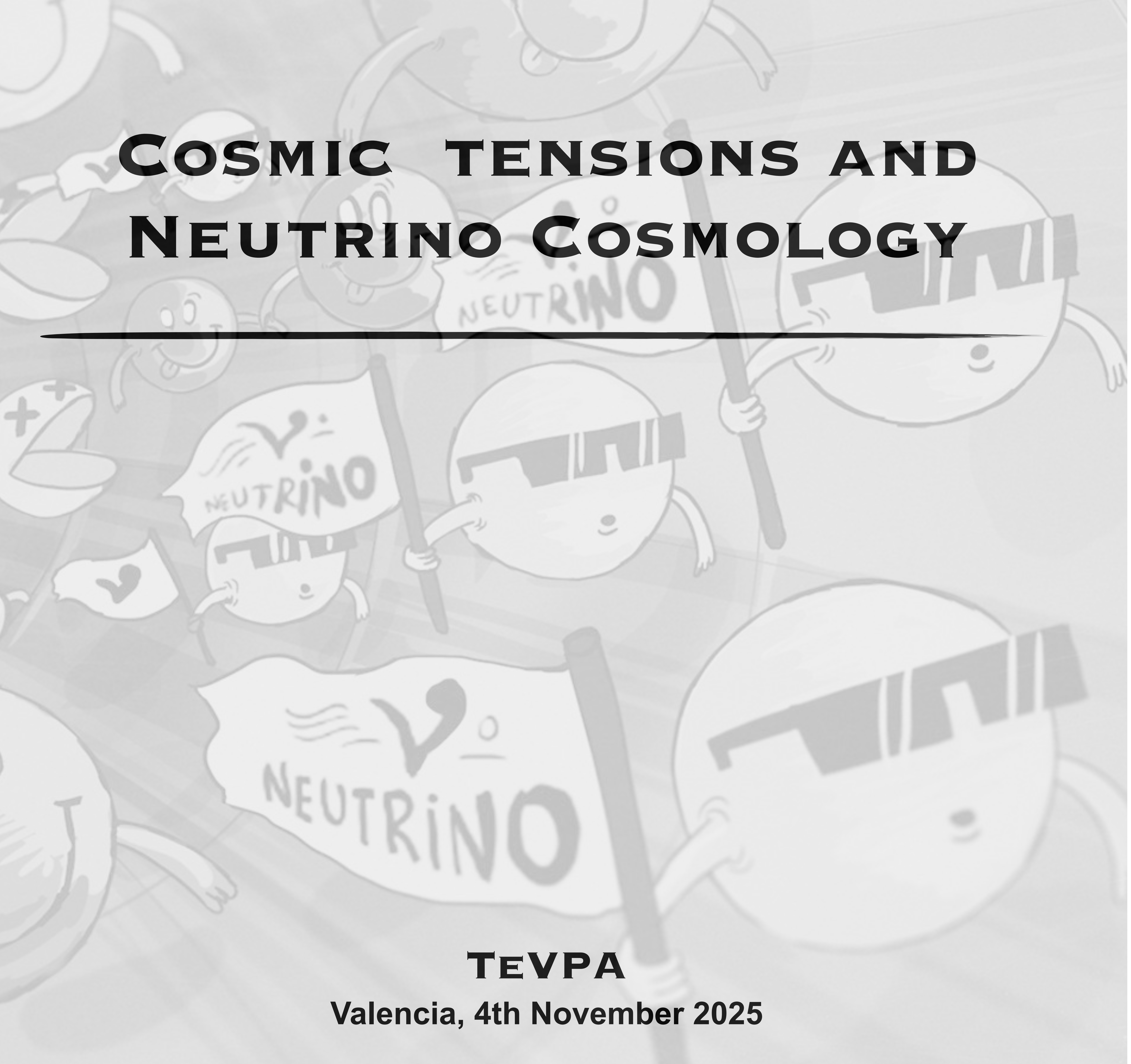

Cosmic tensions and Neutrino Cosmology

TeVPA
Valencia, 4th November 2025

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ANOMALIES & TENSIONS IN COSMOLOGY · COSMOVERSE ·

DISCE DOCE · RERUM COGNOSCERE CAUSAS

COSMIC WISPERS CA21106

Slides will be available at

https://github.com/williamgiare/wgcosmo

Precision Neutrino Physics and Cosmology

PHYSICAL REVIEW D **111,** 093006 (2025)

Neutrino masses and mixing: Entering the era of subpercent precision

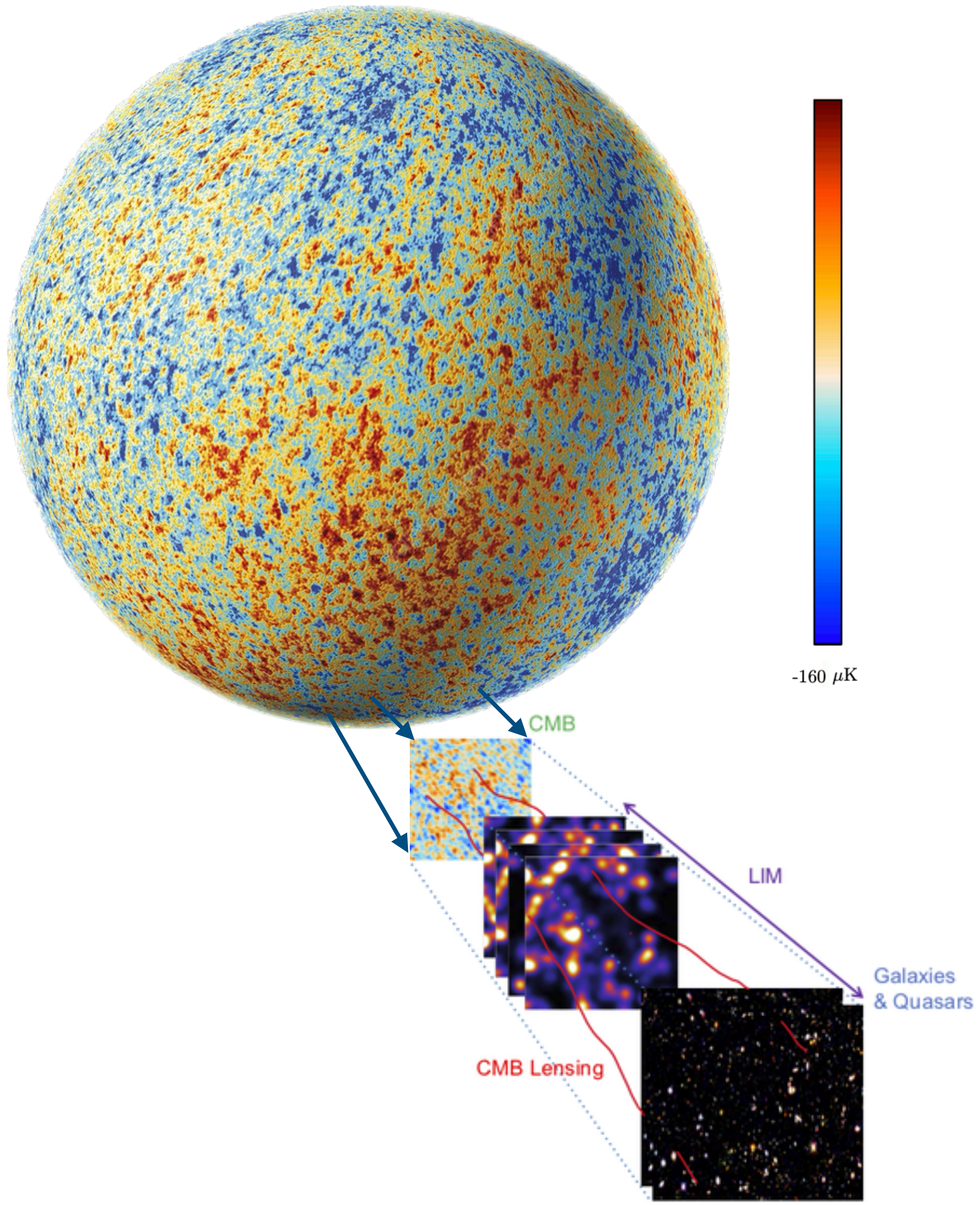
Francesco Capozzi,[1,2] William Giarè,[3] Eligio Lisi,[4] Antonio Marrone,[5,4]
Alessandro Melchiorri,[6,7] and Antonio Palazzo[5,4]

(Received 12 March 2025; accepted 21 April 2025; published 19 May 2025)

We perform an updated global analysis of the known and unknown parameters of the standard three-neutrino (3ν) framework, using data available at the beginning of 2025. The known oscillation parameters include three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and two squared mass gaps, chosen as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)$, where the discrete parameter $\alpha = \mathrm{sign}(\Delta m^2)$ distinguishes normal ordering (NO, $\alpha = +1$) from inverted ordering (IO, $\alpha = -1$). With respect to our previous 2021 update, the combination of accelerator, reactor, and atmospheric neutrino data leads to appreciably reduced uncertainties for θ_{23}, θ_{13}, and $|\Delta m^2|$. In particular, $|\Delta m^2|$ is the first 3ν parameter to enter the domain of subpercent precision (0.8% at 1σ). We underline some issues about common systematics in combined fits that might affect (and possibly weaken) this error estimate. Concerning oscillation unknowns, we find a relatively weak preference for NO versus IO (at 2.2σ), for *CP* violation versus conservation in NO (1.3σ), and for the first θ_{23} octant versus the second in NO (1.1σ). We discuss the current status and qualitative prospects of the mass ordering hint in the plane charted by the mass parameters ($\delta m^2, \Delta m^2_{ee}$), where $\Delta m^2_{ee} = |\Delta m^2| + \frac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$, to be jointly measured by the JUNO experiment with subpercent precision. We also discuss upper bounds on nonoscillation observables, including the effective ν_e mass m_β in β decay, the effective Majorana mass $m_{\beta\beta}$ in $0\nu\beta\beta$ decay, and the sum of neutrino masses Σ in cosmology. We adopt $m_\beta < 0.50$ eV (2σ) from current ^{3}H data and report $m_{\beta\beta} < 0.086$ eV (2σ) from a combined ^{76}Ge, ^{130}Te, and ^{136}Xe data analysis, accounting for parametrized nuclear matrix element covariances. Concerning Σ, current results show tensions within the standard Λ cold dark matter (ΛCDM) cosmological model, pulling Σ toward unphysical values and suggesting possible model extensions. We discuss representative combinations of data, with or without augmenting the ΛCDM model with extra parameters accounting for possible systematics (lensing anomaly) or new physics (dynamical dark energy). The resulting 2σ upper limits are roughly spread around the bound $\Sigma < 0.2$ eV within a factor of 3 (both up- and downward), with different implications for NO and IO scenarios. Bounds from oscillation and nonoscillation data are also discussed in the planes charted by pairs of ($m_\beta, m_{\beta\beta}, \Sigma$) parameters.

DOI: 10.1103/PhysRevD.111.093006

- **Sub-percent *Neutrino Physics and Cosmology***
  (the latter made possible by Planck, ACT, DESI, and many other surveys)



Neutrino Cosmology

Total Neutrino Mass and Ordering

Neutrino oscillations measured by terrestrial experiments indicate that at least two neutrinos are massive:

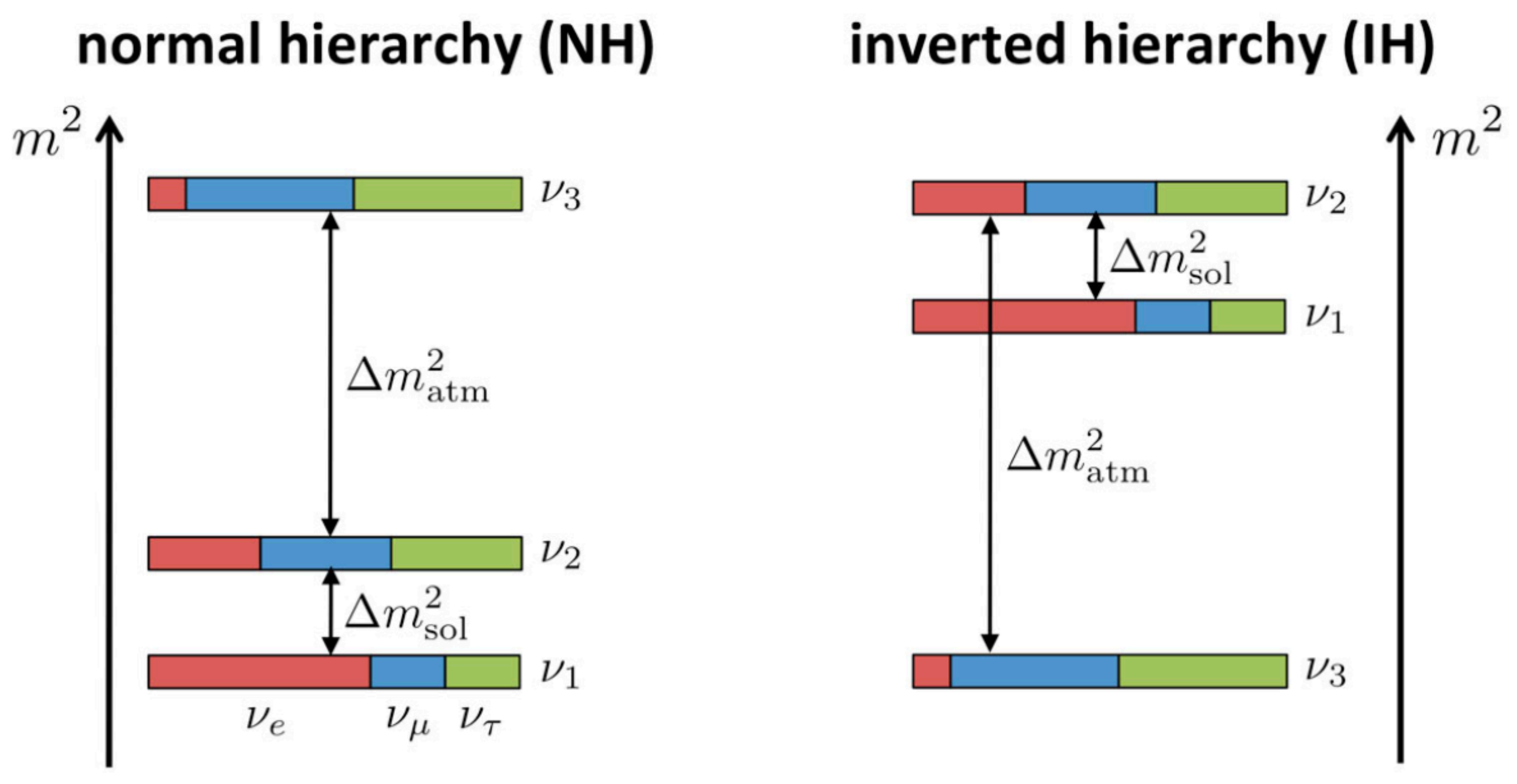
- **Atmospheric splitting**: $|\Delta m^2_{3,1}| = |m_3^2 - m_1^2| \sim 2.55 \times 10^{-3}$ eV^2
- **Solar splitting**: $\Delta m^2_{2,1} = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5}$ eV^2

Since the sign of $|\Delta m^2_{3,1}|$ is unknown, two mass orderings are possible:

1) **Normal Ordering** ($m_1 < m_2 < m_3$)

2) **Inverted Ordering** ($m_3 < m_1 < m_2$)

Credit: Figure taken from S. Vagnozzi — *Weight them all!*



Neutrino Cosmology

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1) **Normal Ordering** ($m_1 < m_2 < m_3$)

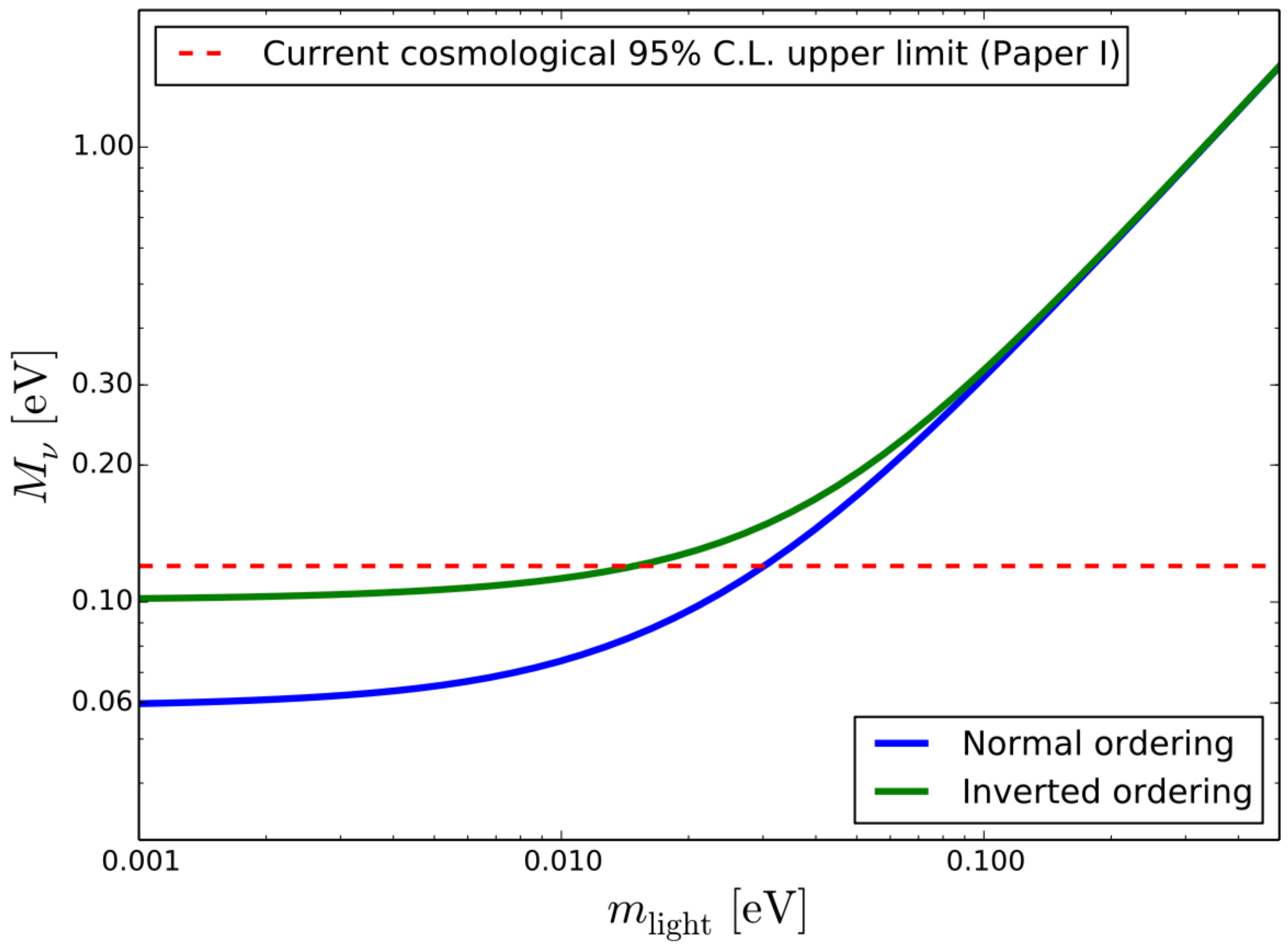
2) **Inverted Ordering** ($m_3 < m_1 < m_2$)

If we set the mass of the lightest neutrino to $m_{\rm light} = 0$, within the two orderings, we get a lower limit on the total mass from neutrino oscillations

1) **Normal Ordering:** $\sum m_\nu > 0.06\,\mathrm{eV}$

2) **Inverted Ordering:** $\sum m_\nu > 0.1\,\mathrm{eV}$

Credit: Figure taken from S. Vagnozzi — *Weight them all!*



Neutrino Tension

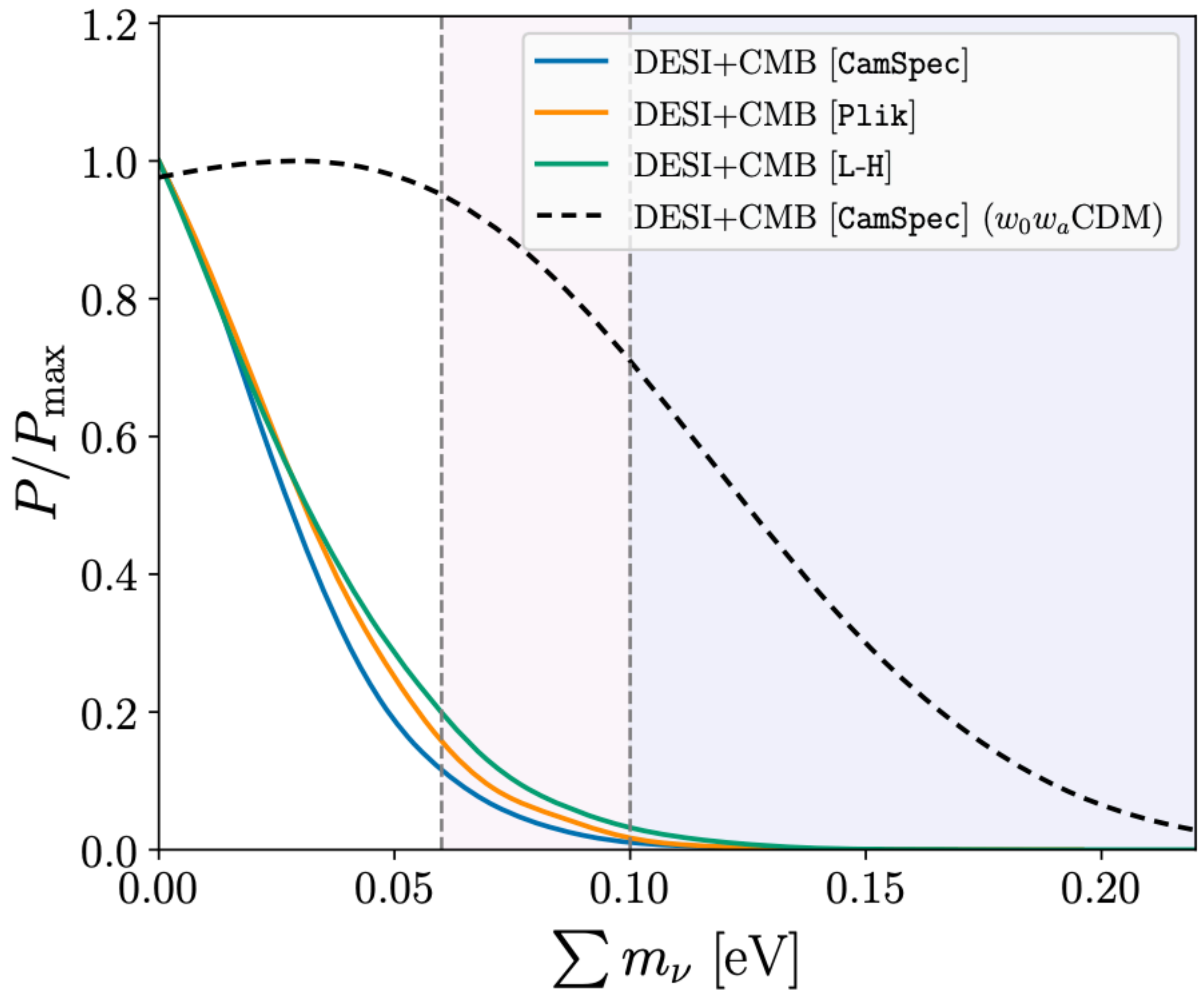
DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

The DESI collaboration

We present baryon acoustic oscillation (BAO) measurements from more than 14 million galaxies and quasars drawn from the Dark Energy Spectroscopic Instrument (DESI) Data Release 2 (DR2), based on three years of operation. For cosmology inference, these galaxy measurements are combined with DESI Lyman-α forest BAO results presented in a companion paper. The DR2 BAO results are consistent with DESI DR1 and SDSS, and their distance-redshift relationship matches those from recent compilations of supernovae (SNe) over the same redshift range. The results are well described by a flat ΛCDM model, but the parameters preferred by BAO are in mild, 2.3σ tension with those determined from the cosmic microwave background (CMB), although the DESI results are consistent with the acoustic angular scale θ_* that is well-measured by Planck. This tension is alleviated by dark energy with a time-evolving equation of state parametrized by w_0 and w_a, which provides a better fit to the data, with a favored solution in the quadrant with $w_0 > -1$ and $w_a < 0$. This solution is preferred over ΛCDM at 3.1σ for the combination of DESI BAO and CMB data. When also including SNe, the preference for a dynamical dark energy model over ΛCDM ranges from $2.8-4.2\sigma$ depending on which SNe sample is used. We present evidence from other data combinations which also favor the same behavior at high significance. From the combination of DESI and CMB we derive 95% upper limits on the sum of neutrino masses, finding $\sum m_\nu < 0.064$ eV assuming ΛCDM and $\sum m_\nu < 0.16$ eV in the w_0w_a model. Unless there is an unknown systematic error associated with one or more datasets, it is clear that ΛCDM is being challenged by the combination of DESI BAO with other measurements and that dynamical dark energy offers a possible solution.

DESI 2025 — [arXiv:2503.14738]



- **CMB+DESI-DR2:** $\sum m_\nu < 0.064$ **eV**
- **Oscillation Experiments NO:** $\sum m_\nu > 0.06$ **eV**
- **Oscillation Experiments IO:** $\sum m_\nu > 0.1$ **eV**

NEUTRINO TENSION

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Neutrino cosmology after DESI: tightest mass upper limits, preference for the normal ordering, and tension with terrestrial observations

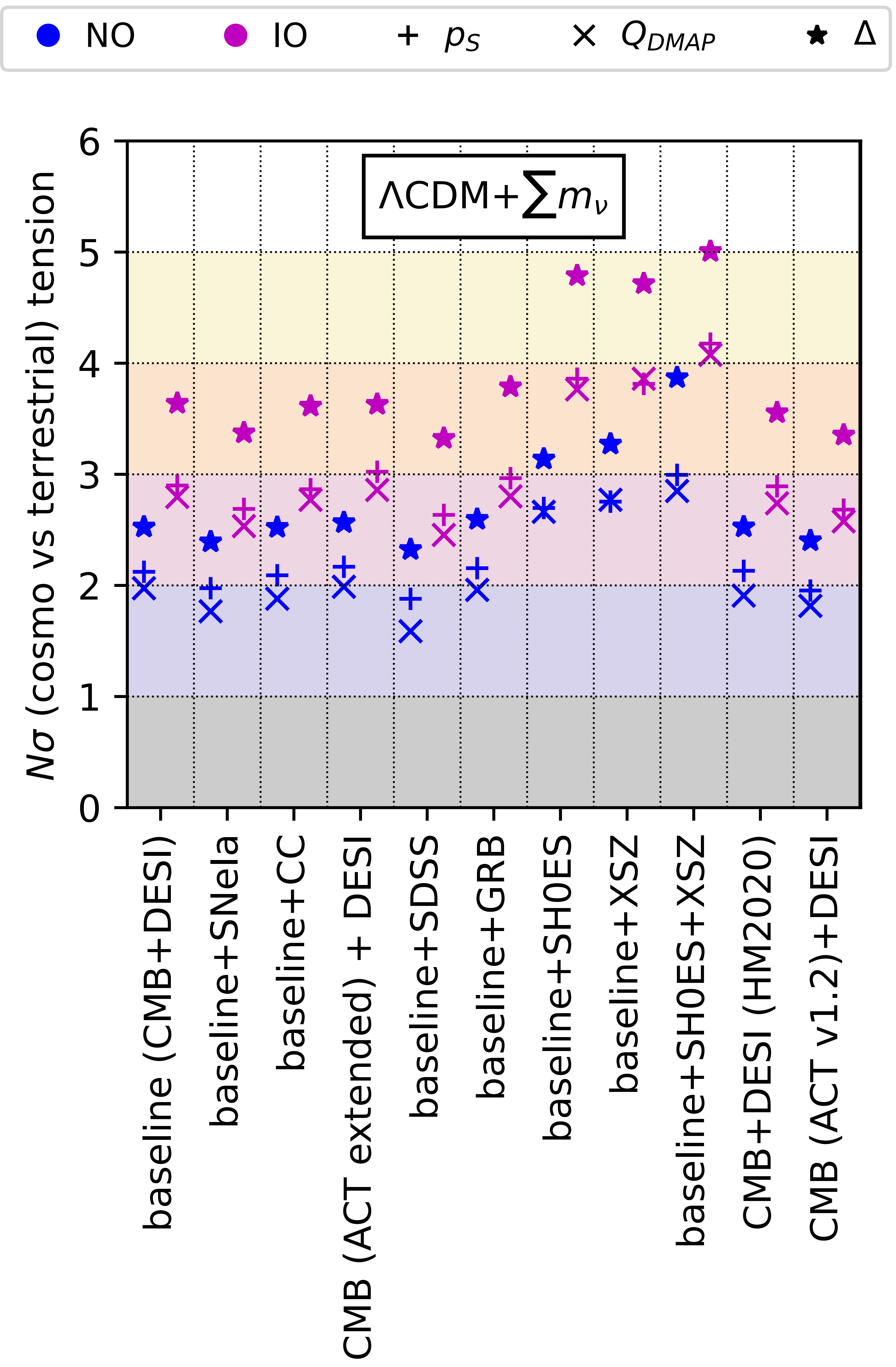
Jun-Qian Jiang[a,b] William Giarè[c] Stefano Gariazzo[d,e,f]
Maria Giovanna Dainotti[g,h,i,j] Eleonora Di Valentino[c] Olga Mena[k]
Davide Pedrotti[b,l] Simony Santos da Costa[b,l] and Sunny Vagnozzi[b,l]

ABSTRACT: The recent DESI Baryon Acoustic Oscillation measurements have led to tight upper limits on the neutrino mass sum, potentially in tension with oscillation constraints requiring $\sum m_\nu \gtrsim 0.06\,\text{eV}$. Under the physically motivated assumption of positive $\sum m_\nu$, we study the extent to which these limits are tightened by adding other available cosmological probes, and robustly quantify the preference for the normal mass ordering over the inverted one, as well as the tension between cosmological and terrestrial data. Combining DESI data with Cosmic Microwave Background measurements and several late-time background probes, the tightest 2σ limit we find without including a local H_0 prior is $\sum m_\nu < 0.05\,\text{eV}$. This leads to a strong preference for the normal ordering, with Bayes factor relative to the inverted one of 46.5. Depending on the dataset combination and tension metric adopted, we quantify the tension between cosmological and terrestrial observations as ranging between 2.5σ and 5σ. These results are strenghtened when allowing for a time-varying dark energy component with equation of state lying in the physically motivated non-phantom regime, $w(z) \geq -1$, highlighting an interesting synergy between the nature of dark energy and laboratory probes of the mass ordering. If these tensions persist and cannot be attributed to systematics, either or both standard neutrino (particle) physics or the underlying cosmological model will have to be questioned.

KEYWORDS: neutrino masses from cosmology, cosmological neutrinos, dark energy experiments, neutrino properties

ARXIV EPRINT: 2407.18047

JCAP01(2025)153



WHAT'S THE MATTER (DENSITY)?

Although all the datasets are well described by a flat ΛCDM model:

- **DESI-2025 BAOs show a mild tension (2.3σ) with Planck.**
- **DESI-2025 BAO+Planck** leads to a **moderate shift (~1.5σ – 2σ)** in Planck's preferred parameter space, notably **favouring a larger H_0 and a lower Ω_m.**
- **DESy5-SN+Planck** favours **larger Ω_m and lower H_0.**

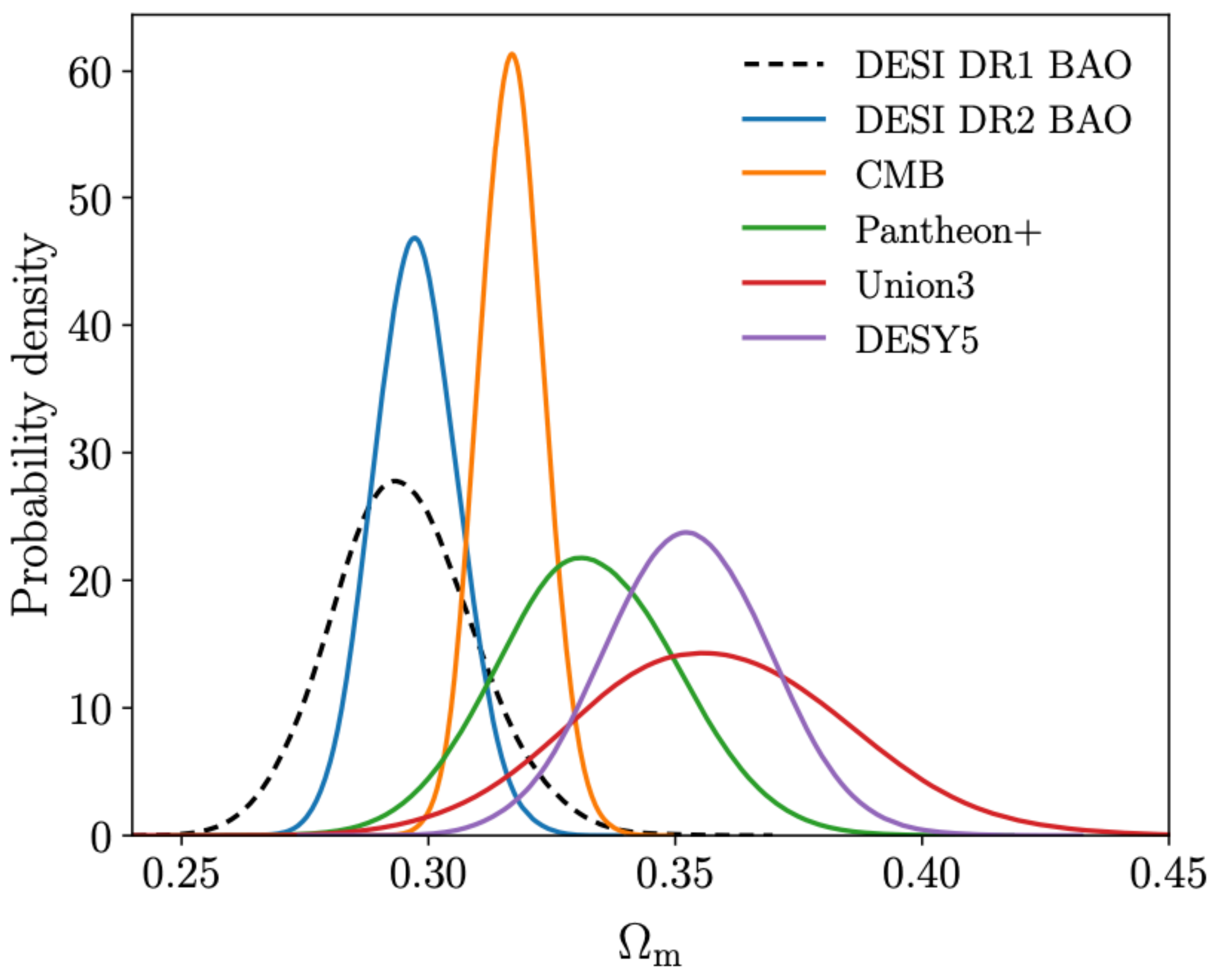
=> Planck+DESI-2025 BAO and Planck+DESy5 SN pull the parameter space in opposite directions.

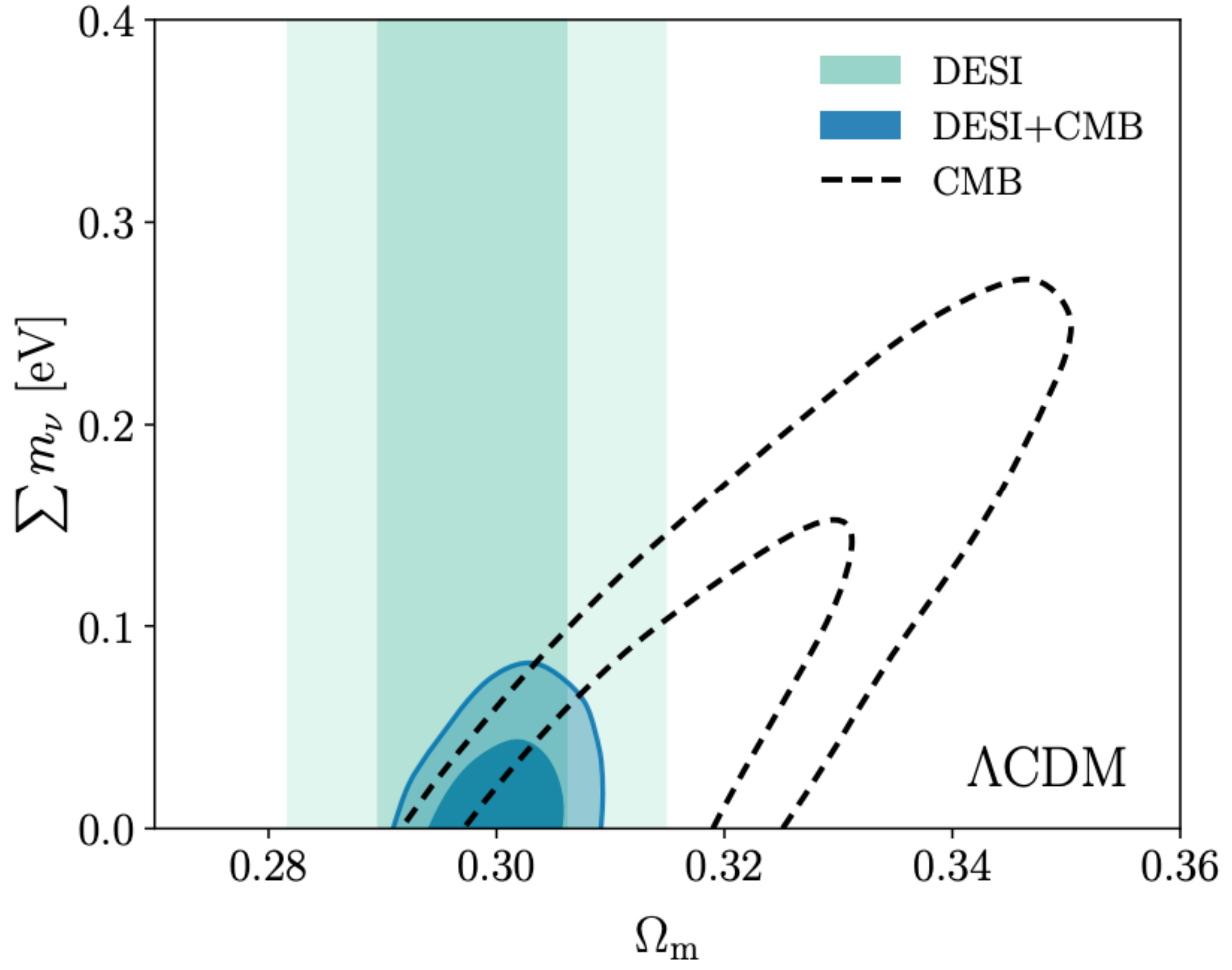
Note that the DESI-2025 BAO preference for lower values of Ω_m is largely responsible for the neutrino tension:

$$\Omega_m h^2 = \Omega_b h^2 + \Omega_c h^2 + \Omega_\nu h^2$$

$$\Omega_\nu h^2 \sim \frac{\sum m_\nu}{93.14\, h^2\, \text{eV}}$$

DESI 2025 — [arXiv:2503.14738]





Evolving Dark Energy

DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

DARK ENERGY SPECTROSCOPIC INSTRUMENT
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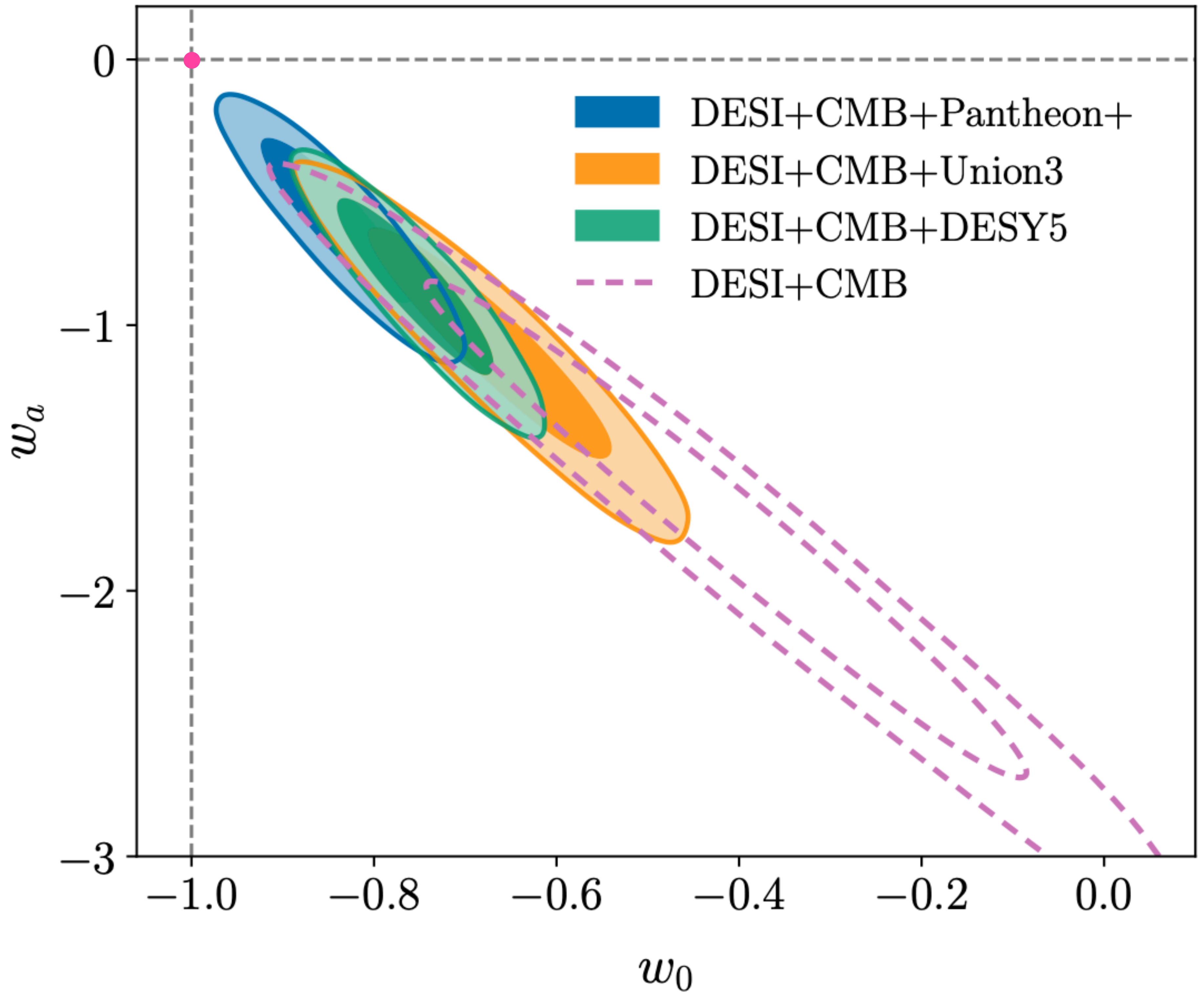
We present baryon acoustic oscillation (BAO) measurements from more than 14 million galaxies and quasars drawn from the Dark Energy Spectroscopic Instrument (DESI) Data Release 2 (DR2), based on three years of operation. For cosmology inference, these galaxy measurements are combined with DESI Lyman-α forest BAO results presented in a companion paper. The DR2 BAO results are consistent with DESI DR1 and SDSS, and their distance-redshift relationship matches those from recent compilations of supernovae (SNe) over the same redshift range. The results are well described by a flat ΛCDM model, but the parameters preferred by BAO are in mild, 2.3σ tension with those determined from the cosmic microwave background (CMB), although the DESI results are consistent with the acoustic angular scale θ_* that is well-measured by Planck. This tension is alleviated by dark energy with a time-evolving equation of state parametrized by w_0 and w_a, which provides a better fit to the data, with a favored solution in the quadrant with $w_0 > -1$ and $w_a < 0$. This solution is preferred over ΛCDM at 3.1σ for the combination of DESI BAO and CMB data. When also including SNe, the preference for a dynamical dark energy model over ΛCDM ranges from $2.8 - 4.2\sigma$ depending on which SNe sample is used. We present evidence from other data combinations which also favor the same behavior at high significance. From the combination of DESI and CMB we derive 95% upper limits on the sum of neutrino masses, finding $\sum m_\nu < 0.064$ eV assuming ΛCDM and $\sum m_\nu < 0.16$ eV in the $w_0 w_a$ model. Unless there is an unknown systematic error associated with one or more datasets, it is clear that ΛCDM is being challenged by the combination of DESI BAO with other measurements and that dynamical dark energy offers a possible solution.

Favored at $\sim 3 - 4\sigma$ level over Λ

Chevallier-Polarski-Linder DE EoS:

$$w(z) = w_0 + w_a(1 - a)$$



Evolving Dark Energy

Reconcile neutrino tension: $\sum m_\nu < 0.16$ eV

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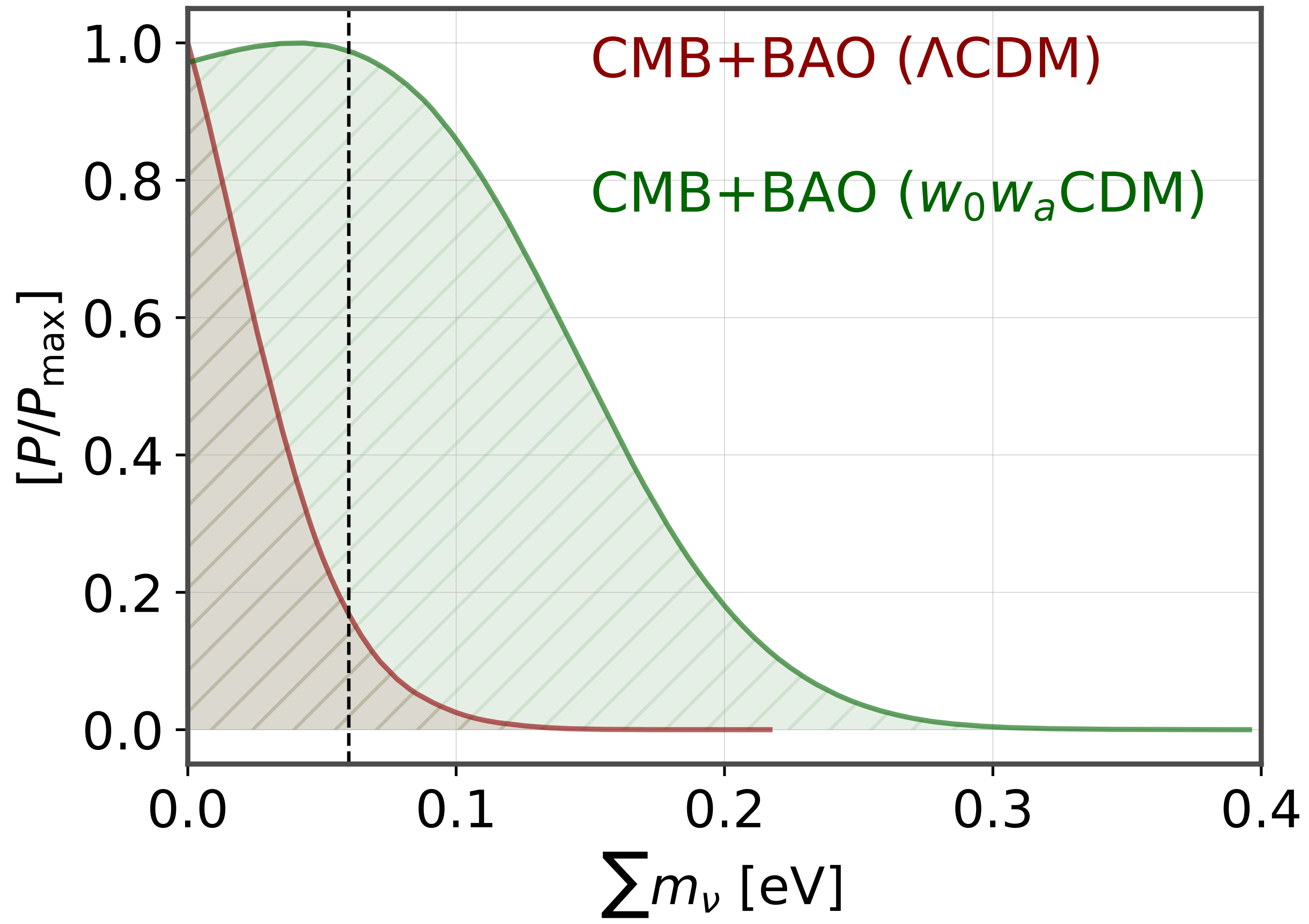
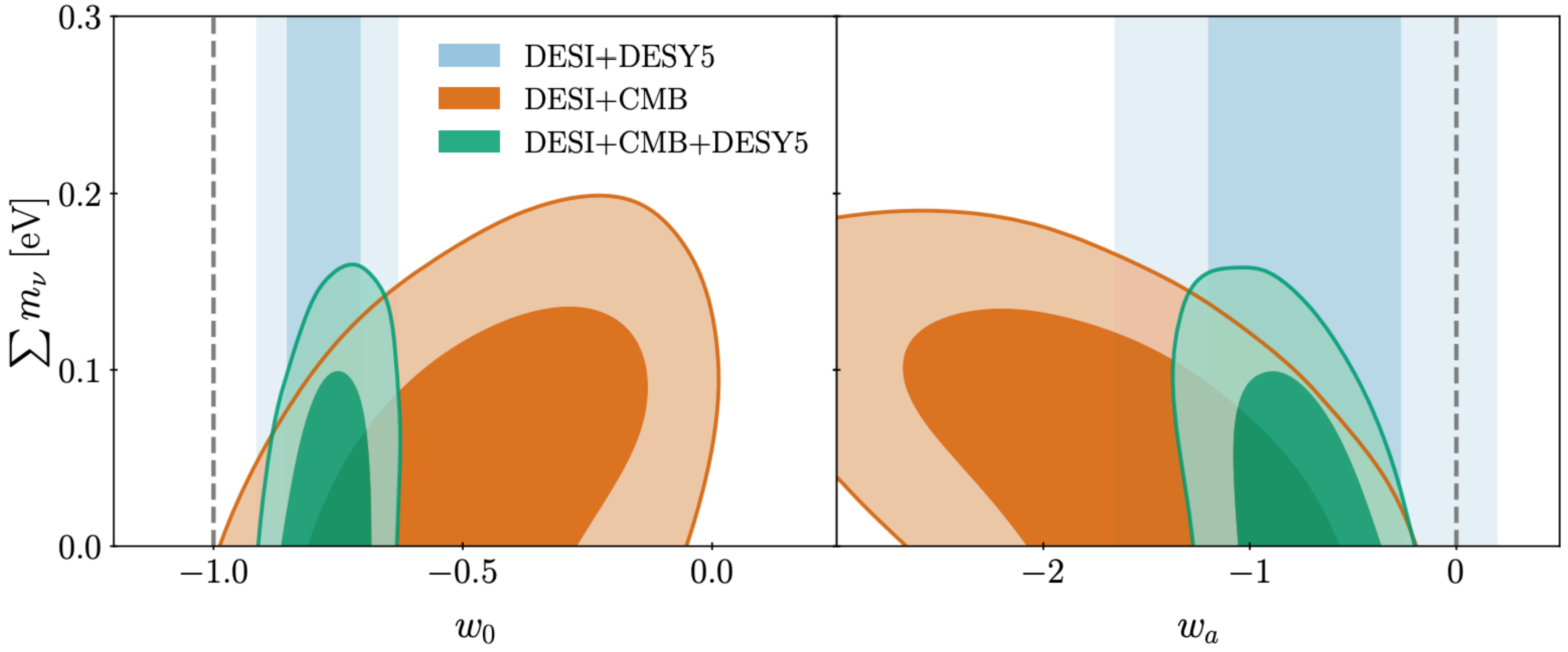


DESI 2025 — [arXiv:2503.14738]



Hubble Tension

5σ tension in the value of the Hubble parameter H_0

Direct Measurement

SH0ES: $H_0 = 73 \pm 1$ km/s/Mpc

Model-independent, based on Type-Ia Supernovae

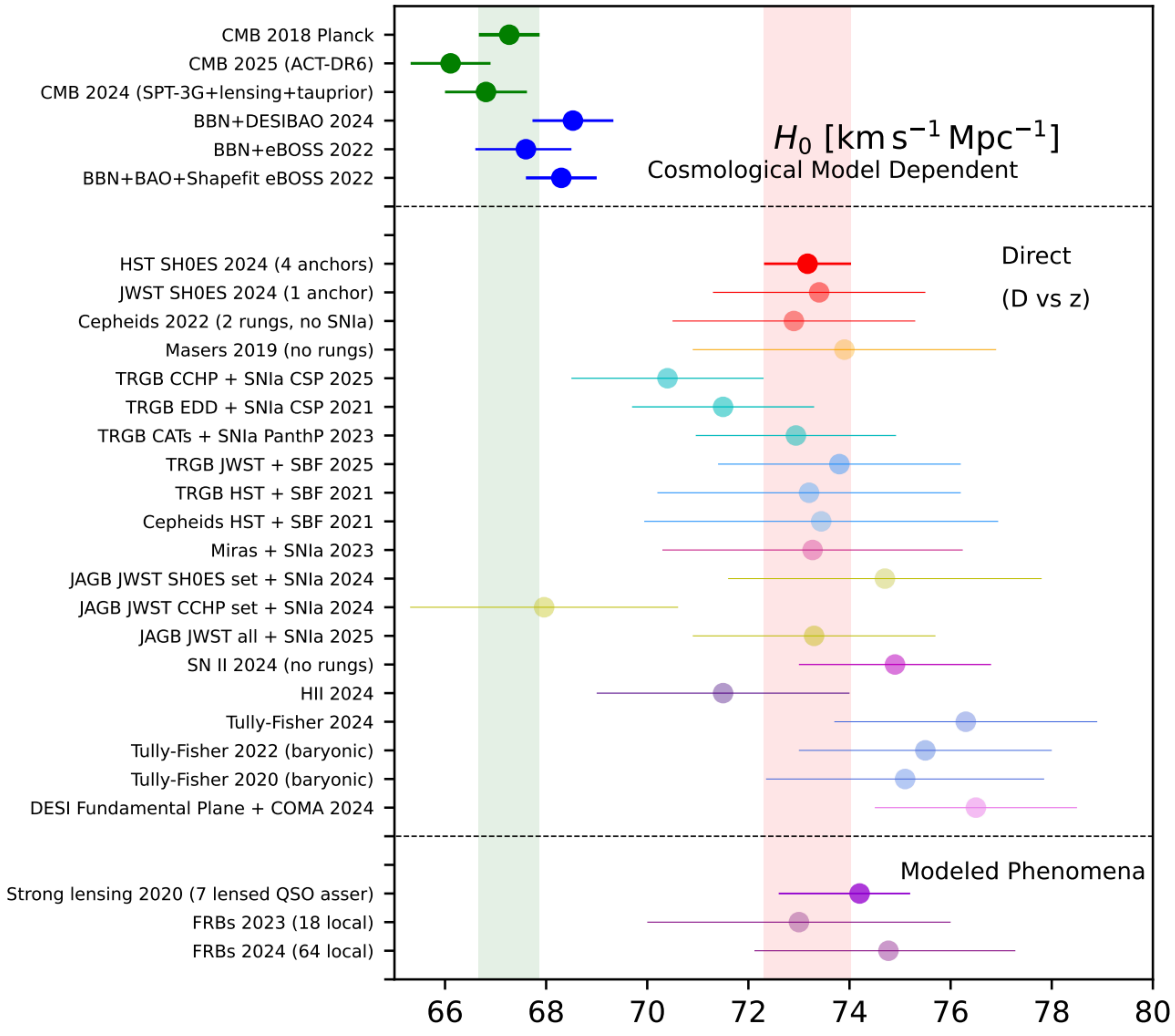
Indirect Measurement

Planck: $H_0 = 67.4 \pm 0.5$ km/s/Mpc

Model-dependent, inferred from CMB measurement (in ΛCDM)

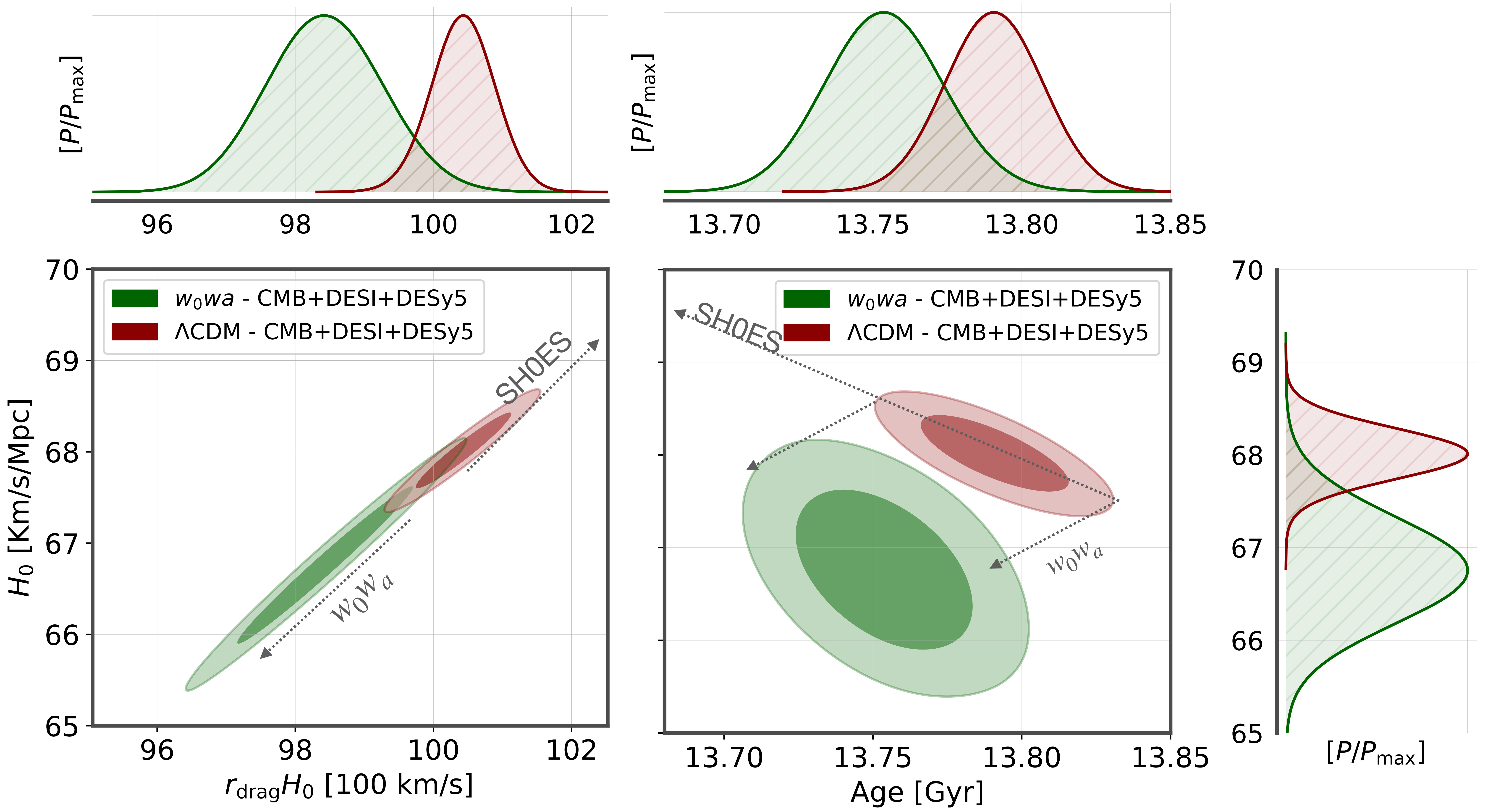
Tension confirmed by many other independent probes

Cosmoverse WP — [arXiv:2504.01669]



Evolving Dark Energy

Fails to reconcile the Hubble Tension



WG & *E. Di Valentino* [arXiv: 25xx.xxxx]

Interacting Dark Energy

PHYSICAL REVIEW LETTERS **133,** 251003 (2024)

Interacting Dark Energy after DESI Baryon Acoustic Oscillation Measurements

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[2]*Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre RS, Brazil*

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(Received 29 April 2024; revised 14 June 2024; accepted 19 November 2024; published 18 December 2024)

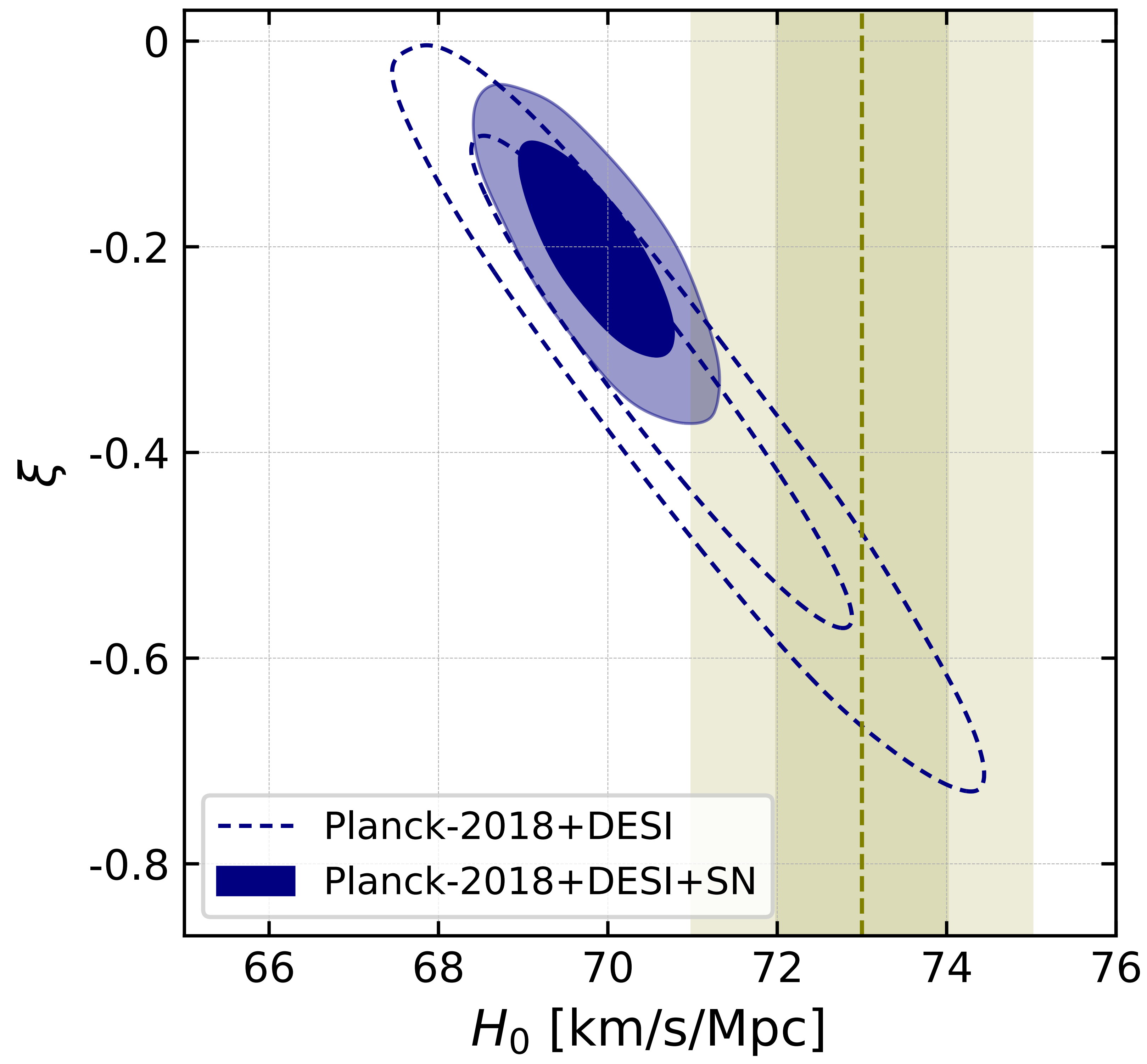
We investigate the implications of the baryon acoustic oscillations measurement released by the Dark Energy Spectroscopic Instrument for interacting dark energy (IDE) models characterized by an energy-momentum flow from dark matter to dark energy. By combining Planck-2018 and Dark Energy Spectroscopic Instrument data, we observe a preference for interactions, leading to a nonvanishing interaction rate $\xi = -0.32^{+0.18}_{-0.14}$, which results in a present-day expansion rate $H_0 = 70.8^{+1.4}_{-1.7}$ km/s/Mpc, reducing the tension with the value provided by the SH0ES Collaboration to less than $\sim 1.3\sigma$. The preference for interactions remains robust when including measurements of the expansion rate $H(z)$ obtained from the relative ages of massive, early-time, and passively evolving galaxies, as well as when considering distance moduli measurements from Type Ia supernovae sourced from the Pantheon-plus catalog using the SH0ES Cepheid host distances as calibrators. Overall, the IDE framework provides an equally good, or better, explanation of both high- and low-redshift *background* observations compared to the lambda cold dark matter model, while also yielding higher H_0 values that align more closely with the local distance ladder estimates. However, a limitation of the IDE model is that it predicts lower Ω_m and higher σ_8 values, which may not be fully consistent with large-scale structure data at the *perturbation* level.

DOI: 10.1103/PhysRevLett.133.251003

IDE introduces **energy-momentum transfer from DM to DE**

$$\nabla_\mu (T_{\rm DM})^\mu{}_\nu = + \frac{Q (v_{\rm DM})_\nu}{a} \qquad \nabla_\mu (T_{\rm DE})^\mu{}_\nu = - \frac{Q (v_{\rm DM})_\nu}{a}$$

We focus on the interacting rate $Q = \xi \mathscr{H} \rho_{\rm DE}$



Early Dark Energy

Impact of ACT DR6 and DESI DR2 for Early Dark Energy and the Hubble tension

Vivian Poulin[1,*] Tristan L. Smith[2,†] Rodrigo Calderón[3,‡] and Théo Simon[1,§]

[1] *Laboratoire univers et particules de Montpellier (LUPM), Centre national de la recherche scientifique (CNRS) et Université de Montpellier, Place Eugène Bataillon, 34095 Montpellier Cédex 05, France*

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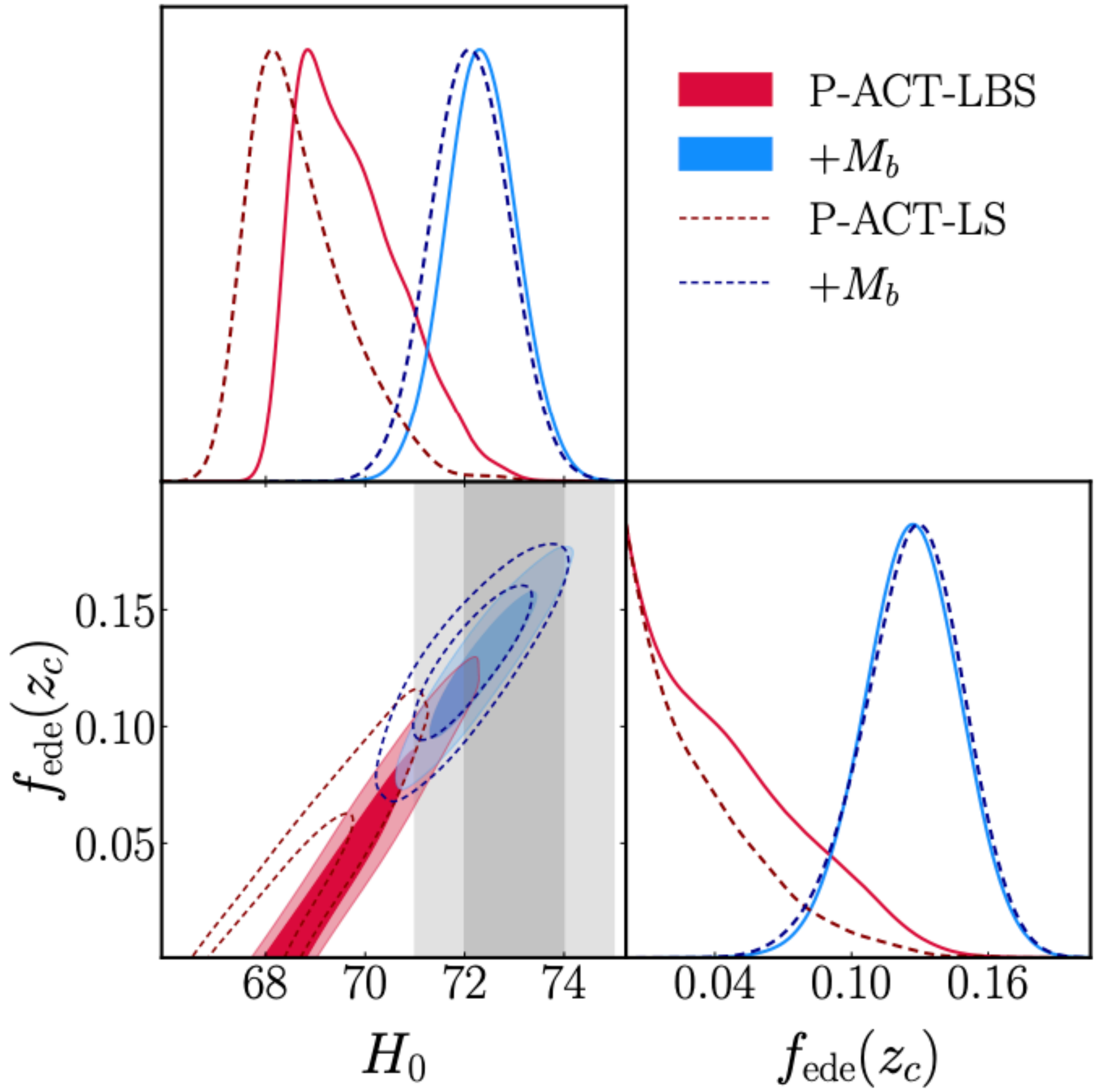
[3] *CEICO, Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21, Prague, Czech Republic*

The data release six of the Atacama Cosmology Telescope (ACT DR6) and the second data release from the Dark Energy Spectroscopic Instrument (DESI DR2) recently became available. In light of these data, we update constraints on the Early Dark Energy (EDE) resolution to the Hubble tension. While ACT DR6 does not favor EDE over the core cosmological model ΛCDM, it allows for a significantly larger maximum contribution of EDE, $f_{\rm EDE}$, in the pre-recombination era than the latest analysis of *Planck* NPIPE despite increased precision at small angular scales. Moreover, EDE rises the value of $H_0 r_s$, improving consistency between CMB and DESI DR2 data. We find a residual tension with SH0ES of $\sim 2\sigma$ for the combination of *Planck* at $\ell < 1000$ + ACT DR6 + lensing + Pantheon-plus + DESI DR2, a significant decrease from 3.7σ for analyses that use NPIPE and SDSS BAO data. A profile likelihood analysis reveals significant prior-volume effects in Bayesian analyses which do not include SH0ES, with confidence intervals of $f_{\rm EDE} = 0.09 \pm 0.03$ and $H_0 = 71.0 \pm 1.1$ km/s/Mpc. When including DESI data, the EDE model with $H_0 = 73$ km/s/Mpc provides a better fit than the ΛCDM model with $H_0 = 68.4$ km/s/Mpc. The inclusion of SH0ES data rises the preference well above 5σ, with $\Delta\chi^2 = -35.4$. Our work demonstrates that after ACT DR6 and DESI DR2, EDE remains a potential resolution to the Hubble tension.

EDE introduces a **DE phase in the Early Universe**, quantified by

$$f_{\rm EDE} = \max_z \left(\frac{\rho_{\rm EDE}(z)}{\rho_c(z)} \right)$$

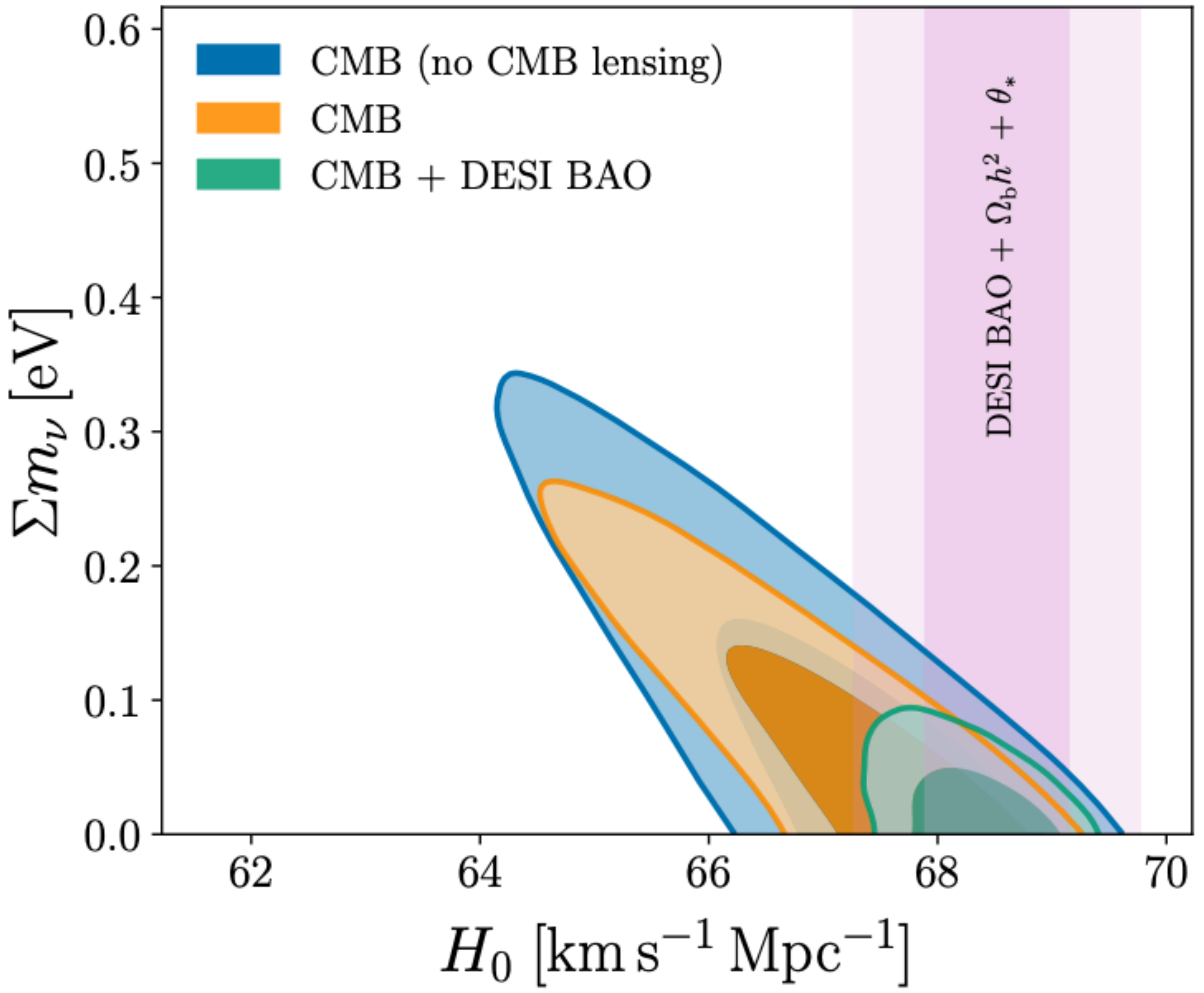
i.e., the maximal fractional contribution to the total energy density



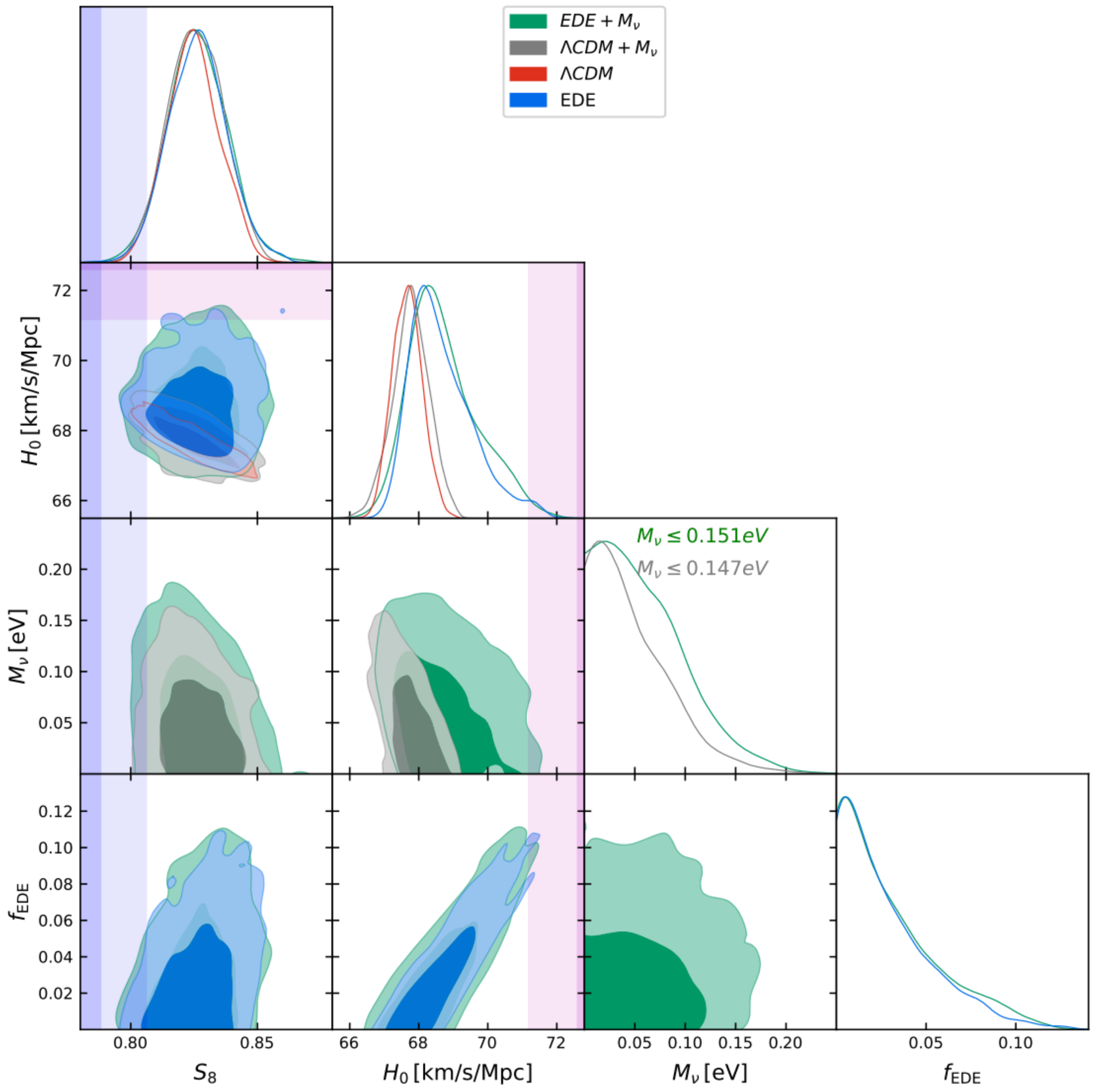
Hubble Tension and Neutrinos

Fail to reconcile the Neutrino Tension

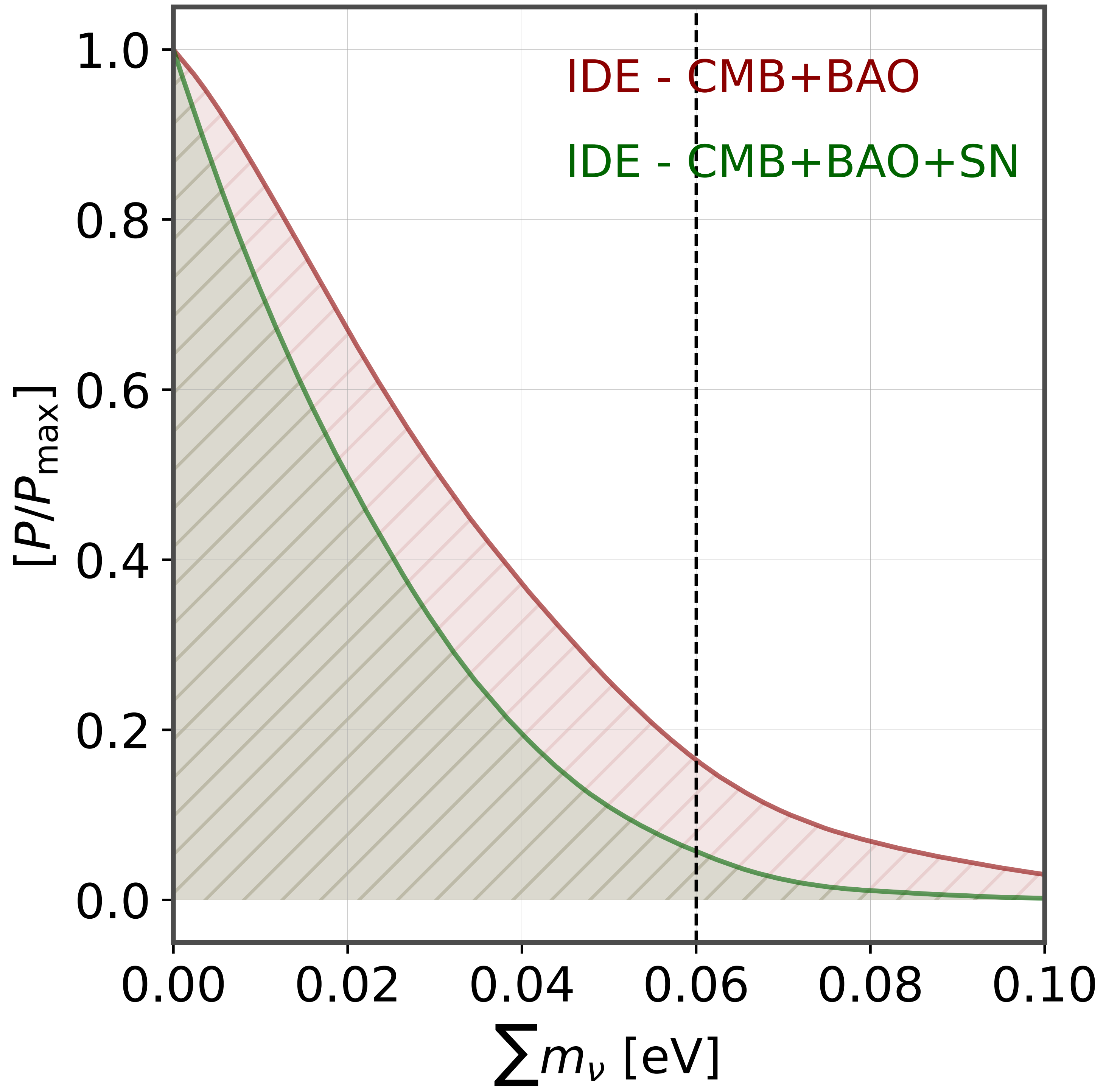
Strong anti-correlation between H_0 and $\sum m_\nu$ → **Models that can increase H_0 typically drag $\sum m_\nu$ towards smaller values**



DESI 2025 — [arXiv:2503.14738]

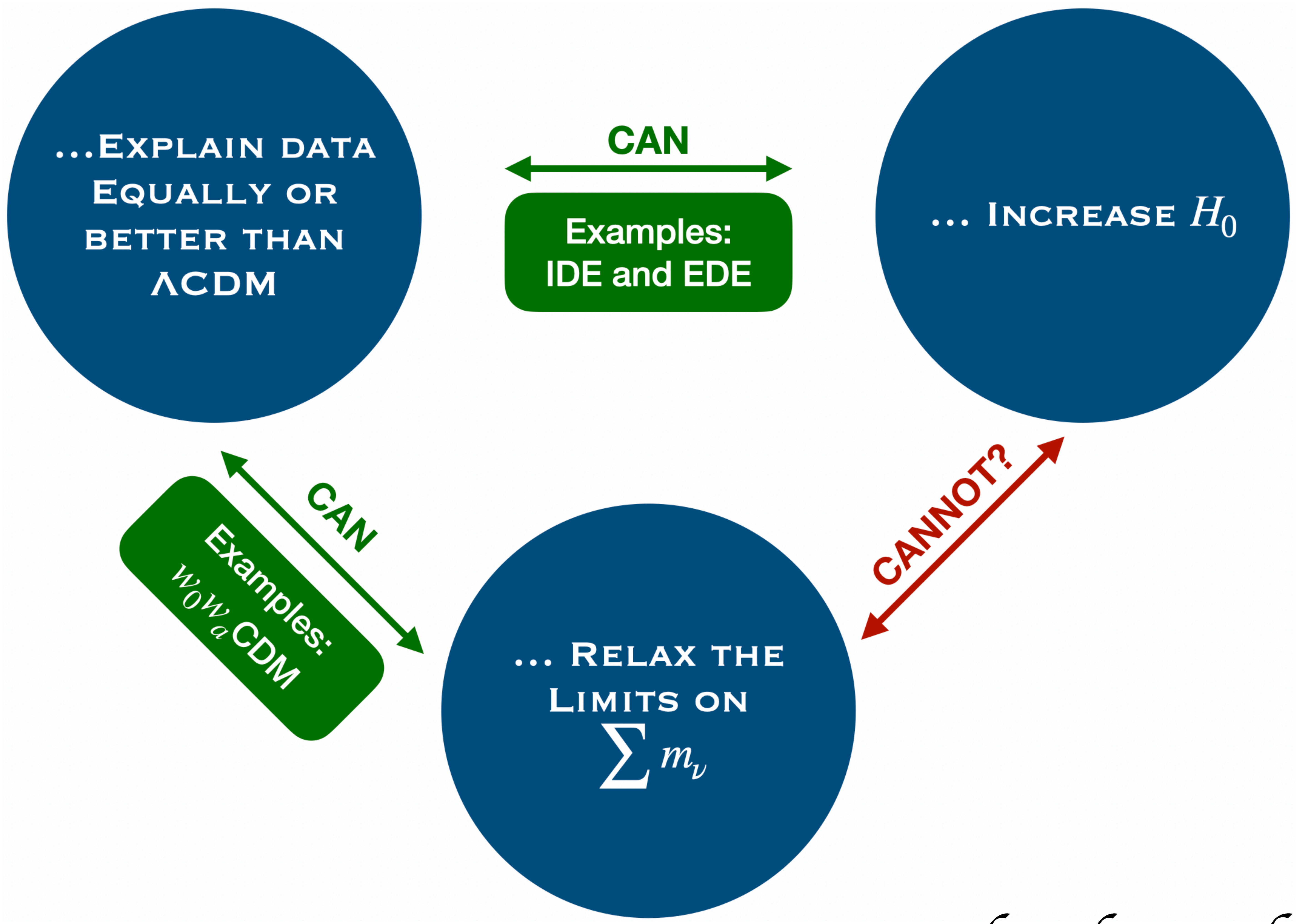


Reeves, *et al.* — [arXiv:2207.01501]



WG [arXiv: 250x.xxxx]

So, We Found Models That Can...



Thank You for your attention!

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- **William Giarè** (The University of Sheffield)
- **Matteo Martinelli** (Osservatorio Astronomico di Roma)
- **Vivian Poulin** (Universite de Montpellier)
- **Elsa Teixeira** (Université de Montpellier)
- **Luca Visinelli** (Università degli Studi di Salerno)

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More info here:

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