Cosmology and CPT violating neutrinos

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The combination Charge Conjugation-Parity-Time Reversal(CPT) is a fundamental symmetry in our current understanding of nature. As such, testing CPT violation is a strongly motivated path to explore new physics. In this paper we study CPT violation in the neutrino sector, giving for the first time a bound, for a fundamental particle, in the CPT violating particle-antiparticle gravitational mass difference. We argue that cosmology is nowadays the only data sensitive to CPT violation for the neutrino-antineutrino mass splitting and we use the latest data release from Planck combined with the current Baryonic-Acoustic-Oscillation measurement to perform a full cosmological analysis. To show the potential of the future experiments we also show the results for Euclid, a next generation large scale structure experiment.

INTRODUCTION

On general grounds, local, relativistic quantum field theory makes only a couple of predictions. CPT invariance [1] is one of them, and undoubtedly the cornerstone of our model building strategy. The CPT Theorem, in short, states that every particle does have the same mass as its anti-particle and, if unstable, also the same lifetime. Its position as one of the sacred cows of particle physics is based on the fact that in order to prove it only three ingredients are needed, all of which are "natural" and have other reasons to be in our theory, way beyond the CPT theorem itself. They are

• Lorentz invariance,
• hermiticity of the Hamiltonian,
• locality.

Precisely because of this, if CPT is found not to be conserved, the impact of such an observation to fundamental physics would be gigantic. It would necessarily mean that at least one of the three assumptions above must be violated [2,3]. And therefore it will automatically imply that our description of nature in terms of local, Lorentz invariant field theory would be dramatically challenged and our model building strategy would need to be seriously revisited.

Largely because of its huge potential implications, the experimental signature of CPT violation was searched in the past and according to the PDG[20], the most stringent limit on it comes from the neutral kaon system[19]. Courtesy of the mixing between $K^0$ and $\bar{K}^0$, the limit on the possible mass difference between them is beyond solid:

$$\frac{|m(K^0) - m(\bar{K}^0)|}{m_K} < 0.6 \times 10^{-18}$$

However it is important to notice that the robustness of the CPT limit from the neutral kaon system is somehow misleading. Although it is nice to have a limit in a dimensionless way, we do not have a concrete theory of CPT violation and therefore the scale with which we are comparing the mass difference, the kaon mass in this case, is in every way, arbitrary. A much stringent limit could have been obtained by using the Planck mass instead, making exactly the same sense as the one we currently use.1

Until we have a full theory on CPT violation, the limit in Eq. (1) should be looked as

$$|m(K^0) - m(\bar{K}^0)| < 0.6 \times 10^{-18} m_K \simeq 10^{-9} \text{eV}. \quad (2)$$

Even more, as for bosons, the parameter entering the Lagrangian is the mass squared, rather than the mass, the bound can alternative be written as $|m^2(K^0) - m^2(\bar{K}^0)| < 0.25 \text{ eV}^2$, which does not look nearly as strong as before. Besides, given that the mass of the kaons is largely due to QCD, this test, cannot tell directly whether elementary particles indeed respect the CPT symmetry. For such a test, a search for CPT violation in the leptonic sector is mandatory. Using charged leptons the most stringent bound comes from electron-positron $g-2$ experiments[21,22] and Hydrogen Antiproton spectroscopy[23]. These measurements however, involve some combination between mass and charge as the testing parameter. On the other hand, in the neutral sector, the discovery of neutrino oscillations established that neutrinos are massive particles and in the so called See-Saw models the light masses are naturally related with the grand unified scale making neutrinos distinctively sensitive to new physics/new scales. This exclusive mass generation mechanism along with the fact that there is no charge contamination comprised in the

1 Some authors argue that the appropriate quantity to compare with $|m(K^0) - m(\bar{K}^0)|$ in the analysis is $\Delta m^2/E$[4], although it is not evident why the merit of the bound should depend on the energy.
test makes neutrinos specially appealing to study CPT violation.

![Diagram](http://example.com/diagram.png)

**FIG. 1:** Scheme for normal ordering mass spectrum with neutrinos and antineutrinos where we illustrate the extended parameters $\Delta_{CPT}$ and $m_l$.

The quantum interference phenomena observed in neutrino oscillation is very sensitive to new physics, and it has been proposed to constrain CPT and Lorentz violation in solar, short and long base line, atmospheric neutrino oscillations experiments. A constrain in full decoherent oscillation regime using the recent discovered ultra high energy neutrinos by IceCube has also been proposed. In general neutrino oscillation physics has shown a strong potential to constraint CPT being comparable or even stronger than that in the kaon system.

Unfortunately, all the experiments mentioned above always measure $\Delta m^2$, and cannot measure the value of the masses themselves, therefore, only CPT violation in the mass differences, i.e. $\Delta m^2_\nu - \Delta m^2_\bar{\nu}$ can be tested. Even more, if the possible violation of CPT has its origin in quantum gravity, we would naturally expect it to appear in the masses themselves and not in the mass differences.

Here we focus on the study of the yet unconstrained CPT violating mass difference between neutrinos and antineutrinos, $\Delta_{CPT} = |m^l_\nu - m^l_\bar{\nu}|$. It is worth noting, nevertheless, that the direct (kinematical) searches for neutrino masses, carried out in tritium $\beta$-decay experiments involve only anti(electron) neutrinos and therefore strictly speaking only bound the masses in the antineutrino sector, not probing anything about the neutrino one. An overall shift on the spectrum, as the one shown in fig. which can potentially be much larger than $\Delta m^2$, cannot be detected in neutrino oscillation experiments or bounded by future direct kinematical searches. This leaves us the only option of using cosmological data for such a purpose.

In this article we give the first bound on CPT violation for the neutrino-antineutrino absolute mass difference $\Delta_{CPT}$ using current cosmological data. We also perform a forecast analysis for future next generation European Space Agency Cosmic Vision mission, Euclid.

## COSMOLOGICAL BOUNDS

Currently cosmology gives the strongest bound on the neutrino mass scale. In the standard cosmological scenario neutrinos are produced thermally therefore, since neutrinos decouple when they are relativistic, the number density for $\nu$ and $\bar{\nu}$ in the cosmic neutrino background is the same. This implies that cosmology is giving a bound in neutrinos and anti-neutrinos separately and therefore is currently the only physical observable to both neutrino and anti-neutrino mass scales. Note that since gravitational interactions can not distinguish particles from antiparticles, cosmology can only constrain the absolute value of the mass difference and have no say on which spectrum is the heaviest/lightest.

In this section we perform a Bayesian analysis for different sets of cosmological observables. The cosmological model is given by $\Lambda$CDM+$m_l+\Delta_{CPT}$ where $\Lambda$CDM stands for the 6 standard cosmological parameters, $m_l$ for the value of the lightest neutrino mass and $\Delta_{CPT} = |m^l_\nu - m^l_\bar{\nu}|$ is the absolute mass difference between neutrinos and anti-neutrinos. The list of the cosmological parameters and the assumed ranges in the analysis are given in table. An extra 94 fast sampling nuisance parameters are included to account for systematic and calibration errors for Planck data, in the case of Euclid forecast an extra nuisance parameter is included.

| Parameter | Prior |
|-----------|-------|
| $\Omega_m$ | $[0.001, 0.1]$ |
| $\Omega_b h^2$ | $[0.01, 0.99]$ |
| $100\Theta_s$ | $[0.01, 1.0]$ |
| $n_s$ | $[0.5, 1.5]$ |
| $\log(10^{10}A_s)$ | $[1, 5]$ |
| $m_l$ (eV) | $[0, 10]$ |
| $\Delta_{CPT}$ (eV) | $[0, 10]$ |

TABLE I: $\Lambda$CDM+$\nu$CPT parameters and the given ranges in where we take flat priors.

The effect of the neutrino masses in cosmology comes mainly via the free streaming of the neutrinos in the cosmic neutrinos background during the growth of the large scale structure. In fig. we show the effect in the temperature-temperature (TT) CMB power spectrum and in the total matter power spectrum for different values of the CPT violating mass splitting $\Delta_{CPT}$ and $m_l = 0.$, the rest of the cosmological parameters are

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2 [http://www.euclid-ec.org/](http://www.euclid-ec.org/)
To perform the cosmological analysis we modify by adding the new abovementioned parameters the publicly available Boltzmann code CLASS [16] to compute the linear evolution of the cosmological perturbations and the MontePython wrapper [15] to perform a Bayesian data analysis on the full set of eight cosmological parameters.

For both neutrinos and anti-neutrinos we fix the atmospheric and solar mass splitting to the value of the global neutrino oscillation results given by \( \nu \)-fit collaboration [31] and we introduce the proper modifications to use \( m_l \) and \( \Delta_{CPT} \) to parametrize the massive neutrinos.

From the current cosmological data we use the combined (TTEE, low-l, lensing) data from Plank2015 [9] and the measurement of the Baryonic Acoustic Oscillation (BAO) scale from SDSS-DR10 SDSS-DR11 and 6dF [10–12]. We do not include the less conservative local measurements of the local expansion rate nor the full matter power spectrum since it is more sensitive to the treatment of the non-linear corrections and does not give a significant improvement in the neutrino masses analysis [18]. In the following we designate by (CMB) the full set of Plank2015 data and by (BAO) the combination of the Baryonic Acoustic Oscillation scale mentioned before.

The mean value and 95% intervals for the two data sets CMB and CMB+BAO and for the two cases, normal and inverted ordering are summarized in tab. II.

In fig. 3 and fig. 4 we show the results of the posterior probability distribution for the new parameters \( m_l \) and \( \Delta_{CPT} \). For the sake of clarity and to make the comparison easier all the one dimensional probability distributions are normalized such that they get the same arbitrary value at the maximum.

In fig. 5 we show the two dimensional 68% and 95% probability contours for the following cases: normal ordering using CMB only (red solid line), inverted ordering

\(^3\) http://www.nu-fit.org
In order to illustrate the potential of the near future data we perform an analysis using a simulated power spectrum for Euclid, details can be found in the Euclid Red Book[30]. For the forecast analysis we produce a simulated matter power spectrum data setting the cosmological parameters to the $ΛCDM$ best fit and $\Delta CPT = m_l = 0$. We do the forecast fit only for normal ordering.

The results of the forecast analysis compared with the most stringent result using BAO measurements are shown in figure 6 for the $\Delta CPT$ parameter. The results for the $95\%$ bound are $\Delta CPT < 0.0088$eV and $m_l < 0.02$eV.

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Parameter & Plank2015 (95\%) & Plank2015 + BAO (95\%) \\
\hline
 & Normal & Inverted & Normal & Inverted \\
\hline
$10^{-2}\Omega_{h}^2$ & $2.210^{+0.036}_{-0.034}$ & $2.206^{+0.032}_{-0.033}$ & $2.238^{+0.031}_{-0.034}$ & $2.240^{+0.028}_{-0.025}$ \\
$\Omega_{cdm}h^2$ & $0.1205^{+0.0031}_{-0.0035}$ & $0.1209^{+0.0030}_{-0.0027}$ & $0.1173^{+0.0022}_{-0.0025}$ & $0.1166^{+0.0021}_{-0.0024}$ \\
$H_0$ & $63.7^{+2.6}_{-3.2}$ & $62.7^{+2.4}_{-3.0}$ & $1.042^{+0.0061}_{-0.0064}$ & $65.97^{+0.99}_{-0.96}$ \\
$n_s$ & $0.9607^{+0.0092}_{-0.0094}$ & $0.959^{+0.010}_{-0.010}$ & $0.969^{+0.0092}_{-0.0094}$ & $0.971^{+0.0094}_{-0.0095}$ \\
$log(10^{10}A_s)$ & $3.108^{+0.053}_{-0.053}$ & $3.117^{+0.055}_{-0.054}$ & $3.112^{+0.050}_{-0.052}$ & $3.141^{+0.039}_{-0.038}$ \\
$\tau_{reio}$ & $0.086^{+0.028}_{-0.029}$ & $0.091^{+0.029}_{-0.029}$ & $0.092^{+0.026}_{-0.027}$ & $0.107^{+0.021}_{-0.023}$ \\
\hline
\end{tabular}
\caption{Mean values and the 95\% regions for the parameters for normal and inverted ordering and for the different sets of cosmological data CMB and CMB+BAO.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{68\% and 95\% probability contours for the light neutrino masses $m_l$ and $\Delta CPT$, where (blue, red) and (solid, dashed) designate (normal, inverted) and (CMB, CMB+BAO) respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{1D posterior probability distribution for the parameters $\Delta CPT$, the blue(dashed) is the most stringent bound with current data shown in fig.4 and the red(solid) the bound using generated Euclid power spectrum data with $\Delta CPT = 0$ and $m_l = 0$.}
\end{figure}

**CONCLUSIONS**

We give, for the first time, a bound on CPT violation in the absolute value of the neutrino-antineutrino mass splitting. Since the kinematical laboratory experiments use only antineutrinos they are not able to give any bound on CPT, hence, for now, the only possibility to bound $\Delta CPT$ is to use cosmological data.

In order to do that we perform a full cosmological analysis using the current CMB, and BAO data. Using only CMB the $95\%$ bounds are $\Delta CPT < 0.26$eV and $\Delta CPT < 0.21$eV for normal and inverted ordering respectively. Adding the BAO data we get a more stringent bound, $\Delta CPT < 0.059$eV and $\Delta CPT < 0.043$eV again for normal and inverted ordering respectively.

To illustrate the potential of the future data by Euclid satellite we perform a forecast analysis where we generate...
a power spectrum for the values $\Delta_{CPT} = 0$ and $m_1 = 0$. Performing the fit together with the Planck2015 data we get that the next generation of large scale structure experiments may give a 95% bound to the CPT violation and light neutrino masses of $\Delta_{CPT} < 0.0088eV$ and $m_1 < 0.02eV$ respectively.

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