NEUTRINO COSMOLOGY

- 2024 EDITION -

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ASTROPARTICLE SYMPOSIUM 2024

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OVERVIEW

1 Cosmological Bounds on Neutrino Species, Mass & Ordering

2 Neutrino - Dark Matter Interactions

3 Outlooks and Conclusions

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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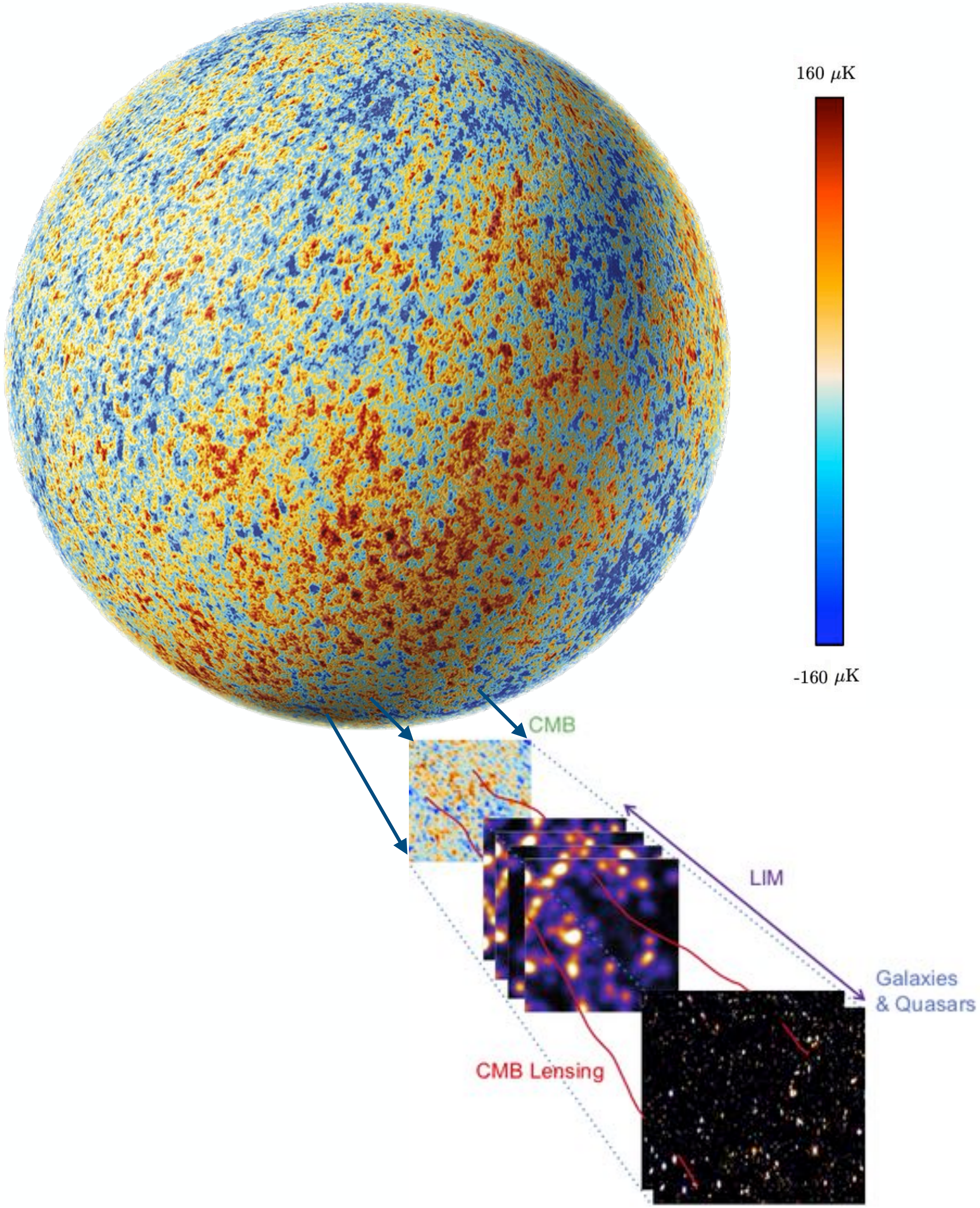
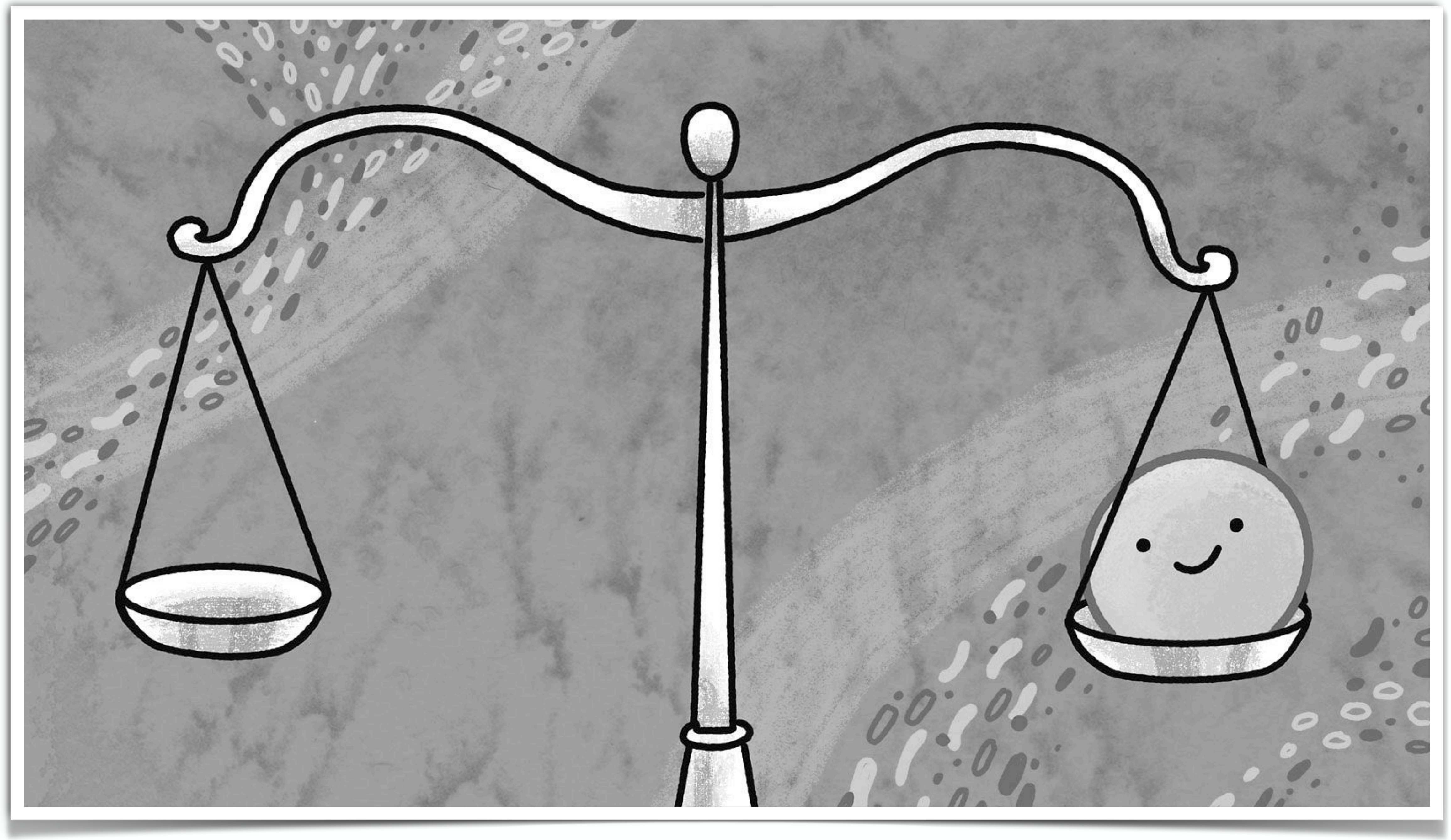
…

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



1 COSMOLOGICAL BOUNDS ON NEUTRINO SPECIES, MASS & ORDERING



Main References:

- **WG,** Forconi, Di Valentino, Melrchiorri — MNRAS 520 (2023) 2 ; [arXiv: 2210.14159]
- Di Valentino, Gariazzo, **WG**, Mena — PRD 108 (2023) 8, 083509 ; [arXiv: 2305.12989]
- **WG,** Mena, Di Valentino — PRD 108 (2023) 10, 103539 ; [arXiv: 2307.14204]
- Gariazzo, **WG**, Mena, Di Valentino — (under review in PRD) ; [arXiv: 2404.11182]
- **WG** — PRD 109 (2024) 12, 12354 ; [arXiv: 2404.12779]
- Jun-Qian Jiang, **WG**, *et. al.* — (under review in JCAP) [arXiv: 2407.18047] *

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"A neutrino mass mismatch could shake cosmology's foundations"

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 $H(z) \propto \left[\Omega_r \cdot (1+z)^4\right]^{1/2}$

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

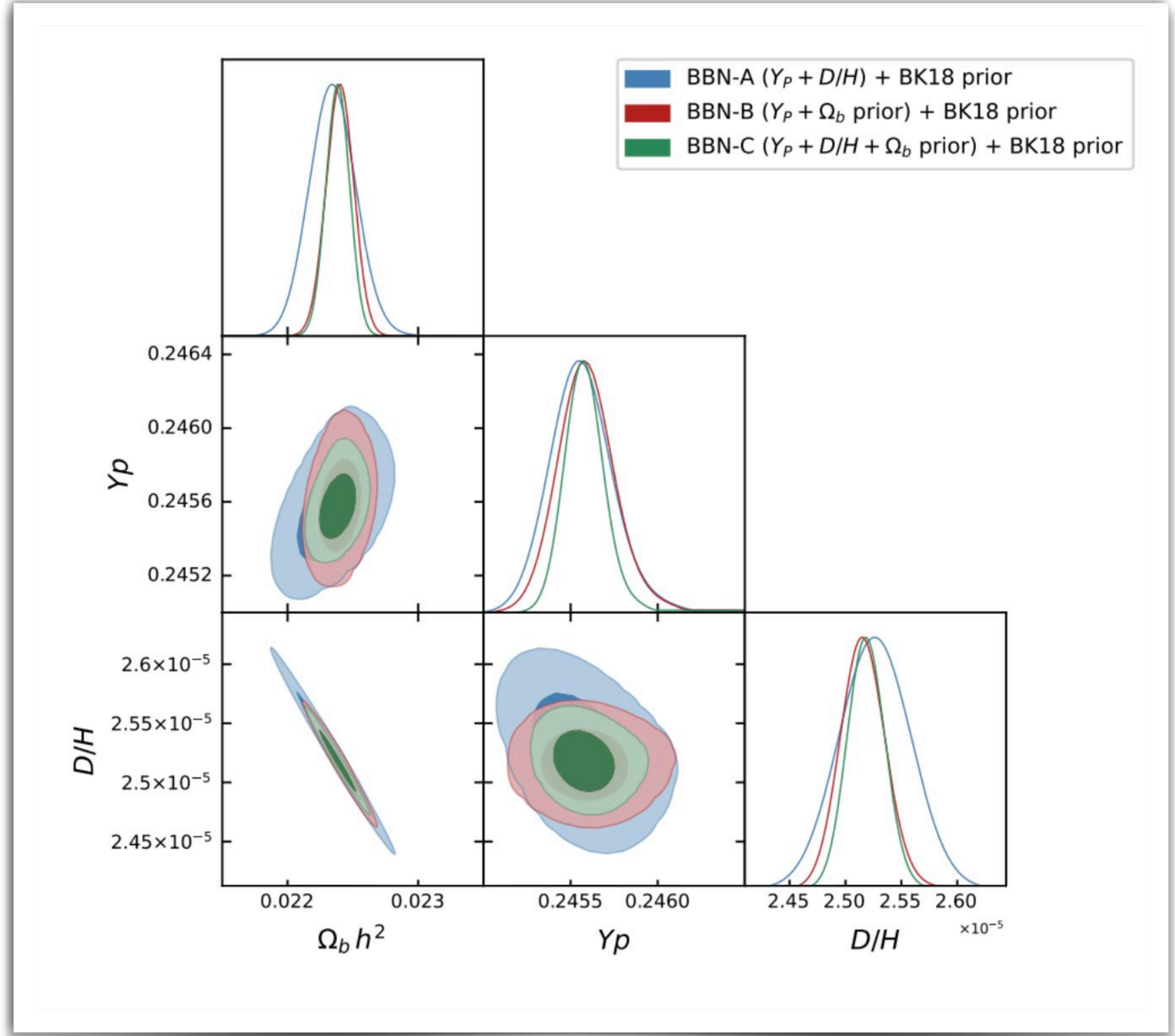
  1) A **higher neutron-to-proton ratio**

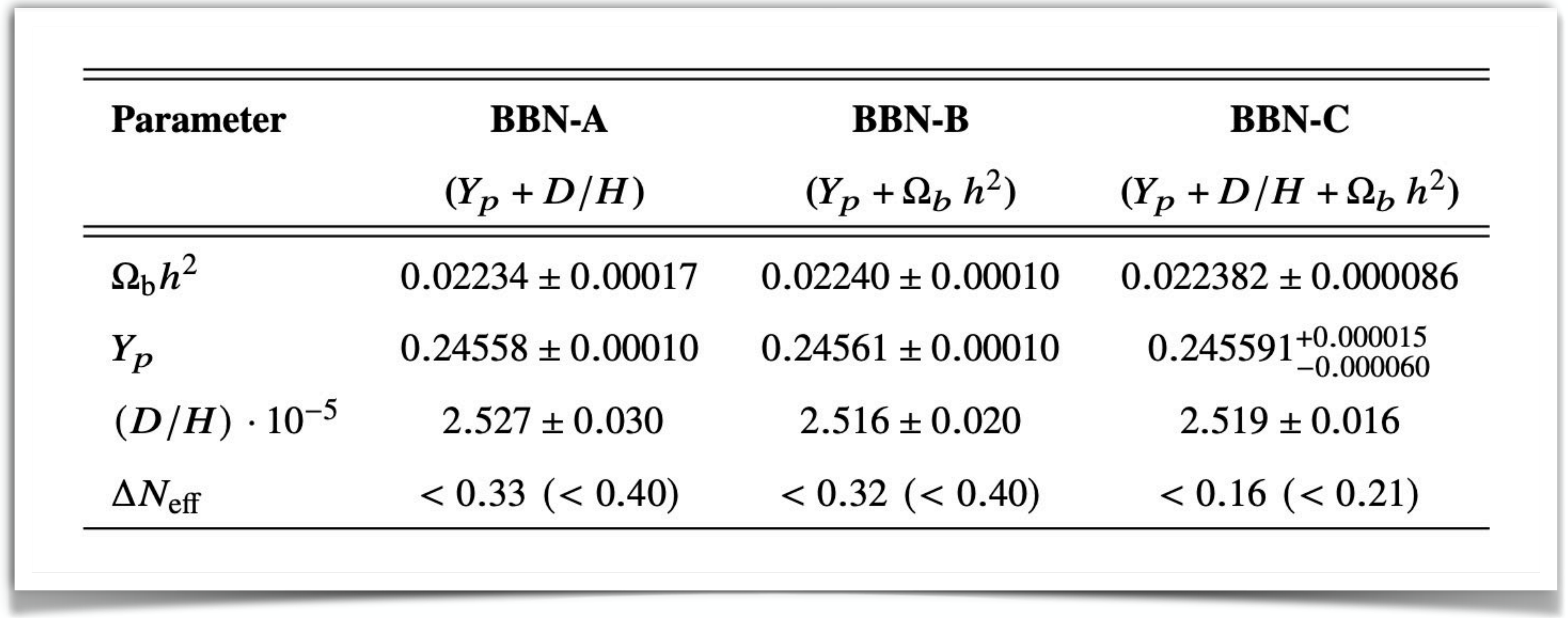
  2) A **larger fraction of primordial Helium and Deuterium**

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

$$\boxed{\Delta N_{\rm eff} < 0.3 - 0.4}$$

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





Parameter	BBN-A $(Y_p + D/H)$	BBN-B $(Y_p + \Omega_b h^2)$	BBN-C $(Y_p + D/H + \Omega_b h^2)$
$\Omega_b h^2$	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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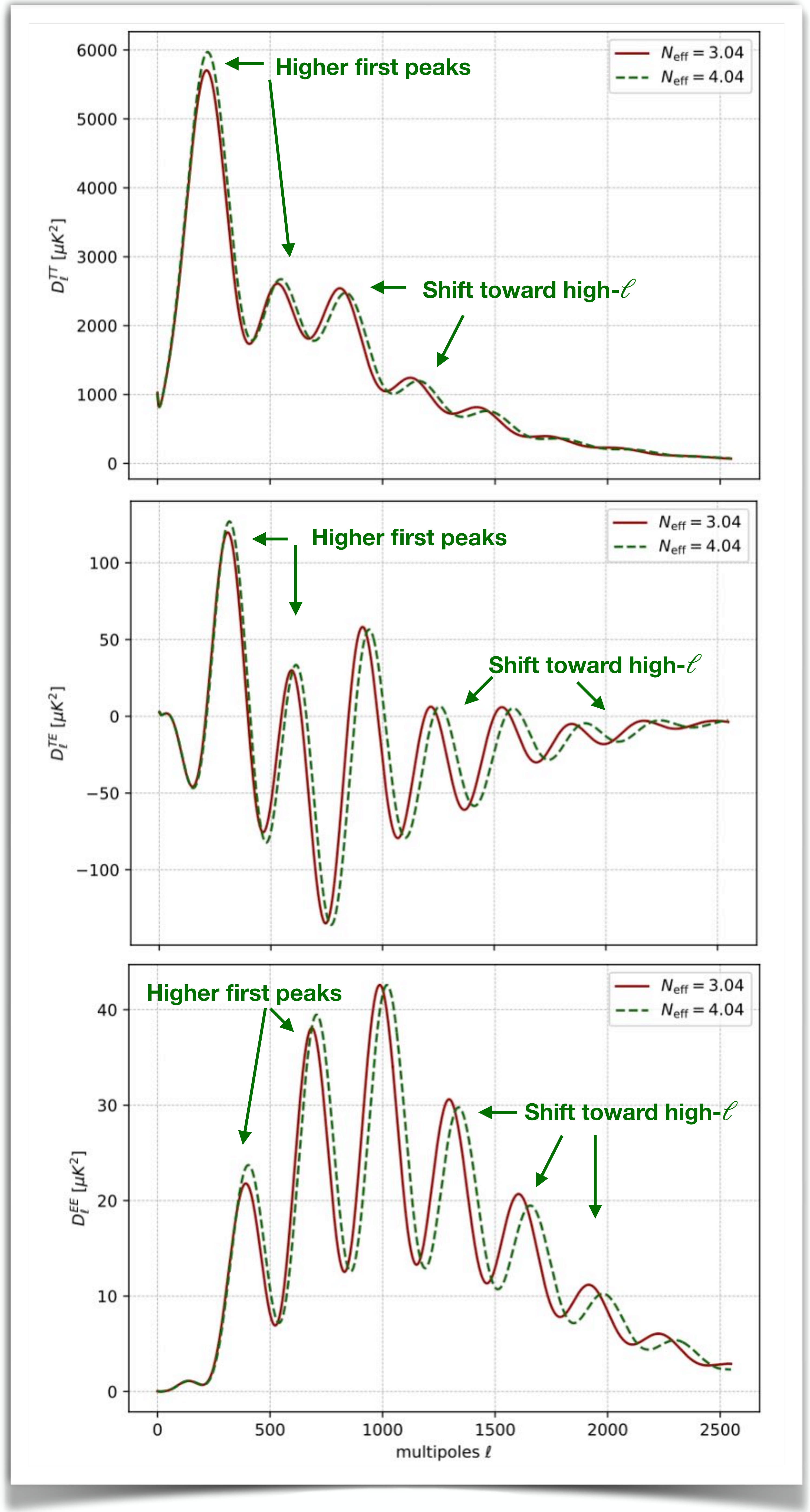
- **CMB:** a higher $N_{\rm eff}$ at recombination implies:

  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.**

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



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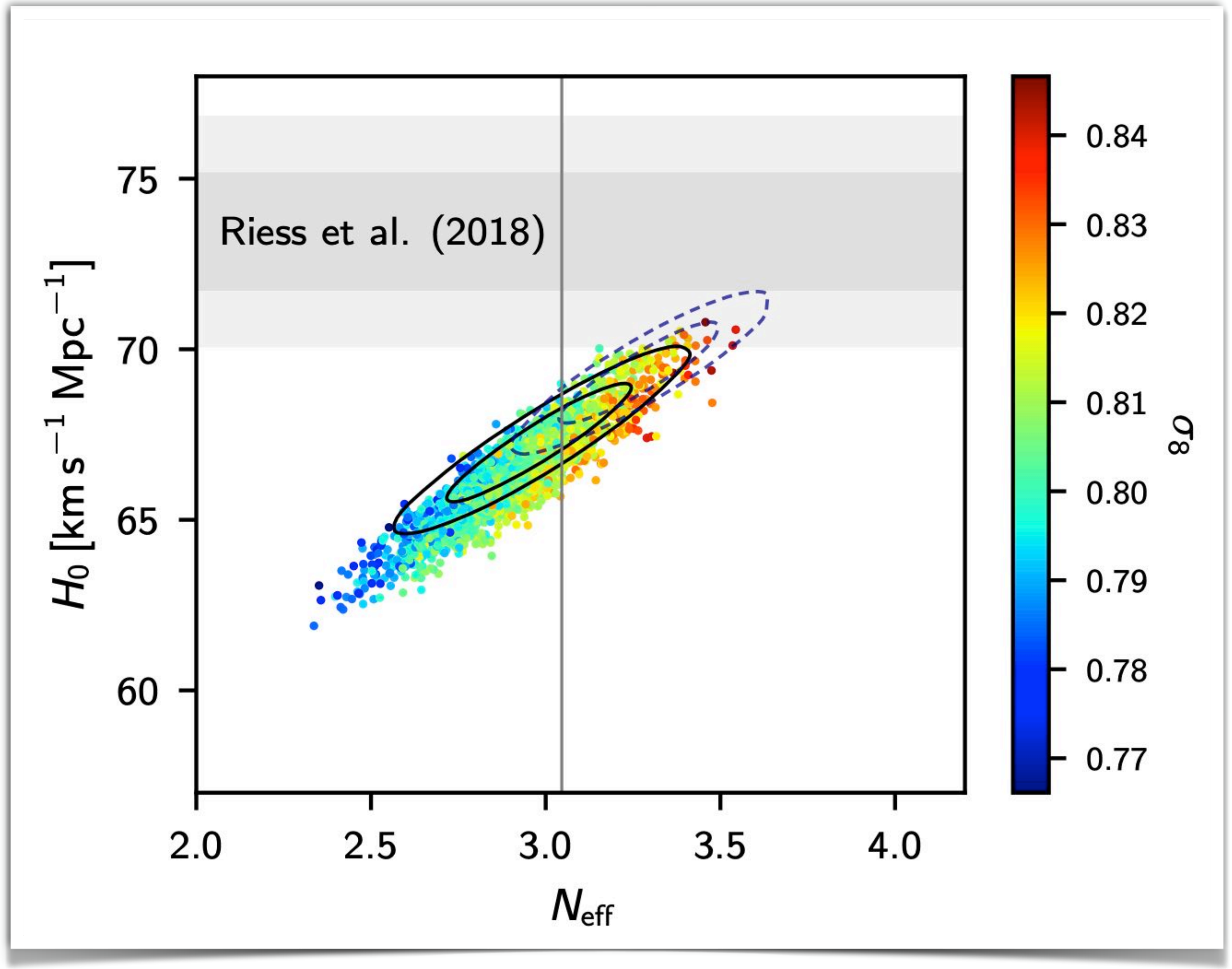
Planck 2018 results. VI

[arXiv:1807.06209]



IMPRINTS IN THE EARLY UNIVERSE

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779

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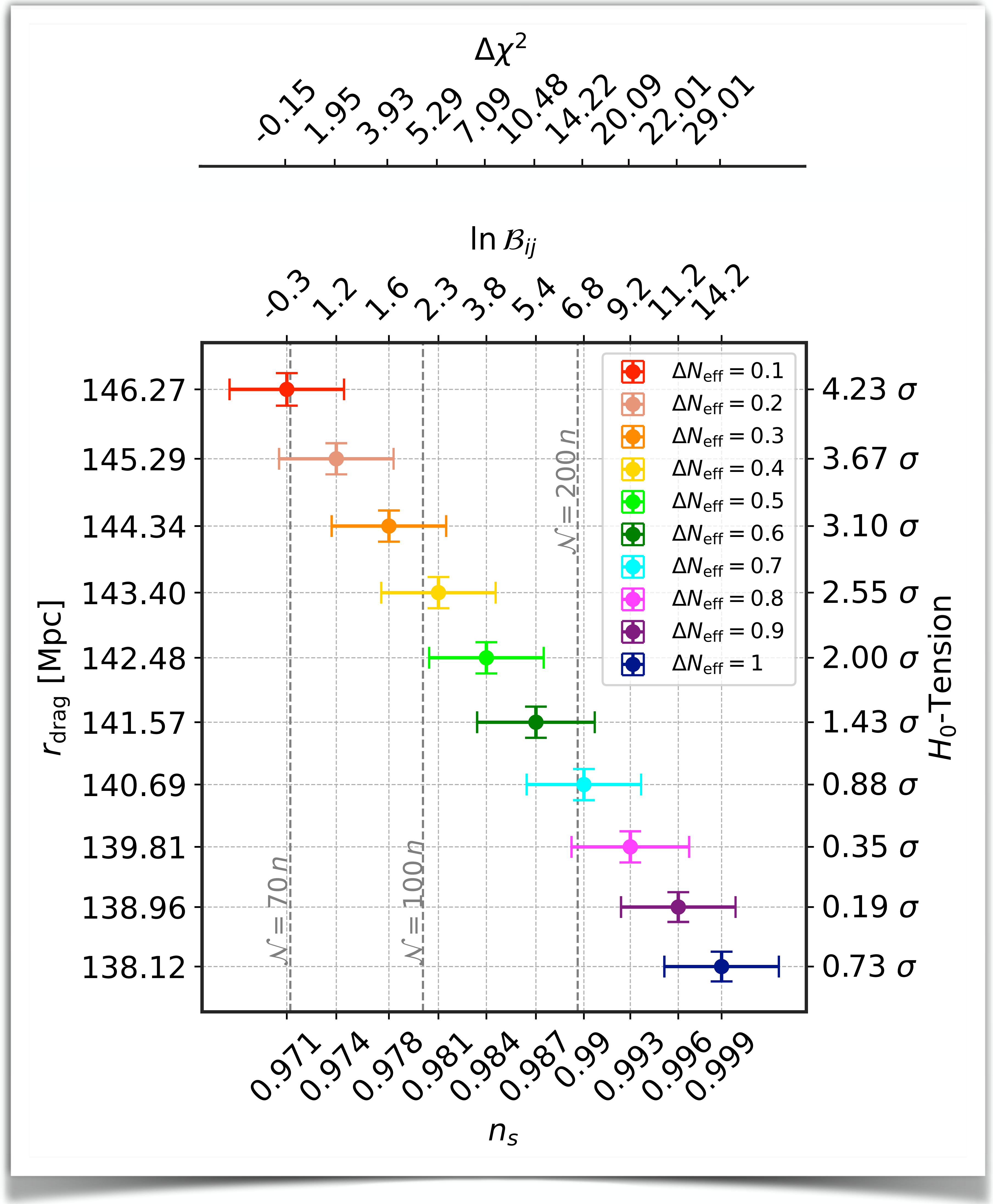

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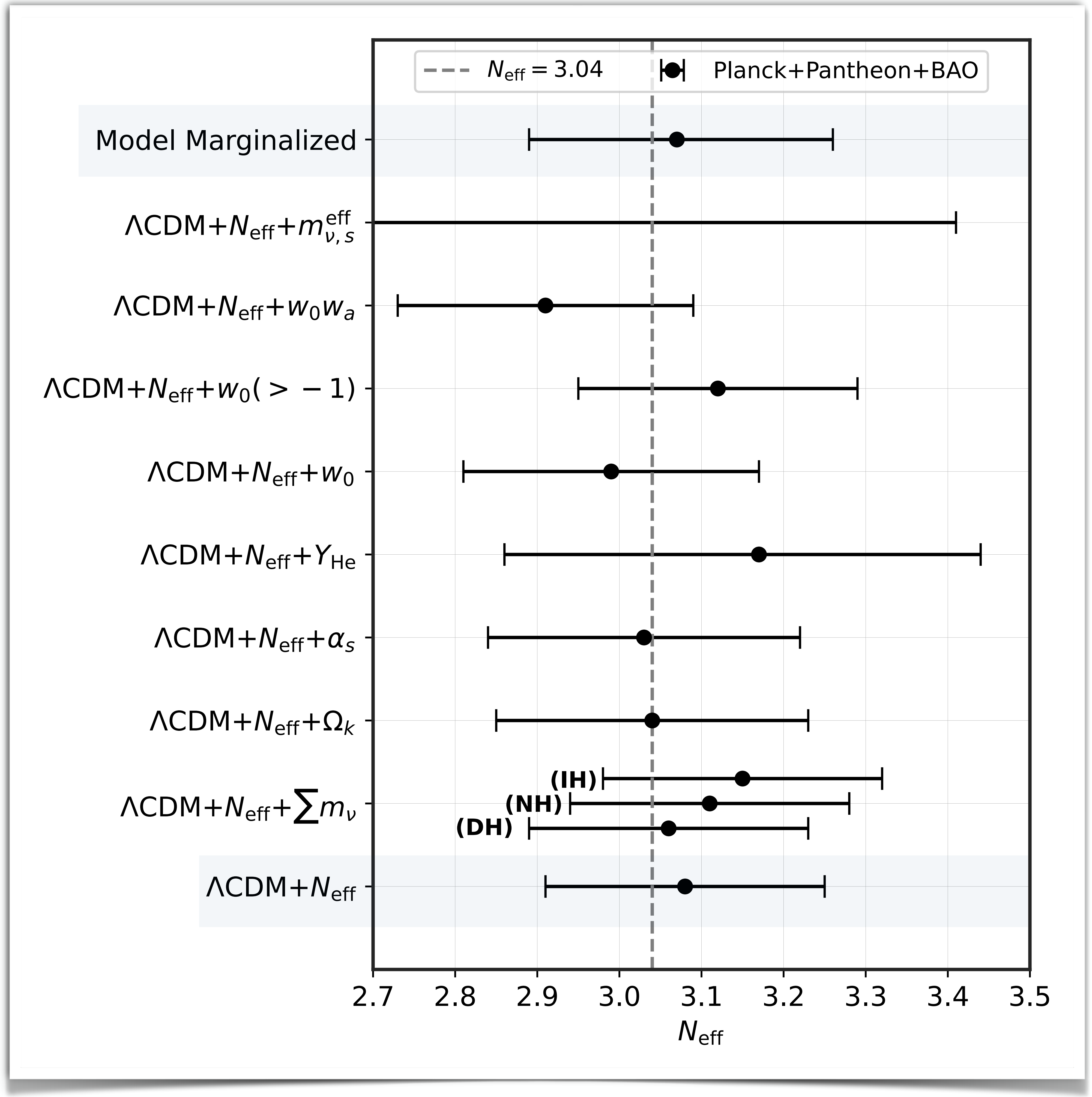
Gariazzo, **WG,** *et al* — (under review in PRD) • arXiv: 2404.11182



IMPRINTS IN THE EARLY UNIVERSE

TOTAL NEUTRINO MASS AND ORDERING

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**.

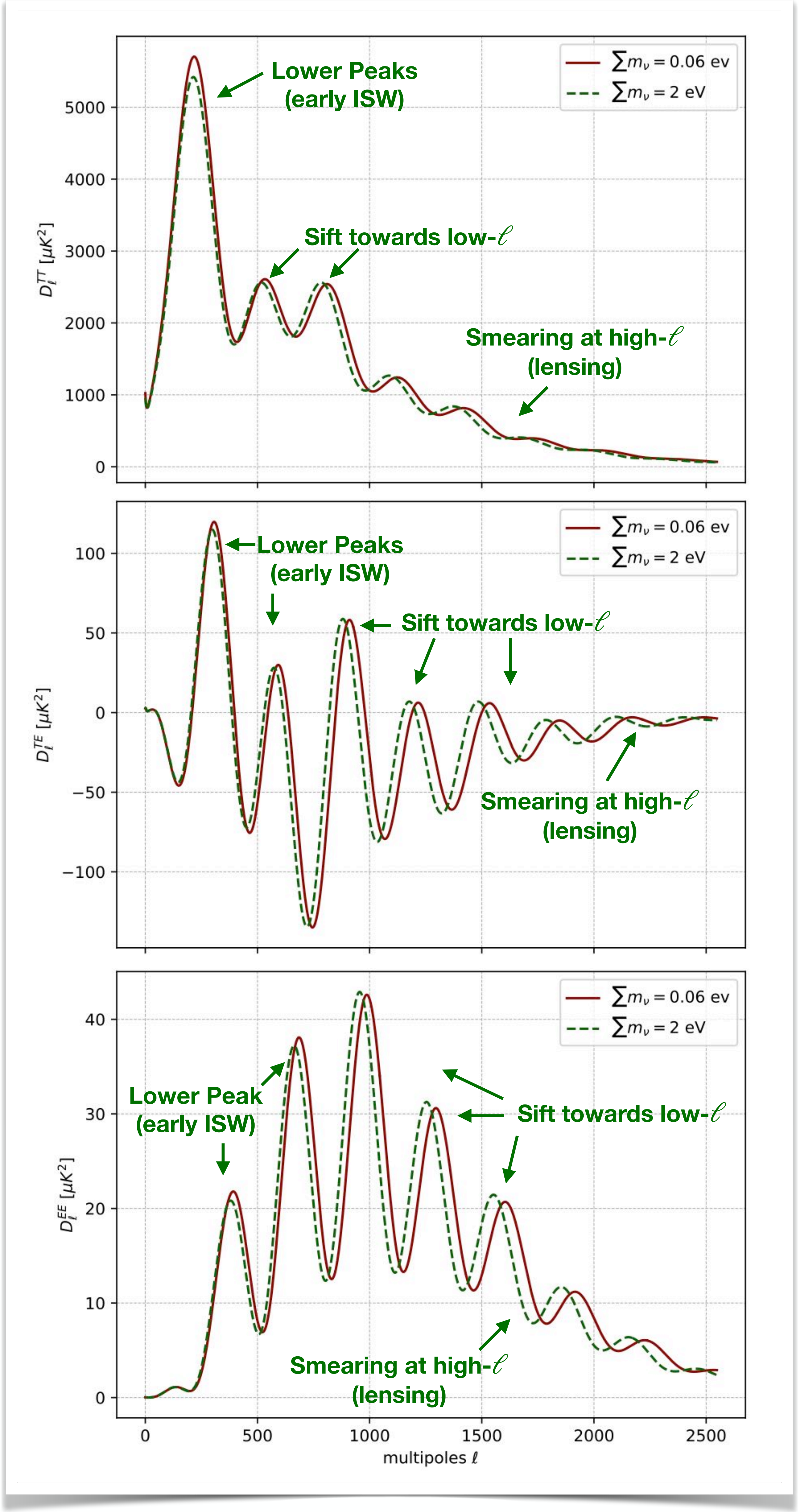
3) it **reduces weak lensing effects** on the CMB by **suppressing the matter power spectrum and CMB spectra at small scales**.

$\sum m_\nu < 0.26\,\mathrm{eV}$ Planck - (TT TE EE)

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

Planck 2018 results. VI

[arXiv:1807.06209]



IMPRINTS IN THE EARLY UNIVERSE

TOTAL NEUTRINO MASS AND ORDERING

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

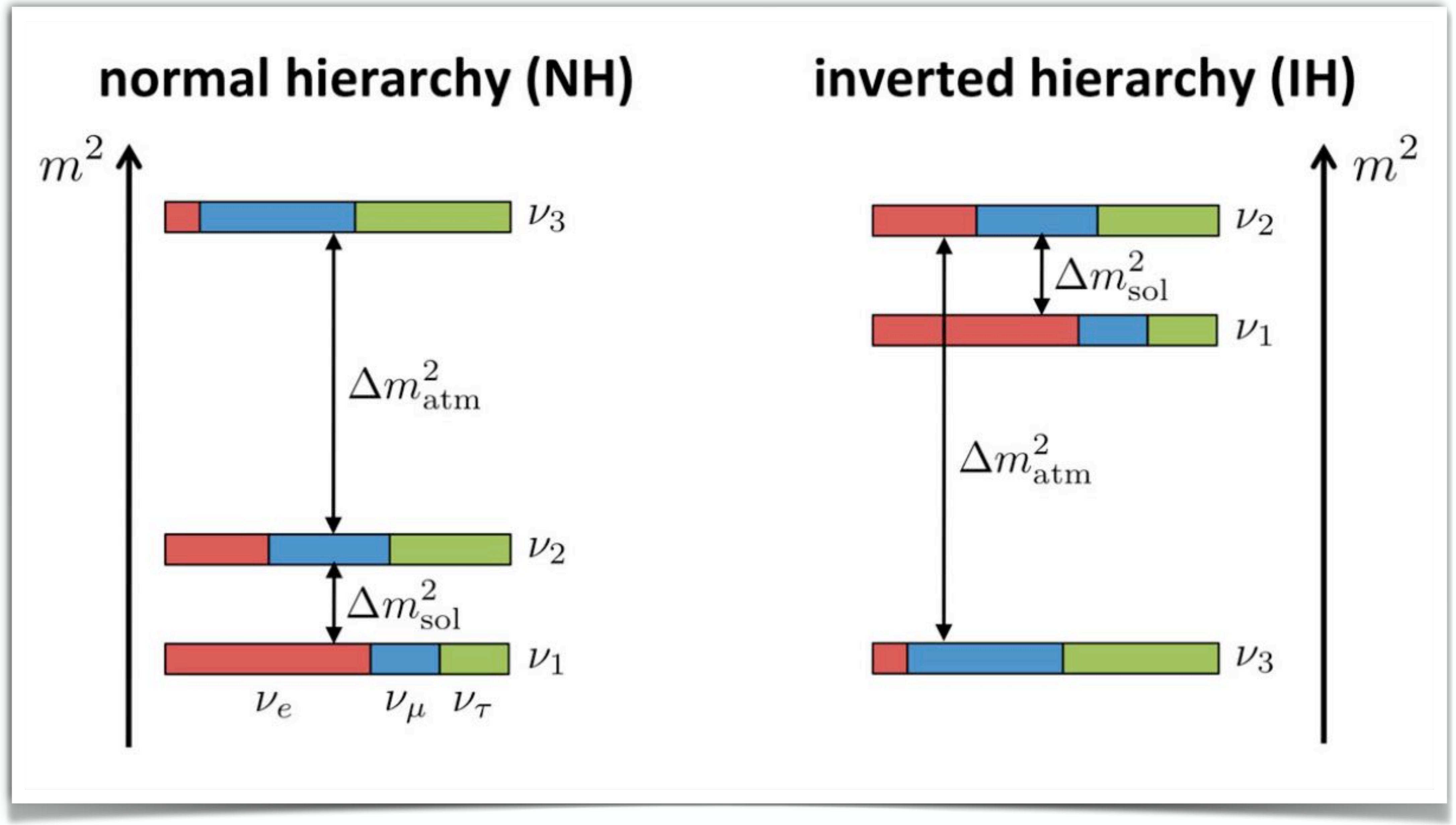
- **Atmospheric splitting**: $|\Delta m^2_{3,1}| = |m_3^2 - m_1^2| \sim 2.55 \times 10^{-3}$ eV^2
- **Solar splitting**: $\Delta m^2_{2,1} = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5}$ eV^2

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!*



Imprints in the Early Universe

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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 an upper limit on the total mass from neutrino oscillations

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

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

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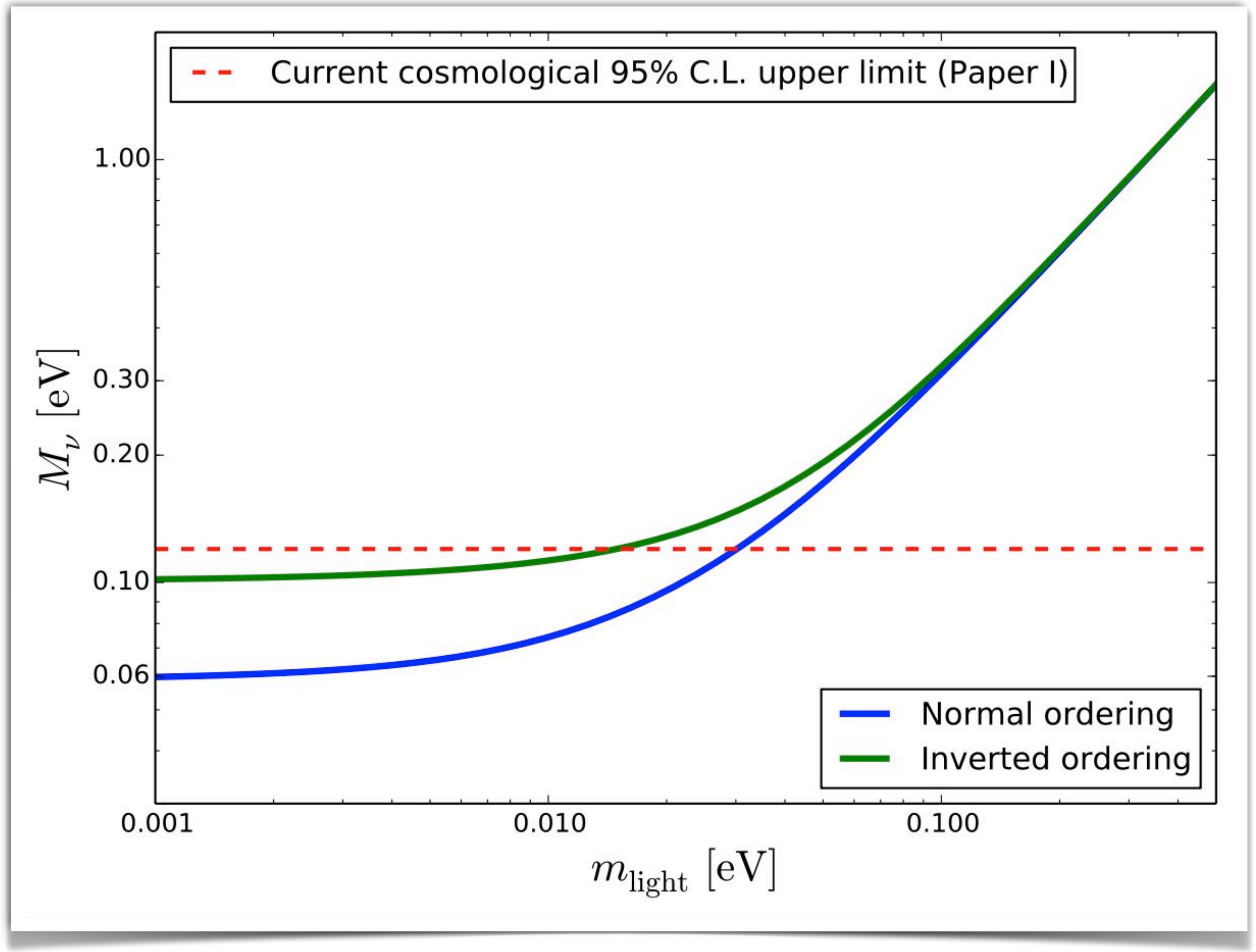

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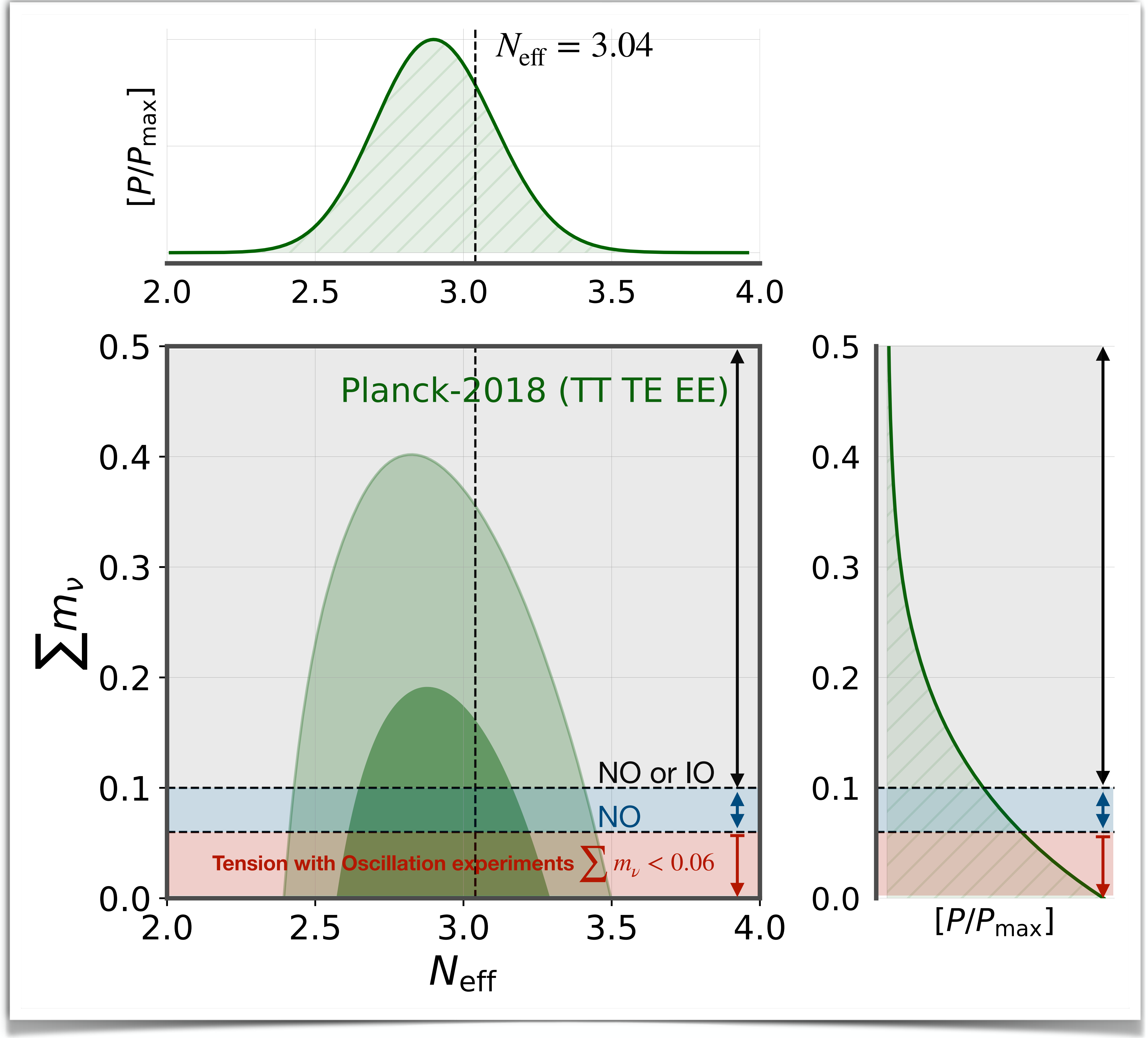
We need to do better!



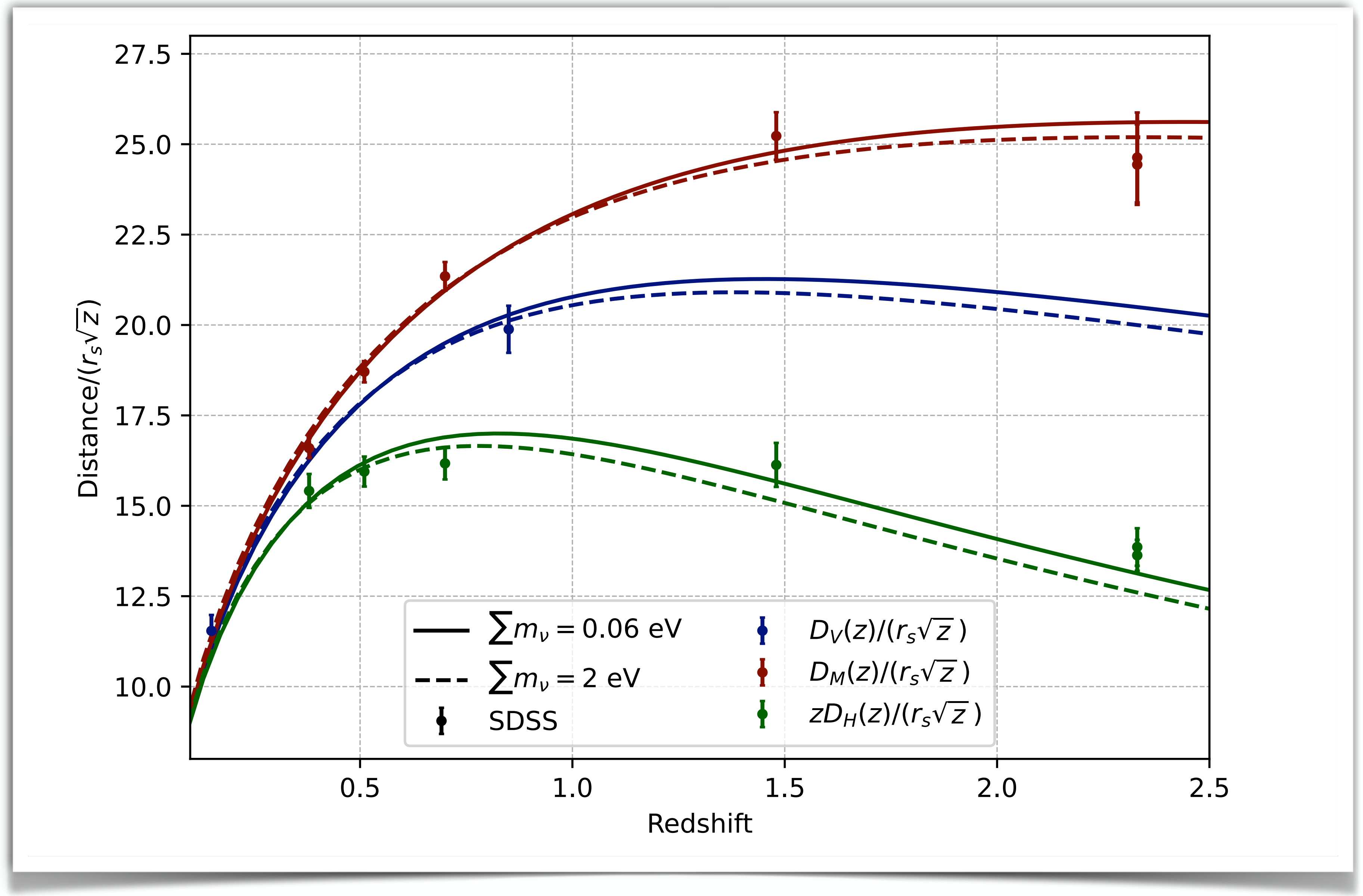
IMPRINTS IN THE LOCAL UNIVERSE

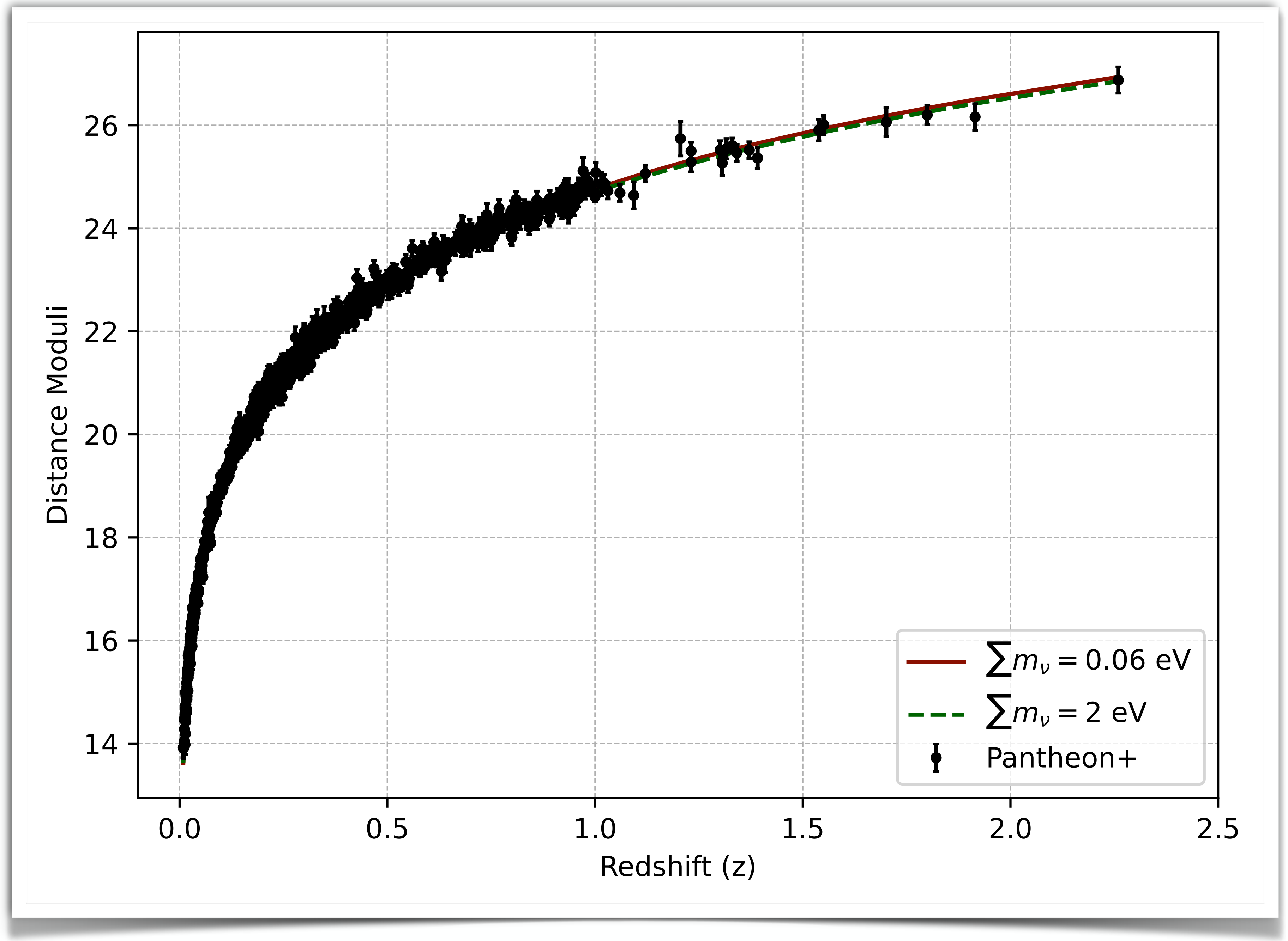
TOTAL NEUTRINO MASS AND ORDERING

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.

2) Neutrinos will suppress structure formation, affecting other local observables such as the matter power spectrum and weak lensing. We can examine the **large-scale structure** of the Universe.





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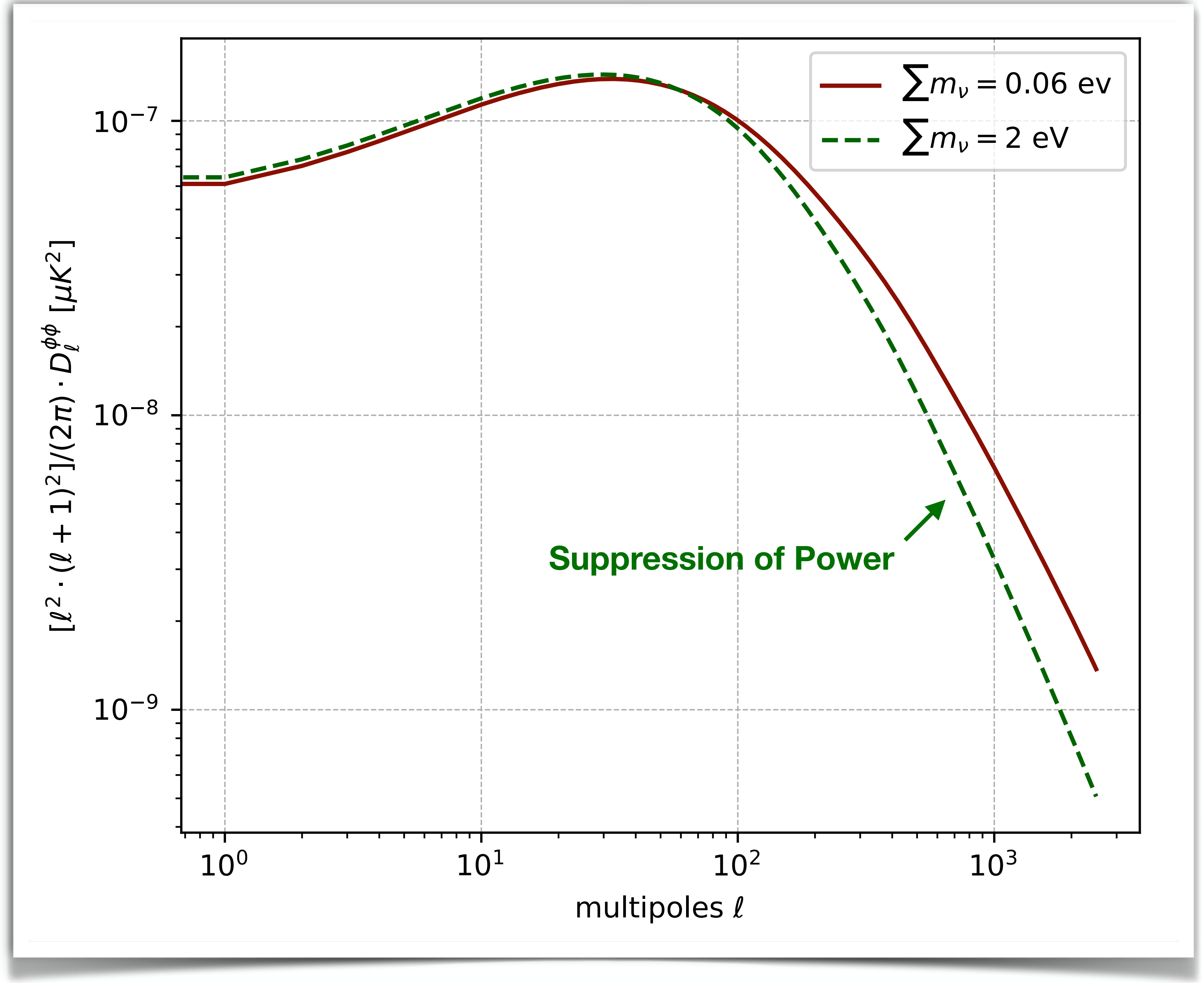
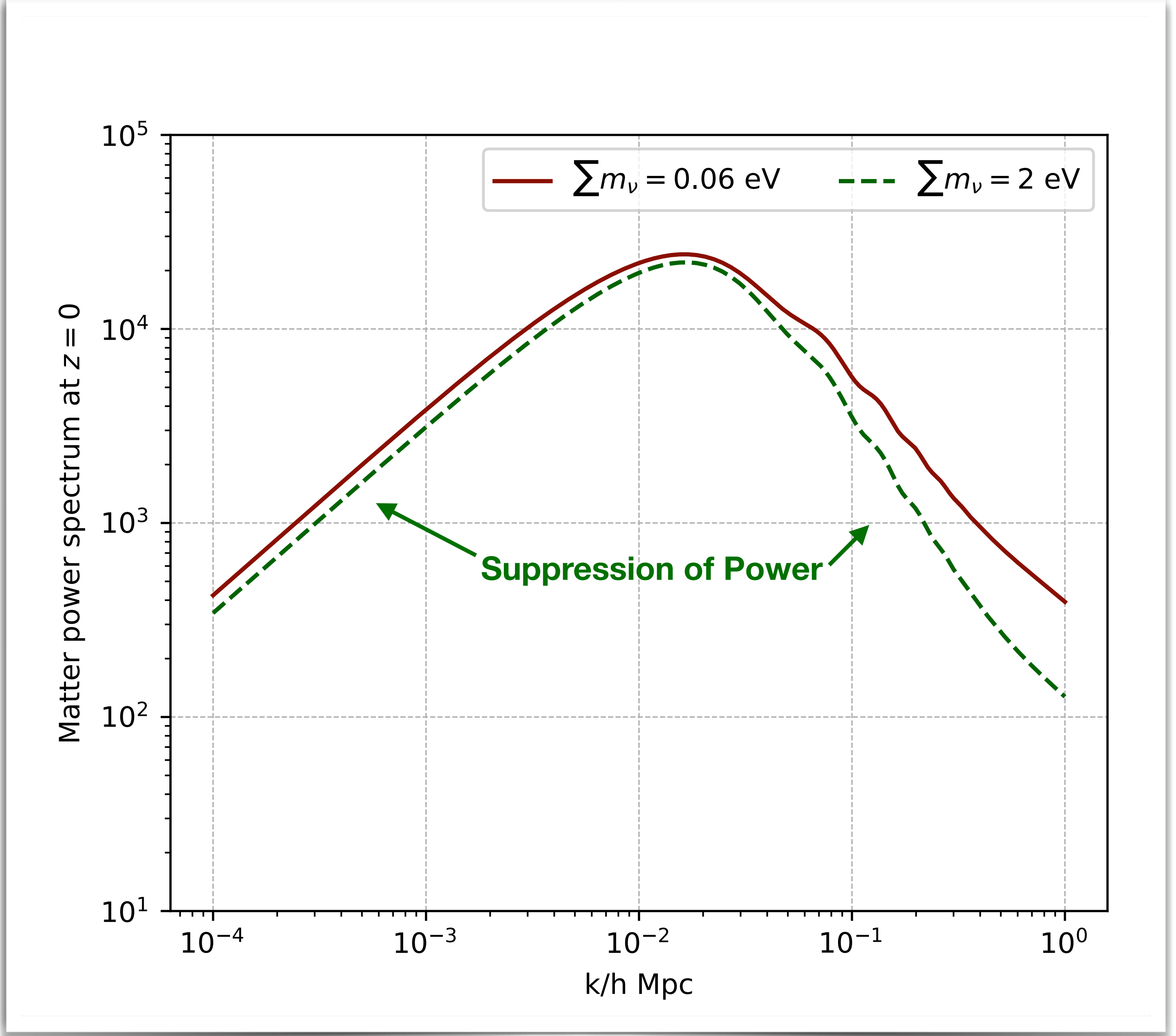




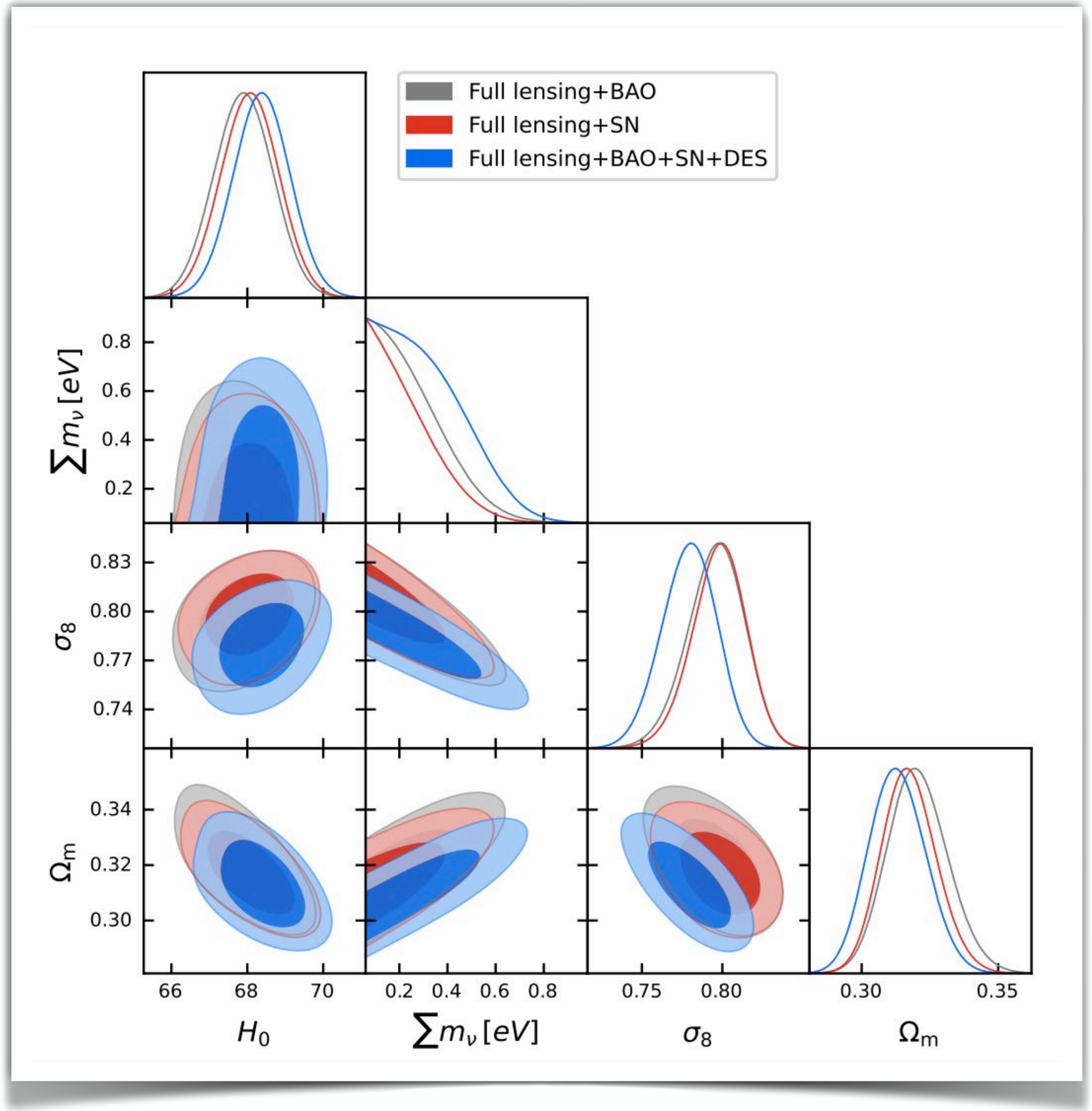
IMPRINTS IN THE LOCAL UNIVERSE

TOTAL NEUTRINO MASS AND ORDERING

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



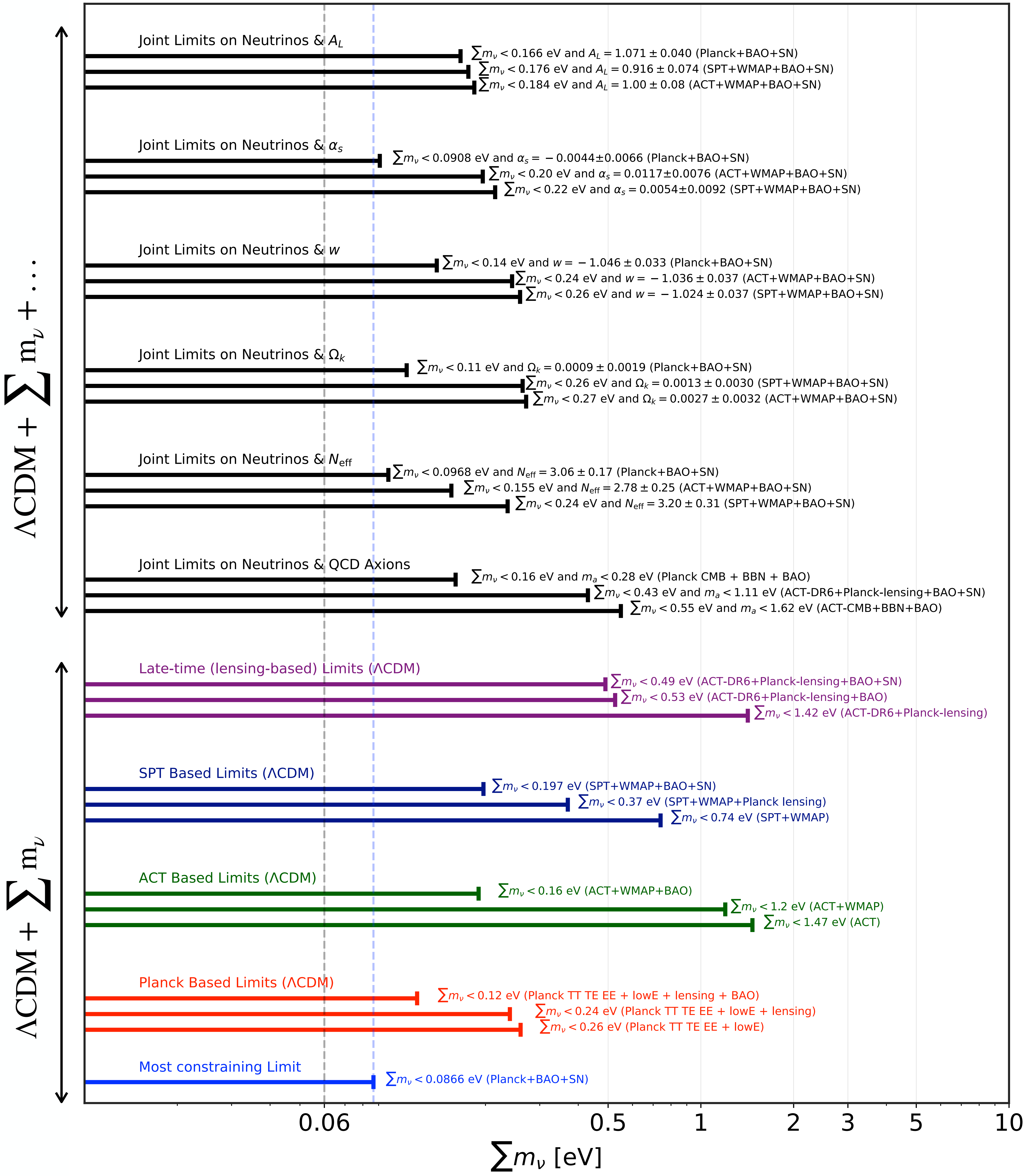
NEUTRINO COSMOLOGY BEFORE DESI BAO

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

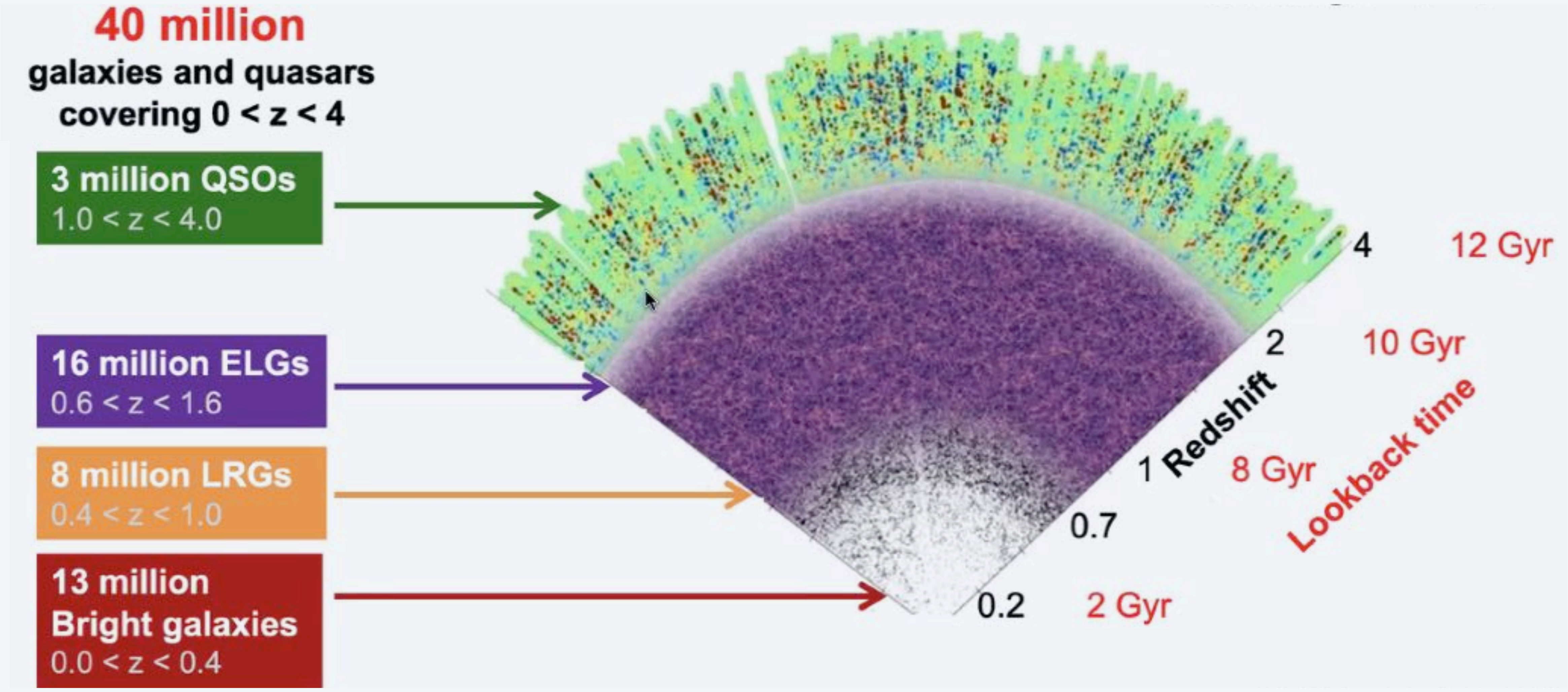
* From **Planck + lensing + pantheon-plus + DR12 (BAO+RSD) + DR16 (BAO only)** as reported in Di Valentino et al. [arXiv: 2106.15267]



NEUTRINO COSMOLOGY AFTER DESI BAO

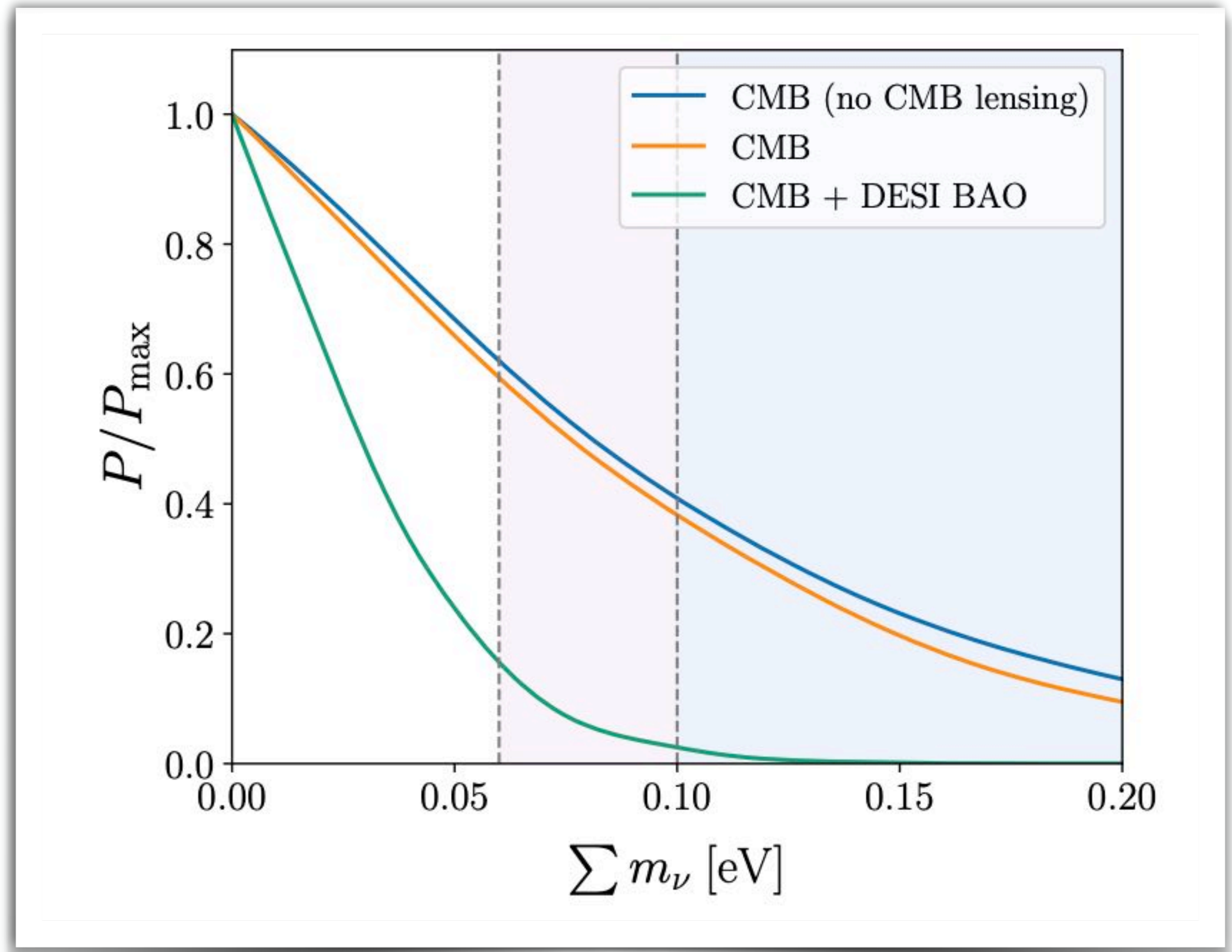
TOTAL NEUTRINO MASS AND ORDERING

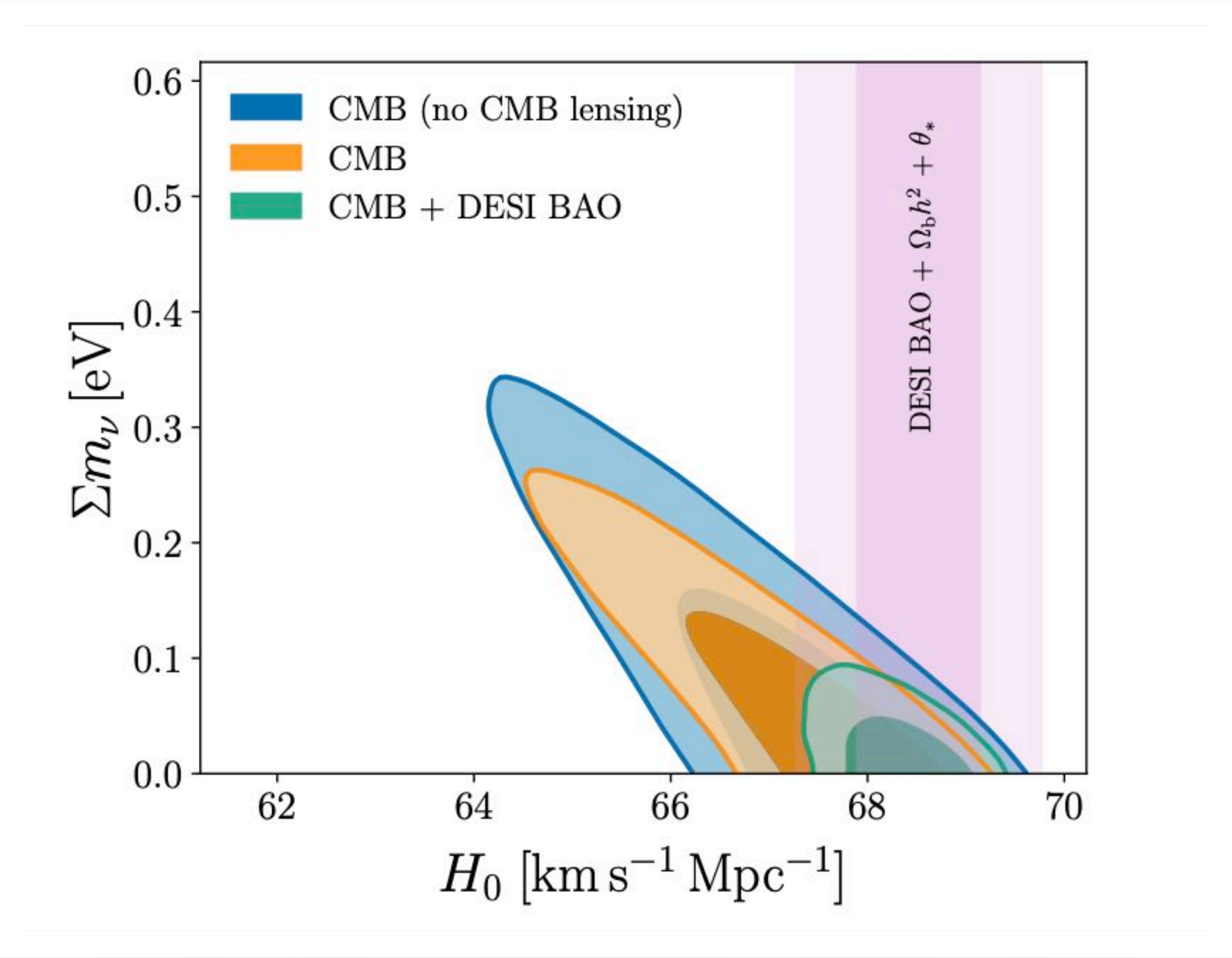
Dataset combination	$\Lambda\mathrm{CDM}+\sum m_\nu$	
	$\sum m_\nu$ (eV)	$B_{\mathrm{NO,IO}}$
baseline (CMB + DESI)	< 0.072	8.1



DESI 2024 VI

[arXiv:2404.03002]





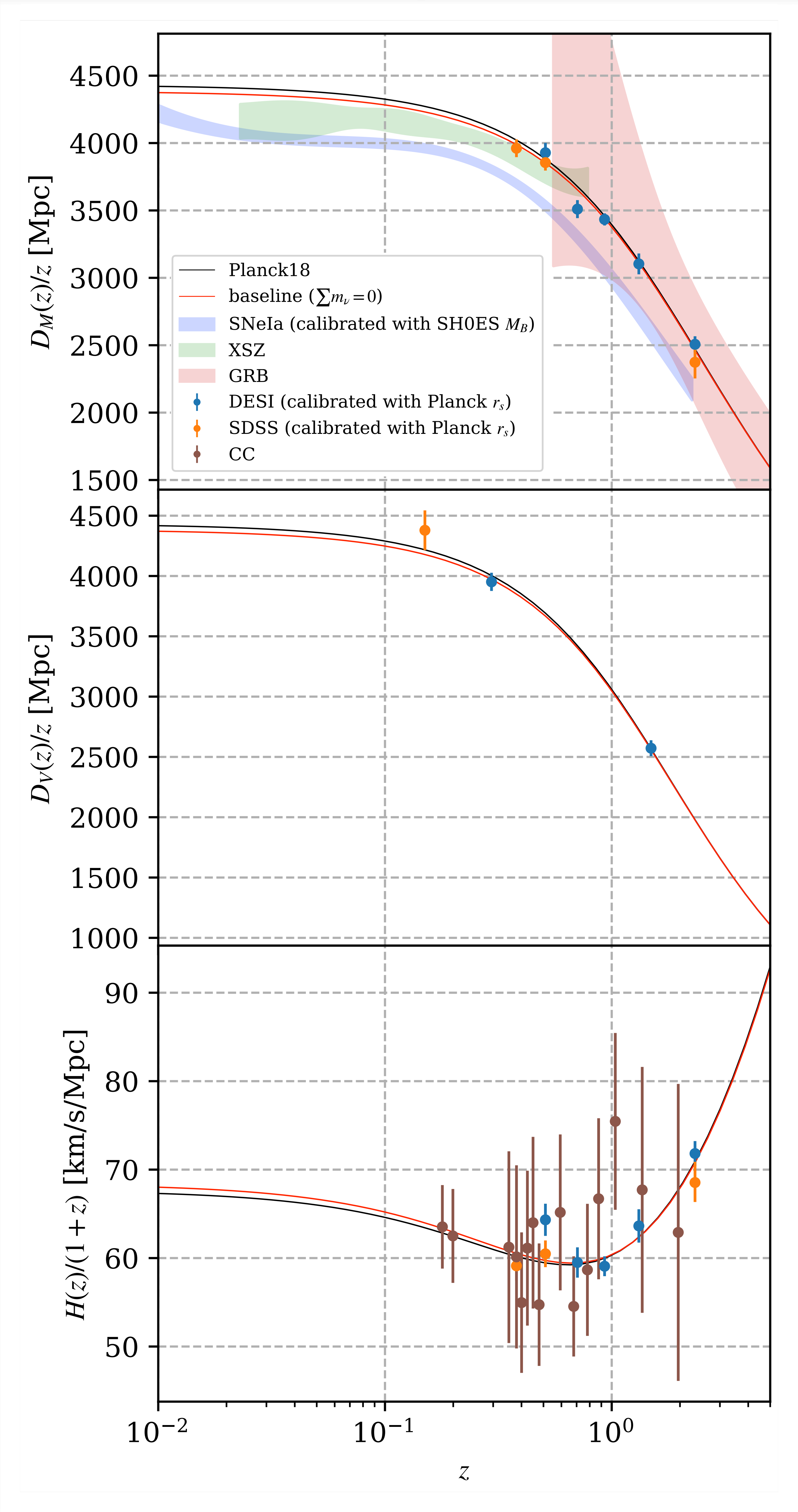
NEUTRINO COSMOLOGY AFTER DESI BAO

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

TOTAL NEUTRINO MASS AND ORDERING

	$\Lambda\mathrm{CDM}+\sum m_\nu$	
Dataset combination	$\sum m_\nu$ (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**.



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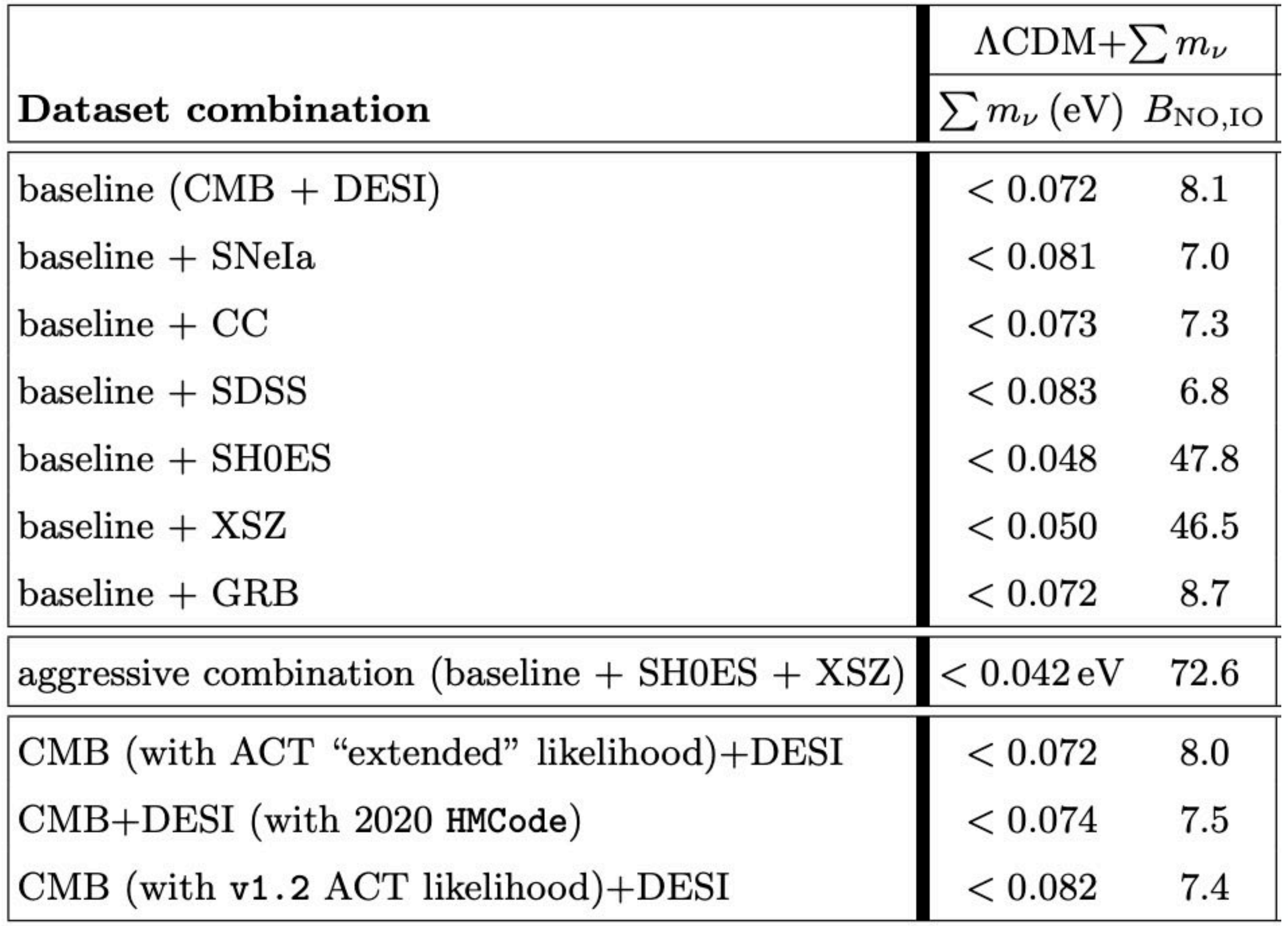

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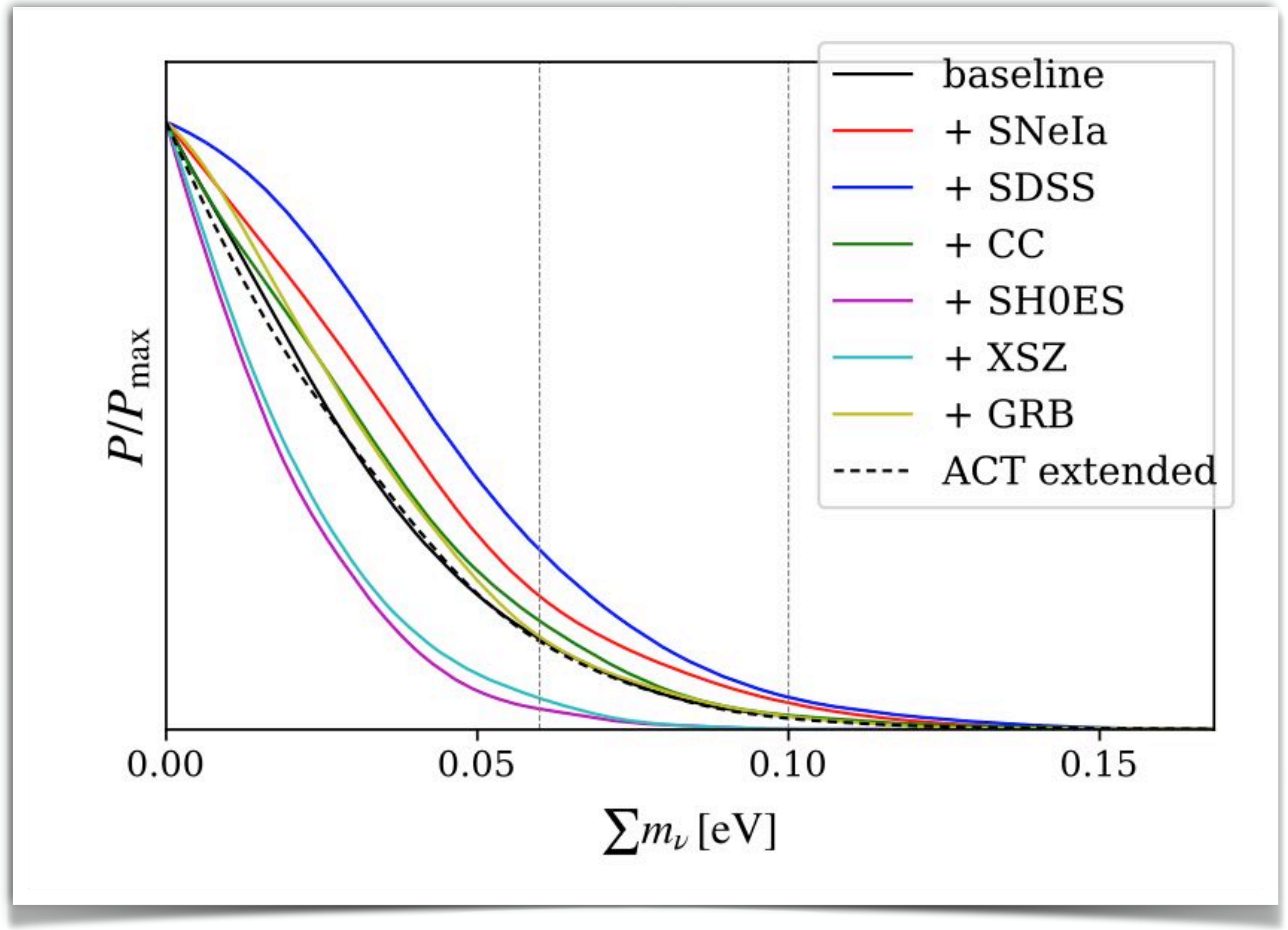
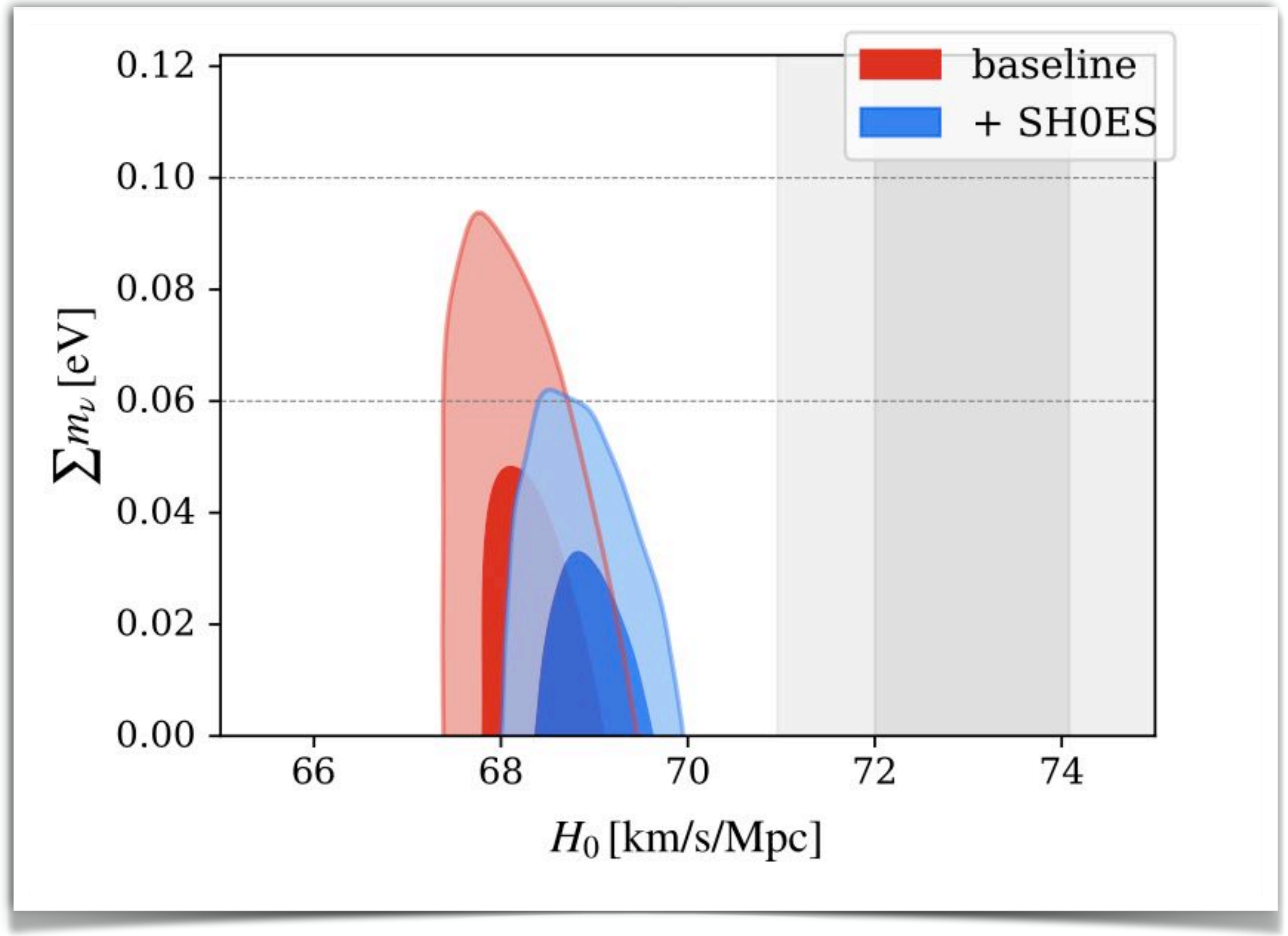




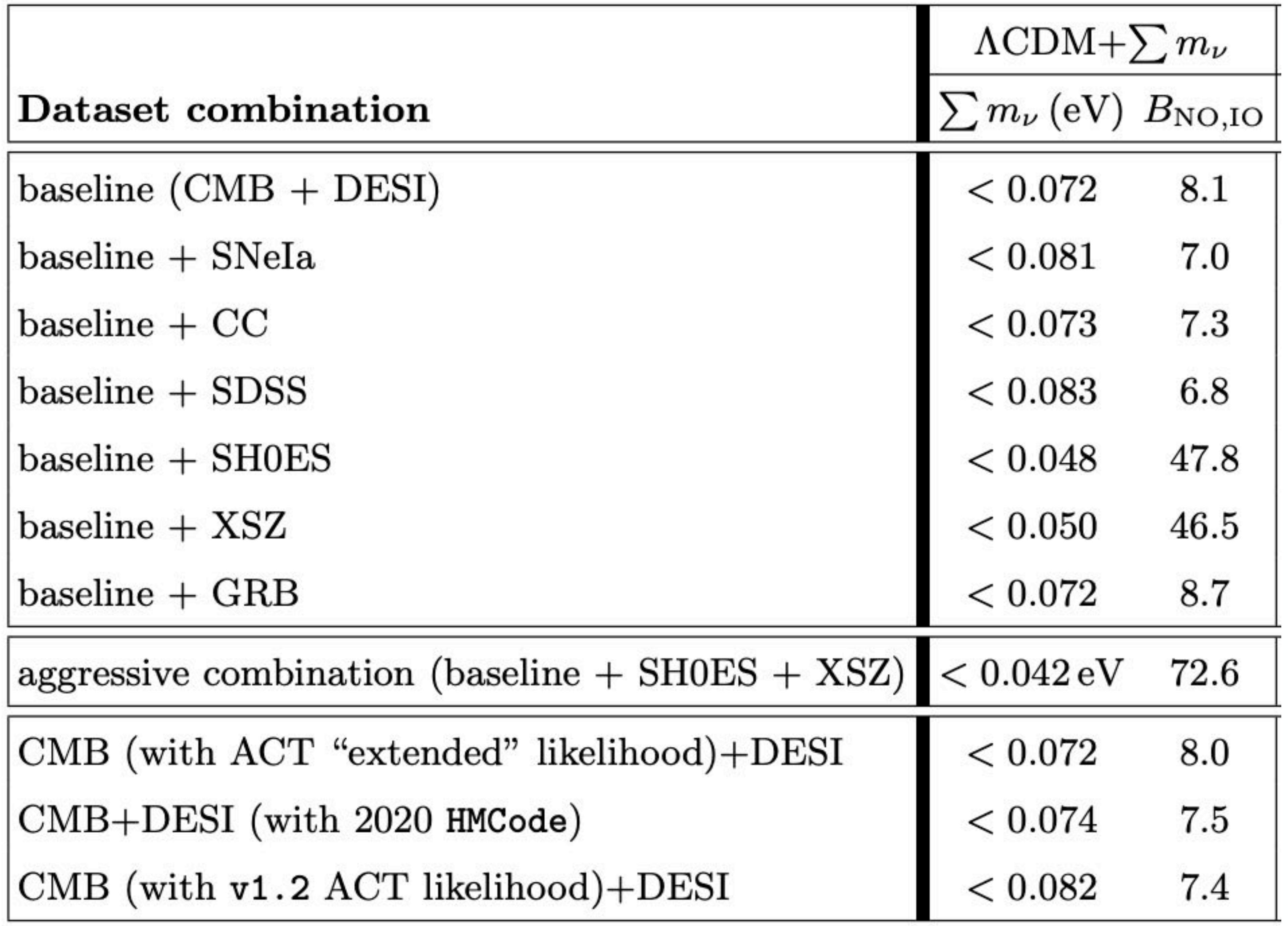
– We pushed the mass limit as far as possible, considering **different datasets**.

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

NEUTRINO COSMOLOGY AFTER DESI BAO

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

TOTAL NEUTRINO MASS AND ORDERING



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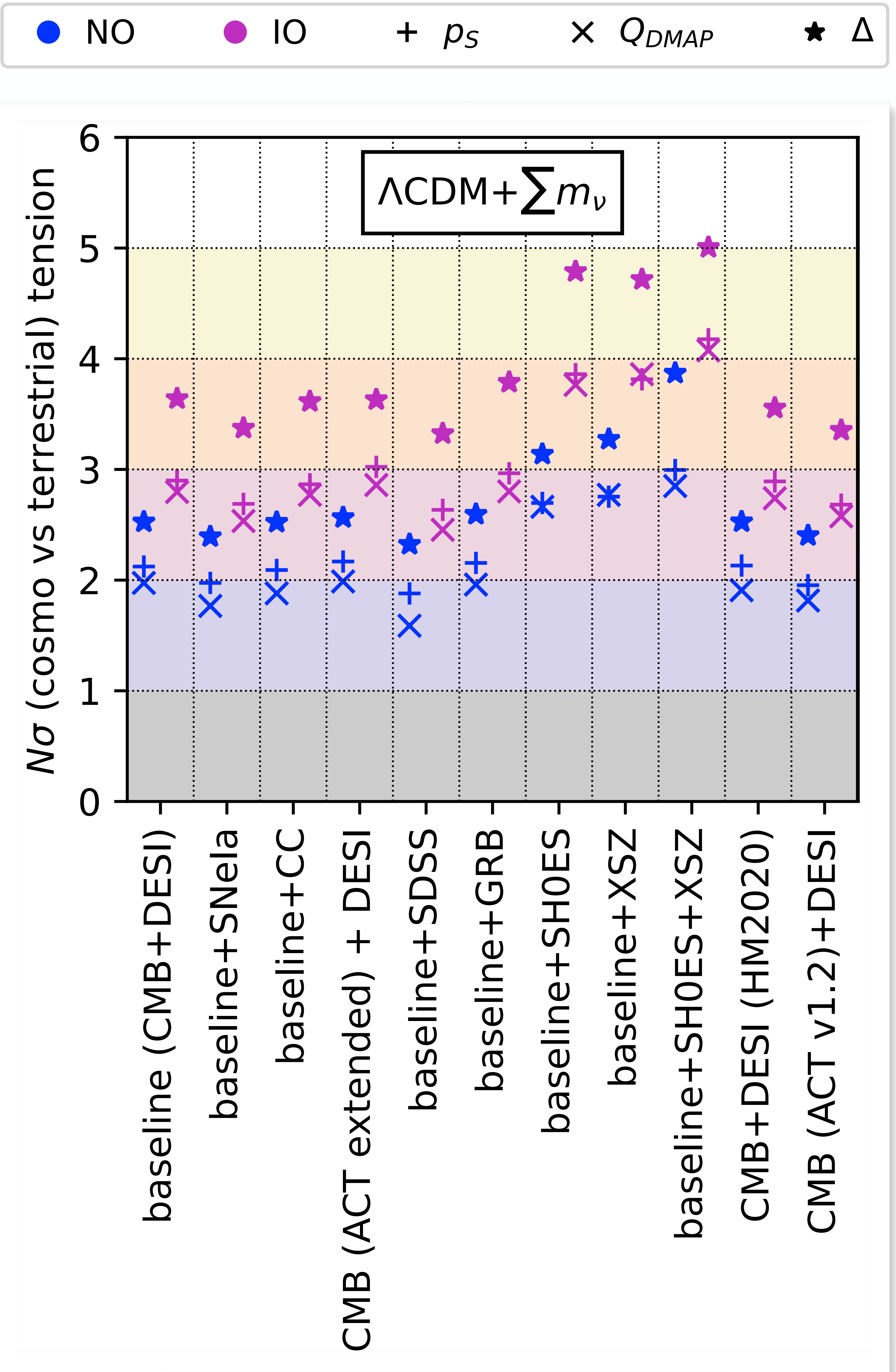

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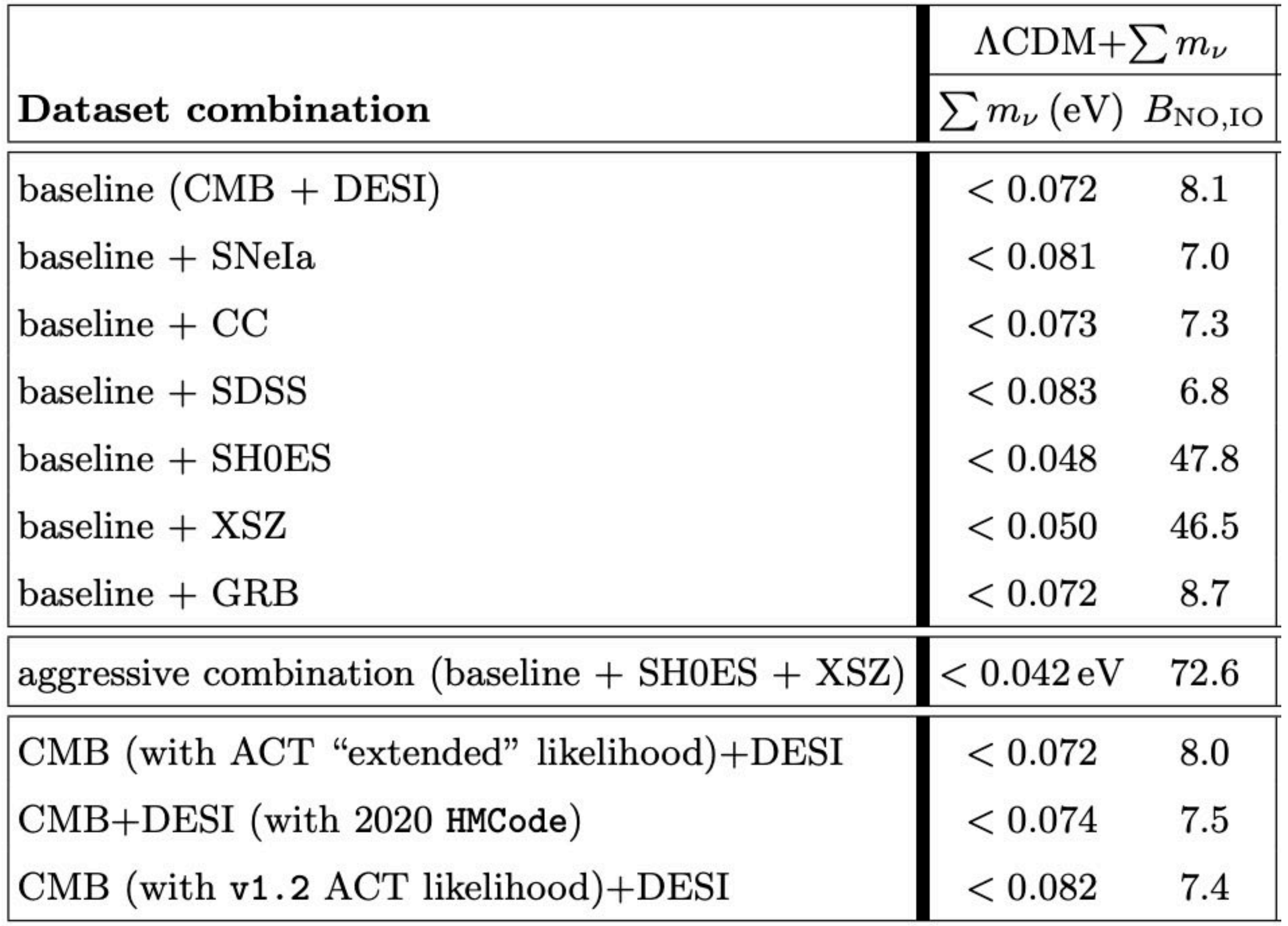
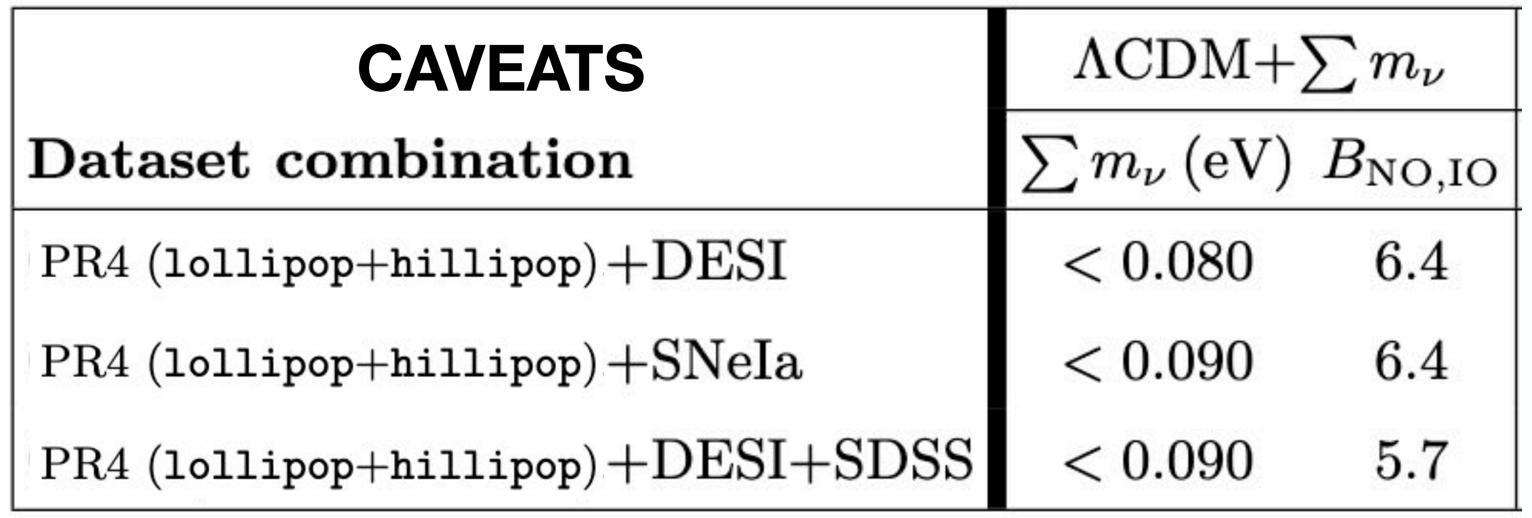
- We quantified the Bayesian ratio between NO and IO: **strong preference for NO**.
- We quantified the **tension between cosmological and terrestrial experiments**

NEUTRINO COSMOLOGY AFTER DESI BAO

TOTAL NEUTRINO MASS AND ORDERING

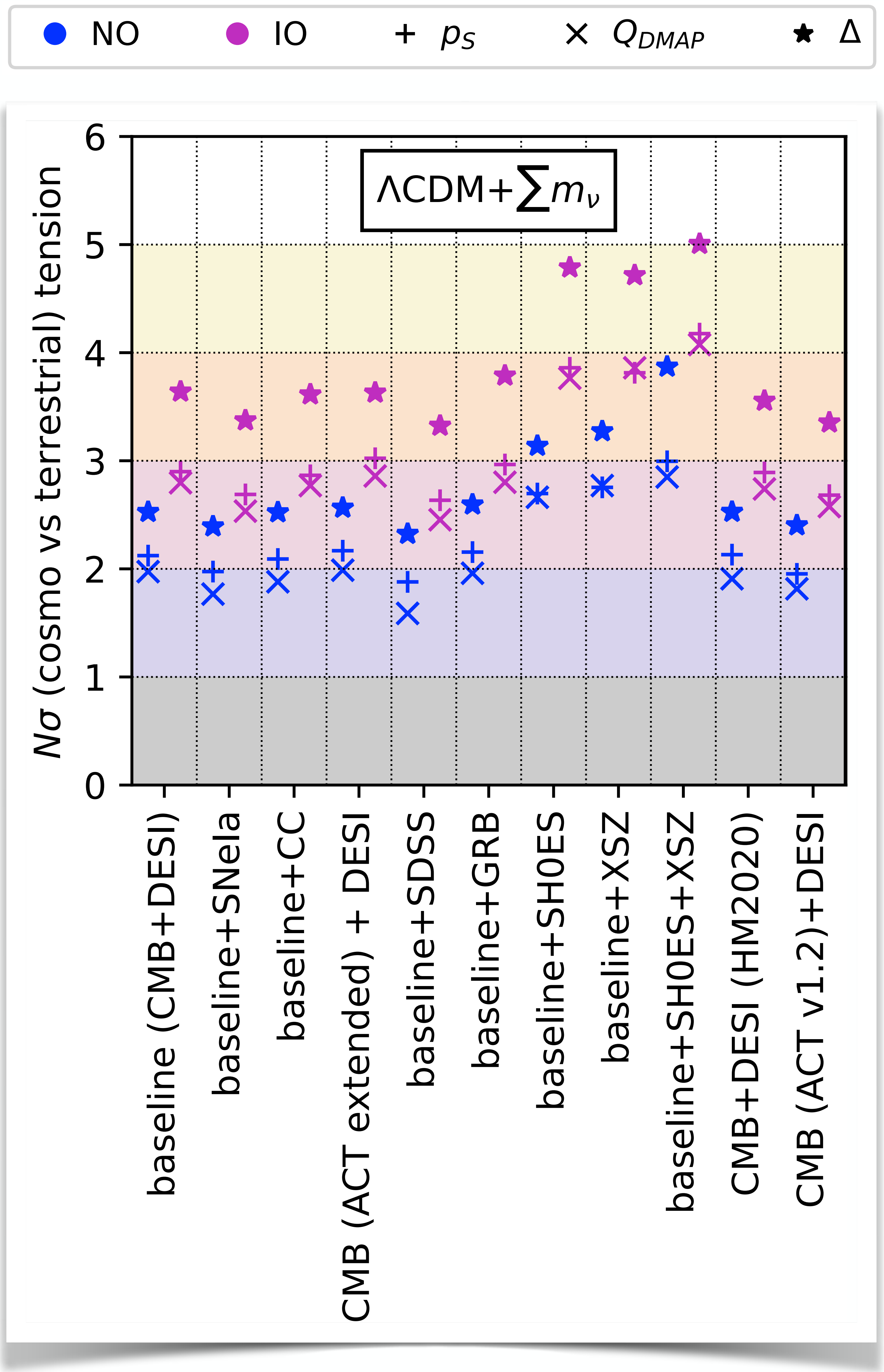


Dataset combination	ΛCDM+$\sum m_\nu$	
	$\sum m_\nu$ (eV)	$B_{\rm NO,IO}$
baseline (CMB + DESI)	< 0.072	8.1
baseline + SNeIa	< 0.081	7.0
baseline + CC	< 0.073	7.3
baseline + SDSS	< 0.083	6.8
baseline + SH0ES	< 0.048	47.8
baseline + XSZ	< 0.050	46.5
baseline + GRB	< 0.072	8.7
aggressive combination (baseline + 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

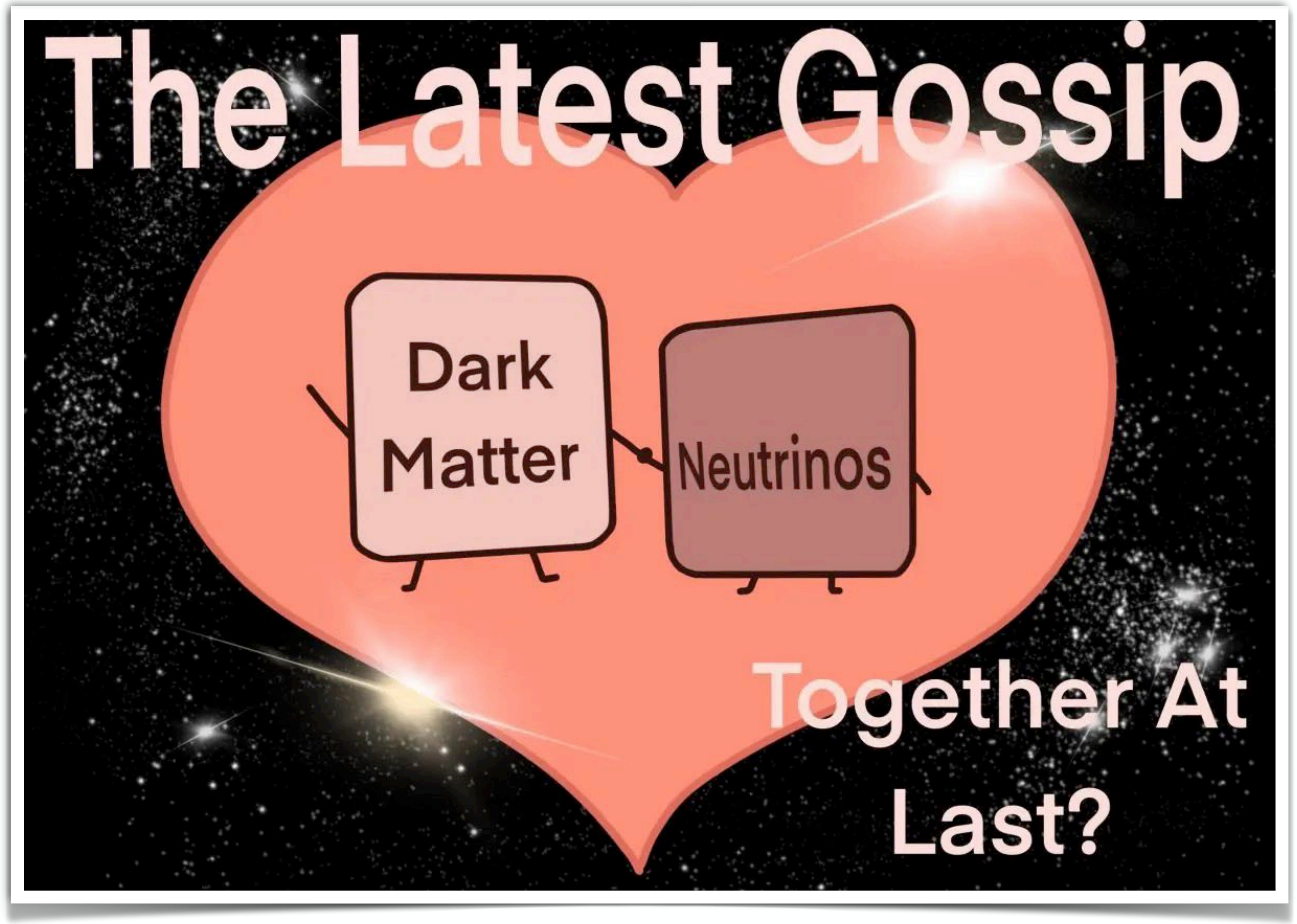


CAVEATS Dataset combination	ΛCDM+$\sum m_\nu$	
	$\sum m_\nu$ (eV)	$B_{\rm NO,IO}$
PR4 (`lollipop`+`hillipop`)+DESI	< 0.080	6.4
PR4 (`lollipop`+`hillipop`)+SNeIa	< 0.090	6.4
PR4 (`lollipop`+`hillipop`)+DESI+SDSS	< 0.090	5.7

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



2 NEUTRINO - DARK MATTER INTERACTIONS



Main References:

- Brax, van de Bruck, Di Valentino, **WG**, Trojanowski — MNRAS Letters 527 (2023) 1 [arXiv:2303.16895] *
- P. Brax, C. van de Bruck, E. Di Valentino, **WG**, S. Trojanowski — PDU 42 (2023) 101321 [arXiv:2305.01383]
- **WG**, Gómez-Valent , Di Valentino, van de Bruck — *PRD* 109 (2024) 6, 063516 [arXiv:2311.09116]

*** Work covered by astrobites.org in the article**

"Dark matter and Neutrinos walk into a (nano)bar(n); can we observe νDM interactions in the CMB?"

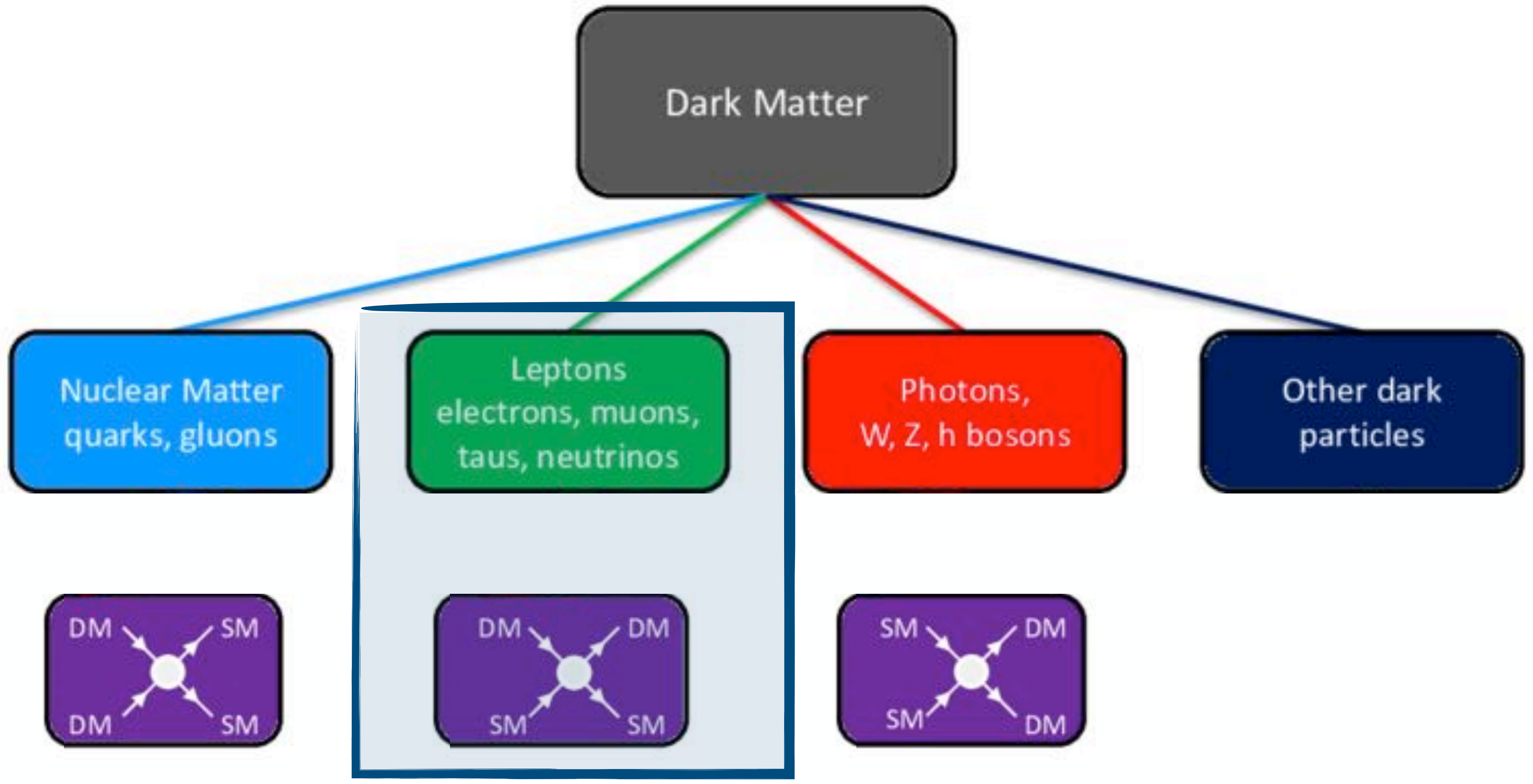
<— (from which the image on the left is taken)

COULD NEUTRINOS AND DM INTERACT?

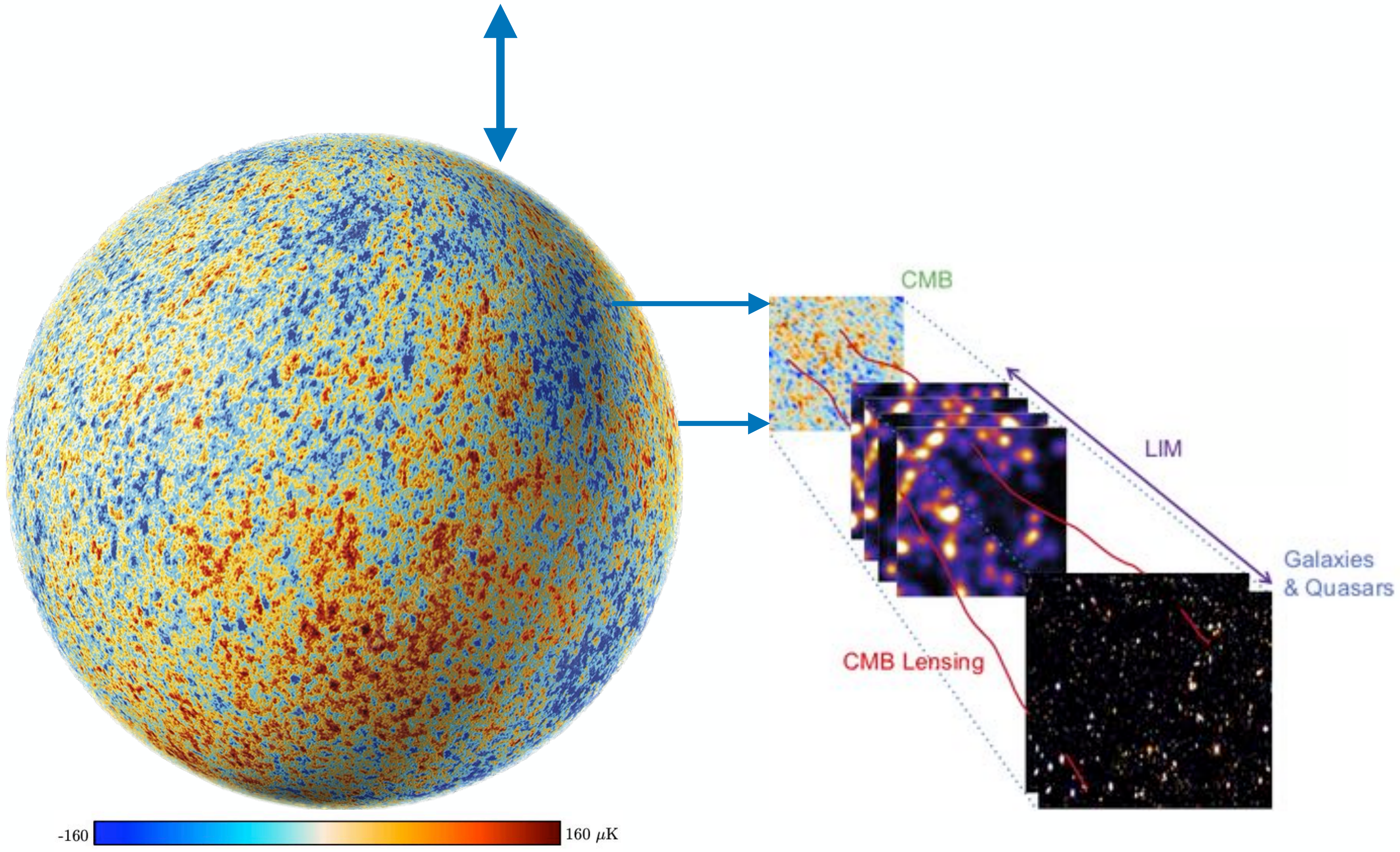
Thanks to the effects left by interactions in various cosmological observables, **cosmology** stands as one of the most **elegant tools to test models** that would be virtually impossible to test in laboratory experiments.

Several possible channels of interactions have been tested and studied both in cosmology and particle physics, including interactions with **photons**, **baryons**, **dark radiations, neutrinos, Dark Energy**

We will focus on the effects left in the Cosmic Microwave Background and Large Scale Structure of the Universe by **Scatter-Like interactions between neutrinos and DM**



$\nu - DM$ scattering



V-DM INTERACTIONS

EQUATIONS IN THE MASSLESS LIMIT

Boltzmann Equations for DM in the Newtonian Gauge:

$$\dot{\delta}_{\rm DM} = -\theta_{\rm DM} + 3\dot{\phi}$$

$$\dot{\theta}_{\rm DM} = k^2\psi - \mathcal{H}\theta_{\rm DM} + \boldsymbol{\frac{4}{3}\frac{\rho_\nu}{\rho_{\rm DM}}\dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right)}$$

Boltzmann Equations for ν in the Newtonian Gauge:

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi}$$

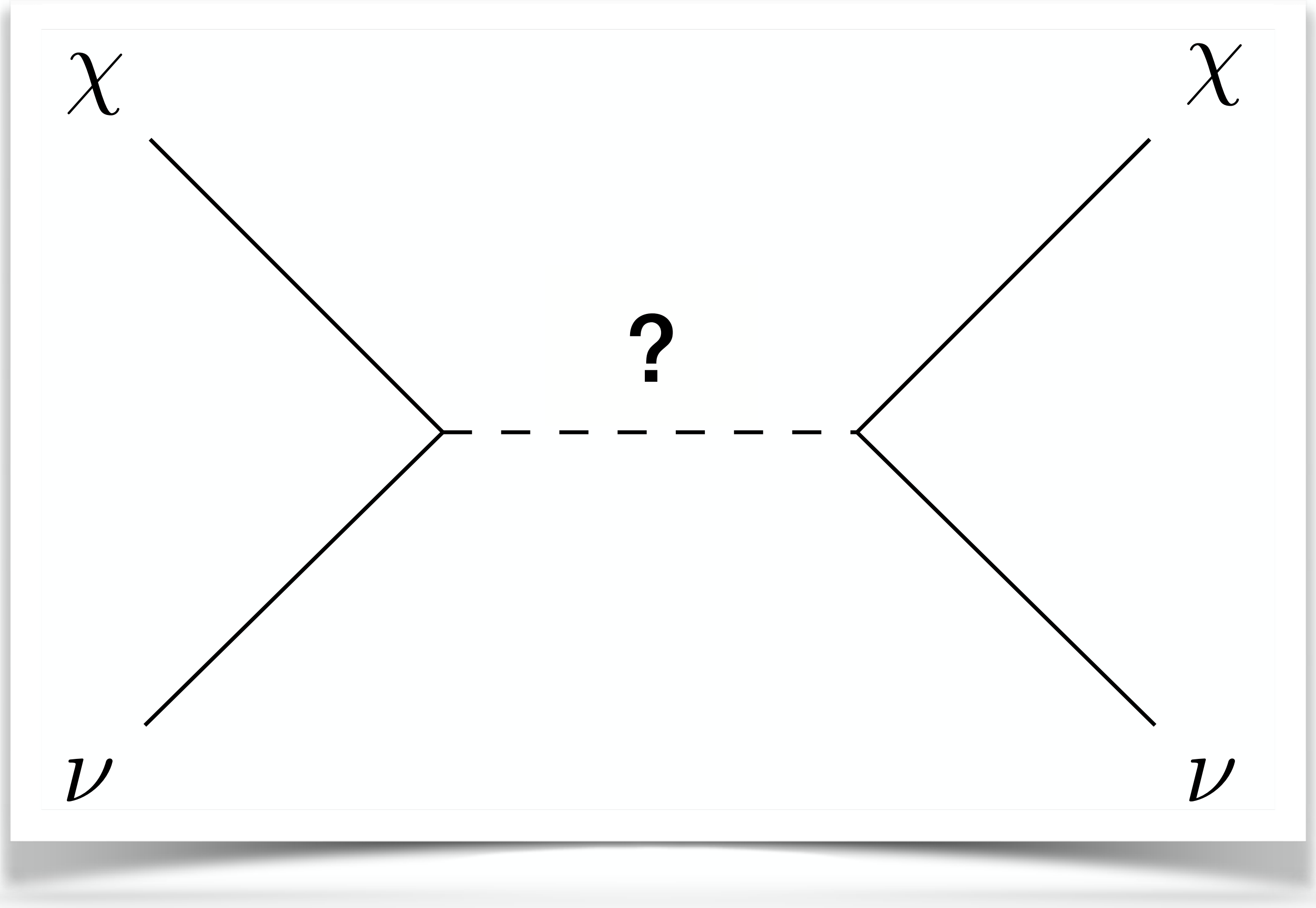
$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) \boldsymbol{- \dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right)}$$

$$\dots$$

Where: $\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu{\rm DM}}$

Brax, van de Bruck, Di Valentino, **WG**, Trojanowski
MNRAS Letters 527 (2023) 1 [arXiv:2303.16895]

WG, Gómez-Valent , Di Valentino, van de Bruck
PRD 109 (2024) 6, 063516 [arXiv:2311.09116]



Other Useful References for vDM Theory

Mangano, et. al., arXiv:0606190

Boehm, et al., arXiv:0112522

Wilkinson, et al. arXiv:1401.7597

Mosbech, et al. arXiv:2011.04206

V-DM Interactions

Imprints in the Matter Power Spectrum

CMB angular spectra are sensitive to the gravitational forces experienced by the coupled photon-baryon fluid before decoupling, **determined by free-streaming neutrinos and DM**

<u>In the presence of interactions:</u>

- **DM experiences damped oscillations** similar to neutrinos
- **Neutrinos do not free-stream anymore,** their anisotropic stress is reduced and they behave more similarly to a relativistic perfect fluid

v-MD interactions can be quantified by an effective interaction strength:

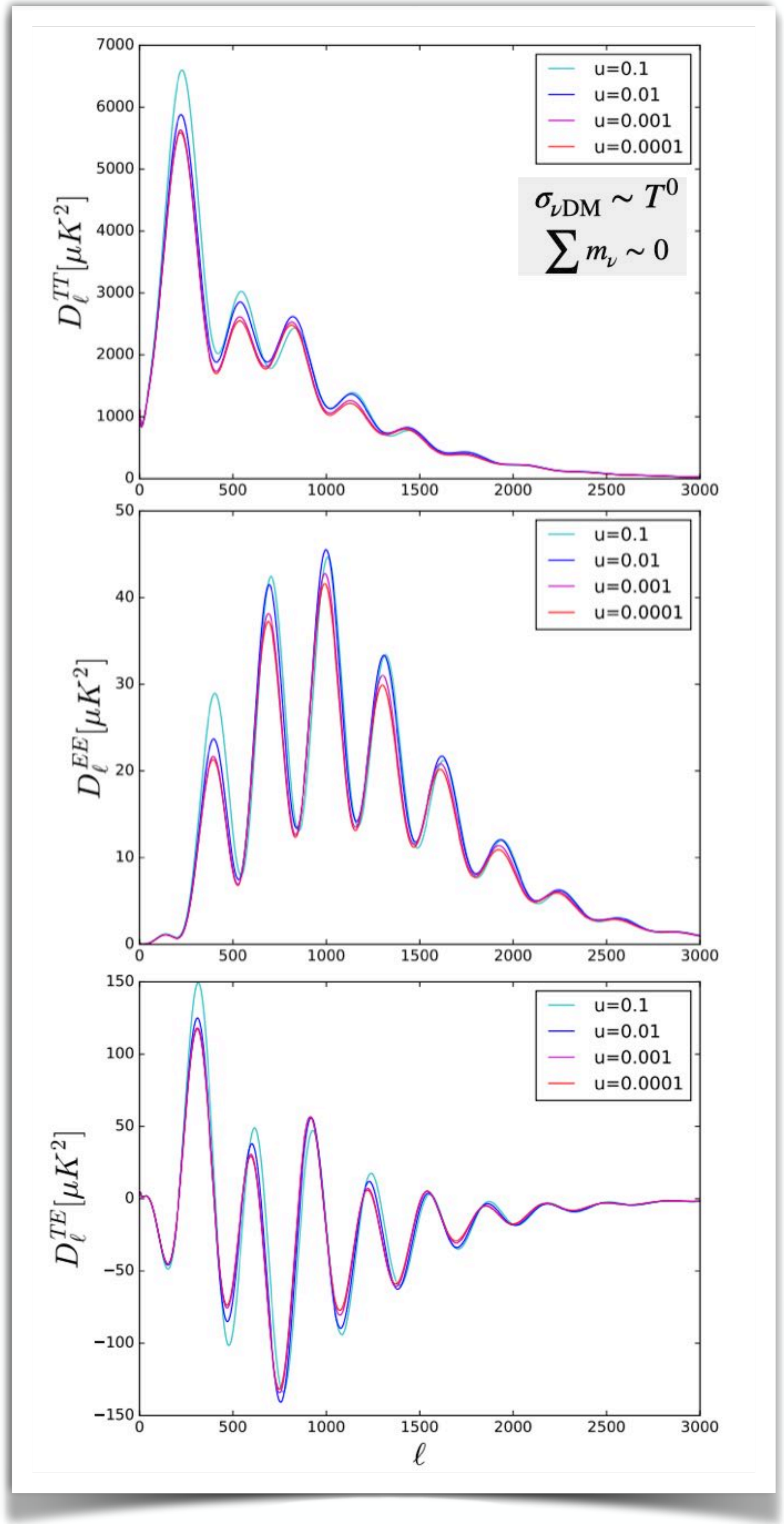
vDM cross-section
$\sigma_{\nu\mathrm{DM}} \sim T^n$

Mass of DM particles

$$u_{\nu\mathrm{DM}} \doteq \left[\frac{\sigma_{\nu\mathrm{DM}}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}}\right]^{-1}$$

Thompson cross-section

E. Di Valentino et al., [arXiv:1710.02559]



V-DM Interactions

Imprints in the Matter Power Spectrum

Interactions lead to an **effective vDM fluid with non-zero pressure.**

- This pressure induces **diffusion-damped oscillations** analogous to the acoustic oscillations in the baryon-photon fluid
- The most remarkable effect on the matter power spectrum is a **suppression of power on small scales**

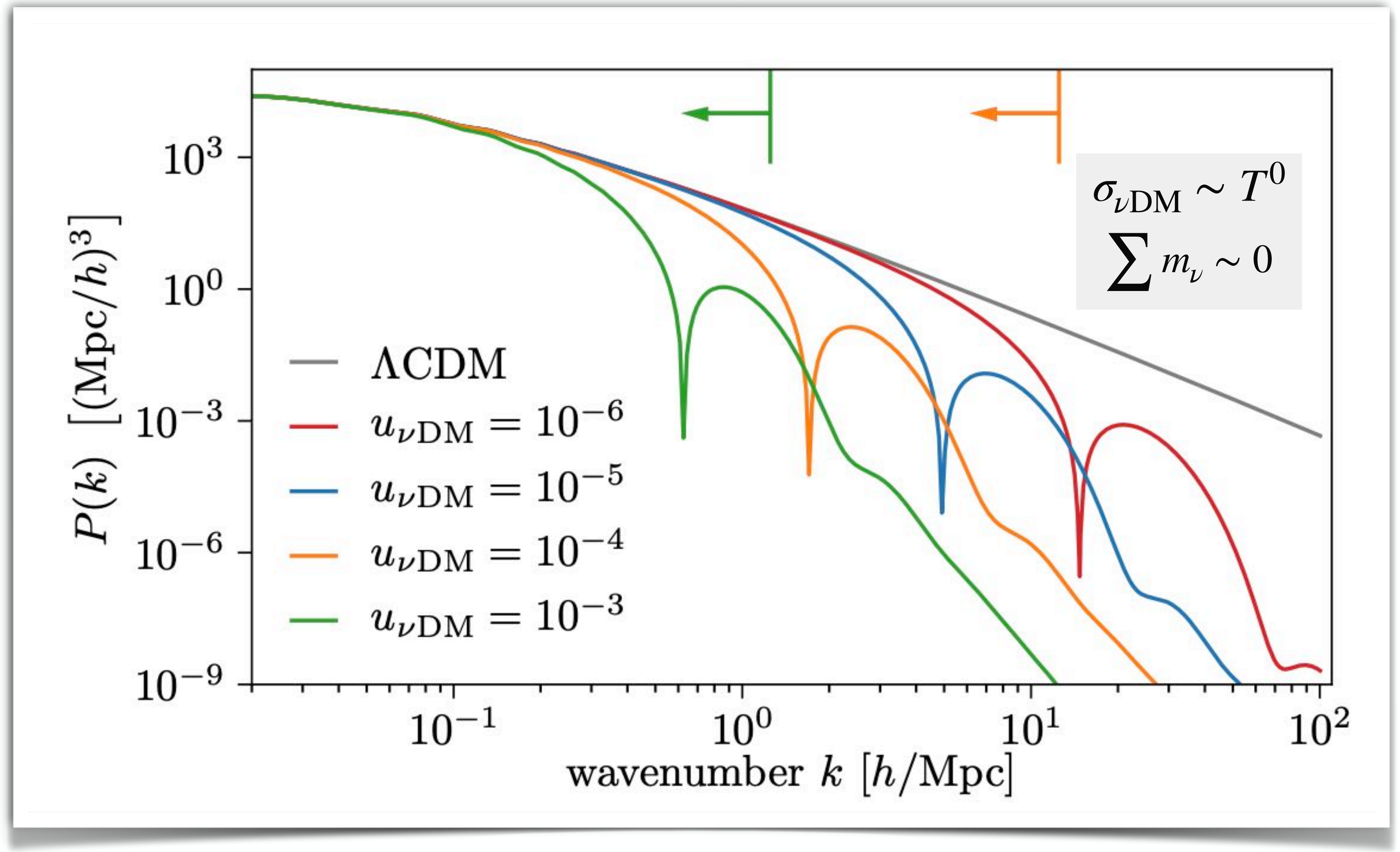
The smaller the interactions the smaller the scale of neutrino damping

Small $u_{\nu\mathrm{DM}}$ → Neutrino Damping at small scales

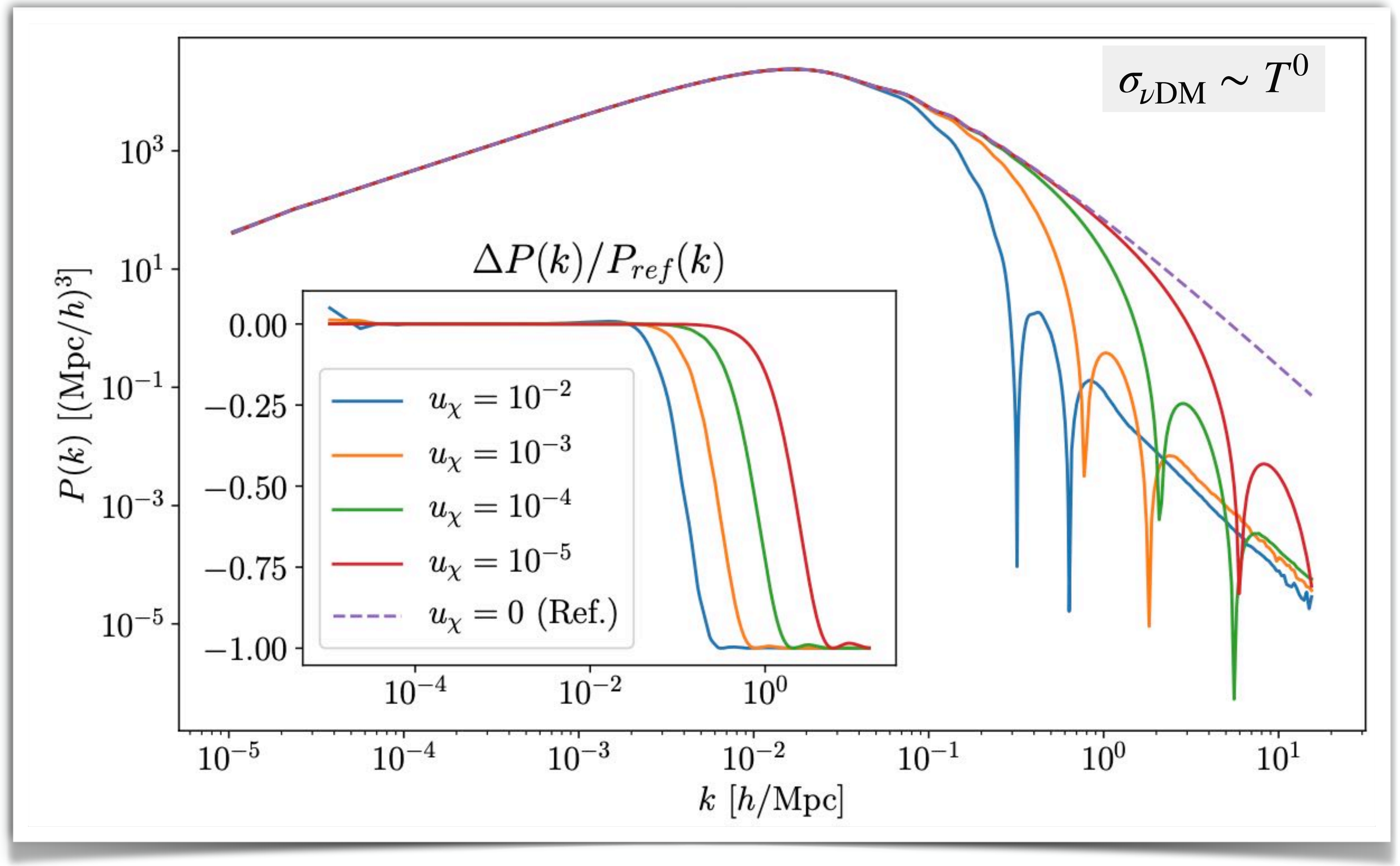
$$\frac{k}{[h/Mpc]} \propto (u_{\nu\mathrm{DM}})^{-1/2}$$

(See also G. Mangano, A. Melchiorri et al, 0606190)

J. Stadler et al. [arXiv:1903.00540]



M. R. Mosbech et al. [arXiv: 2011.04206]



V-DM INTERACTIONS

Brax, van de Bruck, Di Valentino, **WG**, Trojanowski
MNRAS Letters 527 (2023) 1 [arXiv:2303.16895]

IMPRINTS IN SMALL CMB SCALES

- In the high multipole regime, the **spectrum of temperature anisotropies** becomes **proportional to the lensing power spectrum**

$$C_\ell^{TT} \simeq \frac{\ell^2}{2}\left(\langle|\nabla T|^2\rangle\right) C_\ell^{\phi\phi}$$

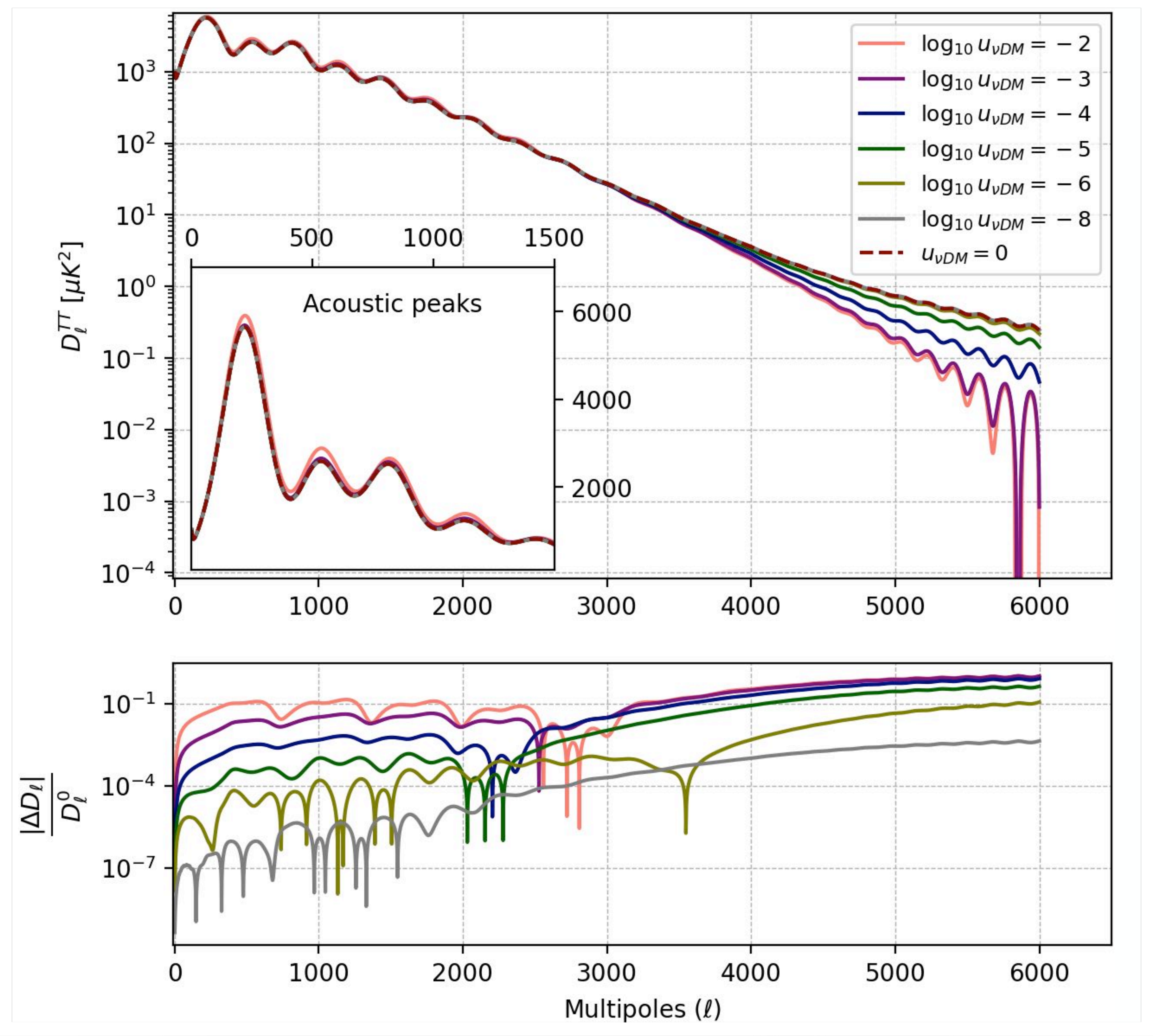
(Lewis and Challinor, 0601594)

Unlensed CMB temperature gradient $\simeq 10^{-9}\mu K^2$

- The **matter power spectrum** affects **the growth of cosmic structures** over time, the distribution of galaxies, and so the **integrated Sachs-Wolfe effect**.

- **As the strength of the interaction decreases, the effects on the CMB spectra should primarily manifest at smaller scales**

- If we want to test vDM interactions in the CMB, **when the interaction strength is small, it is better to look at small scales than at large scales**



Note that: $k \propto \ell \propto 1/\theta \propto 1/R$, so **small scales ↔ high ℓ**

V-DM INTERACTIONS

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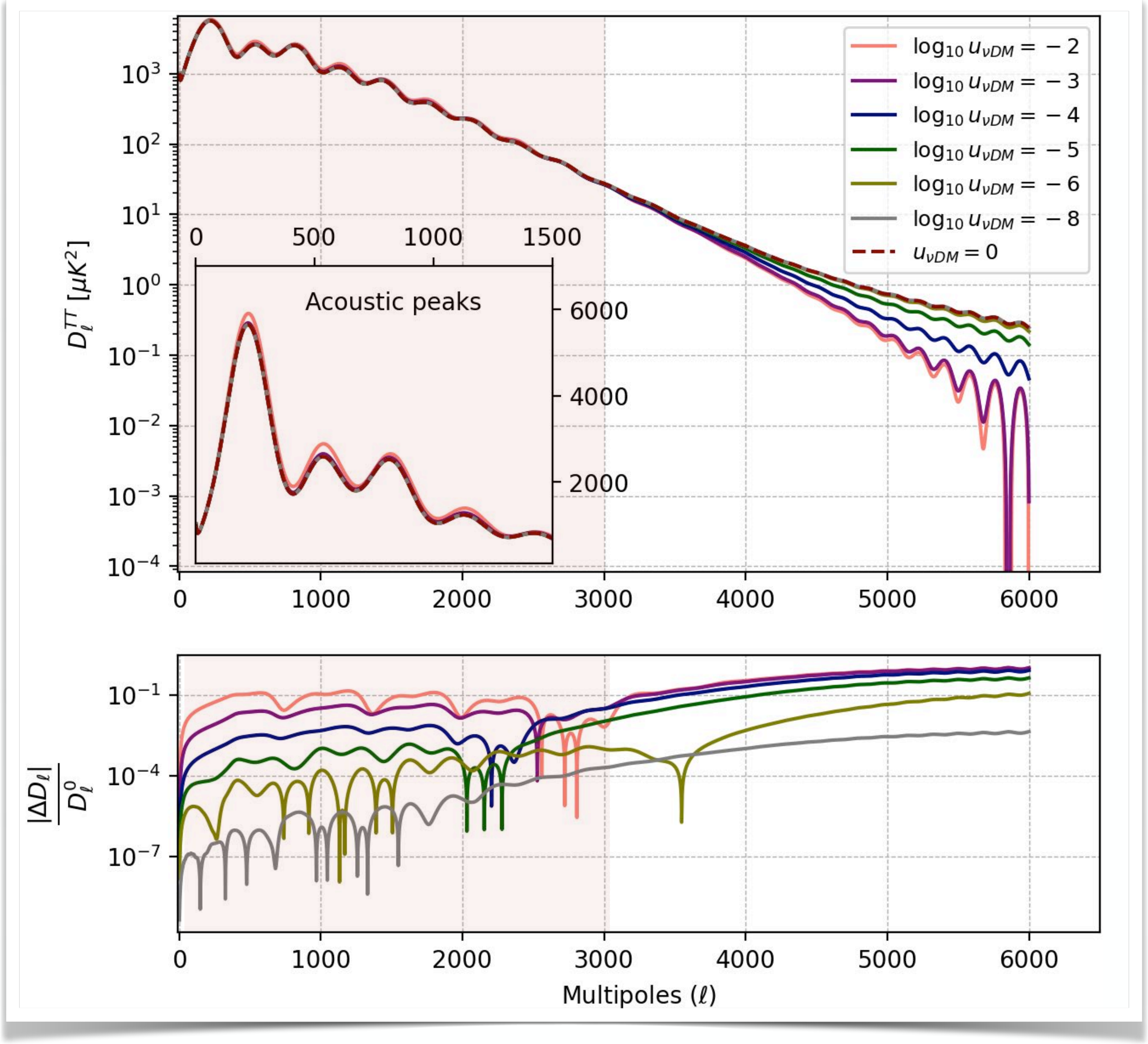
Hopeless



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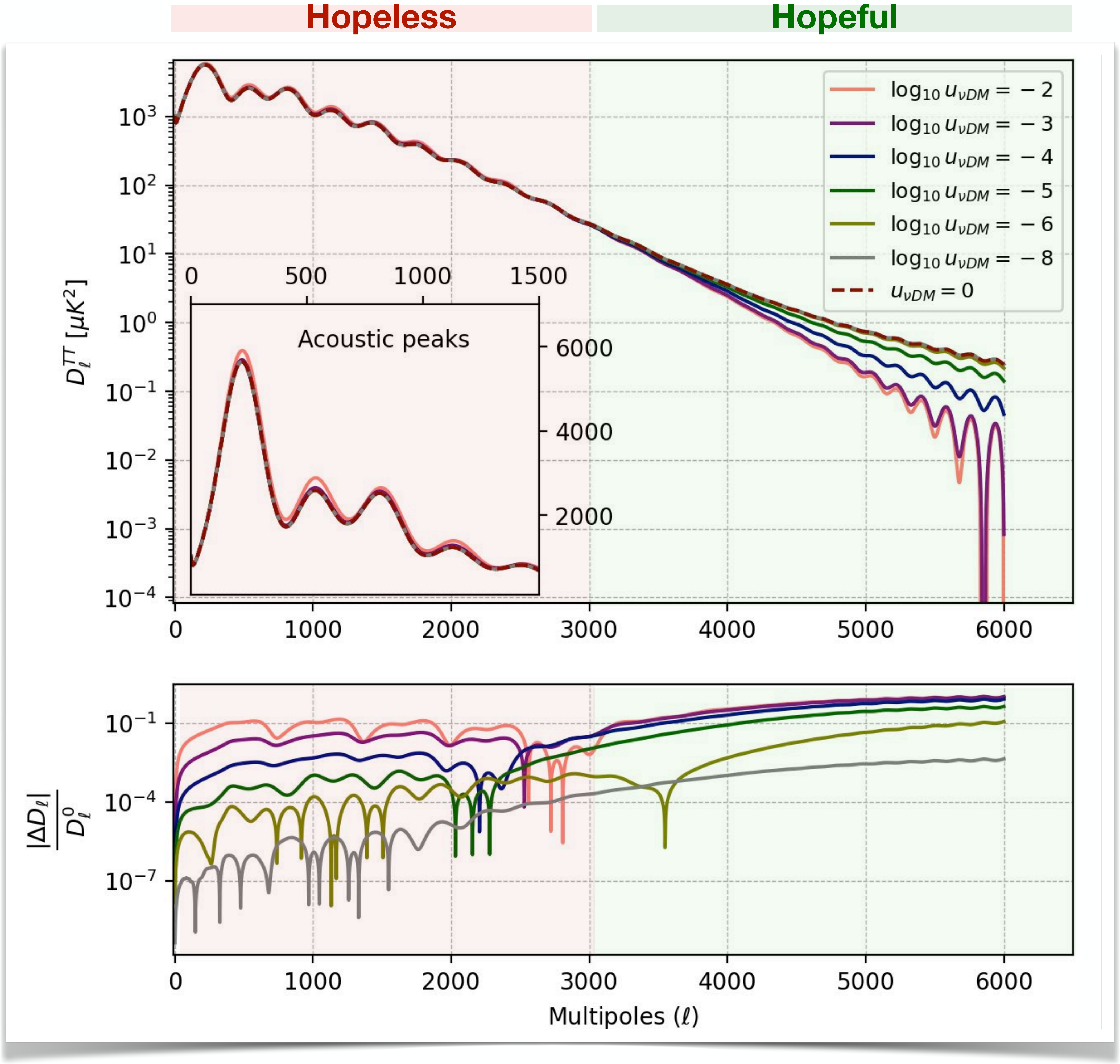

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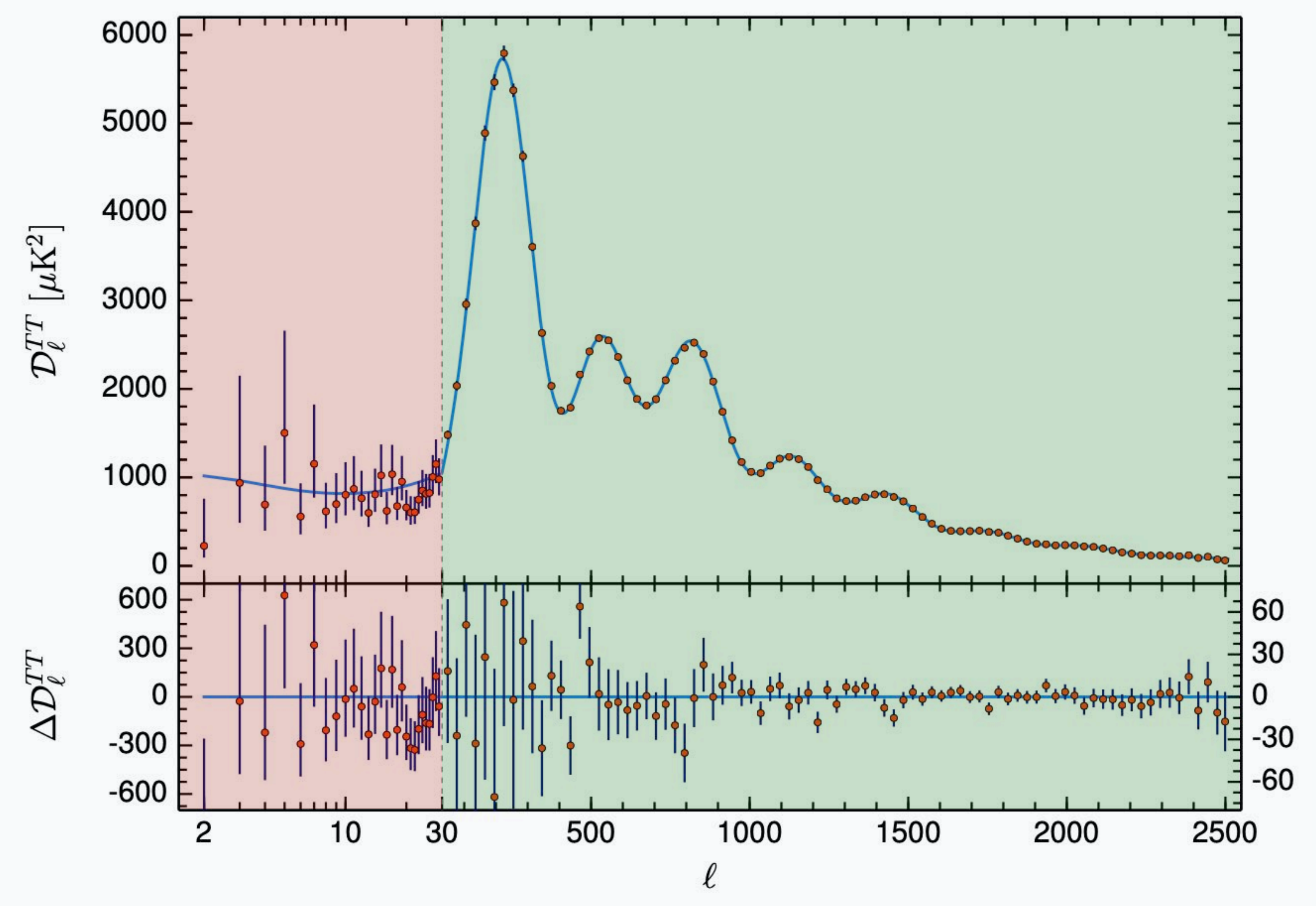
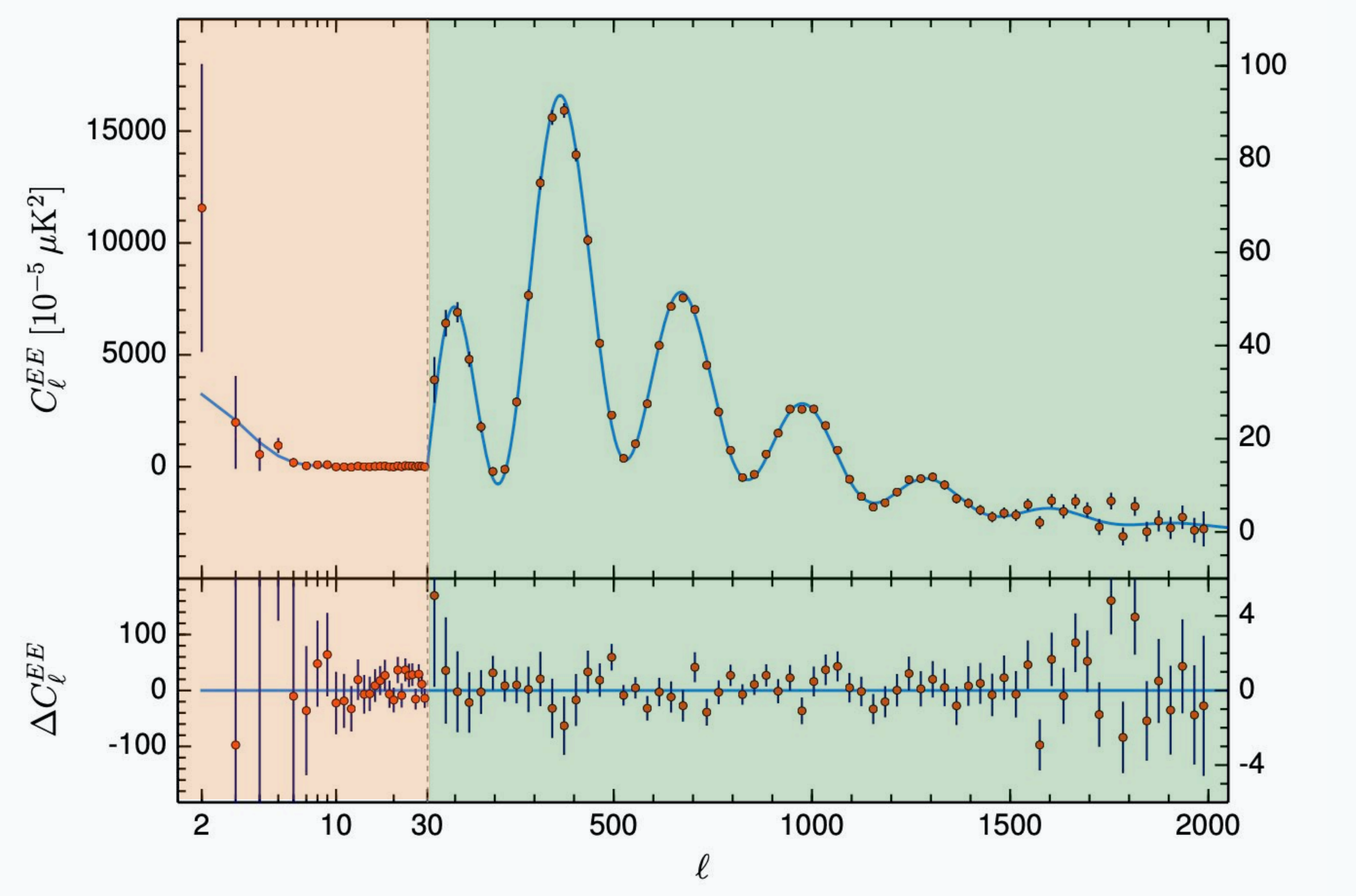
PLANCK 2018

[arXiv:1807.06209]

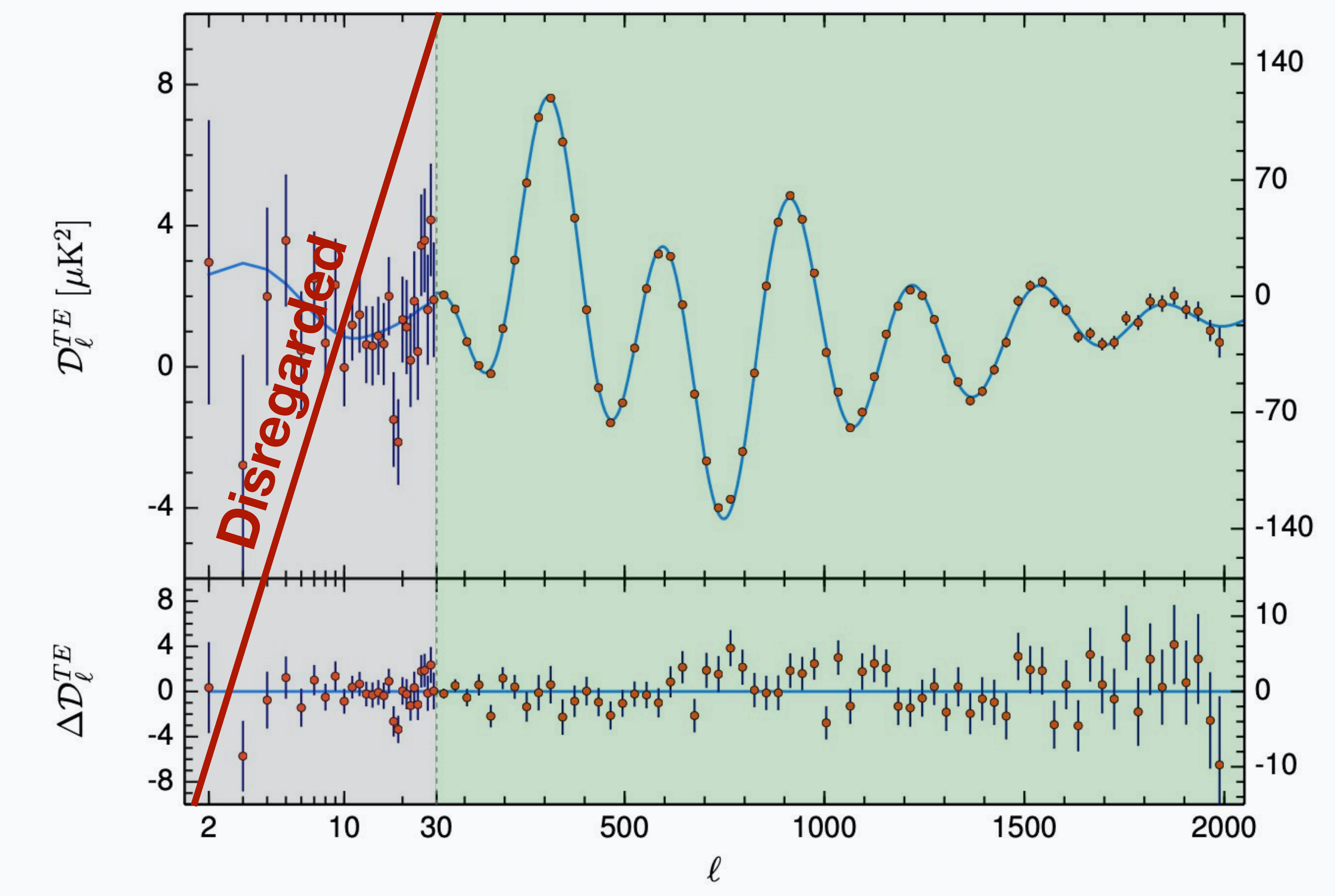
TT SPECTRUM



EE SPECTRUM



TE CROSS-SPECTRUM



Low-multipole temperature data

$2 \leq \ell \leq 30$ in the TT Spectrum

Low-T

Low-multipole Polarization data

$2 \leq \ell \leq 30$ in the EE Spectrum

Low-E

Disregarded

Low-multipole ~~TE data~~

~~$2 \leq \ell \leq 30$~~ in the TE Spectrum

The low-TE data show excess of variance compared to simulations at low multipoles, for reasons that are not understood

High-multipole temperature data

$30 < \ell \lesssim 2500$ in the TT Spectrum

High-multipole EE Polarization data

$30 < \ell \lesssim 2000$ in the EE Spectrum

High-multipole TE data

$30 < \ell \lesssim 2000$ in the TE Spectrum

PLANCK 2018

[arXiv:1807.06209]

WG, Gómez-Valent , Di Valentino, van de Bruck

PRD 109 (2024) 6, 063516 [arXiv:2311.09116]

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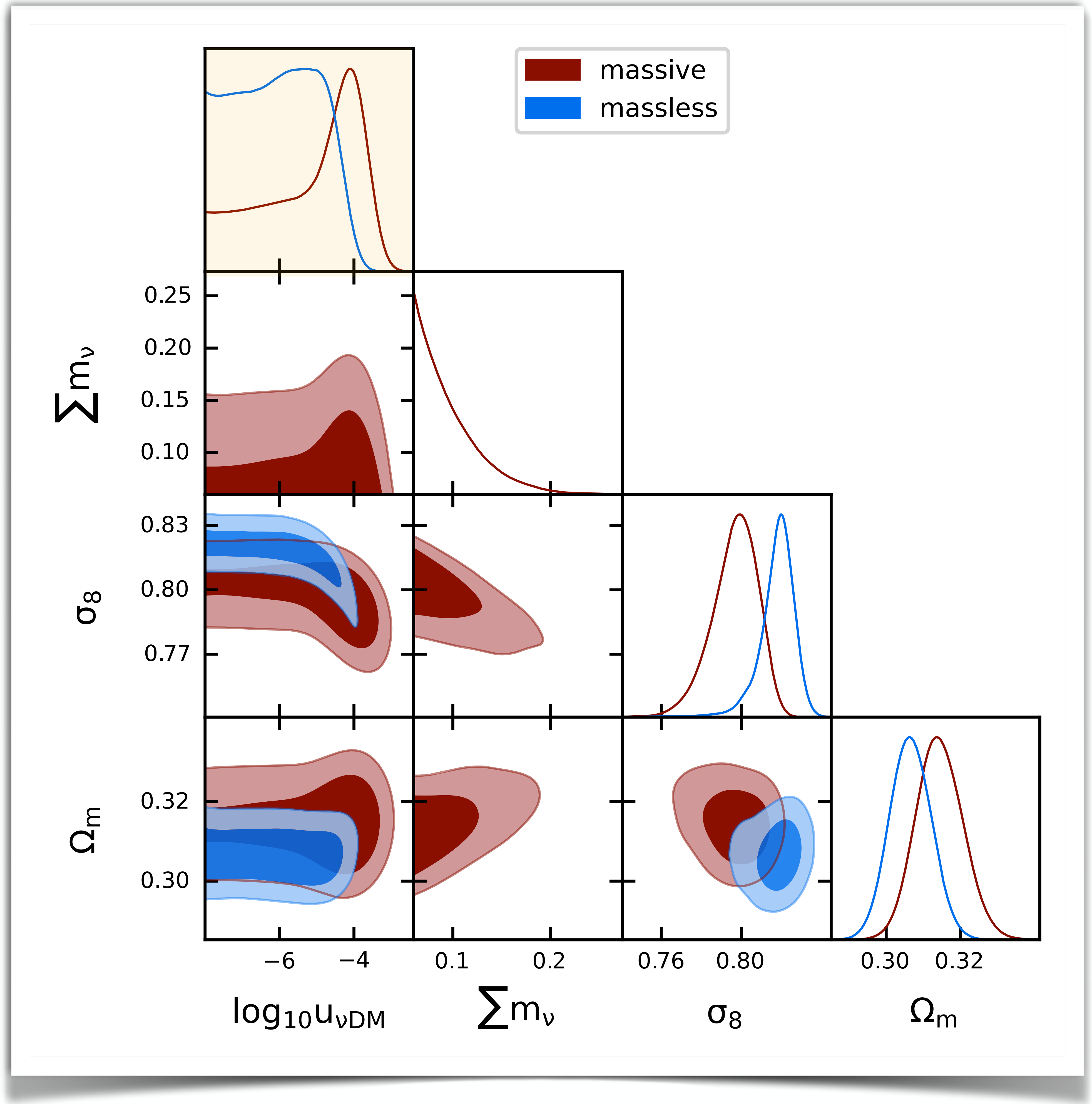
P18+BAO	Mar: < -4.27 PL: < -4.34	Mar: $-4.11^{+0.73}_{-0.93}$ PL: $-5.00^{+0.90}_{-1.80}$

- When neutrinos are regarded as massless particles, the analysis of Planck data combined with BAO measurements, **does not exhibit a clear preference for νDM interactions**

- When neutrinos are regarded as massive particles, both the marginalized probability distribution and the profile likelihood give a **1σ indication in favour of interactions.**

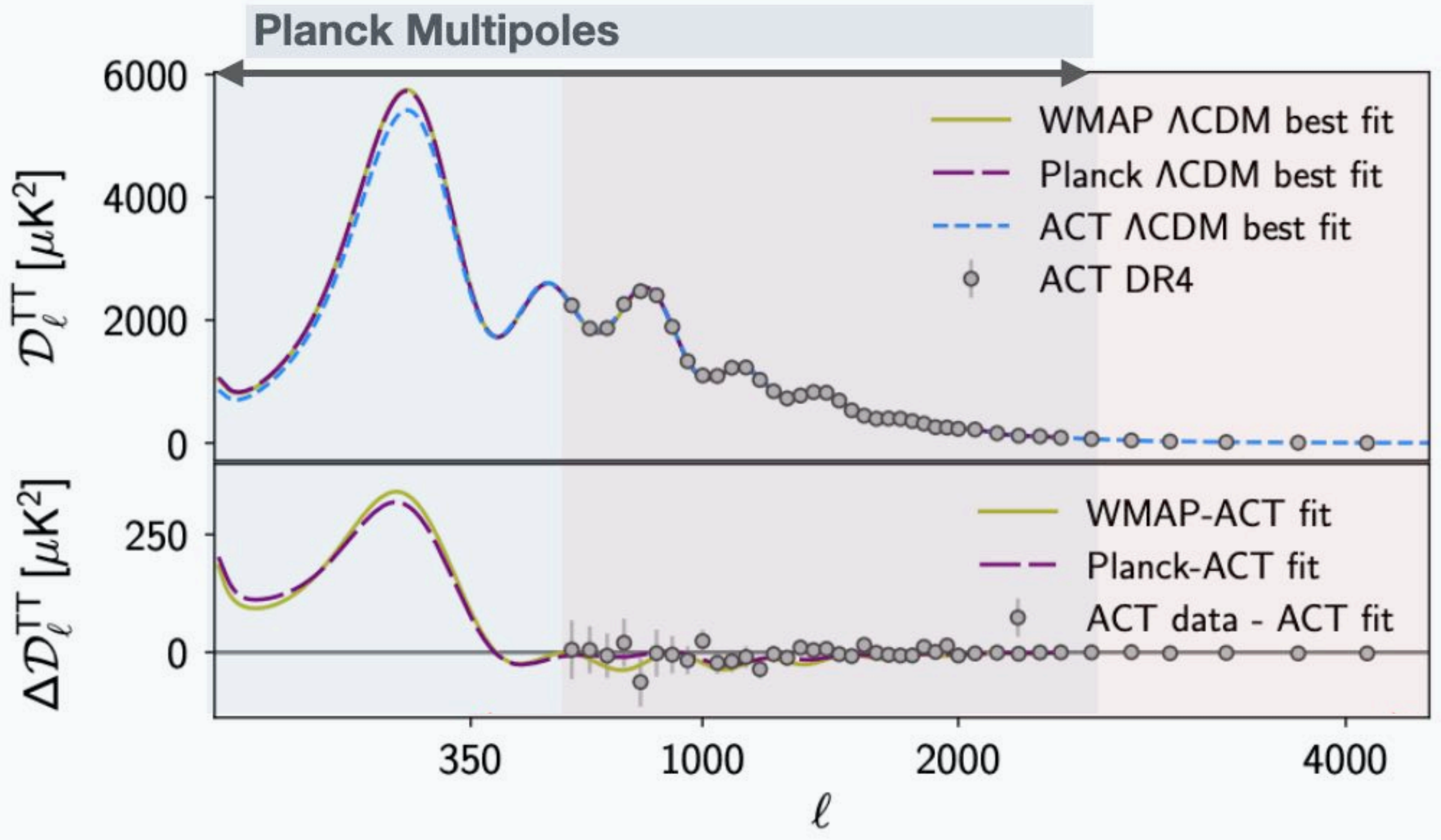
- The **PL analysis confirms** that models with $u_{\nu\mathrm{DM}} \sim 10^{-5} - 10^{-4}$ give a **modest reduction in the** χ^2 value of the fit.



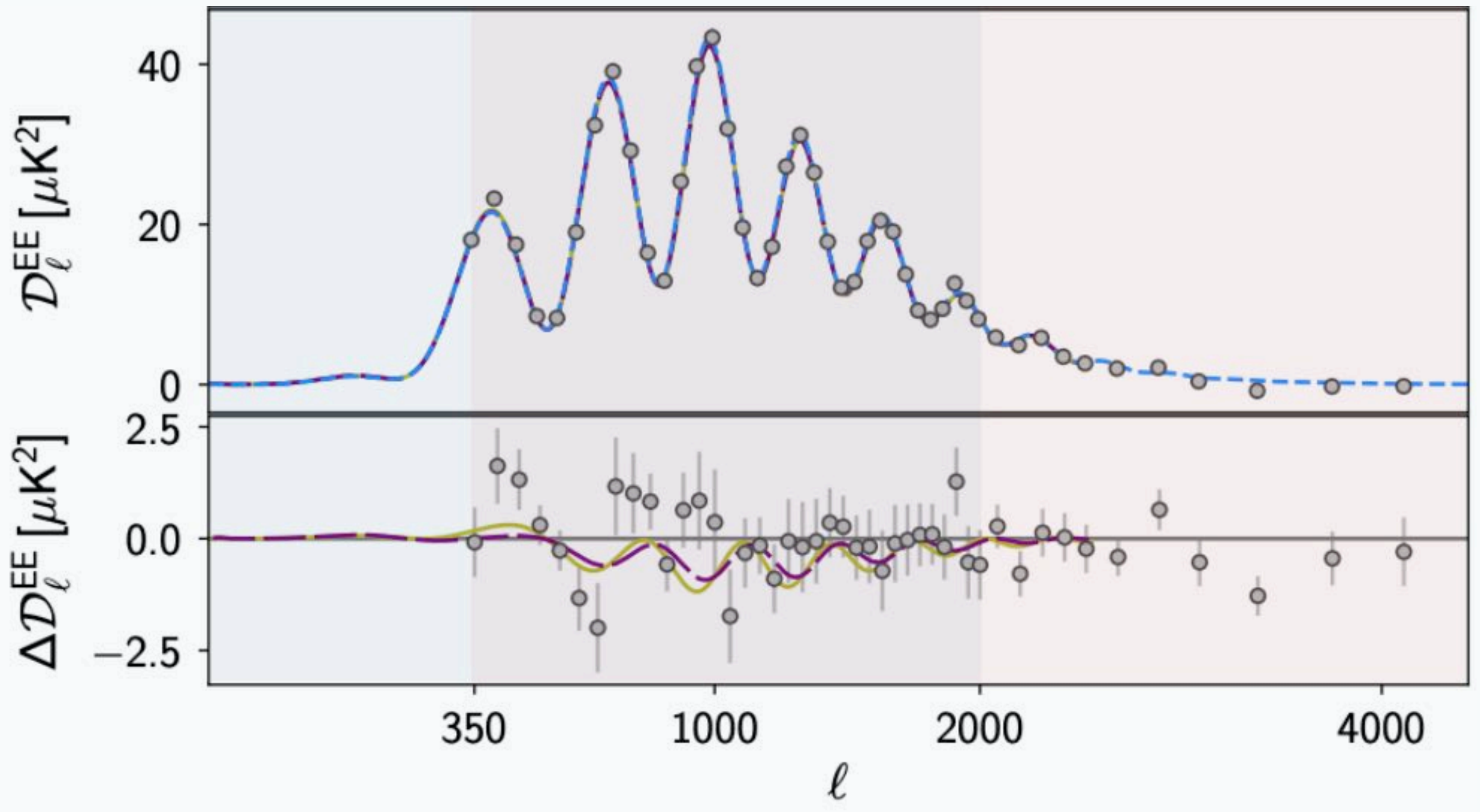
Atacama Cosmology Telescope

arXiv: [2007.07288]

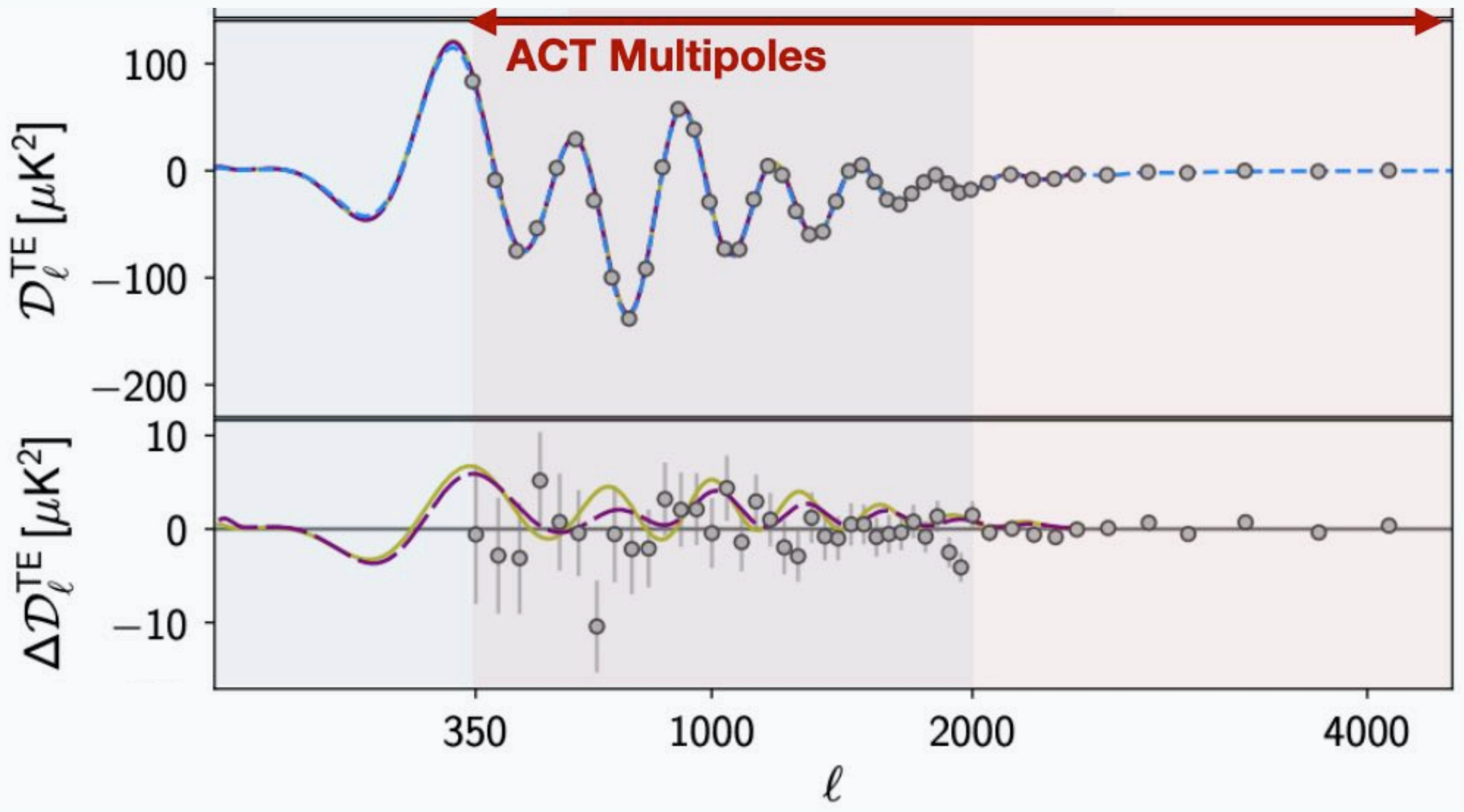
TT Spectrum



EE Spectrum



TE Cross-Spectrum



High-multipole temperature data

$600 < \ell \lesssim 4200$ in the TT Spectrum

High-multipole EE Polarization data

$350 < \ell \lesssim 4200$ in the EE Spectrum

High-multipole TE data

$350 < \ell \lesssim 4200$ in the TE Spectrum

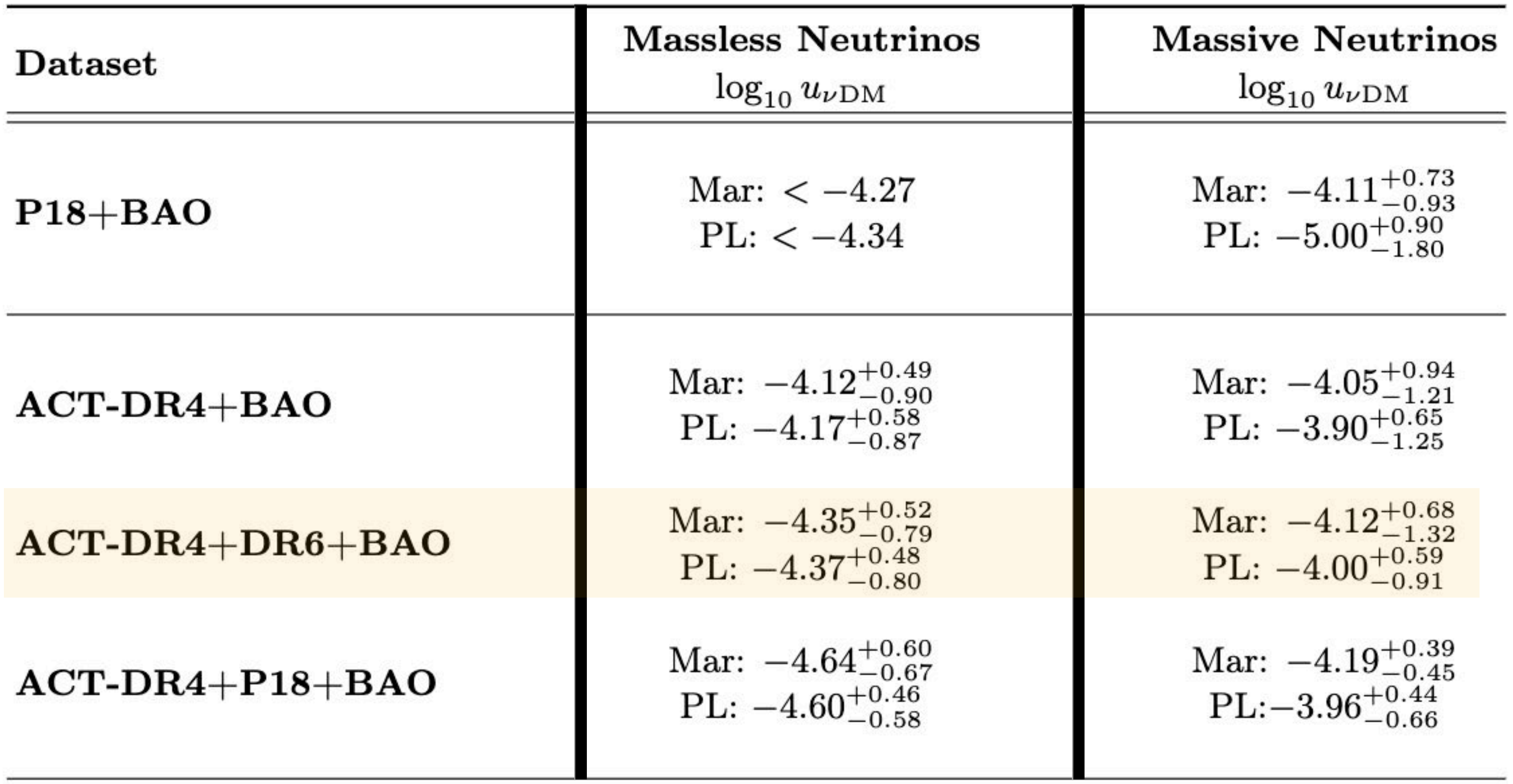
Note:
Planck probes $\ell \in [2,2000]$

ATACAMA COSMOLOGY TELESCOPE

arXiv: [2007.07288]

WG, Gómez-Valent , Di Valentino, van de Bruck

PRD 109 (2024) 6, 063516 [arXiv:2311.09116]



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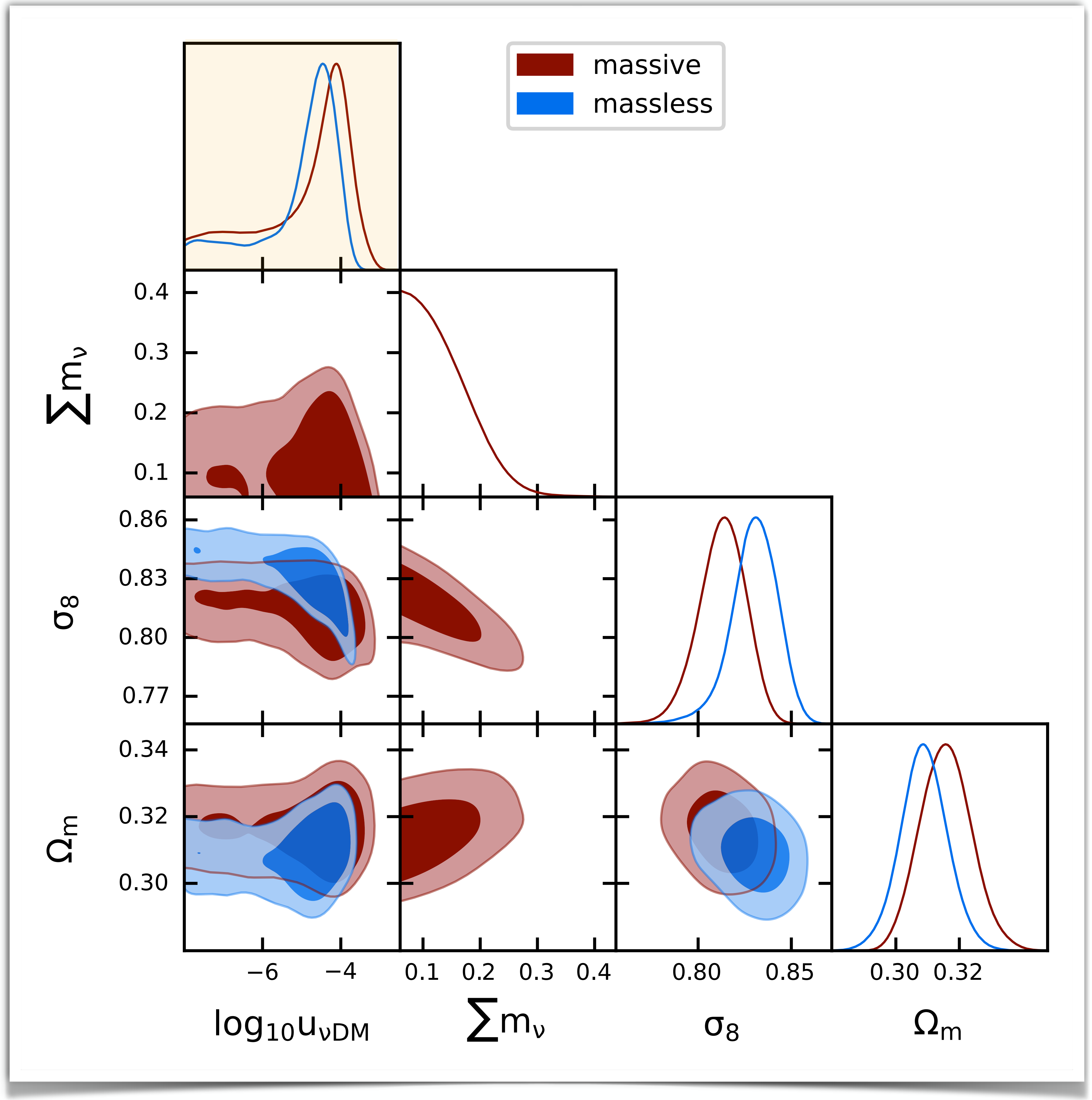
- **ACT** (alone and) in combination with **BAO**, gives **compelling indications for non-vanishing νDM interaction**



ACT & PLANCK (JOINT ANALYSIS)

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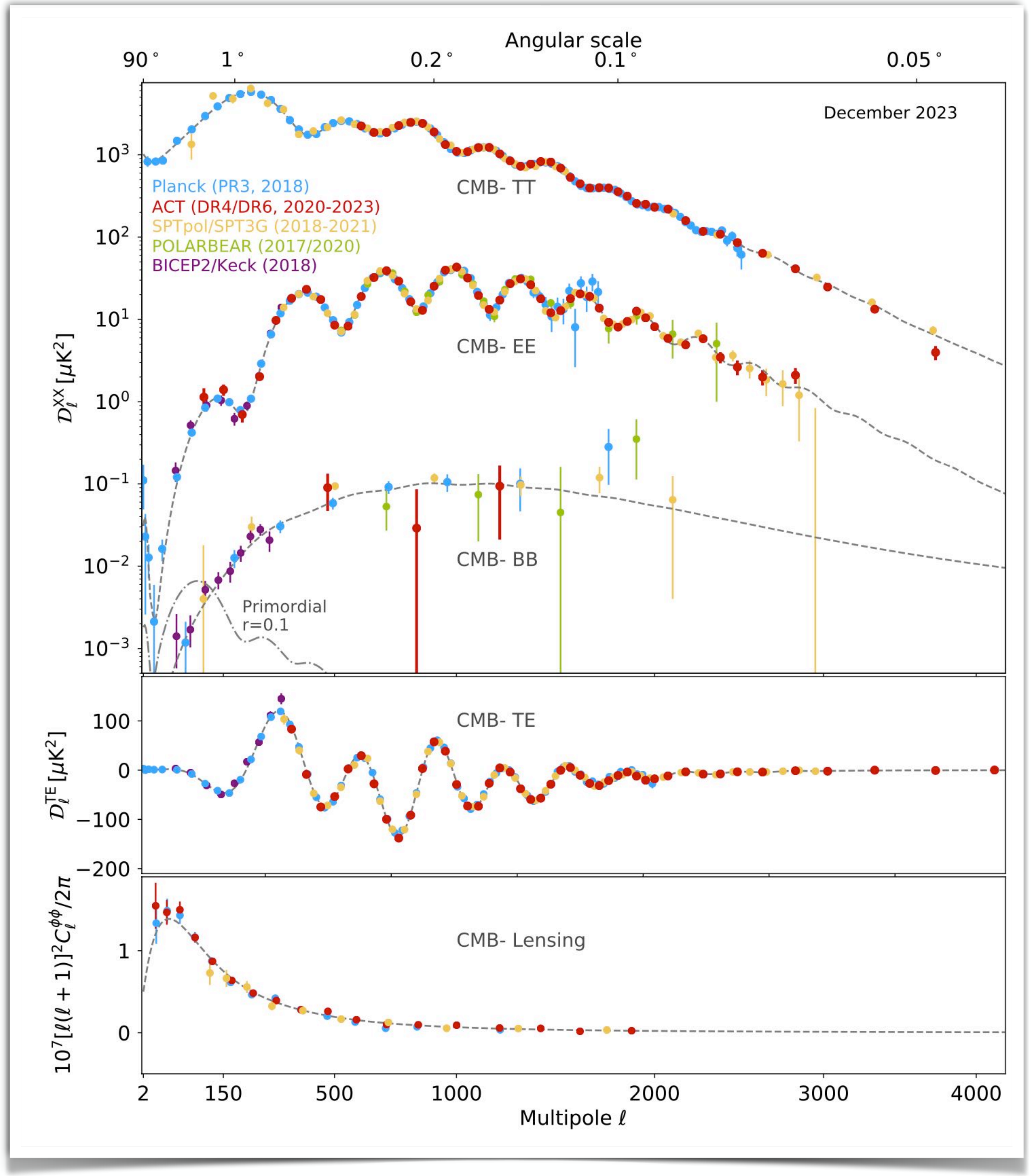

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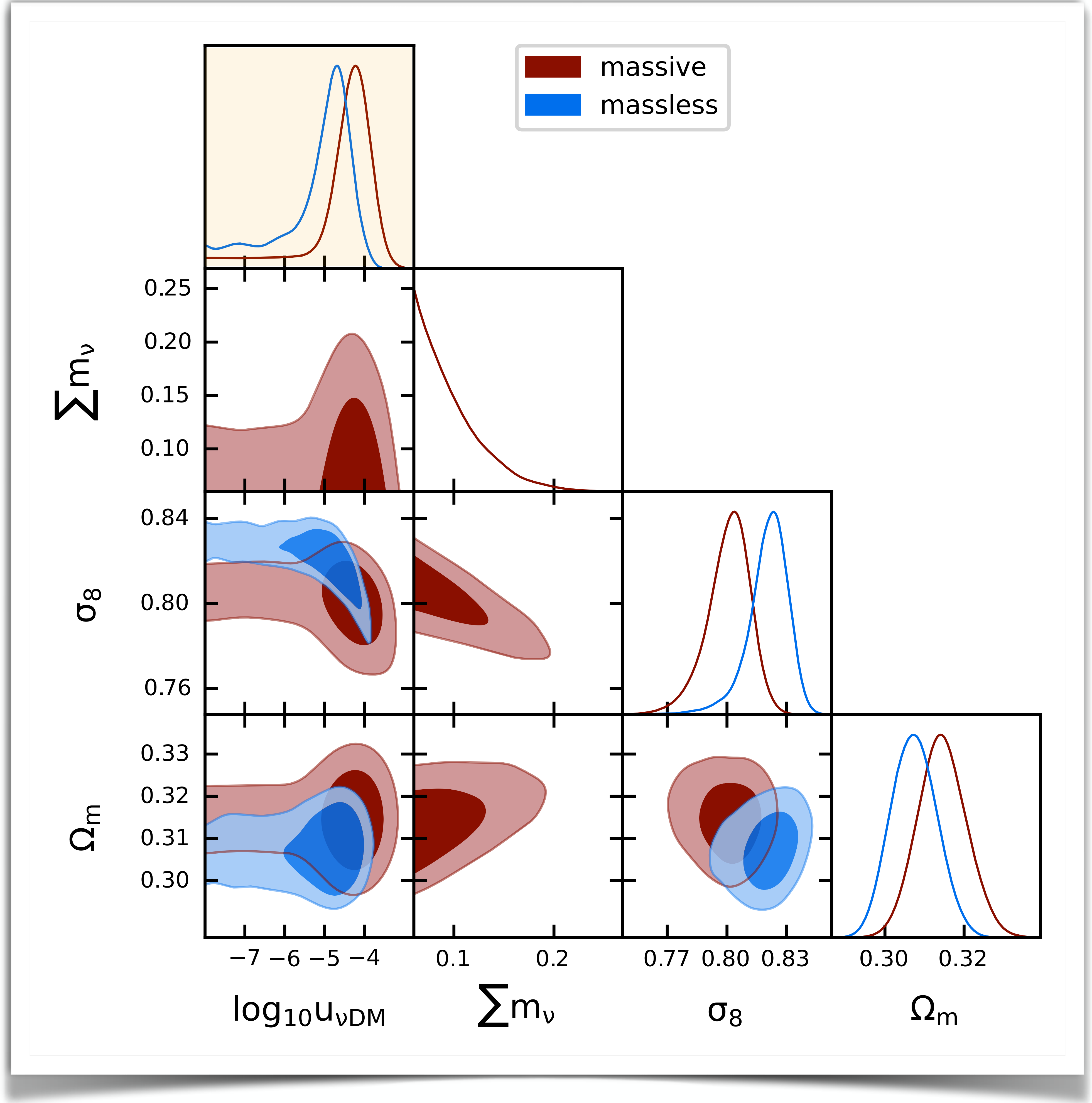
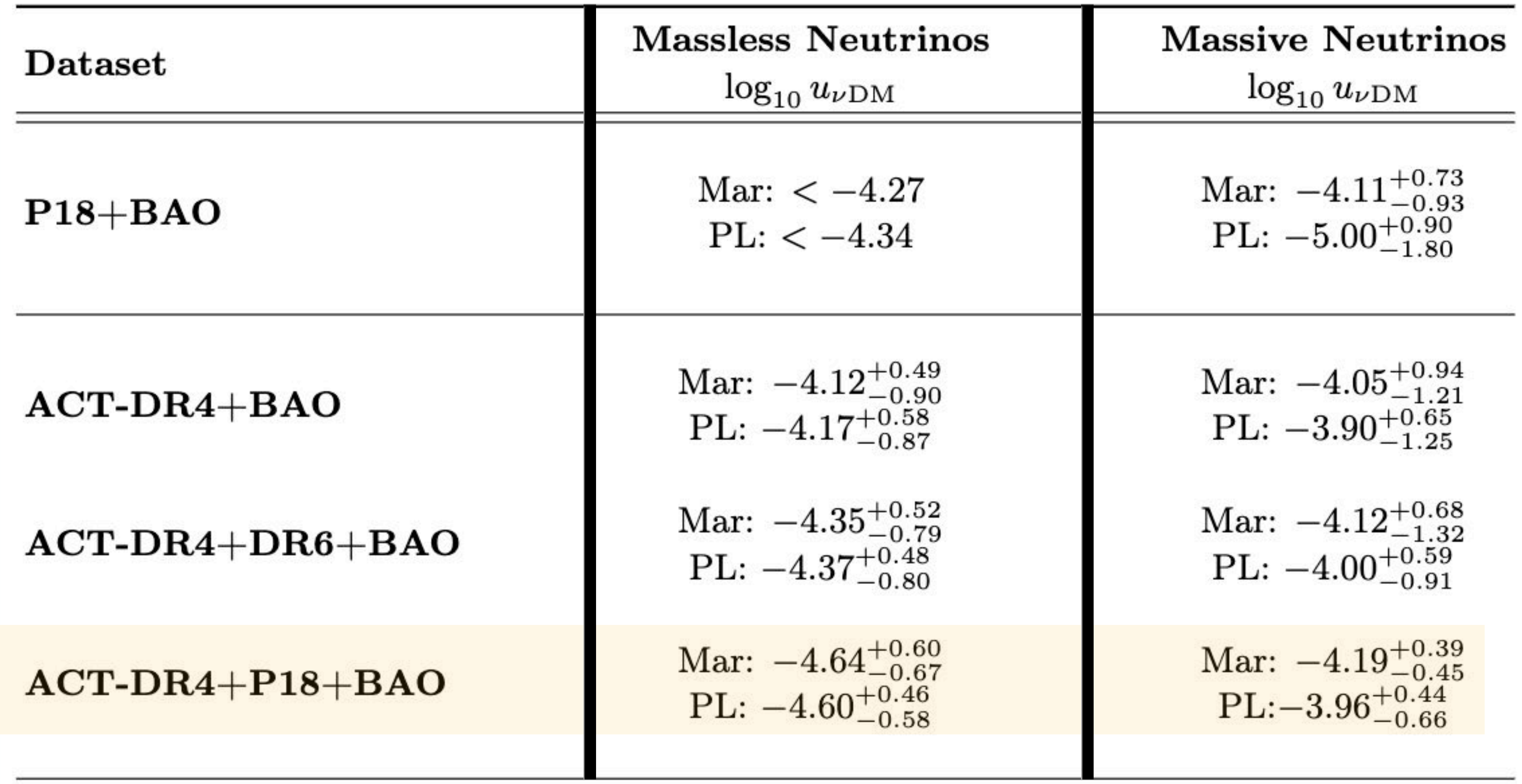
- This indication becomes very robust combining **ACT, Planck** and **BAO** data together



ACT & PLANCK (JOINT ANALYSIS)

P. Brax, C. van de Bruck, E. Di Valentino, **WG**, S. Trojanowski
PDU 42 (2023) 101321 [arXiv:2305.01383]



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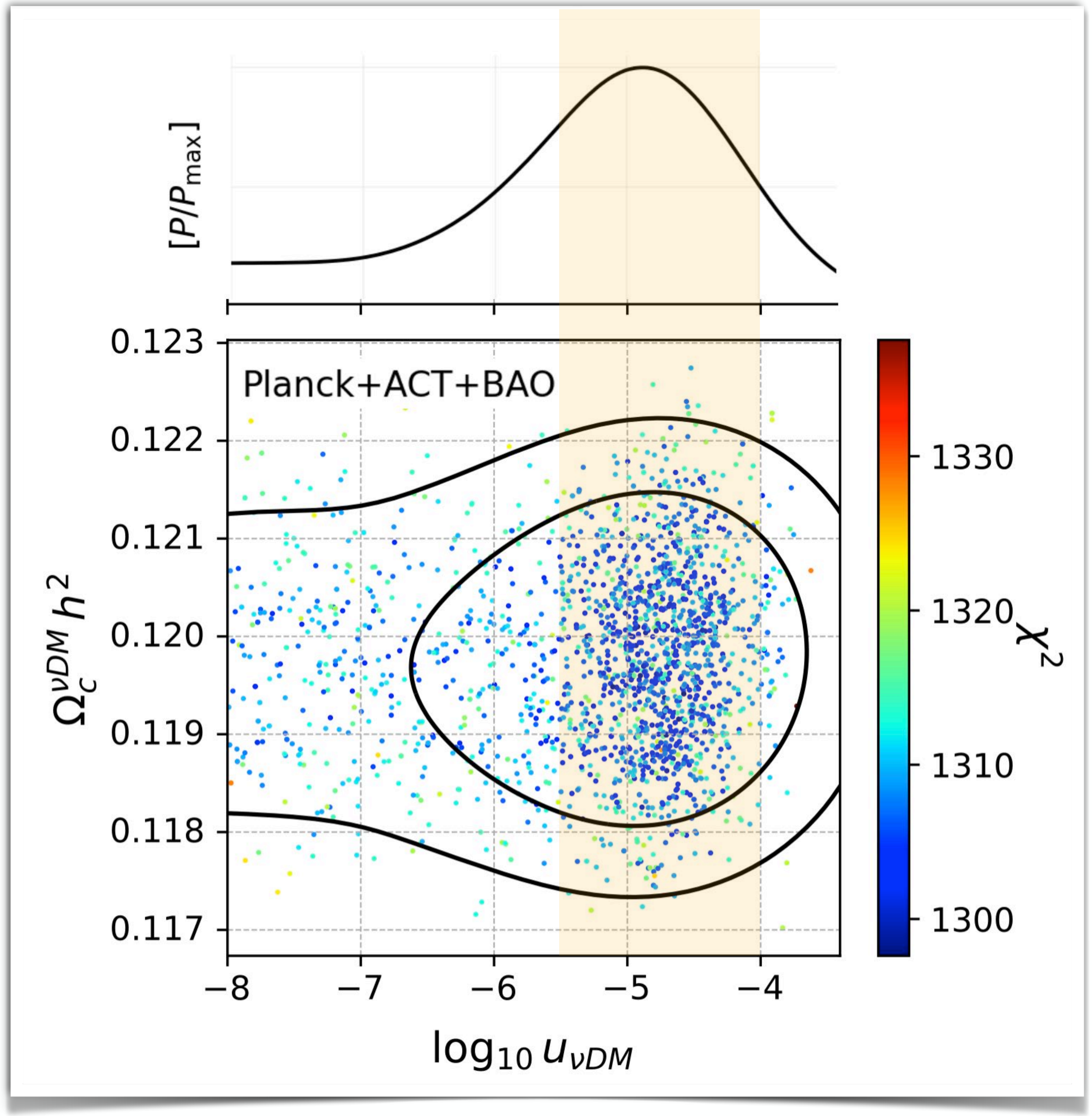

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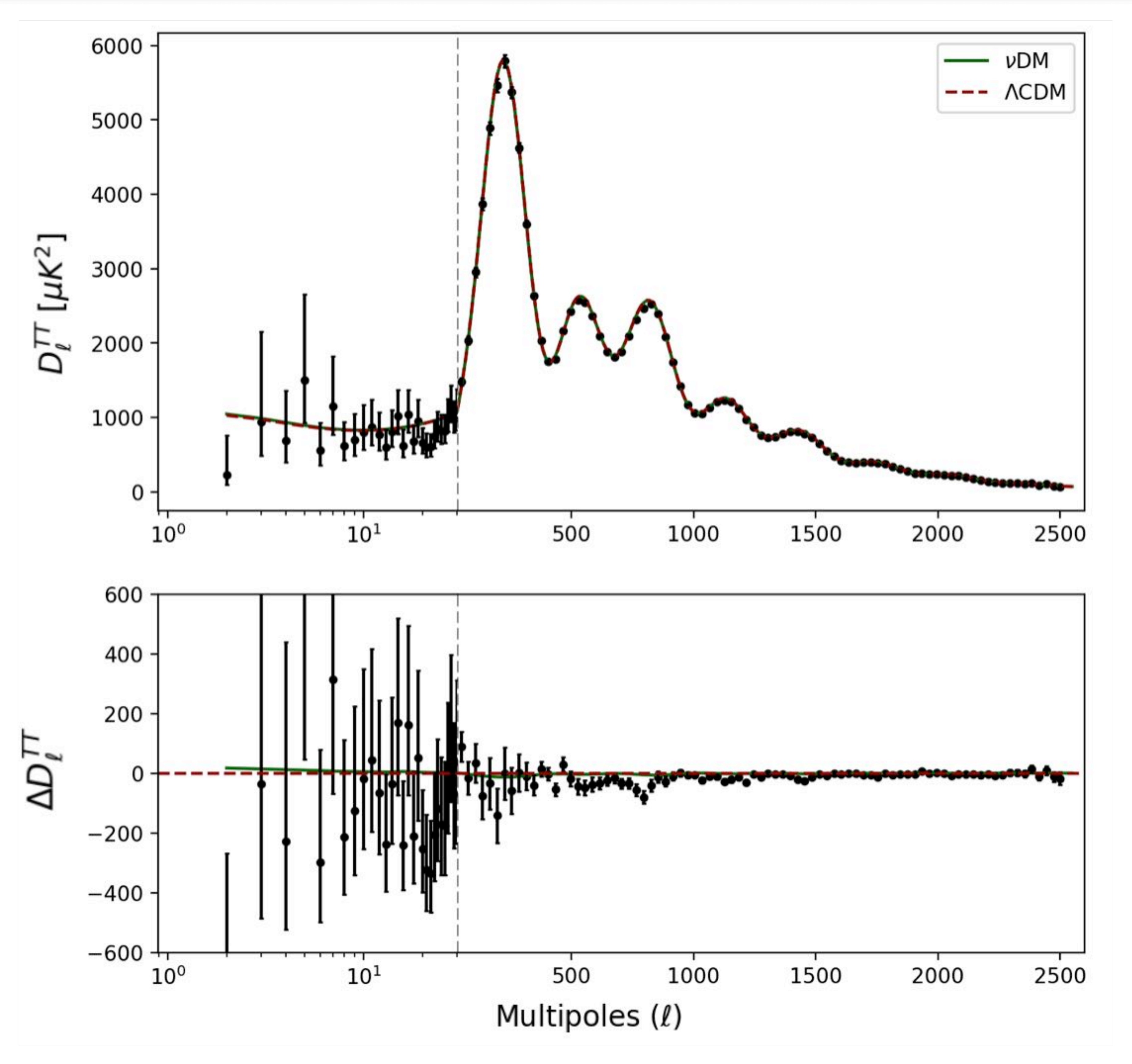
- ν-DM interactions leave the **fit to the Planck data basically unchanged**



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PDU 42 (2023) 101321 [arXiv:2305.01383]

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P18+BAO	Mar: < -4.27 PL: < -4.34	Mar: $-4.11^{+0.73}_{-0.93}$ PL: $-5.00^{+0.90}_{-1.80}$
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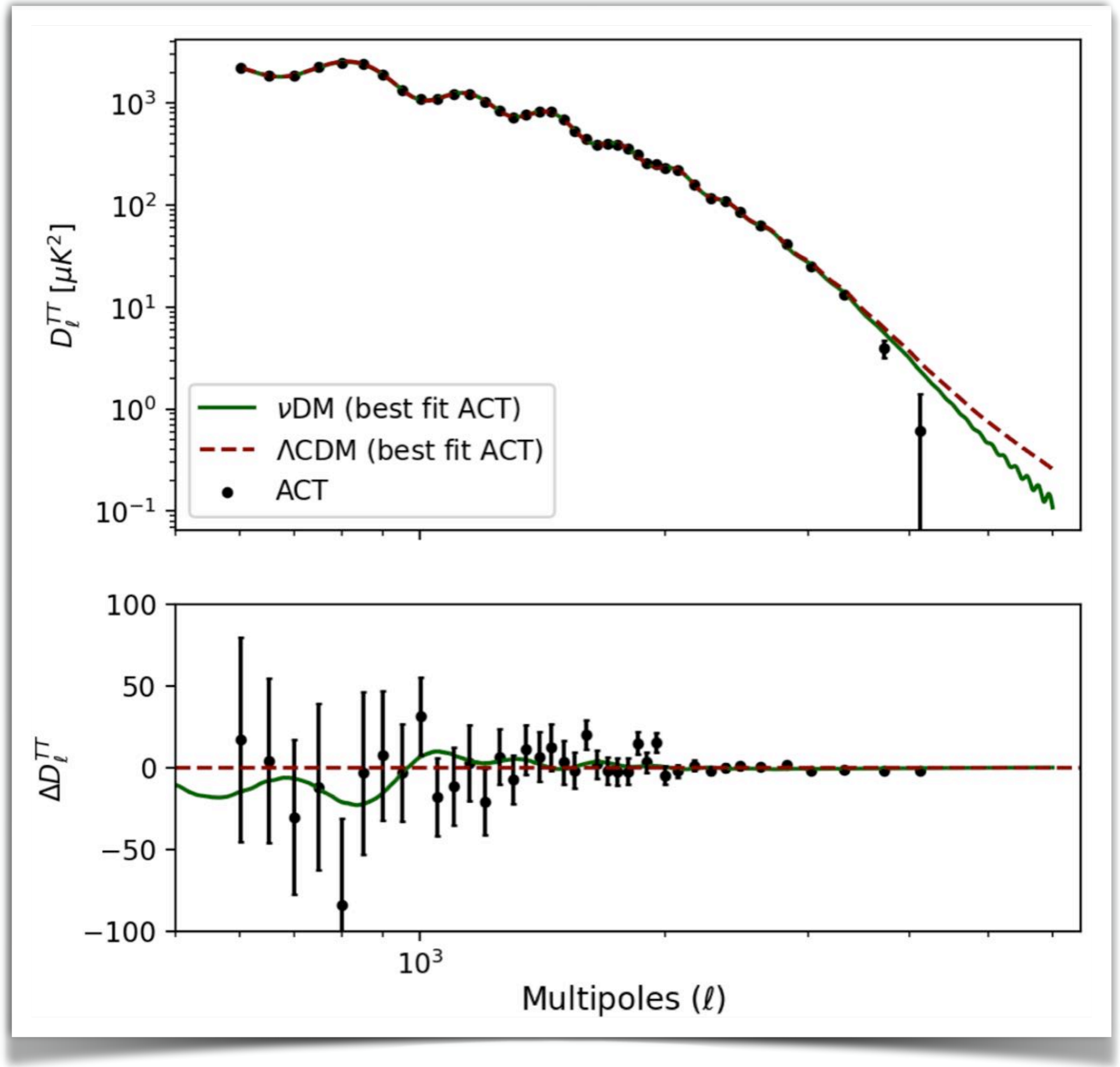
- ν-DM interactions leave the **fit to the Planck data basically unchanged**
- ν-DM interactions **improve the fit to the ACT high-multipole data**



ACT & PLANCK
(JOINT ANALYSIS)

WG, Gómez-Valent , Di Valentino, van de Bruck
PRD 109 (2024) 6, 063516 [arXiv:2311.09116]

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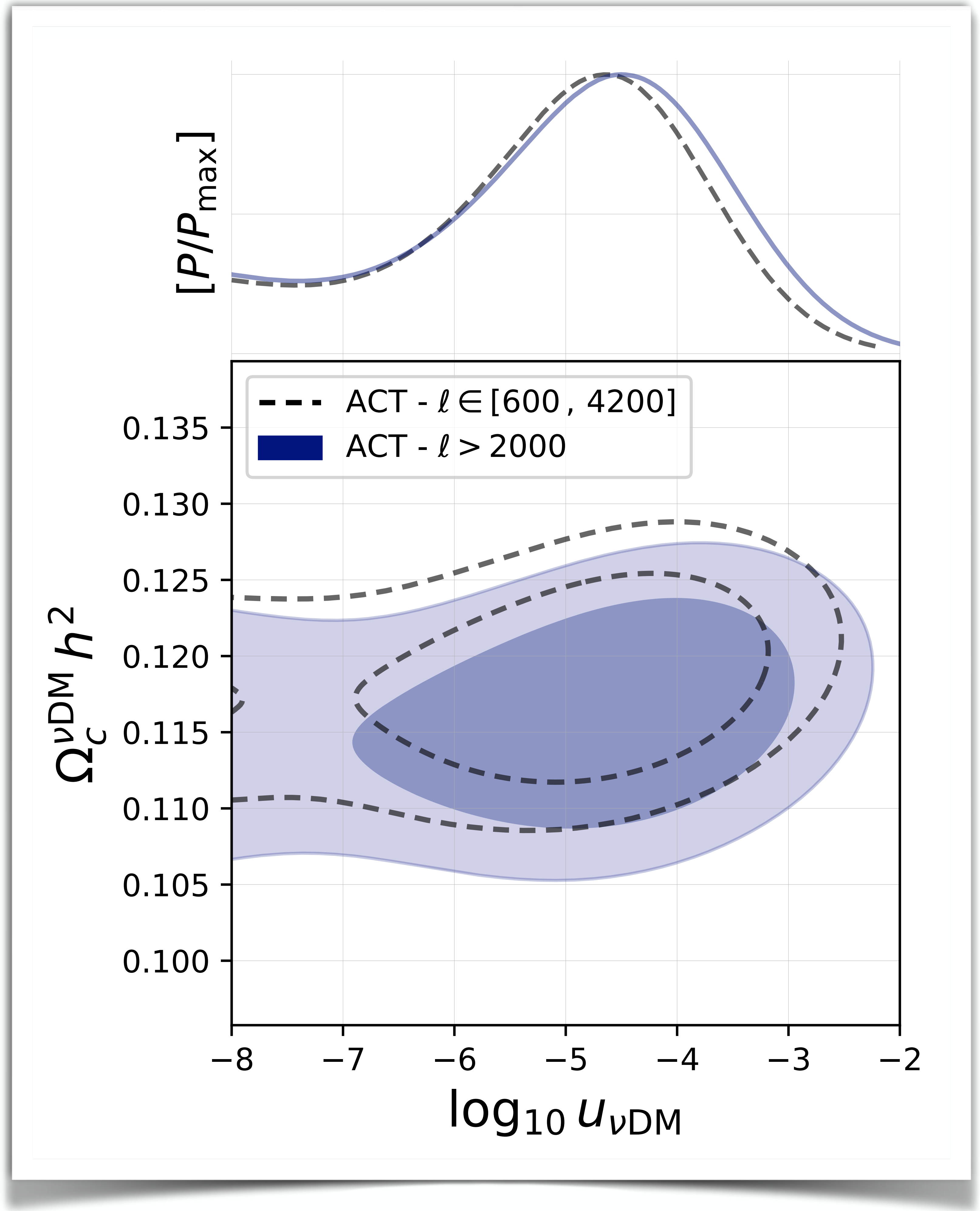
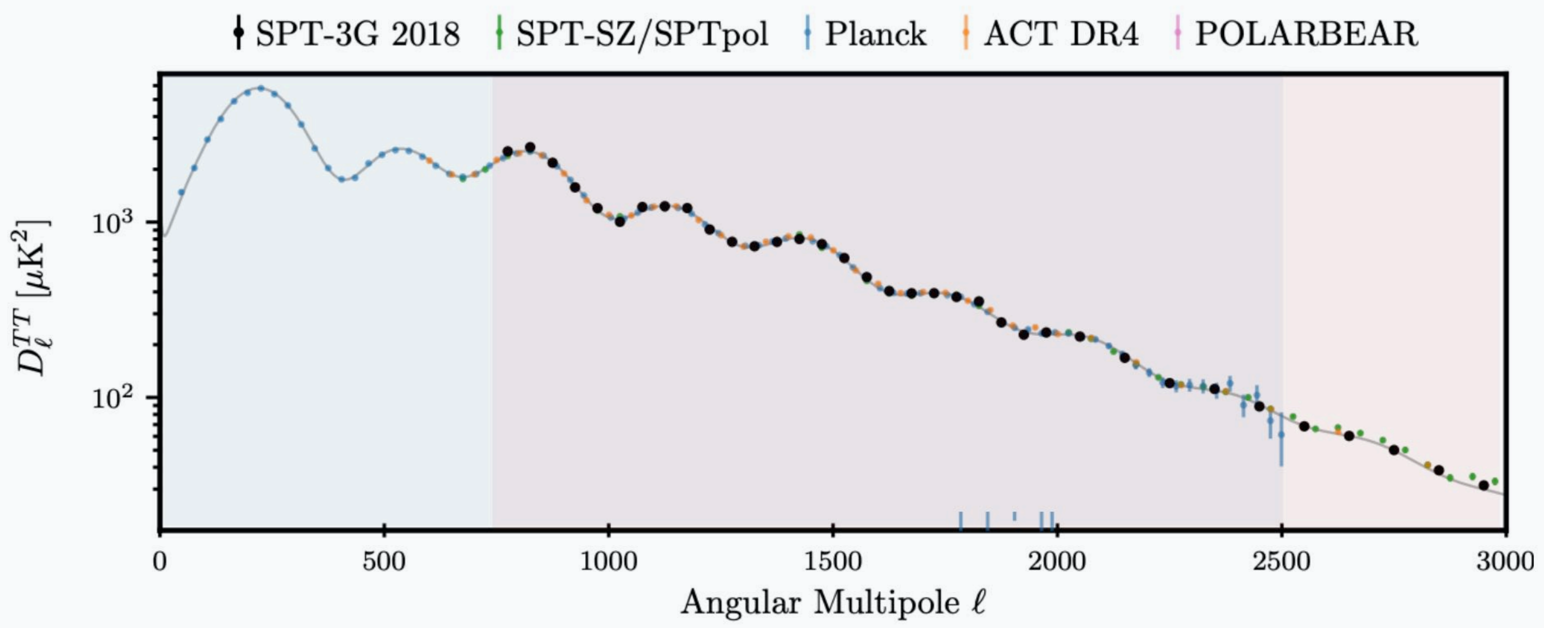
- v-DM interactions leave the **fit to the Planck data basically unchanged**
- v-DM interactions **improve the fit to the ACT high-multipole data**
- **The improvement comes from ACT small-scale data at** $\ell \gtrsim 2000$



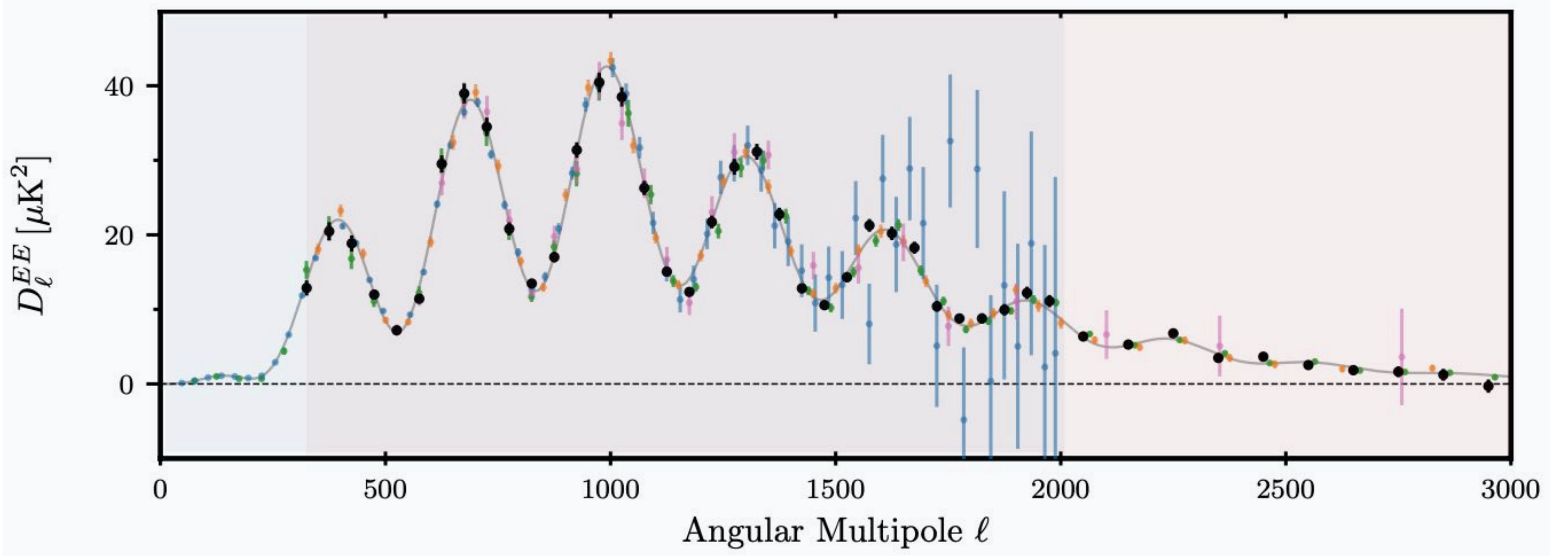
South Pole Telescope

arXiv: [2212.05642]

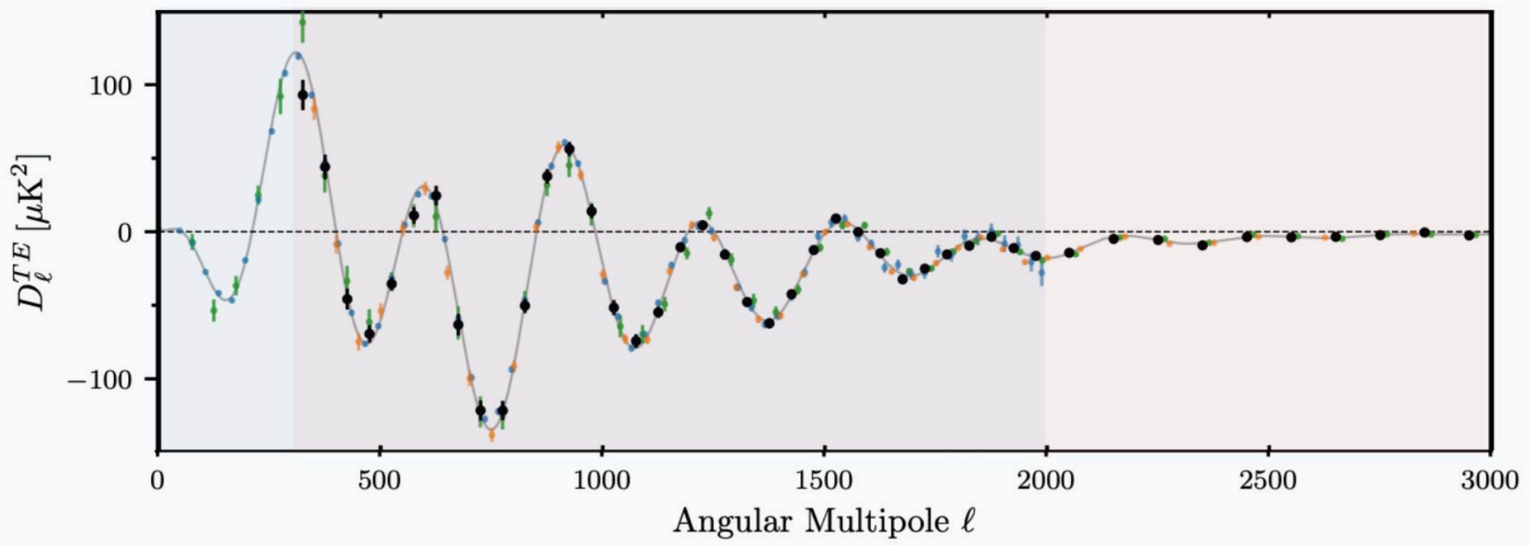
TT Spectrum



EE Spectrum



TE Cross-Spectrum



High-multipole temperature data

$600 < \ell \lesssim 3000$ in the TT Spectrum

High-multipole EE Polarization data

$350 < \ell \lesssim 3000$ in the EE Spectrum

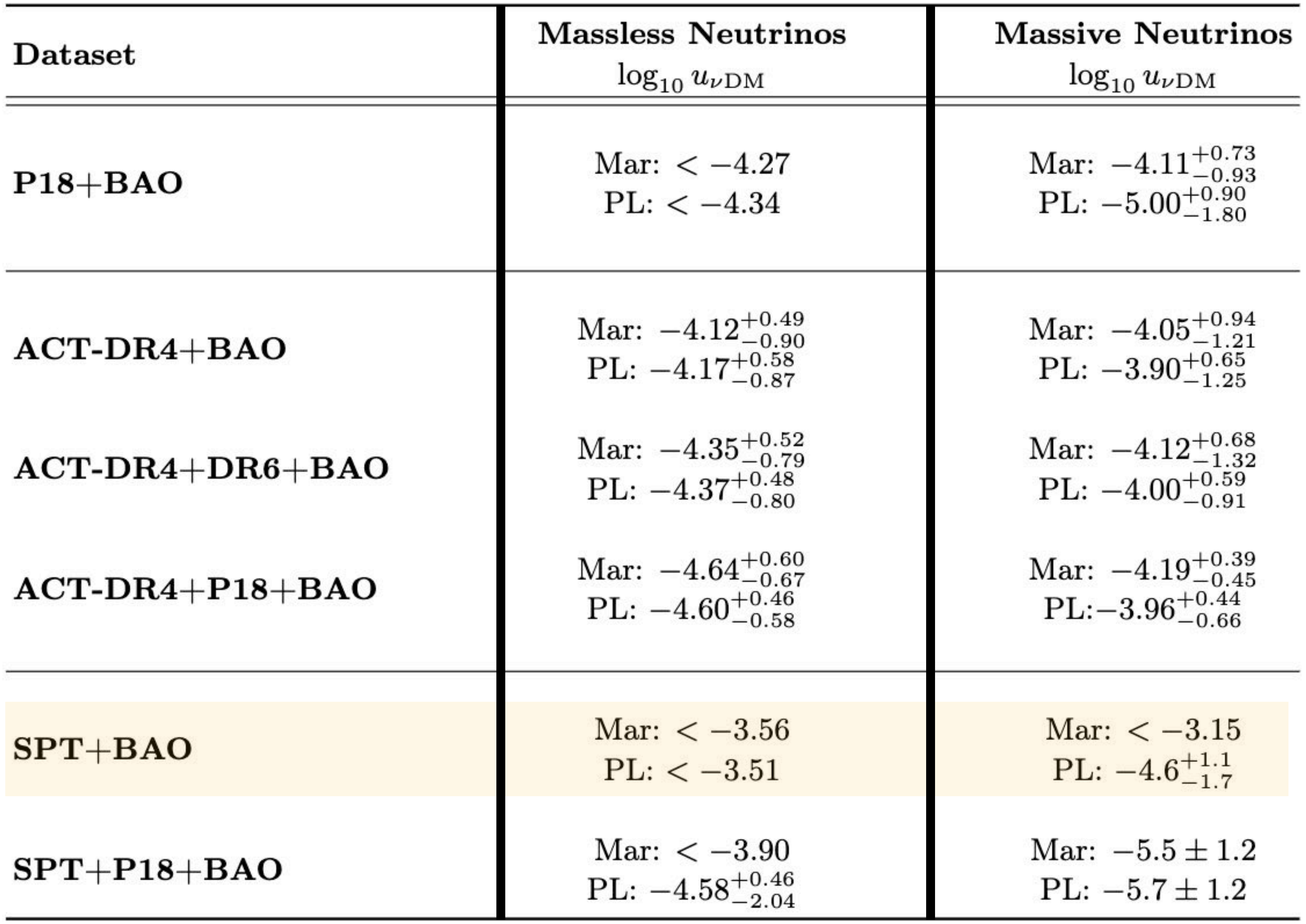
High-multipole TE data

$350 < \ell \lesssim 3000$ in the TE Spectrum

Note:
Planck probes $\ell \sim [2{,}2000]$
ACT probes $\ell \sim [650{,}4200]$

SOUTH POLE TELESCOPE

arXiv: [2212.05642]



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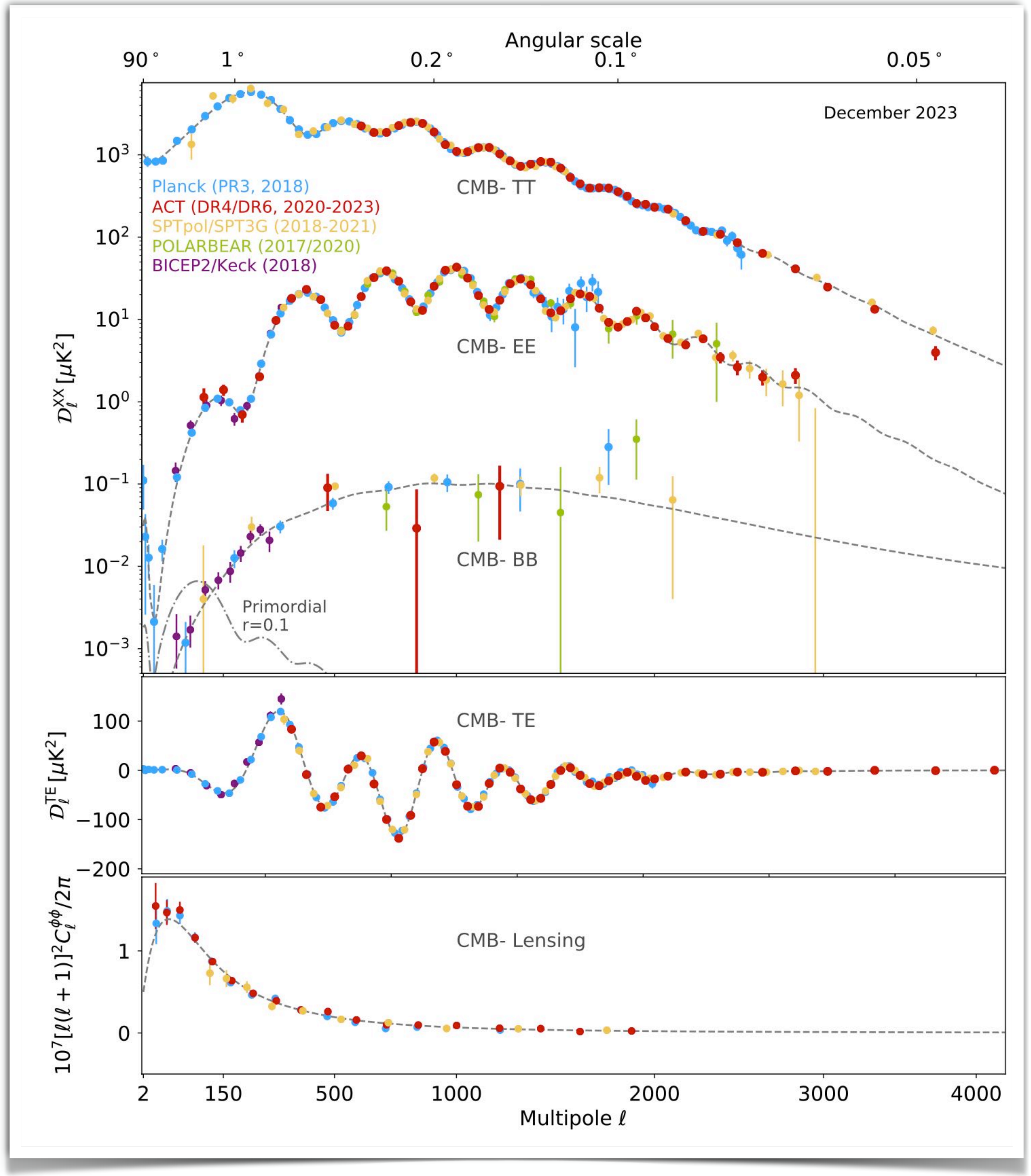
SPT+BAO	Mar: < -3.56 PL: < -3.51	Mar: < -3.15 PL: $-4.6^{+1.1}_{-1.7}$
SPT+P18+BAO	Mar: < -3.90 PL: $-4.58^{+0.46}_{-2.04}$	Mar: -5.5 ± 1.2 PL: -5.7 ± 1.2

- **SPT** probes **intermediate scales** with **larger uncertainties**, so the interpretation of the **result becomes less clear**



SPT & PLANCK (JOINT ANALYSIS)

WG, Gómez-Valent , Di Valentino, van de Bruck

PRD 109 (2024) 6, 063516 [arXiv:2311.09116]

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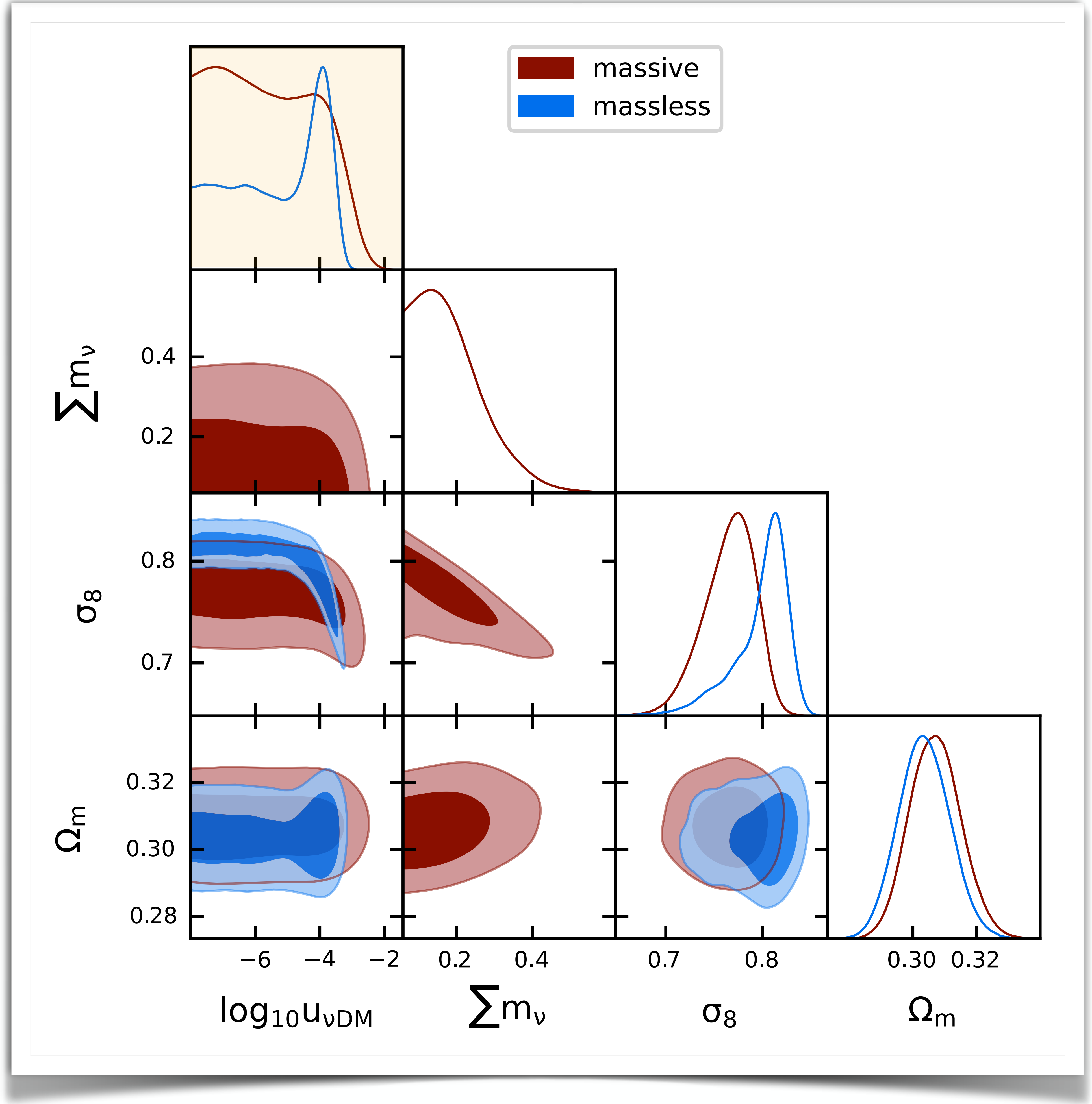

10+ ADDITIONAL TESTS ON NEUTRINO-DM INTERACTIONS

1) We analyzed three different CMB experiments (ACT, Planck, and SPT) alone and in combination with BAO –> **Including/excluding BAO does not make a difference**

2) We considered the different CMB experiment with and without lensing data –> **Including/excluding lensing does not make a difference**

3) We considered different combinations of CMB experiments –> **Preference confirmed combining large and small-scale CMB data**

4) We divided the ACT likelihood into different bins –> **Preference in ACT coming from multipoles larger than 2000**

5) We considered neutrinos massless and massive –> **We obtain similar results for both massive and massless neutrinos**

6) We considered Neff as a free parameter –> **Preference for interactions confirmed when Neff can vary in the cosmological model**

7) We considered a temperature-dependent cross-section –> **We obtain similar results when considering a σ~T^2 cross-section (with and without Neff)**

8) We considered different priors for the interaction strength –> **Marginal impact; we adopt the most conservative large priors spanning 8 orders of magnitude!**

9) We tested that the preference for interaction is given by a reduction of the chi2 –> **The peak of the distribution corresponds to a reduction of the chi2**

10) Along with the usual MCMC analysis, we performed Profile Likelihood analyses –> **Profile Likelihood confirms preference for interactions**

Act & Planck (joint analysis)

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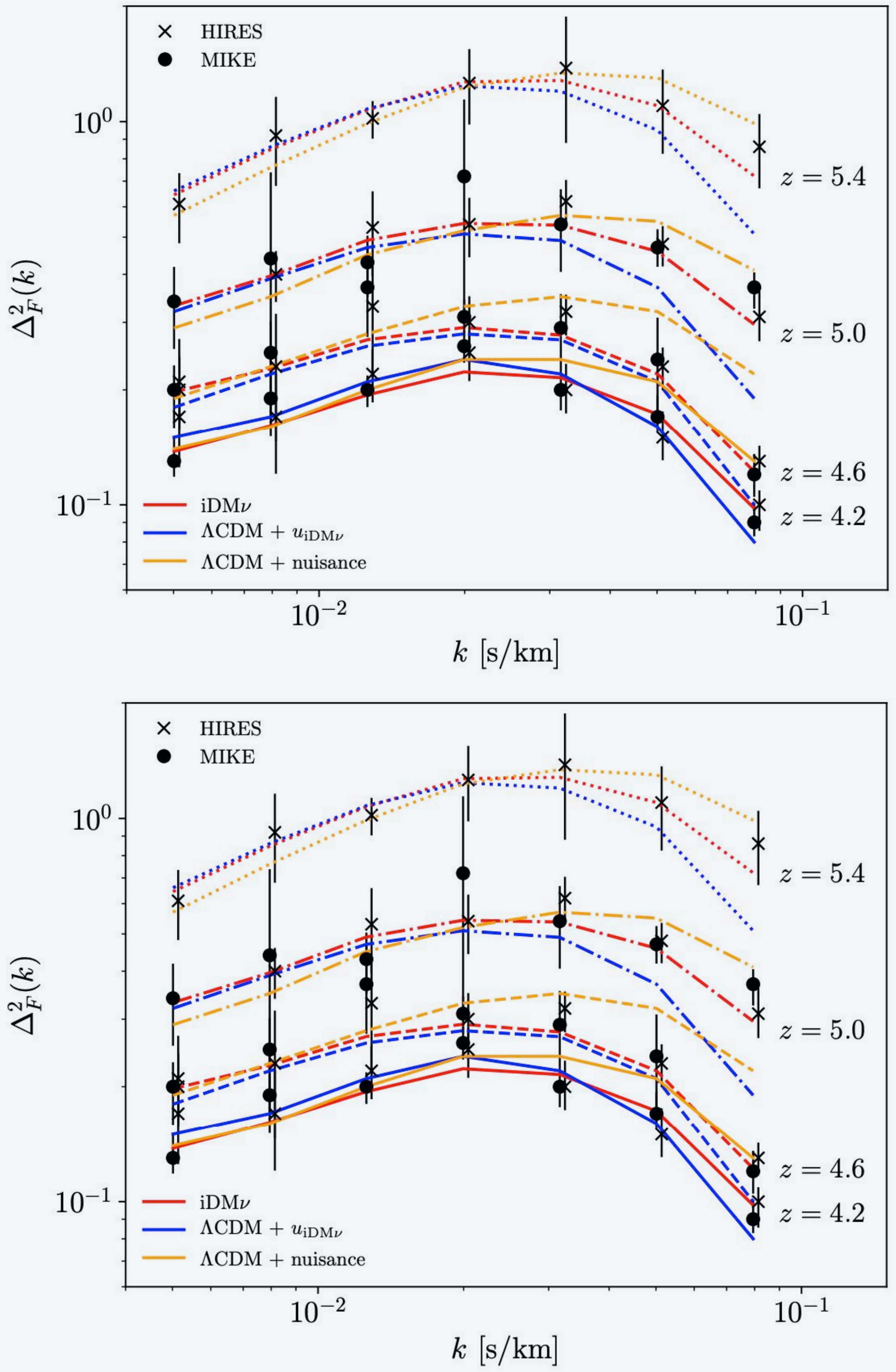
Lyman-α

D.C. Hooper and M. Lucca, [arXiv: 2110.04024]



$$\log_{10} u_{\nu DM} = -5.42^{+0.17}_{-0.08}$$

3 OUTLOOKS AND CONCLUSIONS

Neutrino Cosmology

A powerful avenue for constraining neutrino properties (species, mass, and ordering). Weak — yet relevant — dependence on background cosmology.

Neutrino Mass & Ordering

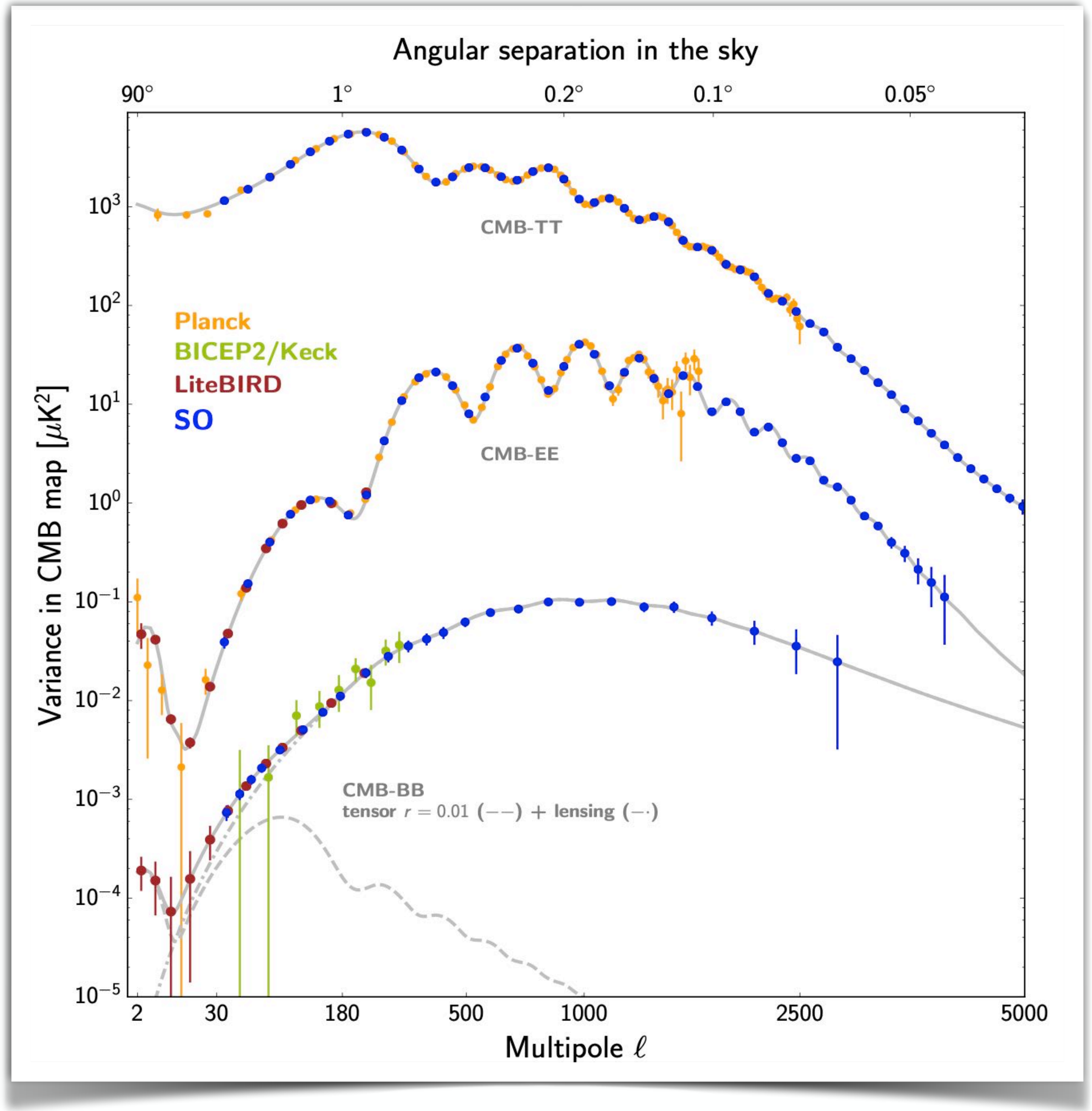
Post-DESI neutrino mass limits strongly disfavor the IO and intriguingly approach oscillation experiment limits for the NO — Signal of new physics beyond ΛCDM?

Neutrino Interactions

Small-scale CMB experiments provide unique observational windows to test scenarios like neutrino-dark matter scattering. — Hints of neutrino-DM scattering in the CMB?

The future is bright and (almost) here!

Upcoming data from large-scale structure surveys and small-scale CMB surveys promise to answer all these questions!



Thank You!