Is Cosmology in Conflict with Neutrino Oscillations?

Based on:
DN, M. Escudero, E. Fernández-Martínez, X. Marcano, V. Poulin [2407.13831]

Asymmetry Essential Asymmetries of Nature

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The quest for the absolute neutrino mass

- From oscillation experiments → two mass splittings *NuFIT 5.3: http://www.nu-fit.org/*

- However, absolute neutrino mass scale still unknown

- Direct constraint from terrestrial experiments: KATRIN

KATRIN collaboration [2406.13516]

$$\sum m_\nu < 1.35\,\mathrm{eV} \quad (90\,\%\,\mathrm{CL})$$

- Constraints from cosmology → The strongest!

Status of m_ν from cosmology

- As of April, the DESI collaboration updated:

$$\sum m_\nu < 0.072\,\mathrm{eV} \quad (95\,\%\,\mathrm{CL}) \quad (\mathrm{CMB} + \mathrm{DESI\,BAO})$$

- Dangerously close to the minimum allowed by oscillations:

$$\sum m_\nu \geq 0.06\,\mathrm{eV} \quad (\text{Normal Ordering})$$

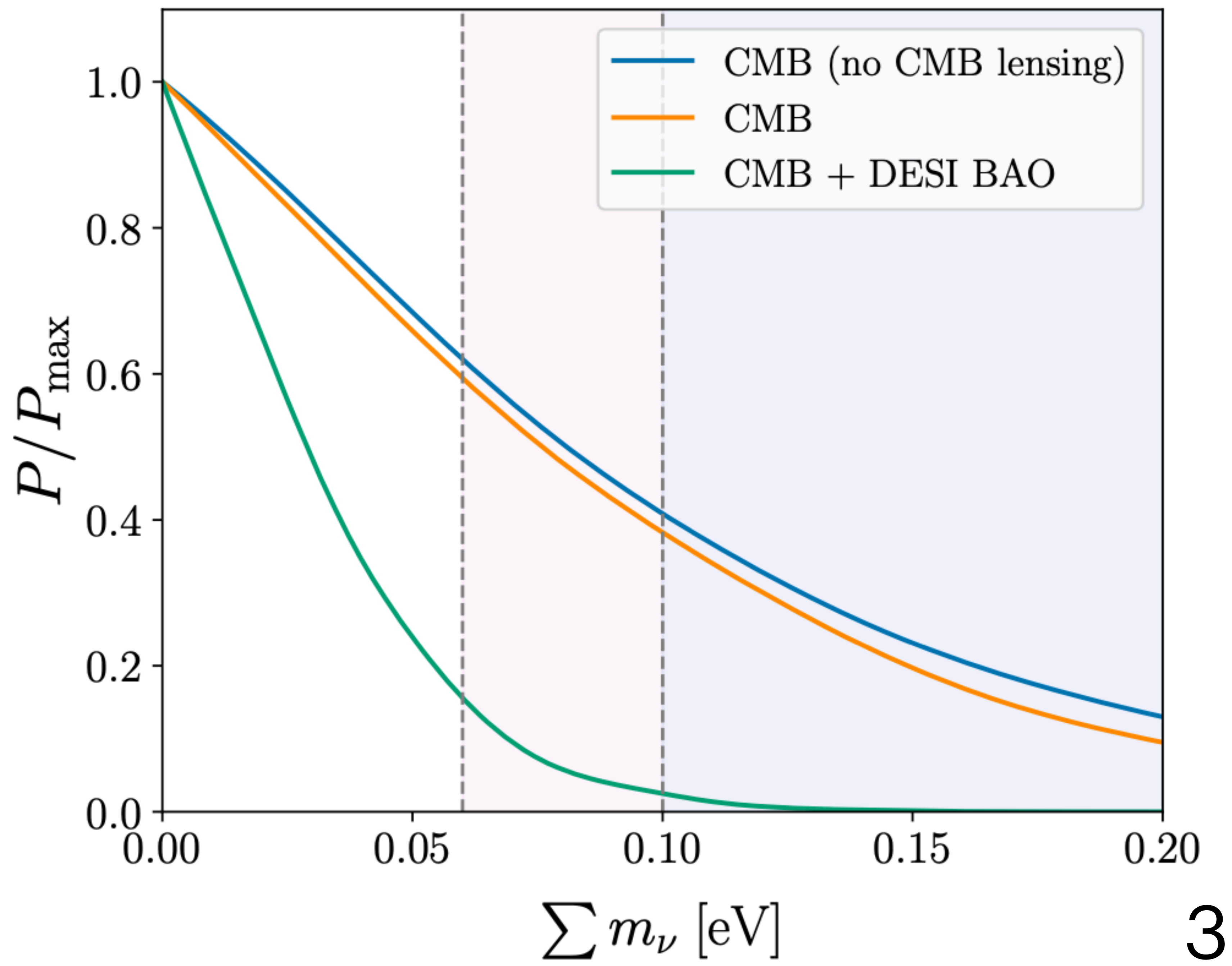
NuFIT 5.3: http://www.nu-fit.org/

$$\sum m_\nu \geq 0.10\,\mathrm{eV} \quad (\text{Inverted Ordering})$$

- Approaching the physical boundary at $\sum m_\nu = 0$

- No hint of a non-zero $\sum m_\nu$

DESI collaboration [2404.03002]



Status of m_ν from cosmology

- In light of this status:

  - ★ What datasets are driving this bound?

  - ★ Which role do possible statistical flukes/anomalies play?

  - ★ Which statistical procedure? Bayesian vs frequentist

    CLASS & MontePython
    Lesgourges et al.

    Procoli
    Karwal et al. [2401.14225]

  - ★ Bound is model-dependent: how does it change beyond ΛCDM?

Massive neutrinos in cosmology

- Neutrinos contribute to the expansion rate of the Universe
- Ultra-relativistic until $T_\nu \simeq m_\nu/3$
- Do not cluster at scales smaller than $L \simeq 80\,\mathrm{Mpc}\frac{(0.1\,\mathrm{eV})}{m_\nu}$

Ideal probe → Direct observation of the matter power-spectrum

(Not competitive as of today)

Massive neutrinos in cosmology

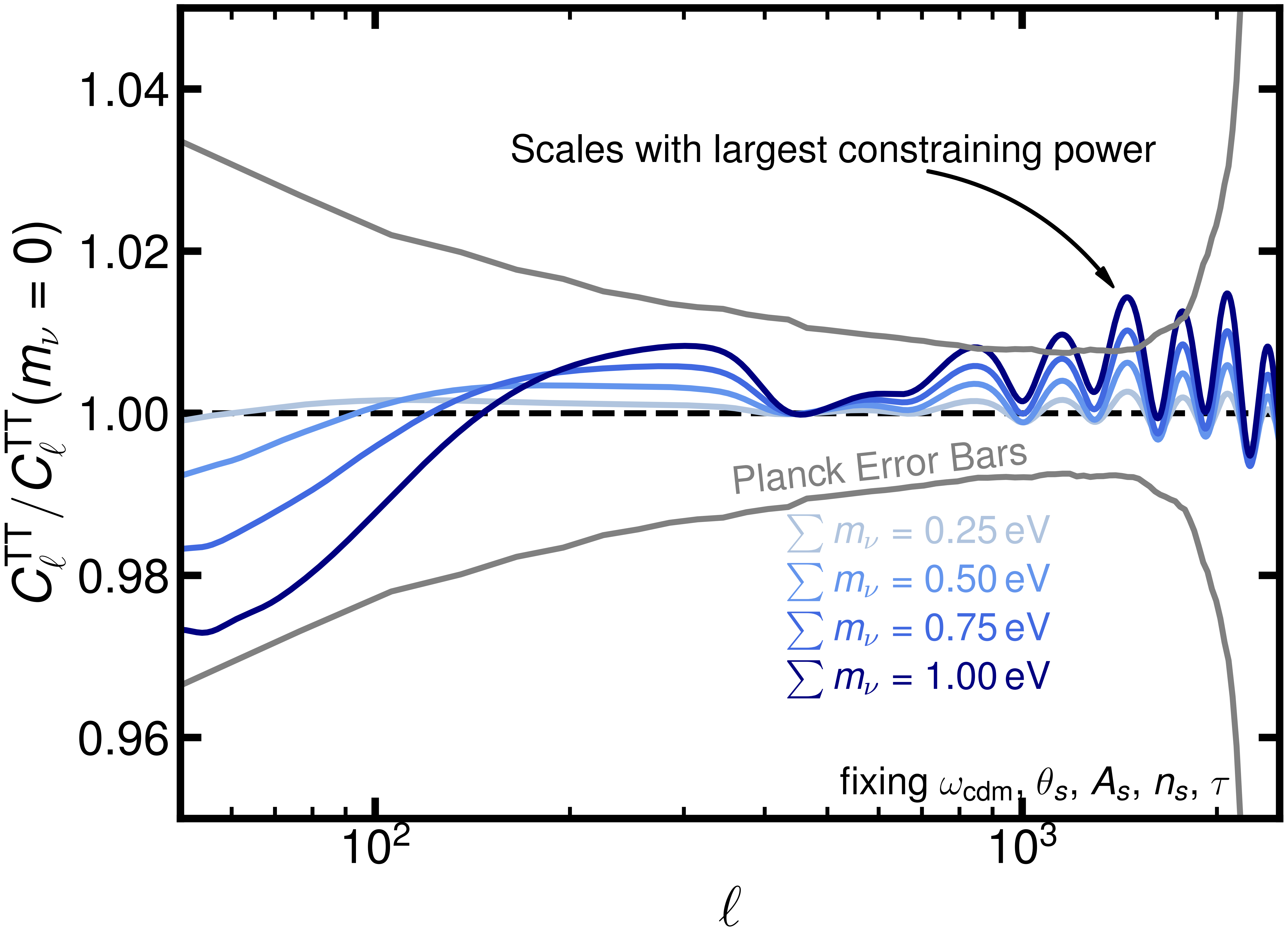
- As of today: CMB (Planck) + BAO and/or Supernovae

- Two main effects in the CMB:
  - ★ Neutrinos affect the Universe expansion ($H \propto \sqrt{\rho}$)
  - ★ Suppress clustering of matter → Less lensing → Sharper peaks

Massive neutrinos in cosmology

- Main constraining power: small angular scales

- This effect also depends on A_s or ω_m



About CMB lensing

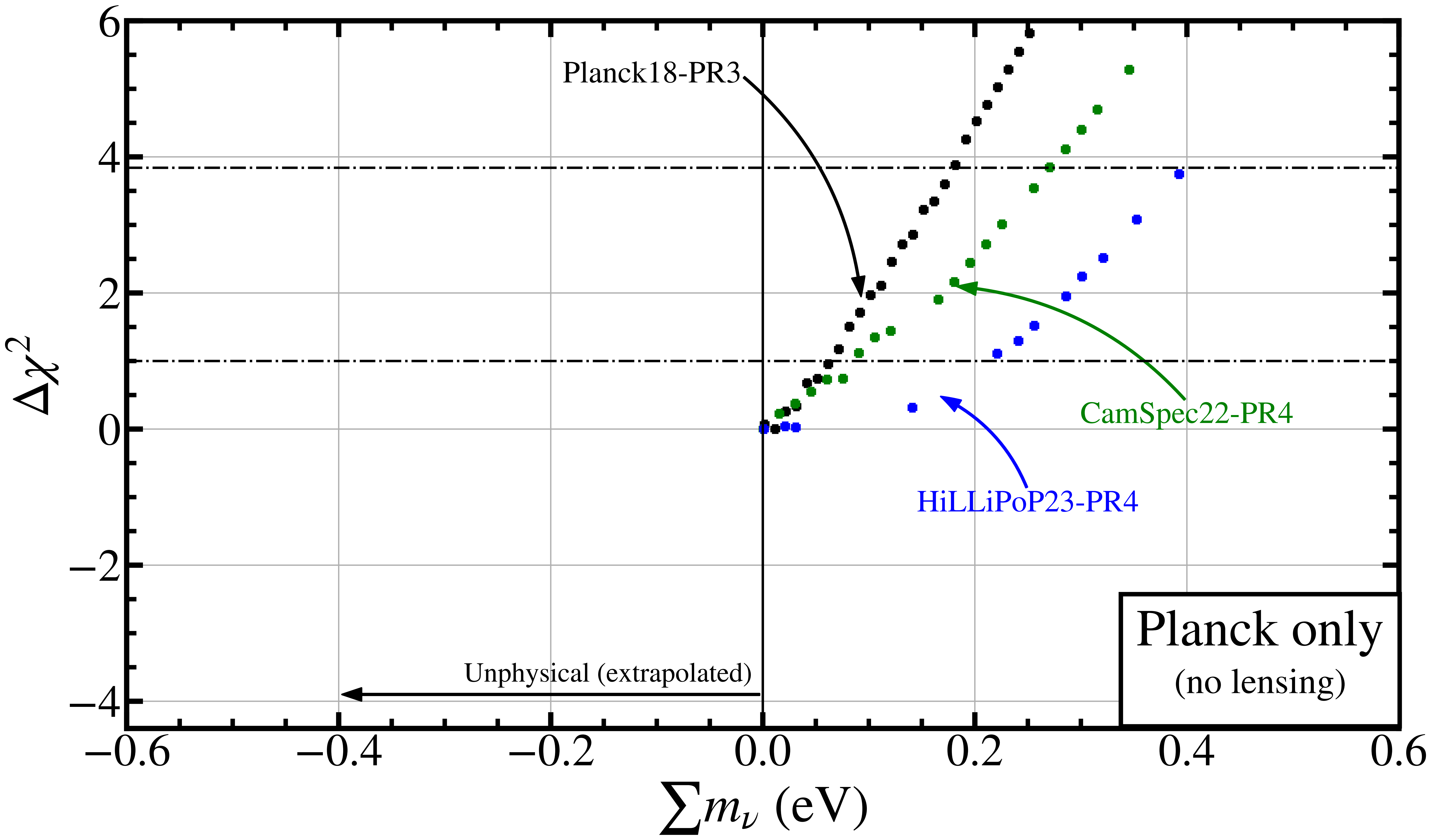
- "Lensing anomaly" reported by the Planck collaboration: *[1807.06209]*
  - ★ Parametrised by an unphysical parameter $A_{\rm lens}$ (standard case $A_{\rm lens} = 1$)
  - ★ An excess of lensing ($A_{\rm lens} > 1$) found at $\sim 3\sigma$

- Opposite effect of massive neutrinos → Anomalously strong $\sum m_\nu$ bound

- After 2018, Planck reanalyses available → Anomaly reduced
  - ★ CamSpec: $\sim 2\sigma$ *Rosenberg et al. [2205.10869]*
  - ★ HiLLiPoP: $\sim 1\sigma$ *Tristam et al. [2309.10034]*

About CMB lensing

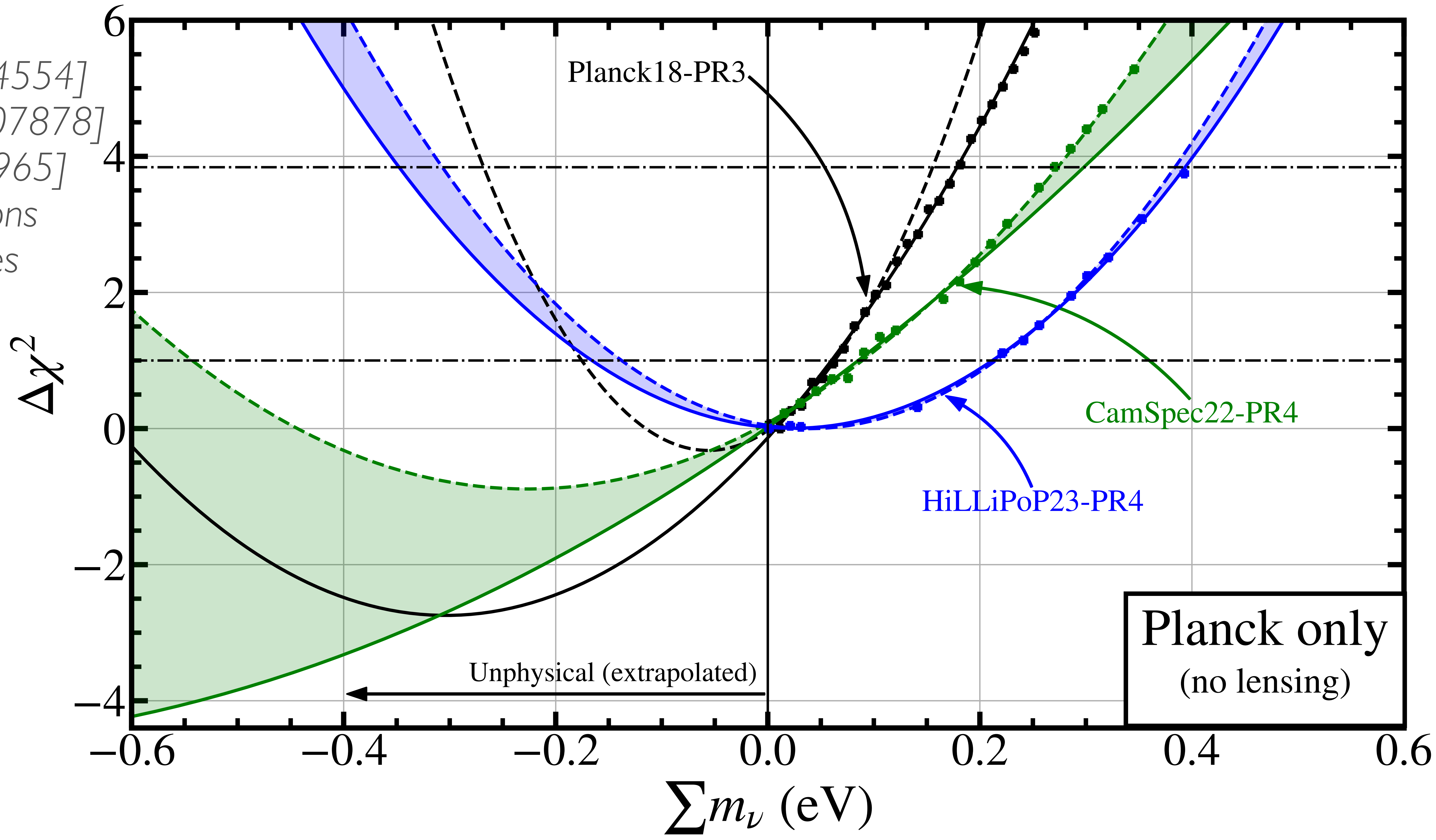
- Significant relaxation of the $\sum m_\nu$ bound with new Planck likelihoods



About CMB lensing

- Significant relaxation of the $\sum m_\nu$ bound with new Planck likelihoods

See:
Allali & Notari [2406.14554]
Green & Meyers [2407.07878]
Elbers et al. [2407.10965]
for other extrapolations
into negative masses



About BAO measurements

- Massive neutrinos alter the expansion rate → Modifies θ_s

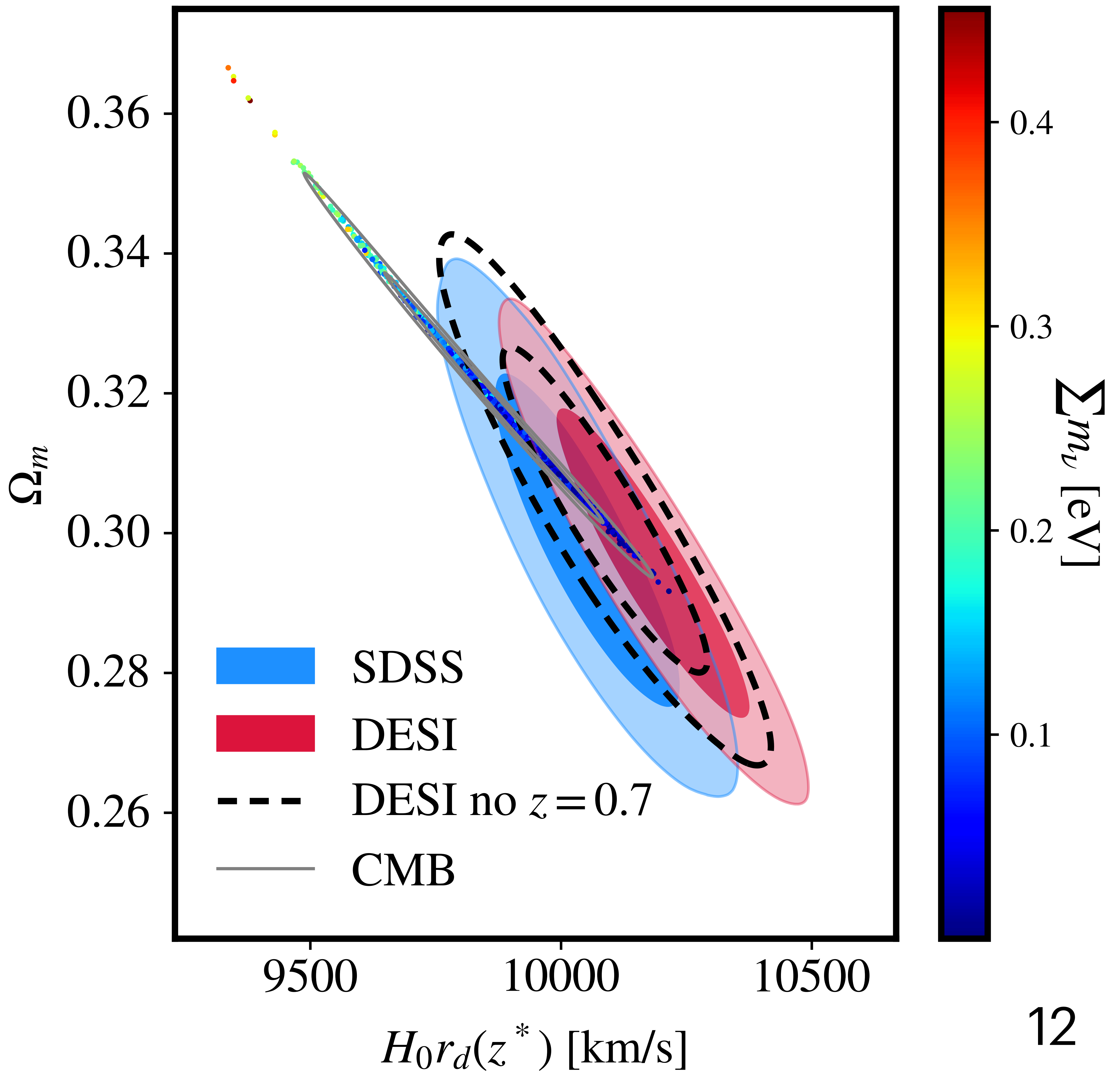
- This can be compensated by adjusting H_0 → CMB "geometrical degeneracy"

- Changing H_0 also changes $\Omega_m = \omega_m / h^2$ → BAO can break this degeneracy

About BAO measurements: DESI-Y1

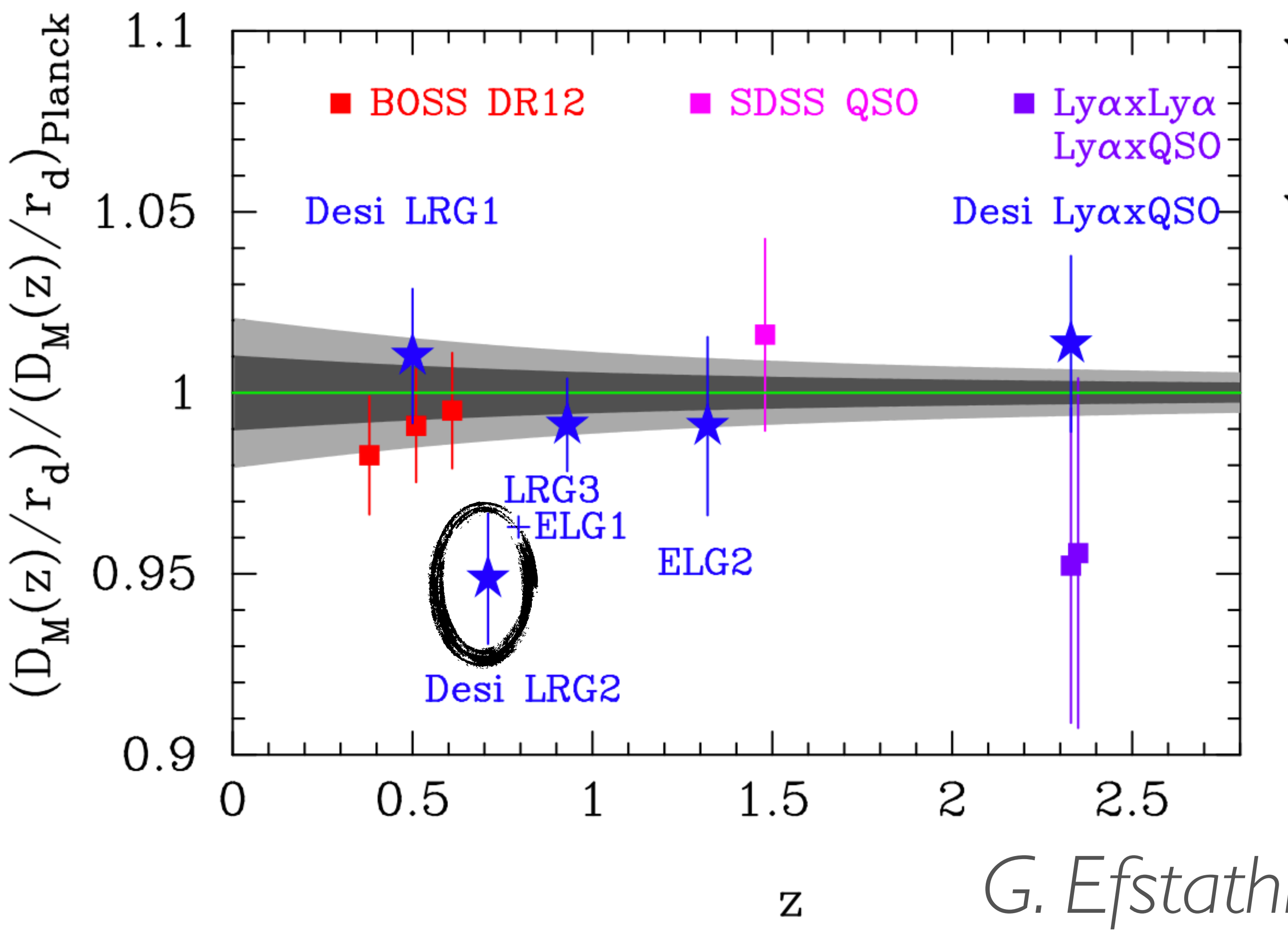
- The agreement with CMB is worse for DESI than for SDSS

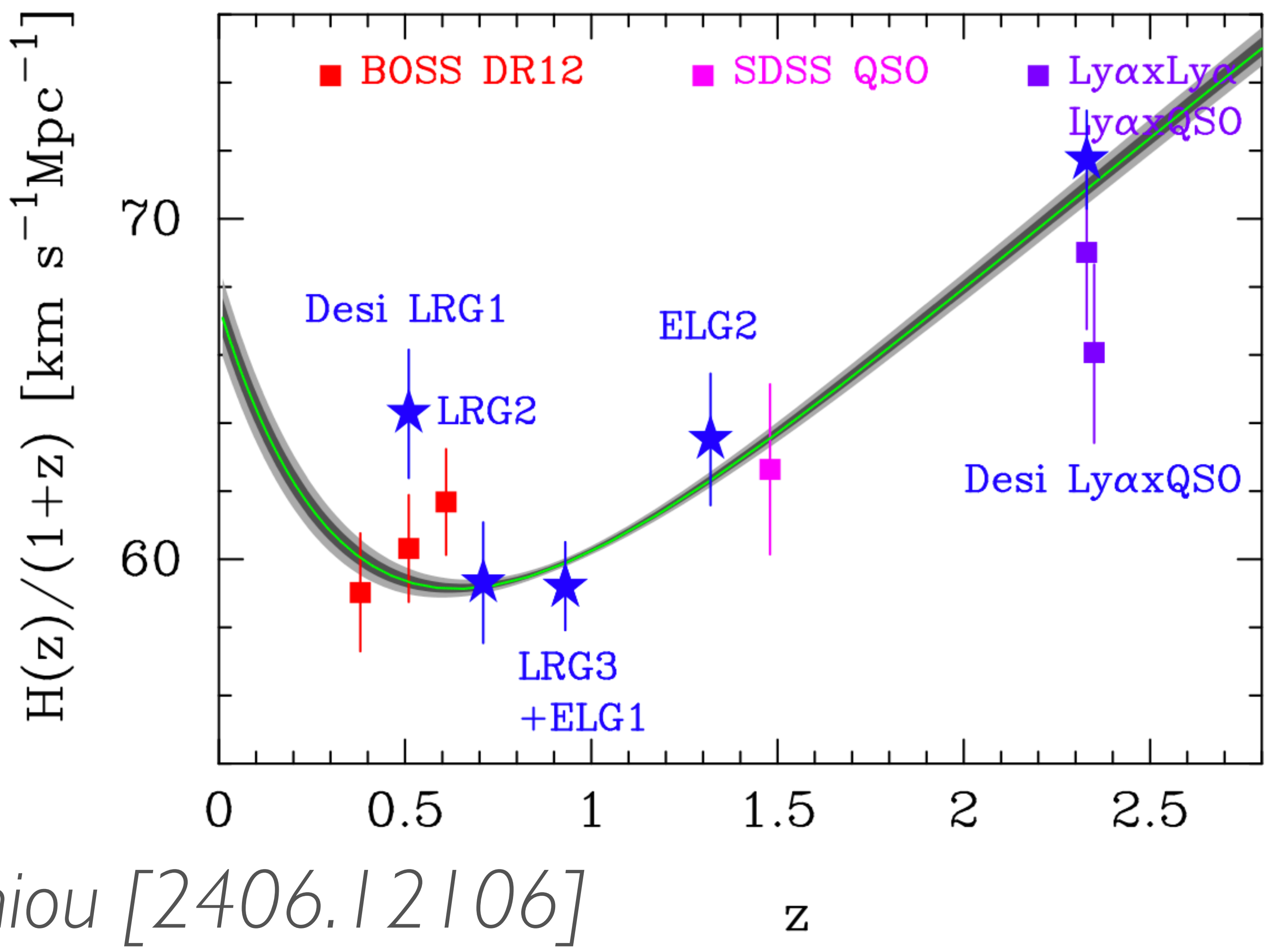
- Best-fit at a higher $H_0 r_d(z^*)$ pushes down $\sum m_\nu$



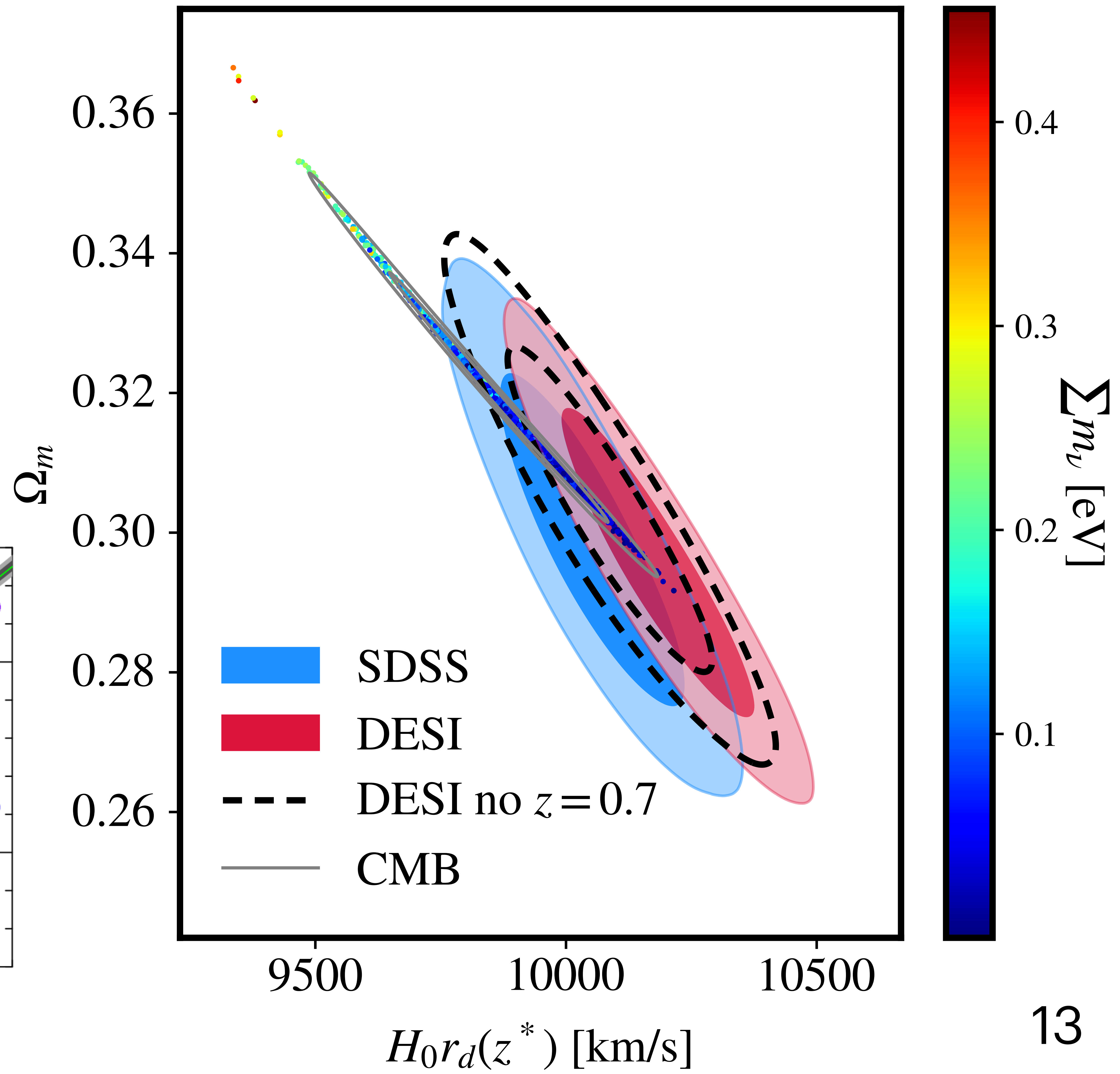
About BAO measurements: DESI-Y1

- Out of 22 BAO points, only 2 disagree with Planck *G. Efstathiou [2406.12106]*
- Interestingly, removal of $z = 0.7$ bin significantly shifts the best-fit



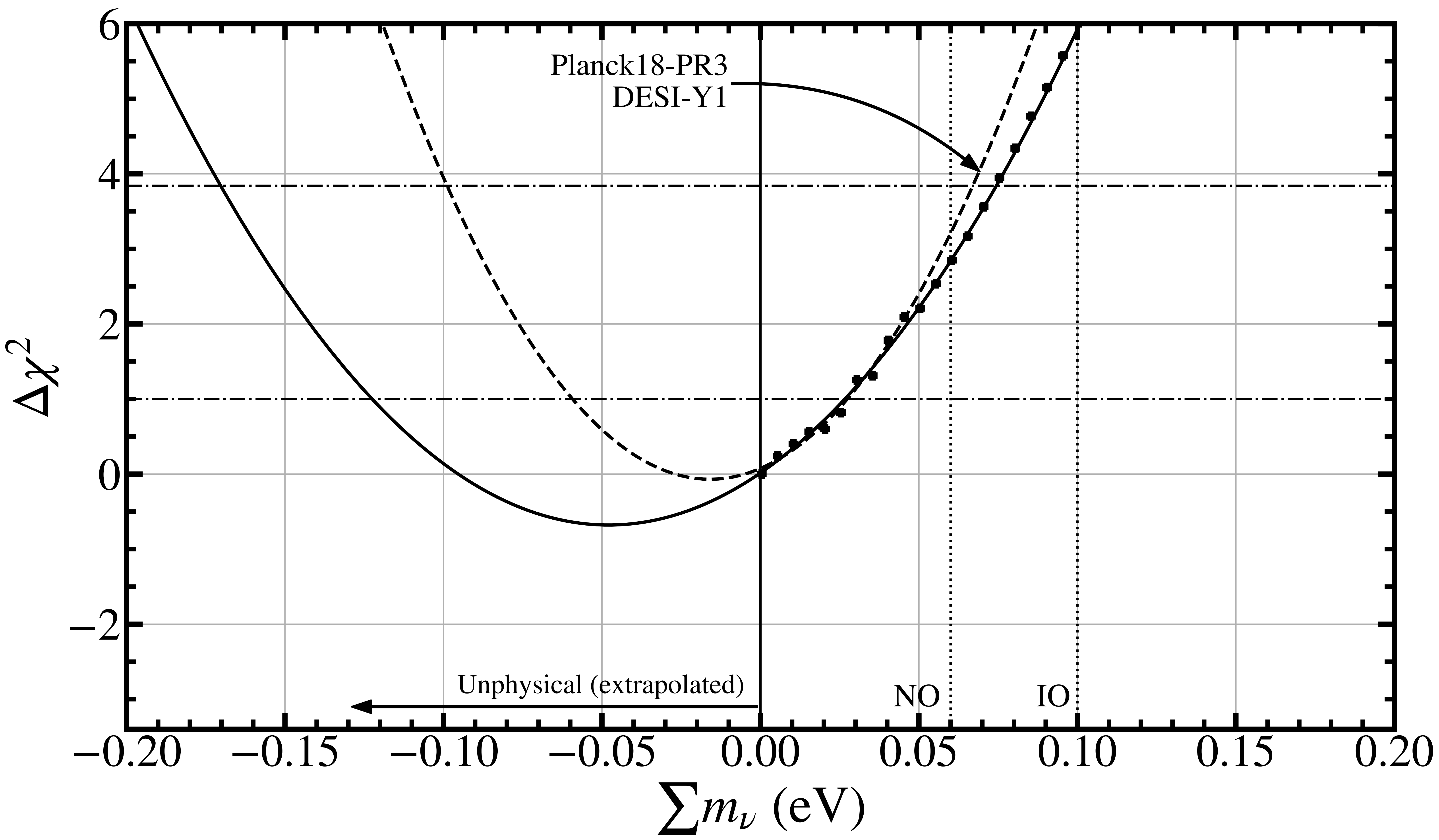


G. Efstathiou [2406.12106]



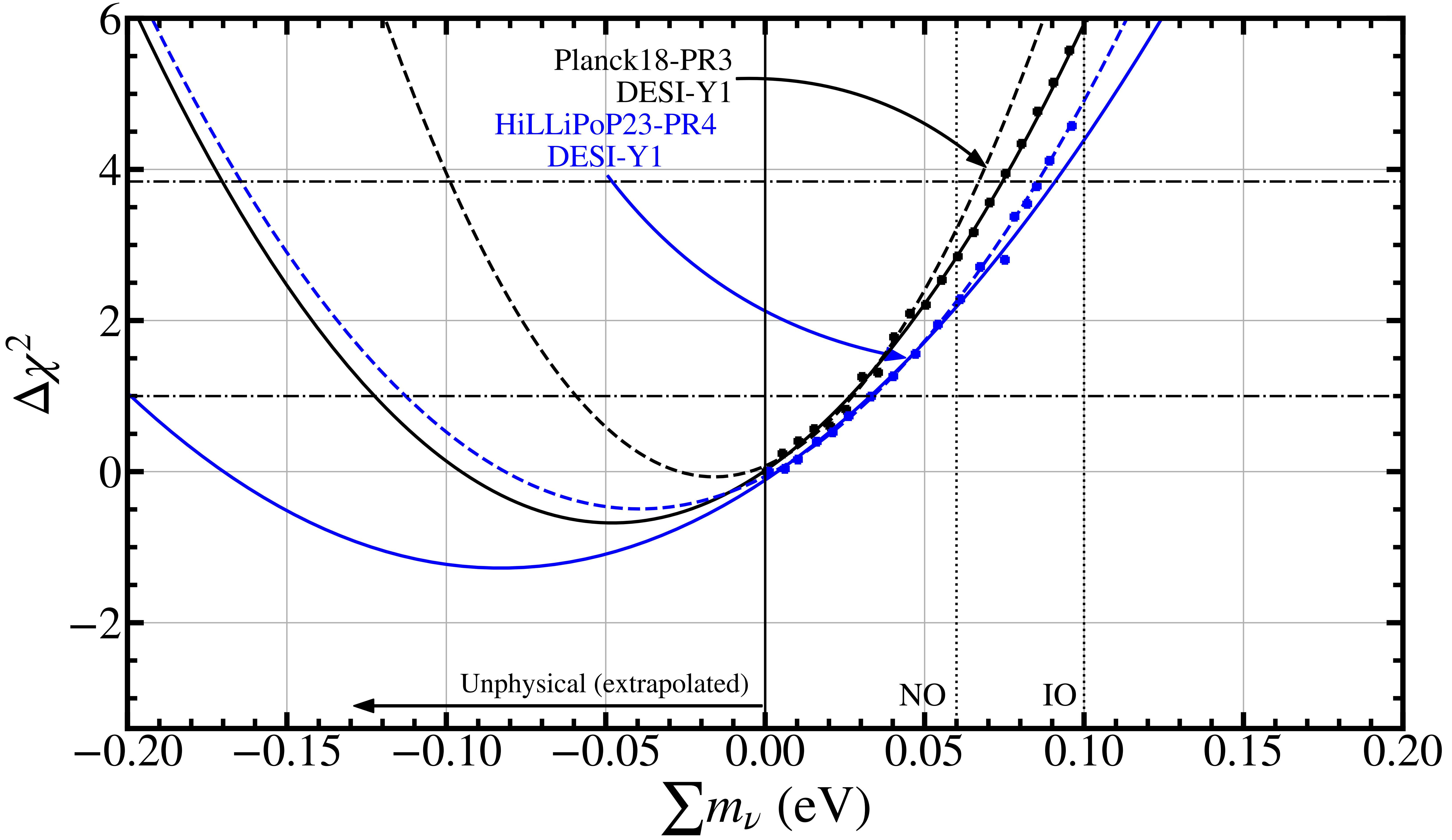
The effect of CMB lensing and DESI BAO

- Both the lensing anomaly and DESI BAO push against $\sum m_\nu \neq 0$



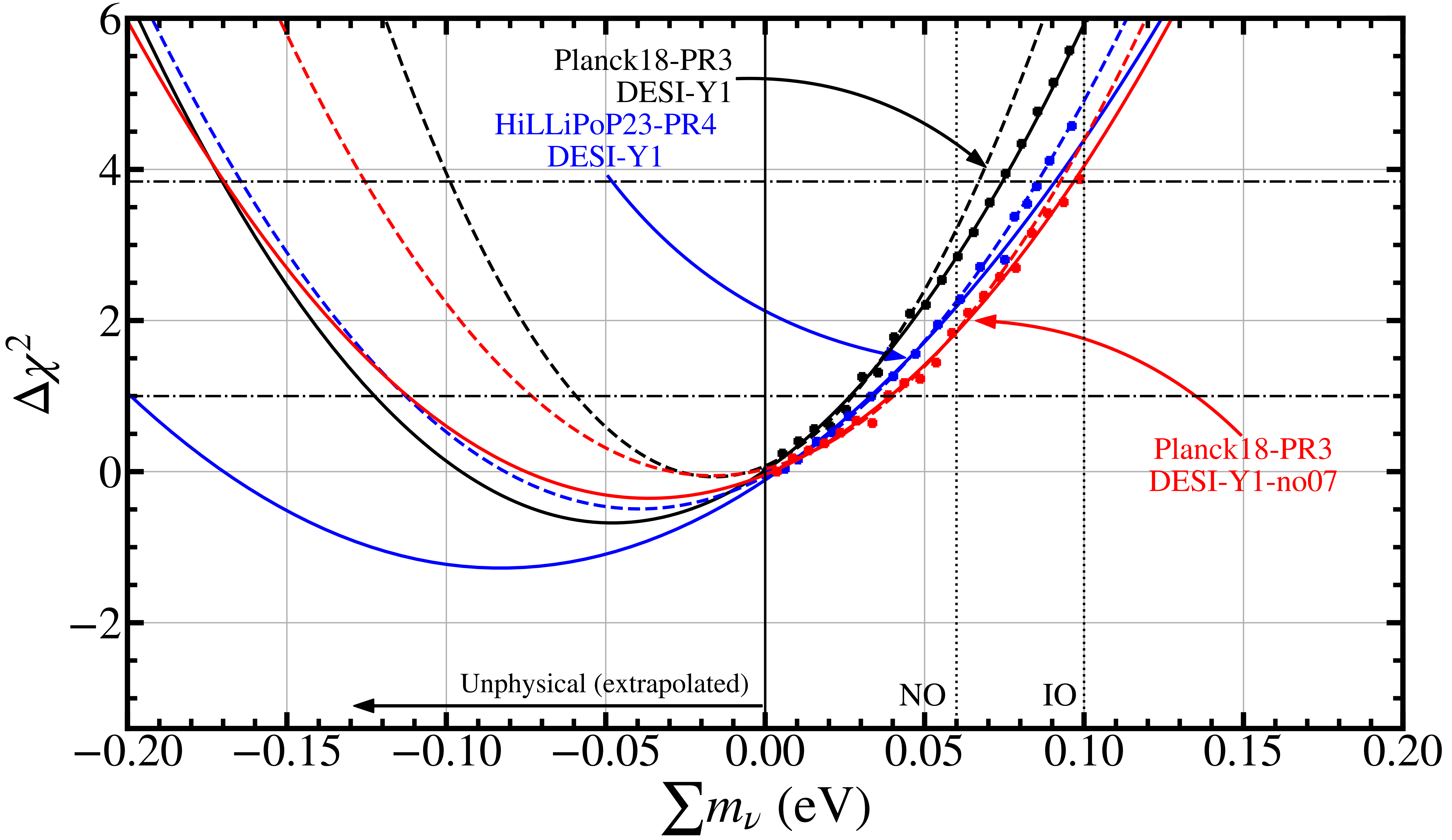
The effect of CMB lensing and DESI BAO

- Using Planck likelihood without lensing anomaly → Bound relaxed



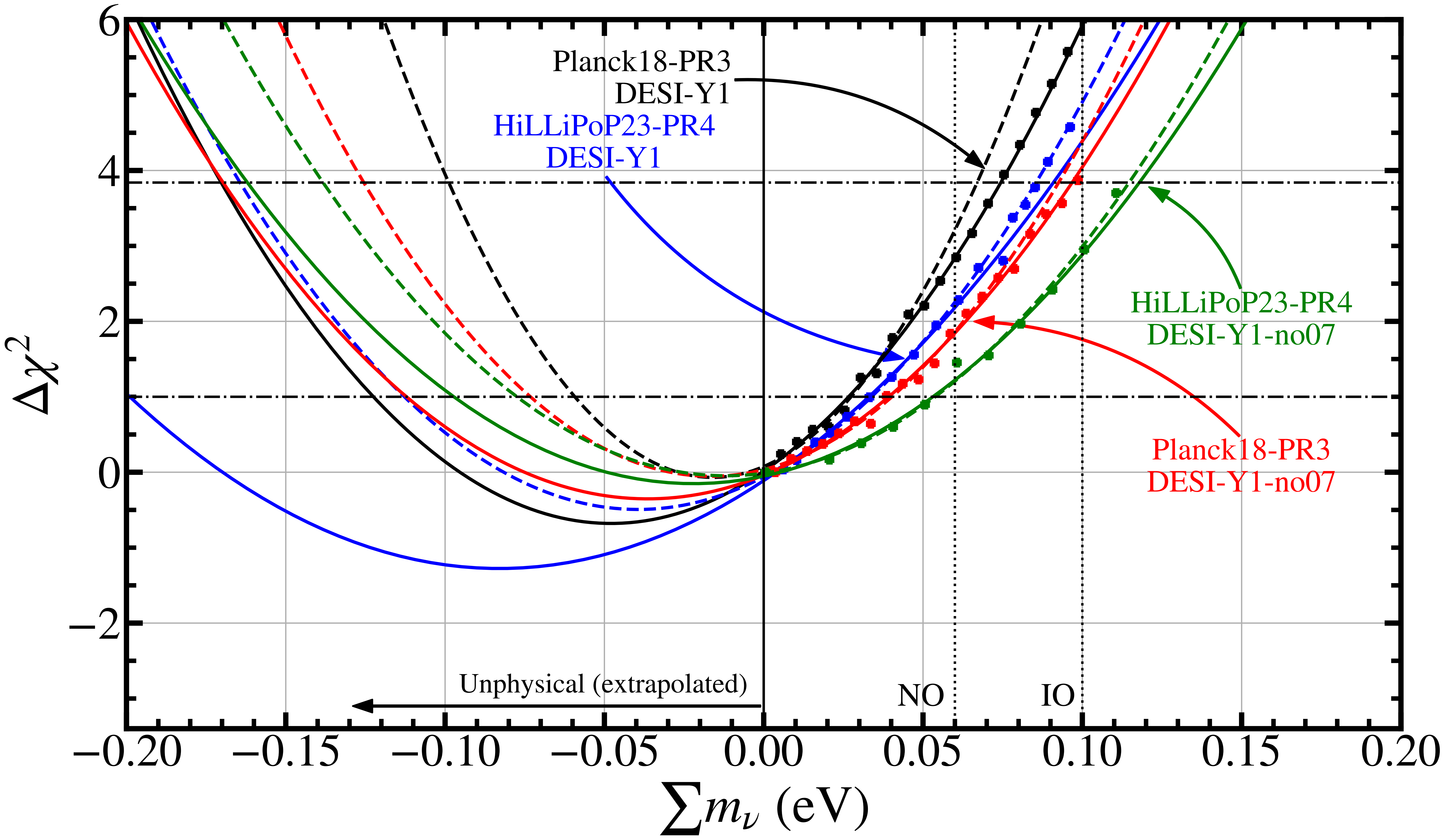
The effect of CMB lensing and DESI BAO

- Removing DESI $z = 0.7$ bin → Bound relaxed



The effect of CMB lensing and DESI BAO

- No lensing anomaly + No $z = 0.7$ bin → Significant relaxation



Bayesian vs Frequentist

Planck + BAO combination	95 % CL $\sum m_\nu$ bound (eV)	
	Bayesian	Frequentist
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

- Overall $\sim 10\,\%$ agreement between Bayesian and frequentist bounds

Bayesian vs Frequentist

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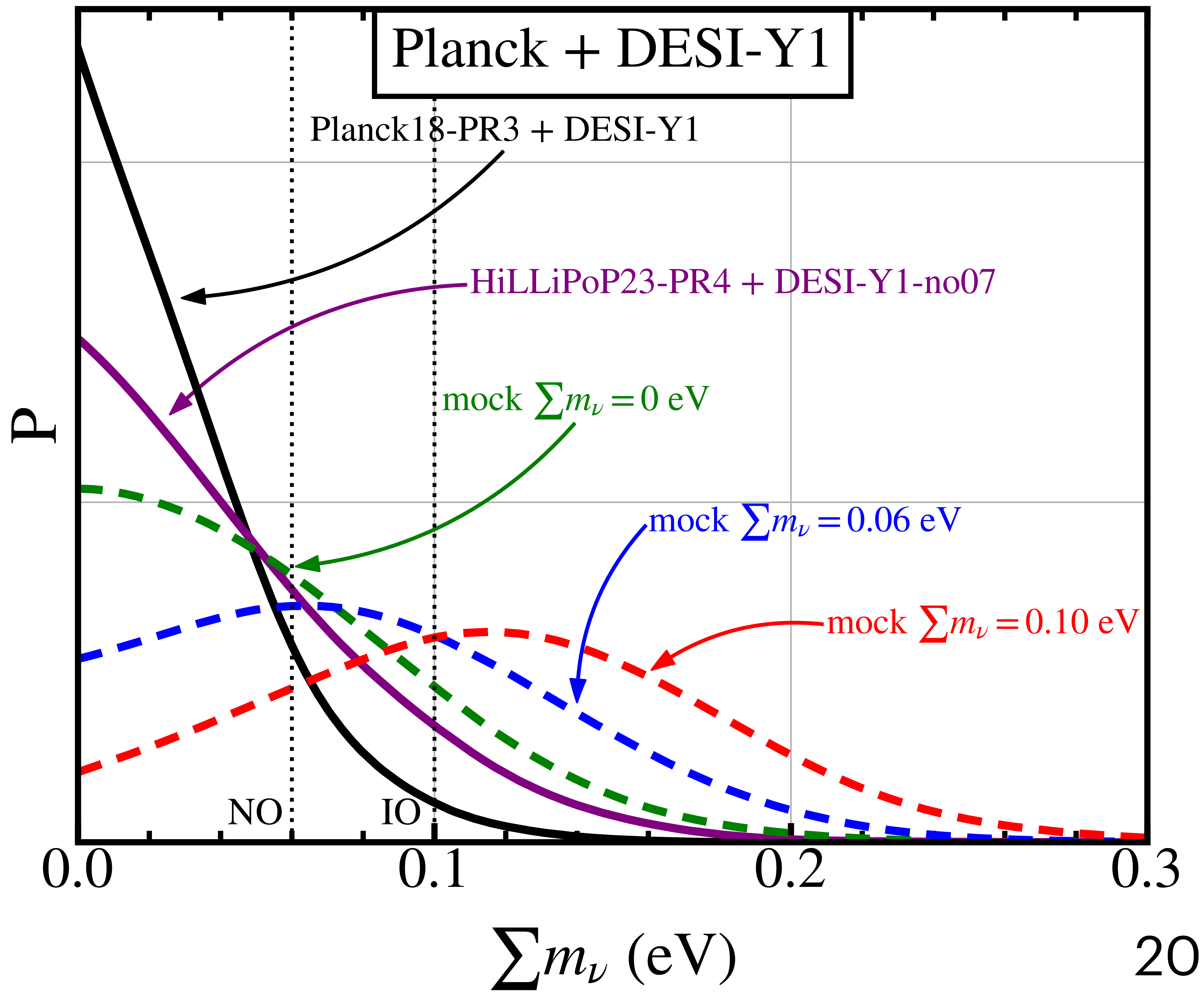
$\sim 30\,\%$ relaxation

No hint of a positive signal?

- Even though the bound is relaxed
  → No positive best-fit

- How unexpected?
  → Perform mock analysis
  → Asses sensitivity

- Bound is stronger even when assuming massless neutrinos ($\sum m_\nu = 0$) !!!



Model-dependence of the bound

- $\sum m_\nu$ dependent on a fit within a cosmological model

- Bound is robust upon standard modifications (e.g. varying N_{eff})

- Also robust upon varying DE equation of state w_0 *DESI collaboration [2404.03002]*

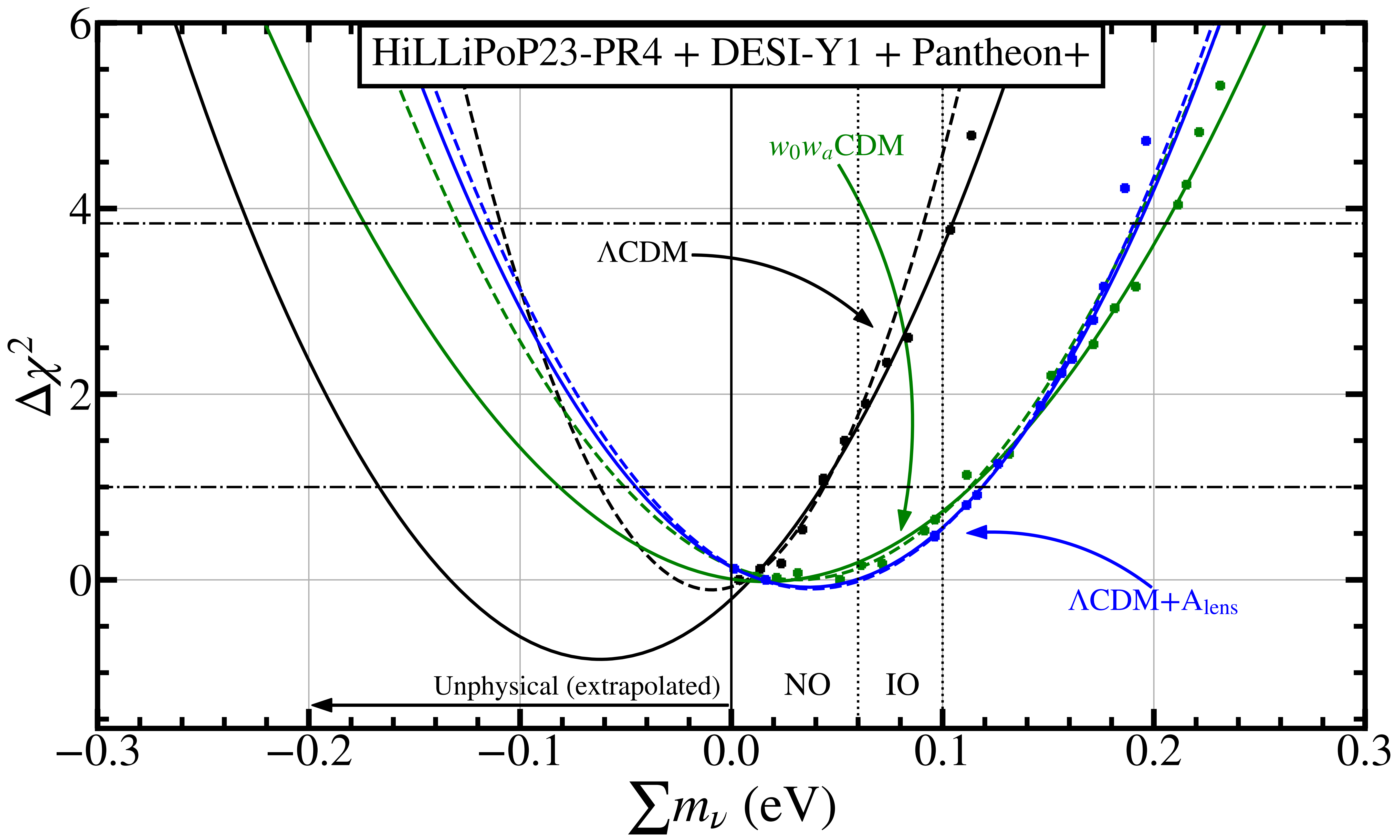
- However, relaxed when assuming a time varying DE equation of state (w_0 and w_a)

DESI collaboration [2404.03002]

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

Model-dependence of the bound

- Varying (w_0, w_a) or $A_{\rm lens}$ relaxes the bound: $\sum m_\nu \lesssim 0.2\,\mathrm{eV}$



Choudhury, Okumura [2409.13022]

- Recently shown that an extended cosmology can only relax up to $\sum m_\nu \lesssim 0.3\,\mathrm{eV}$

Conclusions

- Cosmology offers a great opportunity to measure the neutrino mass scale
- However, it seems it is closing on the allowed parameter space for $\sum m_\nu$
- Critical look: **still early** to conclude that ΛCDM cosmology conflicts ν-oscillations
- Nevertheless: yet no hint of $\sum m_\nu \neq 0$ suggests the presence of some anomaly
- Model dependent bound: can be relaxed up to 0.2 eV or even 0.3 eV

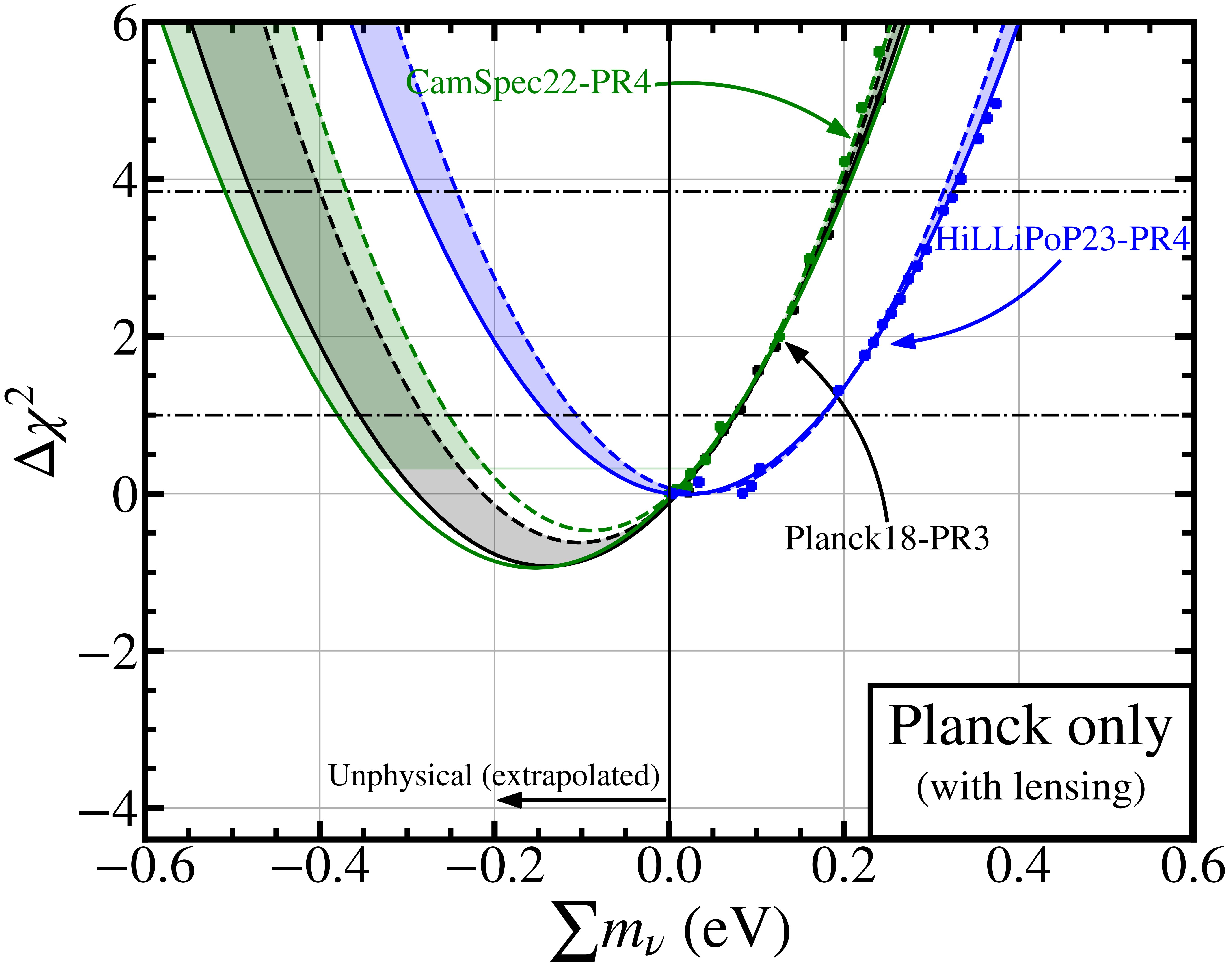
Conclusions

Upcoming years are bound to be promising:
new data from DESI and EUCLID

Thank you for your attention!
Time for questions/comments

Backup

Planck only profiles



The effect of CMB lensing and DESI BAO

- Is there a preference for "negative neutrino masses"?