Cosmological Implications of a Relic Neutrino Asymmetry

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We consider some cosmological consequences of a relic neutrino asymmetry. A relic neutrino degeneracy enhances the contribution of massive neutrinos to the present energy density of the Universe, and modifies the power spectrum of radiation and matter. We also show that even the smallest neutrino mass consistent with the Super–Kamiokande data is relevant for cosmological models, provided that a relic neutrino asymmetry exists.

It is generally assumed that an asymmetry in the number of leptons and antileptons in the Universe would be of the same order as the baryon asymmetry, which is very small as required by Big Bang Nucleosynthesis (BBN) considerations. However since neutrinos are chargeless, a relic neutrino asymmetry does not violate the requirement of universal electric neutrality, and in some specific theoretical scenarios[1] it can grow up to large values in the early universe. In this contribution we summarize some of the cosmological implications of relic degenerate neutrinos, which are characterized by the dimensionless degeneracy parameter $\xi \equiv \mu/T_\nu$, where μ is their chemical potential and T_ν their temperature. Here degenerate refers to a neutrino-antineutrino asymmetry, and not to a degeneracy in mass.

In the case of massless degenerate neutrinos, the main effect of ξ is to increase the total density of radiation, and to postpone the time of equality between radiation and matter. This suppresses matter fluctuations on small scales and produces large observable effects on the spectrum of Cosmic Microwave Background (CMB) anisotropies: it boosts the amplitude of the first peak and shifts all peaks to smaller scales [3]. However, it can be simply described by introducing a larger effective number of massless neutrino families. In the case of massive degenerate neutrinos, there exist some subtle effects, such as the suppression of small scale matter fluctuations caused by the free-streaming of neutrinos, which is more efficient in presence of an asymmetry.

The evidence for neutrino oscillations from Super-Kamiokande [4], if explained by $\nu_\mu \leftrightarrow \nu_\tau$ conversions, requires differences of squared masses of the order $(1-8)\times 10^{-3}$ eV^2, i.e. a lower limit on the value of the neutrino mass of $0.03-0.09$ eV. This bound is saturated when there is a hierarchy in the neutrino mass pattern, and the two neutrino masses are very different. However the contribution of such neutrinos to the present energy density of the Universe is of the order $\Omega_\nu = 0.00075 h^{-2}$ in units of the critical density for a dimensionless Hubble parameter $h = H_0/(100 \text{ km s}^{-1}\text{Mpc}^{-1})$ and a typical value of the mass $m_{SK} = 0.07$ eV, while at the same time they have no visible effect on the power spectra of matter and CMB anisotropies. Therefore a neutrino with m_{SK} is of little relevance for cosmology, unless a relic neutrino asymmetry exists. For instance, the value of Ω_ν for neutrinos with m_{SK} and $\xi = 3$ is of the same order of magnitude as that of baryons [3,5].

BBN requires that a degeneracy for electronic neutrinos is at most of order one, while the constraints on $\xi(\nu_\mu, \nu_\tau)$ are less stringent, in particular if $\xi(\nu_e) > 0$ and the baryon density is larger than in the standard case [6,7]. Interestingly, it was shown [8] that the CMB anisotropy data were compatible with a large neutrino asymmetry $\xi \sim 3.5$ in the framework of the standard cold dark matter (CDM) scenario. More recently, we showed in a systematic analysis [3] that this con-

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[1]For instance, this asymmetry could be generated by resonant active-sterile neutrino conversions [1,2].

clusion also applied to flat models with a cosmological constant, even when CMB data are combined with the Large Scale Structure (LSS) data on the matter power spectrum. It turns out that the most recent data from the BOOMERANG [9] and MAXIMA [10] experiments could be explained by the existence of a large ξ, as shown in [11,12].

We plot in figure 1 the LSS and CMB allowed regions in (ξ, n) parameter space, corresponding to $\Omega_\Lambda = 0$ and 0.7 (see [3] for the details). Here n is the spectral index of the primordial density perturbations ($n = 1$ is the natural prediction of inflation). In the case of degenerate neutrinos with m_{SK}, the effect of ξ is enhanced (dotted lines in the figure). The CMB allowed regions do not show this distinction, given the smallness of the effect and the imprecision of the data. One can see that LSS and CMB constraints on n are shifted in opposite direction with ξ: indeed, the effects of ξ and n both produce a higher CMB peak, while to a certain extent they compensate each other in $P(k)$. For $\Omega_\Lambda \gtrsim 0.7$ the power spectrum has a too high peak, so we find no allowed window for a neutrino degeneracy. In the other extreme case $\Omega_\Lambda = 0$, we find the allowed region $3.5 \lesssim \xi \lesssim 6$. Finally, for $\Omega_\Lambda = 0.5 - 0.6$, a good agreement was found up to $\xi \simeq 3$ [3].

We have explored the sensitivity of future CMB experiments to m_{SK} in the presence of a relic neutrino asymmetry [13]. A positive evidence would be of tremendous importance for our understanding of neutrino models, since it would probe the absolute value of the neutrino mass, while neutrino oscillations are sensitive to the difference of squared masses. Since ξ enhances the effect of the mass, but introduces a new degree of freedom in the model, it is not obvious whether the scheduled experiments have the required sensitivity.

The precision with which the future satellite missions Microwave Anisotropy Probe (MAP) and Planck could measure a large degeneracy parameter $\xi \sim \mathcal{O}(1)$ was calculated in [14]. To see the effect of m_{SK} we will skip MAP and focus on the capabilities of Planck, as well as those of the future Sloan Digital Sky Survey (SDSS), that will probe the shape of the matter power spectrum on the largest scales, modulo a biasing factor b^2 that

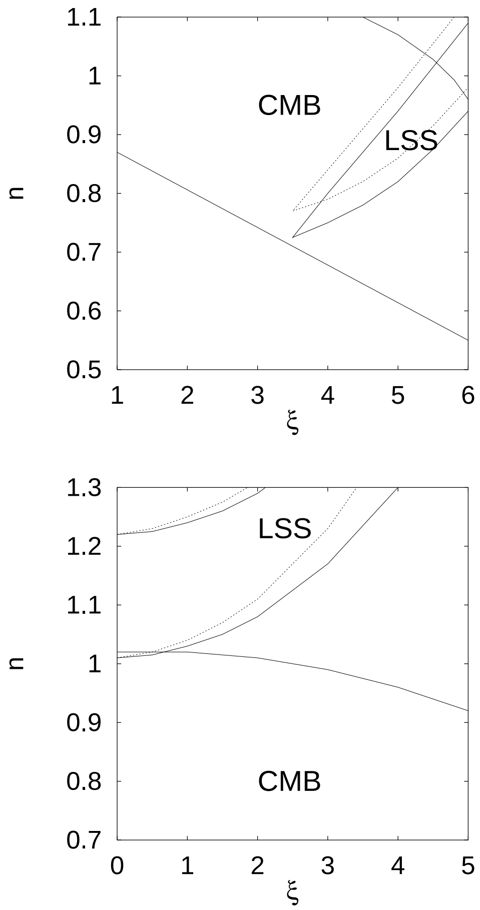

Figure 1. LSS and CMB constraints in (ξ, n) space, for $\Omega_\Lambda = 0$ (upper) and $\Omega_\Lambda = 0.7$ (lower), and $m_\nu = 0$ (solid lines) and $m_\nu = 0.07$ eV (dotted lines). The allowed regions are those where the labels are.

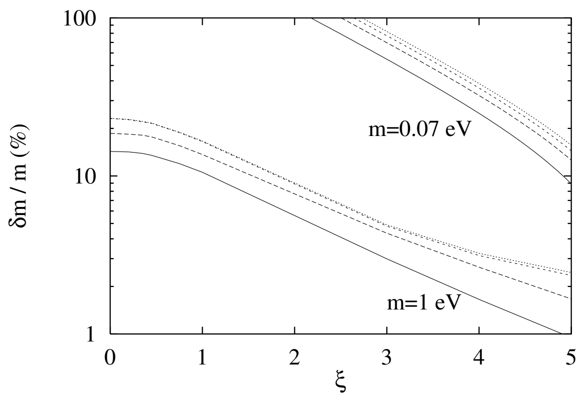

Figure 2. $\delta m/m$ versus ξ for Planck and SDSS.

reflects the discrepancy between the total matter fluctuations in the Universe, and those actually seen by the instruments. The combination of CMB and LSS data is crucial for the mass extraction for ordinary neutrinos [15]; in our case it is even more important, due to the enhanced free streaming effect on small scale matter fluctuations. Since the sensitivities of Planck and SDSS are already known, it is possible to assume a "fiducial" cosmological model that would fit the future data, and to forecast the error with which each parameter would be extracted. For such a model, one can compute [16] the power spectra of CMB anisotropies and the linear power spectrum of matter fluctuations $P(k)$, expanded in Fourier space. Then the 1σ error on each parameter θ_i can be calculated from the reduced Fisher matrix F_{ij} as $\delta\theta_i/\theta_i = (F^{-1})_{ii}^{1/2}$ (see [13] for details).

For a fiducial model with degeneracy ξ and $m = 0$, our results are in good agreement with ref. [14]. For $\xi = 3.5$ we find for Planck $\delta\xi/\xi = 2.5\%$ (without polarization), a small error that reflects the large effect of ξ on the amplitude and shape of the acoustic peaks [3,8,14]. It is limited by a small parameter degeneracy between ξ and Ω_{CDM}, or equivalently between ξ and the cosmological constant, since one has that $\Omega_{CDM} + \Omega_\Lambda = 1 - \Omega_b$, and the only effect of ξ is to change the time of equality, which is one of the main effects of Ω_Λ. Since this holds also for the polarization and matter spectra, the degeneracy is not removed by including the information from polarization and the SDSS: $\delta\xi/\xi$ is reduced only from 2.5% to 2.3%.

In the case of massive degenerate neutrinos, the results for $\delta m/m$ as a function of ξ are shown in Fig. 2. From top to bottom, the four curves refer to Planck without and with polarization, and Planck + SDSS with $k_{max} = 0.1$ or $0.2h$ Mpc^{-1}. The upper and lower curves refer to $m = 0.07$ and 1 eV, respectively. For m_{SK} and $\xi = 2.75$, the temperature mode measured by Planck could bring marginal evidence for m_{SK}: $\delta m/m = 102\%$. Including polarization, we find $\delta m/m = 93\%$. Finally, significant progress is made with the SDSS: for $k_{max} = 0.1h$ Mpc^{-1} we obtain $\delta m/m = 84\%$ (59% for $0.2h$ Mpc^{-1}). This leads to a clear detection, especially if we recall that when $m \to 0$ the above errors, when large, are overestimated, as pointed out in [15]. When the neutrino degeneracy is as large as $\xi = 3.5$, we get $\delta m/m = 37\%$ for Planck + SDSS.

We also plot in Fig. 2 the results for $m = 1$ eV. Such a mass could explain the results from the LSND [17] experiment via neutrino oscillations with $\Delta m^2 \simeq 0.1 - 1$ eV^2. An eV neutrino is also required in cold + hot dark matter models, because it produces $\Omega_\nu \gtrsim 0.01h^{-2}$. It has been shown that such a mass could be extracted with $\sim 20\%$ precision by Planck + SDSS, and our estimated errors are consistent with [15]. In the presence of a relic neutrino asymmetry, they are lowered from $\delta m/m = 15 - 20\%$ (for $\xi = 0$) to $3 - 4\%$ (for $\xi = 3$), depending on k_{max}.

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