TENSIONS AND NEUTRINO PHYSICS

FEDERICO BIANCHINI

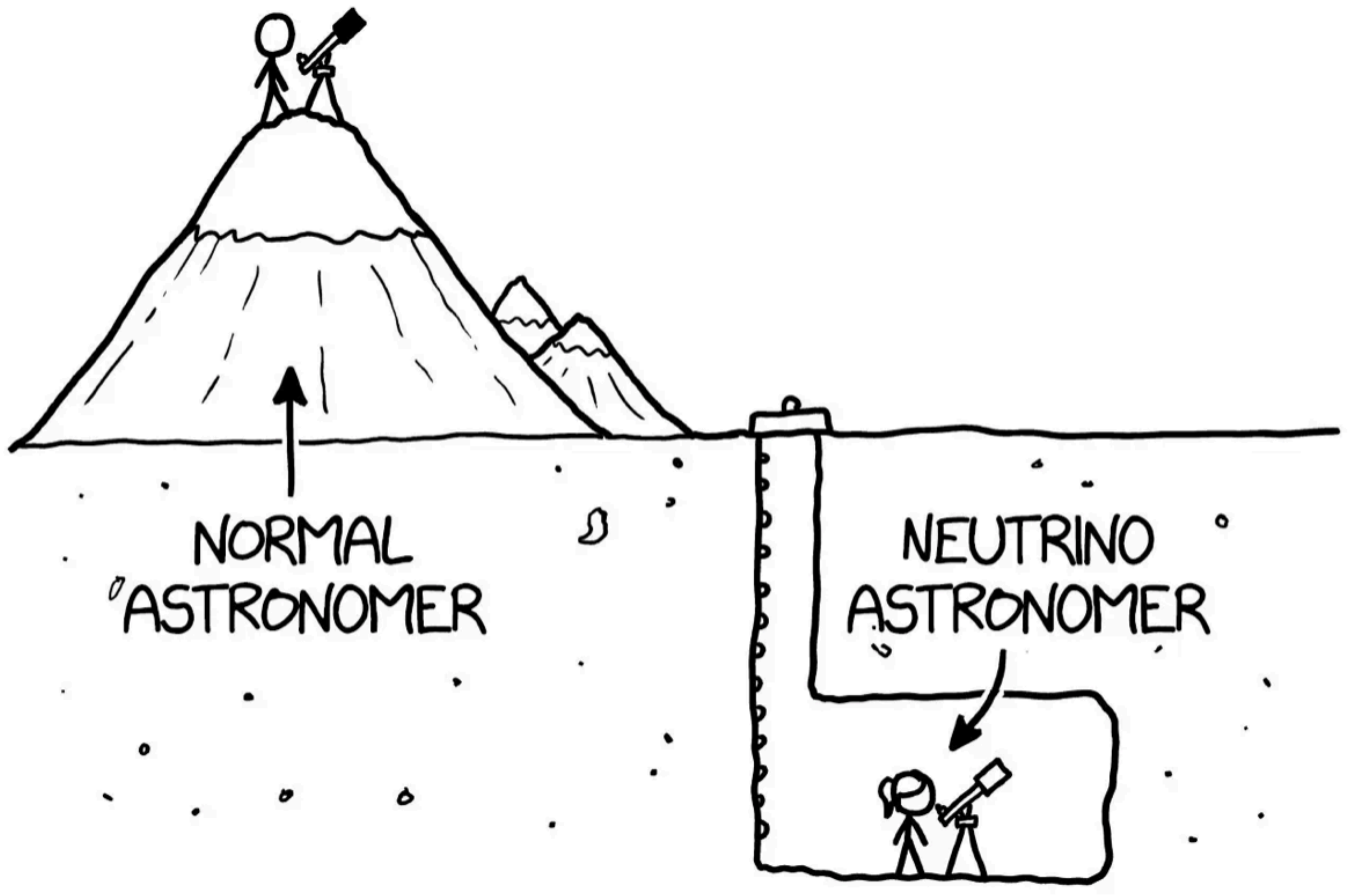
W/ ALEX FRIEDLAND, MANU SCHAAN, KIMMY WU

SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC
KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

Roadmap

- Neutrino cosmology primer
- Cosmological bounds on $\sum m_\nu$ and $N_{\rm eff}$
  - Current/upcoming CMB surveys
  - Role of CMB lensing
  - Interplay with cosmological tensions



Randall Munroe

Why study neutrinos?

- Most elusive SM particles!
- Second most abundant species ~300/cm^3
- Oscillations imply BSM physics
- Short baseline anomalies

Neutrino flavor eigenstates


Neutrino mass eigenstates

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- Most elusive SM particles!
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- Absolute mass scale
- Mass hierarchy
- Dirac vs Majorana
- CP phase
- Additional sterile neutrinos

Neutrino flavor eigenstates

Neutrino mass eigenstates

Cosmology is complementary to lab searches

Cosmology

sensitive to sum of neutrino masses $\Sigma m\nu$

(and how many there are)

Neutrino oscillations

sensitive to mass-squared differences

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Beta decay

sensitive to effective electron neutrino mass

Neutrinoless double beta decay

sensitive to effective Majorana mass

Constraining the neutrino sector since the 60s

Neutrinos ⟷ **Cosmology**

light, weakly-interacting particles

gravitation on the largest scales

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

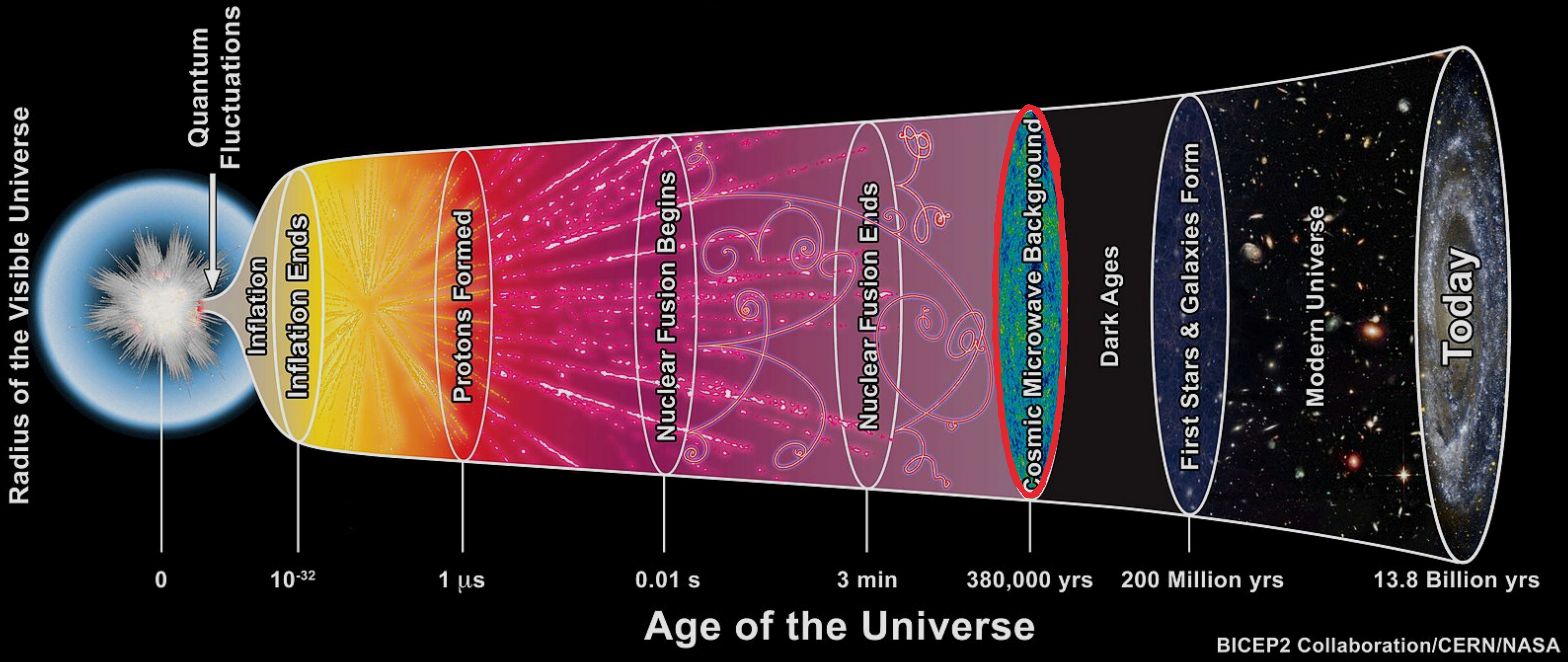
S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200\ eV/c^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6\ eV/c^2$ for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec $= (13 \times 10^9\ \text{years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time 1)

$$\rho < 2 \times 10^{-28}\ g/cm^3.$$

Neutrino cosmology 101



Dolgov02,Lesgourgues&Pastor06,Hannestad10,Gerbino+23

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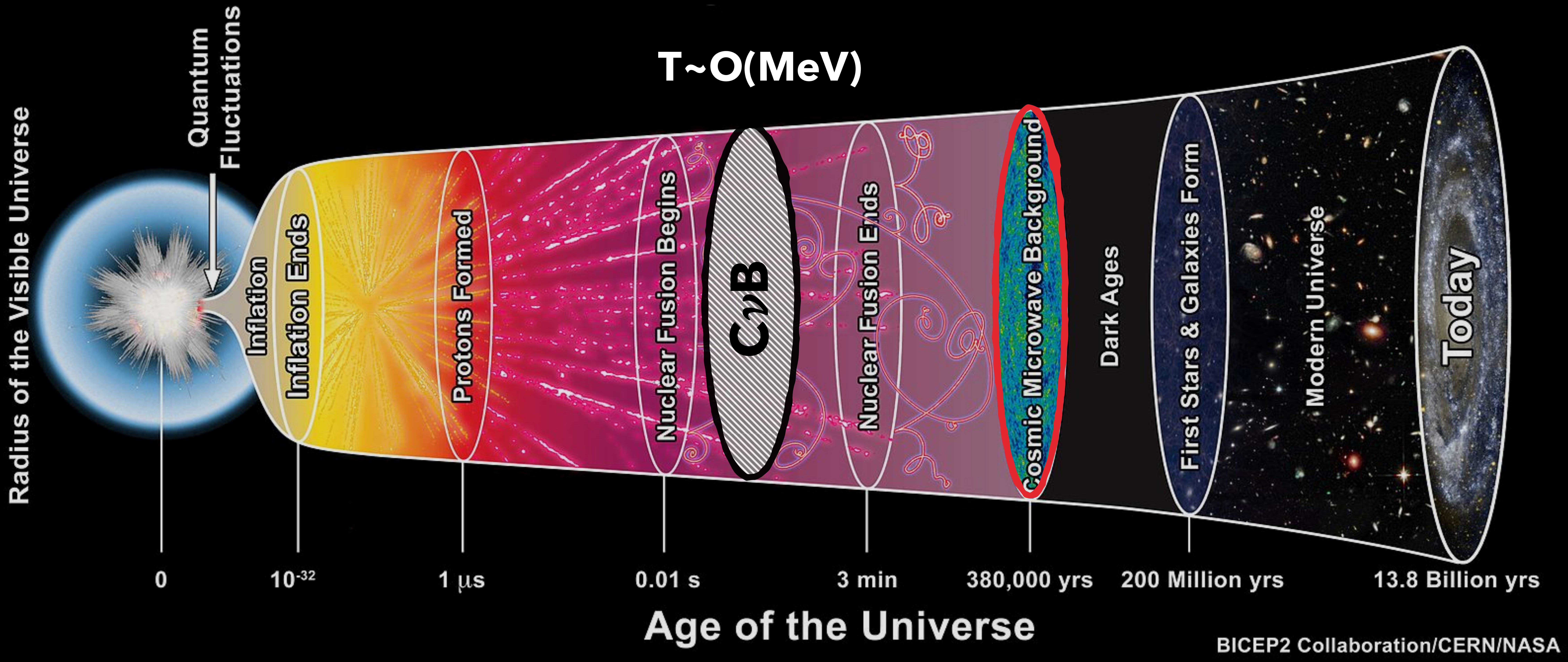

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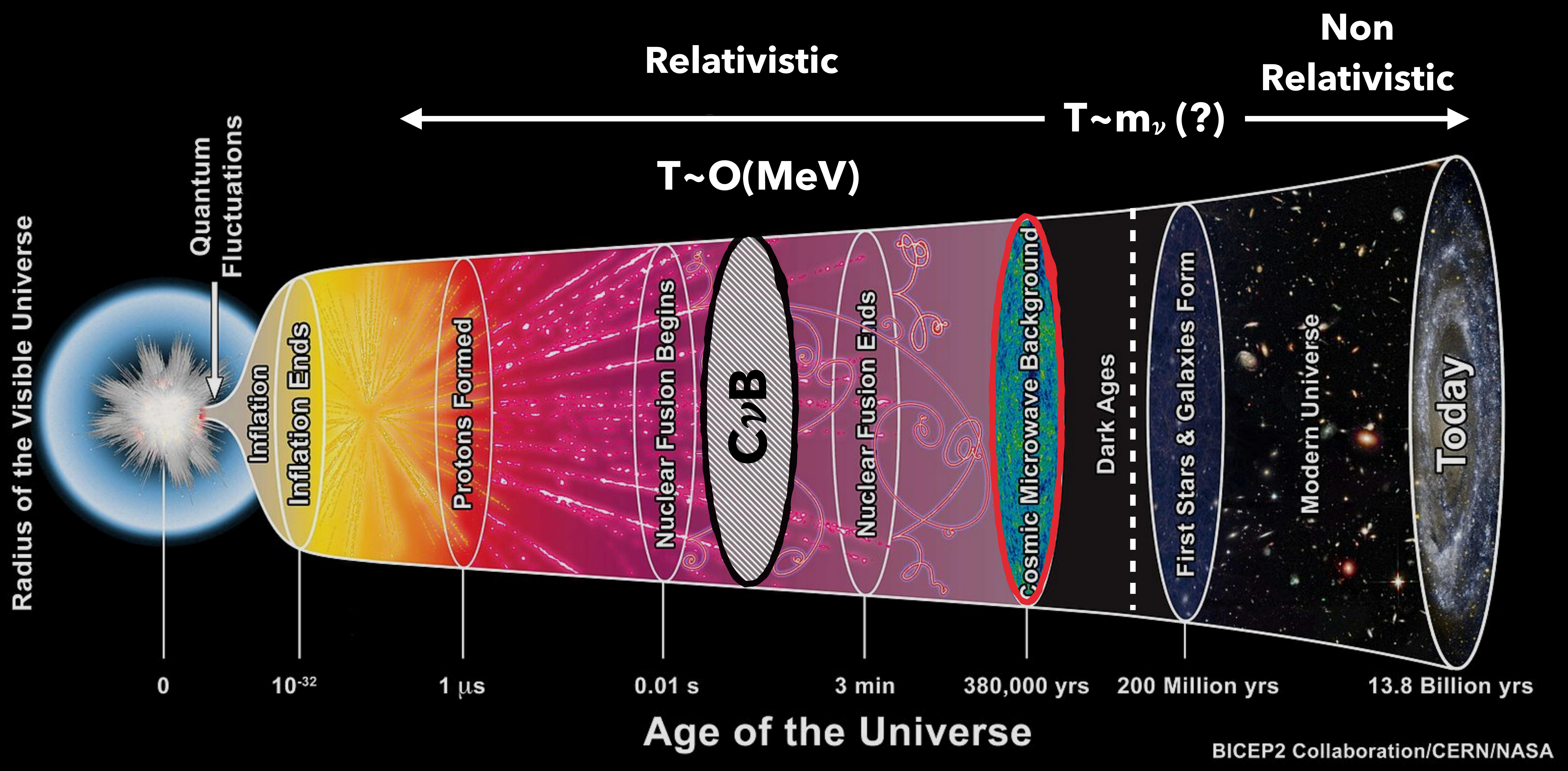

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What does cosmology really measure?

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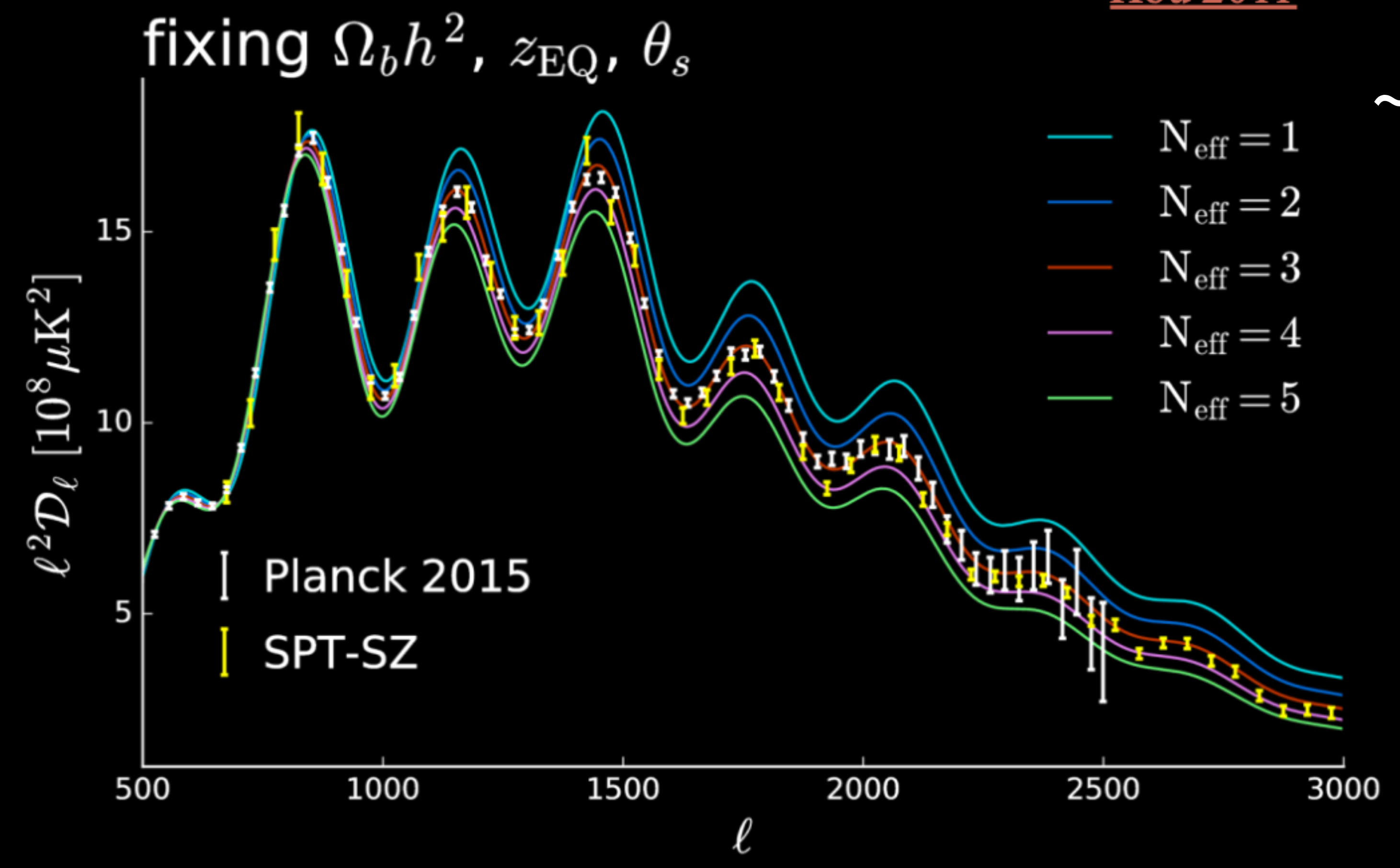
Early times (~radiation)

Change of the expansion rate encoded by the effective number of relativistic degrees of freedom $N_{\rm eff}$
–> affects matter-radiation equality, Silk damping scale, drag effects on photon perturbations

$$H(a) \propto \rho_{\rm rad}(a) = \rho_\gamma(a)\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right]$$

$N_{\rm eff}$ ~3.044

Hou 2011



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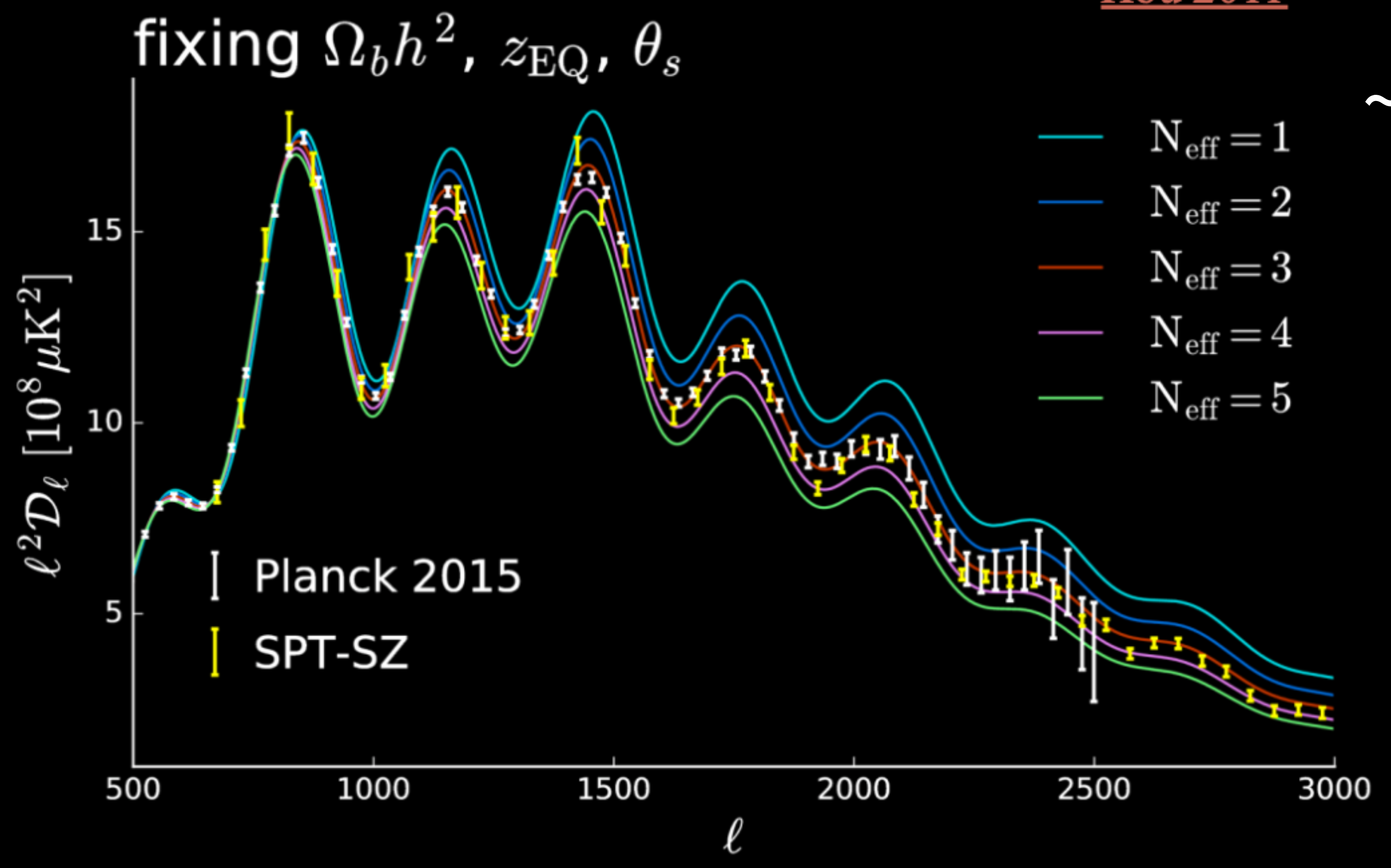
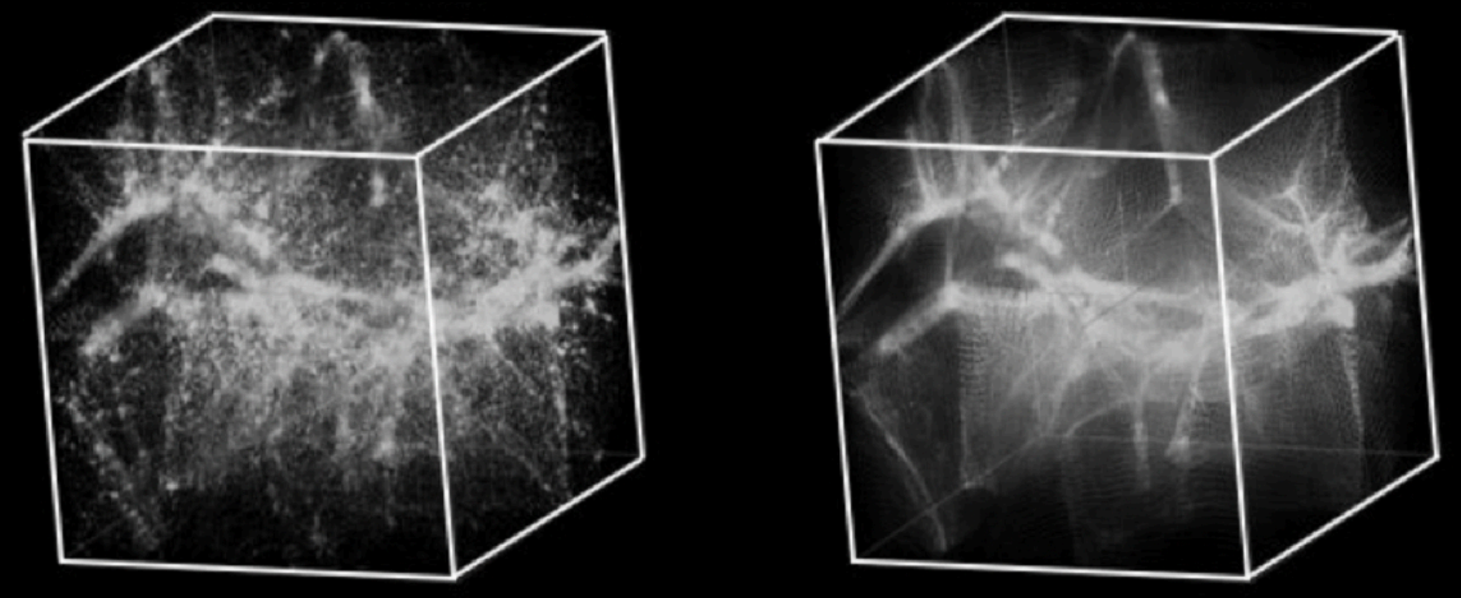


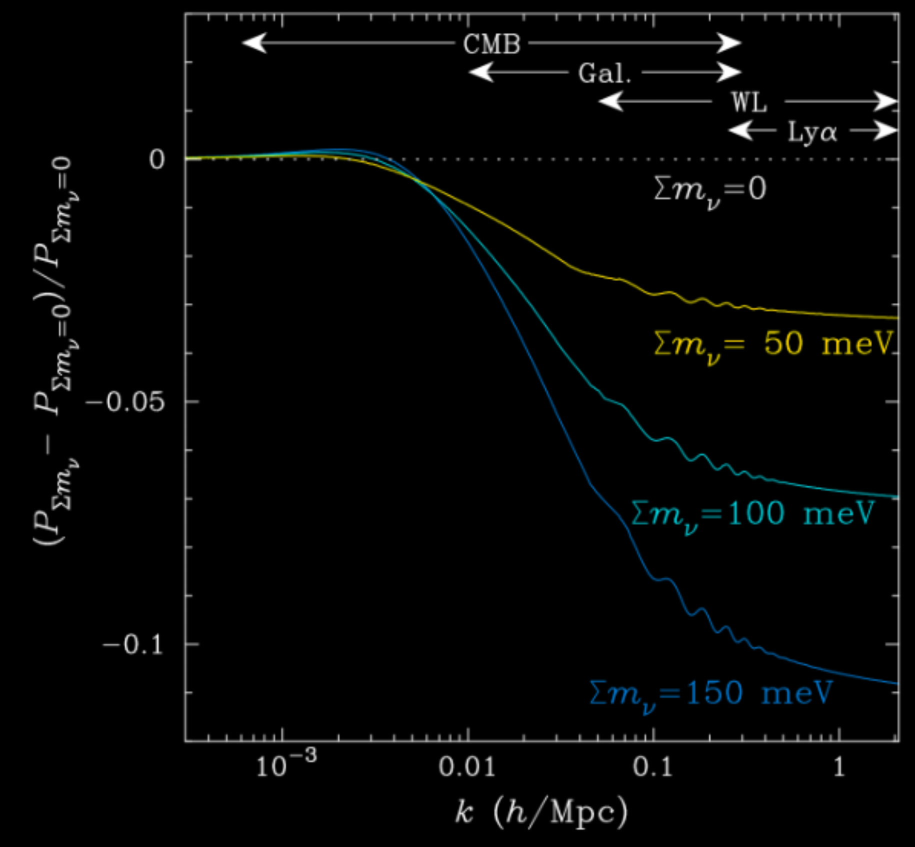
Late times (~matter)

Growth of structures suppressed below the neutrino free-streaming length, resulting in a scale-dependent damping of $P_{\delta\delta}(k)(\rightarrow C_L^{\phi\phi})$

$$k_{\rm fs} = 0.018\,\Omega_m^{1/2}\left(\frac{\sum m_\nu}{1{\rm eV}}\right)^{1/2} h{\rm Mpc}^{-1}$$



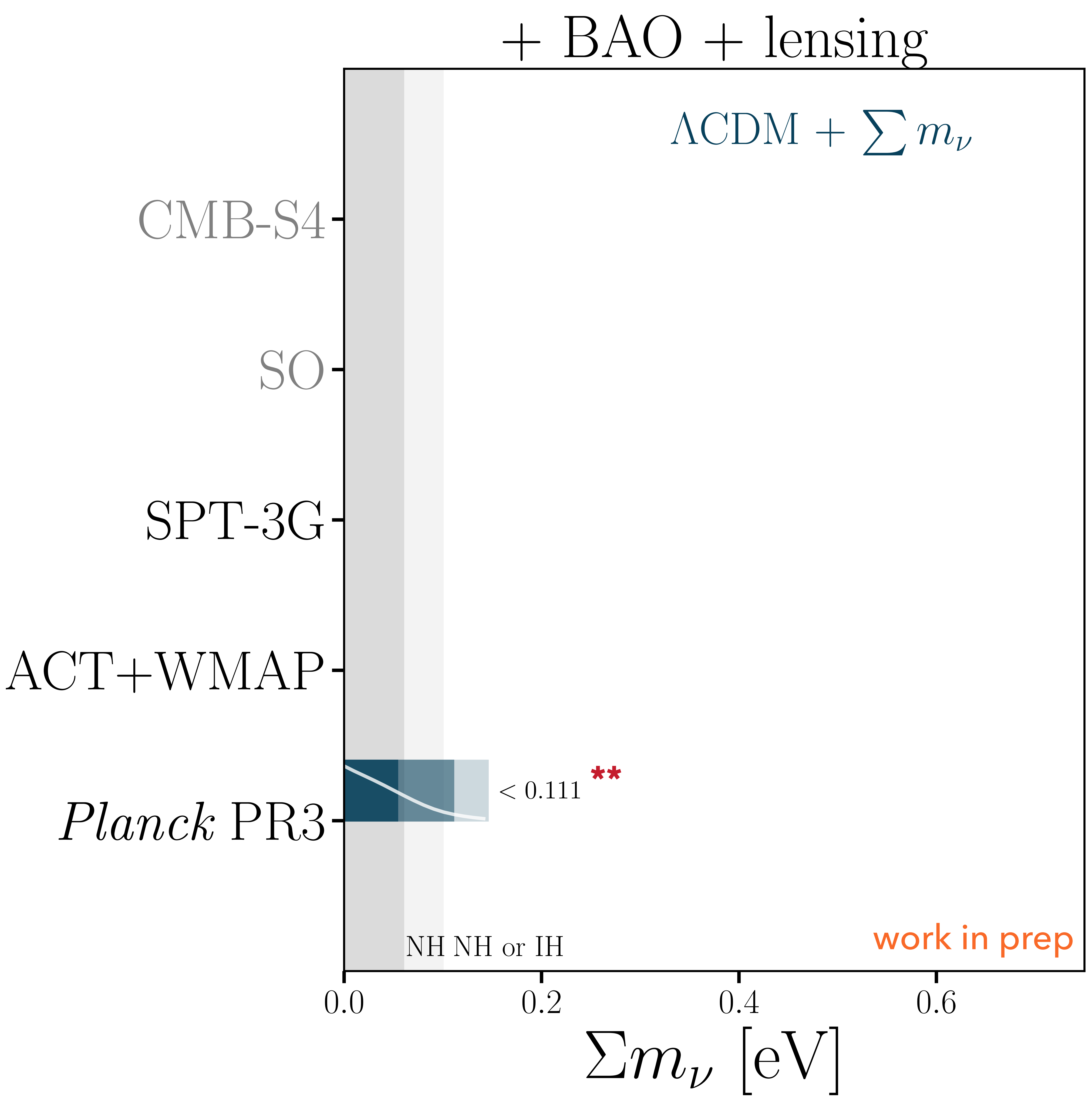
credits: Katrin Heitmann



Abazajian+15

Current constraints on massive neutrinos*

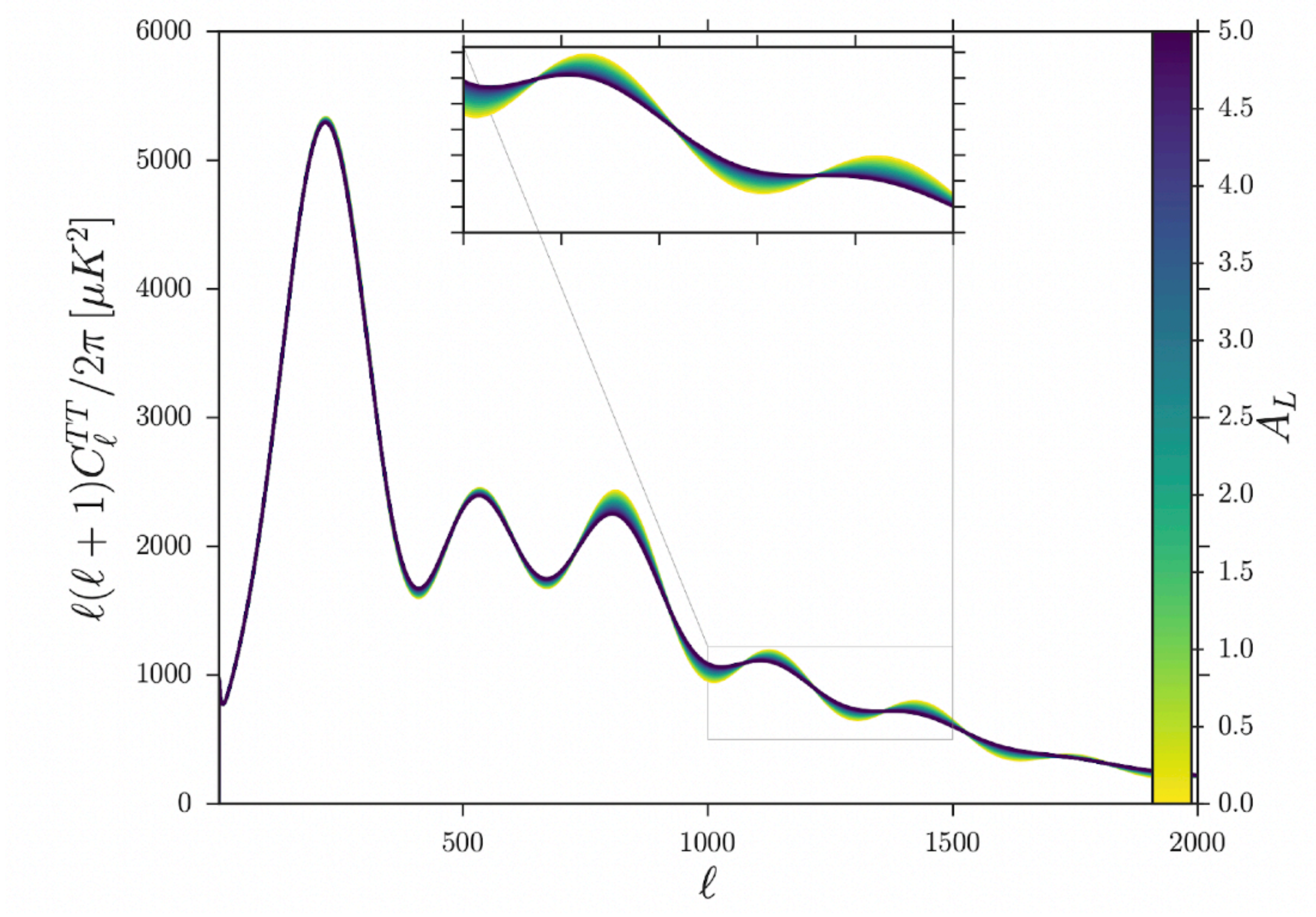
- 🔥 **Disclaimer**: cosmological bounds are model dependent, always state what you vary/assume!
- Baryonic acoustic oscillations (BAO) included to break geometrical degeneracies
- **Tightest upper limit from Planck**
  $\sum m_\nu < 0.11$ **eV** (2σ)
- Limits approaching the minimal mass in the inverted hierarchy scenario…

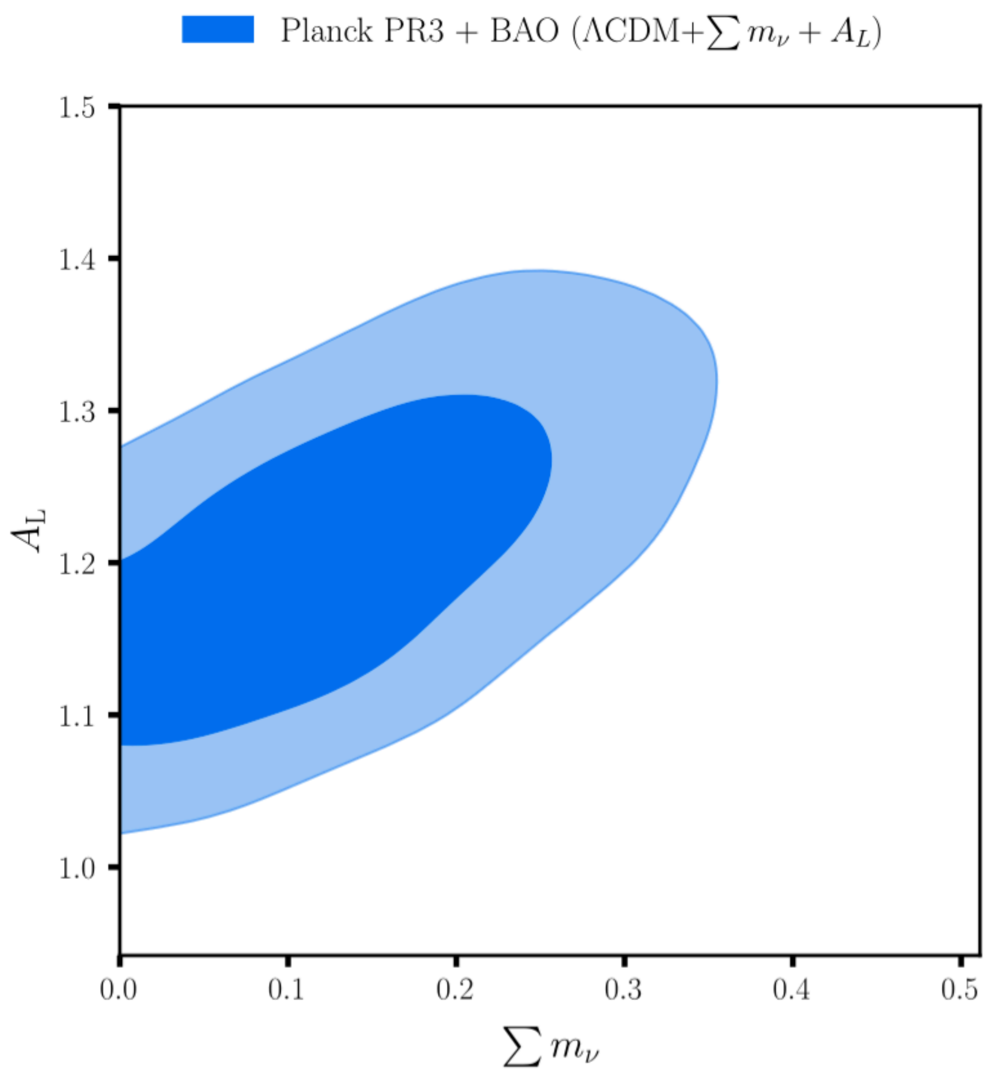


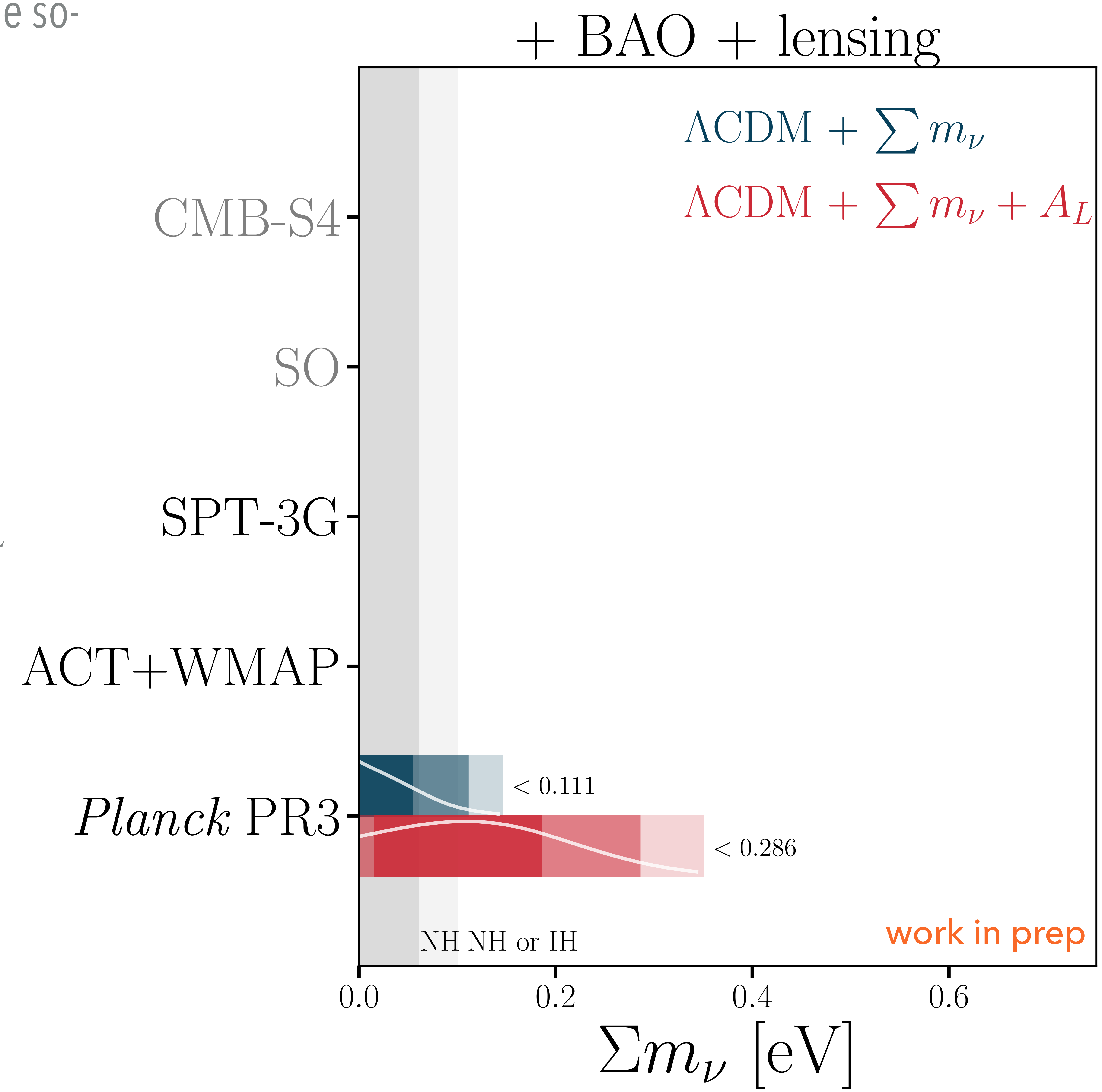
* three degenerate families of massive neutrinos
** 95% C.L.

Current constraints on massive neutrinos — A_L

- Planck's artificially large sensitivity to $\sum m_\nu$ stems from the so-called **lensing anomaly**
- CMB acoustic peaks smearing effect phenomenologically parametrized as $C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi}$
- Planck TT drives preference for $A_L > 1 @ \approx 2.8\sigma$*
- Remove the primary CMB sensitivity to lensing by $\int p(\theta) dA_L$



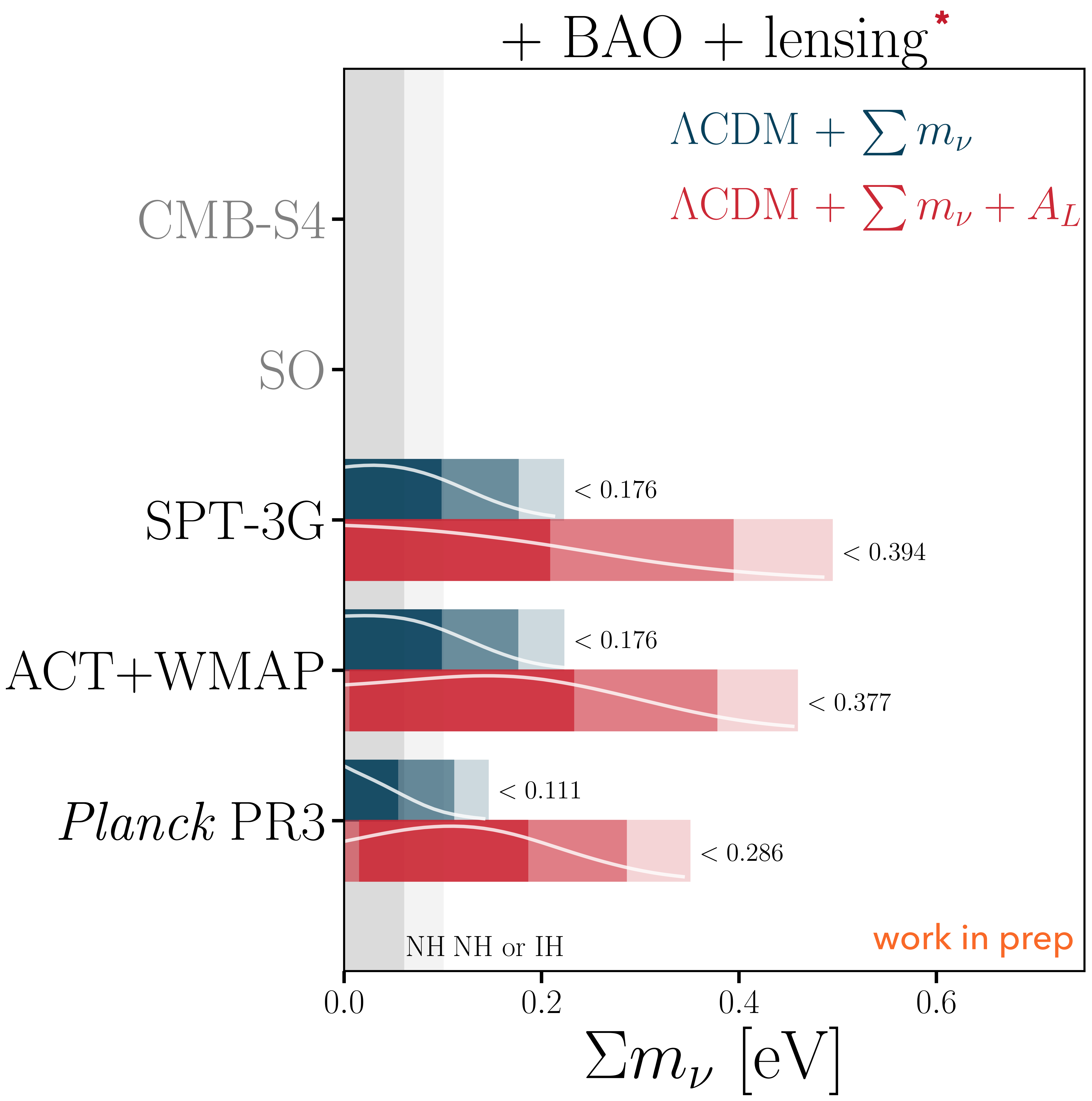




*The magnitude and significance of the anomaly depend on the Planck data release and likelihood, see e.g. Rosenberg+22

Current constraints on massive neutrinos — ground-based

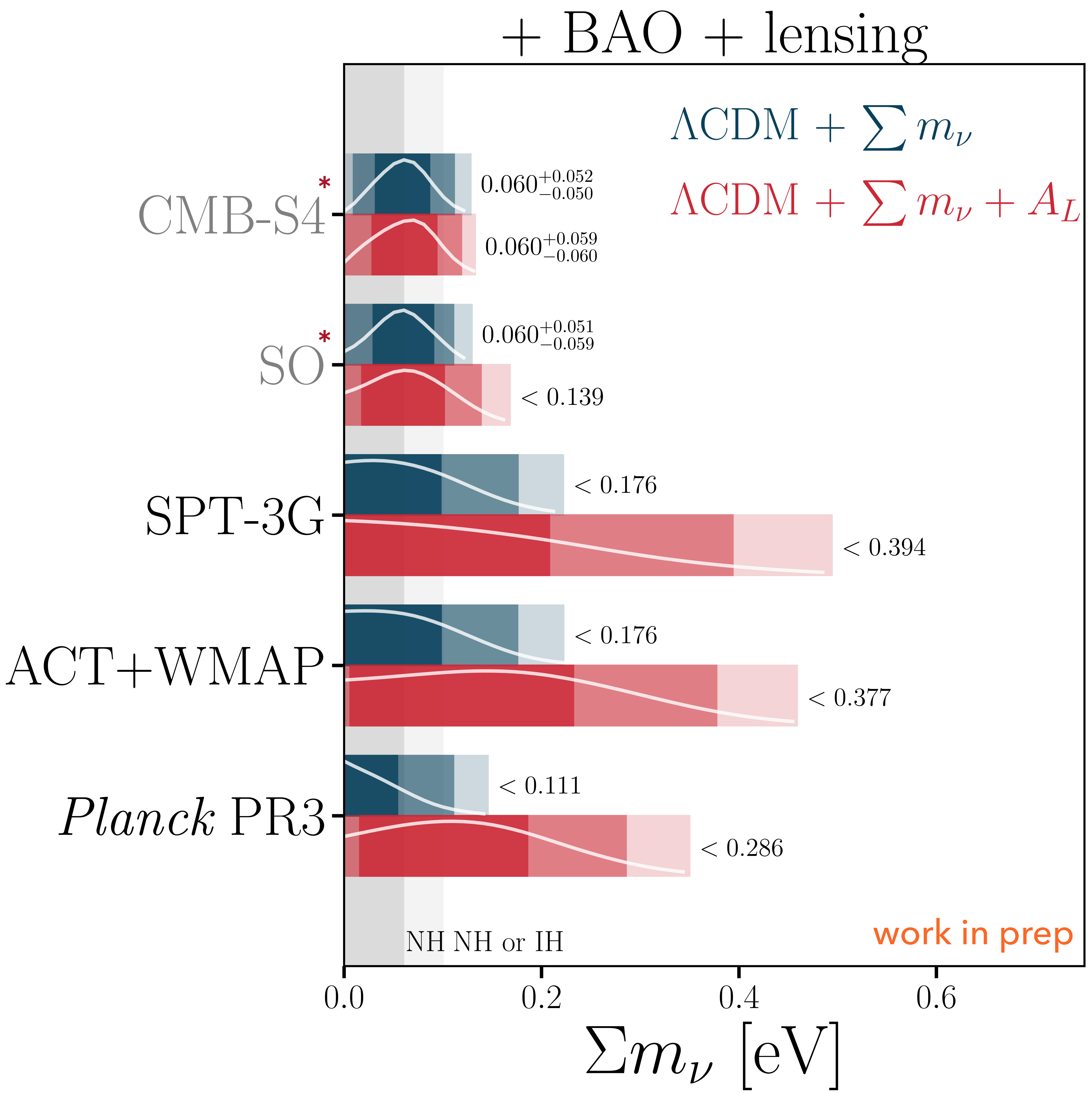
- Ground-based experiments soon to be competitive with Planck
- They don't see the same excess of lensing in the 2pt function
- Peak of the posterior shifts to $\sum m_\nu > 0$ values



*Planck PR4 lensing

Future constraints on massive neutrinos

- Projected sensitivity from CMB-S4 + upcoming BAO at the level of $\sigma(\sum m_\nu) \sim 25$ meV
- Include LSS clustering, Nx2 CMB-LSS cross-correlation, cluster counts to robustly bring sensitivity to $\sigma(\sum m_\nu) \sim 20$ meV
- Desiderata: break $\tau - \sum m_\nu$ degeneracy with future large-scale polarization measurements for $\sigma(\sum m_\nu) \sim 15$ meV

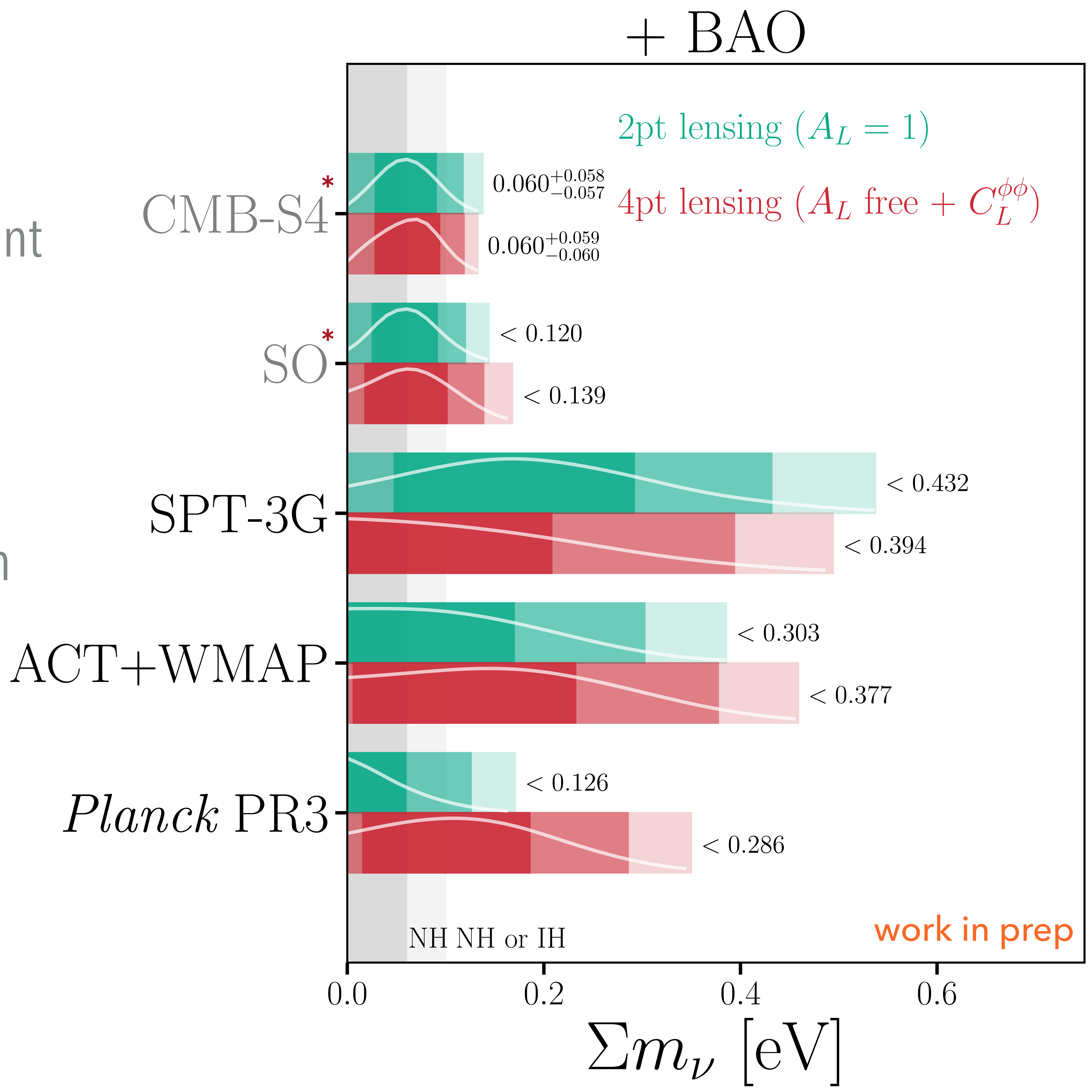


* Forecast: DESI BAO + internal lensing reconstruction

Neutrino constraints from 2pt vs 4pt CMB lensing

- Mass bounds from 2pt vs 4pt lensing are ~ consistent for SPT/ACT (at the level of ~0.3 - 0.4 eV)

- CMB-S4 will enable an internal consistency check on neutrino sensitivity from lensing



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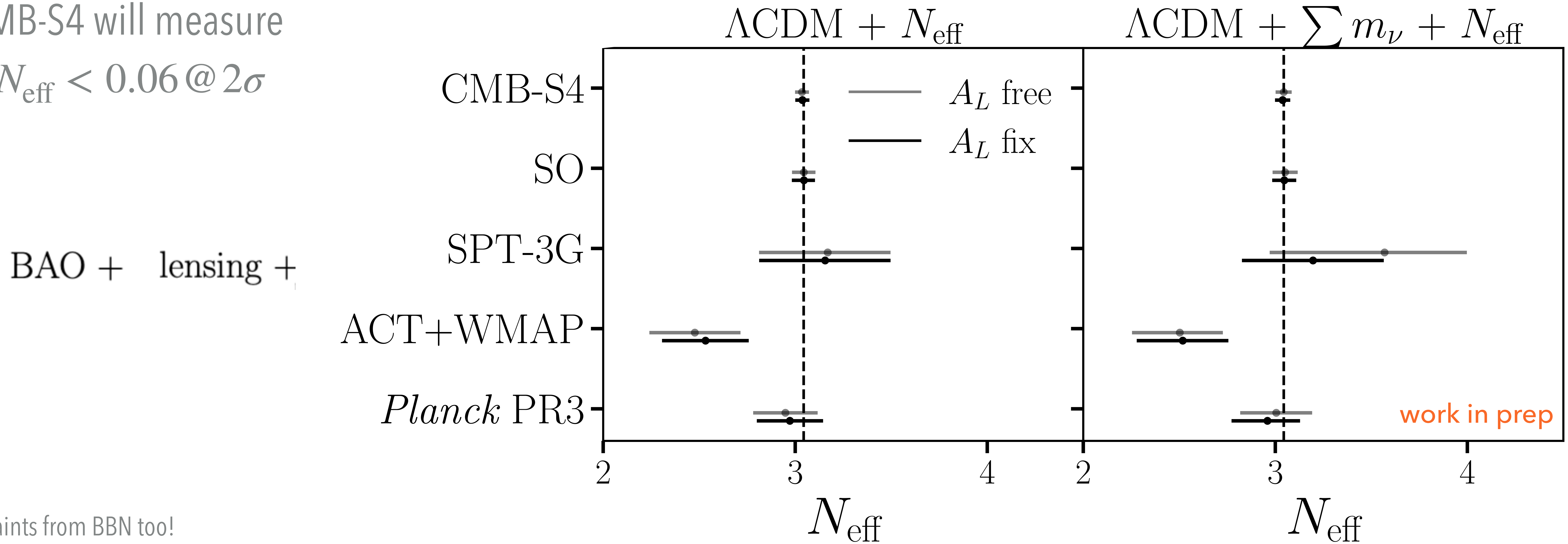
Let there be light (relics)!*

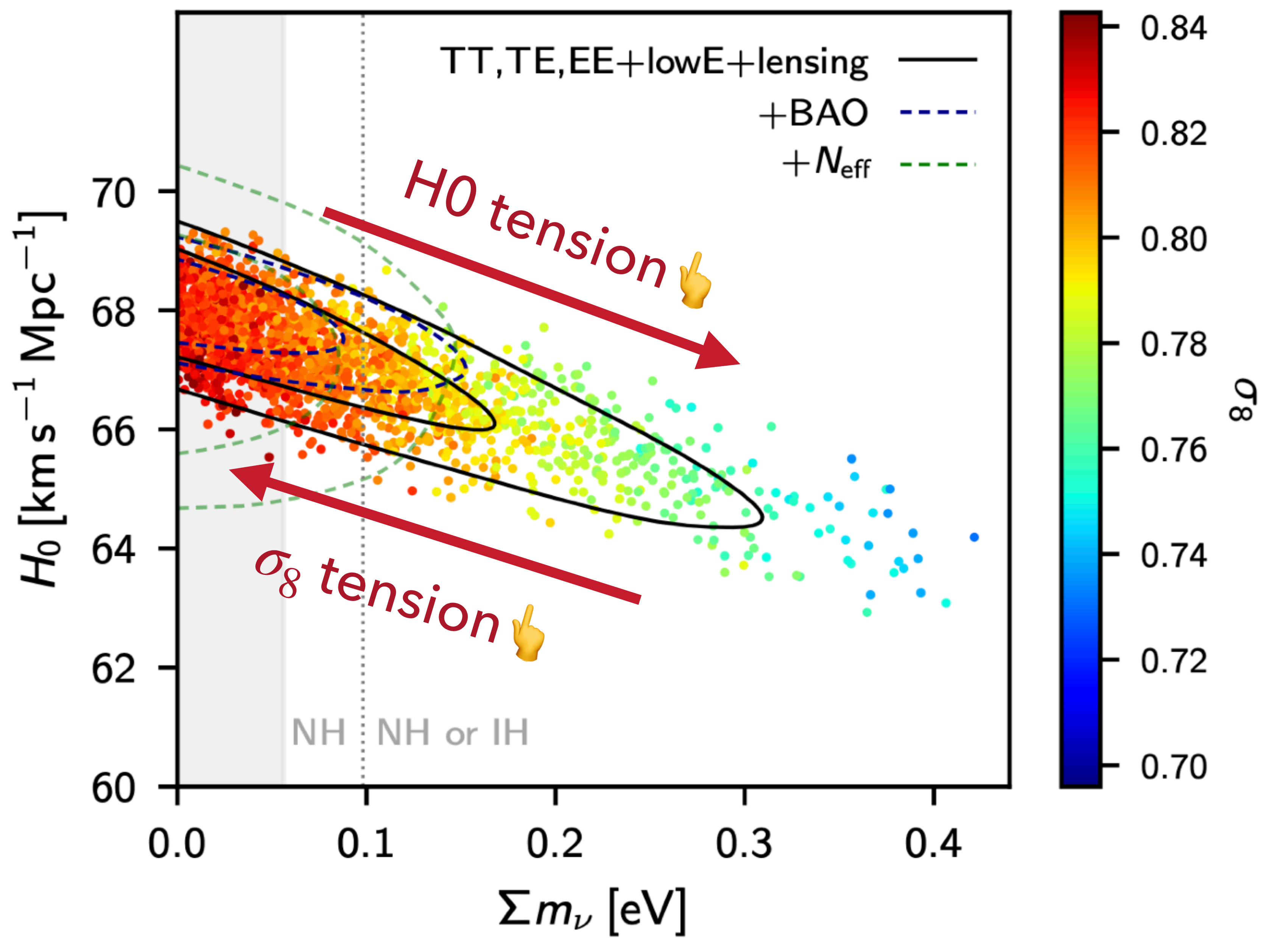
- $N_{\rm eff} = 2.97 \pm 0.17 \rightarrow$ indirect detection of the CνB @ ~17σ!
- Fourth light thermalized neutrino excluded $> 5\sigma$ ==> tension w/ oscillations data?
- Constraints fairly insensitive to lensing anomaly or whether we open $\sum m_\nu$
- CMB-S4 will measure $\Delta N_{\rm eff} < 0.06 @ 2\sigma$

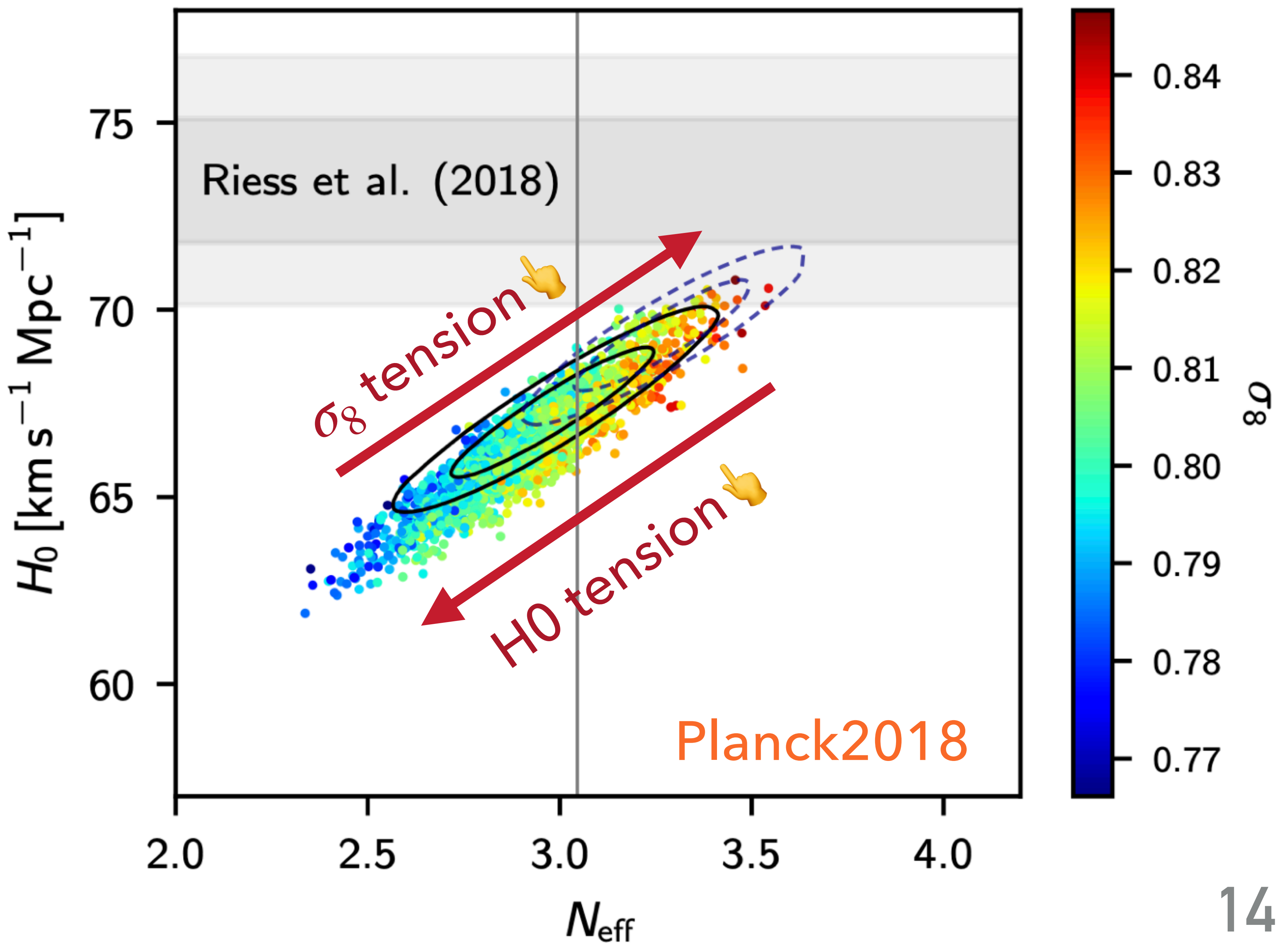


* Tight constraints from BBN too!

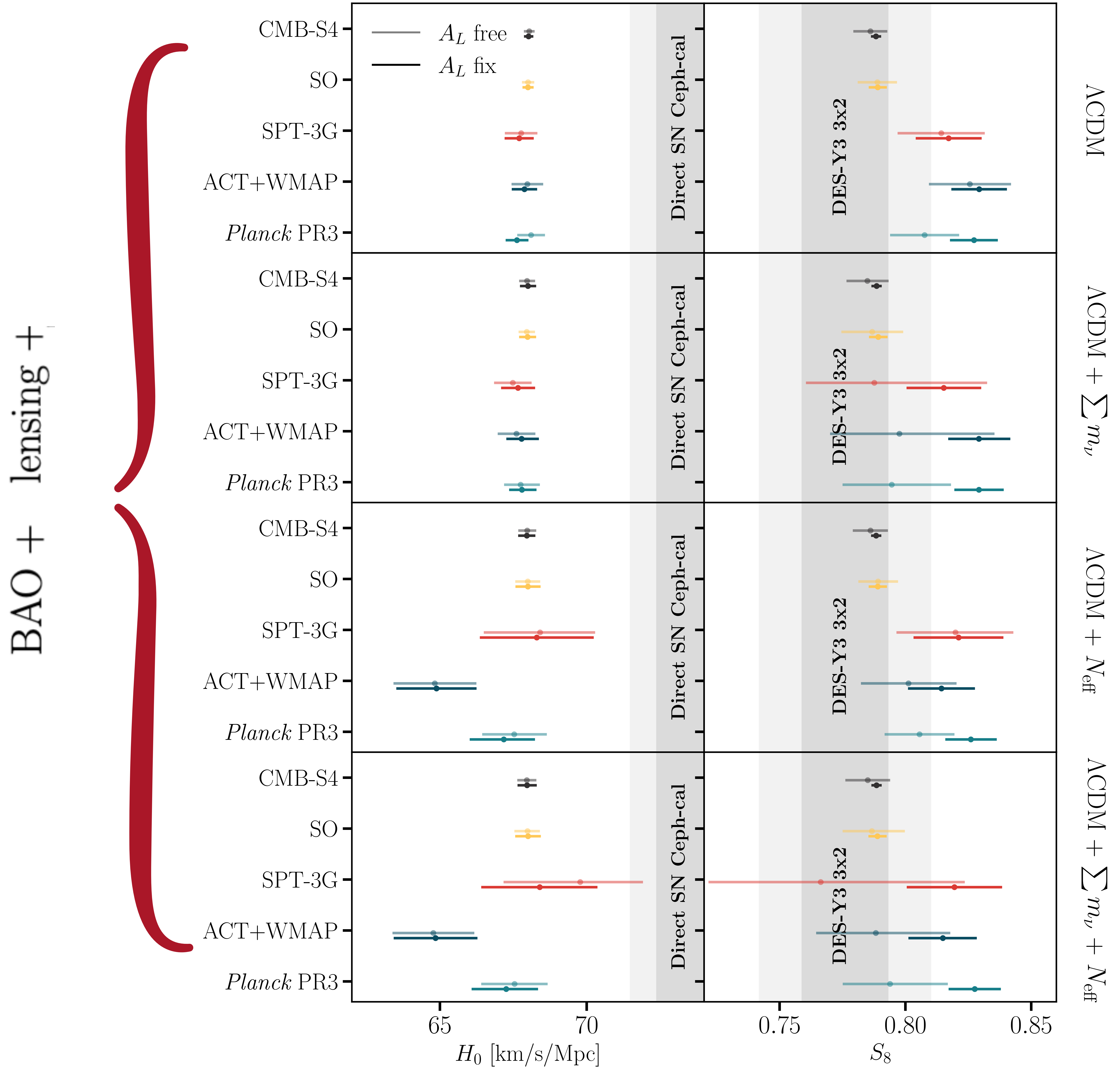
Cosmological tensions & neutrino sector

- The neutrino sector has been invoked since the early Planck releases to explain the H0/S8 tensions (see Wyman+13,Battye&Moss13, Haman&Hasenkamp13,++)
  - Evidence for non-standard neutrino arises from the combination of discordant datasets (Planck vs local H0 / SZ clusters / …)
- No one-size-fits-all solution
  - Increasing the neutrino mass –> pushes H0 low
  - Increasing # of relativistic species –> pushes S8 high





Tensions cntd



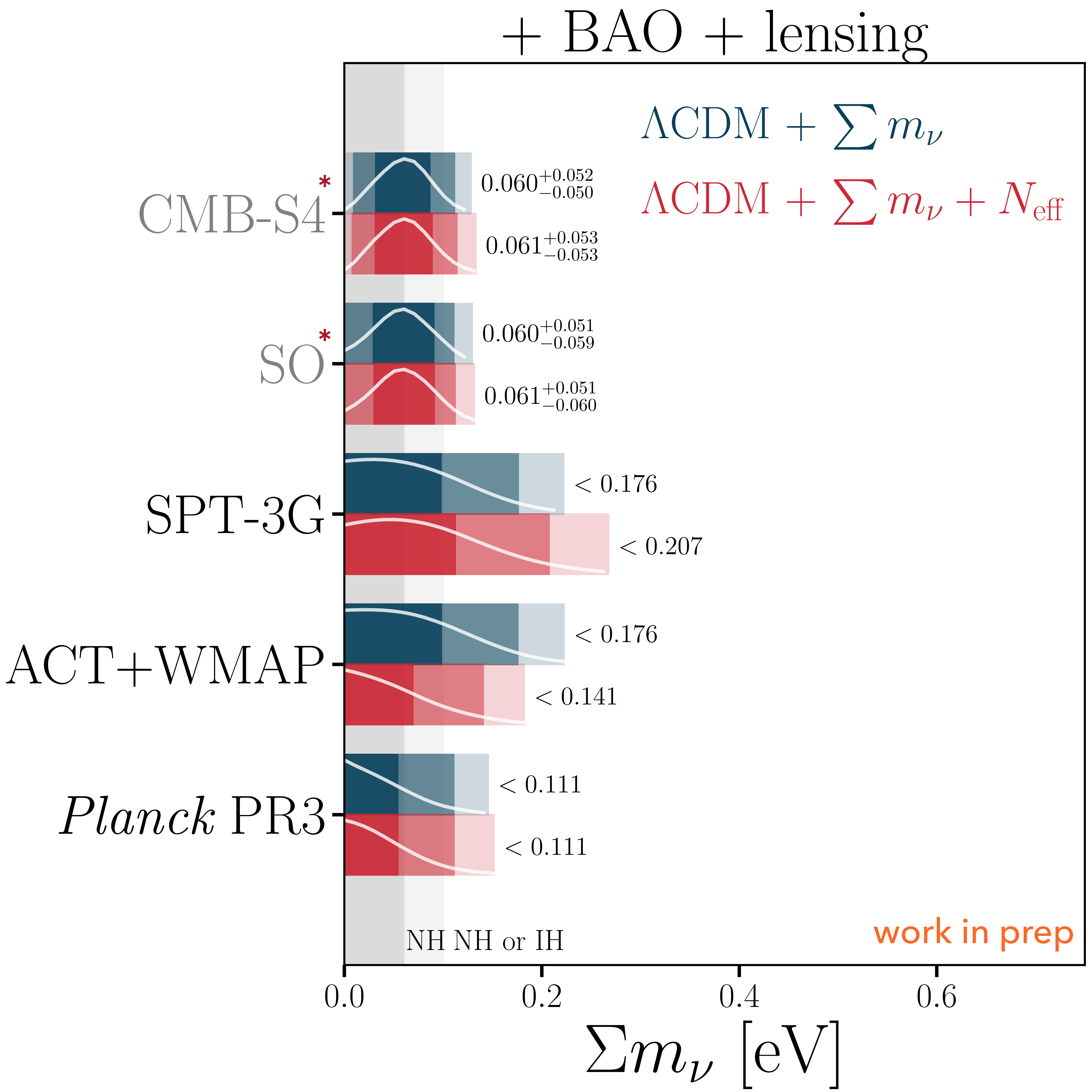
work in prep

Conclusions

- Cosmology complementary/competitive with lab searches
- Planck consistent with 3 active neutrinos and $\sum m_\nu \lesssim 0.1$ eV (but lensing anomaly!)
- Minimal extensions in the neutrino sector cannot fully accomodate cosmological tensions
- Next-generation surveys can make a 3-5σ measurement of $\sum m_\nu$
- Going forward: degeneracies with τ and other params (w!)


Thanks!

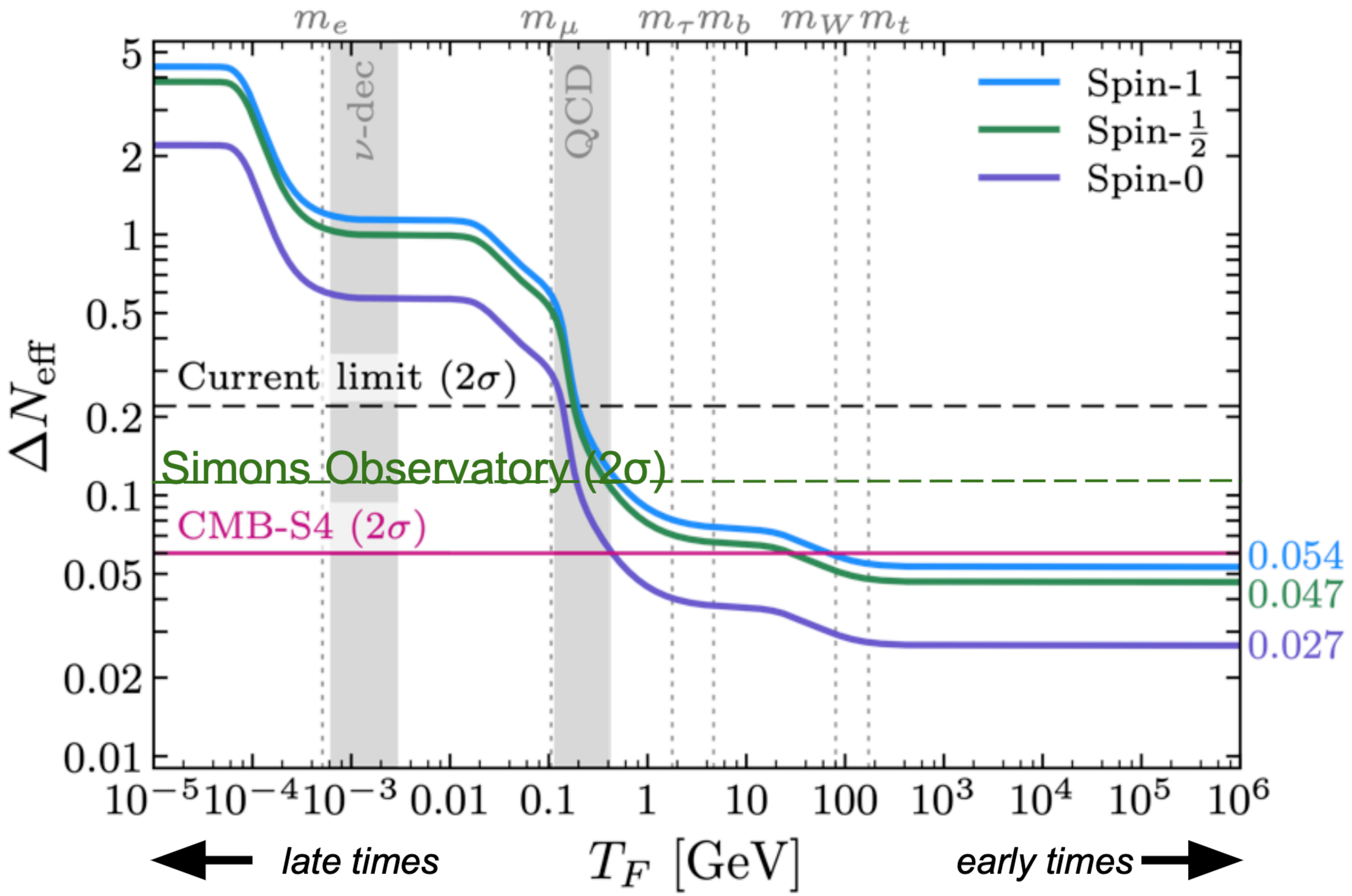
Mass bounds mostly unaffected by $N_{\rm eff}$



* Forecast: DESI BAO + internal lensing reconstruction

#2 The Dark Universe

CMB-S4 will detect or strongly constrain departures from the thermal history of the Universe predicted by the Standard Model of particle physics



- Measure the TT, TE, EE + lensing power spectra

Science reqt #2

- **ΔNeff < 0.06 at 95% C.L.**

CMB-S4