Fermi National Accelerator Laboratory

PROBING THE BIG BANG WITH LEP *

David N. Schramm

The University of Chicago,
5640 S. Ellis Avenue, Chicago, IL 60637
and
NASA/Fermilab Astrophysics Center,
Fermi National Accelerator Laboratory
Box 500, Batavia, IL 60510-0500

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ABSTRACT

It is shown that LEP probes the Big Bang in two significant ways: (1) nucleosynthesis and (2) dark matter constraints. In the first case, LEP verifies the cosmological standard model prediction on the number of neutrino types, thus strengthening the conclusion that the cosmological baryon density is $\sim 6\%$ of the critical value. In the second case, LEP shows that the remaining non-baryonic cosmological matter must be somewhat more massive and/or more weakly interacting than the favorite non-baryonic dark matter candidates of a few years ago.

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INTRODUCTION

In some sense, LEP has positively tested the standard model of cosmology, the Big Bang, in much the same way it has positively tested the standard model of particle physics, $SU(3) \times SU(2) \times U(1)$. In fact, this is the first time that a particle accelerator (as opposed to a telescope) has been able to provide a test of the basic Big Bang model. LEP probes the Big Bang in two ways::

1) through nucleosynthesis and neutrino counting; and

2) through limiting dark matter candidates.

This particular discussion will focus on the first of these, but it is important to realize that the nucleosynthesis arguments are the definitive arguments for non/baryonic matter, thus by LEP supporting the standard Big Bang Nucleosynthesis results, LEP is also indirectly supporting the argument for non-baryonic matter which LEP results do constrain.

As to Big Bang Nucleosynthesis (BBN) itself, it is worth remembering that along with the 3K background radiation, the agreement of the observed light element abundances with the nucleosynthetic predictions is one of the major cornerstones of the Big Bang. The new COBE[1] results have given renewed confidence in the $3K$ background argument, just as LEP has given us renewed confidence in the BBN arguments. Because the microwave background probes events at temperatures $\sim 10^4 K$ and times of $\sim 10^5$ years, whereas the light element abundances probe the Universe at temperatures $\sim 10^{10} K$ and times of ~ 1 sec, it is the nucleosynthesis results that have led to the particle-cosmology merger we have seen over the last decade.

HISTORY OF BIG BANG NUCLEOSYNTHESIS

Before going into the specific argument as to sensitivity of BBN to the number of neutrino families (N_ν), let us review the history of BBN. In particular, it should be noted that there is a symbiotic connection between BBN and the $3K$ background dating back to Gamow and his associates Alpher and Herman. The initial BBN calculations of Gamow's

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group[2] assumed pure neutrons as an initial condition and thus were not particularly accurate but their inaccuracies had little effect on the group's predictions for a background radiation.

Once Hayashi (1950) recognized the role of neutron-proton equilibration, the framework for BBN calculations themselves has not varied significantly. The work of Alpher, Follin and Herman[3] and Taylor and Hoyle[4], preceeding the discovery of the 3K background, and Peebles[5] and Wagoner, Fowler and Hoyle,[6] immediately following the discovery, and the more recent work of our group of collaborators[7,8,9,10] all do essentially the same basic calculation, the results of which are shown in Figure 1. As far as the calculation itself goes, solving the reaction network is relatively simple by the standards of explosive nucleosynthesis calculations in supernovae, with the changes over the last 25 years being mainly in terms of more recent nuclear reaction rates as input, not as any great calculational insight.

With the exception of the effects of elementary particle assumptions to which we will return, the real excitement for BBN over the last 25 years has not really been in redoing the calculation. Instead, the true action is focused on understanding the evolution of the light element abundances and using that information to make powerful conclusions. In particular, in the 1960's, the main focus was on ^4He which is very insensitive to the baryon density. The agreement between BBN predictions and observations helped support the basic Big Bang model but gave no significant information at that time with regard to density. In fact, in the mid-1960's, the other light isotopes (which are, in principle, capable of giving density information) were generally assumed to have been made during the t-tauri phase of stellar evolution,[11] and so, were not then taken to have cosmological significance. It was during the 1970's that BBN fully developed as a tool for probing the Universe. This possibility was in part stimulated by Ryter, Reeves, Gradstajn and Audouze[12] who showed that the t-tauri mechanism for light element synthesis failed. Furthermore, ^2H abundance determinations improved significantly with solar wind measurements[13] and the inster-
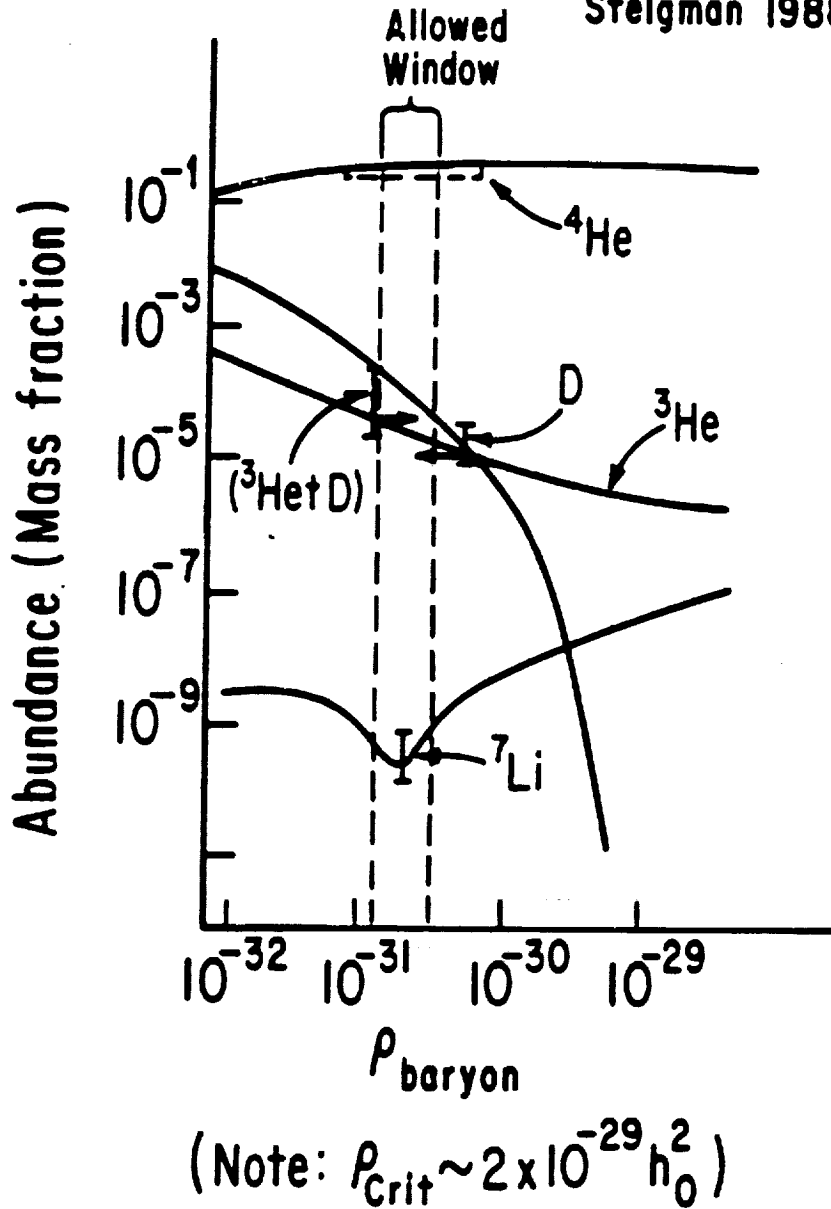
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Figure 1. Big Bang Nucleosynthesis abundance yields (mass fraction) versus baryon density for a homogeneous universe.

stellar work from the Copernicus satellite.[14] Reeves, Audouze, Fowler and Schramm[15] argued for cosmological ^2H and were able to place a constraint on the baryon density excluding a universe closed with baryons. Subsequently, the ^2H arguments were cemented when Epstein, Lattimer and Schramm[16] proved that no realistic astrophysical process other than the Big Bang could produce significant ^2H. It was also interesting that the baryon density implied by BBN was in good agreement with the density implied by the dark galactic halos.[17]

By the late 1970's, a complimentary argument to ^2H had also developed using ^3He. In particular, it was argued[18] that, unlike ^2H, ^3He was made in stars; thus, its abundance would increase with time. Since ^3He like ^2H monotonically decreased with cosmological baryon density, this argument could be used to place a lower limit on the baryon density[19] using ^3He measurements from solar wind[13] or interstellar determinations.[20] Since the bulk of the ^2H was converted in stars to ^3He, the constraint was shown to be quite restrictive.[8]

It was interesting that the lower boundary from ^3He and the upper boundary from ^2H yielded the requirement that ^7Li be near its minimum of $^7Li/H \sim 10^{-10}$, which was verified by the Pop II Li measurements of Spite and Spite,[21] hence, yielding the situation emphasized by Yang et al.[8] that the light element abundances are consistent over nine orders of magnitude with BBN, but only if the cosmological baryon density is constrained to be around 6% of the critical value.

The other development of the 70's for BBN was the explicit calculation of Steigman, Schramm and Gunn,[22] showing that the number of neutrino generations, N_ν, had to be small to avoid overproduction of ^4He. (Earlier work had noted a dependency of the ^4He abundance on assumptions about the fraction of the cosmological stress-energy in exotic particles,[23,4] but had not actually made an explicit calculation probing the quantity of interest to particle physicists, N_ν.) To put this in perspective, one should remember that the mid-1970's also saw the discovery of charm, bottom and tau, so that it almost seemed

as if each new detection produced new particle discoveries, and yet, cosmology was arguing against this "conventional" wisdom. Over the years this cosmological limit on N_ν improved with ^4He abundance measurements, neutron lifetime measurements and with limits on the lower bound to the baryon density; hovering at $N_\nu \lesssim 4$ for most of the 1980's and dropping to slightly lower than 4[24,9] just before LEP and SLC turned on.

BIG BANG NUCLEOSYNTHESIS: Ω_b AND N_ν

The power of Big Bang Nucleosynthesis comes from the fact that essentially all of the physics input is well determined in the terrestrial laboratory. The appropriate temperatures, 0.1 to $1MeV$, are well explored in nuclear physics labs. Thus, what nuclei do under such conditions is not a matter of guesswork, but is precisely known. In fact, it is known for these temperatures far better than it is for the centers of stars like our sun. The center of the sun is only a little over $1keV$. Thus temperatures are below the energy where nuclear reaction rates yield significant results in laboratory experiments, and only the long times and higher densities available in stars enable anything to take place.

To calculate what happens in the Big Bang, all one has to do is follow what a gas of baryons with density ρ_b does as the universe expands and cools. As far as nuclear reactions are concerned the only relevant region is from a little above $1MeV$ ($\sim 10^{10}K$) down to a little below $100keV$ ($\sim 10^9K$). At higher temperatures, no complex nuclei other than free single neutrons and protons can exist, and the ratio of neutrons to protrons, n/p, is just determined by $n/p = e^{-Q/T}$, where

$$Q = (m_n - m_p)c^2 \sim 1.3MeV.$$

Equilibrium applies because the weak interaction rates are much faster than the expansion of the universe at temperatures much above $10^{10}K$. At temperatures much below 10^9K, the electrostatic repulsion of nuclei prevents nuclear reactions from proceeding as fast as the cosmological expansion separates the particles.

Because of the equilibrium existing for temperatures much above $10^{10}K$, we don't

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have to worry about what went on in the universe at higher temperatures. Thus, we can start our calculation at $10MeV$ and not worry about speculative physics like the theory of everything (T.O.E.), or grand unifying theories (GUTs), as long as a gas of neutrons and protons exists in thermal equilibriuim by the time the universe has cooled to $\sim 10MeV$.

After the weak interaction drops out of equilibrium, a little above $10^{10}K$, the ratio of neutrons to protons changes more slowly due to free neutrons decaying to protons, and similar transformations of neutrons to protons via interactions with the ambient leptons. By the time the universe reaches 10^9K ($0.1MeV$), the ratio is slightly below $1/7$. For temperatures above 10^9K, no significant abundance of complex nuclei can exist due to the continued existence of gammas with greater than MeV energies. Note that the high photon to baryon ratio in the universe ($\sim 10^{10}$) enables significant population of the MeV high energy Boltzman tail until $T \lesssim 0.1\ MeV$. Once the temperature drops to about 10^9K, nuclei can exist in statistical equilibrium through reactions such as $n + p \leftrightarrow^2 H + \gamma$ and $H + p \leftrightarrow^3 He + \gamma$ and $^2D + n \leftrightarrow^3 H + \gamma$, which in turn react to yield ^4He. Since ^4He is the most tightly bound nucleus in the region, the flow of reactions converts almost all the neutrons that exist at 10^9K into ^4He. The flow essentially stops there because there are no stable nuclei at either mass-5 or mass-8. Since the baryon density at Big Bang Nucleosynthesis is relatively low (much less than $1g/cm^3$), only reactions involving two-particle collisions occur. It can be seen that combining the most abundant nuclei, protons, and ^4He via two body interactions always leads to unstable mass-5. Even when one combines ^4He with rarer nuclei like ^3H or ^3He, we still get only to mass-7, which, when hit by a proton, the most abundant nucleus around, yields mass-8. (A loophole around the mass-8 gap can be found if $n/p > 1$ so that excess neutrons exist, but for the standard case $n/p < 1$). Eventually, ^3H radioactively decays to ^3He, and any mass-7 made radioactively decays to ^7Li. Thus, Big Bang Nucleosynthesis makes ^4He with traces of ^2H, ^3He, and ^7Li. (Also, all the protons left over that did not capture neutrons remain as hydrogen.) For standard homogeneous BBN, all other chemical elements are made later

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in stars and in related processes. (Stars jump the mass-5 and -8 instability by having gravity compress the matter to sufficient densities and have much longer times available so that three-body collisions can occur.) With the possible exception of ^7Li,[8,25,26] the results are rather insensitive to the detailed nuclear reaction rates. This insensitivity was discussed in ref. [8] and most recently using a Monte Carlo study by Krauss *et al.*[26] An n/p ratio of $\sim 1/7$ yields a ^4He primordial mass fraction,

$$Y_p = \frac{2n/p}{n/p + 1} \approx \frac{1}{4}$$

The only parameter we can easily vary in such calculations is the density that corresponds to a given temperature. From the thermodynamics of an expanding universe we know that $\rho_b \propto T^3$; thus, we can relate the baryon density at $10^{11}K$ to the baryon density today, when the temperature is about 3 K. The problem is that we don't know today's ρ_b, so the calculation is carried out for a range in ρ_b. Another aspect of the density is that the cosmological expansion rate depends on the total mass-energy density associated with a given temperature. For cosmological temperatures much above 10^4K, the energy density of radiation exceeds the mass-energy density of the baryon gas. Thus, during Big Bang Nucleosynthesis, we need the radiation density as well as the baryon density. The baryon density determines the density of the nuclei and thus their interaction rates, and the radiation density controls the expansion rate of the universe at those times. The density of radiation is just proportional to the number of types of radiation. Thus, the density of radiation is not a free parameter if we know how many types of relativistic particles exist when Big Bang Nucleosynthesis occurred.

Assuming that the allowed relativistic particles at $1MeV$ are photons, e, μ, and τ neutrinos (and their antiparticles) and electrons (and positrons), Figure 1 shows the BBN yields for a range in present ρ_b, going from less than that observed in galaxies to greater than that allowed by the observed large-scale dynamics of the universe. The ^4He yield is almost independent of the baryon density, with a very slight rise in the density due to the

ability of nuclei to hold together at slightly higher temperatures and at higher densities, thus enabling nucleosynthesis to start slightly earlier, when the baryon to photon ratio is higher. No matter what assumptions one makes about the baryon density, it is clear that ^4He is predicted by Big Bang Nucleosynthesis to be around 1/4 of the mass of the universe.

As noted above, BBN yields all agree with observations using only one freely adjustable parameter, ρ_b. Recent attempts to circumvent this argument[27], by having variable n/p ratios coupled with density inhomogeneities inspired by a first order quark-hadron phase transition, fail in most cases to fit the Li and ^4He even when numerous additional parameters are added and fine-tuned. In fact, it can be shown[28] that the observed abundance constraints yield such a robust solution that nucleosynthesis may constrain the quark-hadron phase transition more than the phase transition alters the cosmological conclusions.

This narrow range in baryon density for which agreement occurs is very interesting. Let us convert it into units of the critical cosmological density for the allowed range of Hubble expansion rates. From the Big Bang Nucleosynthesis constraints[8,9,10,25,26,27], the dimensionless baryon density, Ω_b, that fraction of the critical density that is in baryons, is less than 0.11 and greater than 0.02 for $0.4 \lesssim h_0 \lesssim 0.7$, where h_0 is the Hubble constant in units of $100 km/sec/Mpc$. The lower bound on h_o comes from direct observational limits and the upper bound from age of the universe constraints[29]. Note that the constraint on Ω_b means that the universe *cannot be closed with baryonic matter*. If the universe is truly at its critical density, then nonbaryonic matter is required. This argument has led to one of the major areas of research at the particle-cosmology interface, namely, the search for non-baryonic dark matter.

Another important conclusion regarding the allowed range in baryon density is that it is in very good agreement with the density implied from the dynamics of galaxies, *including their dark halos*. An early version of this argument, using only deuterium, was described over ten years ago[30]. As time has gone on, the argument has strengthened, and the

fact remains that galaxy dynamics and nucleosynthesis agree at about 6% of the critical density. Thus, if the universe is indeed at its critical density, as many of us believe, it requires most matter not to be associated with galaxies and their halos, as well as to be nonbaryonic. We will return to this point later.

Let us now look at the connection to N_ν. Remember that the yield of ^4He is very sensitive to the n/p ratio. The more types of relativistic particles, the greater the energy density at a given temperature, and thus, a faster cosmological expansion. A faster expansion yields the weak-interaction rates being exceeded by the cosmological expansion rate at an earlier, higher temperature; thus, the weak interaction drops out of equilibrium sooner, yielding a higher n/p ratio. It also yields less time between dropping out of equilibrium and nucleosynthesis at $10^9 K$, which gives less time for neutrons to change into protons, thus also increasing the n/p ratio. A higher n/p ratio yields more ^4He. Quark-hadron induced variations[27] in the standard model *also* yield higher ^4He for higher values of Ω_b. Thus, such variants still support the constraint on the number of relativistic species.[28]

In the standard calculation we allowed for photons, electrons, and the three known neutrino species (and their antiparticles). However, by doing the calculation (see Figure 2) for additional species of neutrinos, we can see when ^4He yields exceed observational limits while still yielding a density consistent with the ρ_b bounds from ^2H, ^3He, and now ^7Li. (The new ^7Li value gives approximately the same constraint on ρ_b as the others, thus strengthening the conclusion.) The bound on ^4He comes from observations of helium in many different objects in the universe. However, since ^4He is not only produced in the Big Bang but in stars as well, it is important to estimate what part of the helium in some astronomical object is primordial—from the Big Bang—and what part is due to stellar production after the Big Bang. The pioneering work of the Peimberts[31] showing that ^4He varies with oxygen has now been supplemented by examination of how ^4He varies with nitrogen and carbon. The observations have also been systematically reexamined by Pagel[32]. The conclusions of Pagel[32], Steigman *et al.*[33] and Walker *et al.*[10] all agree
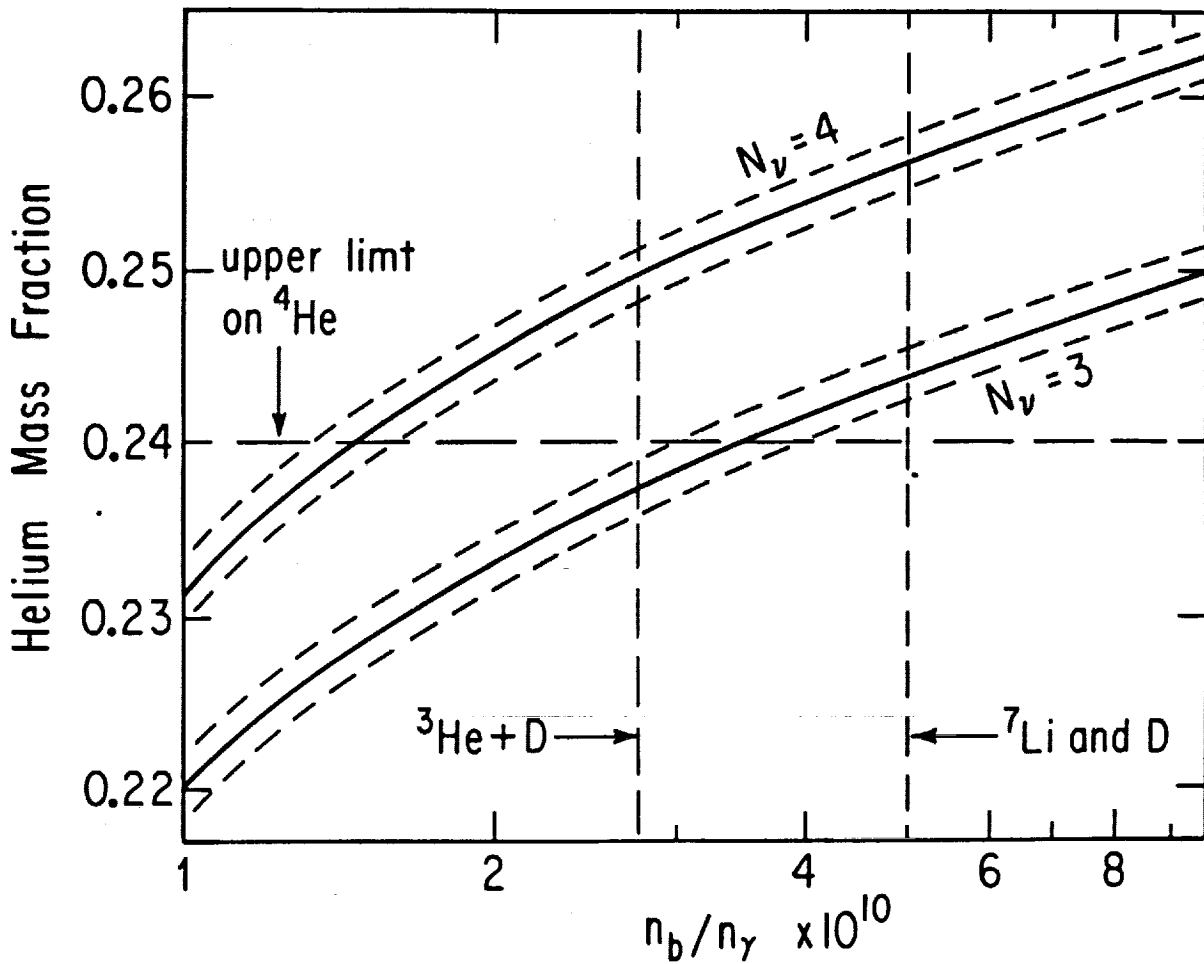
Figure 2. Helium mass fraction versus the cosmological baryon-to-photon ratio. The vertical line is the lower bound on this ratio from considerations of ^2H and ^3He (see Yang *et al.*) (Using ^7Li as a constraint would move the vertical line only slightly to the left.) The horizontal line is the current upper bound of 0.24. The width of the lines for $N_\nu = 3$ and 4 is due to $\tau_n = 890 \pm 4s$. Note that $N_\nu = 4$ appears to be excluded barring a systematic error upward in Y_p which would be contrary to current systematic trends.

that the ^4He mass fraction, Y_p, extrapolated to zero heavy elements, whether using N, O, or C, is $Y_p \sim 0.23$ with an upper bound of 0.24.

The other major uncertainty in the ^4He production used to be the neutron lifetime. However, the new world average of $\tau_n = 890 \pm 4s(\tau_{1/2} = 10.3\ min)$ is dominated by the dramatic results of Mampe et al.[34] using a neutron bottle. This new result is quite consistent with a new counting measurement of Byrne et al.[35] and within the errors of the previous world average of $896 \pm 10s$ and is also consistent with the precise C_A/C_V measurements from PERKEO[36] and others. Thus, the old ranges of $10.4 \pm 0.2\ min$, used for the half-life in calculations,[37,8] seem to have converged towards the lower side. The convergence means that, instead of the previous broad bands for each neutrino flavour, we obtain relatively narrow bands (see Figure 2). Note that $N_\nu = 4$ is excluded. In fact, the upper limit is now $N_\nu < 3.4$.[9,10]

The recent verification of this cosmological standard model prediction by LEP, $N_\nu = 2.96 \pm 0.14$, from the ALEPH, DELPHI, L3 and OPAL collaborations presented elsewhere in this volume as well as the SLC results, thus, experimentally confirms our confidence in the Big Bang. (However, we should also remember that LEP and cosmology are sensitive to different things.[38] Cosmology counts all relativistic degrees of freedom for $m_x \lesssim 10 MeV$ with $m_x \lesssim 45 GeV$.

While ν_e and ν_μ are obviously counted equally in both situations, a curious loophole exists for ν_τ since the current experimental limit $m_{\nu_\tau} < 35 MeV$ could allow it not to contribute as a full neutrino in the cosmology argument[39]. It might also be noted that now that we know $N_\nu = 3$, we can turn the argument around and use LEP to predict the primordial helium abundance ($\sim 24\%$) or use limits on ^4He to give an additional upper limit on Ω_b (also $\lesssim 0.10$). Thus, LEP strengthens the argument that we need non-baryonic dark matter if $\Omega = 1$. In fact, note also that with $N_\nu = 3$, if Y_p is ever proven to be less than ~ 0.235, standard BBN is in difficulty. Similar difficulties occur if Li/H is ever found below $\sim 10^{-10}$. In other words, BBN is a falsifiable theory. (The same cannot be said for

many other astrophysical theories.)

Let us now put the nucleosynthetic argument on Ω_b into context.

DARK MATTER

The arguments requiring some sort of dark matter fall into two separate and quite distinct areas. First are the arguments using Newtonian mechanics applied to various astronomical systems that show that there is more matter present than the amount that is shining. These arguments are summarized in the first part of Table 1. It should be noted that these arguments reliably demonstrate that galactic halos seem to have a mass ~ 10 times the visible mass.

Note however that Big Bang Nucleosynthesis requires that the bulk of the baryons in the universe are dark since $\Omega_{vis} << \Omega_b$. Thus, the dark halos could in principle be baryonic[17]. Recently arguments on very large scales[40] (bigger than cluster of galaxies) hint that Ω on those scales is indeed greater than Ω_b, thus forcing us to need non-baryonic matter. However, until these arguments are confirmed, we must look at the inflation paradigm.

This is the argument that the only long-lived natural value for Ω is unity, and that inflation[41] or something like it provided the early universe with the mechanism to achieve that value and thereby solve the flatness and smoothness problems. Thus, our need for exotica is dependent on inflation and Big Bang Nucleosythesis and not on the existence of dark galatic halos. This point is frequently forgotten, not only by some members of the popular press but occasionally by active workers in the field.

Table 2 summarizes both the baryonic and non-baryonic dark matter candidates. Some baryonic dark matter must exist since we know that the lower bound from Big Bang Nucleosynthesis is greater than the upper limits on the amount of visible matter in the universe. However, we do not know what form this baryonic dark matter is in. It could be either in condensed objects in the halo, such as brown dwarfs and jupiters (objects with $\lesssim 0.08 M_\odot$ so they are not bright shining stars), or in black holes (which at the time of

TABLE I

"OBSERVED" DENSITIES

$$\left[\Omega \equiv \rho/\rho_c \text{ where } \rho_c = 2 \cdot 10^{-29} h_0^2 \text{g/cm}^3 \text{and } h_o \equiv \frac{H_o}{100 \text{ km/sec/mpc}}\right]$$

Newtonian Mechanics
    (cf. Faber and Gallagher[58])

Visible $\Omega \sim 0.007$
                                                     (factor of 2 accuracy)

Binaries
Small groups
Extended flat relation curves $\Omega \sim 0.07$
                                                     (factor of 2 accuracy)

Clusters
Gravitational lenses $\Omega \sim 0.1 \text{ to } 0.3$

Big Bang Nucleosynthesis (with $t_u \gtrsim 10^{10}$yrs.)
    (c.f. Walker *et al.*[10] and ref. therein) $\Omega_b = 0.065 \pm 0.045$

Preliminary Large Scale Studies

    IRAS red shift study and peculiar velocities $\Omega \gtrsim 0.3$
        (Ref. [40])

    Density redshift counts $\Omega \sim 1 \pm 0.6$
        (Loh and Spillar[59])

Inflation Paradigm
    (Guth[41]) $\Omega = 1$

TABLE II

"DARK MATTER CANDIDATES"

Baryonic (BDM)

Brown Dwarfs and/or Jupiters	$M \lesssim 0.08 M_\odot$
Blackholes	$M \gtrsim 1 M_\odot$
Hot intergalactic gas	$M \sim 1 GeV, \ (T \sim 10^6 K)$
Failed galaxies	$M \gtrsim 10^5 M_\odot$

Non Baryonic

Hot (HDM)

Low Mass Neutrinos	$m_\nu \sim 20 \pm 10 eV$

Cold (CDM)

Massive Neutrinos	$m_\nu \sim 3 GeV \ (\gtrsim 45 GeV)^*$
WIMPS, Lightest Supersymmetric Particle (Photino, Gravitino, Sneutrino)	$m_{susy} \sim 4 GeV \ (\gtrsim 20 GeV)^*$
Axions	$m_a \sim 10^{-5} eV$
Planetary mass black holes	$M \sim 10^{15} g - 10^{30} g$
Quark nuggets	$M \sim 10^{15} g$
Topological debris (monopoles higher dimensional knots, balls of wall, etc.)	$M \gtrsim 10^{16} GeV$

* After LEP

nucleosynthesis would have been baryons). Or, if the baryonic dark matter is not in the halo, it could be in hot intergalactic gas, hot enough not to show absorption lines in the Gunn-Peterson test, but not so hot as to be seen in the x-rays. Evidence for some hot gas is found in clusters of galaxies. However, the amount of gas in clusters would not be enough to make up the entire missing baryonic matter. Another possible hiding place for the dark baryons would be failed galaxies, large clumps of baryons that condense gravitationally but did not produce stars. Such clumps are predicted in galaxy formation scenarios that include large amounts of biasing where only some fraction of the clumps shine.

Hegyi and Olive[42] have argued that dark baryonic halos are unlikely. However, they do allow for the loopholes mentioned above of low mass objects or of massive black holes. It is worth noting that these loopholes are not that unlikely. If we look at the initial mass function for stars forming with Pop I composition, we know that the mass function falls off roughly like a power law for standard size stars as was shown by Salpeter. Or, even if we apply the Miller-Scalo mass function, the fall off is only a little steeper. In both cases there is some sort of lower cut-off near $0.1 M_\odot$. However, we do not know the origin of this mass function and its shape. No true star formation model based on fundamental physics predicts it.

We do believe that whatever is the origin of this mass function, it is probably related to the metalicity of the materials, since metalicity affects cooling rates, etc. It is not unreasonable to expect the initial mass function that was present in the primordial material which had no heavy elements, only the products of Big Bang Nucleosynthesis would be peaked either much higher than the present mass function or much lower—higher if the lower cooling from low metals resulted in larger clumps, or lower if some sort of rapid cooling processes ("cooling flows") were set up during the initial star formation epoch, as seems to be the case in some primative galaxies. In either case, moving either higher or lower produces the bulk of the stellar population in either brown dwarfs and jupiters or in massive black holes. Thus, the most likely scenarios are that a first generation of condensed

objects would be in a form of dark baryonic matter that could make up the halos, and could explain why there is an interesting coincidence between the implied mass in halos and the implied amount of baryonic material. However, it should also be remembered that to follow through with this scenario one would have to have the condensation of the objects occur prior to the formation of the disk. Recent observational evidence,[43], seems to show disk formation is relatively late, occurring at red shifts $Z \lesssim 1$. Thus, the first several billion years of a galaxy's life may have been spent prior to the formation of the disk. In fact, if the first large objects to form are less than galactic mass, as many scenarios imply, then mergers are necessary for eventual galaxy size objects. Mergers stimulate star formation while putting early objects into halos rather than disks. Mathews and Schramm[44] have recently developed a galactic evolution model which does just that and gives a reasonable scenario for chemical evolution. Thus, while making halos out of exotic material may be more exciting, it is certainly not impossible for the halos to be in the form of dark baryons. One application of William of Ockham's famous razor would be to have us not invoke exotic matter until we are forced to do so.

Non-baryonic matter can be divided following Bond and Szalay[45] into two major categories for cosmological purposes: hot dark matter (HDM) and cold dark matter (CDM). Hot dark matter is matter that is relativistic until just before the epoch of galaxy formation, the best example being low mass neutrinos with $m_\nu \sim 20eV$. (Remember $\Omega_\nu \sim \frac{m_\nu(ev)}{100h_0^2}$).

Cold dark matter is matter that is moving slowly at the epoch of galaxy formation. Because it is moving slowly, it can clump on very small scales, whereas HDM tends to have more difficulty in being confined on small scales. Examples of CDM could be massive neutrino-like particles with masses greater than several GeV or the lightest supersymmetric particle which is presumed to be stable and might also have masses of several GeV. Following Michael Turner, all such weakly interacting massive particles are called "WIMPS." Axions, while very light, would also be moving very slowly[46] and, thus, would clump on small scales. Or, one could also go to non-elementary particle candidates, such

as planetary mass blackholes [47] or quark nuggets of strange quark matter, also found at the quark-hadron transition. Another possibility would be any sort of massive toplogical remnant left over from some early phase transition. Note that CDM would clump in halos, thus requiring the dark baryonic matter to be out between galaxies, whereas HDM would allow baryonic halos.

When thinking about dark matter candidates, one should remember the basic work of Zeldovich,[48], later duplicated by Lee and Weinberg[49] and others,[50] which showed for a weakly interacting particle that one can obtain closure densities, either if the particle is very light, $\sim 20eV$, or if the particle is very massive, $\sim 3GeV$. This occurs because, if the particle is much lighter than the decoupling temperature, then its number density is the number density of photons (to within spin factors and small corrections), and so the mass density is in direct proportion to the particle mass, since the number density is fixed. However, if the mass of the particle is much greater than the decoupling temperature, then annihilations will deplete the particle number. Thus, as the temperature of the expanding universe drops below the rest mass of the particle, the number is depleted via annihilations. For normal weakly interacting particles, decoupling occurs at a temperature of $\sim 1MeV$, so higher mass particles are depleted. It should also be noted that the curve of density versus particle mass turns over again (see Figure 3) once the mass of the WIMP exceeds the mass of the coupling boson[51,52,53] so that the annihilation cross section varies as $\frac{1}{E^2}$, independent of the boson mass. In this latter case, $\Omega = 1$ can be obtained for $M_x \sim 1TeV \sim (3K \times M_{Planck})^{1/2}$, where $3K$ and M_{Planck} are the only energy scales left in the calculation (see Figure 3).

A few years ago the preferred candidate particle was probably a few GeV mass WIMP. However, LEP's lack of discovery of any new particle coupling to the $Z°$ with $M_x \lesssim 45GeV$ clearly eliminates that candidate[54,56] (see Figures 4A and 4B). In fact, LEP also tells us that any particle in this mass range must have a coupling $\lesssim 10\%$ of the coupling of ν's to the $Z°$, or it would have shown up in the N_ν experiments. The consequences of this for
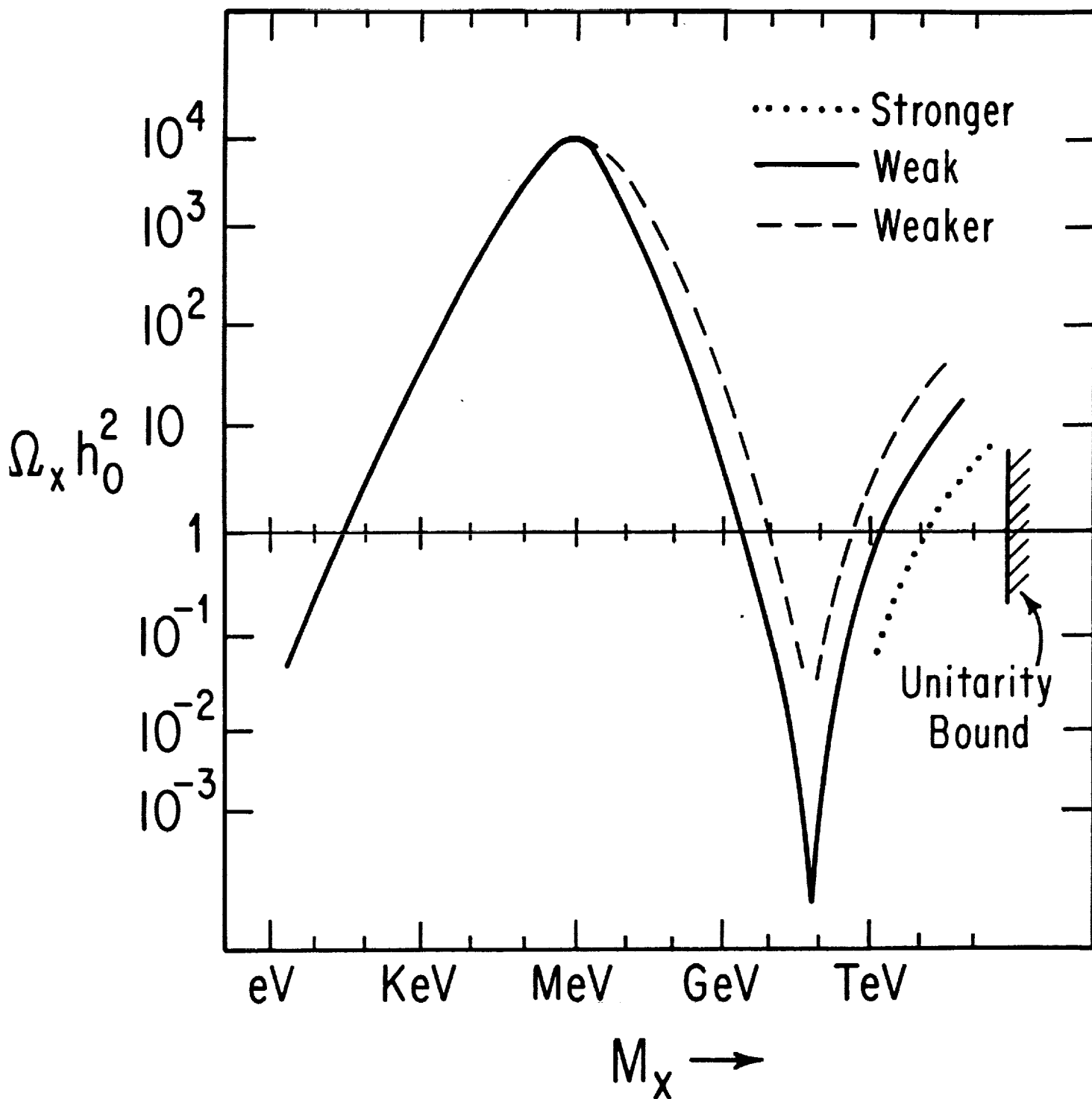
Figure 3. $\Omega_x h_0^2$ versus M_x for weakly interacting particles showing three crossings of $\Omega h_0^2 = 1$. Note also how curve shifts at high M_x for intereactions weaker or stronger than normal weak interaction (where normal weak is that of neutrino coupling through Z^0). Extreme strong couplings reach a unitarity limit at $M_x = 340 TeV$.
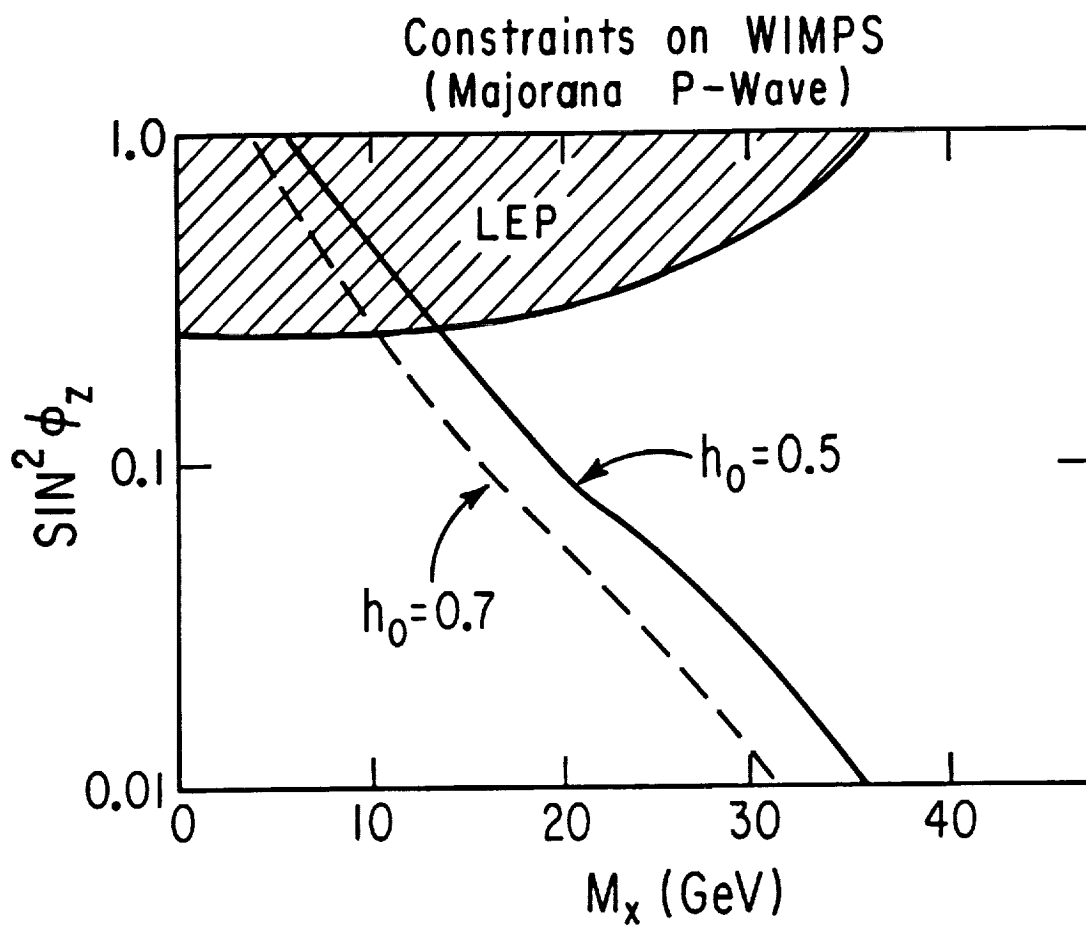
Figure 4A. Constraints on WIMPS of mass M_x versus $Sin^2\phi_z$, the relative coupling to the Z^0. The constraints are shown assuming Majorana particles (p-wave interactions). The diagonal lines show the combinations of M_x and $Sin^2\phi_z$ that yield $\Omega = 1$. The cross-hatched region is what is ruled out by the current LEP results. Note that $\Omega = 1$ with $h_0 = 0.5$ is possible only if $M_x \gtrsim 15 GeV$ and $Sin^2\phi_z < 0.3$. The new LEP run should lower this bound on $Sin^2\phi$ to $\lesssim 0.1$.

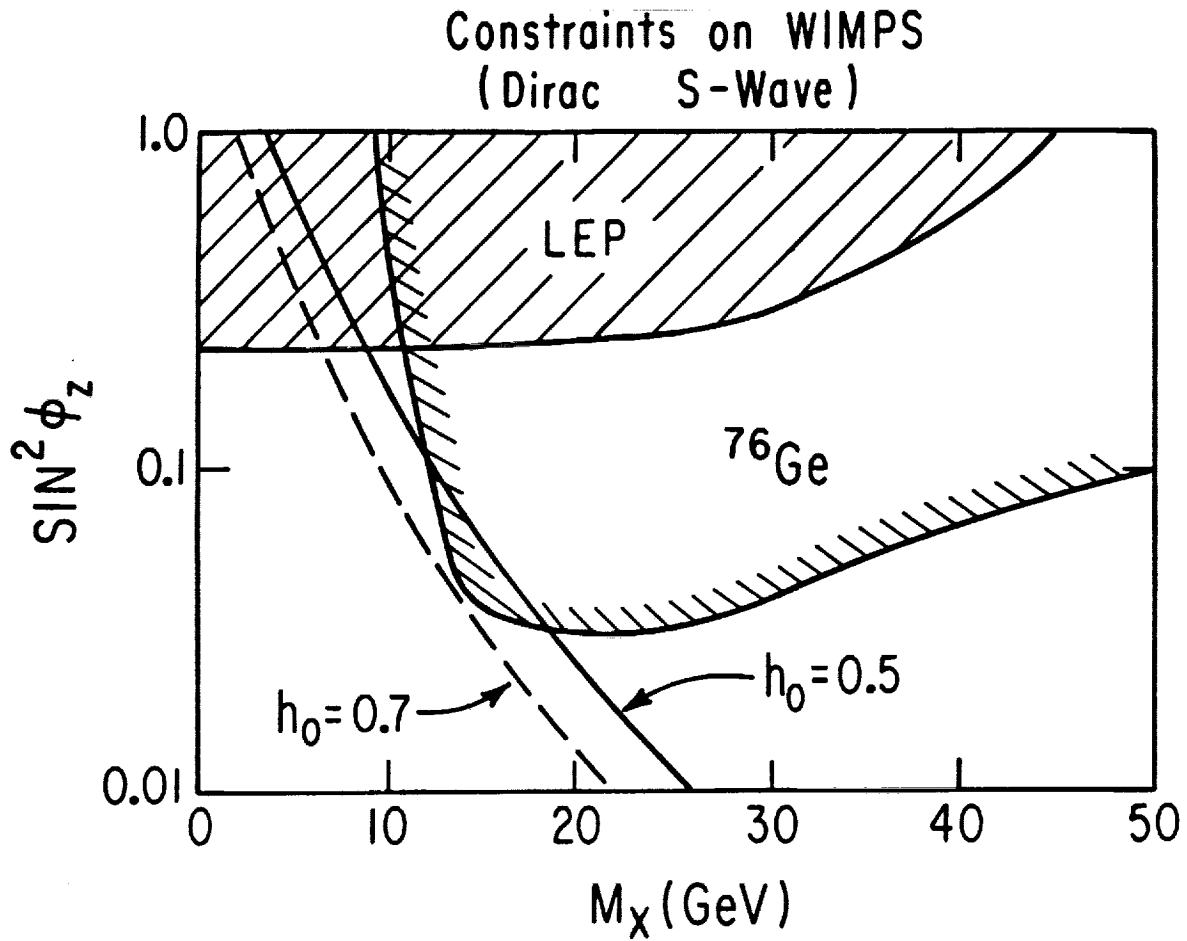Constraints on WIMPS
(Dirac S-Wave)

Figure 4B. This is the same as 4A but for Dirac particles (s-wave interactions), the ^{76}Ge region is that ruled out by the Caldwell *et al.* double-β decay style experiments. Note that while a small window for $\Omega = 1$, $h_0 = 0.5$, currently exists for $M_x \sim 10 GeV$, the combination of future ^{76}Ge experiments plus the new LEP run should eliminate this and leave only $M_x \gtrsim 20 GeV$ and $Sin^2 \phi \lesssim 0.03$.

$\Omega = 1$ dark matter are shown in Figures 4A and 4B for both Dirac (s-wave) and Majorana (p-wave) particles. Dirac particles are further constrained by the lack of detection in the ^{76}Ge experiments of Caldwell et al.[55]. The possibility of some other WIMP not coupling to the Z° is constrained by the non-detection of other bosons, including squarks, sleptons and/or a $Z\prime$, at $UA - 2$ and CDF, as reported at this meeting. Thus, with the exception of a few minor loopholes, whether the particle is supersymmetric or not, it is required to have an interaction weaker than weak and/or have a mass greater than about $20GeV$. We discuss this in detail in Ellis et al.[56] Future dark matter searches should thus focus on more massive and more weakly interacting particles.

Also, as Dimopoulos[51] has emphasized, the next appealing crossing of $\Omega = 1$ (see Figure 3) is $\gtrsim 1TeV$ (but, in any case, $\lesssim 340TeV$ from the unitarity bound[53]), which can be probed by SSC and LHC as well as by underground detectors. Thus, after LEP, the favoured CDM particle candidate is either a $10^{-5}eV$ axion or a gaugino with a mass of many tens of GeV. Of course an HDM ν_τ with $m_{\nu_\tau} \sim 20 \pm 10eV$ is still a fine candidate as long as galaxy formation proceeds by some mechanism other than adiabatic gaussian matter fluctuations[57]

CONCLUSION

LEP has tested the standard cosmological model, the Big Bang, in almost as dramatic a fashion as it has tested the standard particle model, $SU_3 \times SU_2 \times U_1$. The result is a continued confidence in the Big Bang and in the standard model conclusion that $\Omega_b \sim 0.06$. LEP has also constrained what the other 90+% of the Universe can be. It has even eliminated the favoured mass particles of a few years ago.

ACKNOWLEDGMENTS

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