

Exploring new frontiers in cosmology,
GGI Florence, 27.07.2026

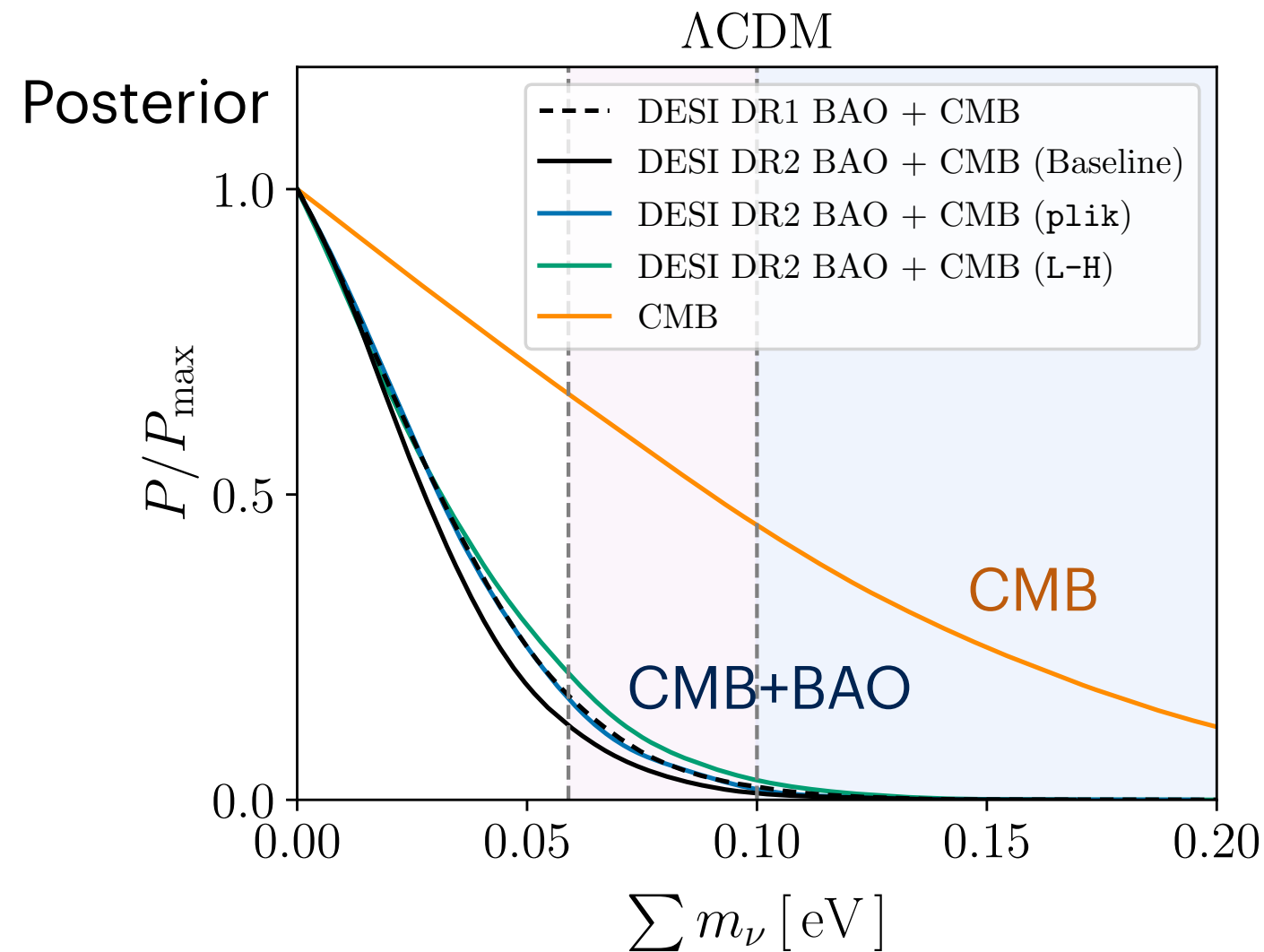
**Constraints on neutrino mass
in light of
cosmological tensions**



J. Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

Tension on Σm_ν between cosmology and laboratory



Calabrese et al. 2503.14454

- **Cosmology with Λ CDM:** $\Sigma m_\nu < 0.055 \text{ eV}$ (95%, Planck+ACT+SPT+DESI)

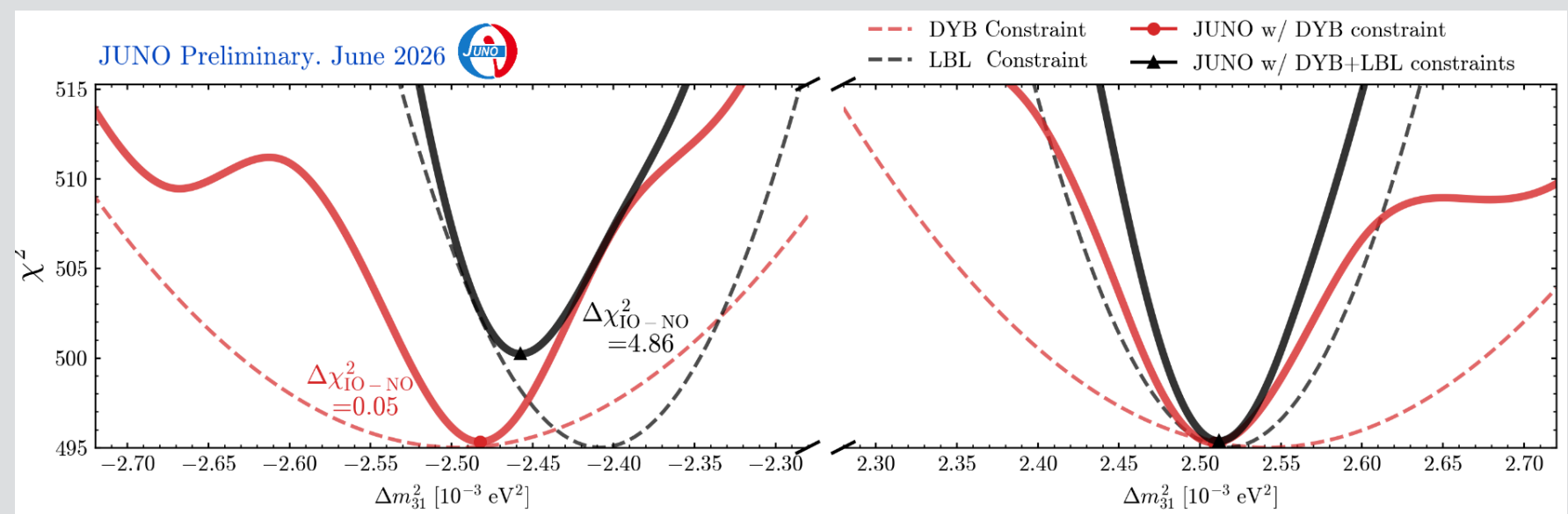
Camhuis et al. 2506.20707

- **Laboratory (oscillations):**
 - $\Sigma m_\nu > 0.058 \text{ eV}$ (95%, Normal Hierarchy),
 - $\Sigma m_\nu > 0.098 \text{ eV}$ (95%, Inverted hierarchy)

Tension on Σm_ν between cosmology and laboratory

Λ CDM

Posterior Now favoured by combination of reactor and accelerator long-baseline experiments including JUNO:
normal hierarchy favoured at 2.3σ

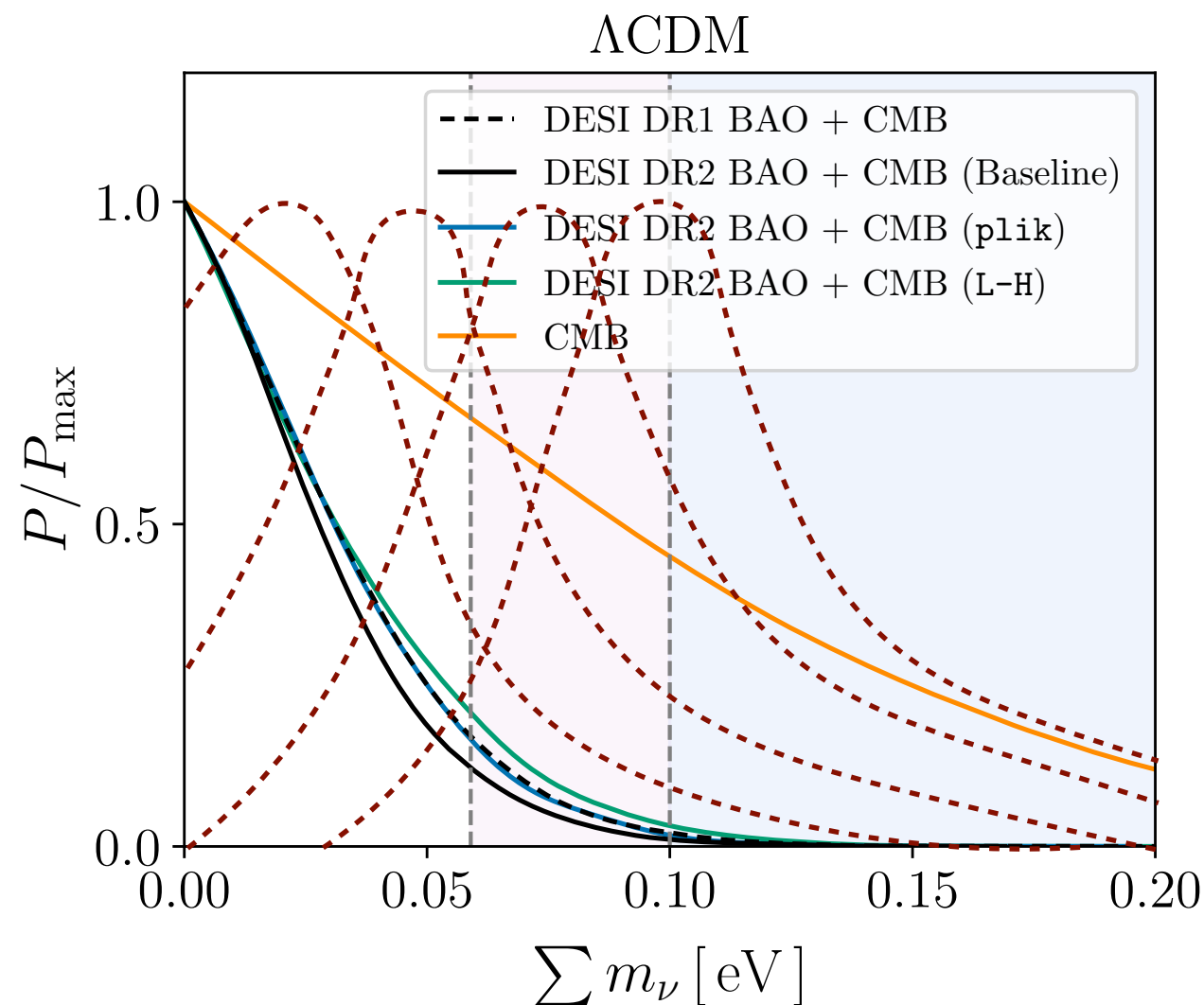


JUNO Preliminary, June 2026 (Neutrino26, PASCOS26)

- Cosmology with Λ CDM: $\Sigma m_\nu < 0.055$ eV (95%, Planck+ACT+SPT+DESI) Lupuis et al. 2506.20707
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Explaining the Σm_ν tension

1. **Statistical fluke**, unaccounted systematics, future observations may still bring evidence for non-zero mass while assuming Λ CDM...



Explaining the Σm_ν tension

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2. We live in a **neutrinoless Universe**

e.g. decay into massless (pseudo)scalar $\nu_i \bar{\nu}_i \longrightarrow \phi$

e.g. Beacom et al. astro-ph/0404585, Escudero et al. 2007.04994,
Barenboim et al. 2011.01502, Franco Abellan et al. 2112.13862,
Craig et al. 2405.00836

Explaining the Σm_ν tension

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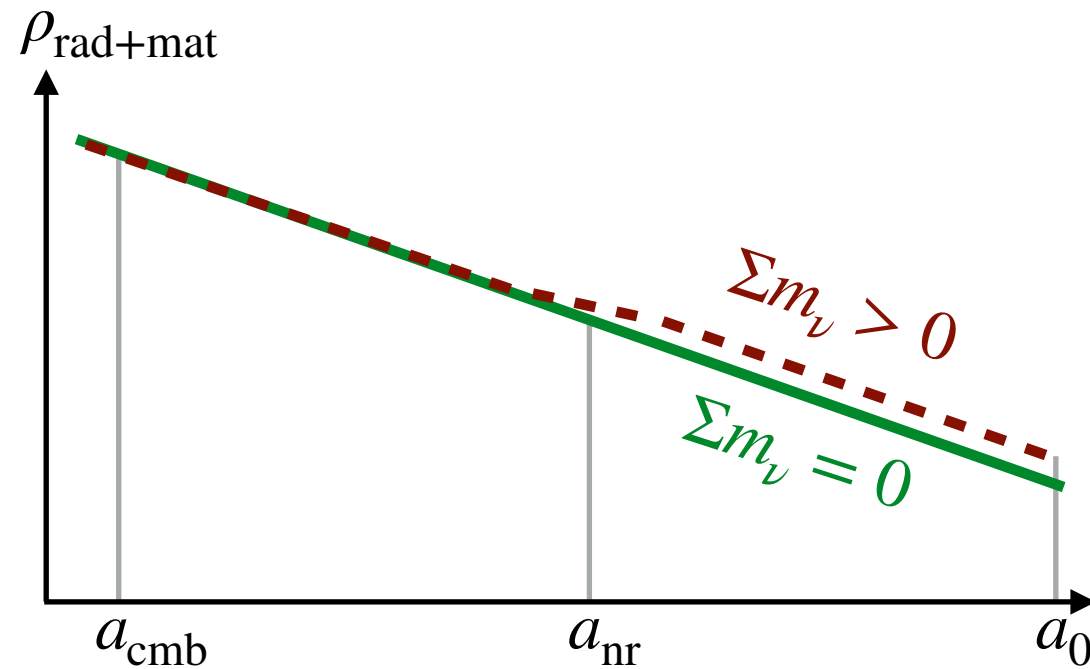
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3. Neutrino mass bounds are (cosmological) model-dependent and **Λ CDM is not the right framework** (as suggested by other tensions; common origin and solution?)

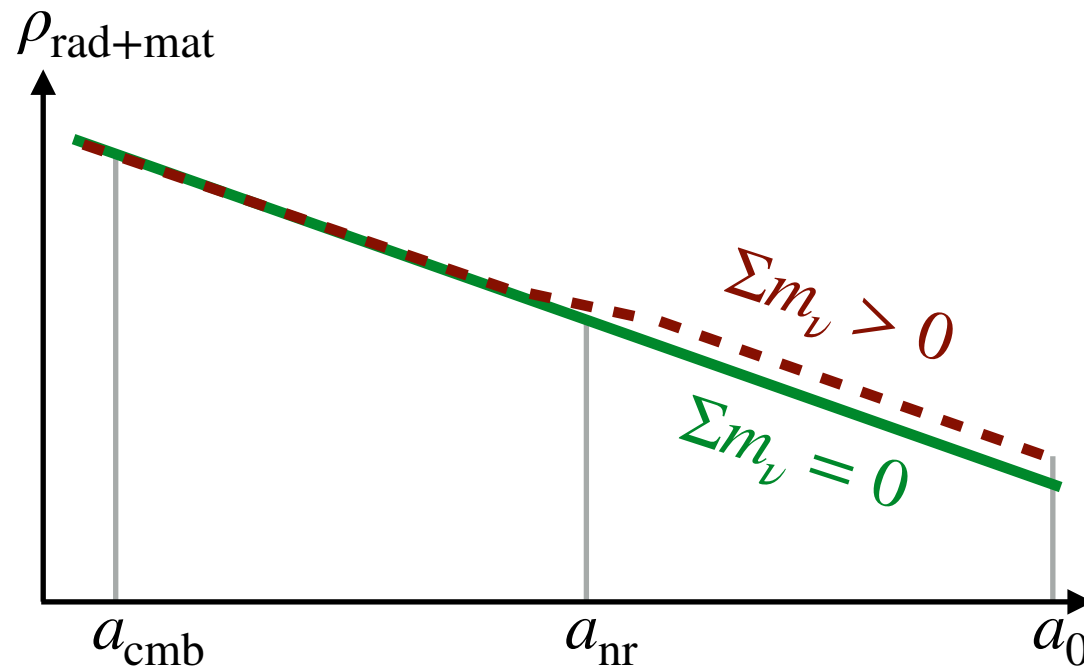
Testable cosmological effects of Σm_ν

- Geometrical effect [$d_A(z)$, $H(z)$]

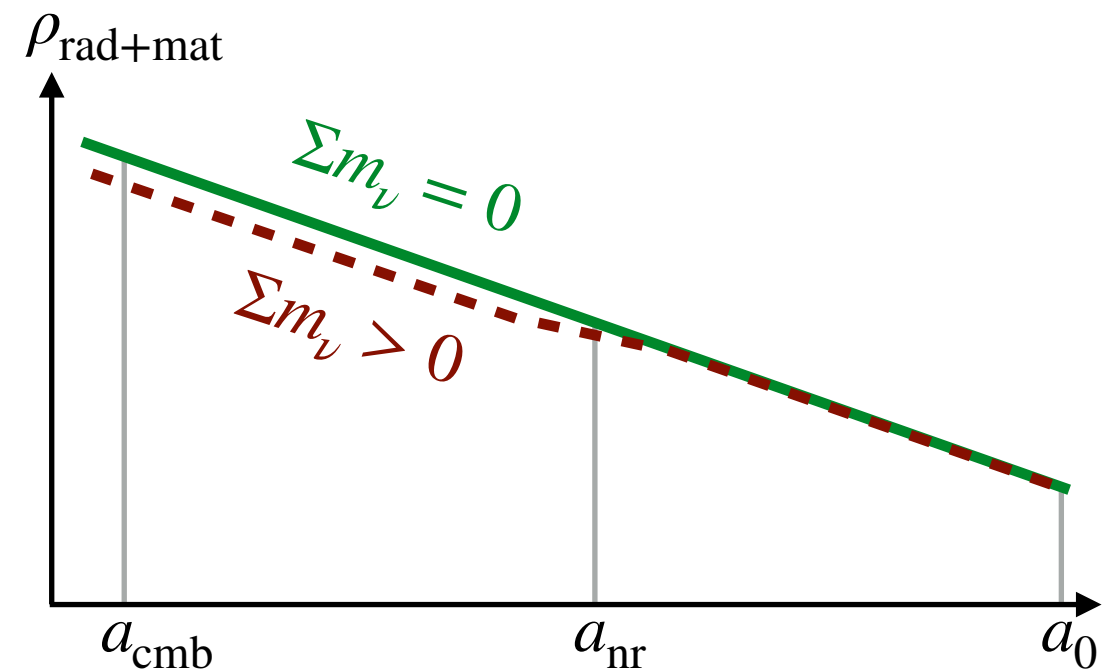


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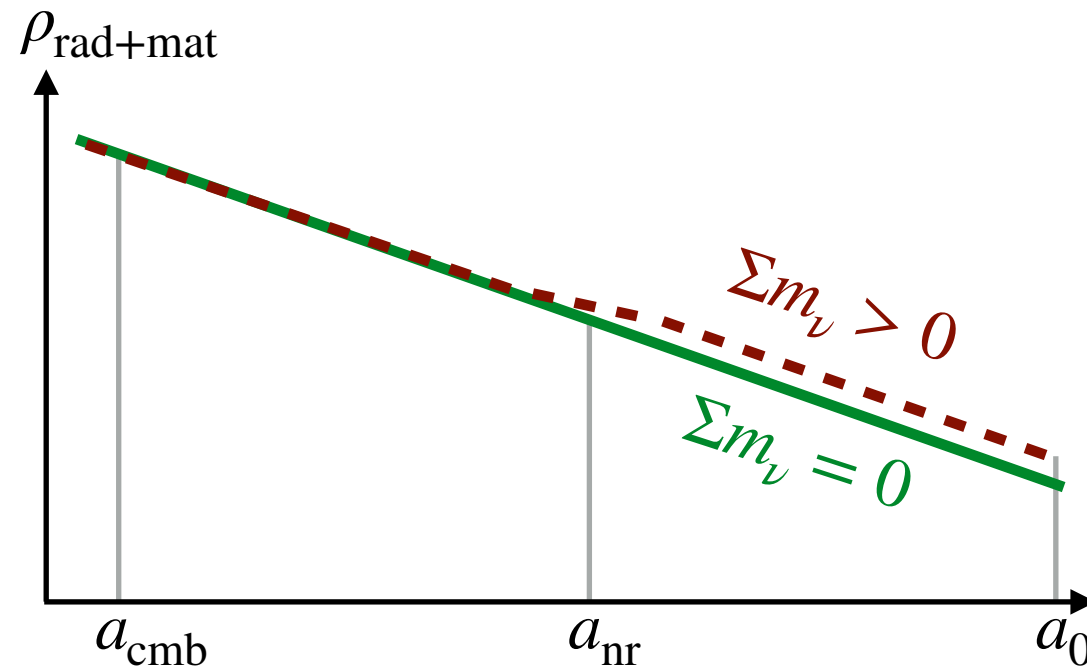


or

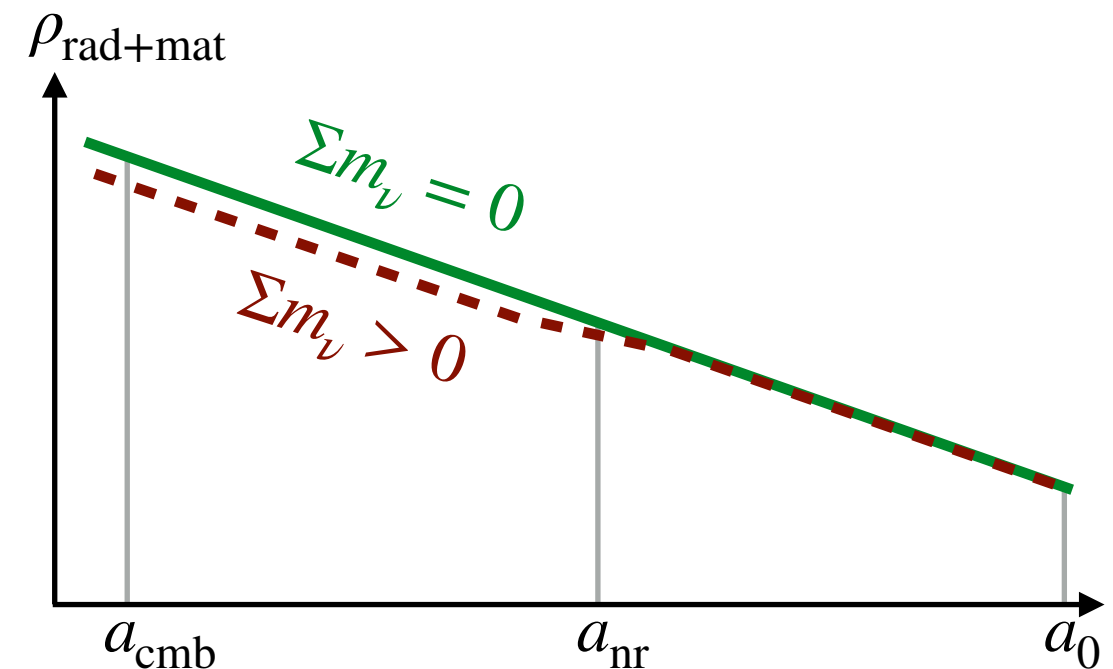


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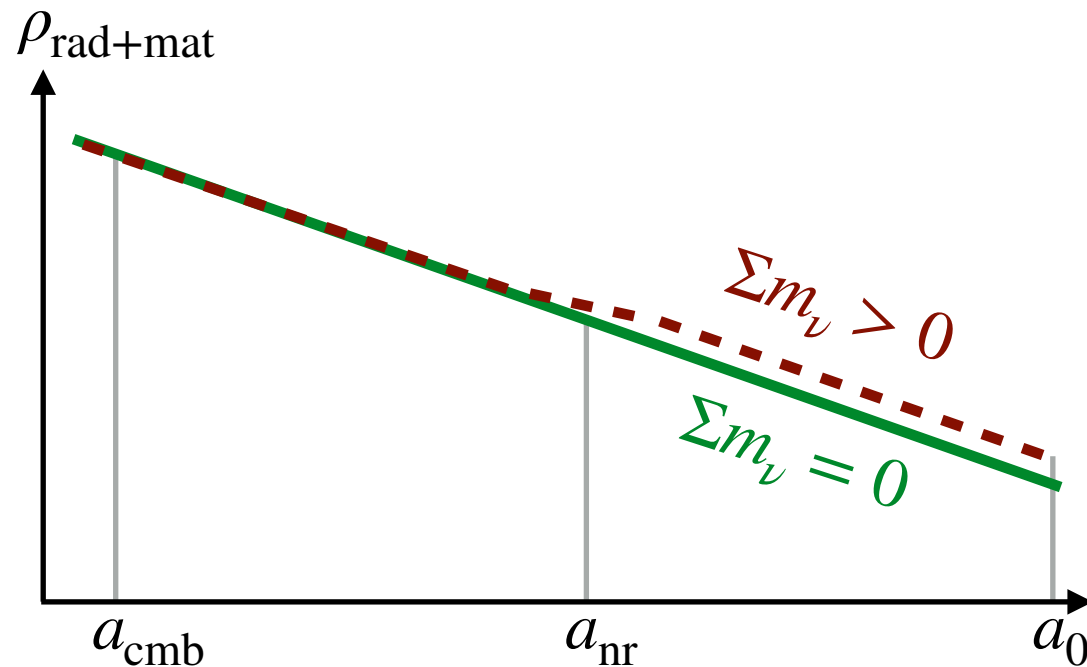
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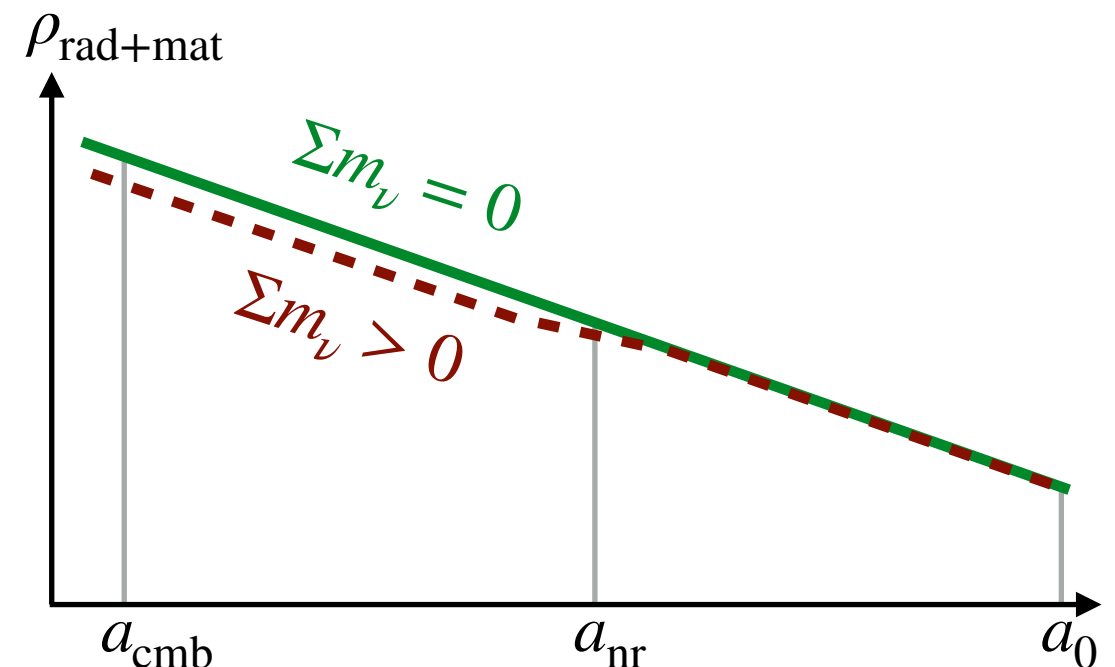
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Testable cosmological effects of Σm_ν

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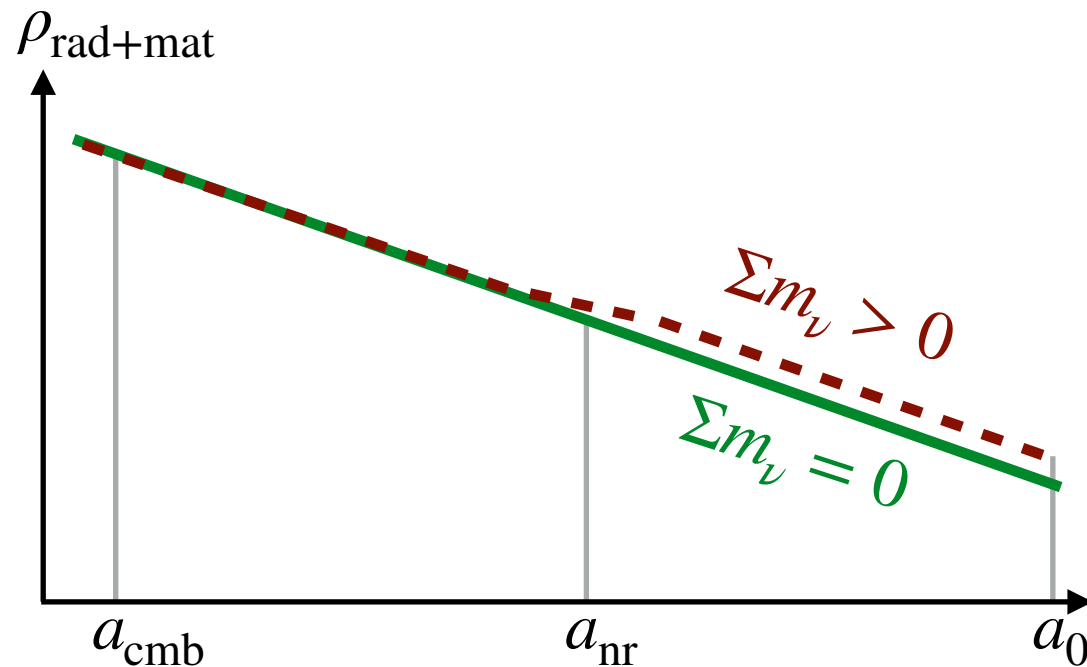
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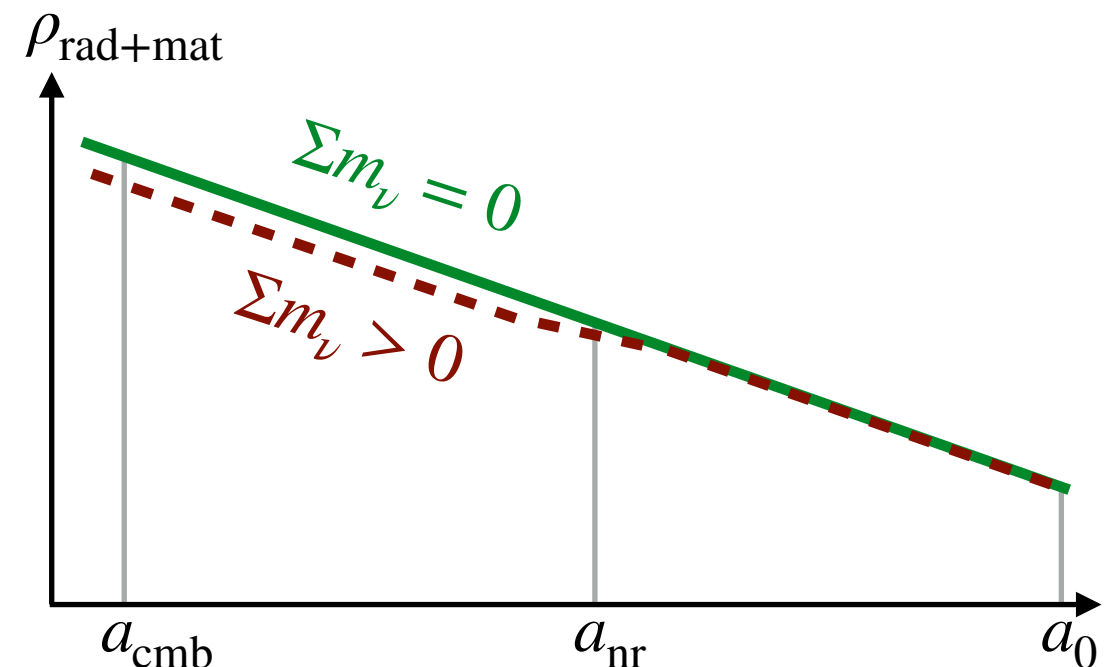
- Early ISW effect on CMB
- Free-streaming effect on structure growth [$P(k)$]

Testable cosmological effects of Σm_ν

- Geometrical effect [$d_A(z)$, $H(z)$]



or



- Early ISW effect on CMB
 - Free-streaming effect on structure growth [$P(k)$]
- 
- Free-streaming effect on CMB 4-point [CMB lensing spectrum]
 - Free-streaming effect on CMB 2-point TT,TE,EE [CMB lensing: smoothing, tail]

Testable cosmological effects of Σm_ν

- Geometrical effect [$d_A(z)$, $H(z)$]: **strong** (BAO+CMB peak scale: < 0.1 eV , 95%)
- Early ISW effect on CMB: **subdominant** (WMAP alone: < 1.2 eV, 95%)
- Free-streaming effect on $P(k)$: **subdominant** from galaxy full-shape
- Free-streaming effect on CMB 4-point: **subdominant**
- Free-streaming effect on CMB 2-point TT,TE,EE: **strong**
(CMB data indicates significant lensing effect)

Elbers et al. 2407.10965, LoVerde & Weiner 2410.00090, Sharma & JL 2510.15835, ...

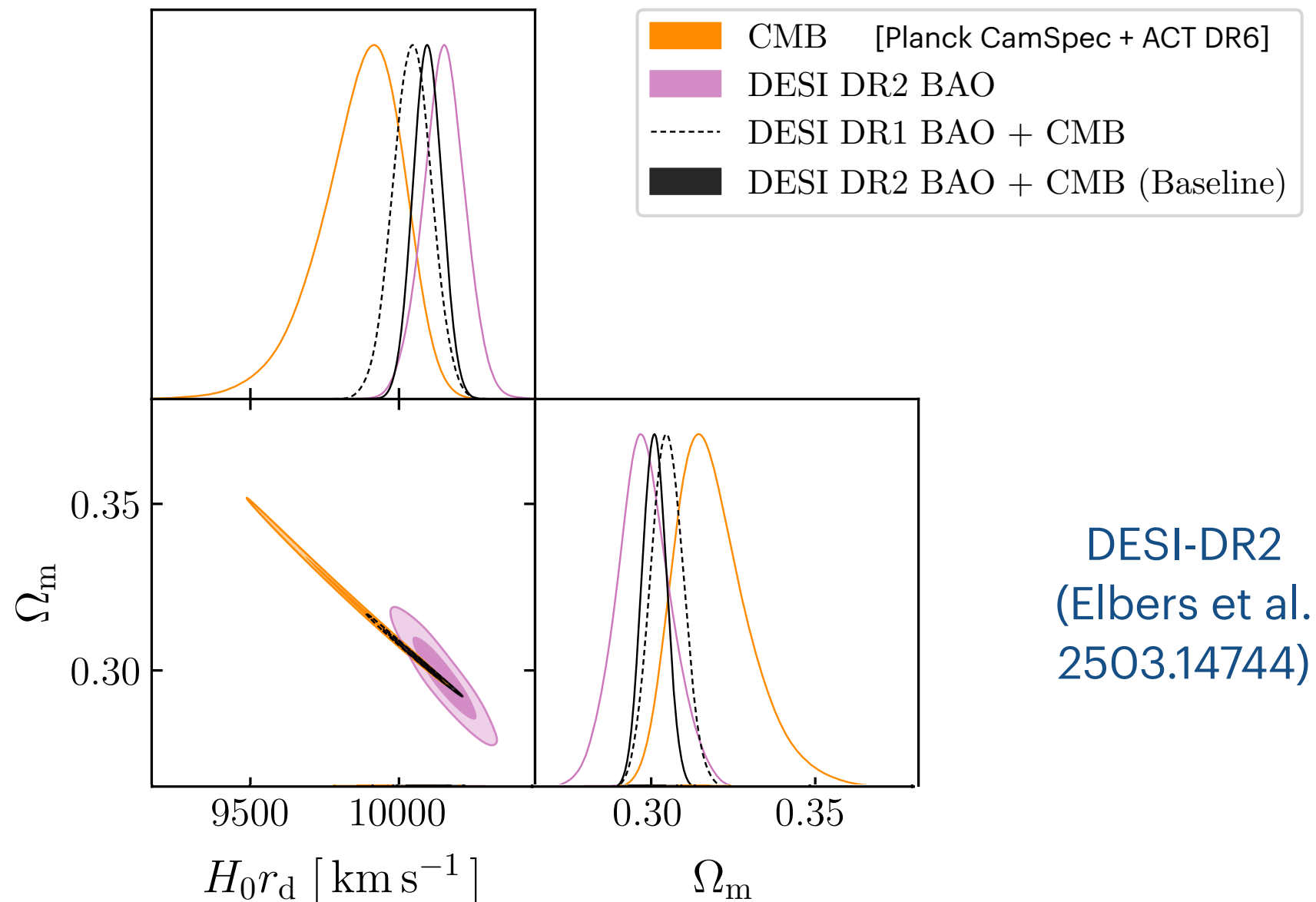
Role of CMB/BAO tension

- CMB peak / BAO scale measure $[H_0 r_d] / \frac{H_0}{H(z)}$ and $[H_0 r_{d,s}] / \int_0^z \frac{H_0}{H(\tilde{z})} d\tilde{z}$ at $\neq z$
- $\frac{H(z)}{H_0}$ = expansion history normalised to 1, depends on:
 - DE parameters ($\Omega_\Lambda = 1 - \Omega_m, w_0, w_a, \dots$),
 - curvature (Ω_k),
 - neutrino mass (Σm_ν), ...
- In Λ CDM: only $H_0 r_d$ and Ω_m ($= 1 - \Omega_\Lambda$)

Role of CMB/BAO tension

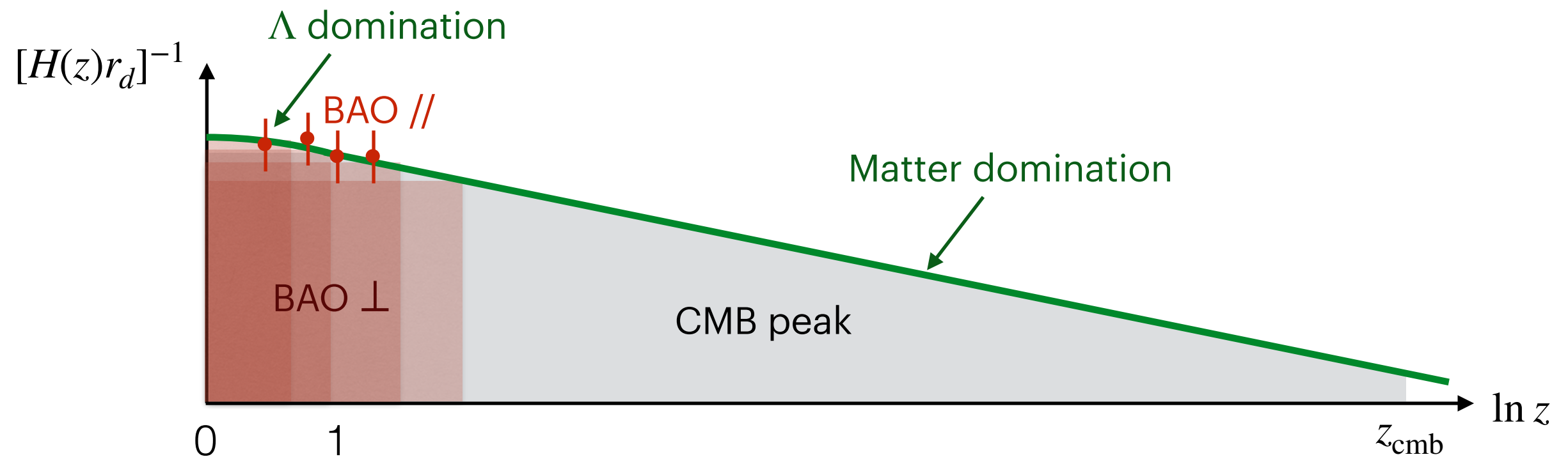
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- Tension in Λ CDM:



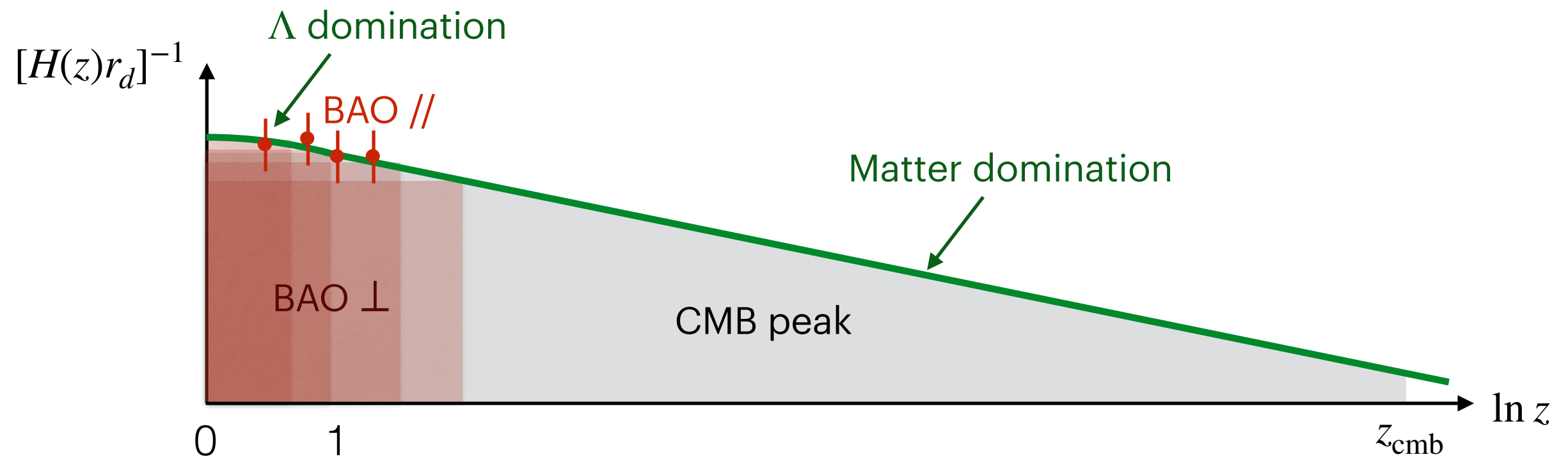
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+ additional integral constraints from
distant (uncalibrated) supernovae (Pantheon+, Union, DES)

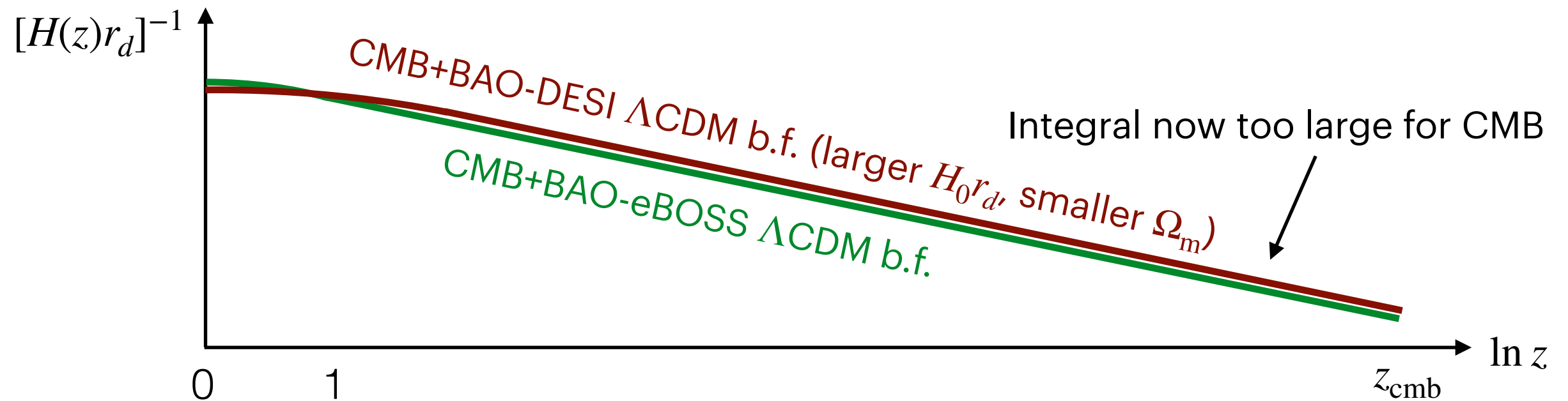
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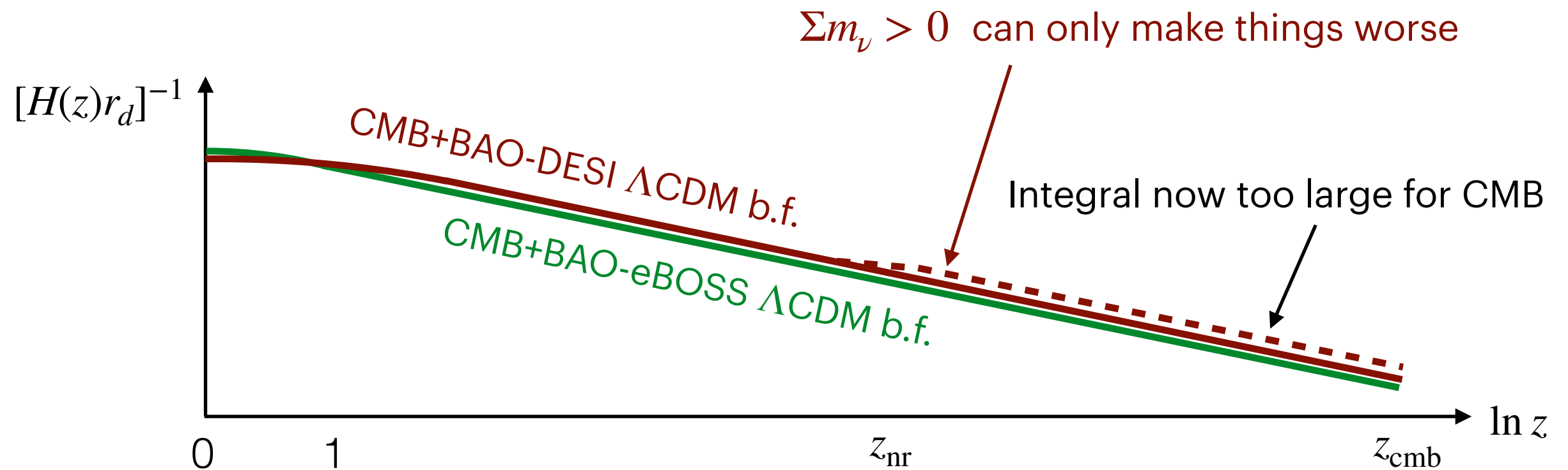
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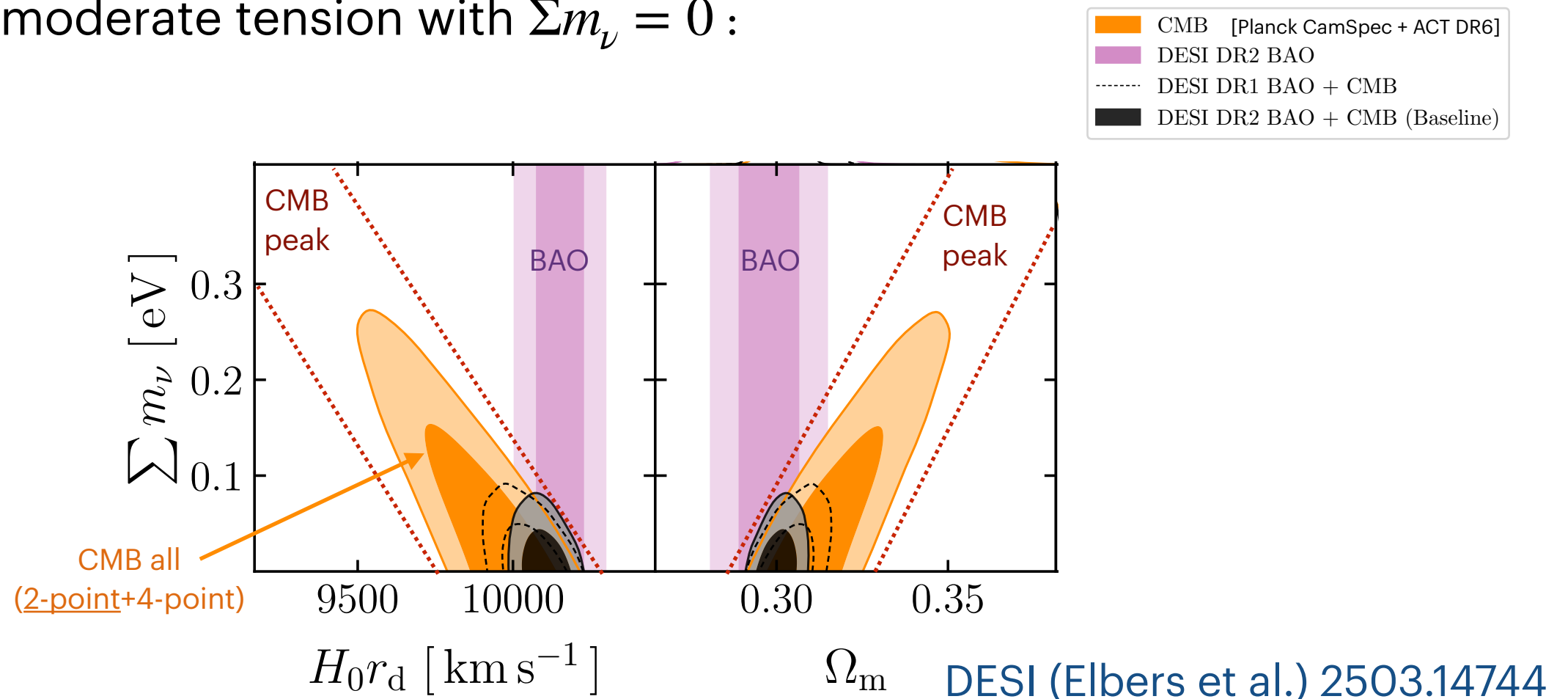
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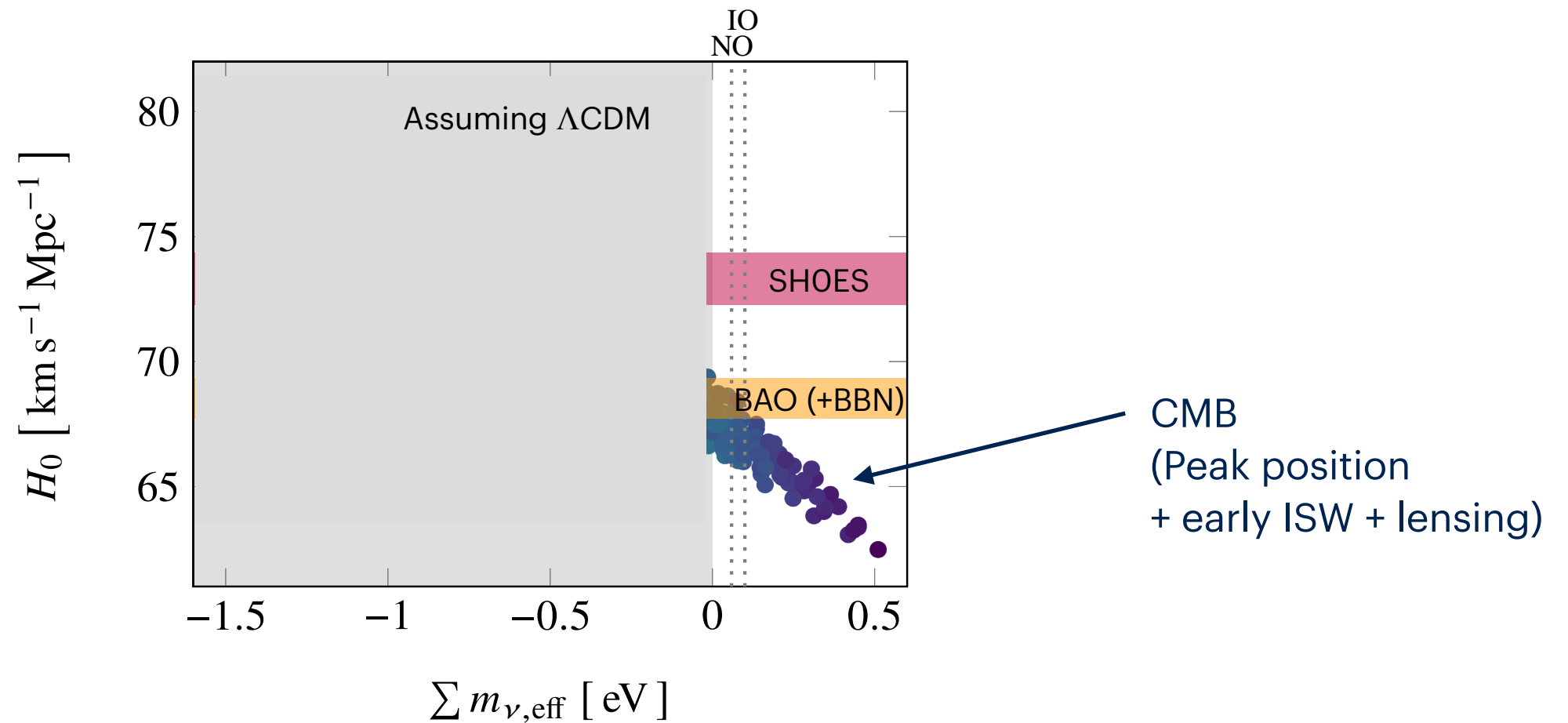
- CMB/BAO tension in Λ CDM: $\Sigma m_\nu > 0$ can only make things worse
- already a moderate tension with $\Sigma m_\nu = 0$:



- CMB 2-point worsens it, but tension fundamentally driven by **geometrical effect**

Role of CMB/BAO + Hubble tension

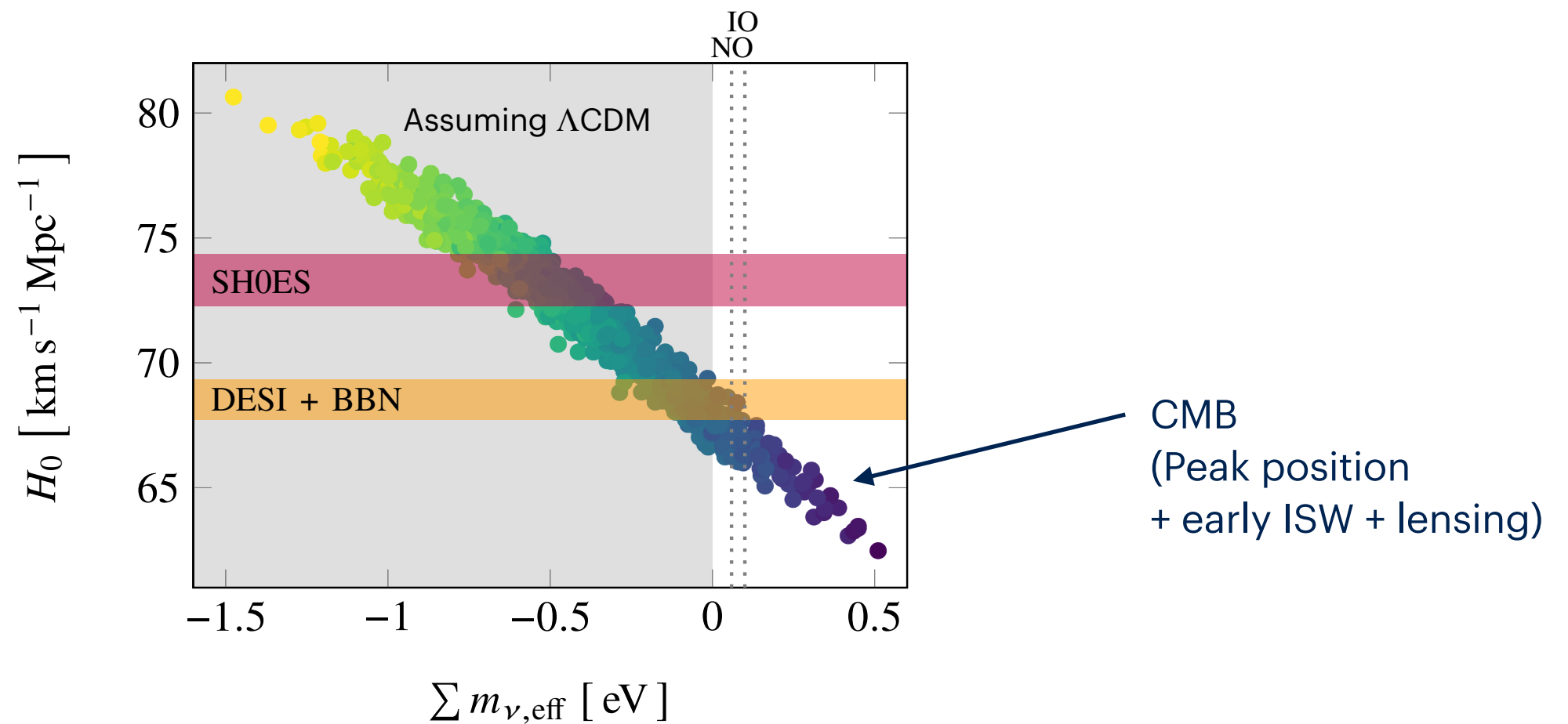
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Adapted from Elbers et al. 2407.10965

Role of CMB/BAO + Hubble tension

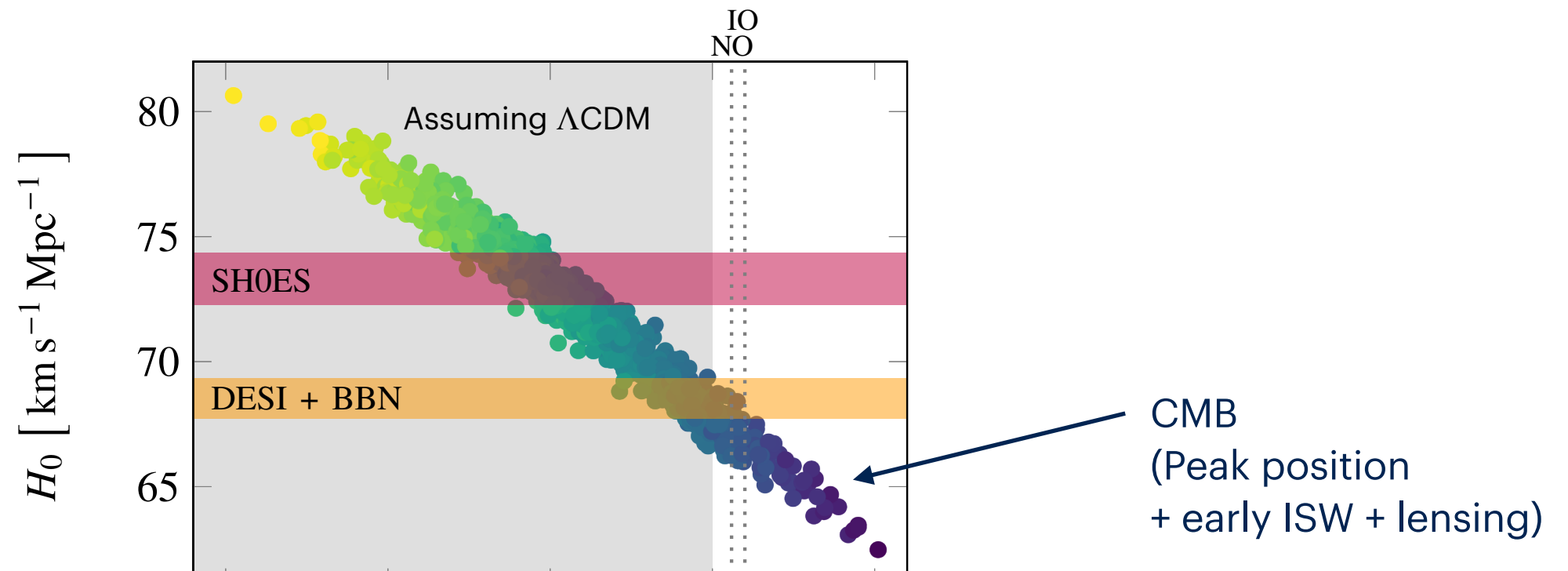
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Elbers et al. 2407.10965

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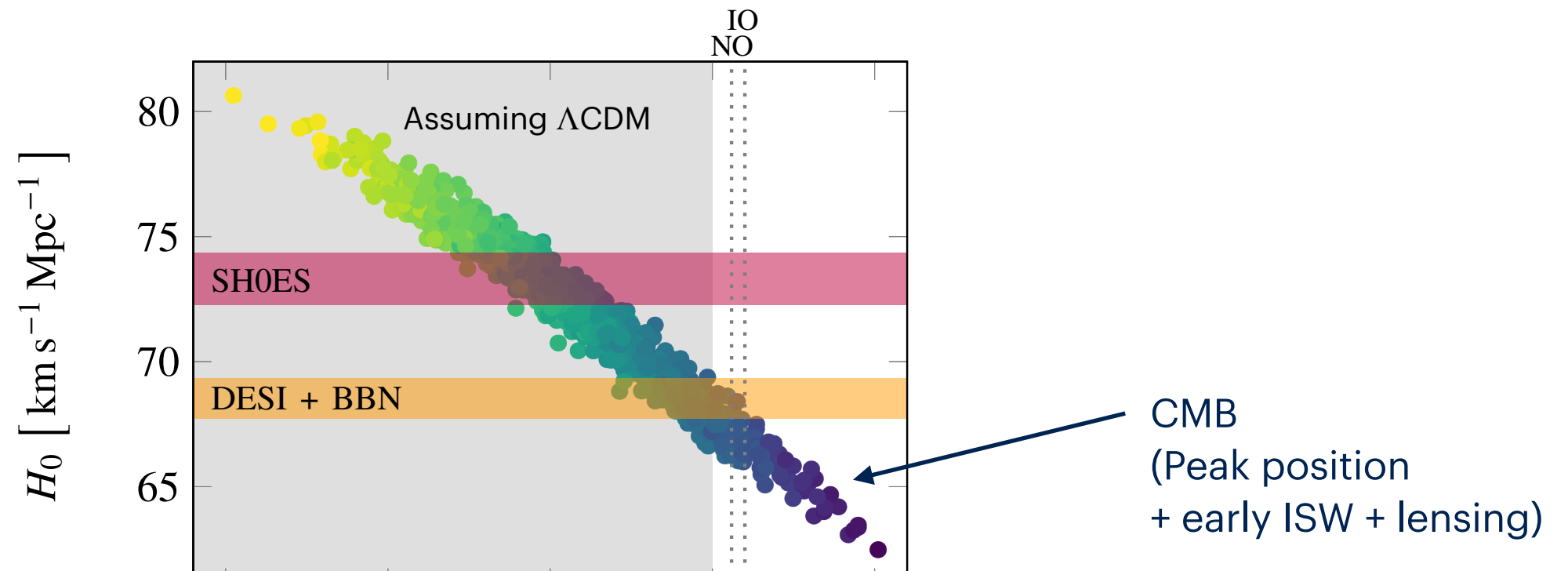
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Elbers et al. 2407.10965

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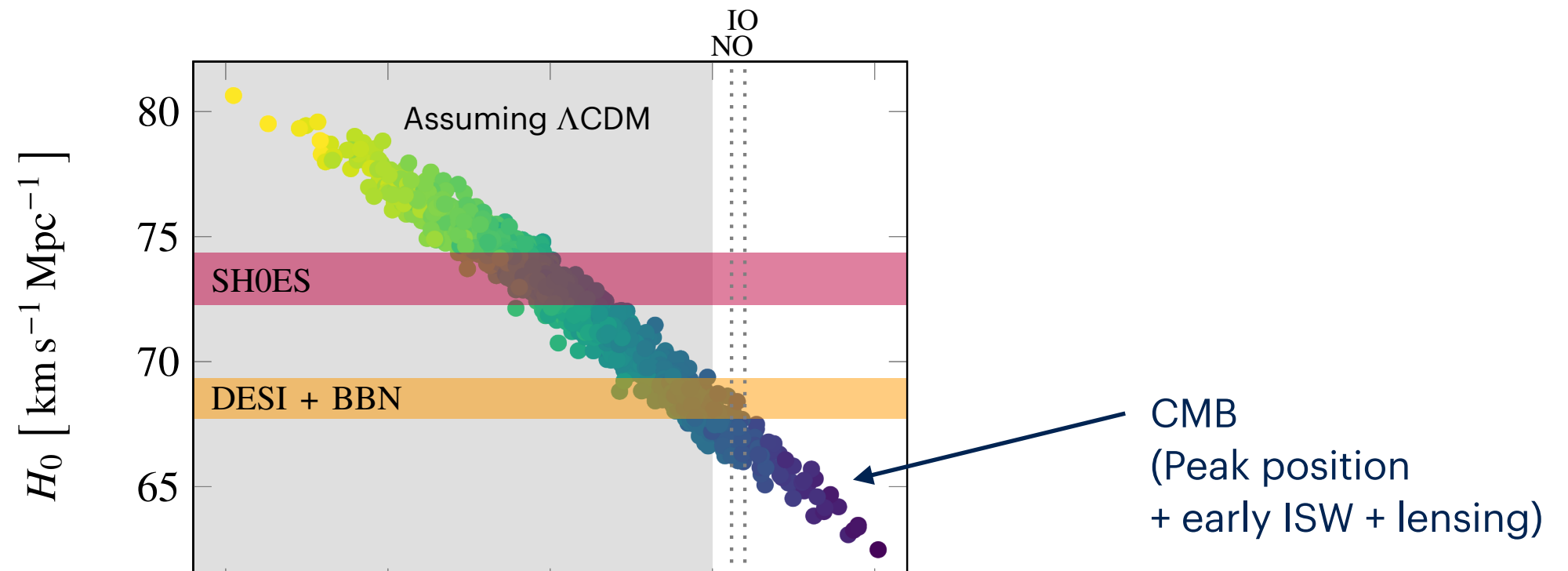
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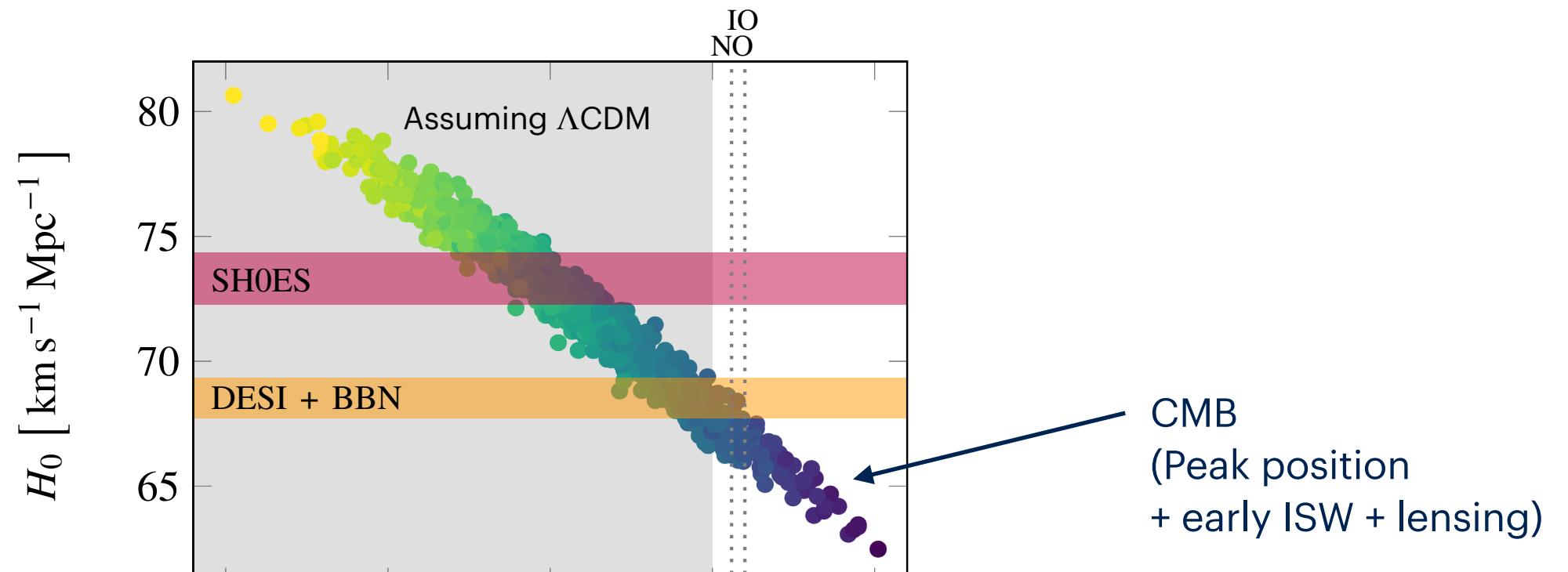
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Elbers et al. 2407.10965

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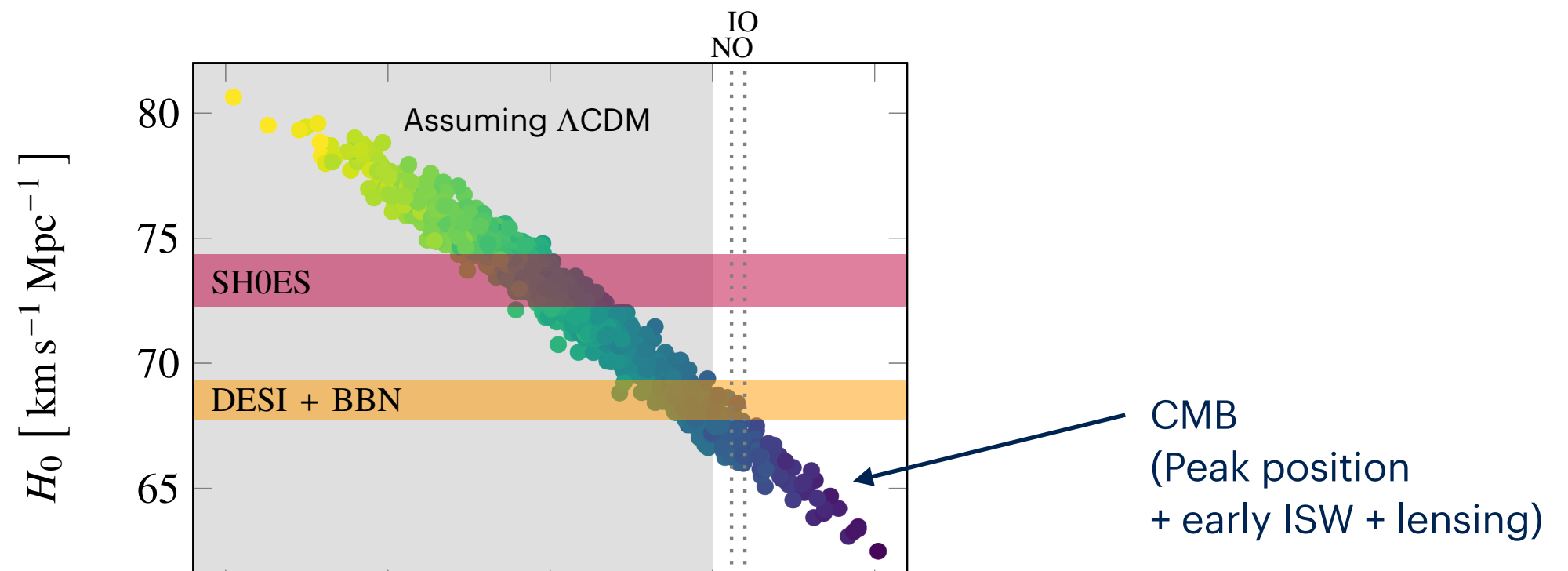
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Elbers et al. 2407.10965

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Terminology:

- ~~negative neutrino mass~~
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- ~~unphysical neutrino mass~~
- effect opposite to neutrino (mass)
- negative effective neutrino mass

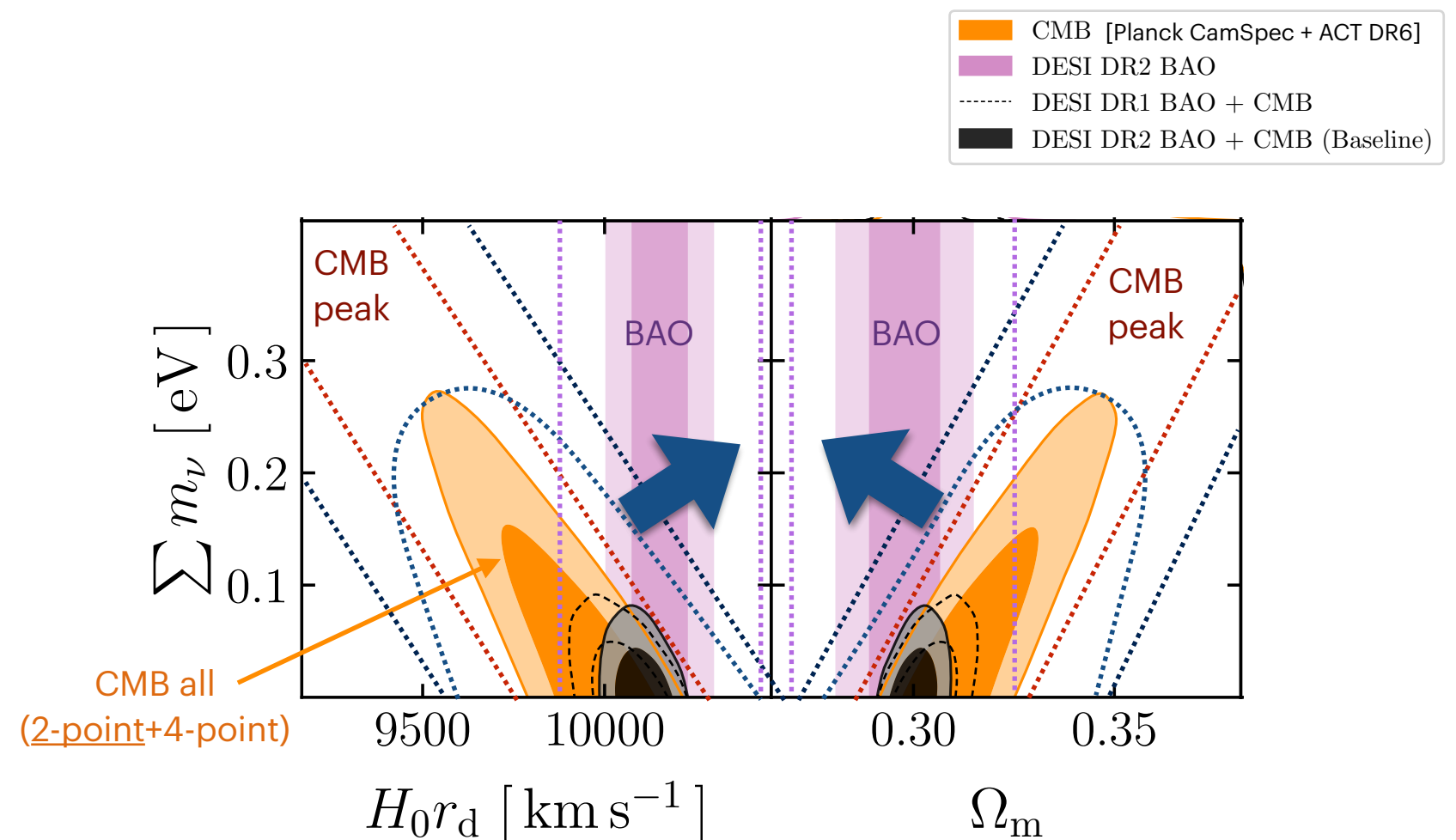


Elbers et al. 2407.10965

How to relax the neutrino mass bound?

Any model relaxing CMB/BAO tension also relaxes neutrino mass bound !

1. Add freedom in expansion history
2. Add freedom in lensing effects in 2-point CMB
3. Add freedom in $\theta_s \leftrightarrow$ CMB peak scale relation

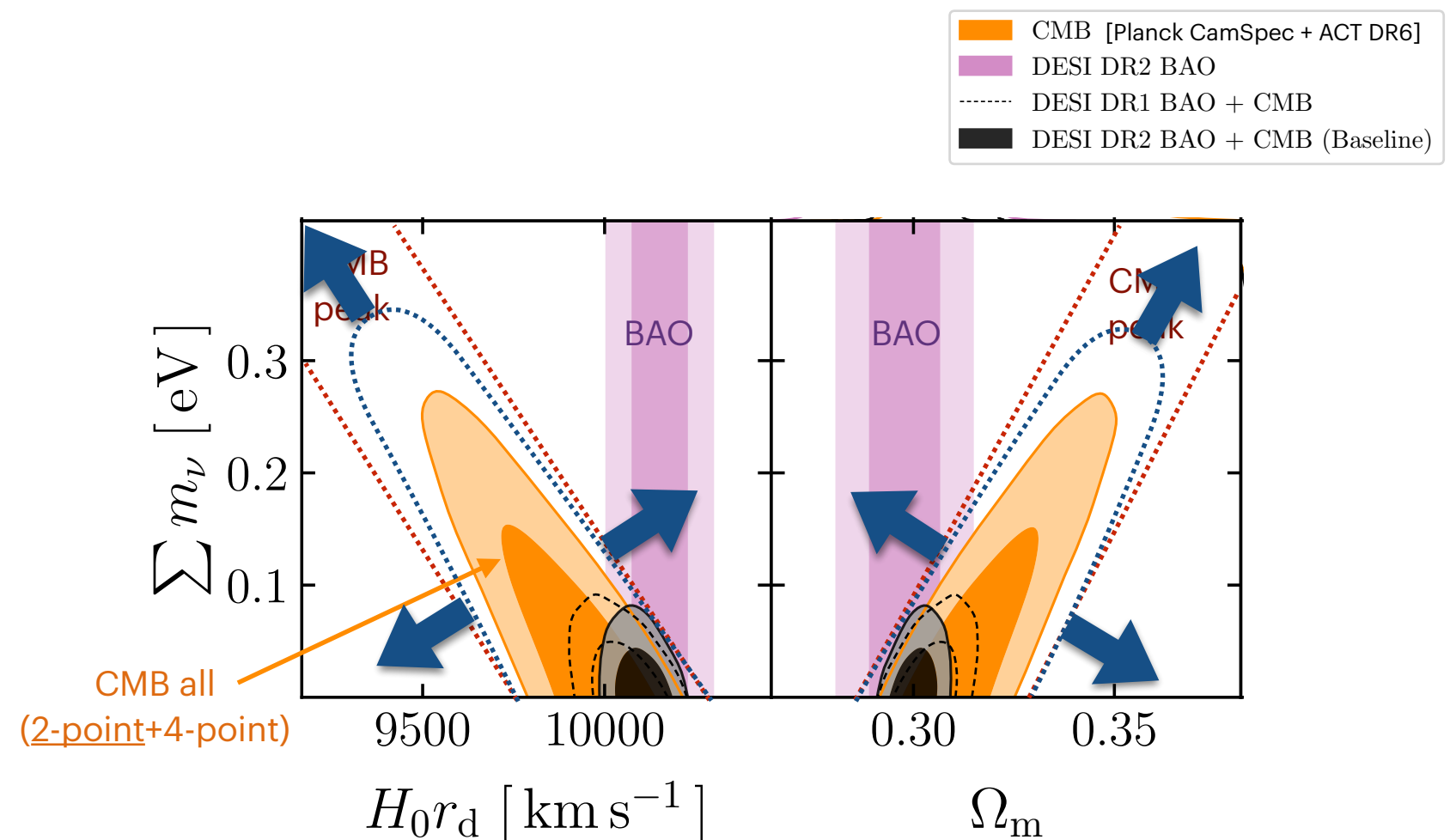


DESI (Elbers et al.) 2503.14744

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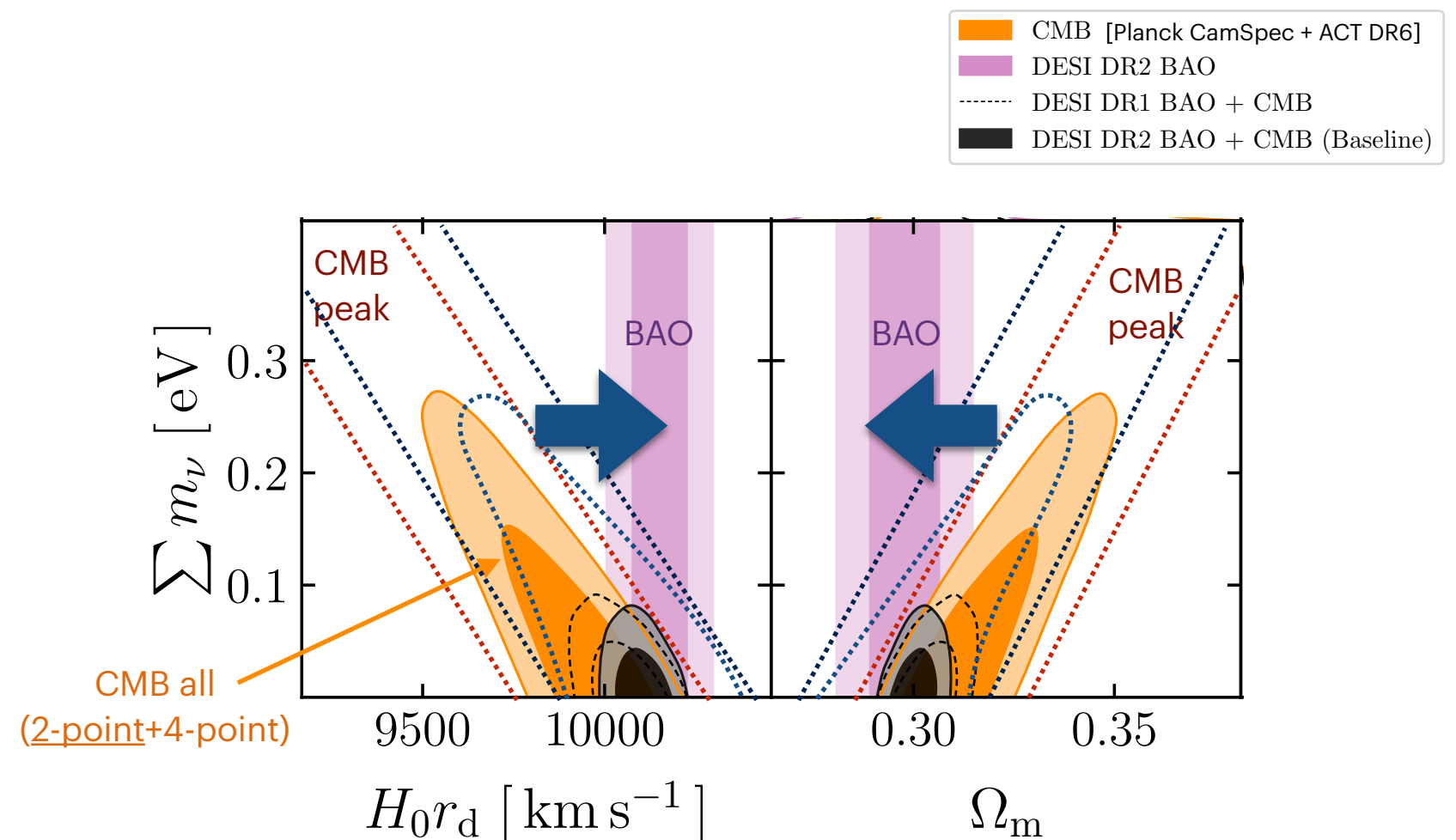


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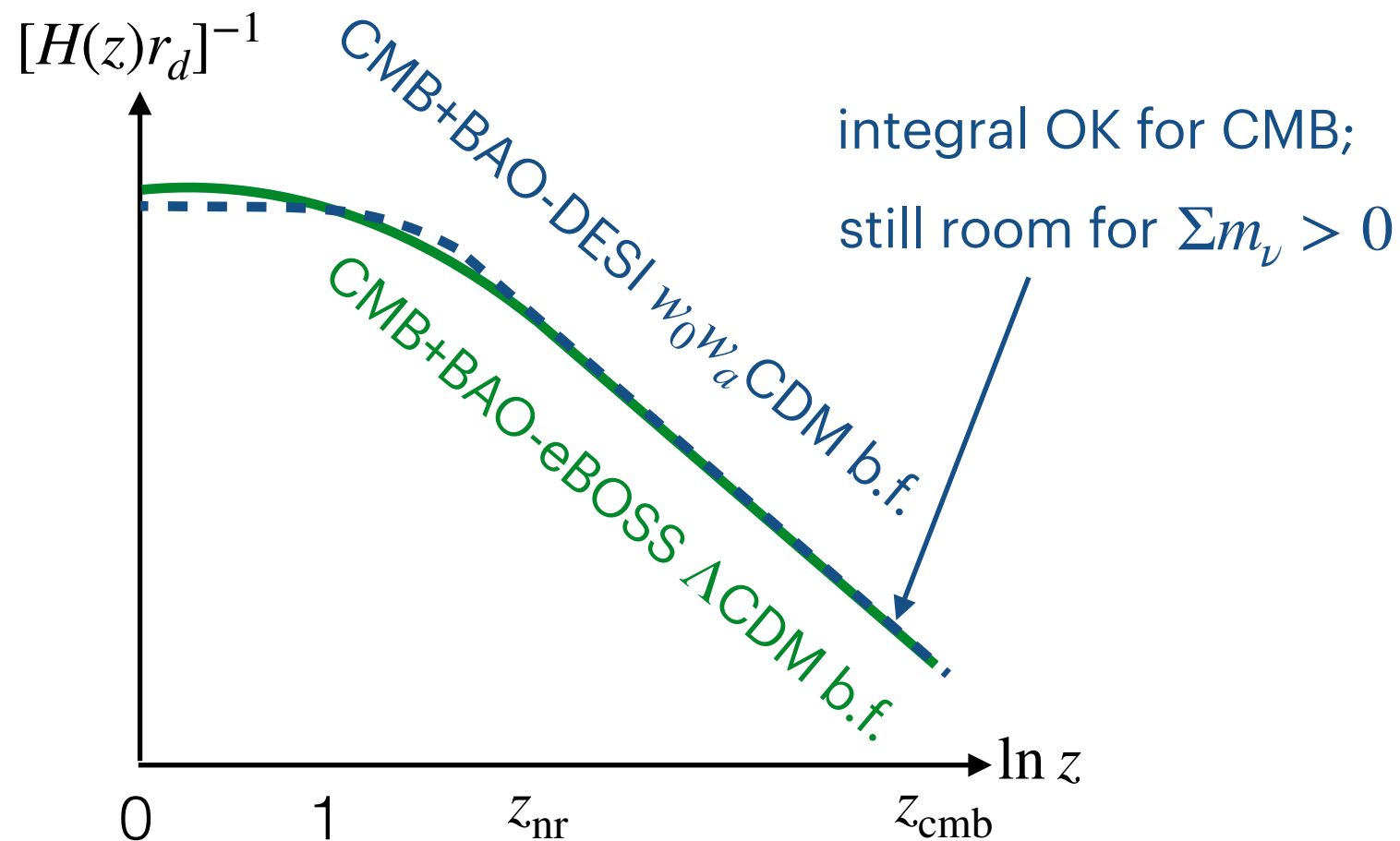
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DESI (Elbers et al.) 2503.14744

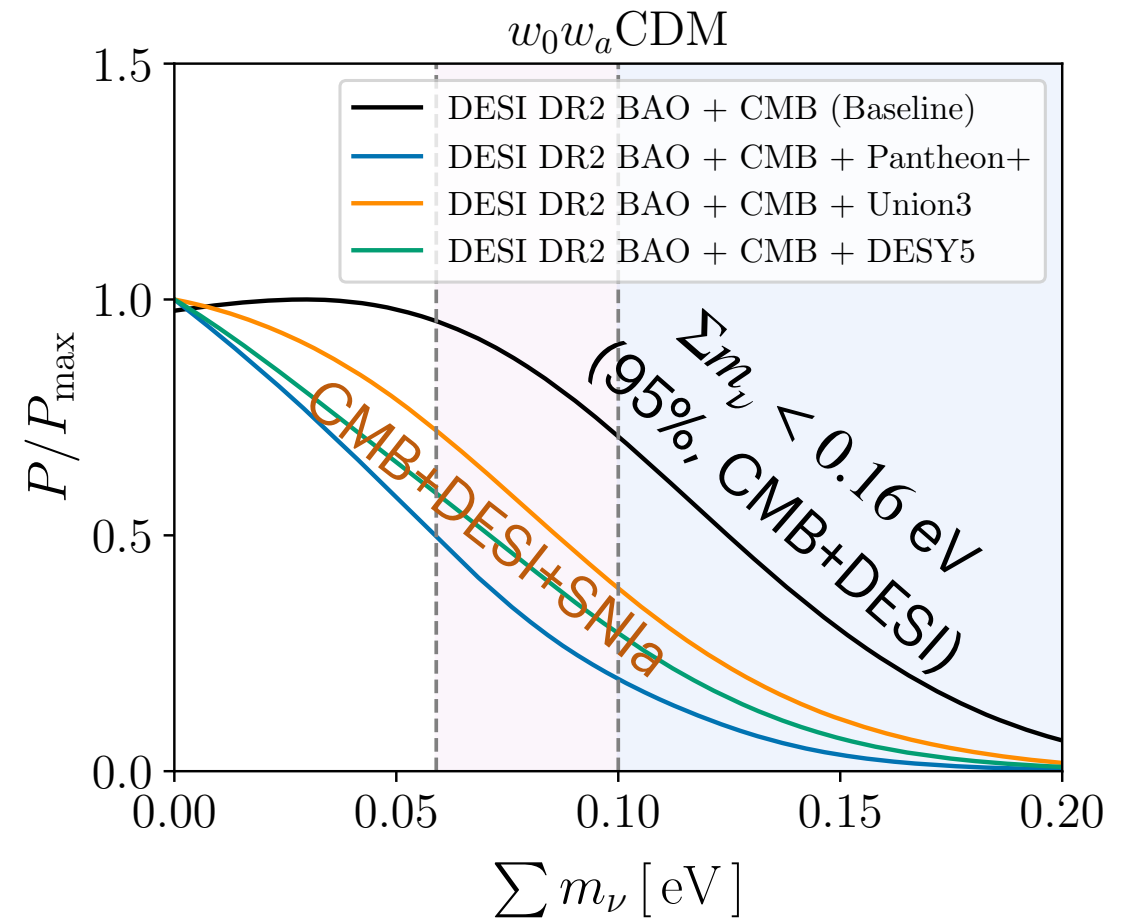
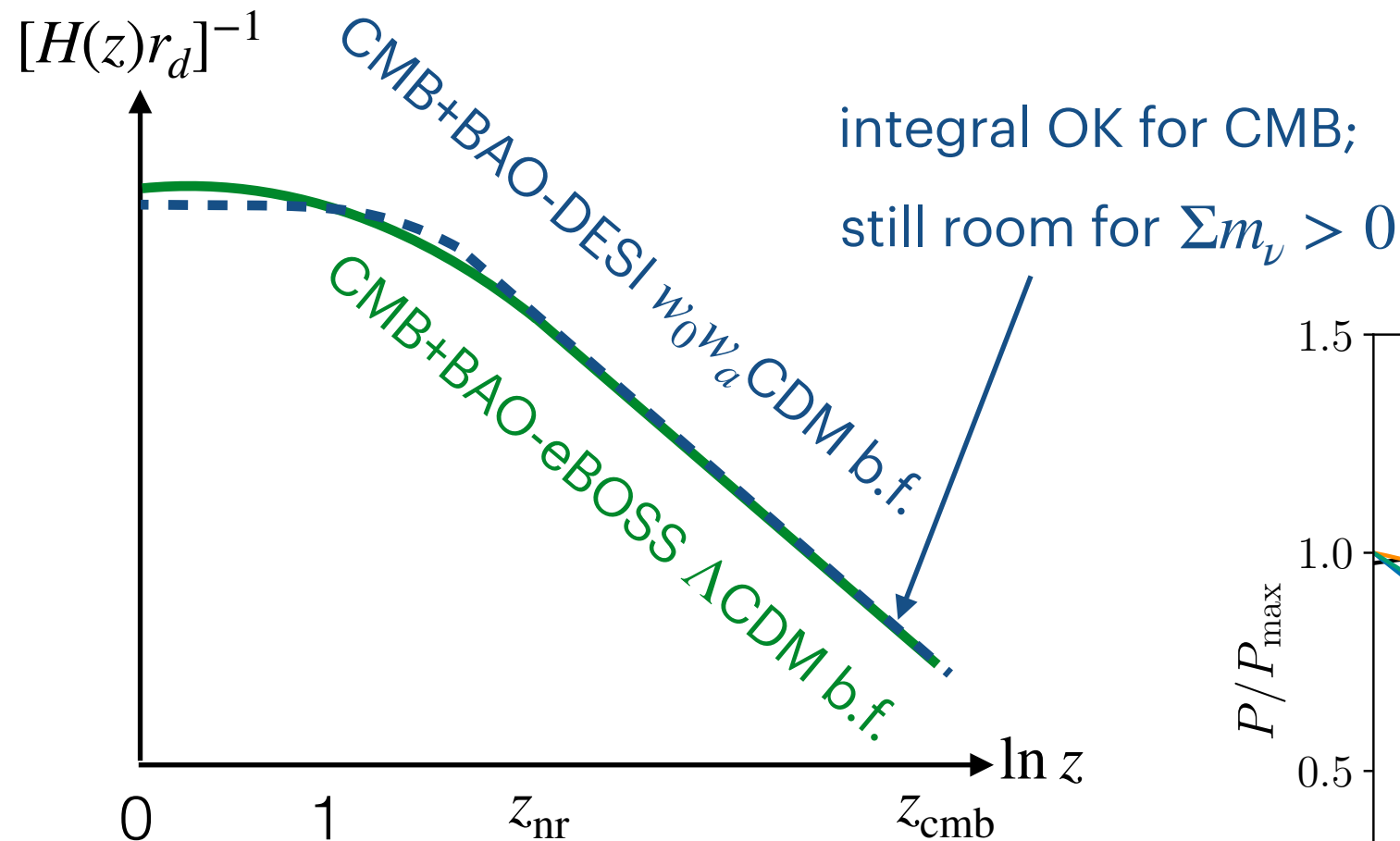
1. Add freedom in late expansion history: dynamical dark energy

- dynamical DE with e.g. CPL parametrisation: $w(z) = w_0 + w_a z/(1 + z)$



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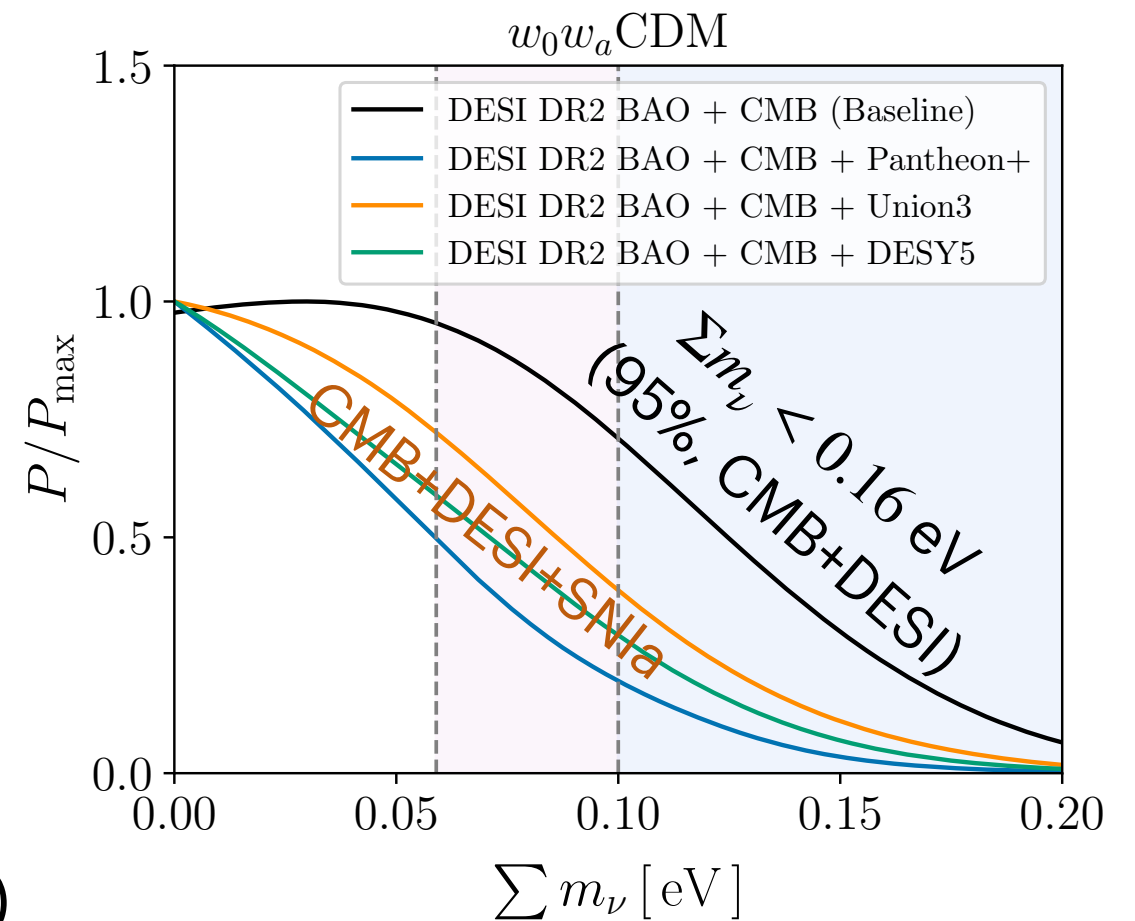
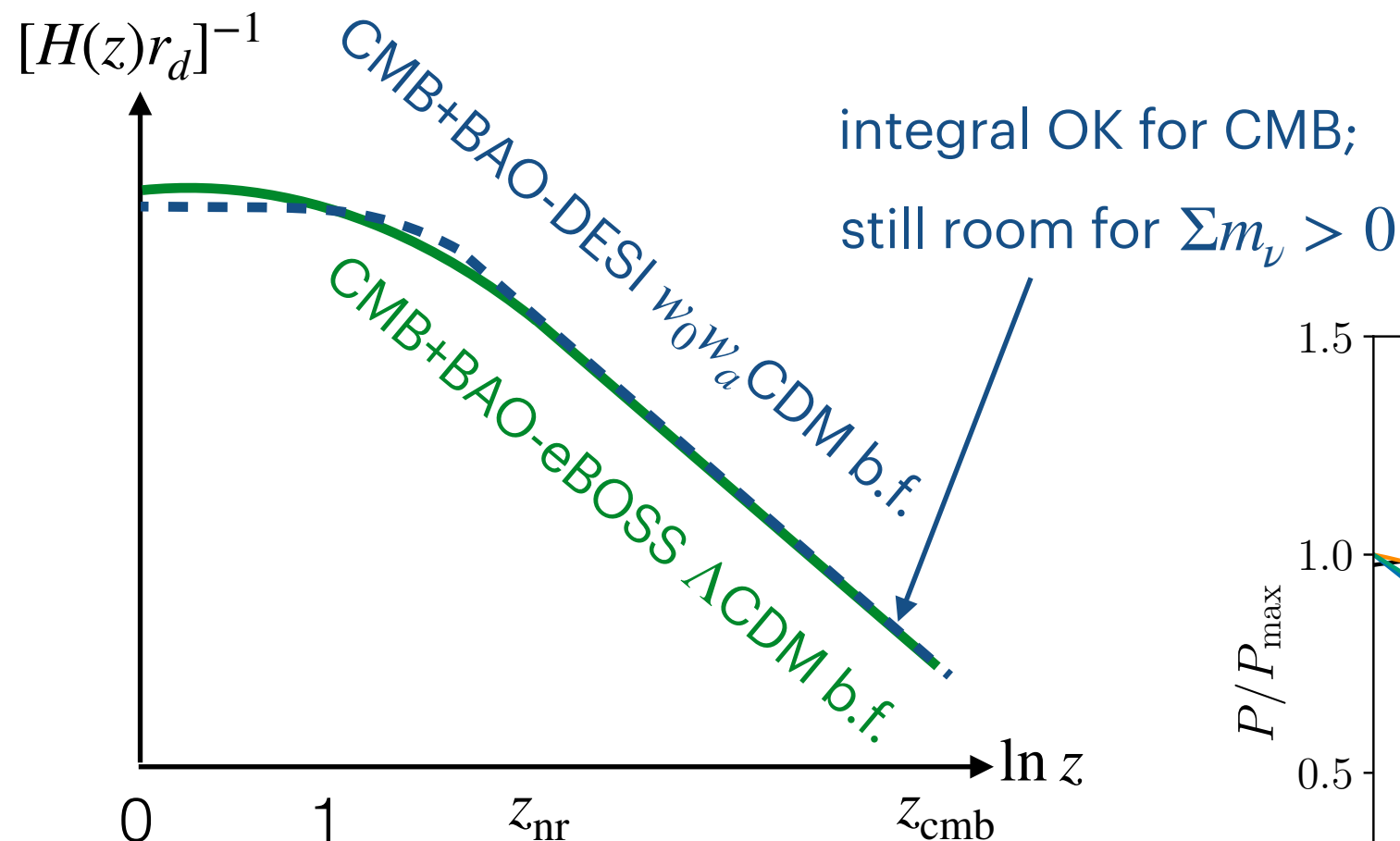
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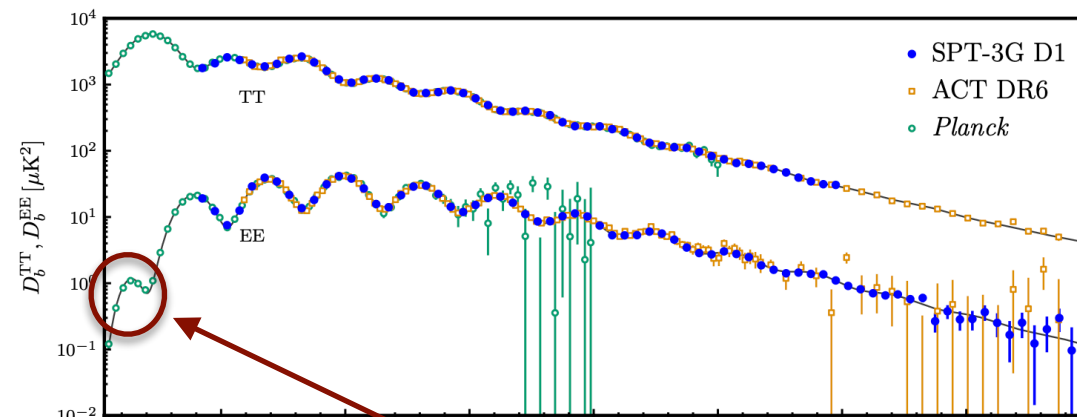


DESI (Elbers et al.) 2503.14744

- 2 tensions solved (not Hubble)
- plays well with SNIa (higher Ω_m possible)
- theoretical issues (phantom DE, ...)

2. Add freedom in lensing effects in 2-point CMB

- Amplitude of primary CMB spectra given by $e^{-2\tau} A_s$



- Degeneracy $\tau \leftrightarrow A_s$ only lifted by **small-scale CMB polarisation**:
Measurement of **reionisation optical depth** $\tau = 0.054 \pm 0.007$ dominated by Planck
- Amplitude of CMB lensing effects given approx. by $(1 - 8f_\nu) A_s$
- $\tau \leftrightarrow \Sigma m_\nu$ degeneracy Allison et al. 2005, Liu et al. 2005, Archidiacono et al. 2006, ...

2. Add freedom in lensing effects in 2-point CMB

Higher τ

Higher A_s (from CMB), more CMB lensing

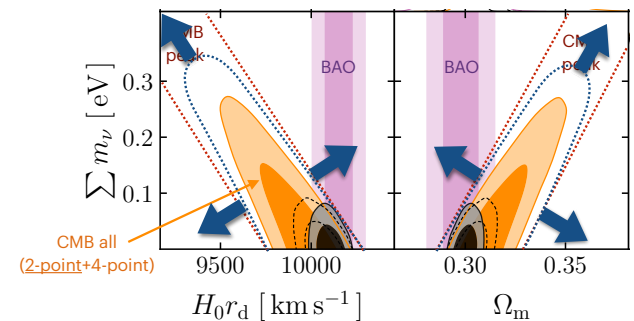
Higher Σm_ν still compatible with observed CMB lensing (CMB 2-point)

Intersection between BAO and CMB contours with higher $H_0 r_d$ / lower Ω_m

Resolution of CMB/DESI and Σm_ν tensions without dynamical DE

(H_0 also slightly larger: reduced tension)

All 3 tensions removed/reduced with $\tau \simeq 0.055 \longrightarrow \sim 0.09$



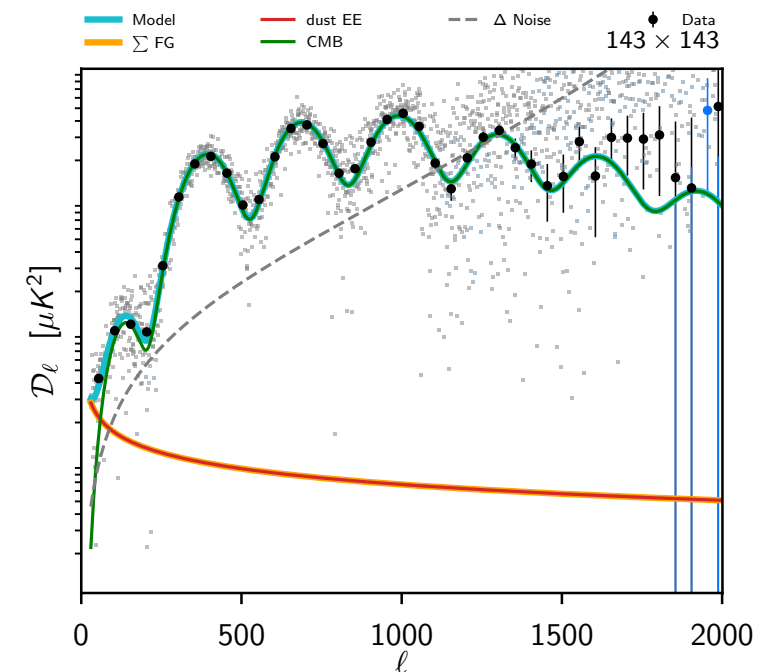
2. Add freedom in lensing effects in 2-point CMB

- PROS:

- Solve / reduce 3 tensions **without new physics**.
- Low $\tau = 0.054 \pm 0.007$ (68%) only from **Planck**.
- High τ compatible with **WMAP**: $\tau = 0.089 \pm 0.014$ (68%)
- τ measurement by Planck difficult due to **foregrounds**.

- CONS:

- Planck / WMAP posteriors **compatible** ($\sim 2\sigma$), much higher S/N in Planck.
- Not so many **polarised foregrounds** on large angular scales (thermal dust).
- Previous tensions reformulated as a **new $\sim 5\sigma$ “tension on τ ”**
- Still $\sim 1.5\text{-}2\sigma$ with **high Ω_m from SNIa** [may worsen when adding weak lensing]



2. Add freedom in lensing effects in 2-point CMB

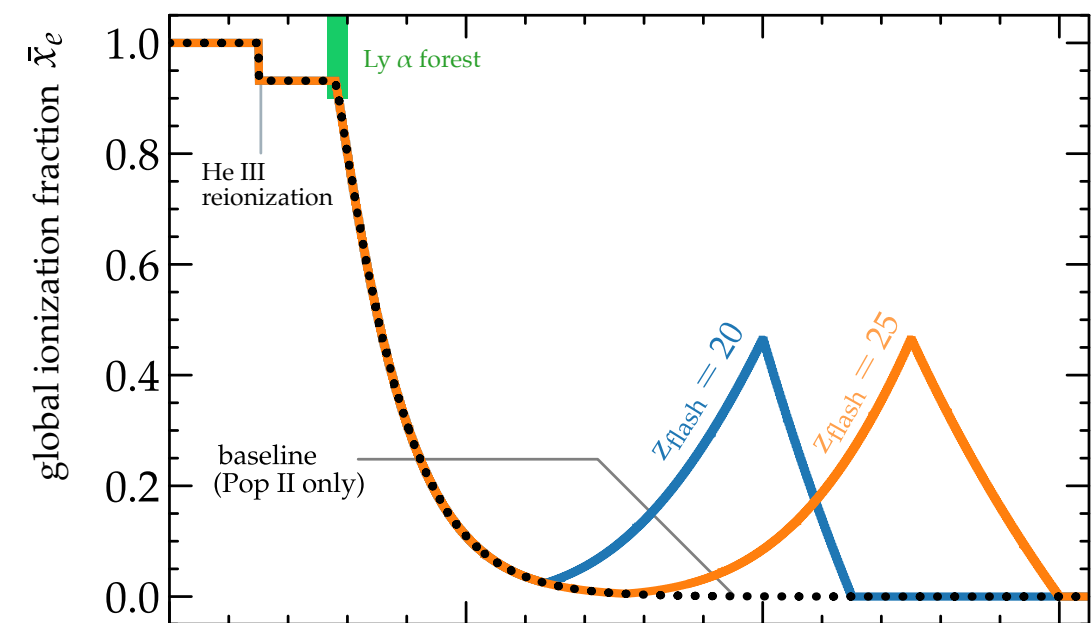
- High- τ solutions might be compatible with astrophysics:
 - Lyman- α in quasar spectra: reionisation ends around $z \simeq 6.5$
 - patchy kinetic SZ effect: most Universe reionised very quickly

- Compatible with $\tau \sim 0.09$ assuming

Pop III.1 star flash-ionisation

followed by inhibition and cooling

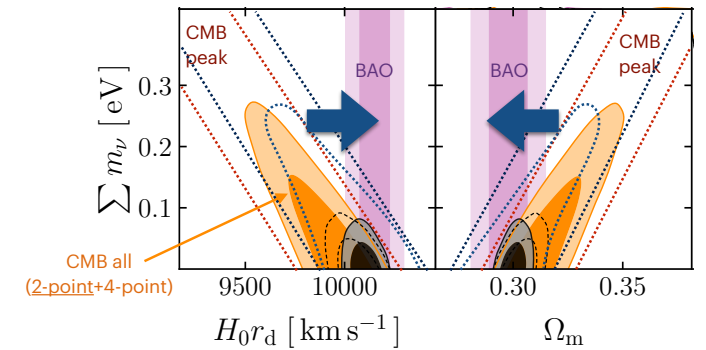
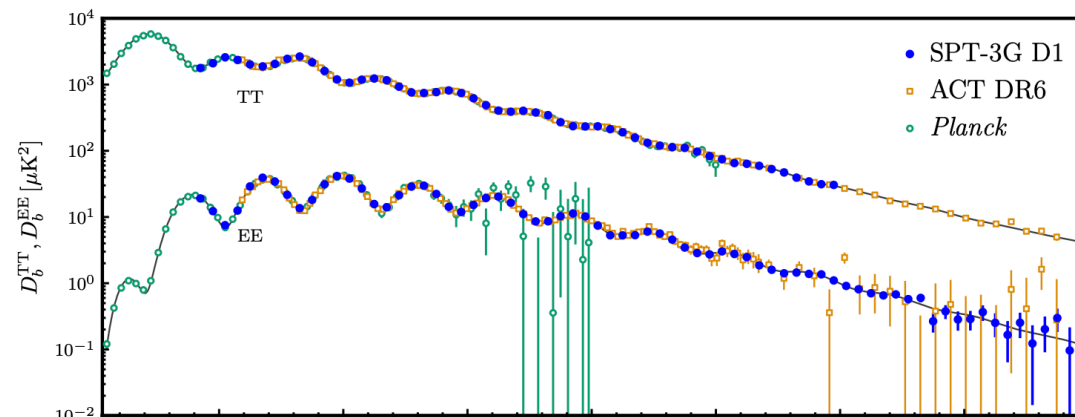
- Model also explains early SMBH
- Requires BSM physics: early mini-halos with heating by DM annihilation



Aggarwal et al. 2606.19459

3. Change $\theta_s \leftrightarrow$ CMB peak scale relation

- CMB observations constrain l_n^{peak}



- Relation $l_n^{\text{peak}} \leftrightarrow \theta_s$ inferred from fitting full spectra to data
- $\theta_s = r_s/r_a(z_{\text{dec}})$ gives geometrical constraint complementary to BAO
- Relation $l_n^{\text{peak}} \leftrightarrow \theta_s$ independent of Λ CDM parameters
- With additional dark radiation, **neutrino drag effect**: $l_n^{\text{peak}} \leftrightarrow \theta_s + \delta\theta(\Delta N_{\text{eff}})$
Bashinsky & Seljak astro-ph/0310198; JL et al, *Neutrino Cosmology*, CUP 2013
- Tiny effect, but relevant for CMB (not BAO: error bars on θ_s)

3. Change $\theta_s \leftrightarrow$ CMB peak scale relation

- $\Delta N_{\text{eff}} > 0$ can solve CMB/BAO tension and reduce Hubble tension
- Strong upper bounds from BBN and CMB full shape (damping tail)
- ΔN_{eff} may increase after BBN (entropy release in dark sector)
- Free-streaming DR disfavoured by CMB, self-interacting DR less constrained

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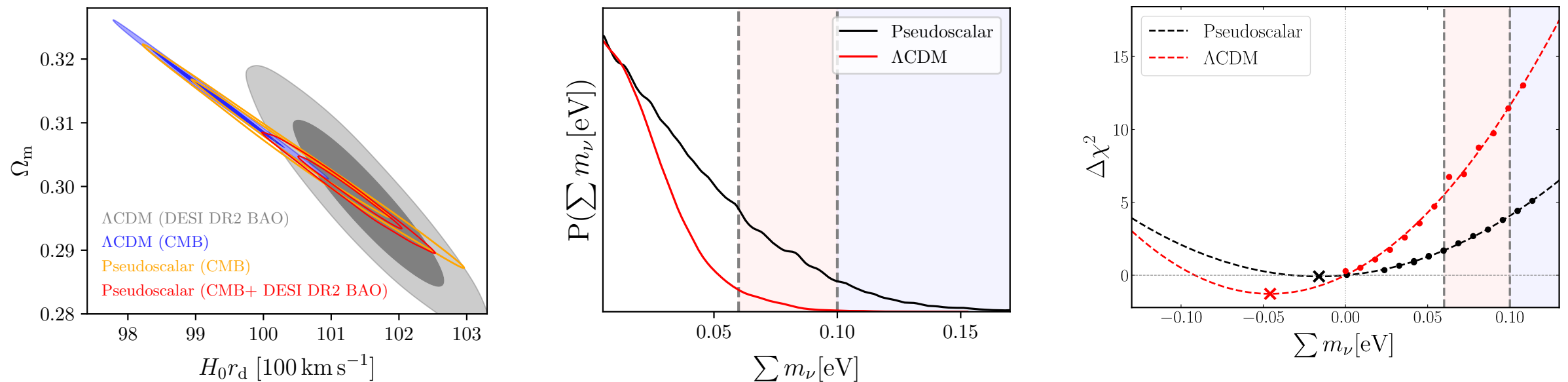
Example: sterile neutrino with secret interactions (mediated by pseudo-scalar)

Archidiacono et al. astro-ph/1404.5915

- Interaction $\mathcal{L} \sim \phi \bar{\nu}_4 \gamma_5 \nu_4$ with $m_\phi \simeq 0$, $m_{\nu_4} \sim \text{eV}$
- Non-trivial evolution of sterile neutrino + scalar fluid
 - ν_4 production through oscillations, suppressed by interactions: $\Delta N_{\text{eff}} < 1$,
 - $\nu_4 + \phi$ recouple well before recombination: self-interacting DR,
 - annihilation $\nu_4 \bar{\nu}_4 \rightarrow \phi$ just before recombination ($m_{\nu_4} \sim T$): ΔN_{eff} increases.

3. Change $\theta_s \leftrightarrow$ CMB peak scale relation

Recoupled Dark Radiation Sharma, Archidiacono, JL 2605.18716



- CMB/BAO tension solved, no need for dynamical DE
- Neutrino tension solved: $\sum m_\nu < 0.10 \text{ eV}$ (95%, Planck+SPT+DESI-DR2)
- Hubble tension reduced: $6\sigma \longrightarrow 2.4\sigma$ (Planck+SPT+DESI-DR2)
- Small decrease in Ω_m : not favoured by SNIa, but insignificant (stays at $\sim 2\sigma$)

3. Change $\theta_s \leftrightarrow$ CMB peak scale relation

- PROS:

- Requires new physics to solve / reduce 3 tensions, but grounded on solid particle physics
- Existence of light sterile neutrinos still debated after MiniBoone.

New experiment under discussion.

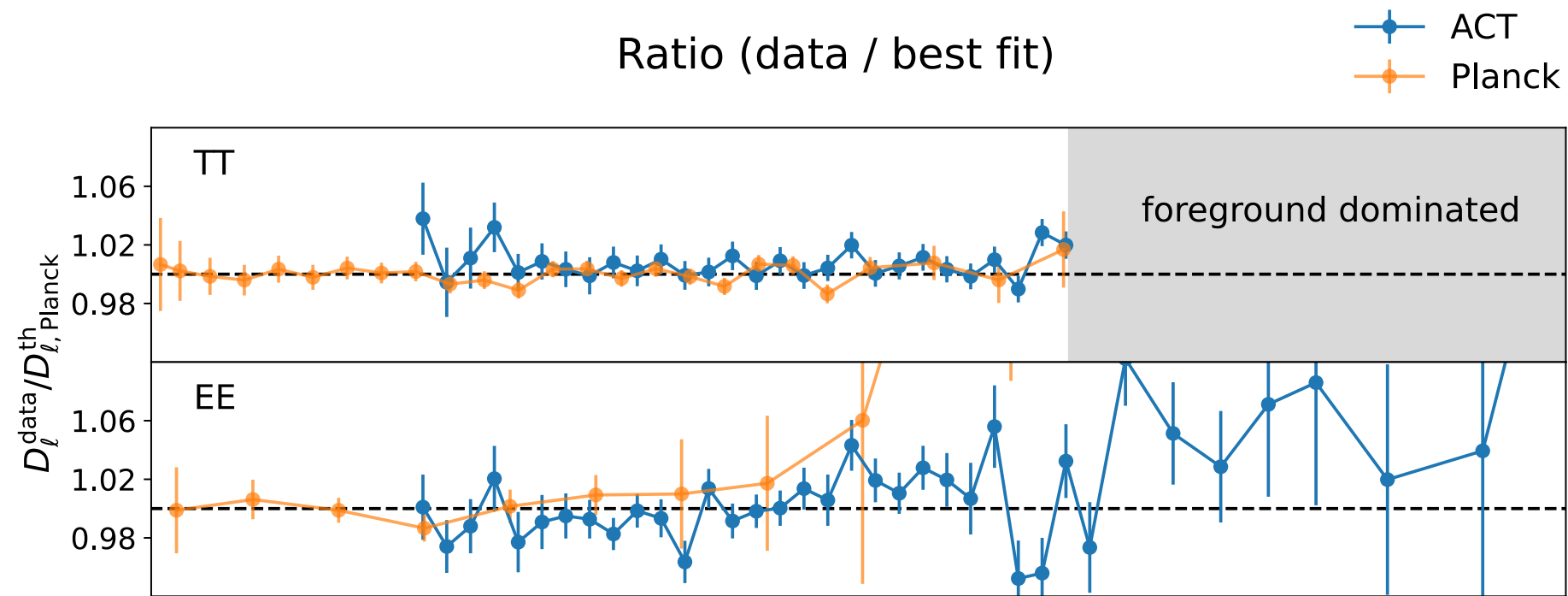
Diaz et al. 1906.00045

- CONS:

- Works well with Planck+SPT, not Planck+SPT+ACT
- ACT: stronger bound on $N_{\text{eff}} = 2.73 \pm 0.14$ (68%, Planck+ACT)
- Recoupled DR model requires $N_{\text{eff}} \sim 3.1 - 3.2$

3. Change $\theta_s \leftrightarrow$ CMB peak scale relation

- However: suspicious **contradictory N_{eff} results** between Planck+ACT and Planck+SPT ($\sim 3\sigma$). Tension between measured high- l tails?



ACT (Louis et al.) 2503.14452

3. Change $\theta_s \leftrightarrow$ CMB peak scale relation

- However: suspicious **contradictory N_{eff} results** between Planck+ACT and Planck+SPT ($\sim 3\sigma$). Tension between measured high- l tails?
- Issue with **foreground modelling?**
 - Not only: consistent and conservative foreground modelling in [Tristram et al. 2511.04733](#), and:
- But combined bound compatible with our model at 2σ

$$N_{\text{eff}} = 3.20_{-0.23}^{+0.21} \quad (\text{Planck})$$

$$N_{\text{eff}} = 2.45_{-0.25}^{+0.17} \quad (\text{ACT})$$

$$N_{\text{eff}} = 3.23_{-0.38}^{+0.32} \quad (\text{SPT})$$

$$N_{\text{eff}} = 3.031 \pm 0.130 (\text{stat}) \pm 0.045 (\text{fg}) \quad (\text{Planck+ACT+SPT}).$$

3. Change $\theta_s \leftrightarrow$ CMB peak scale relation

- However: suspicious **contradictory N_{eff} results** between Planck+ACT and Planck+SPT ($\sim 3\sigma$). Tension between measured high- l tails.

- Issue with **foreground modelling?**

- Not only: consistent and conservative foreground modelling in [Tristram et al. 2511.04733](#), and:

$$N_{\text{eff}} = 3.20^{+0.21}_{-0.23} \quad (\text{Planck})$$

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- Issue with **polarised beams modelling?**

- Not enough freedom in ACT?

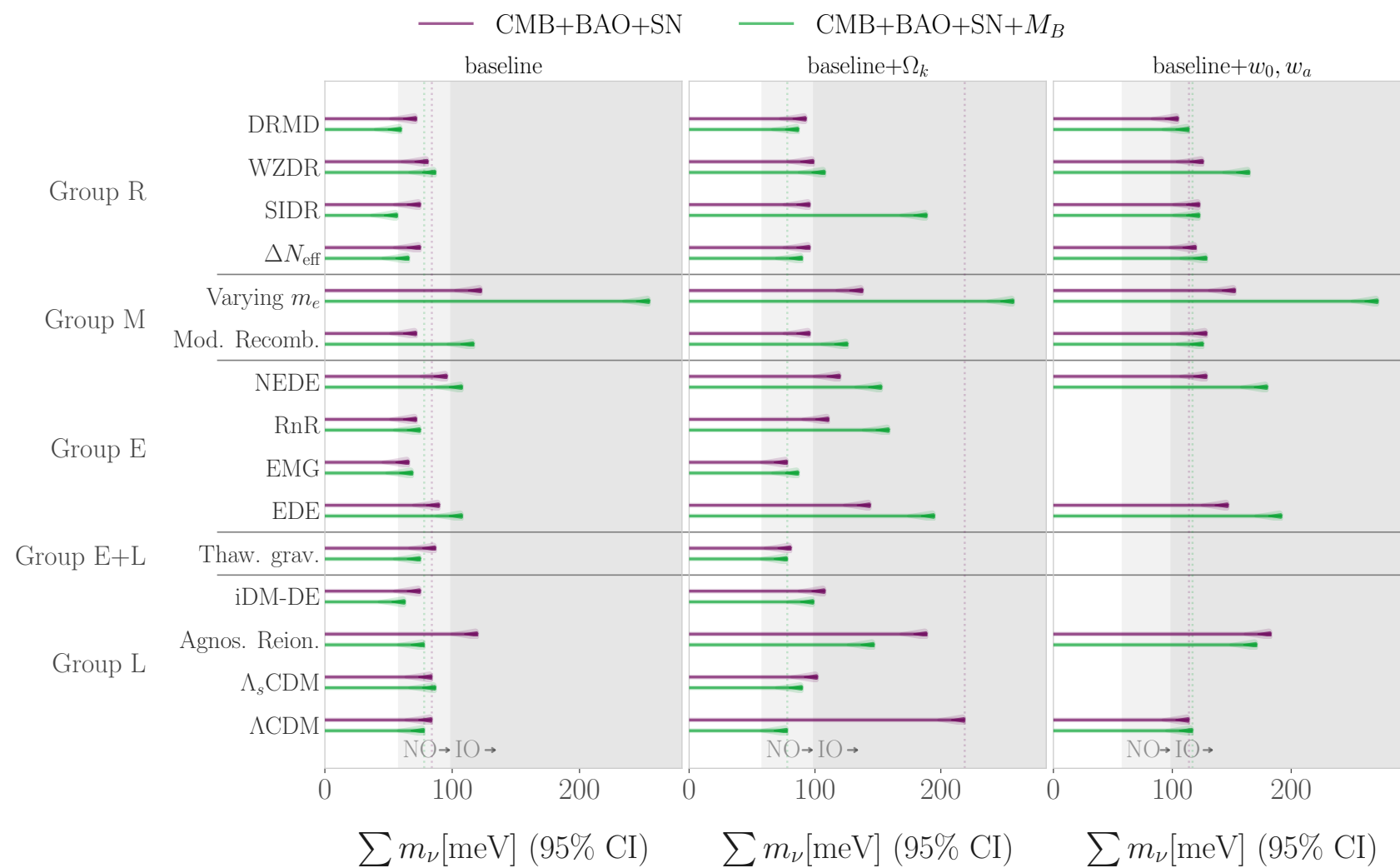
- Too much freedom in SPT?

- Project to launch calibrated polarised source on a satellite for SO

Conclusion

- Just 4 examples (neutrinoless, DDE, high- τ , RDR); **other ones** (e.g. DM $\rightarrow$ DE)

(But not so many: see, e.g., H0 world cup)



Schöneberg et al. 2607.13283

Conclusion

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- Encouraging: some models may resolve/reduce several tensions at the same time

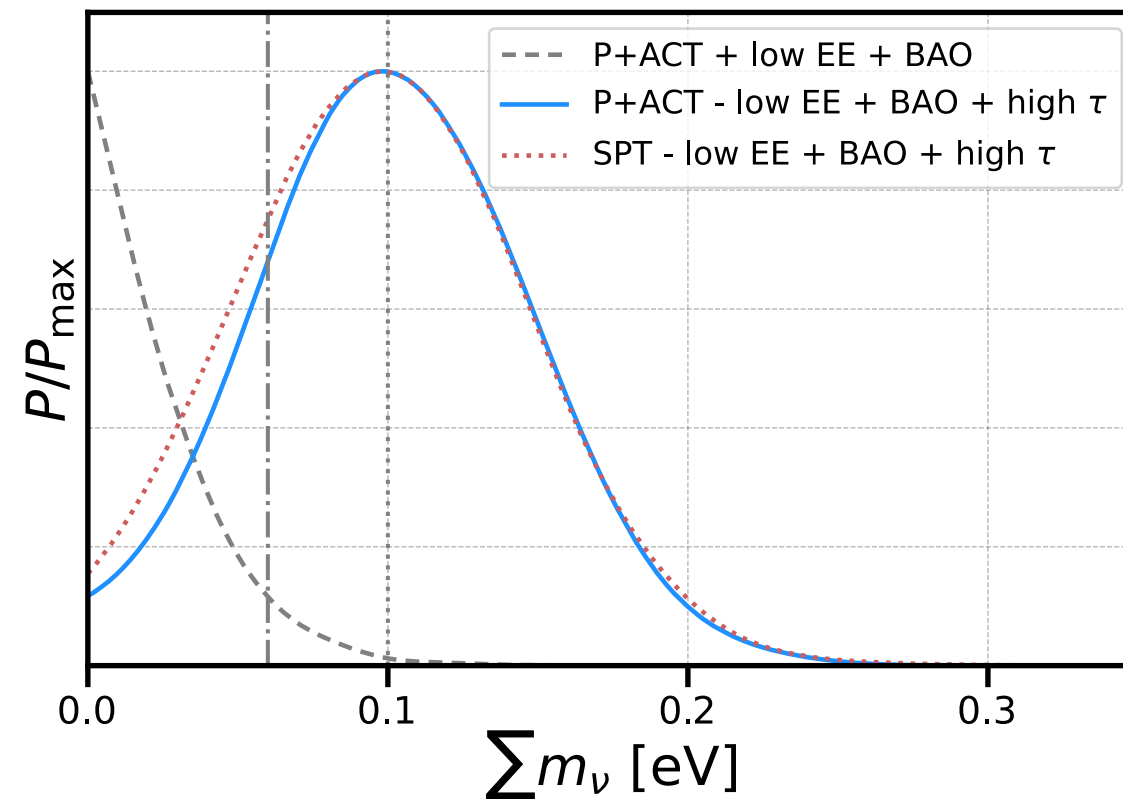
Conclusion

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- Independent tests of these models:
 - Neutrinoless: data from SN, neutrino telescopes, oscillation experiments
 - Dynamical DE: better SNIa, galaxy surveys;
 - High- τ : LiteBird, SKA, Hera
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 - RDR: SO, future oscillation experiments
- Cosmological bounds on neutrino mass fragile because dominated by generic effects (geometry, CMB lensing) with lot of parameter degeneracy
- Need to probe a more direct effect: scale-dependent growth factor induced by free-streaming (DESI, Euclid, LSST full-shape)

Claim of 2σ mass detection in Sullivan, De Belsunce and Ivanov 2606.30903



To be taken with grain of salt:

Based on arbitrary “Gaussian τ prior” centred on 0.11 and of width 0.006...