the deuterium abundance in a high-redshift hydrogen cloud could be measured. Distant hydrogen clouds are observed in absorption against even more distant quasars. Many absorption features are seen – the Lyman series of hydrogen and the lines of various ionization states of carbon, oxygen, silicon, magnesium, and other elements. Because of the large hydrogen abundance, Lyα is very prominent. In the rest frame Lyα occurs at 1216Å, so that for a cloud at redshift z Lyα is seen at $1216(1+z_{\rm cloud})$Å. The isotopic shift for deuterium is $-0.33(1+z)$Å, or expressed as a Doppler velocity, $-82\,{\rm km\,s^{-1}}$. Adams' idea was to detect the deuterium Lyα feature in the wing of the hydrogen feature. (The same technique is used to detect deuterium in the local ISM.)

His proposal has much to recommend it: For $z \gtrsim 3$, Lyα is shifted into the visible part of the spectrum and thus can be observed from Earth; "Lyα clouds" are ubiquitous with hundreds being seen along the line of sight to a quasar of this redshift, and judged by their metal abundance, anywhere from 10^{-2} of that seen in solar system material to undetectably small levels, these clouds represent nearly pristine samples of cosmic material. There are technical challenges: Because the expected deuterium abundance is small, ${\rm D/H} \sim 10^{-5} - 10^{-4}$, clouds of very high column density, $n_H \gtrsim 10^{17}\,{\rm cm}^{-2}$, are needed; because hydrogen clouds are ubiquitous, the probability of another, low column-density cloud sitting in just the right place to mimic deuterium – an interloper – is not negligible; many clouds have broad absorption features due to large internal velocities or complex velocity structure; and to ensure sufficient signal-to-noise bright QSOs and large-aperture telescopes are a must. Based upon his experience, Tytler has estimated that no more than one in thirty quasars has a cloud suitable for determining the primeval deuterium abundance.

Since the commissioning of the HiRes spectrograph on Keck-I, a number of detections, tentative detections, upper limits and lower limits for the primeval deuterium – not all consistent with one another – have been reported [18]. However, a confusing situation is now becoming clear. Tytler and his collaborators [19] have made a strong case for a primeval deuterium abundance of (D/H) = $(2.7 \pm 0.3) \times 10^{-5}$, based upon two clouds. One of the clouds is at redshift 3.572 along the line of sight to quasar Q1937-1009; the other is at redshift 2.504 along the line of sight to quasar Q1009+2956. The metal abundances in these clouds are around 10^{-3} of solar, so that any depletion of deuterium due to stellar processing should be negligible. In addition, they have observed the clouds for which others had claimed a much higher abundance, and, with better data, they have shown that the absorption features are not deuterium [20].

It would be premature to conclude that the value of the primeval deuterium abundance has been completely settled, or that all potential systematic errors are fully understood [21]. For example, because the hydrogen Lyα feature is so saturated, it is the hydrogen abundance, not deuterium, that is most difficult to determine; in addition, the clouds usually consist of more than one velocity component, which complicates the analysis. However, Tytler and his collaborators have made a strong case for a primeval deuterium abundance of (D/H) $\simeq (2.7 \pm 0.3) \times 10^{-5}$, with a possible systematic uncertainty of comparable size. The case will be made very firm when a few more clouds of similar deuterium abundance are found, or conversely, the case could fall apart. Both Keck and HST observations are ongoing. The UV capability of HST allows a search at lower redshift where there are fewer clouds and the problem of interlopers mimicking deuterium is less severe.

3 The Baryon Density and Its Cosmic Implications

To be definite and to allow for possible systematic uncertainty, we take as a provisional primeval deuterium abundance, $(\mathrm{D/H})_P = (2.7 \pm 0.6) \times 10^{-5}$. This pegs the baryon density at $(4.0 \pm 0.8) \times 10^{-31}\,\mathrm{g\,cm^{-3}}$, or as a fraction of critical density, $\Omega_B = (0.022 \pm 0.004)h^{-2}$ (theoretical uncertainty included). This lies near the high end of the pre-Keck BBN concordance interval and narrows the range considerably.

This big-bang determination of the baryon density is consistent with other, independent methods: (1) The density of baryons in gas at redshifts between two and four is constrained by the measured Lyα opacity of the ubiquitous hydrogen clouds previously discussed and the baryon density inferred by this method is $\Omega_{\rm gas} \simeq (0.01 - 0.02)h^{-2}(h/0.65)^{1/2}$ [22]. (2) Most of the baryons in clusters of galaxies exist in the form of hot x-ray emitting gas. Assuming that galaxy clusters represent a fair sample of material in the Universe, the cluster baryon fraction, which is determined from x-ray measurements to be $f_B = (0.07 \pm 0.007)h^{-3/2}$ [23], can be used to infer the universal baryon density Ω_B from the matter density Ω_M:

$$\frac{\Omega_B}{\Omega_M} = f_B \qquad \Rightarrow \qquad \Omega_B h^2 = (0.017 \pm 0.002)(h/0.65)^{1/2}(\Omega_M/0.3)\,. \tag{1}$$

(3) The height of the Doppler peak in the angular power spectrum of CBR anisotropy depends the baryon density (see Fig. 7); while the data do not yet determine the baryon density very precisely, they are consistent with the BBN value.

Next, consider the implications of the nucleosynthesis determination of the baryon density. First and foremost, it is the linchpin in the case for the two dark matter problems central to astrophysics and cosmology.

1. The big-bang determination together with measurements of the total amount of matter, provide firm evidence for nonbaryonic dark matter (see Fig. 3). Dynamical measurements of the density of matter that clusters, based upon galaxy-cluster mass determinations, measurements of peculiar velocities, and the frequency of gravitational lensing, indicate that Ω_M is at least 0.3 [24]; nucleosynthesis puts the baryonic contribution at a value far below, $(0.052 \pm 0.01)(0.65/h)^2$. Particle physics provides three compelling candidates for the nonbaryonic matter: a very light axion (mass $\sim 10^{-5}\,\mathrm{eV}$); a light neutrino species (mass $\sim \mathcal{O}(10\,\mathrm{eV})$); and the lightest supersymmetric particle (neutralino of mass $30\,\mathrm{GeV}$ to $500\,\mathrm{GeV}$). That most of the matter is nonbaryonic receives additional support: There is no model for the formation of structure without nonbaryonic matter that is consistent with the anisotropy of the CBR.

2. The BBN determination also implies that most of the baryons are in a form yet to be identified. Stars and closely related material ("luminous matter") contribute less than 1% of the critical density, $\Omega_{\rm LUM} \simeq 0.003h^{-1}$; since this is almost a factor of ten lower than the BBN determination of the baryon density, it follows that most of the baryons are not optically bright ("dark").

The fact that the fraction of critical density in gas at redshifts two to four and in gas at the time of formation of clusters, redshifts one or less, is consistent with the nucleosynthesis value for the baryon density, suggests that the bulk of the "dark" baryons are diffuse, hot gas. In clusters, this is clear – most of the baryons are in the hot intracluster gas that shines bright in x ray. Individual galaxies have shallower potential wells and the gas would have a temperature of only around $10^5\,\mathrm{K}$, making it difficult to detect. There is some evidence, absorption of quasar light by singly ionized helium, for diffuse, intergalactic gas [25]. While most of the dark baryons are likely in the form of diffuse, hot gas, some fraction of the dark baryons, perhaps 10%, are likely to be in the form of dark stars (or MACHOs), e.g., white dwarfs, neutron stars, brown dwarfs and so on. There is evidence from microlensing that dark stars comprise a portion of the the halo of our own galaxy [26].

Turning a previous argument around, accepting the baryon density based upon the primeval deuterium abundance, the cluster baryon fraction can be used to infer the matter density:

$$\Omega_M = \Omega_B / f_B = (0.35 \pm 0.1)(0.65/h)^{1/2}. \tag{2}$$

Taken at face value, this implies that the matter density, while much larger than the baryon density, is far from unity. (This technique is not sensitive to a smooth component such as vacuum energy, and does not preclude $\Omega_0 = 1$ with $\Omega_{\rm VAC} \sim 0.65$, or an even more exotic smooth component.) However, important assumptions underlie the determination of the cluster baryon fraction: the gas is supported by its thermal motions only and not magnetic fields or bulk motion; the gas is not clumped; and clusters provide a fair sample of matter in the Universe. If any one of these assumptions is not valid, the cluster gas fraction would be lower and the estimate for Ω_M correspondingly higher. There is some evidence that this may be the case – cluster masses determined by gravitational lensing appear to be systematically larger than those determined by x-ray measurements [27], perhaps as much as a factor of two.

4 Nuclear Cosmology Clarifies Galactic Chemistry

Chemical evolution issues have been interwoven into the study of BBN from the start. In order to extrapolate contemporary abundances to primordial abundances the use of stellar and Galactic chemical-evolution models is unavoidable. The difficulties are well illustrated by ^{3}He: generally the idea that the sum D+^{3}He is constant or slowly increasing seems to be true, but the details, e.g., predicted increase during the last few Gyr, are inconsistent with a measurement of the ^{3}He abundance in the local ISM.

The pinning down of the baryon density turns the tables around. Primeval abundances become fixed and comparison with contemporary abundances can be used to reveal the details of stellar and Galactic chemical evolution. Nuclear physics in the early Universe provides tracers to study Galactic chemistry! For sake of illustration we continue to our provisional baryon density, $(4.0 \pm 0.8) \times 10^{-31}\,\mathrm{g\,cm^{-3}}$, and remind the reader that conclusions could change if the value for the primeval deuterium abundance changes.

Beginning with deuterium, our assumed primeval abundance, $\mathrm{D/H} = (2.7 \pm 0.6) \times 10^{-5}$, is not quite a factor of two larger than the present ISM abundance, $\mathrm{D/H} = (1.5 \pm 0.1) \times 10^{-5}$, determined by Hubble Space Telescope observations [28]. This implies 1) little nuclear processing over the history of the Galaxy; and/or 2) significant infall of primordial material into the disk of the Galaxy. The metal composition of the Galaxy, which indicates significant processing through stars, together with the suggestion that even more metals may have been made and ejected into the IGM (apparently this happens at least in clusters of galaxies), means that option one is less likely than option two. Even more intriguing is the fact that the inferred abundance of deuterium in the pre-solar nebula, $\mathrm{D/H} = (2.6 \pm 0.4) \times 10^{-5}$ [29], indicates less processing in the first 10 Gyr of Galactic history than in the past 5 Gyr, perhaps suggesting a decreasing rate of infall and/or a change in the distribution of stellar masses.

Moving on to ^{3}He, the primeval value corresponding to our assumed deuterium abundance is $^3\mathrm{He/H} \simeq 10^{-5}$. The pre-solar value, measured in meteorites and more recently in the outer layer of Jupiter, is $^3\mathrm{He/H} = (1.2 \pm 0.2) \times 10^{-5}$ [29], comparable to the primeval value. The value in the present ISM, $^3\mathrm{He/H} = (2.1 \pm 0.9) \times 10^{-5}$, is about twice as large as the primeval value [12]. On the other hand, the primeval sum of deuterium and ^{3}He, $(3.7 \pm 0.7) \times 10^{-5}$ relative to H, is essentially equal to that determined for the pre-solar nebula, $(3.8 \pm 0.4) \times 10^{-5}$, and for the present ISM, $(3.7 \pm 1) \times 10^{-5}$. This indicates little net ^{3}He production beyond the burning of deuterium to ^{3}He, and conflicts with conventional models for the evolution of ^{3}He which predict a significant increase in D+^{3}He (due to ^{3}He production by low-mass stars), as well as unconventional models where ^{3}He is efficiently burned. The constancy of

D+^{3}He might be actually be a coincidence: In models put forth to explain certain isotopic anomalies (^{18}O/^{16}O and ^{12}C/^{13}C) [30], ^{3}He is produced during the main-sequence phase and then destroyed during post-main-sequence evolution. While empirical evidence supports the idea that the D+^{3}He remains roughly constant, clearly much remains to be learned about the chemical evolution of ^{3}He.

Finally, consider ^{7}Li. The predicted primeval abundance, ^{7}Li/H $= (5 \pm 2) \times 10^{-10}$, is a factor of two to three larger than that measured in the atmospheres of pop II halo stars, ^{7}Li/H $= (1.5 \pm 0.3) \times 10^{-10}$. There are two plausible explanations. The abundance determinations in these old halo stars are sensitive to the model atmospheres used, and there could be as much as 50% uncertainty due to this. Or lithium could have been depleted in these old stars. The observation of ^{6}Li in at least one pop II halo, which is much more fragile than ^{7}Li, limits stellar depletion to a factor of two or less [31]; further, the fact that the ^{7}Li abundance is at most weakly dependent upon stellar mass also argues for a depletion of at most a factor of two or so [32]. (Both arguments seem to be validated since the ratio of the pop II abundance to primeval abundance is about a factor of two.) If depletion is important, as seems likely, further, high-quality observations of these old halo stars should begin to reveal dispersion in the ^{7}Li abundance due to the difference in rotation rates and/or ages. Tidally locked binaries, where the rotation rate is known, are especially useful. When the final details of the ^{7}Li story are in, much will have been learned about the role of rotation and mixing in stellar evolution.

5 Helium-4: A Loose End

Helium-4 plays a different role and presents different challenges. First, the primeval yield of ^{4}He is relatively insensitive to the baryon density – pinning down the baryon density to 20% pegs its value to 1% precision (see Fig. 5). Secondly, the chemical evolution of ^{4}He is straightforward – the abundance of ^{4}He slowly increases due to stellar production. Helium-4 was the first important test of BBN; a high-precision determination of the primeval ^{4}He abundance will guarantee that it has an important future role too.

Here is the present situation: Assuming our provisional value for the primeval deuterium abundance, the predicted primeval ^{4}He abundance is $Y_P = 0.2475 \pm 0.002$ (including theoretical uncertainty). There have been two recent determinations of the primeval abundance based upon the He/H ratio measured in regions of hot, ionized gas (HII regions) found in metal-poor, dwarf emission-line galaxies. Using one sample and extrapolating to zero metallicity, Olive and Steigman [33] infer $Y_P = 0.232 \pm 0.003\,(\mathrm{stat}) \pm 0.005\,(\mathrm{sys})$; using a new sample of objects Izotov et al [34] infer $Y_P = 0.243 \pm 0.003\,(\mathrm{stat})$. Both data sets are shown in Fig. 4. In brief, the current situation is ambiguous, both as to the primeval ^{4}He abundance and as to the consistency of the big-bang prediction.

There has been much debate about ^{4}He; there is a general consensus that systematic error is the limiting factor at present. Many effects have to be considered to achieve the desired accuracy: corrections for doubly ionized ^{4}He and neutral ^{4}He have to be made; absorption by dust and by stars have to be accounted for; collisional excitation must be accounted for; potential systematic errors exist in the input atomic physics; and extrapolation to zero metallicity must be made in the absence of a well motivated model. (Regarding the last point, because there is more than one post-big-bang source of ^{4}He, the relationship between Y_P and metallicity is almost certainly not single-valued.)

Olive and Steigman argue that the systematic error is no larger than 0.005, and their estimate of the primordial ^{4}He abundance is discrepant with the prediction based upon deuterium. (Hata et al [36] have even gone so far as to argue for a crisis; for another view see Ref. [37].) Others, including Pagel, Skillman, Sasselov and Goldwirth, believe that the current systematic error budget is larger – more like 0.010 or 0.015 – in which case the discrepancy is at most two sigma. And of course, the Izotov et al value for Y_P is consistent with the big-bang prediction.

Turning to the data themselves; the two samples are in general agreement, except for the downturn at the lowest metallicities which is seen in the data analyzed by Olive and Steigman. (Skillman has recently also expressed concern about the use of the lowest metallicity object, IZw18 [38].) Visually, the data make a strong case for a primordial ^{4}He abundance that is greater than 0.22 and less than about 0.25.

To be more quantitative about this statement and to derive very conservative upper and lower bounds to Y_P, we have carried out a nonparametric Bayesian analysis which makes minimal assumptions about systematic error and the relationship between Y_P and metallicity. We write the ^{4}He abundance of a given object as $Y_i = Y_P + \Delta Y_i$. To obtain a lower bound to Y_P we take a flat prior for ΔY_i, $0 < \Delta Y_i < 1 - Y_P$, which accounts for the fact that stellar contamination increases the ^{4}He abundance. To obtain an upper bound to Y_P we take a different flat prior, $-Y_P < \Delta Y_i < 0$, which accounts for possible systematic error that might lead to an underestimation of the ^{4}He abundance in an object. The likelihood distributions for the lower bound to Y_P (first method) and for the upper bound (second method) are shown in Fig. 6. The 95% confidence intervals for the two bounds are:

$$\begin{array}{ll} \text{Conservative Lower Limit :} & Y_P(\text{lower}) = 0.220^{+0.006}_{-0.012} \\ \text{Conservative Upper Limit :} & Y_P(\text{upper}) = 0.253^{+0.015}_{-0.005} \end{array} \tag{3}$$

While one certainly would like to do better in pinning down Y_P, this very conservative analysis illustrates the strength of the case for a primeval ^{4}He mass fraction between 22% and 25%. (Recently, Hogan et al have carried out a similar analysis to derive a similar lower limit to Y_P [35].)

At the moment ^{4}He is a loose end. Once the systematic uncertainties are under control, ^{4}He has an important role to play in the high-precision era, as a test of the consistency of BBN. Skillman and others are talking about a new assault on Y_P – putting together a larger, more homogeneous set of low-metallicity galaxies in order to better understand, and hopefully reduce, systematic error. It will be interesting to see if it turns out to be the loose end that unravels the tapestry or if it is woven back into the tapestry. The resolution of the ^{4}He problem could even involve new physics – a short lived tau neutrino of mass greater than a few MeV could lower the prediction for Y_P by as much as $\Delta Y = 0.012$ – but it is certainly premature to give much weigh to this possibility.

6 A New Test of The Standard Theory

Almost overnight, the discovery of the Cosmic Background Radiation transformed cosmology from the realm of a handful of astronomers to a branch of physics. Moreover, it was considerations of big-bang nucleosynthesis that led Gamow, Peebles and others to predict the existence of the CBR [1]. In the next decade, the CBR will likely return the favor by providing an important new check of big-bang nucleosynthesis.

The BBN test is part of a larger program to harvest the wealth of information about the early Universe that is encoded in the anisotropies of the CBR. The anisotropy of the CBR is most naturally described by its multipole decomposition

$$\frac{\delta T(\theta,\phi)}{T} = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)\,. \tag{4}$$

For a theory like inflation, where the underlying density perturbations that lead to the anisotropy are gaussian, all information is encoded in the variance of the multipole amplitudes. (The multipoles are gaussian distributed with zero mean, with the *rms* temperature difference between directions on the sky separated by angle θ given roughly by $\sqrt{l(l+1)C_l/2\pi}$ with $l \approx 180^\circ/l$.) The angular power spectrum, $C_l \equiv \langle |a_{lm}|^2 \rangle$, depends not only on the spectrum of density perturbations, but also upon cosmological parameters, including the baryon density.

The angular power spectrum, shown in Fig. 7, is characterized by a featureless (Sachs-Wolfe) plateau from $l = 2$ to $l \sim 100$; and a series of (acoustic or Doppler) peaks and valleys from $l = 200$ to $l \sim 2000$; for $l \gg 2000$ anisotropy is strongly damped by photon diffusion which smears out anisotropy on smaller scales [39]. The plateau arises due to differences in the gravitational potential on the last scattering surface (Sachs-Wolfe effect). The peaks and valleys arise due to photon-baryon acoustic oscillations driven by gravity, and their amplitudes and spacings depend upon the contribution of baryons to the matter density (see Fig. 7).

When the two new satellite-experiments, NASA's MAP to be launched in August 2000 and ESA's Planck to be launched in 2005, map the sky with angular resolution of 0.1° (or better), they will determine the variance of about 2500 multipoles to an accuracy essentially limited by sky coverage and sampling variance. From this it should be possible to determine precisely a number of cosmological parameters, including the total energy density (Ω_0) and the fraction of critical density contributed by matter (Ω_M), a cosmological constant (Ω_Λ), and neutrinos (Ω_ν); the Hubble constant (H_0); the power-law index of the spectrum of density perturbations (n) and deviation from an exact power law ($dn/d\ln k$); the contribution of gravitational waves to the anisotropy (tensor to scalar ratio T/S); and the baryon density

($\Omega_B h^2$). In particular, the baryon density should ultimately be determined to a precision of around 5% [40].

Even before MAP flies a host of balloon-borne and ground-based experiments (e.g., CBI, MAXIMA, VCA, VSA, BOOMERANG, QMAT, and TOPHAT) will cover a significant fraction of the sky with angular resolution of less than one degree. These experiments may be able to delineate the first two or three acoustic peaks and thereby determine the baryon density to 25% or so.

Certainly within a decade, and probably much sooner, there will be an independent, high-precision determination of the baryon density which is based on very different physics – gravity-driven, acoustic oscillations of the photon-baryon fluid when the Universe was around 300,000 years of age. If this determination of the baryon density agrees with that based upon big-bang nucleosynthesis it will be an impressive confirmation of the standard cosmology as well as the standard cosmology and general relativity.

7 Probing Particle Physics with New Precision

For almost two decades, big-bang nucleosynthesis has also been a powerful probe of fundamental physics, best illustrated by the BBN limit to the number of light neutrino species. In 1977 Gunn, Schramm and Steigman argued that big-bang helium production set a limit of less than seven light neutrino species [41]; by 1980 the limit had been refined to less than four neutrino species. Not until the Z^0-factories at SLAC and CERN came on line in 1989 did the laboratory limit become competitive (see Fig. 8). Today, the LEP limit based upon the shape of the Z^0 resonance stands at $N_\nu = 2.989 \pm 0.024$ (95% cl), a truly impressive achievement.

While it is unlikely that the big-bang nucleosynthesis limit will ever achieve such precision, it will improve significantly when the baryon density is determined accurately. Moreover, the cosmological and laboratory limits are complementary: The neutrino limit based upon the shape of the Z^0 counts the number of particle species that are less massive than half the Z^0 mass, weighted by their coupling to the Z^0. BBN constrains the energy density contributed by relativistic particle species around the time of primeval nucleosynthesis and thus is sensitive to any particle species lighter than about 1 MeV. Historically, both have been expressed as a limit to the number of neutrino species.

Let's quickly review the physics of the big-bang nucleosynthesis limit. The amount of ^{4}He synthesized depends strongly upon the expansion rate, which determines the neutron fraction at the epoch of nucleosynthesis, and weakly upon the baryon density, which determines reaction rates (see Fig. 5). A faster expansion rate leads to more ^{4}He production because the neutron fraction freezes out at a higher value; higher baryon density leads to more production of ^{4}He as nuclear reactions begin earlier when the neutron fraction is higher. The expansion rate itself is determined by the energy density in relativistic particles, parameterized by the effective number of massless particle species,

$$g_* = \sum_{m \lesssim 1\,\mathrm{MeV}}^{\mathrm{Fermi}} g_i (T_i/T)^4 + \frac{7}{8} \sum_{m \lesssim 1\,\mathrm{MeV}}^{\mathrm{Bose}} g_i (T_i/T)^4 \,, \tag{5}$$

where T_i is the temperature of species i. A species that interacts more weakly than neutrinos can have a lower temperature than the plasma temperature [42]. The particles in the standard model contribute 10.75 to the sum, with each neutrino species contributing 1.75.

In the absence of precise knowledge of the baryon density and the measured primeval ^{4}He abundance, setting a big-bang limit requires a *lower limit* to the baryon density and an upper limit to the value of the primeval ^{4}He abundance. For more than a decade the lower limit to the baryon density was based upon the upper limit to the big-bang production of D+^{3}He. The upper limit to the primeval production of ^{4}He was assumed to be 25% (and sometimes as low as 24%). Much progress has been made on the former – the provisional value of the primeval deuterium abundance pegs the baryon density to a precision of 20% at a value that is a factor of three above the previous lower limit.

Pinning down the baryon density improves the big-bang neutrino limit significantly. A recent Bayesian analysis assuming a primeval ^{4}He abundance $Y_P = 0.242 \pm 0.003$ gave the following 95% credible intervals for N_ν: $N_\nu = 3.0 - 3.7$, assuming the D+^{3}He lower bound to the baryon density (constrained by metal production), and $N_\nu = 3.0 - 3.2$, assuming $(\mathrm{D/H})_P = (2.5 \pm 0.75) \times 10^{-5}$ [43] (in both cases the prior $N_\nu \geq 3$ was enforced).

The determination of the baryon density from the primeval deuterium abundance will have a similarly dramatic impact on the big-bang limit as the commissioning of the Z^0 factories did on the laboratory limit. When the baryon density is known to a precision of 5% and when the systematic uncertainties in the ^{4}He abundance are reduced, an upper limit as precise as 3.1 neutrino species is likely. Together, the cosmological and laboratory neutrino limits work hand in hand to constrain new physics.

8 Concluding Remarks

Big-bang nucleosynthesis is a cornerstone of the standard cosmology. Together with the CBR it provides compelling evidence that the early Universe was hot and dense. This opened the door to the study of the earliest moments and helped to forge the symbiotic relationship between particle physics and cosmology. The inner space – outer space connection has led to very interesting and attractive ideas about the earliest moments, including inflation and cold dark matter. These ideas are now being tested by a host of experiments and observations and in process a new window to fundamental physics is being opened [44].

For more than two decades BBN has also provided the best determination of the baryon mass density, which has led to three important conclusions: baryons cannot provide the closure density; most of the baryons are dark and most of the dark matter is nonbaryonic.

As we have tried to emphasize and illustrate, the pegging of the baryon density by a determination of the primeval deuterium abundance will advance BBN to a new, precision era. The harvest to come is impressive: An accurate determination of a fundamental parameter of cosmology; light-element tracers to study Galactic and stellar chemical evolution; and new precision in probing fundamental physics. Finally, there are two important tests of BBN on the horizon: a precision check of the predicted primeval ^{4}He abundance by new measurements; and a comparison of the BBN value for the baryon density with that derived from CBR anisotropy.

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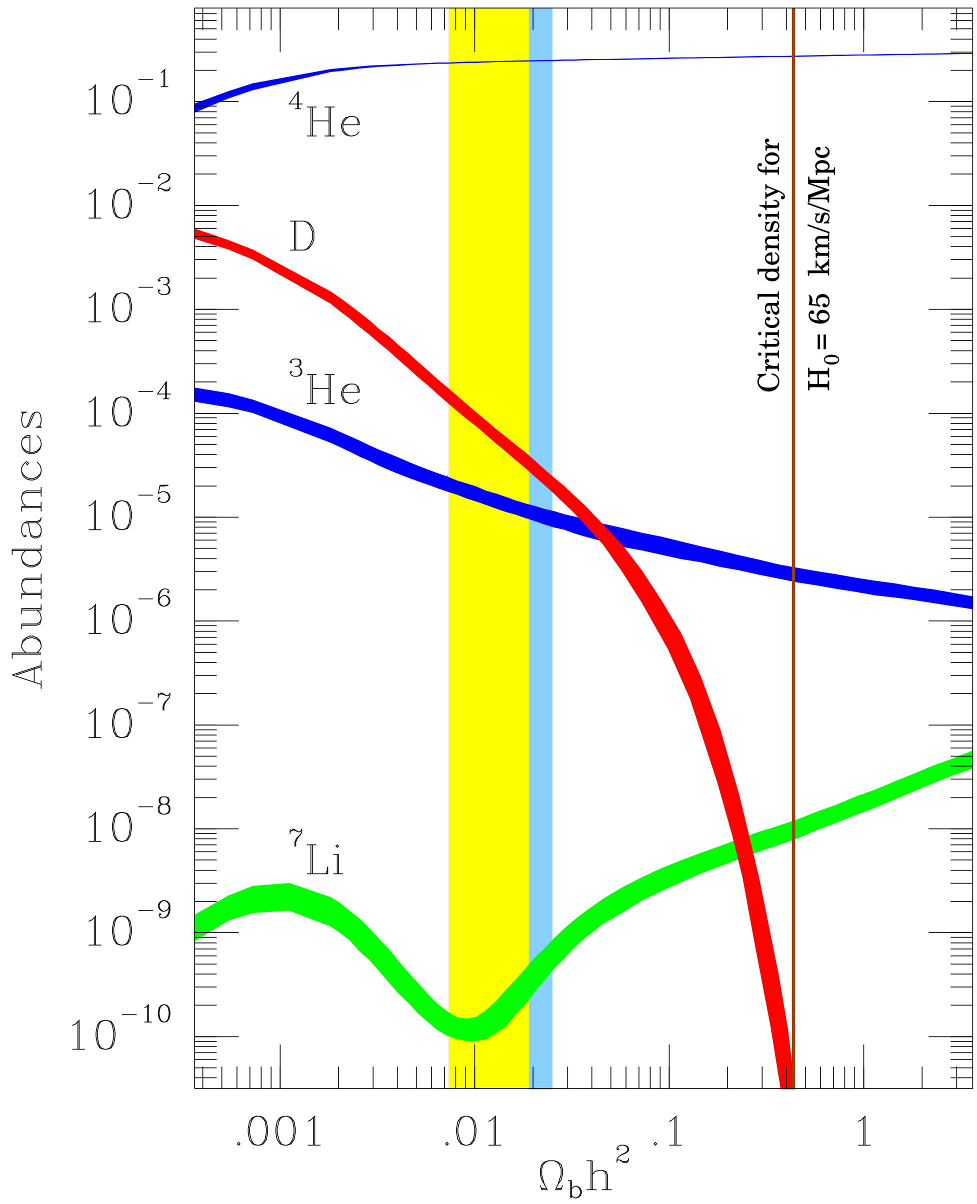

Figure 1: Summary of big-bang production of the light elements. The widths of the curves indicate the 2σ theoretical uncertainties, and the vertical band is the Copi et al [16] consistency interval where the predicted abundances of all four light elements agree with their measured primeval abundances. The darker band in the consistency interval corresponds to Tytler et al's determination of the primeval deuterium abundance (Figure courtesy of K. Nollett).

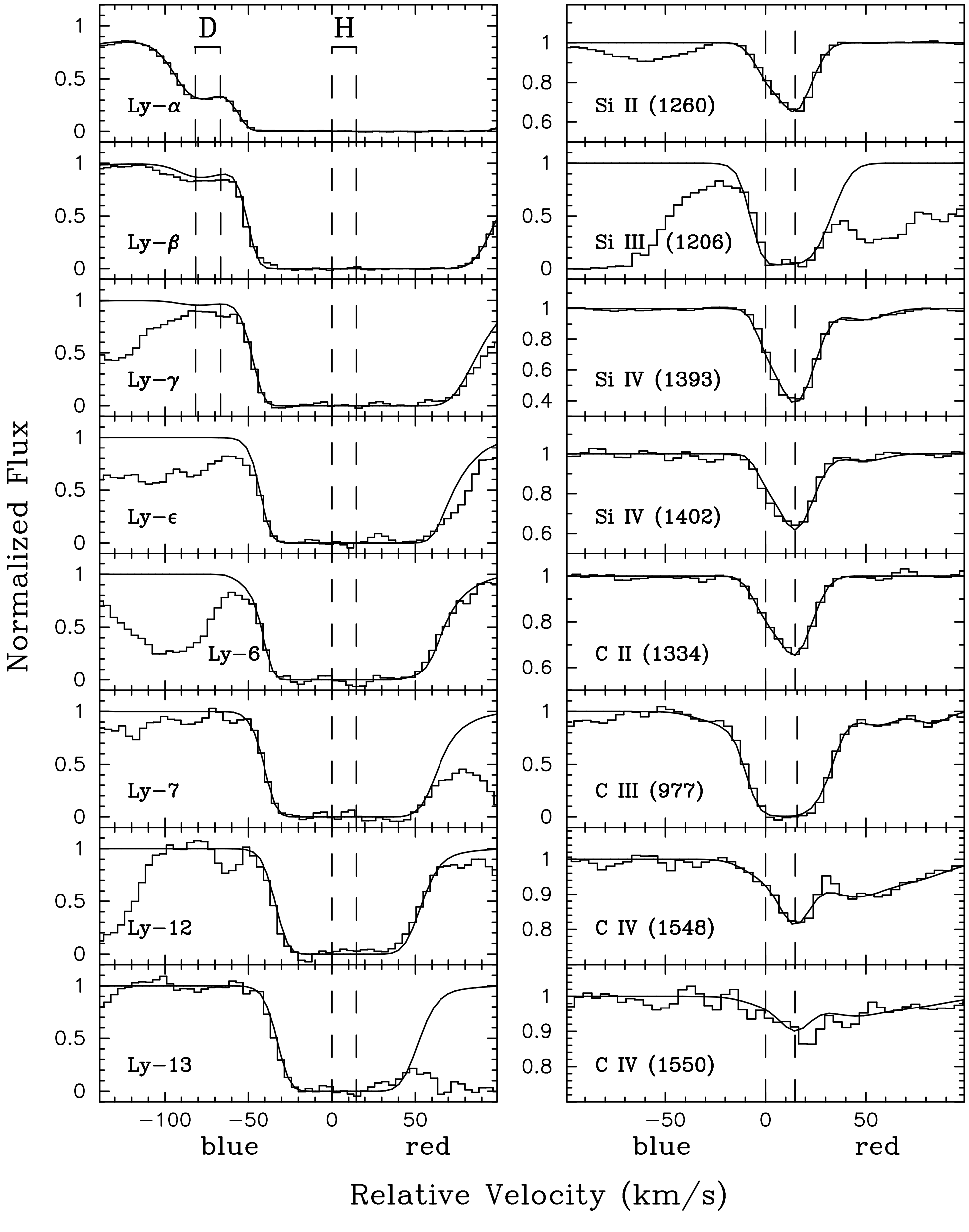

Figure 2: Portion of the Keck HiRes spectrum of Q1937-1009. Solid line indicates the model fit and the deuterium Ly-α feature is indicated. The left panels show the Lyman series for the cloud and the right panels show the narrow metal lines associated with the cloud, which are crucial to determining the positions of the two components of the cloud (from Ref. [19]).

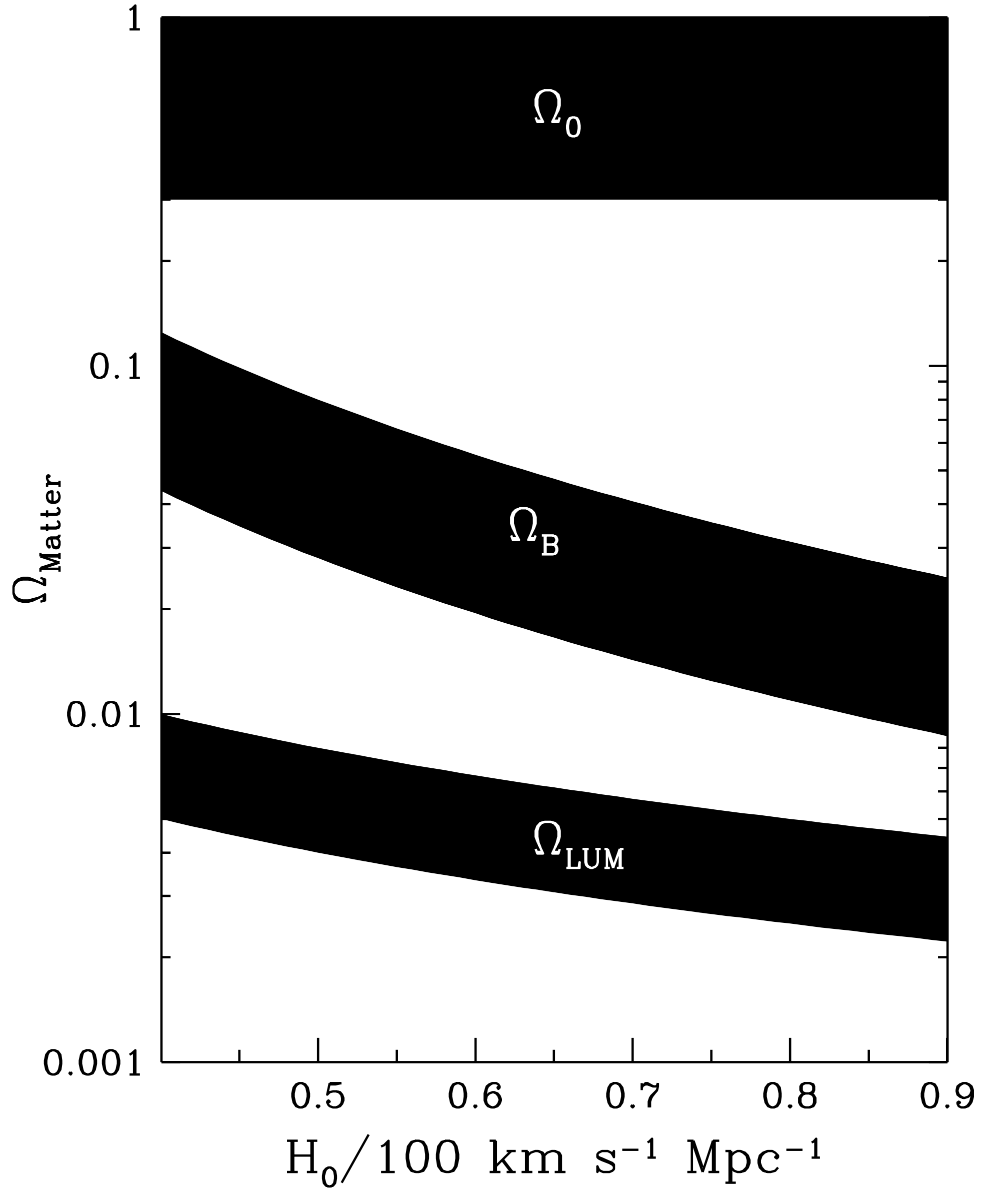

Figure 3: Summary of knowledge of the matter density Ω_M. The lowest band is luminous matter, in the form of bright stars and associated material; the middle band is the pre-Keck big-bang nucleosynthesis concordance interval; the upper region is the estimate of the total matter density based upon dynamical methods [24]. The gaps between the bands illustrate the two dark matter problems: most of the ordinary matter is dark and most of the matter is nonbaryonic.

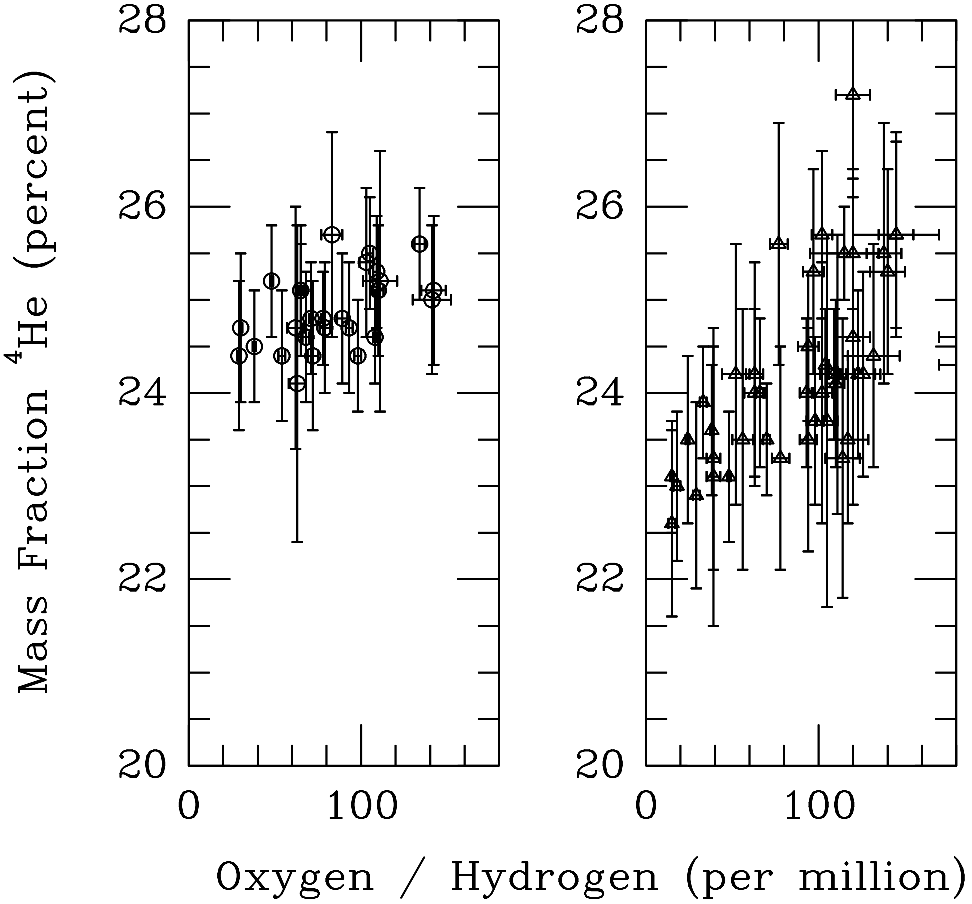

Figure 4: Helium-4 abundance vs. oxygen abundance in metal-poor, dwarf emission-line galaxies. Right panel (triangles) is the sample analyzed by Olive and Steigman [33]; left panel (circles) is the new sample of Izotov et al [34].

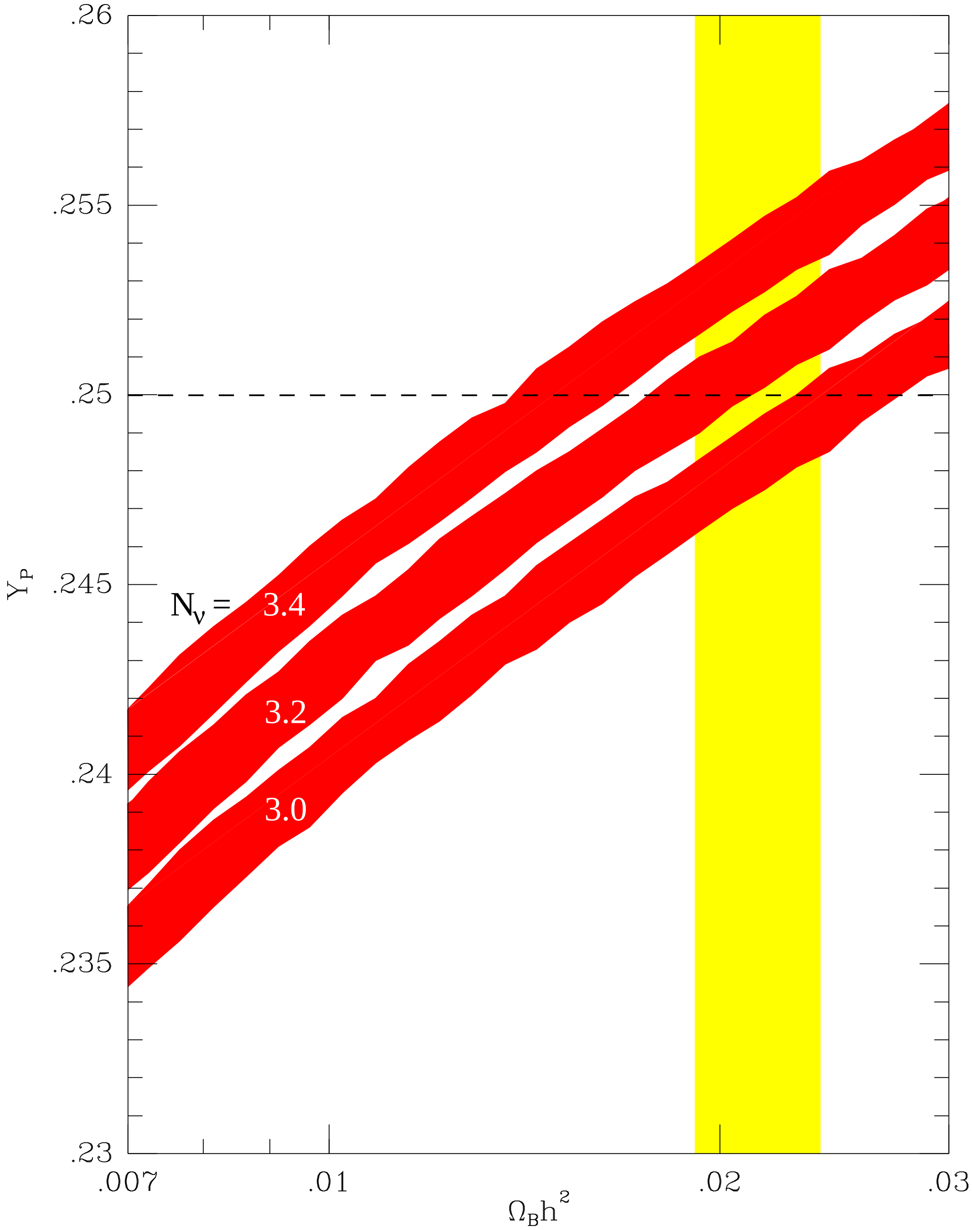

Figure 5: ^{4}He production for $N_\nu = 3.0, 3.2, 3.4$. The vertical band indicates the baryon density consistent with $(D/H)_P = (2.7 \pm 0.6) \times 10^{-5}$ and the horizontal line indicates a primeval ^{4}He abundance of 25%. The widths of the curves indicate the two-sigma theoretical uncertainty.

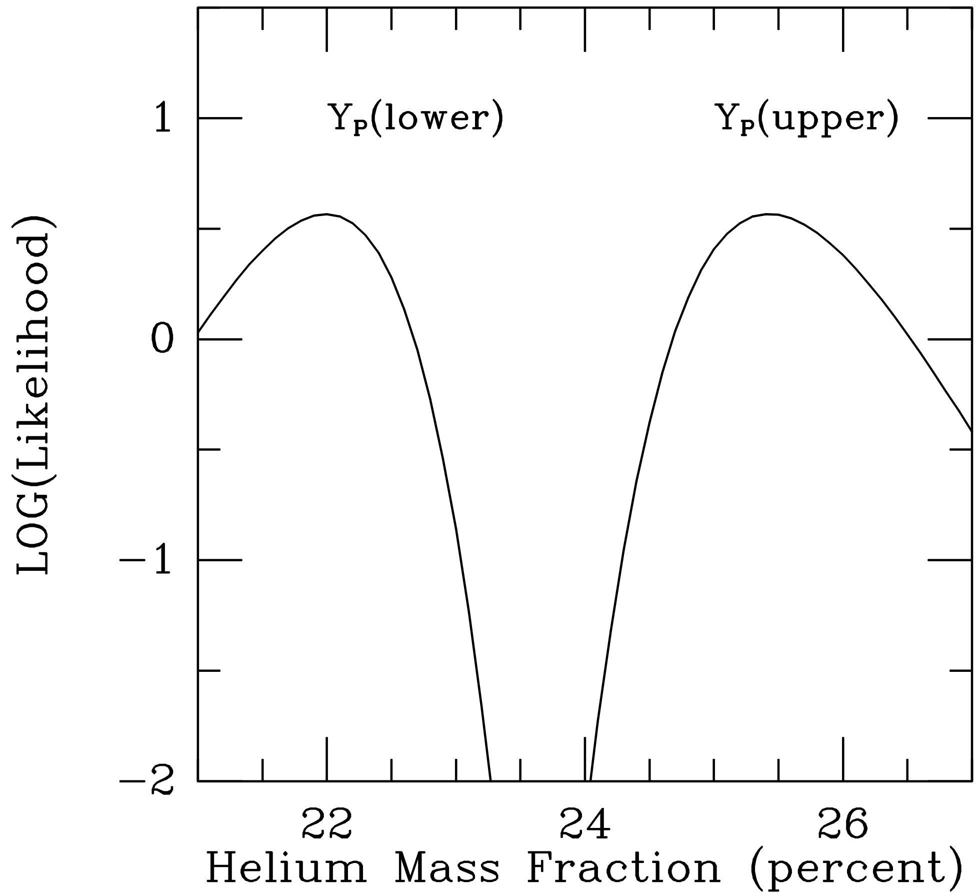

Figure 6: Likelihood functions (unnormalized) for the conservative lower limit to Y_P (left) and conservative upper limit to Y_P (right). These results are based upon the HII regions in the sample analyzed by Olive and Steigman with metallicity O/H$\leq 10^{-4}$; qualitatively similar results obtain for different metallicity cuts and for the Izotov et al sample.

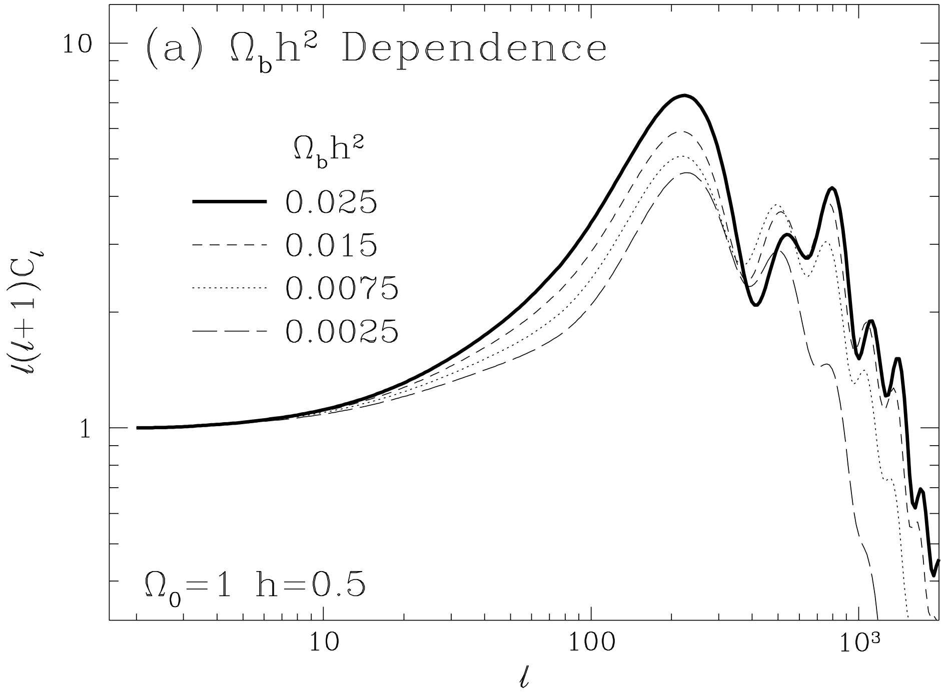

Figure 7: Dependence of the angular power spectrum of CBR anisotropy on baryon density for cold dark matter models (courtesy of Martin White).

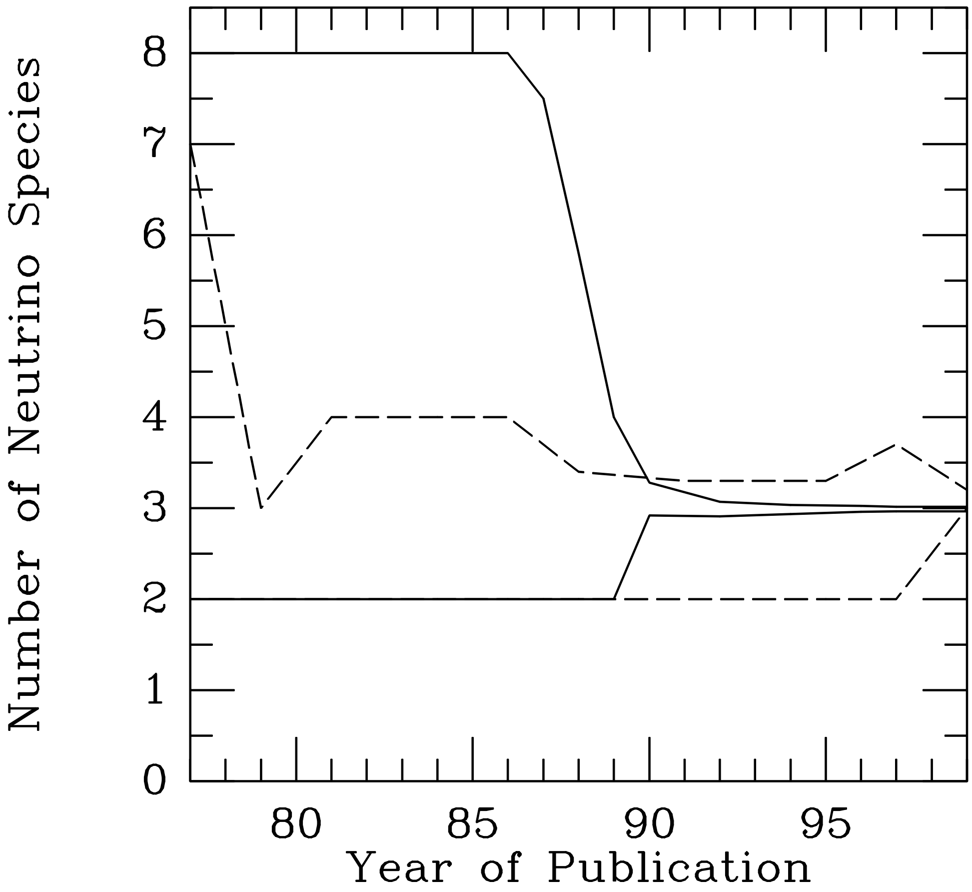

Figure 8: Cosmological (broken curve) and laboratory (solid curve) limits (95% cl) to the number of neutrino species. An ultimate cosmological limit of 3.1 neutrino species has been "anticipated."