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Future precision cosmology and neutrinos

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In the next decade future measurements of the Cosmic Microwave Background anisotropies are expected to reach the sensitivity to constrain the inverse and direct neutrino hierarchies. A cosmological detection of non-zero neutrino mass seems therefore around the corner. However one important aspect is often neglected: current predictions are done under the assumption of the standard ΛCDM model, while several hints for tensions and anomalies are currently present in current data that stills leave as open the possibility of new physics.

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1. Introduction

Neutrino ground based experiments (under the three standard neutrinos theoretical framework) and cosmological data (under the additional assumption of the ΛCDM model) have now established that neutrinos must have masses with a *total* absolute mass scale in the range:

$$0.06 \text{ eV} \leq \Sigma m_\nu \leq 0.2 \text{ eV} \tag{1.1}$$

The upper limit comes essentially from the recent measurements of Cosmic Microwave Background (CMB, hereafter) anisotropies made by the Planck satellite [1]. This limit is model dependent but clearly shows the power of CMB measurements to constrain Σm_ν. Neutrinos are indeed the only known particles that can change their cosmological evolution from the relativistic regime ($m_\nu c^2 < kT_{CMB}$) to the non-relativistic regime $m_\nu c^2 > kT_{CMB}$ after the CMB epoch of decoupling of $T_{CMB} \sim 0.3$ eV (see e.g. [2]). This leaves significant imprints on cosmic structures that are directly and easily observable as (lensed) CMB anisotropies but also in the distribution of galaxies and in the weak lensing from dark matter clustering. What I will briefly illustrate in this proceeding is how much the cosmological limit can be further improved in the next years.

Indeed, there are two major goals for future cosmological measurements:

- To reach a sensitivity such to exclude $\Sigma m_\nu < 0.09$ eV at high confidence, in order to exclude the neutrino inverted hierarchy, i.e. **test the neutrino mass hierarchy**
- To reach a sensitivity well below $\Sigma m_\nu < 0.06$ eV again at high confidence in order to have a **guaranteed discovery of the neutrino mass**.

In what follows, I will also discuss some caveats present in current forecasts and predictions.

2. Constraints on neutrino masses from future CMB measurements: a guaranteed discovery in ten years from now ?

After the results from Planck mission, with an expected final data release around the end of 2017, several ground based and balloon-borne CMB experiments are planned or already under construction that will complement them in many ways. In Table 1 I report the expected sensitivities to Σm_ν expected from several future experiments, taking the results from the analyses of [3], [4] and [5].

A crucial issue for near-future CMB experiment will be the "delensing" of the angular spectra. Dark matter clustering gravitationally lenses the CMB spectra. This produces mainly two effects: a conversion of polarization E modes into B modes that could limit the sensitivity to "genuine" B-modes from primordial gravitational waves and a "smearing" of the acoustic peaks in the E polarization power spectra, that could reduce the sensitivity to other cosmological parameters. A clear "delensing" of the CMB maps (and a clear measurement of the lensing potential) can significantly improve the constraints on cosmological parameters. Delensing can be done in two ways: internally [8], i.e. using the CMB data itself, or externally by using external datasets [6] that correlates with the CMB lensing signal as the Cosmic Infrared Background (see e.g. [7]).

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Experiment Planck+	Sensitivity on Σm_ν CMB delensed	Sensitivity on Σm_ν CIB delensed	Reference
BICEP3	0.30 eV	0.074 eV	[3]
EBEX10K	0.17 eV	0.072 eV	[3]
AdvActpol	0.078 eV	0.055 eV	[3]
SPIDER	0.31 eV	0.074 eV	[3]
Simons Array	0.096 eV	0.055 eV	[3]
CLASS	0.25 eV	0.067 eV	[3]
SPT-3G	0.10 eV	0.062 eV	[3]
Stage-IV [3]	0.048 eV	0.049 eV	[3]
CORE-M5	0.056 eV	0.056 eV	[5]
Stage3+DESI	0.022 eV	0.022 eV	[4]
Stage-IV+DESI	0.019 eV	0.019 eV	[4]
CORE-M5+DESI	0.026 eV	0.026 eV	[5]

Table 1: Expected sensitivities on the total neutrino mass from several future CMB experiments. The cases below the double line are expected after year 2020.

Near future CMB experiments will not have enough sensitiviity and angular resolution to delens using the CMB polarization data but this could in principle be done by cross correlating with the already measured CIB detected by Planck at frequencies of 545 GHz and 857 GHz. However, while the feasibility of the method has been demonstrated with the Planck data itself [9], it is clearly too early to safely assume that an optimal cross-correlation with the CIB can be obtained (external tracers are not perfectly correlated with the underlying lensing potential) and systematics as due to unaccounted galactic dust contamination can be fully removed.

As in [3], we therefore consider for each experiment two cases: the first case is the expected constraint obtained after internal delensing. The second case considers the possibility of delensing the CMB dataset by including information from the already measured Cosmic Infrared Background (that highly correlates with the lensing signal in the CMB maps). As we can see from Table I, thanks to delensing methods based on CIB cross-correlations, already combinations of Planck and near future (< 2020) CMB experiments can reach a sensitivity of $\sim \Delta\Sigma m_\nu = 0.05$ eV, enough to start to discriminate between neutrino hierarchies at the level of ~ 2 standard deviations. Similar results based on the more conservative internal delensing will start to be obtained in CMB surveys as Stage-IV and CORE that are expected after year 2020.

Further combination with information from weak lensing of Baryonic Acoustic Oscillation future surveys , could further reduce the uncertainty to $\sim \Delta\Sigma m_\nu = 0.02$ eV, enough for a guaranteed discovery of the neutrino mass.

Considering the schedule of all these experiments we could therefore safely forecast a robust exclusion of the neutrino inverted hierarchy (or a detection for a neutrino mass if $\Sigma m_\nu > 0.1$ eV) from cosmological data in the next five years and a guaranteed "cosmological" discovery for the neutrino mass in the next ten years.

3. What could go wrong...

There are however several important caveats that need to be addressed. The forecasts presented in the previous section are obtained under the assumption of the ΛCDM model. Unfortunately the ΛCDM model, while producing a reasonable good fit to current the data, it does only in between two-three standard deviations. This means that **new physics beyond ΛCDM could still be present and this could drastically change the forecasts discussed in the previous section**.

Let us briefly report here the current most interesting anomalies and tensions, starting with the so-called **internal** anomalies, i.e. present in the Planck data itself:

- **The A_{lens} anomaly**. Planck CMB angular spectra show "more lensing" than expected [1]. Indeed, parametrizing the effect of lensing on CMB specra by the A_{lens} parameter introduced in [10], the most recent Planck analysis [11] gives $A_{lens} = 1.15^{+0.13}_{-0.12}$ at 95% C.L., i.e. a value higher than the expected $A_{lens} = 1$ at more than two standard deviations. This anomaly affects the current constraints from Planck on neutrino masses biasing them towards smaller values. It is not clear if the anomaly is induced by unknown systematics or new physics. From a theoretical point of view is not easy to have a model that mimics $A_{lens} > 1$. It may require a modification to general relativity at CMB scales [12].
- **Consistency with Planck CMB lensing power spectrum**. CMB lensing power spectrum can be reconstructed from Planck maps considering trispectrum measurements[1]. The lensing dataset, when combined with Planck CMB spectra, brings the value of A_{lens} back in to agreement with the standard expectation of one. However the lensing power spectrum dataset is inconsistent with the Planck CMB spectra at more than two standard deviations when variation in A_{lens} are considered. For example, the effective χ^2 of the cosmological models in $m_\nu + A_{lens}$ analysis is increased by $\Delta\chi^2 \sim 17$ when the lensing dataset (that consists of just eight datapoints) is included. Constraints on neutrino mass from a combination of Planck and CMB lensing power spectrum data are *weaker* respect to the value obtained when considering Planck CMB spectra alone ($\Sigma m_\nu < 0.32$ eV from Planck+lensing instead of $\Sigma m_\nu < 0.19$ eV at 68% C.L.). This clearly shows a tension between these two datasets.

As we can understand, since these anomalies are present (or correlated) with the lensing of the CMB photons that, as discussed in the previous section, is crucial for well constraining neutrino masses, it is important to take current and future constraints on neutrino masses with some grain of salt. The possibility that systematics or new physics are affecting current cosmological constraints on neutrino masses is not only open but it seems as favoured by the data itself. Clearly, we are not in the situation of safely assume that these anomalies will go away in future data, since, for example, the A_{lens} anomaly has survived at least two data releases from the Planck collaboration.

But, to make things even less assuring, also inconsistencies between Planck and other datasets are present, in particular:

- **Tension between local and CMB measurements of the Hubble constant.** The value of the Hubble constant derived from Planck data (under the assumption of ΛCDM) is more than 3 standard deviations smaller than what inferred from direct luminosity distance measurements from Riess et al., 2016 [13]. An higher value of the Hubble constant is also suggested by the recent H0LiCOW results [14]. A possible solution to the tension could be obtained by introducing a dark energy equation of state $w < -1$. In few words, if not due to systematics, the tension could be due to wrong assumptions on the dark energy component (see e.g. [15]).

- **Tension between CMB and cosmic shear measurements** Planck constraints on the σ_8 vs Ω_m plane are in tension, at more than two standard deviations, with current constraints from the CFHTLenS [16] and KIDS-450 [17] cosmic shear surveys. The tension is solved when introducing a variation in A_{lens} that affects the CMB data only (see e.g. [18]).

- **Tensions in cross correlations** CMB lensing in Planck maps should correlate with galaxy surveys at high redshift. This indeed the case and a recent analysis detected a cross-correlation between Planck CMB lensing and H-ATLAS galaxies at high statistical significance. The amplitude of the signal is however about 3 standard deviations larger than what expected in standard ΛCDM [19].

It is clear from all these anomalies and tensions that, albeit the ΛCDM is providing a good fit to current data, extensions are still well possible and systematics in current datasets may well be present. This is a quite important point: we can't simply fully believe current and future constraints on neutrino masses based on ΛCDM if the model itsefl is not fully consistent with the whole cosmological data.

4. Conclusions

In this brief proceeding I wanted to emphatize two points: 1) Cosmology can potentially test the neutrino hierarchy and the neutrino mass scale in the next 5-10 years. 2) Current forecasts are based on the assumption of the ΛCDM model while current data are not fully consistent with it.

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