NEUTRINO PHYSICS AND COSMOLOGY *

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ABSTRACT

I provide a brief overview of recent developments related to neutrinos and cosmology, concentrating on probes for cosmologically interesting neutrino masses, and the reasons for supposing such masses might exist. In particular, I focus on the recent interest in light eV scale neutrinos as hot dark matter, and also on recent issues associated with Big Bang Nucleosynthesis which are relevant to neutrinos, including the necessity for some baryonic dark matter and an upper bound the the total amount of such matter—an issue relevant to the recent claimed observation of "macho" candidates for some or all of the galactic halo dark matter.

1. Introduction

Neutrino physics has played a central role in the development of the standard model of the weak and electromagnetic interactions, and it is quite likely that it may carry us beyond this model in the coming years. The confirmation that any neutrino has a non-zero mass would be the most important result in particle physics in several decades, because it would provide the first evidence of physics beyond the standard model. For this reason, substantial effort has been devoted in the last few years to terrestrial experimental explorations of this possibility. However, because the implications of a non-zero neutrino mass would be most dramatic for astrophysics and cosmology, it is not surprising that the most sensitive probes of such a possibility derive from research in these areas. New results have been obtained in the last few years which are relevant to neutrinos with masses ranging from TeV scales to sub-eV scales. Most of the current interest has of late focussed on the possibility that neutrinos are light, at the eV scale or lighter, and it is this possibility I shall focus on here. Two areas in which neutrino physics is particularly important in this regard involve the issue of dark matter, associated with observed large scale structure in the Universe, and the physics of Big Bang

* Invited lecture at the 12th International Workshop on the Weak Interactions and Neutrinos, August 1993. To appear in the proceedings

Nucleosynthesis. These will form the basis of this review.

2. Neutrinos as Dark Matter, or Deju Vu All Over Again

A dozen years ago the idea that the electron neutrino might have a mass in the range of 30-50 eV was especially seductive. In the first place, laboratory beta decay experiments gave evidence of just such a mass for the electron neutrino. In the second place, neutrinos with this mass automatically evolve in the early universe to lead to a closure density today, thus providing a clear and simple possibility for dark matter. The arguments with yield the current neutrino relic density are simple and straightforward, involving no new physics beyond simple weak interaction cross sections measured in the laboratory. Given that these interactions were in equilibrium during the expansion of the universe up until the temperature dropped below about $2MeV$, neutrinos lighter than this were as abundant as photons at these early times. Having dropped out of equilibrium at this time, whereas photons remained in equilibrium until $T \approx .1eV$, implies that the nuetrino density was diluted somewhat compared to photons during the period of electron-positron annihilation. As a result, the number density of massless or light neutrinos is about 1/10 of that of photons in the microwave background today. This photon background, with a mean energy per particle of about $10^{-4}eV$, contributes about 10^{-4} of closure density density today. Thus, one directly arrives at the following result for light neutrinos:

$$\Omega_\nu \approx 10^{-5} \times \frac{m_\nu}{10^{-4}eV}$$

With this estimate came the heyday of neutrino cosmology. Things quickly slid downhill however. First, evidence for a non-zero electron neutrino mass from beta decay disappeared. Current upper limits are in the range of only 7 eV, and double beta decay puts an limit on a Majorana neutrino mass of about 1 eV. Next, computer simulations of a universe dominated by neutrinos quickly began to provide evidence that such a universe was too "clumpy" at large scales, compared to observations[1]. A qualitative understanding of this is quite straightforward. As long as neutrinos are relativistic, they will be able to escape out of any potential well except for that of a black hole. Thus, in the early universe, any "clump" of neutrinos will evaporate if the temperature is greater than the neutrino rest mass. As a result, primordial fluctuations in neutrinos will be dissipated. Such fluctuations cannot be dissipated on scales larger than the horizon, however, because, by the definition of the horizon, neutrinos cannot free-stream over distances in excess of the horizon distance. Since the horizon grows with time, any primordial lump of neutrinos coming in the horizon will dissipate, until the temperature of the universe falls below the neutrino rest mass. Thus, the smallest scale on which neutrino fluctuations will not have dissipated is the horizon scale at this time. For a 30 eV neutrino, this corresponds to a scale which would encompass a mass of about 10^{15} solar masses, or about the size of a supercluster of galaxies. Thus, in a neutrino dominated universe, the first objects to collapse are supercluster-sized. These objects must then fragment if they are to form galaxies. As a result, in a neutrino dominated universe, fluctuations on supercluster sizes must be comparable to those on galaxy sizes, which is not what is observed.

The solution to this problem is to have a particle which becomes non-relativistic at earlier times. In this case, primordial fluctuations on smaller scales will be preserved when they enter the horizon. In particular, if such a particle is non-relativistic when the universe has a temperature of about 1 keV—when the scale of modern day galaxies first entered the horizon—then galaxy scales will be the first to collapse. Such particles became dubbed "cold" dark matter, to be contrasted with neutrino "hot" dark matter.

Thus, large scale structure observations played a vital role in the death of a 30 eV neutrino-dominated universe. As we shall soon see, they have also more recently played a vital role in reviving light neutrino dark matter. First, however, several other factors have recently contributed to the ressurection of light neutrinos in cosmology.

(a) Numerology and Solar Neutrinos: Recent evidence. based essentially entirely on the observations of the Homestake Cl solar neutrino detector, and also the Kamiokande water detector, suggests that there is either a paucity of ^7Be neutrinos compared to high energy ^8B neutrinos coming from the sun, or else the ^8B spectrum is distorted. Both possibilities appear incompatible with possible alterations of solar physics, and therefore suggest the existence of new neutrino physics. The simplest possibility involves a non-zero mass for the muon neutrino in the range of 10^{-3} eV. In this case, one might wonder what the masses of the other neutrino flavors will be. A simple argument, based on diagonalizing a neutrino mass matrix with a large Majorana mass, M, for the right handed neutrino, and smaller, Dirac masses, m_D coupling left and right handed states, implies that there should be one left-handed light neutrino state with mass $\approx m_D/M^2$. Now, if the Dirac mass term m_D is related to either known quark or lepton masses, then one can derive the following relation between expected masses for the muon and tau neutrino states:

$$\frac{m_{\nu_\tau}}{m_{\nu_\mu}} \approx (\frac{m_x}{m_y})^\alpha$$

Here α can be either 1 or 2, and $x = t, \tau...$ and $y = c, \mu...$ Depending upon the choice one can derive the "remarkable" fact that a muon neutrino mass in the range of 10^{-3} eV, "predicts" a tau neutrino mass in the range of 10 eV!. This would of course imply that tau neutrinos might make up a significant fraction of the mass of the universe today.

(b) Supernova Stagnation: To date, no one has convincingly demonstrated on a computer that collapsing stars will succeed in blowing off their outer shells to form a visible supernova. It is thought that neutrino interactions may play a significant role in depositing energy in the outer parts of the star to facilitate this. Recently, Fuller and collaborators[2] have argued that oscillations between electron neutrinos and tau neutrinos would raise the average electron neutrino energy interacting in the outer shell and provide enough extra "kick" to blow off the outer part of the star. They have in addition argued that this would require a tau neutrino mass in the range of, you guessed it, 10 eV.

Finally, if these reasons alone are not enough to convince you that the tau neutrino has a mass of 10 eV, we return to Large Scale Structure. Clearly, in order to have a definite prediction for the nature of observed clustering of mass in the universe one must have a better basis than the rough qualitative arguments I presented earlier. Nevertheless, what the rough analysis I presented does point out is that the horizon size at any given time determines which fluctuations will be damped and which will not.

Clearly then, if one could be provided with the magnitude for primordial fluctuations on every scale, *at the time that scale crosses the horizon*, one could determine the general features of structure formation, for any sort of dark matter,at least as long as analytical approximations remain valid. This "spectrum" of primordial fluctuations contains all the unknown physics relevant to the early universe.

Long before anyone had suggested a plausible mechanism to generate primordial fluctuations a very sensible proposal was made by Harrison, Zeldovich, Peebles and Yu. They suggested the "spectrum" of primordial fluctuations would obey the following relation: fluctuations just entering the scale of the horizon at any time would be constant:

$$(\frac{\delta\rho}{\rho})_{horizoncrossing} = constant.$$

They suggested this for good reason. In general the other alternatives—either a monotonically growing or falling spectrum of primordial fluctations as new scales entered the horizon, or one which was peaked at some specific wavelength—were all unsatisfactory. The first would produce too large fluctations today on the scale of Cosmic Microwave Background measurements, the second too many primordial small black holes, and the latter would suggest that processes in the early universe picked out some special, macroscopic scale, which seemed unnatural.

Today it is conventional to describe the spectrum of primordial fluctuations in terms of a "power spectrum", related to the Fourier transform of energy density fluctuations on a scale with comoving wavenumber, k:

$$P(k) \approx \mid \int \Delta\rho(x) e^{ikx} dx \mid ^2$$

It is then straightforward to derive a relationship between the mangitude of fluctuations on some wavelength scale $\lambda \approx k^{-1}$:

$$(\frac{\delta\rho}{\rho}) = k^3 P(k)$$

As indicated earlier, all of the physics is then embedded in the function P(k). A scale-free spectrum is then defined by

$$P(k) \approx k^n$$

As can be straightforwardly derived[3], if $n = 1$, the spectrum is a flat Harrison-Zeldovich spectrum. Of course, once fluctuations come inside the horizon, causal processes can affect their growth, and the shape of the resulting power spectrum will deviate from its primordial form which is maintained only on large wavelengths. For example, in a neutrino dominated universe the power spectrum will by cut-off at the scale where neutrino free streaming begins to play a role. Several power spectra, calculated for various dark matter models are shown in figure 1[4].

Once a primordial power spectrum is given, and a dark matter model assumed, then all that remains to compare theory and observations is to normalize the spectrum to observations at one scale, and then compare the agreement, or lack thereof, at all other scales. It has been conventional to normalize all spectra at the scale $r = 8h^{-1}Mpc$, where the galaxy-galaxy correlation function becomes of order unity.

Beginning in about 1990, new comprehensive surveys of structure on very large scales began to be reported which apparently gave trouble for Cold Dark Matter. Several independent results suggested significantly more structure on large scales than had previously been inferred. These included comprehensive analyses of the angular two-point correlation function of galaxies when projected on the sky, and also galaxy counting based on new observations with the Infrared Astronomical Satellite (IRAS).

In terms of the power spectrum the problems for pure $n = 1$ spectra in cold or hot dark matter universes can be succinctly described. Cold dark matter models normalized on this scale predict too little structure on larger scales, with a power spectrum which is thus too small on these scales, while hot dark matter predicts too little structure on smaller scales, with a power spectrum which falls off to quickly on these scales.

Since the remarkable observation by the DMR instrument aboard COBE of anisotropies in the Cosmic Microwave Background on large angular scales, however, our picture can be dramatically altered. Because the scales of the fluctuations observed are much larger than the horizon was at the time the CMB was created, COBE is thus viewing purely primordial fluctuations, unaffected by later causal physics, we hope. In this case, it no longer makes sense to normalize power spectra at $r = 8h^{-1}$ Mpc. Rather, one should normalize them at COBE scales.

In this case, if one normalizes a cold dark matter matter model to the COBE result, one finds that one must increase the overall amplitude of fluctuations, so that one can simultaneously fit the recent large scale structure observations and COBE with CDM. The problem now occurs at "small", galactic, scales, where one predicts too much power.

How can one resolve this problem? One way which has been suggested—indeed, the reason I am discussing all this here— is to have a "mixture" of cold and hot dark matter[5]. In this case, one might hope to maintain power on large scales while suppressing it on small scales. In general, if one makes up dark matter with two components, one which clusters and one which doesn't, the growth of fluctuations on some scale as a function of the scale factor of the universe $a(t)$ is given by:

$$\frac{\delta\rho}{\rho} = [a(t)]^{\alpha}; \quad \alpha = 1/4[(24f+1)^{1/2} - 1]$$

where f is the fraction of clustering to unclustering matter. As can be seen, if $f = 1, \alpha = 1$, while for $f = 0, \alpha = 0$. If one considers $\Omega_\nu \approx 0.3, \Omega_{CDM} \approx 0.7$ then on scales smaller than the neutrino free-streaming length, $\alpha \approx 0.8$, and the ratio of the size of fluctuations on such scales today compared to what they would be in a pure CDM universe is almost a factor of 1/6. For large scales, where both neutrinos and CDM can cluster, $\alpha \approx 1$, and growth is identical to a standard CDM cosmology. What tau neutrino mass would correspond to the above scenario? As you might have guessed, about 10 eV fits the bill.

Since a "mixed" dark matter scenario was first proposed to resolve the problems with CDM, much work has gone into numerical simulations, all of which suggest a better agreement with data than for pure CDM. Is there therefore a smell of grand synthesis in the air. Could solar neutrinos, supernovae, and large scale structure all be pointing towards the same thing: a 10 eV tau neutrino?

Or is it just the smell of kimchi? After all, we must not forget that allowing two components for the dark matter allows us another free parameter. It is not surprising that the theory then fits the observations better. Moreover, there are other ways of improving CDM's fit with observation. Inflationary models are now recognized to generally predict $n < 1$. In this case it is also possible to produce more power on large scales for a fixed amount of power on small scales.

But what about the incessant problem of producing too much power on small scales in CDM models? This may be no problem at all. After all, we must remember that numerical simulations of dark matter only produce the power spectrum for the dark matter, not the luminous matter. Until full scale simulations are performed which include hydrodynamics and dissipation for baryonic matter, I for one will remain skeptical of all small scale predictions.

Nevertheless, in spite these remarks, it is clear that neutrino dark matter is once again "in". It remains to be seen, on the basis of more CMB measurements, better observations of large scale structure, and better numerical simulations, whether neutrino dark matter remains so. Clearly, direct observations of neutrino oscillations for an eV scale tau neutrino, or perhaps kinematic evidence for a non-zero tau neutrino mass from the next supernova in our galaxy[6] wouldn't hurt either.

3. BBN: Triumph or Tragedy

The connection between neutrinos and Big Bang Nucleosynthesis is well known in at least one case: the number of neutrino families. BBN also has other direct implications for neutrinos, from limiting the masses of heavy neutrinos, to limiting their interactions, as I will soon describe. In addition, there is an important indirect connection with neutrino cosmology. BBN puts limits on Ω_{baryon}, and thus limits the possibilities for baryonic dark matter. There are two important aspects to this. First, BBN arguments imply that there must be signficant baryonic dark matter. Second, to date it has placed an upper limit which is compatible with galactic halo densities. This is important, because it implies in principle that all of our galactic halo might be baryonic, and there might be no need for exotic, even neutrino, dark matter in our galaxy. In light of the recent claimed observations of microlensing in our galaxy related to massive compact objects this issue has taken on a new urgency.

What I would like to do is review the present situation regarding all of these issues, concentrating on recent developments and, most important, on the existing uncertainties. Big Bang Nucleosynthesis has been one of the great success stories of cosmology. Based on the simplest possible model for an expanding universe, and bolstered by well understood physics, predictions have been made for the abundance of light elements created in the Big Bang expansion. These predictions, which vary by over ten orders of magnitude have been, up to the present time, in remarkable qualitative, and where possible, quantitative agreement with observation.

This is not to suggest that controversy does not remain. While the theory of BBN is now quite standard, even allowing for certain uncertainties introduced by possible effects coming from the QCD phase transition, what is by far more uncertain are the measurements and what we can infer from them. I believe that it is fair to say that in spite of several well publicized potential challenges, at this time BBN remains alive and well. Nevertheless, we are at the threshold of making several more precise tests which will in any case allow BBN to be an even stronger probe of early universe cosmology.

Crucial to both the limit on Ω_B and N_ν is the comparison between the observed

^4He abundance in the universe and that predicted by the theory. The fact that approximately 1/4 of the universe, by weight, is ^4He provided the first definitive success of BBN. Simple arguments, based on the strength of the weak interactions and therefore the abundance of neutrons and protons at the time these interactions froze out in the early universe immediately pinpointed this as the expected range for primordial ^4He. This great success has recently become the source of some concern. Observations suggest, for reasons I will shortly outline, that the primordial abundance of 4He is between 22-24% by weight. Nevertheless, utilizing limits obtained by a combination of upper limits on observed D and 3He, one finds that BBN predictions are apparently only consistent with observations if the primordial abundance of 4He is greater than 23.7%[7,8]. This is disturbingly close to the claimed upper limit of 24%. Moreover, it is well above the best fit value which several authors claim is close to, or even below 23%.

Is this a problem for BBN? I think not. In order to determine the actual primordial abundance astronomers try to measure the helium content in stars with smaller and smaller abudances of heavy elements, such as oxygen and nitrogen. Such stars are presumably older, because the material in them has been less processed. Based on extrapolating the observed trend in Helium as a function of either oxygen or nitrogen, or some other heavy element, one might hope to infer the actual primordial abundance. Considering, for example, one statistical fit for a relation between helium and nitrogen abundances[9] it is clear that while a best fit relation may extrapolate, at low metallicity, to a value near or below 23%, systematic errors are at least as important as statistical ones. From data like this, it is not clear, that a distinction between an upper limit of 24% and 23.7% is meaningful. For example, without a first principles understanding of the helium-nitrogen relation, one sensible way to estimate the uncertainty in this relation is to examine the uncertainty on the lowest metallicity point, which has a one sigma uncertainty which reaches as high as 24%.

While I think the present uncertainties imply that BBN predictions remain safe, these same uncertainties point out more generally the danger in over-interpreting the data. For example, the ^4He abundance also is central for the argument which gives an upper limit on the number of neutrinos. Specifically, an upper limit on the sum of primordial $D +^3 He$ yields a lower limit on the baryon density of the universe at the time of BBN. Because the predicted ^4He abundance rises monotonically with increasing baryon density see figure 2), putting a lower limit on this latter quantity also puts a lower limit on the predicted ^4He abundance, i.e. the value of 23.7% quoted earlier. Now the predicted 4He abundance also increases monotonically with the number of relativistic neutrino species present during BBN. Thus, an observational lower bound on ^4He puts an upper bound on extra neutrinos. If an upper bound of 24% on ^4He is used, a bound of $N_\nu < 3.3$ has been claimed[10]. However, it is very important to recognize that if one raises the upper bound on ^4He to $\approx 24.2\%$, this upper bound on N_ν increases to ≈ 3.5. None of these arguments takes away from the power of BBN to limit the number of new particles in nature. However, we have seen, with the 17 keV neutrino, that there may be a world of theoretical difference between 3.4 and 3.6 extra effective species in the radiation gas at $T \approx 1$ MeV. Before hanging ones theory on the hope of being able to distinguish between the BBN predictions for 3.4 and 3.6 species, some appreciation of the uncertainties in the limits on ^4He and the other light elements is warranted. Finally, what if the actual primordial abundance of 4He were less than 23.7%? What might the weak link in BBN then be? My own suspicion is that the $D +^3 He$ limit might be revisable upwards. In this case a lower baryon density would be allowed, and thus a lower abundance of ^4He. I find this particularly attractive because it would also make the BBN predictions for the baryon abundance in the universe closer to the observed abundance of luminous matter. In this case, what you see would be what you get, a possibility I find appealing.

Nevertheless, what might be appealing, and what is actual true can be different. At present BBN is perfectly consistent, if constrained. And one of its central predictions is that there should be significant baryonic dark matter. The lower bound on Ω_B from BBN is about 0.015[11]. This is at least a factor of 2 above the observed abundance of luminous material in the Universe. Thus, we should expect significant baryonic dark matter in our galaxy, even if it may not be enough to account for the observed galactic rotation curves.

A more interesting question therefore becomes: Is the BBN upper limit on Ω_B consistent with baryons making up the complete galactic halo? This issue has taken on renewed interest with the observation by two groups of claimed microlensing events due to compact halo objects in our galaxy. If the frequency of such events persists, this would imply a significant baryonic component of our galactic halo.

Using an updated BBN Monte Carlo code, new reaction rates, and taking into account for the first time correlations between elemental abundances, Pete Kernan and I have just completed a re-analysis of BBN predictions. Our results suggest that an upper limit of 24% for ^4He yields an upper bound on Ω_B of .07, significantly below the estimates for galactic halo densities. This suggests that either: (a) our halo is not baryonic, or (b) the actual primordial ^4He abundance is greater than 24%.

Finally, what about the limits on N_ν from BBN? Our estimates suggest an upper limit which is now much closer to 3.1 rather than 3.3. Is this still interesting, now that LEP has confirmed the actual number of light neutrinos is identically 3? The answer is yes. BBN probes for all relativistic species in equilibrium at $T \approx 1$ MeV, independent of their identity. This can include other exotic particles, or even right handed neutrino states which might not couple to the Z particle directly. In this regard, Appelquist, Terning, and I have recently shown that one can derive strong constraints on extended technicolor models by the requirement that right handed neutrinos must not have significant abundances at the time of BBN[12]

4. Conclusions

We are living in interesting times. Cosmology is a field which is slowly becoming data-rich. In our lifetimes we may be privileged to learn the identity of the dark matter which dominates the mass density of the universe, as well as the processes in the early universe which were responsible for the generation of all observed structures in the universe. As we progress, neutrino physics will undoubtedly continue to play as vital a role in cosmology as it has in unravelling the nature of the electroweak theory.

I would like to thank the organizers of this meeting for their wonderful hospitality,

and for such an interesting choice of topics.

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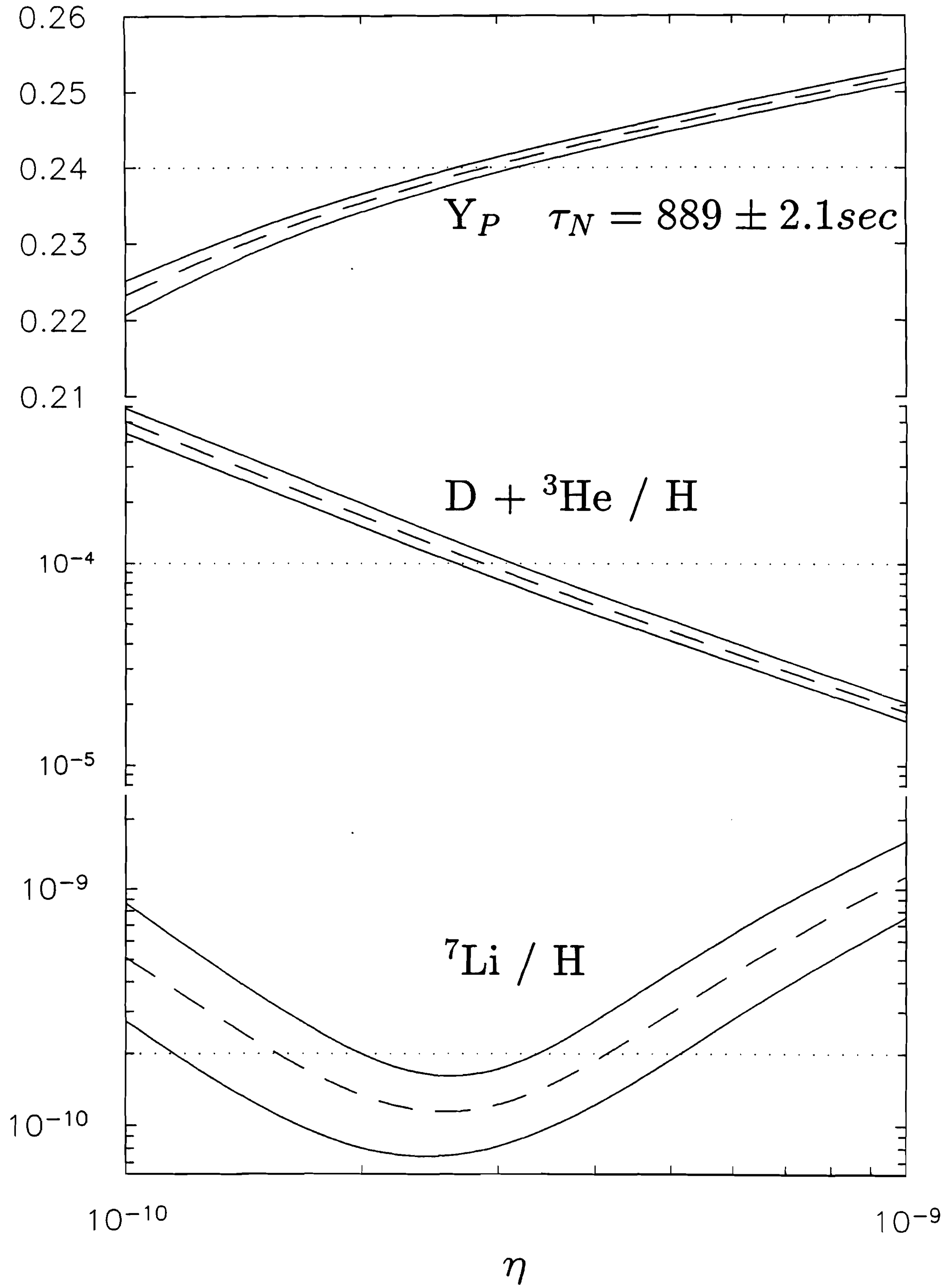
Figure Captions:

Figure 1: Power Spectra for several different cosmological models involving different dark matter candidates: CDM (solid), $n \neq 1$ CDM (dotted), HDM (short dashed), Λ CDM (long dashed), MDM (dot-short-dashed), and BDM (dot-long-dashed) (from reference 4)

Figure 2: Big Bang Nucleosynthesis predictions (taken from ref. 11)


0.26
0.25
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0.23
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0.21
$Y_P \quad \tau_N = 889 \pm 2.1 sec$
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10^{-5}
${}^7Li / H$
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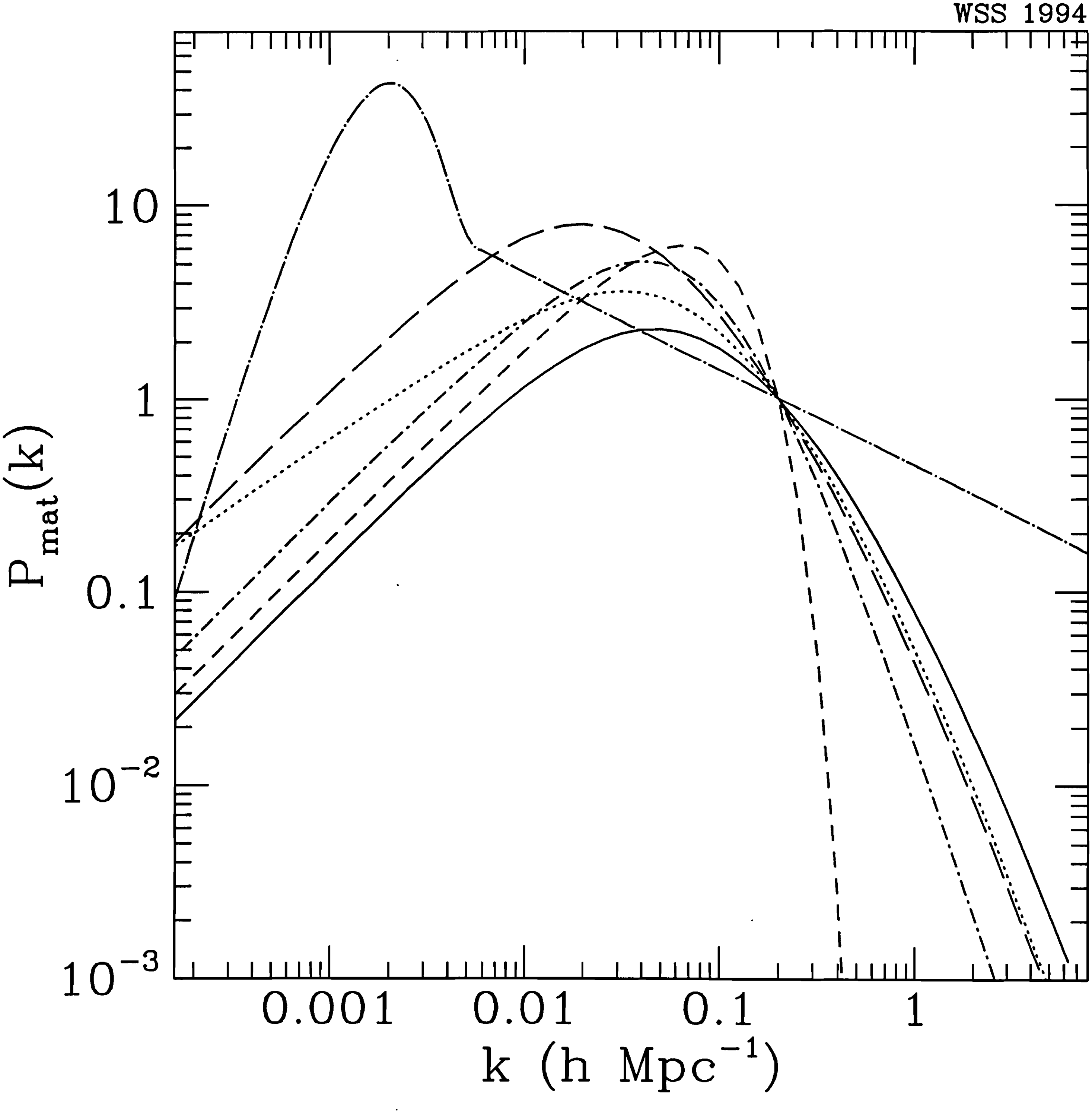
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k (h Mpc^{-1})