Is the $H_0$ tension suggesting a 4th neutrino’s generation?

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Flavour oscillations experiments are suggesting the existence of a sterile, 4th neutrino’s generation with a mass of an eV order. This would mean an additional relativistic degree of freedom in the cosmic inventory, in contradiction with recent results from the Planck satellite, that have confirmed the standard value $N_{e\,\text{ff}} \approx 3$ for the effective number of relativistic species. On the other hand, the Planck best-fit for the Hubble-Lemaître parameter is in tension with the local value determined with the Hubble Space Telescope, and adjusting $N_{e\,\text{ff}}$ is a possible way to overcome such a tension. In this paper we perform a joint analysis of three complementary cosmological distance rulers, namely the CMB acoustic scale measured by Planck, the BAO scale model-independently determined by Verde et al., and luminosity distances measured with JLA and Pantheon SNe Ia surveys. Two Gaussian priors were imposed to the analysis, the local expansion rate measured by Riess et al., and the baryon density parameter fixed from primordial nucleosynthesis by Cooke et al.. For the sake of generality, two different models are used in the tests, the standard ΛCDM model and a generalised Chaplygin gas. The best-fit gives $N_{e\,\text{ff}} \approx 4$ in both models, with a Chaplygin gas parameter slightly negative, $\alpha \approx -0.04$. The standard value $N_{e\,\text{ff}} \approx 3$ is ruled out with $\approx 3\sigma$.

I. INTRODUCTION

The panorama on neutrino flavour oscillation experiments is very robust. Data from different experimental setups converge into a concise explanation, in which neutrino flavour oscillations are driven by two large and one small mixing angle, and two hierarchical mass differences [1]. Such framework provides a precise prediction on flavour transitions of atmospheric, solar, reactor and accelerator neutrinos, in an energy range that varies from sub-MeV to several GeV, and distances that varies from few meters to astrophysical distances. These predictions have been corroborated by different experimental results on the last decades.

However, experiments that find neutrino flavour conversion signals that are not easily accommodated in the 3-neutrino mixing framework are piling up. More than 15 years ago the LSND experiment [2] observed an appearance of electron anti-neutrinos in a muon anti-neutrinos flux, which if explained through mass-driven flavour oscillations would suggest a mass scale incompatible with others oscillation experiments results. Recently Mini-Boone [3] confirmed the main features of LSND results, both in neutrino and anti-neutrino channels, strengthening the hypothesis that maybe there is a fourth neutrino family, which does not couple with weak gauge bosons (hence, sterile neutrinos), but participate in flavour neutrino oscillations with a mass scale of order $\sim 1$ eV.

Although the above mentioned results can be well explained by a fourth neutrino family, it seems that they are incompatible with disappearance experiments, such as Minos/Minos+ [4], NEOS [5] and Daya Bay [6], that found no strong conversion to sterile neutrinos (see for instance [7] for a comprehensive comparison between experiments). Therefore, assuming that these experimental results should be explained by new physics on neutrino sector, it seems that such new physics would have to go beyond the simple addition of an extra neutrino family. As stated in [8], the neutrino sector seems quite baroque.

Nevertheless, most of the solutions proposed to accommodate all oscillation neutrino experiments results would add an extra degree of freedom in the relativistic species that would be produced in the early universe. It is then worthwhile to revisit the cosmological results on this subject [9] [10]. In the present contribution we analyse two distance rulers that are sensitive to the number of relativistic species, namely the CMB and BAO acoustic scales, complemented by SNe Ia luminosity distances observations and by the current priors on the local expansion rate and baryonic density.

The paper is organised as follows. In the next section we discuss why the tension between Planck and HST measurements of $H_0$ can be alleviated with a higher $N_{e\,\text{ff}}$ value. In section 3 we describe the tests to be performed, and in section 4 we show the results of our joint analysis. In section 5 some conclusions are outlined.

II. THE ACOUSTIC HORIZON

The acoustic horizon, given by

$$r_s(z) = \int_z^\infty \frac{c_s}{H(z')} dz',$$  \hspace{1cm} (1)

has two important values in the context of cosmological data. When we are dealing with the CMB acoustic scale $\theta_*$, the acoustic horizon is evaluated at the redshift of last scattering ($z_s \approx 1090$), so that $r_s \equiv r_s(z_s)$. In the case of BAO, the acoustic horizon is evaluated at the drag epoch ($z_d \approx 1060$), which we will refer to as $r_d \equiv r_s(z_d)$. The sound speed is given by

$$\frac{c_s}{c} = \left[3 + \frac{9 \Omega_{b0}}{4 \Omega_{\Lambda0}} (1 + z)^{-1}\right]^{-1/2},$$  \hspace{1cm} (2)
and the spatially-flat standard model Hubble-Lemaitre function by
\[
H(z) = H_0 \sqrt{(1 - \Omega_{m0}) + \Omega_{m0}(1 + z)^3 + \Omega_{R0}(1 + z)^4},
\]
(3)
In the above expressions, \( \Omega_{m0} = \Omega_{dark0} + \Omega_0 \) and \( \Omega_{R0} = \Omega_{\gamma0} + \Omega_{\gamma0} \) are, respectively, the density parameters of total matter (dark matter + baryons) and radiation (neutrinos + photons), and \( H_0 = 100 h \text{ km/s Mpc}^{-1} \) is the Hubble-Lemaitre parameter. The radiation density parameter can be expressed as
\[
\Omega_{R0} = \Omega_{\gamma0} [1 + 0.68 (N/3)],
\]
(4)
where \( N \) is the number of neutrinos species. In a rough estimation, neglecting the contribution of the baryonic and dark sectors for \( z \gg 1 \), and taking the observed \( \Omega_{\gamma0} h^2 = 2.47 \times 10^{-5} \) \[11\], we have
\[
r_s \propto \frac{h}{\sqrt{2.47 [1 + 0.68 (N/3)]}}.
\]
(5)
Let us consider a hypothetical observational probe of the acoustic scale, and let \( h \) be the value obtained when the number of species is fixed in \( N = 3 \). For an arbitrary \( N \), the same probe will give a Hubble-Lemaitre parameter \( h \) such that
\[
\frac{N}{3} = 2.47 \left( \frac{h^2}{h_s^2} \right) - 1.47.
\]
(6)
Using for \( h \) the Planck value \( h = 0.68 \) \[11\], and for \( h \) the local value \( h = 0.73 \) \[12\], it follows that \( N \approx 4.1 \).

III. STANDARD RULERS

We will consider two standard rulers in our analysis. The first is given by the position of the first peak in the CMB spectrum of anisotropies, more precisely the angular scale
\[
\theta_s = \frac{r_s}{D_A(z_s)},
\]
(7)
where \( D_A \) is the comoving angular diameter distance to the last scattering surface,
\[
D_A(z_s) = \int_0^{z_s} \frac{c}{H(z)} dz.
\]
(8)
Its observed value is \( 100 \theta_s = 1.04109 \pm 0.00030 \) \[13\]. The second ruler comes from BAO’s observations, and can be encompassed, in an approximately model-independent way, in the acoustic horizon derived by Verde et al., \( r_d h = 101.2 \pm 2.3 \) \[14\]. We will complement the analysis by fitting the luminosity distances to supernovas Ia of the JLA compilation \[15\]. Compared to previous surveys, it has the advantage of allowing the light-curve recalibration with the model under test. Although it was also used to derive the Verde et al. acoustic horizon at the drag epoch \[14\], this fitting is insensitive to \( N_{eff} \), and will be used for better constraining the matter density. Anyway, in order to control the effect of a double counting, we will also use the Pantheon SNe Ia compilation \[16\] in the analysis, which contains supernovas not used in the Verde et al. fitting. As Gaussian priors of our analysis, we will take the Riess et al. local value of the Hubble-Lemaitre parameter \[12\], \( h = 0.7348 \pm 0.0106 \), and the Cooke et al value for the baryonic density parameter, \( \Omega_{b0} h^2 = 0.2226 \pm 0.00023 \), which comes from nucleosynthesis constraints \[18\].

For the sake of generality, our tests will be performed with two different models. The first is the standard model, for which the indication of a 4th neutrino generation will already be manifest. This possibility will be verified by testing an extension of the standard model given by the generalised Chaplygin gas \[19–26\], with a Hubble function given, with the addition of radiation, by
\[
\frac{H(z)}{H_0} = \left((1 - \Omega_{m0}) + \Omega_{m0}(1 + z)^3(1+\alpha)\right)^{1/(1+\alpha)} + \Omega_{R0} (1 + z)^4.
\]
(9)
In the binomial expansion of the brackets, we have a leading term \( \Omega_{m0}(1 + z)^3 \), which shows that, for the present purpose of background tests, the baryonic content can be absorbed in the above defined gas. For \( \alpha = 0 \) we recover the standard \( \Lambda \)CDM model. Perturbative tests are outside the scope of this paper, but let us comment that, although the adiabatic generalised Chaplygin gas is ruled out by the observed matter power spectrum \[27\], non-adiabatic versions with negative \( \alpha \) present a good concordance when tested against background and LSS observations \[28–34\].

IV. JOINT ANALYSIS AND RESULTS

On the basis of Bayesian Statistics, we defined the joint log-likelihood as a function of the parameter array \( \mathbf{p} \), adding to the CMB log-likelihood,
\[
\log \mathcal{L}_{CMB}(\mathbf{p}) = -0.5 \left( \frac{1000 \delta_{r_0}(\mathbf{p}) - 1.04109}{0.00030} \right)^2,
\]
(10)
a log-likelihood for \( r_d h \),
\[
\log \mathcal{L}_{BAO}(\mathbf{p}) = -0.5 \left( \frac{r_d h(\mathbf{p}) - 101.2}{2.3} \right)^2,
\]
(11)
and the log-likelihood of supernovae. For the Chaplygin gas the set of free cosmological parameters were \( \mathbf{p}_c = \{H_0, \Omega_{dark0} h^2, \Omega_{m0} h^2, \alpha\} \), with free nuisance parameters due to corrections on SNe light-curves, \( \mathbf{p}_n = \{\alpha_s, \beta_s, M_B, \Delta M\} \) for JLA SNe likelihood \[15 \] or \( \mathbf{p}_n = \{M_B\} \) for Pantheon SNe likelihood \[16\], so that \( \mathbf{p} = \{\mathbf{p}_c, \mathbf{p}_n\} \). We explored the parameter space via PyMultiNest module for Python, setting 1500 live points
and parameter sampling efficiency. Besides the Gaussian priors previously mentioned, all other parameters had uniform priors presented on Table I. The results of our joint analysis are summarised in Fig. 1. We see that slightly negative values of $\alpha$ are favoured when using JLA, and that even in the standard model case a 4th neutrino’s generation is suggested by the data. The 2\sigma confidence intervals for some parameters are presented on Table II. The standard value $N_{eff} = 3$ is marginally ruled out with 99% of confidence in all considered scenarios.

V. CONCLUDING REMARKS

The above results show that overcoming the $H_0$ tension between the CMB and HST observations may require a number of relativistic species that corroborates current experimental results in the neutrinos section of the standard model of particle physics. Indeed, the obtained best-fit $N_{eff} \approx 4$ might be a clear signature of an additional, sterile, neutrino’s family. We should stress, however, that the analysis we have performed includes only background tests, involving measurements of angular diameter and luminosity distances. The number of relativistic species also affects observations in the perturbative sector of cosmology, because the ratio between the matter and radiation densities defines, for example, the turnover of the matter power spectrum through the horizon scale value at the time of matter-radiation equality. Although the data do not determine this turnover precisely enough, a joint analysis of background and LSS observations would be complementary to the present results. Furthermore, a sterile neutrino with 1 eV mass would contribute with $\approx 8\%$ of a warm component in the present dark matter [35]. On the other hand, despite the possibility presented here of conciliating the CMB acoustic scale with local $H_0$ measurements by adding a relativistic degree of freedom, the best-fit of the full CMB spectrum with the $\Lambda$CDM model actually ask for a lower $H_0$, and this tension still awaits for a resolution. The definite value of $N_{eff}$ remains, therefore, a subject for further studies. Nevertheless, the results shown in the present contribution, together with the experimental results arising in the neutrino’s section, seems to positively point to the existence of an extra, sterile neutrino flavour.

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FIG. 1: Probability distribution functions and marginalised confidence regions for our free parameters, for both the ΛCDM model and generalised Chaplygin gas.

TABLE II: Best-fit values and 2σ credible regions of some cosmological parameters for generalised Chaplygin gas and ΛCDM models using both JLA and Pantheon SNe compilation sets.
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