Particle cosmology in the era of tensions

Exploring New Frontiers in Cosmology - 16 July 2026

Martina Gerbino (INFN Ferrara)

~~Particle~~ Neutrino cosmology in the era of tensions (with a focus on CMB)

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Neutrinos and Cosmology

Pioneering and stringent bounds on neutrino properties from Cosmology already competitive with lab

$$m_\nu < 400\,\mathrm{eV} \qquad (\rho_\nu < \rho_{\mathrm{tot}})$$

$$m_\nu < 8\,\mathrm{eV} \qquad (\rho_\nu < \rho_{\mathrm{DM}})$$

Gershtein-Zeldovich (1966)
Cowsik-McClelland (1972)

+ lower bounds for very heavy neutrinos
Szalay&Marx(1976)
Hut; Lee&Weinberg; Sato&Kobayashi(1977)

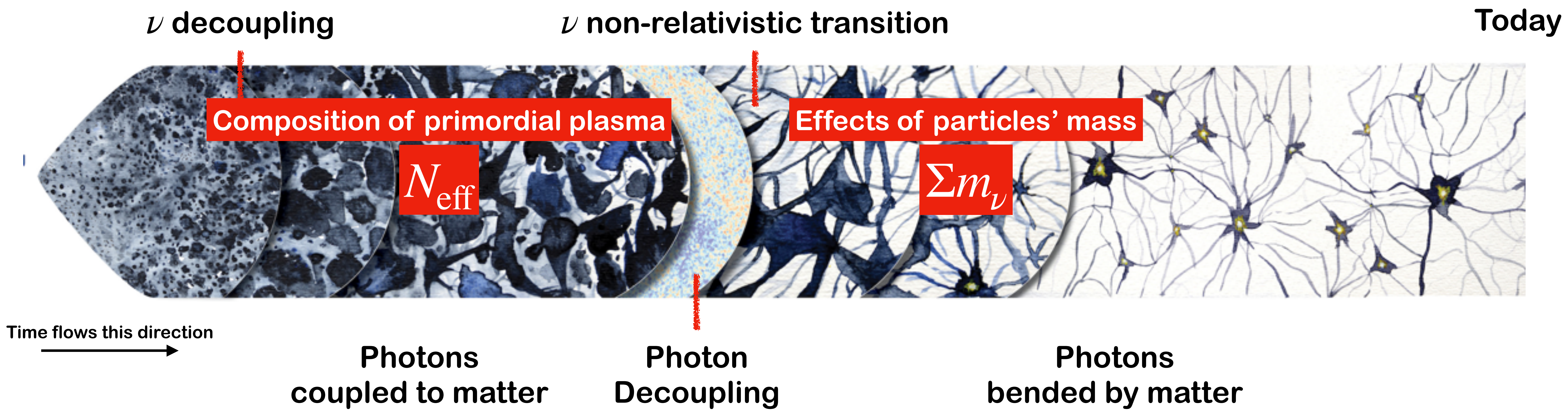
+ from numerical sims
structure formation with hot DM is top-down, incompatible with observations (1980s)

$$N_\nu < 4$$

Schramm&Kawano (1989)
Olive+ (1990)

(Stringent) bound on the family number required not to spoil BBN

Cosmic neutrinos



ν decoupling

ν non-relativistic transition

Today

Composition of primordial plasma

N_{eff}

Effects of particles' mass

Σm_ν

Time flows this direction

Photons coupled to matter

Photon Decoupling

Photons bended by matter

$$\rho_\nu \propto (T_\nu/T_\gamma)^4\, N_{\text{eff}}$$

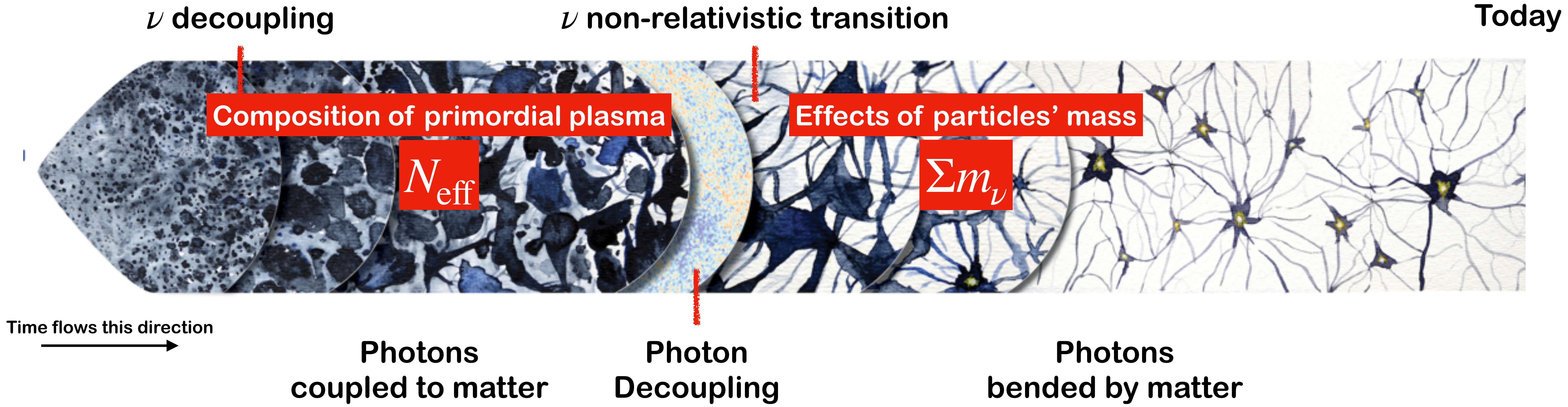
$$\rho_\nu \propto \Sigma m_\nu (T_\nu/T_\gamma)^3$$

$$\boxed{N_{\text{eff}} \equiv \frac{\rho_{\text{rad}} - \rho_\gamma}{\rho_\nu^{\text{st}}} = 3.044}$$

$$\boxed{\Sigma m_\nu = \Sigma_{i=1,2,3} m_{\nu,i}}$$

Distorsions due to non-inst decoupling
radiative corrections,
flavour oscillations
Dolgov, 1997, Mangano+,2005
Bennett+2020,Froustey+2020,Akita+2020

Cosmic neutrinos



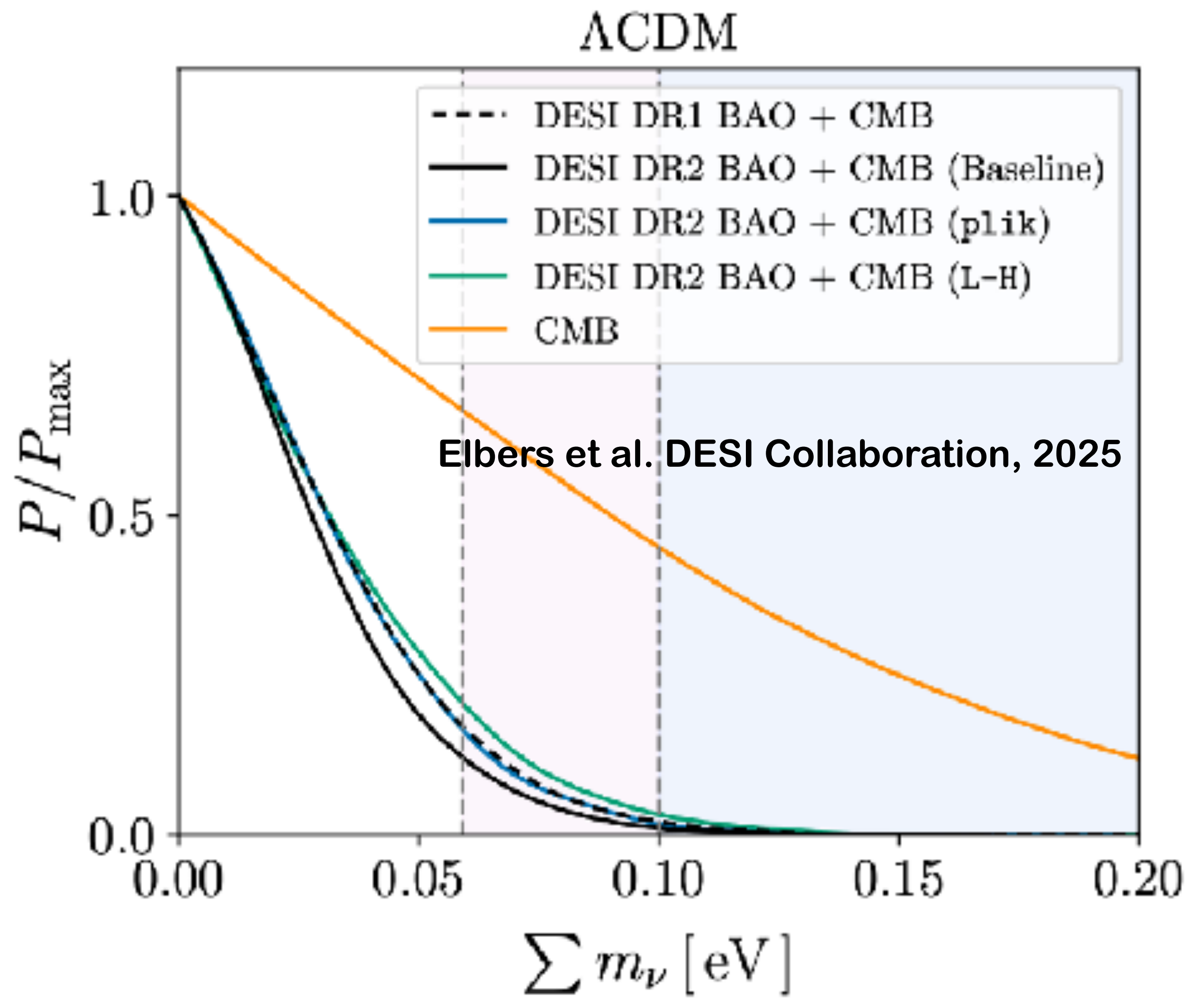
$$\rho_\nu \propto (T_\nu/T_\gamma)^4 \, N_{\text{eff}}$$

$$\rho_\nu \propto \Sigma m_\nu (T_\nu/T_\gamma)^3$$

Early-time expansion rate (angular scales, BBN abundances)
Phase of acoustic oscillations (CMB peaks, BAO)

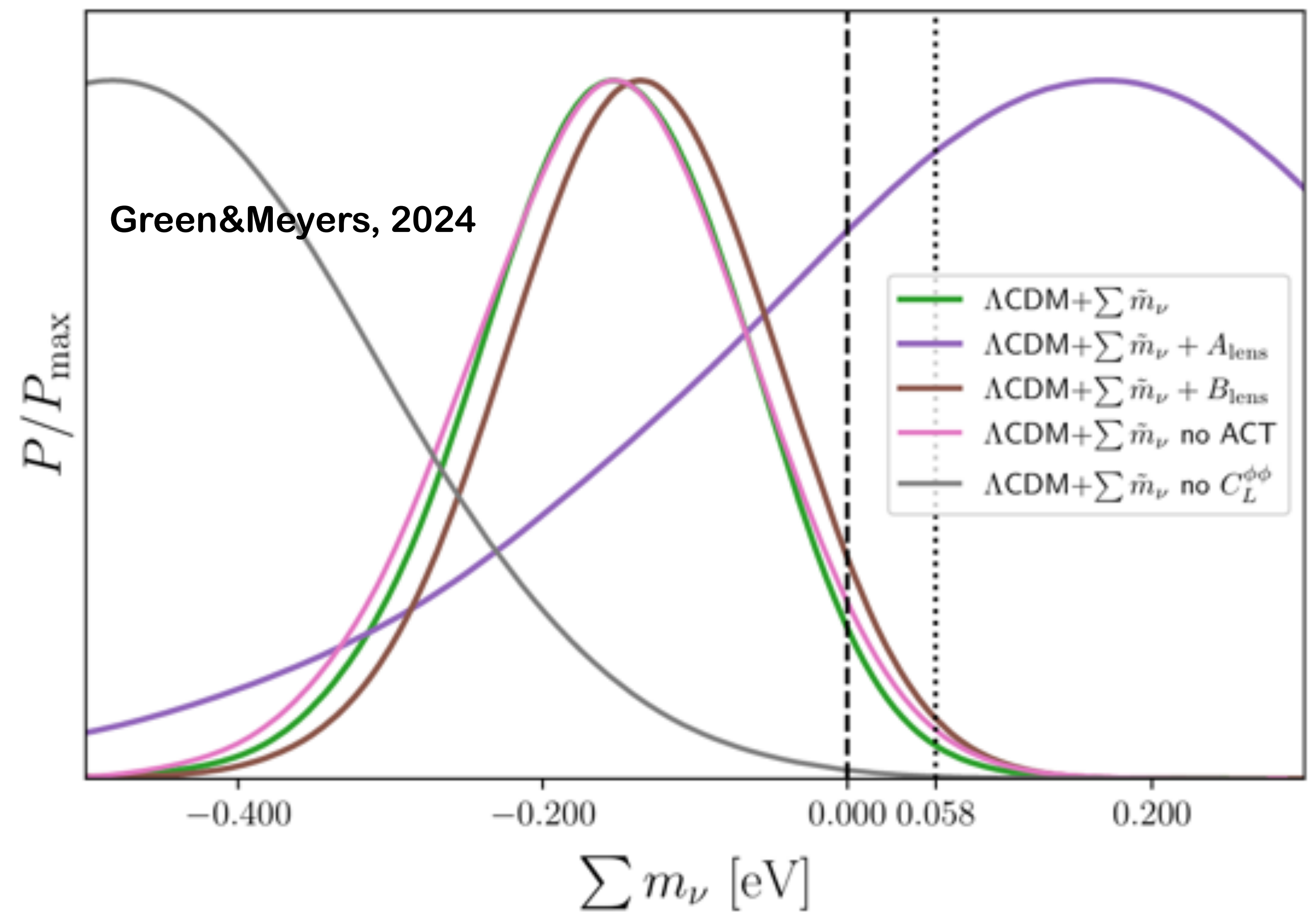
Late-time expansion rate (angular scales)
Scale-dependent clustering suppression
(Matter power full shape, lensing, CMB tail)

Neutrino puzzles (again!)

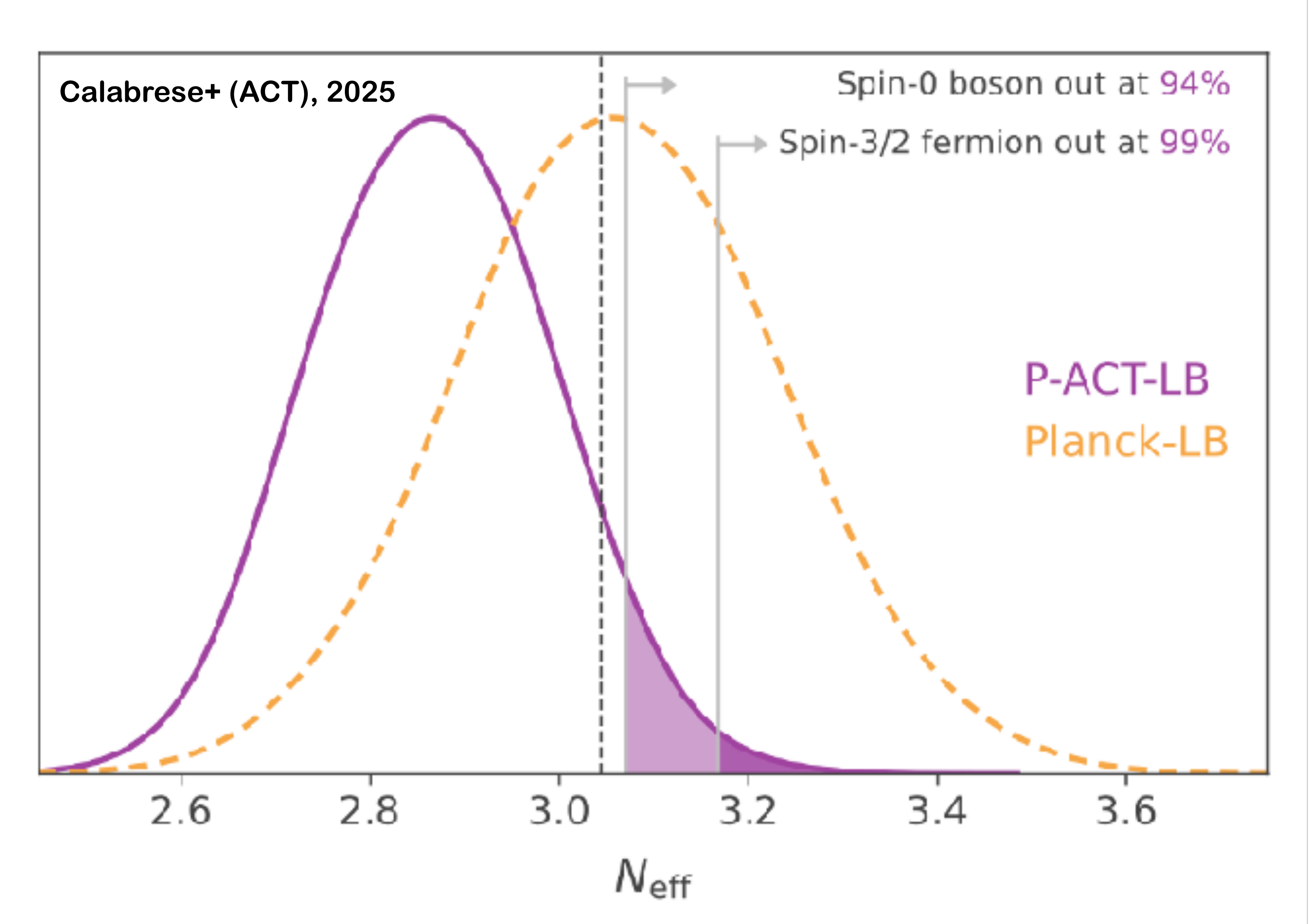


Elbers et al. DESI Collaboration, 2025

Too tight to be good?



Green&Meyers, 2024



Calabrese+ (ACT), 2025

Too low to be good?

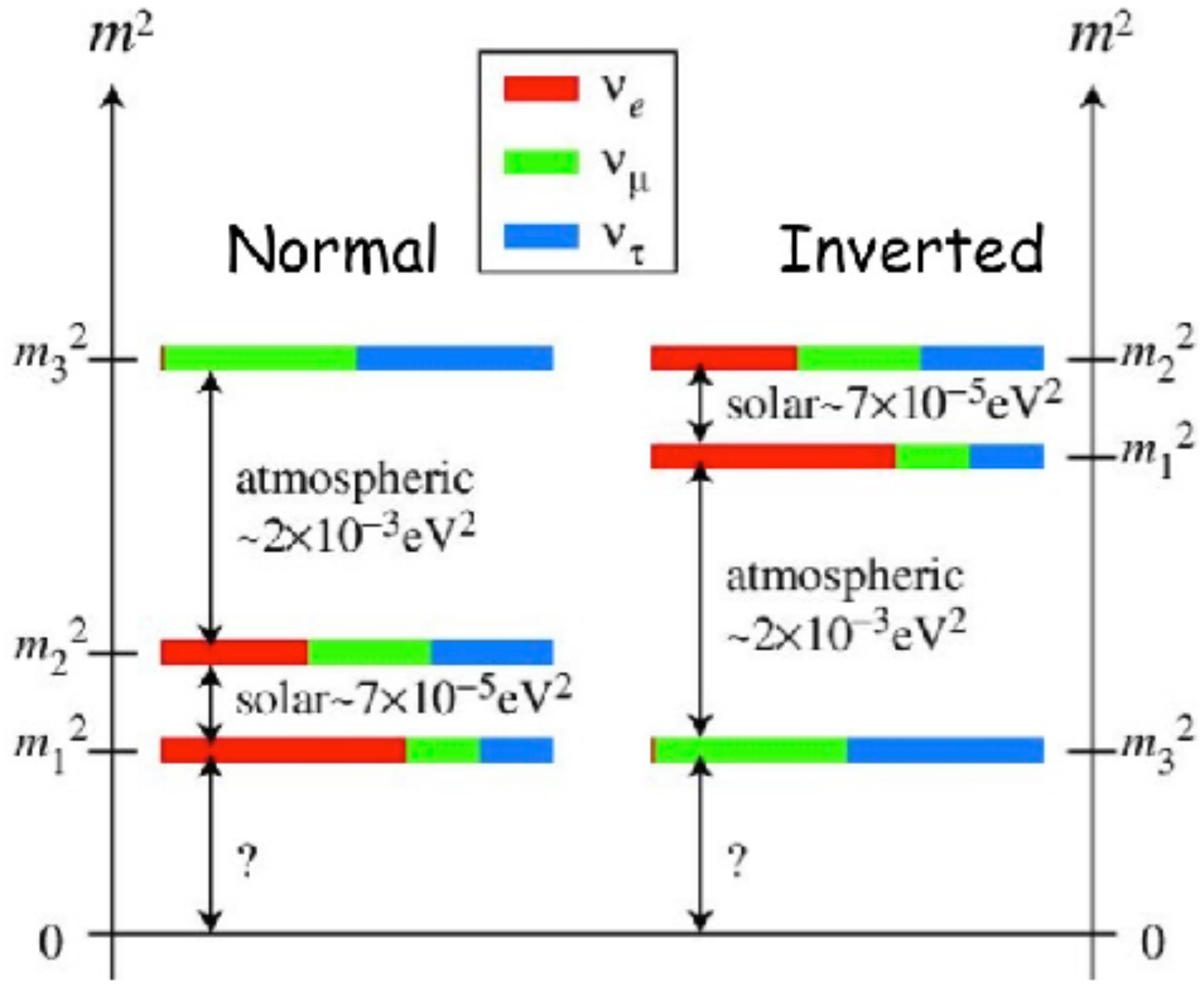
Neutrino puzzles (again!)

$$0.06\,\mathrm{eV} \leq \Sigma m_\nu \leq 1.35\,\mathrm{eV}$$

From oscillations

From b-decay

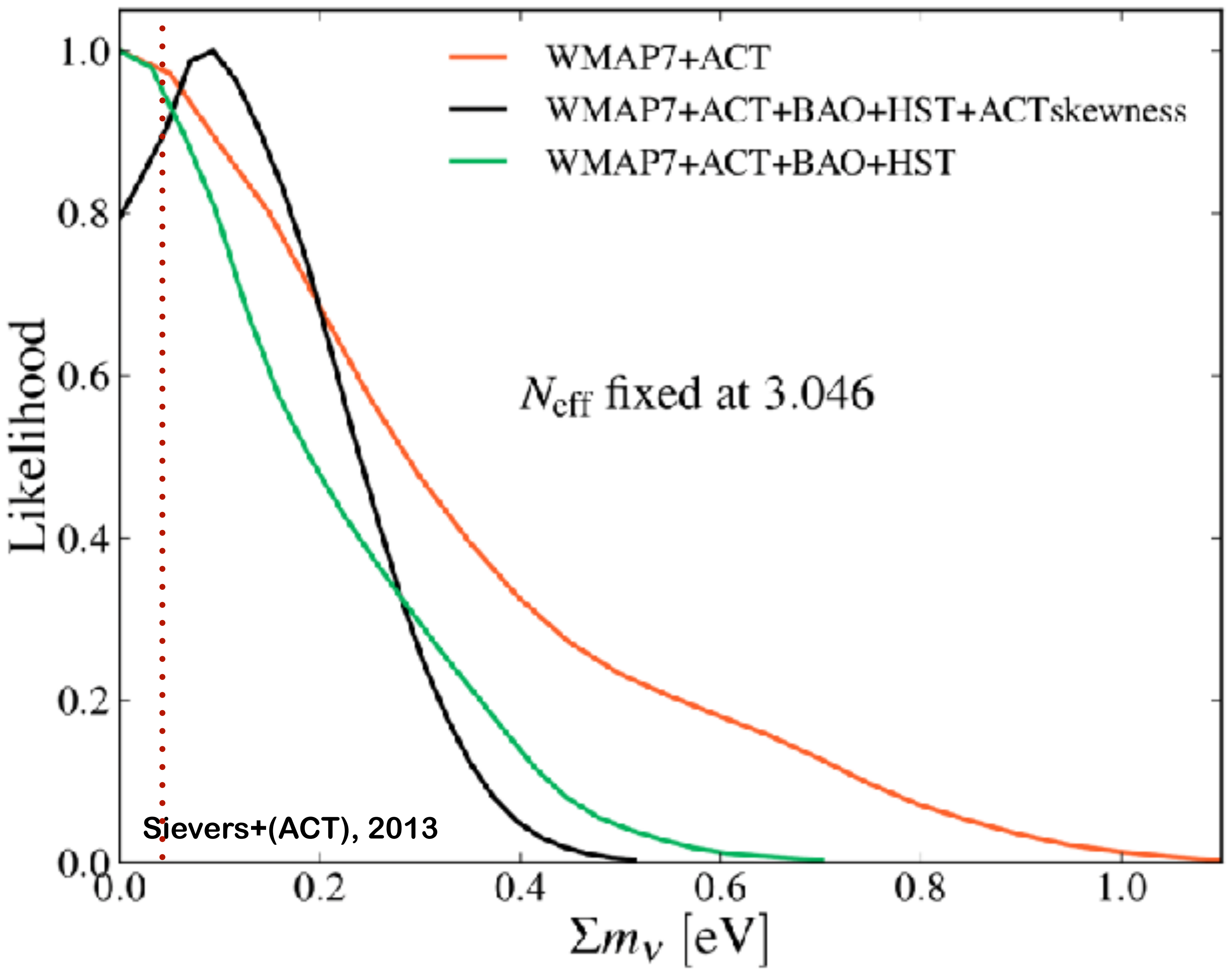
$$\mathscr{P}_{\nu_\alpha \to \nu_\beta} \propto \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



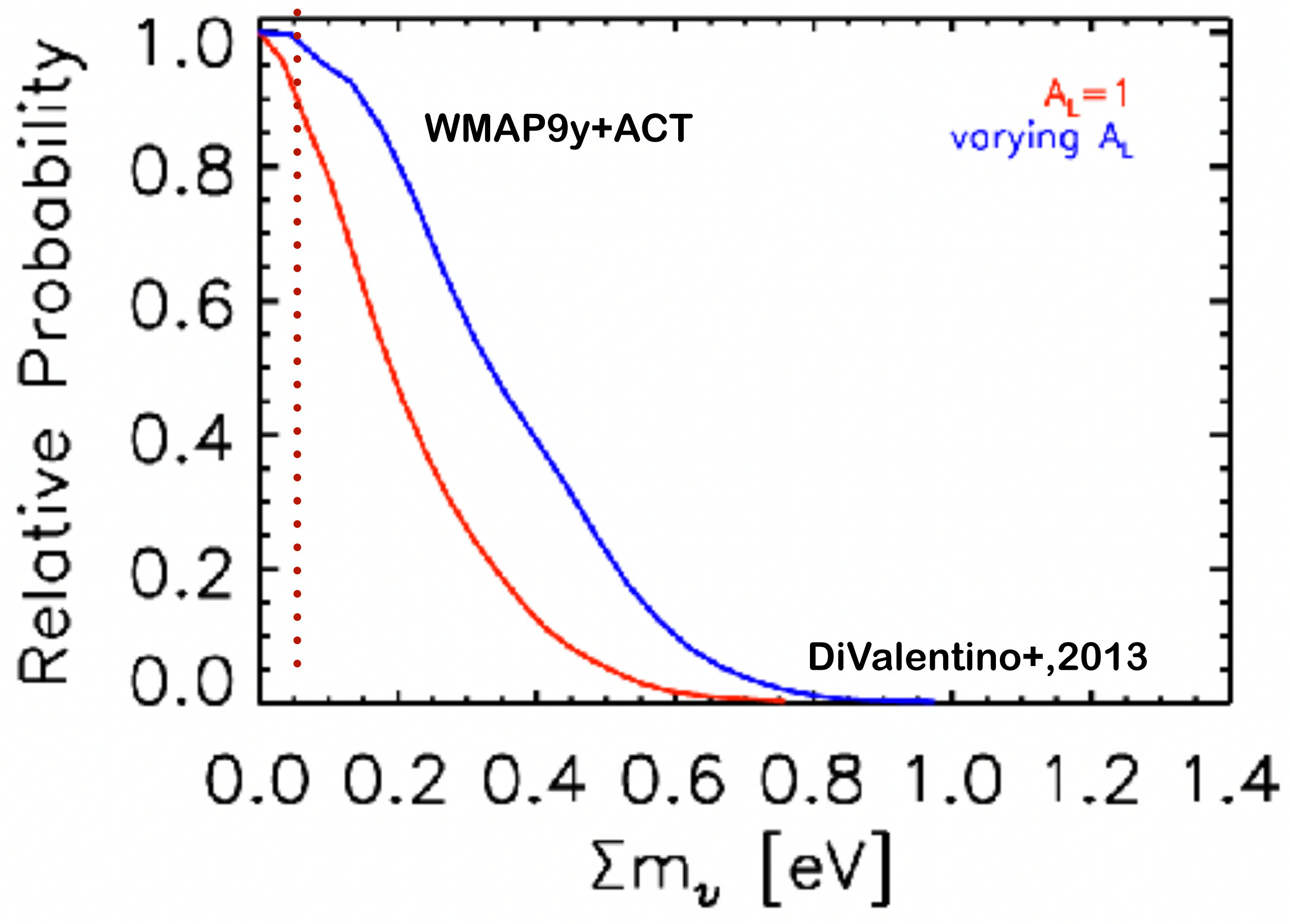
If the mass scale is below 0.06eV, unexpected behaviour!

A glance to the (recent) past

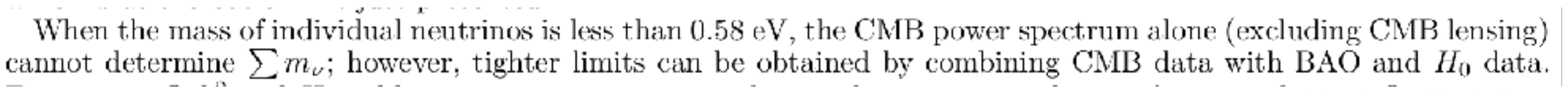
Shallower constraints, yet similar trend towards low masses…



Sievers+(ACT), 2013



DiValentino+,2013

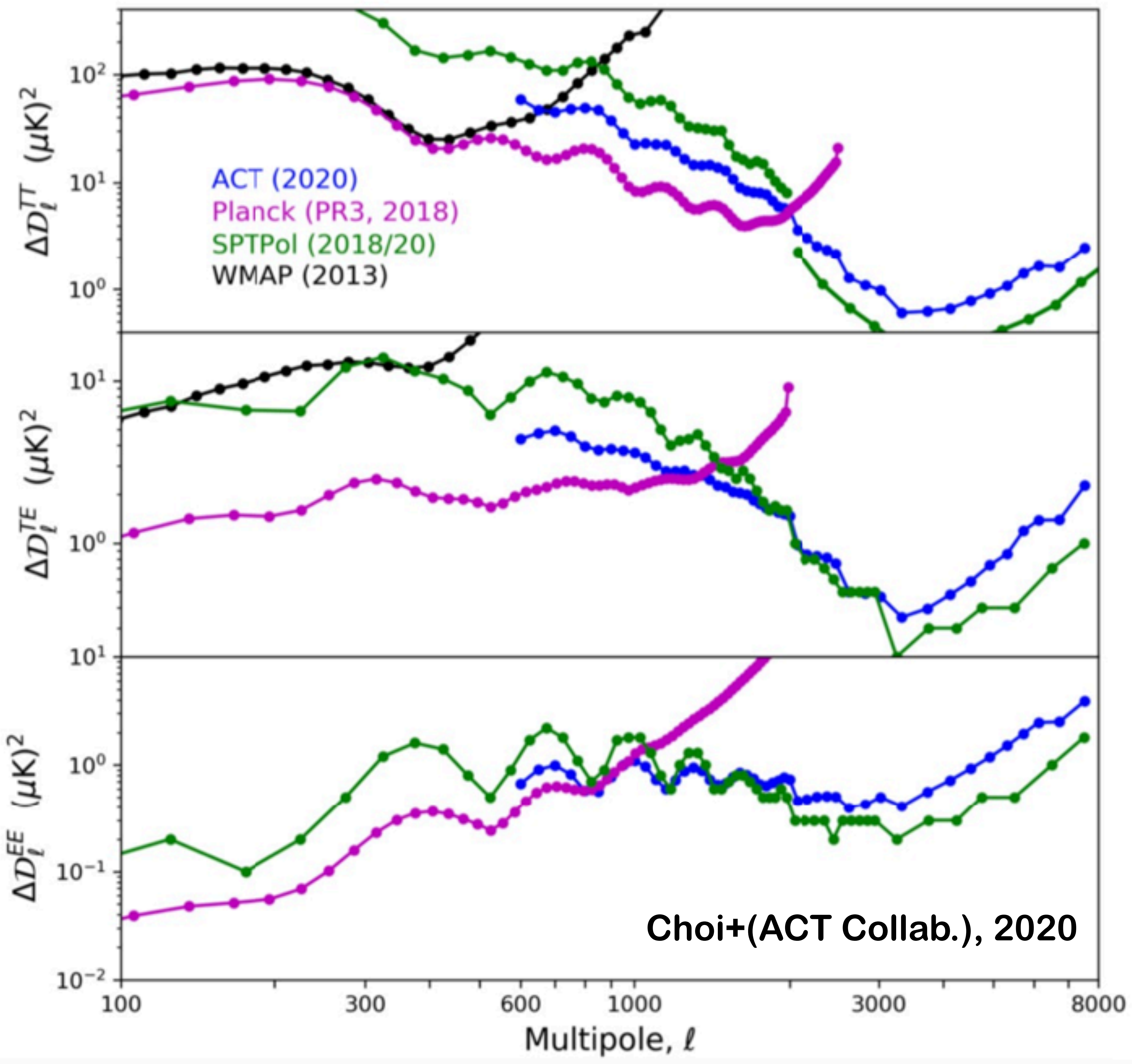


When the mass of individual neutrinos is less than 0.58 eV, the CMB power spectrum alone (excluding CMB lensing) cannot determine $\sum m_\nu$; however, tighter limits can be obtained by combining CMB data with BAO and H_0 data.

Hinshaw+(WMAP), 2013

And then came Planck

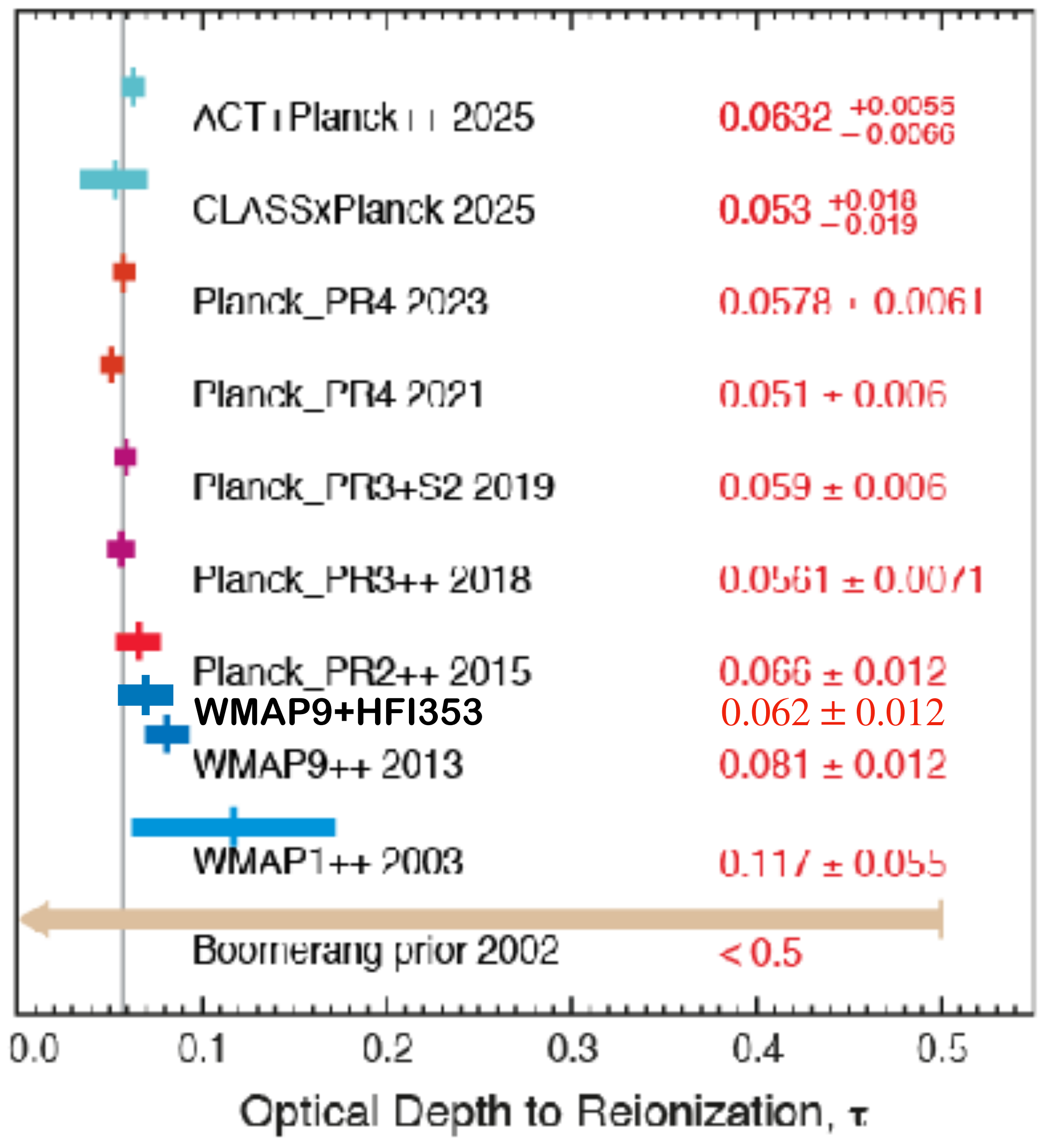
Game changer:
Wide range of scales
observed by a single experiment
(CVL in T up to 1500)



Choi+(ACT Collab.), 2020

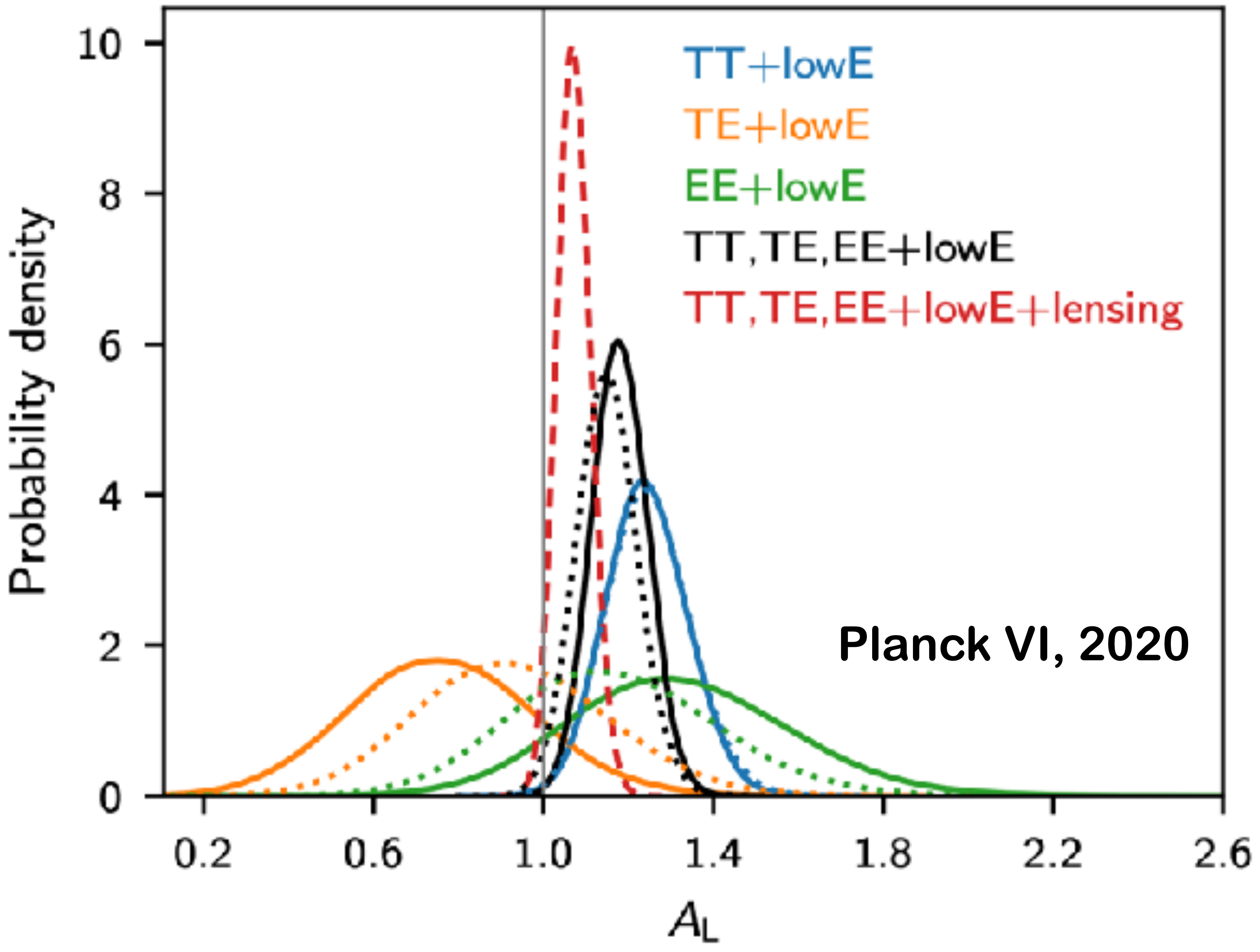
BUT

Optical depth too low?



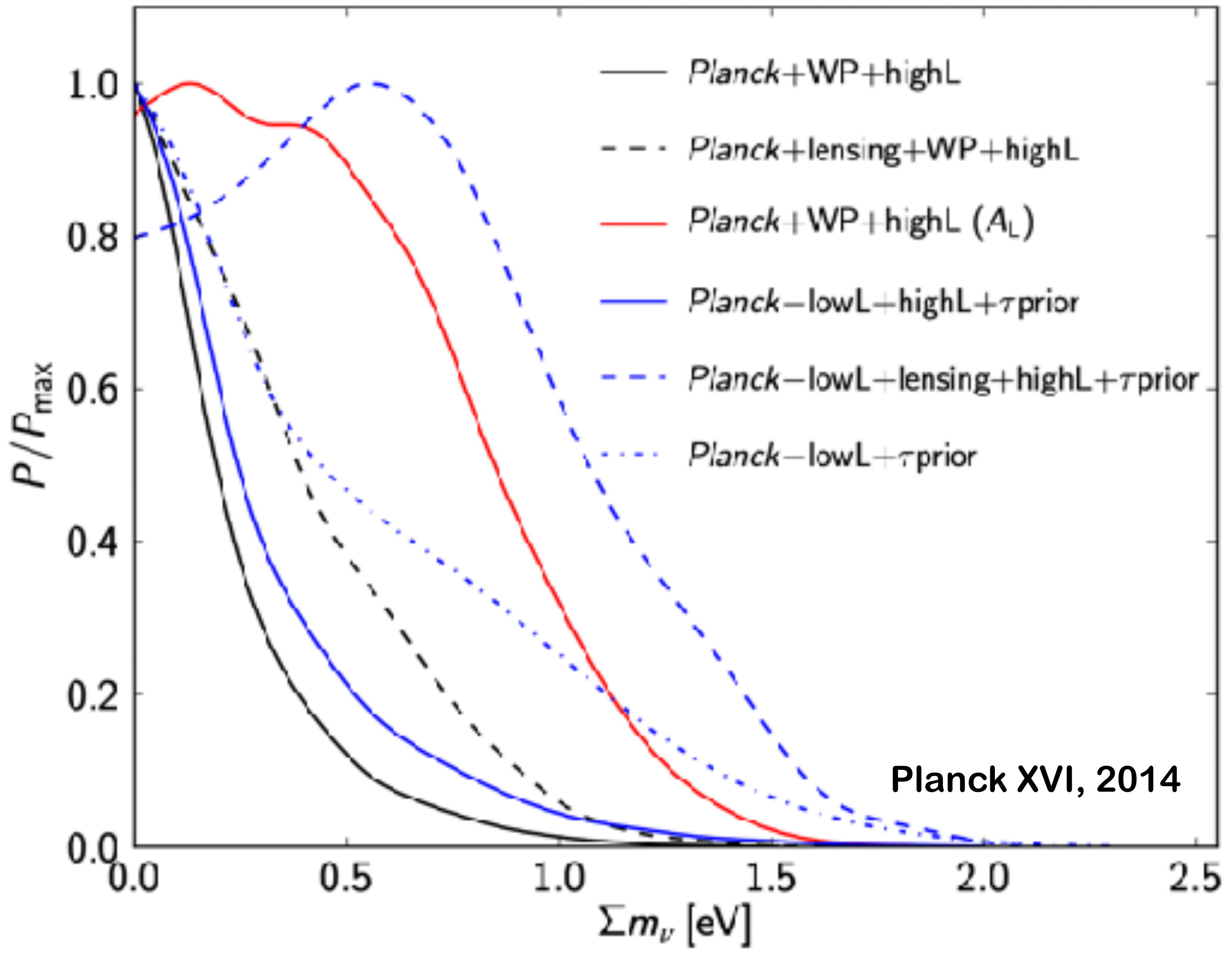
Adapted from LAMBDA - Jun 2025

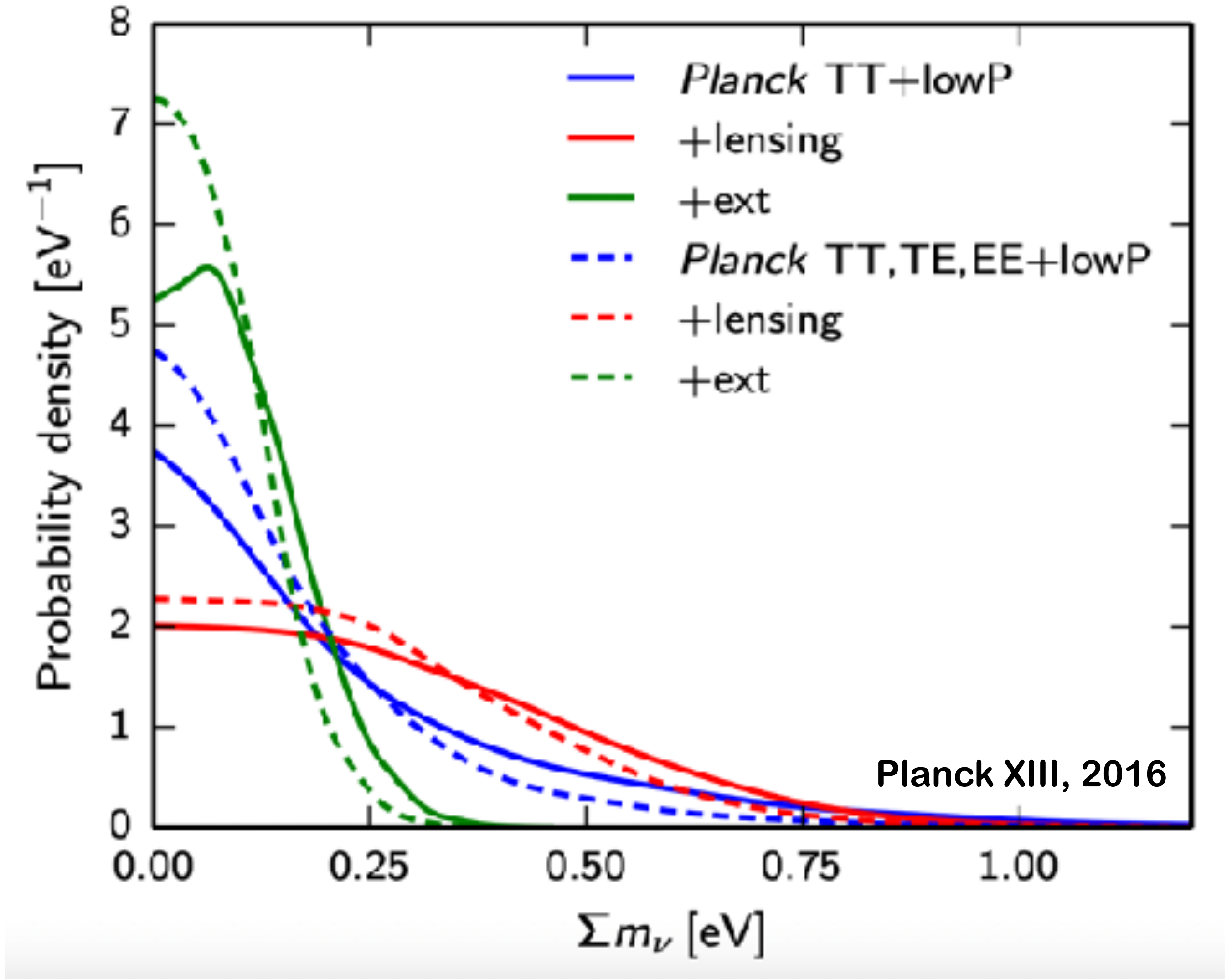
Too much
lensing smoothing?

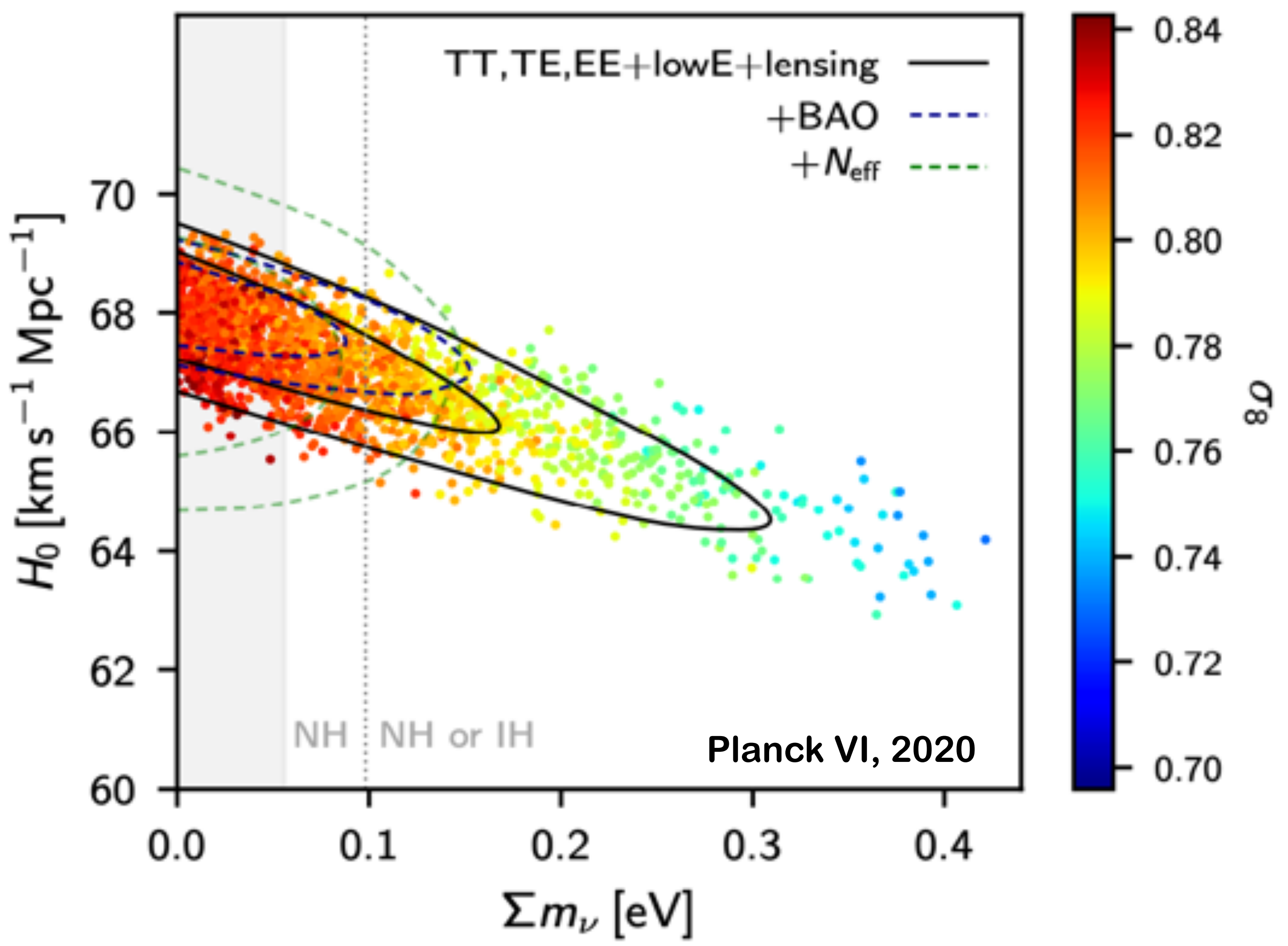


Planck VI, 2020

Evolution of Planck constraints







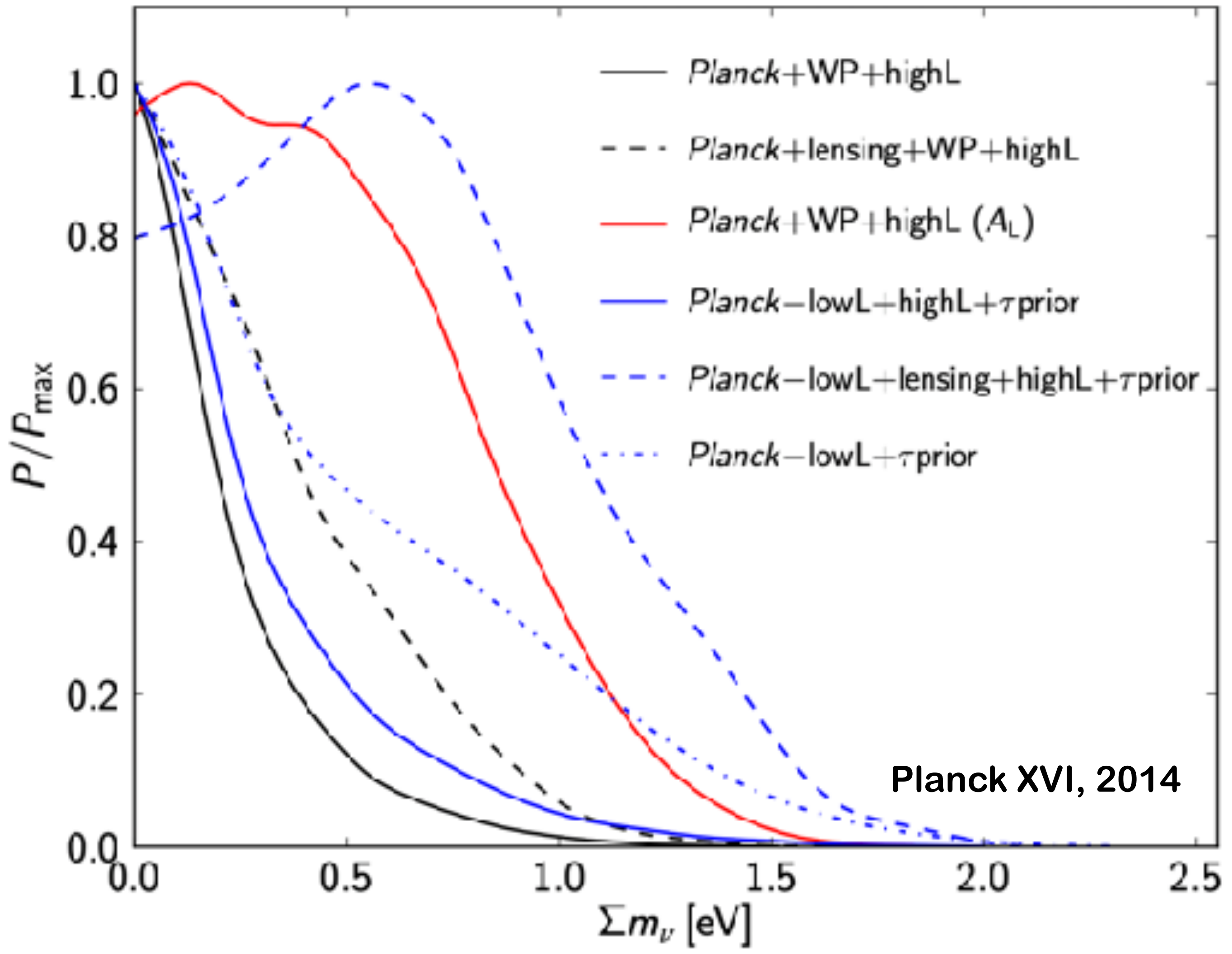
Partial T, no P
lowE from WMAP9y

Full T, contaminated P
lowE from Planck-LFI

Full T&P
lowE from Planck-HFI

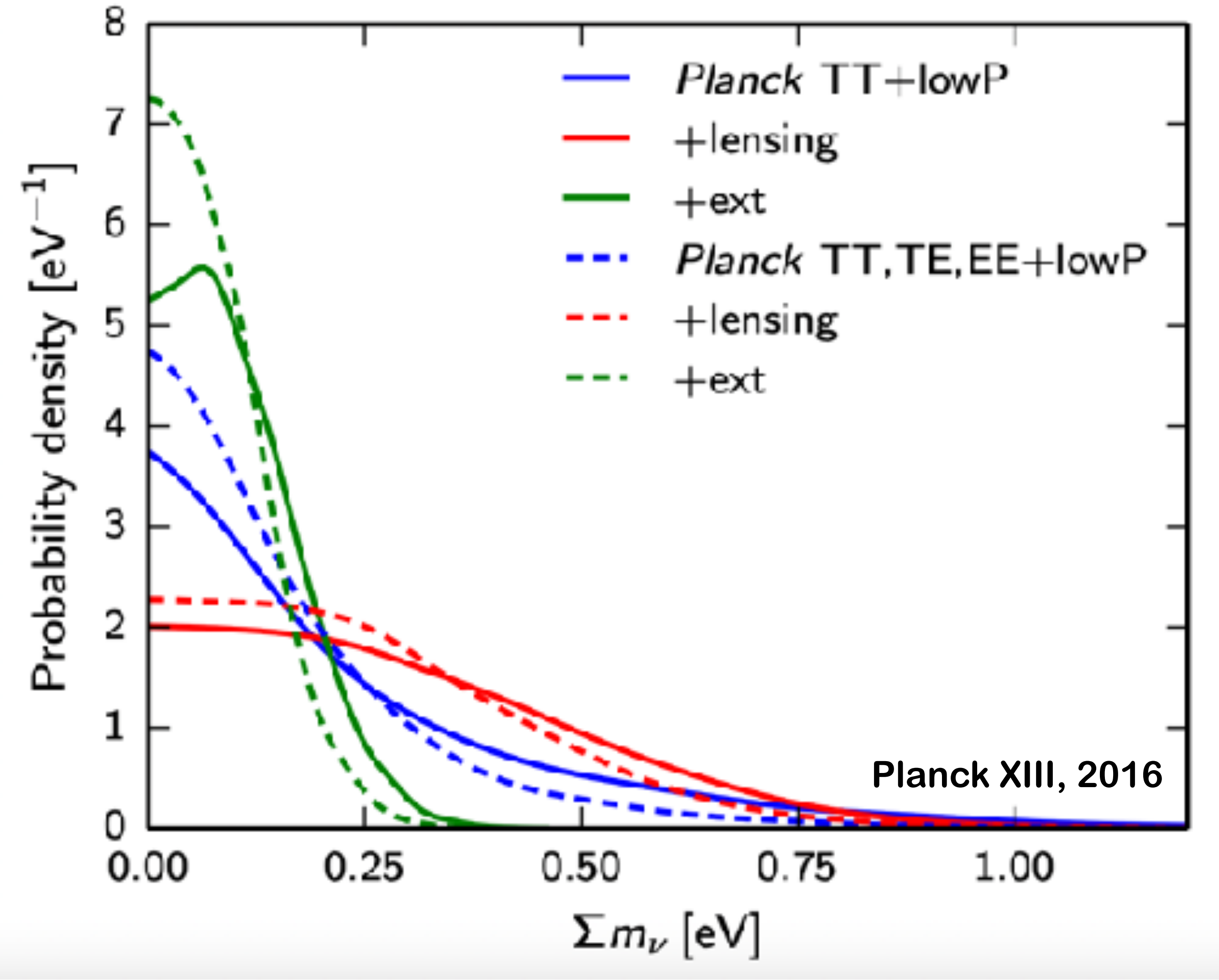
Clear improvement as more data are added and as tau estimates improve and move to lower value

tau-driven?



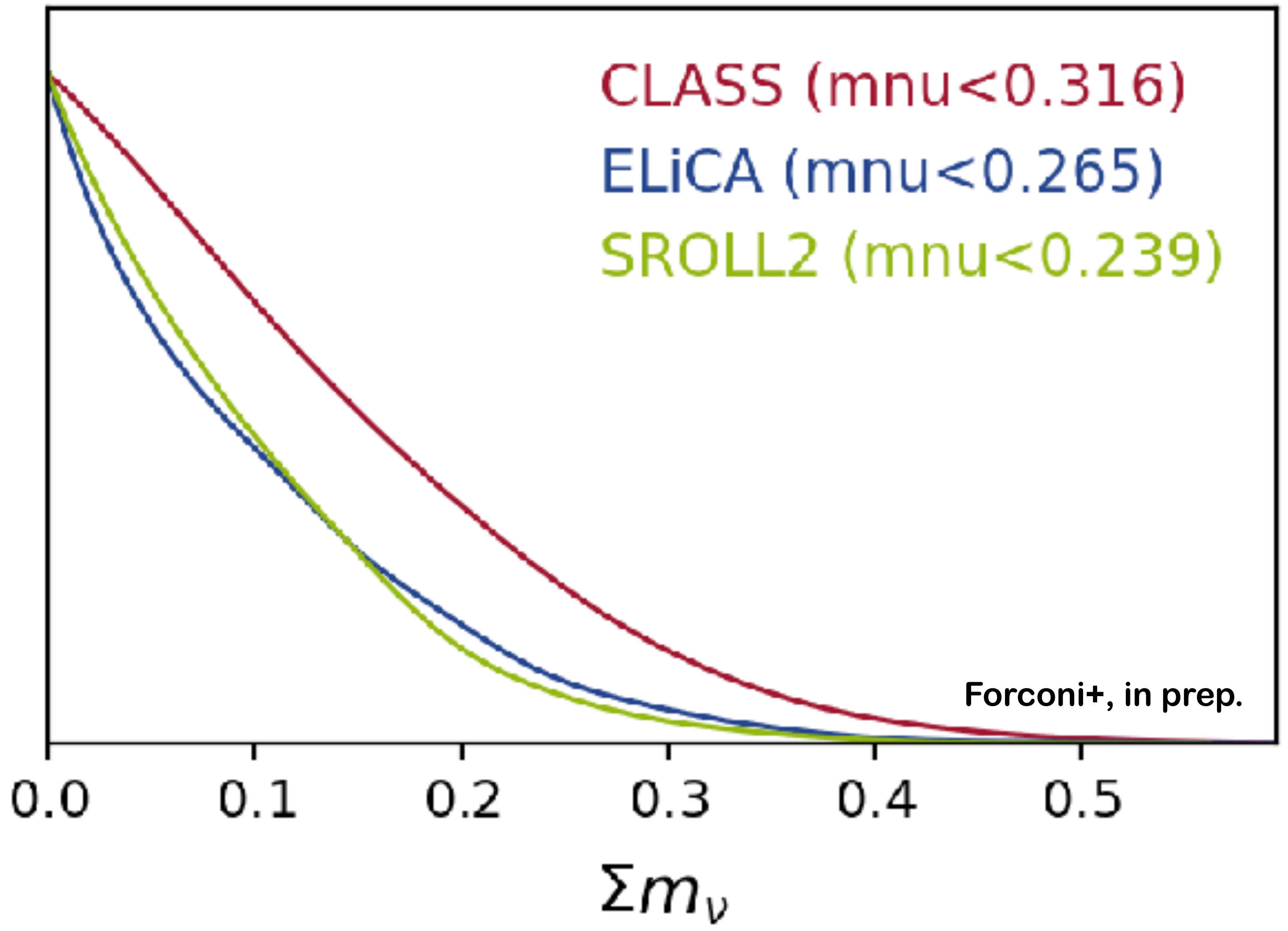
Planck XVI, 2014

lowE from WMAP9y or Gauss prior



Planck XIII, 2016

Replace WMAP with LFI

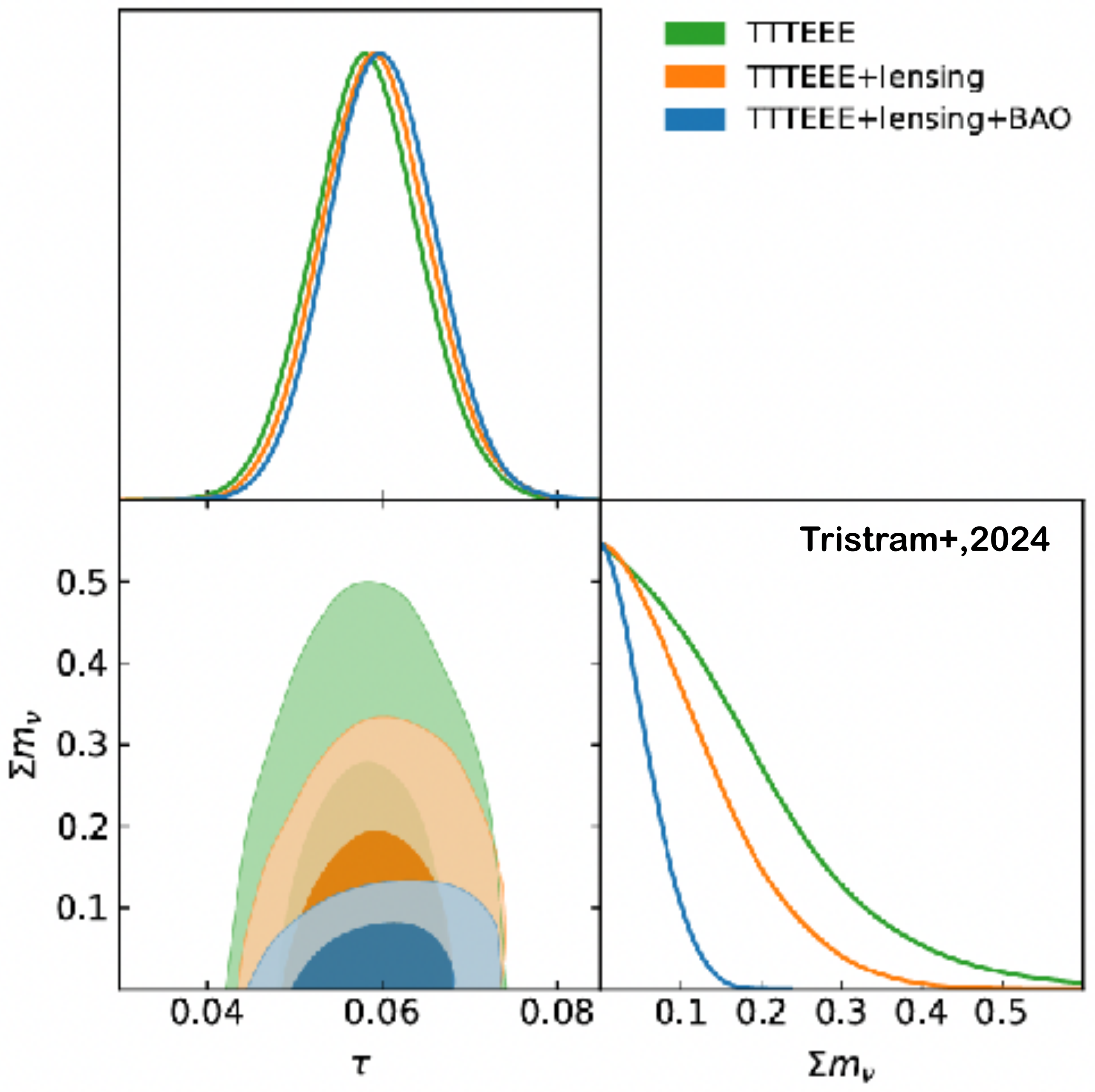


Forconi+, in prep.

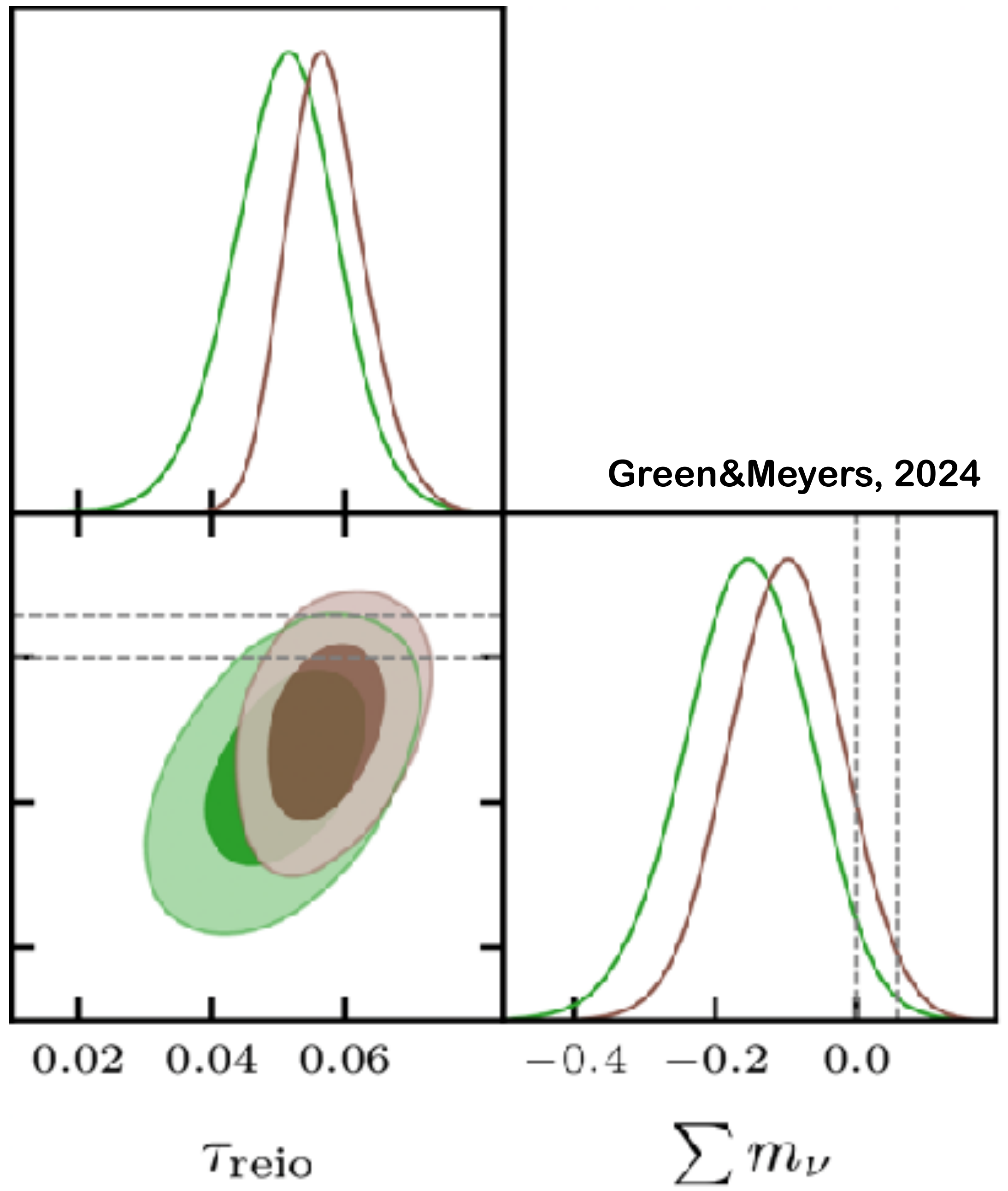
Compare HFI (SRoll2), WMAP (ELiCA), CLASSxHFI

Preference for low masses remains stable to changes in lowE

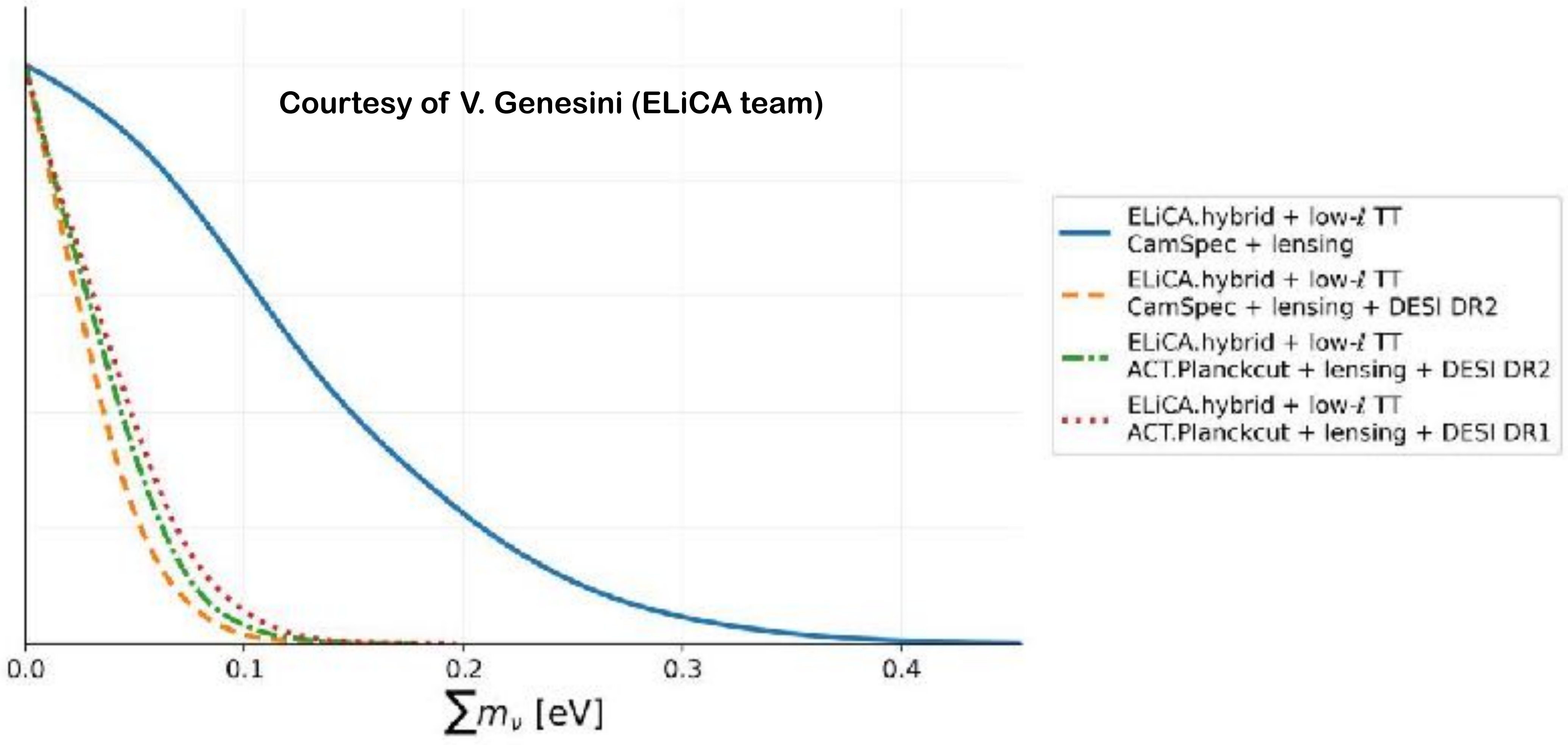
PR3 (legacy Planck)-driven?



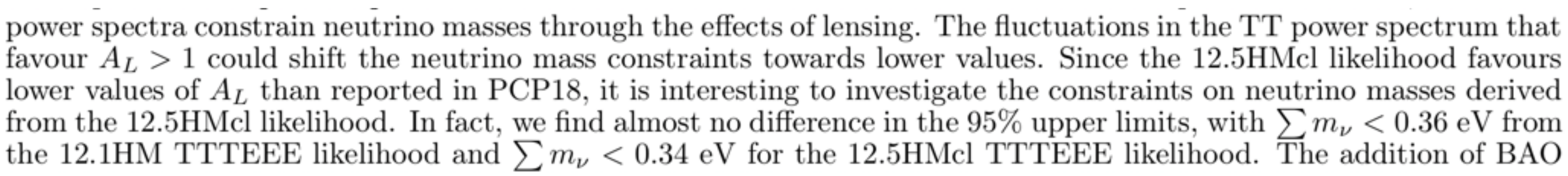
Tristram+,2024



Green&Meyers, 2024



Courtesy of V. Genesini (ELiCA team)

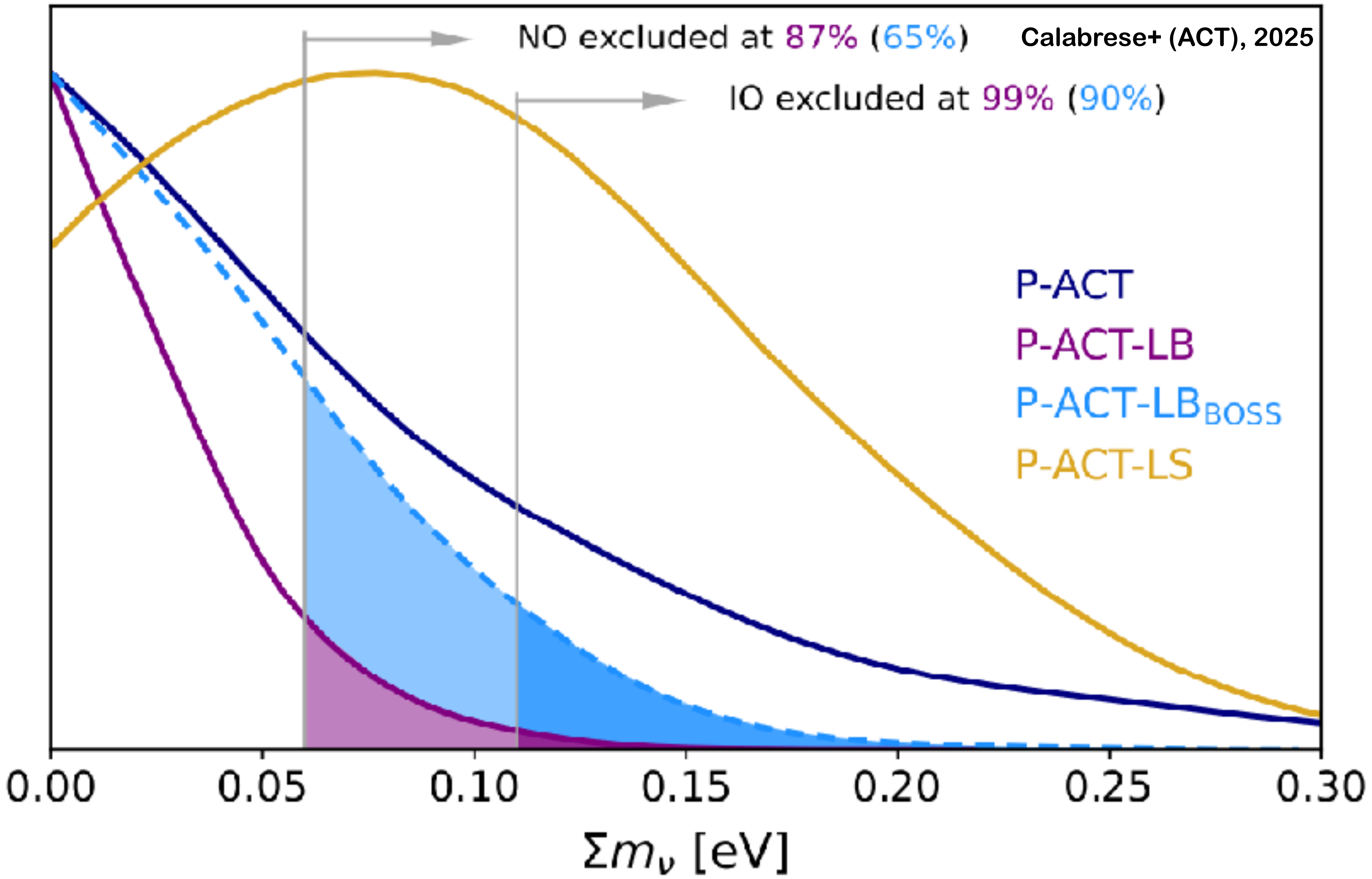


power spectra constrain neutrino masses through the effects of lensing. The fluctuations in the TT power spectrum that favour $A_L > 1$ could shift the neutrino mass constraints towards lower values. Since the 12.5HMcl likelihood favours lower values of A_L than reported in PCP18, it is interesting to investigate the constraints on neutrino masses derived from the 12.5HMcl likelihood. In fact, we find almost no difference in the 95% upper limits, with $\sum m_\nu < 0.36$ eV from the 12.1HM TTTEEE likelihood and $\sum m_\nu < 0.34$ eV for the 12.5HMcl TTTEEE likelihood. The addition of BAO

Efstathiou&Gratton, 2019

Preference for low masses remains stable to changes in data reduction/likelihood pipeline

Planck-driven?



$$\sum m_\nu < 0.082 \text{ eV} \quad (95\%, \text{P-ACT-LB}),$$
$$< 0.083 \text{ eV} \quad (95\%, \text{W-ACT-LB}).$$

P-ACT:
Planck is cut l<1000(TT), l<600(TE/EE)
-> no Alens anomaly

W-ACT: Planck replaced by WMAP

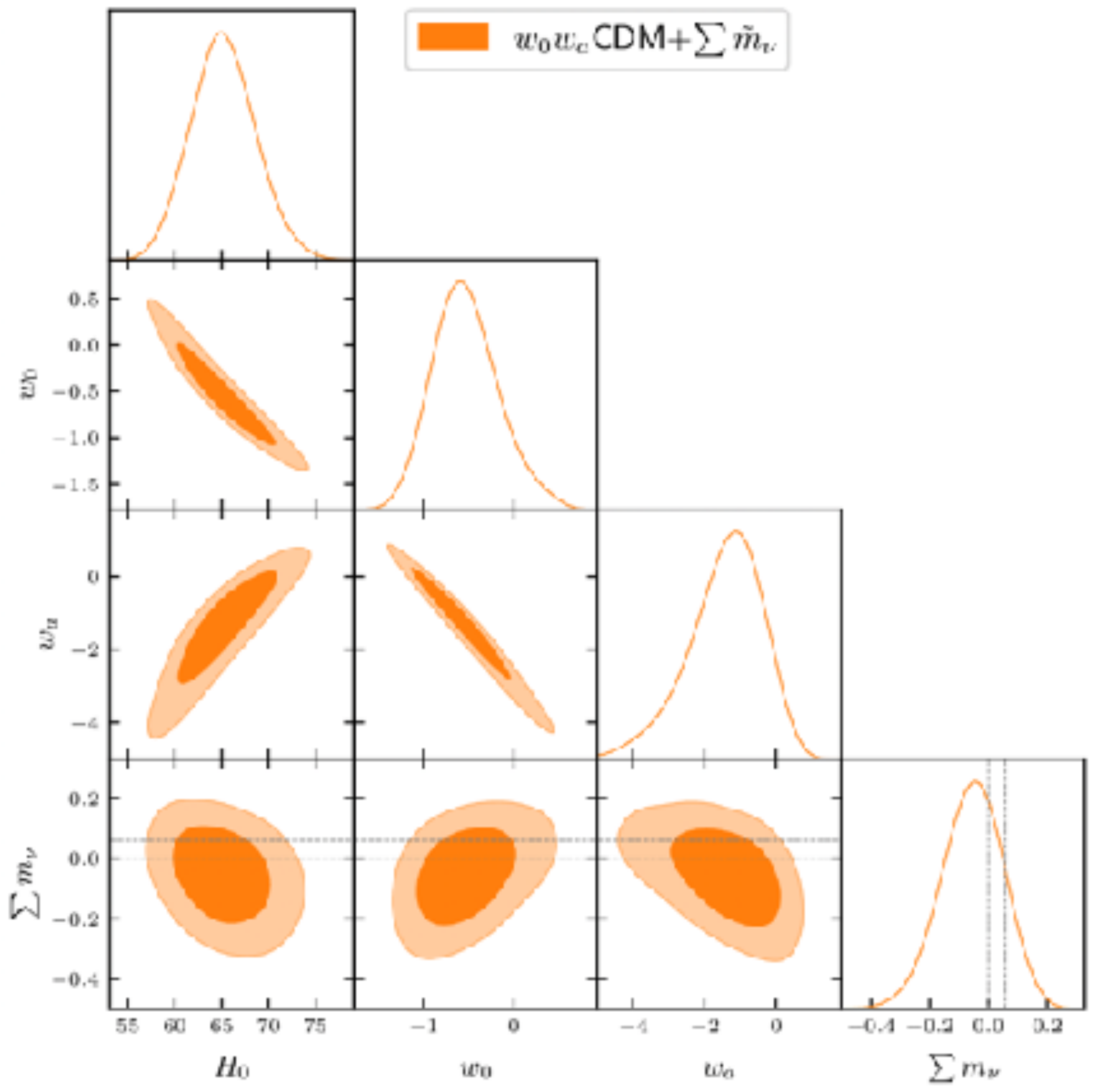
Preference for low masses remains stable to changes in large-to-intermediate scales

Implications for fundamental physics

From a LCDM viewpoint:
Hint for dynamical dark energy?
Hard to reconcile with DDE

Enhanced clustering:
No BSM neutrinos,
low masses as a proxy for other BSM cosmological components
-> long-range DM forces
-> unaccounted-for primordial trispectrum

Green&Meyers, 2024



From a HEP viewpoint:
Low masses are indication for BSM neutrino properties, such as:

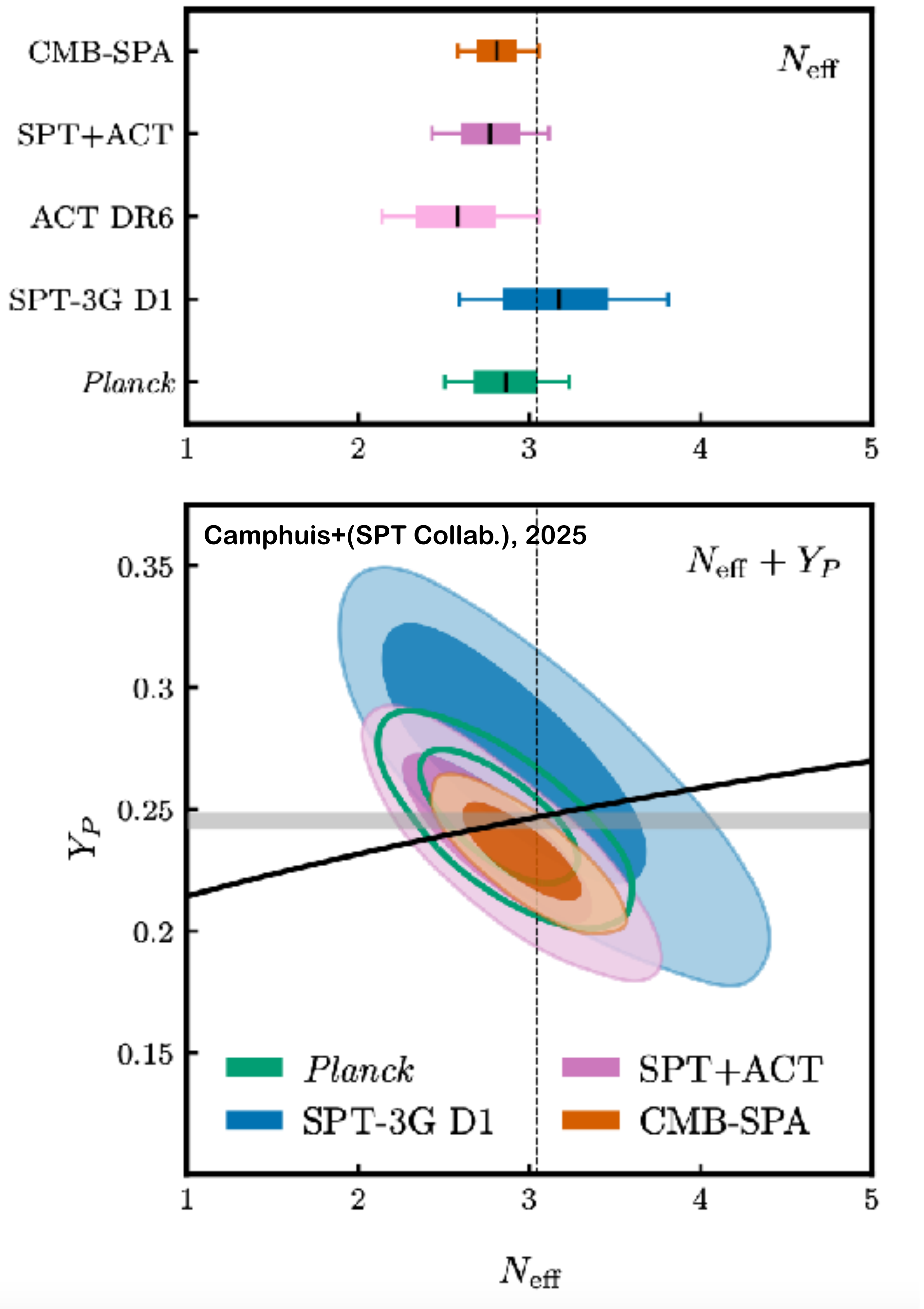
Neutrino decay -> must be invisible to evade EM constraints,
Also implies new physics at TeV scale (collider synergy?),

Annihilation -> more complicated, hard to avoid bounds on thermalisation of
Annihilation products

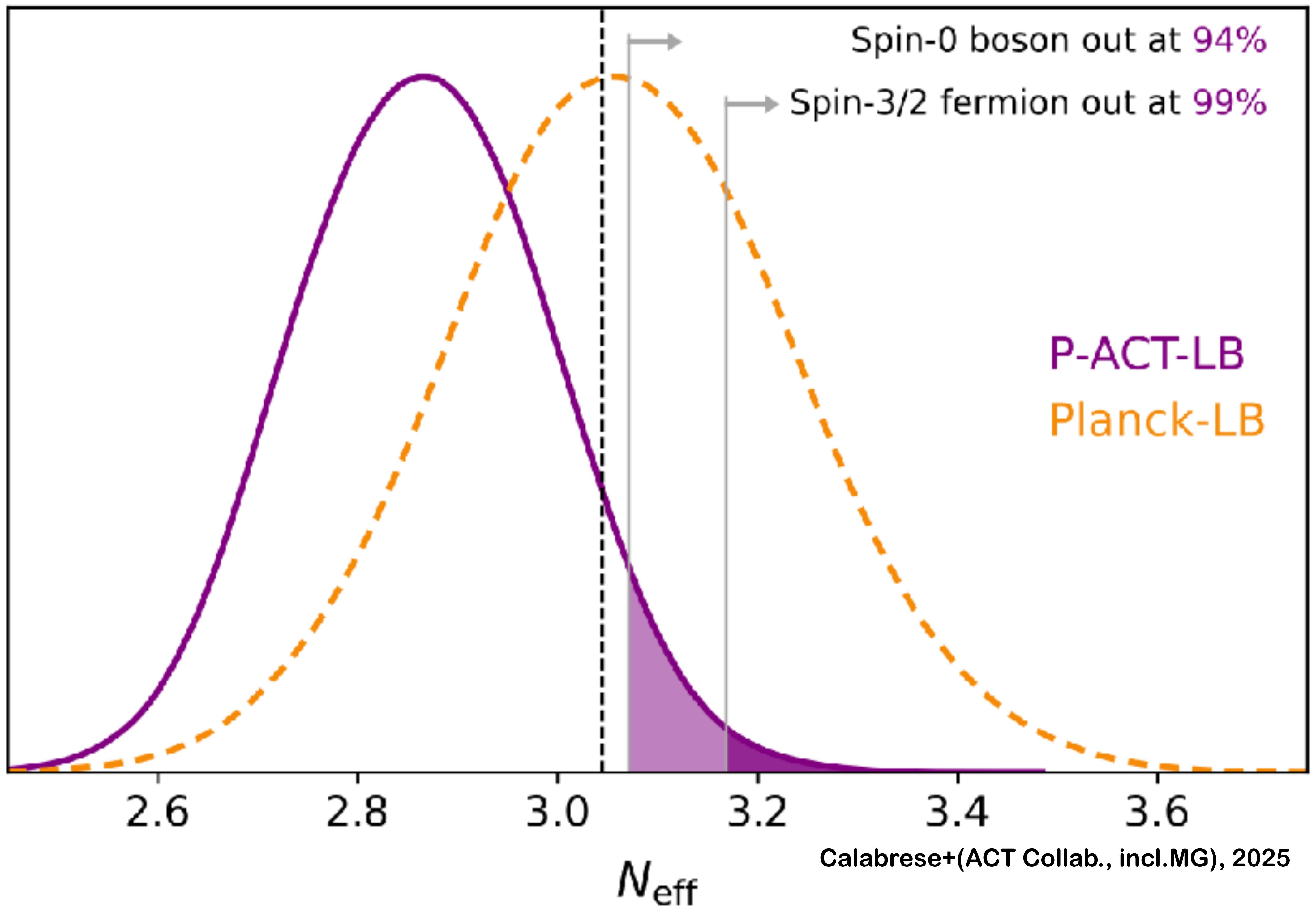
Cooling to allow clustering -> may be fine tuned,
requires new interactions with DM at z~100,
Synergy with Lya/small-scale surveys;

Mass varying -> coupling to (new) scalars, chameleon neutrinos

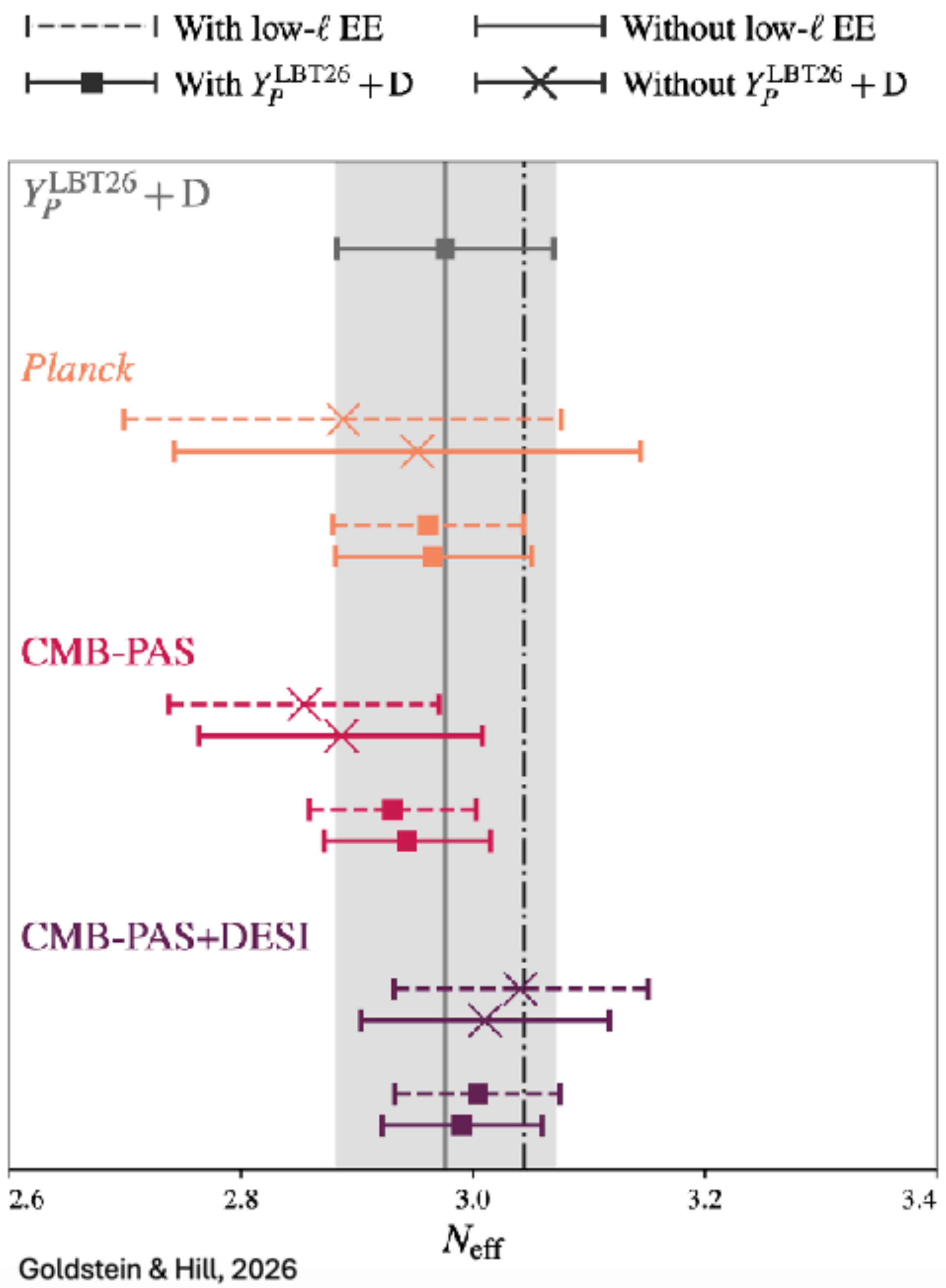
What's the matter with Neff?



Camphuis+(SPT Collab.), 2025



Calabrese+(ACT Collab., incl.MG), 2025

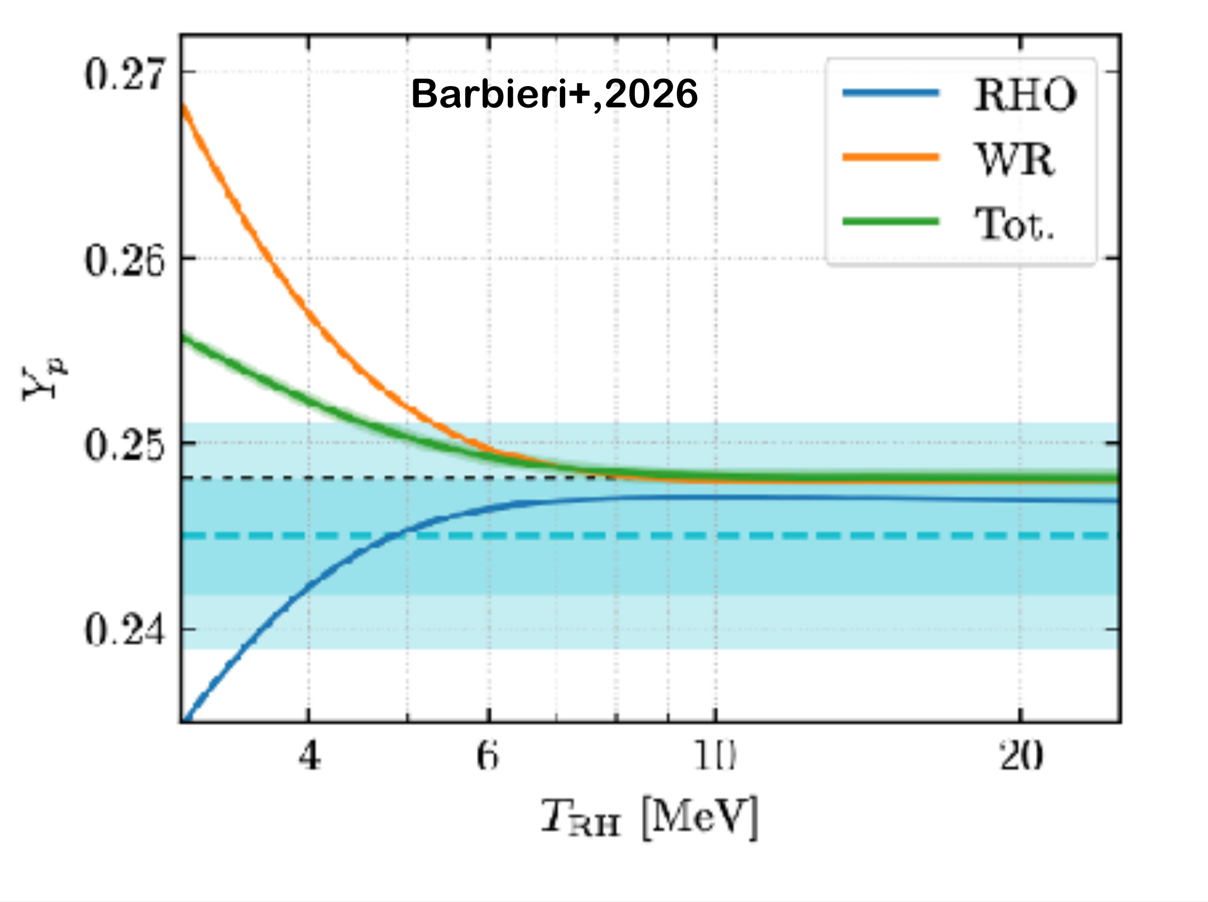


Goldstein & Hill, 2026

Posterior probability shifted towards low Neff

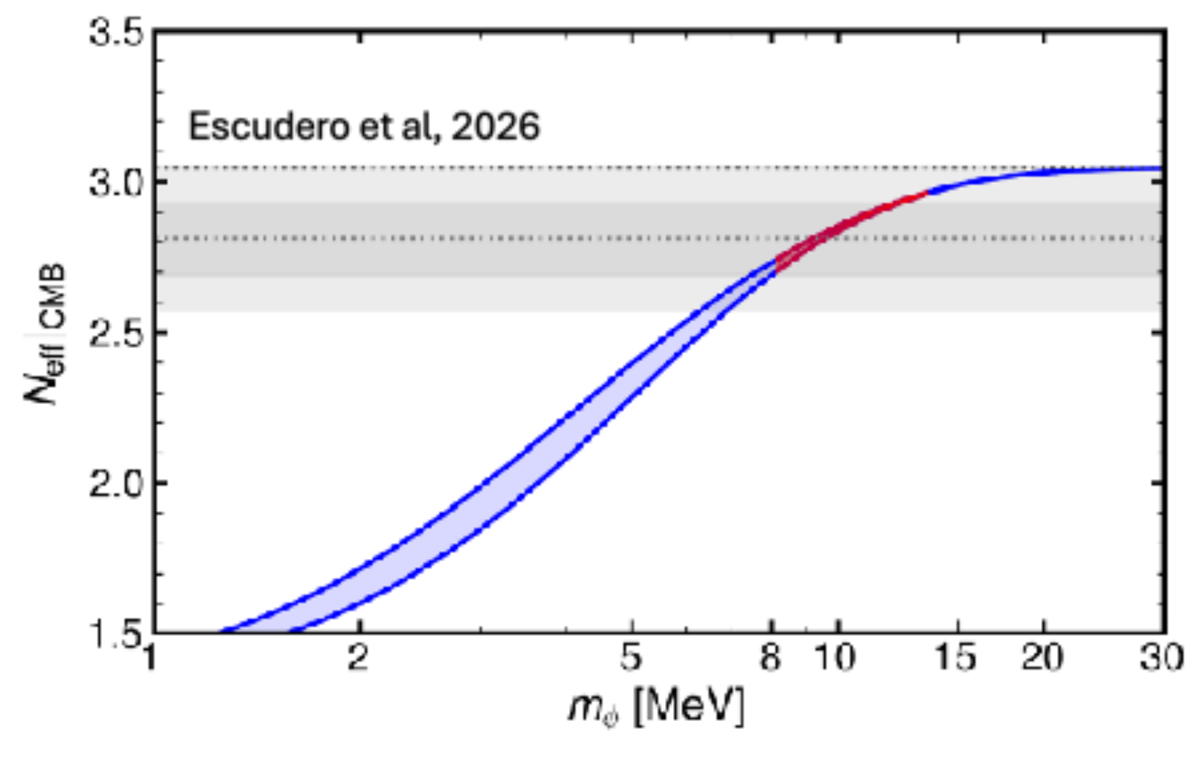
Implications for fundamental physics

- Low (~**MeV**) reheating temperature spoils **BBN**



- **Early neutrino decoupling**
Fixed by SM interactions,
need time-dependent interactions

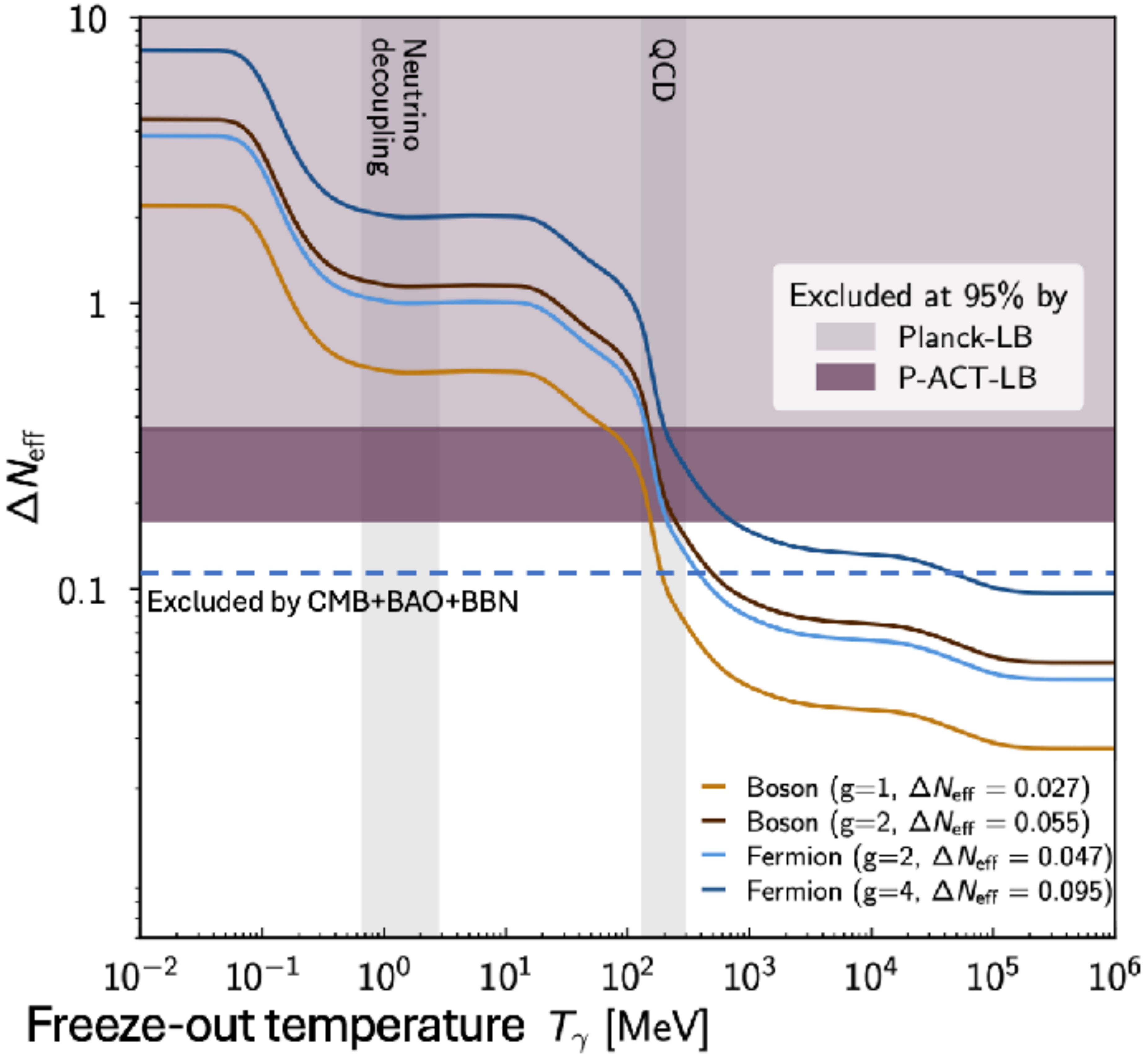
- **EM energy injection to heat photons**
Can work if injection happens between
0.05 s < t < 100 s



Tiny window for BSM scenarios

Implications for fundamental physics

Interpreting DNeff in terms of new particle content in thermal equilibrium



Large couplings ⟷ **Small couplings**

Measuring $N_{\rm eff}$, we can probe the decoupling temperature of additional ***thermal*** light species (e.g. ALPs)

$$\Gamma(T_d) = H(T_d)$$

bosons

$$\Delta N_{\rm eff} = \frac{g_X}{2}\begin{pmatrix} 8/7 \\ 1 \end{pmatrix}\left(\frac{g_{*s}(T_d)}{10.75}\right)^{-4/3}$$

fermions

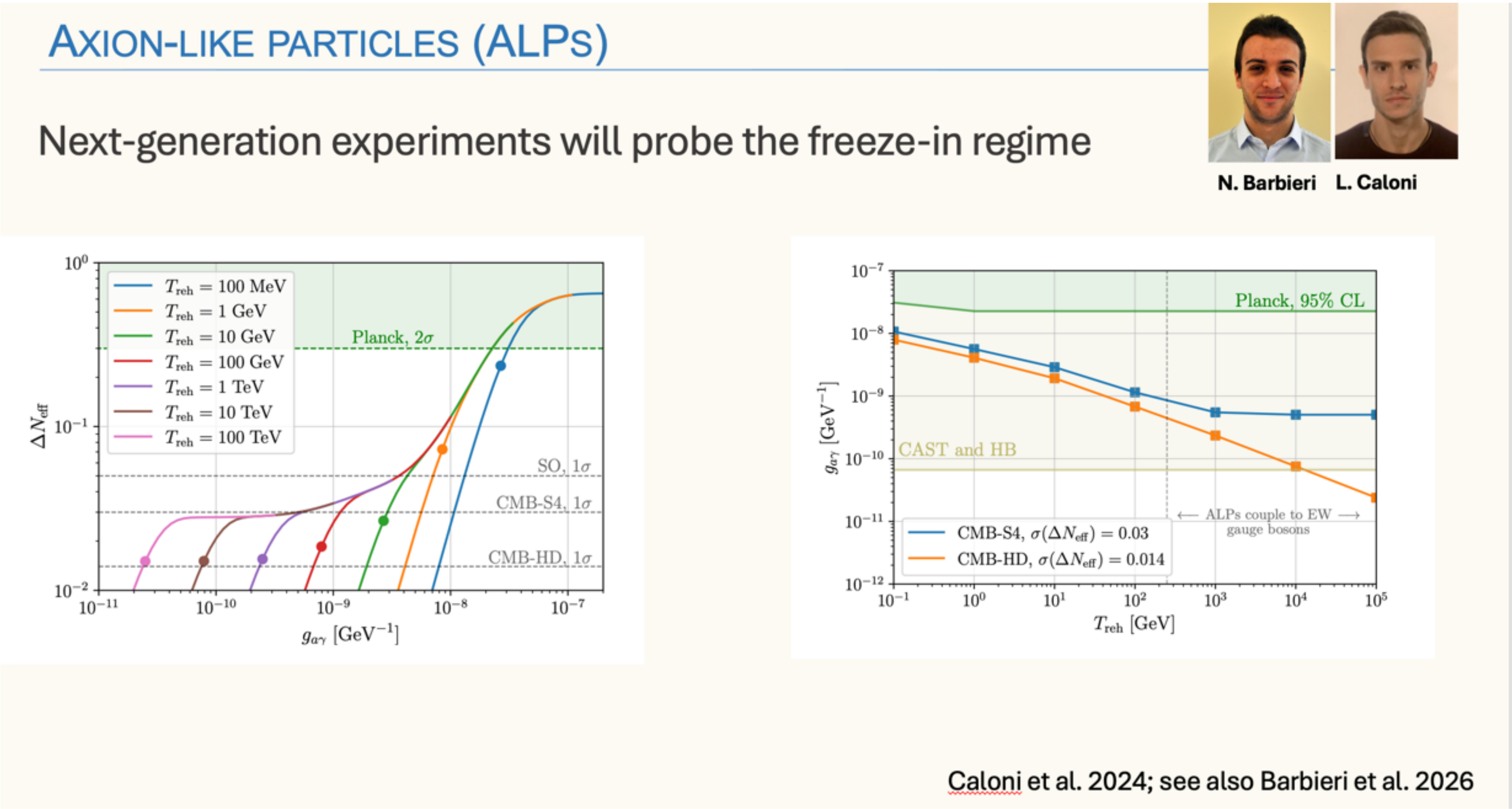
Current data exclude particles that were in thermal equilibrium after the QCD phase transition

Calabrese et al. (ACT Collaboration, 2025) with integration from Goldstein & Hill 2026

Slide courtesy: M. Lattanzi

Implications for fundamental physics

Interpreting DNeff in terms of new particle content not necessarily in thermal equilibrium



AXION-LIKE PARTICLES (ALPS)

Next-generation experiments will probe the freeze-in regime

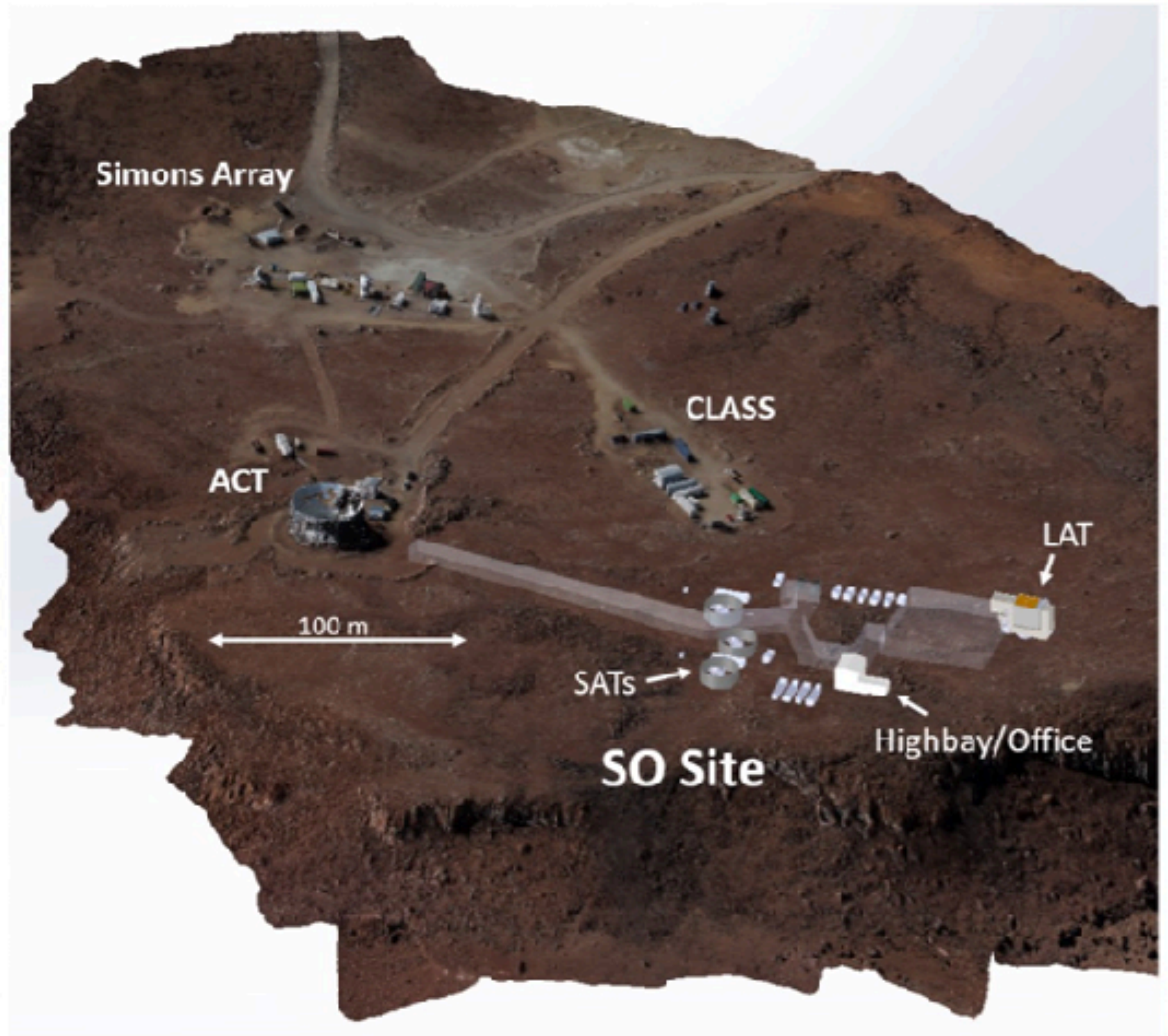
N. Barbieri **L. Caloni**

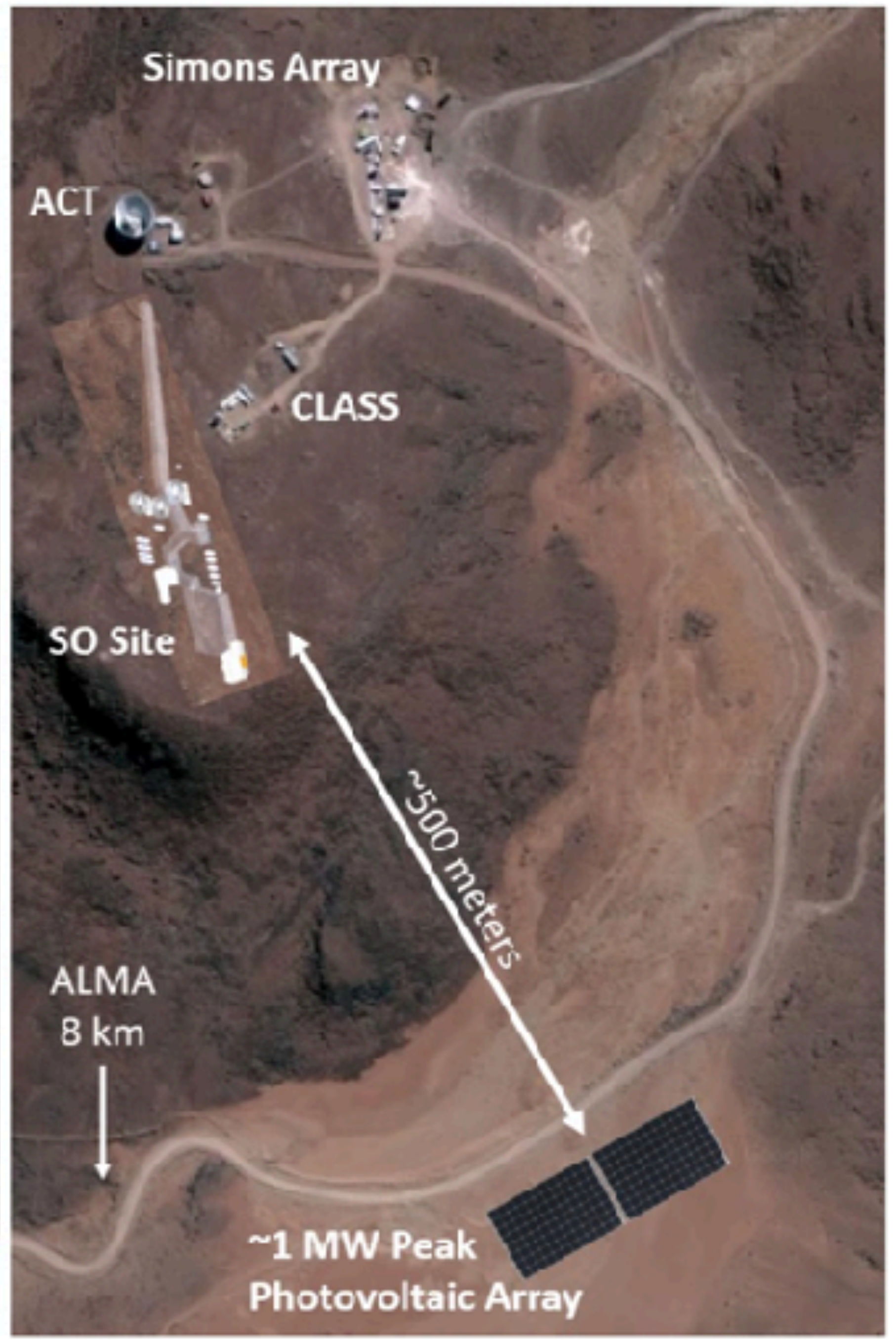
Caloni et al. 2024; see also Barbieri et al. 2026

Slide courtesy: M. Lattanzi

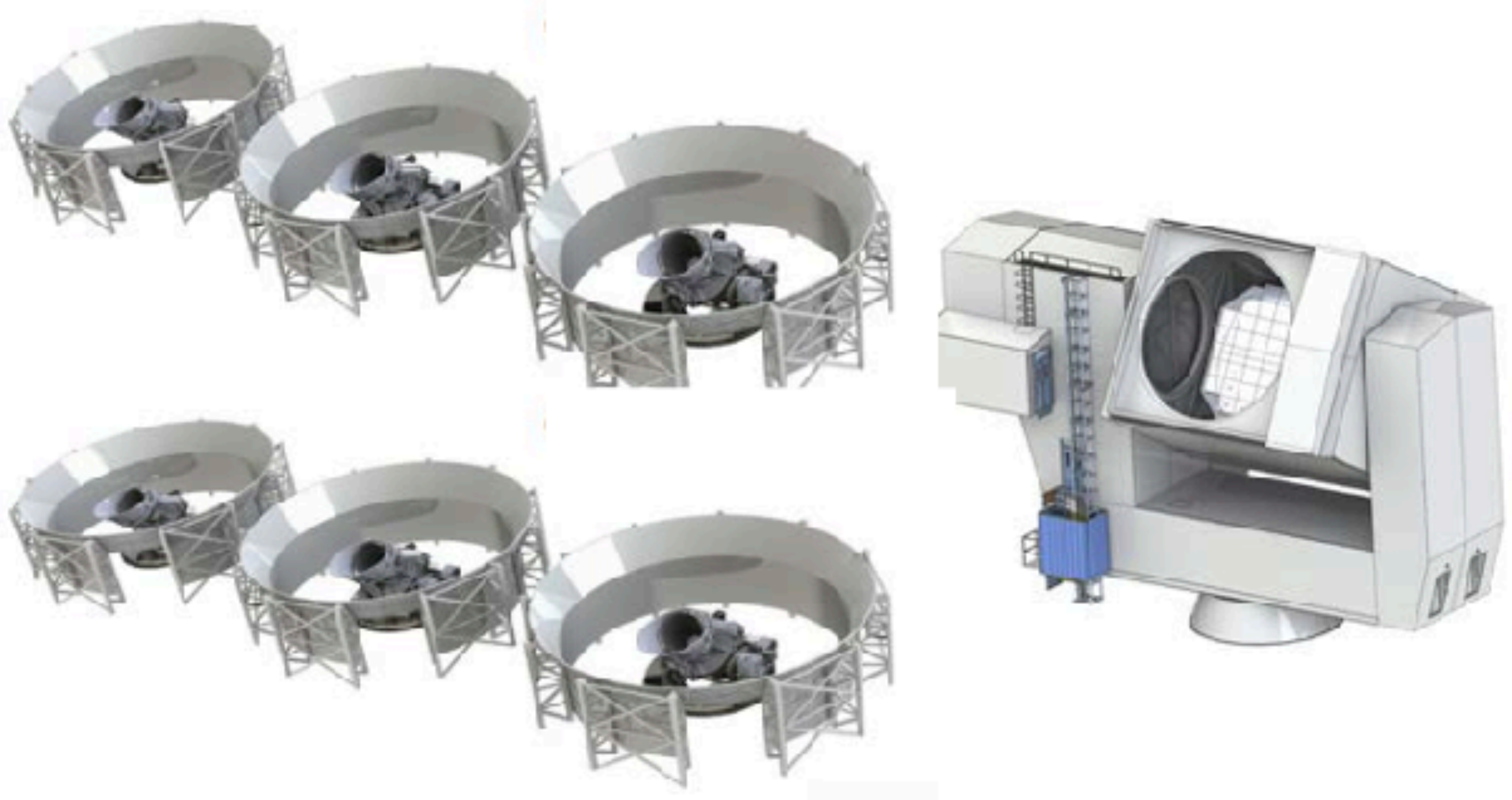
What next?

The Simons Observatory





Six 0.5-m Small Aperture Telescopes
One 6-m Large Aperture Telescope fully populated with 13 tubes



a little over 123,000 detectors
6 frequency bands in the mm

Operations started!

Green Observatory, replacing 70% of the power at the site with Solar Energy

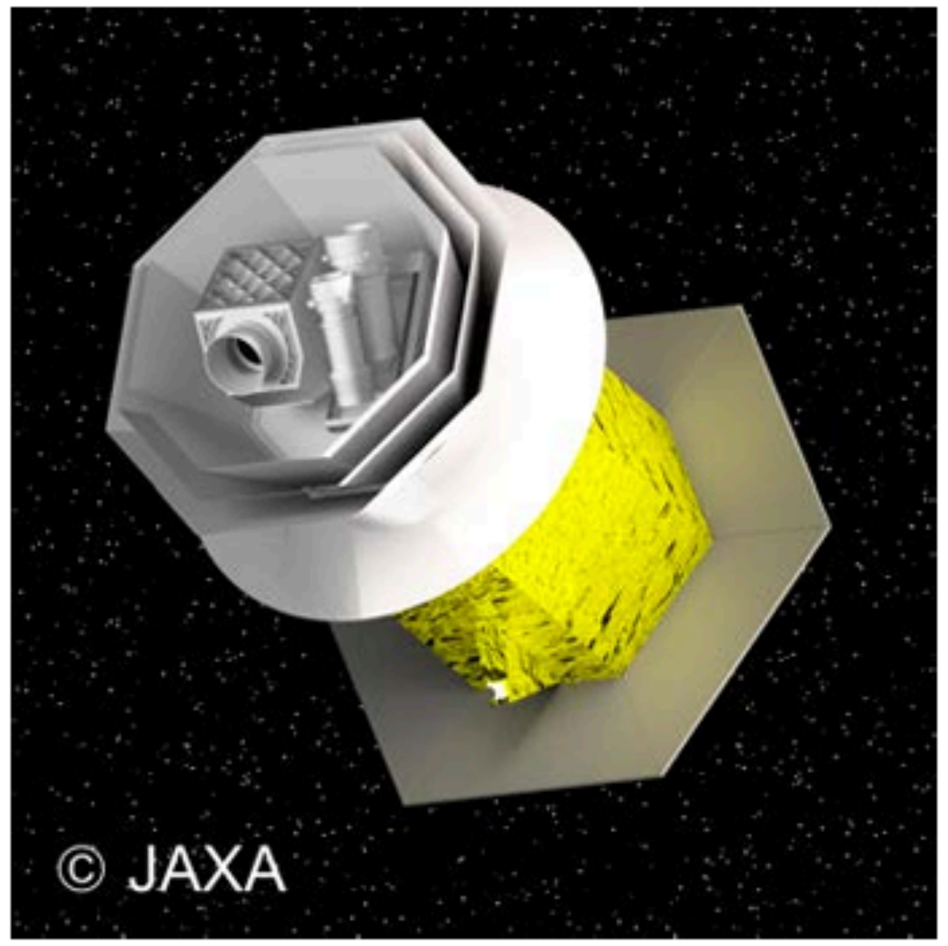
Large international collaboration
15+ countries, 60+ institutions
~375 collaborators

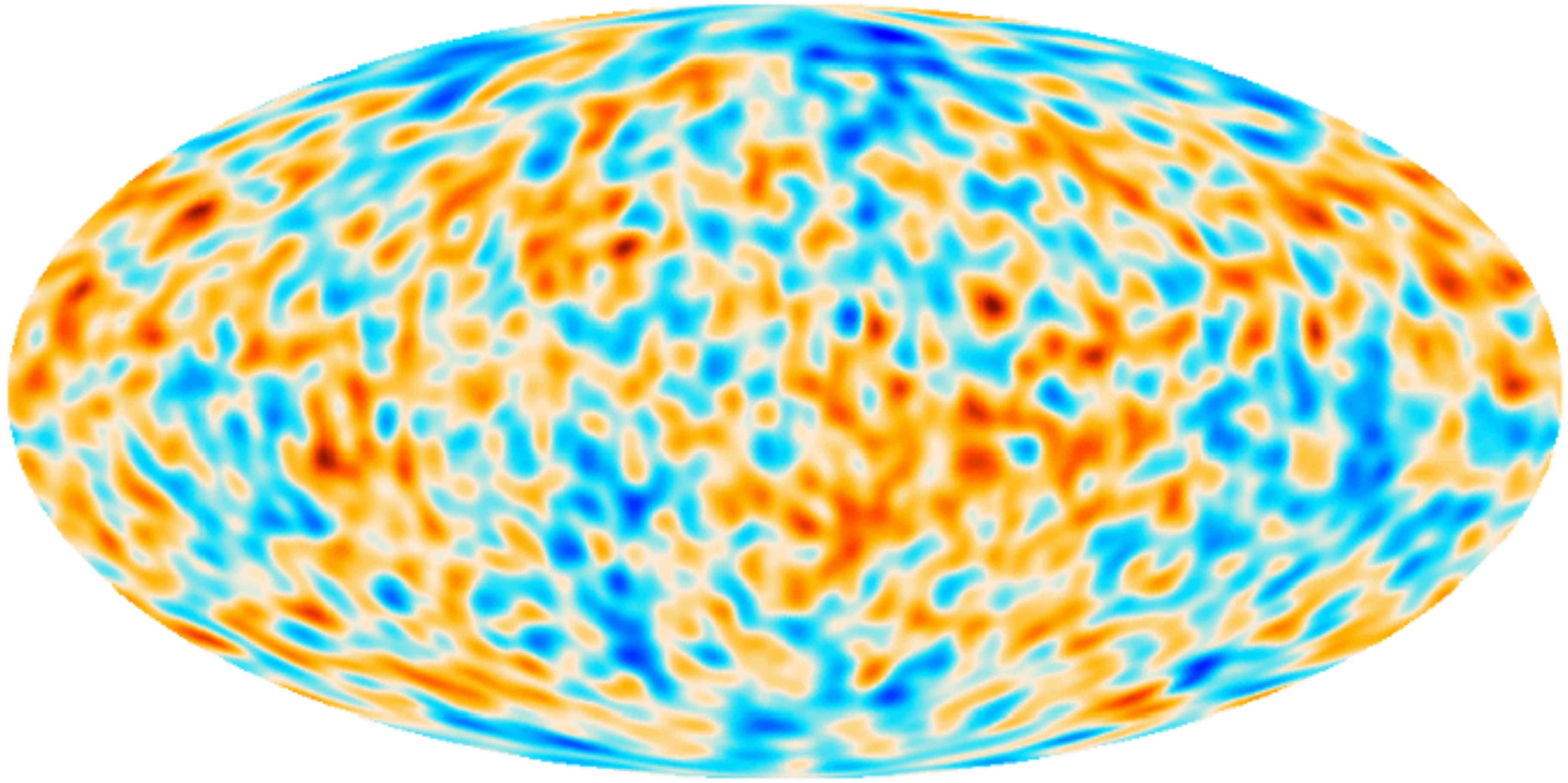
Slide courtesy of E. Calabrese

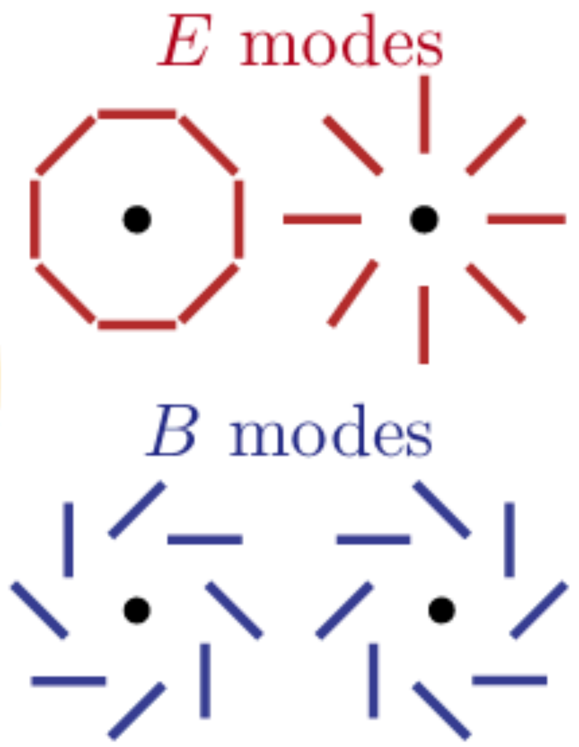
LiteBIRD overview

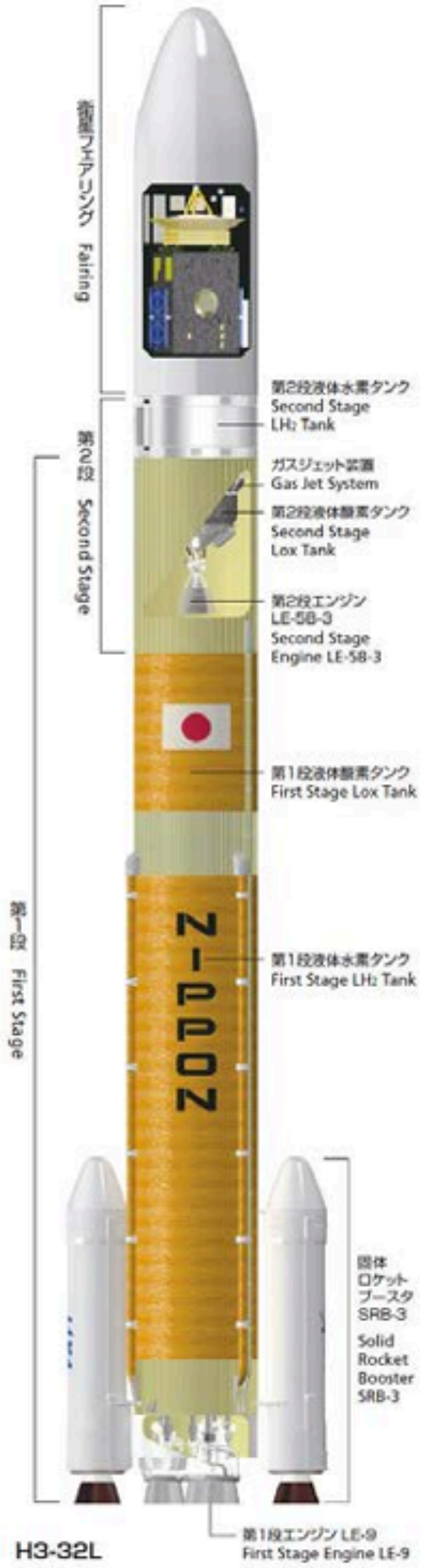
📖 LiteBIRD collaboration PTEP 2023

- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket.
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**





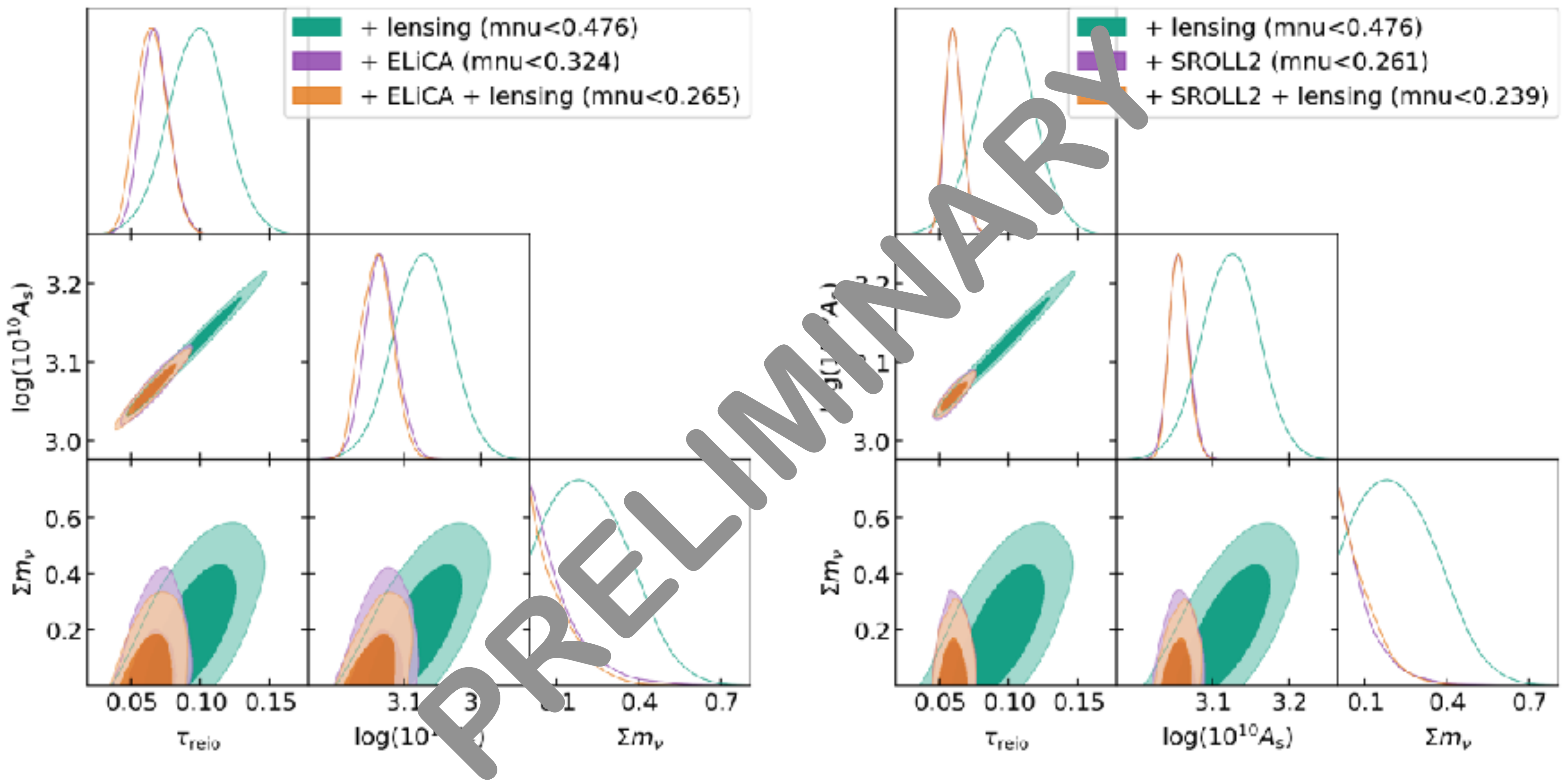




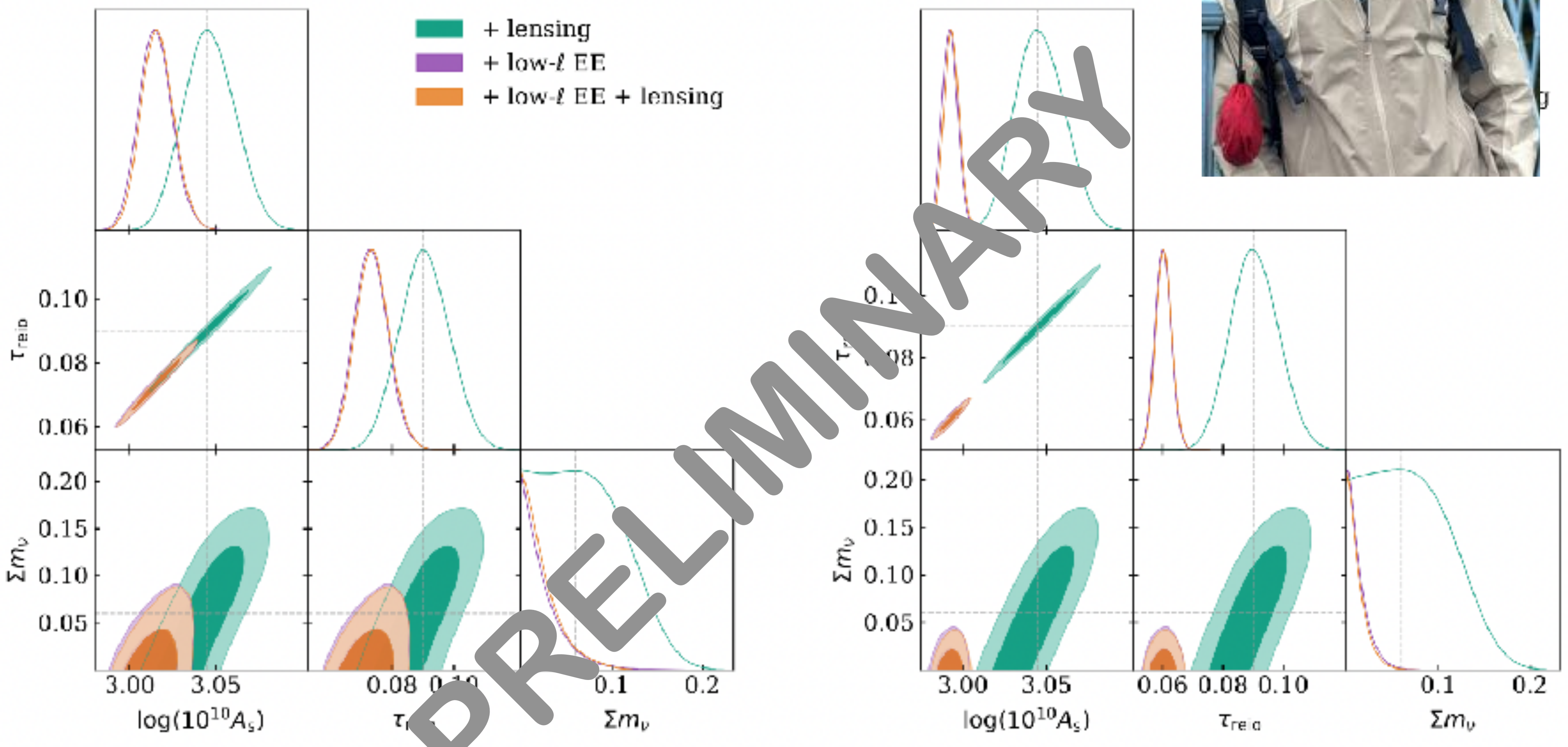
Slide courtesy of T. Matsumura

What next: solving the mnu puzzle?

Forconi+, in prep



PRESENT: no significant tensions between low-E only and lensing-only



(a) *Planck* +S4-like

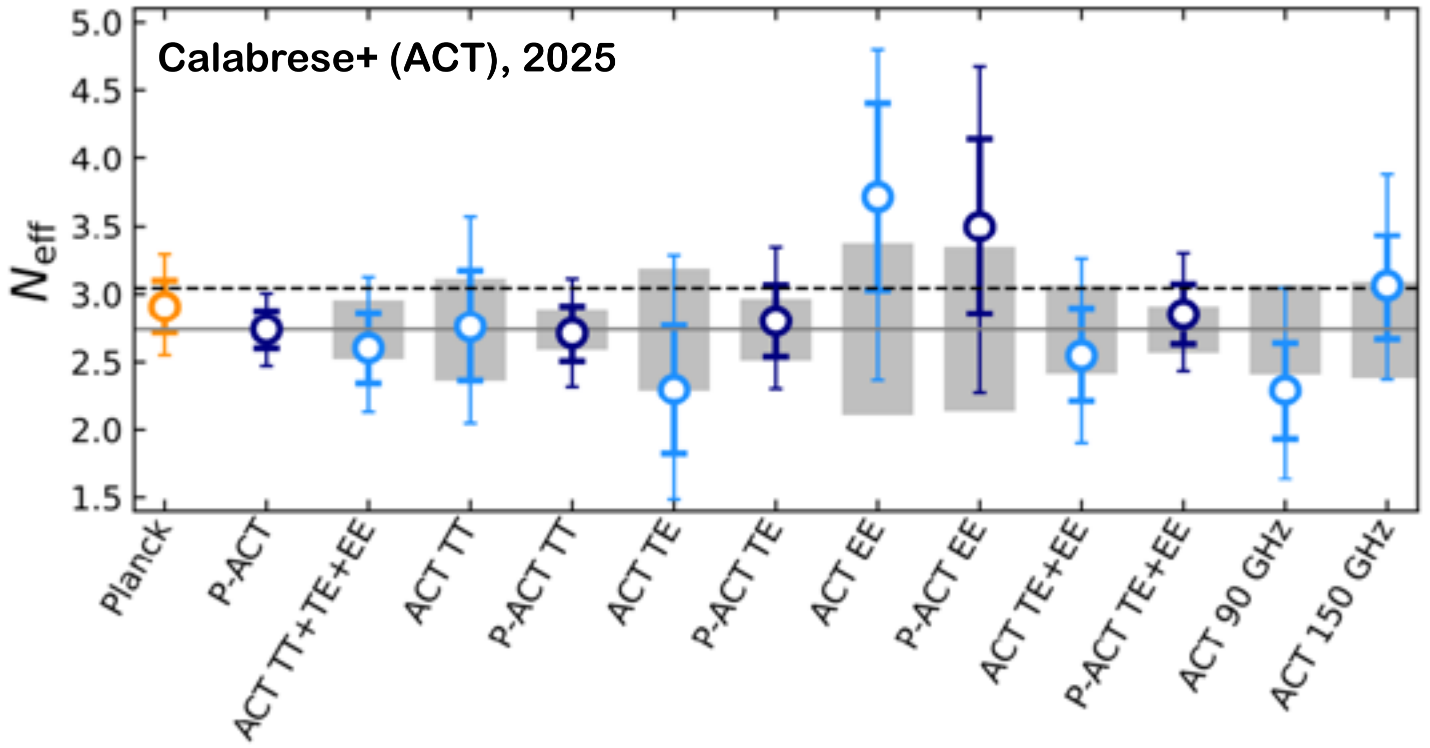
(b) LiteBIRD +S4-like

FUTURE: improved sensitivity can open more monitoring channels

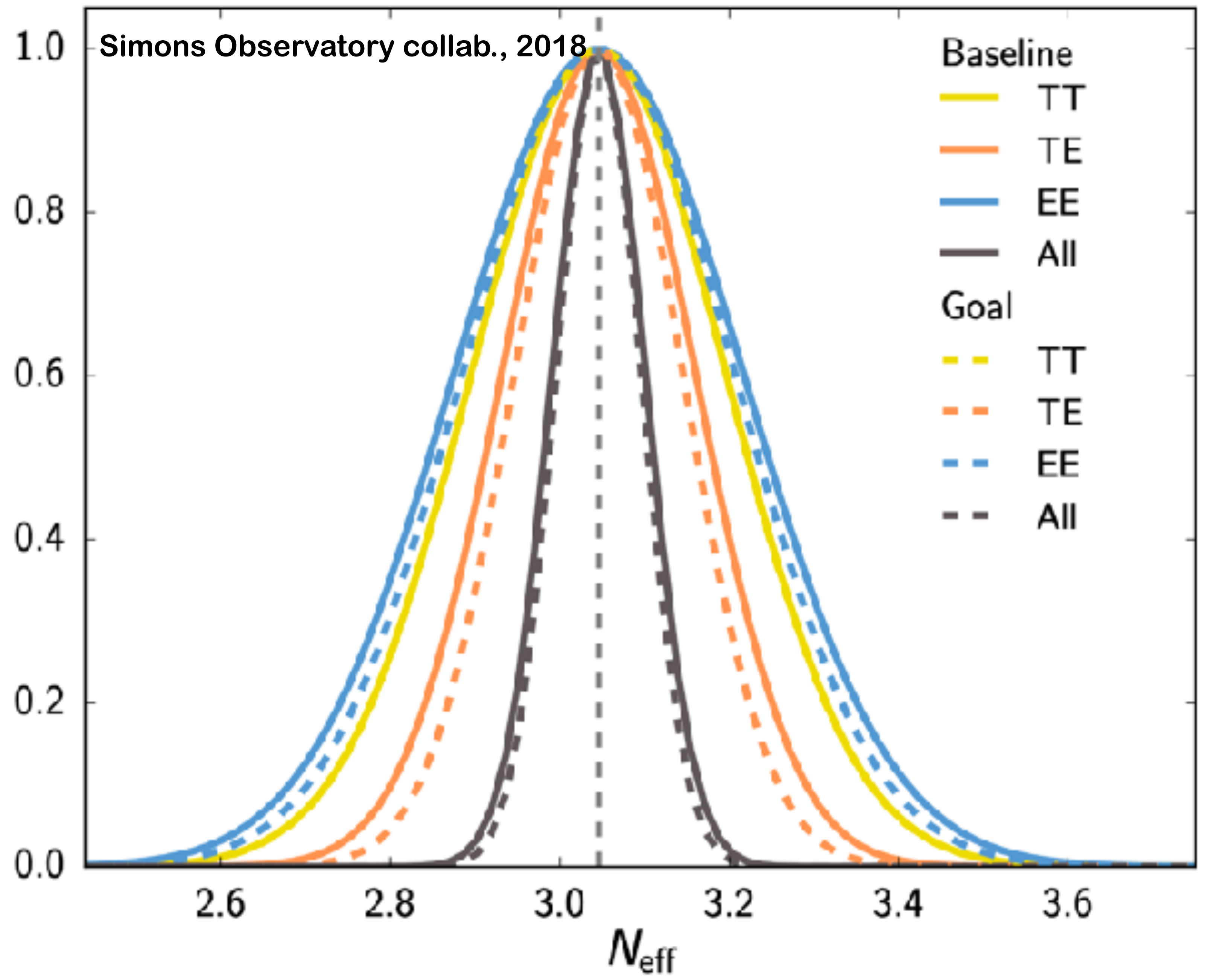
Independent tau estimates (LiteBIRD)
Comparable constraining power from lowE (Planck/LiteBIRD) and lensing (S4-like) on tau
Inter experiments cross-checks

What we can learn beyond state-of-the-art:
First detection or change paradigm!

What next: solving the Neff puzzle?


Calabrese+ (ACT), 2025

$\sigma(N_{\rm eff}) = 0.045$ **SO 2025-2034**


Simons Observatory collab., 2018

Comparable power from T and E
Neff constraints mostly driven by ground-based

What we can learn beyond state-of-the-art:
Neff low at higher significance?
Explore details of neutrino decoupling
Explore new regimes (freeze-in, new interactions, etc)

~~Conclusions~~ A few thoughts

- “Orange” flags: very tight bounds on mnu; Neff mildly <3
- Robust to (CMB) data tests (replace data, cut scales, change likelihood)
- If taken at face value: important implications for fundamental physics

- New-gen experiments can shed independent light (confirm or rule out)

- Note #1:
  synergy with lab/astro is key to get independent confirmation of BSM results

- Note #2:
  synergy among cosmo surveys is key to enable meaningful comparisons and checks

- Note #3:
  effective/phenomenological approaches are useful. However, results must be interpreted and communicated appropriately, especially to external communities (i.e., meaning of “negative” masses etc)

- Note #4:
  tensions/fluctuations expected. Important to keep an open yet (statistically) professional eye on them

- Note #5:
  key to work on robustness of the results. Improve null tests, inter/intra checks, enhance simulations, etc.

- Note #6:
  physics is (mostly) data driven, not (entirely) model driven. Avoid to “read” the data in light of the (preferred) model