Neutrinos: What the CMB Can Show, and What Other Experiments Can Show the CMB

Towards Coordination of the European CMB Programme

Paris, September 13th, 2019

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Neutrinos are part of the standard model of particle physics….

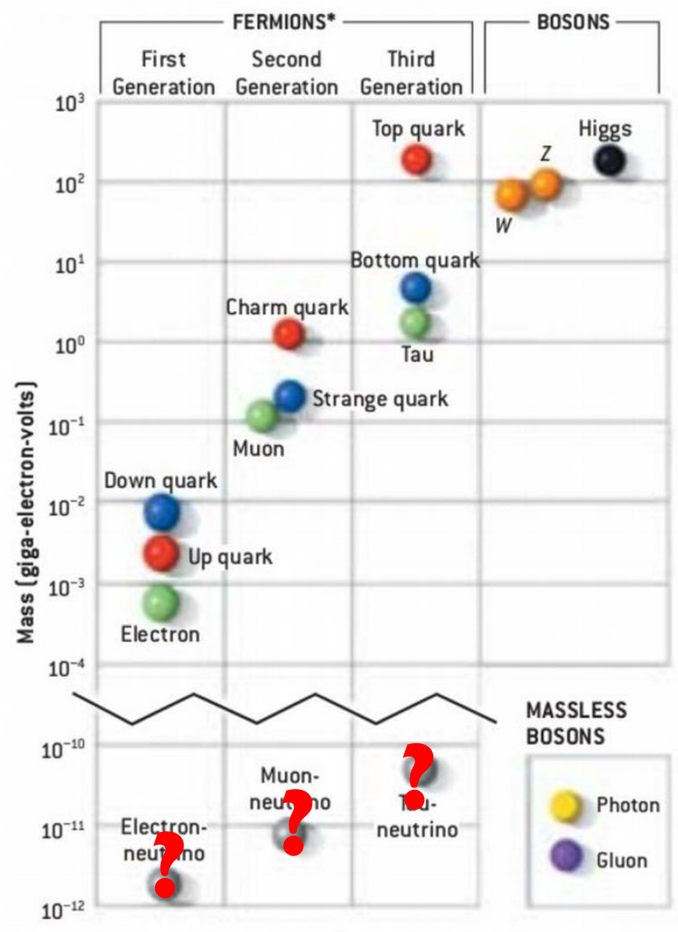

Image credit: G. Kane

… however their properties might be related to physics beyond the SM

Many open questions to date:

- absolute mass scale?
- origin of (small) masses?
- origin of mixing pattern?
- mass hierarchy?
- Majorana or Dirac?
- CP violation?

Three-neutrino mixing

Neutrino flavour eigenstates are superpositions of the mass eigenstates

$$|\nu_\alpha> = \sum_i U^*_{\alpha i}|\nu_i>$$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$
$$\times\, \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

PMNS matrix

3 mixing angles
1 CP-violating Dirac phase
2 CP-violating Majorana phases

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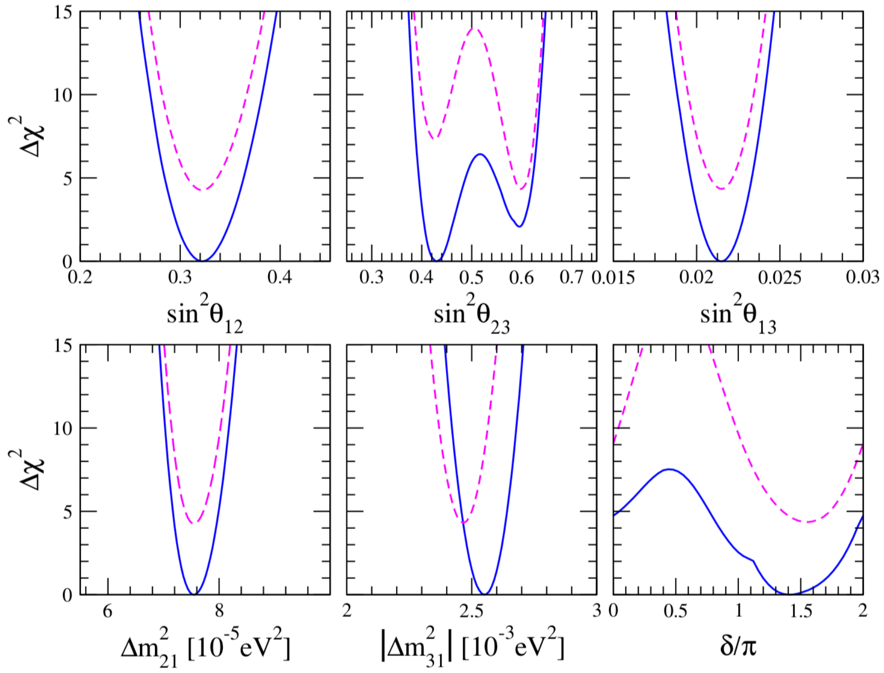
$$\times \, \mathrm{diag}(1, \; e^{i\frac{\alpha_{21}}{2}}, \; e^{i\frac{\alpha_{31}}{2}}) \; .$$

PMNS matrix

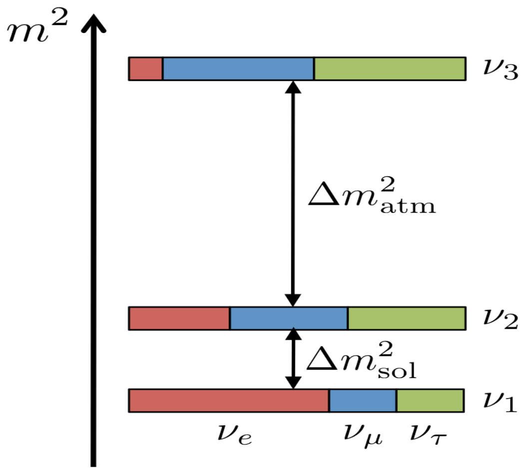
3 mixing angles
1 CP-violating Dirac phase
2 CP-violating Majorana phases

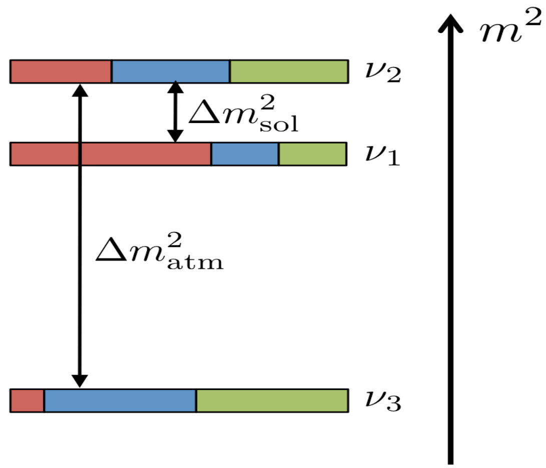
+ 3 masses (1 mass scale, 2 mass differences)



Gariazzo et al. 2018; see also Capozzi et al. 2018; Esteban et al. 2018

normal hierarchy (NH) **vs.** **inverted hierarchy (IH)**





Σm_ν > 0.06 eV

Σm_ν > 0.10 eV

The **absolute mass scale** can be measured through:

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2} < 2.05 - 2.3 \text{ eV @ 95\%CL}$$

(Troisk-Mainz)

- neutrinoless double beta decay

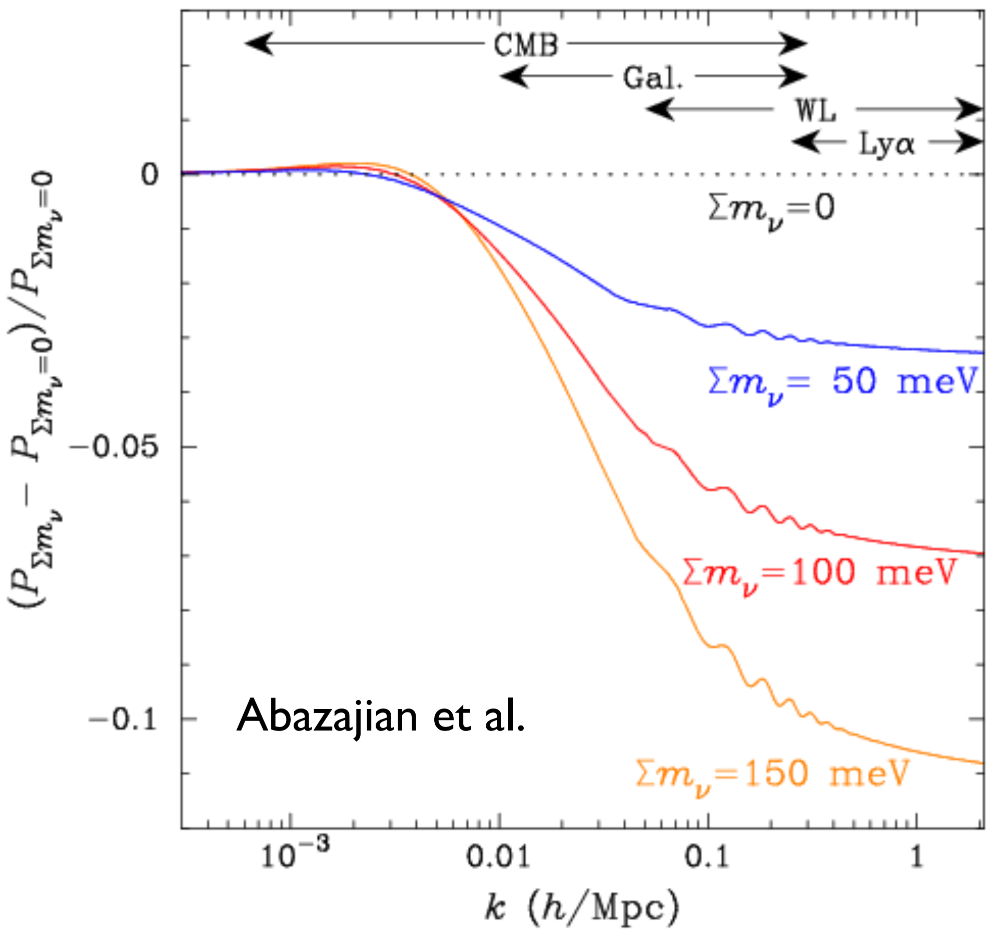
$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right| \quad < \; 0.06 - 0.16 \text{ eV @ 90\%CL}$$

(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i \quad < 0.12 - 0.24 \text{ eV @ 95\%CL}$$

(Planck+$\cdots$)



In a Universe with neutrinos, small-scale density perturbations are suppressed due to collisionless damping (free-streaming).

Neutrinos are collisionless and have large thermal velocities (they have been relativistic for most of the history of the Universe).

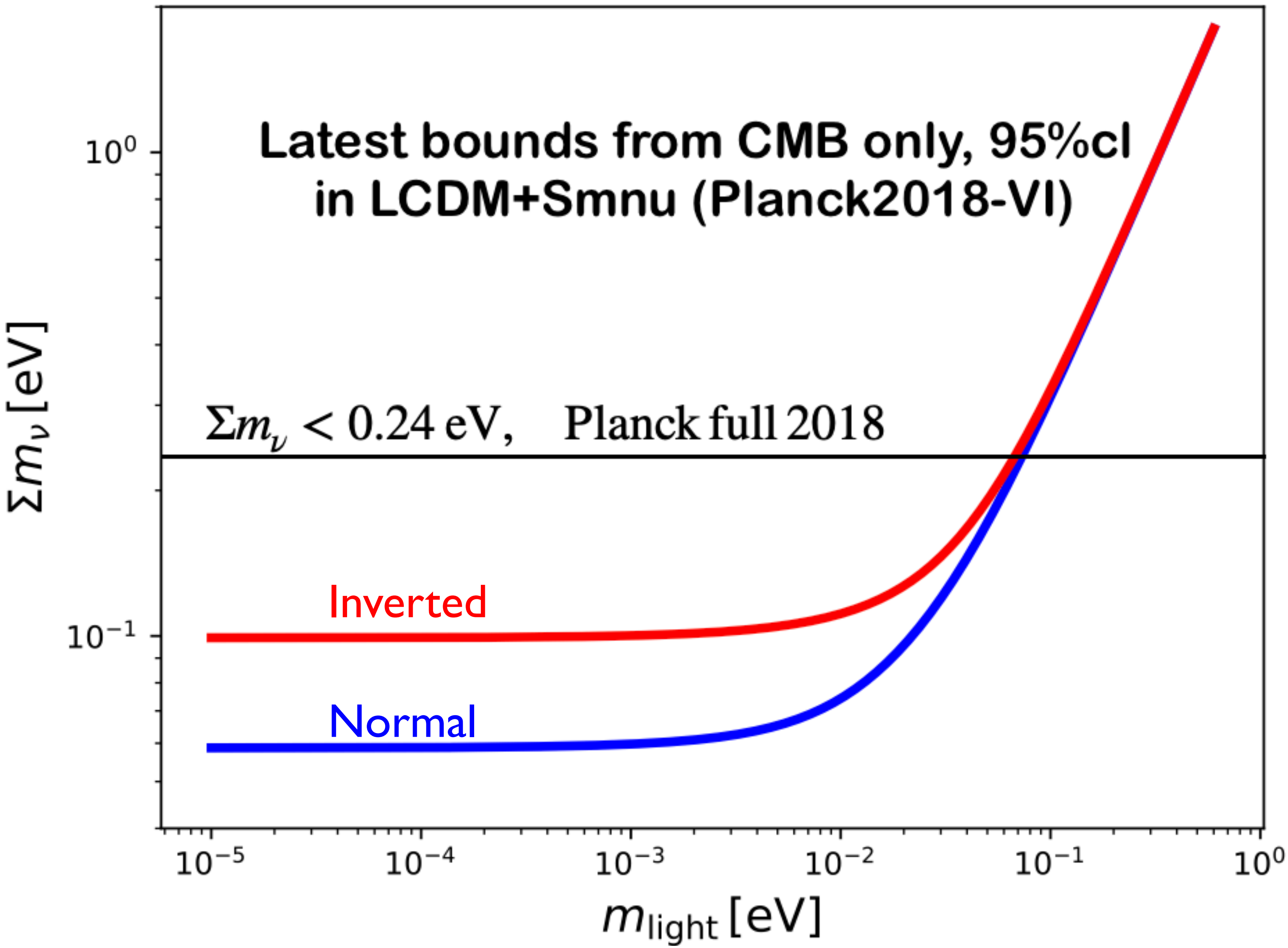
They do not cluster below a critical scale, the free-streaming length (corresponding to the scale of the horizon at the time of the nonrelativistic transition).

In principle the effect can be seen directly in the matter power spectrum

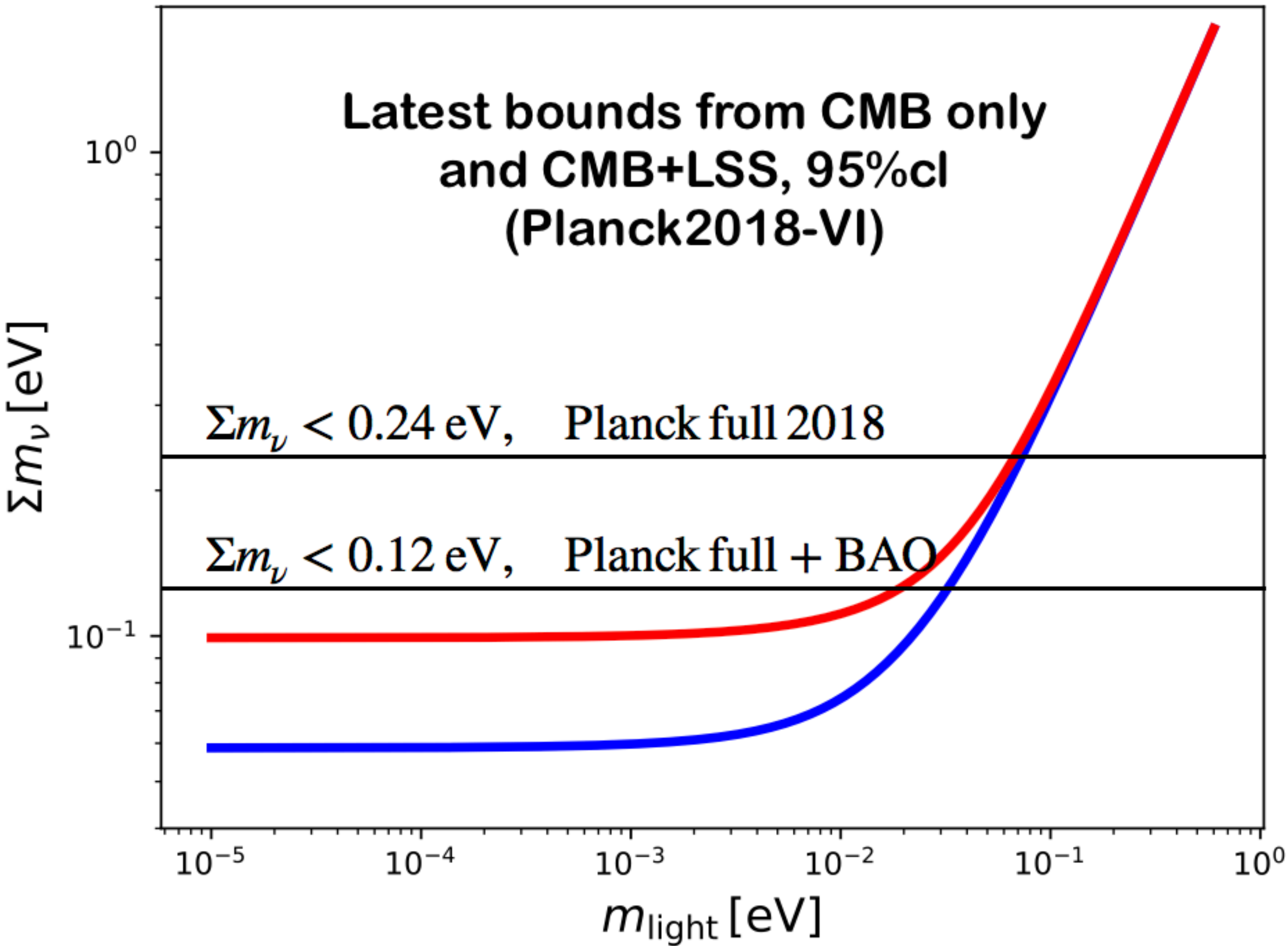
There are issues however: non-linearities, scale-dependent bias……

At small scales:

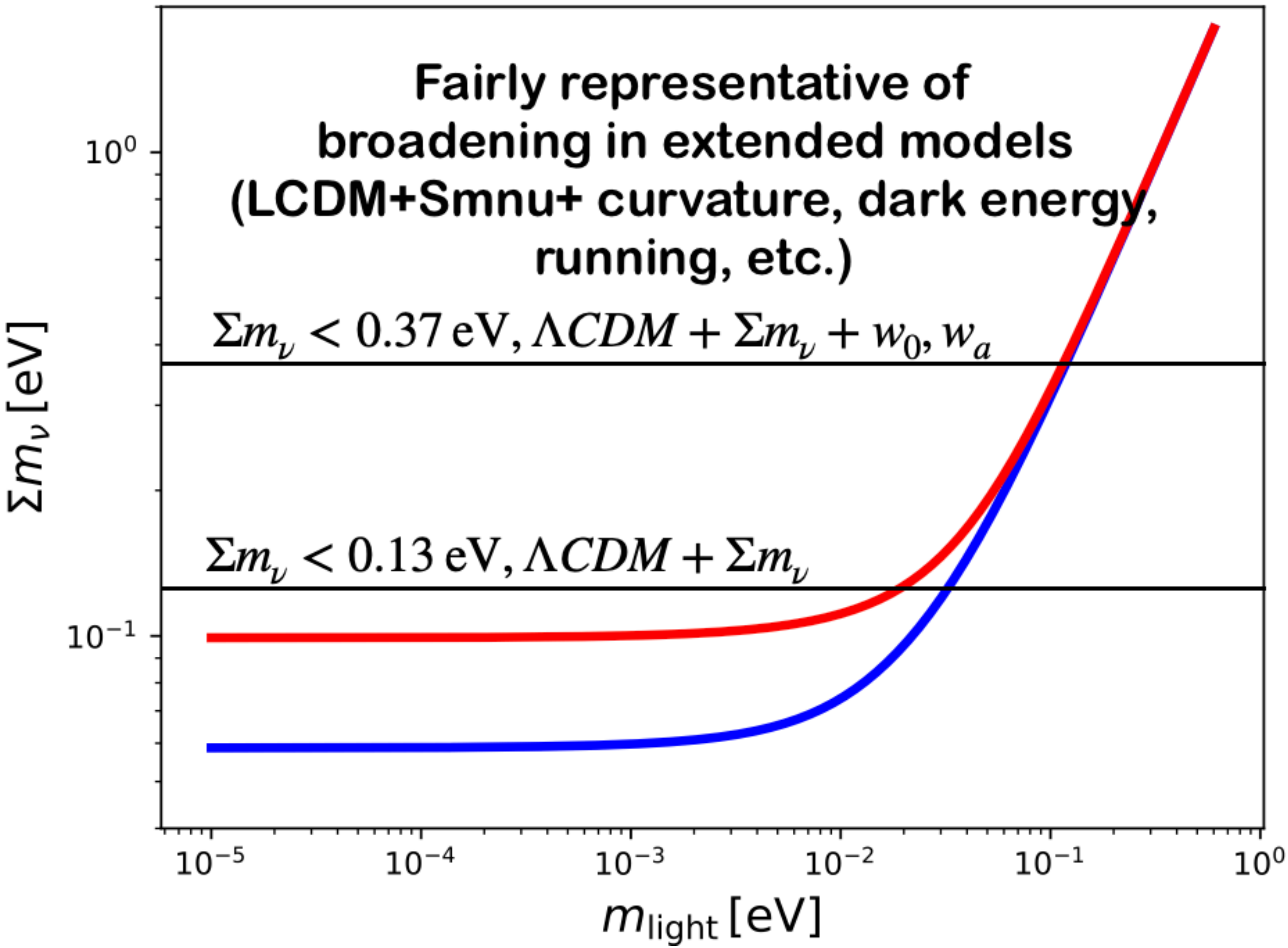
$$\frac{P(M_\nu) - P(M_\nu = 0)}{P(M_\nu = 0)} = -8\frac{\Omega_\nu}{\Omega_m}$$



Latest bounds from CMB only, 95%cl
in LCDM+Smnu (Planck2018-VI)
$\Sigma m_\nu < 0.24$ eV, Planck full 2018
Inverted
Normal
10^0
10^{-1}
Σm_ν [eV]
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0
$m_{\rm light}$ [eV]



Latest bounds from CMB only
and CMB+LSS, 95%cl
(Planck2018-VI)
$\Sigma m_\nu < 0.24$ eV, Planck full 2018
$\Sigma m_\nu < 0.12$ eV, Planck full + BAO
Σm_ν [eV]
$m_{\rm light}$ [eV]
10^0
10^{-1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0



Fairly representative of
broadening in extended models
(LCDM+Smnu+ curvature, dark energy,
running, etc.)
$\Sigma m_\nu < 0.37\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu + w_0, w_a$
$\Sigma m_\nu < 0.13\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu$
10^0
10^{-1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
Σm_ν [eV]
m_light [eV]

To increase sensitivity to neutrino masses AND reduce model dependency, we need:

- Precise measurement of the CMB lensing signal (both from 2- and 4-point correlation functions)
- Cosmic variance limited measurement of the reionization optical depth
- other CMB probes of structure formation, e.g. SZ galaxy clusters

+ non CMB information

- BAO information to reduce geometrical degeneracies
- Full shape of the matter power spectrum
- CMB/LSS cross correlations

SO Forecasts for neutrino mass bounds

- CMB lensing from SO combined with DESI BAO

$$\sigma(\Sigma m_\nu) = 0.04\,\mathrm{eV}\ [0.03\,\mathrm{eV}]$$

- Sunyaev-Zeldovich cluster counts from SO calibrated with LSST weak lensing

$$\sigma(\Sigma m_\nu) = 0.04\,\mathrm{eV}\ [0.03\,\mathrm{eV}]$$

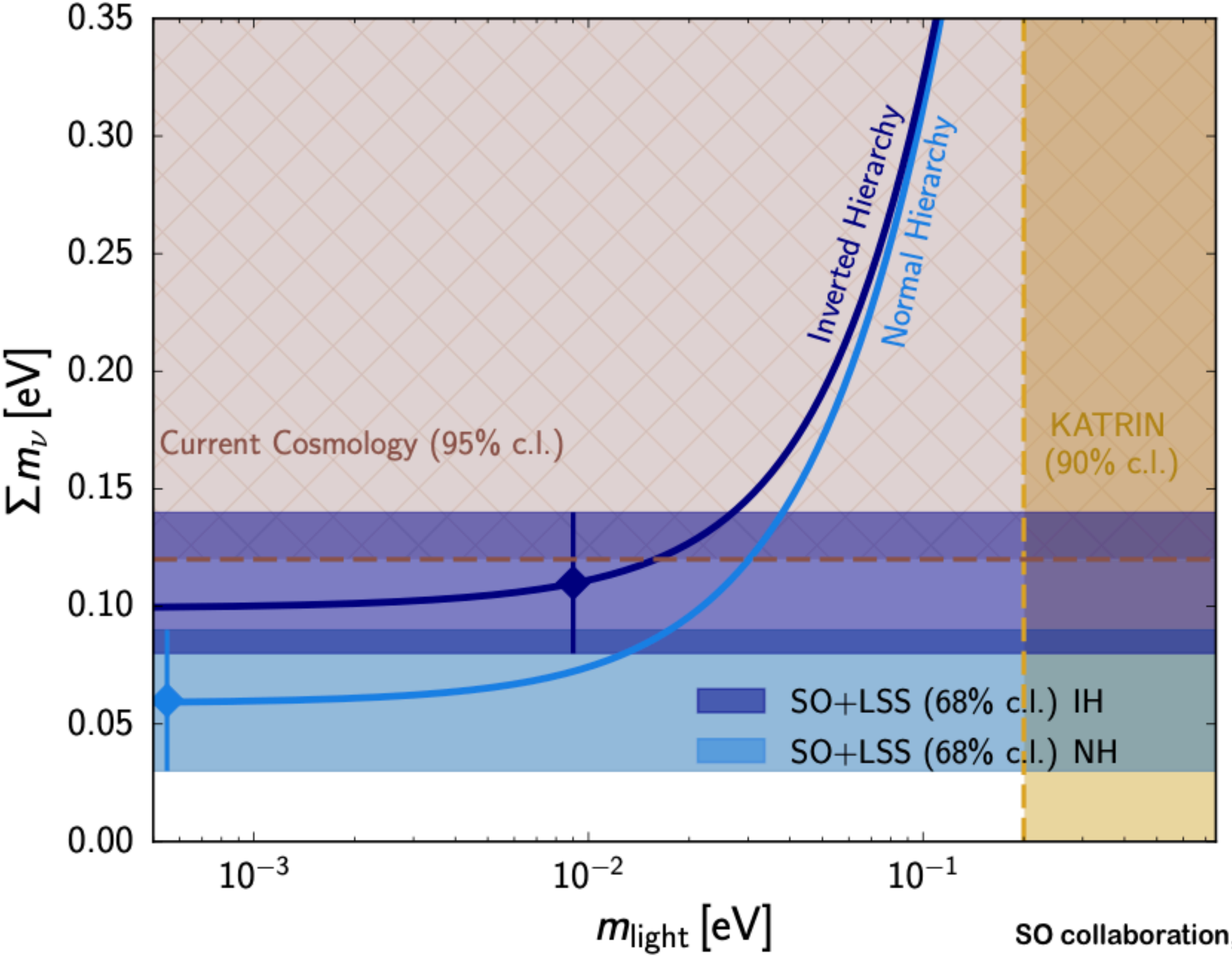
- thermal SZ distortion maps from SO combined with DESI BAO

$$\sigma(\Sigma m_\nu) = 0.05\,\mathrm{eV}\ [0.04\,\mathrm{eV}]$$

- legacy SO dataset combined with cosmic-variance-limited measurement of reionization optical depth

$$\sigma(\Sigma m_\nu) = 0.02\,\mathrm{eV}$$

SO collaboration, 2018

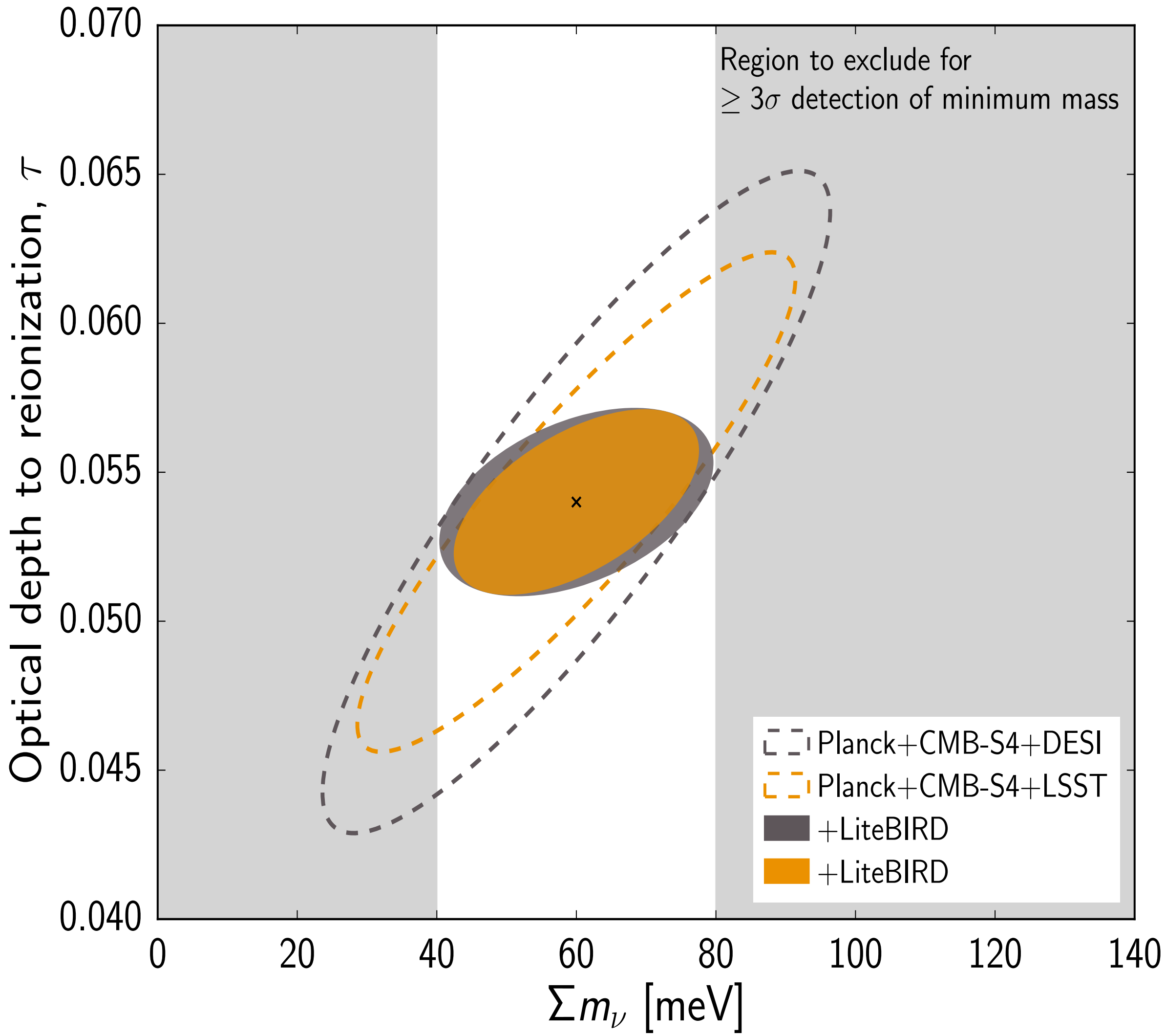


SO collaboration, 2018

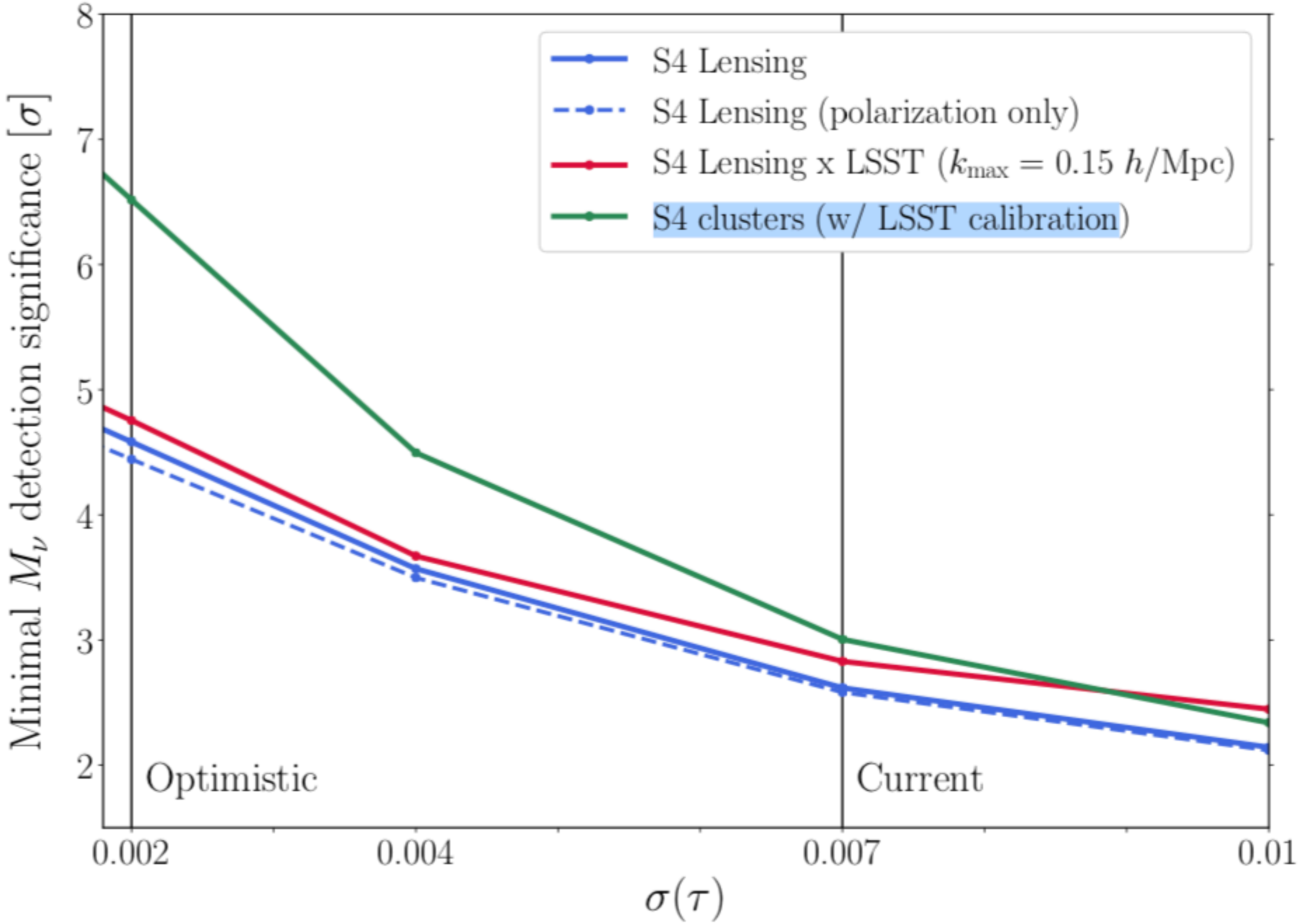
Σm_ν w/ improved τ

- $\sigma(\Sigma m_\nu)$ = 15 meV
- $\geq 3\sigma$ detection of minimum mass for normal hierarchy
- $\geq 5\sigma$ detection of minimum mass for inverted hierarchy

Caveat:
No systematic error included yet.

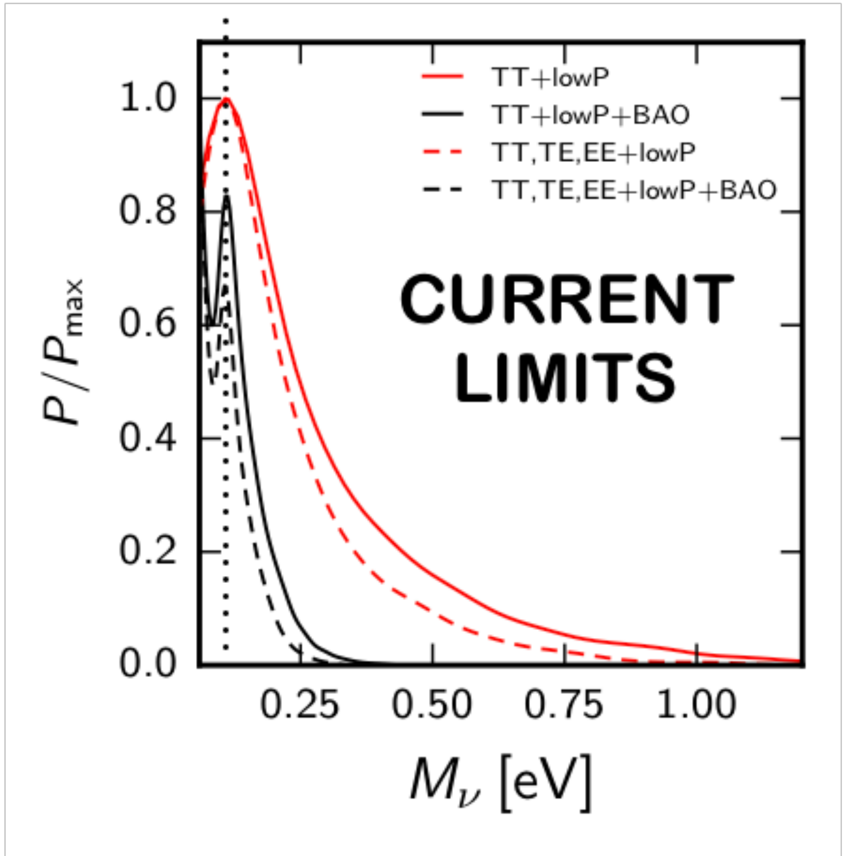


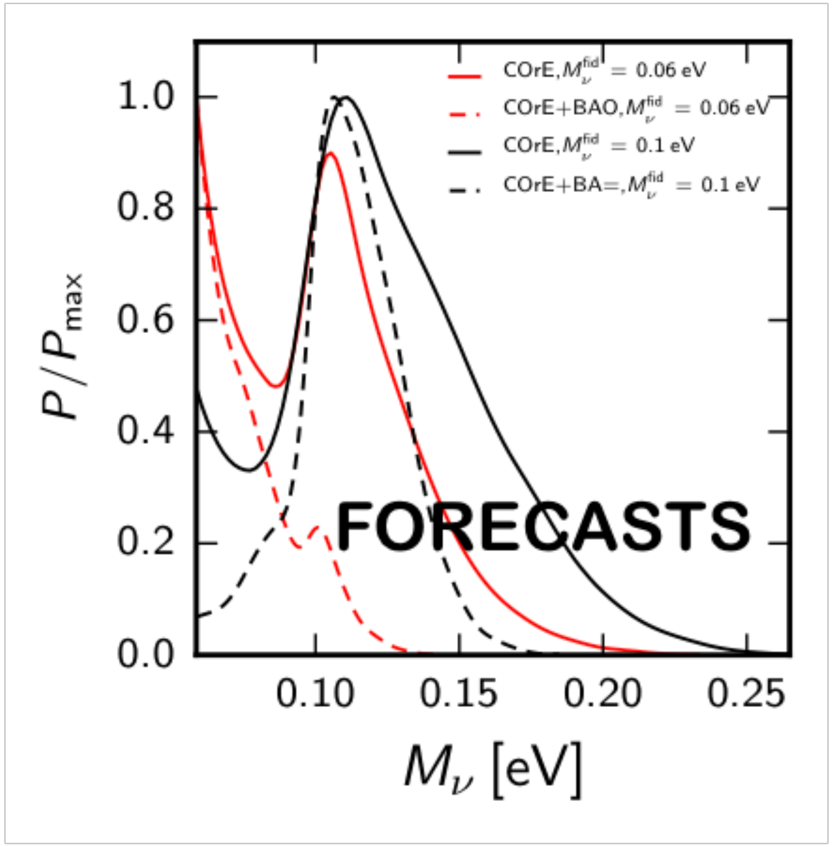
Credit: M. Hazumi



S4 Lensing
S4 Lensing (polarization only)
S4 Lensing x LSST ($k_{\rm max} = 0.15\ h/\mathrm{Mpc}$)
S4 clusters (w/ LSST calibration)
Optimistic
Current
Minimal M_ν detection significance [σ]
$\sigma(\tau)$
0.002
0.004
0.007
0.01
2
3
4
5
6
7
8

Sensitivity to the hierarchy





Gerbino,Lattanzi,Mena,Freese 2016

$$\mathcal{P}(h=NH):\mathcal{P}(h=IH)$$

$$\mathcal{P}(h=NH):\mathcal{P}(h=IH)$$

.... **3:2**

.... **0.06eV mass -> 9:1**

.... **0.1eV mass -> 1:1**

See also Hannestad&Schwetz,2016

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- tritium beta decay

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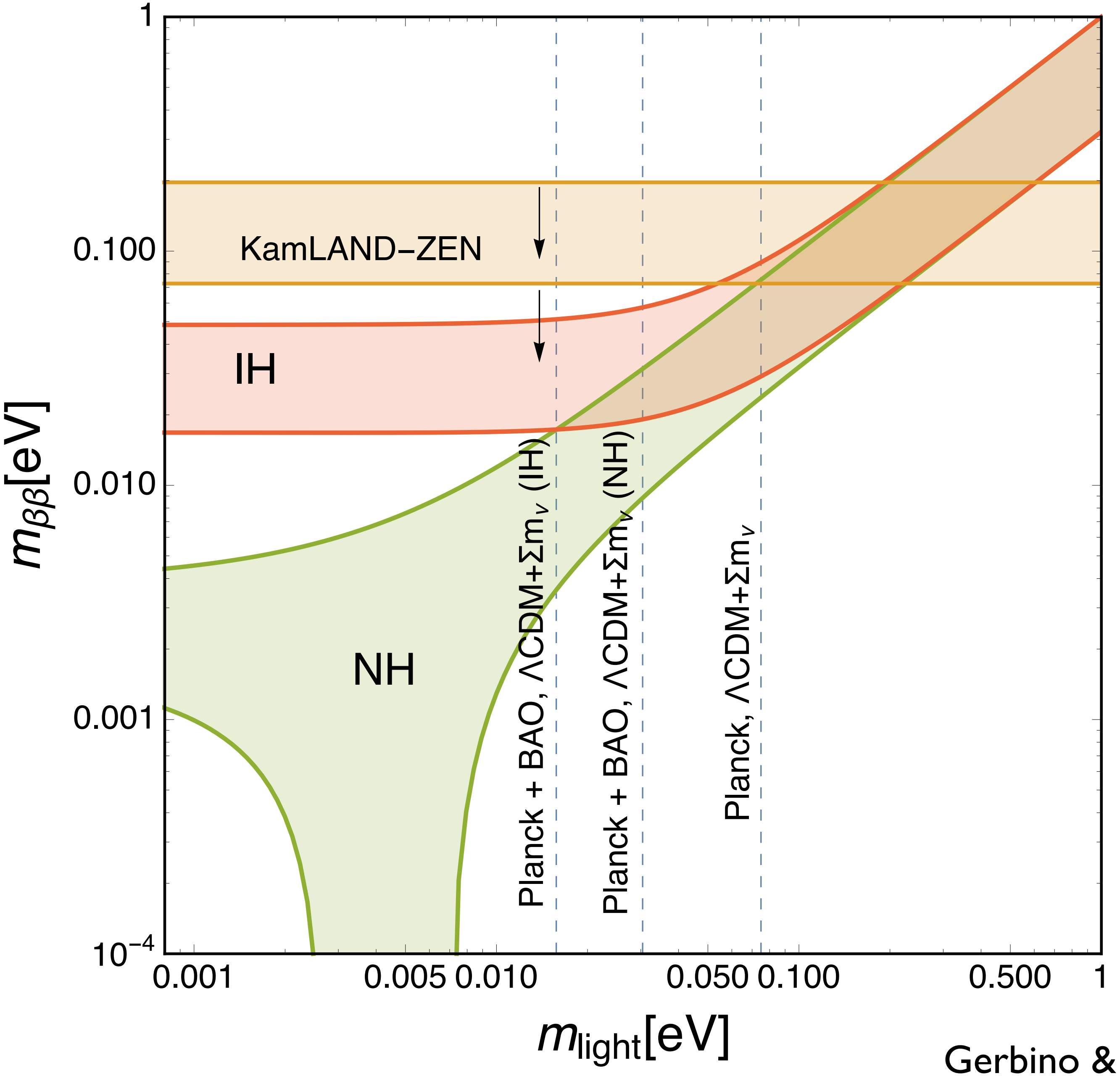
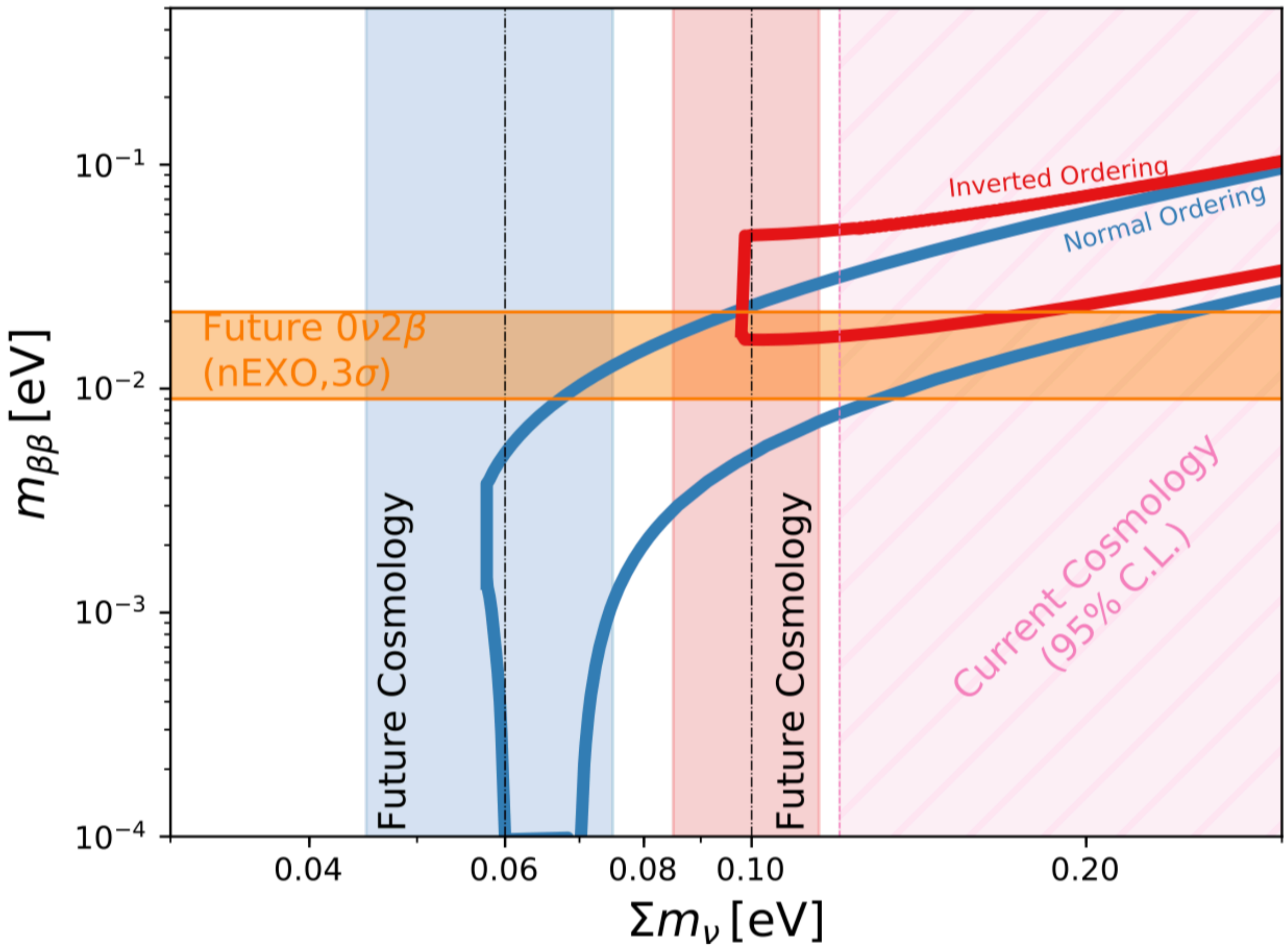
(Planck+$\cdots$)

Complementarity with laboratory probes



Gerbino & Lattanzi 2018

Complementarity with laboratory probes



S4 collaboration, 2019

Several interesting scenarios are possible (I am being sketchy here):

- Concordant signals from both cosmology and 0nu2b. Neutrinos are Majorana. Hierarchy might be determined or not.

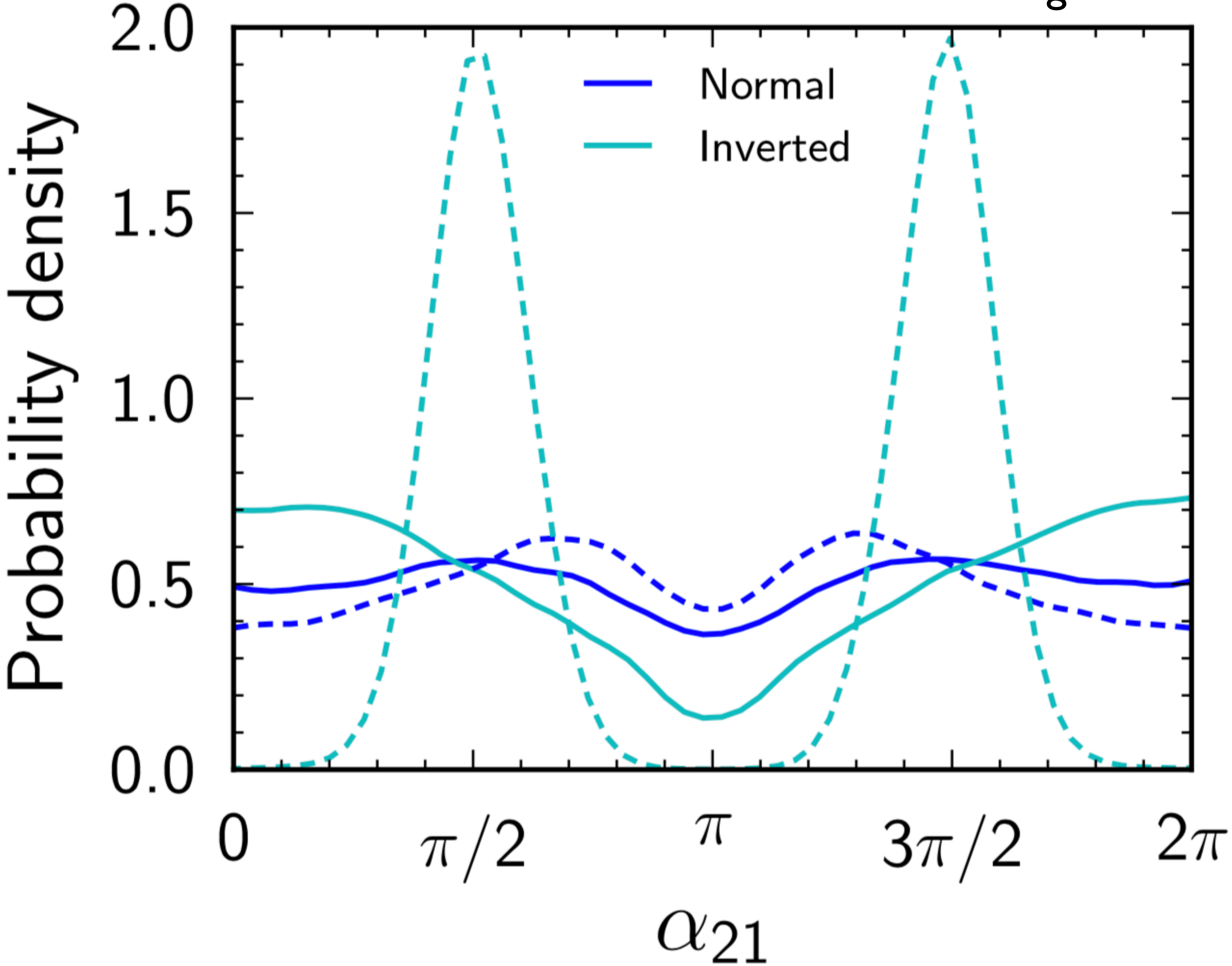
- Signal from cosmology with Mnu<0.1 eV, no signal from 0nu2b. Hierarchy is normal. Majorana/Dirac undetermined.

- Signal from cosmology with Mnu > 0.1 eV, no signal from 0nu2b. Neutrinos are Dirac. Hierarchy is undetermined.

- No signal from cosmology, signal from 0nu2b. OR we see discordant signals. Neutrinos are Majorana. New physics? E.g. BSM neutrino interactions?

Measuring the Majorana phases?

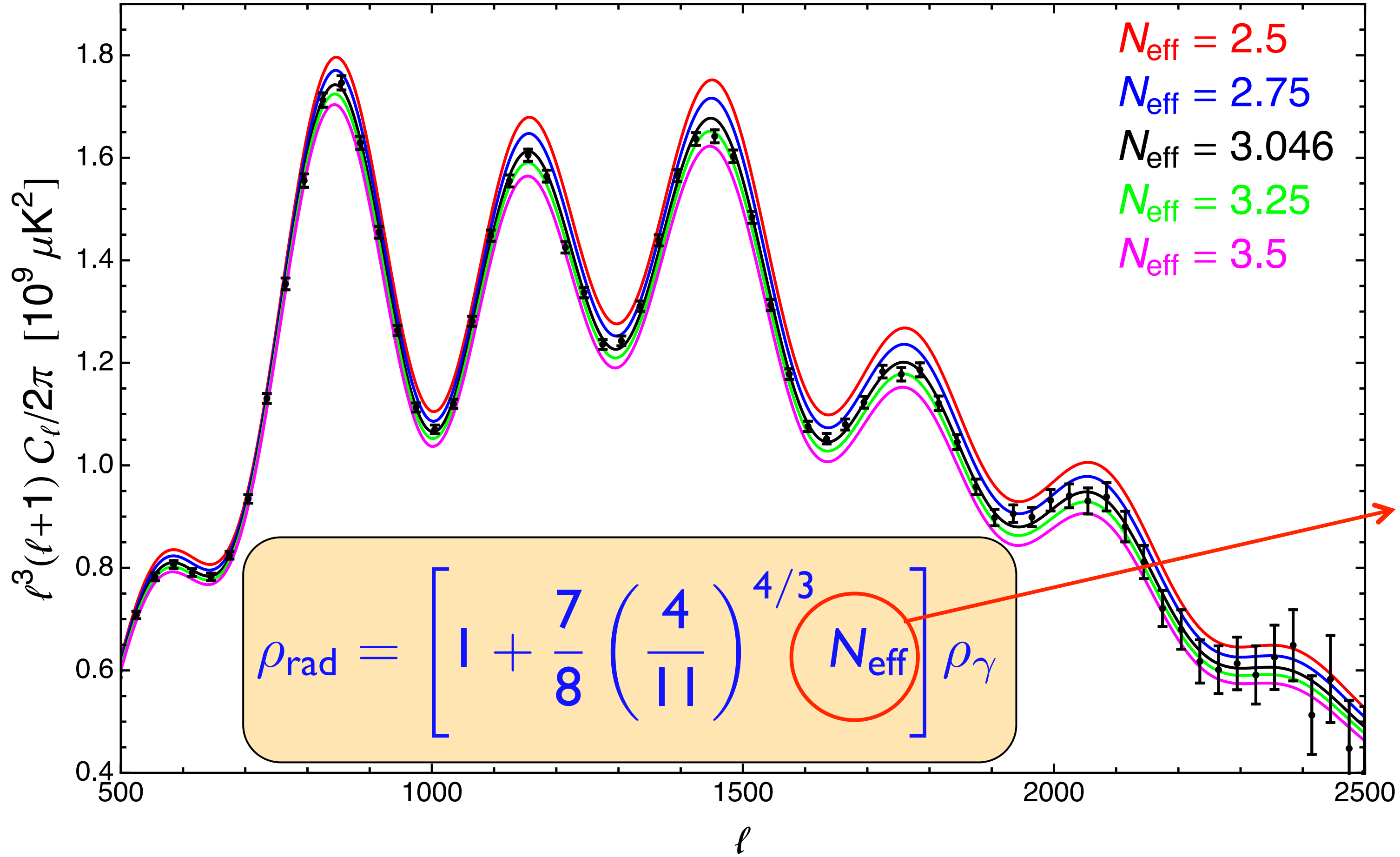
Next-gen cosmo+0nu2b



Gerbino, ML, Melchiorri 2017

Effective number of relativistic species

Planck 2018 + BAO: Neff = 2.99+/- 0.17

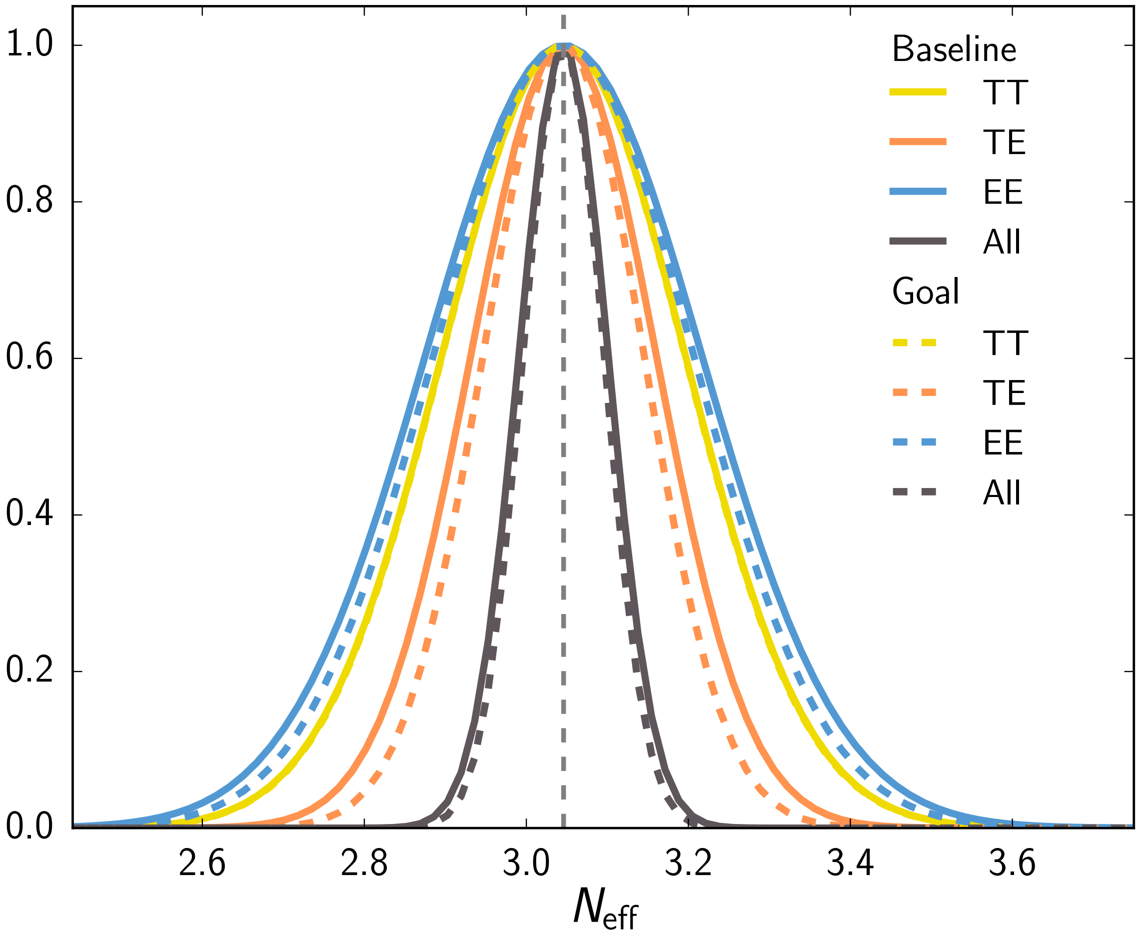


$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Due to non-instantaneous decoupling, the standard expectation is **$N_{\rm eff}$ = 3.045** (updated calculation from de Salas & Pastor 2016; see also Dolgov 2002, Mangano et al. 2005)

(note I am showing ~ $l^4\,C_l$, not $l^2\,C_l$)

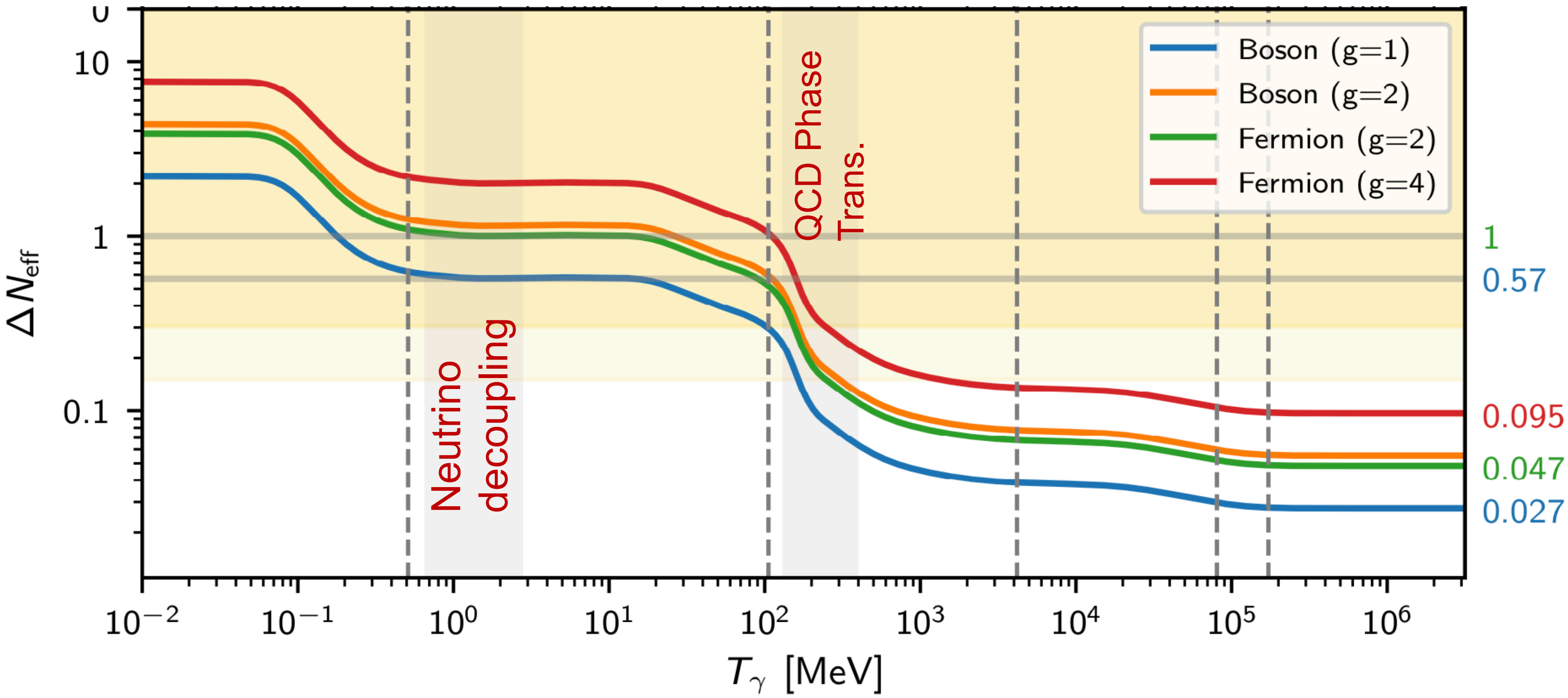


Primary CMB temperature and polarization power spectra from SO

$$\sigma(N_{\mathrm{eff}}) = 0.07\;[0.05]$$

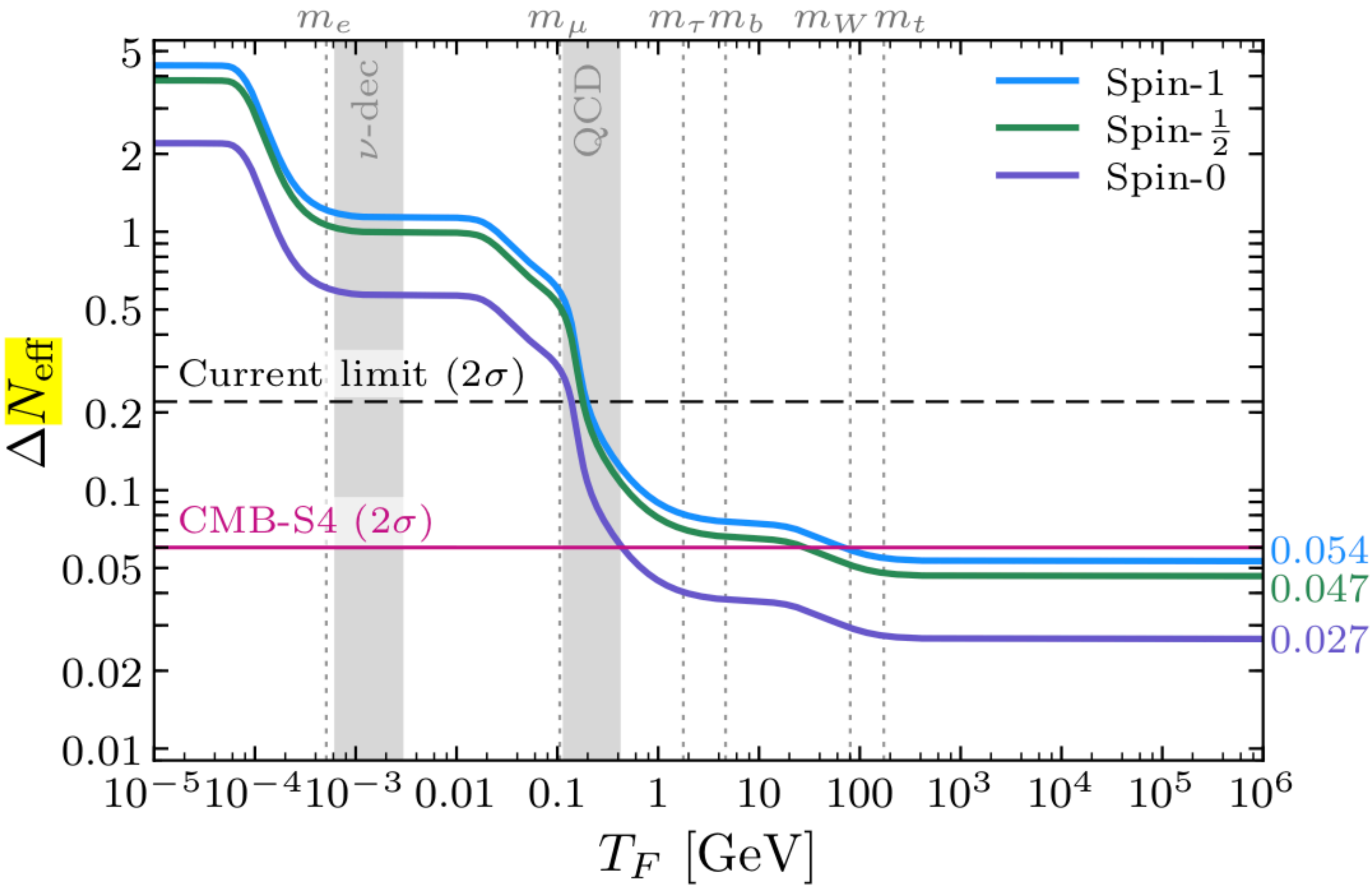
SO collaboration, 2018

Decoupling temperature of relativistic species



An extra neutrino that was in thermal equilibrium in the early Universe should decouple at T>~100 MeV

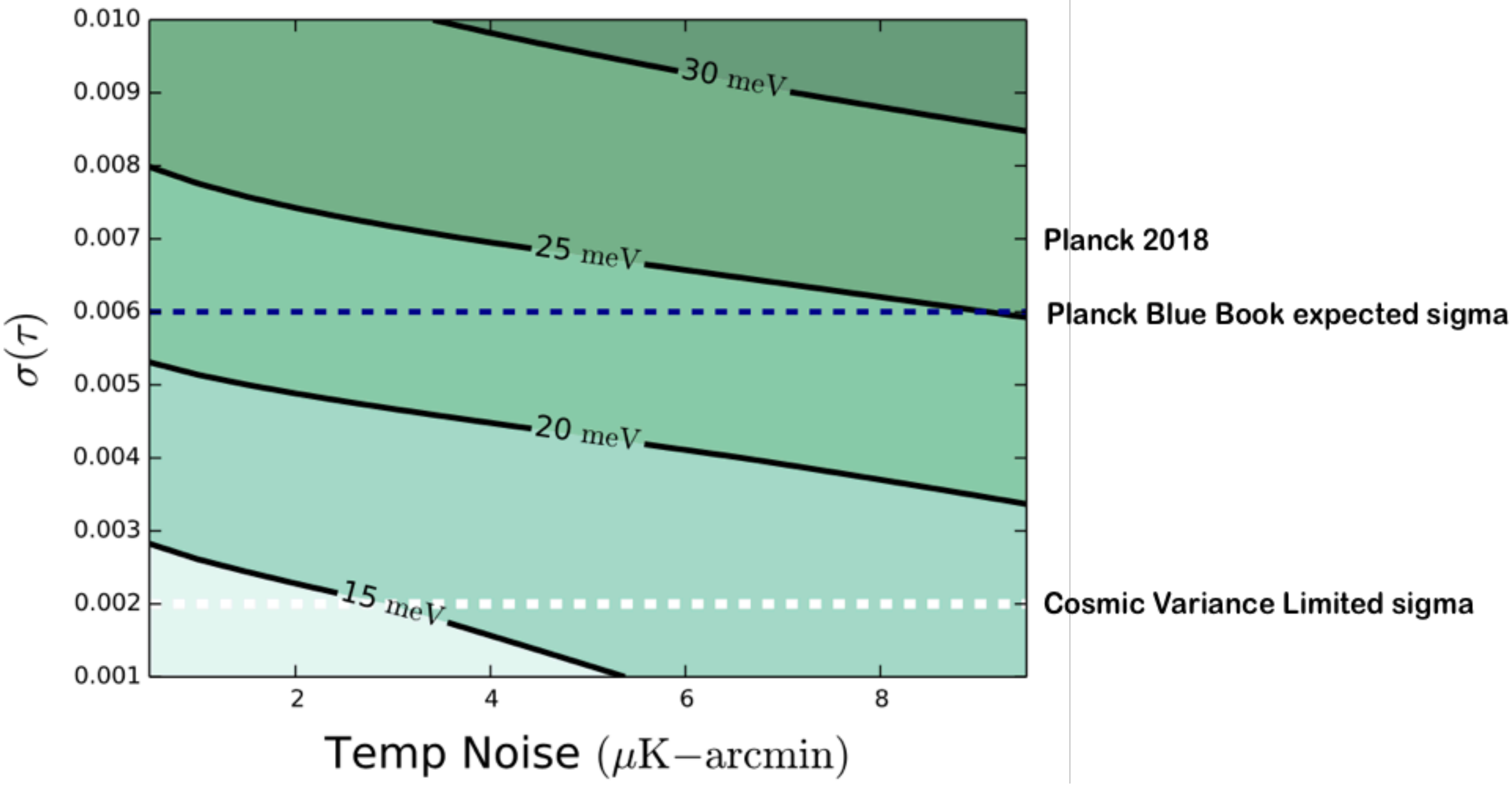
Planck collaboration, VI 2018



S4 collaboration, 2019

Conclusions

BACKUP SLIDES



0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
2
4
6
8
$\sigma(\tau)$
Temp Noise $(\mu\mathrm{K{-}arcmin})$
30 meV
25 meV
20 meV
15 meV
Planck 2018
Planck Blue Book expected sigma
Cosmic Variance Limited sigma

Model dependency

TABLE 3 | Constraints on Σm_ν from different extensions to the ΛCDM model for the indicated datasets.

Extension to ΛCDM	**Σm_ν[meV]**	**Dataset**
$\Lambda\mathrm{CDM} + \Sigma m_\nu$	<254	Planck TT+lowP+lensing+BAO[a]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + \Omega_K$	<368	Planck TT+lowP+lensing+BAO[a]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + w$	<372	Planck TT+lowP+lensing+BAO[a]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + N_{\mathrm{eff}}$	<323	Planck TT+lowP+lensing+BAO[a]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + A_L$	<413	Planck TT+lowP+lensing+BAO[a]
$\Lambda\mathrm{CDM} + \Sigma m_\nu$	62 ± 16	CORE TT,TE,EE,PP+BAO [132]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + \Omega_K$	63 ± 21	CORE TT,TE,EE,PP+BAO [132]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + w$	48^{+22}_{-17}	CORE TT,TE,EE,PP+BAO [132]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + N_{\mathrm{eff}}$	68^{+15}_{-17}	CORE TT,TE,EE,PP+BAO [132]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + Y_{\mathrm{He}}$	62 ± 16	CORE TT,TE,EE,PP+BAO [132]
$\Lambda\mathrm{CDM} + \Sigma m_\nu + r$	60^{+15}_{-17}	CORE TT,TE,EE,PP+BAO [132]