NEUTRINOS IN COSMOLOGY

Martina Gerbino
OKC, Stockholm University

Neutrino cosmology

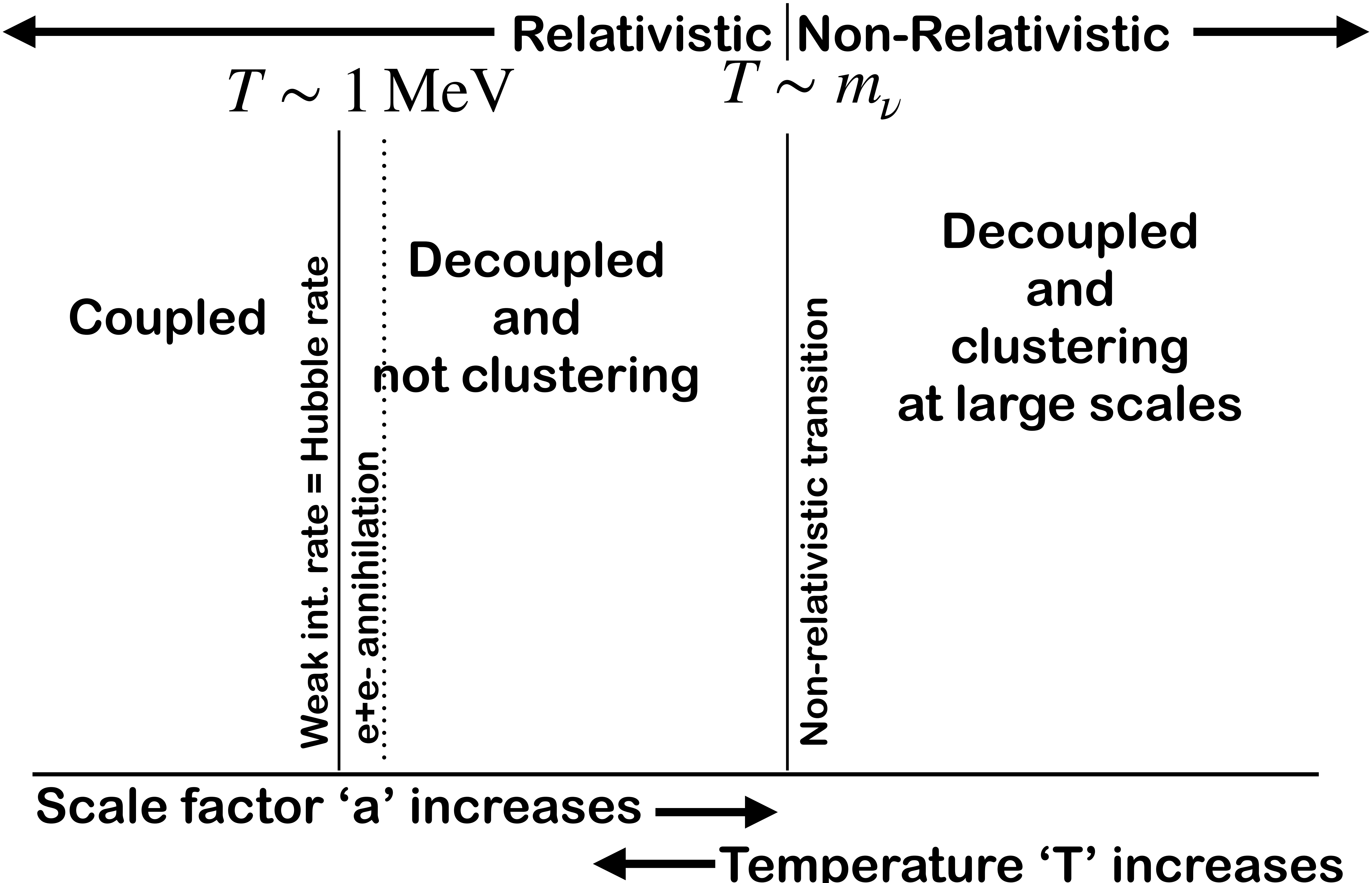
BOOK:

- 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

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

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

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

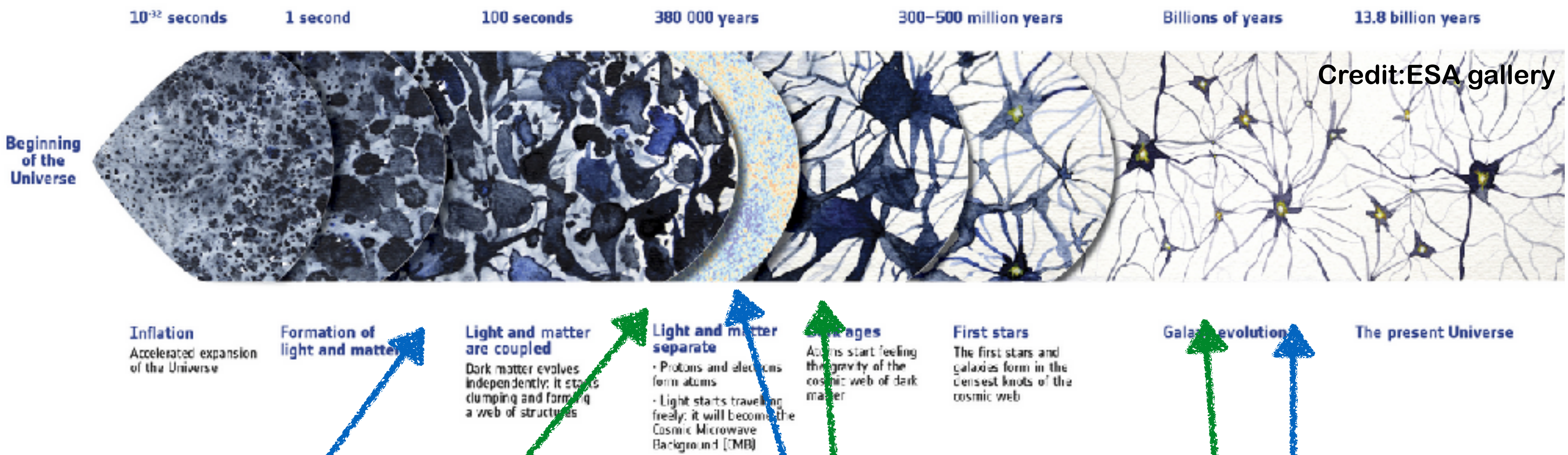
$$\Sigma m_\nu = \Sigma_{i=1,2,3} m_{\nu,i}$$

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

Scale factor 'a' increases →

← Temperature 'T' increases

Basics of neutrino cosmology



Contribution to early expansion

Contribution to metric fluctuations (early ISW)

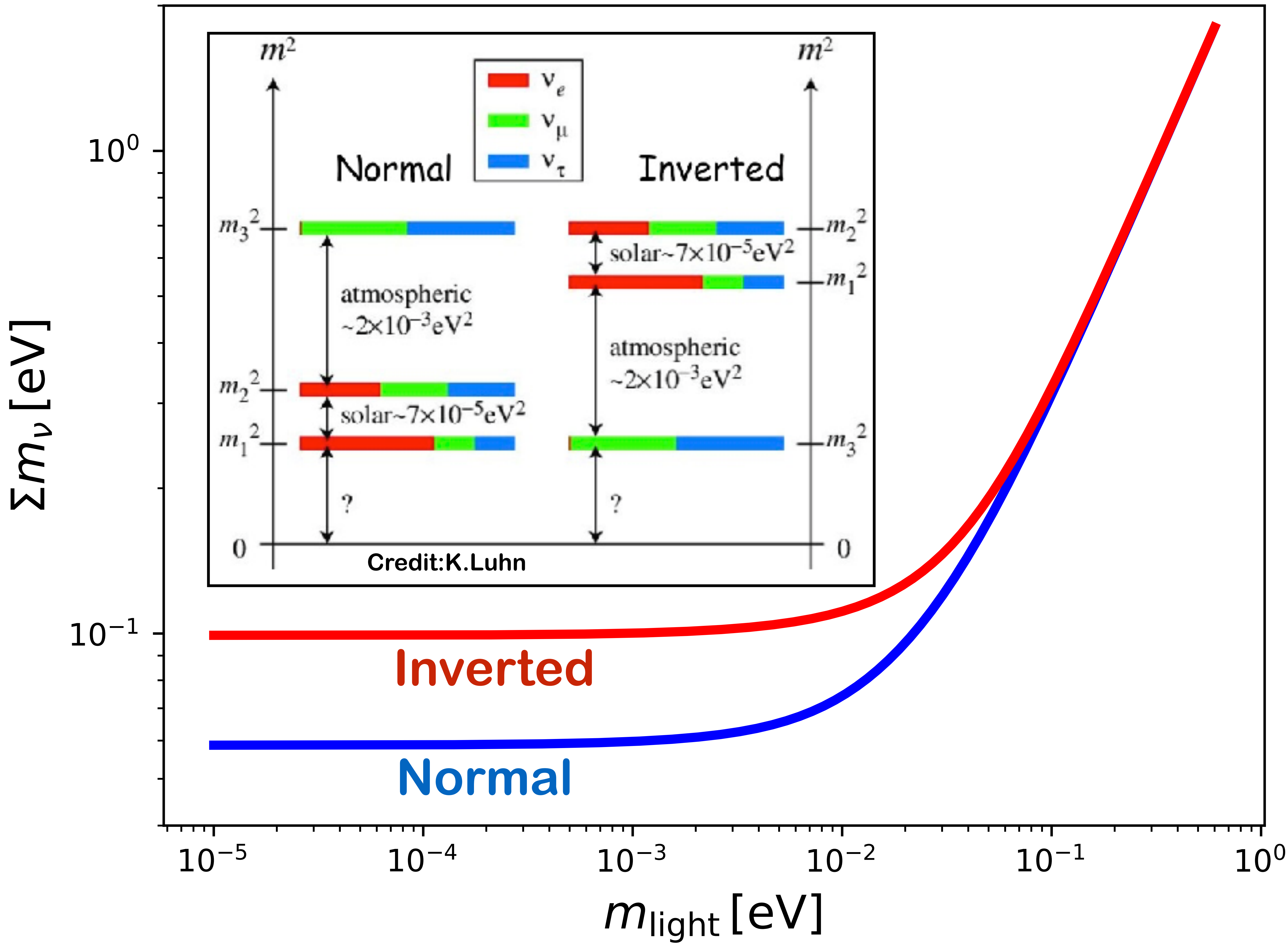
Contribution to late expansion

Slow down of early growth of structures

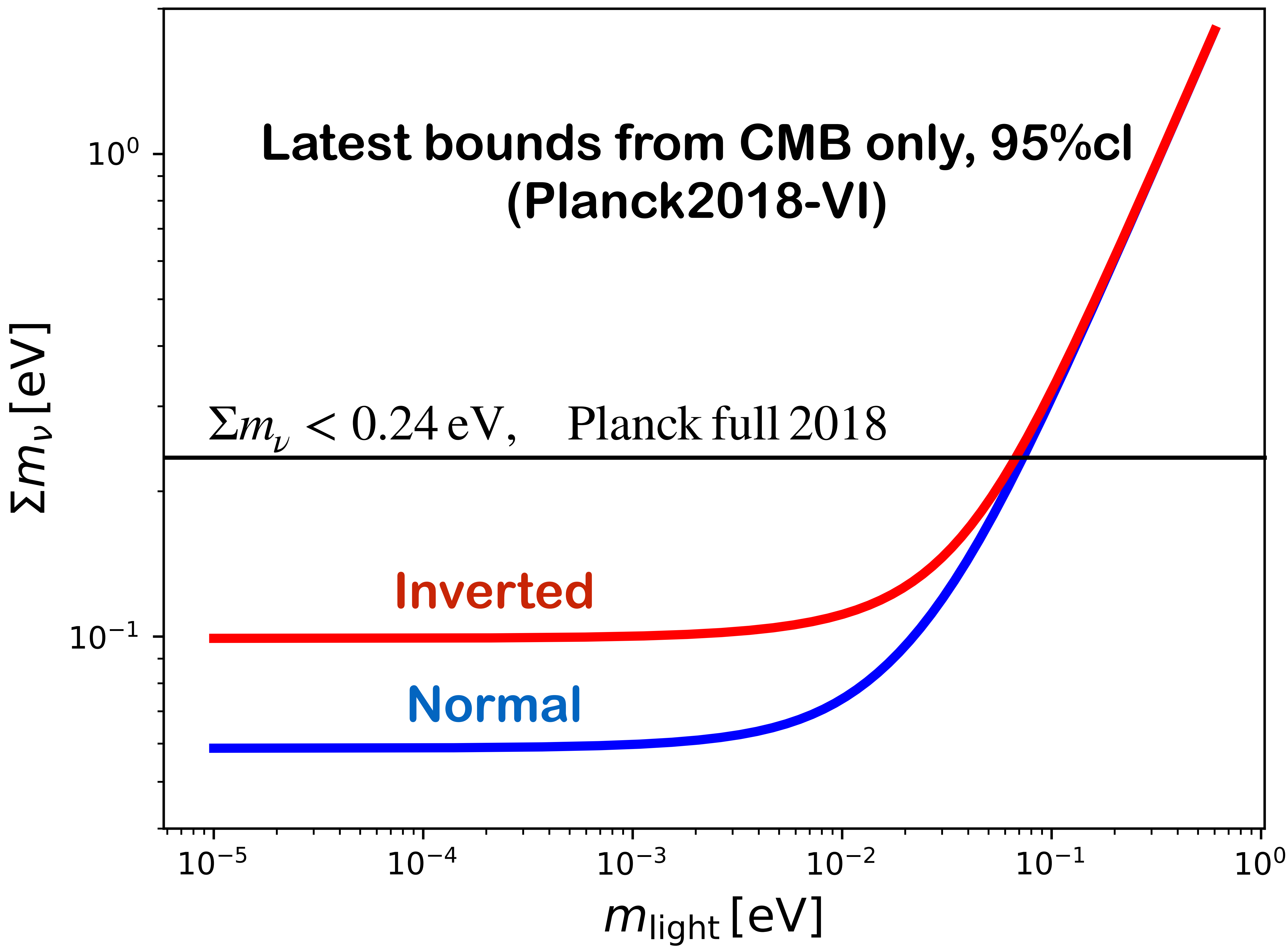
Free-streaming and power suppression

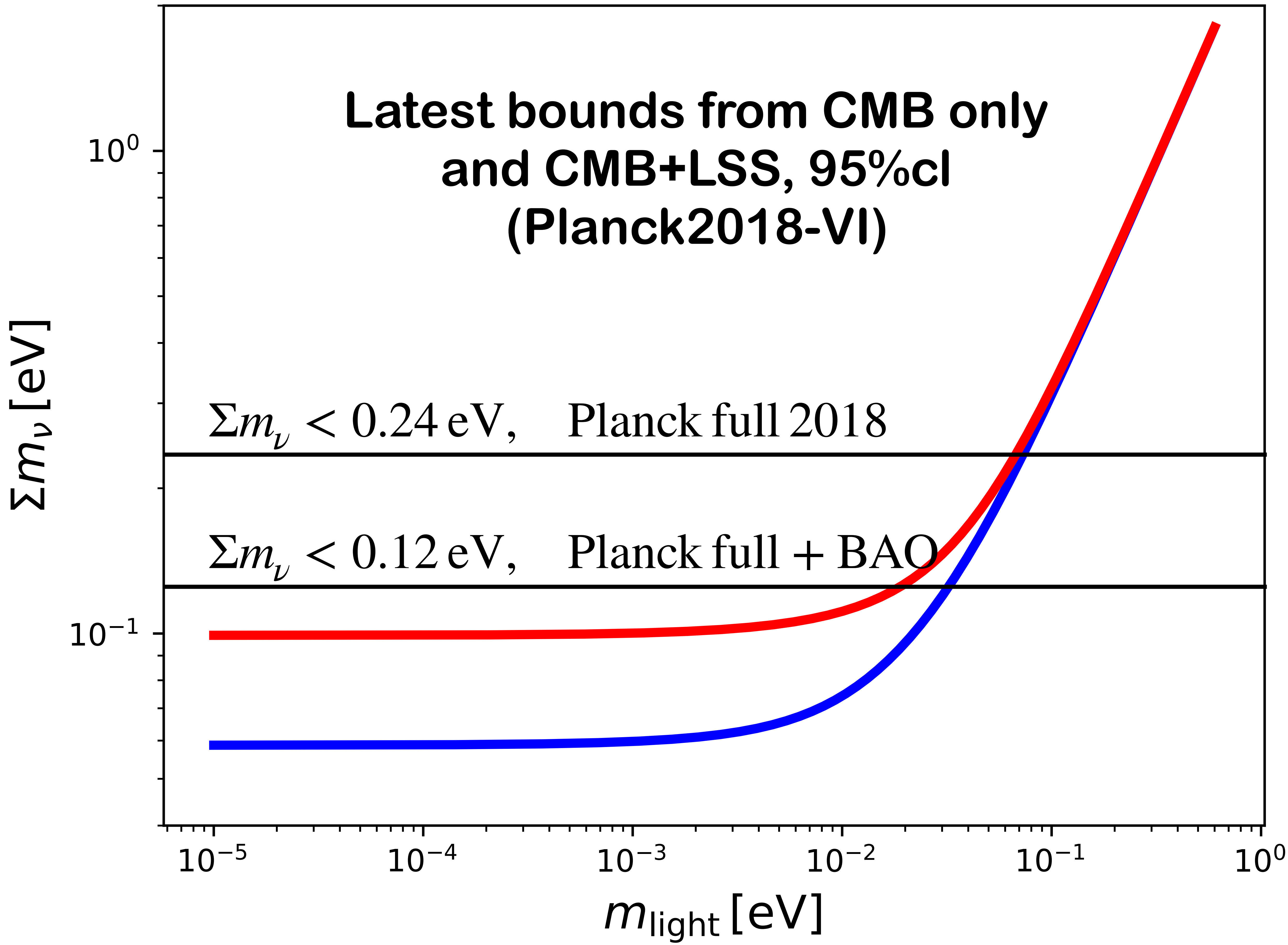
Slow down of late growth of structures

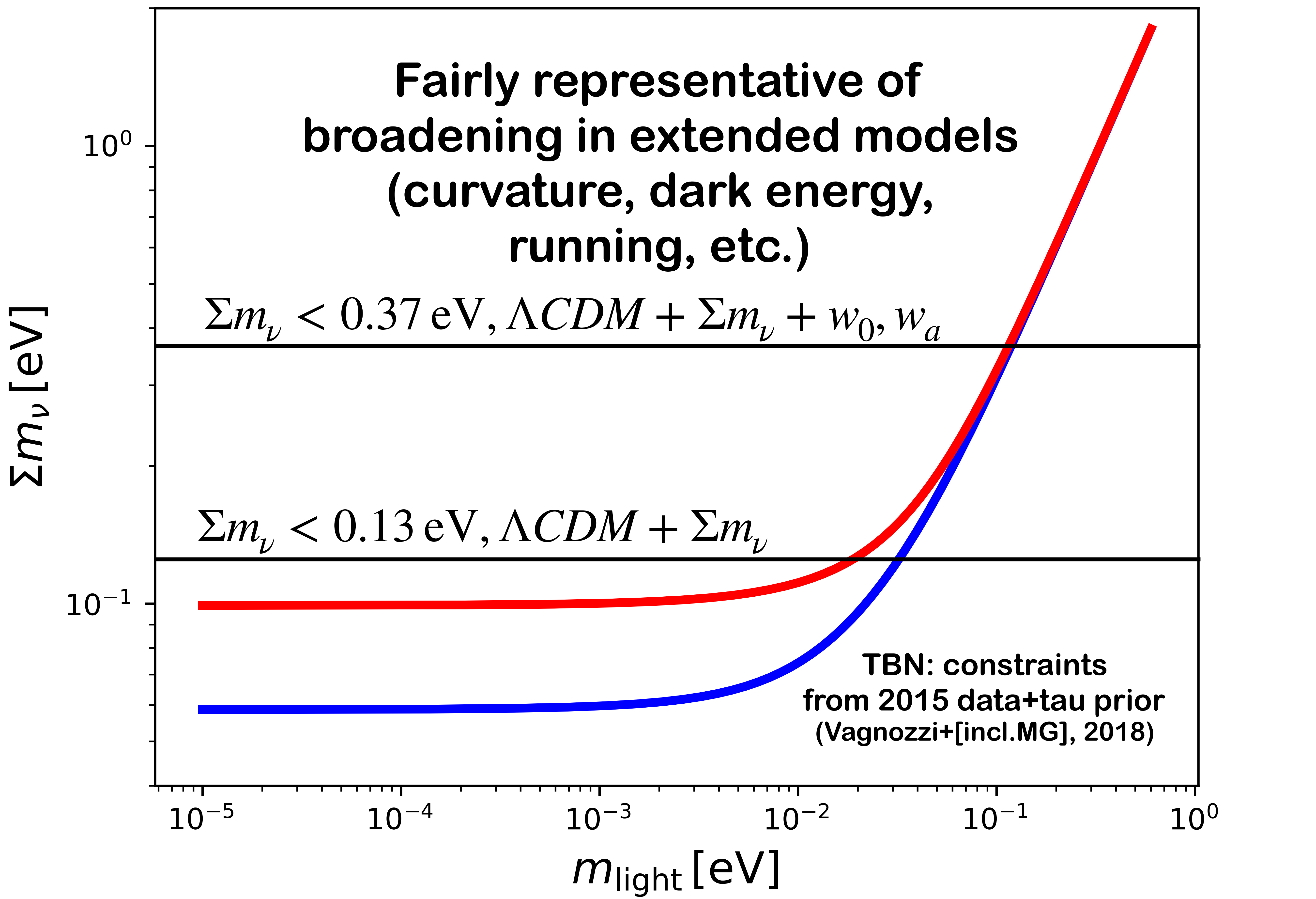
Slide adapted from J.Lesgourgues, talk@Neutrino2018



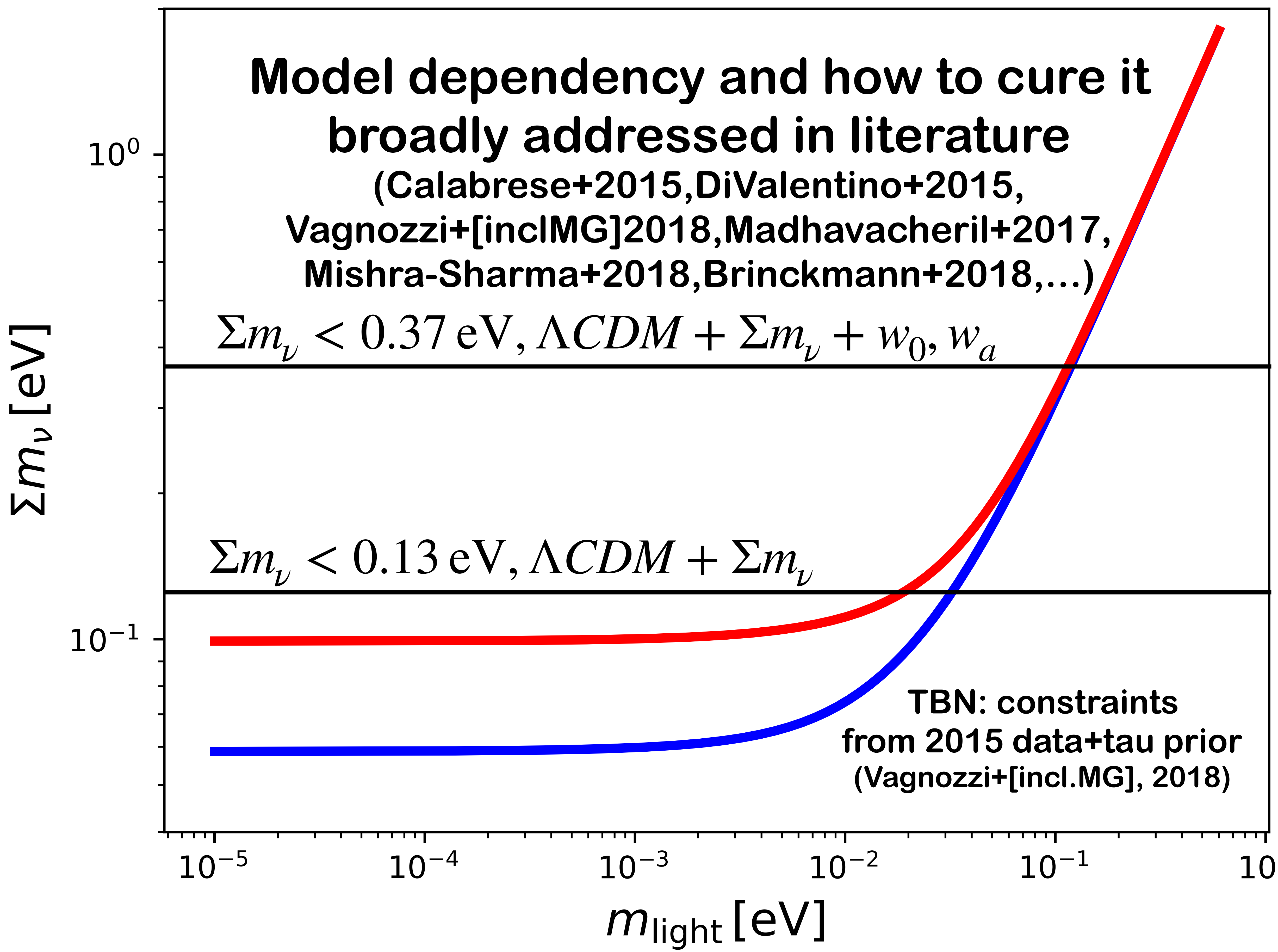
m^2
ν_e
ν_μ
ν_τ
Normal
Inverted
m_3^2
m_2^2
m_1^2
atmospheric $\sim 2\times10^{-3}\mathrm{eV}^2$
solar $\sim 7\times10^{-5}\mathrm{eV}^2$
?
0
Credit:K.Luhn
10^0
10^{-1}
Σm_ν [eV]
Inverted
Normal
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
m_{light} [eV]


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



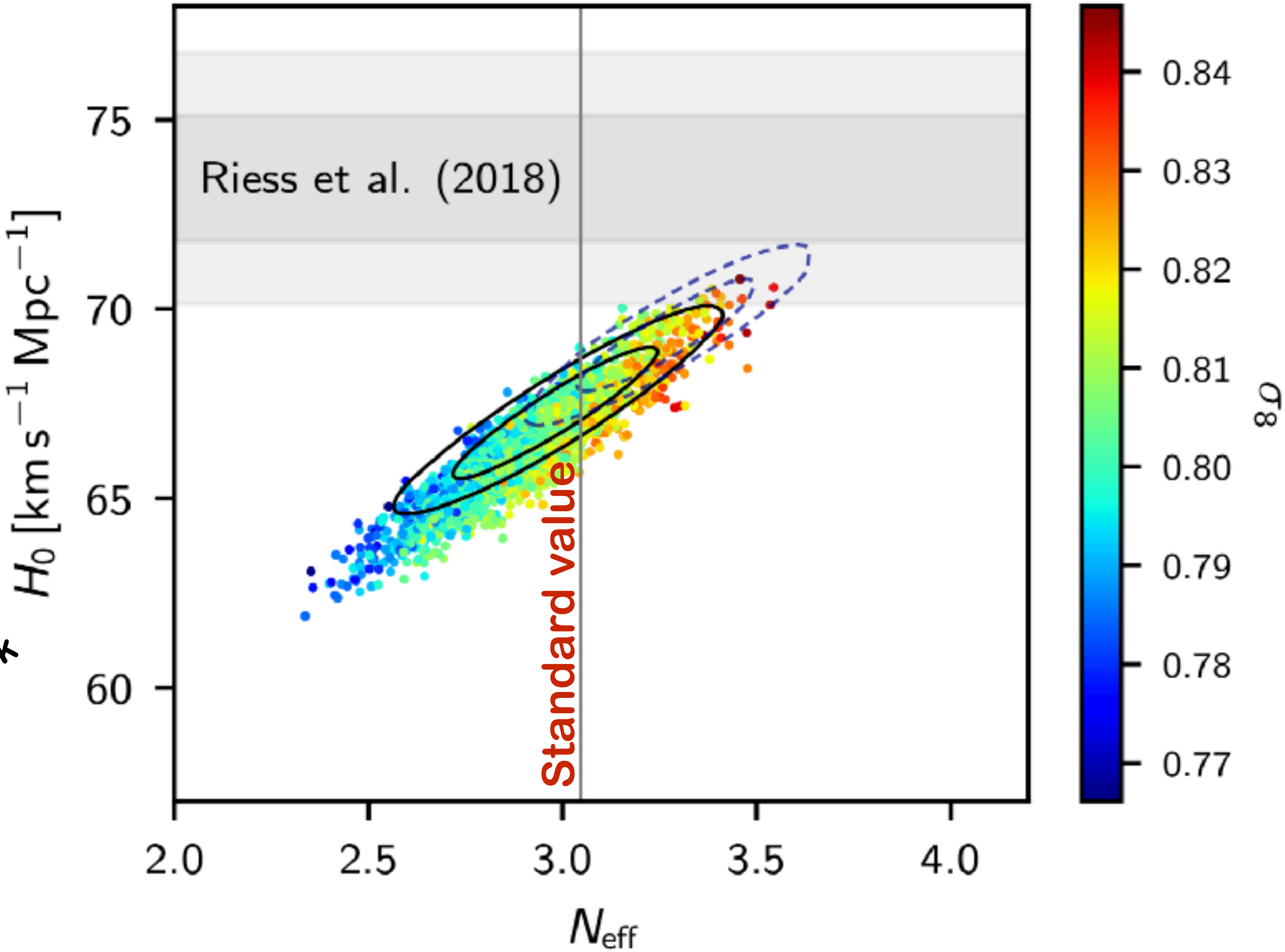
Fairly representative of broadening in extended models (curvature, dark energy, running, etc.)
$\Sigma m_\nu < 0.37\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu + w_0, w_a$
$\Sigma m_\nu < 0.13\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu$
TBN: constraints from 2015 data+tau prior
(Vagnozzi+[incl.MG], 2018)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



Model dependency and how to cure it
broadly addressed in literature
(Calabrese+2015,DiValentino+2015,
Vagnozzi+[inclMG]2018,Madhavacheril+2017,
Mishra-Sharma+2018,Brinckmann+2018,...)
$\Sigma m_\nu < 0.37\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu + w_0, w_a$
$\Sigma m_\nu < 0.13\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu$
TBN: constraints
from 2015 data+tau prior
(Vagnozzi+[incl.MG], 2018)
Σm_ν [eV]
$m_{\rm light}$ [eV]
10^0
10^{-1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0

Current limits on Neff

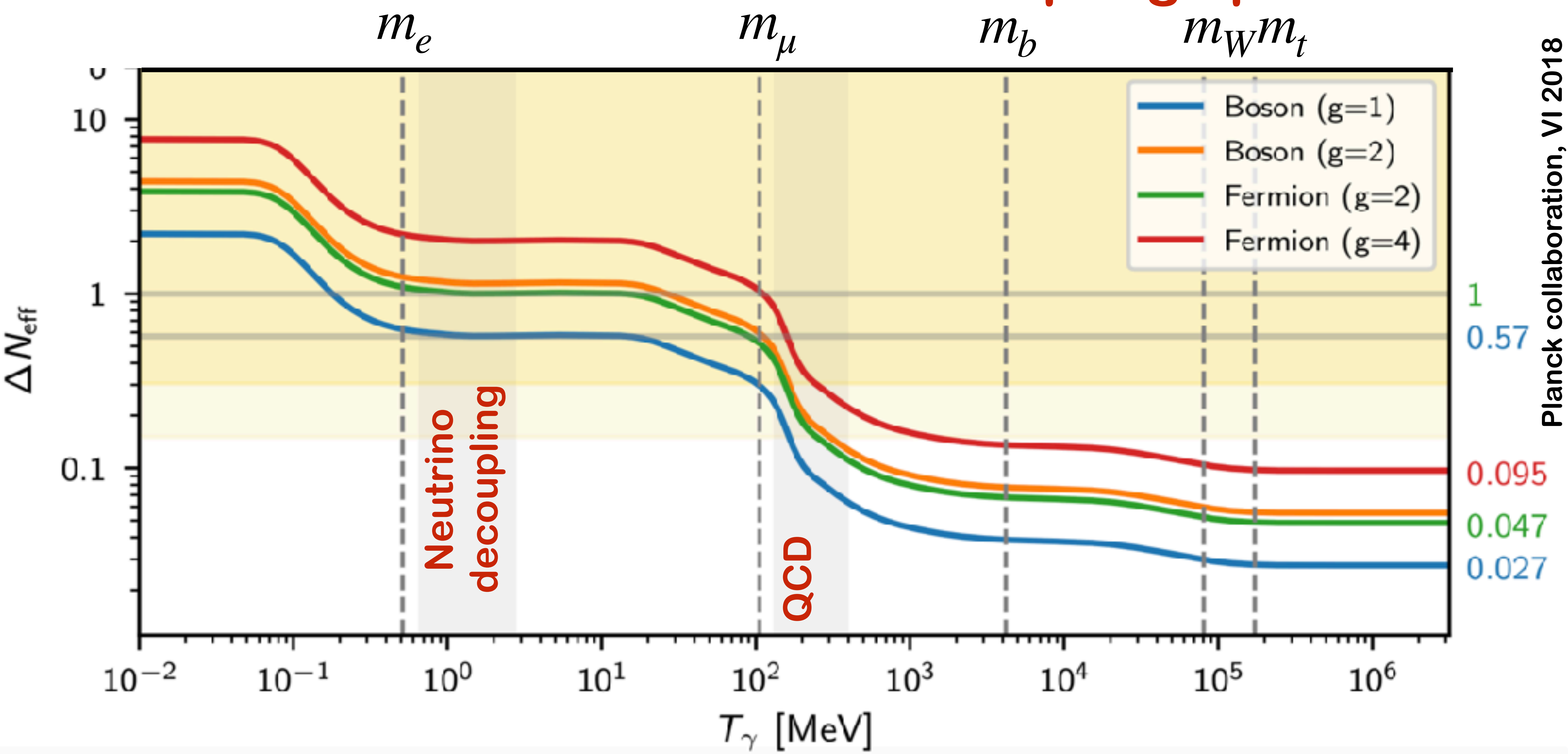
$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}, 95\,\%\,c.l., \text{Planck2018 + BAO}$$



Planck collaboration, VI 2018

see V.Poulin talk
see M.Rigault talk

Contribution to Neff from decoupling species

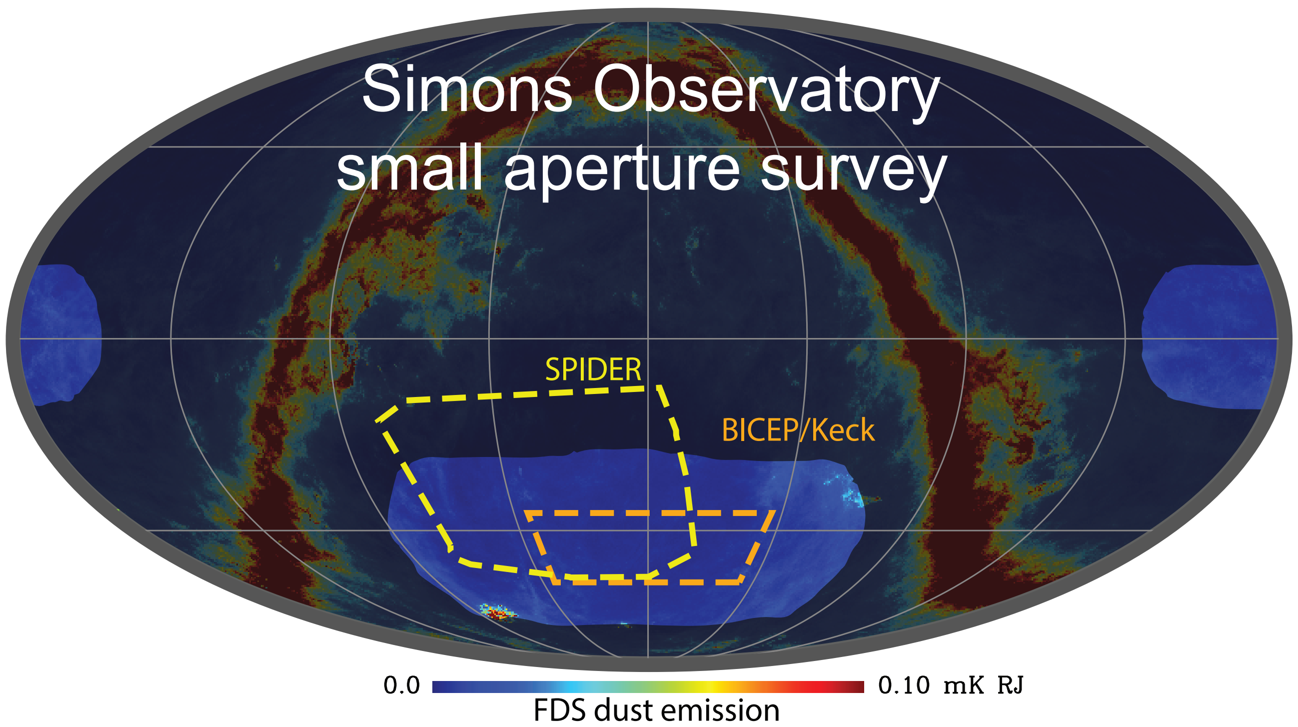


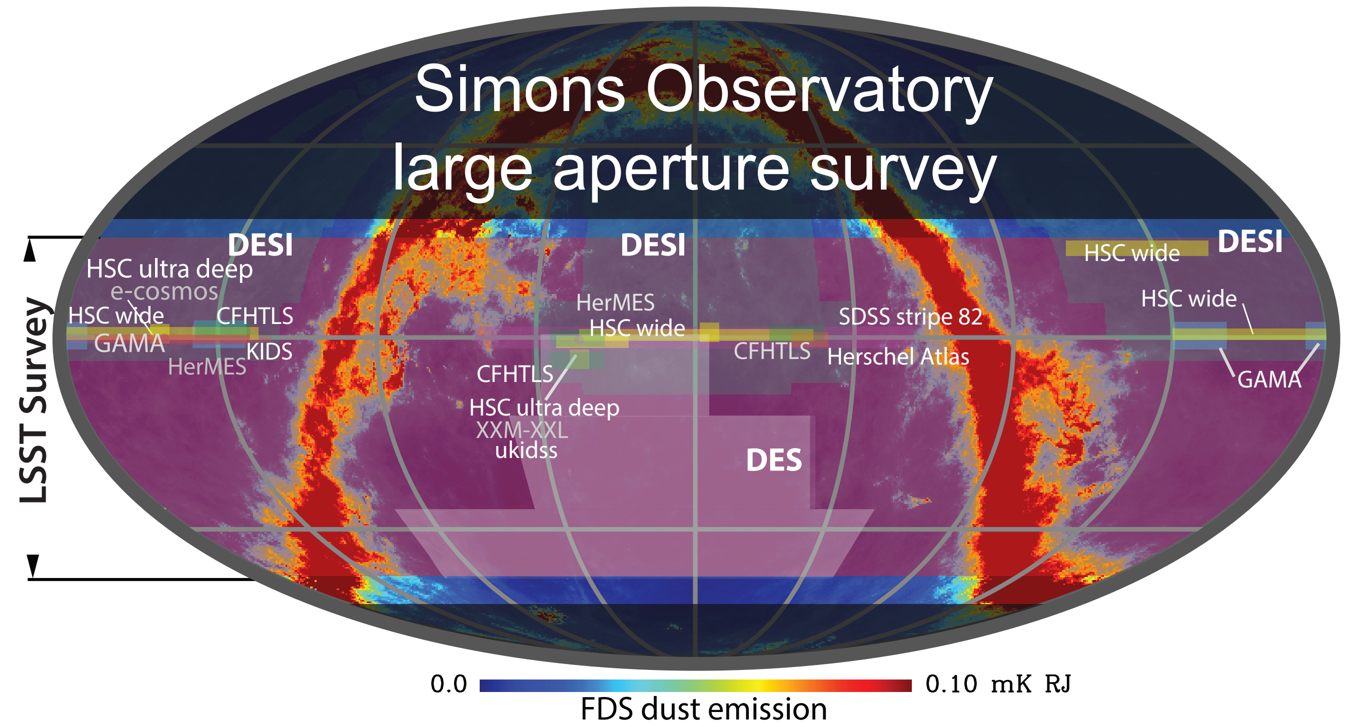
Presence of additional fully thermalised species decoupling after QCD phase transition excluded at 95%c.l.

~eV thermalised sterile neutrino excluded at 7sigma *see J.Kopp talk*

Non-standard models needed to make SBL compatible with cosmology

Simons Observatory (SO) in a nutshell





- **Multi-frequency CMB experiments observing from Cherro Toco (Chile)**
- **Start observing from ~2020. Initial configuration:**
  - ✴ **3 small-aperture telescopes devoted primarily to primordial tensor-to-scalar ratio measurements**
  - ✴ **1 large-aperture telescope devoted primarily to damping tail, gravitational lensing, bispectrum, Sunyaev–Zel'dovich effects, and delensing science**

Forecast paper is out: arXiv:1808.07445 [astro-ph.CO]
data products: https://www.simonsobservatory.org/publications.php

Route to robust 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

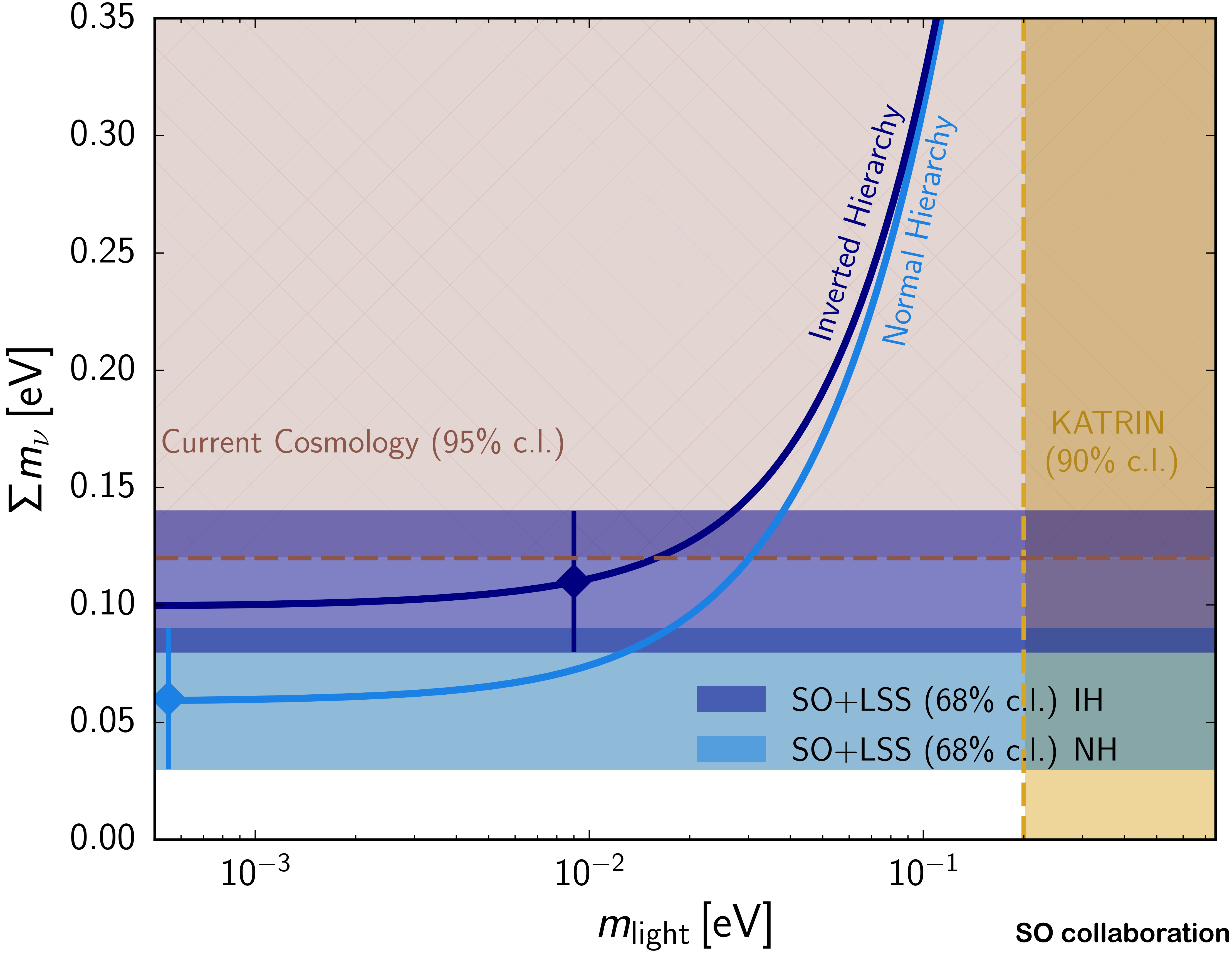
$$\sigma(\Sigma m_\nu) = 0.05\,\mathrm{eV}\ [0.04\,\mathrm{eV}]$$

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

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

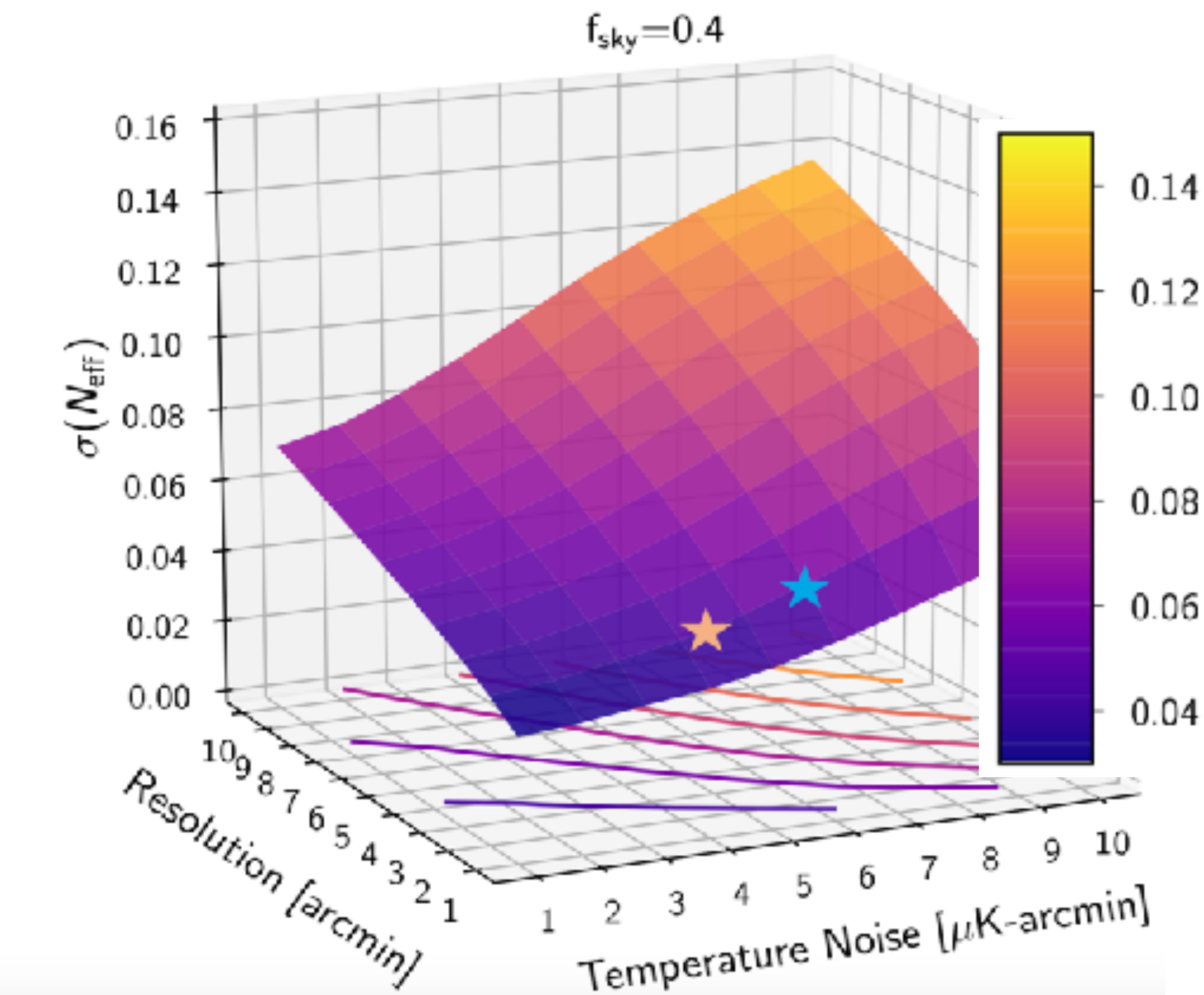
SO collaboration, 2018

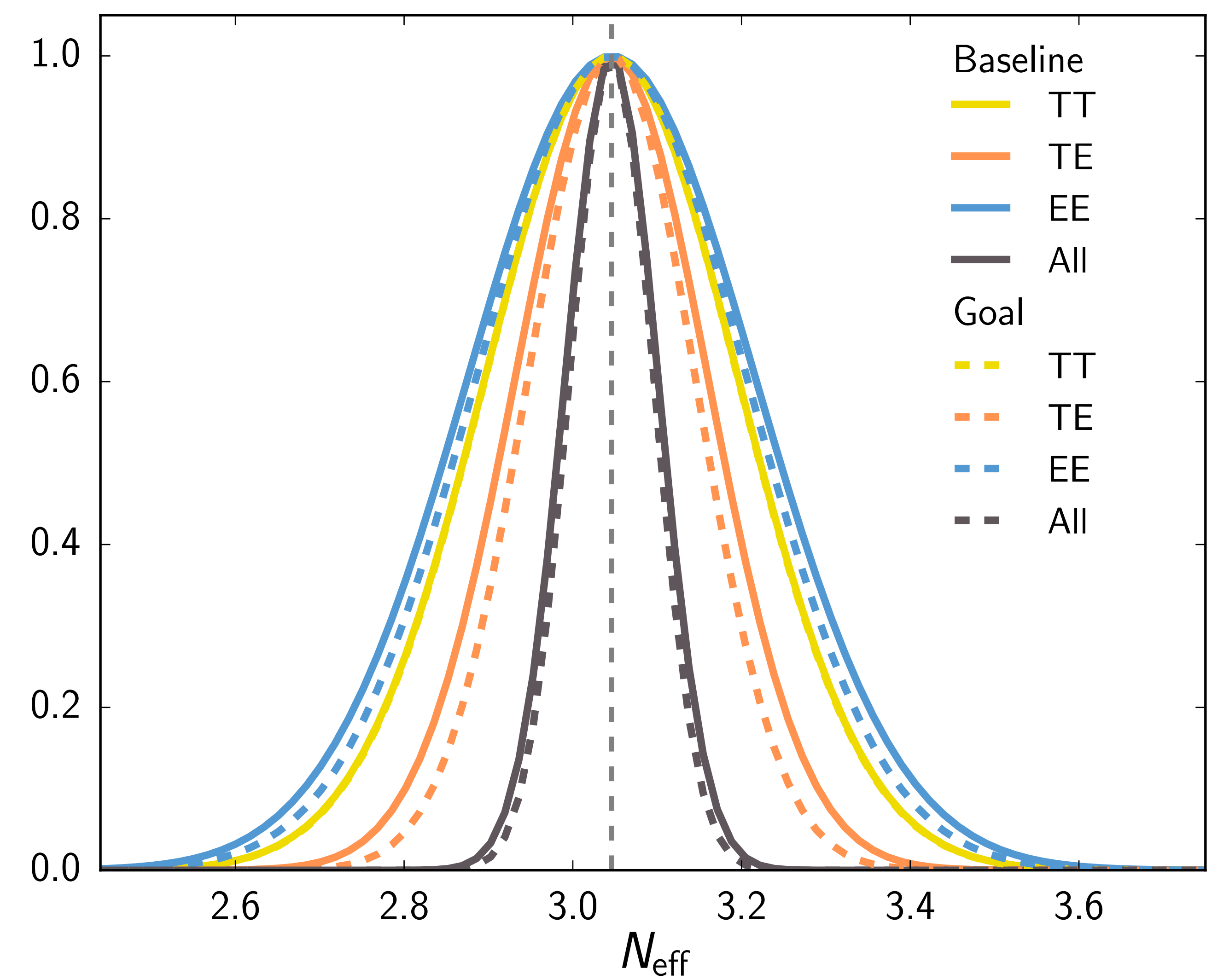
Route to robust neutrino mass bounds



SO collaboration, 2018

Route to improved bounds on Neff



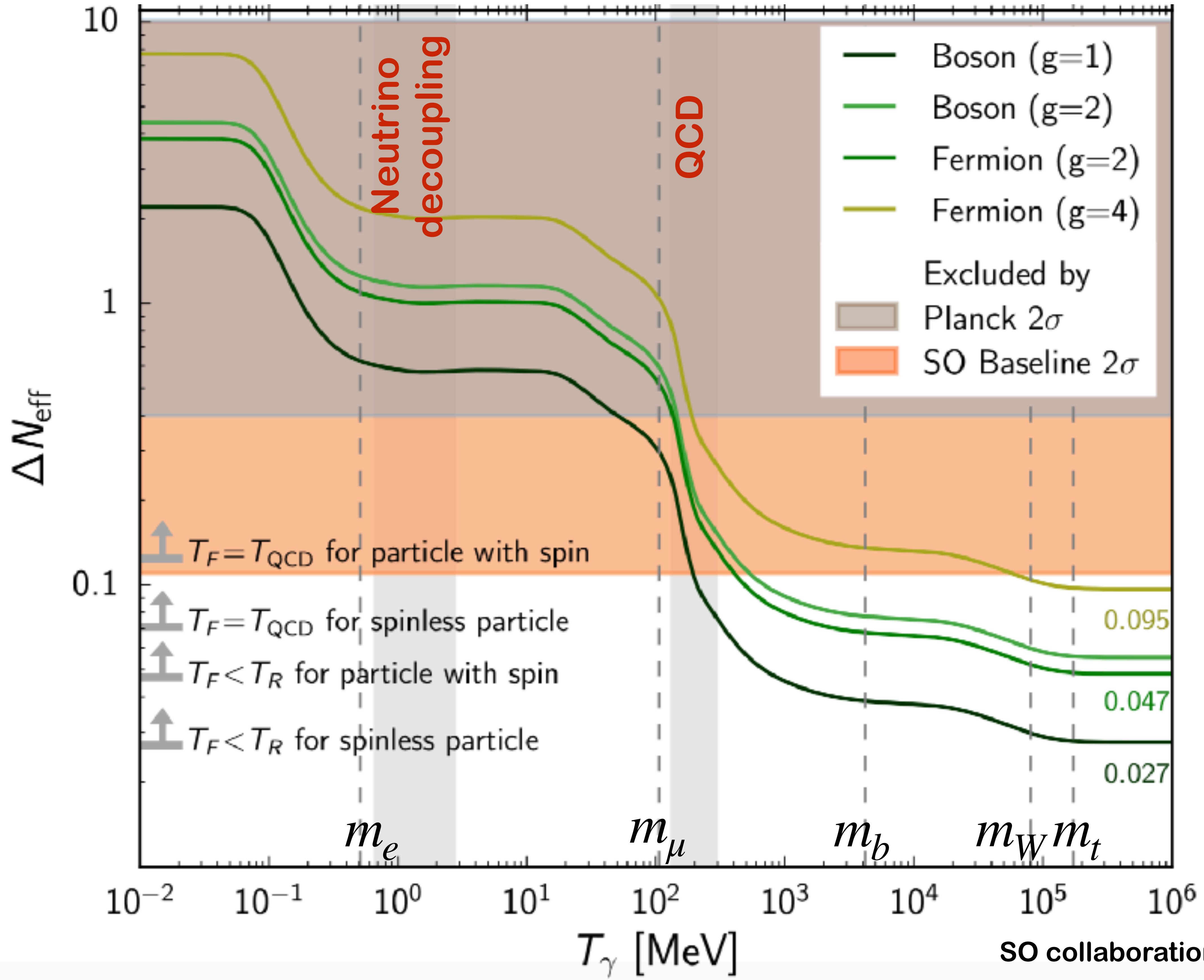


Primary CMB temperature and polarization power spectra from SO

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

SO collaboration, 2018

Route to improved bounds on Neff

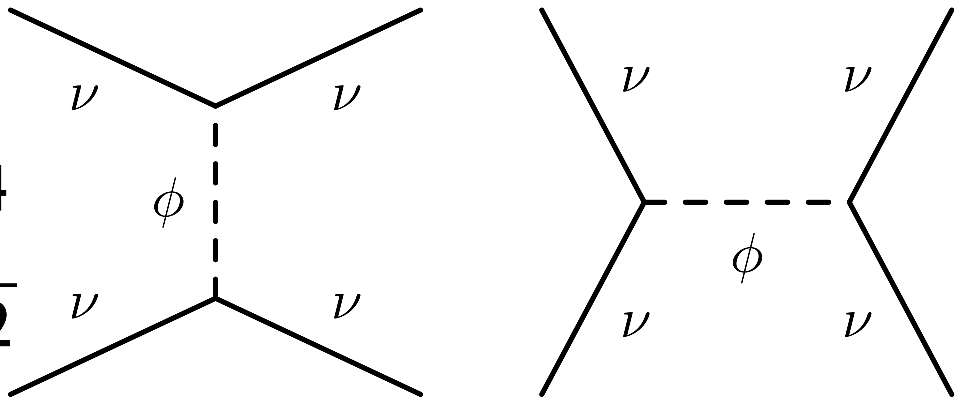


SO collaboration, 2018

Scalar-mediated neutrino interactions

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

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



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

Parameterizing the interaction strength through:

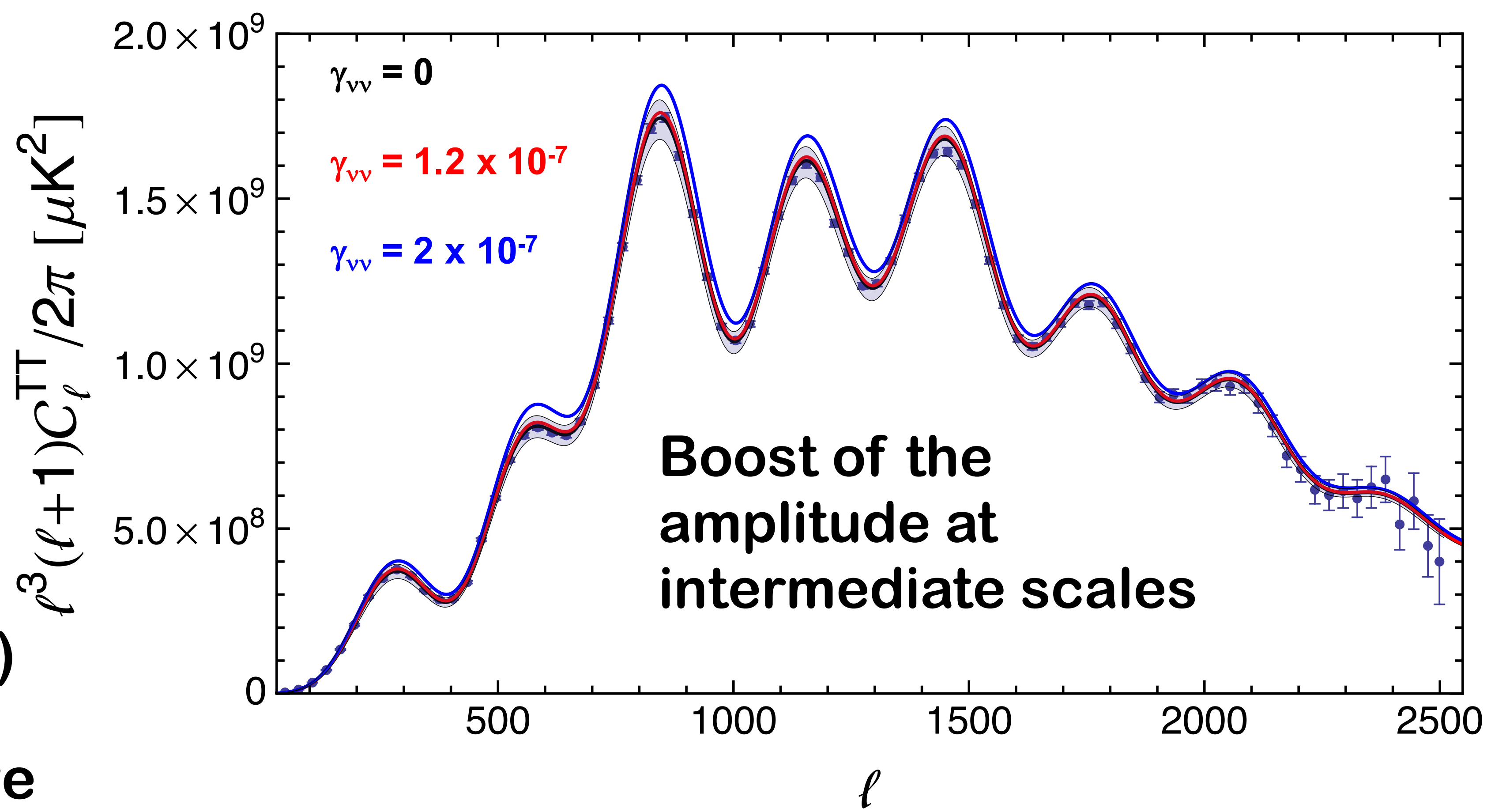
$$\Gamma_{\nu\nu} \equiv \gamma_{\nu\nu}^4 T$$

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

CONCLUSIONS

Determine CnB properties from neutrino peculiar effects on cosmological observables

Strong and robust constraints from cosmology

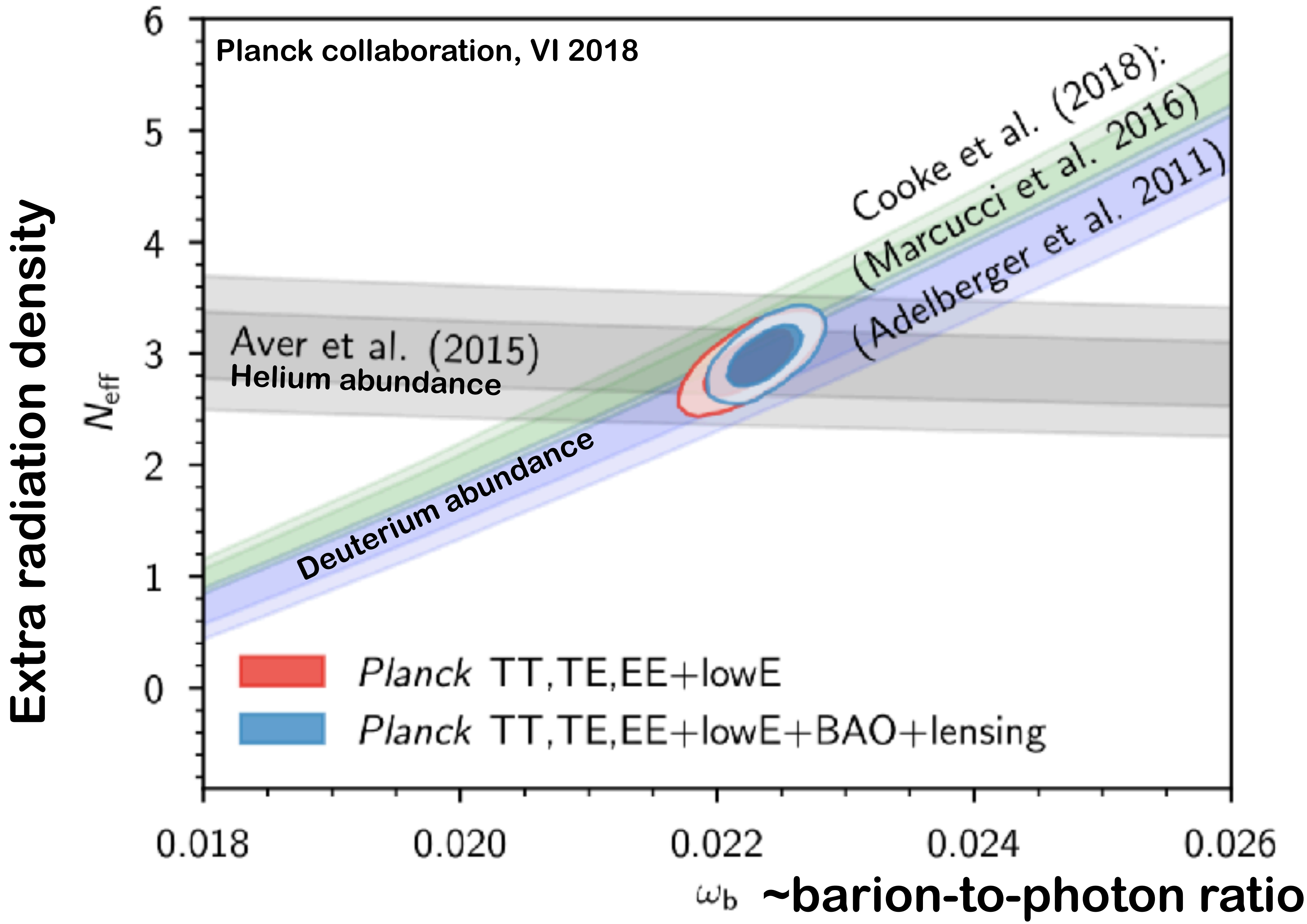
Neutrino masses: getting closer to cornering inverting hierarchy

Neff: no preference for an additional thermalised species

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

BACKUP SLIDES

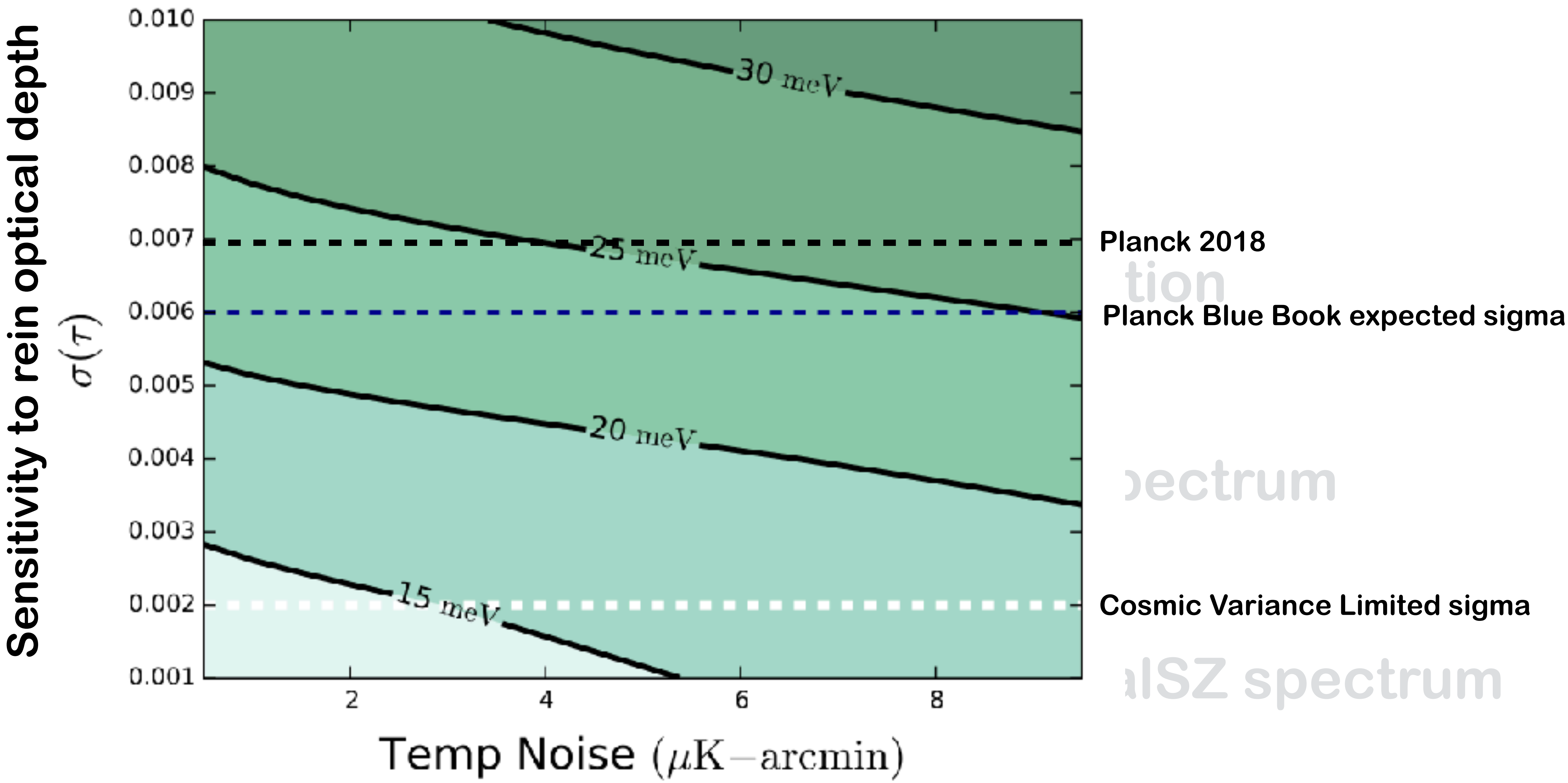
Comparison with BBN predictions



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

Route to robust neutrino mass bounds

CMB-S4 science book

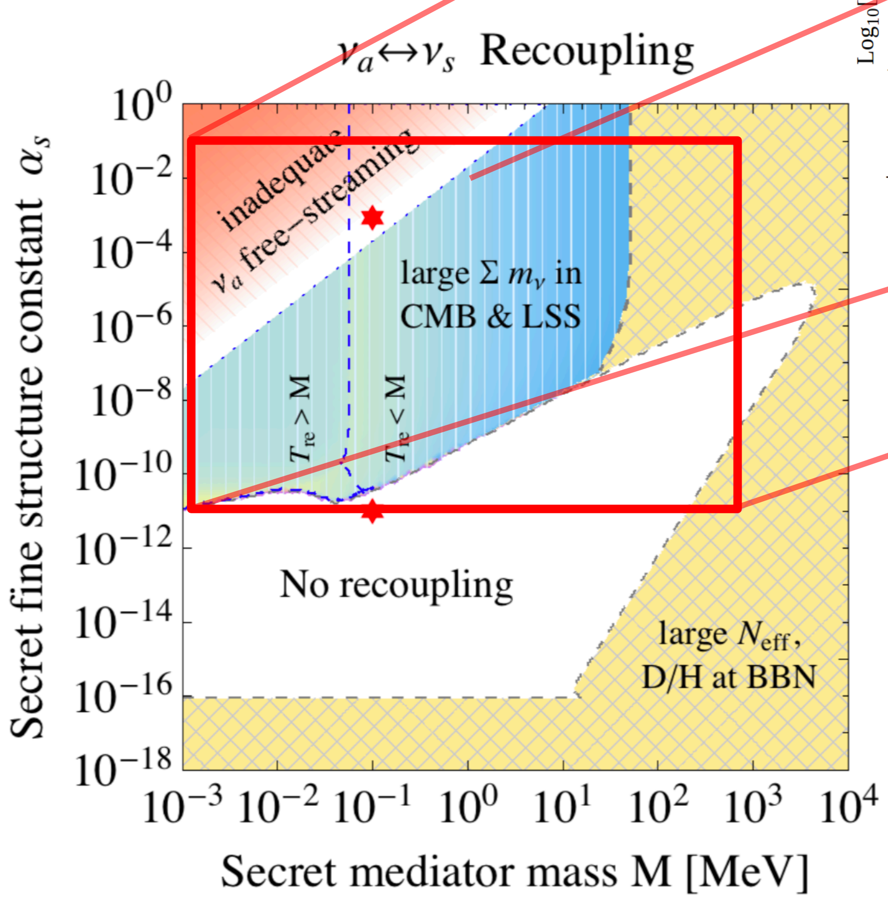


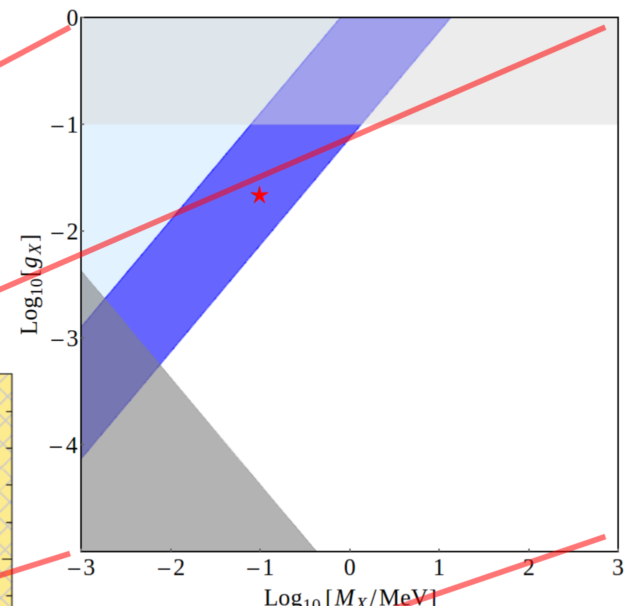
Experiment noise

- Cosmic-variance-limited measurements of tau

Sterile neutrino interactions and SBL anomalies

Sterile neutrino interpretation of SBL is in disagreement with cosmology (implies ΔN_{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.

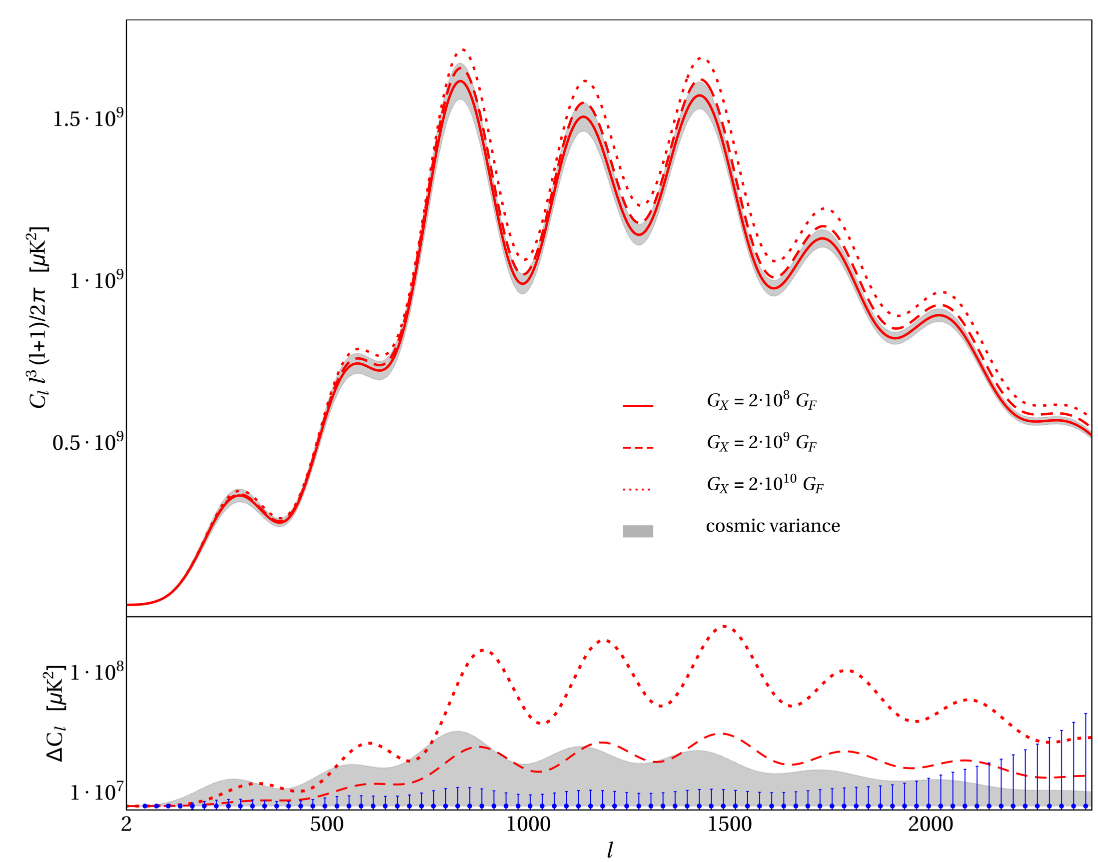




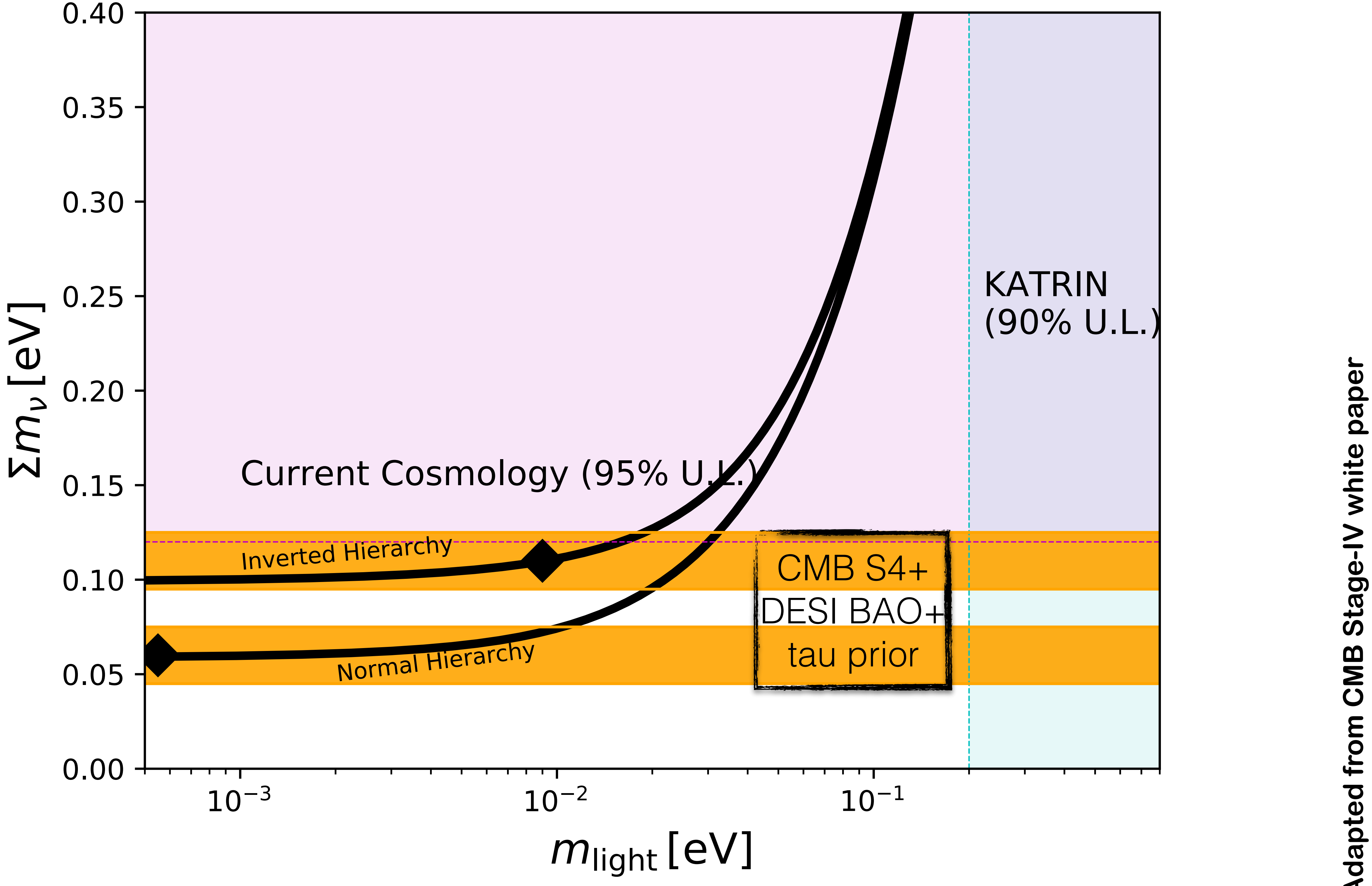
$$\mathcal{L}_s = g_X \bar{\nu}_s \gamma_\mu \frac{1}{2} (1 - \gamma_5) \nu_s X^\mu$$

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

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)

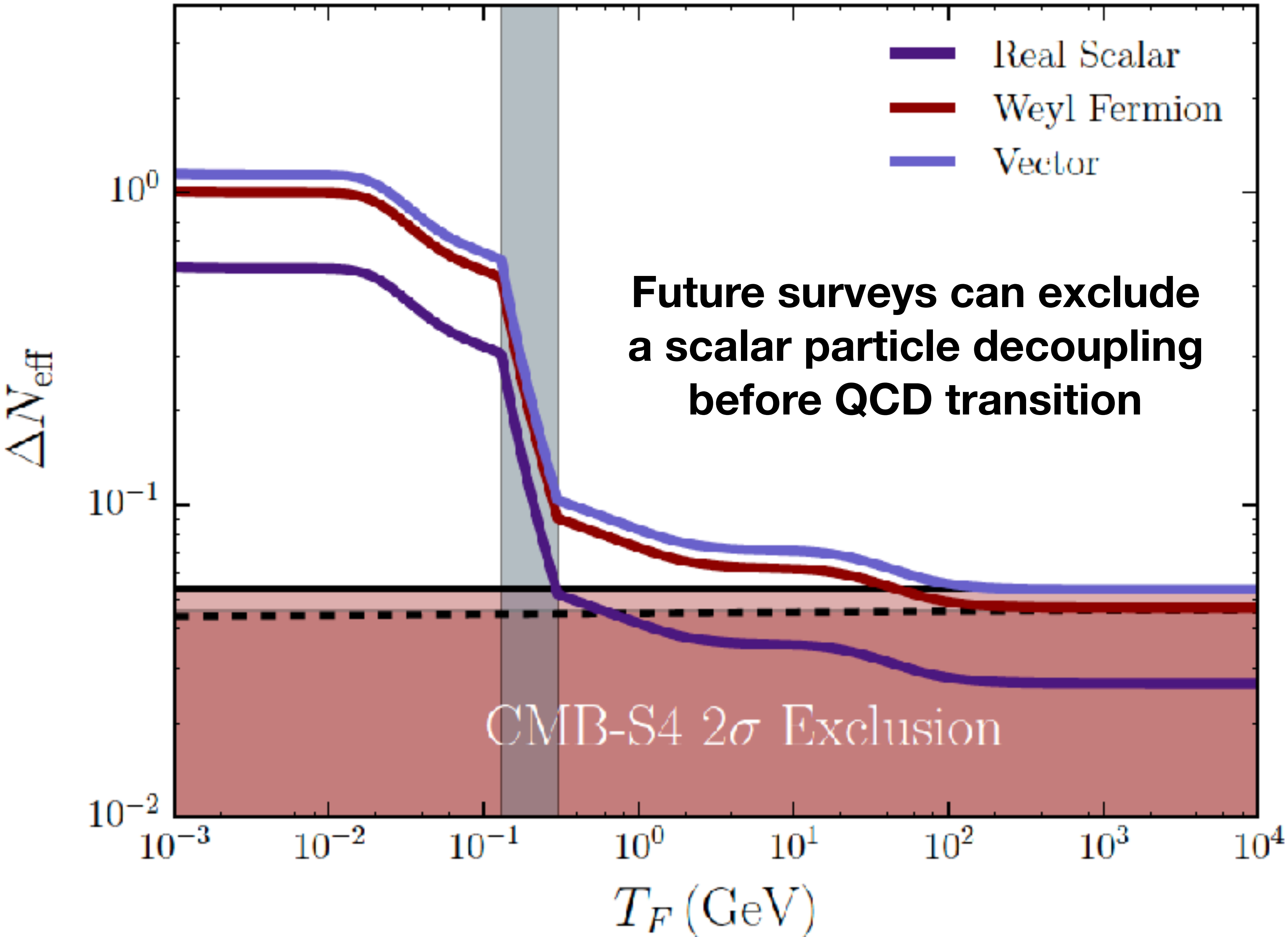


Future - Massive neutrinos



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

Future - Relativistic species



Future surveys can exclude a scalar particle decoupling before QCD transition

CMB Stage-IV white paper

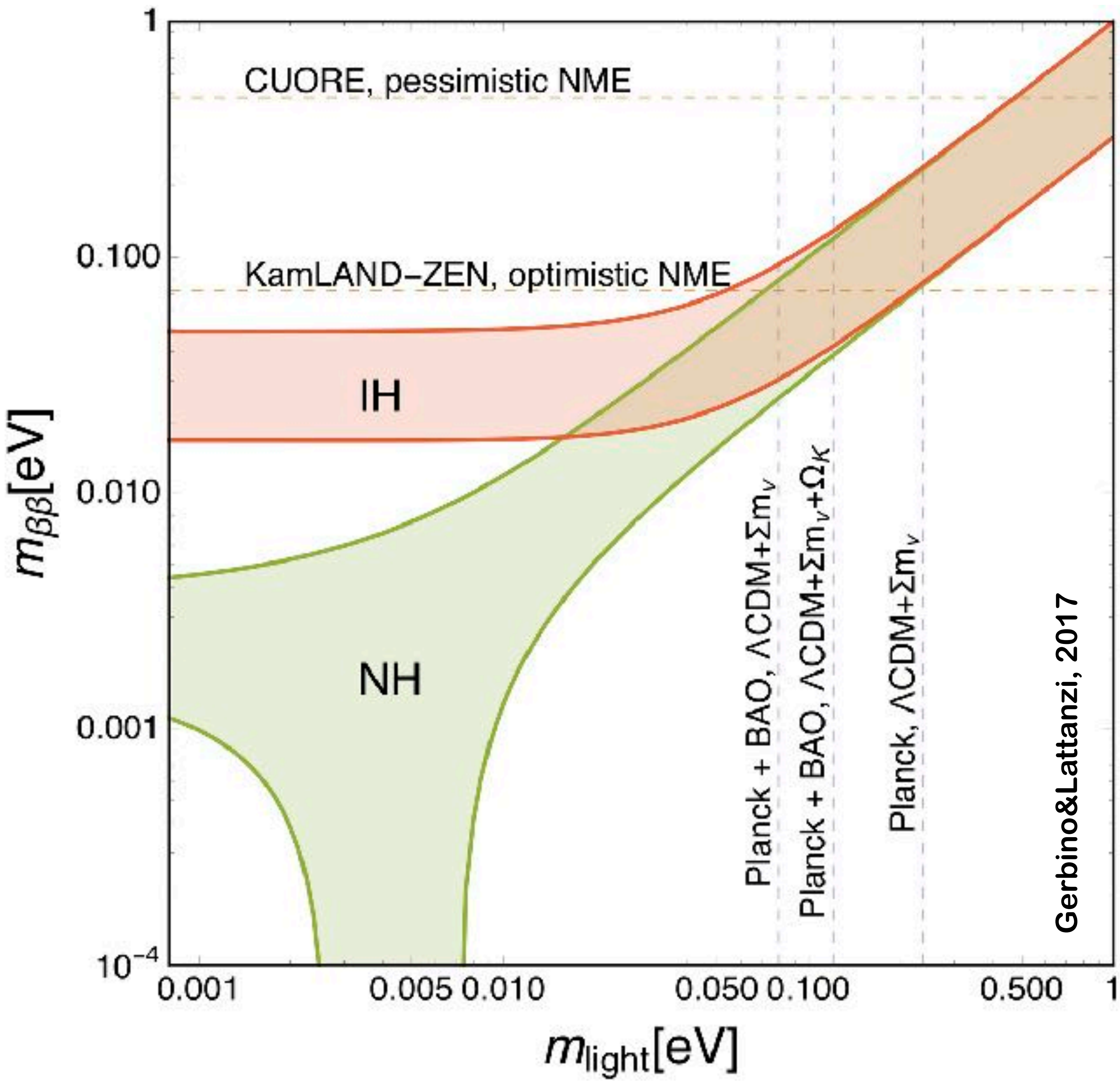
Moreover: the physics of non-instantaneous decoupling will be probed at ~2sigma level

Model assumptions

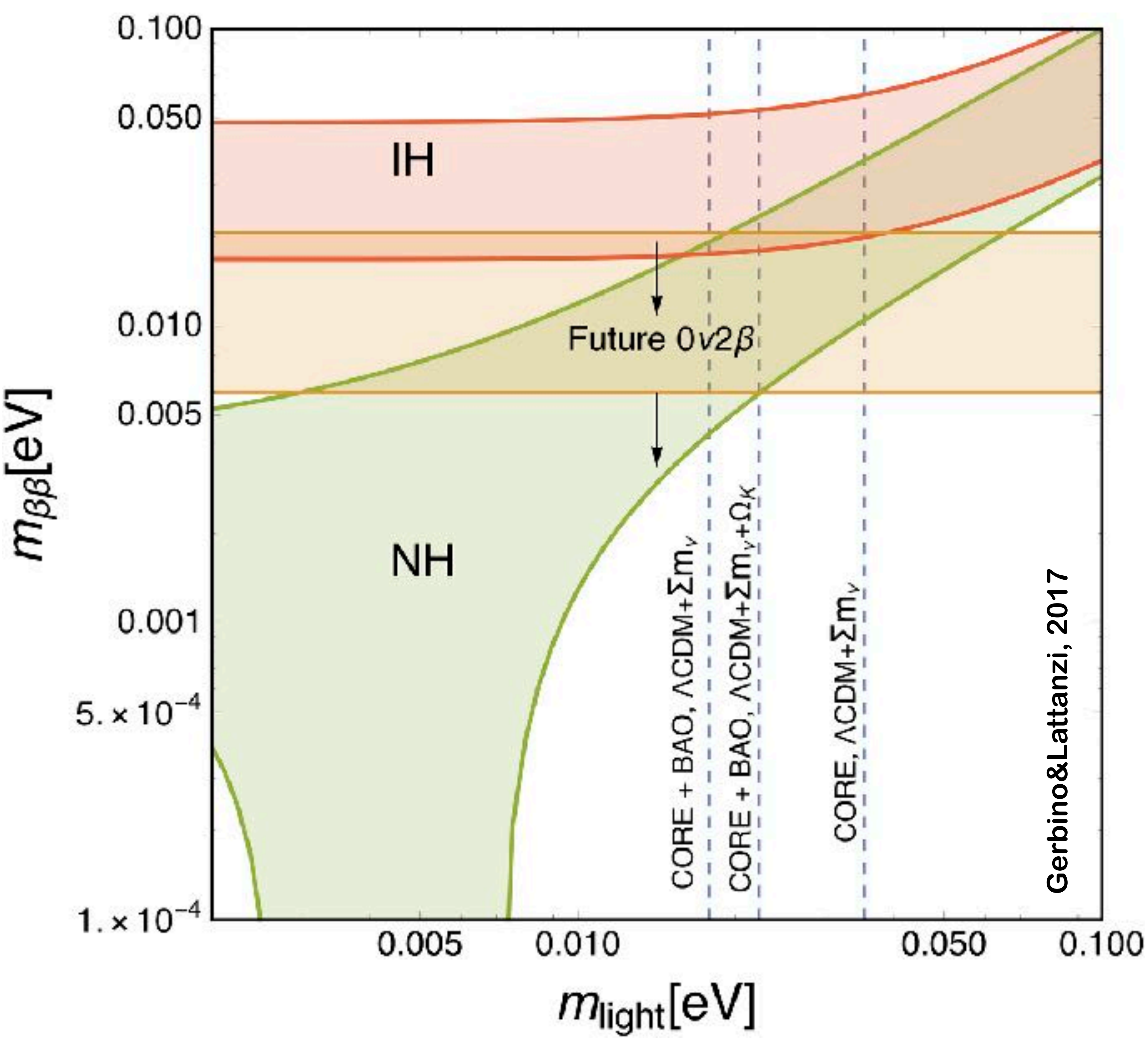
The ΛCDM model assumes:

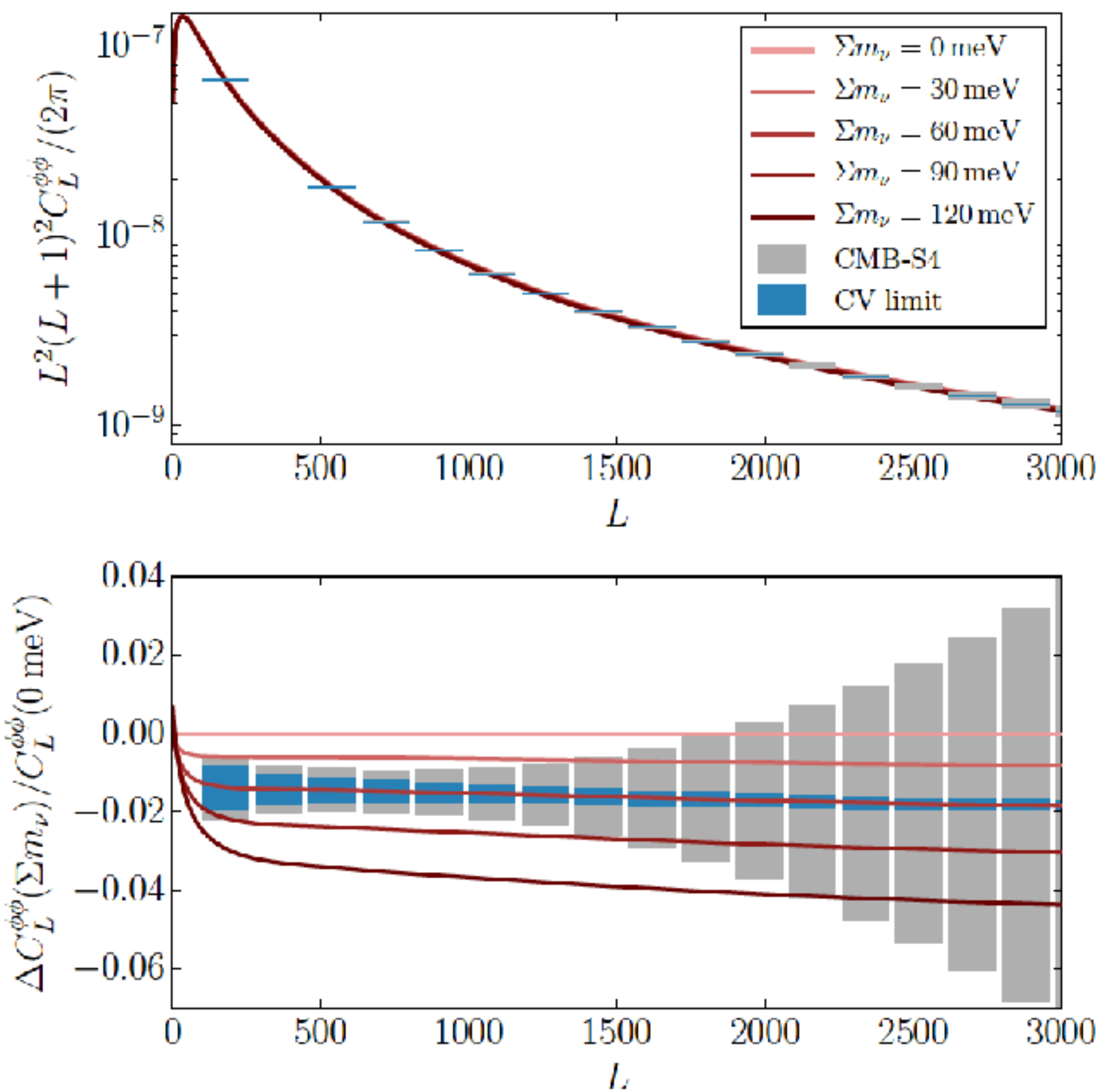
- only weak and gravitational interactions;
- perfect lepton symmetry (zero chemical potential);
- no entropy generation after neutrino decoupling beyond e^+e^- annihilation;
- neutrinos are stable;
- in general, there are no interactions that could lead to neutrino scattering/ annihilation/decay

Complementarity with laboratory searches



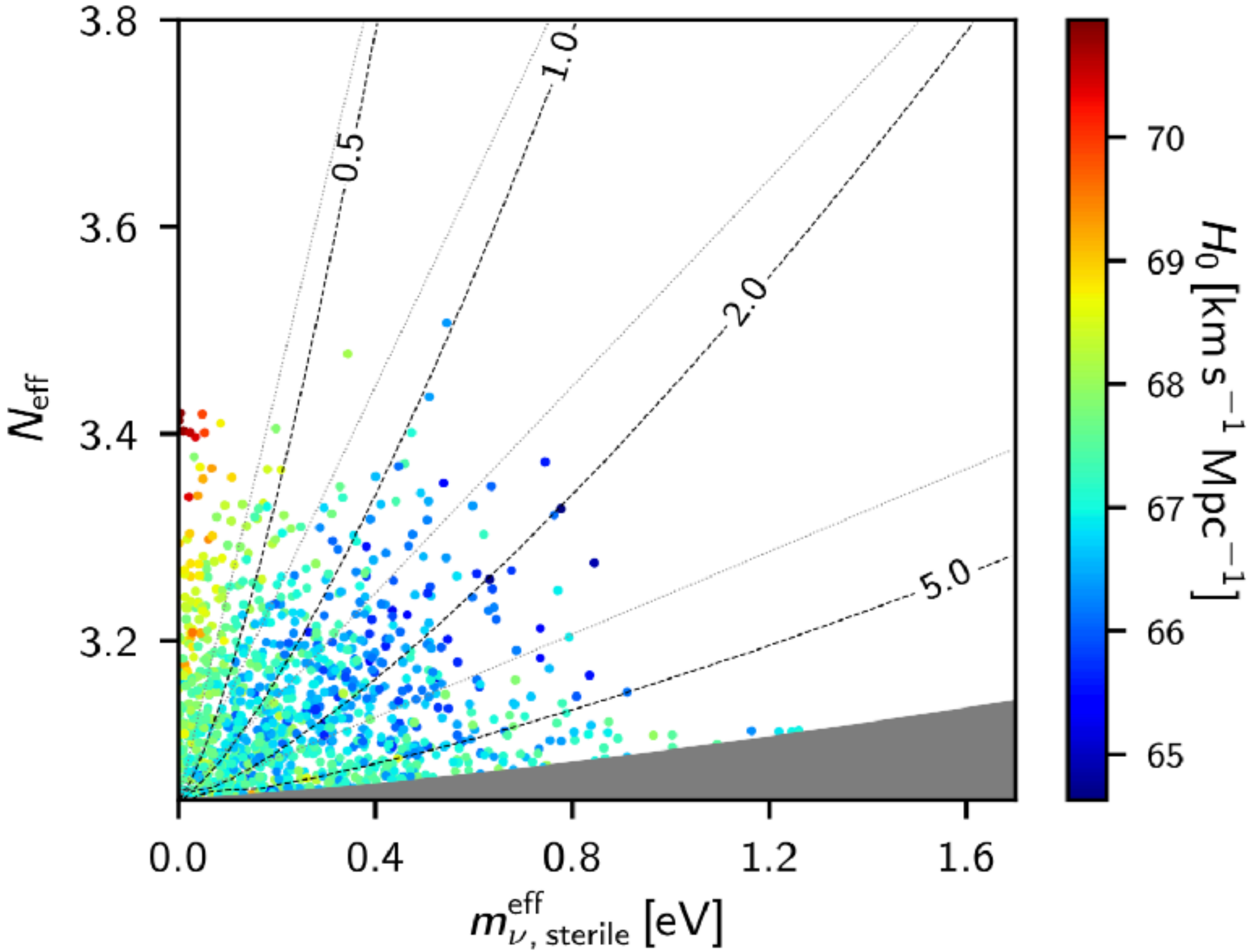
Complementarity with laboratory searches




10^{-7}
10^{-8}
10^{-9}
$L^2(L+1)^2C_L^{\phi\phi}/(2\pi)$
0
500
1000
1500
2000
2500
3000
L
$\Sigma m_\nu = 0$ meV
$\Sigma m_\nu = 30$ meV
$\Sigma m_\nu = 60$ meV
$\Sigma m_\nu = 90$ meV
$\Sigma m_\nu = 120$ meV
CMB-S4
CV limit
0.04
0.02
0.00
−0.02
−0.04
−0.06
$\Delta C_L^{\phi\phi}(\Sigma m_\nu)/C_L^{\phi\phi}(0\ \mathrm{meV})$

Current limits on Neff-meff

Planck collaboration, VI 2018



~eV thermalised sterile neutrino excluded at 7sigma

Non-standard models needed to make SBL compatible with cosmology

Effects on background quantities

Expansion rate

$$H(z)^2 = H_0^2 \left[(\Omega_c + \Omega_b)(1+z)^3 + \Omega_\gamma (1+z)^4 + \Omega_\Lambda + \frac{\rho_\nu(z)}{\rho_{\mathrm{crit},0}} \right]$$

modifies the angular size of the sound horizon at recombination $\theta_s = r_s / D_A$

modifies the angular scale of the Silk damping $\theta_d = \frac{r_d}{D_A} \propto \frac{1/\sqrt{H}}{1/H}$

$$1 + z_{\mathrm{eq}} = \frac{\Omega_c + \Omega_b}{\Omega_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\mathrm{eff}} \right]}$$

Matter-radiation equality

Perturbation effects

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

Free streaming scale

$$\delta_m(k \gg k_{\rm fs}) \propto a^{1-(3/5)\Omega_\nu/\Omega_m}$$

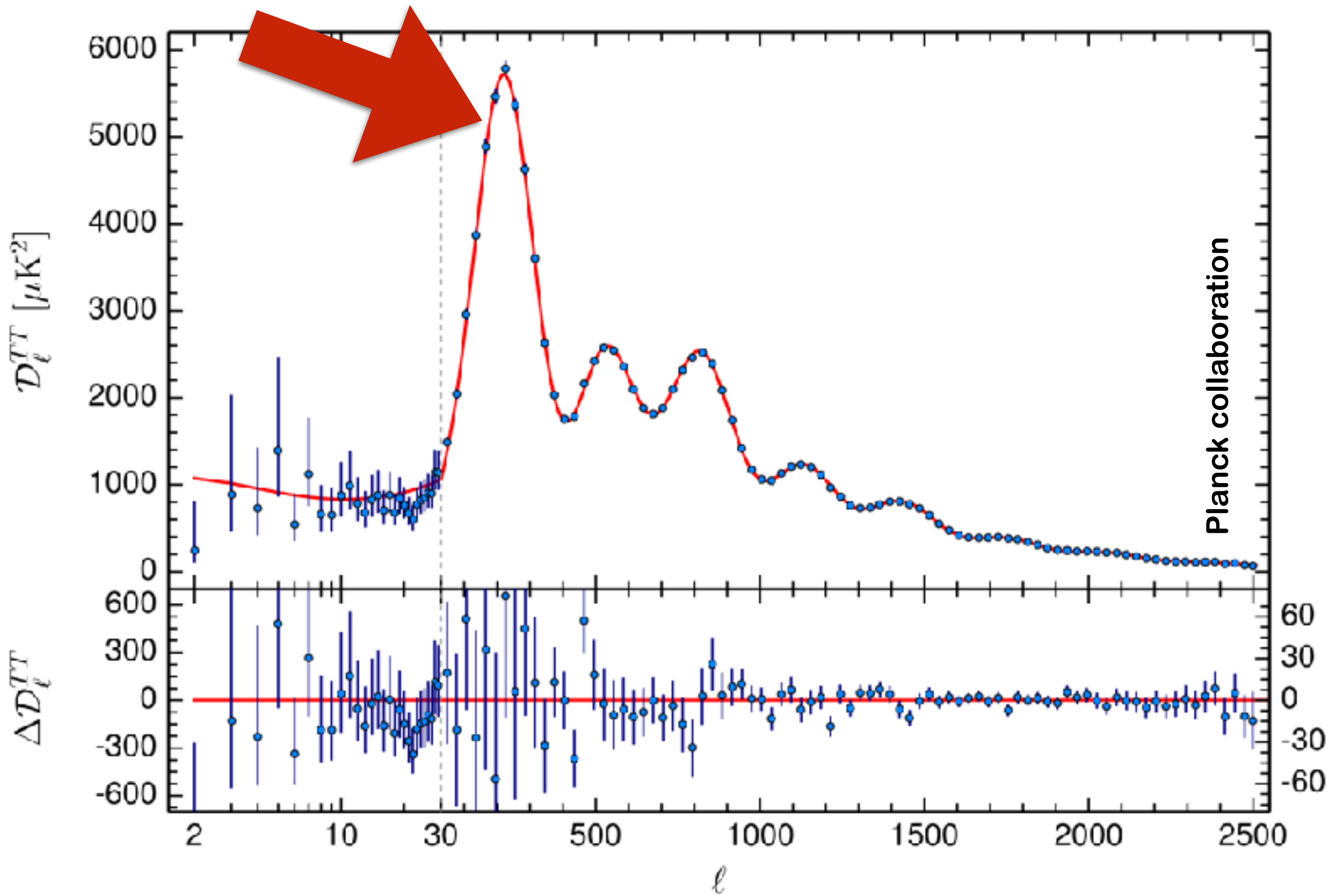
Suppressed growth

$$k_p r_s + \phi = p\pi$$

Acoustic phase shift

Effects on the CMB spectrum

sound horizon at recombination
matter-equality

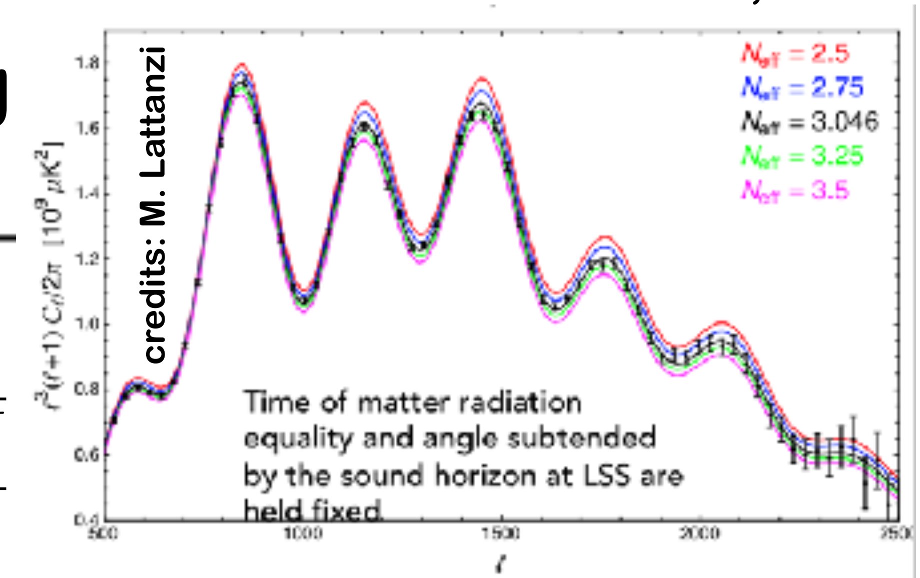


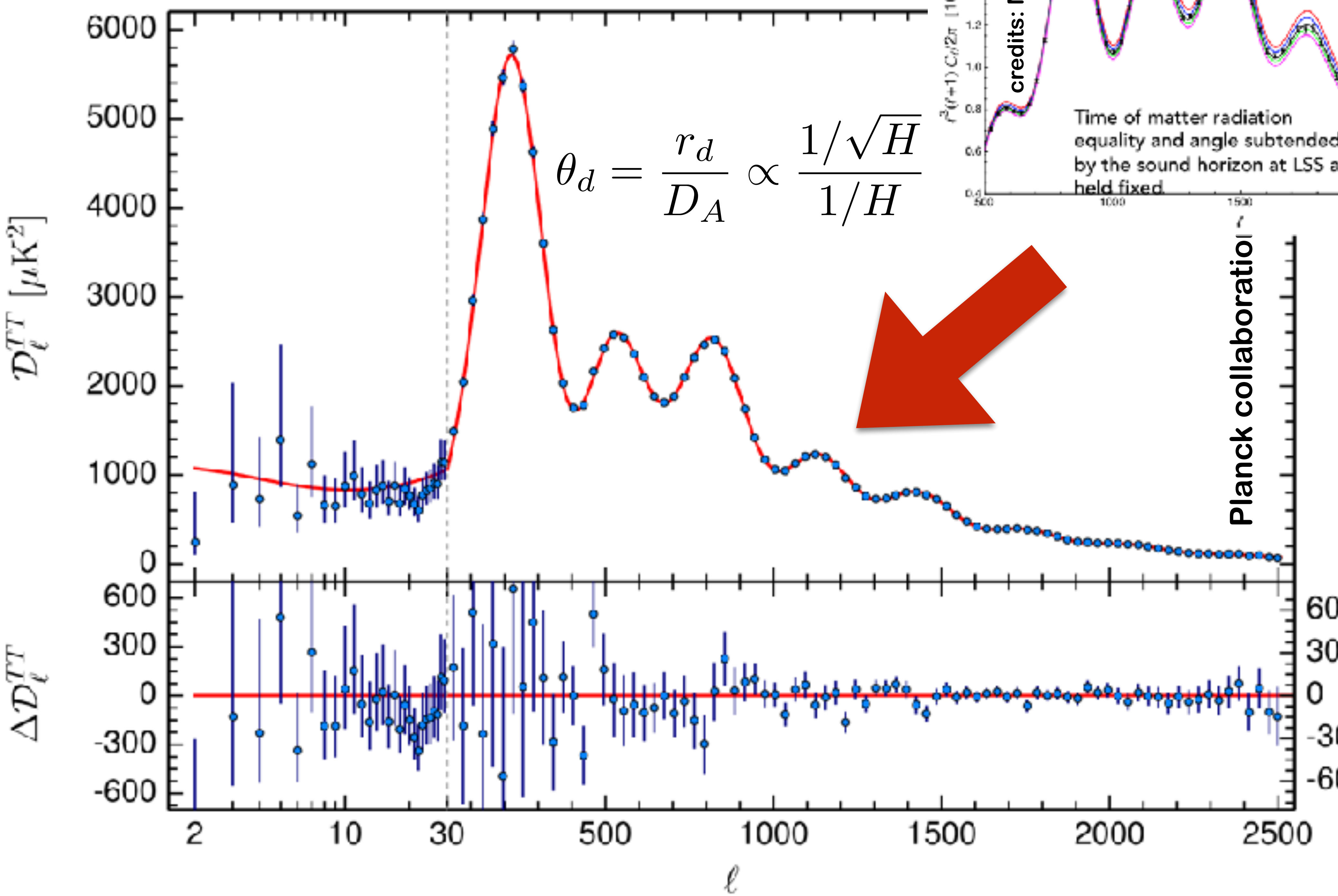
Effects on the CMB spectrum

Hou et al, 2014

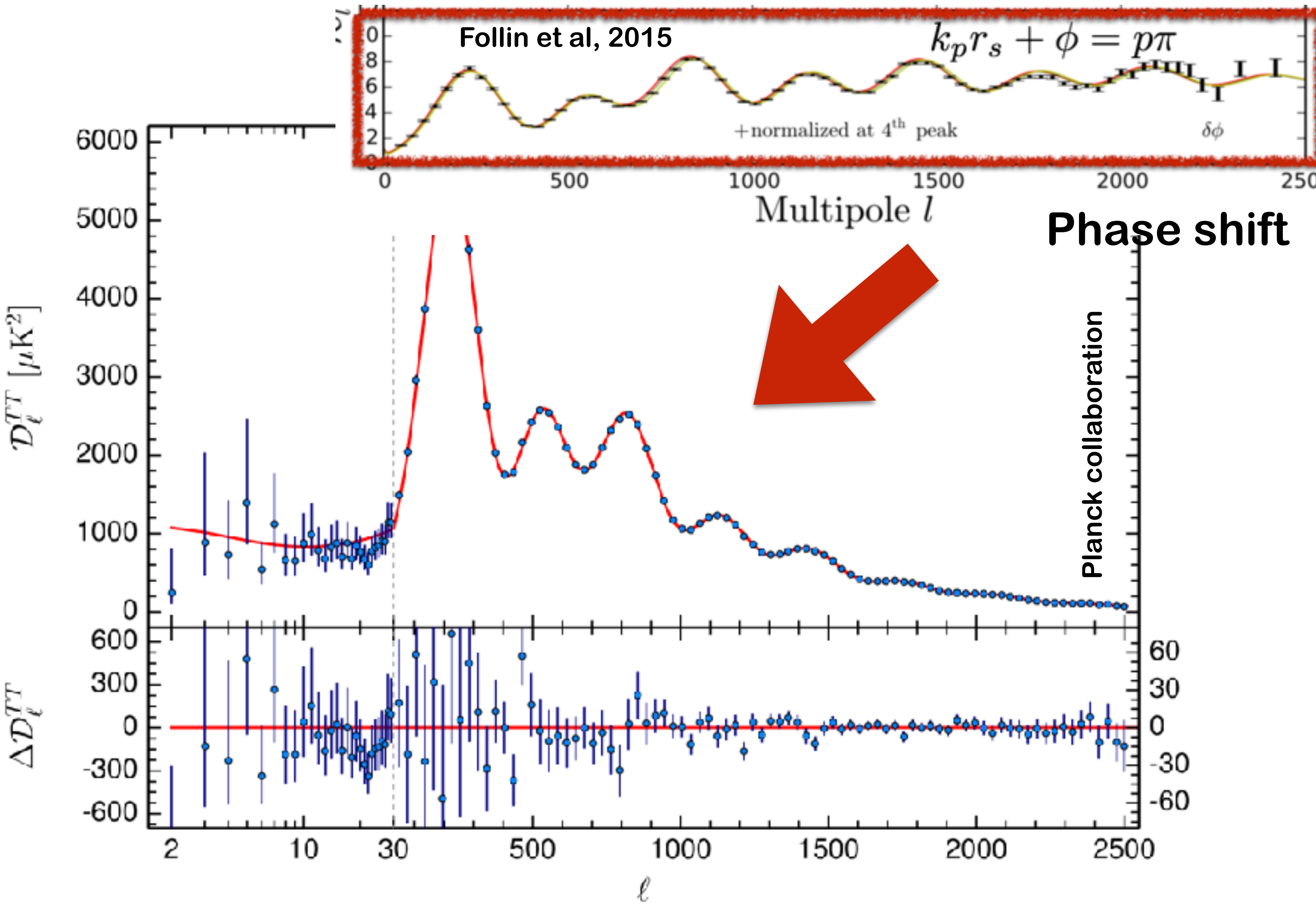
Silk damping

$$\theta_d = \frac{r_d}{D_A} \propto \frac{1/\sqrt{H}}{1/H}$$



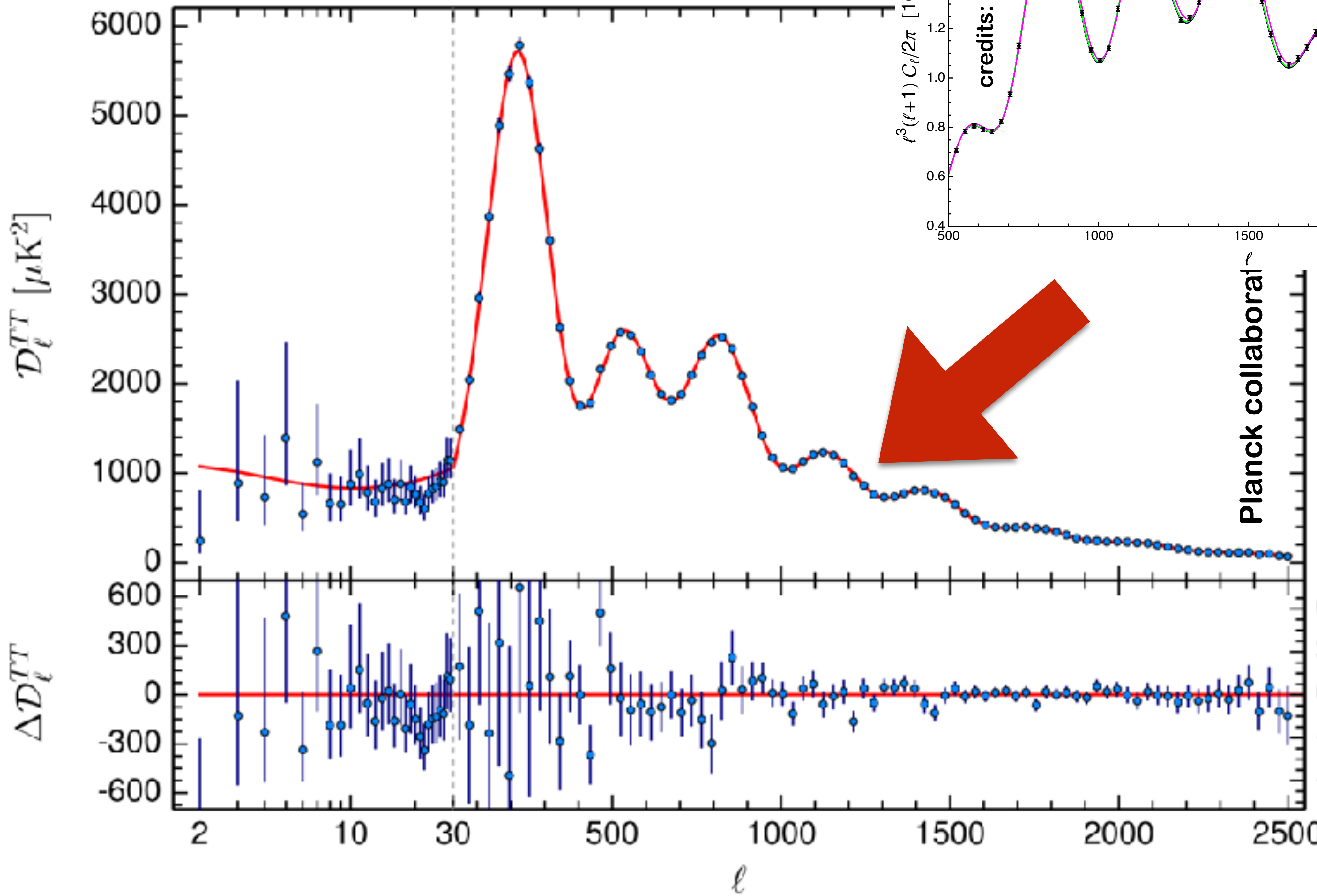


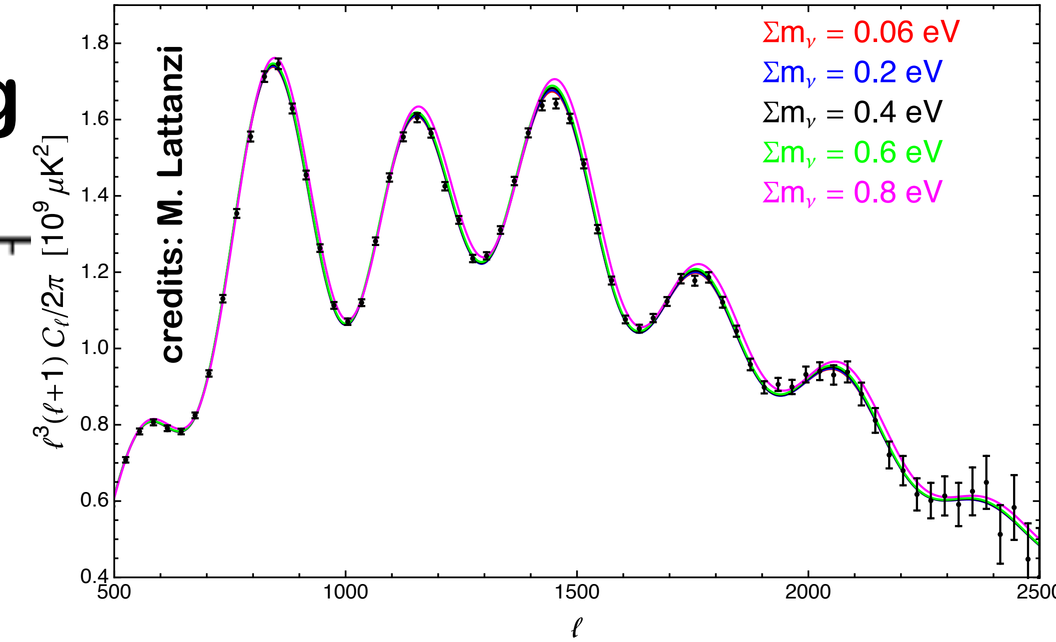
Effects on the CMB spectrum



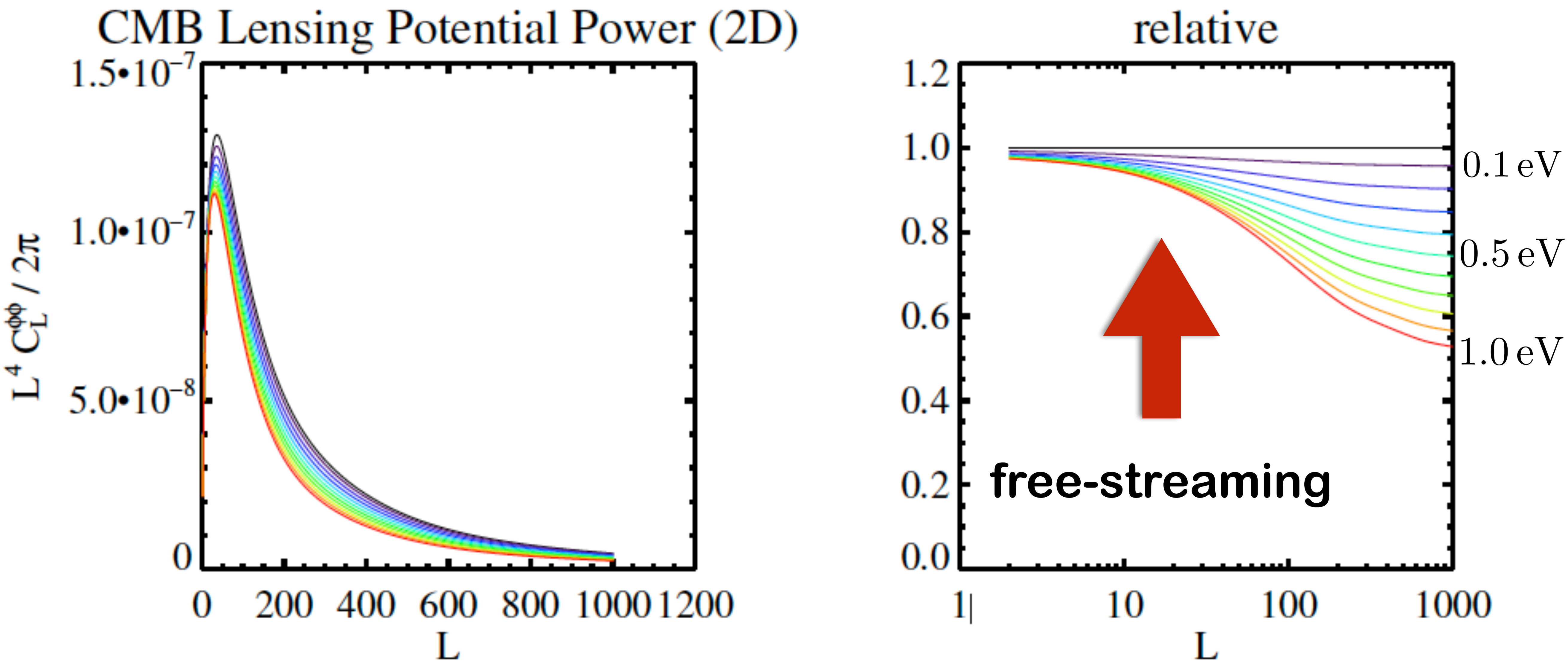
Effects on the CMB spectrum

CMB lensing





Effects on the lensing spectrum

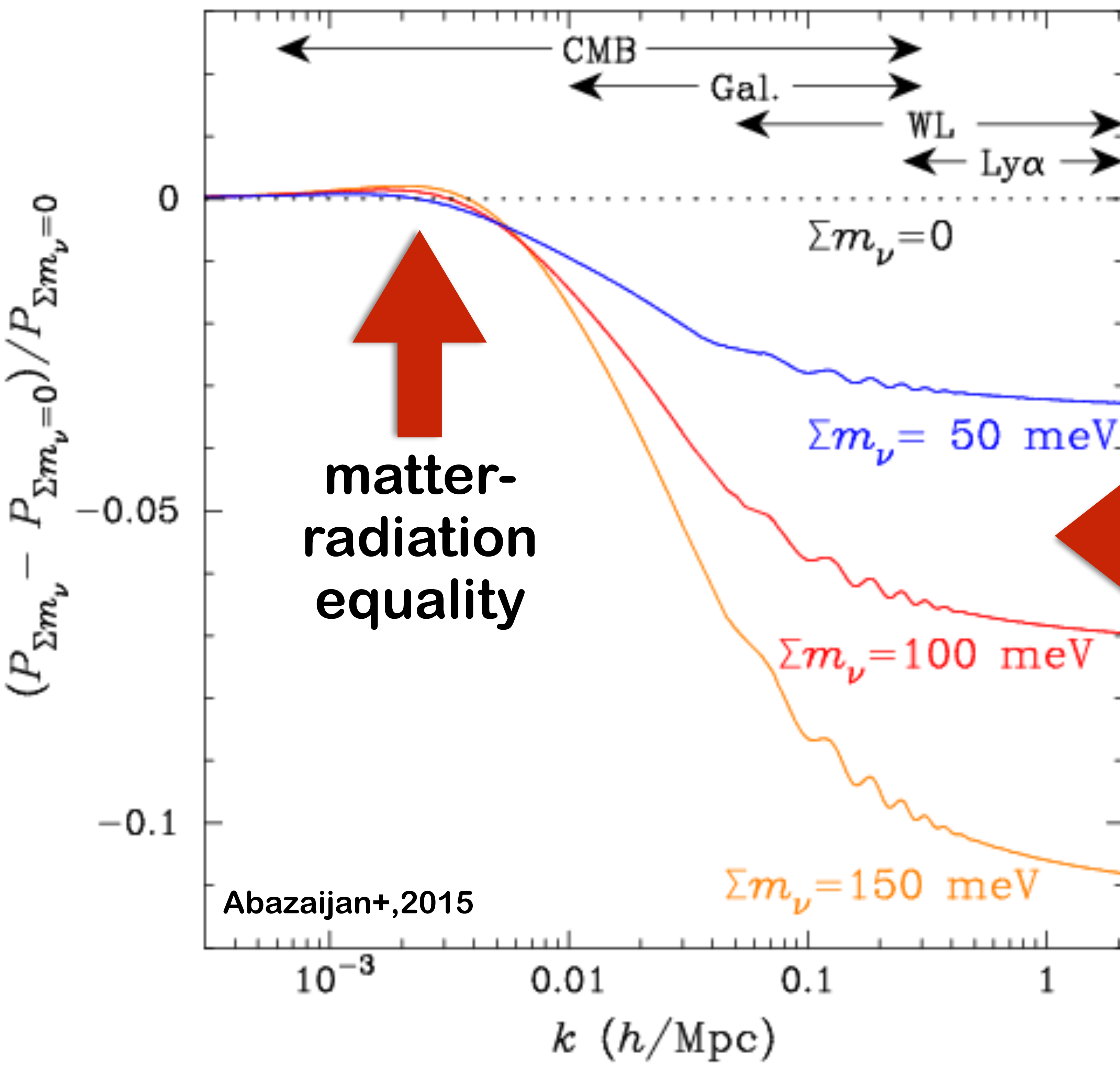


Lensing reconstruction is also crucial to delens CMB spectra

Sharper peaks improves limits on Neff

Stage-IV Science Book

Effects on the matter spectrum

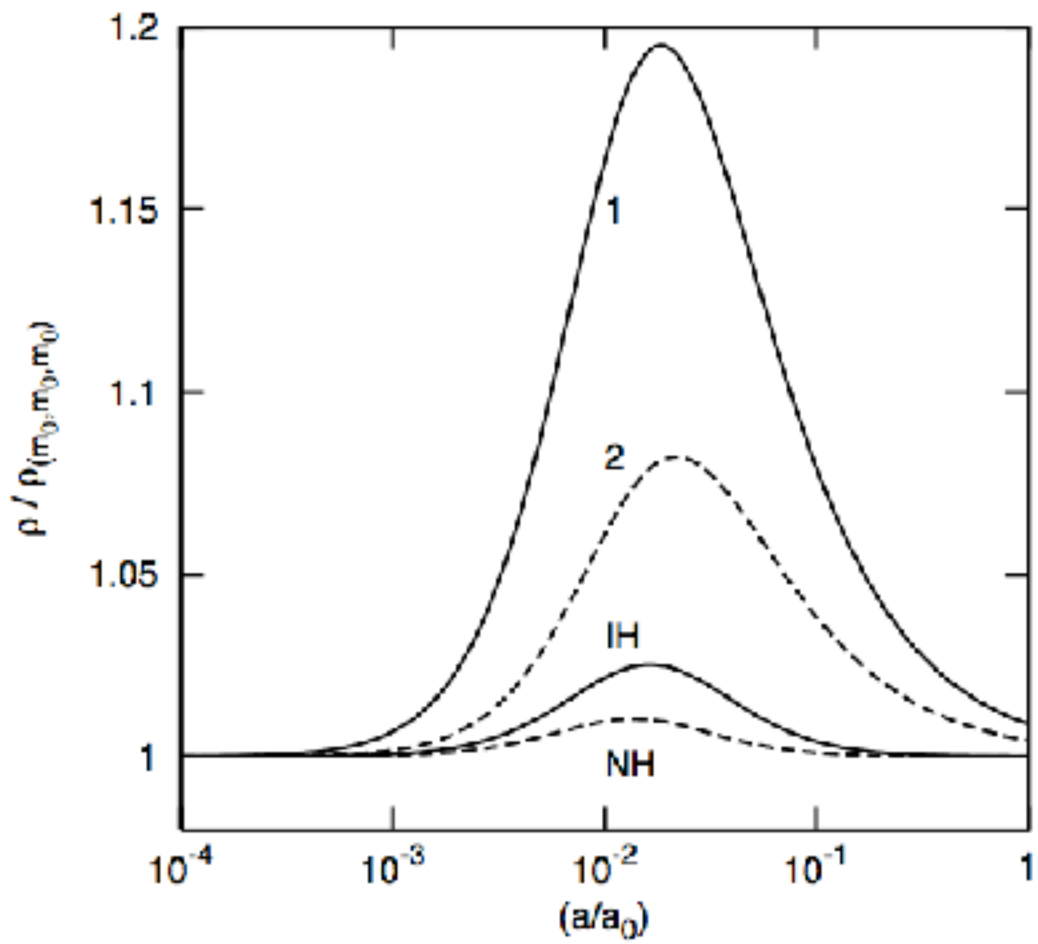


- free-streaming
- sound horizon at baryon decoupling
- phase shift

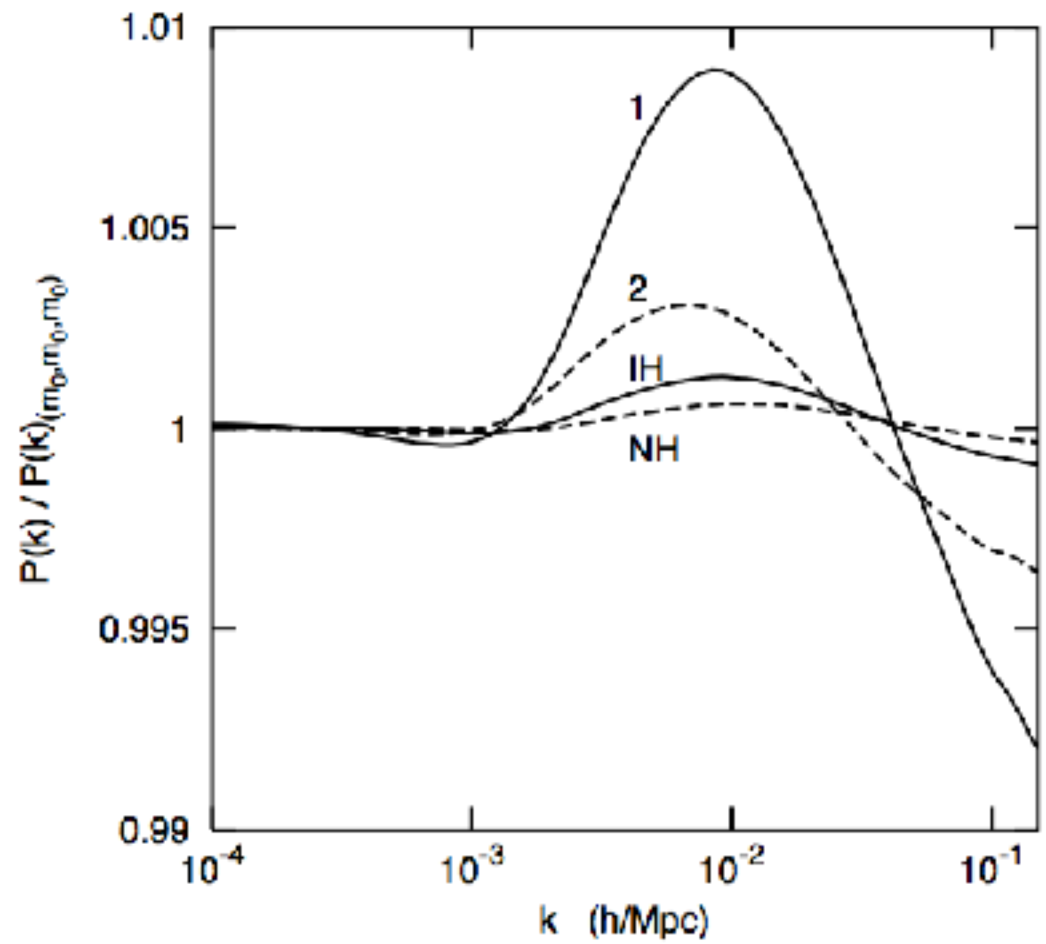
Sensitivity to the hierarchy

Physical effects due to different distribution of the sum of the masses for the 2 hierarchies

Total nu energy density



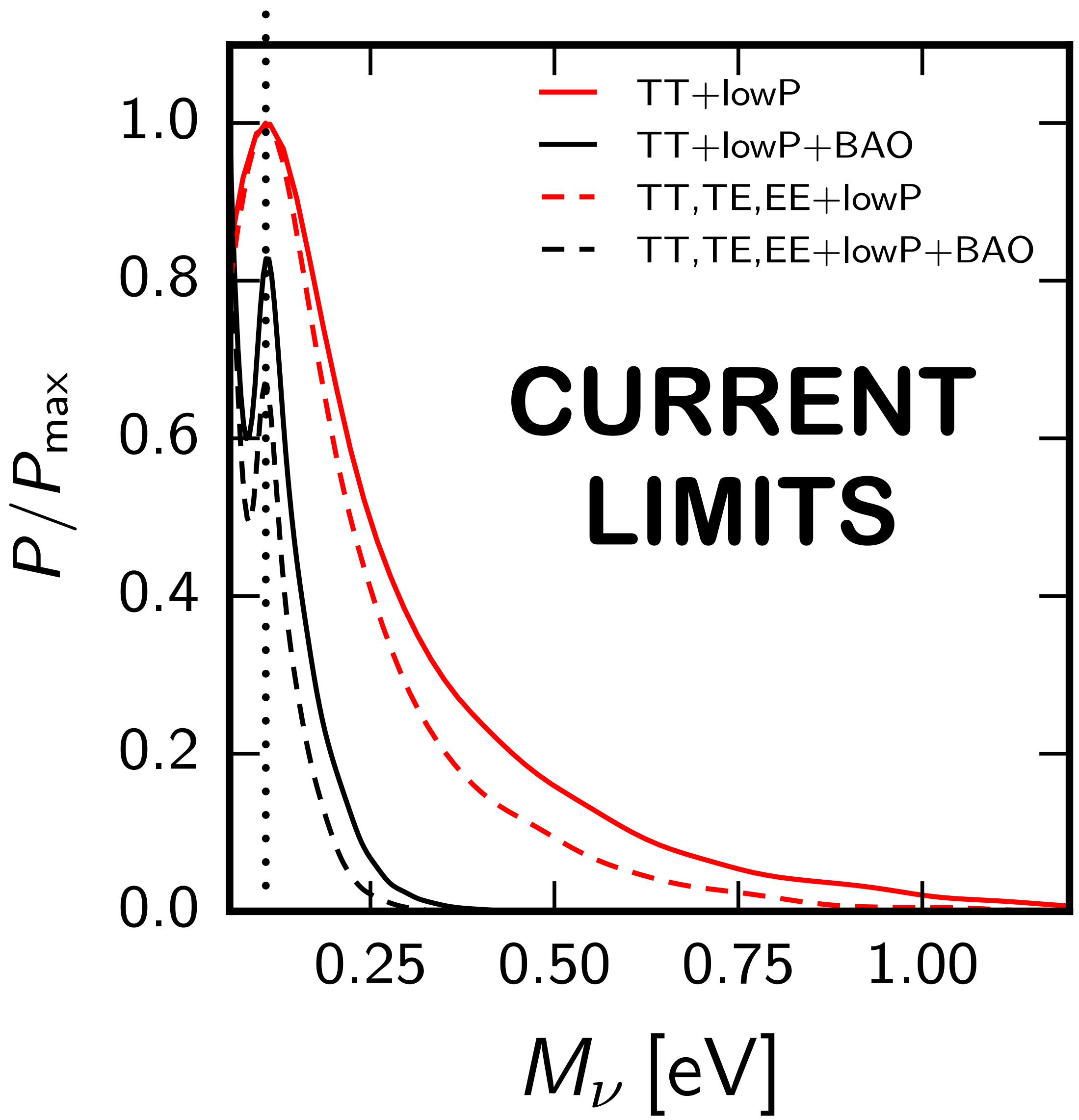
Matter power spectrum

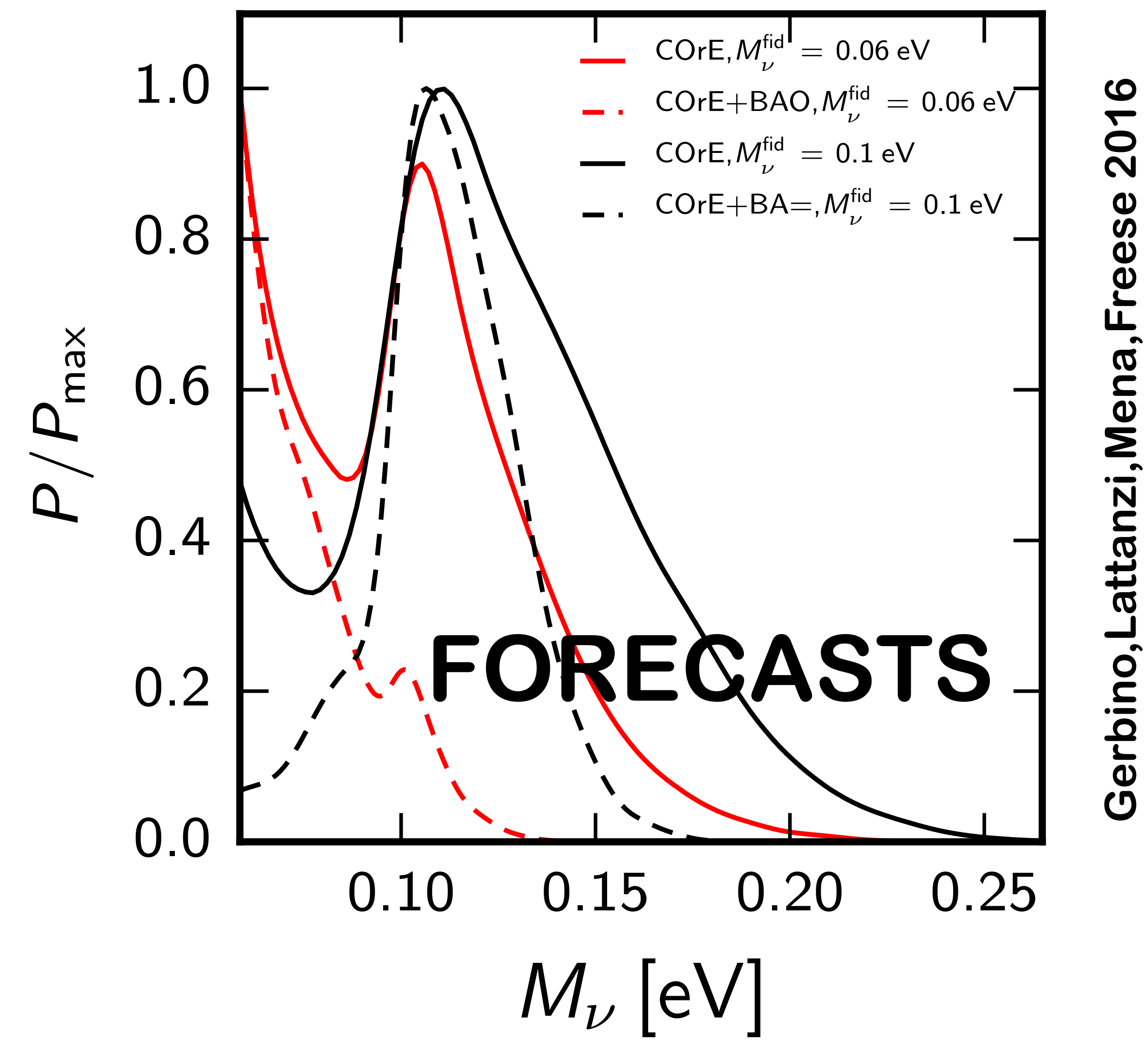


Lesgourgues&Pastor, 2006

Are current (and future) data sensitive to these effects? How much?

Sensitivity to the hierarchy





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

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

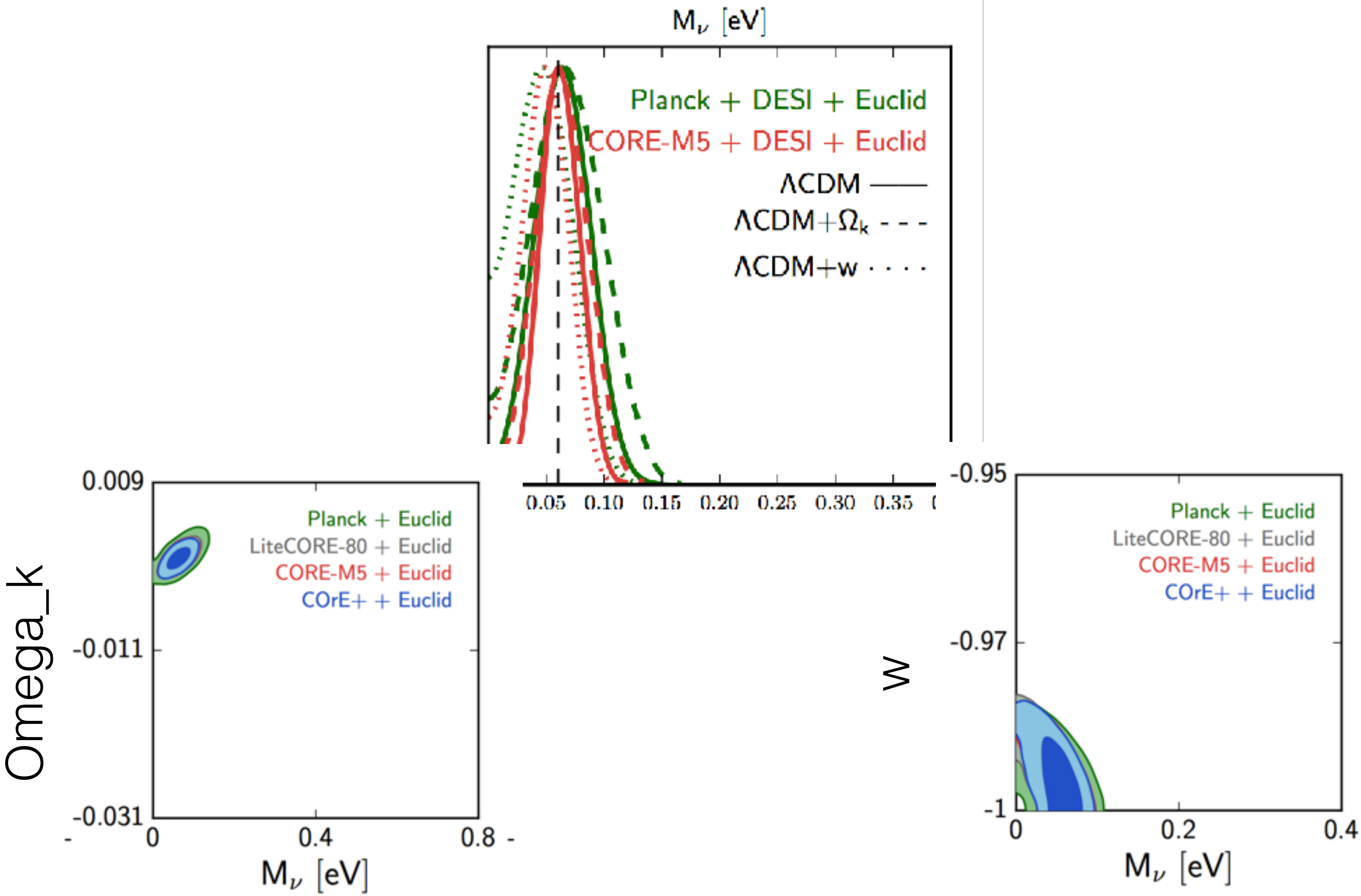
3:2

0.06eV mass -> 9:1

0.1eV mass -> 1:1

See also Hannestad&Schwetz,2016

Robustness wrt the underlying cosmology



CORE collaboration (DiValentino et al),2016

Neff modifies the expansion rate

$$H^2 = H_0^2 \left(\frac{\Omega_{\rm rad}}{a^4} + \frac{\Omega_m}{a^3} + \Omega_\Lambda \right)$$