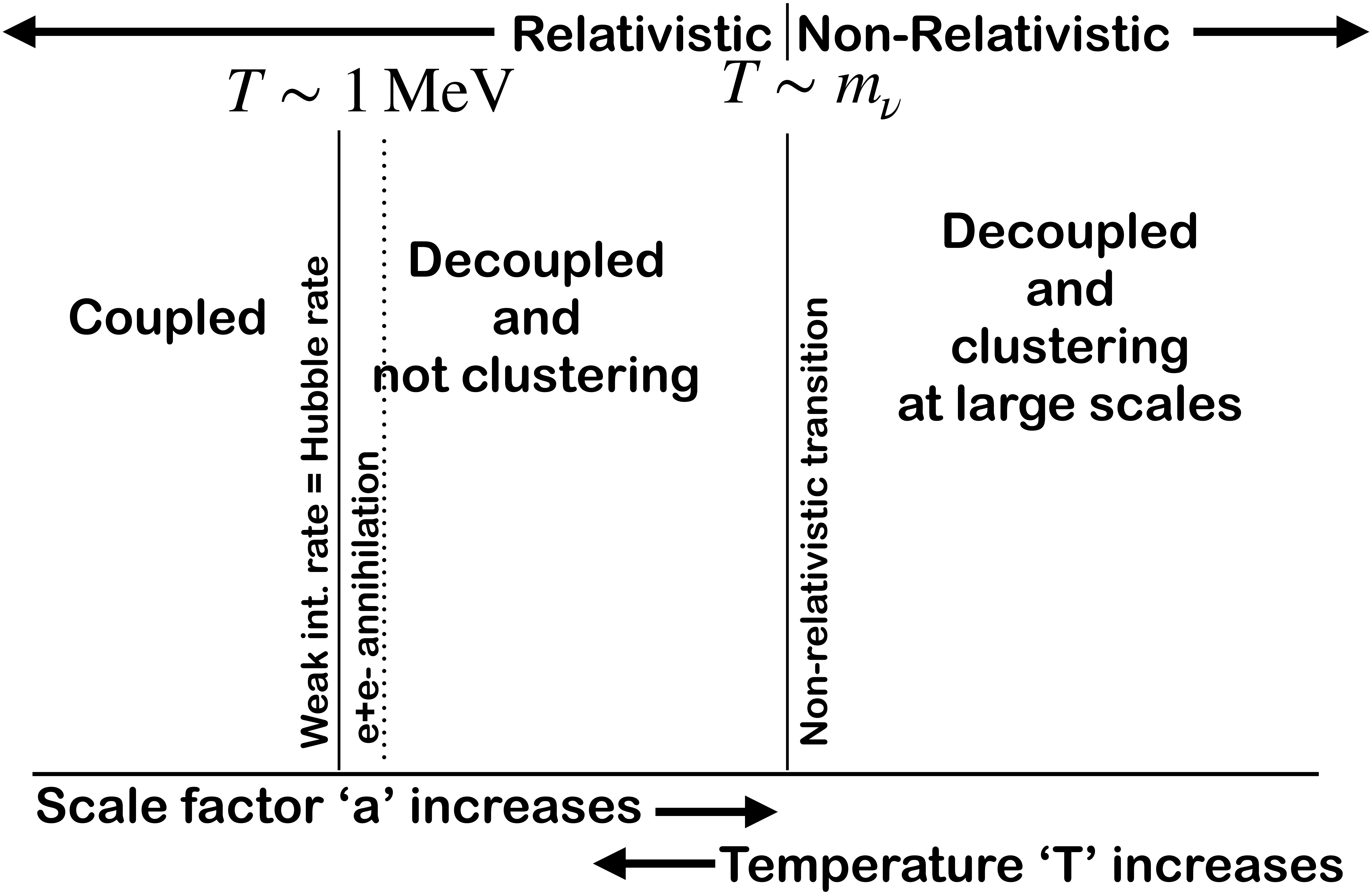
COSMOLOGICAL CONSTRAINTS ON NEUTRINO PHYSICS

Workshop on Connecting Insights in Fundamental Physics: Standard Model and Beyond
Corfu, 4 September 2019

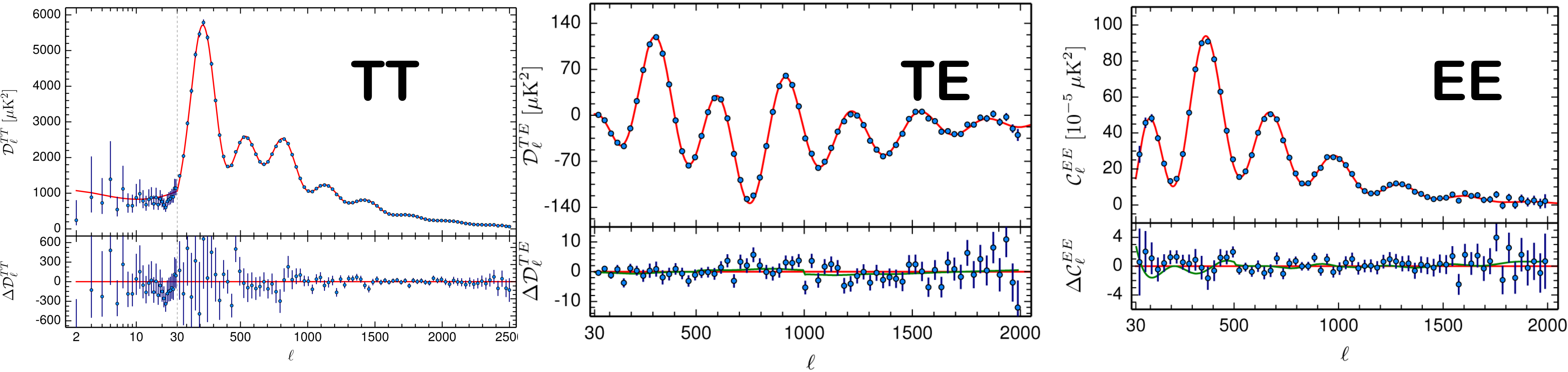
Martina Gerbino
Argonne National Laboratory

Results from Planck Coll., SO Coll., S4 Coll., and work in collaboration with Katie Freese, Elena Giusarma, Shirley Ho, Massimiliano Lattanzi, Olga Mena, Sunny Vagnozzi

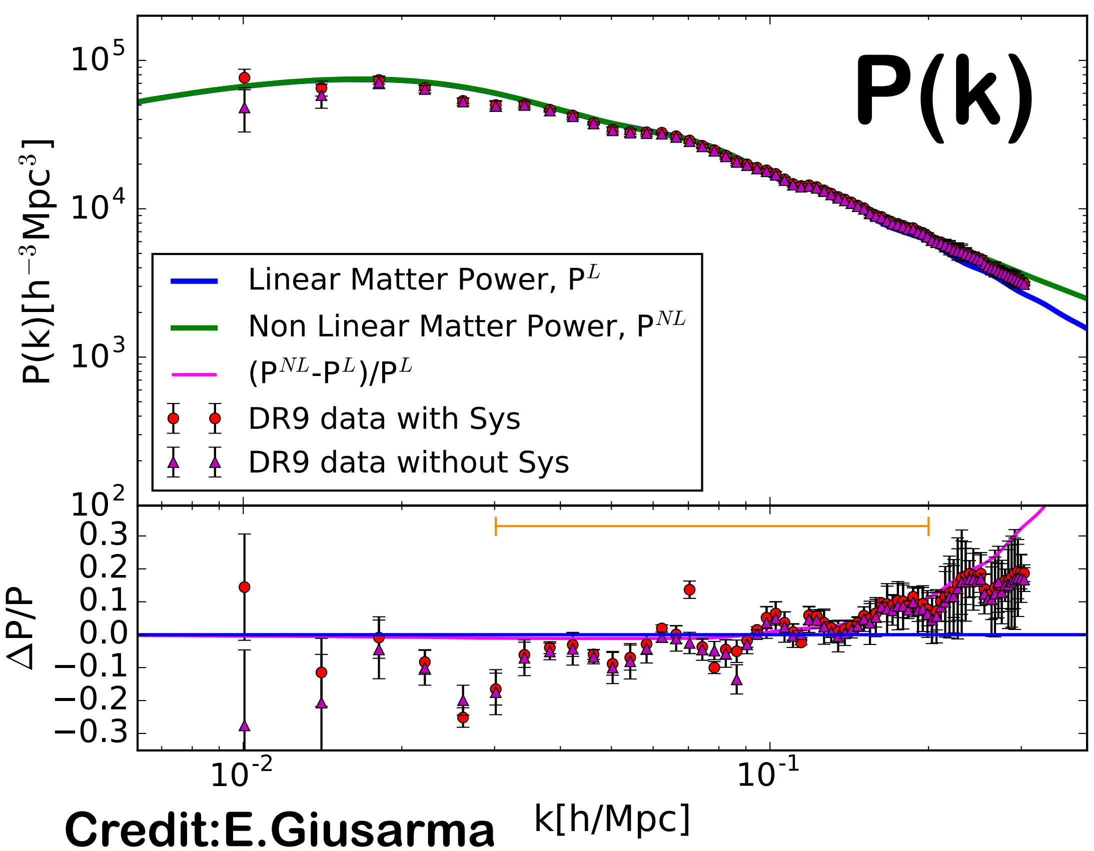
Basics of neutrino cosmology



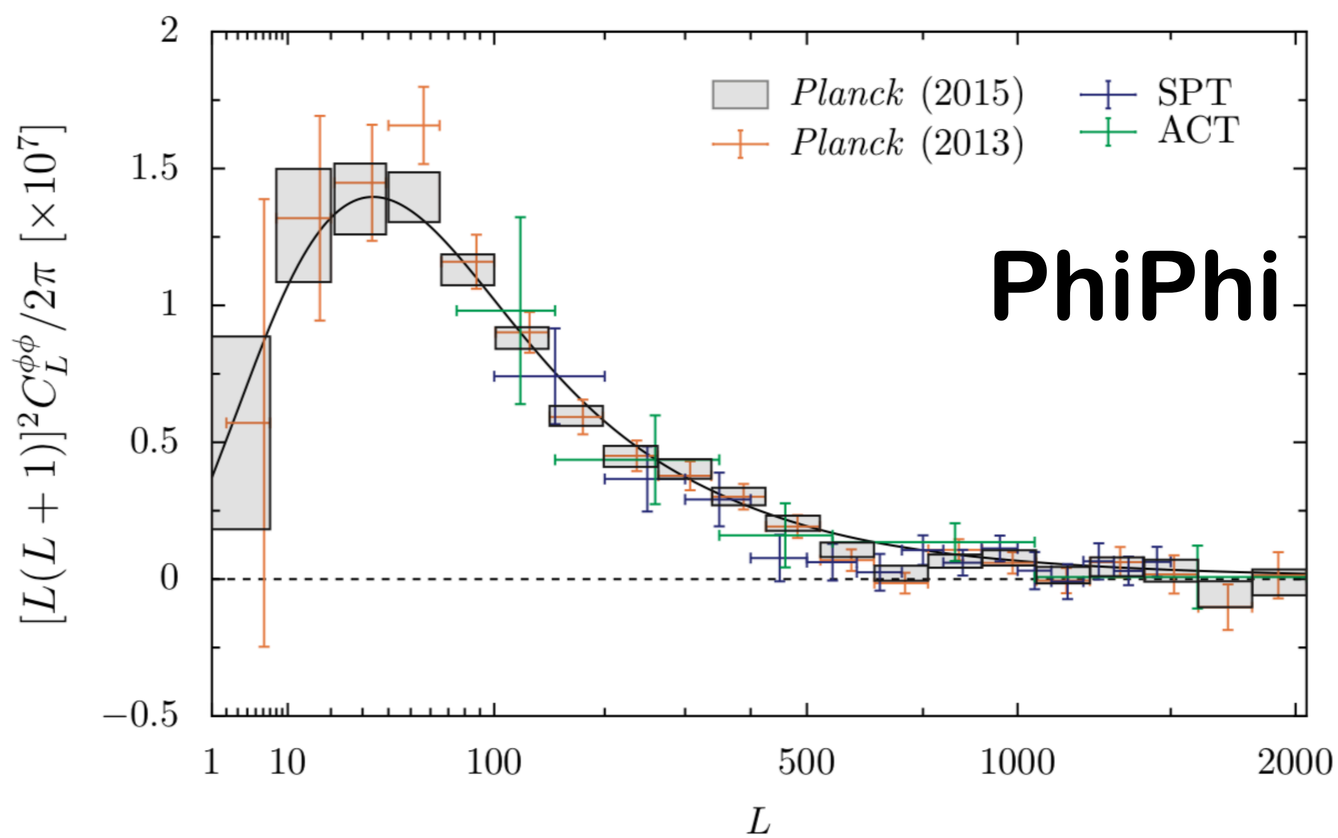
What we observe



Planck collaboration



Credit:E.Giusarma



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

$$N_{\mathrm{eff},\nu} \equiv \frac{\sum_i \rho_{\nu,i}}{\rho_{\nu,0}} = \frac{g/(2\pi)^3 \sum_i \int p_i^3 f_\nu(p_i, T_i) dp}{7/120\pi^2 T_\nu^4}$$

← **Temperature 'T' increases**

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

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

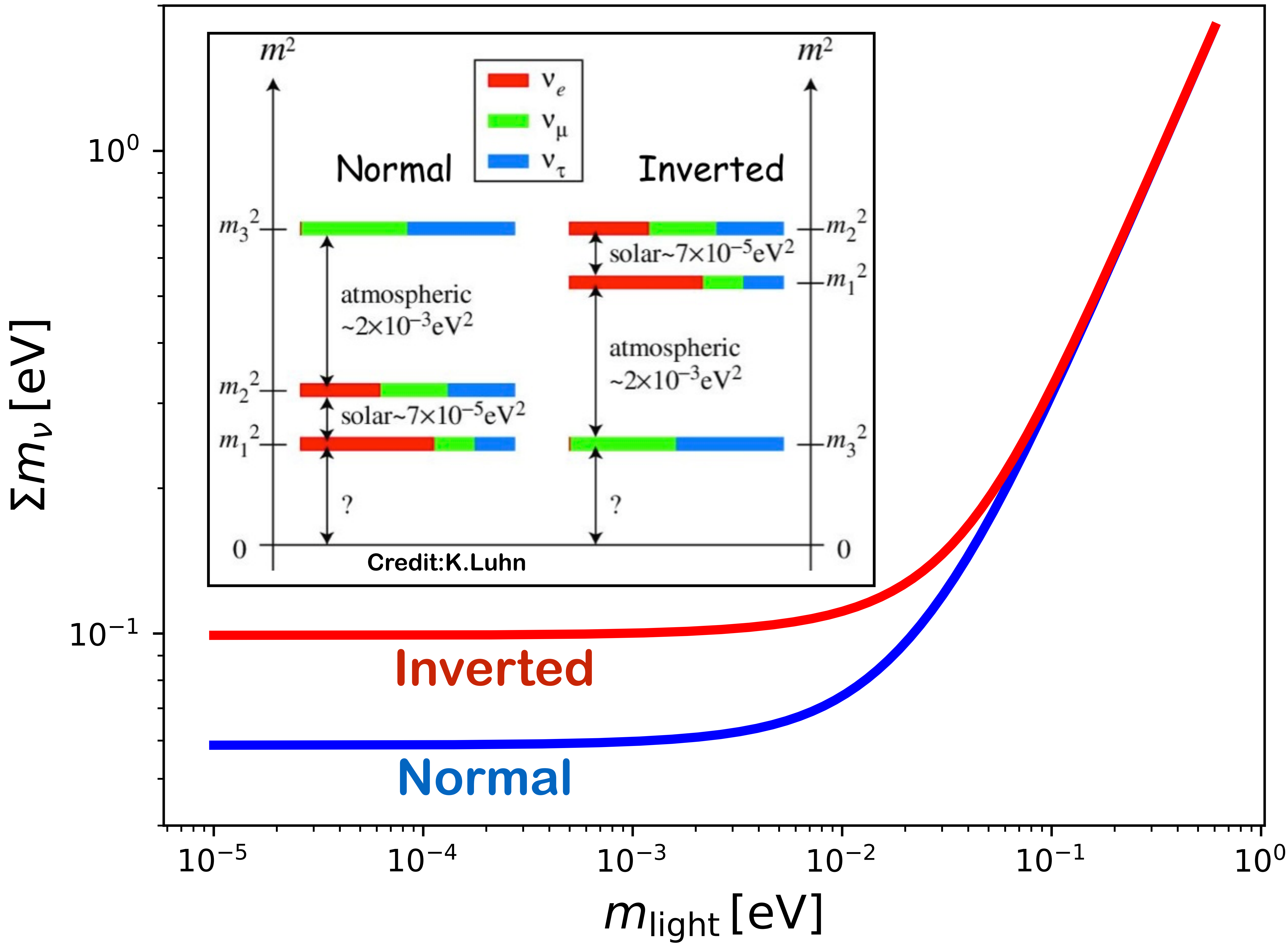
Free streaming scale

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

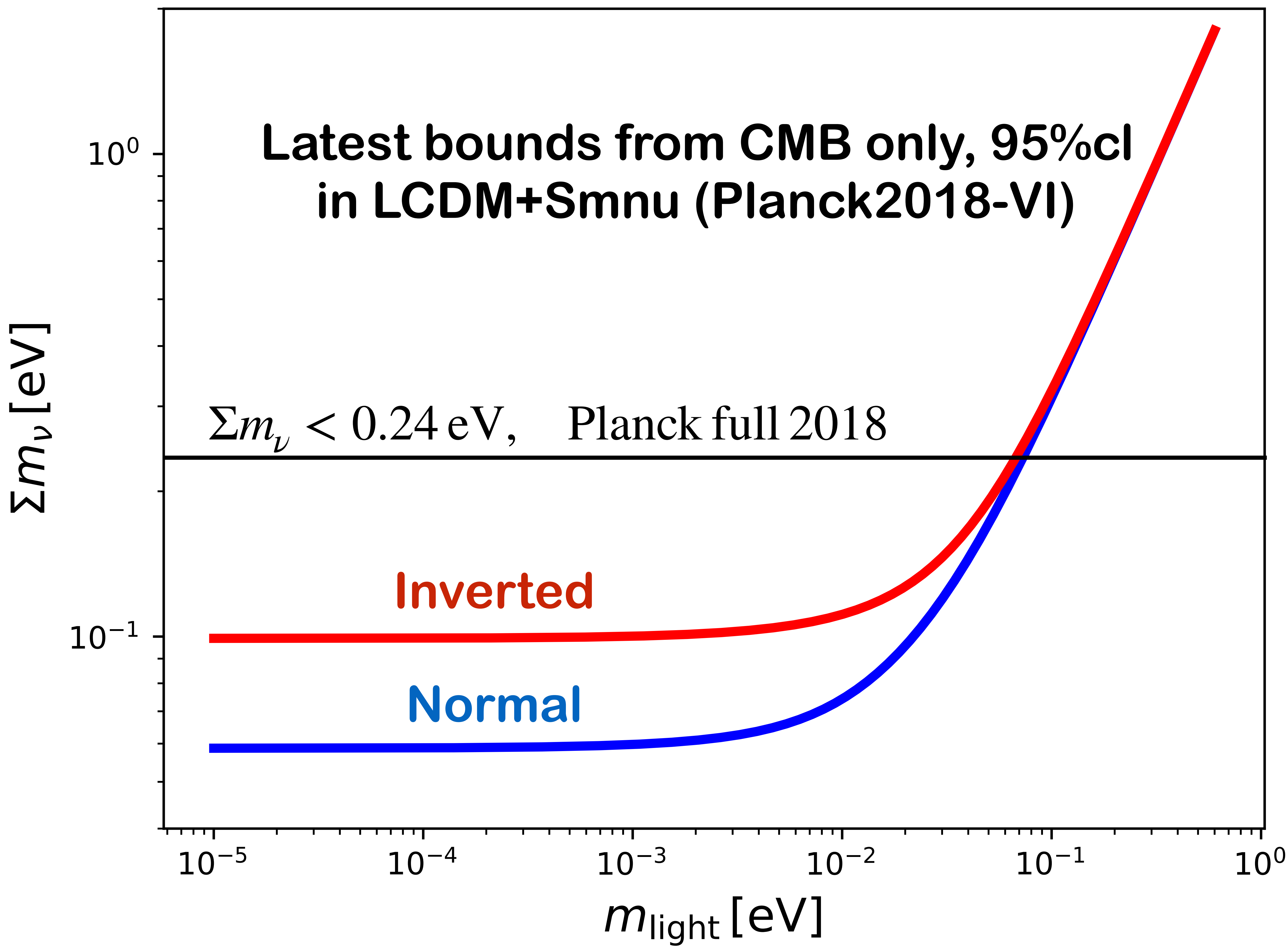
Suppressed growth

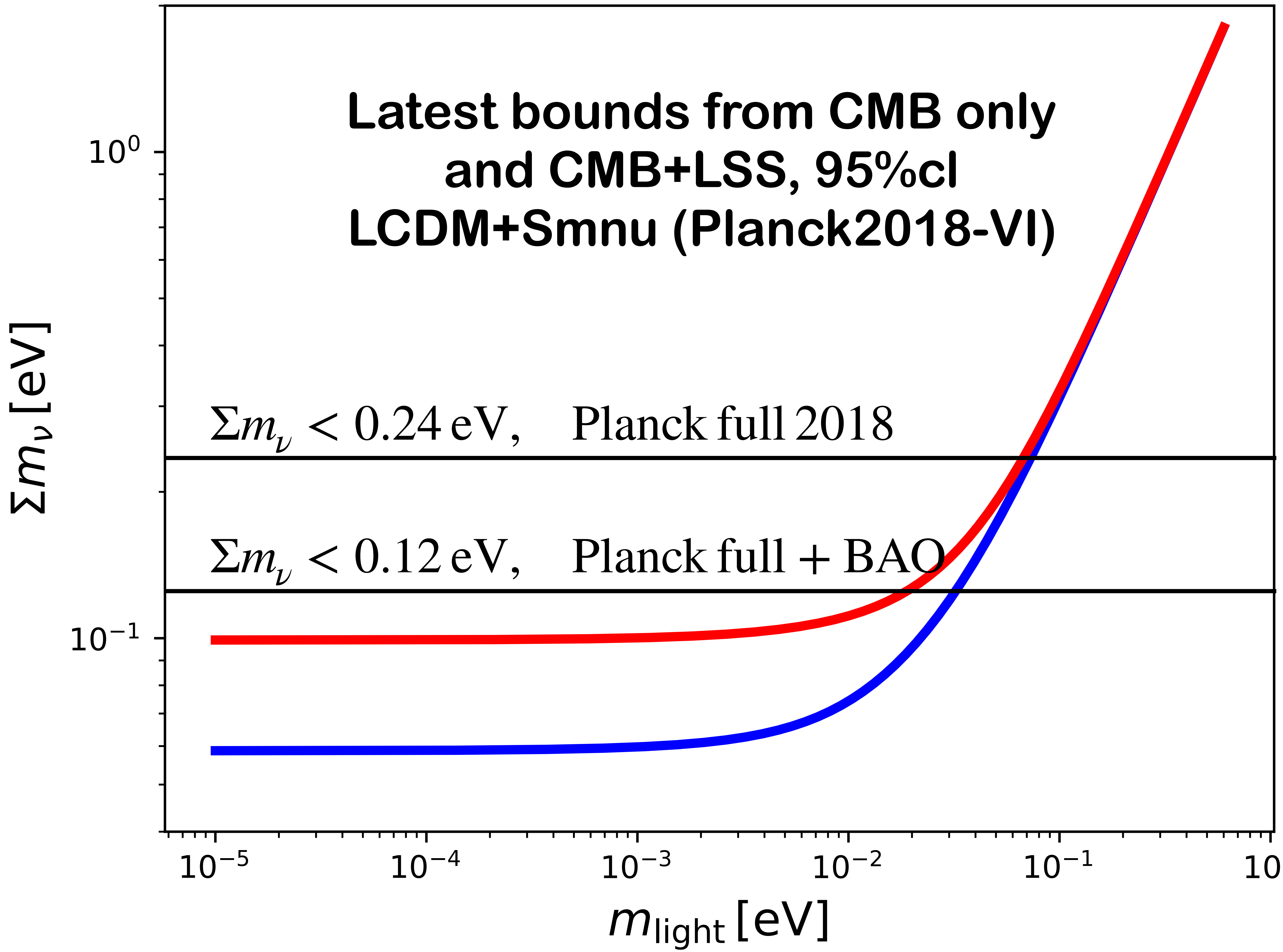
$$k_p r_s + \phi = p\pi$$

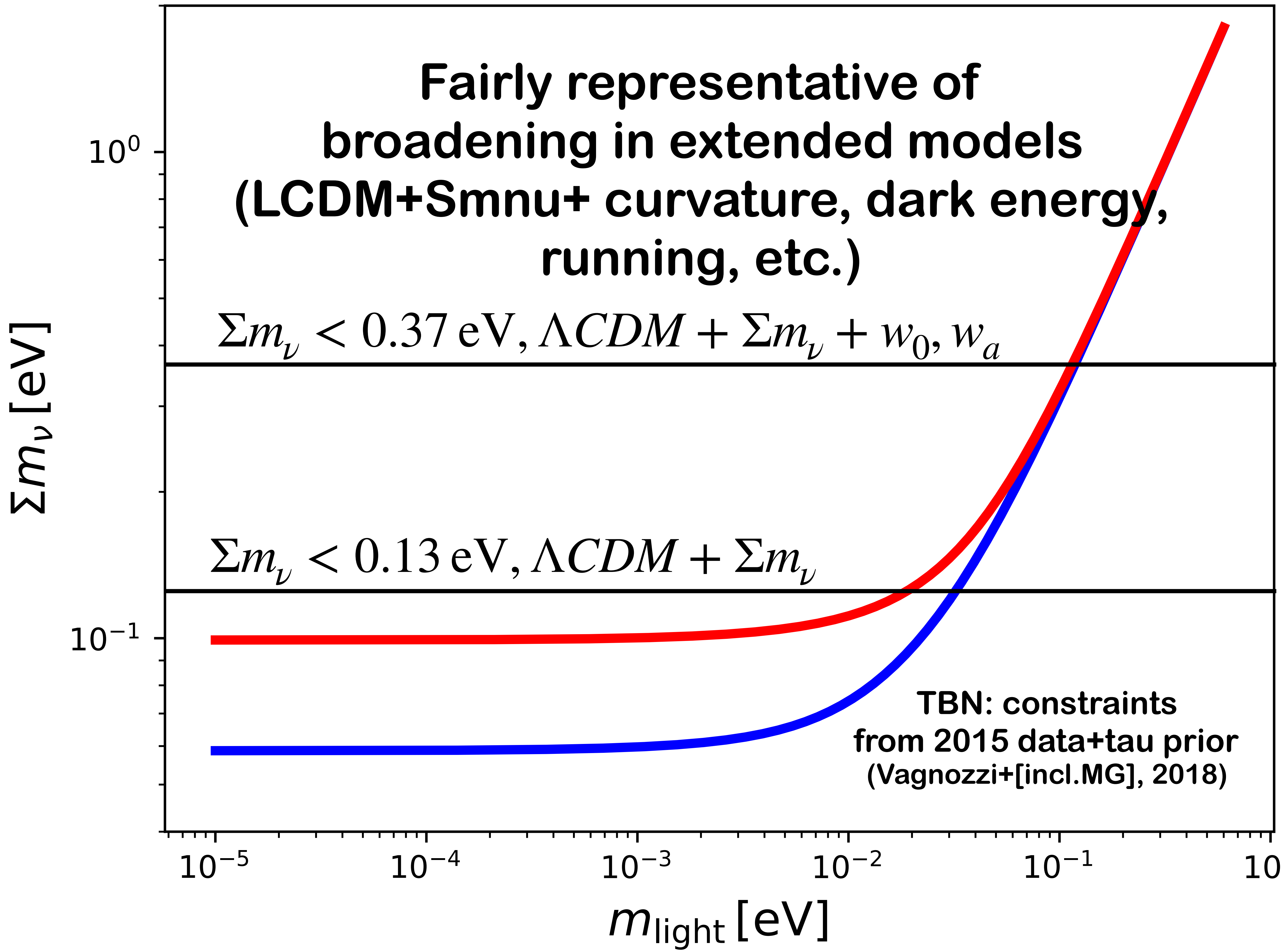
Acoustic phase shift



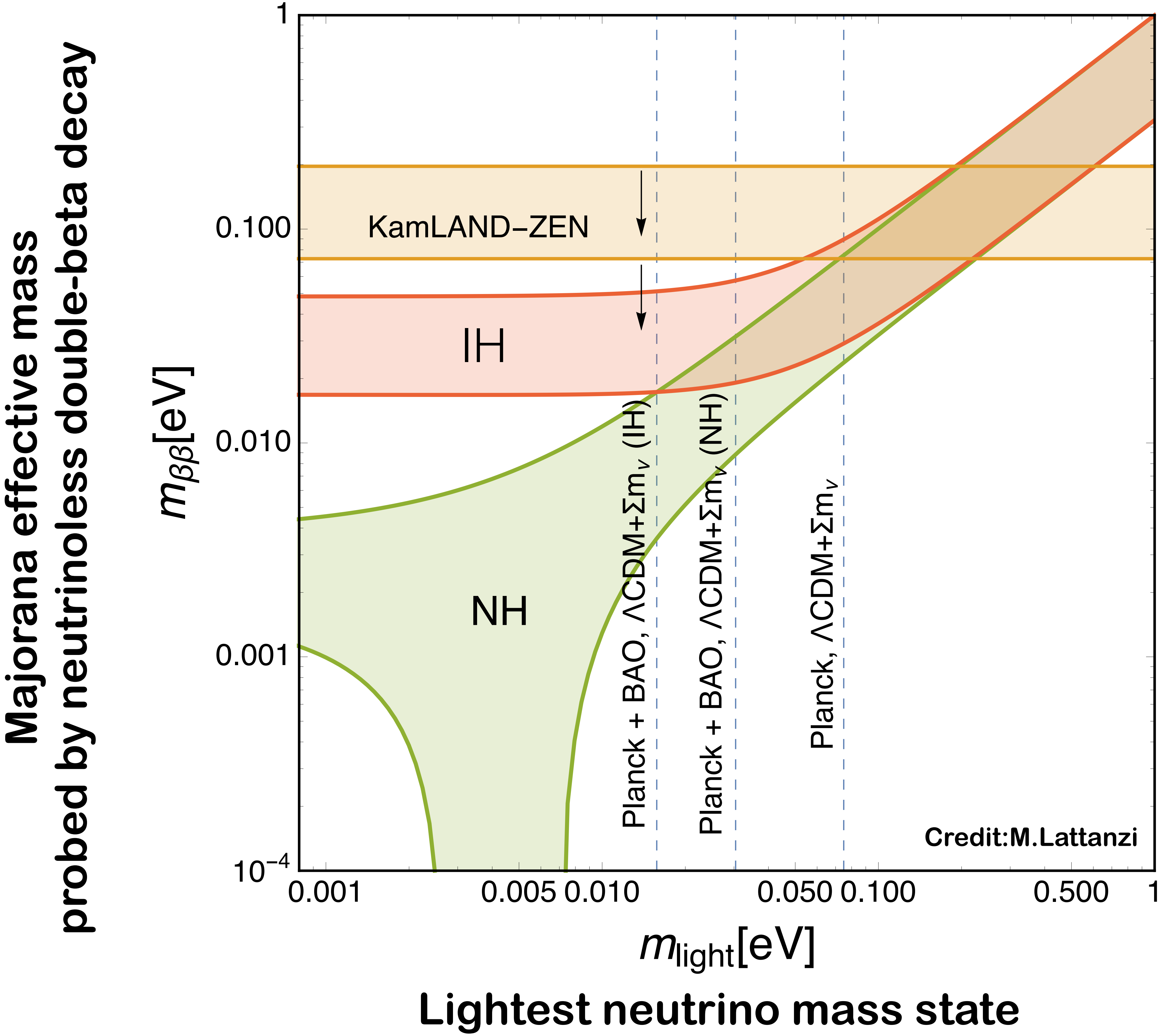
m^2
ν_e
ν_μ
ν_τ
Normal
Inverted
m_3^2
m_2^2
m_1^2
atmospheric
$\sim 2\times10^{-3}\mathrm{eV}^2$
solar$\sim 7\times10^{-5}\mathrm{eV}^2$
?
0
Credit:K.Luhn
Inverted
Normal
10^0
10^{-1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Σm_ν [eV]
m_{light} [eV]


Latest bounds from CMB only, 95%cl
in LCDM+Smnu (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
LCDM+Smnu (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]



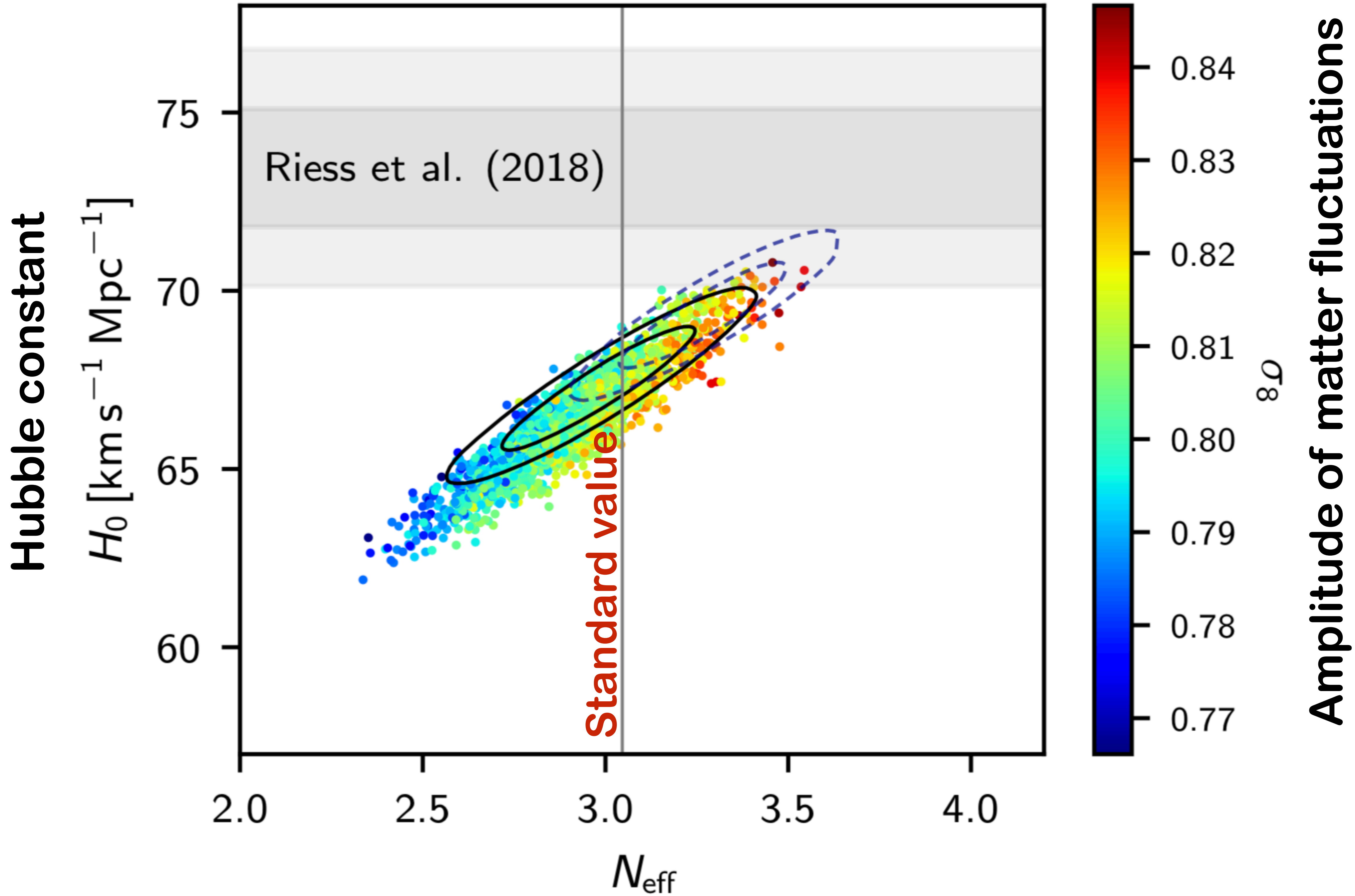
Fairly representative of
broadening in extended models
(LCDM+Smnu+ curvature, dark energy,
running, etc.)
$\Sigma m_\nu < 0.37\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu + w_0, w_a$
$\Sigma m_\nu < 0.13\,\mathrm{eV}, \Lambda CDM + \Sigma m_\nu$
TBN: constraints
from 2015 data+tau prior
(Vagnozzi+[incl.MG],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


Majorana effective mass
probed by neutrinoless double-beta decay
$m_{\beta\beta}$[eV]
1
0.100
0.010
0.001
10^{-4}
KamLAND−ZEN
IH
NH
Planck + BAO, ΛCDM+Σm_ν (IH)
Planck + BAO, ΛCDM+Σm_ν (NH)
Planck, ΛCDM+Σm_ν
Credit:M.Lattanzi
0.001
0.005 0.010
0.050 0.100
0.500
1
m_{light}[eV]
Lightest neutrino mass state

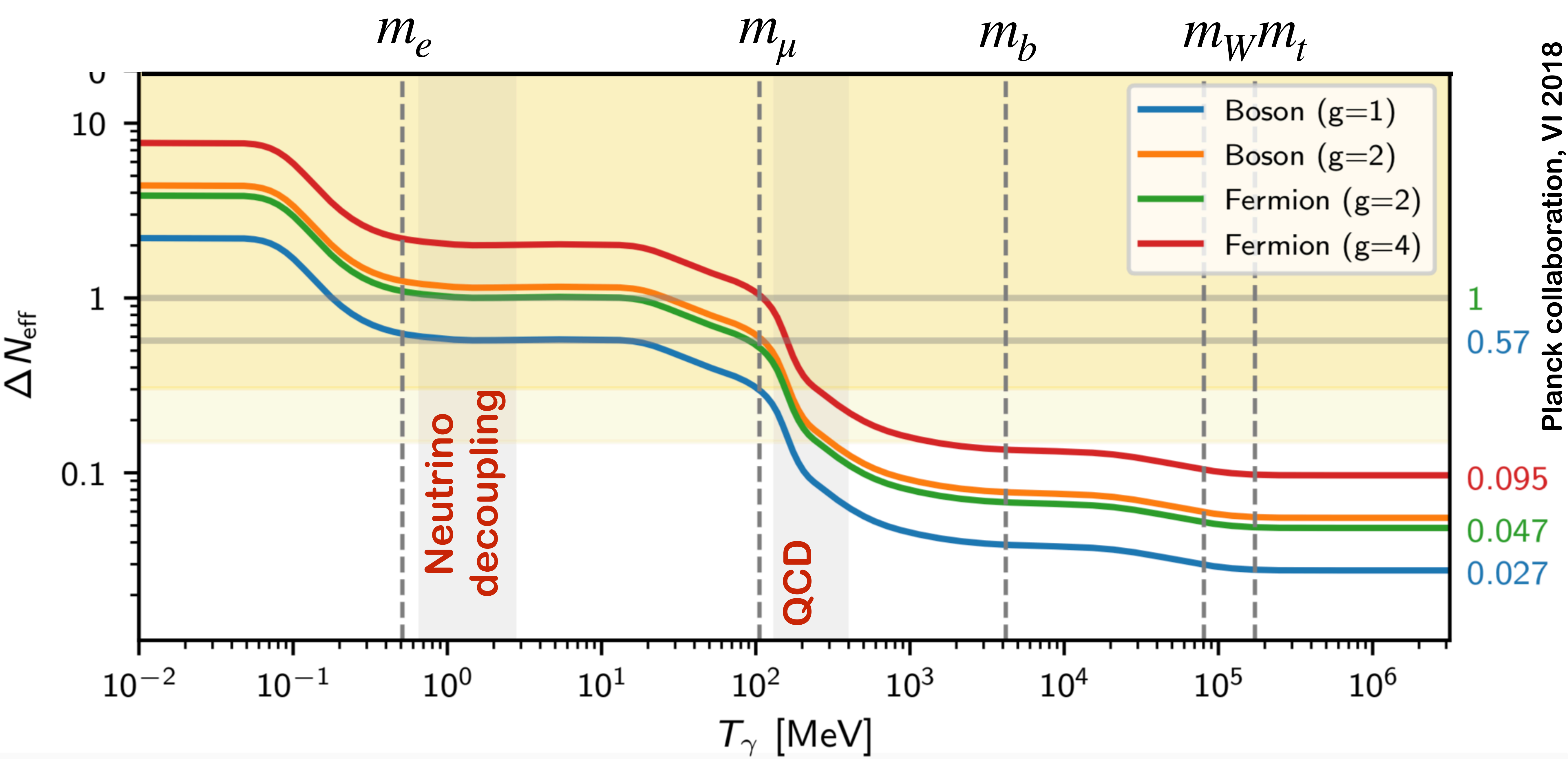
Current limits on Neff

Planck collaboration, VI 2018

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

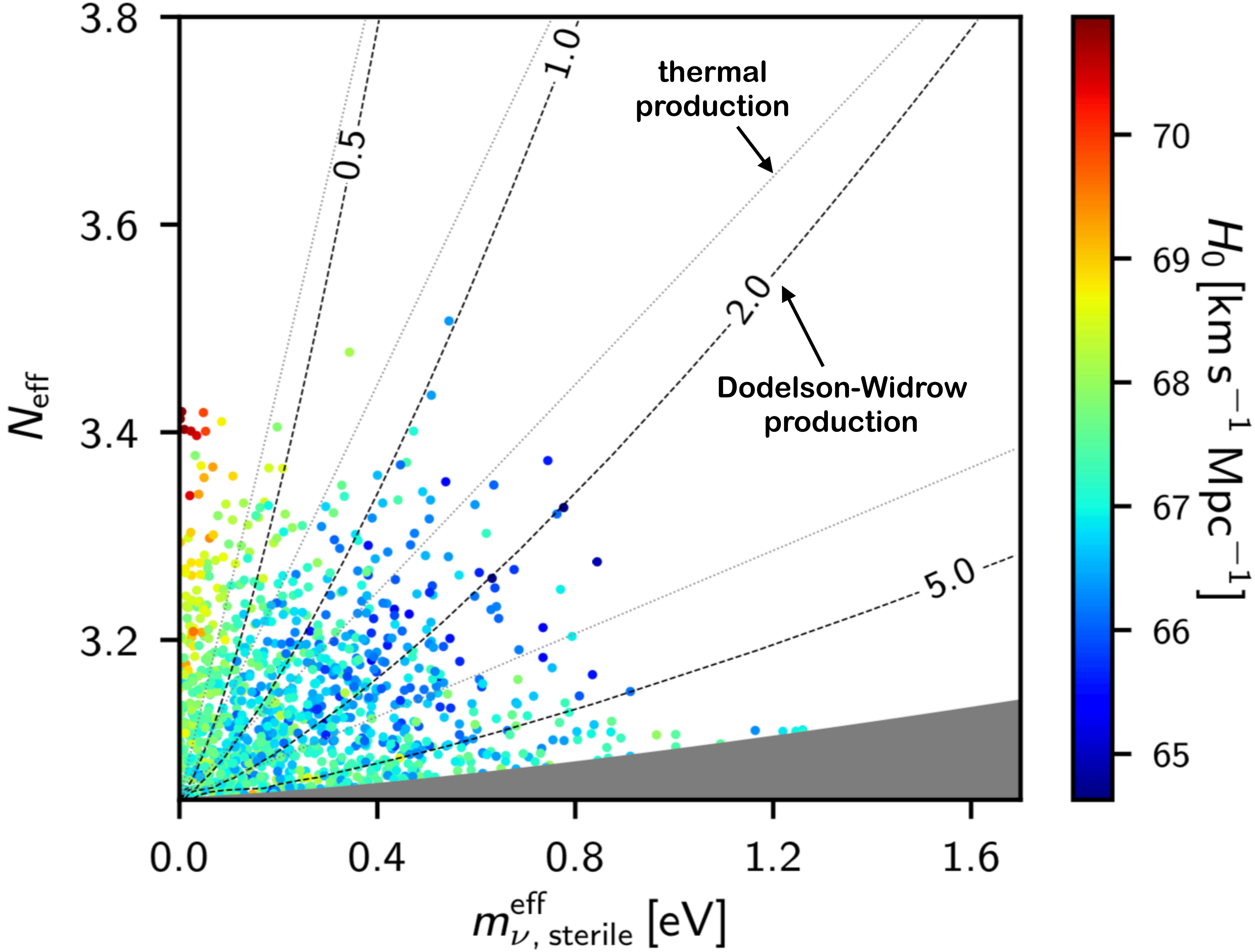


Neff as a proxy for extra light species



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

Current limits on Neff-meff



~eV thermalised sterile neutrino excluded at 7sigma

Non-standard models needed to make SBL compatible with cosmology

What next in neutrino cosmology

A new generation of ultimate cosmological surveys is approaching: Simons Observatory, Euclid, LiteBIRD, CMB-S4, DESI, LSST, SKA …
Does it mean that we are moving:

1) **Towards the first detection of the neutrino mass scale?**

2) **Towards the first probe of the physics of neutrino decoupling, and of BSM content at very early times?**

How to achieve robustness

1) External redundancy and complementarity: Individual probes of very high and comparable sensitivity, cross-correlations,…
2) Internal redundancy and complementarity: Individual channels (e.g. temperature and polarisation; shear and galaxy; …) of high and comparable sensitivity
3) Know your instruments: extensive work on ‘mock’ calibration, sensitivity and systematics in preparation of the real analysis

Route to robust neutrino mass bounds

- **CMB lensing from SO combined with DESI BAO**

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

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

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

- **thermal SZ distortion maps from SO combined with DESI BAO**

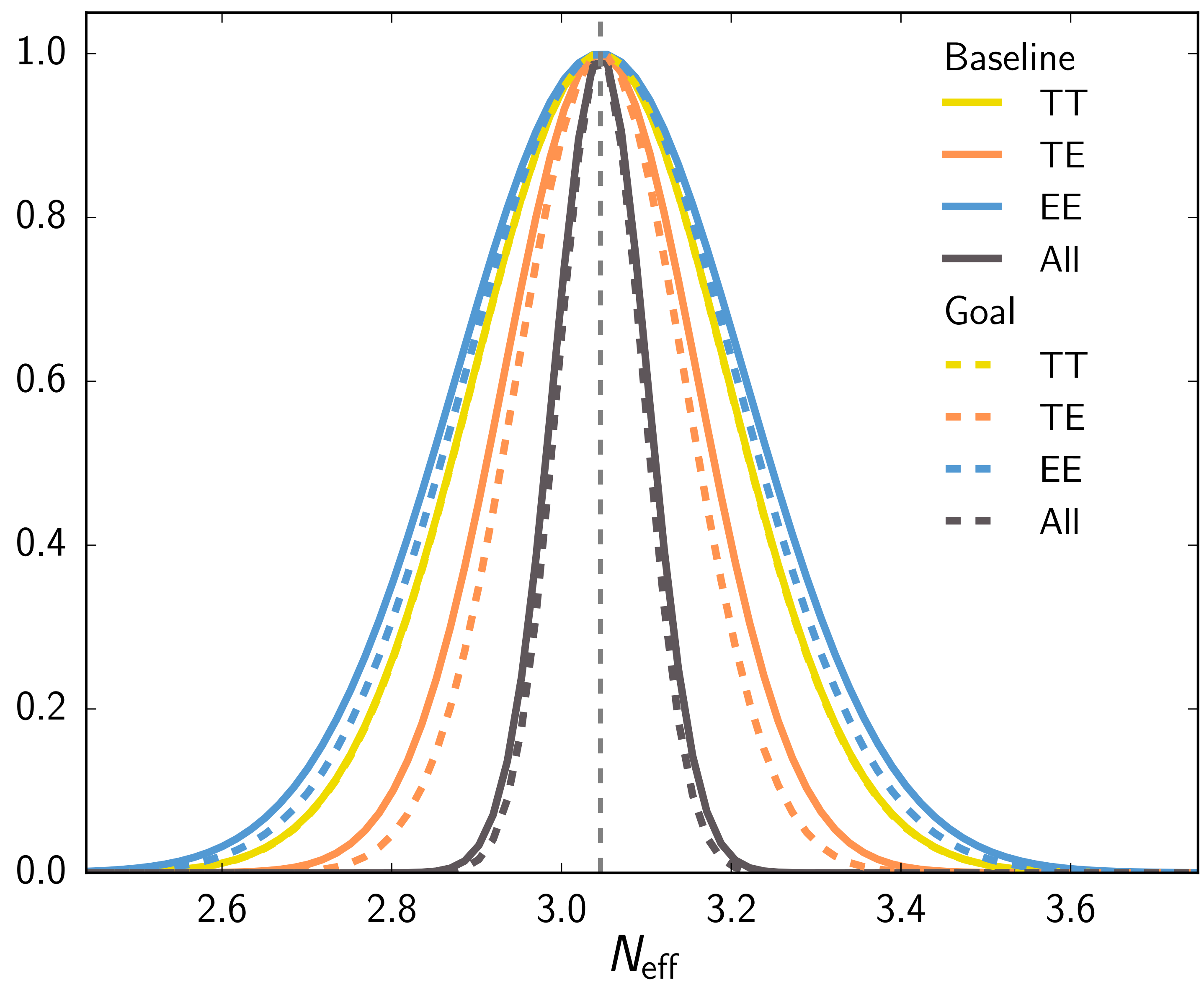
$$\sigma(\Sigma m_\nu) = 0.05\,\text{eV}\ [0.04\,\text{eV}]$$

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

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

SO collaboration, 2018

Route to improved bounds on Neff



Primary CMB temperature and polarization power spectra from SO

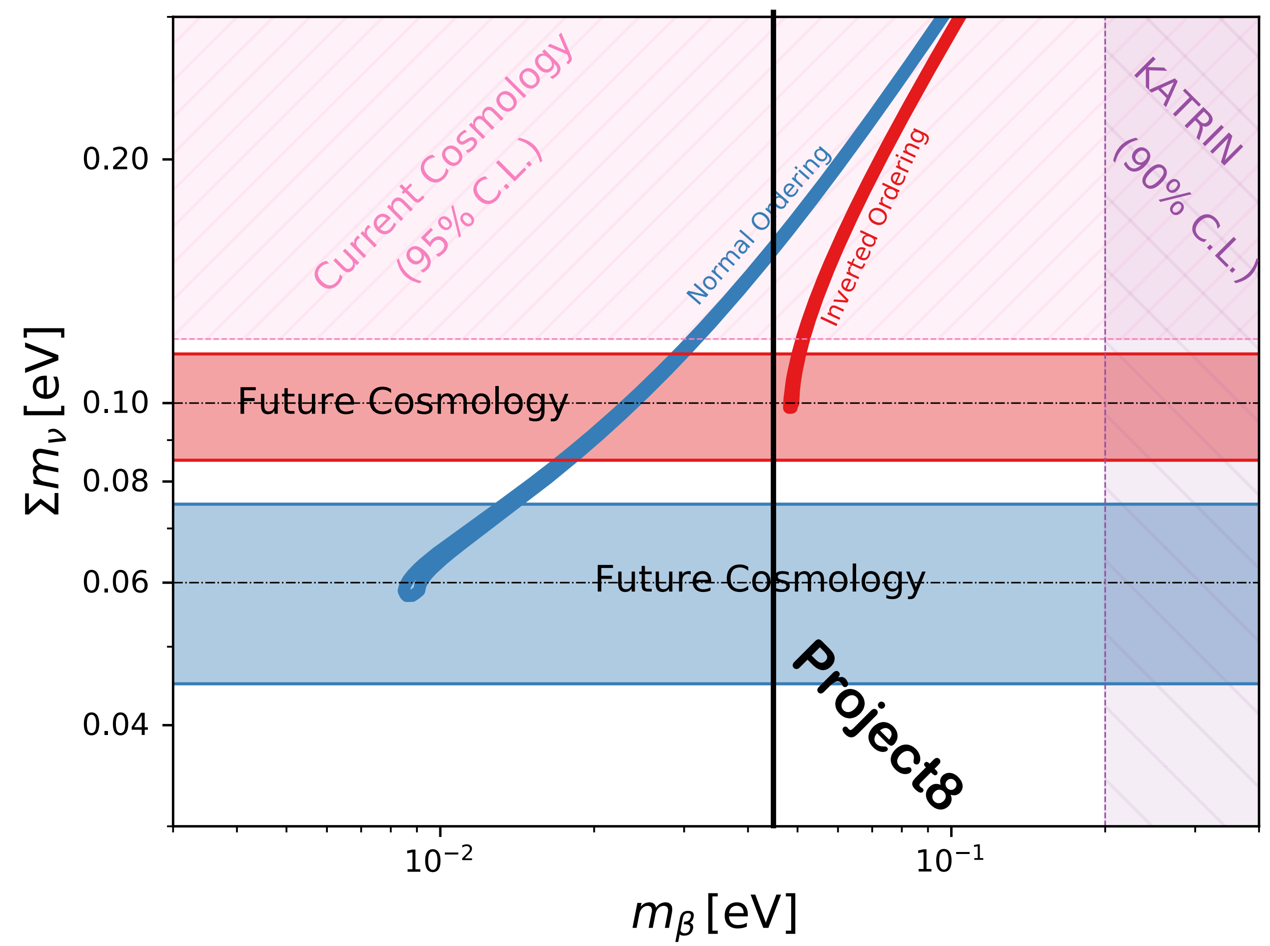
$$\sigma(N_{\mathrm{eff}}) = 0.07\ [0.05]$$

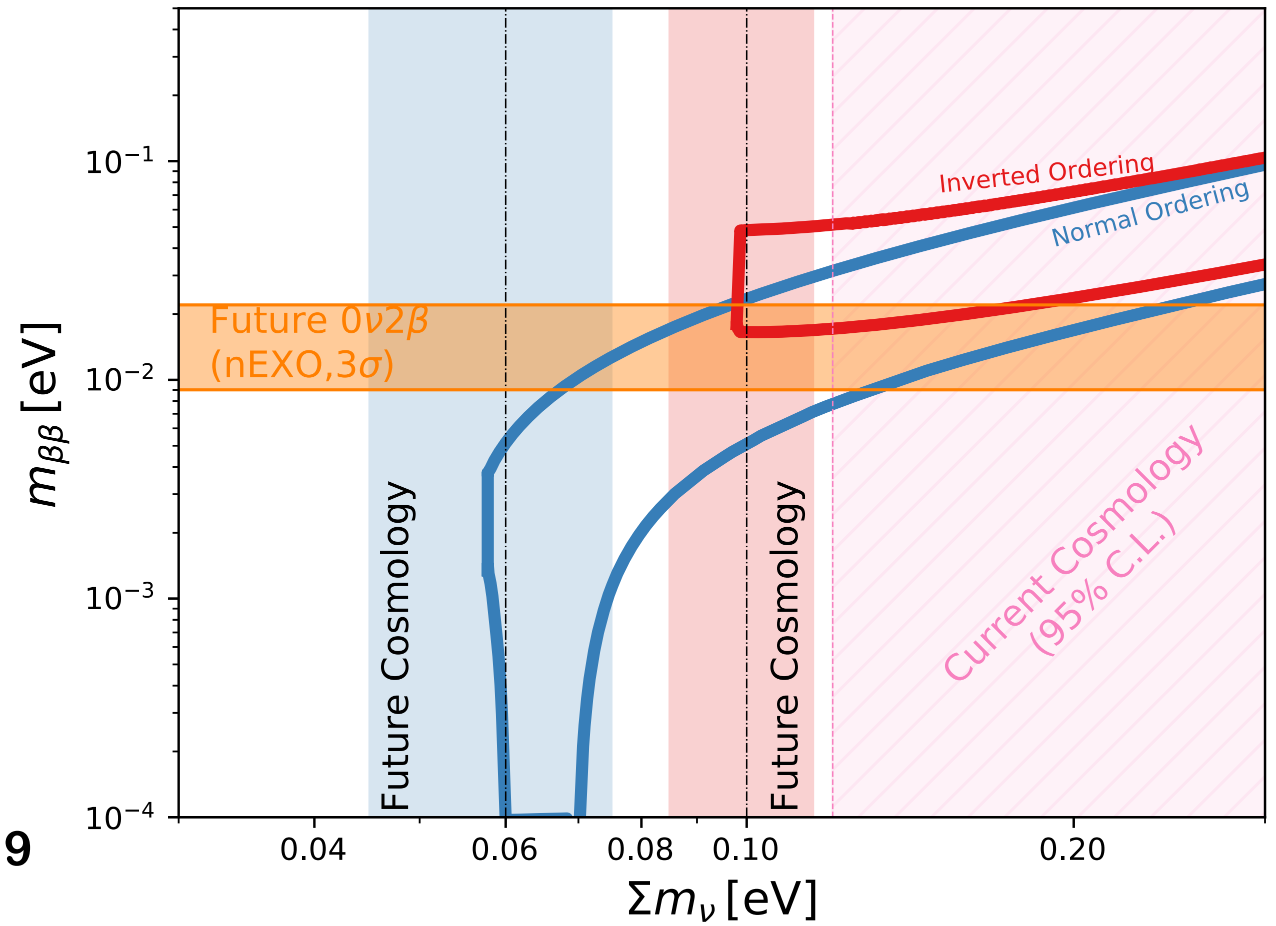
SO collaboration, 2018

Expected sensitivity from S4-like surveys
~15 meV

Complementarity with laboratory searches:

1) **independent cross-checks**
2) **interesting scenarios if in disagreement**

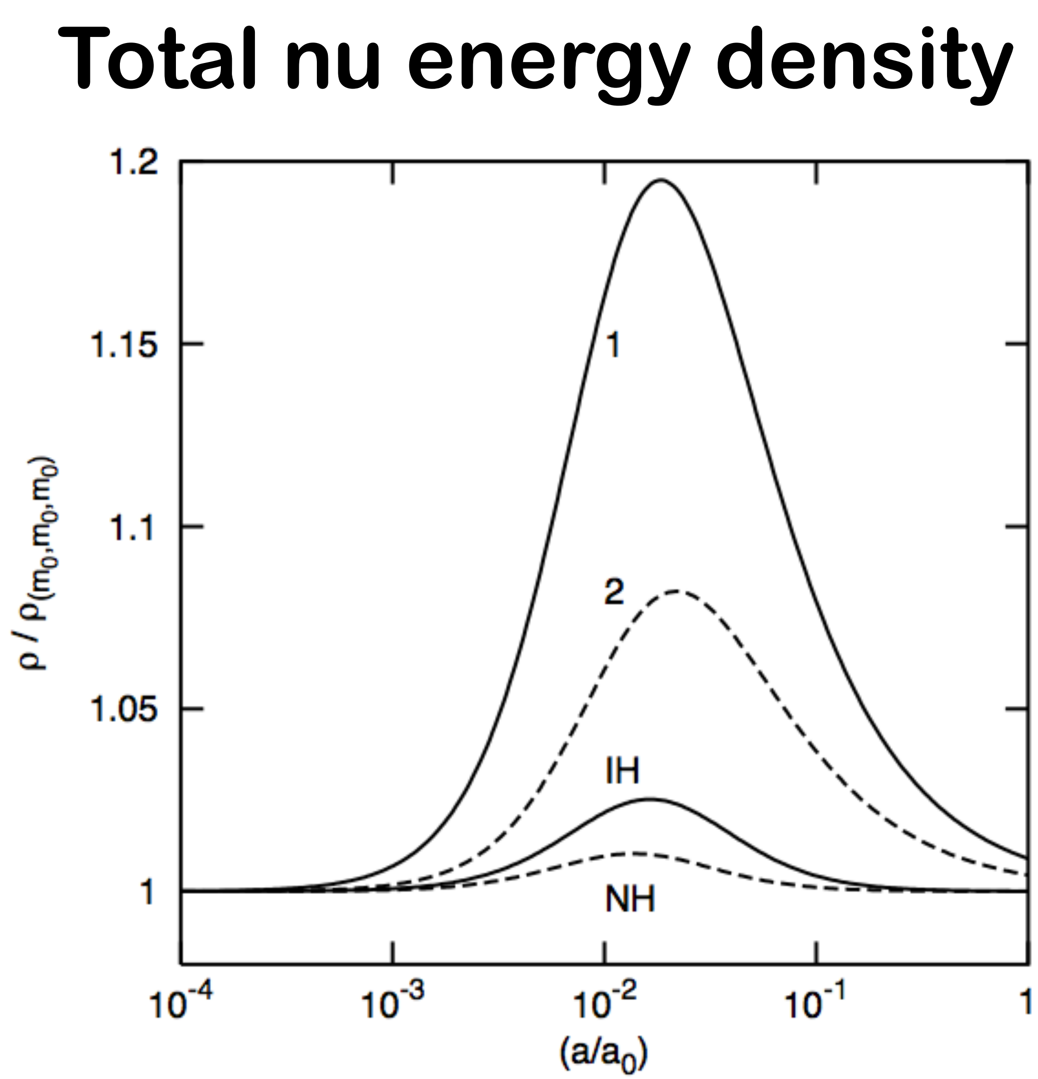


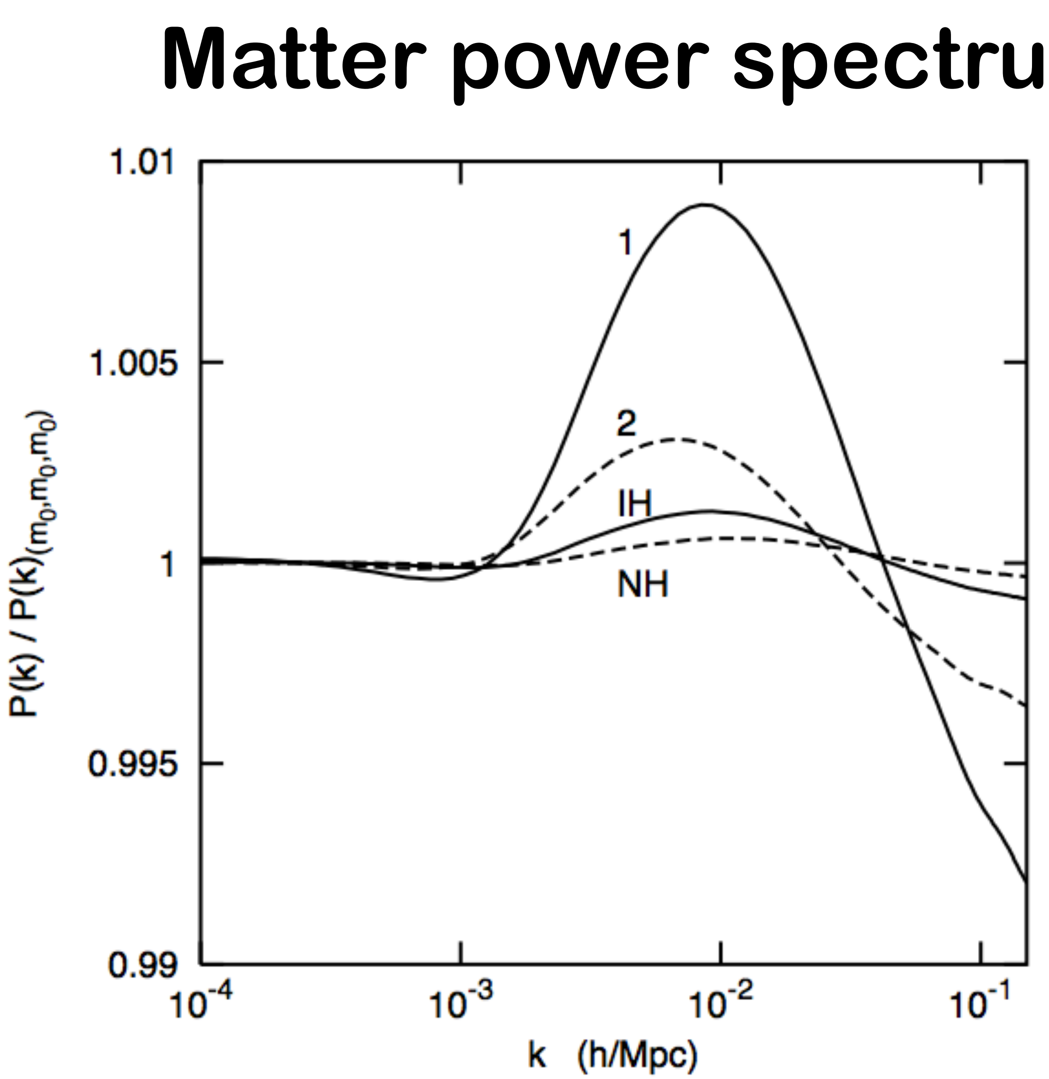


Stage-4 collaboration, 2019

Sensitivity to the hierarchy

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

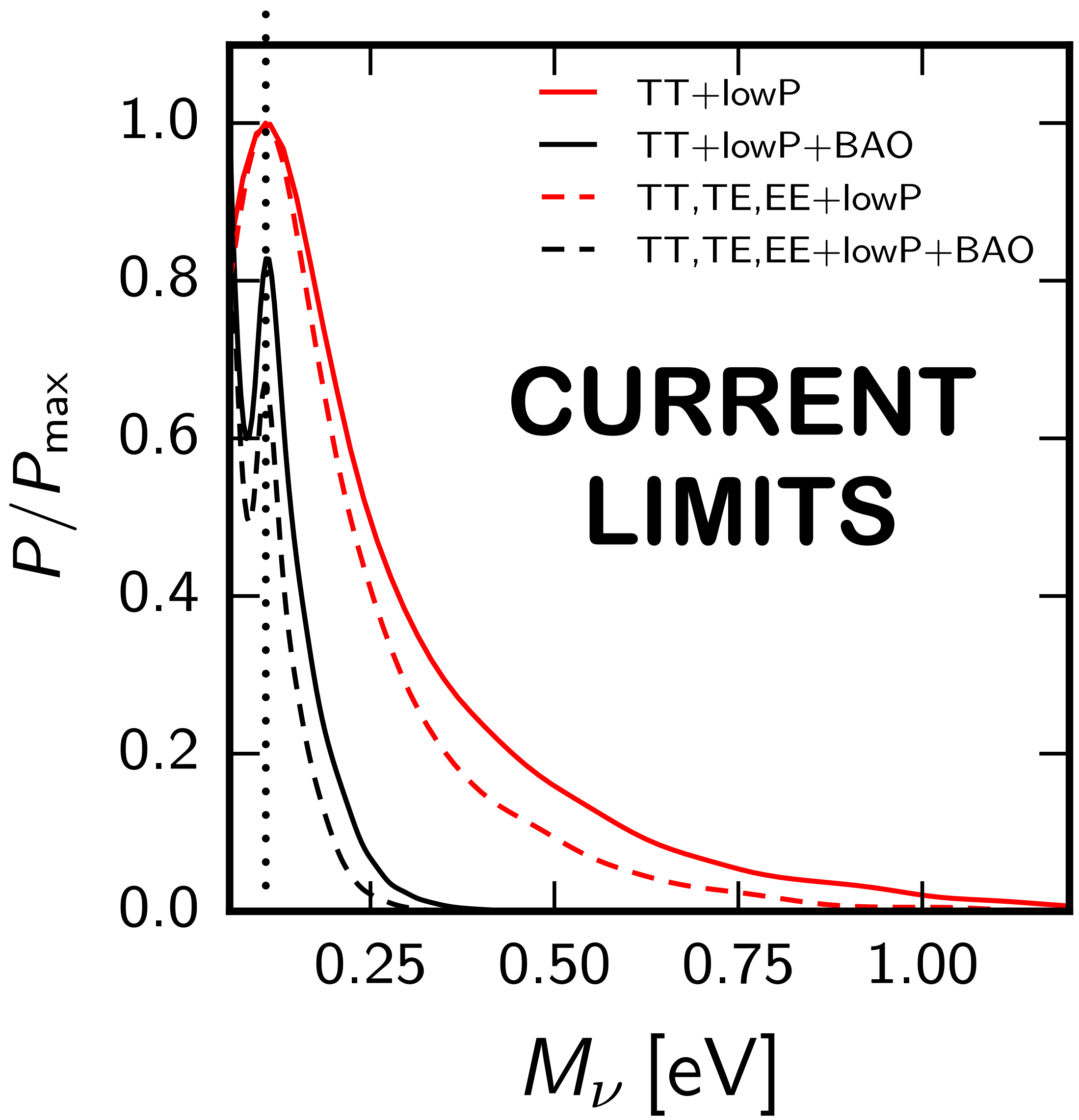


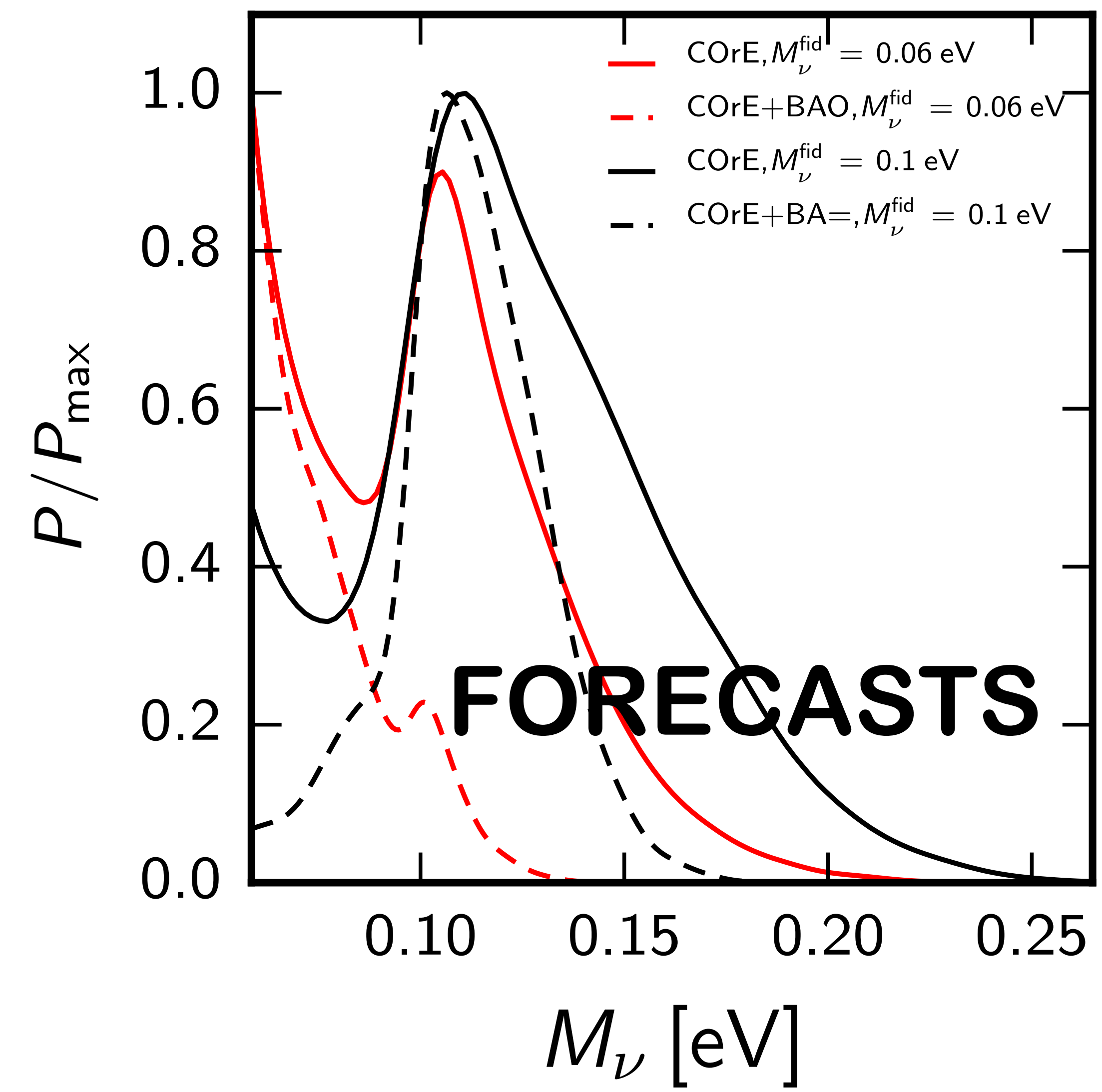


Lesgourgues&Pastor, 2006

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

Sensitivity to the hierarchy





Gerbino,Lattanzi,Mena,Freese 2016

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

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

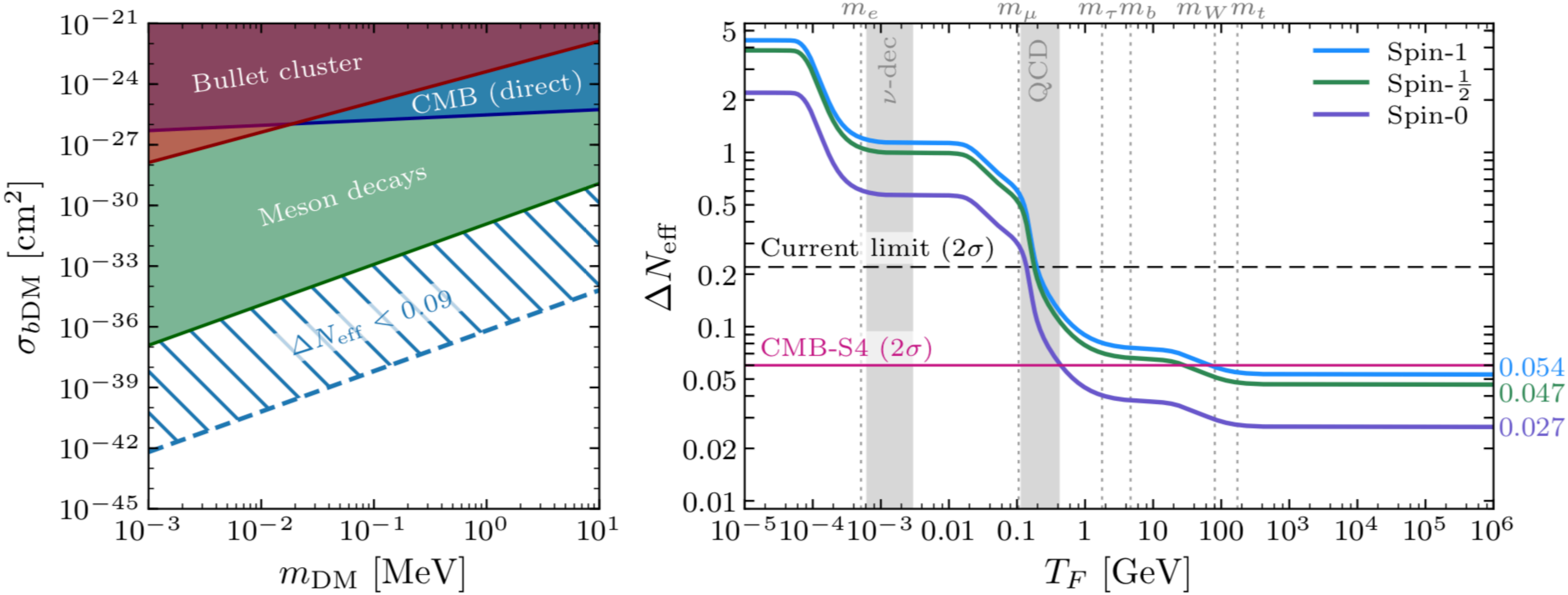
.... **3:2**

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

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

See also Hannestad&Schwetz,2016

Route to improved bounds on Neff



Stage-4 collaboration, 2019

CMB-S4 will achieve sensitivity 1) to relics that froze out well before the quark-hadron phase transition; 2) to the details of neutrino decoupling

sigma(Neff)=0.03

CONCLUSIONS

Determine CnB properties from neutrino peculiar effects on cosmological observables

Strong and robust constraints from cosmology

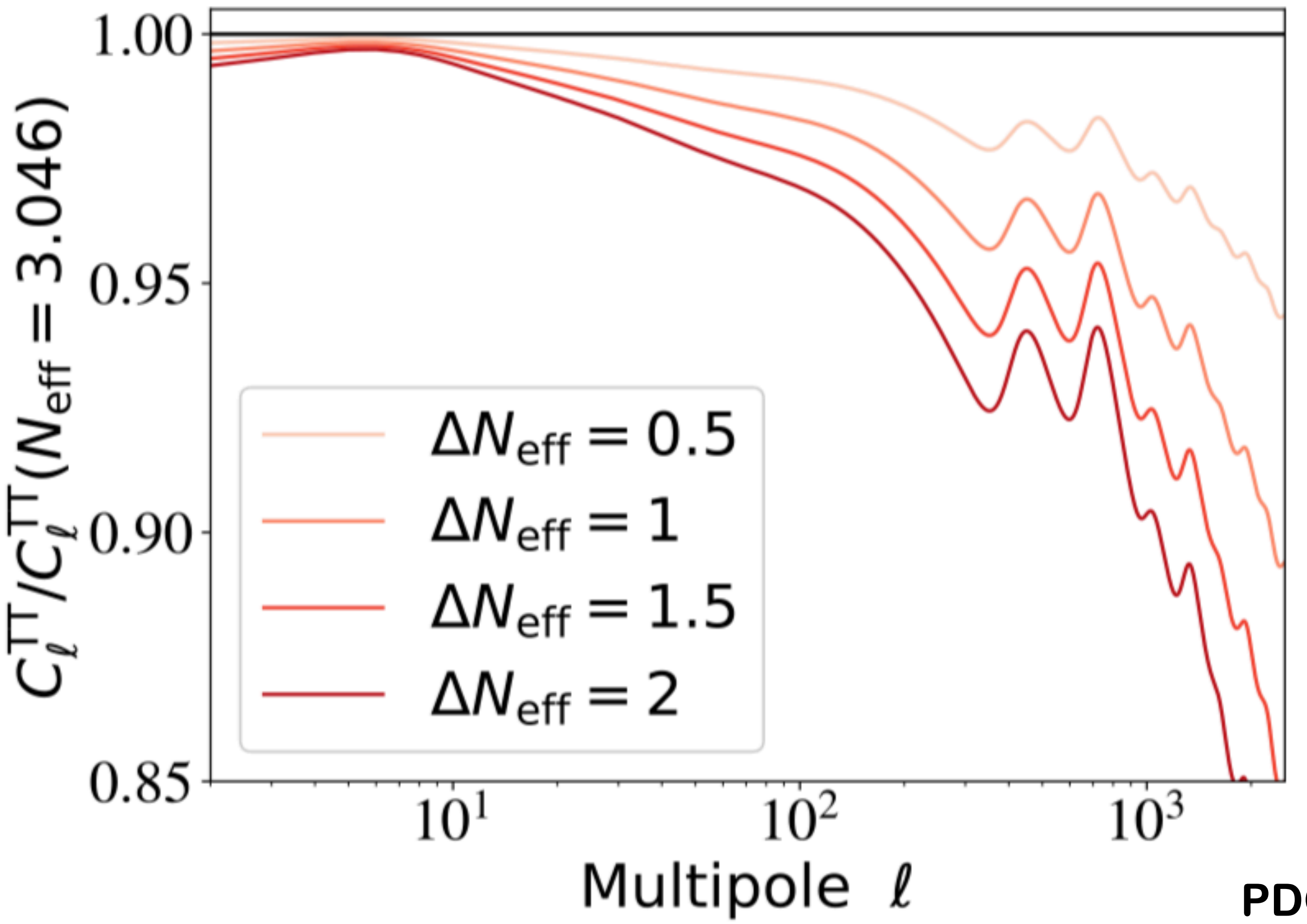
Neutrino masses: getting closer to cornering inverting hierarchy
Neff: no preference for an additional thermalised species

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

They would probe BSM scenarios and be complementary to lab and astro searches

BACKUP SLIDES

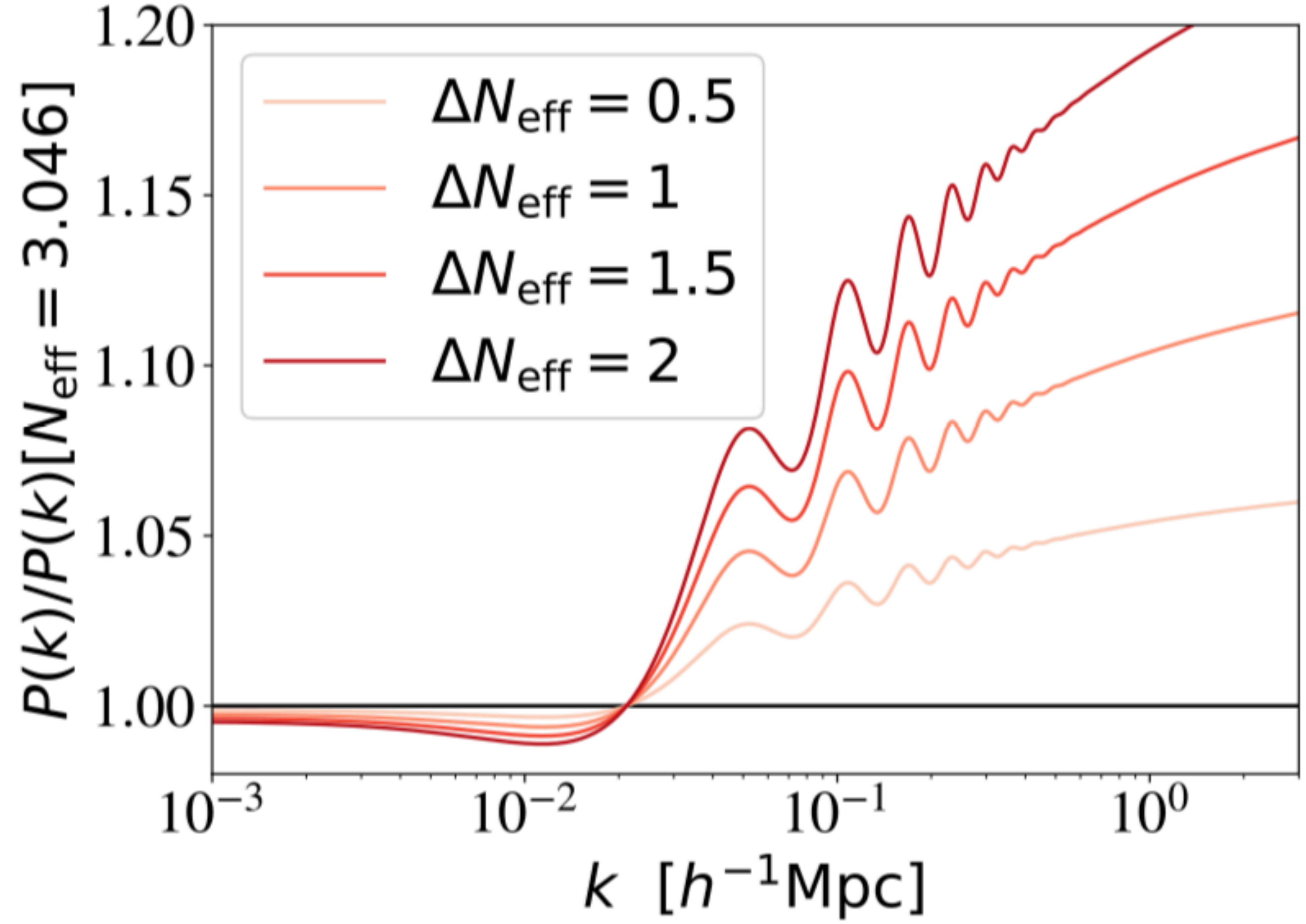
CMB power spectrum



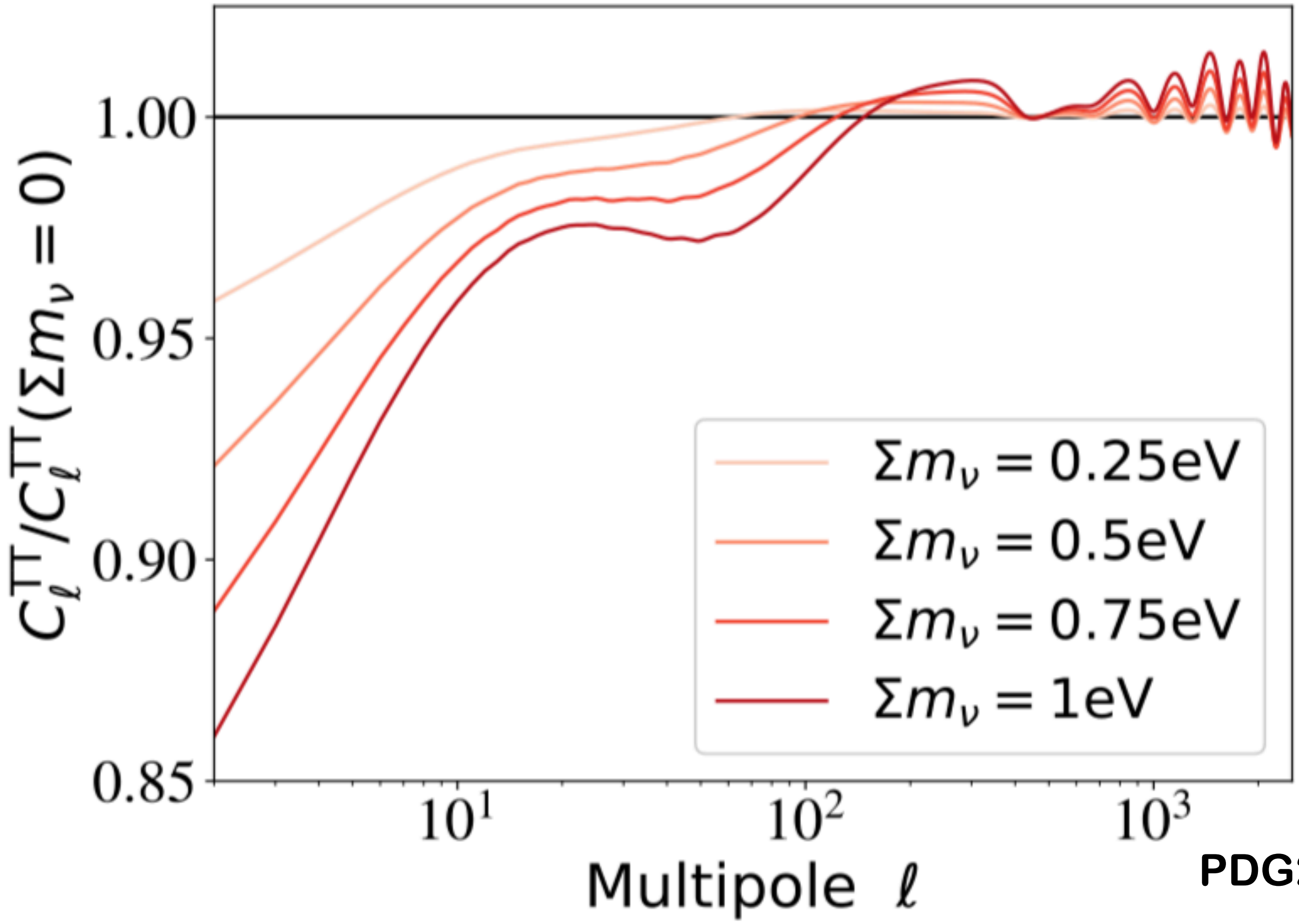
PDG2018

Figures obtained with fixed z_eq,z_L, obh2,tau

Matter power spectrum



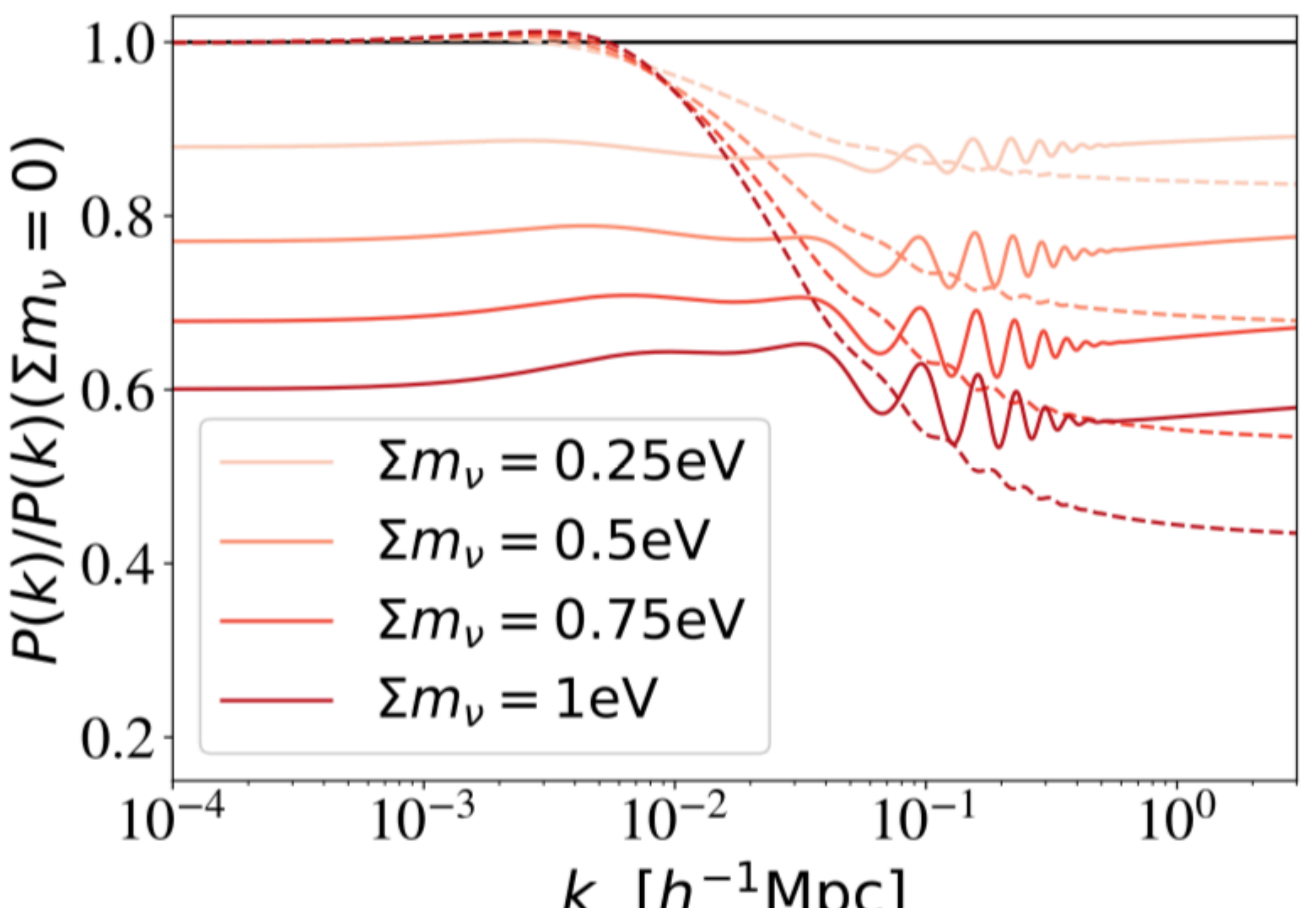
CMB power spectrum



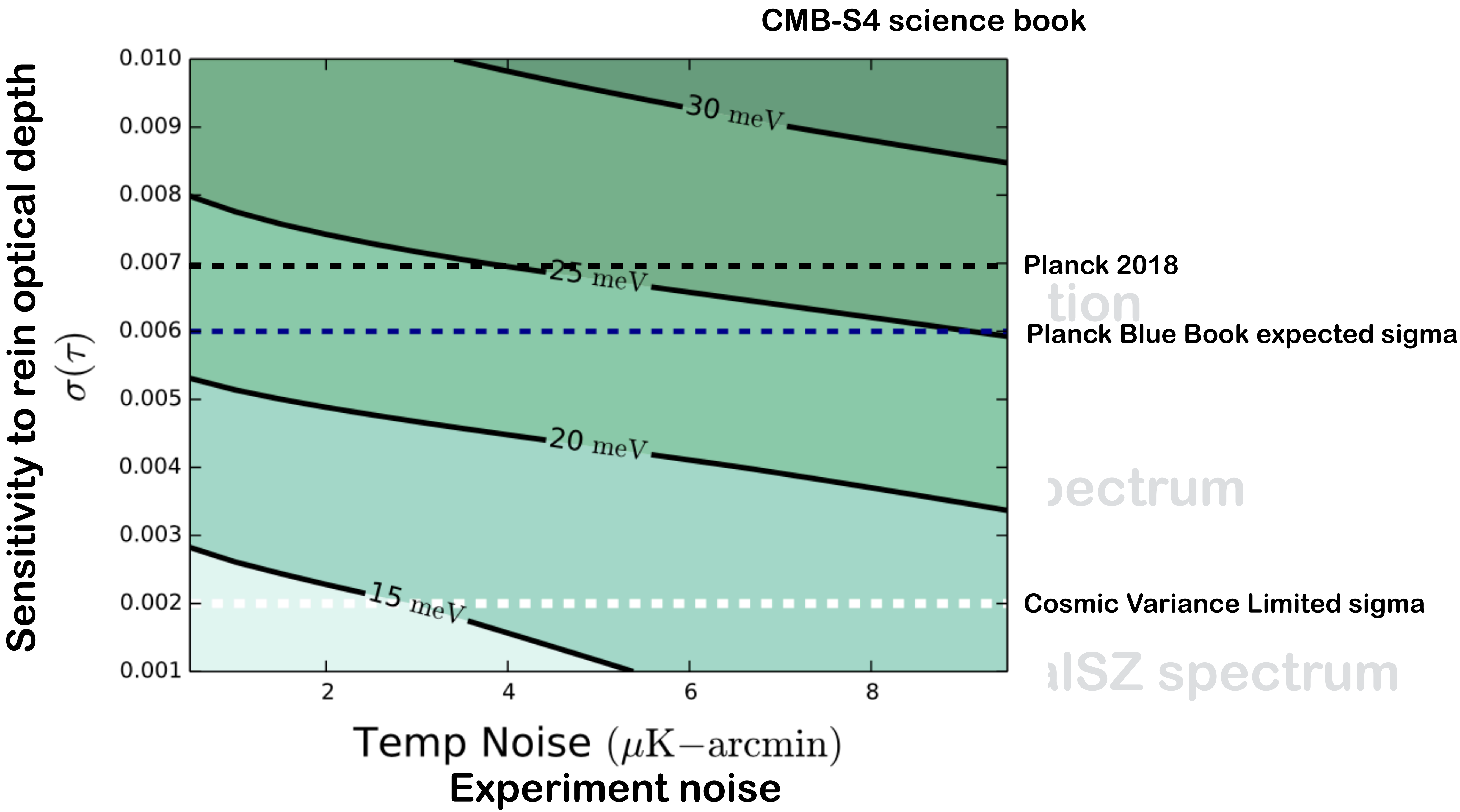
PDG2018

Figures obtained with fixed och2, obh2,tau,theta (solid); fixed omh2,obh2, Olambda (dashed)

Matter power spectrum



Route to robust neutrino mass bounds



- Cosmic-variance-limited measurements of tau

Neff as a proxy for extra light species

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

Light relics decoupling when thermalised with the primordial plasma

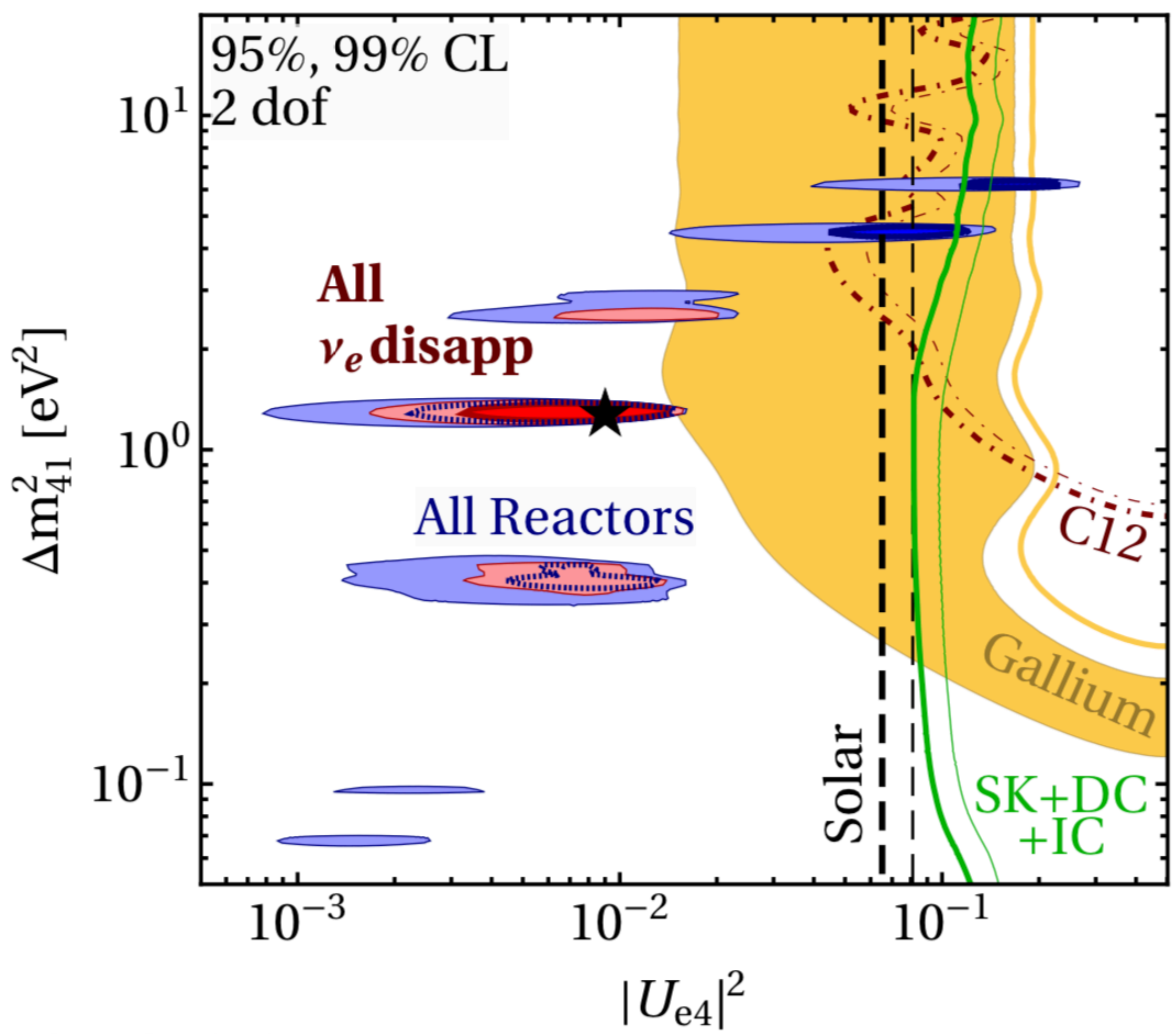
$$\Delta N_{\rm eff} = g\left(\frac{43}{4 g_{*,s}}\right)^{\frac{4}{3}} \times \begin{cases} 1/2, & \text{fermion} \\ 4/7, & \text{boson} \end{cases}$$

↓

Effective dof at decoupling

Light sterile in cosmology

Dentler+,2018



Anomalies in oscillations would require light sterile with large mixing angle.

If they exist, oscillations in the early Universe would create a population of sterile

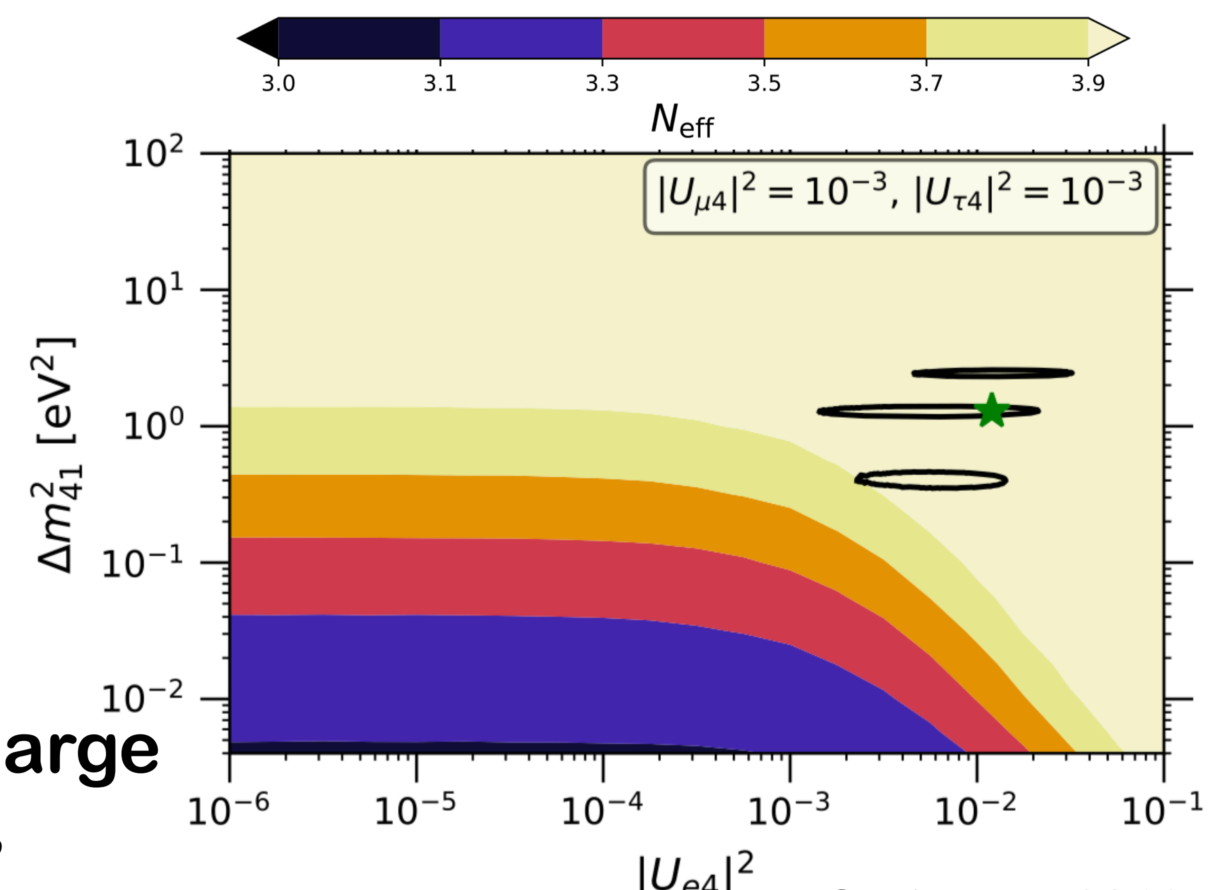
θ

Δm^2

$\rightarrow$

$\Delta N_{\rm eff}$

$$\Omega_{\nu,s}h^2 = \frac{m_{\rm eff}}{94\,{\rm eV}}$$



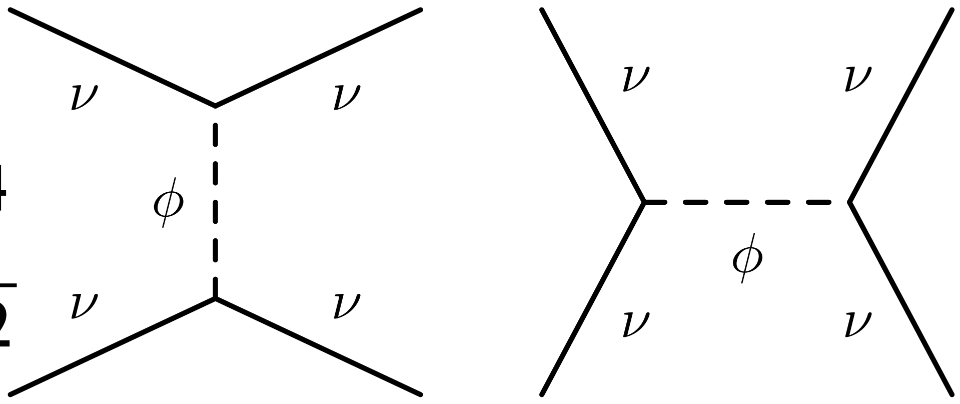
Gariazzo+,2019

Lab best fit is at odds with cosmology: too large contribution to Neff for large mixing angles (quick thermalisation of the sterile with active)

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:

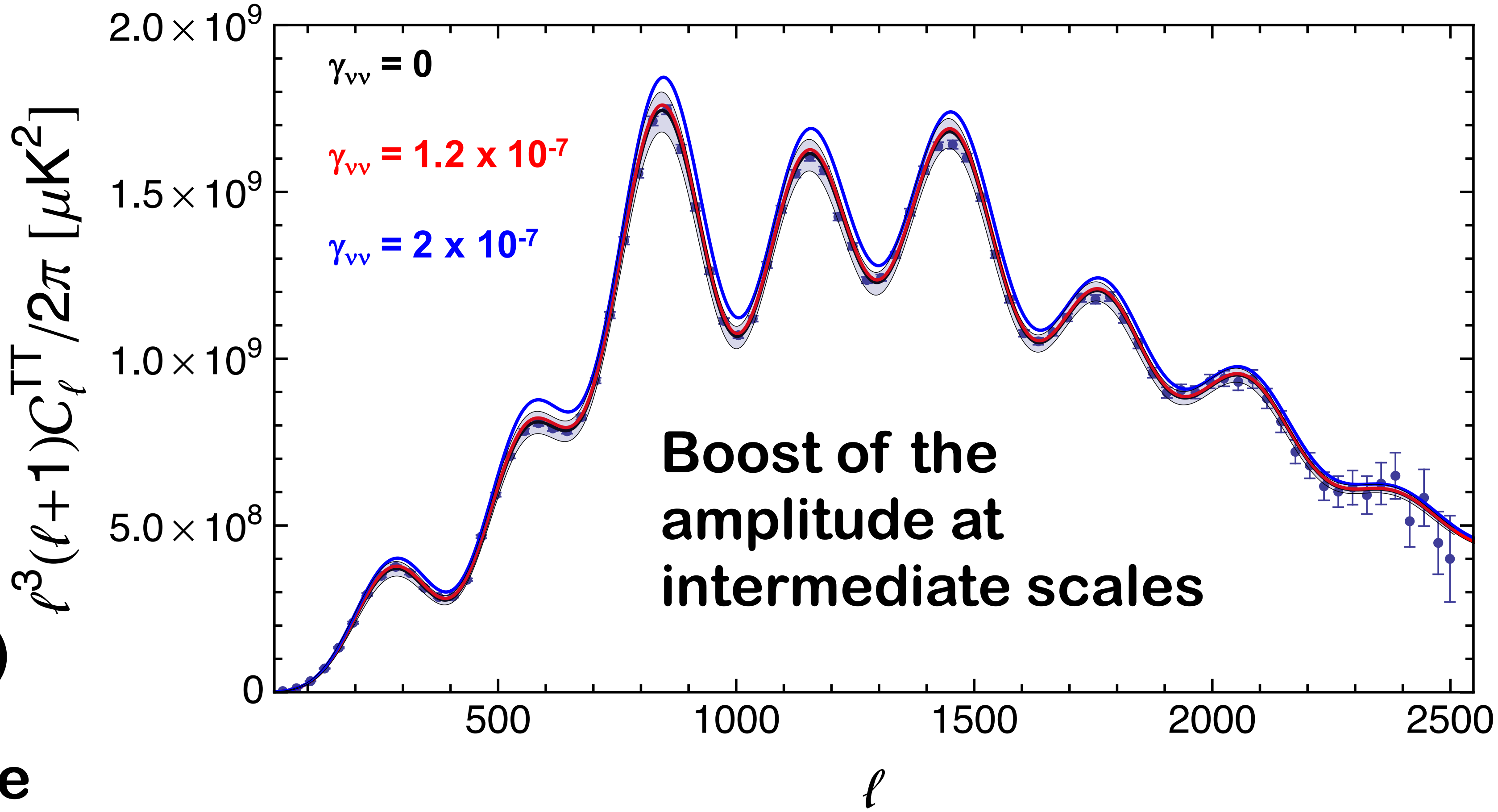
$$\Gamma_{\nu\nu} \equiv \gamma_{\nu\nu}^4 T$$

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)**

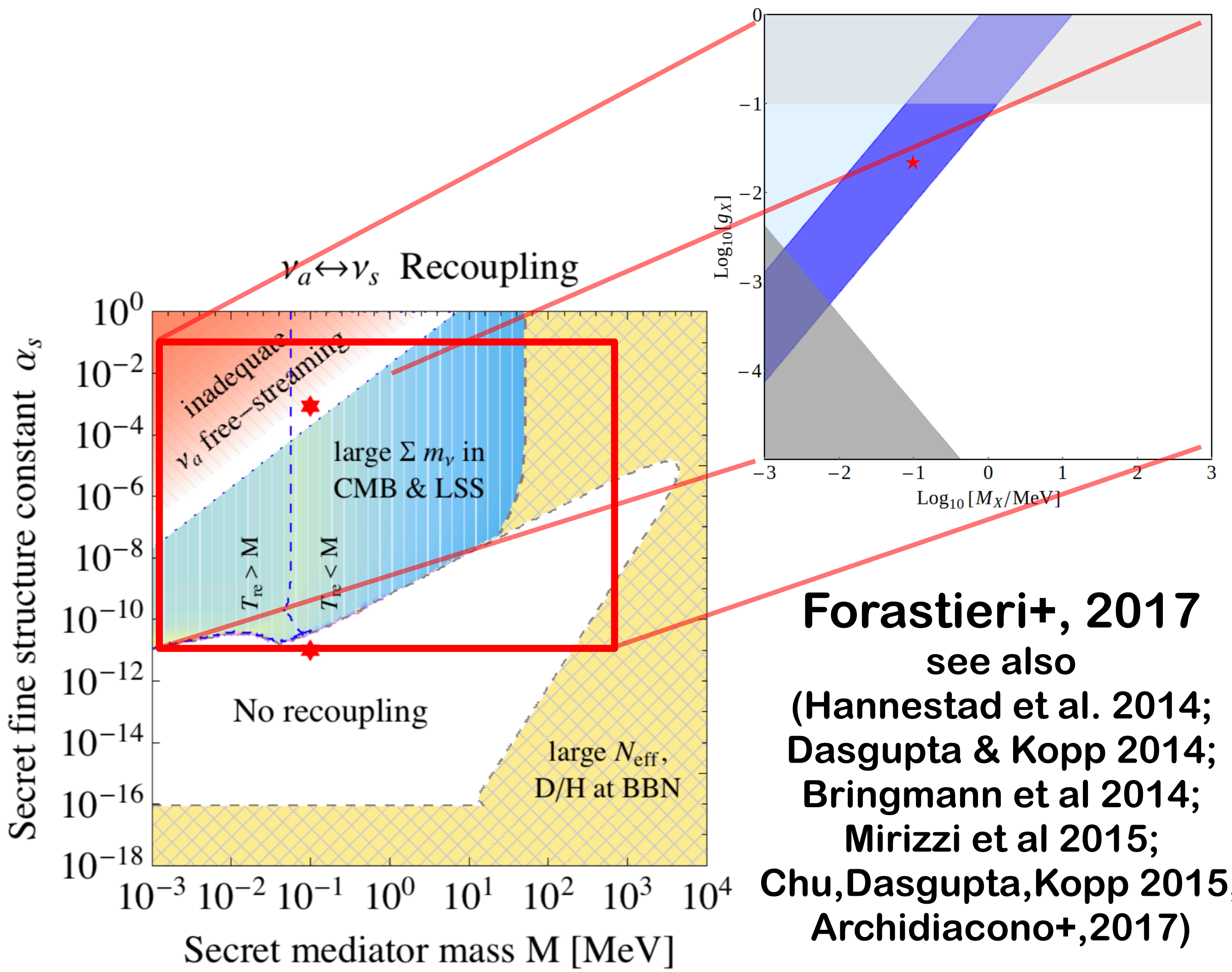
Future CMB bounds will improve by ~ 1 order of magnitude in $\gamma_{\nu\nu}^4$



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

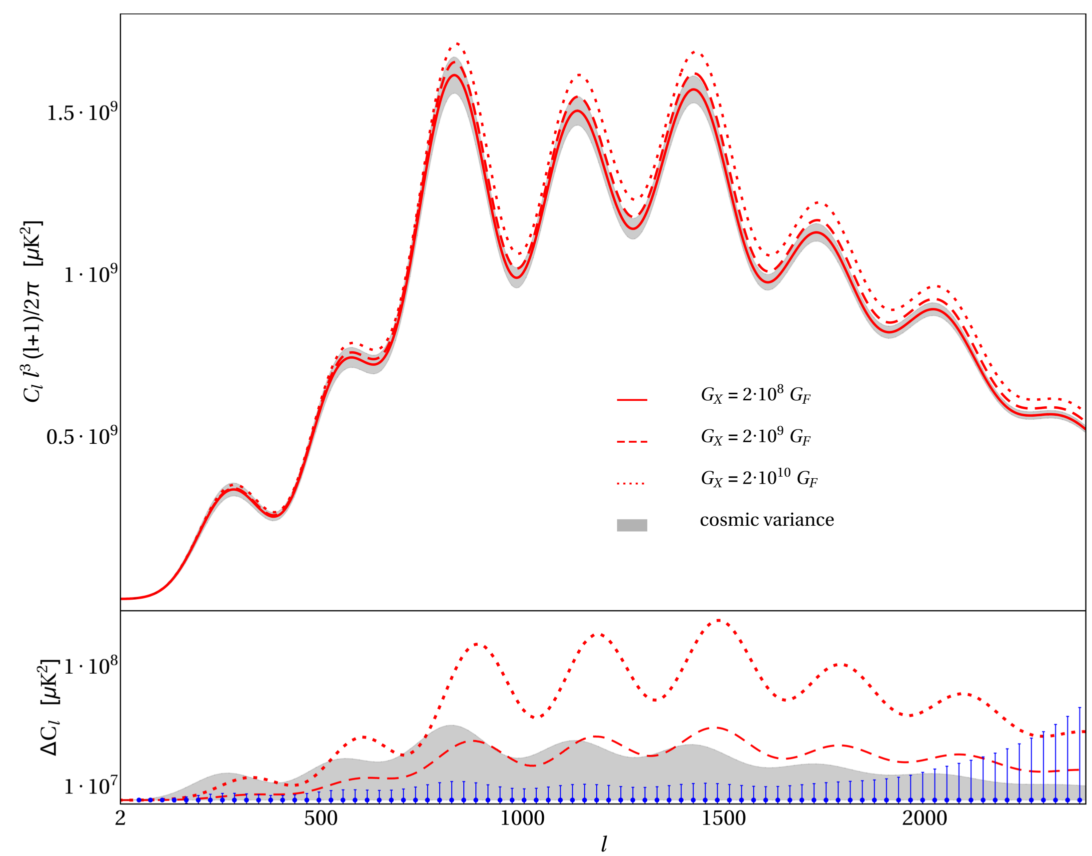
Sterile neutrino interactions and SBL anomalies

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.



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

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

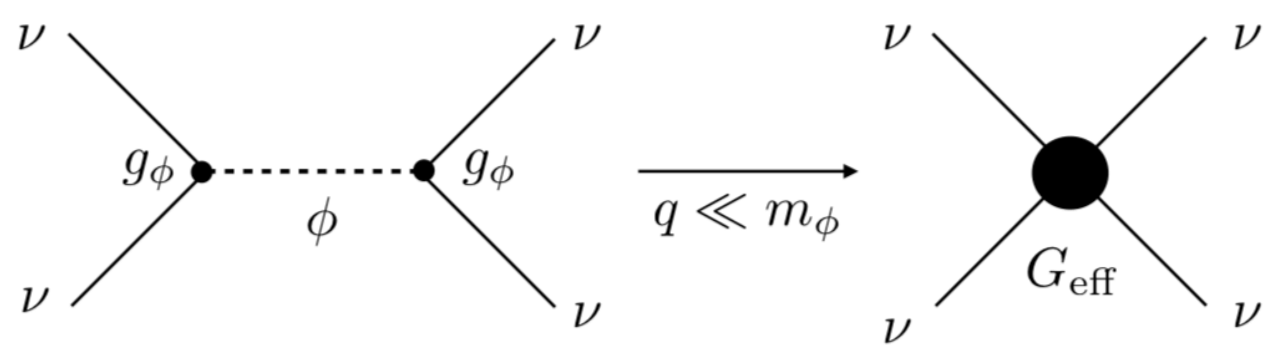


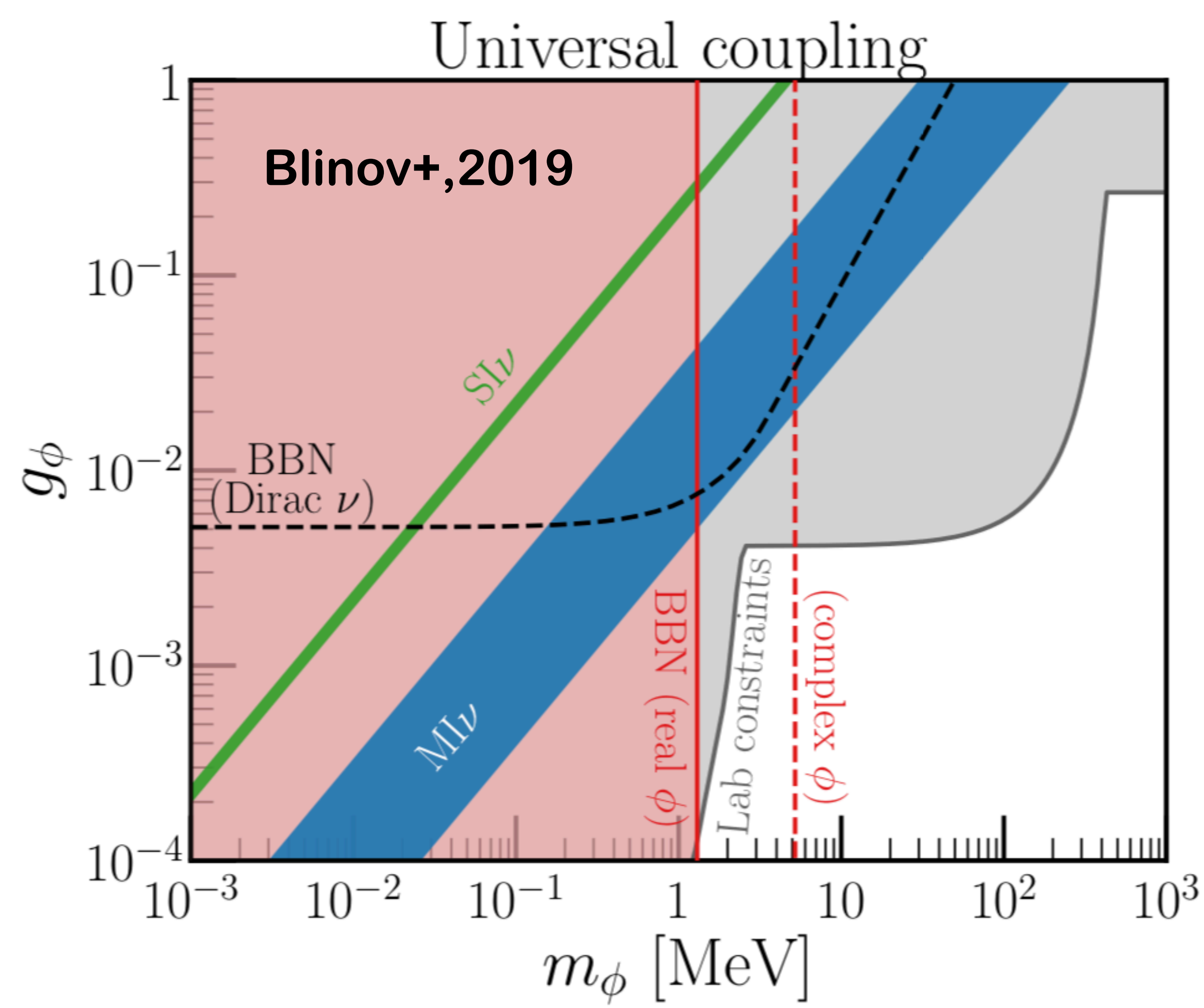
Forastieri+, 2017
see also
(Hannestad et al. 2014; Dasgupta & Kopp 2014; Bringmann et al 2014; Mirizzi et al 2015; Chu,Dasgupta,Kopp 2015; Archidiacono+,2017)

Scalar-mediated neutrino interactions

HEAVY MEDIATOR (m_phi>keV)

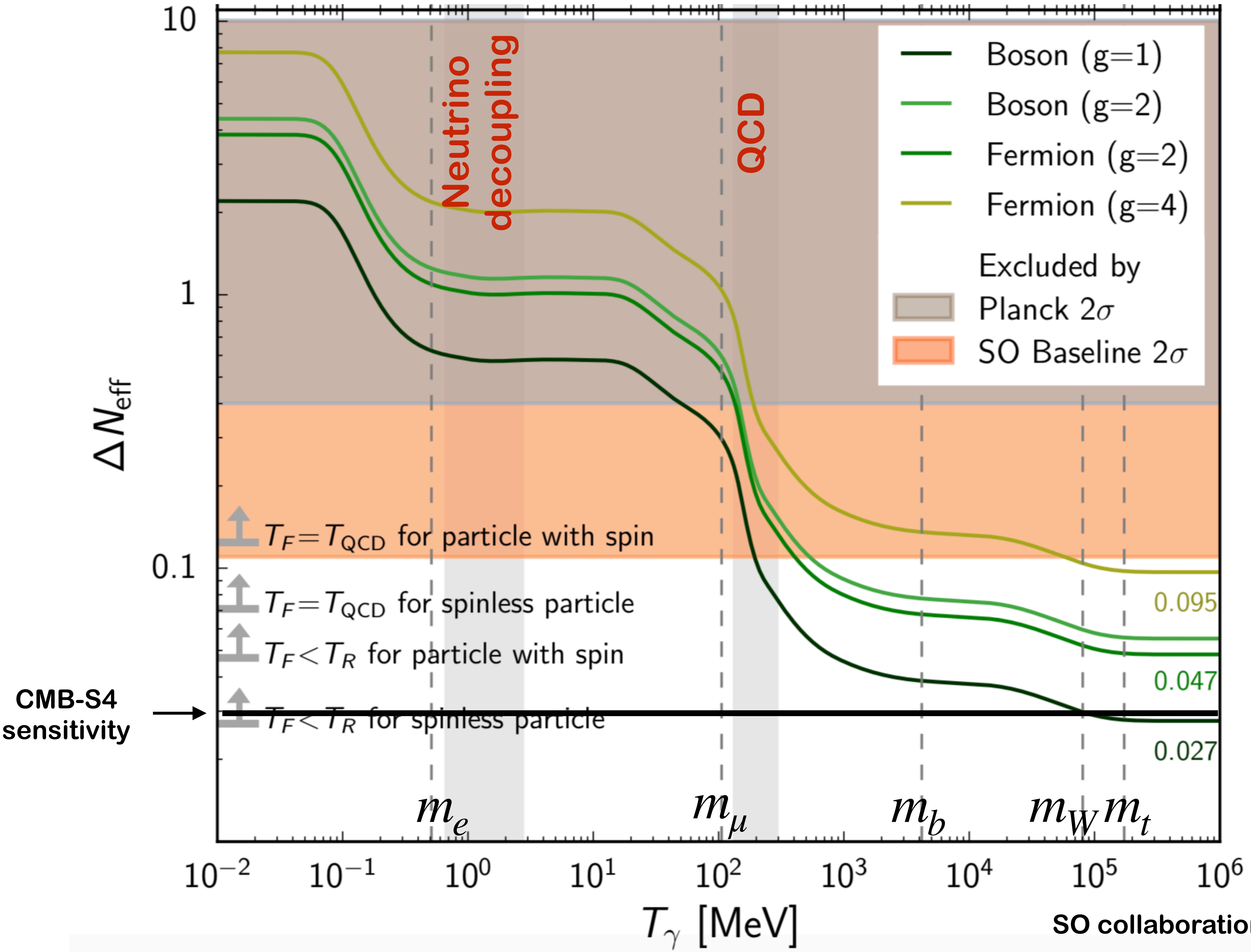
Parameterizing the universal coupling g_ij=g_nu delta_ij as Geff=g_nu^2/m_phi^2





Mildly interacting -> Geff<10^-4 MeV^-2
Strongly interacting -> 10^-2 MeV^-2<Geff<10^-1 MeV^-2

Route to improved bounds on Neff



SO collaboration, 2018