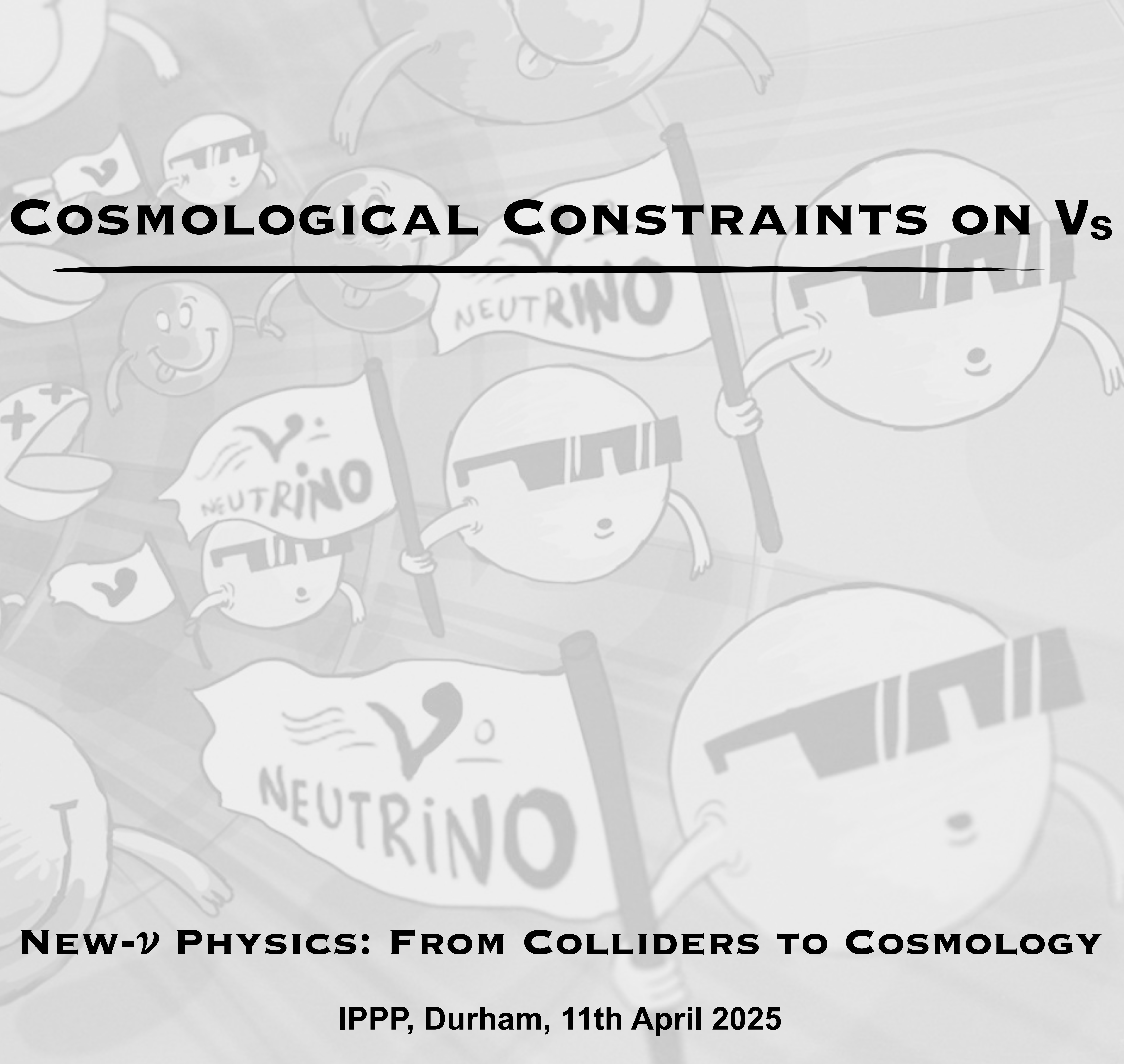

Cosmological Constraints on νs

William Giarè

w.giare@sheffield.ac.uk williamgiare.com

Research Associate in Theoretical Cosmology

School of Mathematical and Physical Sciences
The University of Sheffield

New-ν Physics: From Colliders to Cosmology

IPPP, Durham, 11th April 2025

Slides available at

https://github.com/williamgiare/wgcosmo/talks

The Story of Neutrinos is a Story of Success!

- **1930 — *Wolfgang Pauli Postulates the existence of Neutrinos***
- **1956 — *Discovery of Electron Neutrino*** by C. Cowan and F. Reines
- **1958 — *Neutrino oscillation hypotesis*** by Pontecorvo
- **1962 — *Discovery of the Muon Neutrino*** by Lederman, Schwartz & Steinberger
- **1998 — *Discovery of Atmospheric Neutrino Oscillations*** by Super Kamiokande
- **2000 — *Discovery of the Tau neutrino*** by DONUT at Fermilab
- **2001 — *Discovery of solar neutrino oscillations*** by Sudbury Neutrino Observatory

...

"I have done a terrible thing, I have postulated a particle that cannot be detected"

— Wolfgang Pauli —

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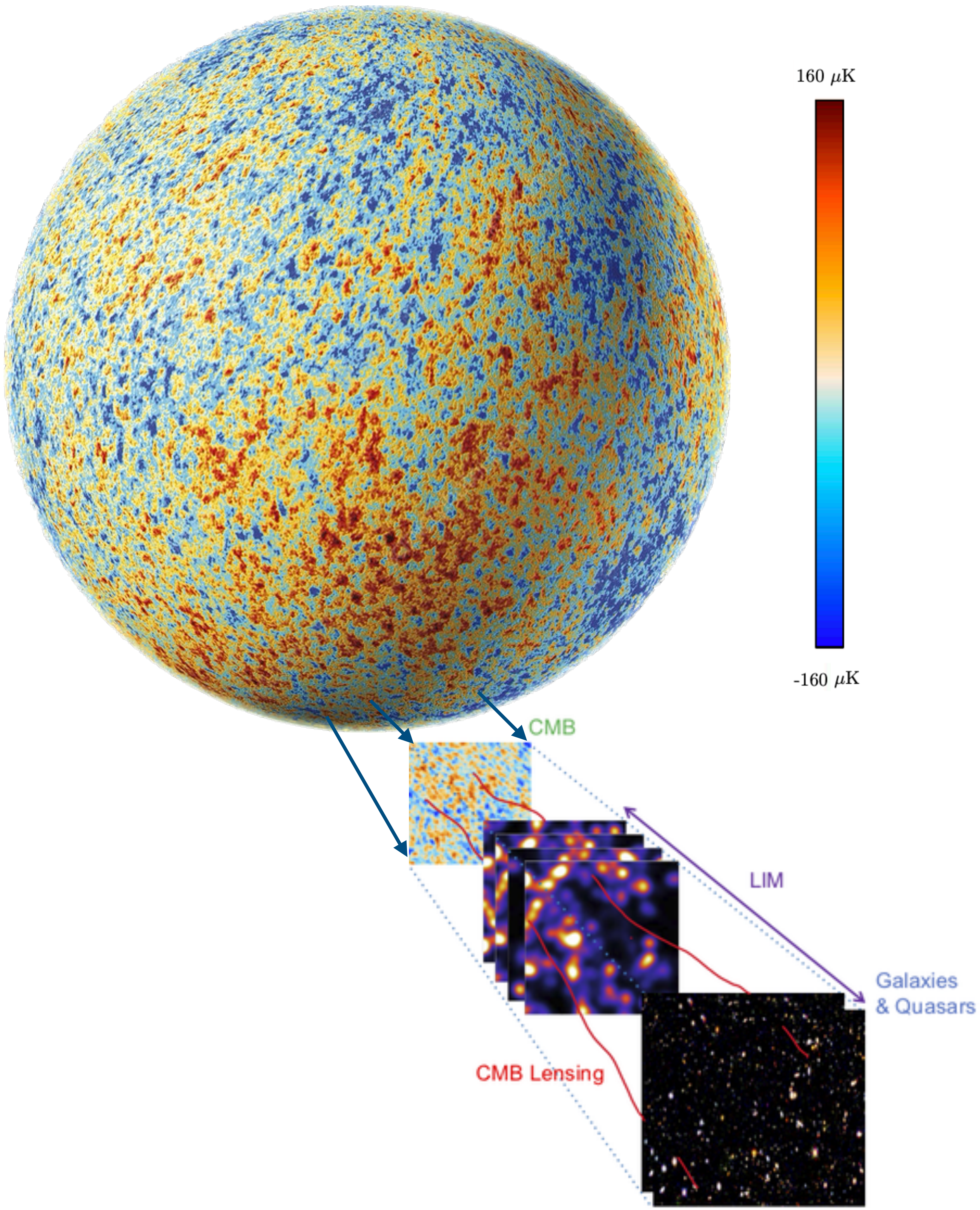
…

- **Now — *Neutrino Astrophysics and Cosmology*** by Planck, ACT, SDSS, DESI, and many other cosmological and astrophysical surveys



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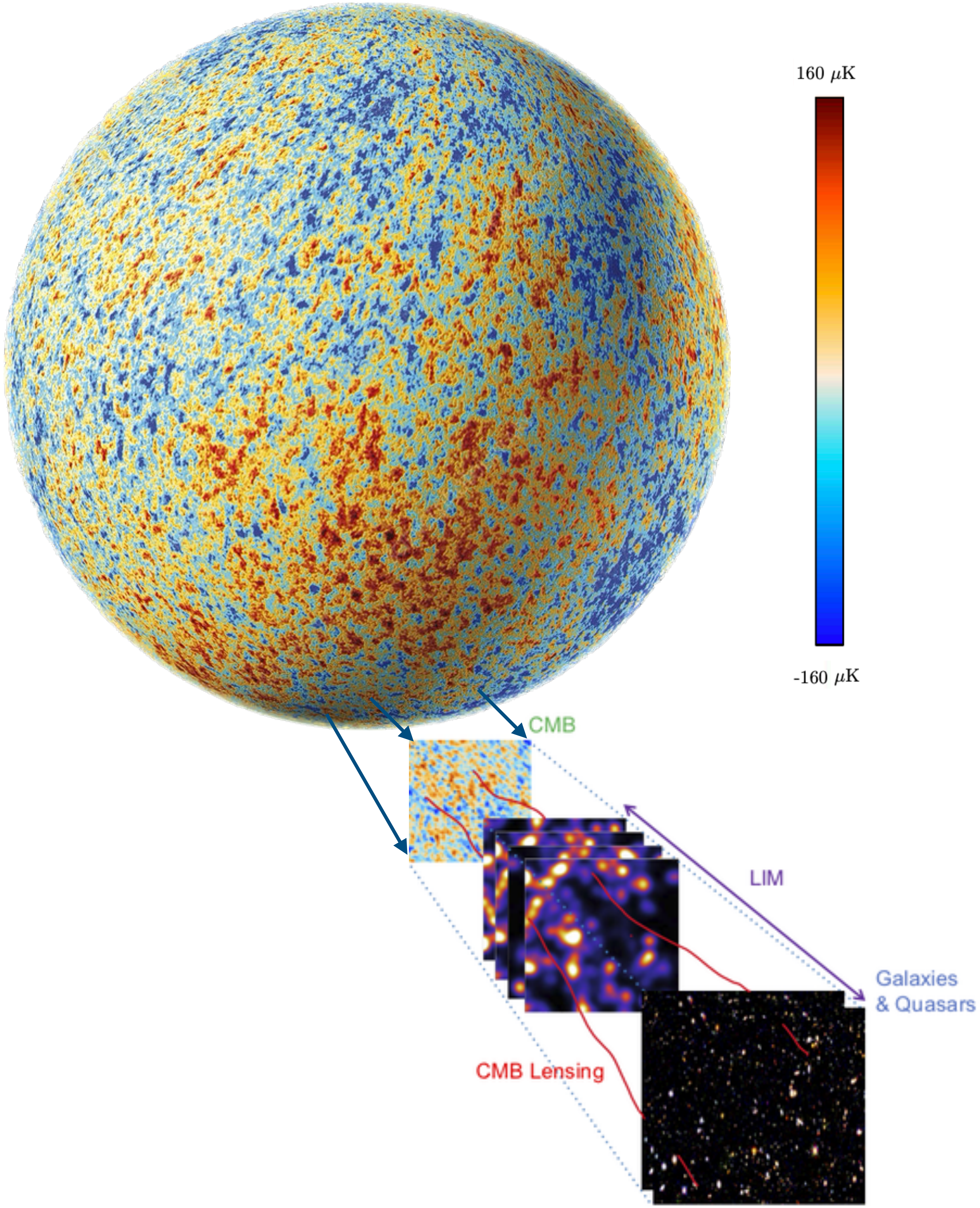


How Many νs ?

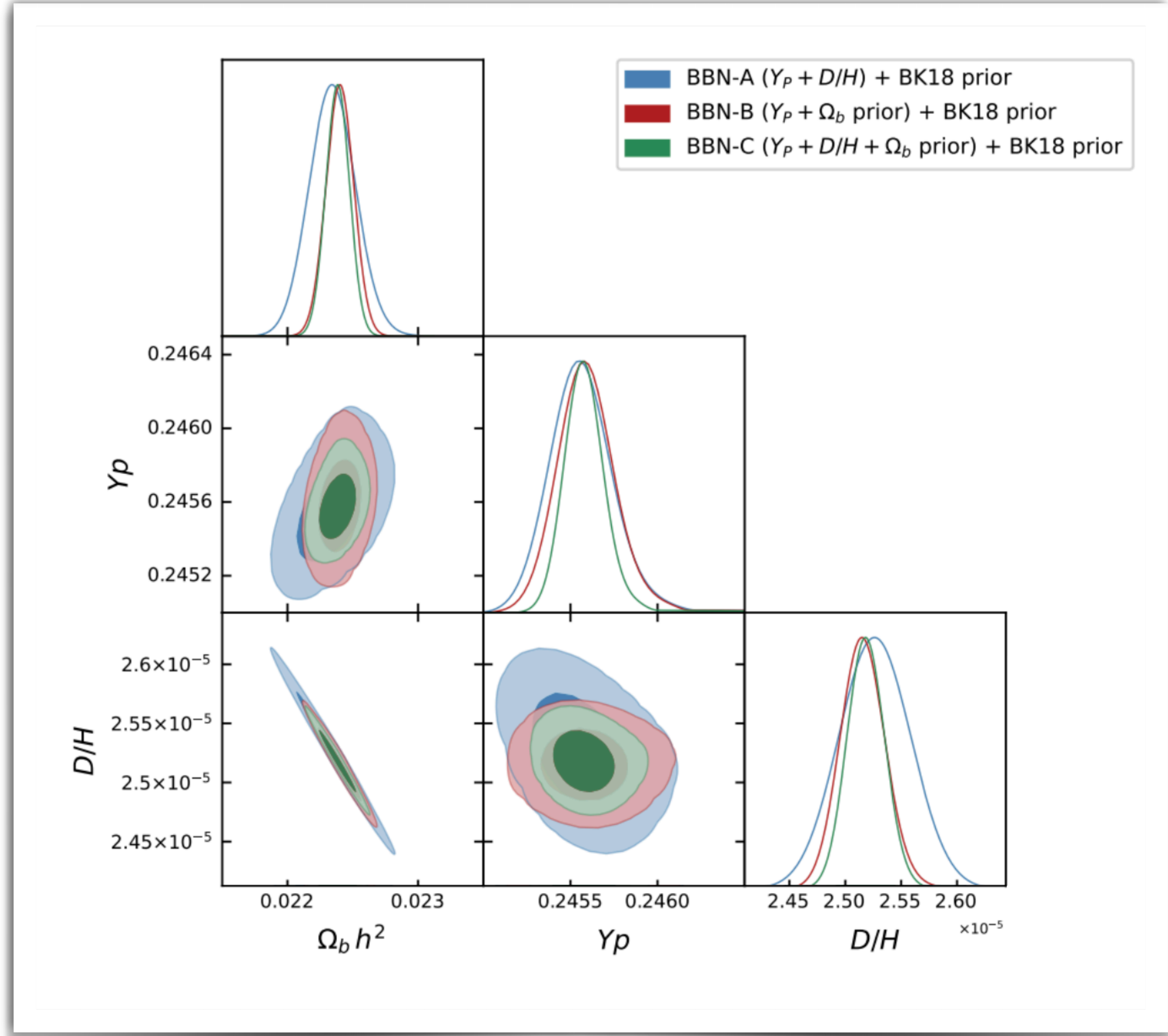
WG, M. Forconi *et al.* — MNRAS 520 (2023) 2 • arXiv: 2210.14159

Number of Neutrino Species

The amount of the radiation energy density is commonly parameterized in terms of the effective number of relativistic degrees of freedom

$$\Omega_r \simeq \Omega_\gamma \left(1 + 0.23\, N_{\rm eff}\right)$$

In the Standard model of cosmology and Particle physics $N_{\rm eff} = 3.04$. A larger $N_{\rm eff}$ will increase $H(z) \propto \left[\Omega_r \cdot (1+z)^4\right]^{1/2}$



- **BBN:** A higher $N_{\rm eff}$ during BBN implies a **larger freeze-out temperature of the weak interactions** and so:

  1) A **higher neutron-to-proton ratio**

  2) A **larger fraction of primordial Helium and Deuterium**

  3) A **higher fraction of other primordial elements** with respect to hydrogen.

$$\boxed{\Delta N_{\rm eff} \lesssim 0.3}$$

Parameter	BBN-A	BBN-B	BBN-C
	$(Y_p + D/H)$	$(Y_p + \Omega_b h^2)$	$(Y_p + D/H + \Omega_b h^2)$
$\Omega_b h^2$	0.02234 ± 0.00017	0.02240 ± 0.00010	0.022382 ± 0.000086
Y_p	0.24558 ± 0.00010	0.24561 ± 0.00010	$0.245591^{+0.000015}_{-0.000060}$
$(D/H)\cdot 10^{-5}$	2.527 ± 0.030	2.516 ± 0.020	2.519 ± 0.016
$\Delta N_{\rm eff}$	$< 0.33\ (< 0.40)$	$< 0.32\ (< 0.40)$	$< 0.16\ (< 0.21)$

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- **CMB:** a higher $N_{\rm eff}$ at recombination implies:

  1) **Changing the matter-radiation equivalence and enhancing the early ISW.** This contributes to the primary anisotropy, **increasing the first acoustic peaks.**

  2) **Reducing the sound horizon** and the angular scale of the acoustic peaks. This gives a **horizontal shift of the peak positions towards higher multipoles.**

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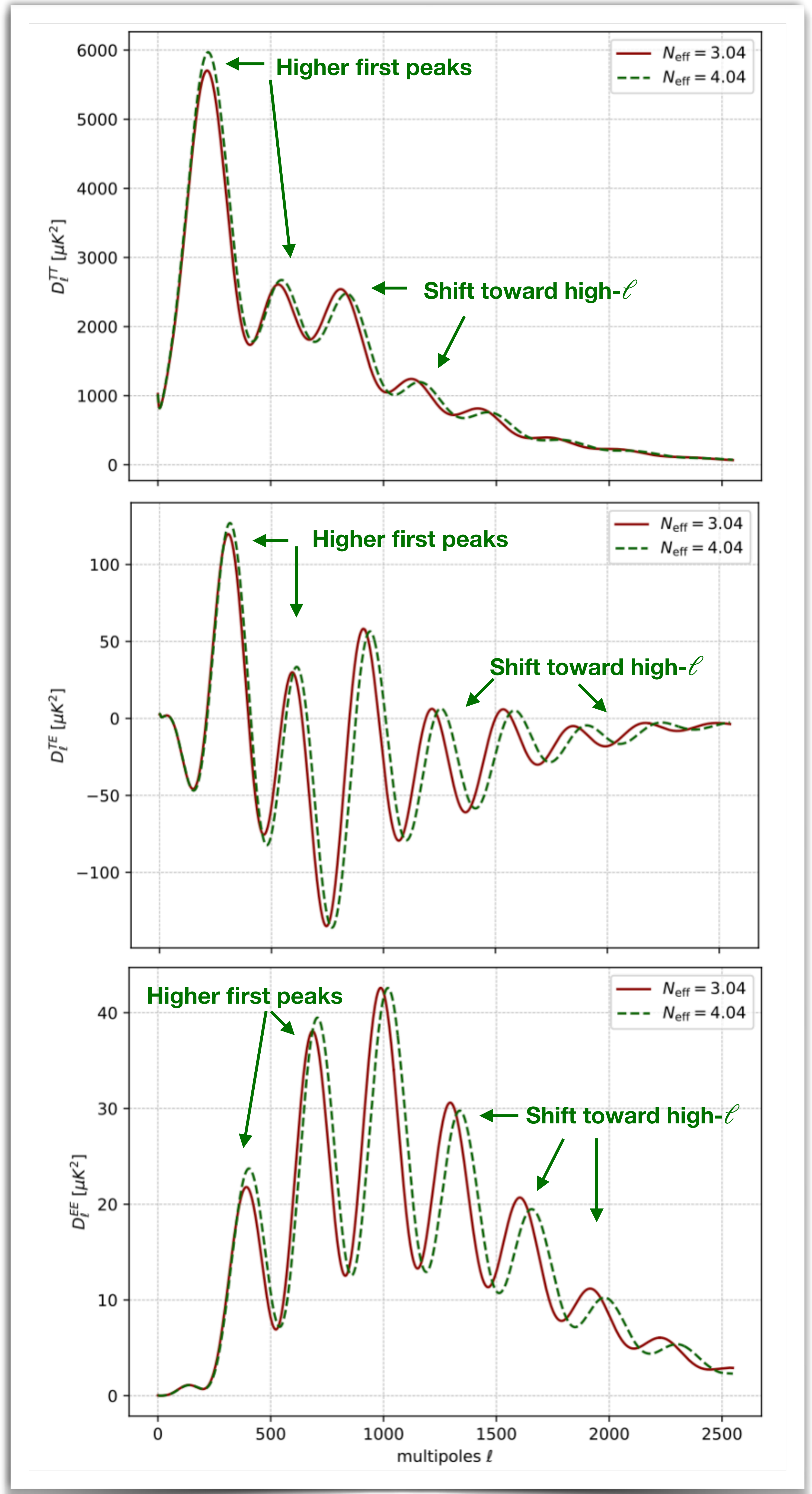

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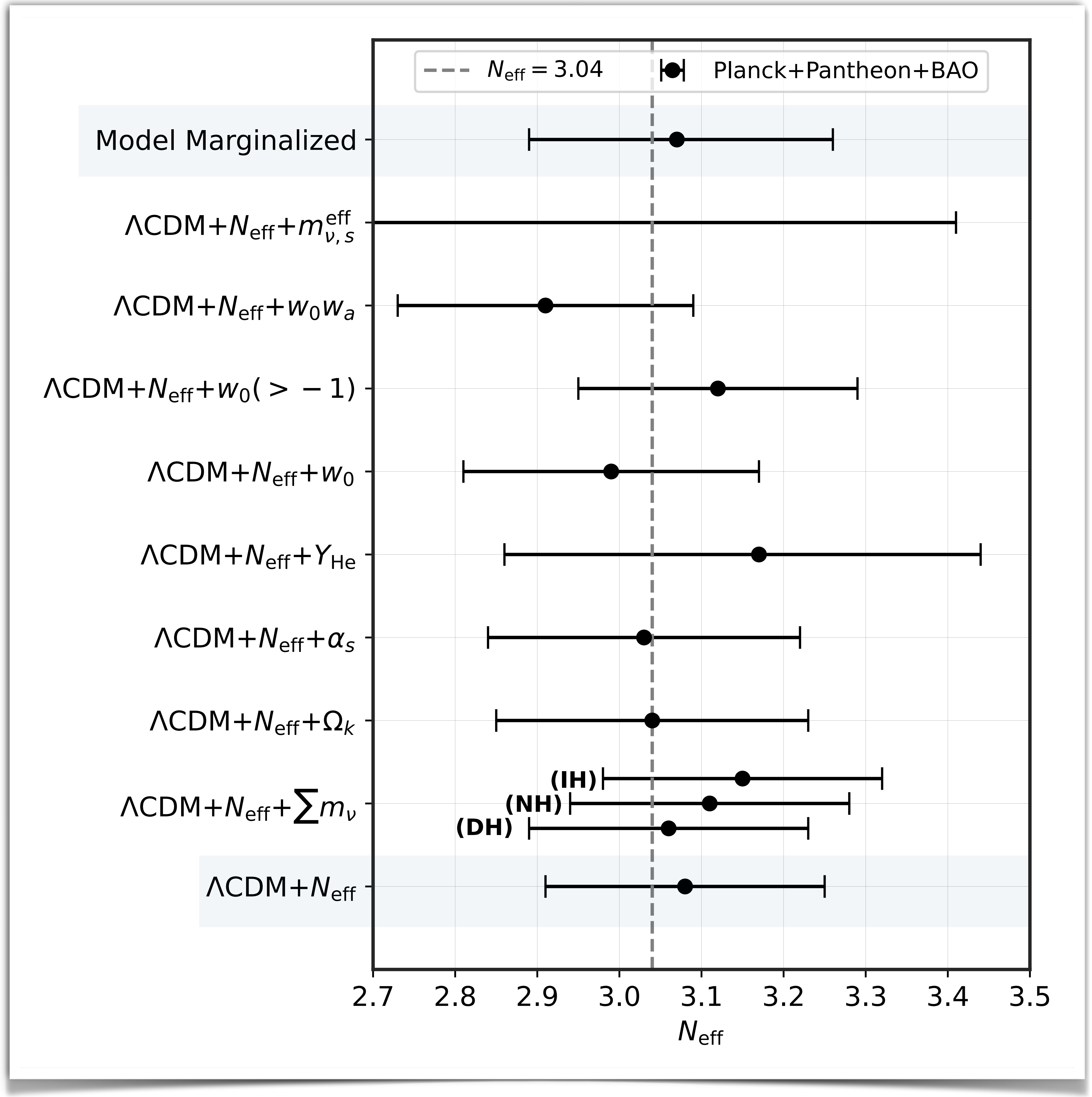
Gariazzo, **WG,** *et al* • arXiv: 2404.11182



How Massive νs ?

Total Neutrino Mass and Ordering

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

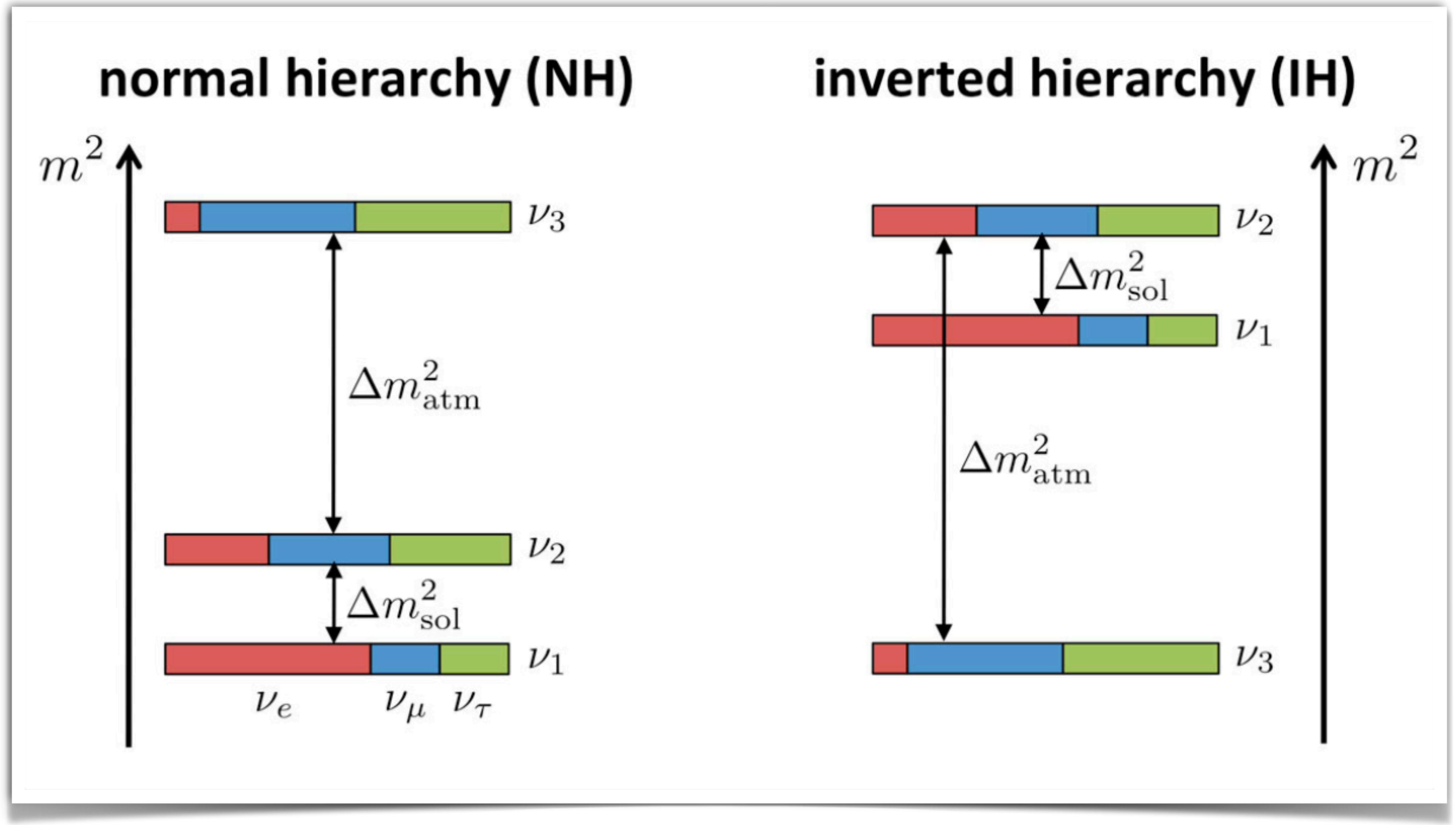
- **Atmospheric splitting**: $|\Delta m^2_{3,1}| = |m_3^2 - m_1^2| \sim 2.55 \times 10^{-3}$ eV^2
- **Solar splitting**: $\Delta m^2_{2,1} = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5}$ eV^2

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!*



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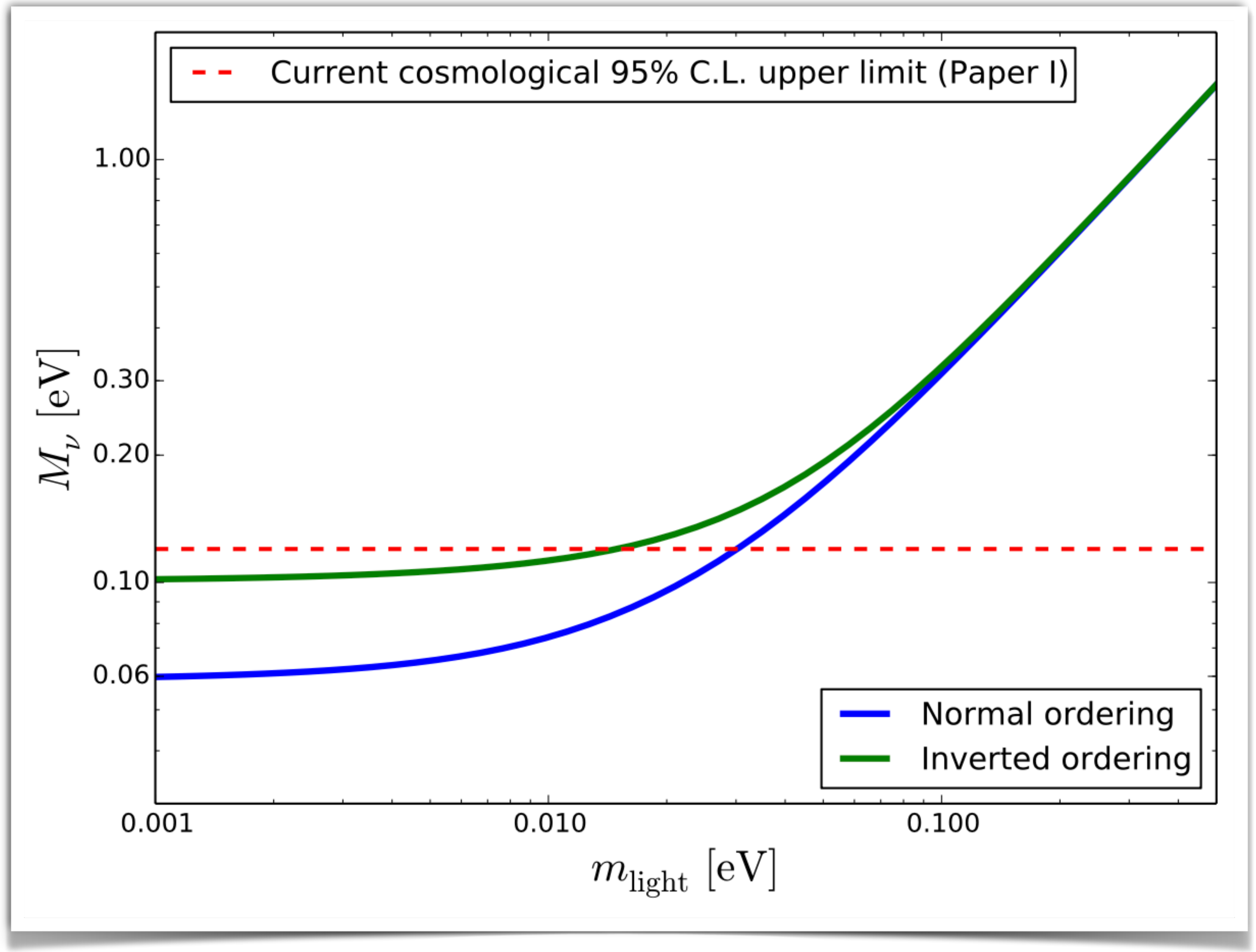
If we set the mass of the lightest neutrino and set it to $m_{\rm light} = 0$, within the two orderings, we get a lowerlimit on the total mass from neutrino oscillations

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!*



How Massive νs ?

Early Universe Constraints

The total neutrino mass $\sum m_\nu$ impacts the CMB in various ways:

1) it **boosts the late-time non-relativistic density**, affecting the scale-angle relations on the last scattering surface and the **late ISW effects**.

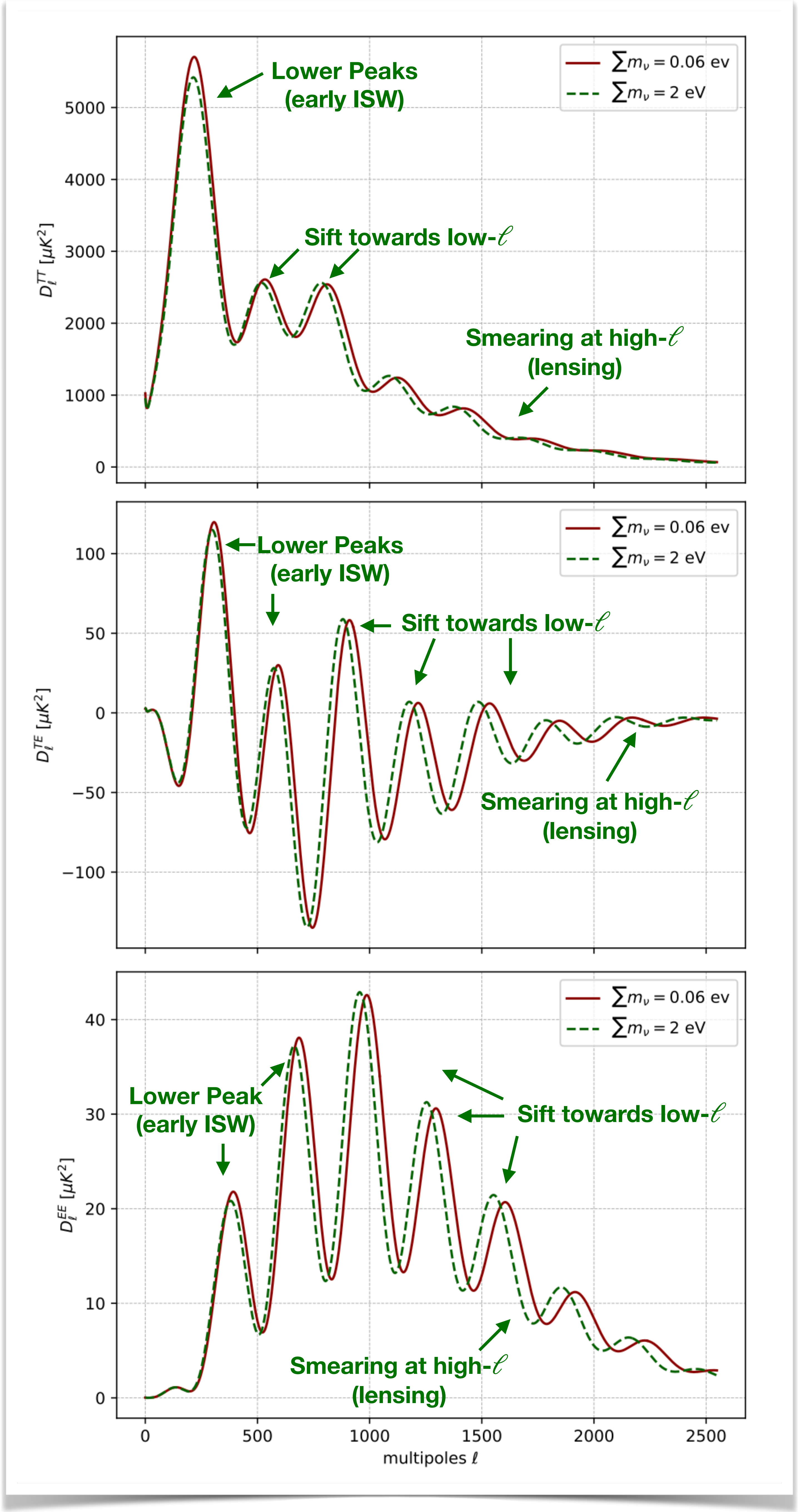
2) affects the non-relativistic transition of neutrinos by changing the pressure-to-density ratio and causing metric fluctuations observable in the **early ISW effect**.

3) it **reduces weak lensing effects** on the CMB by **suppressing the matter power spectrum and CMB spectra at small scales**.

$\sum m_\nu < 0.24\,\mathrm{eV}$ Planck - (TT TE EE) + lensing

Planck 2018 results. VI

[arXiv:1807.06209]



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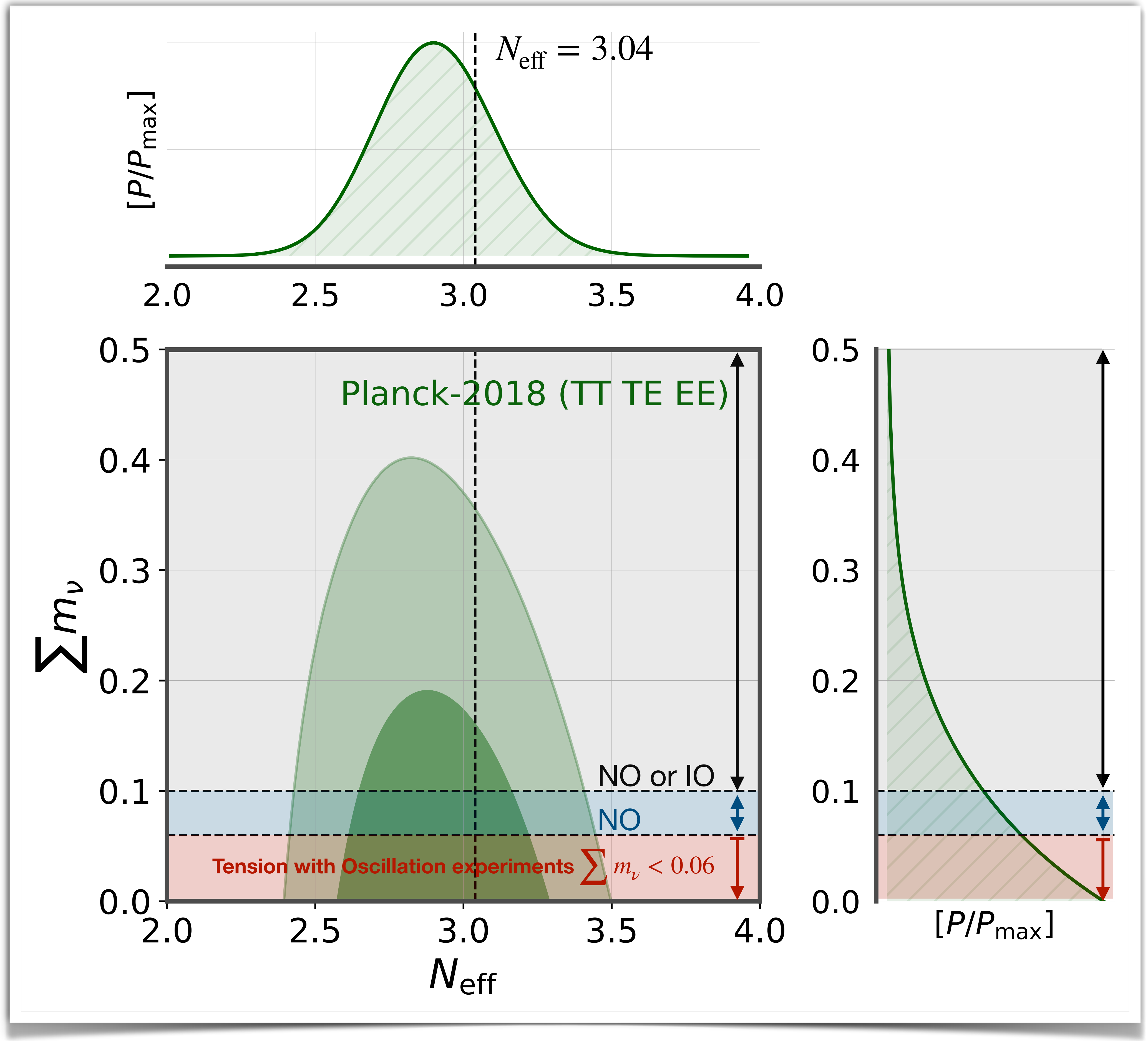
We can do better!

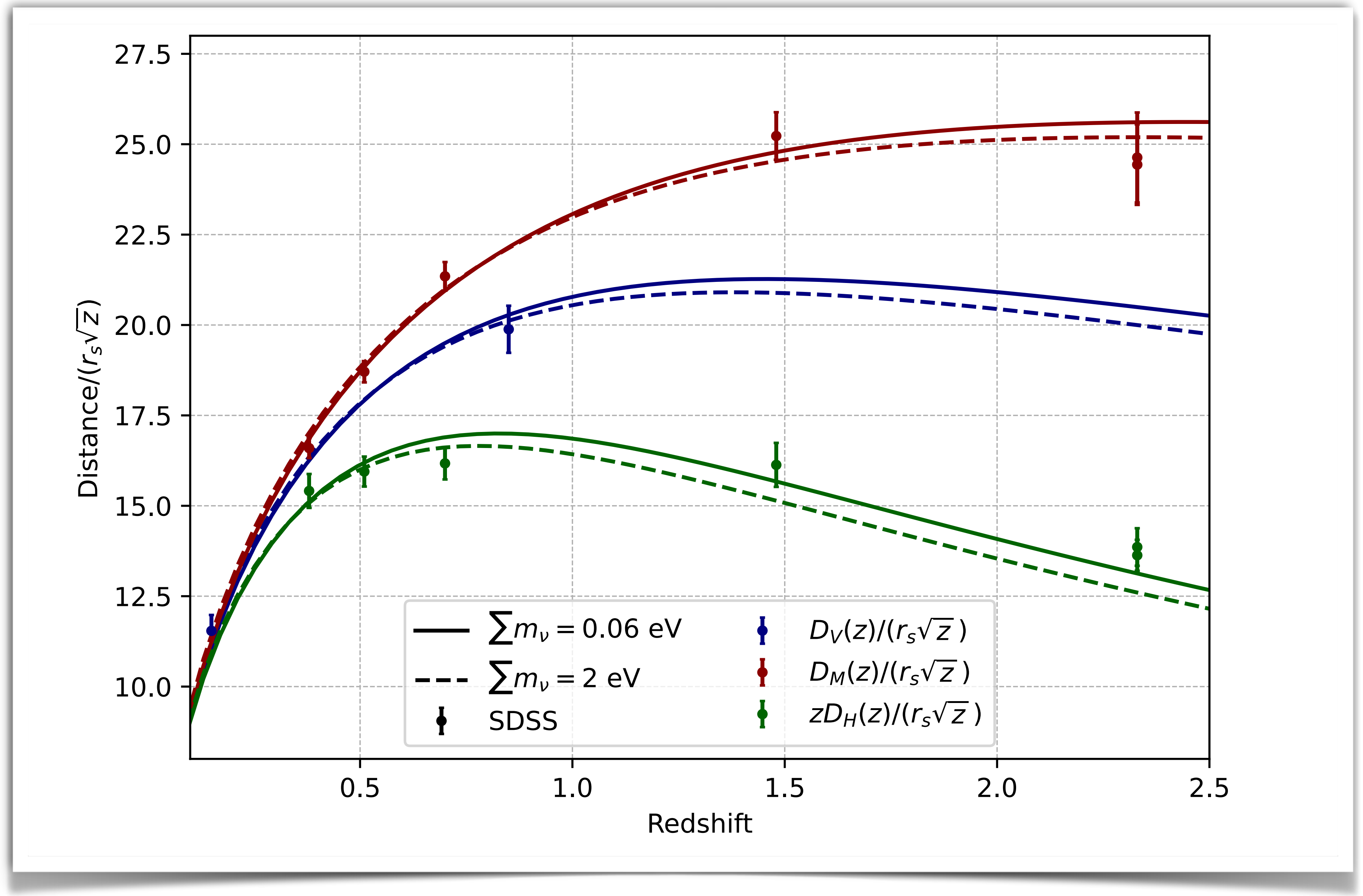


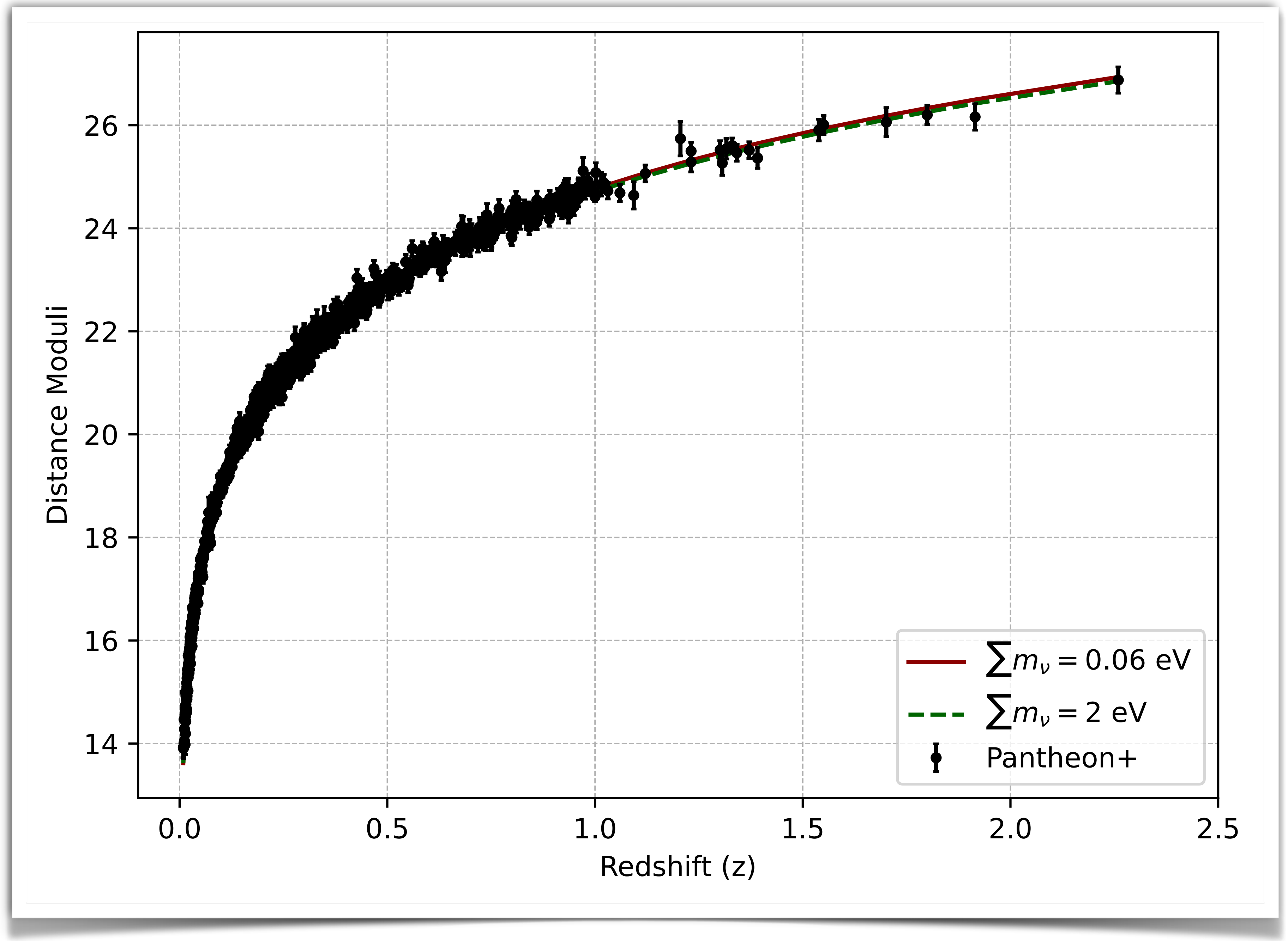
How Massive Vs ?

Late Universe Constraints

How can we improve the CMB limit on Neutrinos?

1) Neutrinos will become non-relativistic particles, contributing to the matter energy density at late times. Depending on their mass, they will alter **cosmic distances**, measured by BAO and, in part, Supernovae.





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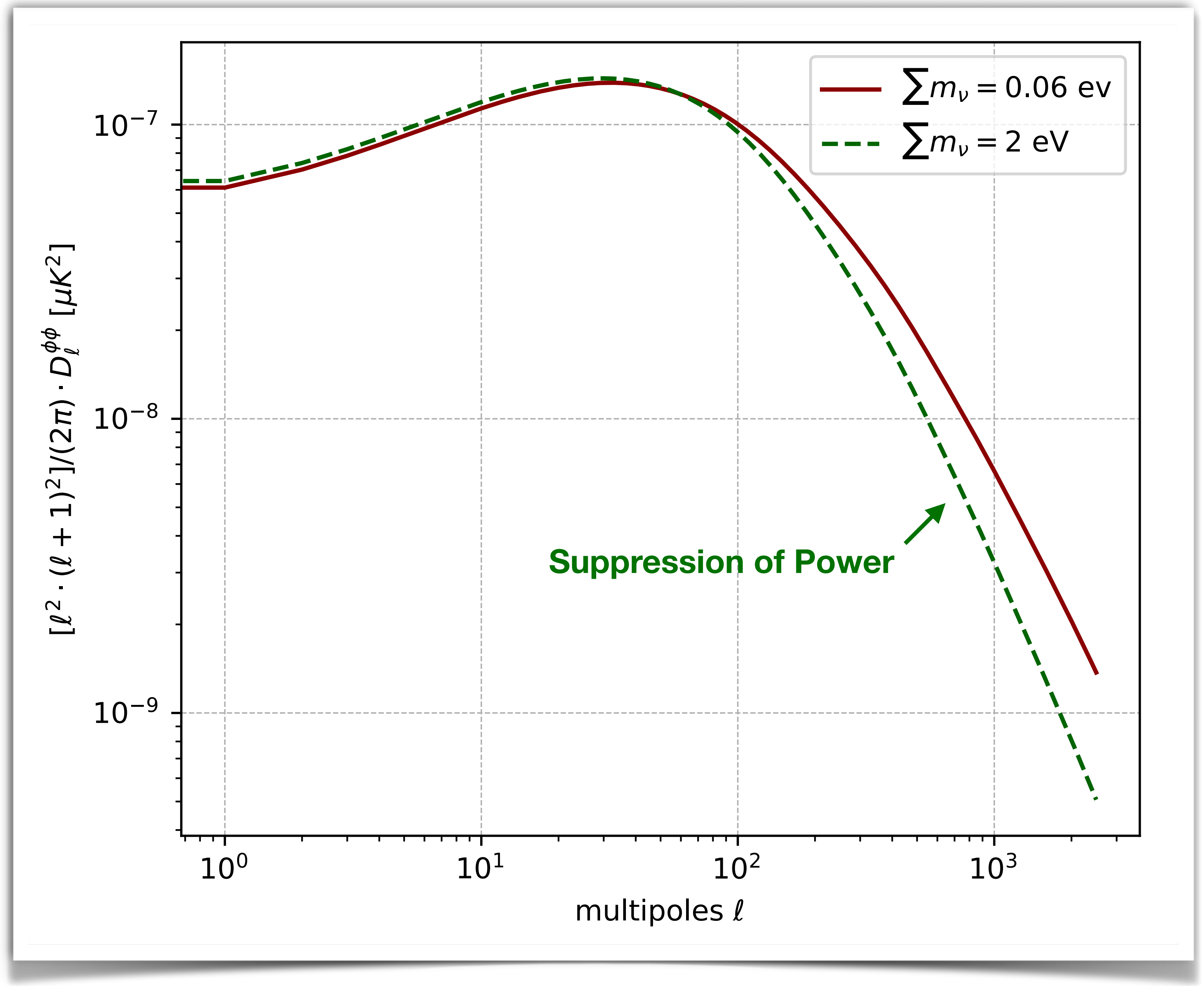

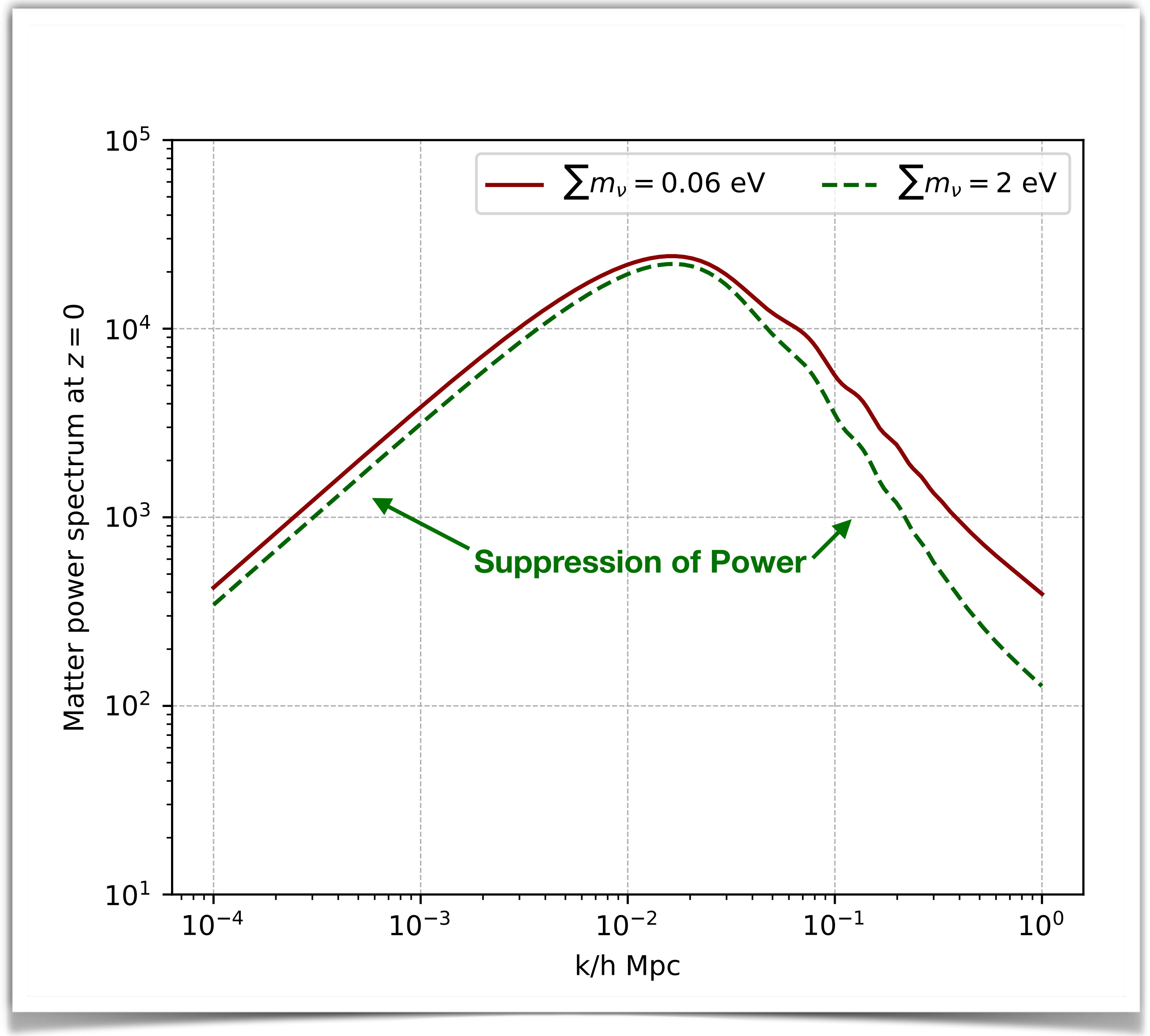

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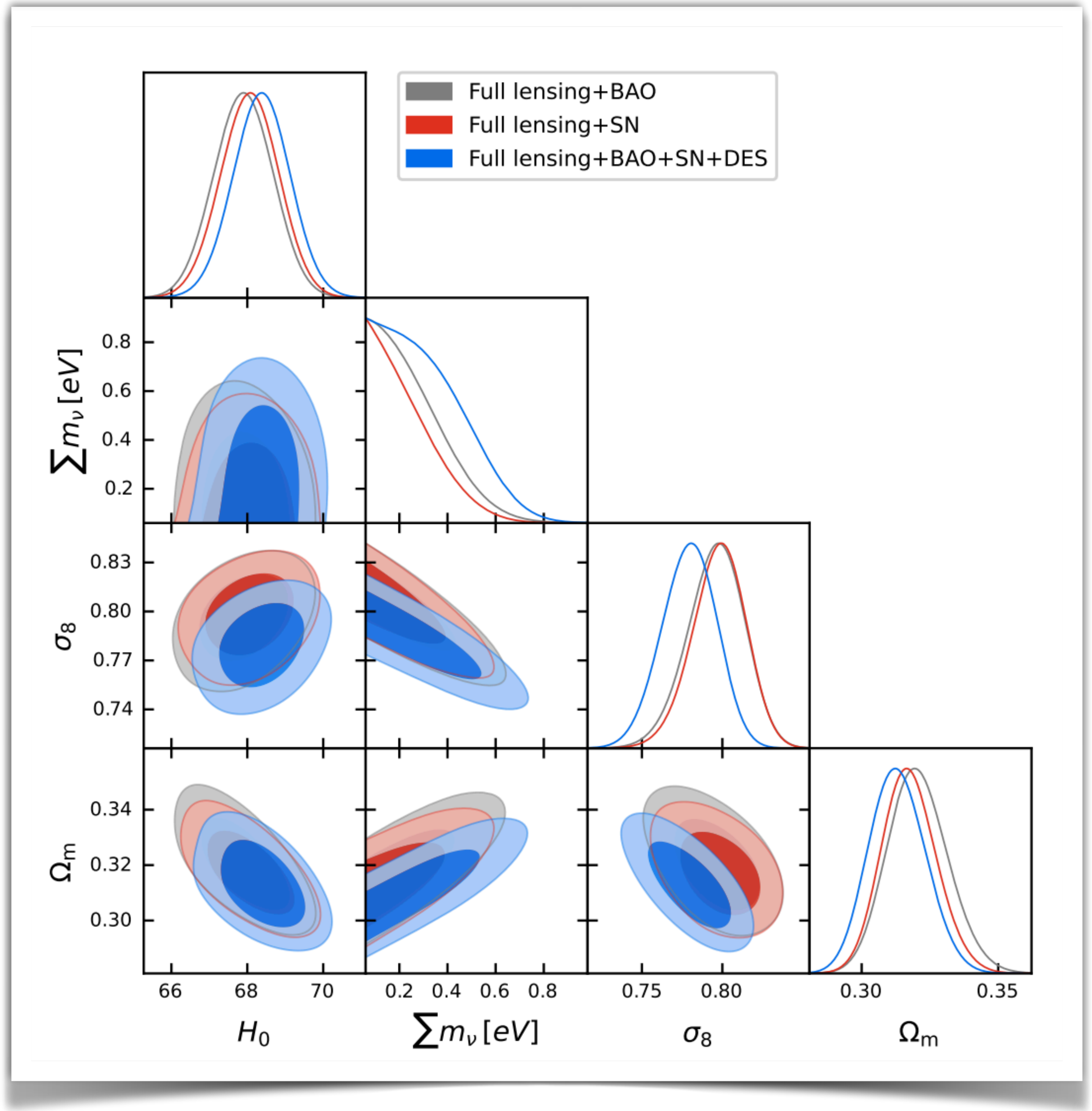
Local probes are approaching a level of precision comparable to CMB.

Dataset	$\sum m_\nu$ $[eV]$
ACT-DR6	< 3.32
ACT-DR6 + BAO	< 1.10
ACT-DR6 + BAO + DES	< 0.773
ACT-DR6 + BAO + SN	< 0.717
ACT-DR6 + BAO + DES + SN	< 0.722
ACT+Planck lensing	< 1.42
ACT+Planck lensing + BAO	< 0.527
ACT+Planck lensing + BAO + DES	< 0.664
ACT+Planck lensing + BAO + SN	< 0.490
ACT+Planck lensing + BAO + DES + SN	< 0.606

WG, *et. al* — PRD 108 (2023) 10, 103539 • arXiv: 2307.14204



How Massive Vs ?

Mass and Ordering After DESI BAO

Dark Energy Spectroscopic Instrument (DESI) survey Year 1 results

DESI 2024 VI: cosmological constraints from the measurements of baryon acoustic oscillations

DARK ENERGY SPECTROSCOPIC INSTRUMENT

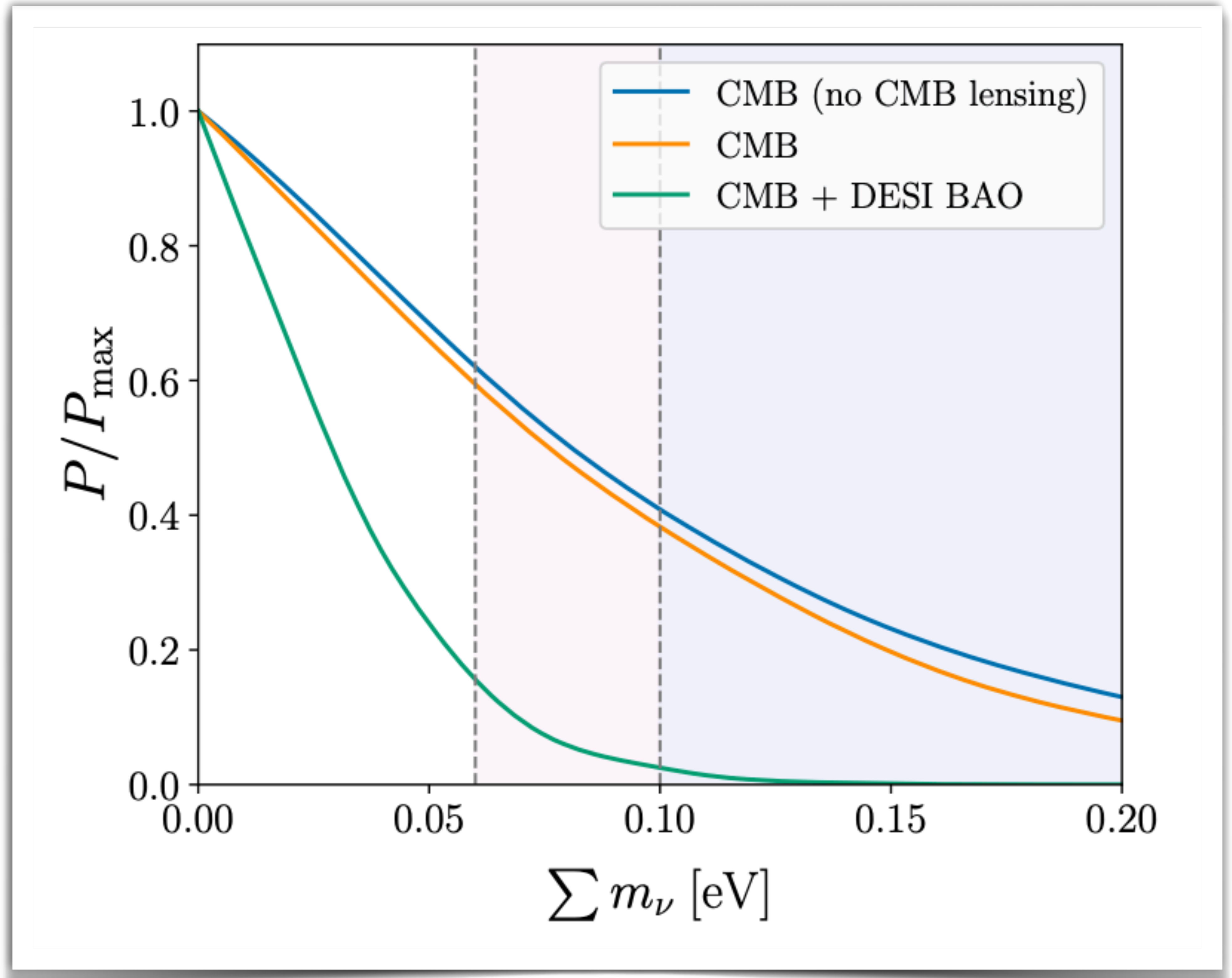
U.S. Department of Energy Office of Science

The DESI collaboration

E-mail: spokespersons@desi.lbl.gov

Abstract: We present cosmological results from the measurement of baryon acoustic oscillations (BAO) in galaxy, quasar and Lyman-α forest tracers from the first year of observations from the Dark Energy Spectroscopic Instrument (DESI), to be released in the DESI Data Release 1. DESI BAO provide robust measurements of the transverse comoving distance and Hubble rate, or their combination, relative to the sound horizon, in seven redshift bins from over 6 million extragalactic objects in the redshift range $0.1 < z < 4.2$. To mitigate confirmation bias, a blind analysis was implemented to measure the BAO scales. DESI BAO data alone are consistent with the standard flat ΛCDM cosmological model with a matter density $\Omega_m = 0.295 \pm 0.015$. Paired with a baryon density prior from Big Bang Nucleosynthesis and the robustly measured acoustic angular scale from the cosmic microwave background (CMB), DESI requires $H_0 = (68.52 \pm 0.62)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. In conjunction with CMB anisotropies from *Planck* and CMB lensing data from *Planck* and ACT, we find $\Omega_m = 0.307 \pm 0.005$ and $H_0 = (67.97 \pm 0.38)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Extending the baseline model with a constant dark energy equation of state parameter w, DESI BAO alone require $w = -0.99^{+0.15}_{-0.13}$. In models with a time-varying dark energy equation of state parametrised by w_0 and w_a, combinations of DESI with CMB or with type Ia supernovae (SN Ia) individually prefer $w_0 > -1$ and $w_a < 0$. This preference is 2.6σ for the DESI+CMB combination, and persists or grows when SN Ia are added in, giving results discrepant with the ΛCDM model at the 2.5σ, 3.5σ or 3.9σ levels for the addition of the Pantheon+, Union3, or DES-SN5YR supernova datasets respectively. For the flat ΛCDM model with the sum of neutrino mass $\sum m_\nu$ free, combining the DESI and CMB data yields an upper limit $\sum m_\nu < 0.072$ (0.113) eV at 95% confidence for a $\sum m_\nu > 0$ ($\sum m_\nu > 0.059$) eV prior. These neutrino-mass constraints are substantially relaxed if the background dynamics are allowed to deviate from flat ΛCDM.

DESI 2024 VI — [arXiv:2404.03002]



- **CMB+DESI-DR1:** $\sum m_\nu < 0.072$ **eV**
- **Oscillation Experiments NO:** $\sum m_\nu > 0.06$ **eV**
- **Oscillation Experiments IO:** $\sum m_\nu > 0.1$ **eV**

How Massive Vs ?

Mass and Ordering After DESI BAO

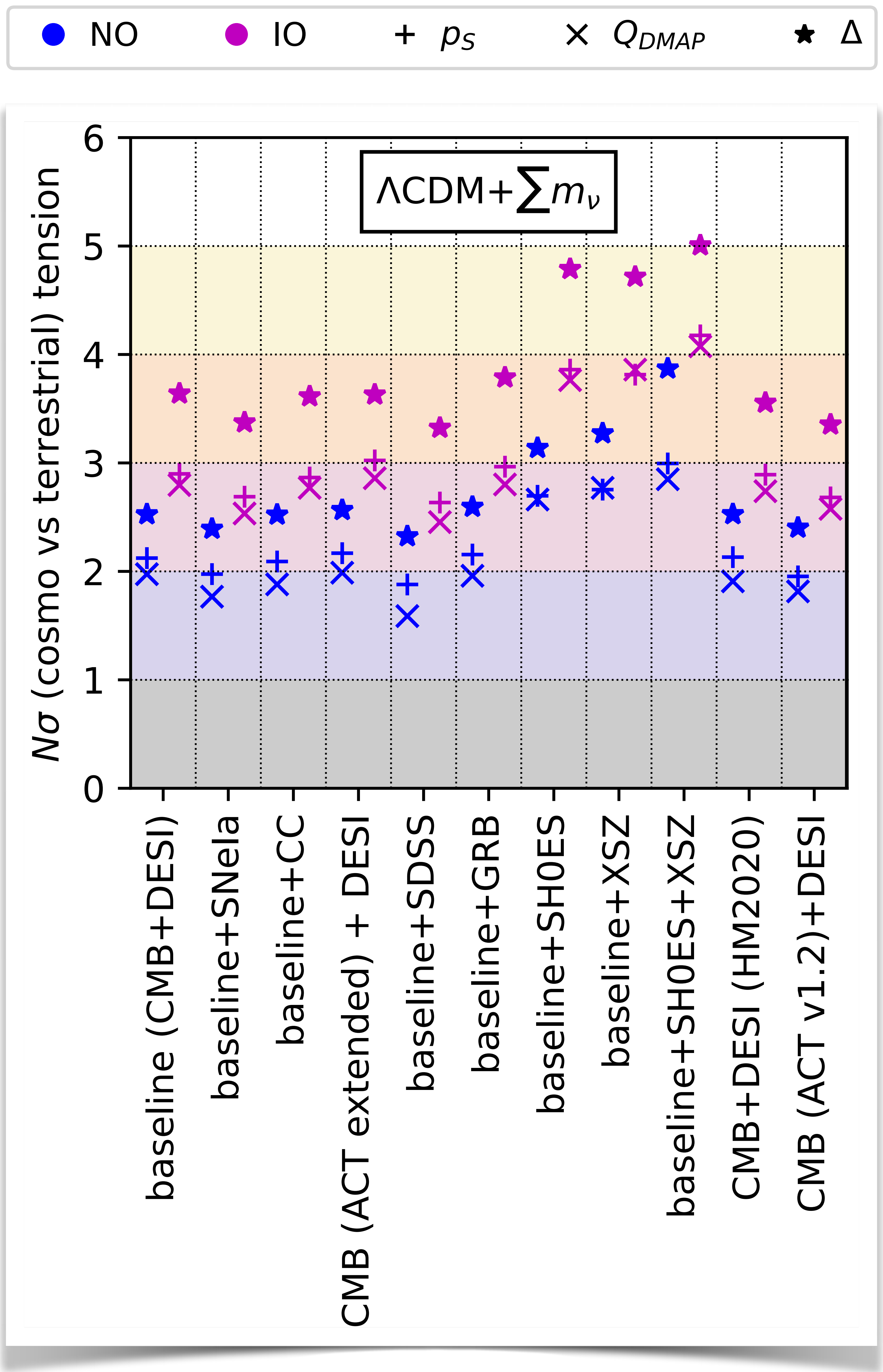
Dataset combination	ΛCDM+$\sum m_\nu$ $\sum m_\nu$ (eV)	$B_{\mathrm{NO,IO}}$
baseline (CMB + DESI)	< 0.072	8.1
baseline + SNeIa	< 0.081	7.0
baseline + CC	< 0.073	7.3
baseline + SDSS	< 0.083	6.8
baseline + SH0ES	< 0.048	47.8
baseline + XSZ	< 0.050	46.5
baseline + GRB	< 0.072	8.7
aggressive combination (baseline + SH0ES + XSZ)	< 0.042 eV	72.6
CMB (with ACT "extended" likelihood)+DESI	< 0.072	8.0
CMB+DESI (with 2020 HMCode)	< 0.074	7.5
CMB (with v1.2 ACT likelihood)+DESI	< 0.082	7.4

– We pushed the mass limit as far as possible, considering **different datasets**.

– We quantified the Bayesian ratio between NO and IO: **strong preference for NO**.

– We quantified the **tension between cosmological and terrestrial experiments**

Jun-Qian Jiang, **WG,** *et. al.*, [arXiv: 2407.18047]



How Massive Vs ?

Mass and Ordering After DESI BAO

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

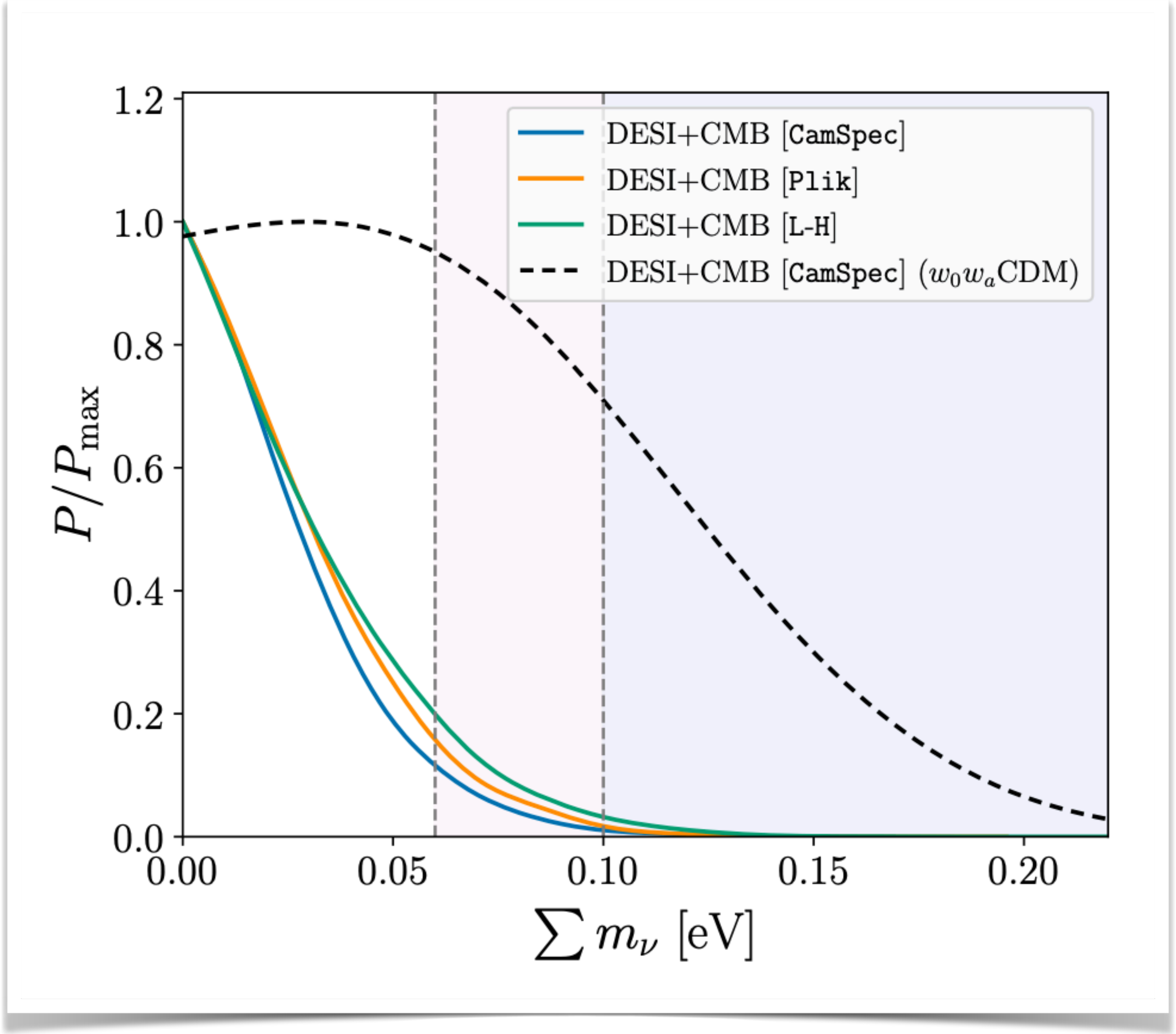
DARK ENERGY SPECTROSCOPIC INSTRUMENT

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**

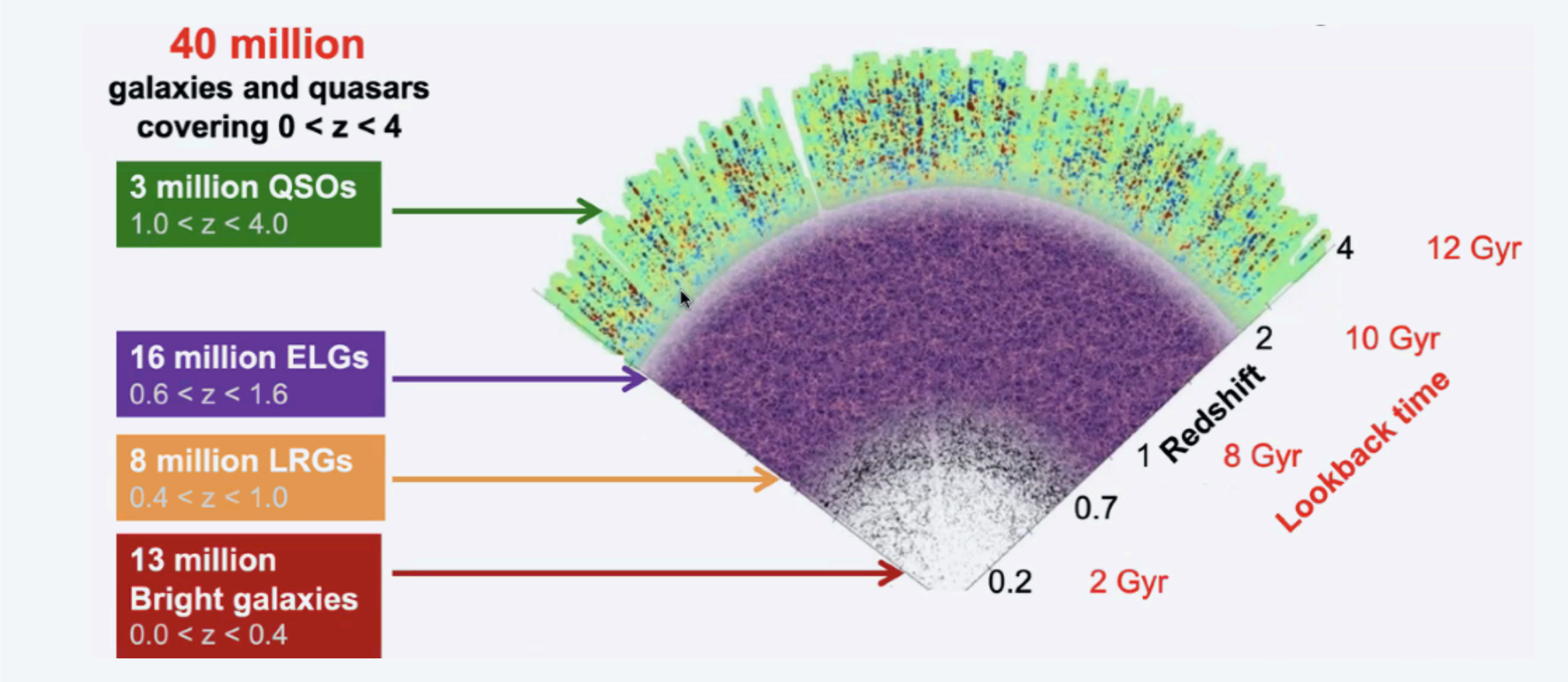
Oscillation Experiments NO: $\sum m_\nu > 0.06$ **eV**

Oscillation Experiments IO: $\sum m_\nu > 0.1$ **eV**

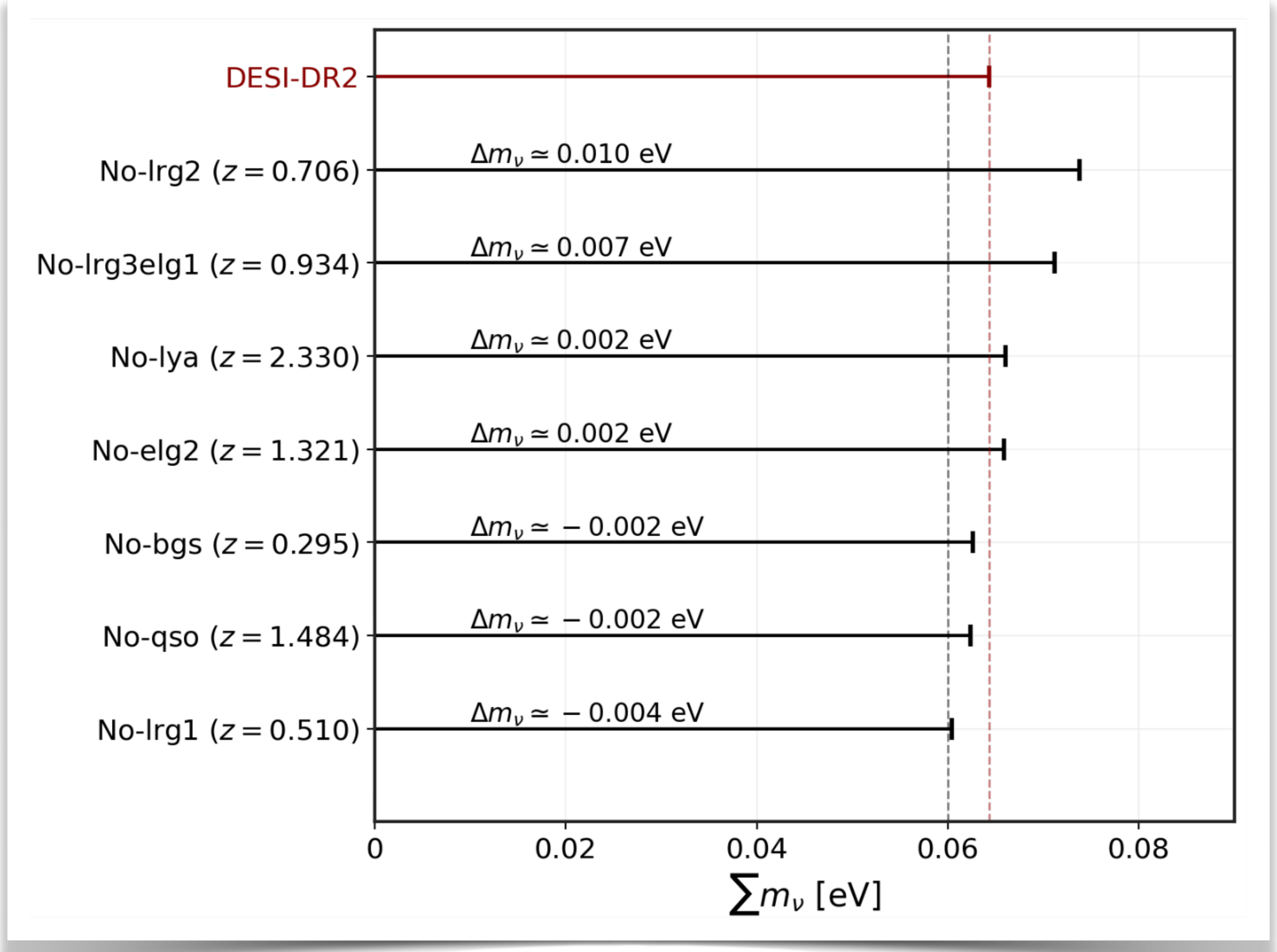
How Massive Vs ?

Possible Implications

Model	Data set	$\sum m_\nu$ (2σ)
ΛCDM $+ \sum m_\nu$	CMB	< 0.175 eV
	CMB+DESI	< 0.065 eV
	CMB+DESI+PP	< 0.073 eV
	CMB+DESI+DESy5	< 0.091 eV
ΛCDM$+\sum m_\nu+A_{\rm lens}$	CMB	< 0.616 eV
	CMB+DESI	< 0.204 eV
	CMB+DESI+PP	< 0.255 eV
	CMB+DESI+DESy5	< 0.287 eV
w_0w_aCDM$+\sum m_\nu$	CMB	< 0.279 eV
	CMB+DESI	< 0.211 eV
	CMB+DESI+PP	< 0.155 eV
	CMB+DESI+DESy5	< 0.183 eV



WG & E. Di Valentino — *in preparation*



– Undetected **systematics in DESI BAO** Data (e,g, BAO at z~0.7 in 3σ tension with SDSS)

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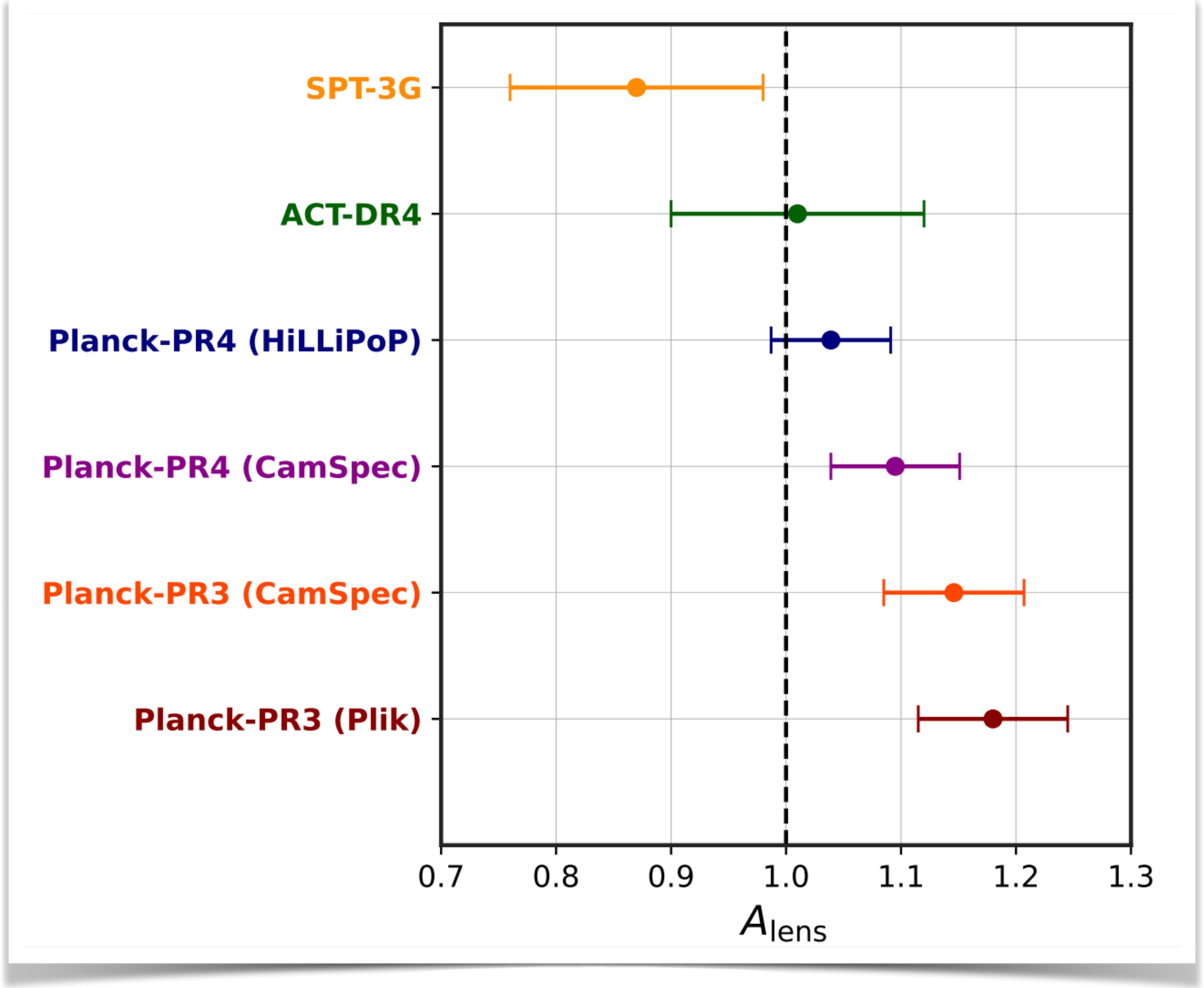
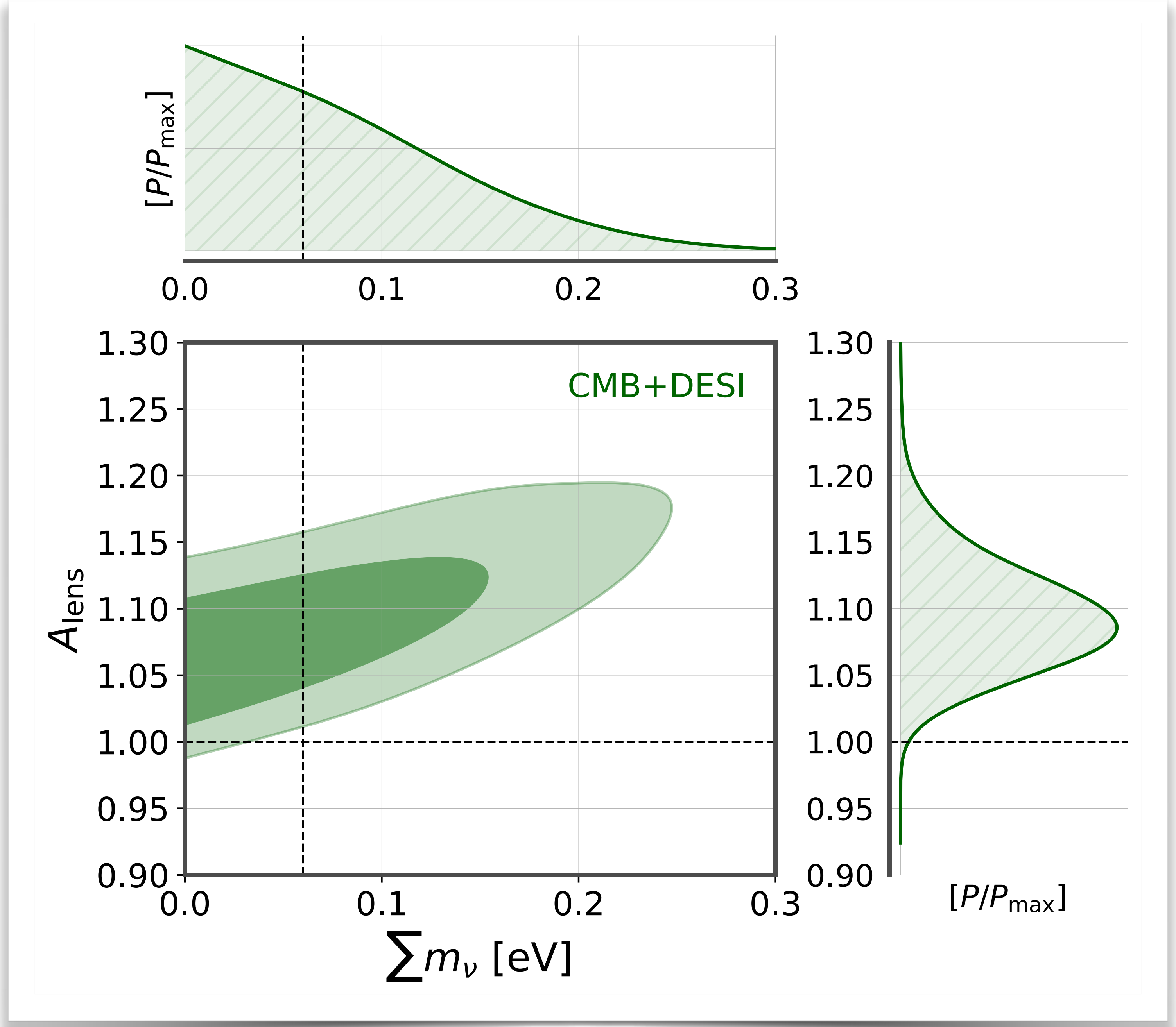
– Undetected **systematics in CMB Data** (e.g., lensing anomaly).





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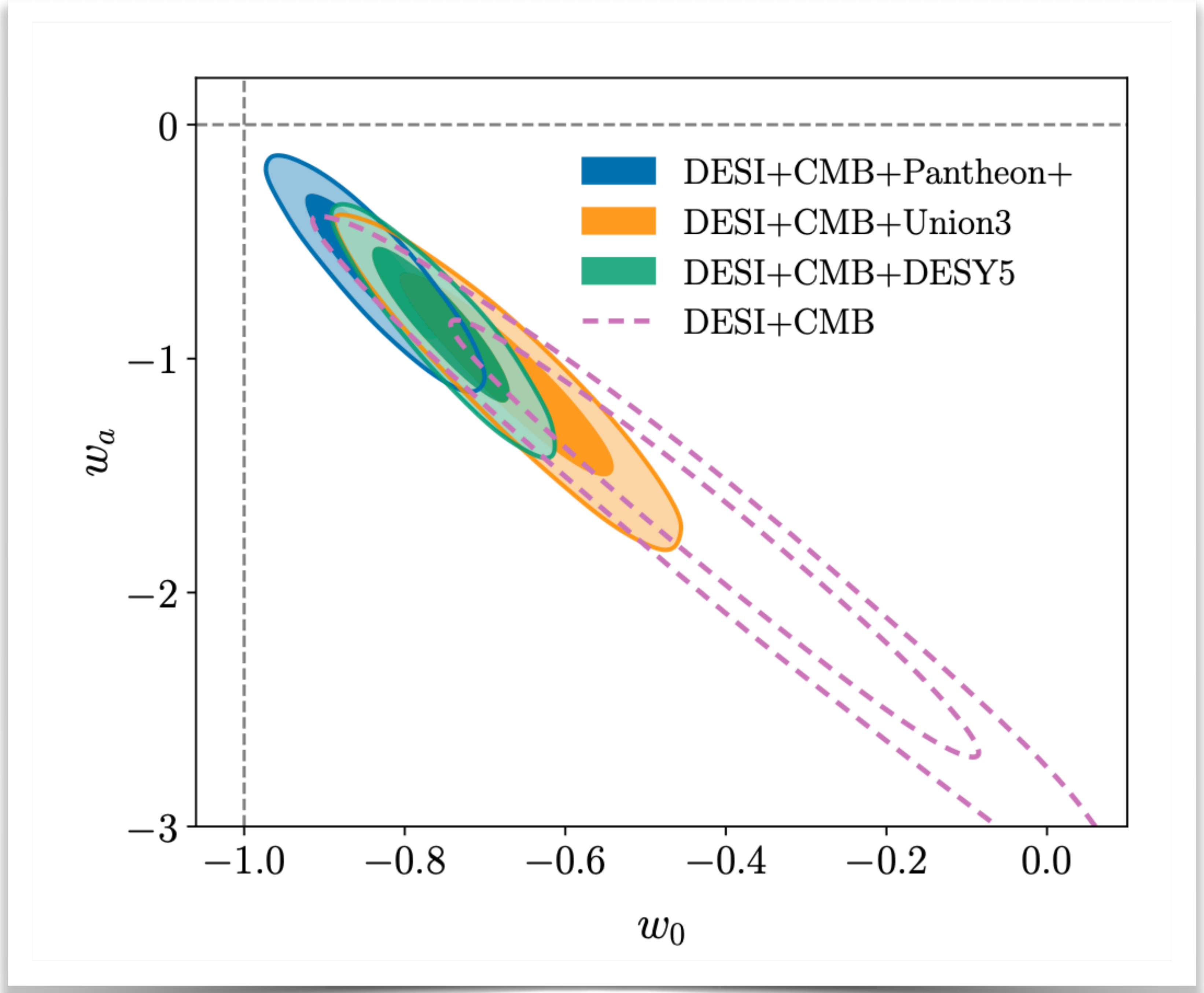
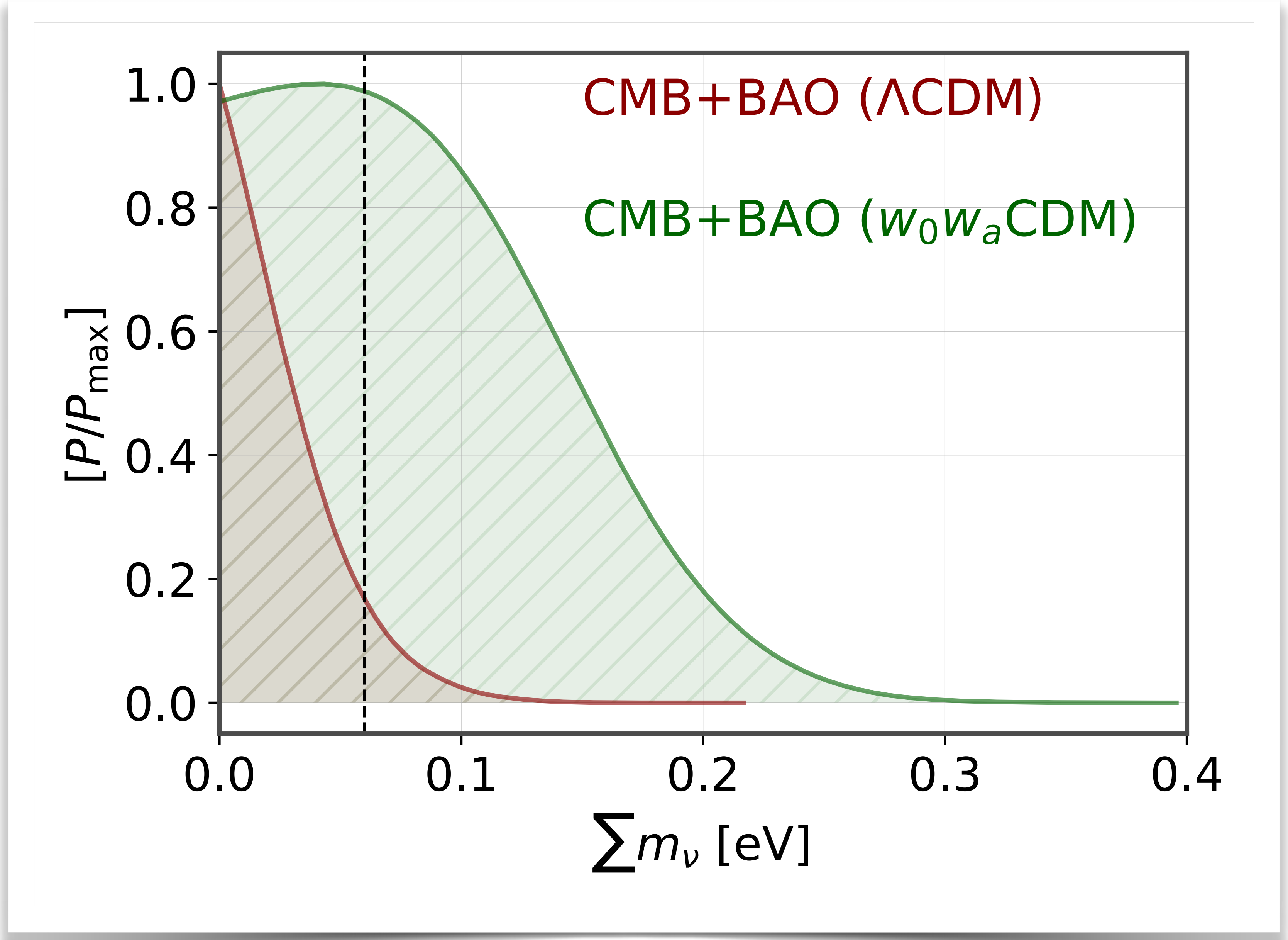
– Undetected **systematics in DESI BAO** Data (e,g, BAO at z~0.7 in 3σ tension with SDSS)

– Undetected **systematics in CMB Data** (e.g., lensing anomaly).

– **New Physics** Beyond ΛCDM (e.g., Dynamical Dark Energy)





Outlooks and Conclusions

Neutrino Cosmology

- Cosmology is a powerful tool for constraining neutrino properties such as ν-species, mass, and ordering.
- Caveat: weak-to-relevant dependence on the overall cosmological model.

Neutrino Species

- Most recent **BBN data are in good agreement with 3-ν families**, constraining $\Delta N_{\rm eff} \lesssim 0.3$
- Most recent **CMB data are in good agreement with 3-ν families**, constraining $\Delta N_{\rm eff} \lesssim 0.3$
- Modest dependence on the overall model of cosmology!

Neutrino Mass & Ordering

- **Post-DESI neutrino mass limits strongly disfavor the IO** (assuming ΛCDM cosmology)
- **Post-DESI neutrino mass upper limit** $\sum m_\nu < 0.064$ **eV is extremely close to the lower limit** $\sum m_\nu > 0.06$ **eV by oscillation experiments!**

Status and Prospects

- **Possible systematics** in DESI BAO data (e.g., DESI datapoint at z=0.706)
- **Possible systematics** in CMB data (e.g., lensing anomaly)
- **Possible hints of New Physics** (e.g., Dynamical Dark Energy)

Conservative Cosmological mass limit: $\sum m_\nu < 0.2$ **eV** (but significant model dependence: **within a factor of 3**)

Thank You!

Backup Slides

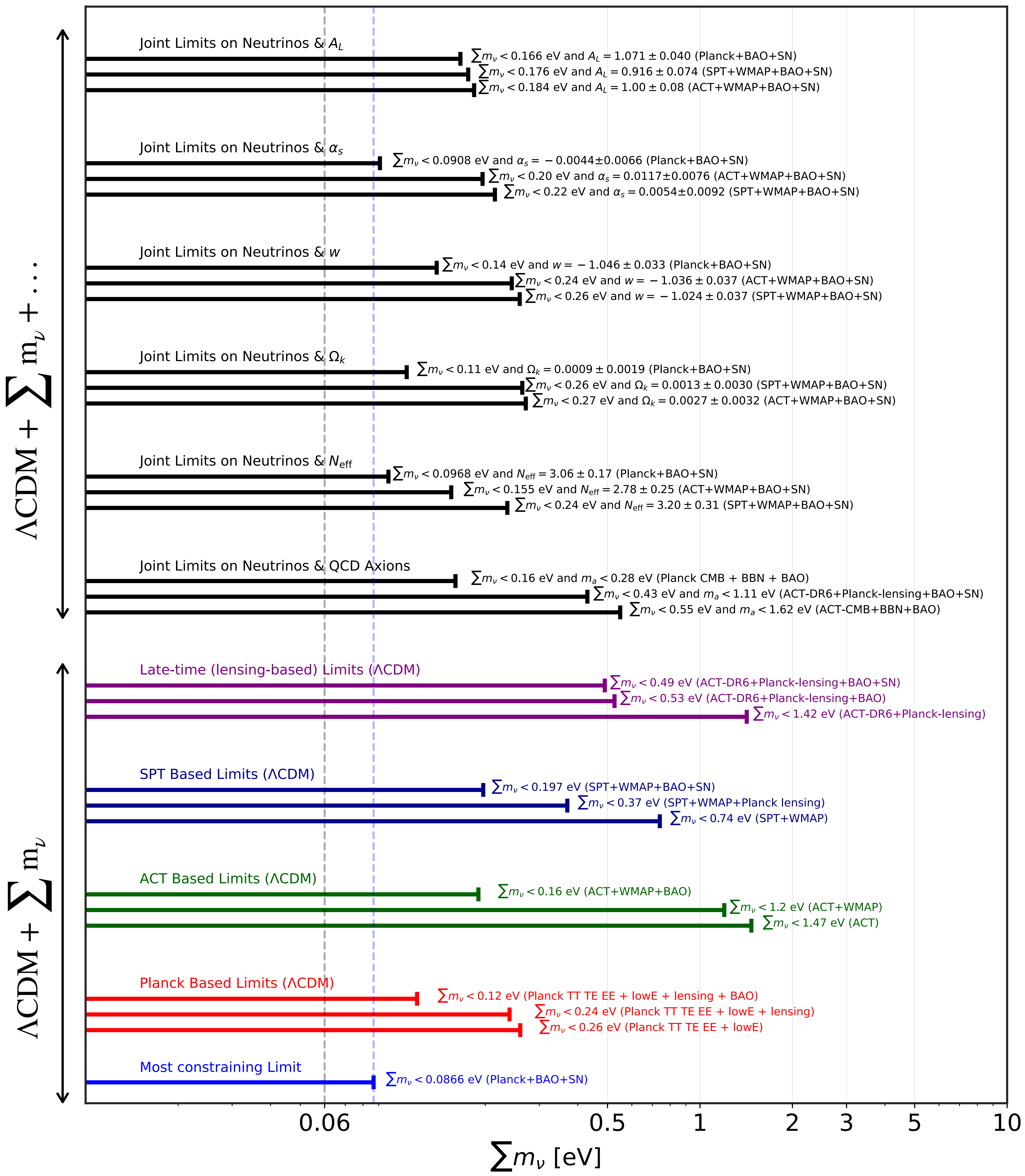
Neutrino Cosmology Before DESI BAO

Total Neutrino Mass and Ordering

Most constraining limits from independent CMB experiments

Dataset	$\sum m_\nu$ [eV]
Most constraining *	0.0866
Planck+lensing+BAO	0.12
ACT+WMAP+BAO	0.16
SPT+WMAP+BAO	0.20
ACT-DR6+Planck-lensing+BAO+SN	0.49

* From **Planck + lensing + pantheon-plus + DR12 (BAO+RSD) + DR16 (BAO only)** as reported in Di Valentino et al. [arXiv: 2106.15267]



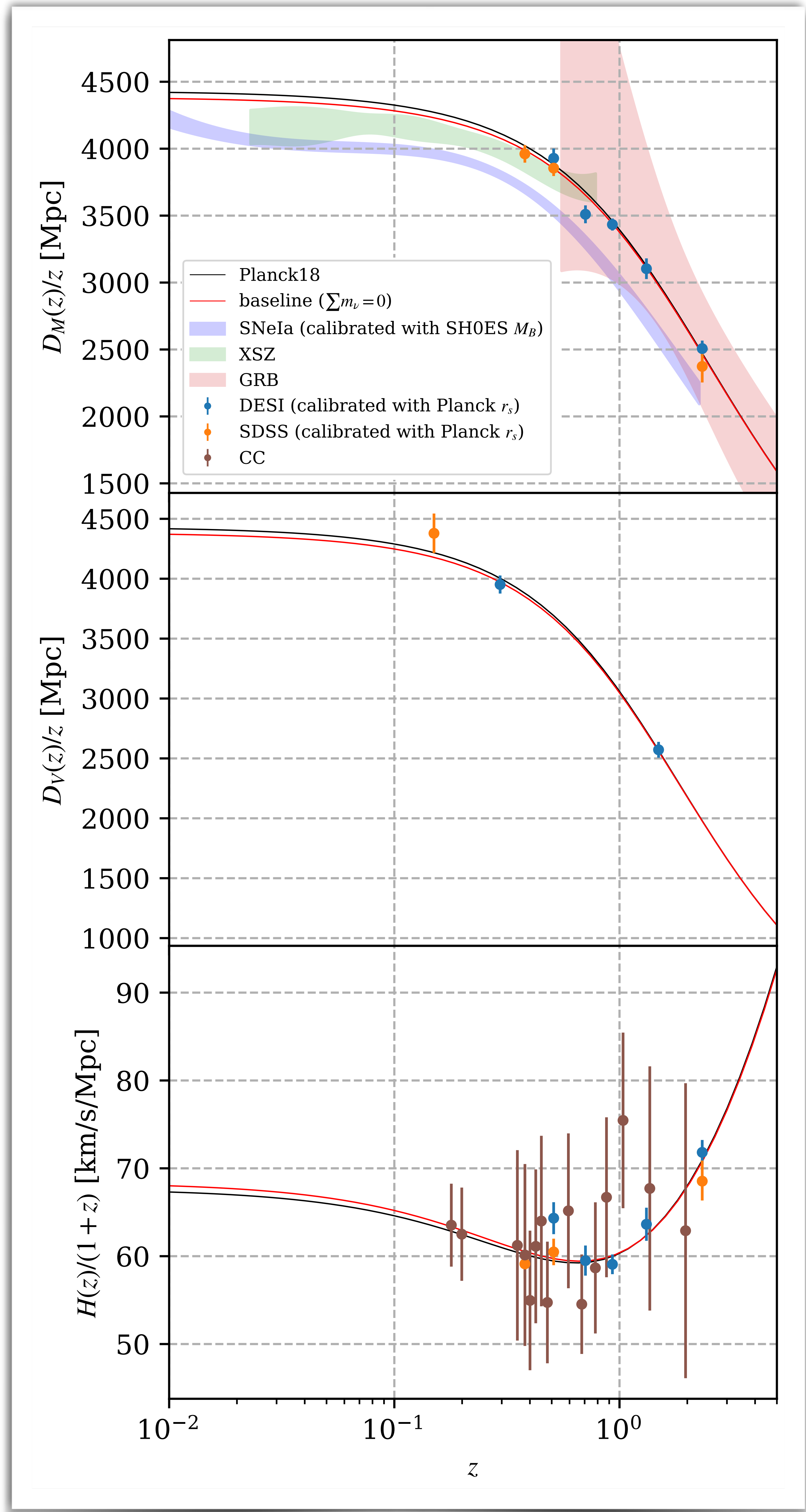
Neutrino Cosmology After DESI BAO

Jun-Qian Jiang, **WG,** *et. al.*, [arXiv: 2407.18047]

Total Neutrino Mass and Ordering

Dataset combination	ΛCDM+$\sum m_\nu$ $\sum m_\nu$ (eV)	$B_{\mathrm{NO,IO}}$
baseline (CMB + DESI)	< 0.072	8.1
baseline + SNeIa	< 0.081	7.0
baseline + CC	< 0.073	7.3
baseline + SDSS	< 0.083	6.8
baseline + SH0ES	< 0.048	47.8
baseline + XSZ	< 0.050	46.5
baseline + GRB	< 0.072	8.7
aggressive combination (baseline + SH0ES + XSZ)	< 0.042 eV	72.6
CMB (with ACT "extended" likelihood)+DESI	< 0.072	8.0
CMB+DESI (with 2020 `HMCode`)	< 0.074	7.5
CMB (with `v1.2` ACT likelihood)+DESI	< 0.082	7.4

– We pushed the mass limit as far as possible, considering **different datasets**.



Neutrino Cosmology After DESI BAO

Total Neutrino Mass and Ordering

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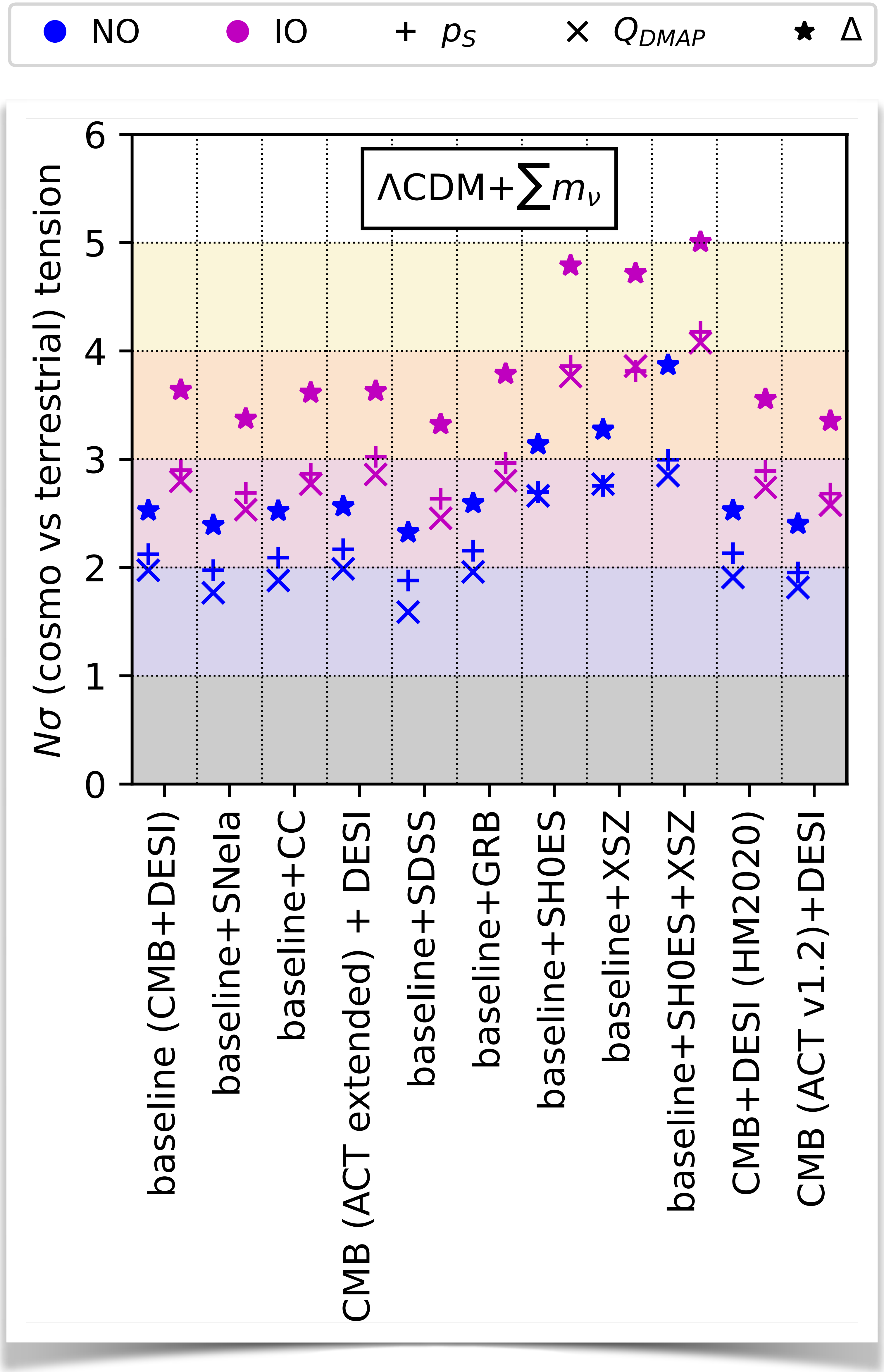
CMB (with v1.2 ACT likelihood)+DESI	< 0.082	7.4

CAVEATS

Dataset combination	ΛCDM+$\sum m_\nu$ $\sum m_\nu$ (eV)	$B_{\mathrm{NO,IO}}$
PR4 (lollipop+hillipop)+DESI	< 0.080	6.4
PR4 (lollipop+hillipop)+SNeIa	< 0.090	6.4
PR4 (lollipop+hillipop)+DESI+SDSS	< 0.090	5.7

Jun-Qian Jiang, **WG,** *et. al.*, [arXiv: 2407.18047]



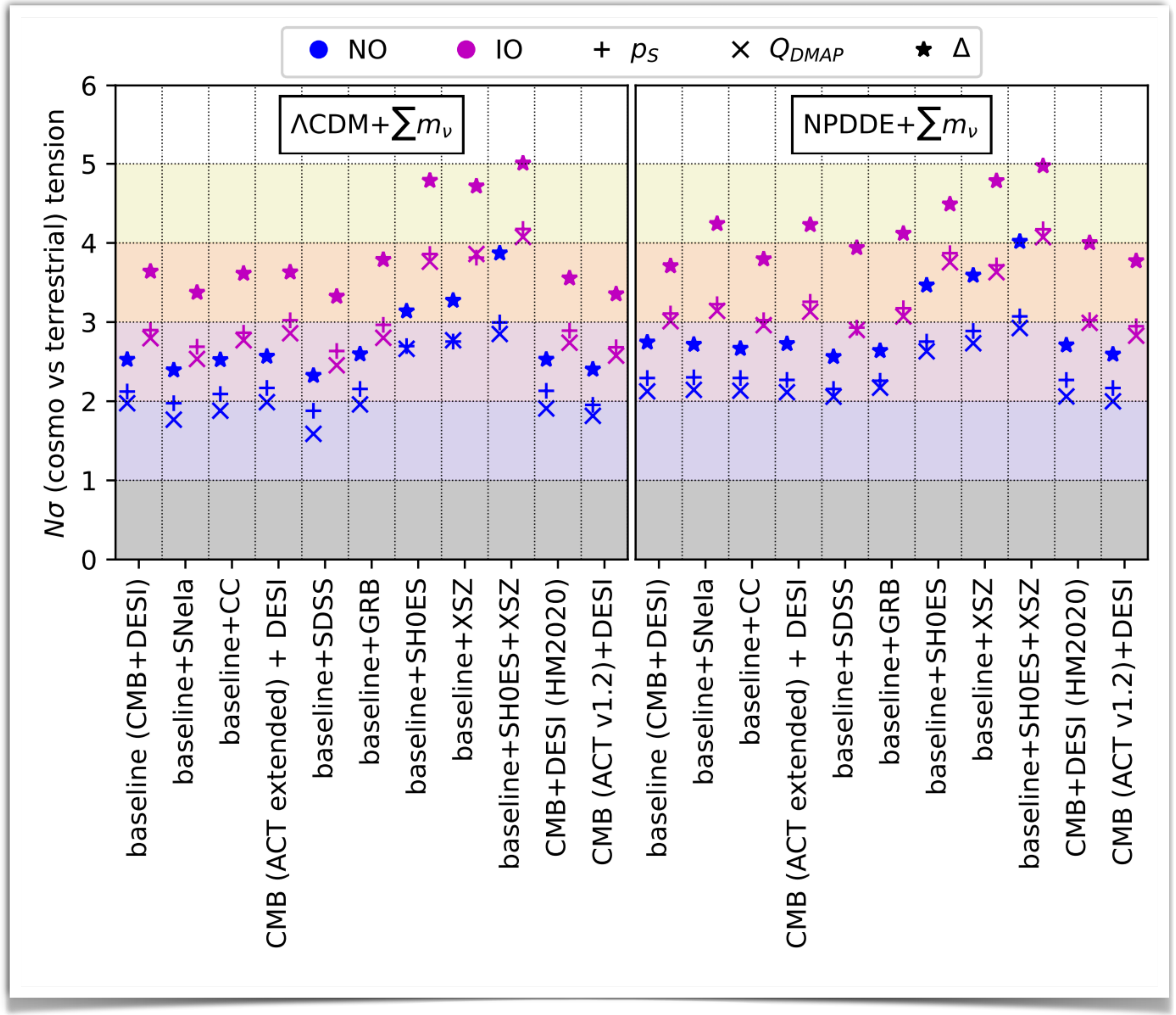
Handle New Physics with care!

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

Jun-Qian Jiang,[1,2,α] William Giarè,[3,β] Stefano Gariazzo,[4,5,6,γ] Maria Giovanna Dainotti,[7,8,9,10,δ] Eleonora Di Valentino,[3,ϵ] Olga Mena,[11,ζ] Davide Pedrotti,[2,12,η] Simony Santos da Costa,[2,12,θ] and Sunny Vagnozzi[2,12,ι]

[1] *School of Physical Sciences, University of Chinese Academy of Sciences, No.19(A) Yuquan Road, Beijing 100049, China*
[2] *Department of Physics, University of Trento, Via Sommarive 14, 38123 Povo (TN), Italy*
[3] *School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom*
[4] *Instituto de Fisica Teorica (IFT), Universidad Autonoma de Madrid-CSIC, C/ Nicolás Cabrera 13-15, E-28049 Madrid, Spain*
[5] *Department of Physics, University of Turin, via P. Giuria 1, 10125 Turin (TO), Italy*
[6] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, via P. Giuria 1, 10125 Turin (TO), Italy*
[7] *Division of Science, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[8] *Graduate University for Advanced Studies (SOKENDAI), Shonankokusaimura, Hayama, Kanagawa 240-0115, Japan*
[9] *Space Science Institute, 4765 Walnut Street Suite B, Boulder, CO 80301, USA*
[10] *Nevada Center for Astrophysics, University of Nevada, 4505 Maryland Parkway, Las Vegas, NV 89154, USA*
[11] *Instituto de Física Corpuscular (IFIC), University of Valencia-CSIS, E-46980, Valencia, Spain*
[12] *Trento Institute for Fundamental Physics and Applications (TIFPA)-INFN, Via Sommarive 14, 38123 Povo (TN), Italy*
(Dated: July 26, 2024)

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 $\sum m_\nu \gtrsim 0.06\,\mathrm{eV}$. 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 $\sum m_\nu < 0.05\,\mathrm{eV}$. 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.



Statistical Metrics

Jun-Qian Jiang, **WG,** *et. al.,* [arXiv: 2407.18047]

Q- Statistics

statistic evaluates the "cost" of explaining datasets together (i.e. with the same parameter values) as opposed to describing them separately (i.e. each dataset can chose its own preferred parameter values). Given two datasets A and B, the test statistics is computed as:

$$Q \equiv -2\ln\mathcal{L}_{AB}(\hat{\theta}_{AB}) + 2\ln\mathcal{L}_A(\hat{\theta}_A) + 2\ln\mathcal{L}_B(\hat{\theta}_B)\,, \tag{5}$$

where $\hat{\theta}_D$ denotes the parameter values which "best" describe dataset D, and $\mathcal{L}$ denotes the likelihood for the datasets given the parameter values. In the context of Bayesian analyses, $\hat{\theta}_D$ is set to the "maximum a posteriori" parameter values (MAP, the point at which the posterior assumes its maximum value), which in general does depend on the prior choice: see Refs. [215, 216], where the corresponding test statistics is denoted by $Q_{\rm DMAP}$ (difference of log-likelihoods at their MAP point).

Δ-statistics

The parameter differences test statistics instead measures the distance between posterior distributions for the parameters θ of two different datasets [217, 218]. We define the difference as $\Delta\theta \equiv \theta_1 - \theta_2$, where θ_1 and θ_2 are two points in the shared parameter space. If A and B are independent datasets, the posterior distribution for $\Delta\theta$ is given by the following:

$$\mathcal{P}_\Delta(\Delta\theta) = \int \mathcal{P}_A(\theta)\mathcal{P}_B(\theta-\Delta\theta)\,d\theta\,. \tag{6}$$

The probability for a given parameter shift between the two posteriors is given by the following integral:

$$\Delta = \int_{\mathcal{P}_\Delta(\Delta\theta)>\mathcal{P}_\Delta(0)} \mathcal{P}_\Delta(\Delta\theta)d\Delta\theta\,. \tag{7}$$

Suspiciousness

Finally, for what concerns the Bayesian suspiciousness, the starting point is the Bayesian evidence ratio, defined as follows:

$$R \equiv \frac{\mathcal{Z}_{AB}}{\mathcal{Z}_A\mathcal{Z}_B}\,, \tag{8}$$

where the numerator corresponds to the evidence when the datasets A and B are described by the same set of parameters θ, whereas in the denominator different parameters may be preferred by the two datasets.[13] As discussed in Ref. [216], R depends on the prior volume in such a way that small values of R, indicative of a possible tension between datasets, can be artificially increased by increasing the prior volume. This is the reason why we do not directly use the Bayesian evidence ratio in what follows. We instead adopt the information ratio I, based on the Kullback-Leibler divergence, to remove the prior dependence. In particular, we start from the log-information ratio, given by:

$$\ln I = \mathcal{D}_A + \mathcal{D}_B - \mathcal{D}_{AB}\,, \tag{9}$$

where the Kullback-Leibler divergence is defined as:

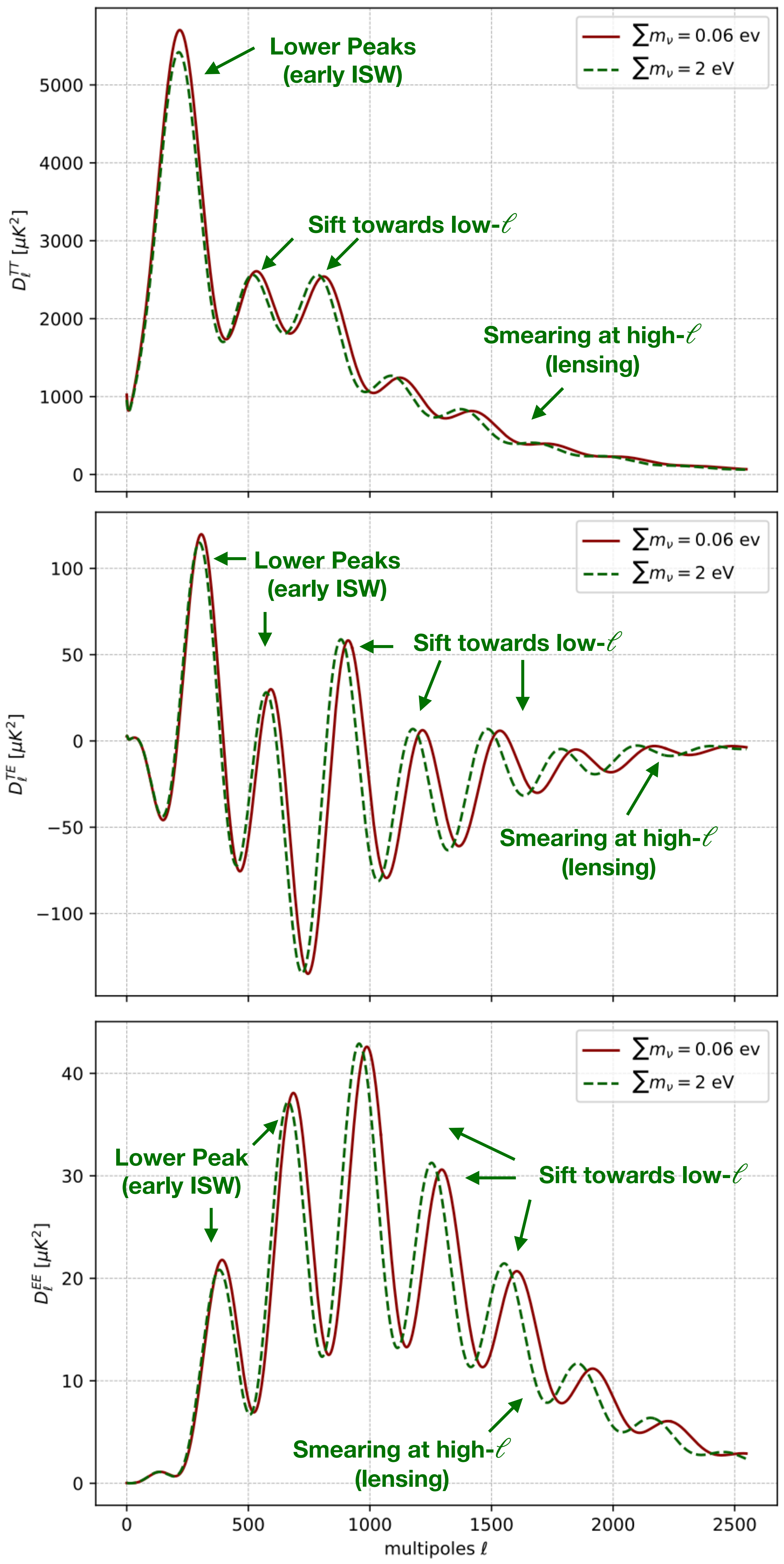
$$\mathcal{D}_D = \int \mathrm{d}\theta\,\mathcal{P}_D \ln\left(\frac{\mathcal{P}_D}{\Pi}\right)\,. \tag{10}$$

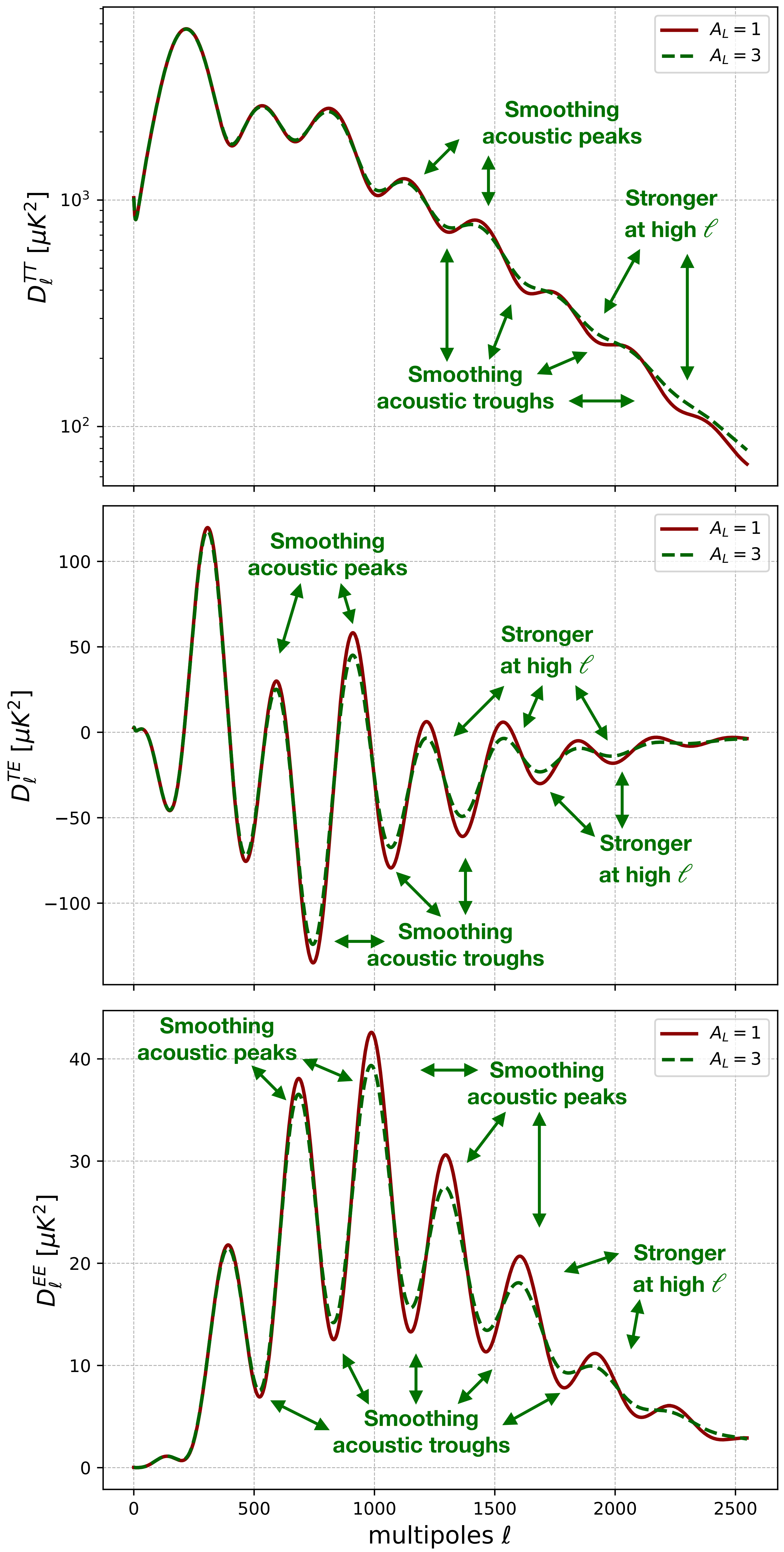
Using the log-information ratio we can cancel the prior dependence of the Bayesian evidence ratio R and define the suspiciousness parameter S as follows [219]:

$$\ln S \equiv \ln R - \ln I\,. \tag{11}$$

LENSING ANOMALY VS NEUTRINO MASS

Model	Data set	$\sum m_\nu$ (2σ)
ΛCDM $+ \sum m_\nu$	CMB	< 0.175 eV
	CMB+DESI	< 0.065 eV
	CMB+DESI+PP	< 0.073 eV
	CMB+DESI+DESy5	< 0.091 eV
ΛCDM$+\sum m_\nu$$+A_{\rm lens}$	CMB	< 0.616 eV
	CMB+DESI	< 0.204 eV
	CMB+DESI+PP	< 0.255 eV
	CMB+DESI+DESy5	< 0.287 eV
w_0w_aCDM$+\sum m_\nu$	CMB	< 0.279 eV
	CMB+DESI	< 0.211 eV
	CMB+DESI+PP	< 0.155 eV
	CMB+DESI+DESy5	< 0.183 eV





Positive or Negative Mass Bounds?

No νs is Good News

Nathaniel Craig[1,2], Daniel Green[3], Joel Meyers[4], and Surjeet Rajendran[5]

[1]*Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[2]*Kavli Institute for Theoretical Physics, Santa Barbara, CA 93106, USA*
[3]*Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA*
[4]*Department of Physics, Southern Methodist University, Dallas, TX 75275, USA*
[5]*Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA*

Abstract

The baryon acoustic oscillation (BAO) analysis from the first year of data from the Dark Energy Spectroscopic Instrument (DESI), when combined with data from the cosmic microwave background (CMB), has placed an upper-limit on the sum of neutrino masses, $\sum m_\nu < 70$ meV (95%). In addition to excluding the minimum sum associated with the inverted hierarchy, the posterior is peaked at $\sum m_\nu = 0$ and is close to excluding even the minumum sum, 58 meV at 2σ. In this paper, we explore the implications of this data for cosmology and particle physics. The sum of neutrino mass is determined in cosmology from the suppression of clustering in the late universe. Allowing the clustering to be enhanced, we extended the DESI analysis to $\sum m_\nu < 0$ and find $\sum m_\nu = -160 \pm 90$ meV (68%), and that the suppression of power from the minimum sum of neutrino masses is excluded at 99% confidence. We show this preference for negative masses makes it challenging to explain the result by a shift of cosmic parameters, such as the optical depth or matter density. We then show how a result of $\sum m_\nu = 0$ could arise from new physics in the neutrino sector, including decay, cooling, and/or time-dependent masses. These models are consistent with current observations but imply new physics that is accessible in a wide range of experiments. In addition, we discuss how an apparent signal with $\sum m_\nu < 0$ can arise from new long range forces in the dark sector or from a primordial trispectrum that resembles the signal of CMB lensing.

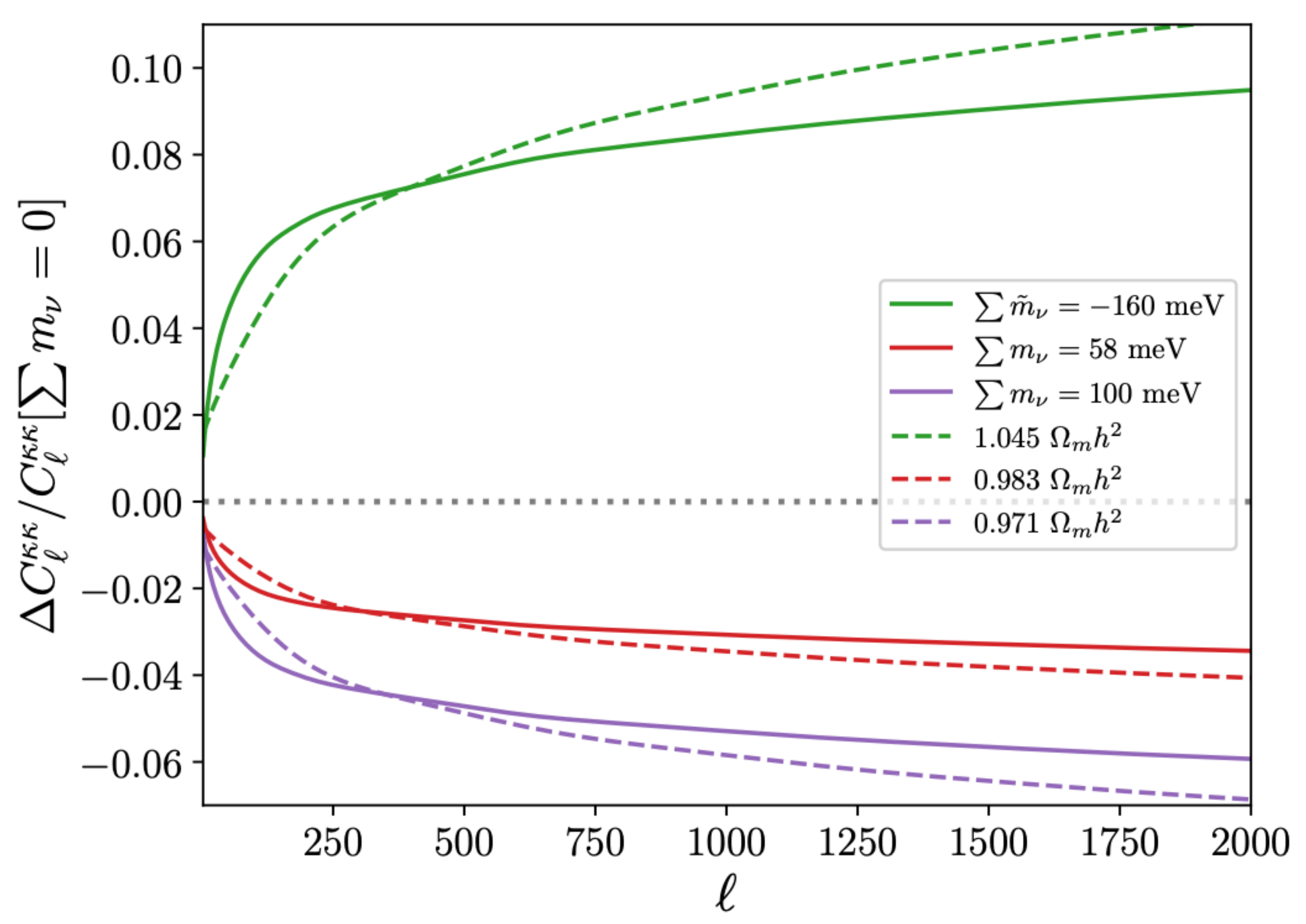
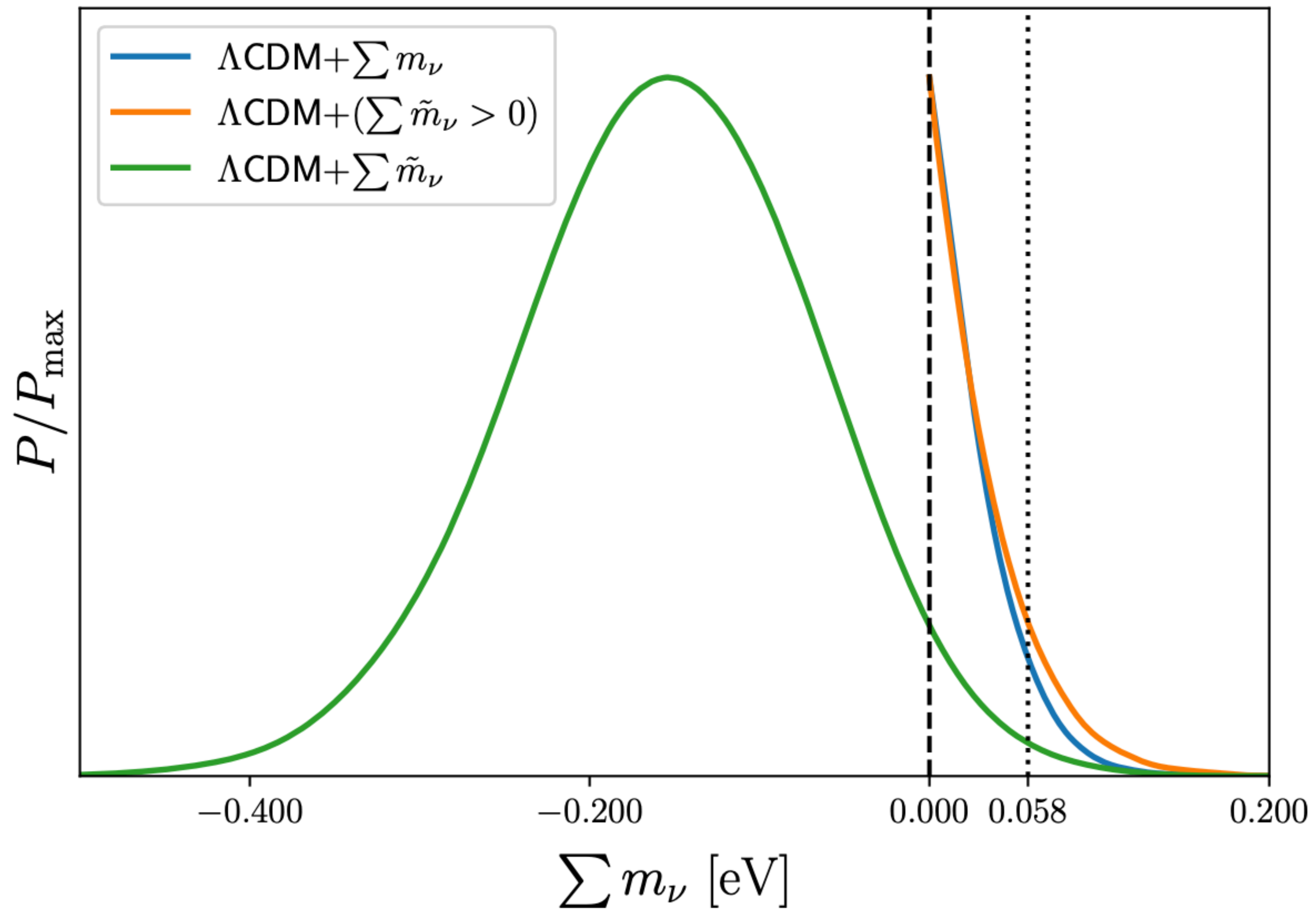


Figure 2: Comparison of the fractional change to the CMB lensing power spectrum from changes to $\Omega_m h^2$ and the introduction of a non-zero neutrino mass.



Positive or Negative Mass Bounds?

Living at the Edge:
A Critical Look at the Cosmological Neutrino Mass Bound

Daniel Naredo-Tuero [1,*] Miguel Escudero [2,†]
Enrique Fernandez-Martinez [1,‡] Xabier Marcano [1,§] and Vivian Poulin [3,¶]

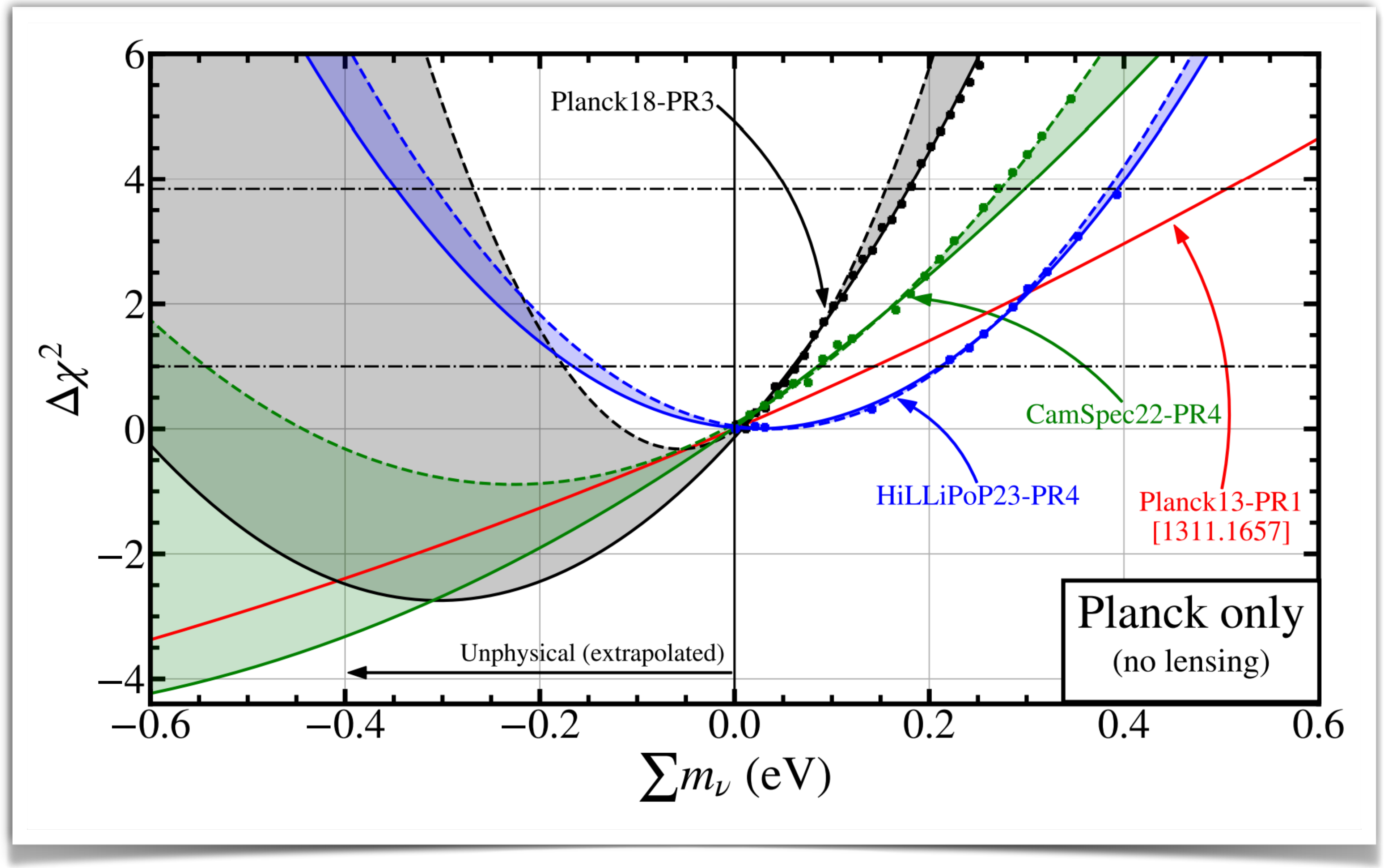
[1] *Departamento de Física Teórica and Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

[2] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

[3] *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*

(Dated: October 29, 2024)

Cosmological neutrino mass bounds are becoming increasingly stringent. The latest limit within ΛCDM from Planck 2018+ACT lensing+DESI is $\sum m_\nu < 0.072\,\mathrm{eV}$ at 95% CL, very close to the minimum possible sum of neutrino masses ($\sum m_\nu > 0.06\,\mathrm{eV}$), hinting at vanishing or even "negative" cosmological neutrino masses. In this context, it is urgent to carefully evaluate the origin of these cosmological constraints. In this paper, we investigate the robustness of these results in three ways: i) we check the role of potential anomalies in Planck CMB and DESI BAO data; ii) we compare the results for frequentist and Bayesian techniques, as very close to physical boundaries subtleties in the derivation and interpretation of constraints can arise; iii) we investigate how deviations from ΛCDM, potentially alleviating these anomalies, can alter the constraints. From a profile likelihood analysis, we derive constraints in agreement at the $\sim 10\%$ level with Bayesian posteriors. We find that the weak preference for negative neutrino masses is mostly present for Planck 18 data, affected by the well-known 'lensing anomaly'. It disappears when the new Planck 2020 HiLLiPoP is used, leading to significantly weaker constraints. Additionally, the pull towards negative masses in DESI data stems from the $z = 0.7$ bin, which contains a BAO measurement in $\sim 3\sigma$ tension with Planck expectations. Without this bin, and in combination with HiLLiPoP, the bound relaxes to $\sum m_\nu < 0.11\,\mathrm{eV}$ at 95% CL. The recent preference for dynamical dark energy alleviates this tension and further weakens the bound. As we are at the dawn of a neutrino mass discovery from cosmology, it will be very exciting to see if this trend is confirmed by future data.



Background Expansion

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \longleftarrow ? \longrightarrow G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Modified Gravity?

Non-standard component?
—e.g., scalar field(s), fluid(s), etc. —

$$H^2(z) = H_0^2 \left[\Omega_r \cdot (1+z)^4 + \Omega_m \cdot (1+z)^3 + \Omega_\Lambda\right]$$

Ω_Λ is a Cosmological Constant term. Assumption is not free from limitations:

- **Asymptotical cosmology:** A positive Λ implies living in an asymptotically de Sitter universe, which seems to contrast with several theories/models of quantum gravity proposing instead an asymptotically anti-de Sitter universe
- **Physical interpretation:** Based on QFT calculations, one would expect a zero-point energy density 10^{50} to 10^{120} orders of magnitude larger than what is inferred by cosmological data
- **Why Now?:** Why are we so lucky to live precisely in the cosmic epoch when such a constant component came to be dominant?

$$H^2(z) = H_0^2 \left[\Omega_r \cdot (1+z)^4 + \Omega_m \cdot (1+z)^3 + \Omega_{\mathrm{DE}}(z)\right]$$

$\Omega_{\mathrm{DE}}(z)$ is a generic DE component with

- **Energy density:** $\rho_{\mathrm{DE}}(z)$
- **Pressure:** $P_{\mathrm{DE}}(z)$
- **Equation of State (EoS):** $w(z) = \dfrac{P_{\mathrm{DE}}(z)}{\rho_{\mathrm{DE}}(z)}$

As for inflation, we get an accelerated phase of expansion if $w(z) < -1/3$

Background Expansion

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

?

$$G_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$H^2(z) = H_0^2\left[\Omega_r \cdot (1+z)^4 + \Omega_m \cdot (1+z)^3 + \Omega_\Lambda\right]$$

$$H^2(z) = H_0^2\left[\Omega_r \cdot (1+z)^4 + \Omega_m \cdot (1+z)^3 + \Omega_{\mathrm{DE}}(z)\right]$$

Distance Duality Relation

Cosmological Distances

$$D_L(z) = (1+z)^2 D_A(z) \propto \int_0^z dz' H(z')^{-1}$$

Luminosity Distance

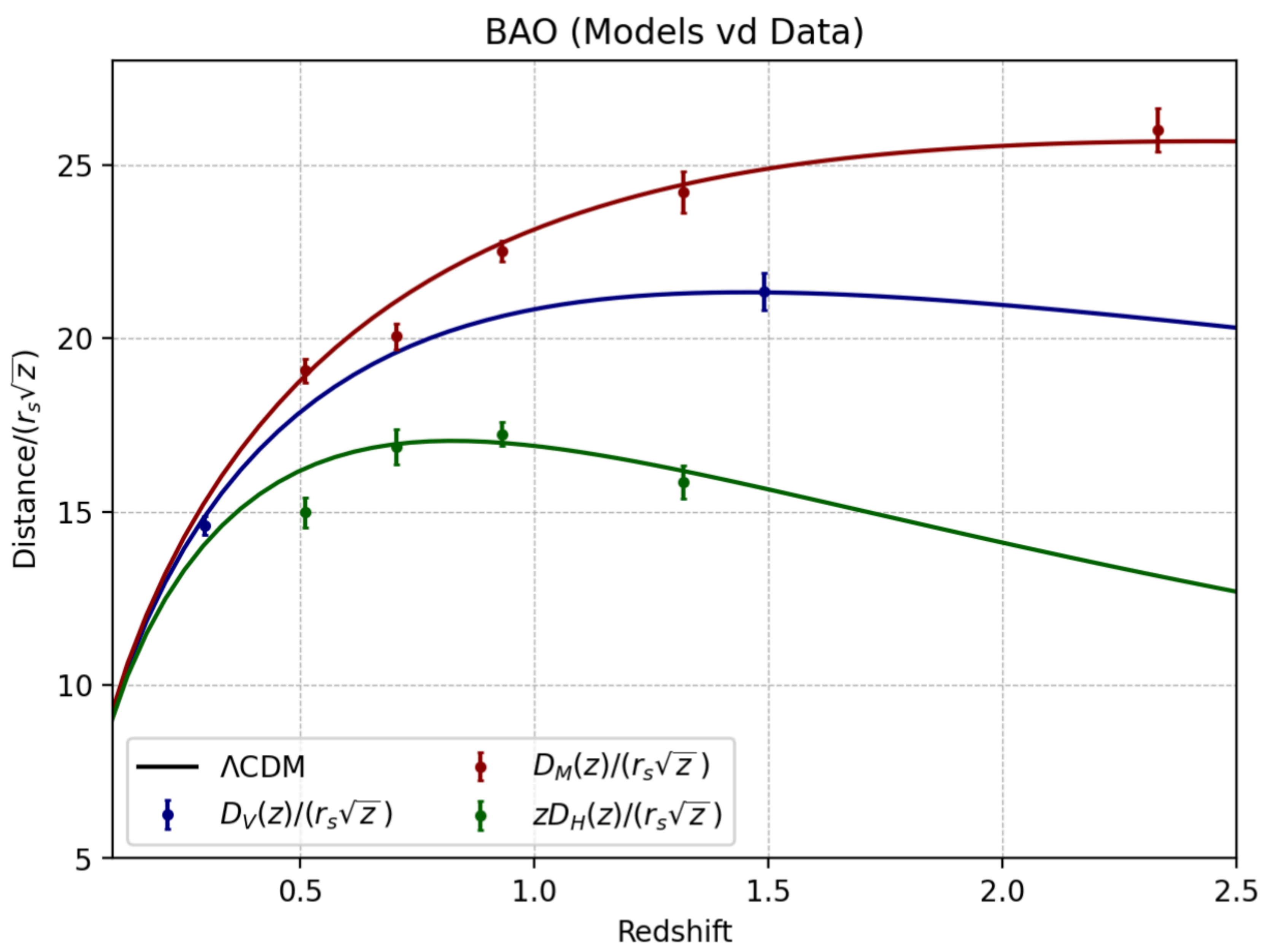
Angular Diameter Distance

Expansion History of the Unierse

Measuring Cosmic Distances

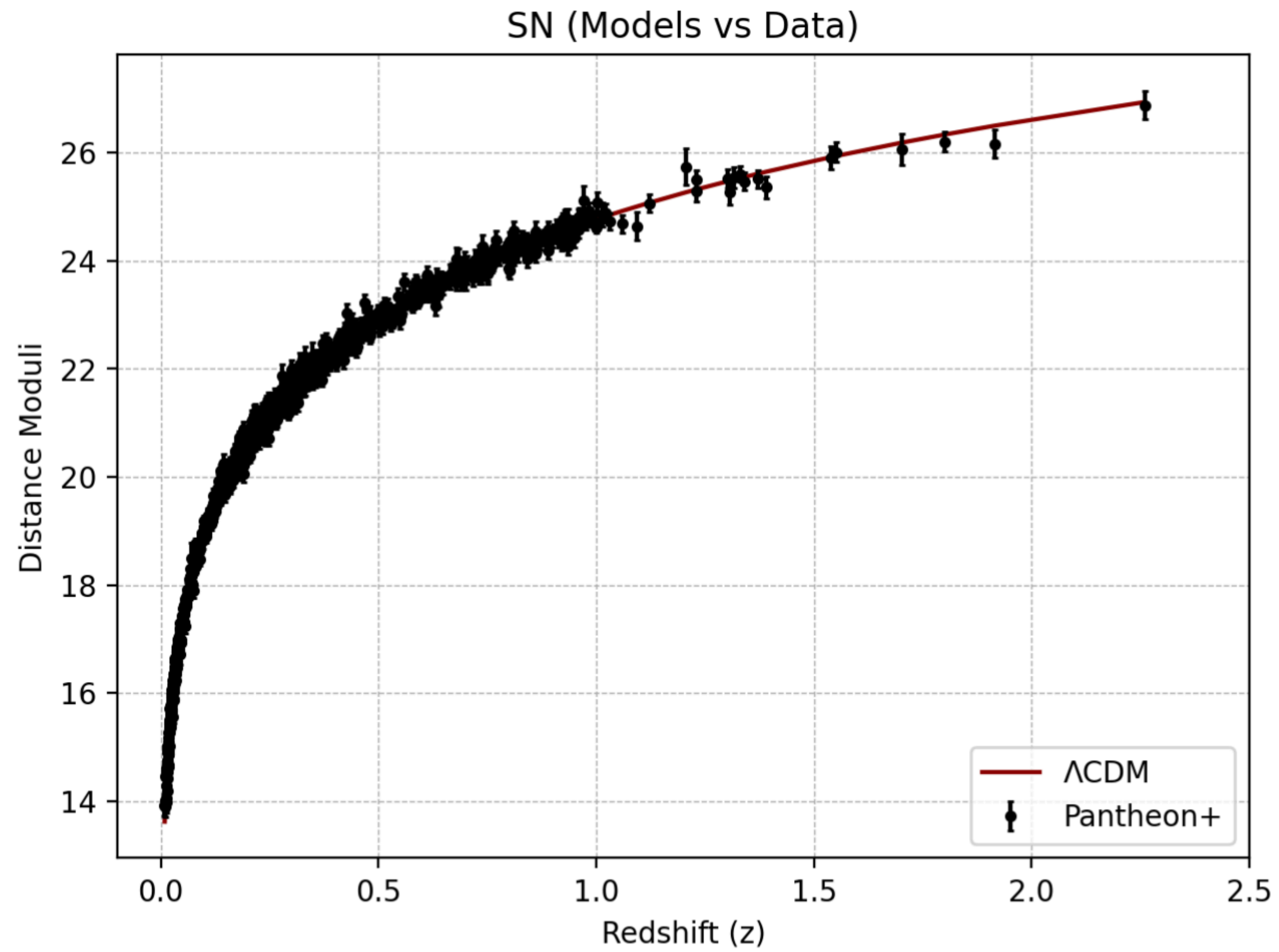
Baryon Acoustic Oscillations

- The **comoving angular diameter distance** $D_M(z) = D_A(z)(1+z)$, i.e., the spatial distance between two objects in the direction perpendicular to the line-of-sight;
- The **line-of-sight distance** $D_H(z) = c/H(z)$, i.e., the distance along the line-of-sight between an observer and an object;
- The **volume-averaged distance** $D_V(z) = [zD_H(z)D_M^2(z)]^{1/3}$, i.e., the quantity to which isotropic BAO measurements are sensitive.
- **Require calibration:** all the distances relative to the sound horizon at the Drag epoch



Type Ia Supernovae

- **Distance Moduli**: $\mu(z)^{\rm th} = 5\log_{10}\left(\dfrac{D_L(z)}{10\,{\rm pc}}\right) - 5$
- **Require calibration:** $\mu(z)^{\rm obs} = m(z) - M$ where $m(z)$ is the observed magnitude of SN at that given z while M is the absolute magnitude defined as the apparent magnitude at 10 parsec



Measuring Cosmic Distances

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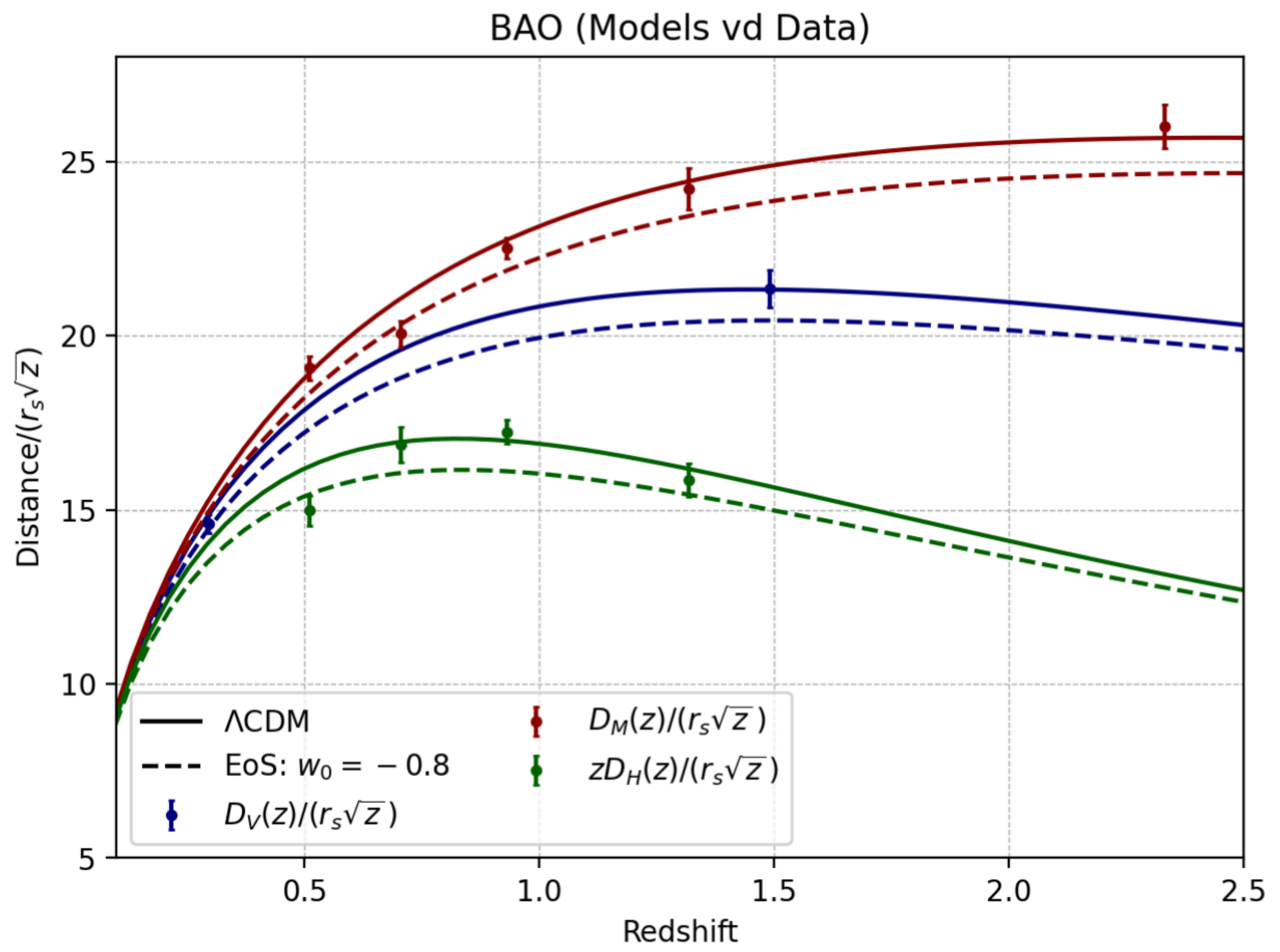

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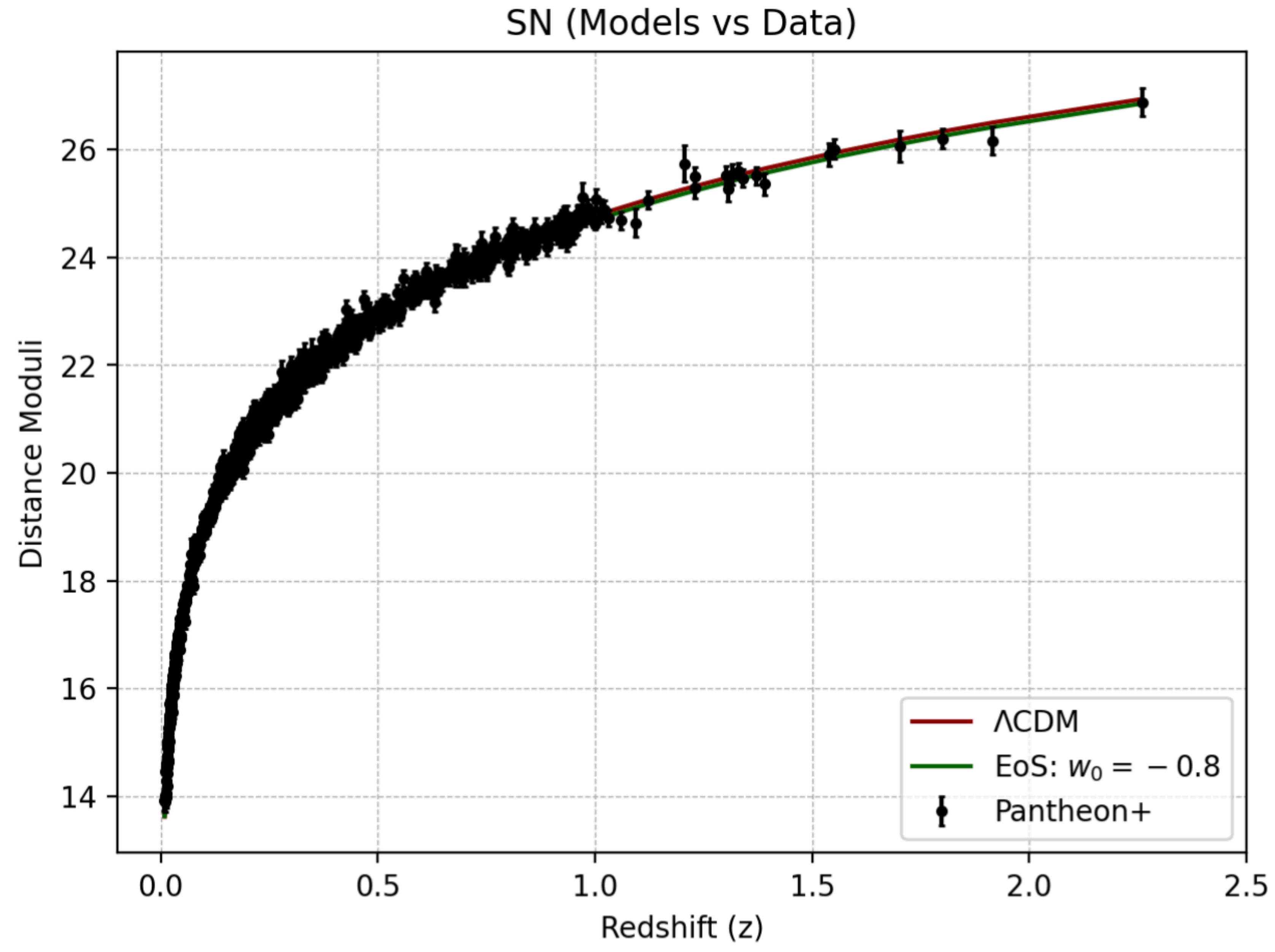


Evidence (?) For Dynamical Dark Energy

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

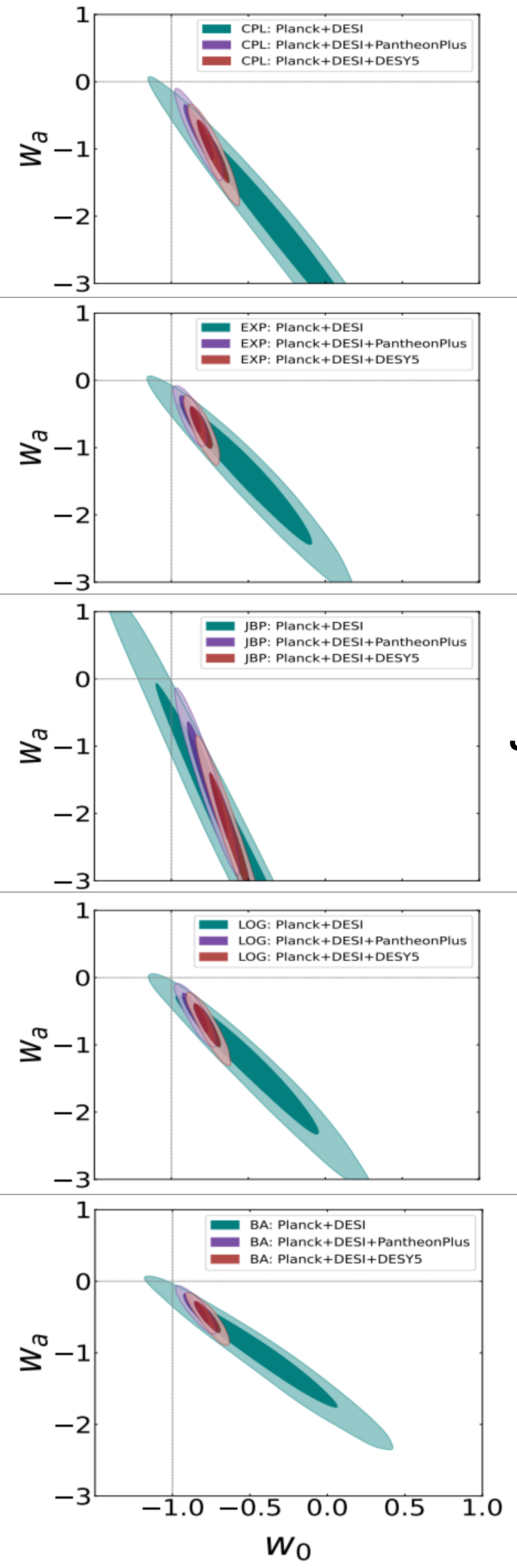
Robust preference for Dynamical Dark Energy in DESI BAO and SN measurements

William Giarè[a,*] Mahdi Najafi,[b,c] Supriya Pan[d,e] Eleonora Di Valentino[a]
and Javad T. Firouzjaee[b,c,f]

Abstract: Recent Baryon Acoustic Oscillation (BAO) measurements released by DESI, when combined with Cosmic Microwave Background (CMB) data from Planck and two different samples of Type Ia supernovae (Pantheon-Plus and DESY5) reveal a preference for Dynamical Dark Energy (DDE) characterized by a present-day quintessence-like equation of state that crossed into the phantom regime in the past. A core *ansatz* for this result is assuming a linear Chevallier-Polarski-Linder (CPL) parameterization $w(a) = w_0 + w_a(1-a)$ to describe the evolution of the DE equation of state (EoS). In this paper, we test if and to what extent this assumption impacts the results. To prevent broadening uncertainties in cosmological parameter inference and facilitate direct comparison with the baseline CPL case, we focus on 4 alternative well-known models that, just like CPL, consist of only two free parameters: the present-day DE EoS (w_0) and a parameter quantifying its dynamical evolution (w_a). We demonstrate that the preference for DDE remains robust regardless of the parameterization: w_0 consistently remains in the quintessence regime, while w_a consistently indicates a preference for a dynamical evolution towards the phantom regime. This tendency is significantly strengthened by DESY5 SN measurements. By comparing the best-fit χ^2 obtained within each DDE model, we notice that the linear CPL parameterization is not the best-fitting case. Among the models considered, the EoS proposed by Barboza and Alcaniz consistently leads to the most significant improvement.

TAKE-AWAY RESULTS:

- We test the preference for Evolving DE against different parametrizations of $w(z)$
- Preference for $w(z) \neq -1$ always confirmed



Chevallier-Polarski-Linder

$$w(a) = w_0 + w_a \cdot (1-a)$$

Exponential

$$w(a) = (w_0 - w_a) + w_a \cdot e^{(1-a)}$$

Jassal-Bagla-Padmanabhan

$$w(a) = w_0 + w_a \times a\,(1-a)$$

Logarithmic

$$w(a) = w_0 - w_a \cdot \ln a$$

Barboza-Alcaniz

$$w(a) = w_0 + w_a \times \frac{1-a}{a^2 + (1-a)^2}$$

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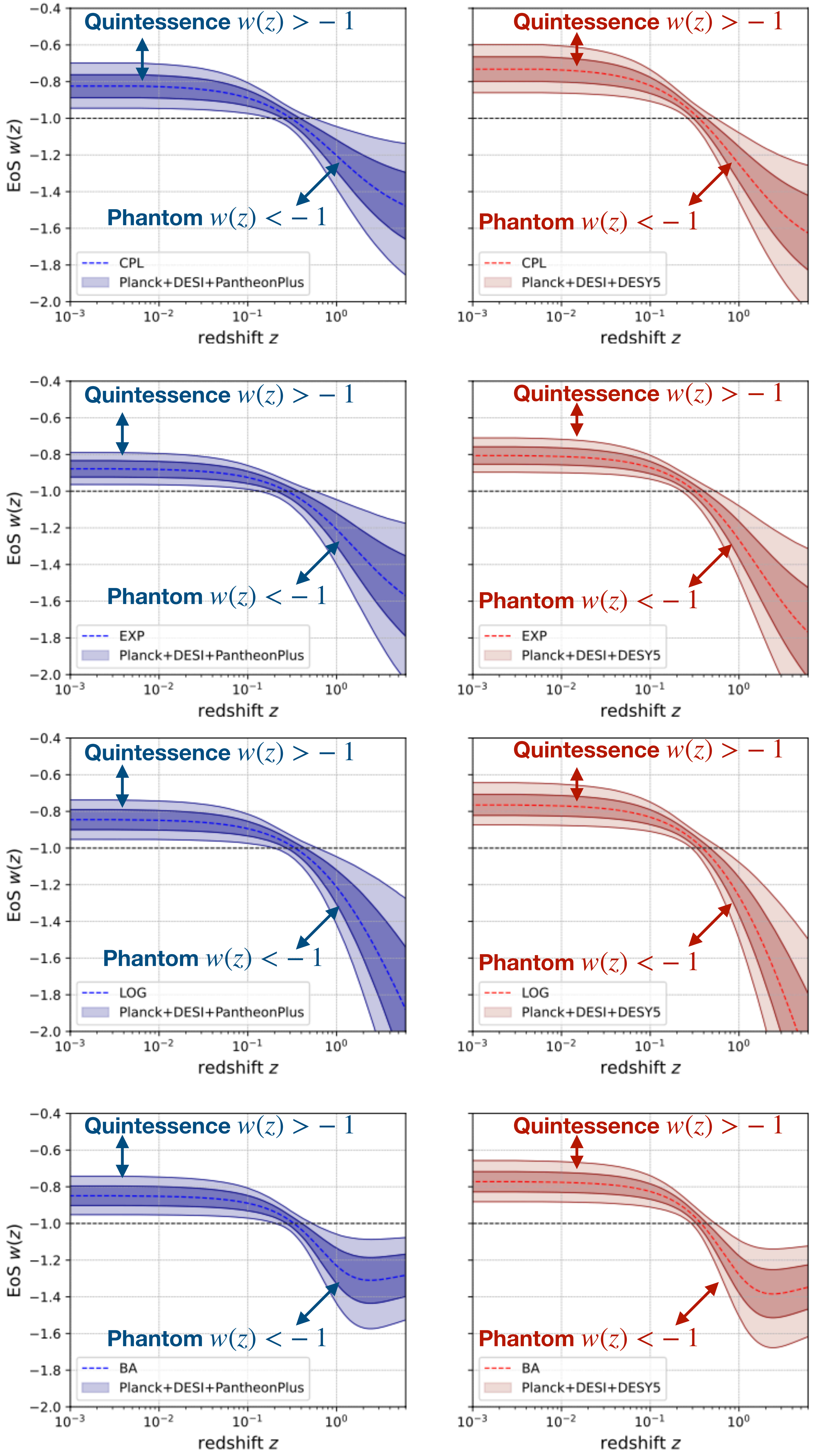
Robust preference for Dynamical Dark Energy in DESI BAO and SN measurements

William Giarè[a,*] Mahdi Najafi,[b,c] Supriya Pan[d,e] Eleonora Di Valentino[a] and Javad T. Firouzjaee[b,c,f]

Abstract: Recent Baryon Acoustic Oscillation (BAO) measurements released by DESI, when combined with Cosmic Microwave Background (CMB) data from Planck and two different samples of Type Ia supernovae (Pantheon-Plus and DESY5) reveal a preference for Dynamical Dark Energy (DDE) characterized by a present-day quintessence-like equation of state that crossed into the phantom regime in the past. A core *ansatz* for this result is assuming a linear Chevallier-Polarski-Linder (CPL) parameterization $w(a) = w_0 + w_a(1-a)$ to describe the evolution of the DE equation of state (EoS). In this paper, we test if and to what extent this assumption impacts the results. To prevent broadening uncertainties in cosmological parameter inference and facilitate direct comparison with the baseline CPL case, we focus on 4 alternative well-known models that, just like CPL, consist of only two free parameters: the present-day DE EoS (w_0) and a parameter quantifying its dynamical evolution (w_a). We demonstrate that the preference for DDE remains robust regardless of the parameterization: w_0 consistently remains in the quintessence regime, while w_a consistently indicates a preference for a dynamical evolution towards the phantom regime. This tendency is significantly strengthened by DESY5 SN measurements. By comparing the best-fit χ^2 obtained within each DDE model, we notice that the linear CPL parameterization is not the best-fitting case. Among the models considered, the EoS proposed by Barboza and Alcaniz consistently leads to the most significant improvement.

TAKE-AWAY RESULTS:

- All parametrizations and datasets produce a **preference for a present-day quintessence** EoS: $w(z_0) > -1$ …
- … **That crossed the phantom divide** in the past somewhen around $z > z_c \sim 0.3$
  $\Rightarrow w(z > z_c) < -1$



EVIDENCE (?) FOR DYNAMICAL DARK ENERGY

Dynamical Dark Energy Beyond Planck? Constraints from multiple CMB probes, DESI BAO and Type-Ia Supernovae

William Giarè[1,*]

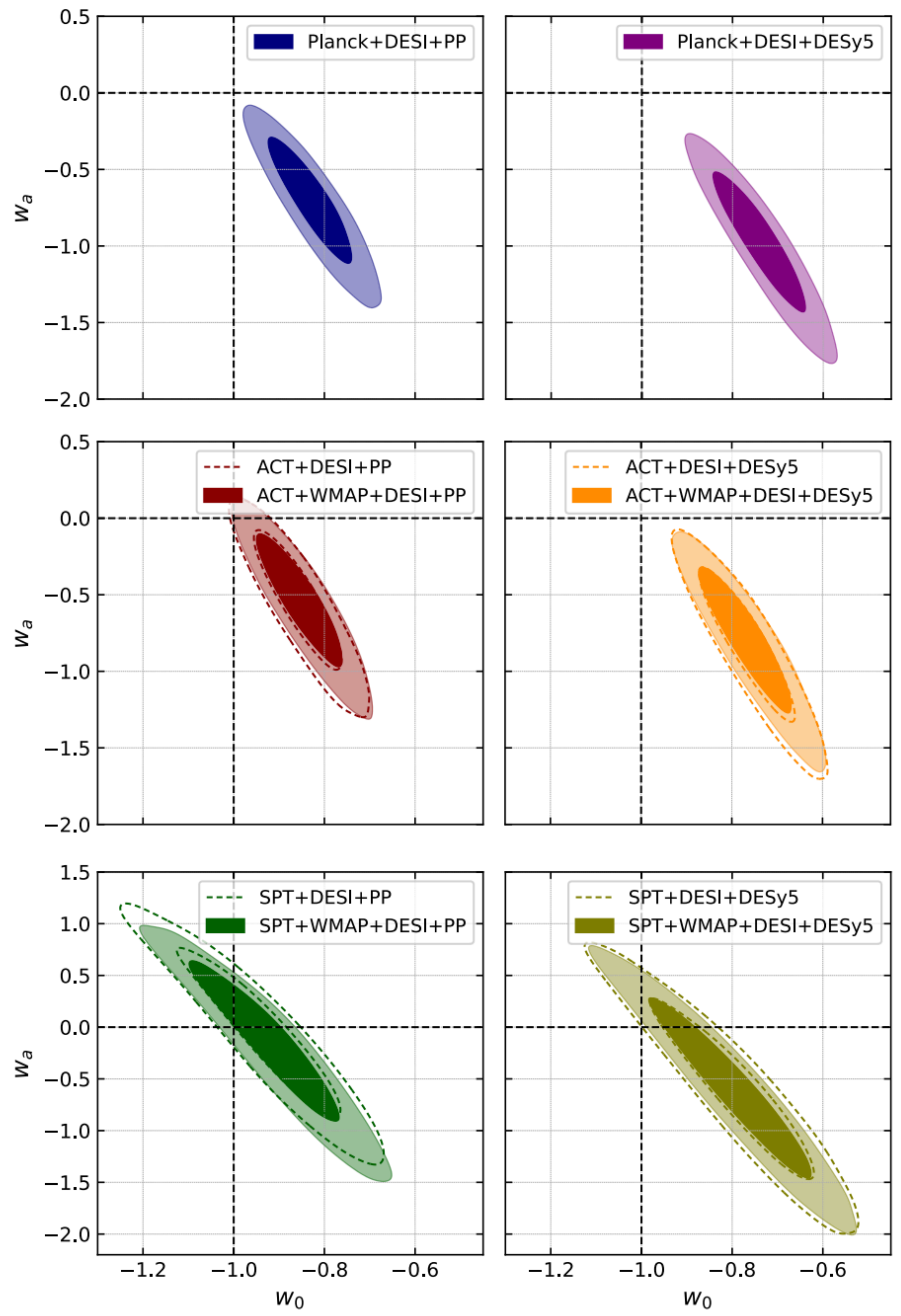
[1] *School of Mathematical and Physical Sciences, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom*

(Dated: September 26, 2024)

Baryon Acoustic Oscillation (BAO) measurements from the Dark Energy Spectroscopic Instrument (DESI) collaboration, when combined with Planck satellite Cosmic Microwave Background (CMB) data and Type Ia Supernovae, suggest a preference for Dynamical Dark Energy (DDE) at a significance level ranging from 2.5σ to 3.9σ. In this work, I test whether, and to what extent, this preference is supported by CMB experiments other than Planck. I analyze the Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT) temperature, polarization, and lensing spectra at small scales, eventually combining them with Planck or WMAP 9-year observations at large angular scales. My analysis shows that ACT and WMAP data, when combined with DESI BAO and Pantheon-plus Supernovae, yield independent constraints with a precision comparable to Planck. Notably, in this case, the cosmological constant value is recovered within two standard deviations. A preference for DDE reappears when Pantheon-plus is replaced with distance moduli measurements from the Dark Energy Survey Supernova program (DESy5). However, it remains less pronounced compared to the Planck-based results. When considering SPT data, no clear preference for DDE is found, although the parameter uncertainties are significantly larger compared to both Planck- and ACT-based constraints. Overall, CMB experiments other than Planck generally weaken the evidence for DDE. I argue that the subsets of Planck data that strengthen the shift toward DDE are the temperature and E-mode polarization anisotropy measurements at large angular scales $\ell \lesssim 30$.

POSSIBLE CAVEATS:

- **DESI BAO are preliminary measurements** released after 1year of observations
- Some BAO and/or SN catalogs are argued to be affected by possible systematics
- **Preference weekend by CMB data other than Planck**
- Planck large-scale (E-mode polarization) measurements strengthen the preference



Evidence (?) For Dynamical Dark Energy

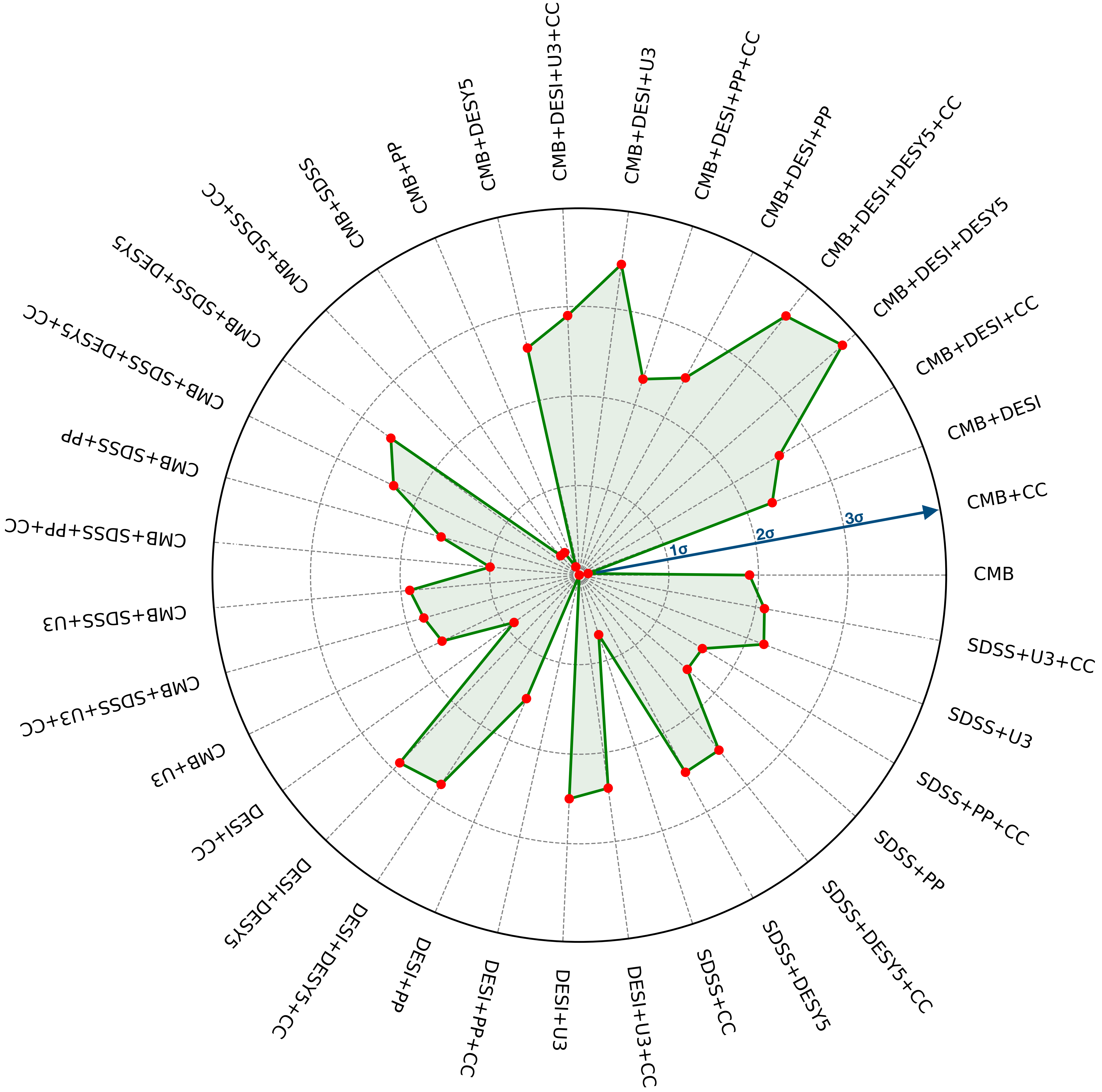
And Yet It Evolves? A Review of what Current Data Can (and Cannot Yet) Say About Evolving Dark Energy

William Giarè,[1,*] Tariq Mahassen,[1,†] Eleonora Di Valentino,[1,‡] and Supriya Pan[2,3,§]

[1] *School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom*
[2] *Department of Mathematics, Presidency University, 86/1 College Street, Kolkata 700073, India*
[3] *Institute of Systems Science, Durban University of Technology, PO Box 1334, Durban 4000, Republic of South Africa*

(Dated: January 12, 2025)

The accelerated expansion of the Universe presents one of the most compelling challenges in contemporary cosmology, traditionally explained by a cosmological constant (Λ) within the ΛCDM paradigm. However, recent observational advancements have opened the door to more complex scenarios, including Dynamical Dark Energy (DDE) characterized by a time-varying equation of state. This focus review examines the robustness of the evidence for DDE as derived from the Chevallier-Polarski-Linder (CPL) parameterization ($w(a) = w_0 + w_a(1-a)$), leveraging the latest constraints from the Dark Energy Spectroscopic Instrument (DESI). By synthesizing data from DESI Baryon Acoustic Oscillations (BAO) with complementary probes such as Planck Cosmic Microwave Background, PantheonPlus, Union3, and DESY5 Type Ia supernovae, and Cosmic Chronometers, we assess the statistical significance and consistency of DDE signals across different dataset combinations. Our analysis highlights the varying degrees of preference for DDE, particularly in scenarios including DESI-BAO and supernovae, where transitions from past phantom-like to present quintessence-like behaviors are observed. These findings underscore the pivotal role of DESI in advancing our understanding of the Dark Energy sector and pave the way for future explorations into alternative cosmological models.



UPS and DOWNS:

- **The strength of the preference can change significantly with the specific dataset...**

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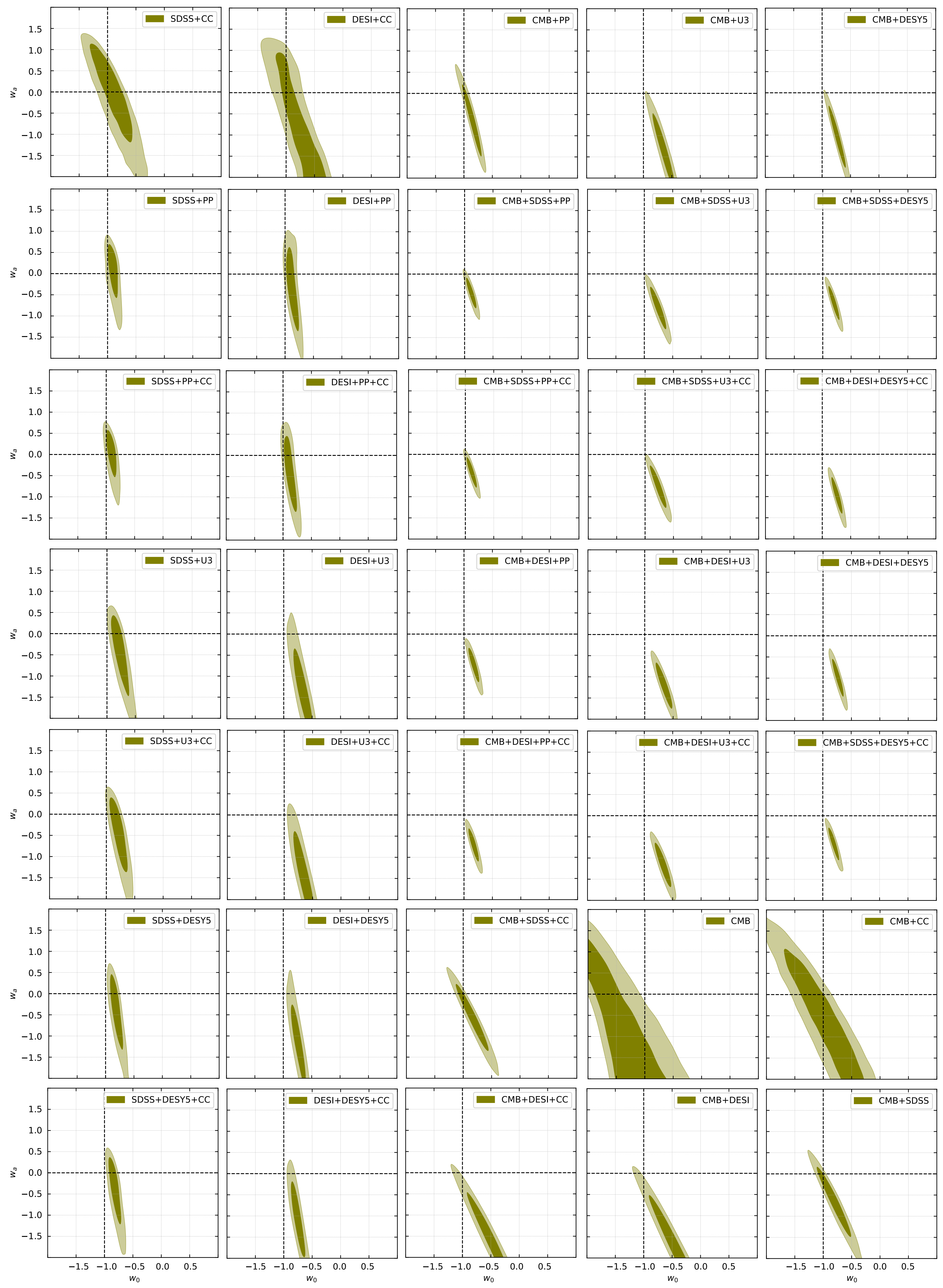
UPS and DOWNS:

- **The strength of the preference can change significantly with the specific dataset...**
- ... but it is found in (independent) most constraining combinations



Hints of New Physics?

Interacting Dark Energy after DESI Baryon Acoustic Oscillation measurements

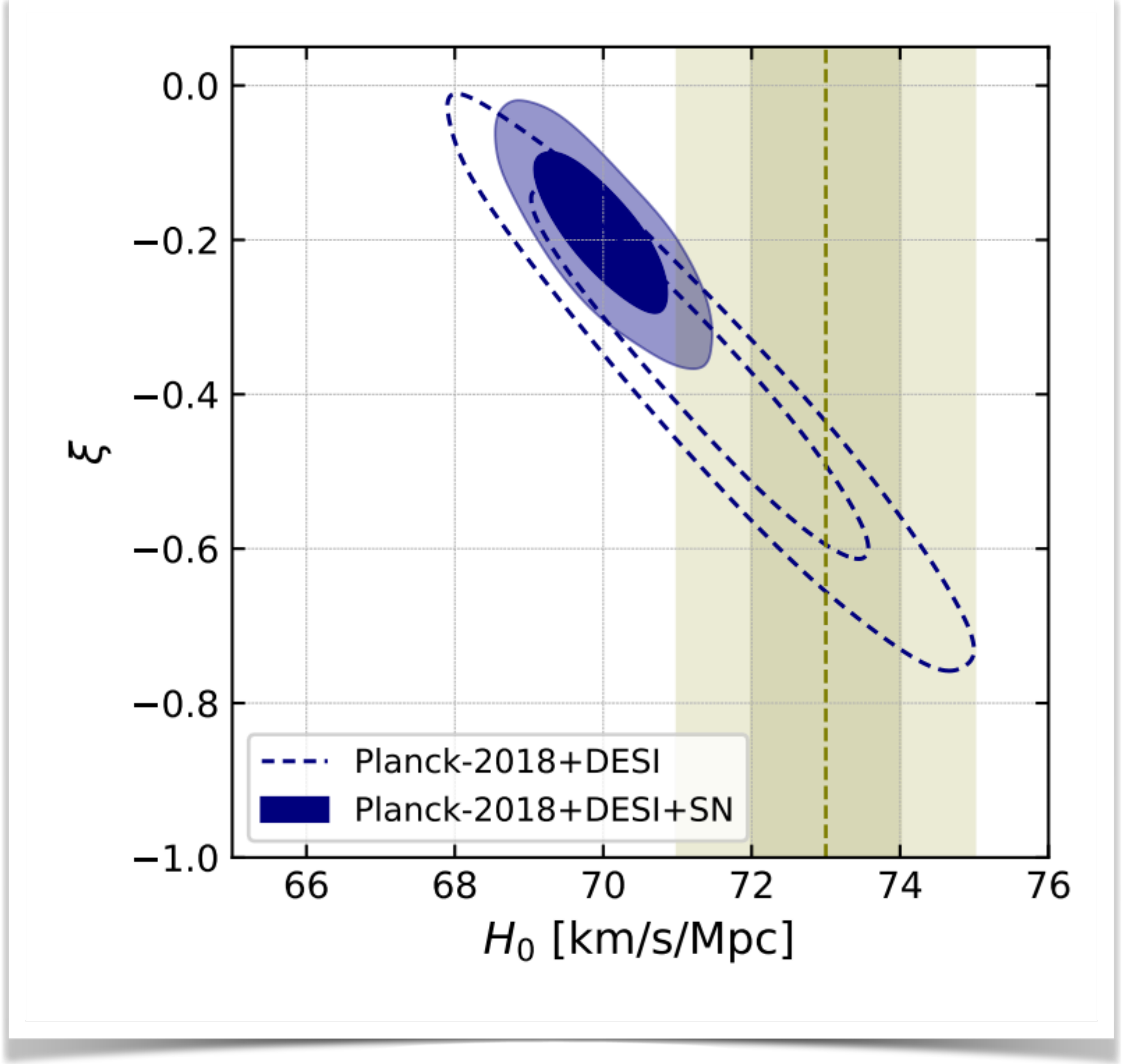
William Giarè,[1,*] Miguel A. Sabogal,[2,†] Rafael C. Nunes,[2,3,‡] and Eleonora Di Valentino[1,§]

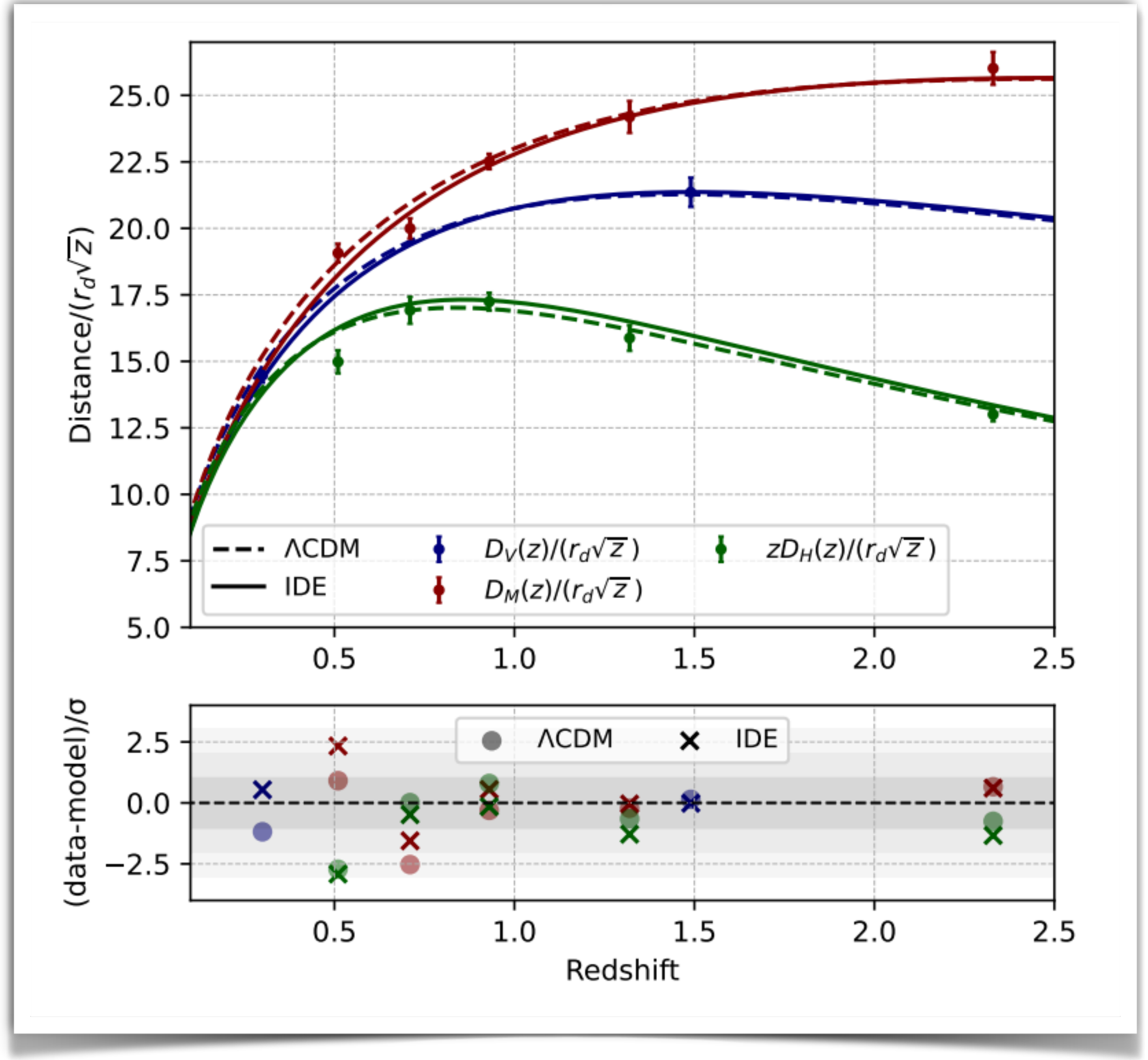
[1] School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom

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

[3] Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais, Avenida dos Astronautas 1758, São José dos Campos, 12227-010, São Paulo, Brazil

We investigate the implications of the Baryon Acoustic Oscillation measurements released by the Dark Energy Spectroscopic Instrument (DESI) for Interacting Dark Energy (IDE) models characterized by an energy-momentum flow from Dark Matter to Dark Energy. By combining Planck-2018 and DESI data, we observe a preference for interactions exceeding the 95% confidence level, yielding a present-day expansion rate $H_0 = 71.4 \pm 1.5$ km/s/Mpc, in agreement with SH0ES. This preference 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, high and low redshift data can be equally or better explained within the IDE framework compared to ΛCDM, while also yielding higher values of H_0 in better agreement with the local distance ladder estimate.





Imprints in the Early Universe

Number of Neutrino Species

The amount of the radiation energy density is commonly parameterized in terms of the effective number of relativistic degrees of freedom

$$\Omega_r \simeq \Omega_\gamma \left(1 + 0.23\, N_{\rm eff}\right)$$

In the Standard model of cosmology and Particle physics $N_{\rm eff} = 3.04.$ A larger $N_{\rm eff}$ will increase $H(z) \propto \left[\Omega_r \cdot (1+z)^4\right]^{1/2}$

- **CMB:** a higher $N_{\rm eff}$ at recombination implies:

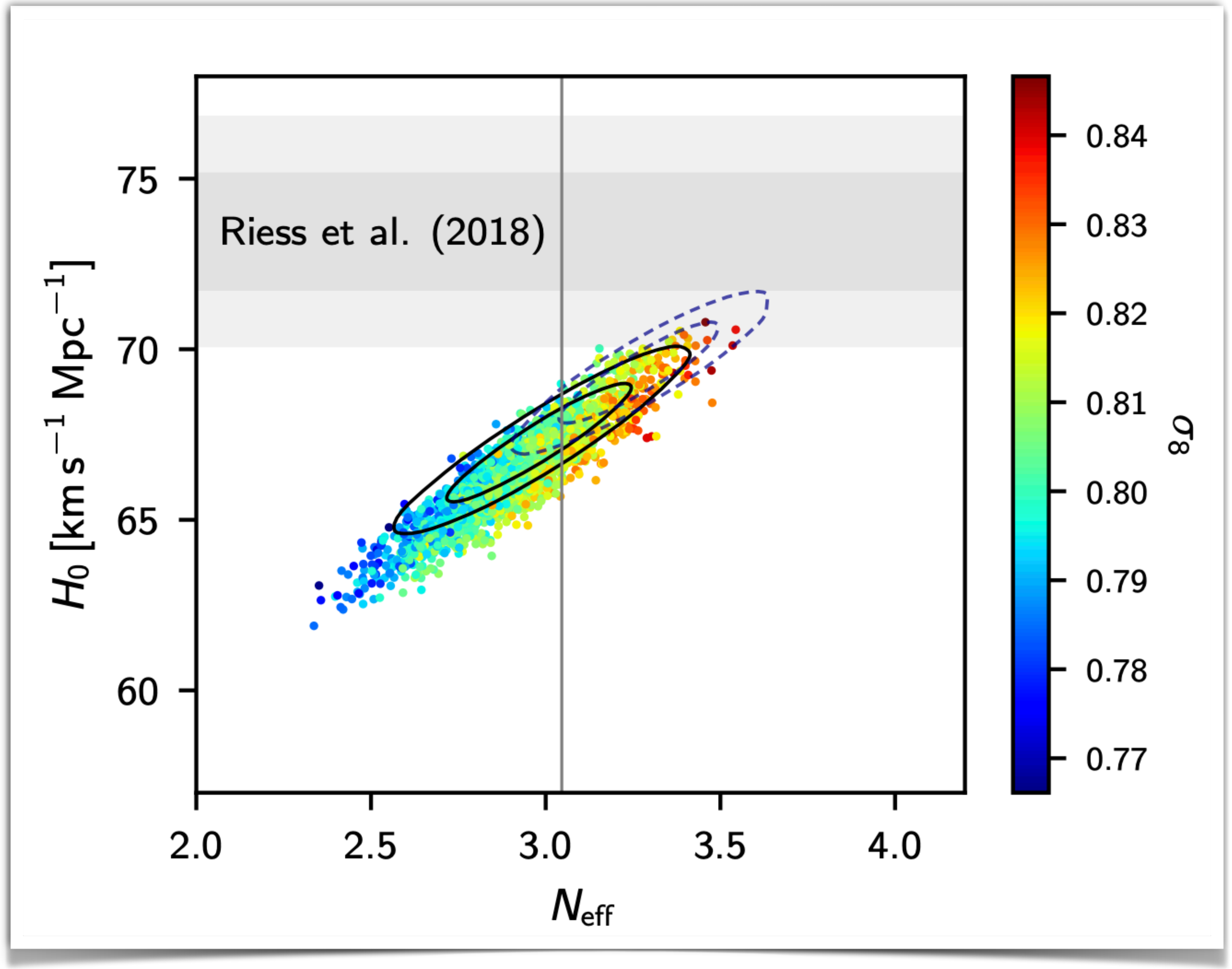
  1) **Changing the matter-radiation equivalence and enhancing the early ISW.** This contributes to the primary anisotropy, **increasing the first acoustic peaks.**

  2) **Reducing the sound horizon** and the angular scale of the acoustic peaks. This gives a **horizontal shift of the peak positions towards higher multipoles.**

$$\boxed{\Delta N_{\rm eff} < 0.34}$$

Planck 2018 results. VI

[arXiv:1807.06209]



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