PROCEEDINGS OF SCIENCE

Euclid's Sensitivity to Neutrino Parameters

M. Archidiacono,[1,2] **J. Lesgourgues,**[3] **S. Casas,**[3] **S. Pamuk,**[4,*] **N. Schöneberg,**[5] **Z. Sakr,**[6,7,8] **G. Parimbelli,**[9,10,11] **A. Schneider,**[12] **F. Hervas Peters,**[13,12] **F. Pace,**[14,15,16] **V. M. Sabarish,**[3,17] **M. Costanzi,**[18,19,20] **S. Camera,**[14,15,16] **C. Carbone,**[21] **S. Clesse,**[22] **N. Frusciante,**[23] **A. Fumagalli,**[24,20] **P. Monaco,**[18,19,25,20] **D. Scott**[26] **and M. Viel**[19,18,10,24,27] **on behalf of the Euclid Consortium**

[1] *Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy*

[2] *INFN-Sezione di Milano, Via Celoria 16, 20133 Milano, Italy*

[3] *Institute for Theoretical Particle Physics and Cosmology (TTK), RWTH Aachen University, 52056 Aachen, Germany*

[4] *Instituto de Física de Cantabria (IFCA), CSIC-Univ. de Cantabria, Avda. de los Castros s/n, E-39005 Santander, Spain*

[5] *Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (IEEC-UB), Martí i Franquès 1, 08028 Barcelona, Spain*

[6] *Institut für Theoretische Physik, University of Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*

[7] *Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse, CNRS, UPS, CNES, 14 Av. Edouard Belin, 31400 Toulouse, France*

[8] *Université St Joseph; Faculty of Sciences, Beirut, Lebanon*

[9] *Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, s/n, 08193 Barcelona, Spain*

[10] *Dipartimento di Fisica, Università degli studi di Genova, and INFN-Sezione di Genova, via Dodecaneso 33, 16146, Genova, Italy*

[11] *SISSA, International School for Advanced Studies, Via Bonomea 265, 34136 Trieste TS, Italy*

[12] *Department of Astrophysics, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*

[13] *Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191, Gif-sur-Yvette, France*

[14] *Dipartimento di Fisica, Università degli Studi di Torino, Via P. Giuria 1, 10125 Torino, Italy*

[15] *INFN-Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*

[16] *INAF-Osservatorio Astrofisico di Torino, Via Osservatorio 20, 10025 Pino Torinese (TO), Italy*

[17] *Hamburger Sternwarte, University of Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany*

[18] *Dipartimento di Fisica - Sezione di Astronomia, Università di Trieste, Via Tiepolo 11, 34131 Trieste, Italy*

[19] *INAF-Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34143 Trieste, Italy*

[20] *IFPU, Institute for Fundamental Physics of the Universe, via Beirut 2, 34151 Trieste, Italy*

[21] *INAF-IASF Milano, Via Alfonso Corti 12, 20133 Milano, Italy*

*Speaker

[22] *Université Libre de Bruxelles (ULB), Service de Physique Théorique CP225, Boulevard du Triophe, 1050 Bruxelles, Belgium*
[23] *Department of Physics "E. Pancini", University Federico II, Via Cinthia 6, 80126, Napoli, Italy*
[24] *Ludwig-Maximilians-University, Schellingstrasse 4, 80799 Munich, Germany*
[25] *INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste TS, Italy*
[26] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada*
[27] *ICSC - Centro Nazionale di Ricerca in High Performance Computing, Big Data e Quantum Computing, Via Magnanelli 2, Bologna, Italy*

E-mail: pamuk@ifca.unican.es

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. The work presented here is based on Archidiacono et al. [1]

12th Neutrino Oscillation Workshop (NOW2024)
2-8, September 2024
Otranto, Lecce, Italy

1. Background

The *Euclid* mission[2] will measure the location and shape of more than 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 is described in [3–5]. 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 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 that enter the Hubble horizon while neutrinos are still too hot to cluster inside gravitational wells. Measuring the WL signal gives a unique method to directly measure the overall amplitude of the matter perturbations

The probe most strongly constraining $\Delta N_{\rm eff}$ is galaxy clustering (GC), where we measure the spatial correlation of galaxies. The two-point correlation function shows an excess at a particular scale, originating from expanding acoustic waves in the primordial plasma. The angular size of these baryonic acoustic oscillations (BAO) is determined by the Universe's expansion history. This is why adding additional massless relics through $\Delta N_{\rm eff}$ 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 biased tracer of the galaxy field. On its own, the GC probe could only be able to measure the amplitude of matter perturbations in combination with proportionality constants called galaxy biases. *Euclid* will be able to construct the GC power spectrum using photometric redshifts, as well as 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. The latter additionally considers redshift space distortions(RSD). We denote these two probes as GCph and GCsp respectively.

The combination of the WL and GC probe can be used to break degeneracies as they measure different tracers (gravitational potential and clustered matter respectively), which are differently affected by $\Delta N_{\rm eff}$ and $\sum m_\nu$. Given that the intervening lenses for WL are mostly clustered galaxies, it is natural to expect a cross-correlation (XC) between the WL and GCph probes. From these probes, we construct two-point statistics.

Additionally to these probes, we add information from 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 the physical constraints of a positive 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[5]. The two most common EBSs are `CAMB` [6] and `CLASS` [7]. While their agreement has been established for past CMB and LSS experiments, the new frontier of precision unlocked by *Euclid* required a new validation at higher precision requirements. 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 [8]. Like this, the `HMCode2020` recipes within `CLASS` and `CAMB` were validated for the first time.

We then formulated a likelihood for `MontePython` [9] as an extension of the existing likelihood formulated in [10]. The modelling of the galaxy bias needs particular care in the presence of massive neutrinos. Else this can bias the measured value and sensitivity for $\sum m_\nu$ [4]. As neutrinos did not cluster inside halos, the RSD is also driven by cold dark matter and baryonic matter only[11]. 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. We observed deviations between MCMC and FI that could be explained by non-Gaussianities of the posterior as well as from prior effects. This confirms the need of using MCMC methods.

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 $h, \Omega_{\rm m}, \Omega_{\rm b}, \sigma_8, n_{\rm s}, \sum m_\nu$). We also studied what happens when opening up the number of additional massless relics $\{\Delta N_{\rm eff}\}$, and/or the Chevallier–Polarski–Linder parameters for the equation of state of dark energy $\{w_0, w_a\}$. Additionally, when adding 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[12].

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 [5]. 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 a 95% confidence level (CL) of $\sum m_\nu < 220\,\mathrm{meV}$ when opening up ΔN_{eff}. The distribution is non-Gaussian due to the prior edge, and therefore we report the upper bound. 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 ten-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 reduced Hubble constant h is broken through the *Euclid* data. 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. The figure is taken from [1].We show how for the minimal mass scenario *Euclid* + CMB could be able to put the inverted hierarchy model into tension. Additionally, this combination will be able to exclude the most common types of dark relics with pre-QCD injections.

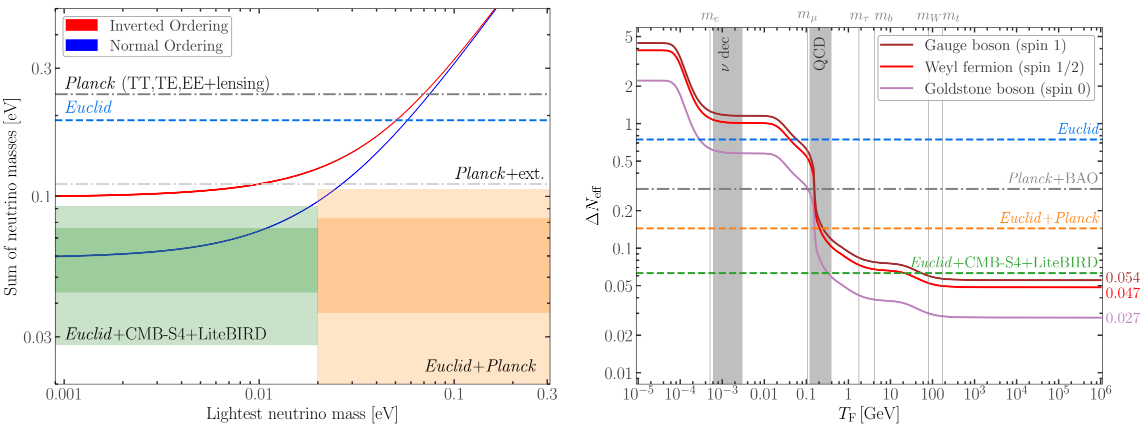

Figure 1: *left*, forecast sensitivity for the $\sum m_\nu$ for different combinations of *Euclid* with or without external CMB data. We compare the sensitivities to current measurements of *Planck* or *Planck* + additional data from supernovae, BAO measurements, and current large-scale structure measurements. 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.;
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.
Both figures are taken from [1]

Acknowledgements: The Euclid Consortium acknowledges the European Space Agency and a number of agencies and institutes that have supported the development of *Euclid*, in particular the Agenzia Spaziale Italiana, the Austrian Forschungsförderungsgesellschaft funded through BMK, the Belgian Science Policy, the Canadian Euclid Consortium, the Deutsches Zentrum für Luft- und Raumfahrt, the DTU Space and the Niels Bohr Institute in Denmark, the French Centre National d'Etudes Spatiales, the Fundação para a Ciência e a Tecnologia, the Hungarian Academy of Sciences, the Ministerio de Ciencia, Innovación y Universidades, the National Aeronautics and Space Administration, the National Astronomical Observatory of Japan, the Netherlandse Onderzoekschool Voor Astronomie, the Norwegian Space Agency, the Research Council of Finland, the Romanian Space Agency, the State Secretariat for Education, Research, and Innovation (SERI) at the Swiss Space Office (SSO), and the United Kingdom Space Agency. A complete and detailed list is available on the *Euclid* web site (`www.euclid-ec.org`).

References

[1] Euclid Collaboration: Archidiacono M., Lesgourgues J., Casas and others , *Euclid preparation. Sensitivity to neutrino parameters*, *A&A, submitted* (2024) arXiv:2405.06047 [`2405.06047`].

[2] Euclid Collaboration: Mellier Y., Abdurro'uf , Acevedo Barroso J. and others , *Euclid. I. Overview of the Euclid mission*, *A&A, accepted* (2024) arXiv:2405.13491 [`2405.13491`].

[3] Particle Data Group: Navas S., Amsler C., Gutsche T. and others , *Review of particle physics*, *Phys. Rev. D* **110** (2024) 030001.

[4] Vagnozzi S., Brinckmann T., Archidiacono M. and others , *Bias due to neutrinos must not uncorrect'd go*, *J. Cosmology Astropart. Phys.* **09** (2018) 001.

[5] Euclid Collaboration: Blanchard A., Camera S., Carbone C. and others , *Euclid preparation. VII. Forecast validation for Euclid cosmological probes*, *A&A* **642** (2020) A191 [`1910.09273`].

[6] Lewis A. and Challinor A., "CAMB: Code for Anisotropies in the Microwave Background." Astrophysics Source Code Library, record ascl:1102.026, Feb., 2011.

[7] Blas D., Lesgourgues J. and T. T., *The Cosmic Linear Anisotropy Solving System (CLASS). Part II: Approximation schemes*, *J. Cosmology Astropart. Phys.* **07** (2011) 034.

[8] Mead A. J., Brieden S., Tröster T. and Heymans C., *`HMCode-2020`: improved modelling of non-linear cosmological power spectra with baryonic feedback*, *MNRAS* **502** (2021) 1401–1422.

[9] Audren B., Lesgourgues J., Benabed K. and others , *Conservative Constraints on Early Cosmology: an illustration of the `Monte Python` cosmological parameter inference code*, *J. Cosmology Astropart. Phys.* **02** (2013) 001 [`1210.7183`].

[10] Casas S., Lesgourgues J., Schöneberg N. and others , *Euclid: Validation of the MontePython forecasting tools*, *A&A* **682** (2024) A90 [2303.09451].

[11] Villaescusa-Navarro F., Banerjee A., Dalal N., Castorina E., Scoccimarro R., Angulo R. et al., *The imprint of neutrinos on clustering in redshift space*, *ApJ* **861** (2018) 53.

[12] Lesgourgues J., Mangano G., Miele G. and Pastor S., *Neutrino Cosmology*, Cambridge University Press (2, 2013).