COSMOLOGICAL IMPLICATIONS OF A RELIC NEUTRINO ASYMMETRY

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We consider some consequences of a cosmological lepton asymmetry in the form of neutrinos. 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. Comparing with current observations of cosmic microwave background anisotropies and large scale structure, we derive some constraints on the relic neutrino degeneracy and on the spectral index in the case of a flat Universe with a cosmological constant. Finally, we calculate the precision with which the small neutrino mass suggested by Super–Kamiokande ($m_{SK} \sim 0.07$ eV) could be constrained by the future Planck satellite and Sloan Digital Sky Survey. Assuming a large relic neutrino asymmetry still allowed by current experimental data, we find that such a mass can be detected.

1 Introduction

It is generally assumed that our Universe contains an approximately equal amount of leptons and antileptons. However, since neutrinos are electrically neutral, a large neutrino asymmetry is an open possibility [1,2,3]. From a particle physics point of view, it can be generated by an Affleck-Dine mechanism without producing a large baryon asymmetry[4,5], or even by active-sterile neutrino oscillations after the electroweak phase transition[6].

We summarize some results concerning the cosmological implications of relic degenerate neutrinos [7] (here degenerate refers to neutrino-antineutrino asymmetry, not to degeneracy in mass). We focus on the anisotropies of the Cosmic Microwave Background (CMB), and on the distribution of Large Scale Structure (LSS). We calculate the power spectrum of both quantities, in the case of massless degenerate neutrinos, and also for neutrinos with a mass of

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0.07 eV, as suggested by experimental evidence for atmospheric neutrino oscillations at Super-Kamiokande.

2 Energy density of massive degenerate neutrinos

When the early Universe was hot enough, the neutrinos were in equilibrium with the rest of the plasma ($e^{\pm}$ and photons) via the weak interactions. In that case the distribution functions f_ν and $f_{\bar{\nu}}$ changed with the Universe expansion, keeping the form of a Fermi-Dirac distribution,

$$f_{\nu,\bar{\nu}}(p) = \frac{1}{\exp\left(\dfrac{p}{T_\nu} \mp \dfrac{\mu}{T_\nu}\right) + 1}. \tag{1}$$

Here p is the magnitude of the 3-momentum and μ is the neutrino chemical potential, which is nonzero if a neutrino-antineutrino asymmetry has been previously produced. Later the neutrinos decoupled when they were still relativistic, and from that moment the neutrino momenta just changed according to the cosmological redshift. At the same time the neutrino degeneracy parameter $\xi \equiv \mu/T_\nu$ is conserved, with a value equal to that at the moment of decoupling. We show in figure 1 the contours in the (m_ν, ξ) plane that correspond to some particular values of $h^2\Omega_\nu$, where Ω_ν is the present neutrino energy density in units of the critical density, and h the reduced Hubble parameter ($H_0 = 100h$ Km s^{-1}Mpc^{-1}).

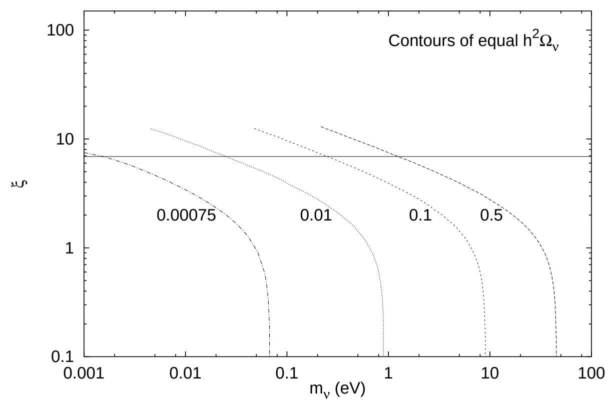

Figure 1: Energy density of degenerate neutrinos as a function of mass and asymmetry.

The presence of a neutrino degeneracy can modify the outcome of primordial nucleosynthesis [8]. In particular, if the degenerate neutrinos are of electron type, they have a direct influence over the weak processes that interconvert neutrons and protons. This last effect depends on the sign of ξ_{ν_e}, and one gets $-0.06 \lesssim \xi_{\nu_e} \lesssim 1.1$ [9]. The most stringent constrain on other species comes from the requirement of a sufficiently long matter dominated epoch: $|\xi_{\nu_\mu,\nu_\tau}| \lesssim 6.9$[9]. This estimate agrees with our analysis in section 4 and places a limit shown by the horizontal line in figure 1 in the case of degenerate ν_μ or ν_τ.

3 Effects on the power spectra

We compute the power spectra of CMB anisotropies and LSS using the code `cmbfast` [10], adapted to the case of one family of degenerate neutrinos.

The effect of ξ and m_ν can be seen in figure 2. Since the neutrino asymmetry delays matter-radiation equality, it boosts the amplitude of the first peak, shifts all peaks to higher multipoles, and suppresses matter fluctuations on small scales. The small mass $m_\nu = 0.07$ eV affects the

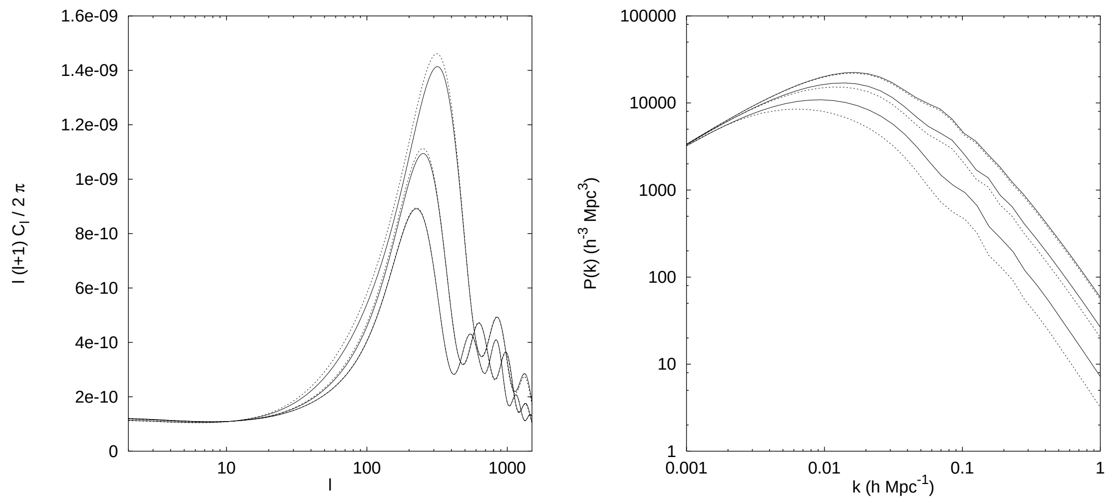

Figure 2: CMB anisotropy and LSS power spectra for different models with one family of massless (solid lines) and $m_\nu = 0.07$ eV (dashed lines) degenerate neutrinos. From bottom to top (from top to bottom for LSS), $\xi = 0, 3, 5$. Other cosmological parameters are fixed.

CMB by a small amount. Indeed, a large degeneracy combined with a small mass can produce a significant value of Ω_ν today: for $\xi = 5$ and $m_\nu = 0.07$ eV, one has $\Omega_\nu = 0.028$, *i.e.* the same order of magnitude as for baryons. The small mass has a major effect on LSS: when the degenerate neutrinos become non-relativistic, their free-streaming suppresses the growth of fluctuations for scales within the Hubble radius. This effect, well-known for non-degenerate neutrinos[11], is enhanced in the presence of a neutrino degeneracy, since the average neutrino momentum is shifted to larger values.

4 Comparison with observations

Since the degeneracy increases dramatically the amplitude of the first CMB peak, we expect large ξ values to be favored in the case of cosmological models known to predict systematically a low peak (unless a large blue tilt is invoked, which puts severe constraints on inflation). Our goal here is not to explore systematically all possibilities, but to briefly illustrate how ξ can be constrained by current observations for flat models with different values of Ω_Λ.

We choose a model with $h = 0.65$, $\Omega_b = 0.05$, $Q_{rms-ps} = 18$ μK, no reionization and no tensor contribution, and look for the allowed window in the space of free parameters (Ω_Λ, ξ, n). The allowed window is defined as the intersection of regions preferred at the 95% confidence level by four independent experimental tests, based on σ_8 estimation, Stromlo-APM redshift survey, bulk velocity reconstruction, and CMB anisotropy measurements.

For $\Omega_\Lambda \geq 0.7$, a case in which a power spectrum normalized to both COBE and σ_8 yields a too high peak (at least for the values of the other cosmological parameters considered here), a neutrino degeneracy can only make things worst, and we find no allowed window at all. In the other extreme case $\Omega_\Lambda = 0$, it is well known that the amplitude required by σ_8 and the shape probed by redshift surveys favor different values of n. We find that the neutrino degeneracy can solve this problem with $\xi \gtrsim 3.5$, but the allowed window is cut at $\xi \simeq 6$ by CMB data. Finally, for $\Omega_\Lambda = 0.5 - 0.6$, a good agreement is found up to $\xi \simeq 3$. This large upper bound is our main result, and could marginally explain the generation of ultra-high energy cosmic rays by the annihilation of high-energetic neutrinos on relic neutrinos with mass $m_\nu = 0.07$ eV[12].

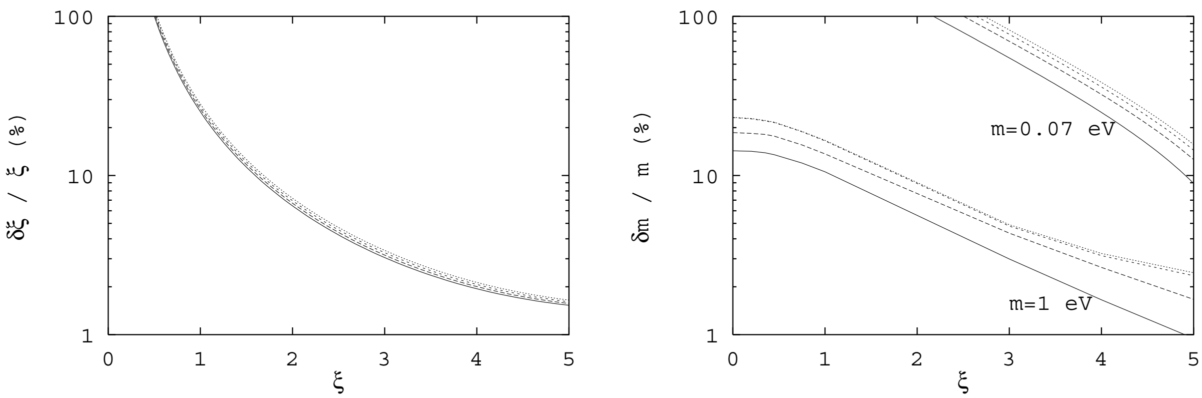

Figure 3: For a fiducial model with ten free parameters (with standard values), we plot the forecasted $1-\sigma$ errors $\delta\xi/\xi$ (when all other parameters are unknown) as a function of ξ in the fiducial model. We do the same for $\delta m/m$. From top to bottom, the four curves refer to *Planck* without and with polarization, and *Planck* + SDSS with two different assumptions on the SDSS data interpretation[13]. For $\delta m/m$ we can distinguish the two cases $m=0.07$ eV and $m=1$ eV, while for $\delta\xi/\xi$ there is no significant difference.

The very light neutrinos suggested by Super–Kamiokande ($m_{SK}\sim 0.07$ eV) are usually assumed to be of little relevance for cosmology, because they have no visible effect on the power spectra of matter and CMB anisotropies. However, we have seen that this conclusion is modified when one considers the combined effects of mass and degeneracy.

Since the sensitivity of *Planck* and of the Sloan digital Sky Survey (SDSS) is already known, it is possible to assume a "fiducial" model, i.e., a cosmological model that would yield the best fit to the future data, and to forecast the error with which each parameters would be extracted, using a Fisher matrix analysis[13]. The most striking result (see fig.3) is that *Planck* and SDSS will be able to m_{SK}, provided that the relic neutrinos are strongly degenerate, with a degeneracy parameter $\xi\gtrsim 2.5$. Such a measurement of the absolute value of the neutrino mass would be crucial for our understanding of theoretical neutrino models.

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