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NEUTRINO COUNTING WITH THE SUPERNOVA AND THE BIG BANG

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It is shown that the recent supernova in the Large Magellanic Cloud can be used to set a limit on the number of neutrino families of < 7. For comparison the standard Big Bang nucleosynthesis arguments are reviewed. Using the primordial Helium as inferred from the He versus C correlations, and using the strengthened Li constraint, the cosmological limit is tightened such that three (or two) neutrino families fit well, but a fourth is beginning to be questionable, although it cannot be totally excluded.

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I. Introduction

Cosmological predictions[1,2] about the number of neutrino families, N_ν, were one of the first examples of the particle–cosmology interface, and are now beginning to be tested with accelerators. However, before going into the cosmological prediction it is worth noting that the recent detection of neutrinos from a supernova (SN) in the Large Magellanic Cloud (LMC) also gives an astrophysically derived limit to N_ν. Let us first go through that argument and then we will review the current status of the cosmological argument.

2. Limits from SN 1987a

Regardless of the validity of the neutrino burst reported by the Mt. Blanc[3] detector, it is clear that neutrinos were detected from SN 1987a by Kamioka[4] and IMB[5]. Both of these H_2O detectors are mainly sensitive to $\bar{\nu}_e + p \to n + e^+$ with cross section

$$\sigma = \sigma_0(g_v^2 + 3g_A^2)E_\nu^2 \tag{1}$$

where $\sigma_0 = 1.7 \times 10^{-44}$ cm^2, E_ν is in MeV, and $(g_v^2 + 3g_A^2) \simeq 4.6$.

If the data is assumed to come from a Fermi–Dirac (F–D) distribution at temperature T and total $\bar{\nu}_e$ energy, $\epsilon_{\bar{\nu}_e}$, both IMB and Kamioka are simultaneously fit with $T \sim 4$ to 4.5 MeV and $\epsilon_{\bar{\nu}_e} \sim 3$ to 4.5×10^{52} ergs if appropriate thresholds are taken into account[6,8]. These figures are in remarkable agreement with the standard model[7] for gravitational core collapse of a massive star, if $N_\nu = 3$. Thus, we have confidence that we have witnessed such a core collapse, and that we have a good understanding of its physics. Let us now turn the argument around and see how sensitive our expected fluxes are to N_ν.

In a collapse to a neutron star, the binding energy, ϵ_B, must be radiated as neutrinos. The initial neutronization burst of ν_e's carries away $f_n \lesssim 10\%$ of the ϵ_B on a timescale of ~ 10 ms. The remaining energy comes out in thermal $\nu - \bar{\nu}$ pairs from reactions like

$$e^+e^- \to \nu\bar{\nu} \tag{2}$$

where through neutral currents all species of neutrinos with $m_\nu \lesssim 10$ MeV will be emitted.

Since electron scattering rates are small compared to $\bar{\nu}_e$ capture, even with five times more free electrons than protons, at most we expect one or two scattering events in the detectors for a SN at 50 Kpc (distance to LMC). Thus, the detectable fraction of ϵ_B is $\epsilon_{\bar{\nu}_e}$, where

$$\epsilon_{\bar{\nu}_e} \approx \frac{(1-f_n)}{2N_\nu}\epsilon_B \tag{3}$$

assuming an equipartition of energy emitted in the various neutrino species, as is found in the detailed models. (While average energy per neutrino is higher for ν_μ and ν_τ, their flux is correspondingly reduced to maintain Eq(3).) The number of counts, n, one expects in a detection of mass, M_D, is

$$n = \frac{\epsilon_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e}\rangle}\frac{\langle\sigma\rangle}{4\pi R^2}\frac{2}{18}\frac{M_D}{m_p} \tag{4}$$

where m_p is the proton mass, $R \approx 50$ Kpc is the distance to LMC, $\langle E_{\bar{\nu}_e} \rangle$ is the average $\bar{\nu}_e$ energy, and $\langle \sigma \rangle$ is the average cross section. For a F–D distribution, $\langle E_{\bar{\nu}_e} \rangle = 3.15 T_{\bar{\nu}_e}$. the averaged cross section, $\langle \sigma \rangle$, needs to be appropriately averaged over a F–D with appropriate threshold factors and efficiencies taken into account. The temperature of ν_e's is found to be ~ 3.2 MeV ($\langle E_\nu \rangle \approx 10$ MeV) to good accuracy. Temperatures are very insensitive to model parameters being determined by microphysics at the neutrinosphere[6,8]. The temperature for $\bar{\nu}_e$'s is somewhat higher due to the smaller opacities enabling the $\bar{\nu}_e$'s to come from deeper in the star. Mayle et al. find $T_{\bar{\nu}_e} \sim 4$ MeV in good agreement with the temperature inferred from the observations. (They do find a higher than thermal high energy tail to the distribution which can effect the high threshold IMB but not Kamioka.) For detectors like Kamioka where the threshold is well below the peak of the cross section weighted distribution, it is reasonable to use

$$\langle \sigma \rangle \approx \sigma_0 (g_v^2 + 3g_A^2) 12 T_{\bar{\nu}_e}^2 \tag{5}$$

(For IMB a more careful proceedure must be applied due to its high threshold.) Substituting into Eq(4) yields

$$n = \frac{(1-f_n)\epsilon_B}{3.15 \cdot 2N_\nu} \frac{\sigma_0 (g_v^2 + 3g_A^2)}{4\pi R^2} T_{\bar{\nu}_e} \frac{4}{3} \frac{M_D}{m_p} \tag{6}$$

or equivalently

$$n = \frac{5.2}{(N_\nu/3)} \left(\frac{1-f_n}{0.9}\right) \left(\frac{\epsilon_B}{2 \times 10^{53}\text{ergs}}\right) \left(\frac{T_{\bar{\nu}_e}}{4\text{MeV}}\right) \left(\frac{M_D}{\text{ktons}}\right) \left(\frac{50\text{Kpc}}{R}\right)^2 \tag{7}$$

which for $M_D = 2.14$ ktons (Kamioka) we obtain a prediction of 11 counts for $N_\nu = 3$. While they do actually observe 11, one should weight their counts by efficiency effects to obtain 16.5 ± 5 (or 14.3 ± 4.3 if one assumes that their two directed events were electron scatterings). Solving for N_ν yields

$$N_\nu = (2 \pm 0.6) \left[\left(\frac{T_{\bar{\nu}_e}}{4\text{MeV}}\right) \left(\frac{\epsilon_B}{2 \times 10^{53}\text{ergs}}\right) \left(\frac{1-f_n}{0.9}\right) \left(\frac{50\text{Kpc}}{R}\right) \right]$$

Let us now see how high we can push this. While models can be found with $f_n > 0.1$, it is obvious that $1 - f_n$ can never exceed unity. The effective $T_{\bar{\nu}_e}$, as used above, varies by $\lesssim 25\%$. (Threshold effects for Kamioka on $\langle \sigma \rangle$ can be included within this range.) The binding energy for $1.4 M_\odot$ neutron stars (the mass of the collapsing core) is found to vary from 1.5 to 3×10^{53} ergs for a wide range of equation-of-state assumptions[9]. Thus, we choose 3×10^{53} ergs (4×10^{53} ergs) as an upper bound. The distance to the LMC varies in the astronomical literature by $< 7\%$. We'll adopt an extreme limit of 10%, with most variations going towards longer rather than shorter distances. Combining all these extreme values yields

$$N_\nu < 6.6 (8.9).$$

A more careful calculation taking into account different thresholds for both IMB and Kamioka to obtain measured $\epsilon_{\bar{\nu}_e}$ for predicted yields at the $T_{\bar{\nu}_e}$ inferred from the data yields essentially the same result ($N_\nu \leq 6.7(9.0)$) as given above. Thus, SN 1987a gives a limit on N_ν comparable to accelerator experiments.

3. Cosmological Bounds

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 1 MeV, 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 known what nuclei do in the centers of stars like our sun. The center of the sun is only a little over 1 KeV. This energy is 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. Unfortunately, for stellar astrophysics this means that nuclear reaction rates must be extrapolated to many orders of magnitude below their laboratory-observed values. The Big Bang does not have this problem. It goes through temperatures and densities where the reaction rates are known and well confirmed with laboratory measurements.

To calculate what happens, 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 1 MeV down to a little below 100 KeV. At higher temperatures, no complex nuclei other than single neutrons and protons can exist, and the ratio of neutrons to protons, n/p, is just determined by $n/p = e^{-Q/T}$ where $Q = 1.3$ MeV. 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 10^9 K, the electrostatic repulsion of nuclei, prevents nuclear reactions from proceeding as fast as the cosmological expansion separates the particles.

Because of equilibrium existing for temperatures much above 10^{10} K, for these calculations we don't have to worry about what went on in the universe at higher temperatures. Thus, we can start our calculation at 10 MeV and not worry about speculative physics like T.O.E., GUTs, or even the details of the confinement of quarks, as long as a gas of neutrons and protons exists in thermal equilibrium by the time the universe has cooled to 10 MeV. The equilibrium ratio of neutrons to protons is near unity above 10 MeV, and drops to less than one-third by 10 MeV.

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 10^9 K (0.1 MeV), the ratio is slightly below 1/7. For temperatures above

10^9 K, no complex nuclei can be produced because the simplest, complex nucleus, ^2D, is so weakly bound that the ambient photons fragment any ^2D back into its constituent neutrons and protons at temperatures above 10^9 K. Once the temperature drops to about 10^9 K, ^2D can survive. Then, rapidly, the ^2D adds neutrons and protons, making ^3T and ^3He. These, in turn, add neutrons and protons to produce ^4He, or ^3T and ^3He can collide to also 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 10^9 K into ^4He. The flow essentially ceases 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 1 gram/cm^3) only reactions involving two-particle collisions occur. It can be seen that combining the most abundant nuclei neutrons, protons, and ^4He via 2-body interactions always lead to unstable mass-5. Even when one combines ^4He with rarer nuclei lie ^3T or ^3He, we still only get to mass-7 which when hit by a proton, the most abundant nucleus around, yields mass-8. Eventually, ^3T radioactively decays to ^3He, and any mass-7 made, radioactively decays to ^7Li. Thus, Big Bang nucleosynthesis makes ^4He with traces of ^2D, ^3He, and ^7Li. (Also, all the protons left over that did not capture neutrons remain as Hydrogen.) All other chemical elements are made later in stars and in related processes. (Stars jump the mass-5 and -8 instability by having gravity compress the matter to sufficient densities that 3-body collisions can occur and jump the mass-5 and -8 gaps.) A neutron/proton ratio of $\sim 1/7$ yields a resultant ^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 in the density of the gas which 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, 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 th total mass-energy density associated with a given temperature. For cosmological temperatures much above 10^4 K, 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 occured.

Assuming that the allowed relativistic particles at 1 MeV are photons, e, μ, and τ neutrinos (and their antiparticles) and electrons (and positrons), we have calculated the Big Bang nucleosynthetic 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 deuterium's ability to hold together at slightly higher temperatures and at higher densities, thus enabling nucleosynthesis to start slightly earlier, when the neutron/proton ratio was higher. No matter what assumptions one makes about the baryon density, it is clear that ^4He is predicted by Big Bang nucleosynthesis to have to be around 25% of the mass of the universe. This was first noted by Hoyle and Taylor[10] and later found by Peebles[11] and by Wagoner, Fowler, and Hoyle[12]. The current results do not differ in any qualitative way from Wagoner, Fowler, and Hoyle's.

The fact that the observed Helium abundance in all objects is about 20 to 30% was certainly a nice confirmation of these ideas. Since stars produce only a yield of 2% in all the heavy elements combined, stars cannot easily duplicate such a large yield. While the predicted Big Bang yields of the other light elements were also calculated in the 1960's, they were not considered important at that time, since it was assumed in the 1960's that these nuclei were made in more significant amounts in stars[13]. However, work by our group at Chicago[14], and others, thoroughly established Big Bang nucleosynthesis and enabled it to be a tool for probing the universe, as opposed to a consistency check by showing that other light element abundances had major contributions from the Big Bang and that the effects of stellar contributions were relevant could be removed by appropriate techniques to obtain constraints on the Big Bang yields for those isotopes. Thus, Big Bang predictions for all the four light isotopes are now very relavent.

In particular, it was demonstrated in the early 1970's that contrary to the ideas of the 1960's, deuterium cound not be made in any significant amount by *any* astrophysical process other than the Big Bang itself[15]. The Big Bang deuterium yield decreases rapidly with an increase in ρ_b. Since at high densities the deuterium gets more completely converted to heavier nuclei, this quantitatively means that the present density of baryons must be below $\sim 5 \times 10^{-31}$ g/cm^3 in order for the Big Bang to have produced enough deuterium to explain the observed abundances. Similar though more complex arguments were also developed for ^3He, and most recently[16] for ^7Li so that it can be said that only if the baryon density is between 2×10^{-31} g/cm^3 and 5×10^{-31} then all the observed light element abundances are consistent with the Big Bang yields. If the baryon density were outside of this range, a significant disagreement between the Big Bang and the abundance observations would result. To put this in perspective, it should be noted that for this range in densities, the predicted abundances for the four separate species fall over a range from 25% to one part in $\sim 10^{10}$. [In fact, for lithium to get agreement requires an abundance just at 10^{-10} and, no less, that is what the latest observations show[16].] The Big Bang yields all agree with only one freely adjustable parameter, ρ_b. Recent attempts to circumvent this argument[21] by having variable n/p ratios because they fail to fit the Li even when numerous additional parameters are added and fine-tuned.

This narrow range in baryon density for which concordance occurs is very interesting. Let us convert it into units of the critical cosmological density for the allowed range of Hubble expansion rates. The dimensionless baryon density. From the Big Bang nucleosynthesis constraints[14,17] on the baryon density, Ω_B is that fraction of the critical density which is in baryons. Ω_B is less than 0.12 and greater than 0.03; that is, the universe ***cannot be closed with baryonic matter.*** If the universe is truly at its critical density, then non-baryonic 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 10 years ago[18]. As time has gone on, the argument has strengthened and the fact remains that galaxy dynamics and nucleosynthesis agree at about 10% of the critical density. Thus, if the universe is indeed at its critical density, as many of us believe, it requires most matter to not be associated with galaxies and their halos, as well as to be non-baryonic.

With the growing success of Big Bang nucleosynthesis, the finer details of the results were put into focus. In particular, the ^4He yield was looked at in detail since it is the most abundant of the nuclei, and thus in principle it is the one which observers should be able to measure to higher accuracy. In addition, it 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 form neutrons to change into protons, raising the n/p ratio. A higher n/p ratio yields more ^4He.

In the standard calculation we allowed for photons, electrons, and the three known neutrino species (and their antiparticles). However, by doing the calculation 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 ^2D, ^3He, and now ^7Li. (The new ^7Li value gives 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. To do this we[19] have found that the carbon content of the object can be used to track the additional Helium. Carbon is made in the same mass stars that also produce ^4He, thus as the carbon abundance increases, so must the Helium. (Other heavy elements such as oxygen have been tried for this extrapolation, but these tend to not focus their production as well on the same type stars as those that also produce Helium.) The extrapolation of Helium to zero carbon content in an object should be a good estimate of the primordial Helium.

We obtain ~ 0.235 as our best estimate for the mass fraction of Helium produced in the Big Bang. The upper bound is what is important here. We formally estimate a three standard deviation bound as 0.247. In particular, it seems clear that the primordial ^4He was at least a little less than 25%. Since objects (like our sun) have heavy elements and possibly some associated extra-stellar produced Helium, and still have Helium abundances of 25%, this certainly seems like a *very* safe upper bound. In fact, if anything our estimates are on the high side due to possible systematic errors yielding slight over-estimates. (Pagel[20] finds collisional excitation reduces the 0.235 to 0.233.)

We find (see Figure) that three (or two) types of neutrinos fit the data well, and a fourth only marginally sneeks in if Helium exceeds the 3-σ upper bound, any more neutrinos are strictly prohibited. Since each family contains a neutrino, we are saying that the total number of families is three or at most four. Thus, all the fundamental families of elementary particles may have been discovered already.

It is nice to hear that particle accelerators are beginning to probe this level of sensitivity, and that soon we will know whether or not cosmological theory is able to make reliable predictions about fundamental physics.

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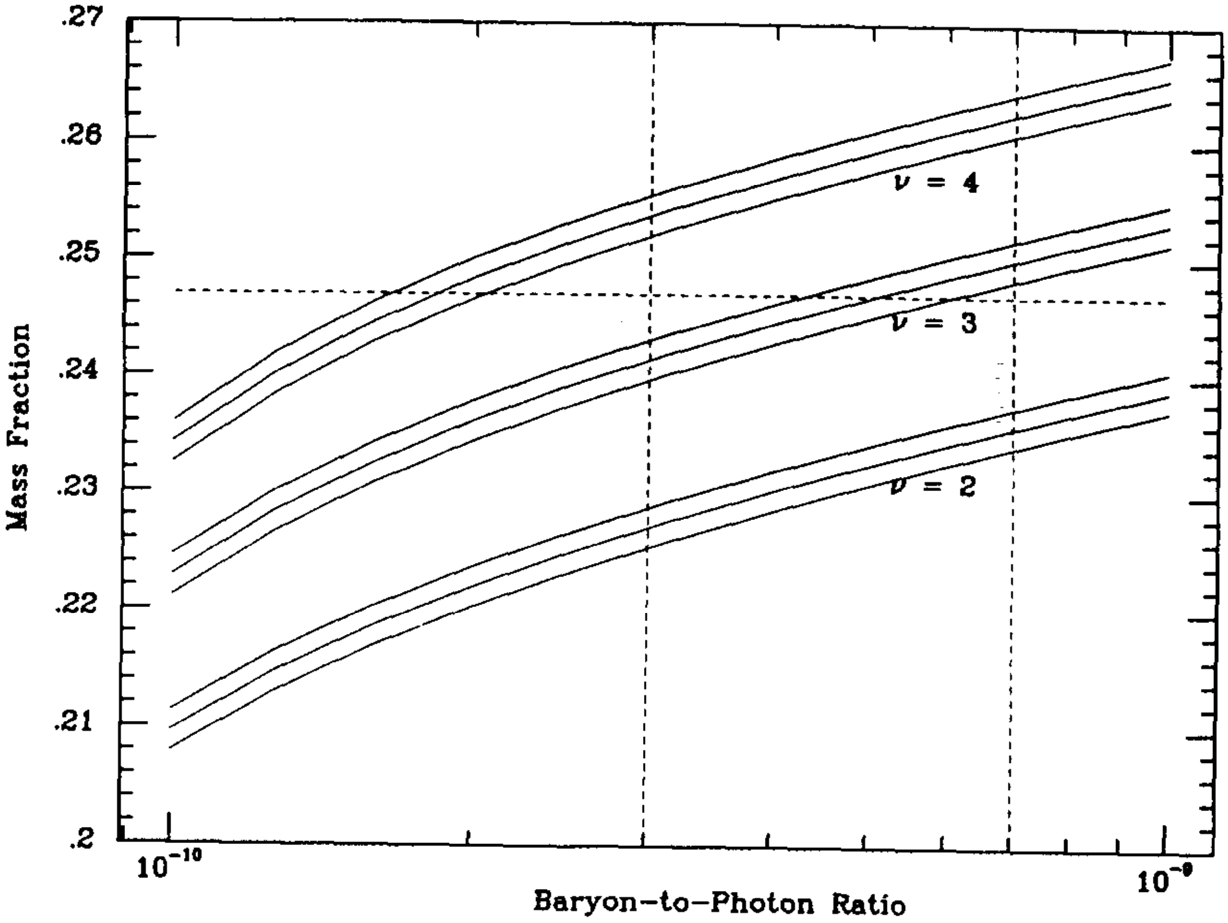

Helium mass fraction versus the baryon to photon ratio. The lower bound of 2×10^{-10} is consistent with the $^3He + D$ and ^7Li constraints, and the upper bound of 7×10^{-10} with the D and ^7Li constraints. The three lines for each neutrino family correspond to neutron half-lives of 10.4, 10.5, and 10.6 minutes.