PoS PROCEEDINGS OF SCIENCE

Euclid preparation: sensitivity to neutrino parameters

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The European Space Agency has launched its newest mission in July 2023. The Euclid mission is planned to create one of the largest galaxy clustering and weak gravitational lensing survey to its date. The complimentary of a wide photometric redshift galaxy survey and spectroscopic survey will provide excellent sensitivity to the history of structure foramtion.
The following presents the newest forecast of *Euclid* done within the collaboration for the mission's main cosmological probes to see how well future data from *Euclid* will be able to constrain parameters from Neutrino physics. This forecast is focused on the summed mass of neutrino species $\sum m_\nu$, as well as the effective number of additional ultra relativistic species $\Delta N_{\rm eff}$.
We show how the upcoming data could lead to unprecedented sensitivity in these parameters and could, together with data from future cosmic microwave background experiments, be able to have a detection of the neutrino mass scale.

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1. Background

The *Euclid* mission[1] is planned to measure the location and shape of close to a billion galaxies over approximately one third of the sky. With a look back time of roughly ten billion years, *Euclid* will produce the largest galaxy catalogue to date. The cosmological information that can be obtained from this can be used to measure the cosmological neutrino mass, $\sum m_\nu$, as well as the effective number of additional ultra-relativistic relics, $\Delta N_{\rm eff}$.
The effect of these quantities on cosmological observables are described in [2–4]. In the following section, we will briefly introduce these observables.

The observable that is mainly constraining the cosmological neutrino mass is the weak lensing (WL) probe. The shapes of background (source) galaxies correlate with each other as they are get lensed by the same foreground (lens) galaxies. This correlation can be directly related to the correlation of the underlying matter field. Adding massive neutrinos suppresses this correlation in a scale dependent way, as it slows down the formation of structure for scales where the neutrinos are free-streaming i.e. where they are still to hot to cluster inside of gravitational wells. Measuring the WL signal gives a unique method to directly measure the overall amplitude of the matter perturbations

The next probe of interest is the Galaxy clustering (GC) probe, where we measure the spacial correlation of galaxies. In the standard cosmological model the matter perturbations all originate from primordial perturbations generated during inflation. At early times these perturbations generated pressure waves (acoustic waves) in the tightly coupled radiation matter fluid. These pressure waves are frozen when radiation and matter decoupled at recombination. This creates an excess in the measured correlation function at the size of these acoustic waves (BAO). The size of these waves depends on the expansion history of the universe. Adding additional massless relics through $\Delta N_{\rm eff}$ or changing the fraction of matter that was still relativistic at recombination through $\sum m_\nu$ creates a measurable signal in the BAO.

Additionally to the BAO, the amplitude of the GC signal is also given by the underlying matter distribution. As galaxies form in over dense regions an over density in the galaxy distribution is related to the over density in the total matter. Contrary the the WL signal this relation is not a direct correspondence, rather the galaxy field is a bias tracer of the galaxy field. In the linear bias model this relation is modelled through a proportionality constant b called the galaxy bias. Alone the GC probe could only be able to measure the amplitude of matter perturbations times this bias. *Euclid* will be able to construct the GC power spectrum using photometric redshifts, as well using spectroscopic ones. While the galaxies for which we have measured photometric redshifts will mainly be used after binning them in tomographic redshift bins, the spectroscopic redshift measurements will allow for the computation of the three-dimensional redshift space power spectrum. We denote these two probes as GCph and GCsp respectively.

The combination of the WL and GC probe can be used to break possible degeneracies and really measure the distribution of matter, making the measurement of $\sum m_\nu$ through GC probes possible. There is additional information in the cross correlation (XC) of these two probes. As the source galaxies get lensed by the foreground structure that the lensing galaxies trace, the XC becomes very natural. From these probes three probes—GCph, WL, and XC—we extract the two point statistics.

Additionally to these probes we additionally add information from redshift space distortions (RSD) and the cosmic microwave background (CMB) to further constrain neutrino parameters and break possible degeneracies.

2. Methodology

The forecast is done using Markov chain Monte Carlo (MCMC) methods to go beyond the standard Fisher information (FI) formalism. This is done, as we expect deviations from Gaussian posteriors for the neutrino parameters, as well as to add physical priors edges at a zero neutrino mass.

The validation of our forecast was done in 3 separate steps. In the first step we validated our Einstein–Boltzmann solver (EBS) by performing multiple FI forecasts where we have compared different EBSs. For this forecast we used the `CosmicFish` code that was validated before within the efforts of the Euclid consortium[4]. The two most common EBSs are `CAMB` [5] and `CLASS` [6]. Even though they have been validated in the past, we did the validation again. This is because *Euclid* will have unprecedented precision on the measurement of the matter power spectrum and thus we have to be sure that our results do not depend on the particular code used. Furthermore the *Euclid* observables will need us to have a good handle on the non-linear corrections to the power spectrum. We performed a thorough analysis of multiple recipes for these non-linear corrections and compared them to N-body simulations. In the presence of massive neutrinos, the best comparison was achieved with the `HMCode2020` recipe [7]. Like this, the `HMCode2020` recipes within `CLASS` and `CAMB` were validated for the first time.

We then formulated a likelihood for `MontePython` [8] as an extension to the existing likelihood formulated in [9]. To perform a robust forecast on the neutrino mass we used particular care to correctly model the measured signal. The scale-dependent suppression of growth due to neutrinos makes the galaxy bias a scale dependent quantity. This scale dependence has to be properly handled as it can bias the measured value and sensitivity for $\sum m_\nu$ [3]. As neutrinos did not cluster inside of halos, the RSD is driven by cold dark matter and baryonic matter only[10]. For this reason, the measured signal has to be additionally modified to describe this defect. In the second step, We validated our likelihood by performing a FI forecast with it. We compare the results to the ones of the first step.

Finally, we ran an MCMC using our `MontePython` likelihood to check for the validity of our FI forecast. Any deviations between MCMC and FI could be explained from non-Gaussianities of the posterior as well as from prior effects. With this we were sure that our previous validation was also valid for an MCMC forecast.

3. Results

The final forecast was performed using `MontePython`. We decided to vary different sets of cosmological parameters for the analysis to study how much the constraints degrade by opening up the parameter space. The baseline model consists of five ΛCDM parameters as well as $\sum m_\nu$ i.e $\{h, \Omega_\mathrm{m}, \Omega_\mathrm{b}, \sigma_8, n_\mathrm{s}, \sum m_\nu\}$. We also studied what happens when opening up the number of additional massless relics $\{\Delta N_\mathrm{eff}\}$, and/or the Chevallier–Polarski–Linder parameters for the equation of state of dark energy $\{w_0, w_a\}$. Additionally when adding additional information from CMB experiments we vary the optical depth of reionisation τ. We assume flat cosmology and three massive neutrinos with degenerate masses. It was shown that the latter choice is appropriate as individual mass splittings are not resolvable with cosmological data[11].

We performed these forecasts for different combinations of the *Euclid* main probes as well as adding additional information from CMB experiments. For the survey specifications of *Euclid* we stick to the pessimistic settings outlined in [4]. We consider two cases for the CMB experiments: We either use a mock likelihood for *Planck* or for a more futuristic setup of CMB-S4 + LiteBird.

For the combination of the main *Euclid* probes we find in the baseline model a sensitivity to the cosmological neutrino mass of $\sigma\left(\sum m_\nu\right) = 56\,\mathrm{meV}$. This degrades to an 95% confidence level (CL) of $\sum m_\nu < 220\,\mathrm{meV}$ when opening up ΔN_{eff}. In this case the posterior is compatible with a 0 mass at the 1-σ level and thus could bias the reported uncertainty. For ΔN_{eff} we find an upper bound of $\Delta N_{\mathrm{eff}} < 0.746$ at a 95% CL. Additionally opening up the dark energy equation of state does not measurably degrade the sensitivity to $\sum m_\nu$ while the 95% CL of ΔN_{eff} degrades to $\Delta N_{\mathrm{eff}} < 0.935$.

Adding CMB to this tightens the constraints in the full 10 parameter model to $\sigma\left(\sum m_\nu\right) = 40\,\mathrm{meV}$ or $\sigma\left(\sum m_\nu\right) = 31\,\mathrm{meV}$ for *Planck* or CMB-S4+LiteBird respectively. The constraints on ΔN_{eff} are dominated by CMB probes but the main degeneracy of ΔN_{eff} with the local expansion speed of the universe h is broken though the *Euclid* data. Like this the combination of *Euclid* and CMB data could provide unprecedented sensitivity to ΔN_{eff} with a forecast sensitivity of $\Delta N_{\mathrm{eff}} < 0.149$ or $\Delta N_{\mathrm{eff}} < 0.069$ for *Euclid* + *Planck* or *Euclid* + CMB-S4 + LiteBird respectively.

The forecast sensitivities are put in a physical context in figure 1.

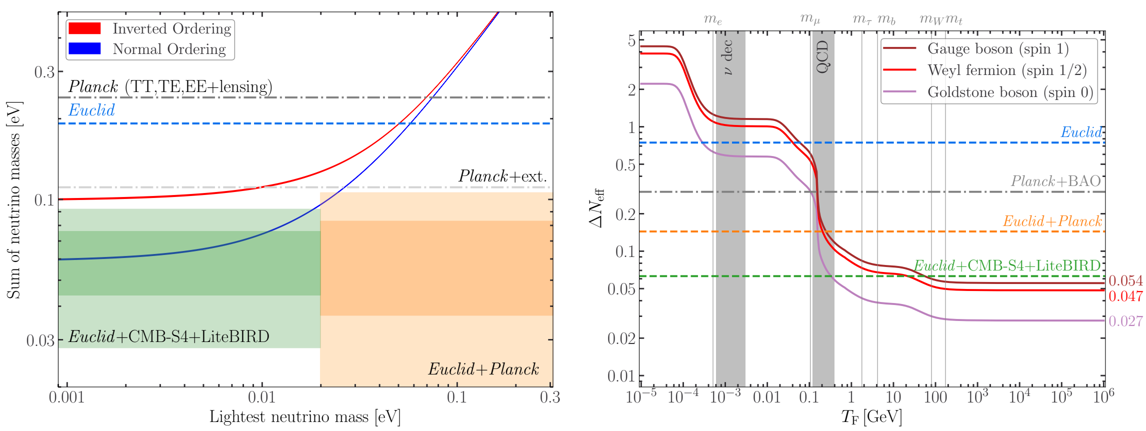

Figure 1: *left*, forecast sensitivity for the $\sum m_\nu$ for different combinations of *Euclid* with or without external CMB data. We compare the sensitivities to current measurements of *Planck* or *Planck* + additional data from supernovae, BAO measurements and current large scale structure measurements. The dashed lines represent the 95% CL. The strike-through lines represent the sum of the neutrino masses from oscillation experiments depending on the ordering and the lowest neutrino mass. We show how for the minimal mass scenario *Euclid* + CMB could be able to differentiate normal or inverted ordering.;
right, Similar to the left plot but for the sensitivity for ΔN_{eff}. The strike-through lines represent contritubtions to ΔN_{eff} from different types of particles and different decoupling temperatures. We show how with future CMB experiments *Euclid* will be able to exclude models with additional relics decoupling even before the QCD phase transition.

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