Non-standard neutrinos and Cosmology

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Cosmology provides stringent constraints on neutrino masses, neutrino effective number and possible non standard interactions of both ordinary and possible extra neutrinos.

1. Introduction

Thanks to recent data about the Cosmic Microwave Background (CMB), Large Scale Structures (LSS) and also Type Ia Supernovæ (SNe), cosmology has become the most sensitive probe of some neutrino properties and a very sensitive probe of others, including non standard ones. Such probes give us indirect access to quite different epochs in the cosmological evolution: the epoch of Big Bang Nucleosynthesis (at $T \sim 1\,\mathrm{MeV}$, during radiation domination), the moment of CMB formation (at $T \sim 1\,\mathrm{eV}$), the epoch of structure formation (long within matter domination). Neutrinos have a prominent rôle in all these epochs and therefore in shaping the cosmological evolution of the Universe, as it is useful to remind in a qualitative way:

- when the Universe was radiation dominated, neutrinos were the main component of the relativistic energy density that was setting the expansion rate;

- after radiation-matter equality, neutrinos turned non-relativistic (because they have a mass, as oscillation experiments testify) and therefore contribute to the matter density of the Universe in the matter dominated phase;

- in the low-redshift epoch of structure formation, neutrinos affect the structure clustering process by free-streaming out of the potential wells; the extent to which this process is effective depends on the possible presence of additional non-standard interactions among neutrinos or between neutrinos and other possible fluids.

As a consequence, cosmological observations have the power of very efficiently constraining the main neutrino properties: (i) their summed mass, (ii) their number, (iii) their possible non-conventional interactions.

I summarize here a few non-exhaustive results on neutrino properties that can be obtained from global fits of cosmological data. The results are obtained with an independent cosmological code (that solves the Boltzmann equations for the different species and computes the CMB and matter power spectra) and a gaussian statistical approach, somewhat different from the standard one. The analysis is mainly based on the work in ref. [1], to which I refer for a full discussion, the compilation of data[2] and a more complete list of reference.

2. Standard neutrino masses and number

Neutrino masses affect in a direct way the matter power spectrum of LSS. When relativistic, neutrinos free-stream out of the galactic structures that are being formed by the clustering force of gravity, thus suppressing their growth.

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[2]Concerning the CMB, the data from the 3yr WMAP release are used. Updating to the 5yr release would probably improve somewhat the results discussed here.

When neutrinos become non relativistic, as a consequence of being massive, they can travel smaller distances and therefore their smoothening effect is felt only on the small scales. Thus the ν mass determines the amount and the time (corresponding to the cosmological scale) of the resulting suppression. Confronting with the observed LSS matter power spectrum allows to derive constraints on $\sum m_\nu$. Recent galaxy surveys measure the matter power spectrum via the distribution of luminous galaxies. This assumes that the galactic matter traces the underlying total matter as parameterized by a bias parameter b, that has to be independently determined or modeled. From this set of data we find in ref. [1]

$$\sum m_\nu < 0.73 \text{ eV}, \;\; 99.9\% \,\text{CL} \;\; [\text{CMB}+\text{LSS}]. \quad (1)$$

Observing the forest of absorption lines at the (redshifted) Lyα frequency in the light of distant quasars also allows to reconstruct the distribution of the intervening matter (mainly at smaller scales compared to the galaxy surveys). While these measurements are still quite plagued by controversy and uncertainties, taking them into account we find in ref. [1]

$$\sum m_\nu < 0.40 \text{ eV}, \;\; 99.9\% \,\text{CL} \;\; [\text{with Ly}\alpha]. \quad (2)$$

The 'number of neutrinos' N_ν parameterizes the amount of energy in all relativistic freely-streaming degrees of freedom, converted in terms of 'neutrino equivalents': N_ν includes the ordinary neutrinos and any extra fermion or boson, as it is formally defined by the relation $\rho_{\text{relativistic}} = \rho_\gamma \left[1 + 7/8 \; N_\nu (T_\nu/T)^4\right]$, where $T_\nu/T = (4/11)^{1/3}$ at $T \ll m_e$. Standard cosmology with 3 neutrinos predicts $N_\nu \approx 3.04$ (the deviation from 3 being due to the incomplete ν_e decoupling at the time of the beginning of e^+e^- annihilations, plus other small corrections). From BBN the constraint $N_\nu = 3.1 \pm 0.6$ is obtained (see e.g. [2] and references therein). Our global fit gives the surprising result

$$N_\nu = 5 \pm 1, \quad (3)$$

which would hint (but just at 2σ) at the presence of extra relativistic species. In general, results of global fits can be misled by problems in any of the pieces of data they contain; in this case the validity of the global fit appears particularly doubtful: N_ν is dominantly determined by non-CMB data, and giving slightly different weight to them can significantly affect the fit because different pieces of data prefer different values of N_ν. In particular, omitting Lyman-α one recovers excellent agreement with the standard value $N_\nu = 3$. Other works claim a 'some σ' preference for $N_\nu > 3$ [4,5]. The agreement among them and with the up-to-date analyses performed by the WMAP Team [6] is imperfect. This issue has been discussed at length in further works [7].

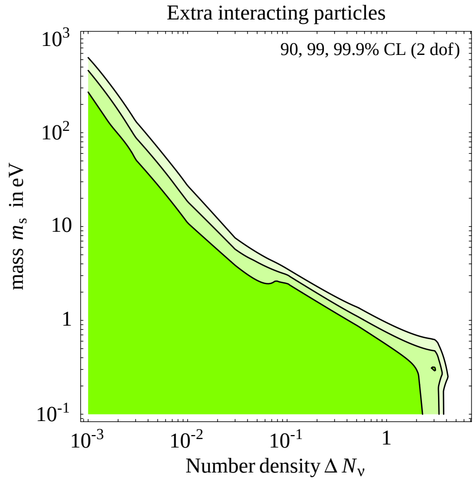

Figure 1. The allowed (shaded) regions individuated by the global cosmological fit if an effective number ΔN_ν of extra neutrinos (on top of the 3 ordinary SM neutrinos) with mass m_s is added.

3. Non-standard interacting neutrinos

We now consider the possibility of having extra (massless) particles that interact among themselves with a mean free path smaller than relevant cosmological scales. We could call these particles 'sticky extra neutrinos' (where, as usual, the word 'neutrinos' is used in the broad effective sense). Parameterizing the density of the sticky particles

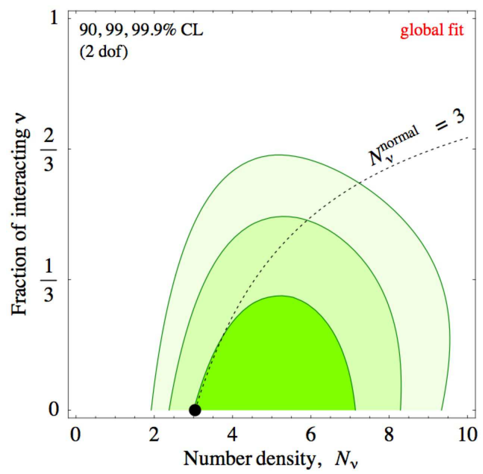

Figure 2. The allowed (shaded) regions individuated by the global cosmological fit in presence of a total number N_ν of effective (massless) neutrinos (including the 3 ordinary neutrinos) of which a certain fraction is interacting.

with the usual 'equivalent number of neutrinos' ΔN_ν, the global fit gives

$$\Delta N_\nu = 0 \pm 1.3. \tag{4}$$

That is, data do not favor the presence of extra massless particles interacting among themselves. Dropping Lyman-α data makes the 1σ constraint two times more stringent.

We can also consider the case in which the extra sticky particles have a non negligible mass $m_{\rm s}$ and are stable, such that when the temperature T falls below $m_{\rm s}$ they form a non-relativistic relic. Again, the parameter ΔN_ν tells the initial abundance of the extra particles in the usual 'neutrino-equivalent' units. Fig.1 shows the result of the global fit: interacting extra particles are constrained to be not too abundant and/or not too heavy. Notice that, like in the case of massive freely-streaming sterile neutrinos, cosmology disfavors the mass values suggested by the LSND anomaly (~ 1 eV) also in this case of tightly-interacting sterile neutrinos.

We finally consider the case in which the ordinary SM neutrinos are involved in interactions with the possible extra particles. That is, the ordinary neutrinos are (at least in part) 'sticky'. More specifically, we consider $N_\nu^{\rm normal}$ neutrinos that behave normally, while $N_\nu^{\rm int}$ neutrinos interact with extra scalars ϕ, such that these interacting $N_\nu^{\rm int}$ neutrinos no longer free stream, but form a tightly coupled fluid together with the scalars. For this case we assume that $m_\nu = m_\phi = 0$, such that the fluid is relativistic. The system can be described by just two parameters: i) the total energy density in relativistic particles, that we describe by the usual 'number of neutrinos' $N_\nu = N_\nu^{\rm normal} + N_\nu^{\rm int} + 4N_\phi/7$; ii) the energy fraction $R = N_\nu^{\rm int}/N_\nu$ that contributes to the fluid. The remaining fraction freely streams. In standard cosmology $R = 0$ and $N_\nu = N_\nu^{\rm normal} = 3.04$. Fig.2 shows how the global fit determines these two parameters. The 'all interacting' case ($R = 1$) is disfavored at 4σ at least. Related analyses claimed slightly different results [8].

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