NEUTRINOS IN COSMOLOGY

Particle Physics & Cosmology (PPC)
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Neutrino cosmology

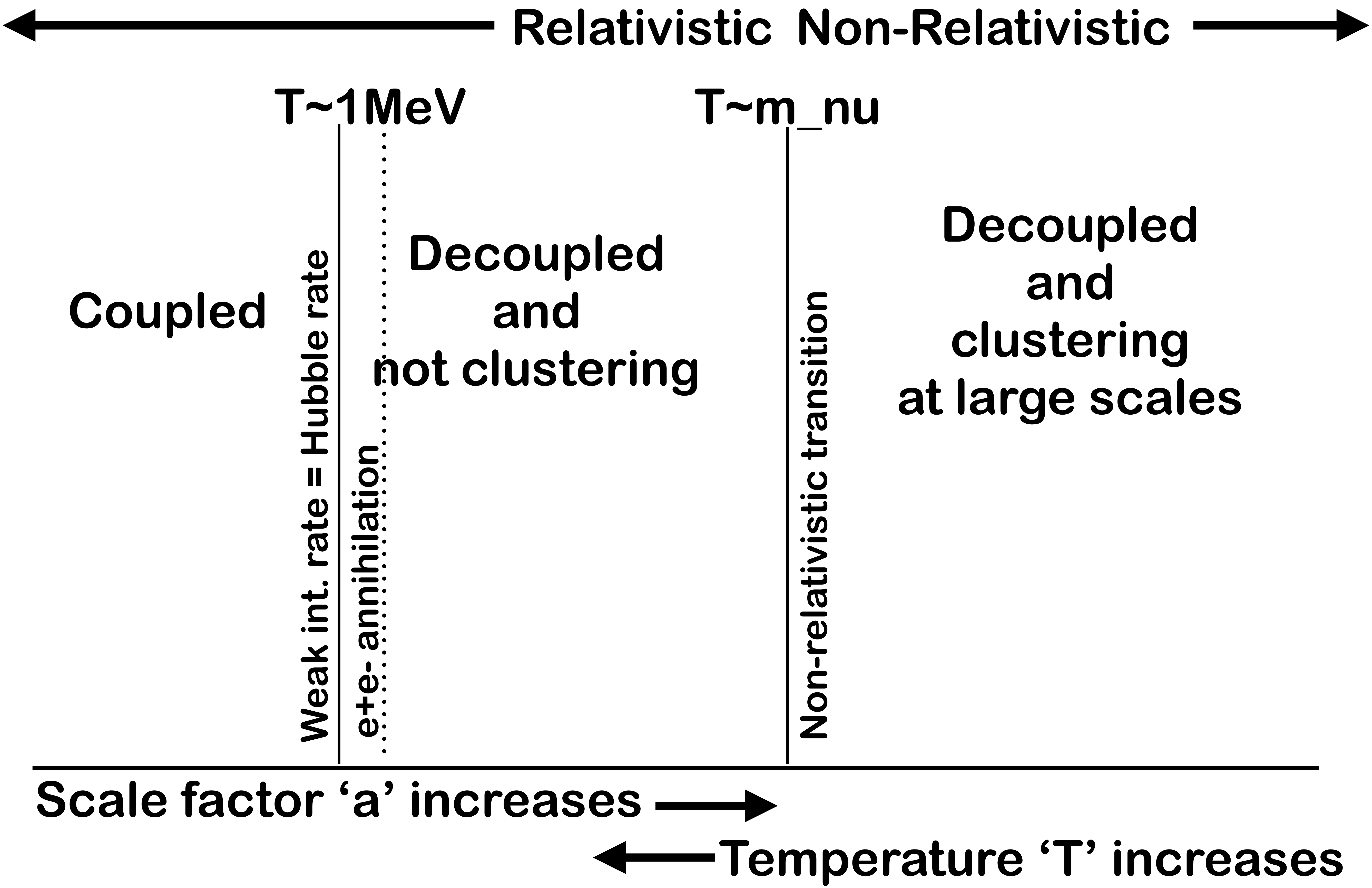
BOOK:

- Lesgourgues, Mangano, Miele, Pastor, ‘Neutrino Cosmology’, Cambridge U.Press, 2013
- Giunti&Kim, ‘Fundamentals of Neutrino Physics and Astrophysics’, Oxford U. Press, 2007

REVIEWS:

- Gerbino&Lattanzi, 2017
- PDG Review on Neutrinos, Lesgourgues&Verde, 2017
- Wong, 2011
- Lesgourgues&Pastor, 2006
- …

Basics of neutrino cosmology



Basics of neutrino cosmology

← Relativistic Non-Relativistic →

T~m_nu

$$\rho_\nu \propto N_{\rm eff}$$

$$\rho_\nu \propto \Sigma m_\nu$$

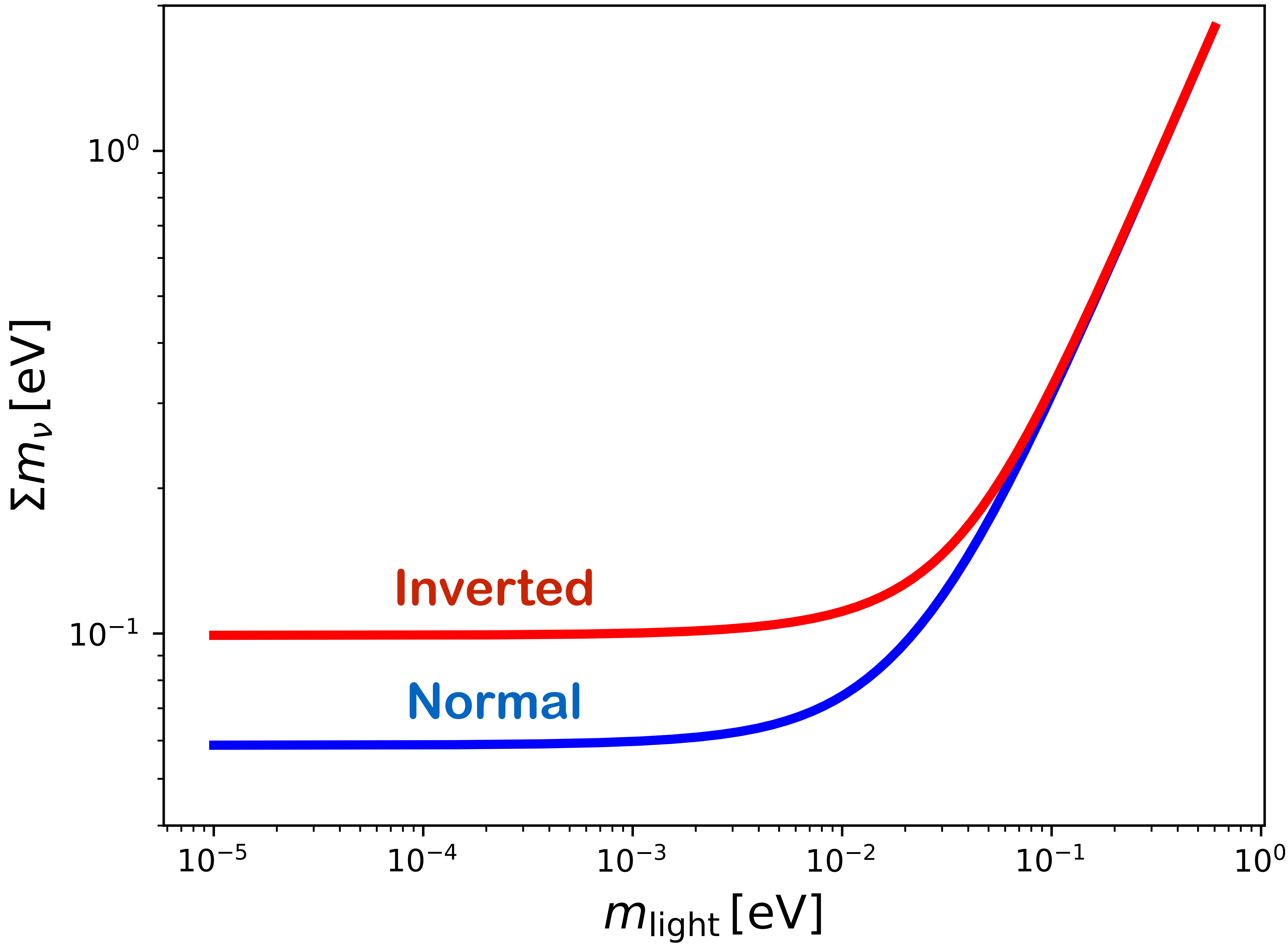
$$N_{\rm eff} = \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm st}} = 3.045$$

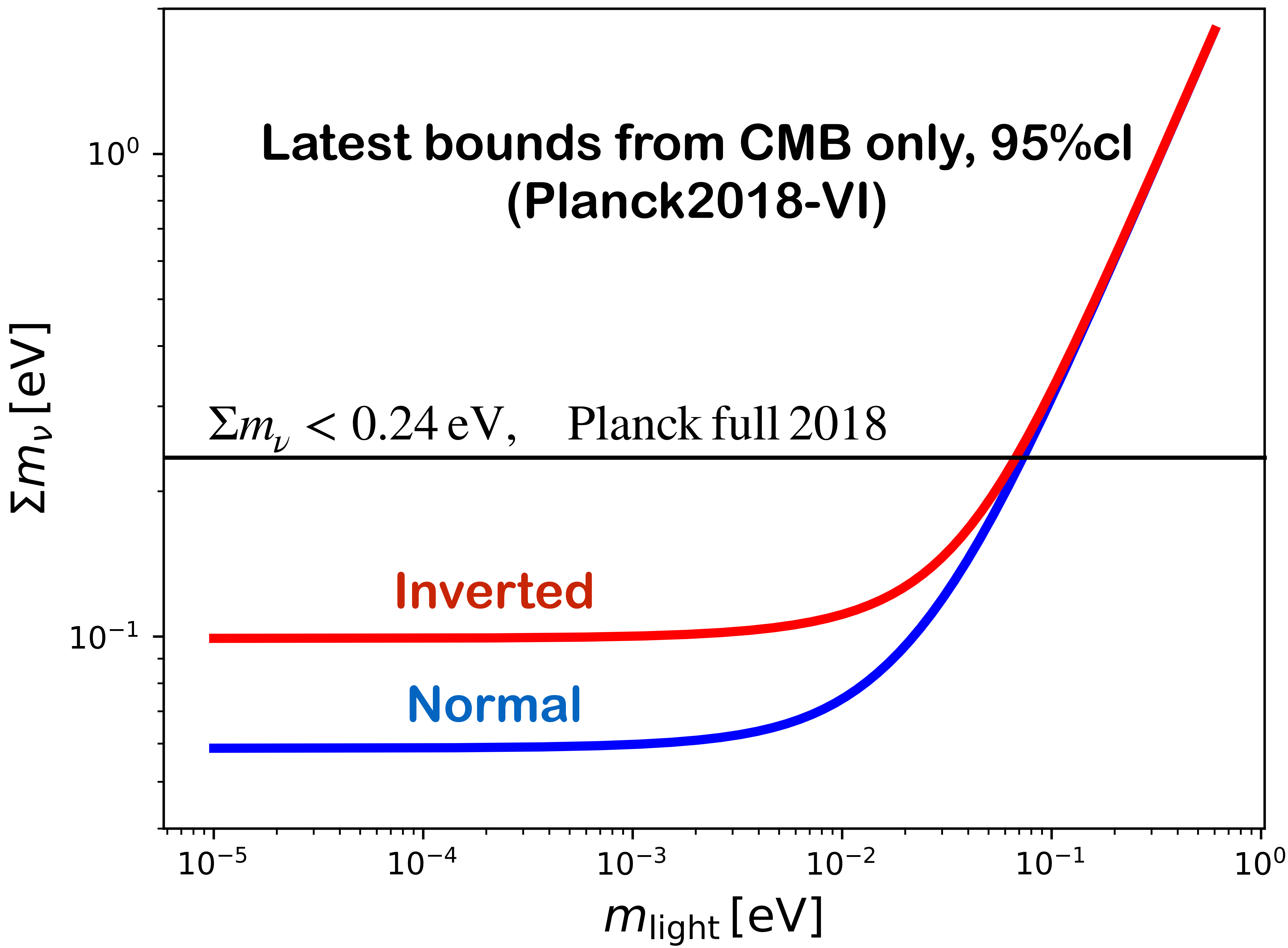
$$\Sigma m_\nu = \Sigma_{i=1,2,3} m_{\nu,i}$$

Distorsions due to non-inst decoupling
radiative corrections,
flavour oscillations
Dolgov, 1997, Mangano+,2005
deSalas&Pastor,2016

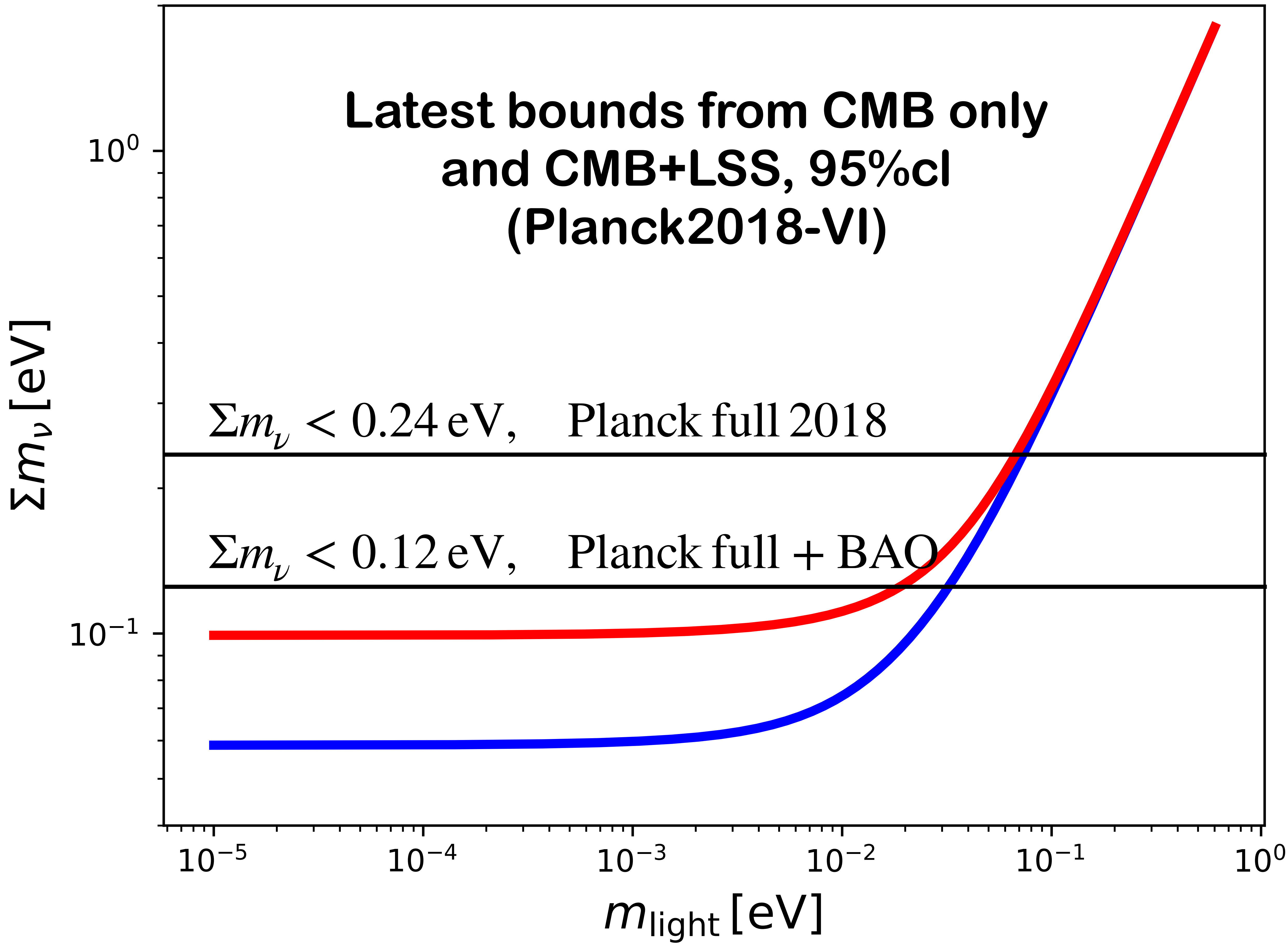
Scale factor 'a' increases →

← Temperature 'T' increases

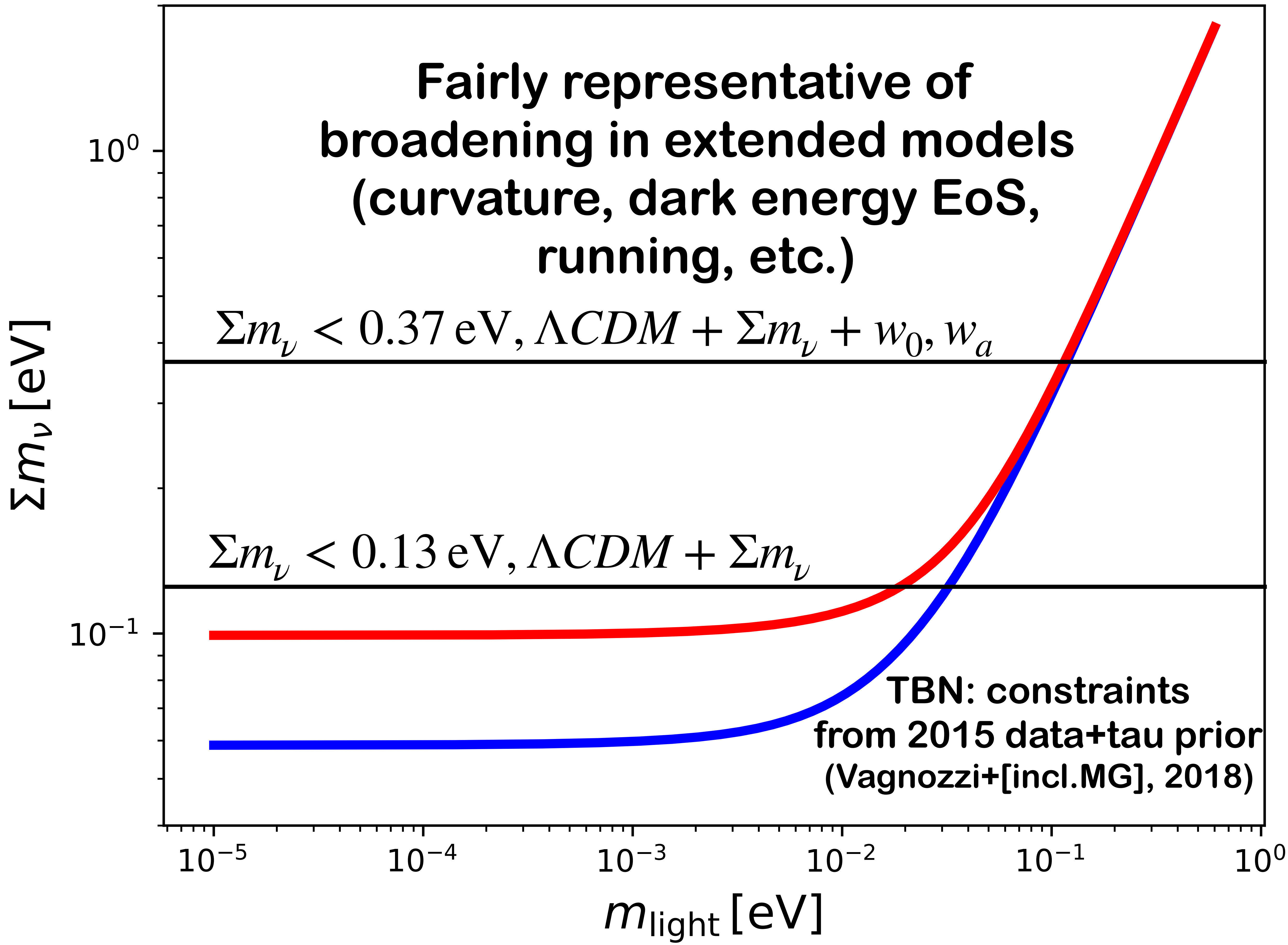

Inverted
Normal
10^0
10^{-1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
Σm_ν [eV]
$m_{\rm light}$ [eV]



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



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



Fairly representative of broadening in extended models (curvature, dark energy EoS, running, etc.)
$\Sigma m_\nu < 0.37\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu + w_0, w_a$
$\Sigma m_\nu < 0.13\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu$
TBN: constraints from 2015 data+tau prior (Vagnozzi+[incl.MG], 2018)
10^0
10^{-1}
Σm_ν [eV]
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
m_{light} [eV]

Route to robust neutrino mass bounds

- Lensing potential reconstruction
- Full shape of the matter power spectrum+BAO, and/or galaxy shear, and/or cross
- Sunyaev-Zeldovich clusters and thermalSZ spectrum
- Cosmic-variance-limited measurements of tau

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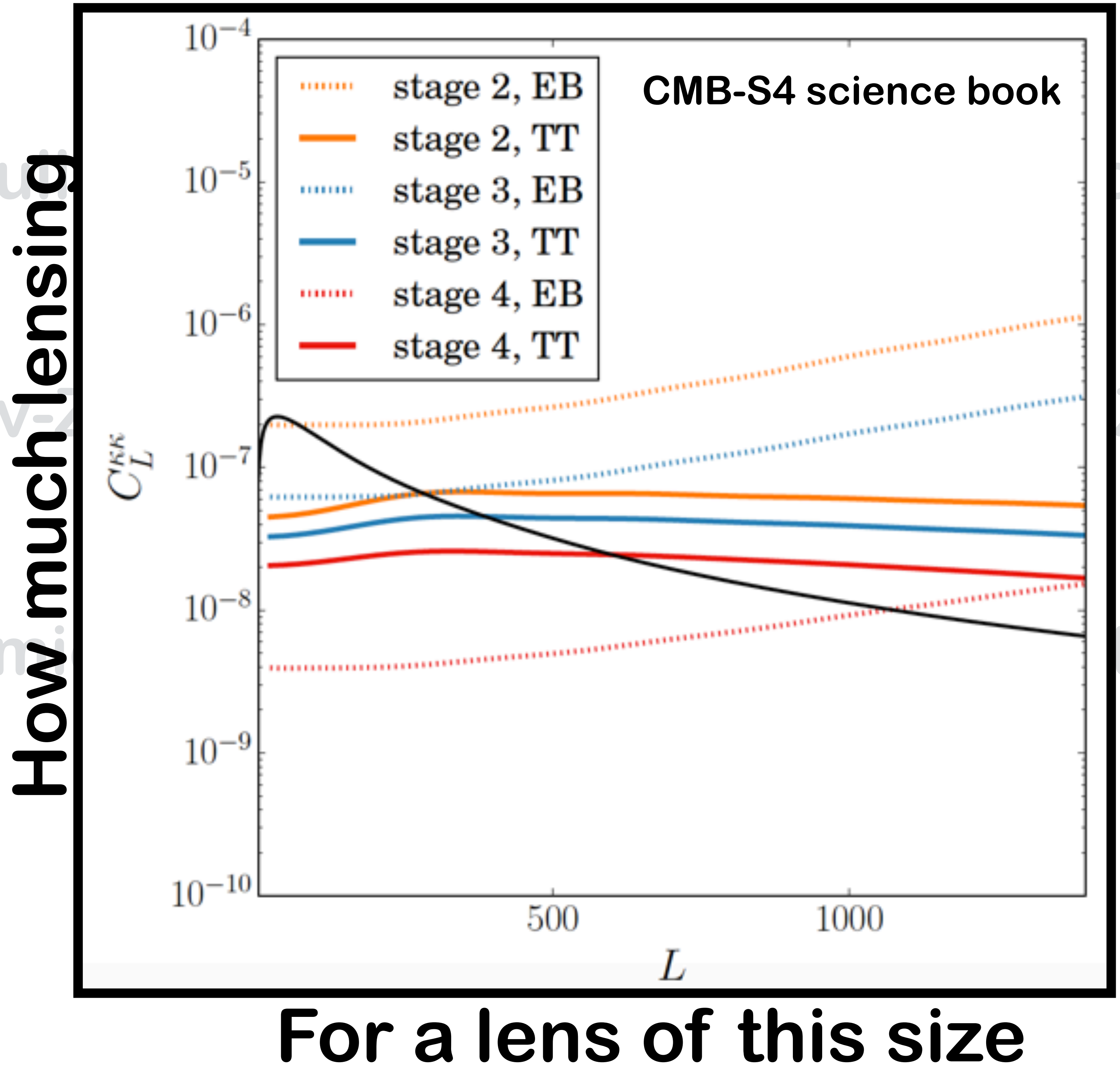

- Full … spectrum
- Sunyaev-Z… Z spectrum
- Cosm… ts of tau

Route to robust neutrino mass bounds

- Lensing potential reconstruction
- **Full shape of the matter power spectrum+BAO, and/or galaxy shear, and/or cross** **(see e.g. Mishra-Sharma+,2018, Brinckmann,Hooper+,2018)**
- Sunyaev-Zeldovich clusters and thermalSZ spectrum
- Cosmic-variance-limited measurements of tau

See T.Brinckmann's poster

Route to robust neutrino mass bounds

- Lensing potential reconstruction
- Full shape of the matter power spectrum+BAO, and/or galaxy shear, and/or cross
- **Sunyaev-Zeldovich clusters and thermalSZ spectrum**

  See e.g. Madhavacheril+, 2017; Salvati+, 2017
- Cosmic-variance-limited measurements of tau

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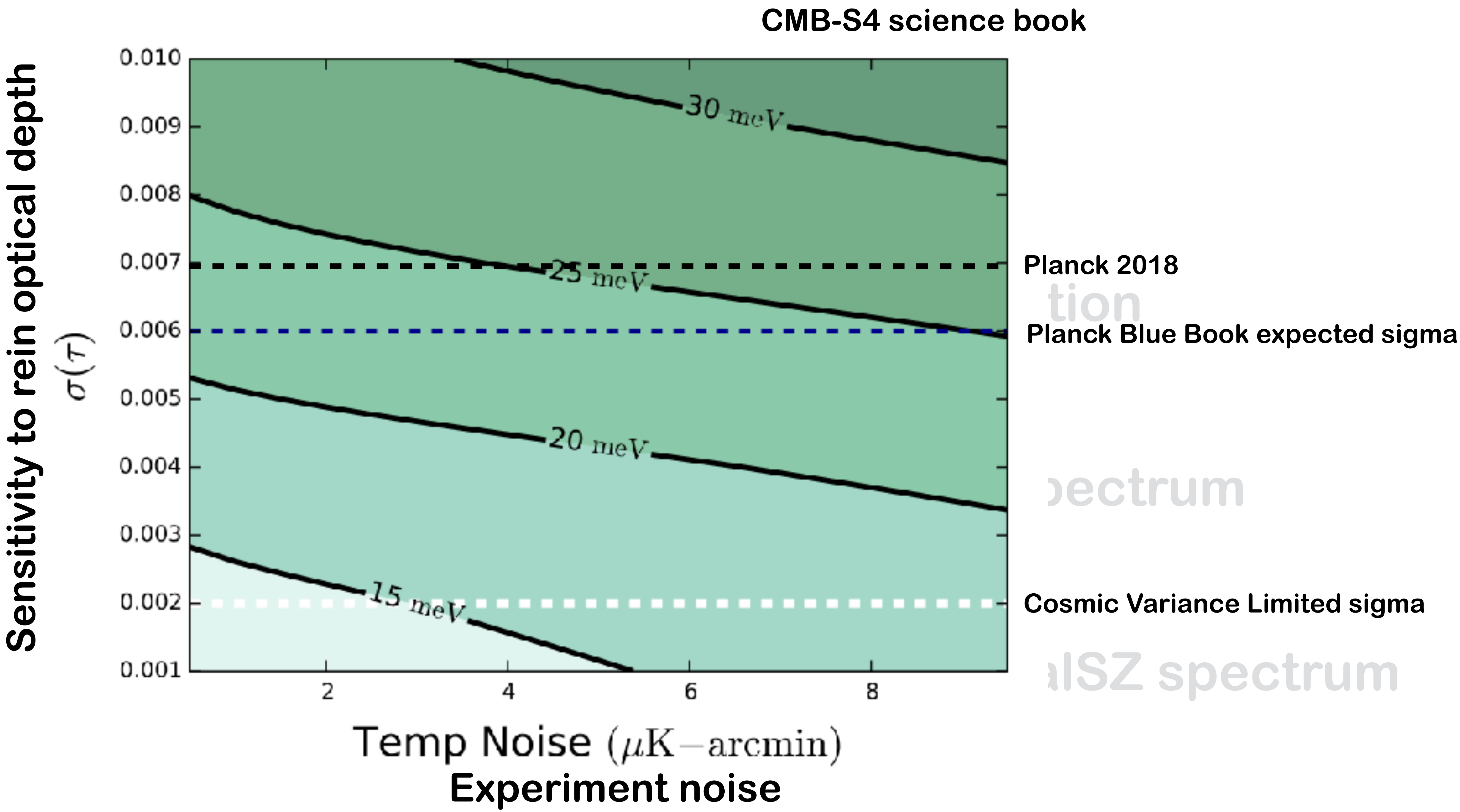
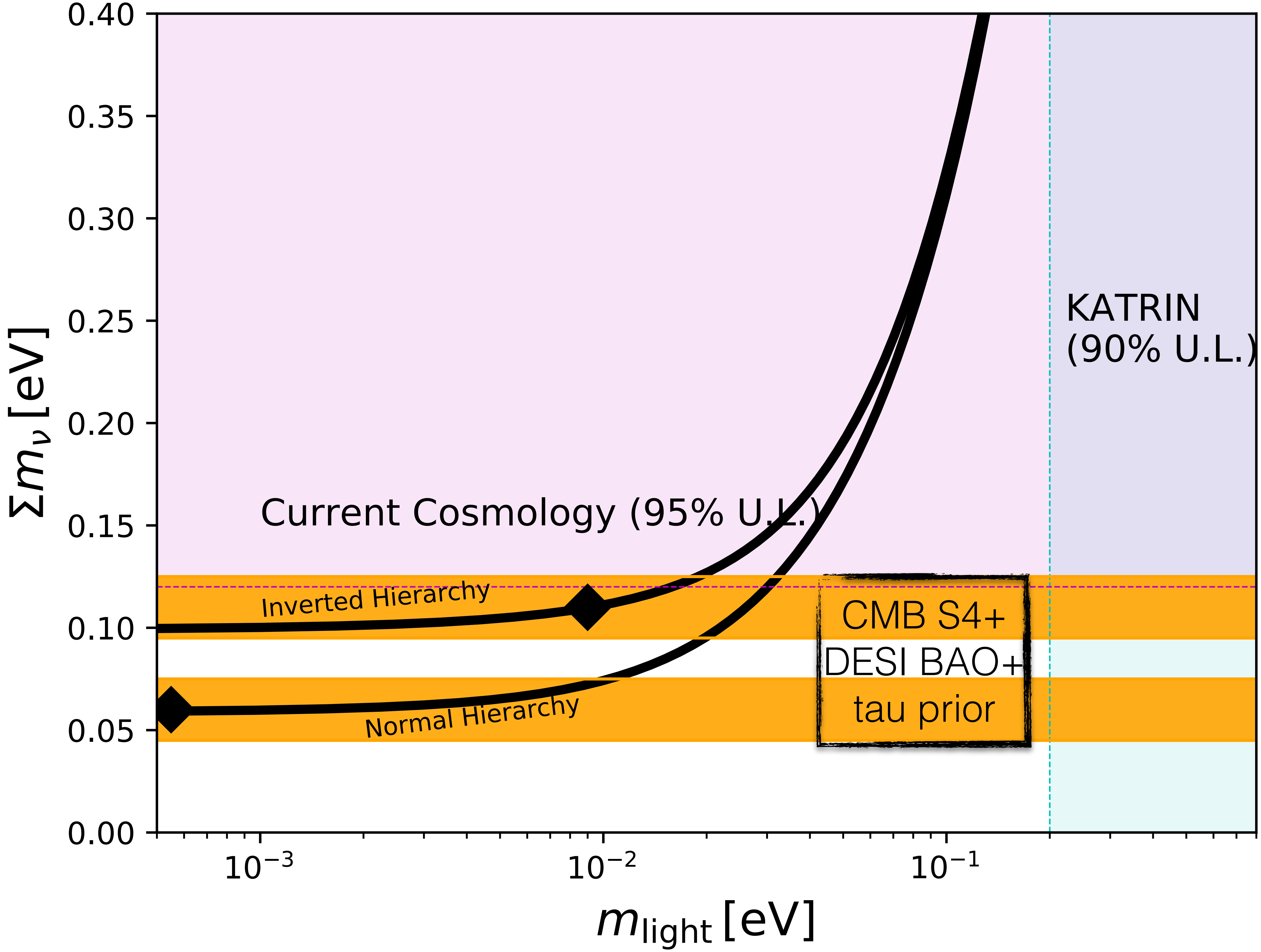


- **Cosmic-variance-limited measurements of tau**

Future - Massive neutrinos

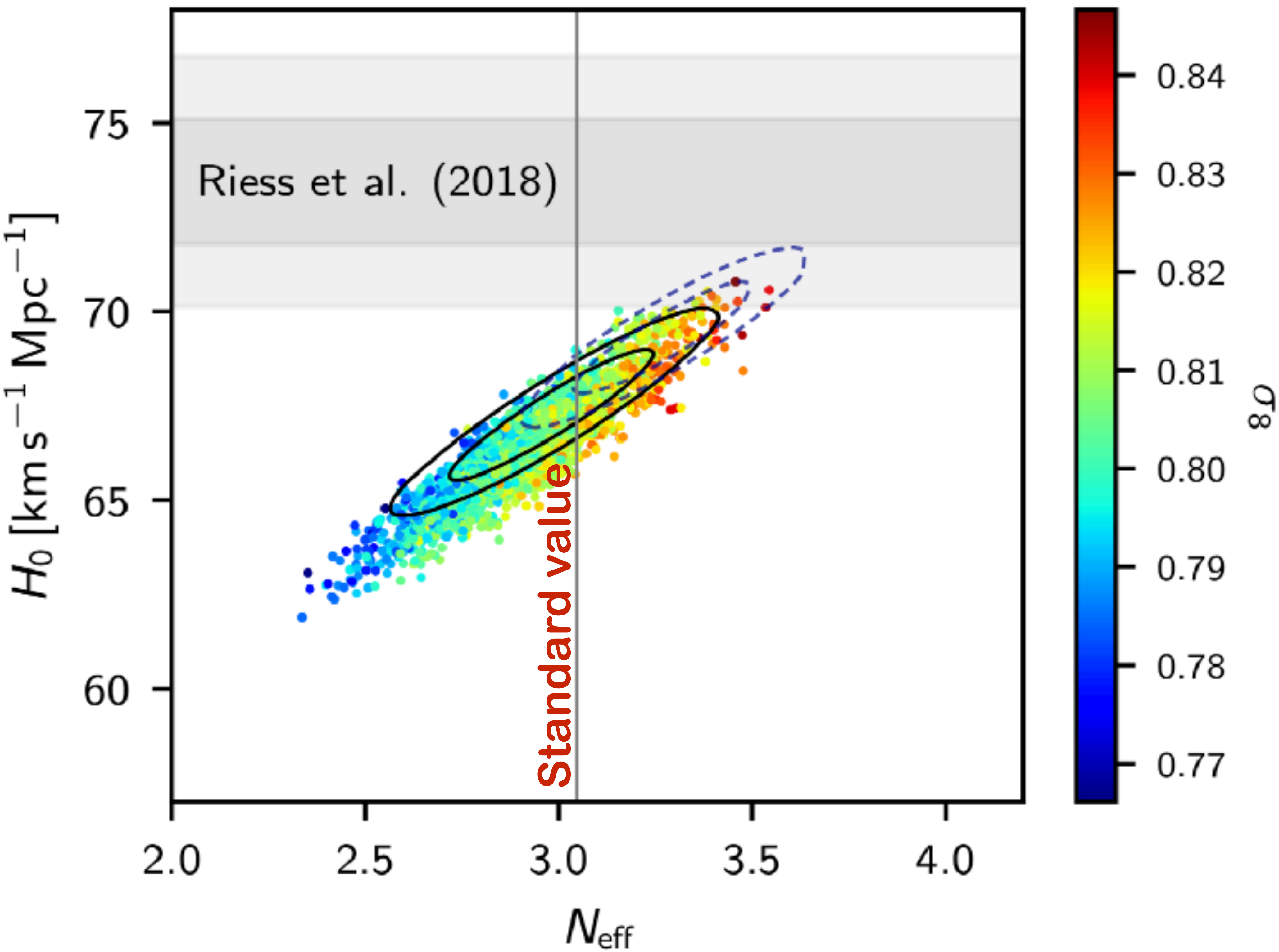


Adapted from CMB Stage-IV white paper

~3sigma detection of minimal mass scenario from combination of multiple probes

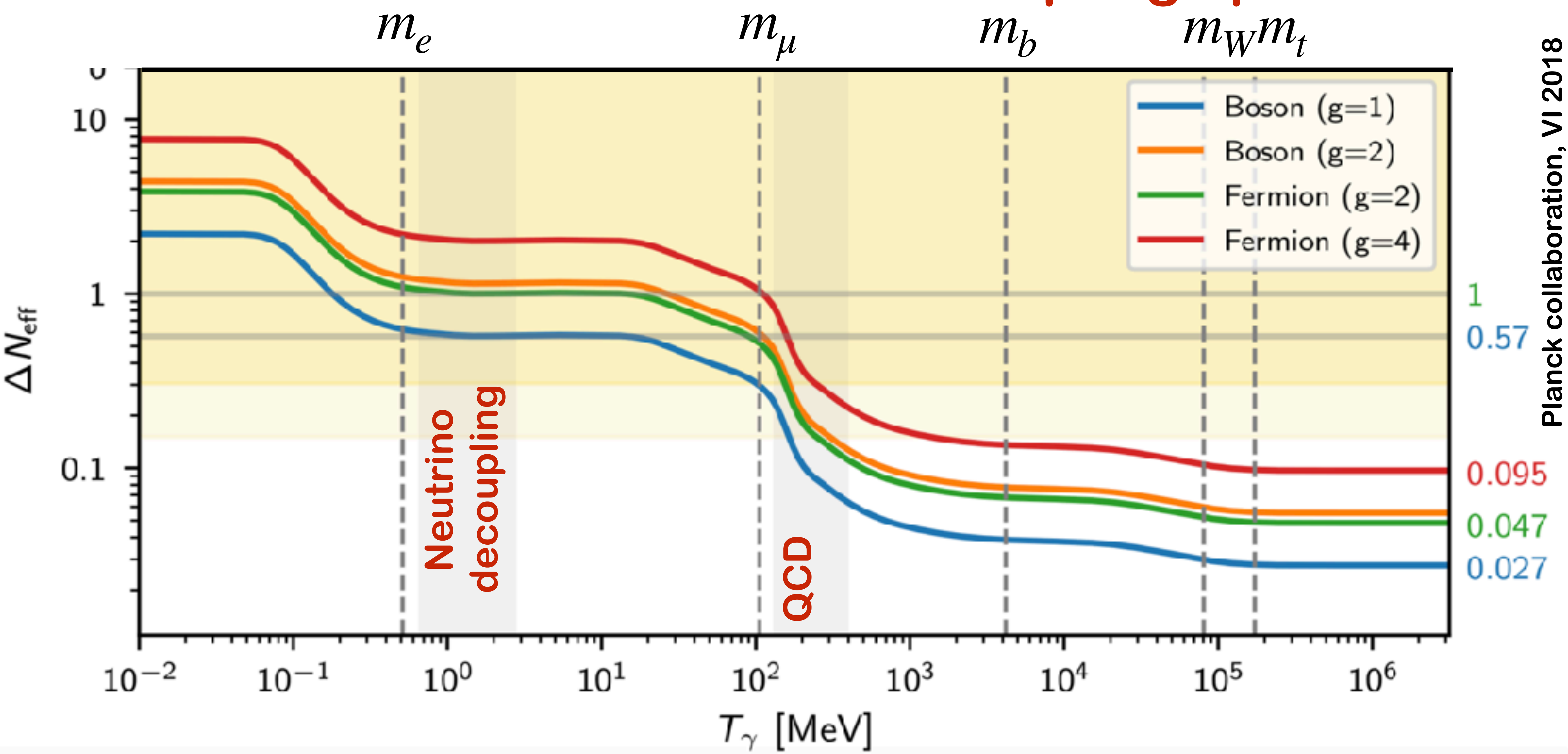
Current limits on Neff

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}, 95\,\%\,c.l., \text{Planck2018 + BAO}$$



Planck collaboration, VI 2018

Contribution to Neff from decoupling species

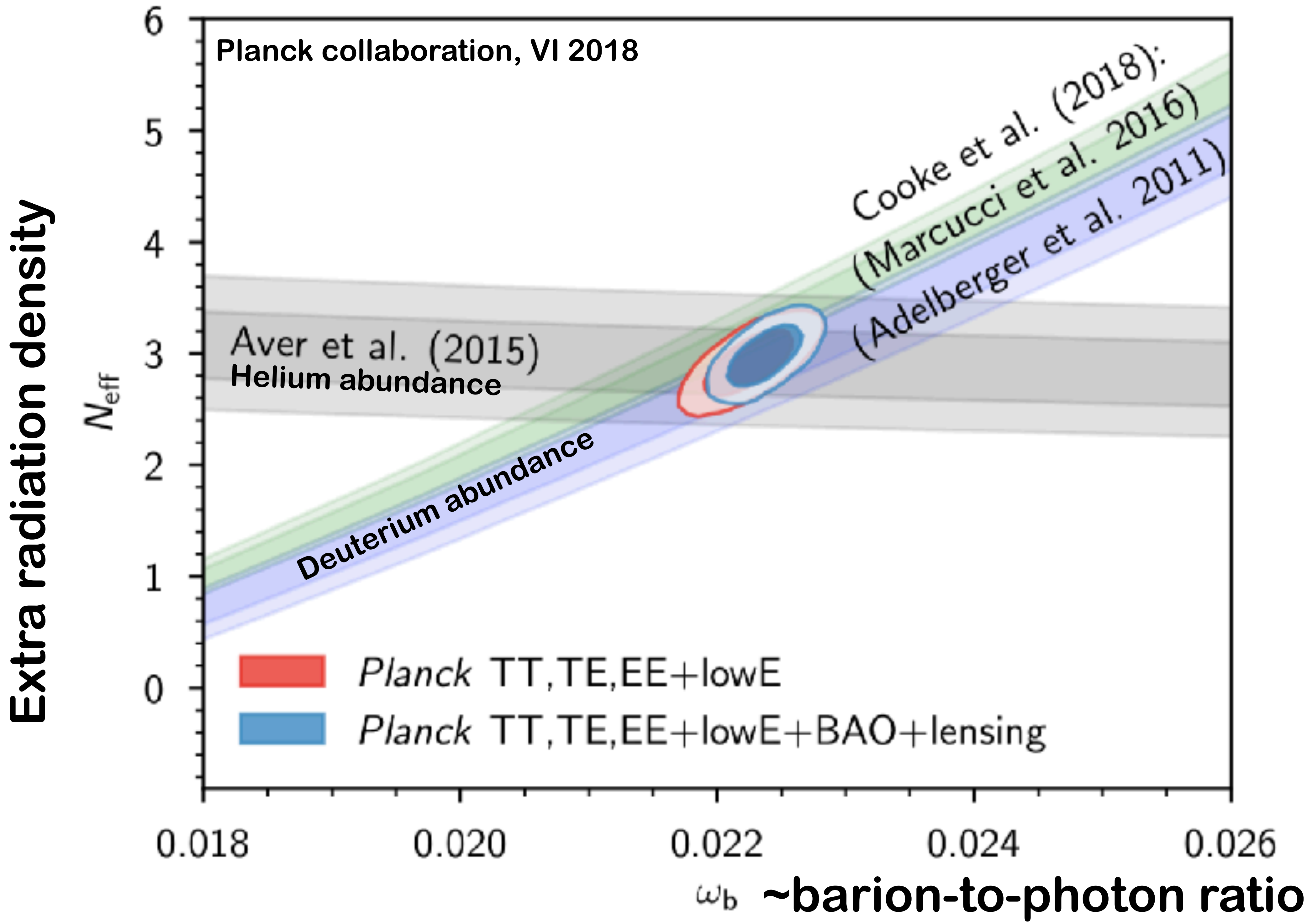


Presence of additional fully thermalised species decoupling between e+e- and mu+mu- annihilation excluded at 95%c.l.

~eV thermalised sterile neutrino excluded at 7sigma

Non-standard models needed to make SBL compatible with cosmology

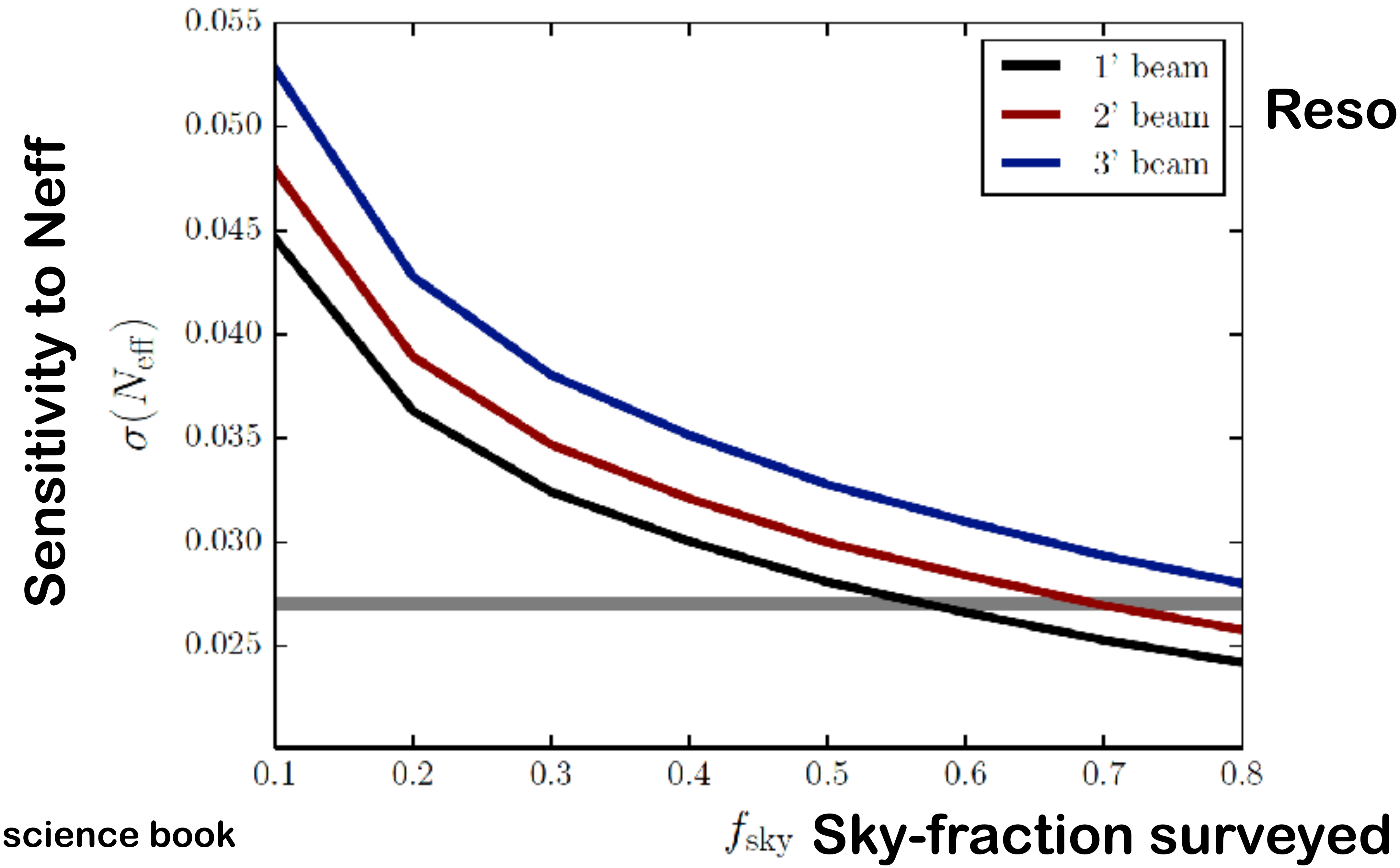
Comparison with BBN predictions



Very good agreement between cosmological bounds (95%cl) and predictions from astrophysical measurements

Route to improved bounds on Neff

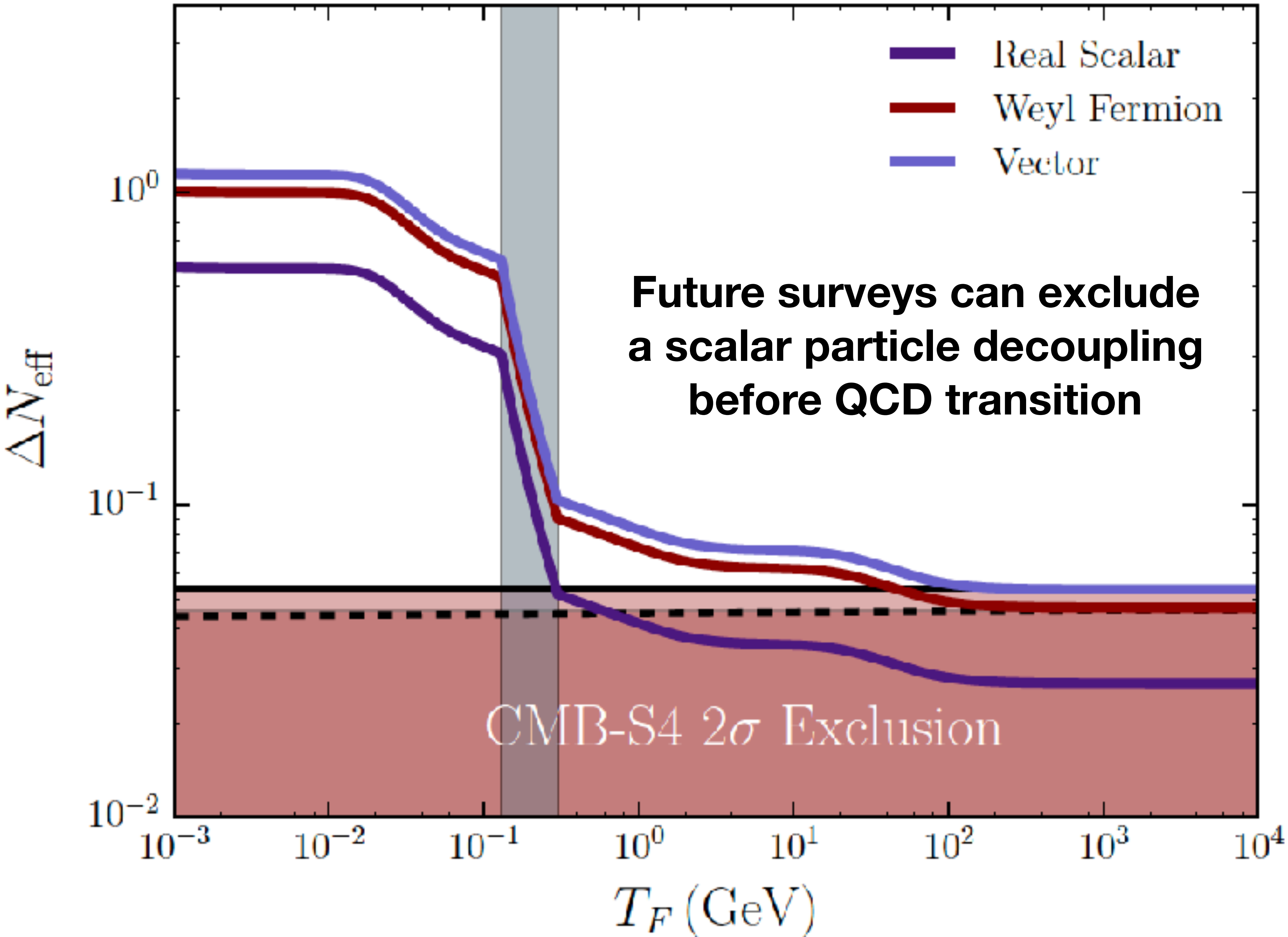
- **Improved measurements of the damping tail both in temperature and polarisation** (see e.g. Hou+,2012; Galli+,2014)
- **Delensing**



Resolution

CMB-S4 science book

Future - Relativistic species



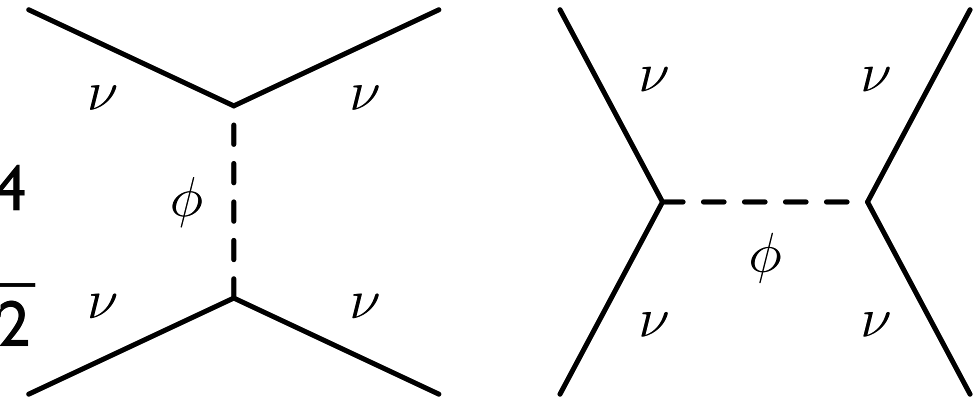
CMB Stage-IV white paper

Moreover: the physics of non-instantaneous decoupling will be probed at ~2sigma level

Scalar-mediated neutrino interactions

$$\mathcal{L} \supset h_{ij}\bar{\nu}_i\nu_j\phi + g_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + h.c.\,,$$

$$\Gamma_{\nu\nu} = \langle\sigma v\rangle n_{\rm eq} \propto g^4 T \qquad \sigma \sim \frac{g^4}{s} \sim \frac{g^4}{T^2}$$



Collisional processes can suppress stress and affect the perturbation evolution of cosmological neutrinos.

Parameterizing the interaction strength through:

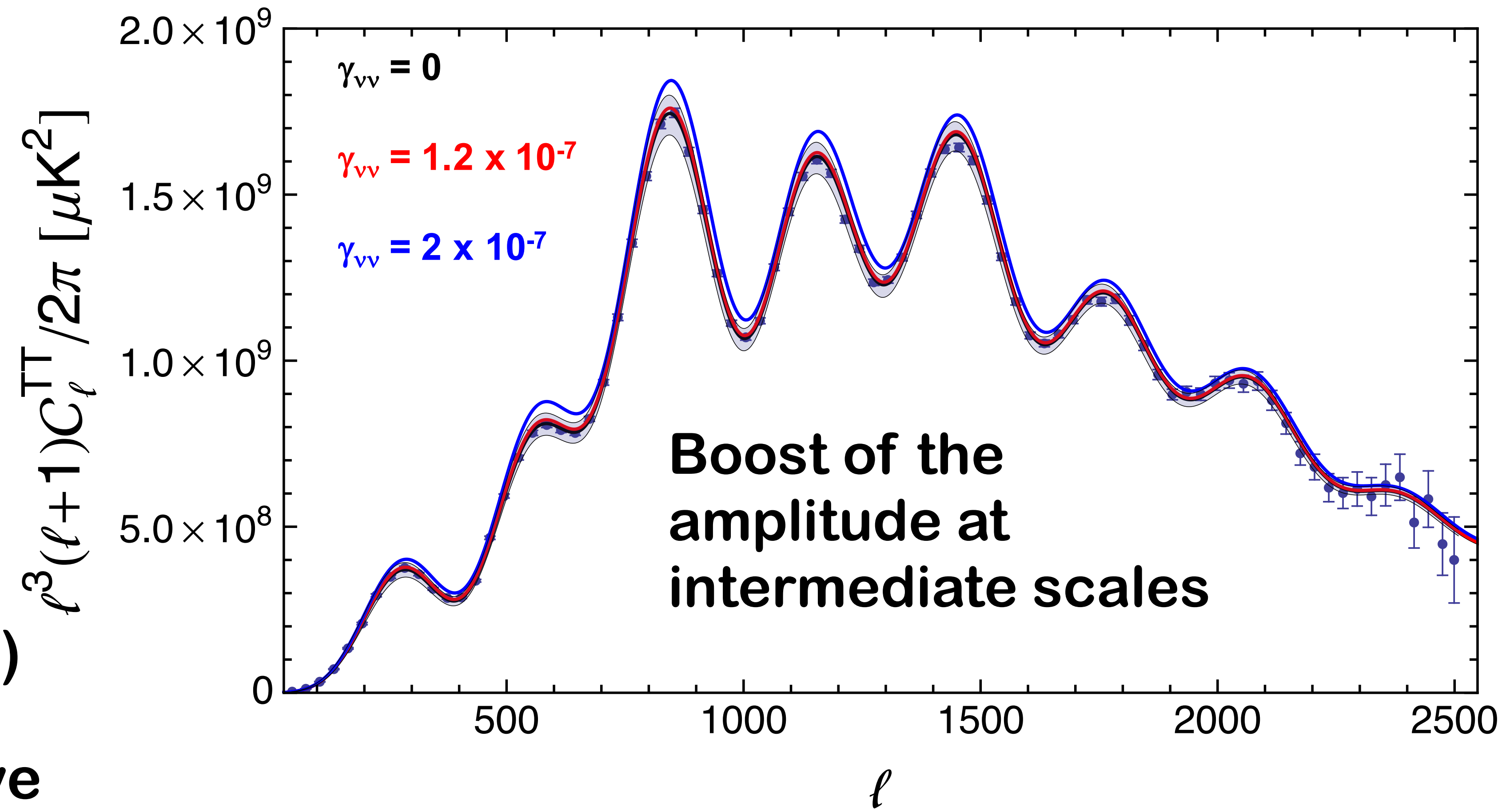
$$\Gamma_{\nu\nu} \equiv \gamma_{\nu\nu}^4 T$$

Planck constraints (95% CL):

$$\gamma_{\nu\nu}^4 < (0.3 \div 0.5) \times 10^{-27}$$

i.e $\gamma_{\nu\nu} \lesssim 10^{-7}$ **(Forastieri+2018)**

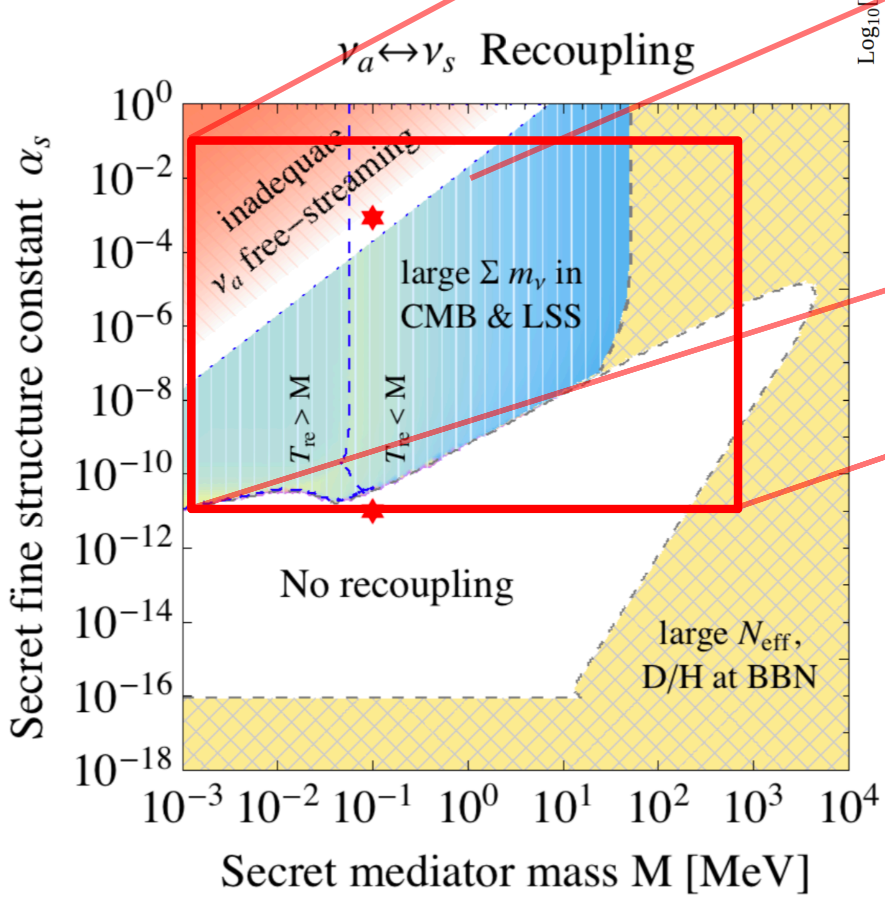
Future CMB bounds will improve by ~ 1 order of magnitude in $\gamma_{\nu\nu}^4$

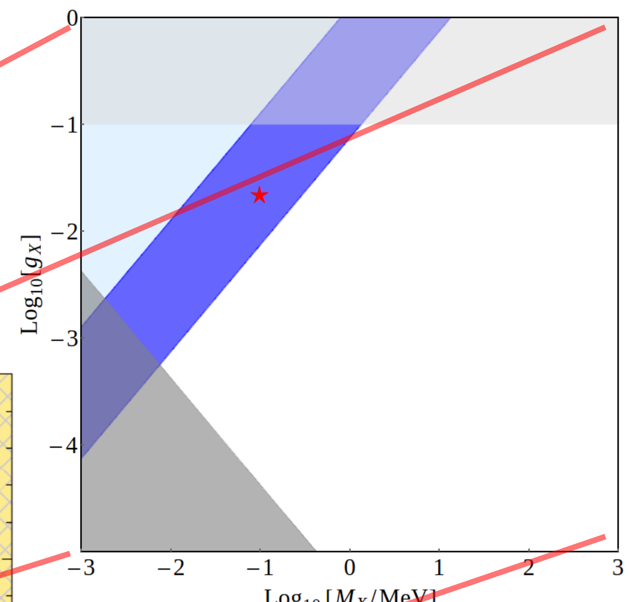


Forastieri+ 2015; Archidiacono & Hannestad 2013; Cyr-Racine & Sigurdson 2013

Sterile neutrino interactions and SBL anomalies

Sterile neutrino interpretation of SBL is in disagreement with cosmology (implies $\Delta N_{eff}=1$)
Are "Secret" interactions in the sterile sector a way out?
Production of sterile neutrinos is delayed, but large values of G_X will leave an observational signature on the CMB spectrum.

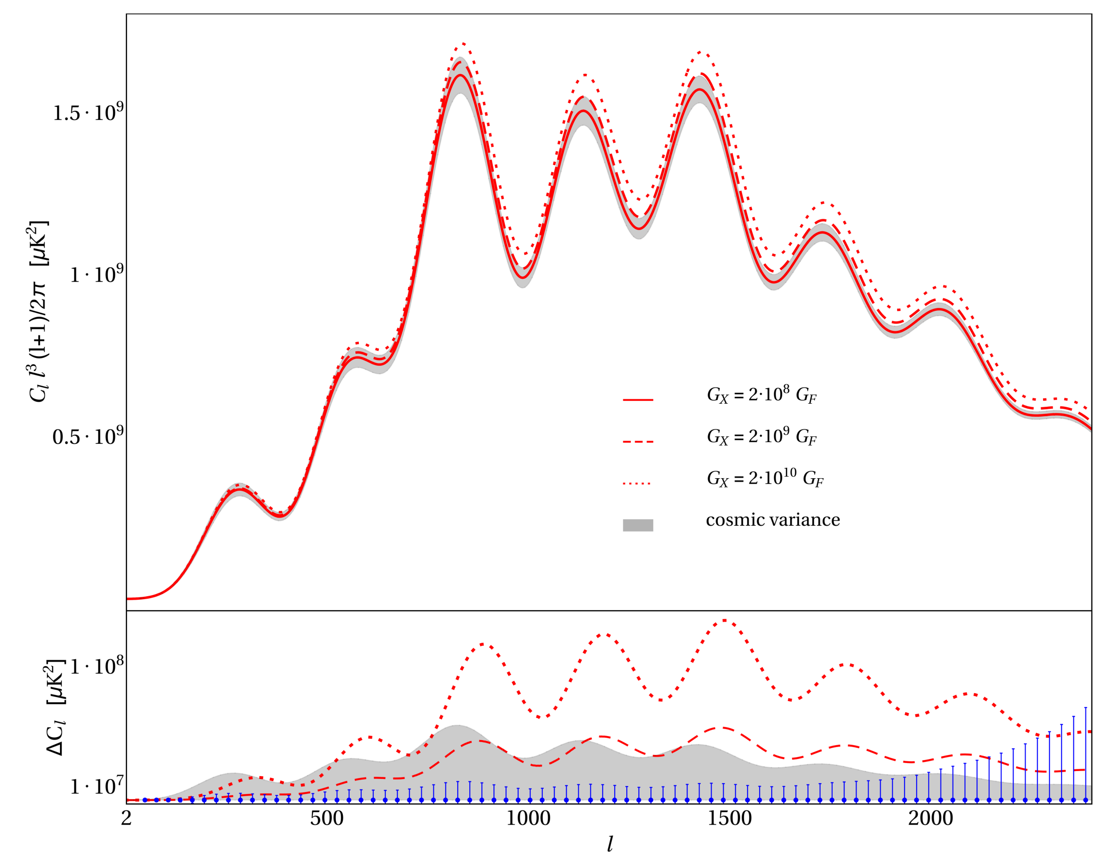




$$\mathcal{L}_s = g_X \bar{\nu}_s \gamma_\mu \frac{1}{2}(1-\gamma_5)\nu_s X^\mu$$

$$G_X \sim g_X^2 / M_X^2$$

Forastieri+, 2017
see also
(Hannestad et al. 2014; Dasgupta & Kopp 2014; Bringmann et al 2014; Mirizzi et al 2015; Chu,Dasgupta,Kopp 2015; Archidiacono+,2017)



CONCLUSIONS

Determine CnB properties from neutrino peculiar effects on cosmological observables

Strong and robust constraints from cosmology

Neutrino masses: getting closer to corner inverting hierarchy
Neff: no preference for an additional thermalised species
Non-standard properties tightly bounded

Next generation surveys would probe the physics of non-instantaneous decoupling and detect the neutrino mass scale with high statistical significance