Neutrino mass scale in the era of precision cosmology

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Abstract. In this work, we study how recent cosmological datasets in combination with particle physics results are able to constrain the neutrino mass scale. In particular, we present current bounds on the electron neutrino mass $m_{\beta}$, the effective Majorana mass $m_{\beta\beta}$ and the total neutrino mass $\Sigma m_\nu$ and we discuss the sensitivity required to future experiments in order to address the issue of neutrino hierarchy.

1. Introduction

Neutrinos are weakly interacting and neutral particles. Because of their elusive nature, many neutrino properties are still debated. In particular, it is not clear if neutrinos are Dirac or Majorana particles. In the former case, neutrino and antineutrino are separate particles and this assures the lepton number to be preserved in interactions; in the latter case, neutrino is its own antiparticle. What is not debated anymore is the fact that neutrinos are massive. The major evidence comes from oscillation experiments, measuring transitions in flight between neutrino flavors: each neutrino flavor is a superposition of mass eigenstates with coefficients given by the neutrino mixing matrix. The latter is parameterized via neutrino mixing angles $\theta_{ij}$ and phases, one $\delta$ if neutrinos are Dirac particles, responsible for CP violation, two additional phases $\phi_1$ and $\phi_2$ if neutrinos are Majorana. In this work, we assume $\delta$ to be negligible, without any loss of generality.

Oscillation experiments can help to constrain these mixing parameters (see [1] for an updated review). In particular, they are sensitive to the mixing angles $\theta_{ij}$ and to the squared mass differences: $\delta m^2 \approx 10^{-5}$ eV$^2$, the difference between the first two eigenstates, and $\Delta m^2 \approx 10^{-3}$ eV$^2$, the difference between the third eigenstate and the mean value of the first two. $\Delta m^2$ can be greater or lower than zero, identifying two mass hierarchies: in the former case, we have normal hierarchy (NH), with the third eigenstate as the most massive; in the latter case, the third eigenstate is the lightest one and the hierarchy is inverted (IH). However, oscillation experiments are not sensitive to the sign of $\Delta m^2$, so they cannot distinguish between the two hierarchies. Moreover, they cannot establish the absolute mass scale of neutrinos, which has to be probed by other kind of observables.

As far as particle physics is concerned, the main experiments looking for the absolute mass scale involve beta and double-beta decay. The goal of beta decay experiments is to assess the shape of the decay spectrum close to the endpoint, since it shows a different behavior as a function of neutrino mass $m_\beta$. Future experiments aim to reach ten times the current sensitivity ($\approx 2$ eV [2]). This is for example the experimental goal of Katrin [3]. While less sensitive than other observables, beta decay is a very powerful probe since it is completely model independent.
Double-beta decay involves the emission of two electrons and two antineutrinos. If neutrinos were Majorana particles, than the two antineutrinos could annihilate and electrons would be the only decay products, giving rise to a process known as neutrinoless double-beta decay. Double-beta decay experiments put limits on the half life $T_{1/2}$ of the isotope involved in the neutrinoless decay. Theoretically, $T_{1/2}$ is expressed as a function of the phase space factor, which is easy to calculate, the nuclear matrix element (NME), more difficult to assess, and the Majorana effective mass $m_{\beta\beta}$ (a combination of massive eigenstates weighted by mixing angles), which is the quantity of interest from the point of view of particle physics. Taking into account the different possible values for NME from nuclear models, the allowed range for the upper limit of $m_{\beta\beta}$ is $[0.2 - 0.4]$ eV [4, 5]. As a result, the main hurdle to deal with when considering double-beta decay experiments is the great uncertainty arising from NME calculation; however, the power of double-beta decay experiments lays in the fact that evidence for $m_{\beta\beta} \neq 0$ would definitively solve the puzzle about neutrino nature [6].

We will now discuss what kind of information we can get from cosmological observables: the cosmic microwave background (CMB) and the large scale structures (LSS), both of them being sensitive to the sum of neutrino masses $\Sigma m_\nu$ [8]. As far as the CMB is concerned, massive neutrinos contribute to the total energy density of the Universe, affecting the expansion rate. The main observable effect is the shift and smearing of the peaks in the CMB power spectrum (the harmonic transform of the two-point correlation function of the anisotropy temperature map). Massive neutrinos also affect the way cosmological structures grow, since they prevent them to form below a certain scale, the neutrino free-streaming scale. The main effect is visible in the matter power spectrum (Fourier transform of the two-point correlation function of the matter density distribution): more massive neutrinos determine less power on small scales. An additional probe comes from the baryon acoustic oscillations (BAO), visible as wiggles in the matter power spectrum. BAO are the results of acoustic oscillations undergone by the primordial plasma, due to the counterbalance between radiative pressure and gravitational attraction. Since neutrinos are part of the primordial content of the Universe, different neutrino masses would leave their imprint in the BAO. The current cosmological limits on the total mass are the tightest constraints on the neutrino mass scale. However, the price to pay is that they are highly model dependent.

2. Data analysis
We choose to follow a Bayesian approach and perform a MCMC analysis. The baseline model is given by the recent global fit to the oscillation parameters from [7]. We assume $\delta m^2, \Delta m^2, \sin \theta_{12}, \sin \theta_{13}$ to be Gaussian distributed around their best fit value, with variance given by the semi-width of the 1σ range. The parameter vector is then $\delta m^2, \Delta m^2, \sin \theta_{12}, \sin \theta_{13}, \phi_1, \phi_2, \Sigma m_\nu$, the last one in order to fix the scale mass. We assume flat priors and build our likelihood as the product of the single Gaussian likelihoods.

We then add further datasets to the baseline. This information are added via additional Gaussian likelihood with parameters reported below (see [9] for further details):

- **Gerda**: $T_{1/2} > 2.1 \cdot 10^{25}$ yr, Gerda experiment, phase 1 [4];
- **P+WP+highℓ**: $\Sigma m_\nu < 0.33 eV$, Planck [10], ACT [11] and SPT [12] TT power spectra plus WMAP9 lowℓ polarization (P+WP);
- **CMB+LSS1a**: $\Sigma m_\nu = (0.36 \pm 0.10) eV$, P+WP marginalized over the weak lensing amplitude parameter $A_L$, CMASS measurements from [13], CFHTlens [14], GGlensing [15] and BAO (6dFGS and LOWZ) [16];
- **CMB+LSS2**: $\Sigma m_\nu = (0.38 \pm 0.11) eV$, same as CMB+LSS1a, replacing CMASS measurements from [13] with [17];
• **CMB+LSS3**: $\Sigma m_\nu = (0.324 \pm 0.099) \text{ eV}$, same as CMB+LSS1a, replacing CMASS measurements from [13] with [18];

• **CMB+LSS4**: $\Sigma m_\nu = (0.27 \pm 0.11) \text{ eV}$, same as CMB+LSS1a, replacing CMASS measurements from [13] with the BAO only constraints from [19];

• **CMB+LSS1b**: $\Sigma m_\nu = (0.35 \pm 0.10) \text{ eV}$, same as CMB+LSS1a, replacing marginalized P+WP with WMAP9 [20];

• **CMB+LSS1c**: $\Sigma m_\nu = (0.27 \pm 0.12) \text{ eV}$, same as CMB+LSS1a, replacing marginalized P+WP with non-marginalized P+WP.

Few additional words have to be spent for the Gerda case. We choose to assess the impact of NME uncertainty introducing the nuisance parameter $\xi$ and marginalizing over it [21]. $\xi$ is defined as the ratio between a reference value for NME and its unknown exact value. We write down $T_{1/2}$ as a function of $m_{\beta\beta}$ and $\xi$ and define the likelihood of $T_{1/2}$ given $m_{\beta\beta}$ and $\xi$. This likelihood is chosen to be a semi-Gaussian in $m_{\beta\beta}$, centered in $m_{\beta\beta} = 0$, with variance given by the lower limit on $T_{1/2}$ from Gerda experiment. The prior on $\xi$ is flat since it represents the less informative choice, with $\xi$ spanning the range $[0.5 - 2]$, which is twice the uncertainty on the NME value.

### 3. Results

Fig.1 represents the parameter space explored by the chains of the MCMC analysis for NH (red) and IH (blue) for the baseline model. We can identify the physical lower limit for the mass scale parameters as a result of oscillation constraints and the degenerate region, at higher masses, where the two hierarchies are indistinguishable. From Fig.1, it is clear that particle physics experiments have to reach a sensitivity lower than 0.1 eV in order to distinguish between the two hierarchies. In Fig.2, we can see what happens if we add information from Gerda, CMB and LSS.

First of all, notice the different sensitivity among datasets. Gerda provides the broadest constraints, while the tightest ones come from the cosmological datasets. Notice also the different location of the peaks for the two cosmological datasets. This is due to the different constraints on $\Sigma m_\nu$ coming from the two datasets, which drive the constraints on the other parameters. We can briefly comment about the impact of NME marginalization. In Fig.3, we compare the case of $\xi$ as a free parameter and $\xi = 1$. It is clear that the main impact of this nuisance parameter is at higher masses, making them more probable.

What can we learn from the other datasets? In Fig.4, the one-dimensional posterior probabilities for the mass scale parameters are reported. As previously said, the different location of the peak of the $\Sigma m_\nu$ posteriors coming from the various CMB+LSS analysis [9], also have an impact on
Figure 2. One-dimensional posterior probability of the mass scale parameters for the listed datasets. NH (IH) on the left (right).

Figure 3. Impact of marginalization over $\xi$ nuisance parameter on the $m_{\beta\beta}$ posterior probability for the Baseline+Gerda combination.

the probability distributions of the other mass-scale parameters, highlighting how effective the combination of cosmological datasets and particle physics experiments could be. The lower limit is still the effect of oscillation data, but all the cosmological datasets hint for $m_\beta$ and $m_{\beta\beta}$ to be in the region $[0-0.2]$ eV. We want to recall that the expected sensitivity from Katrin is $m_\beta < 0.2$ eV and the expected sensitivity from next generation double-beta experiments is $m_{\beta\beta} < 0.1$ eV. As a result, it appears that future experiments would not be able to assess definitive observations. In particular, to be able to distinguish between the two hierarchies, a sensitivity of order of 0.05 eV is required, as shown by the present analysis. This is evident from the left panel in Fig.5, where the 1$\sigma$ and 2$\sigma$ ranges for $m_{\beta\beta}$ for the different combinations of datasets are reported. The vertical dashed line is the future expected sensitivity. Obviously, increasing the sensitivity on $\sum m_\nu$ from cosmology would result in better constraints on $m_{\beta\beta}$ and $m_\beta$. In addition, the right plot in Fig.5 shows the 2$\sigma$ ranges for $m_{\beta\beta}$ assuming the constraint on $\sum m_\nu$ from the dataset CMB+LSS1a. We can see that reducing the variance by a factor of two (center) and ten (bottom) with respect to the current one (top) would almost halve the uncertainty on $m_{\beta\beta}$. 
Figure 4. One-dimensional posterior probability distributions of the mass scale parameters for the listed datasets. NH (IH) on the left (right).

Figure 5. Left panel: 1σ (darker) and 2σ (lighter) ranges of $m_{\beta\beta}$ for the indicated datasets. In blue (red), constraints for normal (inverted) hierarchy. The vertical line is the future double-beta decay experiment sensitivity. Right panels: expected limits on $m_{\beta\beta}$ as a function of current and forecasted limits on $\Sigma m_{\nu}$ (in eV).

4. Conclusions
In this work, we have shown how a combination of cosmological and particle physics datasets is able to constrain the neutrino mass scale. In particular, we have shown that combining oscillation

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\Sigma m_{\nu} = 0.36 \pm 0.01
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results with CMB and LSS data yields the tightest constraints on the effective electron neutrino mass, the Majorana mass and the total neutrino mass. Moreover, improving the observational bounds on $\Sigma m_\nu$ would result in stronger constraints on $m_{\beta\beta}$. Finally, it has also been shown that, given the current bounds on $\Sigma m_\nu$ from cosmology, a sensitivity of better than 0.1 eV is required in order to discriminate between normal and inverted hierarchy.

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