A 2024 Perspective on Neutrino Cosmology

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DISCRETE 2024 03-12-2024

The Context

On April 2024, the DESI collaboration presented the cosmological results from their 1st year of observations. The results have key implications for the neutrino mass.

Implications

Theory: Many neutrino mass models have large regions of parameter space with Σm > 0.073 eV.

In fact, most of the 2-zero neutrino mass textures predict Σm > 0.17 eV. See e.g. Alcaide, Santamaría & Salvadó, 1806.06785.

Experiment: Detection prospects for $m_{\bar{\nu}_e}$ **and** $m_{\beta\beta}$ **are strongly dependent upon** m_i $m_{\nu_{\rm lightest}}$ or equivalently $\sum m_{\nu}$

The Plan/Outline

1) Understand what we actually know about neutrinos in cosmology

2) Critically asses the current cosmological bound on the neutrino mass

Jiang et al. [2407.18047], Allali & Notari [2406.14554] Elbers, Frenk, Jenkins & Pascoli [2407.10965] Wang, Mena Di Valentino & Gariazzo [2405.03368] Bartolez, Esteban, Hajjar, Mena, Salvado [2411.14524] Loverde & Weiner [2410.00090] Choudhury & Okumura [2409.13022] see: Craig et al. [2405.00836], Green & Meyers [2407.07878]

> **(comprehensive profile likelihood analysis of the neutrino mass in cosmology)** Living at the Edge:

A Critical Look at the Cosmological Neutrino Mass Bound **[2407.13831](https://arxiv.org/abs/2407.13831):**

> Daniel Naredo-Tuero \bullet , ^{1, *} Miguel Escudero \bullet , ^{2, †} Enrique Fernandez-Martinez \mathbb{D} ,^{1, \ddagger} Xabier Marcano \mathbb{D} ,^{1, §} and Vivian Poulin \mathbb{D}^{3} , *I*

tools: CLASS & MontePython, Lesgourgues et al. Minimizer: *Procoli* **Karwal et al. 2401.14225**

3) Discuss the potential BSM implications of a cosmological neutrino mass bound that is in tension with the laboratory

Neutrino decays, non-standard neutrino backgrounds, annihilations, late phase transitions, time dependent masses, refractive neutrinos …

Formation of the CNB

At a time $\sim 0.1\,\mathrm{s}$ after the Big Bang when the Universe had a temperature of around $T\sim 2\,{\rm MeV}$ the Cosmic Neutrino Background formed

Key predictions: $T_{\nu} \simeq T_{\gamma}/1.4$ $n_{\nu_i} \simeq 56 \text{ cm}^{-3}$ $N_{\text{eff}} \simeq 3.04$

NLO corrections

Cielo, Escudero, Mangano & Pisanti [2306.05460] Jackson & Laine [2312.07015], [2412.XXXXX] Drewes et al. [2402.18481], [2411.14091] $\Delta N_{\text{eff}} \simeq 0.0007$ $\Delta N_{\text{eff}} \simeq 0.0001$

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Neutrino Evolution

Neutrinos are always a relevant species in the Universe's evolution

Summary

BBN & the CMB provide a powerful (albeit indirect) constraint on the Cosmic Neutrino Background as expected in the Standard Model

This gives us confidence to derive cosmological neutrino mass bounds

Main players of today's bound

Planck DESI

full sky, with 5M galaxies so far **only 5M** galaxies so far

Current bound on the neutrino mass is dominated by Planck

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Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

Neutrinos of $m_{\nu} < 0.5 \text{ eV}$ **become non-relativistic after recombination. That means that their effect on the anisotropies is somewhat small!**

The main implications are:

1) They change the distance between us and the CMB (although this is strongly correlated with Ω_m **and/or** H_0 **)**

$$
D_A = \int_0^{z_\star} \frac{dz}{H(z)}
$$

2) They affect the amount of CMB lensing The larger the neutrino mass the less the CMB light is lensed (although the effect is also correlated with $\Omega_{\text{cdm}}h^2$)

Neutrinos cannot fall in gravitational potentials for $L \leq 20$ Mpc

BAO data can break these parameter degeneracies

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

The effect of neutrino masses in the CMB:

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The Data: CMB anisotropies from Planck

I oteet essesselesisel require This component-separation algorithm, computed over 86 % of the sky. The base-⇤CDM theoretical spectrum best fit to the *Planck* **Latest cosmological results** in This the **and a** local including parties of the Figure in 2018 but in 2020 now man \sim \sim 30. **in 2018 but in 2020 new map** it to inter-call divides the spectra to the spectra to the spectra to the spectra to a problem better than 1 % without invoking a reference model. The fiduadopting the estimates from *EE* (which are about a factor of reanalyses were provided: The n

100⌘

TE fit ⁼ ¹.04, ⇣

- cial theoretical spectra *C*Th ` contained in *C*Th are derived from the best-fit temperature data alone, and the basemodel, additional the beam-leading the beam-leading the beam-leading the Galactic state \mathcal{L} calcalation in the "map-based" approach); or applying independent independent independent independent independent independent in the "map-based" or approach); or approach in the "map-based" or approach); or approach indepe estimates from *T E* and *EE* (the "spectrum-based" approach). In **1) with 8% more data**
- dust amplitudes to the central values of the priors obtained from using the 353-GHz maps. This is clearly a model-dependent procedure that we find the set of multipoles in the set of multipoles. The set of multipoles in the set of multip where the *T T* spectra are measured to cosmic variance, the resulting polarization calibration calibrations are instituted to small changes are in **systematics** tained from the fits on *EE*: $\ddot{}$ **2) with less noise and**

This is critical for neutrino mass inferences because Planck data featured the so called lensing anomaly (~3sigma) in the same parts of the spectrum where the neutrino mass signal appears.

- \sim with the polarization economic p **- Planck 2018:** \sim 2.8σ [1807.06209]
- EE fit = 1.040. The CamSpe \bullet απείς - CamSpec: $\sim 1.7\sigma$ Rosenberg et al. [2205.10869] conservative points alone, and the dot-dashed line shows the pre- δ pec: $\sim 1.7\sigma$ Rosenberg et al. [2205.10869
- ization eciency corrections, leaving an overall temperature-to-- Hillipop: $∼ 0.75σ$ Tristram et al. [2309.10034] The use of spectrum-based polarization eciency estimates CMB power spectra when the lensing amplitude *A*^L is also var-

from the *EE* spectrum is about 2 lower than that derived from

The Data: DESI-Y1 BAO

Measurement of about 5 Million redshift of galaxies and quasars up to redshift ∼ 2.4 **DESI [2404.03002]**

10 *C. Zhao et al.* 100 $s^2 \xi_{\rm gg}(s) \left[h^{-2} \, {\rm Mpc}^2 \right]$ 75 $50 25 \Omega$ -25 100 50 150 200 $s\, [h^{\,-1}\, {\rm Mpc}]$

topoion with Dlanok nrodictions parametrized as (*left*) the ratio of the angle-averaged distance *^D*^V ⌘ (*zD*² **DESI-Y1 BAO data is overall in** 2*σ* **tension with Planck predictions**

Miguel Escudero Abenza (CERN) Neutrinos in Cosmology **Figure 5.** galaxy–galaxy, galaxy–void, and void–void two-point correlation functions for dierent samples, with northern and southern galactic caps combined.

 m_{ν} < $0.082 \,\mathrm{eV}$ (95 % CL CMB+BAO-DESIY1)

Very robust bounds from linear Cosmology Δ*T*/*T* ∼ 10−⁵

What about possible systematics or statistical fluctuations in Planck CMB and/or BAO data?

What is the dependence upon the assumed statistical procedure?

And, all cosmological bounds are cosmological model dependent

What is the dependence upon the assumed Cosmological Model?

Neutrino masses and the Planck lensing anomaly

The neutrino mass bound weakens significantly in Planck implementations not featuring the lensing anomaly

Neutrino masses and the Planck lensing anomaly

The shift is not so significant when adding BAO data but the bound can still vary by 30%!

Naredo-Tuero et al. [2407.13831]

Neutrino masses and DESI BAO data

DESI BAO data is overall in 2σ tension with **Planck predictions and some data points are in tension with SDSS**

Nestles from Stand C **Neutrino masses and DESI BAO data Naredo-Tuero et al. [2407.13831] 730% relaxation** $Planck + DESI-Y1$ Planck + DESI-Y1-no07 CamSpec22-PR CamSpec22-PR4 Phack 18-PR HiLLiPoP23-PR **HiLLiPOP** Planck18-PR3 \vert (a) \vert Unphysical (extrapolated) $\vert d \vert$ NO_i \overline{O} Unphysical (extrapolated) NO_i IO -0.1 $\overline{0.0}$ $\overline{0.2}$ -0.1 $\overline{0.0}$ 0.2 $\sum m_{\nu}$ (eV) $\sum m_{\nu}$ (eV) **Planck2018+DESI-Y1:** $\frac{N}{2}$ / $\frac{N}{2}$ / m_{ν} \ $\frac{N}{2}$ (0.084 eV **95% CL Planck2023+DESI-Y1:** /// _____ > *m*_{*v*} < 0.102 eV 95% CL Planck2023+DES $\text{I} \cdot \text{Y1n00}$ $\text{Z} \cdot \text{bin:}$ $\sum m_{\nu} < 0.125 \text{ eV}$ 95% CL **Hence, still compatible with the minimal value in Inverted Ordering ** Miguel Escudero Abenza (CEAN) Neutrinos in Cosmology NSA New DISCRETE 03-12-2024

Neutrino Masses from Cosmology derived in the fall of the Feldman Series procedure (F.C.), and the fellowing procedure (F.C.), and as those using the naive bounded maximum likelihood vary. varying the equation of state of dark energy in green, and allowing for *A*lens to vary in blue. In the left panel we show the results for plik, in the middle for CamSpec and in the right panel for Hillipop. We clearly see a similar behaviour for all of them and the potential preference for a negative best fit to dissapear when the equation of state of dark energy is allowed to

Neutrino masses and statistical procedure used (B.L.) (² = 3*.*84), all at the same confidence level. **Firstly Musically Neutrino masses and stat** This is because the DESI collaboration used more constant \mathcal{L} Nautring masses and sta Programs indood and old particular dataset, the inverted ordering assumption has **stical proc** This is because that the DESI collaboration used more con-the inverted ordering assumption ordering assumption

Bayesian credible intervals are by definition prior dependent Laytolan creature intervals are by Bayesian credible intervals are by definition prior dependent the neutrino mass in Eq. (1): i) the lensing anomaly in Eq. (1): i) the lensing anomaly in Eq. (1): i) the lensing anomaly is the lensing anomaly in Eq. (1): if α PR4 with ACT lensing, rather than Planck lensing PR3 **n prior depende**

- the fact that the minimum lie beyond the physical re-In addition, in frequentist statistics, when close to a physical boundary masses. Secondary, we are a very concentrate, we also note that the mass statistical statements should be taken but we know that the laboratory the laboratory of the set of the physical term of the set of the physical term o statistical statements should be taken with care

<u>statistical statements should be taken with care</u> $\frac{1}{2}$ to be maximally conservative, one can consider $\frac{1}{2}$ Importantly, we have highlighted before the there is a second theorem of the theorem of t In addition, in frequentist statistics, when close to a physical boundary
- **Numerical comparison between Frequentists vs Bayesian results with flat in many cases on the Bayesian ones.** good agreement between the frequentists and Bayesian the frequentists and Bayesian the frequentists and Bayesia **Numerical compari** P **son between Freque** *m*⌫ = 0*.*10 eV for IO. To gauge the impact of those experimental lower limits on the cosmological neutrino \mathcal{L} $\overline{}$ ists vs Bayesian results with flat there is no lensing anomaly in the Planck likelihood Numerical comparison between Frequentists vs Bayesian results with flat priors.

For example, considering the data set combination of Naredo-Tuero et al. [2407.13831] ing the prior to P*m*⌫ following either the NO or IO con-**Naredo-Tuero et al. [2407.13831]** experimental lower limits on the cosmological neutrino on the cosmological neutrino on the cosmological neutrino

$\sum m_{\nu} < 0.084 \text{ eV}$ [Bayesian],	(5a)	Overall good agreement		
$\sum m_{\nu} < 0.074 \text{ eV}$ [Bounded–Likelihood],	(5b)	$\sum m_{\nu} \in [0 - 3 \text{ eV}]$	between the two	
$\sum m_{\nu} < 0.071 \text{ eV}$ [Feldman–Cousins].	(5c)	Although they		
$\sum m_{\nu} < 0.121 \text{ eV}$ [NO–Bayesian],	(6a)	$\sum m_{\nu} < 0.106 \text{ eV}$ [NO–Bounded–Likelihood],	(6b)	$\sum m_{\nu} \in [0.06 - 3 \text{ eV}]$ questions different \n
$\sum m_{\nu} < 0.096 \text{ eV}$ [NO–Eedman–Cousins],	(6c)	Highlights that		
$\sum m_{\nu} < 0.152 \text{ eV}$ [IO–Bayesian],	(7a)	Highlights that the likelihood is		
$\sum m_{\nu} < 0.138 \text{ eV}$ [IO–Bounded–Likelihood],	(7b)	$\sum m_{\nu} \in [0.1 - 3 \text{ eV}]$	He likelihood is	
$\sum m_{\nu} < 0.127 \text{ eV}$ [IO–Feldman–Cousins],	(7c)			

 Ω is a set of the outliers in Ω

Neutrino Masses from Cosmology CMB (with ACT "extended" likelihood)+DESI *<* 0*.*072 8.0 *<* 0*.*065 12*.*8 CMB+DESI (with 2020 HMCode) *<* 0*.*074 7.5 *<* 0*.*065 10*.*8 CMB (with v1.2 ACT likelihood)+DESI *<* 0*.*082 7.4 *<* 0*.*072 6*.*3

What about other data sets?
 What about other data sets?

Not only the bounds are stringent but there is no sign for a nonzero neutrino mass when combining with other data sets! inverted ordering, *B*NO,IO (with values of *B*NO,IO *>* 1 indicating a preference for the normal ordering) in light of di↵erent dataset not only the bounds are stringent but there is ho sign for a nonmodeled as in Eq. (1) and required to satisfy *w*(*z*) 1 (two rightmost columns).

FIG. 1. Posterior distributions for the sum of the neutrino masses $\sum m_{\nu}$ (in eV) obtained within the 7-parameter Λ CDM+ $\sum m_{\nu}$ model in light of different dataset combinations, as per the color coding.

see also Wang et al. [2405.03368]

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Neutrinos in Cosmology and anti-correlation between the two parameters of the two parameters, which ex-

Naredo-Tuero et al. [2407.13831]

 $\sigma(m_\nu) \simeq 0.06 \,\mathrm{eV}$ $\sigma(m_\nu) \simeq 0.06 \,\mathrm{eV}$

Cosmological model dependence?

The bound is actually fairly robust upon standard modifications to the cosmological model. E.g.: the bound doesn't change if one alters N_{eff} **The bound doesn't change if one allows to vary the equation of state of dark energy**

The bound does change if one allows for more freedom in the Dark Energy sector with a time-dependent equation of state of dark energy:

Cosmological Model Dependence Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

 $\sum m_\nu \lesssim 0.2 \text{ eV}$ $\nu_i \rightarrow \nu_j \phi$

Oldengott et al. [2203.09075](https://arxiv.org/abs/2203.09075) & [2011.01502](https://arxiv.org/abs/2011.01502) Escudero, López-Pavón, Rius & Sandner 2007.04994

Abellán, Poulin et al. 1909.05275, 2112.13862 Medium induced neutrino masses at least: $\sum m_{\nu} \lesssim 0.42 \, \mathrm{eV}$ **Escudero, López-Pavón, Rius & Sandner 2007.04994**

 $\nu_i \rightarrow \nu_4 \phi$

Time Dependent Neutrino Masses

Late phase transition

 $\sum m_{\nu} < 1.4 \text{ eV}$

Dvali & Funcke 1602.03191 Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

 $\sum m_\nu < 3 \text{ eV}$

Esteban & Salvadó 2101.05804 Esteban, Mena & Salvadó 2202.04656

Sen & Smirnov 2306.15718, 2407.02462

Non-standard Neutrino Populations

 $T_{\nu} < T_{\nu}^{\rm SM} + \text{DR}$

 $\sum m_\nu < 3 \text{ eV}$

Farzan & Hannestad 1510.02201 Escudero, Schwetz & Terol-Calvo [2211.01729](https://arxiv.org/abs/2211.01729) Benso, Schwetz & Vatsyayan 2410.23926

 $\langle P_{\nu} \rangle$ > 3.15 $T_{\nu}^{\rm SM}$

 $\sum m_\nu < 3 \text{ eV}$

Oldengott et al. 1901.04352 Alvey, Escudero & Sabti [2111.12726](https://arxiv.org/abs/2111.12726)

Bounds can be significantly relaxed in some extensions of ΛCDM. They require modifications to the neutrino sector.

But Why? and How?

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Not only a background effect:

Massive neutrinos also affect CMB lensing ∝

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Neutrino Decays

Neutrinos decaying with $\tau_{\nu} \lesssim t_U/10$ do not impact D_M(z_{CMB}) **Unstable Neutrinos can relax the bounds on Σm! Effect of induced neutrino Lensing is substantially reduced**

Cosmological Model Dependence Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

 $\sum m_{\nu} < 0.2 \text{ eV}$ $\nu_i \rightarrow \nu_j \phi$

Oldengott et al. [2203.09075](https://arxiv.org/abs/2203.09075) & [2011.01502](https://arxiv.org/abs/2011.01502) Escudero, López-Pavón, Rius & Sandner 2007.04994

 $\nu_i \rightarrow \nu_A \phi$

 $\sum m_\nu \lesssim 0.42 \text{ eV}$ **at least:**

Abellán, Poulin et al. 1909.05275, 2112.13862 Escudero, López-Pavón, Rius & Sandner 2007.04994

Take Away Message:

Time Dependent Neutrino Masses

Late phase transition

 $\sum m_{\nu}$ < 1.4 eV

Dvali & Funcke 1602.03191 Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

 $\sum m_\nu < 3 \text{ eV}$

Esteban & Salvadó 2101.05804 Esteban, Mena & Salvadó 2202.04656

Medium induced neutrino masses

Sen & Smirnov 2306.15718, 2407.02462

Non-standard Neutrino Populations

 $T_\nu < T_\nu^{\rm SM}$ $\sum m_\nu < 3 \text{ eV}$

Escudero, Schwetz & Terol-Calvo [2211.01729](https://arxiv.org/abs/2211.01729) Benso, Schwetz & Vatsyayan 2410.23926 Farzan & Hannestad 1510.02201

 $\langle P_{\nu} \rangle$ > 3.15 $T_{\nu}^{\rm SM}$

 $\sum m_\nu < 3 \text{ eV}$

Oldengott et al. 1901.04352 Alvey, Escudero & Sabti 2111.14870

Cosmology can only constrain $\Omega_{\nu}(z)$ **and not directly** m_{ν} All these models reduce $\Omega_{\nu}(z)$ with respect to the one in <code>ACDM</code> **and are in excellent agreement with all known cosmological data** $\Omega_{\nu}(z)$

Invisible Neutrino Decays

v ≲ 100 TeV

see e.g. Gelmini & Valle PLB 142 (1984) 181 for a model

see Escudero, López-Pavón, Rius & Sandner [2007.04994](http://arxiv.org/abs/arXiv:2007.04994)

Neutrino Decays into lighter neutrinos

$\nu_i \rightarrow \nu_j \phi$ Decays

However, because there is a neutrino in the final state the mass bounds are expected to only be relaxed mildly: Theory: These happen naturally in scenarios with sterile neutrinos and horizontal global and spontaneously broken flavor symmetries, e.g. *L^μ* − *L^τ* **see Gelmini & Valle PLB 142 (1984) 181** ${\bf Couplings:} \ \tau_\nu < t_U$ taking the $L_\mu - L_\tau$ case means $v_{\mu-\tau} < 30 \ {\rm TeV}$ for both global and gauge U(1)

Neutrino Decays into Massless States

$\nu_i \rightarrow \nu_4 \phi$ Decays Can relax the bounds significantly

Have an almost massless sterile state but that:

- **1) Does not to spoil the neutrino mass mechanism**
- 2) Is weakly coupled so that evades constraints on $U_{\alpha 4}$
- **3) But not so weakly coupled so that** $\tau_v < 0.1$ **tu**

Simple solution: Escudero, López-Pavón, Rius & Sandner [2007.04994](http://arxiv.org/abs/arXiv:2007.04994) Add global U(1)_x symmetry with a scalar field and a singlet left-handed state S_L

$$
\mathcal{L} = y\Phi \overline{N}_R S_L \qquad M_{\nu}|^{7\times7} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^t & M_R & y_{\alpha}v_{\Phi} \\ 0 & (y_{\alpha}v_{\Phi})^t & 0 \end{pmatrix}
$$

\n**Provided** $y_{\alpha}v_{\Phi} \ll m_D$
\n• **Seesaw mechanism at play** $m_{\nu} \simeq m_D^2/M_R$
\n• **Right** v_4 **properties**: $m_{\nu_4} \simeq 0$ $U_{\alpha 4} \sim \frac{y_{\alpha}v_{\Phi}}{m_D} \ll 1$
\n**Cosmological decays**: $\Gamma(\nu_i \to \nu_4 \phi) \sim 10^6 t_U^{-1} y_{\alpha}^2 \left(\frac{m_{\nu}}{0.3 \text{eV}}\right)^2 \left(\frac{10^{14} \text{ GeV}}{M_R}\right)$

Neutrinos with a large mass can decay on cosmological timescales while being in agreement with all known laboratory and cosmological data!

Summary

- **We have strong, albeit indirect evidence that the Cosmic Neutrino Background should be there as predicted in the Standard Model**
- **Current cosmological neutrino mass bounds are very stringent. They are getting very close to the minimum expected values from the laboratory**
- **Given our assessment of possible systematic effects and statistical fluctuations we believe that there is currently no significant tension with laboratory**

 $\sum m_\nu < 0.13 \text{ eV}$ at 95% CL seems like a conservative bound within Λ CDM

Cosmological bounds can be significantly relaxed in extensions of ΛCDM. The only thing that cosmological observations can constrain is the energy density in neutrinos.

Relaxing Cosmological Neutrino Mass Bounds with

[2007.04994:](https://arxiv.org/abs/2007.04994)

Unstable Neutrinos

Miguel Escudero, $1a$ Jacobo Lopez-Pavon, $2b$ Nuria Rius, $3b$ and Stefan Sandner, $4b$

Outlook

The ongoing generation of galaxy surveys in combination with CMB data are expected to measure the neutrino mass if the Universe is governed by a ΛCDM cosmology

DESI-Y3 BAO data has already been collected. Its analysis will be presented next year. This data release will clearly close the possibility of statistical fluctuations being behind the strong bound on the neutrino mass.

Euclid will provide also key information into the game in a couple of years.

Outlook: Hubble tension?

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Standard Model Prediction

In the next 5-6 years:

Time for Questions and Comments

Thank you for your attention!

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