

Is Cosmology in tension with ν Oscillations?

Enrique Fernández-Martínez

Based on 2407.13831 in collaboration with:
Daniel Naredo-Tuero, Miguel Escudero, Xabier
Marcano and Vivian Poulin



Evidence for ν mass from oscillations

Evidence for ν mass and mixing from LFV in oscillation phenomenon in many experiments with great agreement

What we already know (1σ)

SNO, Borexino	"Solar sector"	$\left\{ \begin{array}{l} \Delta m_{21}^2 = 7.4_{-0.2}^{+0.2} \cdot 10^{-5} \text{eV}^2 \\ \sin^2 \theta_{12} = 0.308_{-0.011}^{+0.012} \end{array} \right.$
KamLAND		

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SK, T2K, IC
MINOS, NO ν A

“Atm. sector”

$$\begin{cases} |\Delta m_{31}^2| = 2.51_{-0.02}^{+0.02} \cdot 10^{-3} \text{eV}^2 \\ \sin^2 \theta_{23} = 0.47_{-0.02}^{+0.02} \end{cases}$$

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Daya Bay RENO, T2K, NO ν A		$\sin^2 \theta_{13} = 0.0221 \pm 0.0006$

See talk by Iván Esteban

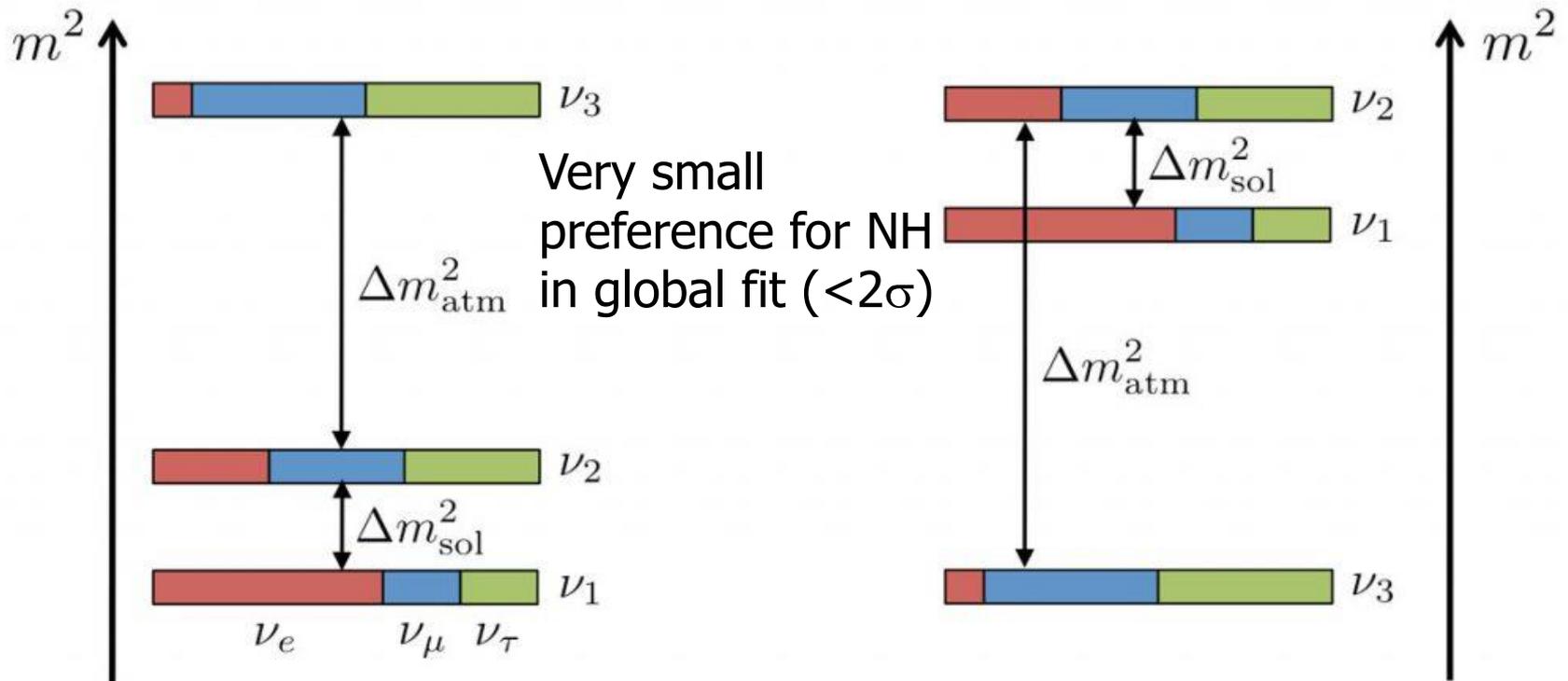
Evidence for ν mass from oscillations

Mass hierarchy? Absolute mass scale?

$sign(\Delta m_{31}^2)$? m_1 ?

normal hierarchy (NH)

inverted hierarchy (IH)



Searches for ν mass from cosmology

Cosmology is instead sensitive to **sum of ν masses**

$$\sum_i m_i$$

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Very stringent bounds when adding recent **DESI** results at **95% CL**:

$$\sum_i m_i \leq 0.072 \text{ eV} \quad (\text{CMB+DESI DR1}) \quad 2404.03002$$

$$\sum_i m_i \leq 0.064 \text{ eV} \quad (\text{CMB+DESI DR2}) \quad 2503.14744$$

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But **minimum** value from oscillation data (more than 3σ):

$$\sum_i m_i \geq 0.059 \text{ eV} \quad \text{for NH if} \quad m_1 = 0$$

$$\sum_i m_i \geq 0.099 \text{ eV} \quad \text{for IH if} \quad m_3 = 0$$

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Also, despite the **very narrow** allowed parameter space left, barely any hint or positive fluctuation in any analysis of cosmological data...

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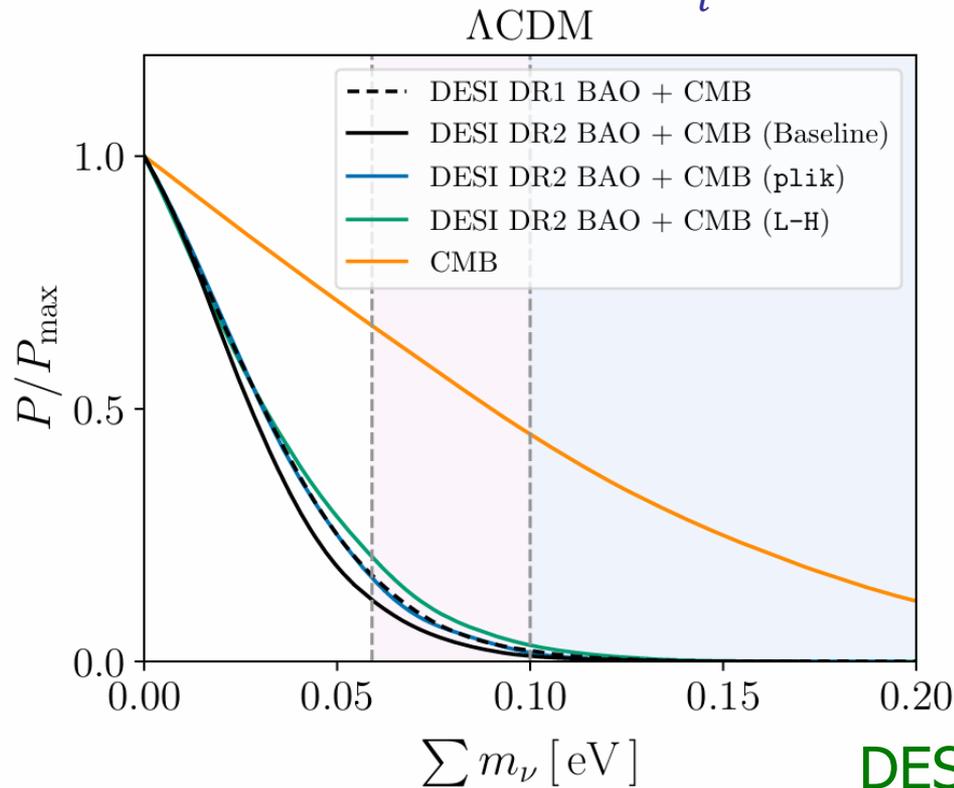
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Where does the sensitivity come from?

Two main effects:

see also M. Loverde and Z. J. Weiner 2410.00090 and
T. Bertólez-Martínez et al 2411.14524

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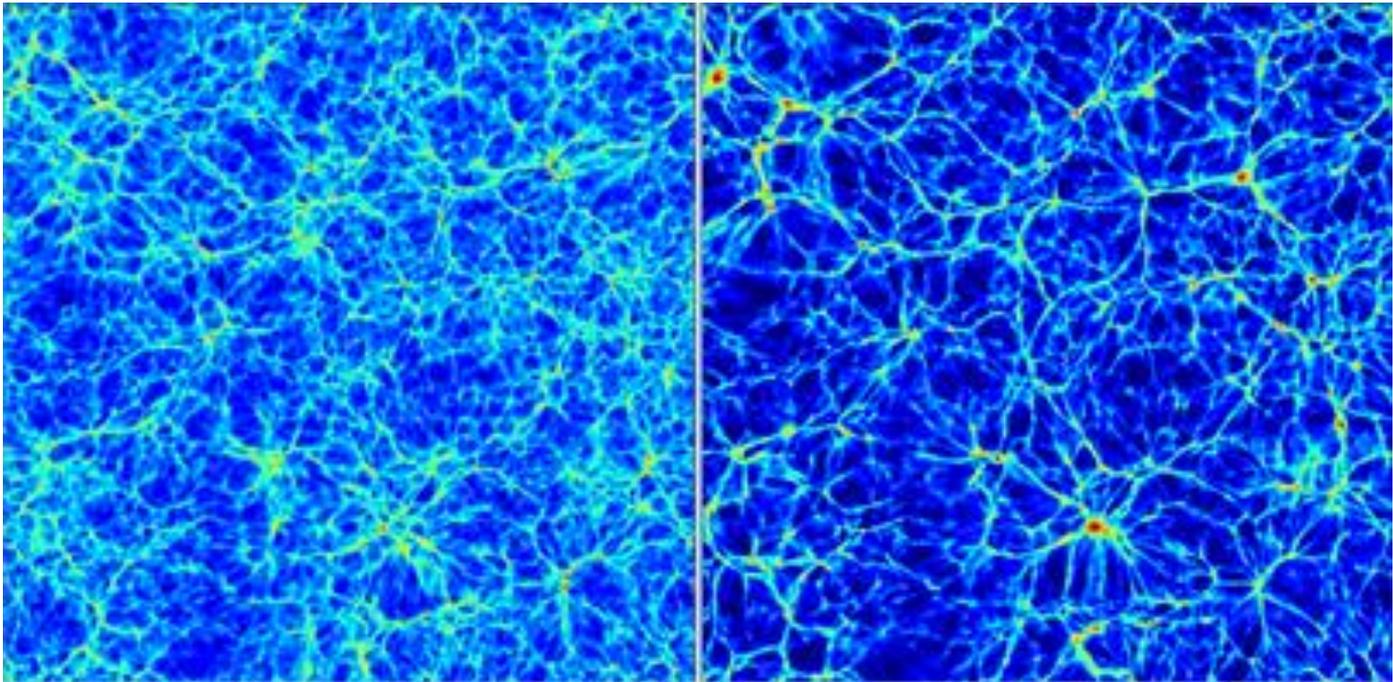
Two main effects:

1) "Perturbations"

ν free stream and suppress formation of **small structures** as they do not fall into the smallest potential wells (scales below $\sim 20\text{Mpc}$)

$$\sum_i m_i = 0$$

$$\sum_i m_i = 1.9 \text{ eV}$$



Plot from S. Agarwal and H. Feldman 1006.0689

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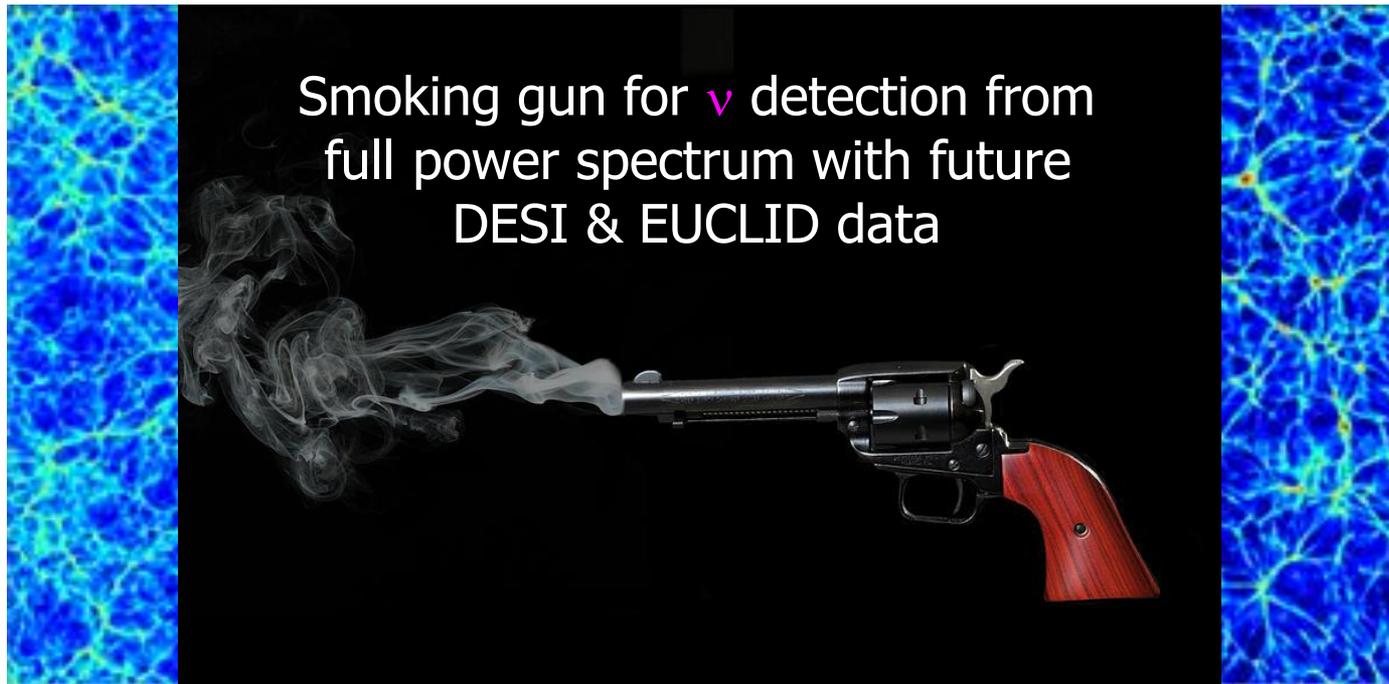
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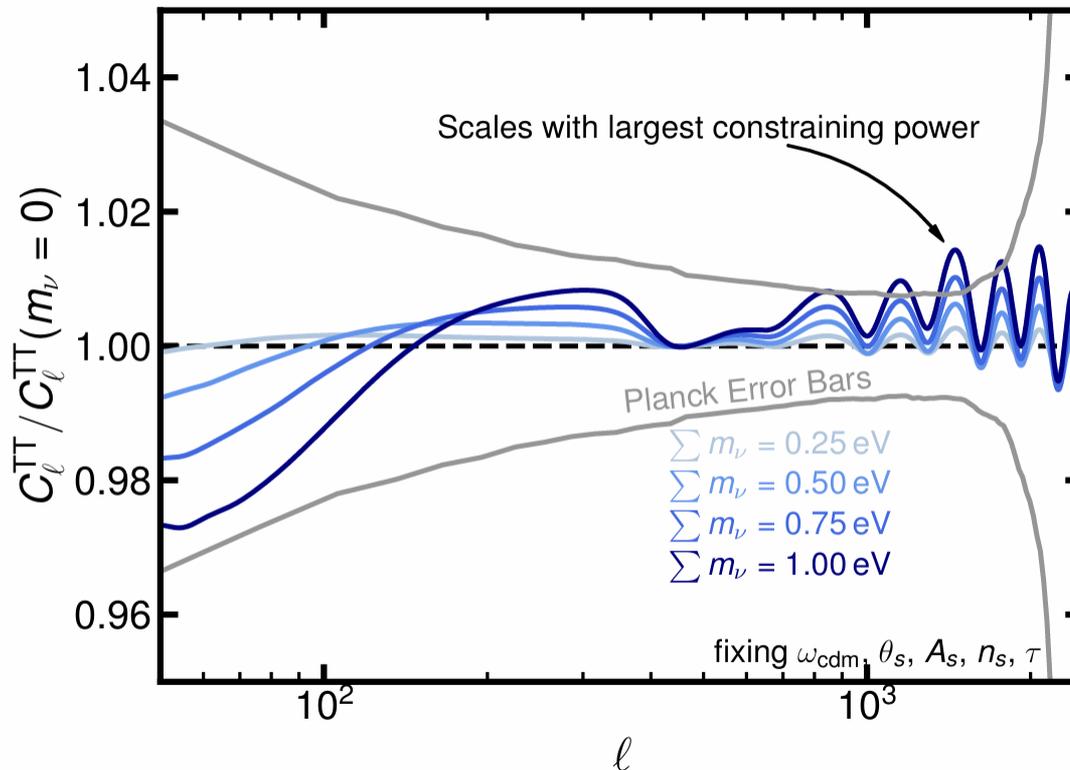
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1) "Perturbations"

Relativistic \mathbf{v} will also reduce the **lensing** of **CMB photons** from **LSS**. At **Planck** this is reflected by sharper peaks, particularly at **small angular scales**



D. Naredo-Tuero, M.
Escudero, EFM, X.
Marcano and V. Poulin
2407.13831

Why never a hint from cosmology?

Most (if not all) cosmological datasets are combined with
Planck data

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Planck 2018 legacy analysis reported a “**lensing anomaly**”.
Namely, if allowed to scale freely, the likelihood prefers stronger lensing than even for massless ν at **2.8σ ($A_{\text{lens}} > 1$)**
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E. Calabrese, A. Slosar, A. Melchiorri, G. F. Smoot and O. Zahn 0803.2309

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Thus, analyses containing **WMAP** or **Planck** data will prefer

$$\sum_i m_i = 0$$

or even larger **lensing**, if allowed

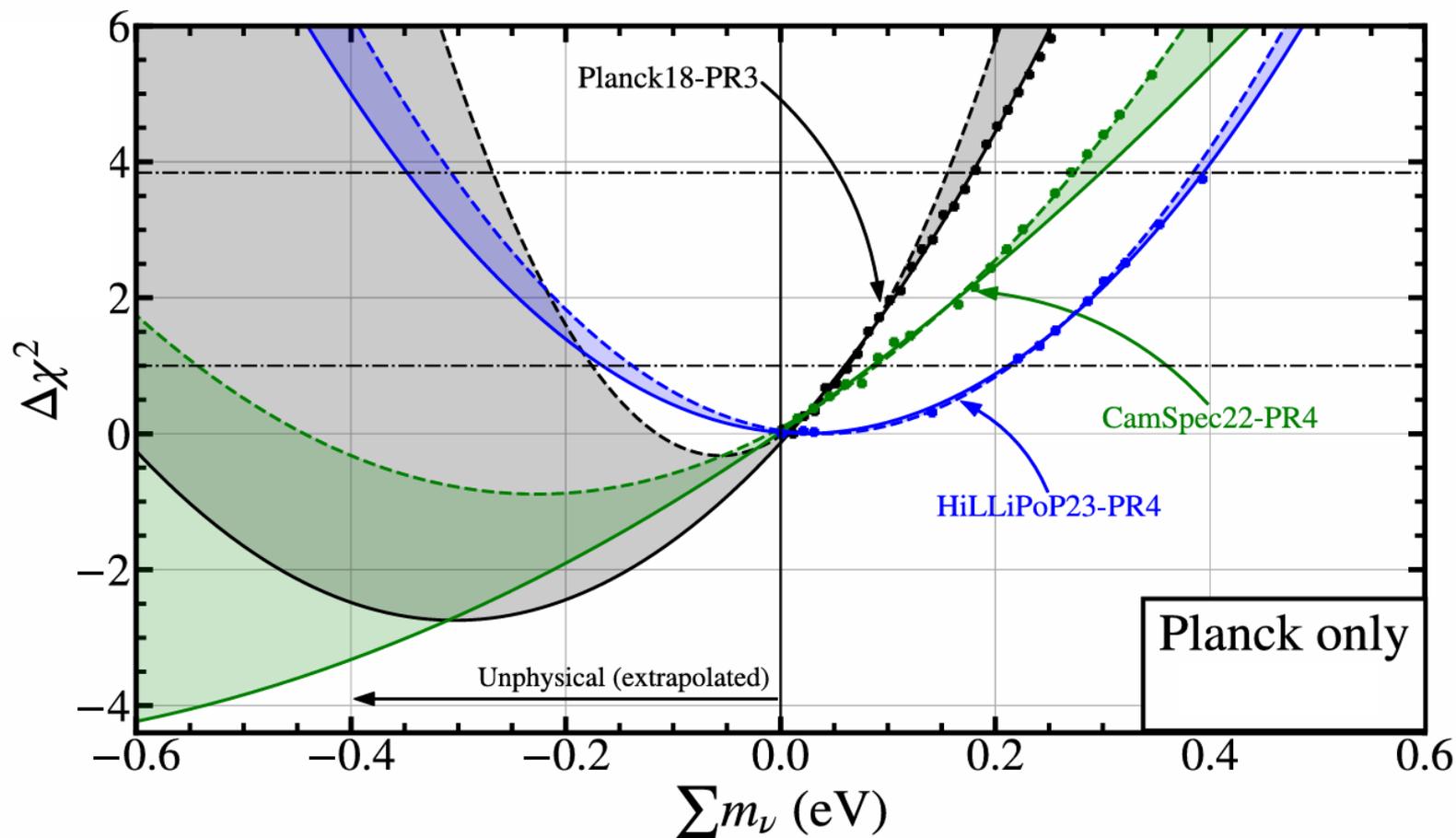
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Planck 2018 1807.06209

Interestingly, subsequent reanalyses by members of Planck improving on several aspects reduce the lensing anomaly:

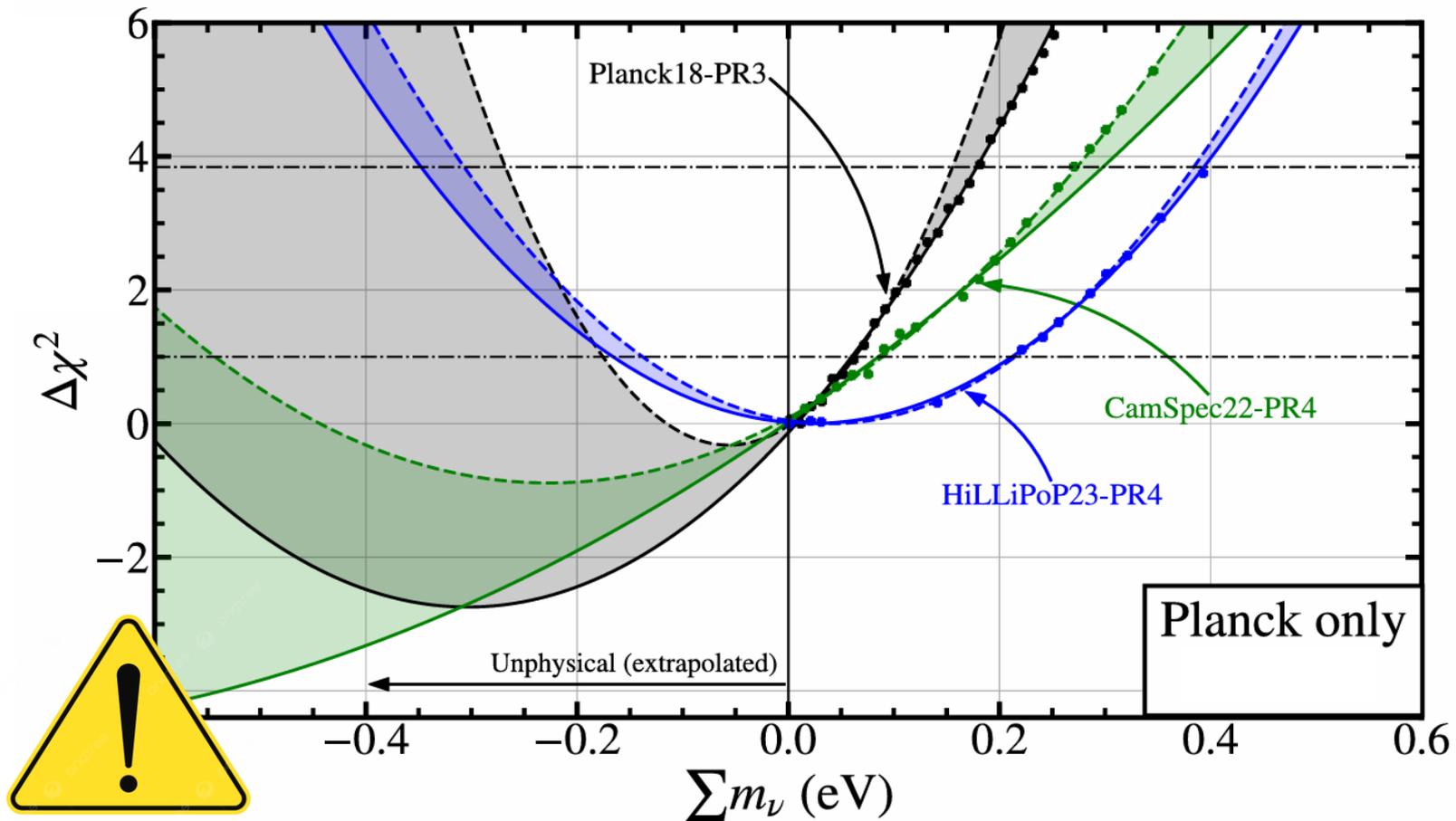
- “CamSpec22” $A_{\text{lens}} > 1$ at 1.7σ
E. Rosenberg, S. Gratton, G. Efstathiou 2205.10869
- “HiLLiPoP23” $A_{\text{lens}} > 1$ at 0.75σ
M. Tristram et al 2309.10034

Bound relaxed with new Planck likelihoods



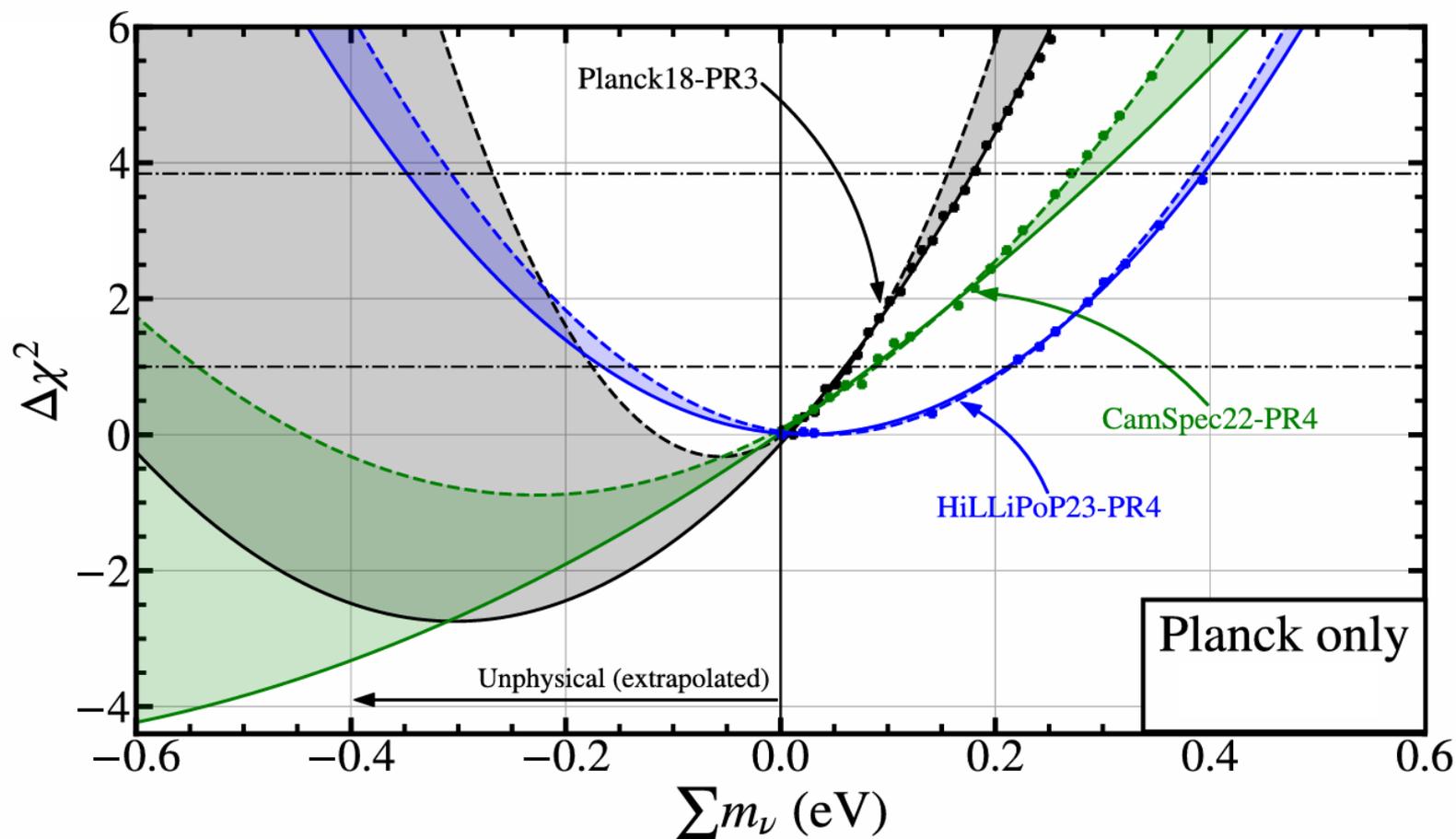
Bound from **Planck** significantly **relaxed** with new likelihoods with reduced **lensing anomaly**

Bound relaxed with new Planck likelihoods



DISCLAIMER!!!: The extrapolation to **negative region** is only a means to derive and compare **frequentist** and **Bayesian** bounds and **NOT** intended to be interpreted physically. The preference for $\Sigma m_i < 0$ is just another reflection of the lensing anomaly and hence absent for **HiLLiPoP23**

Bound relaxed with new Planck likelihoods



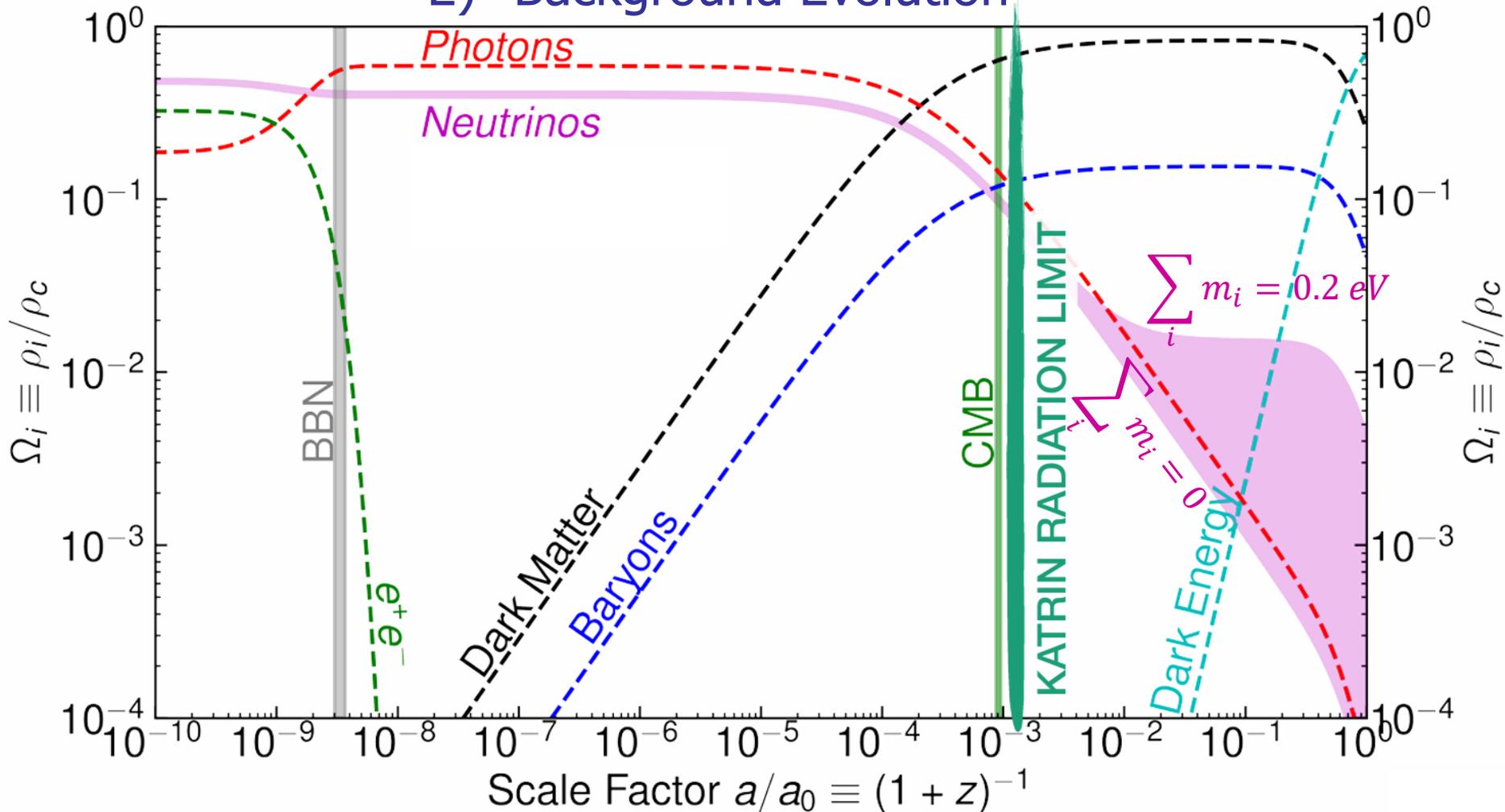
For further discussion for this preference see:

I. J. Allali and A. Notari 2406.14554; D. Green and J. Meyers 2407.07878;
W. Elbers, C. S. Frenk, A. Jenkins, B. Li and S. Pascoli 2407.10965

Where does the sensitivity come from?

Two main effects:

2) "Background Evolution"

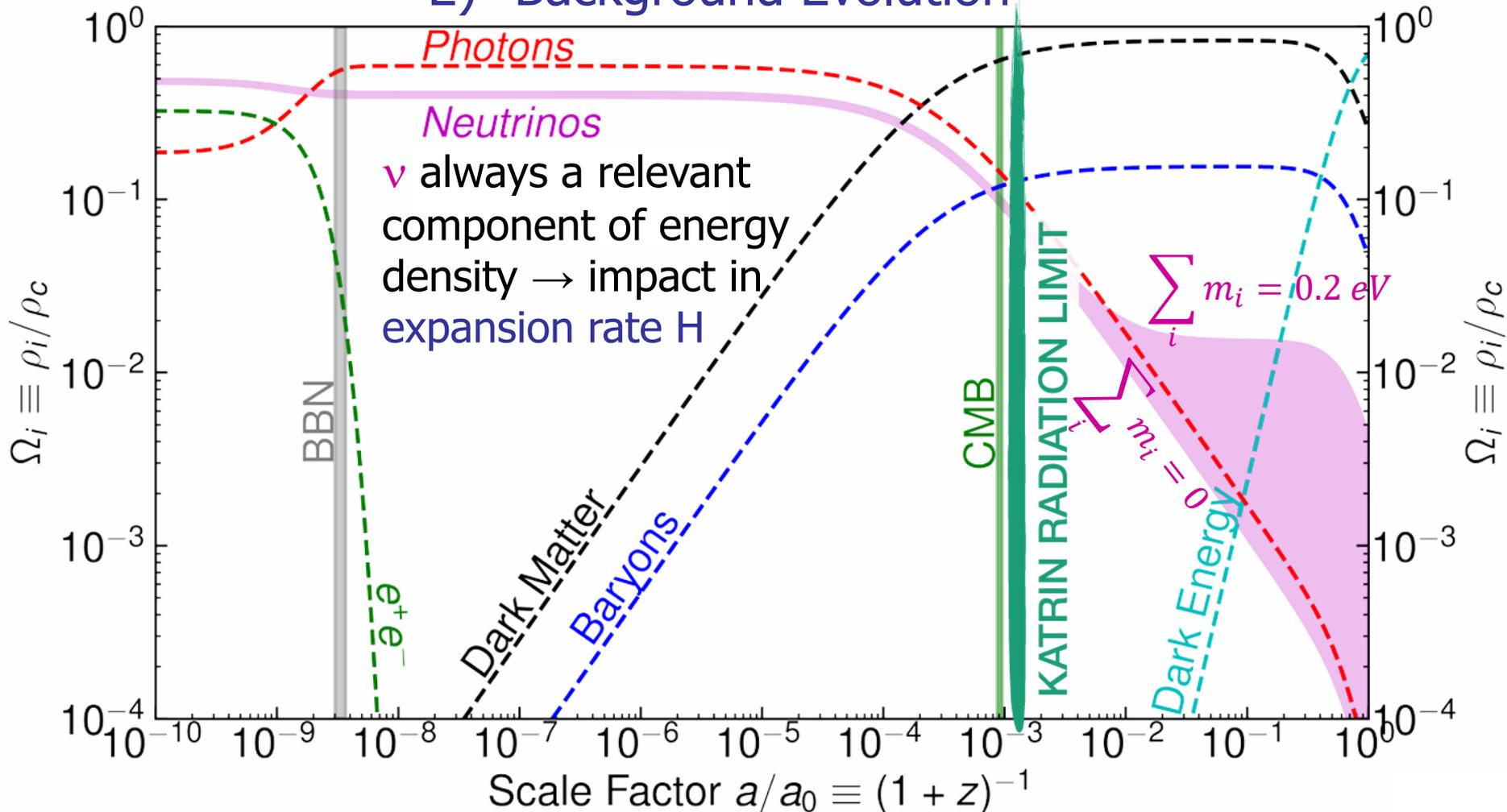


Plot courtesy of Miguel Escudero

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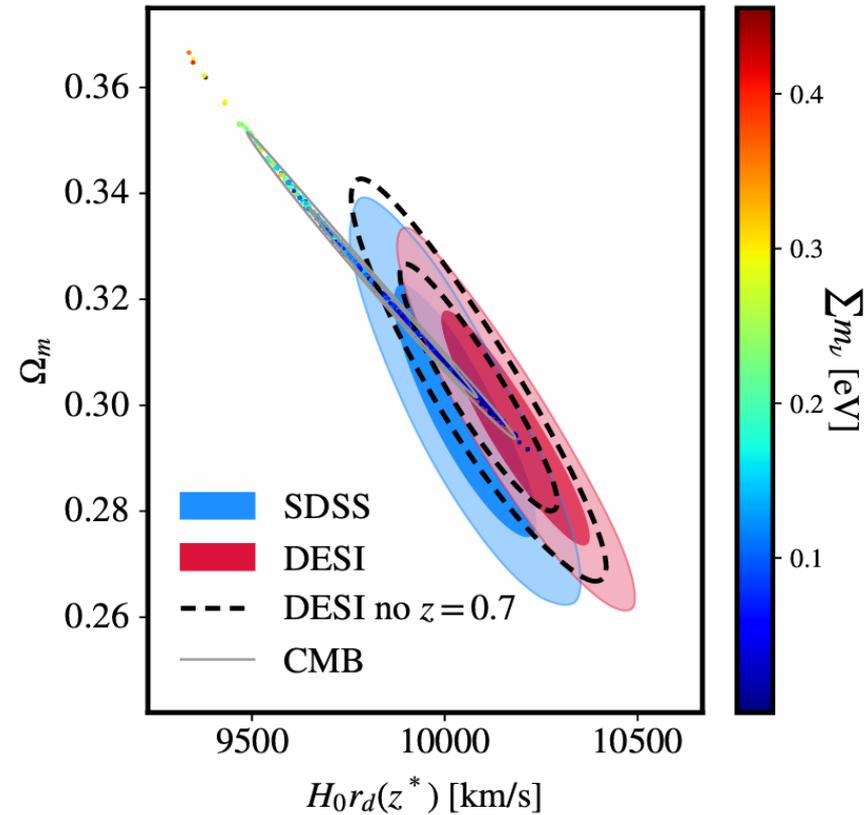
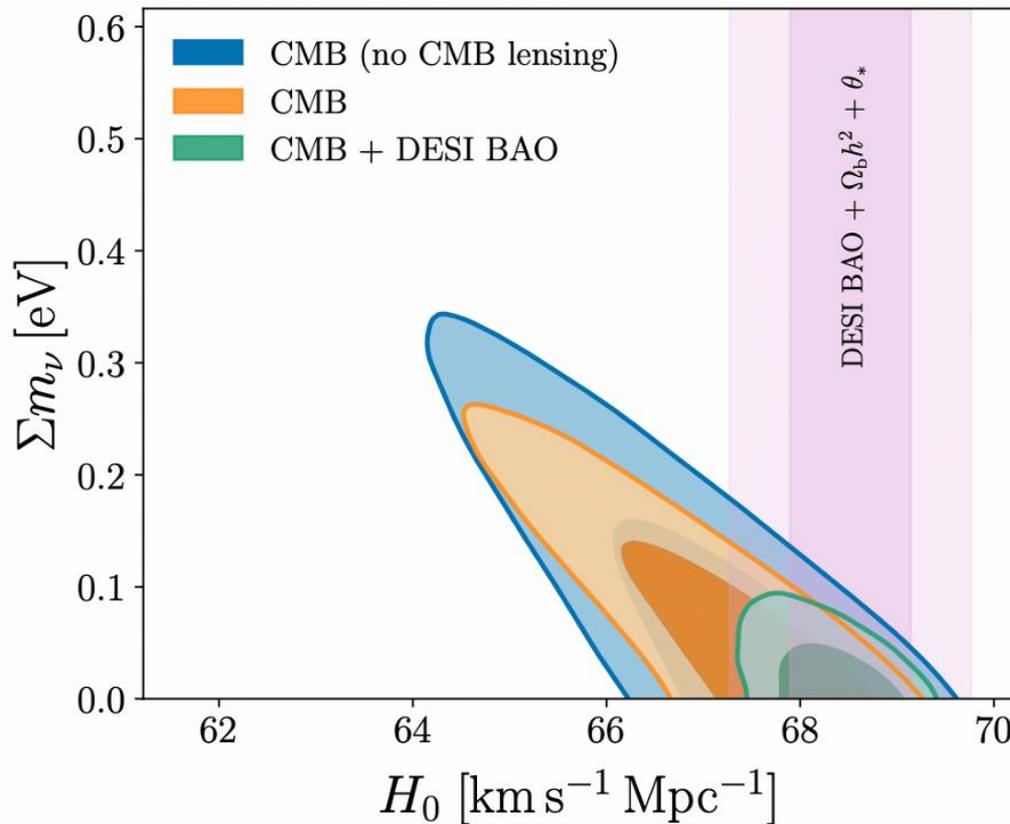


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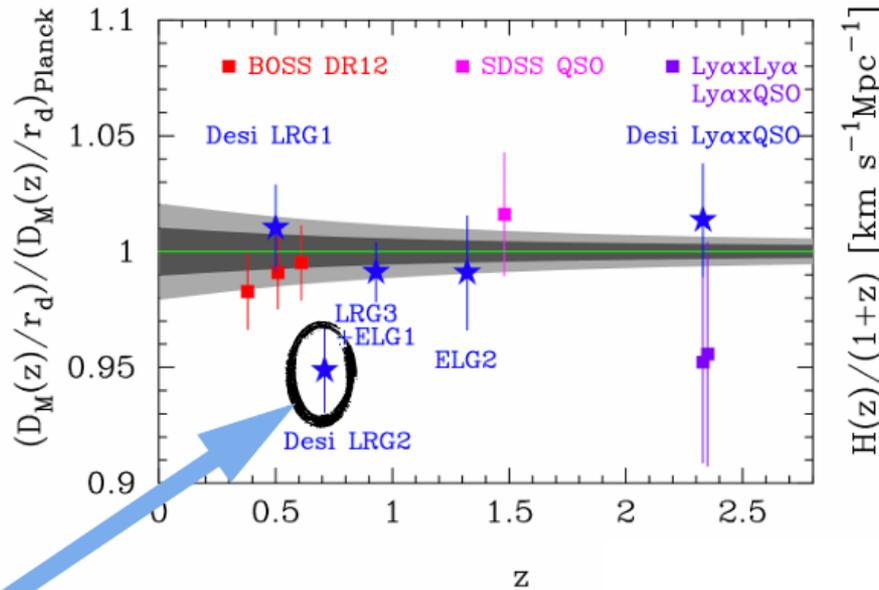
DESI 2404.03002

D. Naredo-Tuero, M. Escudero, EFM,
X. Marciano and V. Poulin 2407.13831

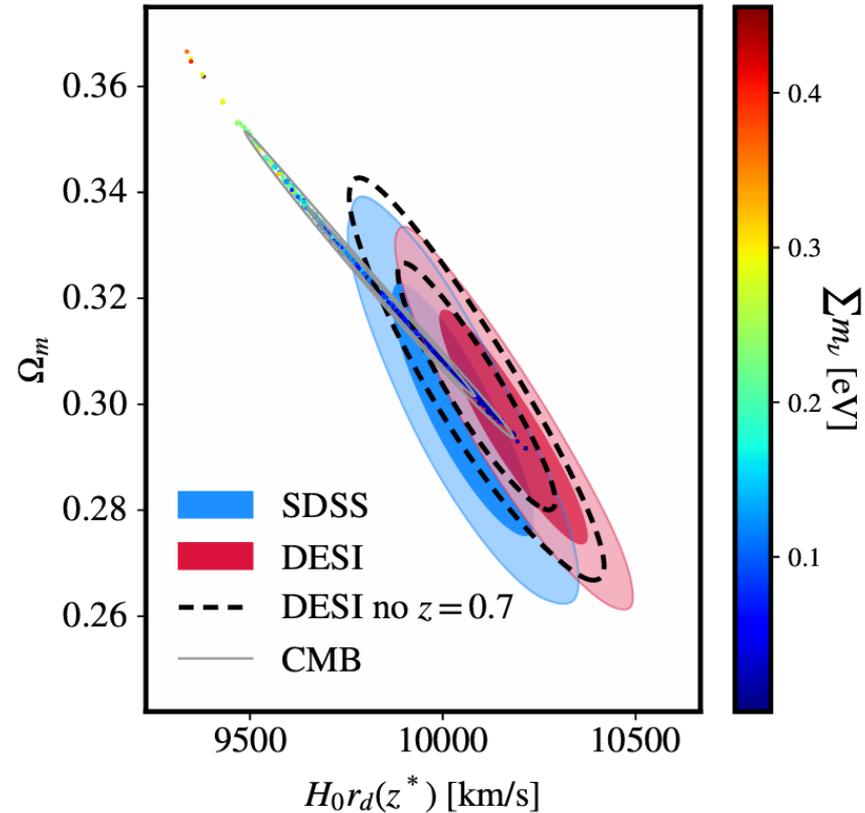
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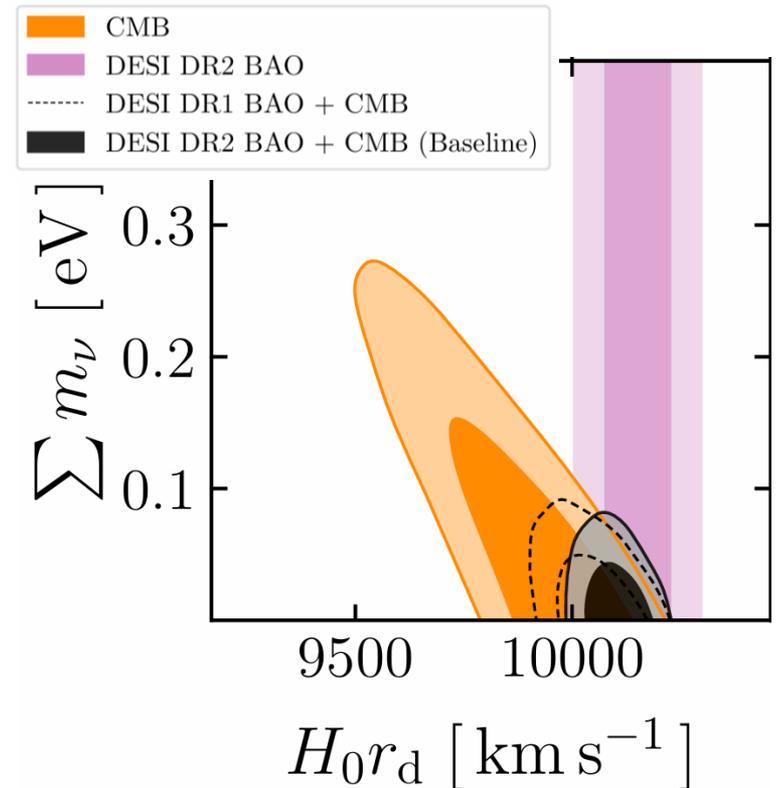
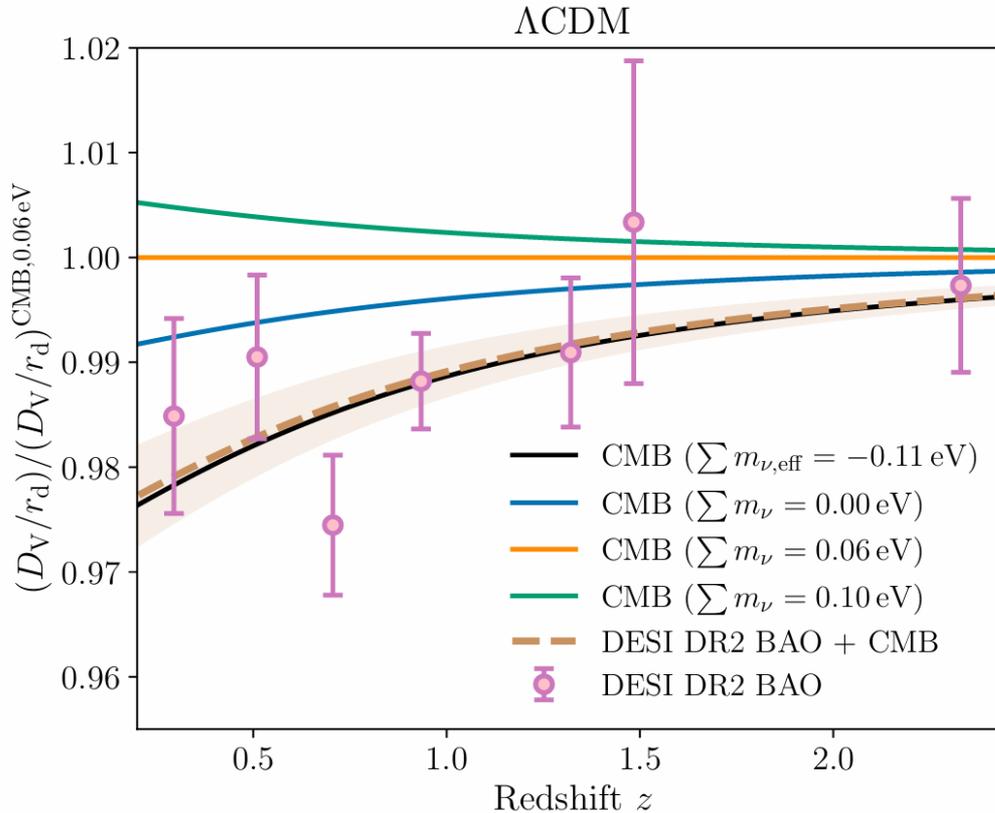
This outlier actually drives most of the preference for large H_0 and hence small ν mass



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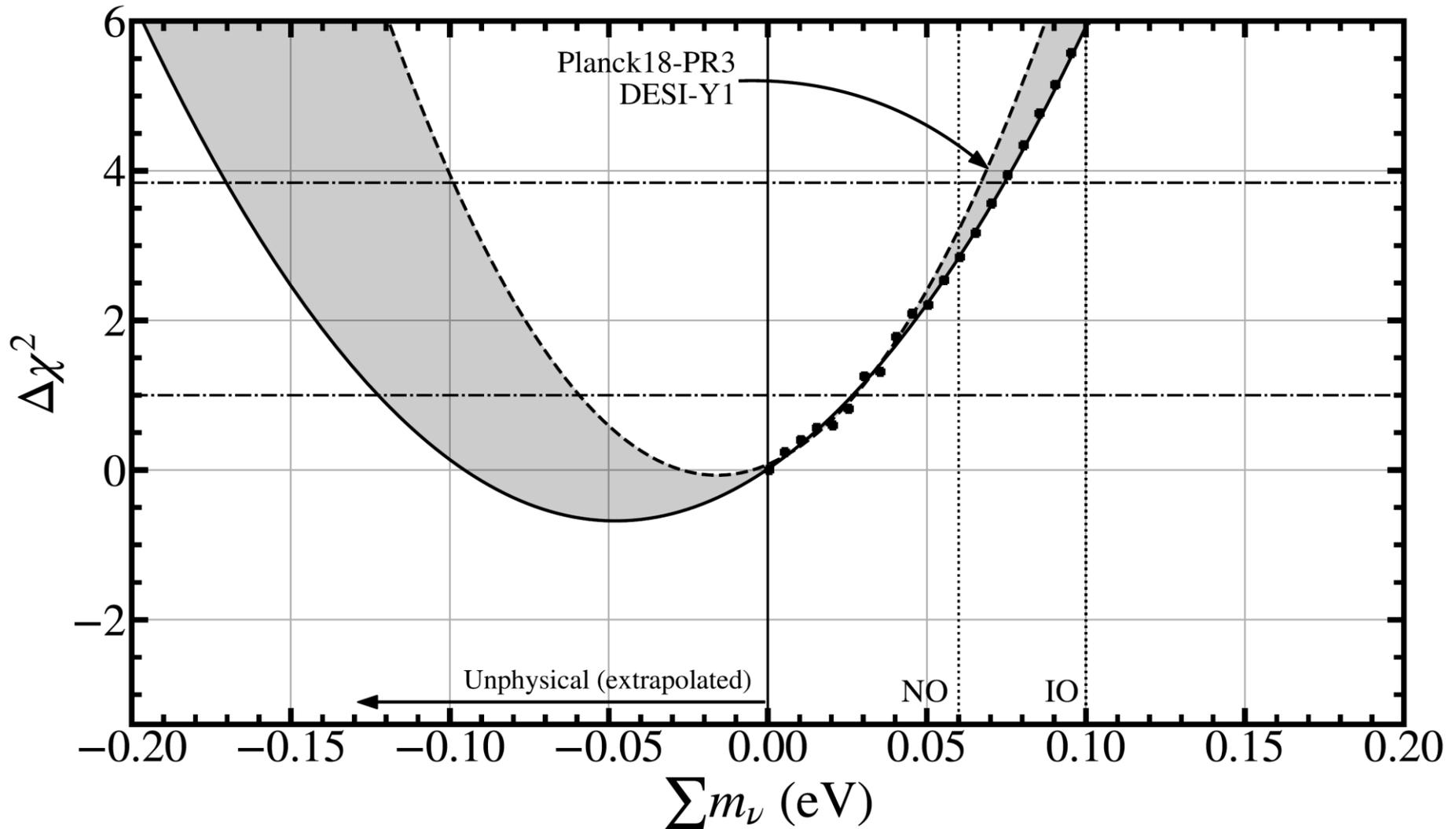
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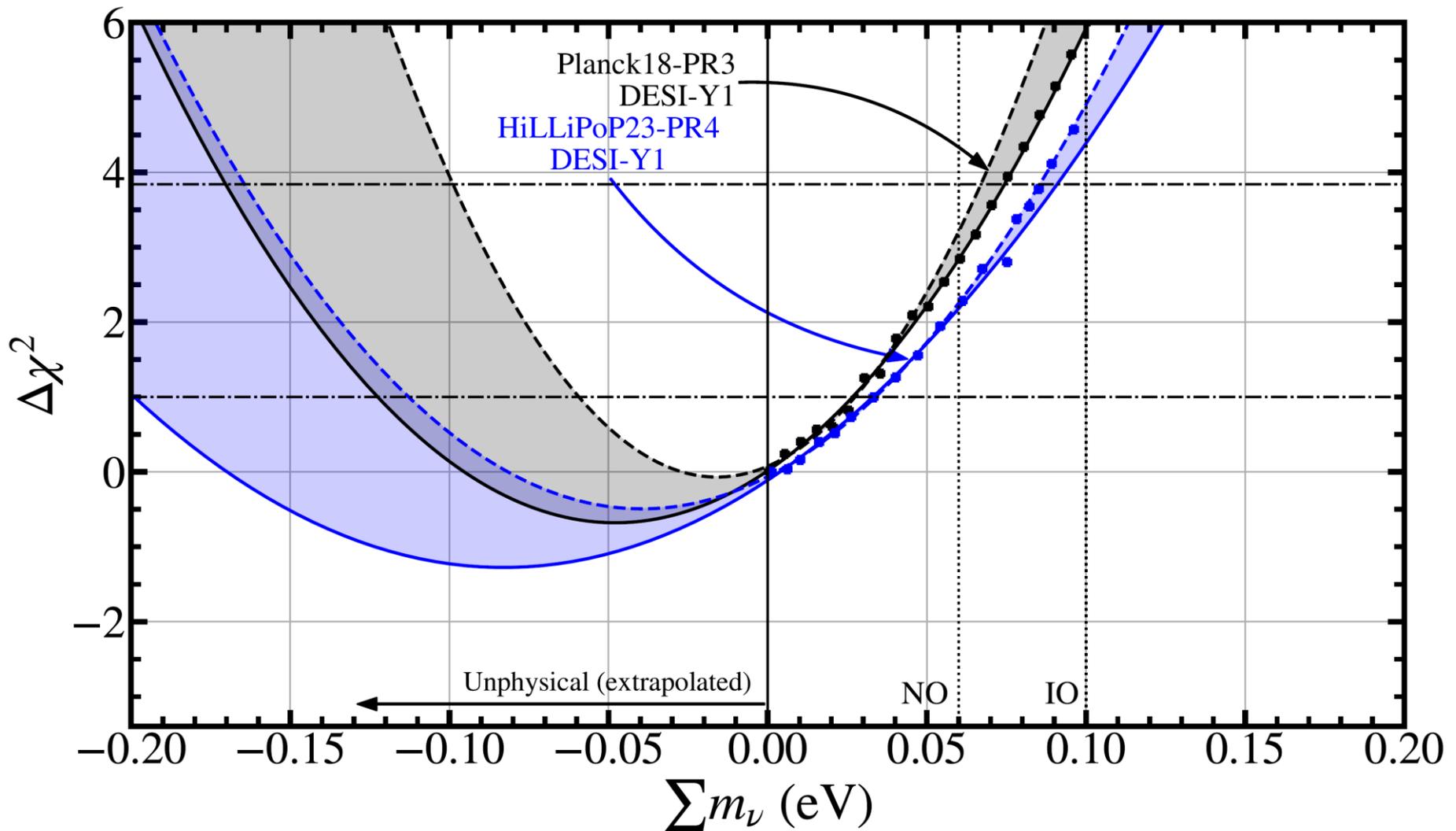


With new DR2 the **outlier** is now closer to the trend but still significant (stronger) preference for **large H_0**
DESI 2503.14744

The two effects together



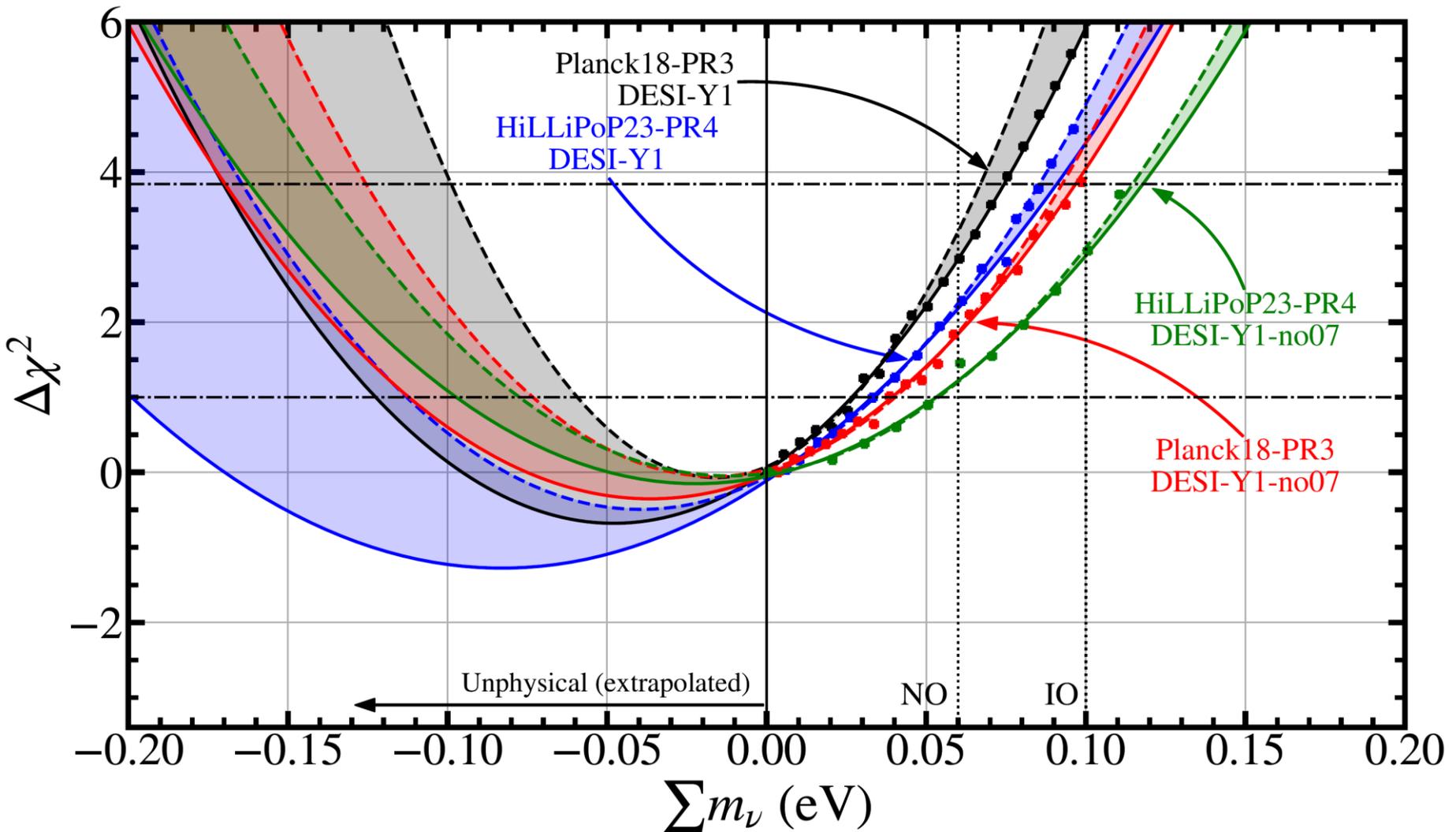
The two effects together



With HiLLiPoP23 lensing anomaly down to 0.75σ from 2.8σ

D. Naredo-Tuero, M. Escudero, EFM, X. Marciano and V. Poulin 2407.13831

The two effects together



Both effects together relax the bound significantly

D. Naredo-Tuero, M. Escudero, EFM, X. Marciano and V. Poulin 2407.13831

The two effects together

95% CL $\sum_i m_i$ (eV)	Bayesian	Frequentist
Dataset		
Planck2018+DESI	0.084	0.071
HiLLiPoP2023+DESI	0.102	0.083
Planck2018+DESI (no z=0.7)	0.107	0.092
HiLLiPoP2023+DESI (no z=0.7)	0.125	0.114

Both effects together **relax the bound** significantly. Compatible with IH
Good ($\sim 10\%$) agreement between **Bayesian** and **frequentist** constraints

The two effects together

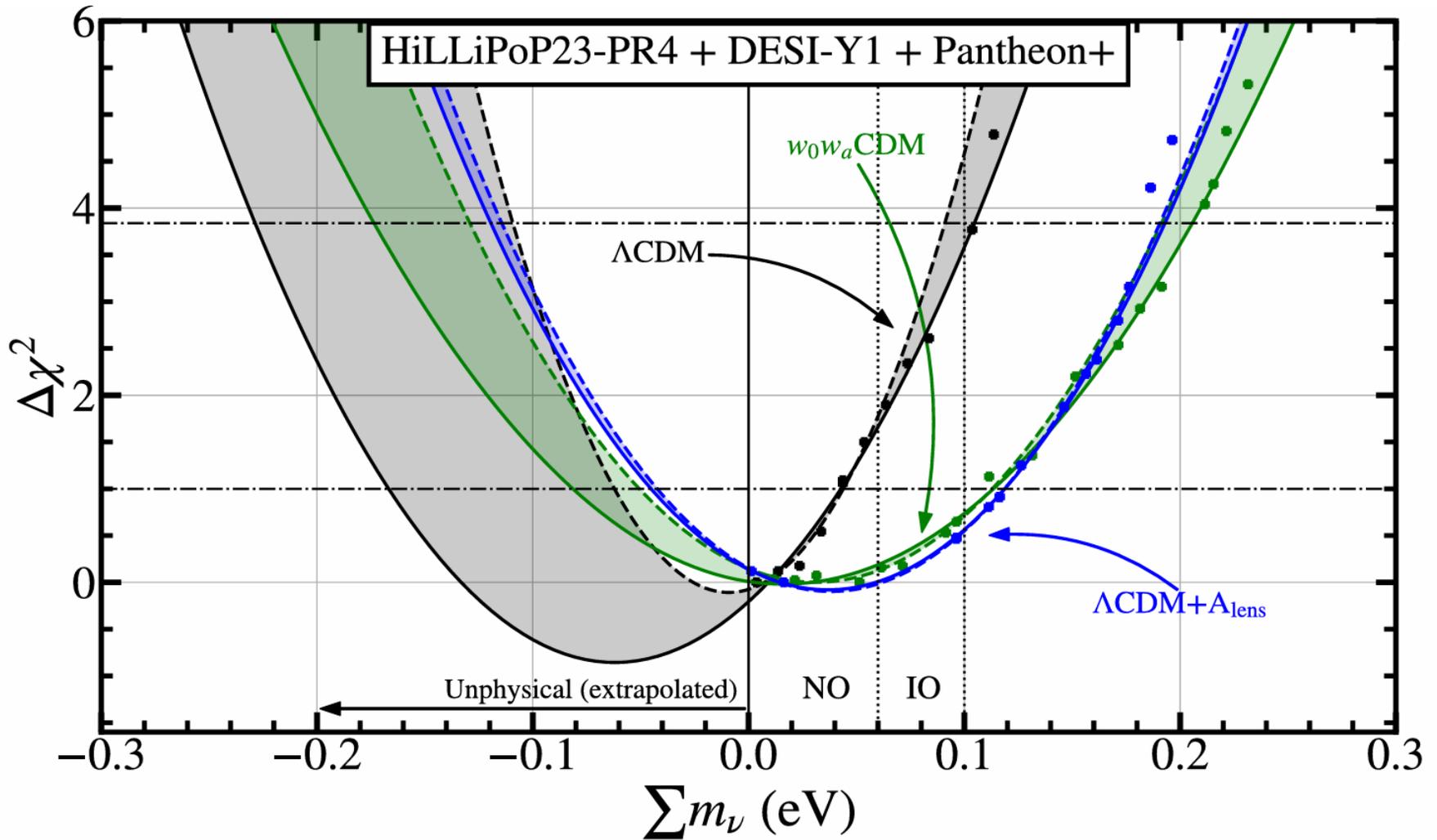
95% CL $\sum_i m_i$ (eV)	Bayesian	Frequentist
Dataset		
Planck2018+DESI DR1	0.084	0.071
HiLLiPoP2023+DESI DR1	0.102	0.083
Planck2018+DESI DR2	0.069	0.064
HiLLiPoP2023+DESI DR2	0.077	

DESI DR2 (2503.14744) last week results strengthen the preference for large H_0 and thus small $\sum_i m_i$

Conclusions

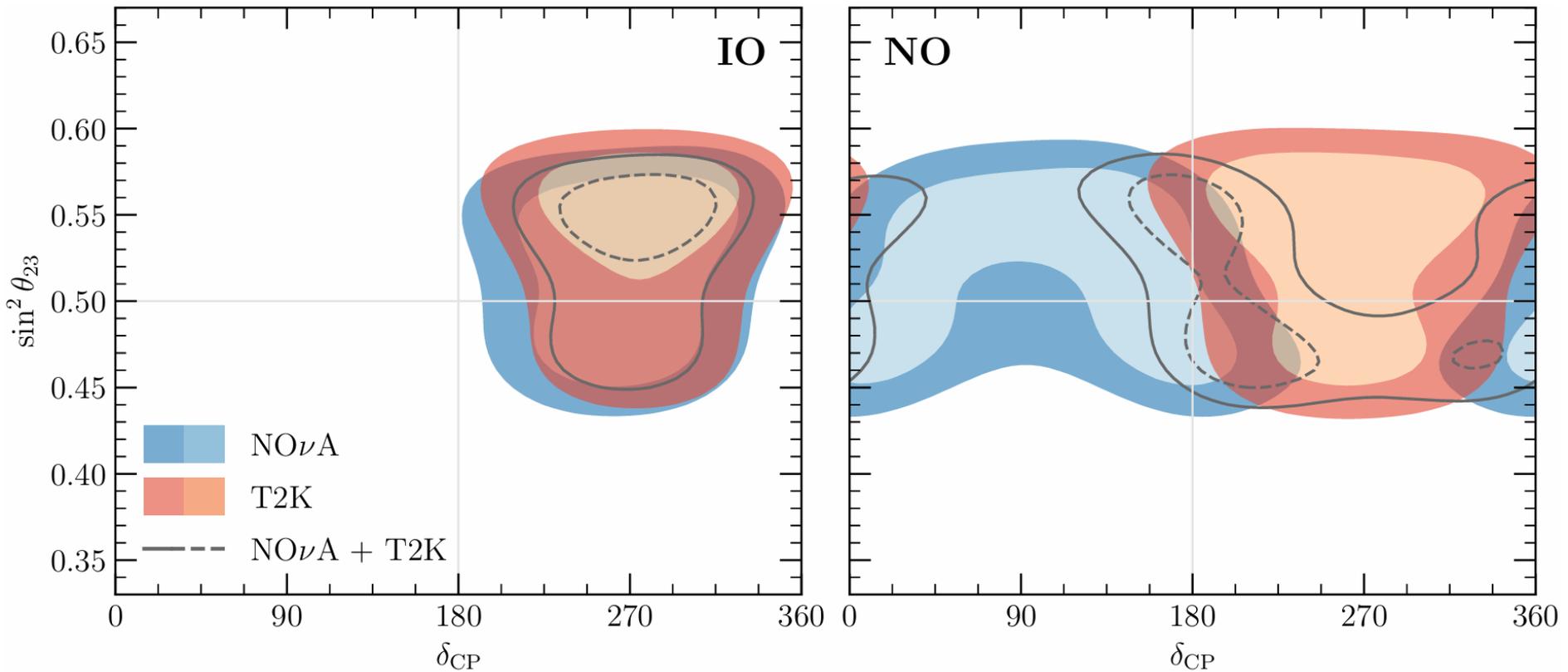
- Present bounds on ν mass from cosmological observables seem to rule out **IH** and even start to be in tension with **NH**
- We studied the consistency of the bounds and where they come from, finding that:
 - **Frequentist** and **Bayesian** approach agree $\sim 10\%$
 - Bounds (and unphysical preference) relax when new **Planck likelihoods** with reduced **lensing anomaly** are used
 - Bounds further relax when the **$z=0.7$** outlier from **DESI 1yr** is not included. New **3yr** data reduce the outlier but strengthen the preference
 - Bounds also relax if **dynamical DE** (w_0-w_a)
- Future bounds from **full shape** power spectrum are a **more robust probe** and will have **great sensitivity**.

Dynamical DE and A_{lens}



Evidence for ν mass from oscillations

$\sim 2\sigma$ tension between the two present measurements of δ



I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. Paulo Pinheiro and T. Schwetz 2410.05380

Searches for ν mass from cosmology

Even stronger bounds when adding additional data:

	Datasets	Σm_ν [eV]
C=Planck	CDS	< 0.093 (2σ)
D=DESI	CDSO	< 0.091 (2σ)
S=SN	CDSA	< 0.071 (2σ)
O=Chronometers (date galaxies based on spectra)	CDSG	< 0.049 (2σ)
A=ADD (Angular diameter distances from galaxy cluster shapes vs models)	CDSOA	< 0.065 (2σ)
G=GRB (γ ray bursts for high z instead of SN)	CDSOG	< 0.049 (2σ)
	CDSAG	< 0.045 (2σ)
	CDSOAG	< 0.043 (2σ)

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EXCELENCIA
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OCHOA