A REVIEW OF NEUTRINO COSMOLOGY

COSMOS meeting on astroparticle and fundamental physics

Martina Gerbino
OKC, Stockholm University

see also Gerbino&Lattanzi2017

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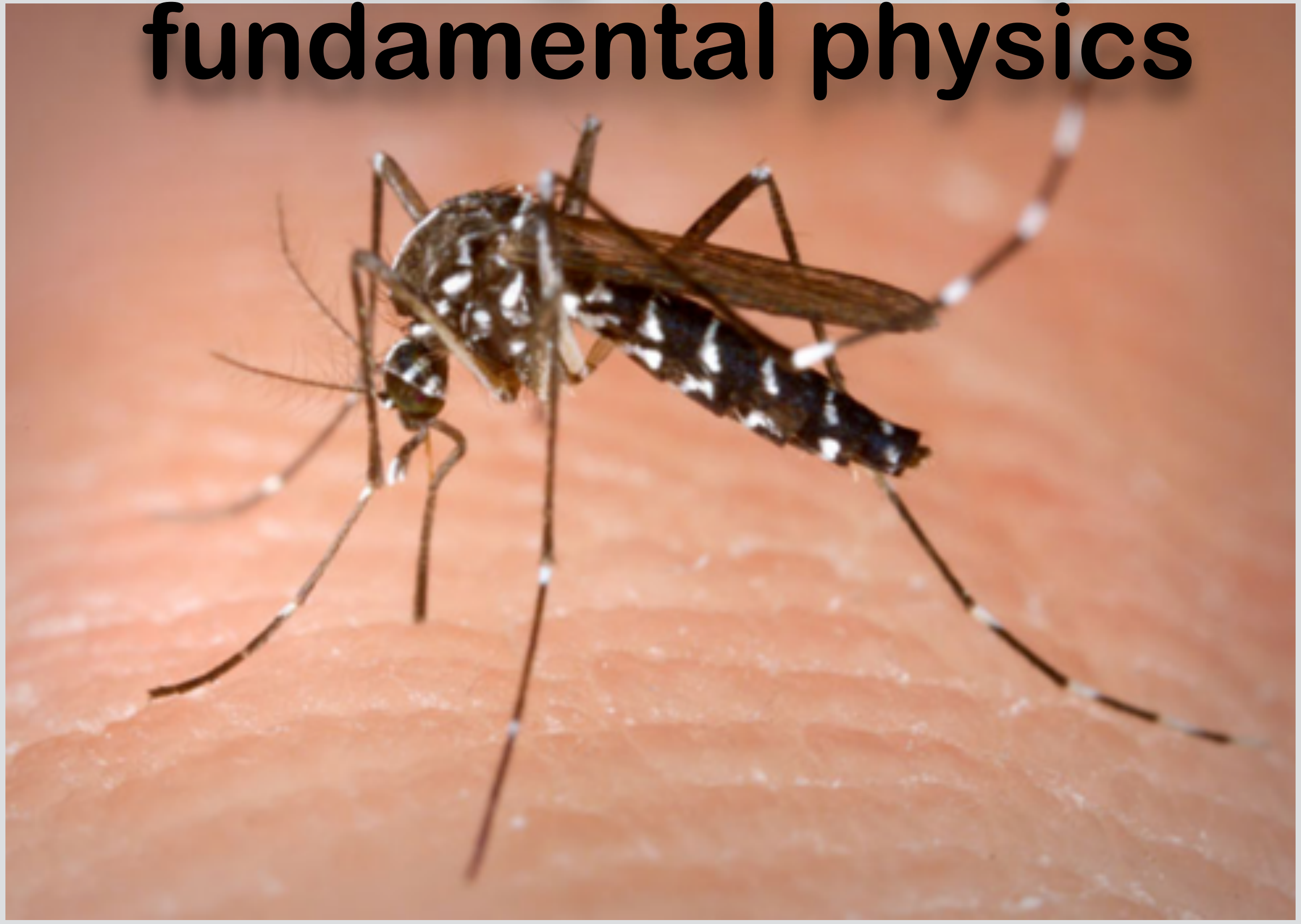

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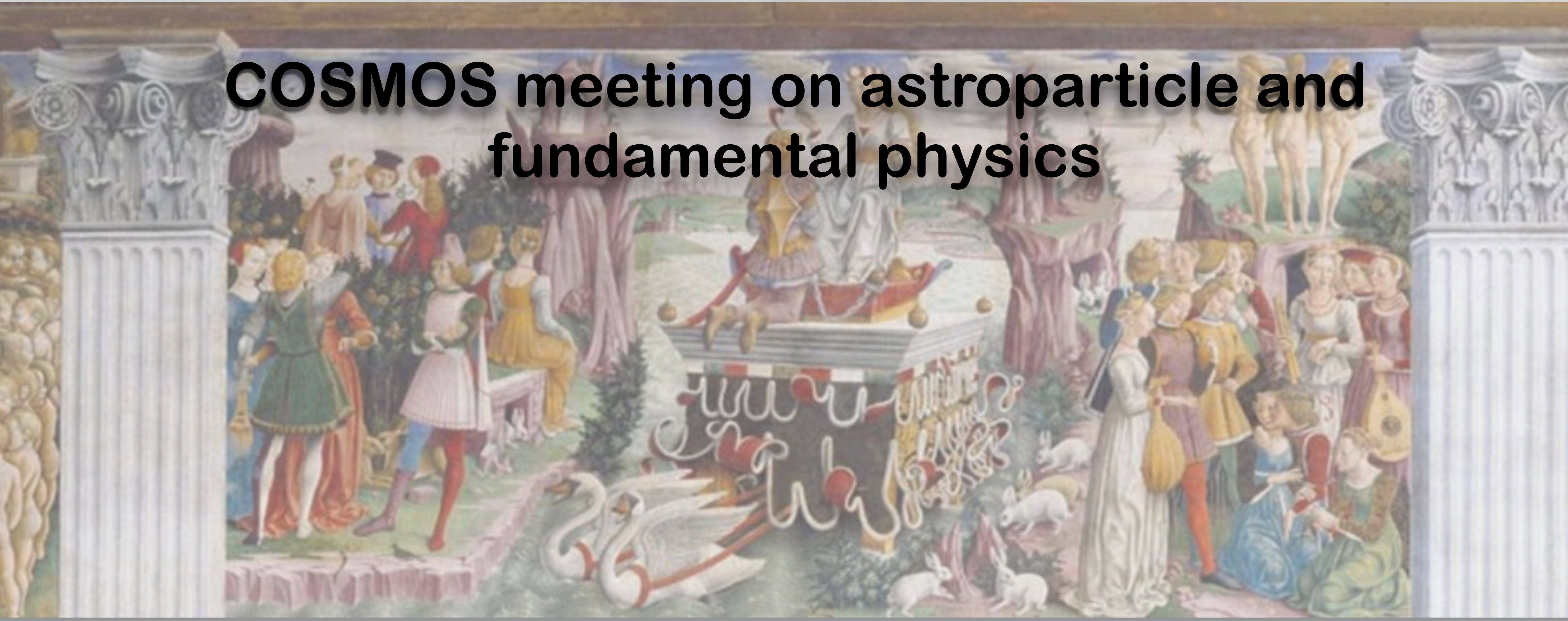
A REVIEW OF NEUTRINO COSMOLOGY



COSMOS meeting on astroparticle and fundamental physics

Martina Gerbino

OKC, Stockholm University

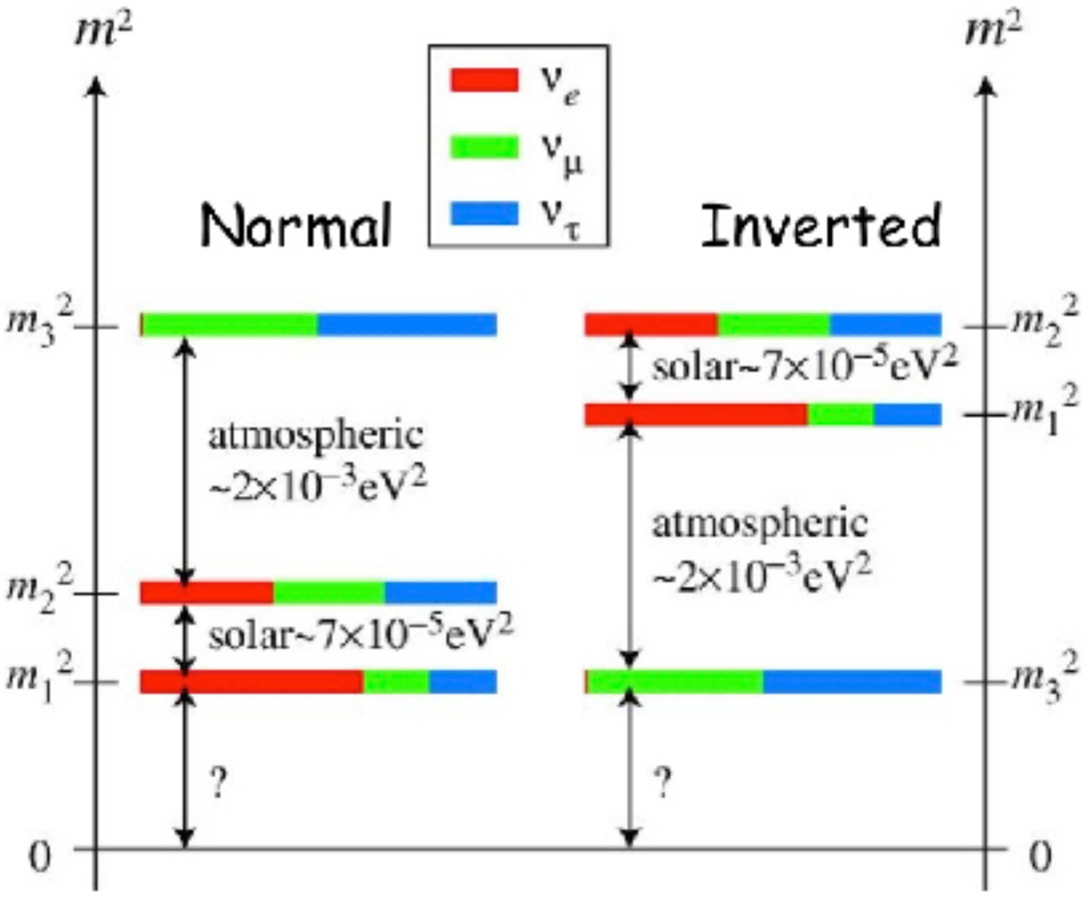
see also Gerbino&Lattanzi2017

What we know, from the lab

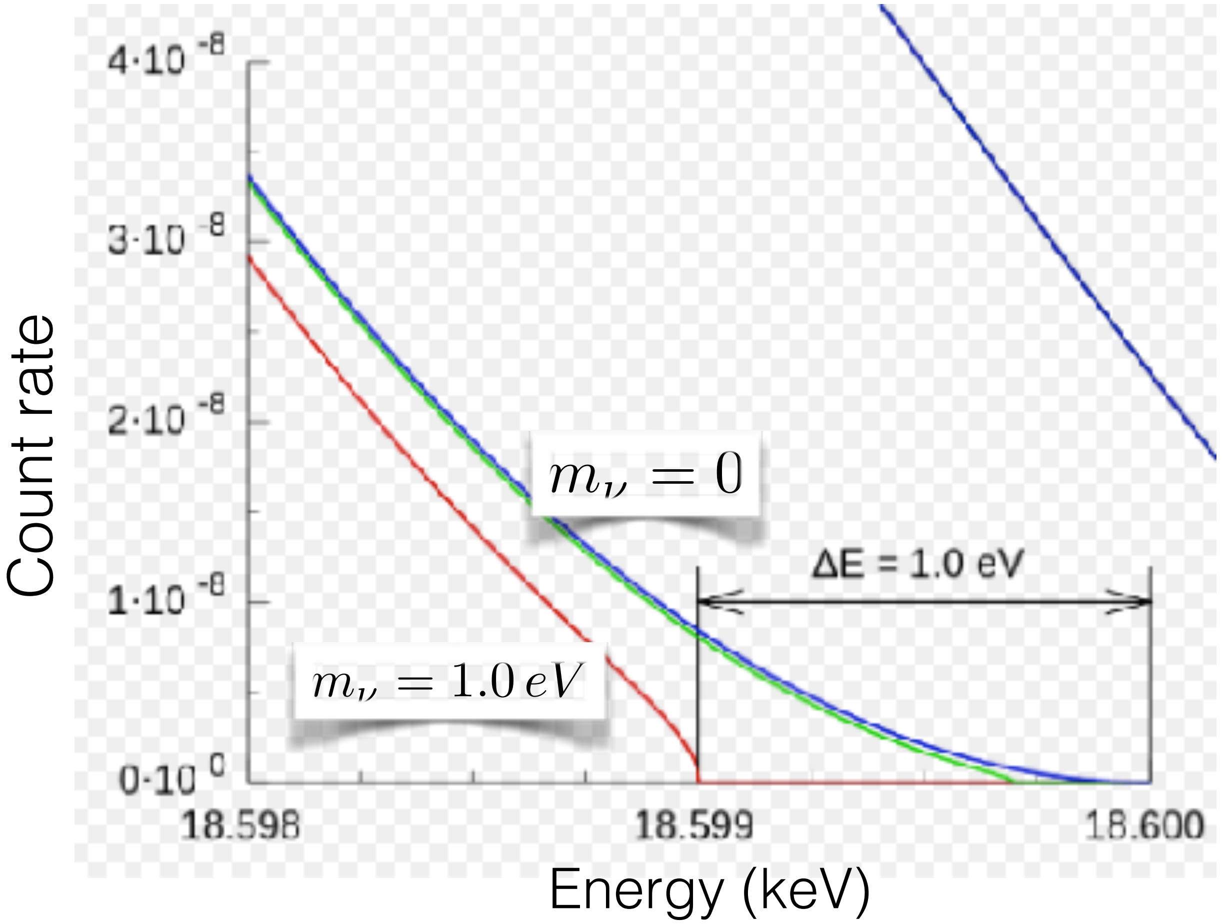
From Z-boson decay —> 3 active neutrino families

From flavour oscillations —> Neutrinos are massive

$$0.06\,\mathrm{eV} < \Sigma m_\nu < 6\,\mathrm{eV}$$



Lower bound
from oscillation experiments

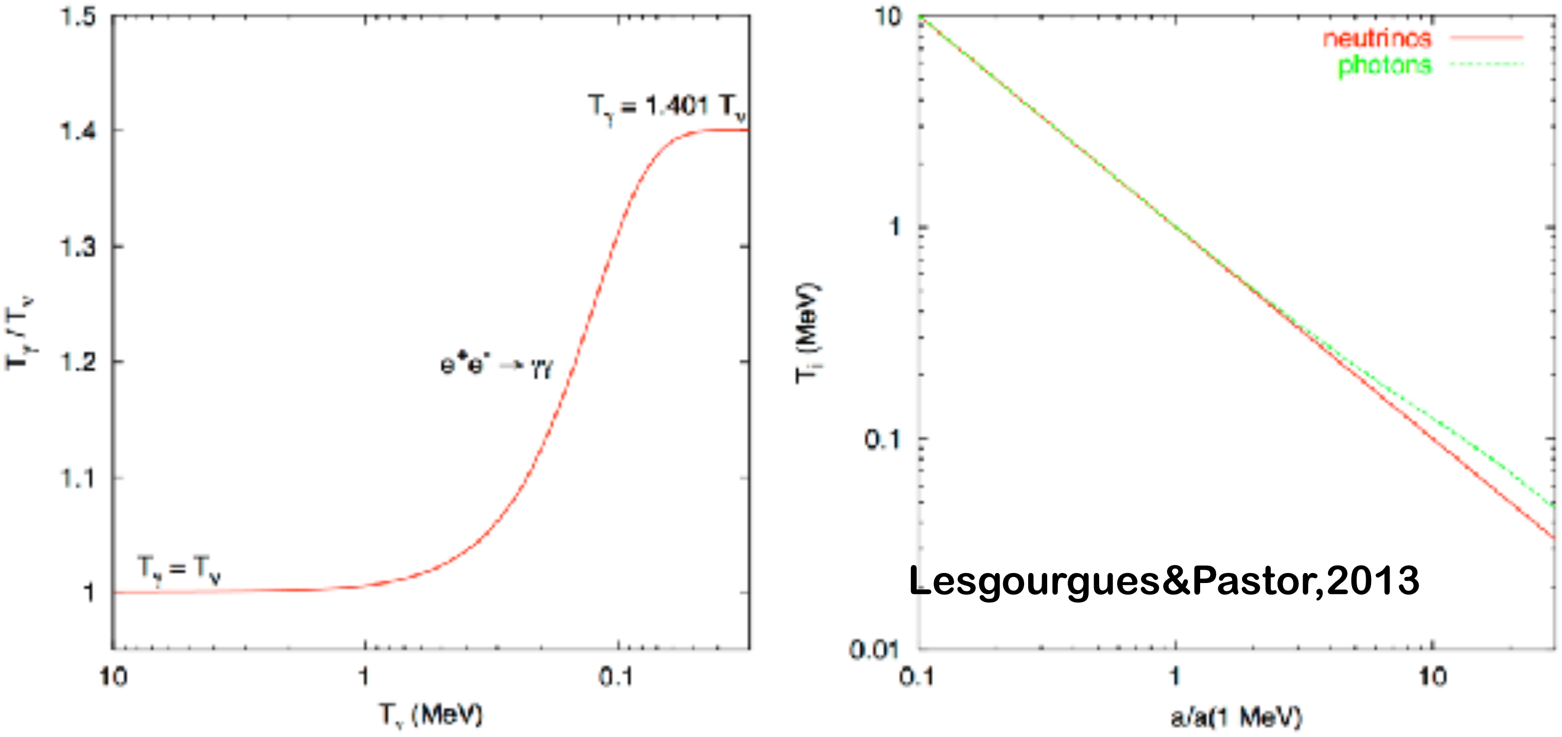


Upper bound
from kinematic measurements

Basics of neutrino cosmology

- Standard cosmological model predicts the existence of a background of relic neutrinos (CνB)
- $\Gamma_w > H$ (T>1MeV) -> Thermal equilibrium with primordial plasma (T_ν=T)
- T < 1 MeV -> neutrino free stream keeping an equilibrium spectrum ($T_\nu \neq T$, $T_\nu \propto 1/a$):

$$f_\nu(p) = \frac{1}{e^{p/T_\nu} + 1}$$



Lesgourgues&Pastor,2013

$$\boxed{T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma}$$

- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species

Neutrino phenomenology

Neutrinos were relativistic in the early Universe

$$\rho_\nu = g_\nu \int p\, f(p) d^3p \propto g_\nu T_\nu^4$$

Contribution to the radiation density

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

with $\rho_x \propto g_x T_x^4,\ T_\nu/T_\gamma = (4/11)^{1/3}$

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

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

Neff could account for any 'extra' radiation component

Neutrino phenomenology

Neutrinos are non-relativistic today

$$\rho_\nu = m_\nu n_\nu = m_\nu g_\nu \int f(p) d^3p \propto m_\nu g_\nu T_\nu^3$$

Contribution to the matter content at late times

$$\Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2 \, \mathrm{eV}}$$

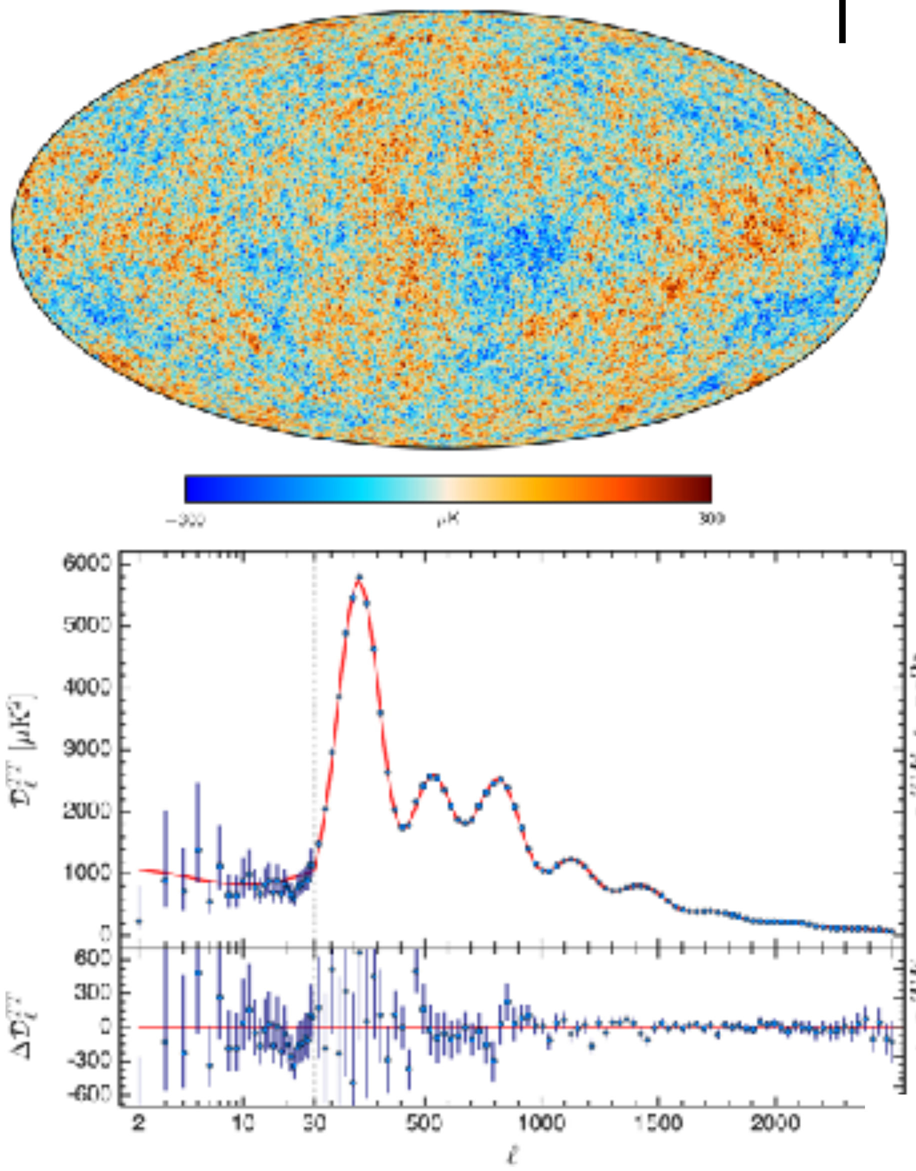
$$\rho_c = \frac{3H^2}{8\pi G}$$

Transition to non-relativistic regime

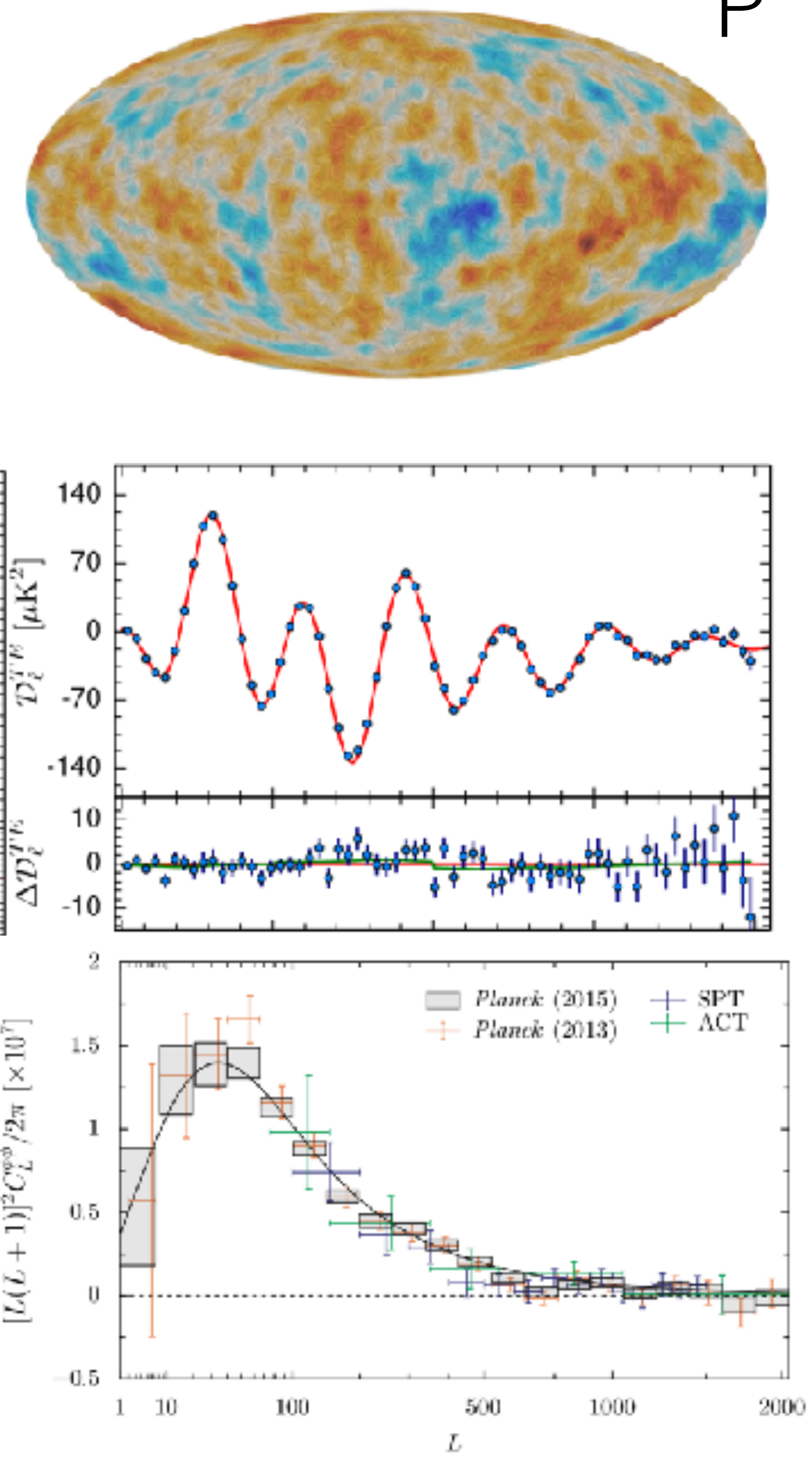
$$< p > \simeq m_\nu \;\rightarrow\; 1 + z_{\rm nr} \simeq 1900 \left(\frac{m_\nu}{\rm eV}\right)$$

What we observe

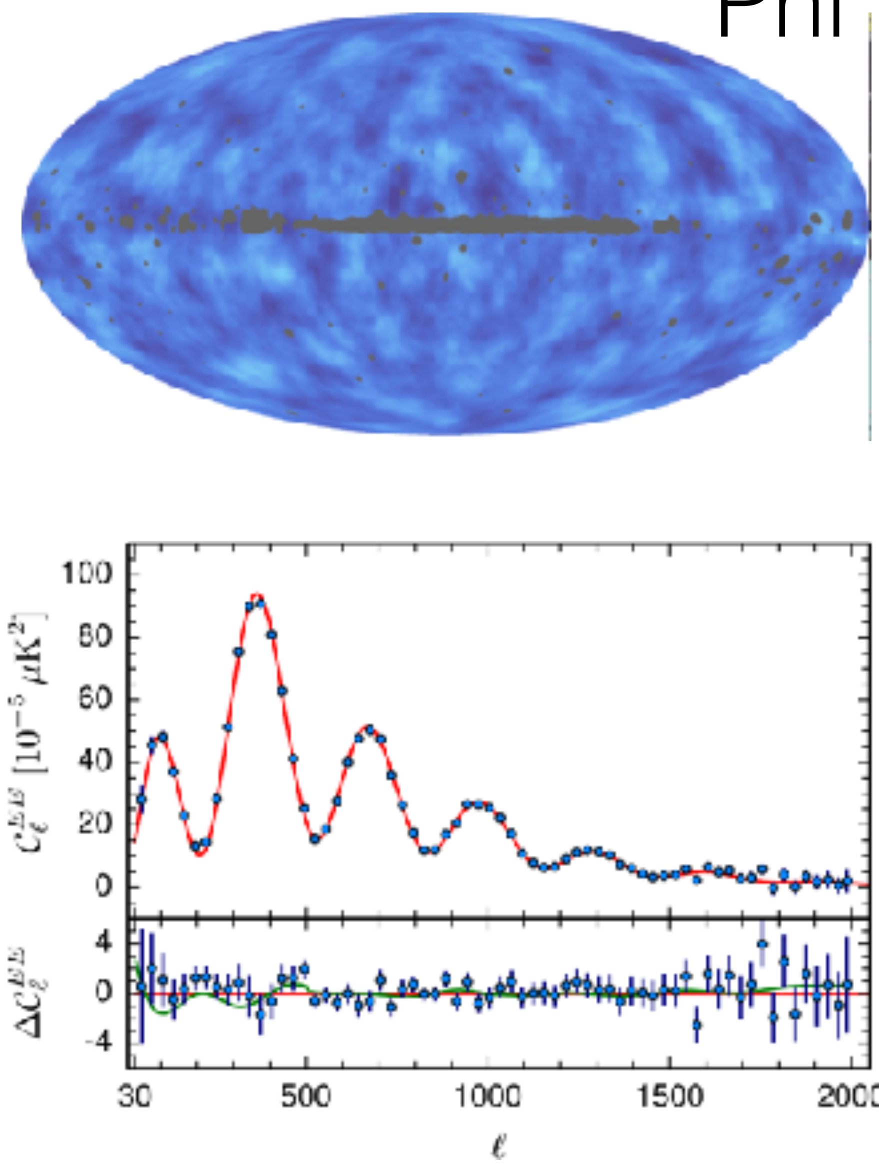
T



P



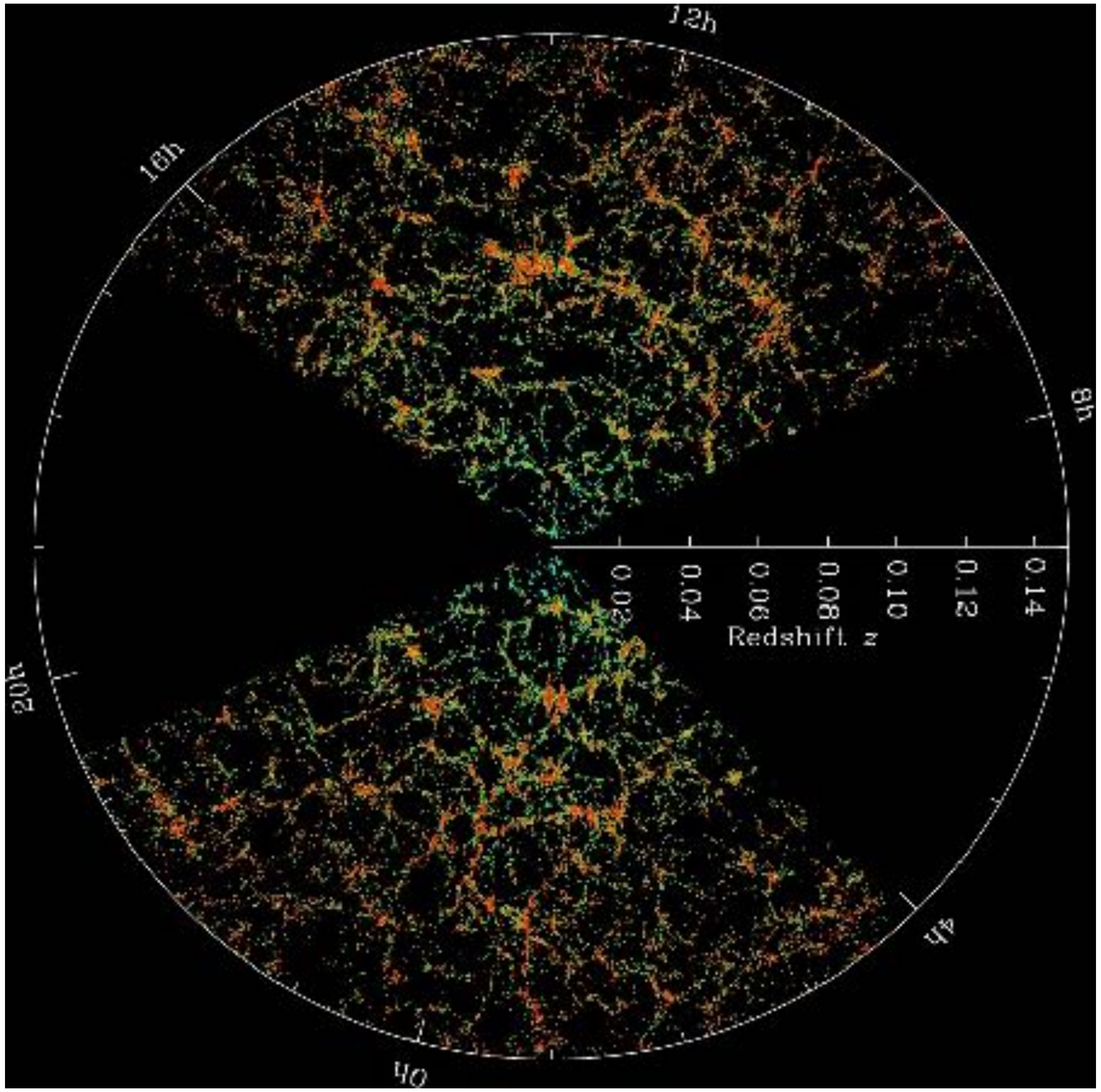
Phi

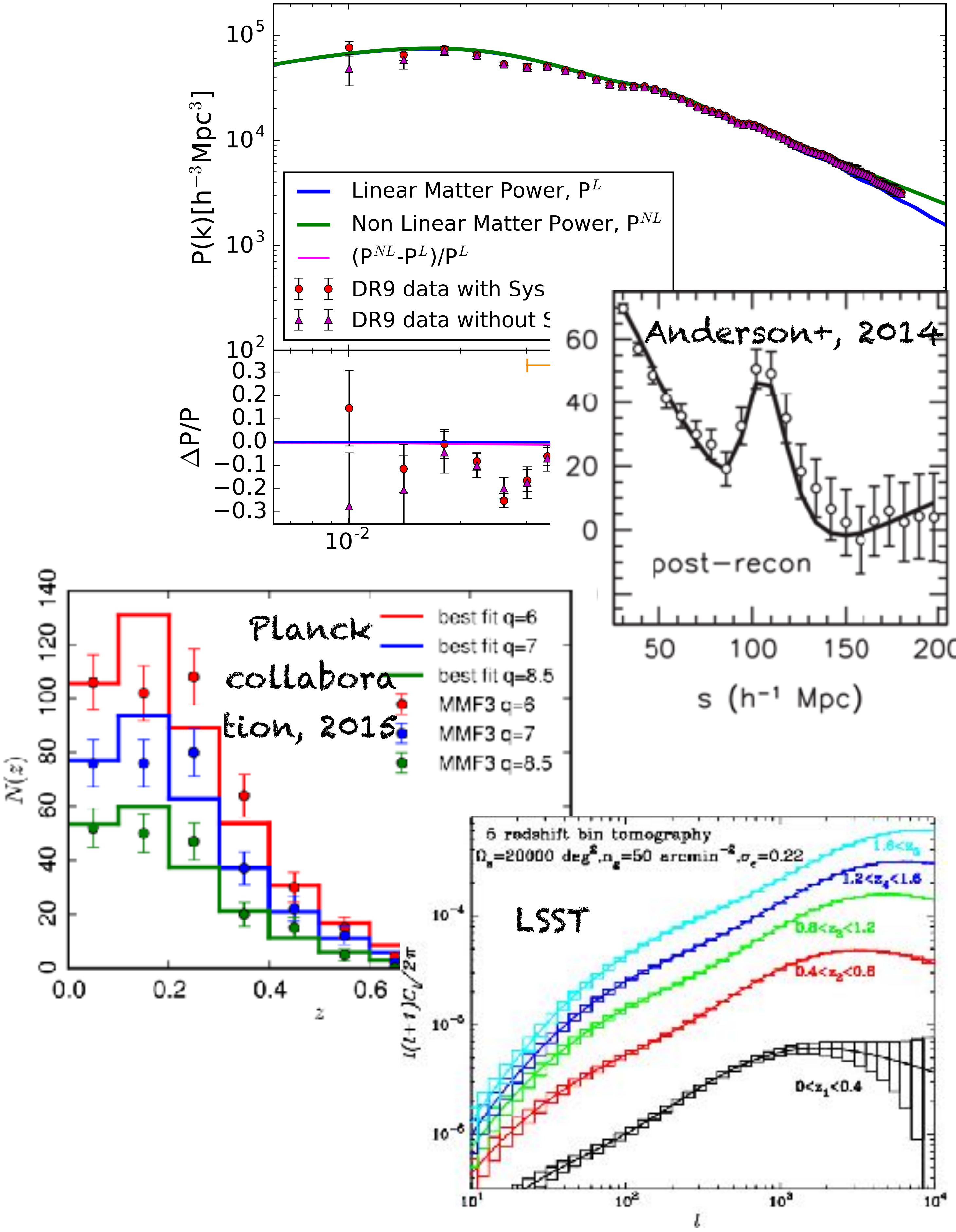


Planck collaboration

What we observe

SDSS-BOSS collaboration





Anderson+, 2014

Planck collaboration, 2015

LSST

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

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

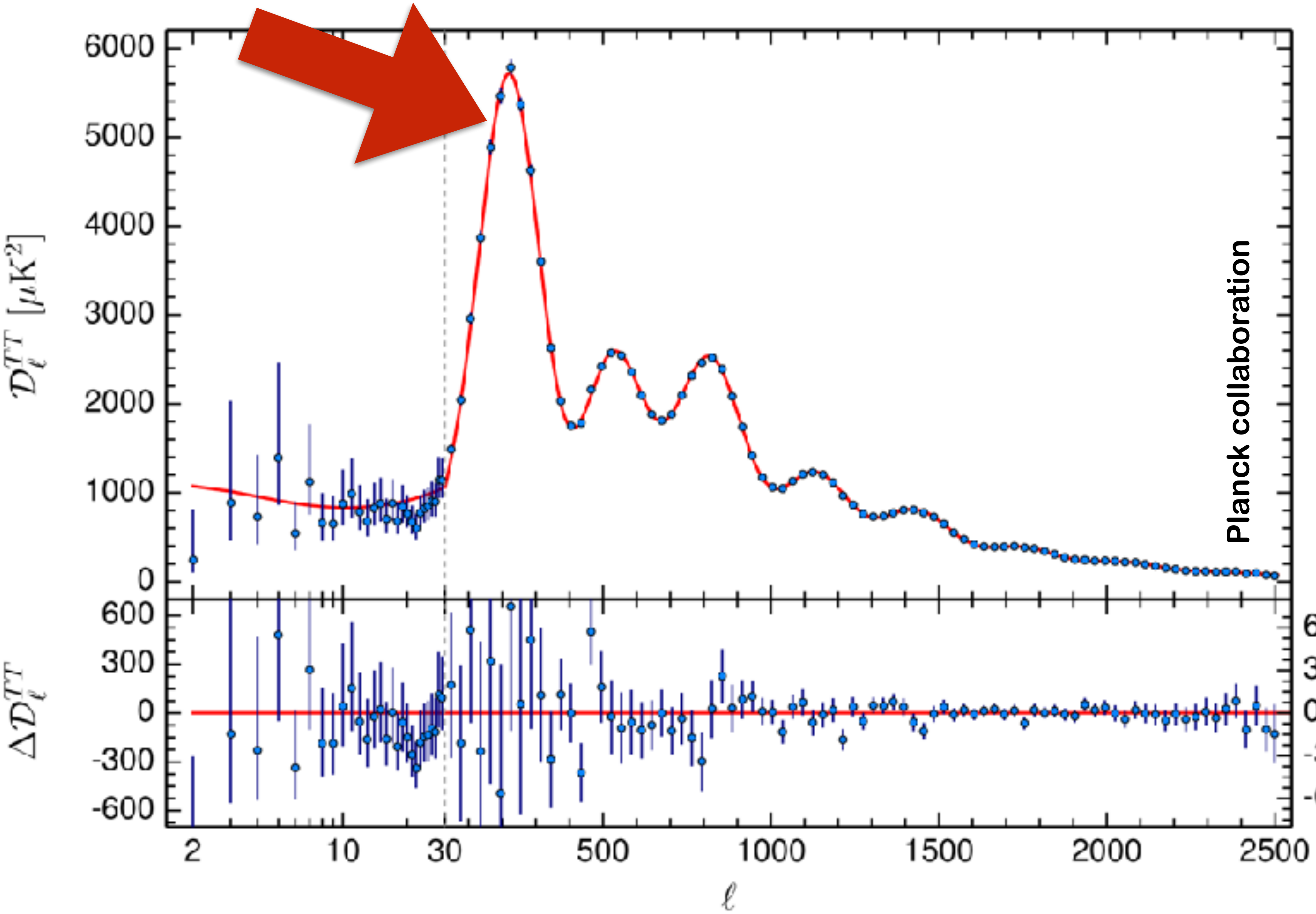
Suppressed growth

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

Acoustic phase shift

Effects on the CMB spectrum

sound horizon at recombination
matter-equality

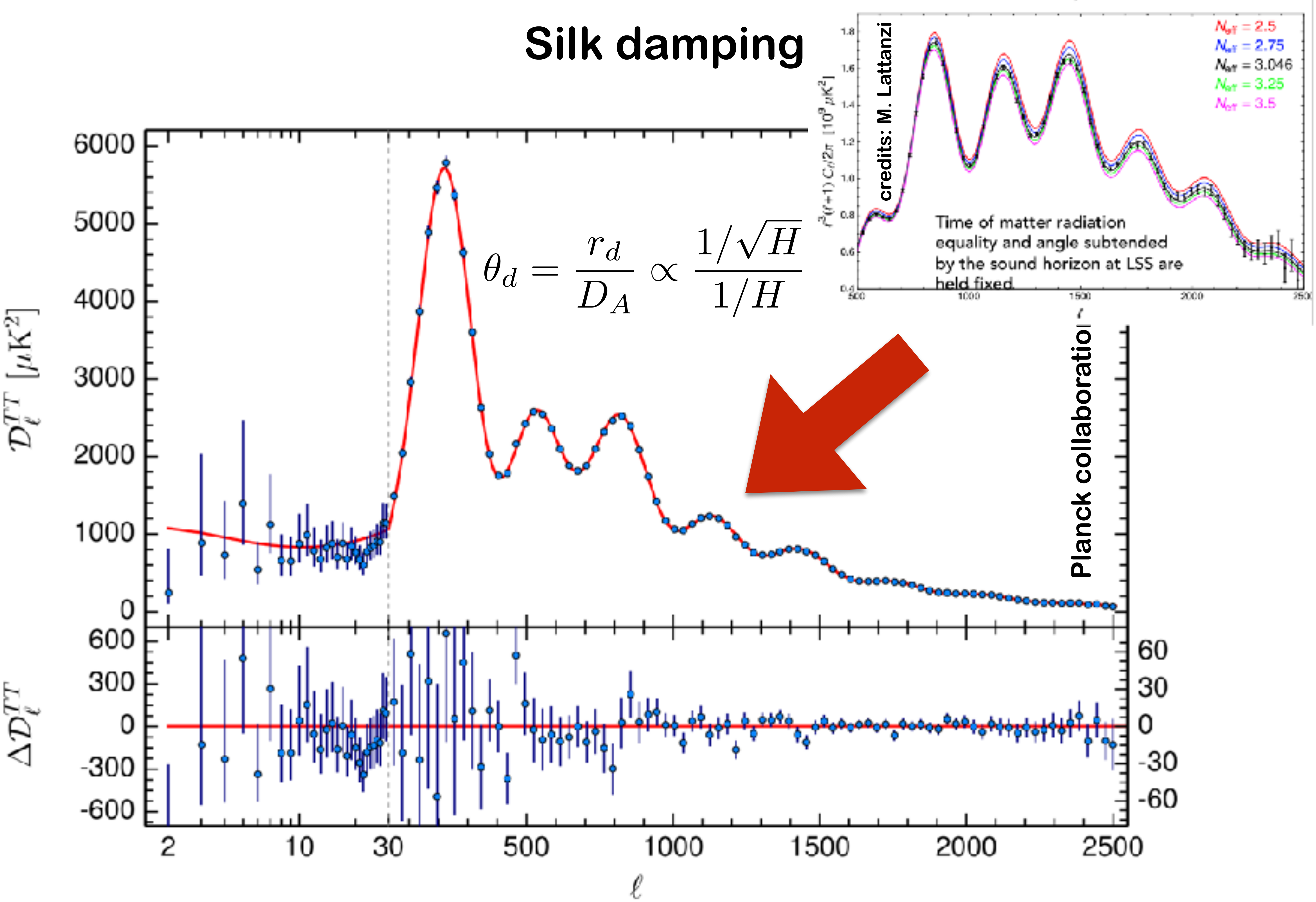


Effects on the CMB spectrum

Hou et al, 2014

Silk damping

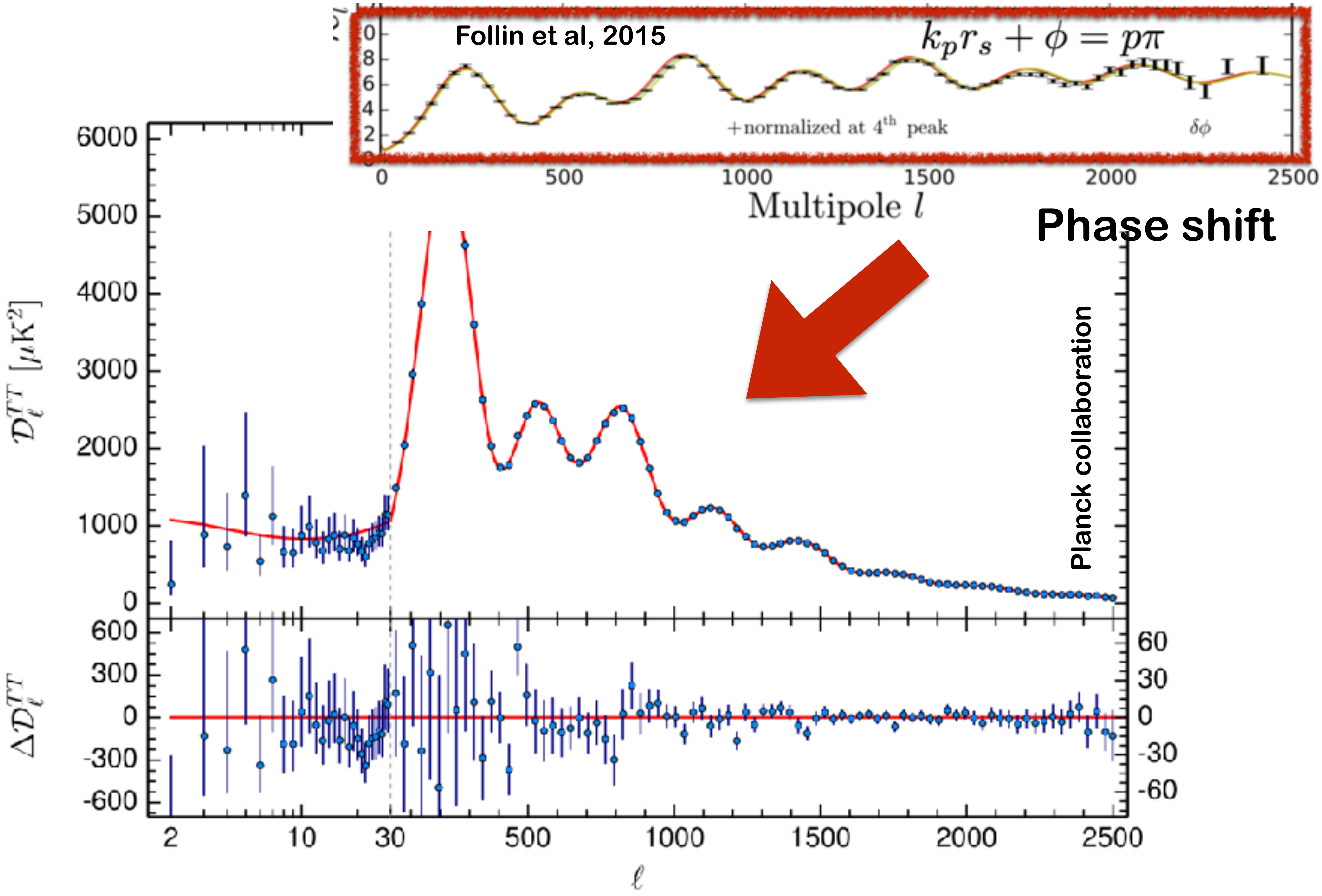
$$\theta_d = \frac{r_d}{D_A} \propto \frac{1/\sqrt{H}}{1/H}$$



credits: M. Lattanzi

Planck collaboration

Effects on the CMB spectrum



Follin et al, 2015

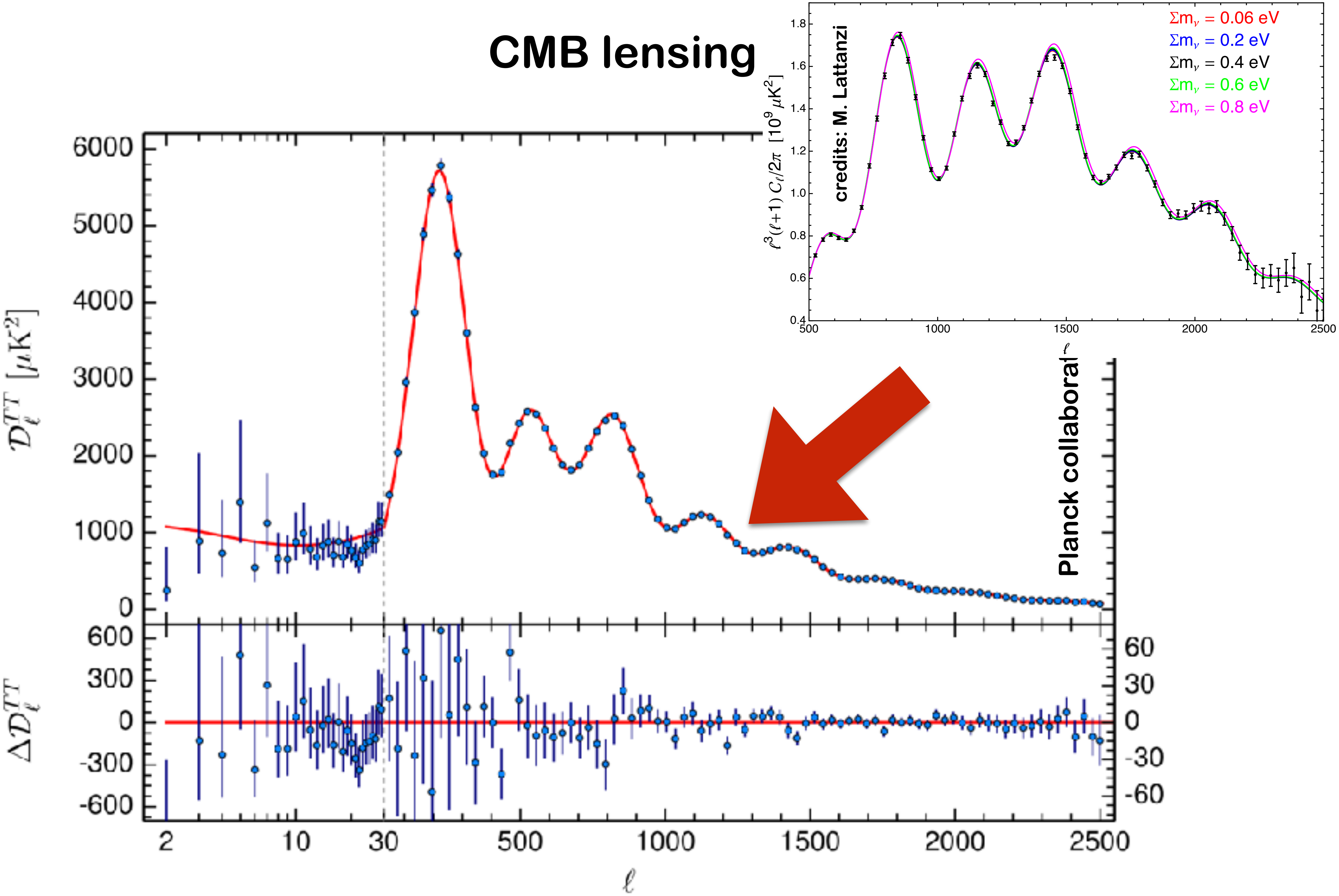
$$k_p r_s + \phi = p\pi$$

Phase shift

Planck collaboration

Effects on the CMB spectrum

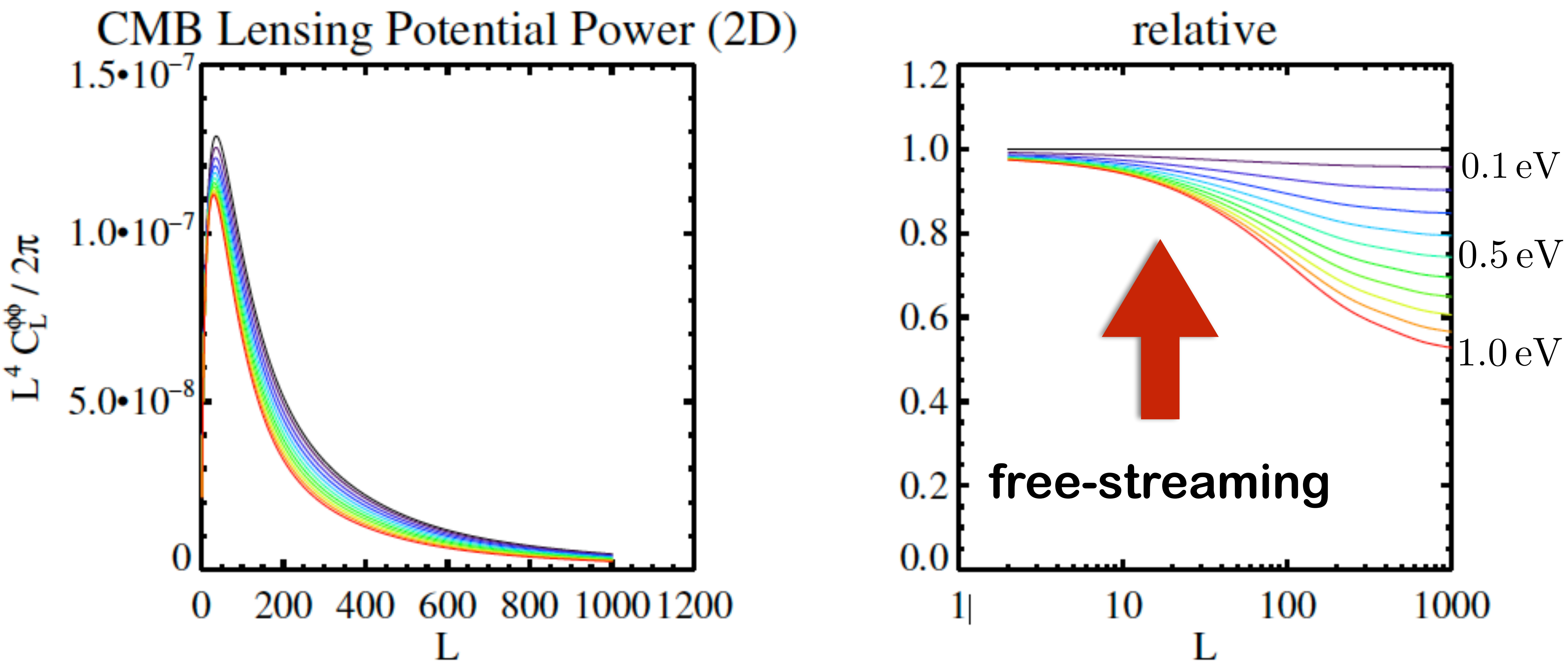
CMB lensing



credits: M. Lattanzi

Planck collabora

Effects on the lensing spectrum

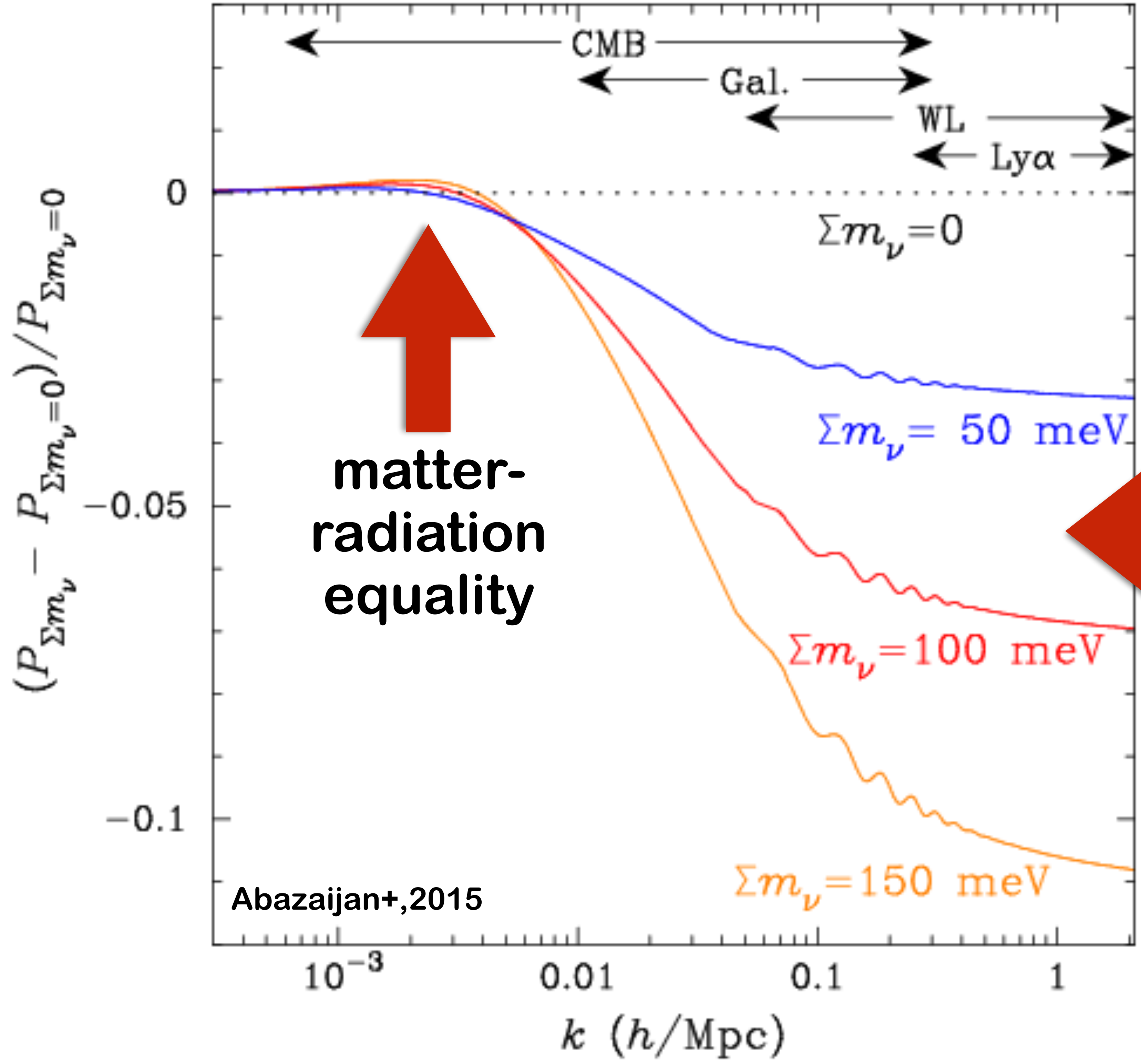


Lensing reconstruction is also crucial to delens CMB spectra

Sharper peaks improves limits on Neff

Stage-IV Science Book

Effects on the matter spectrum

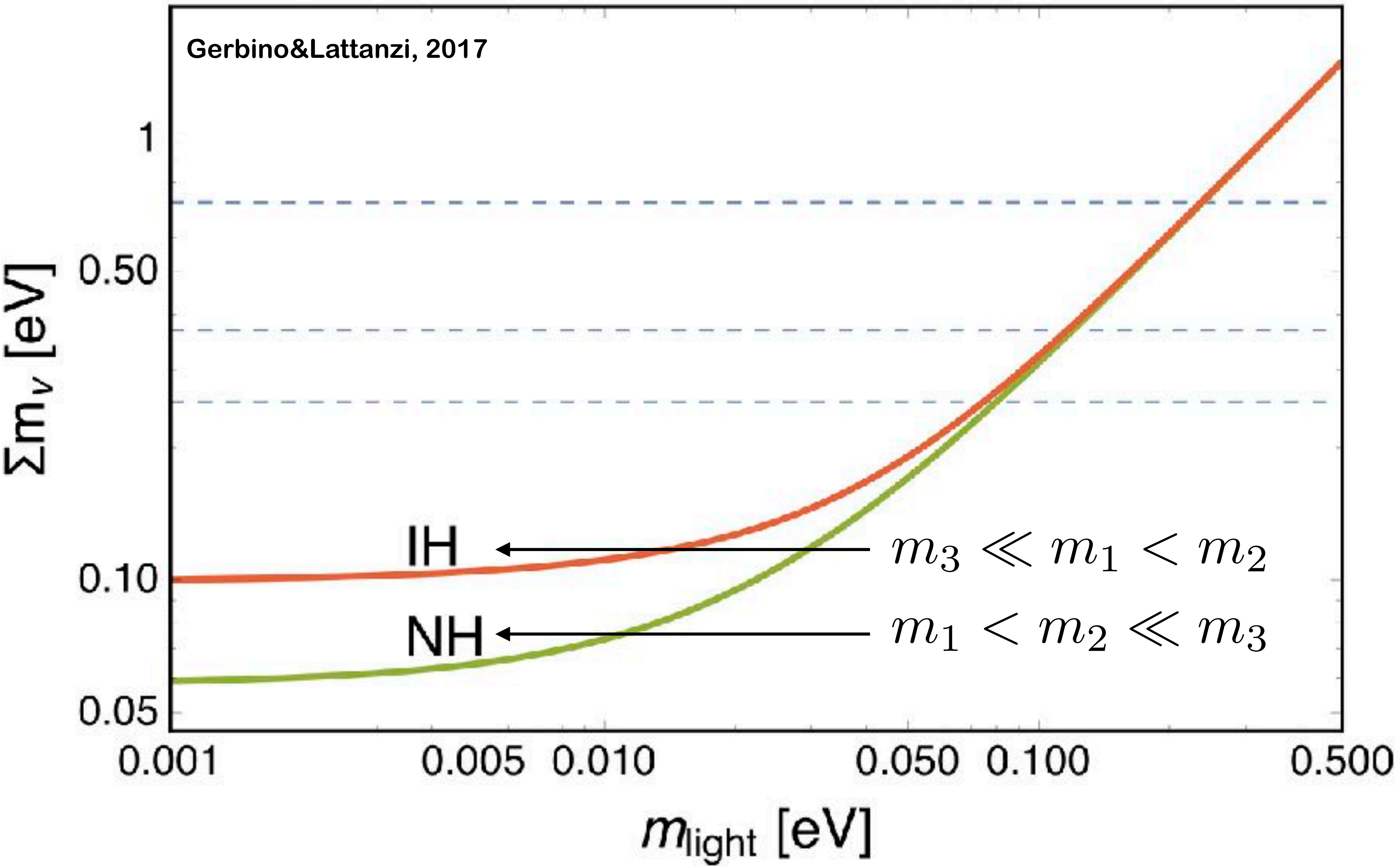


Abazaijan+,2015

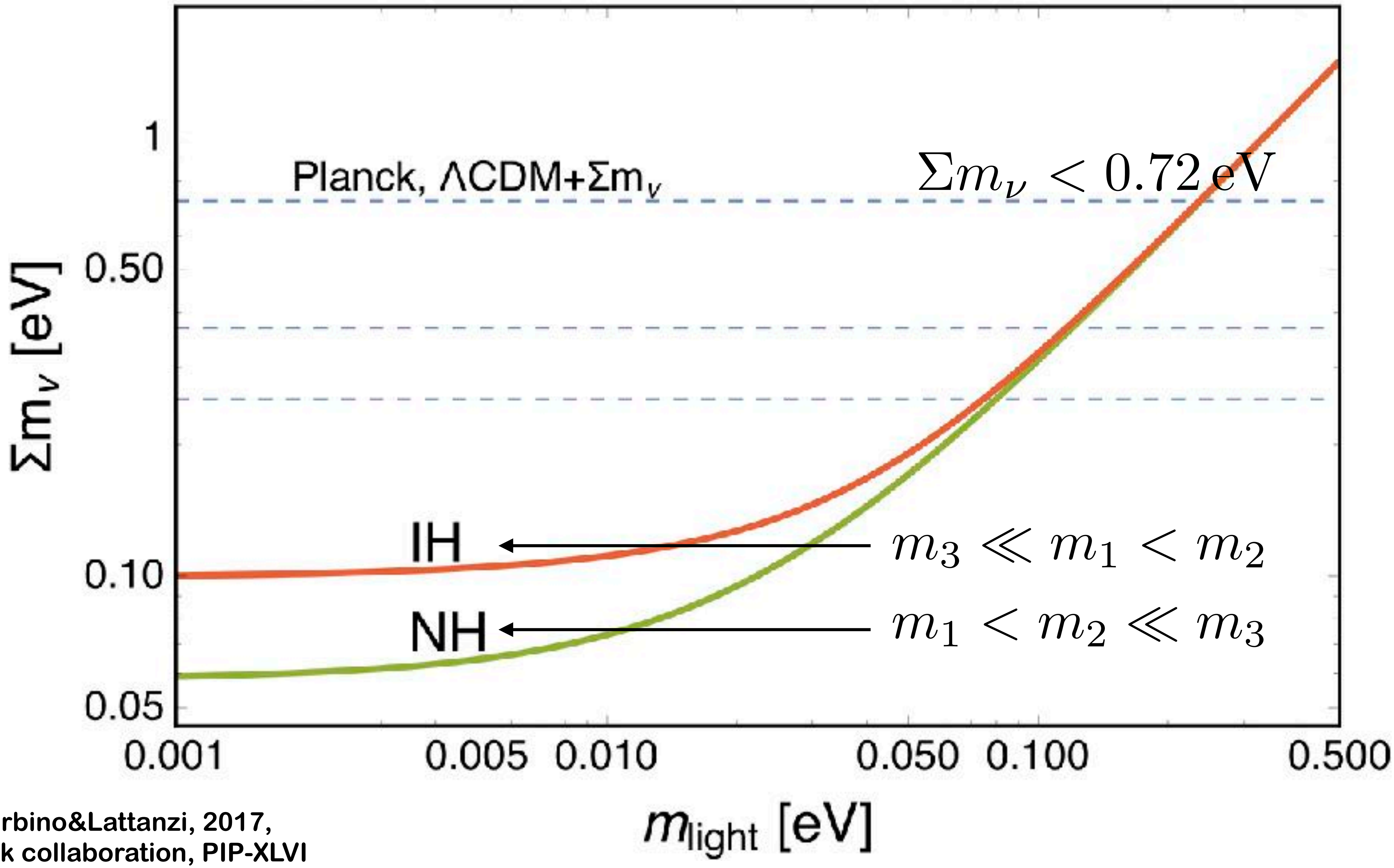
matter-radiation equality

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

Current limits on the neutrino mass scale

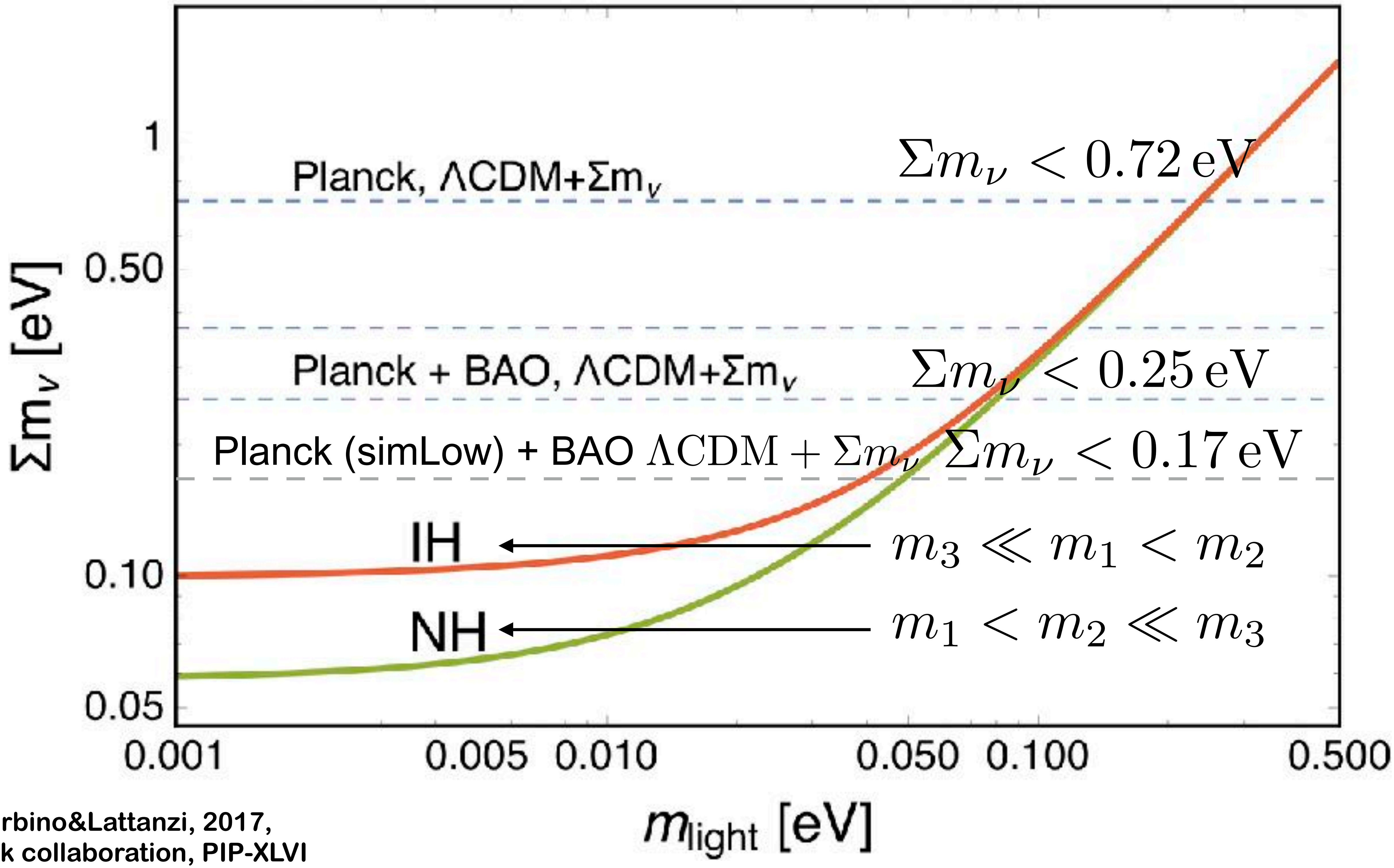


Current limits on the neutrino mass scale



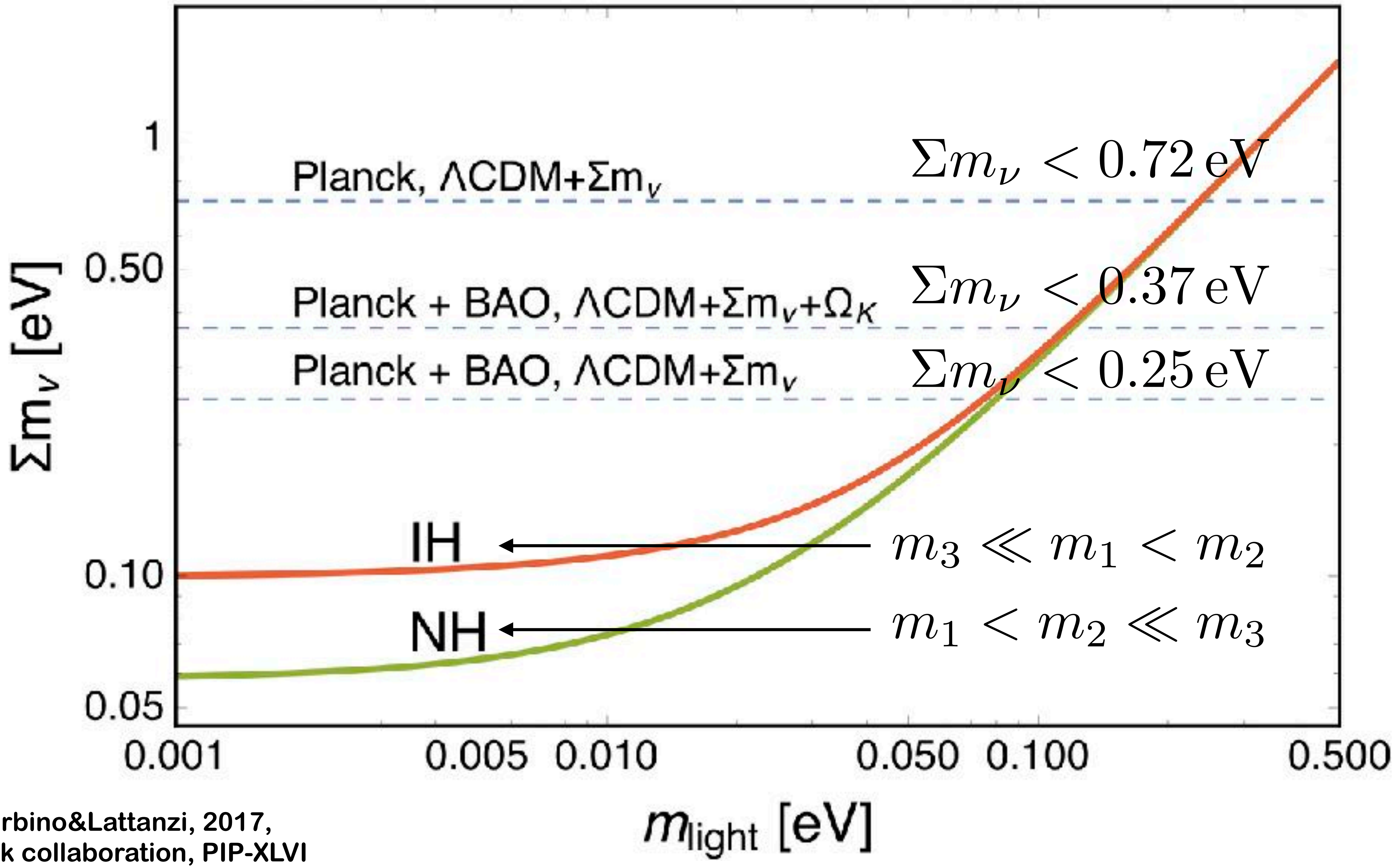
Gerbino&Lattanzi, 2017,
Planck collaboration, PIP-XLVI
Planck collaboration, AXIII

Current limits on the neutrino mass scale



Gerbino&Lattanzi, 2017,
Planck collaboration, PIP-XLVI
Planck collaboration, AXIII

Current limits on the neutrino mass scale



$\Sigma m_\nu < 0.72\,\mathrm{eV}$

$\Sigma m_\nu < 0.37\,\mathrm{eV}$

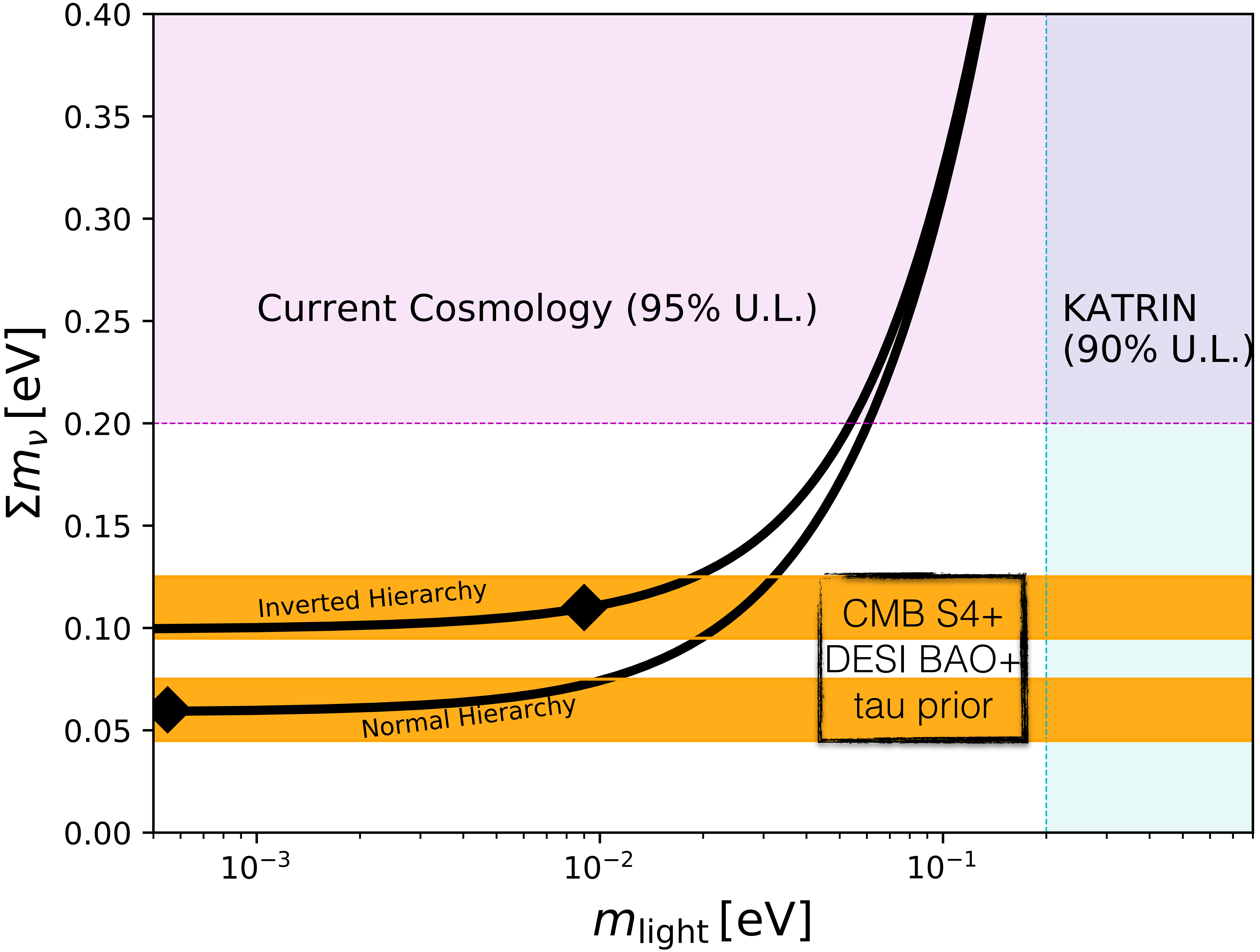
$\Sigma m_\nu < 0.25\,\mathrm{eV}$

$m_3 \ll m_1 < m_2$

$m_1 < m_2 \ll m_3$

Gerbino&Lattanzi, 2017,
Planck collaboration, PIP-XLVI
Planck collaboration, AXIII

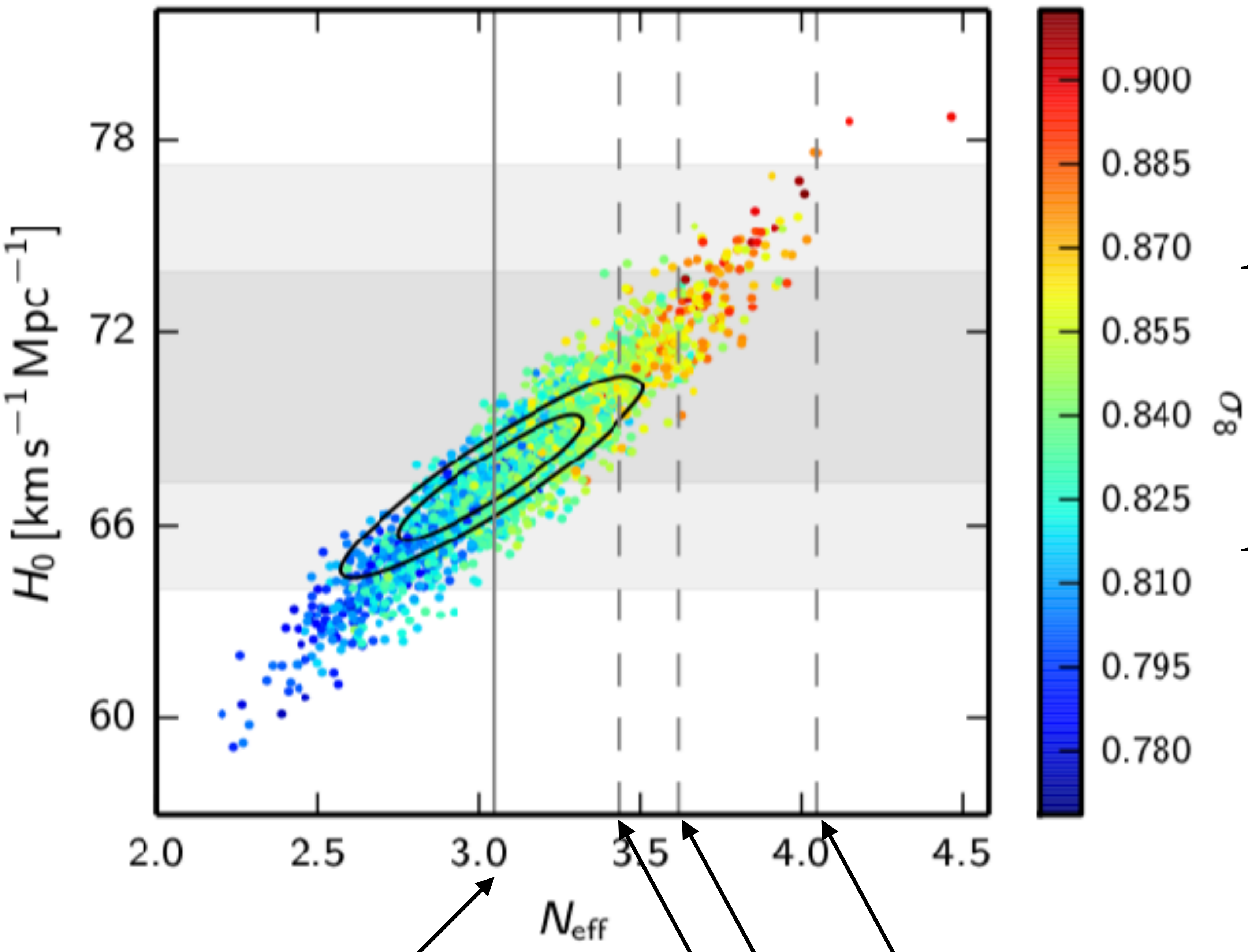
Future - Massive neutrinos



Adapted from CMB Stage-IV white paper

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

Current limits on Neff



Standard value

Fully-thermalized additional species

Planck

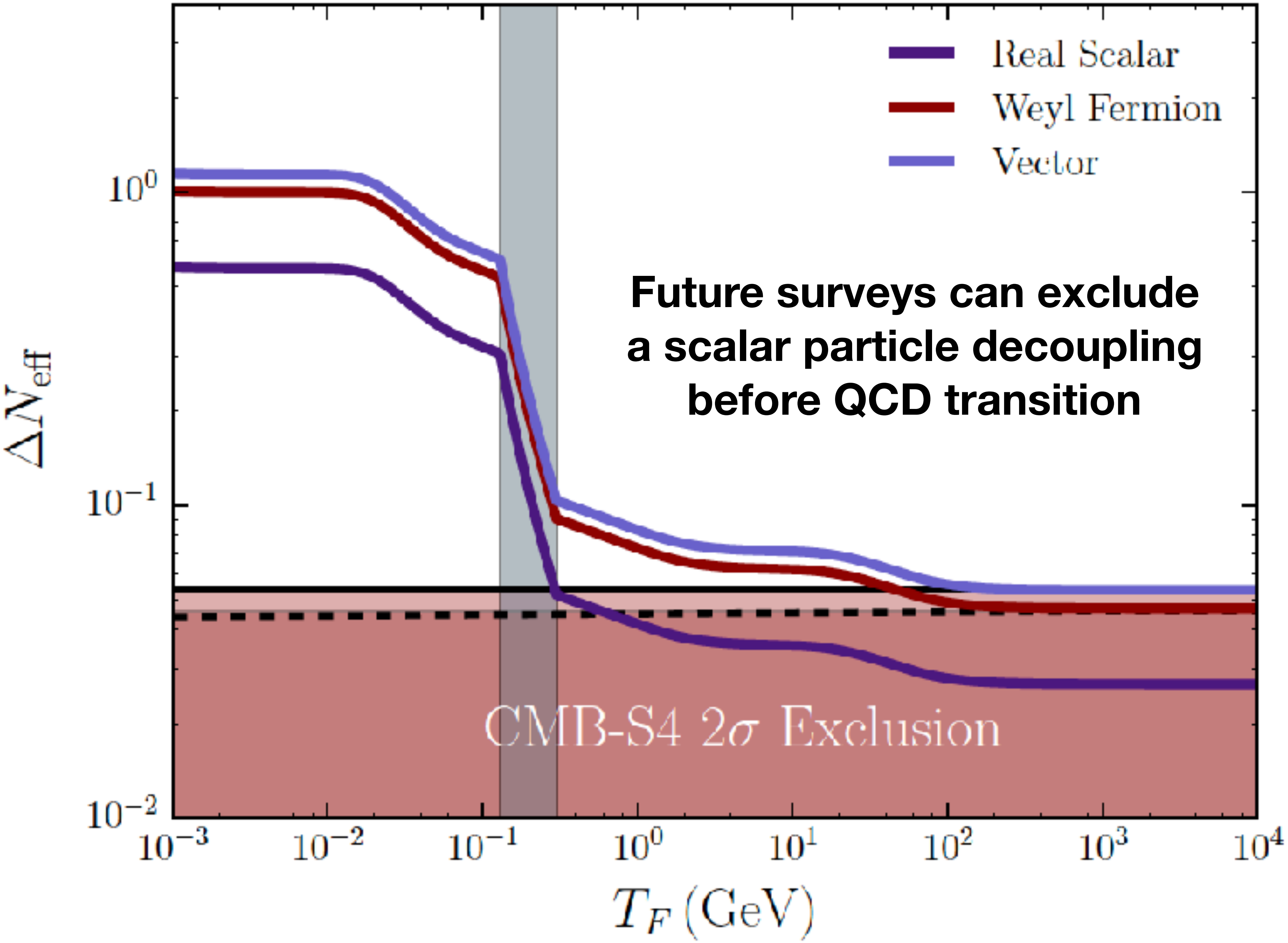
$$N_{\mathrm{eff}} = 3.13 \pm 0.32$$

Planck+BAO

$$N_{\mathrm{eff}} = 3.15 \pm 0.23$$

Planck collaboration, XIII

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

CONCLUSIONS

Determine CnB properties from neutrino peculiar effects on cosmological observables

Strong and robust constraints from cosmology

Neutrino masses: getting closer to the non-degenerate region
Neff: no preference for an additional thermalised species

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

BACKUP SLIDES

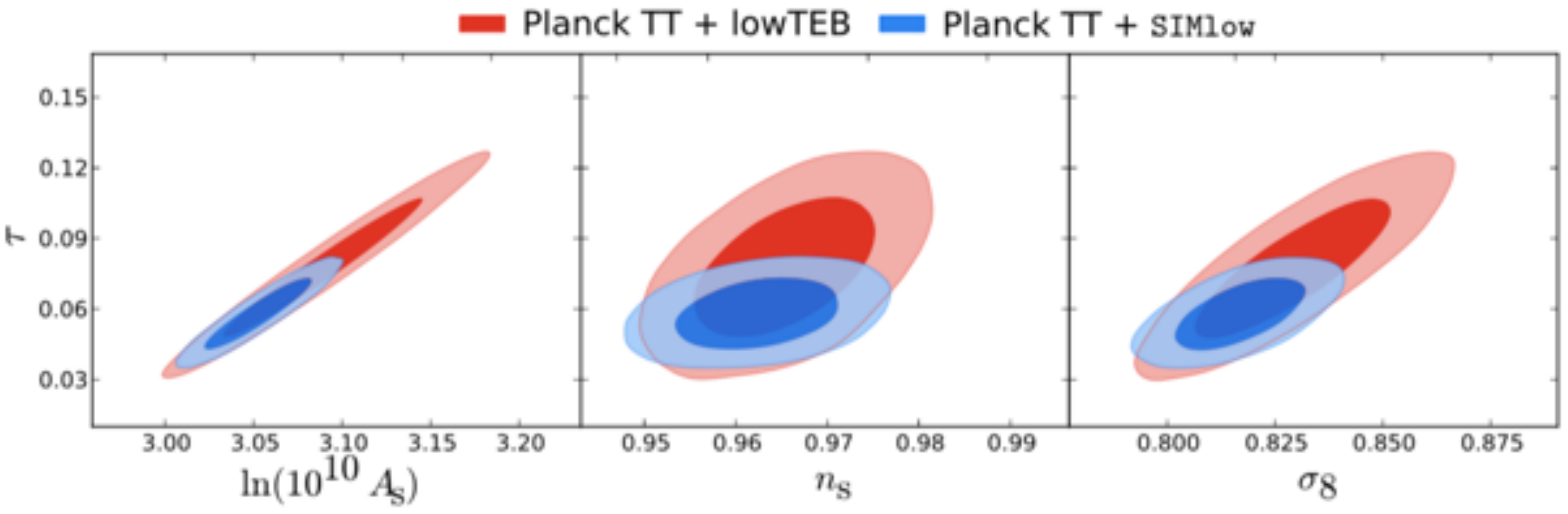
Model assumptions

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

Towards Planck 2018 results

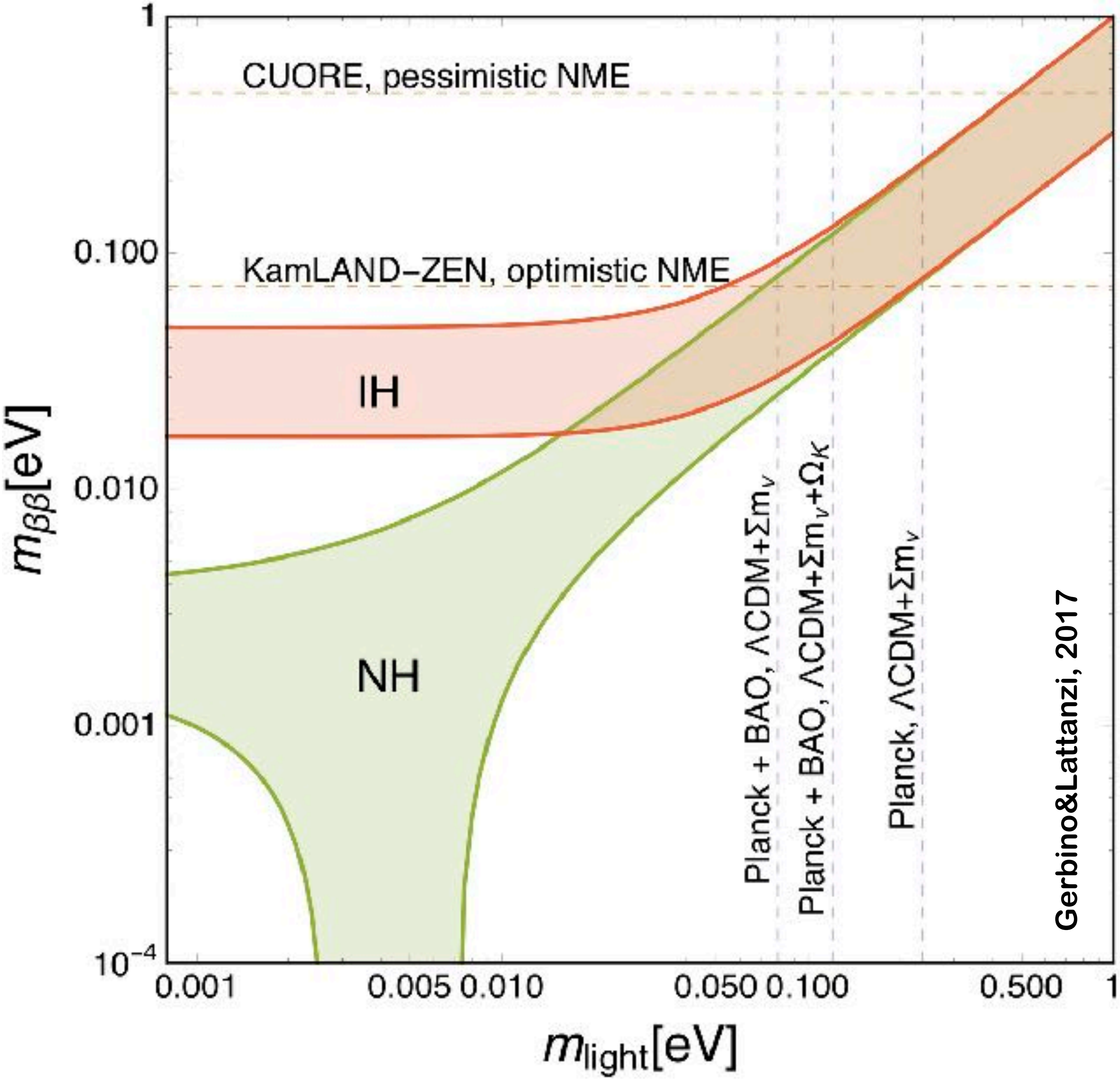
Parameter	PlanckTT+lowP 95% limits	PlanckTT+SIMlow 95% limits	PlanckTTTEEE+lowP 95% limits	PlanckTTTEEE+SIMlow 95% limits
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.053^{+0.044}_{-0.046}$	$-0.040^{+0.038}_{-0.041}$	$-0.039^{+0.032}_{-0.034}$
Σm_ν [eV]	<0.715	<0.585	<0.492	<0.340
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$2.97^{+0.58}_{-0.53}$	$2.99^{+0.41}_{-0.39}$	$2.91^{+0.39}_{-0.37}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.242^{+0.039}_{-0.040}$	$0.250^{+0.026}_{-0.027}$	$0.244^{+0.026}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.014}_{-0.014}$	$-0.003^{+0.014}_{-0.013}$
$r_{0.002}$	<0.103	<0.111	<0.0987	<0.111
w	$-1.54^{+0.62}_{-0.50}$	$-1.57^{+0.61}_{-0.49}$	$-1.55^{+0.58}_{-0.48}$	$-1.59^{+0.58}_{-0.46}$
$A_{\rm L}$	$1.22^{+0.21}_{-0.20}$	$1.23^{+0.20}_{-0.18}$	$1.15^{+0.16}_{-0.15}$	$1.15^{+0.13}_{-0.12}$



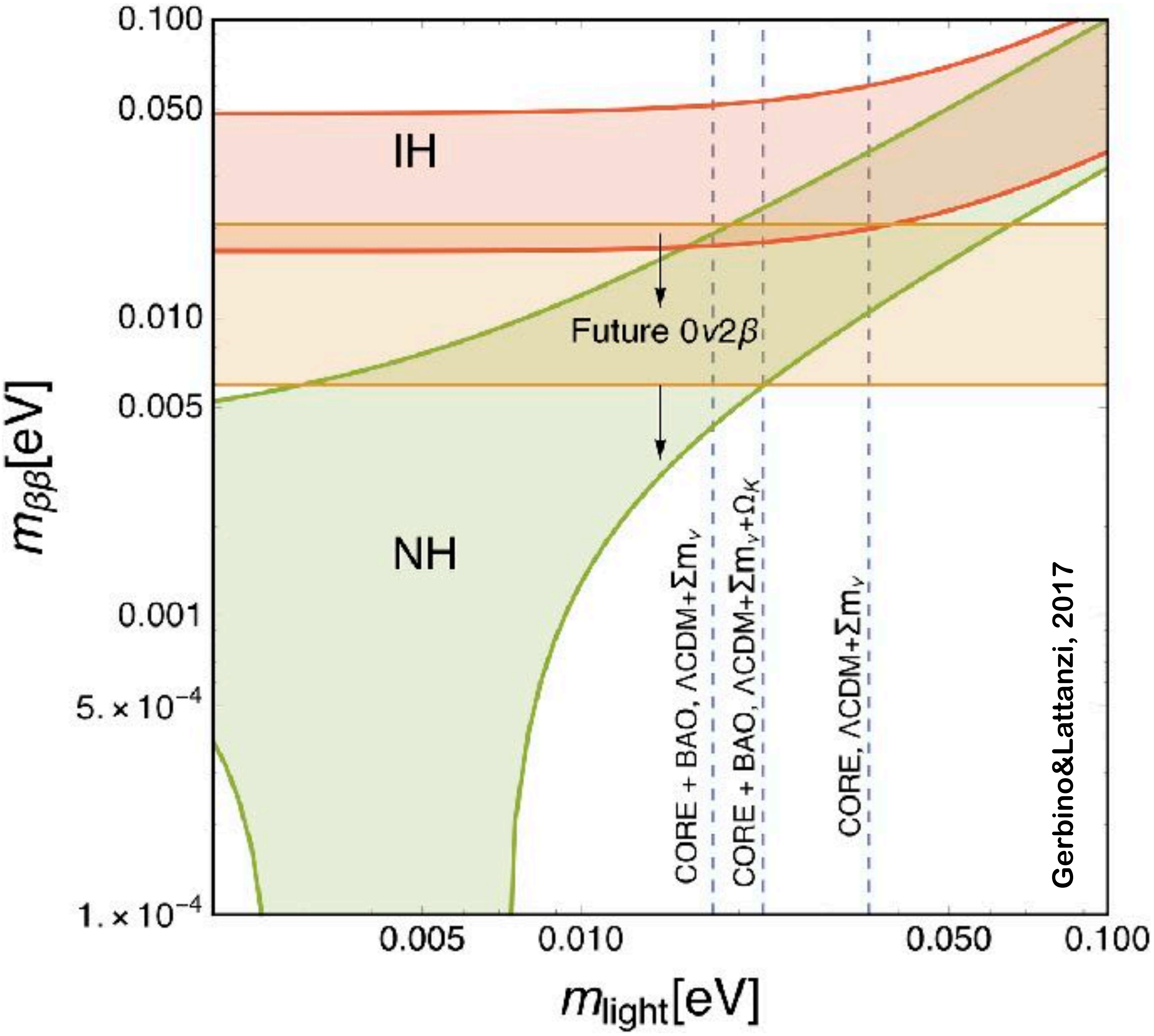
Planck collaboration, PIP-XLVI

Improved polarisation data
Refined measurements of the reionisation optical depth tau

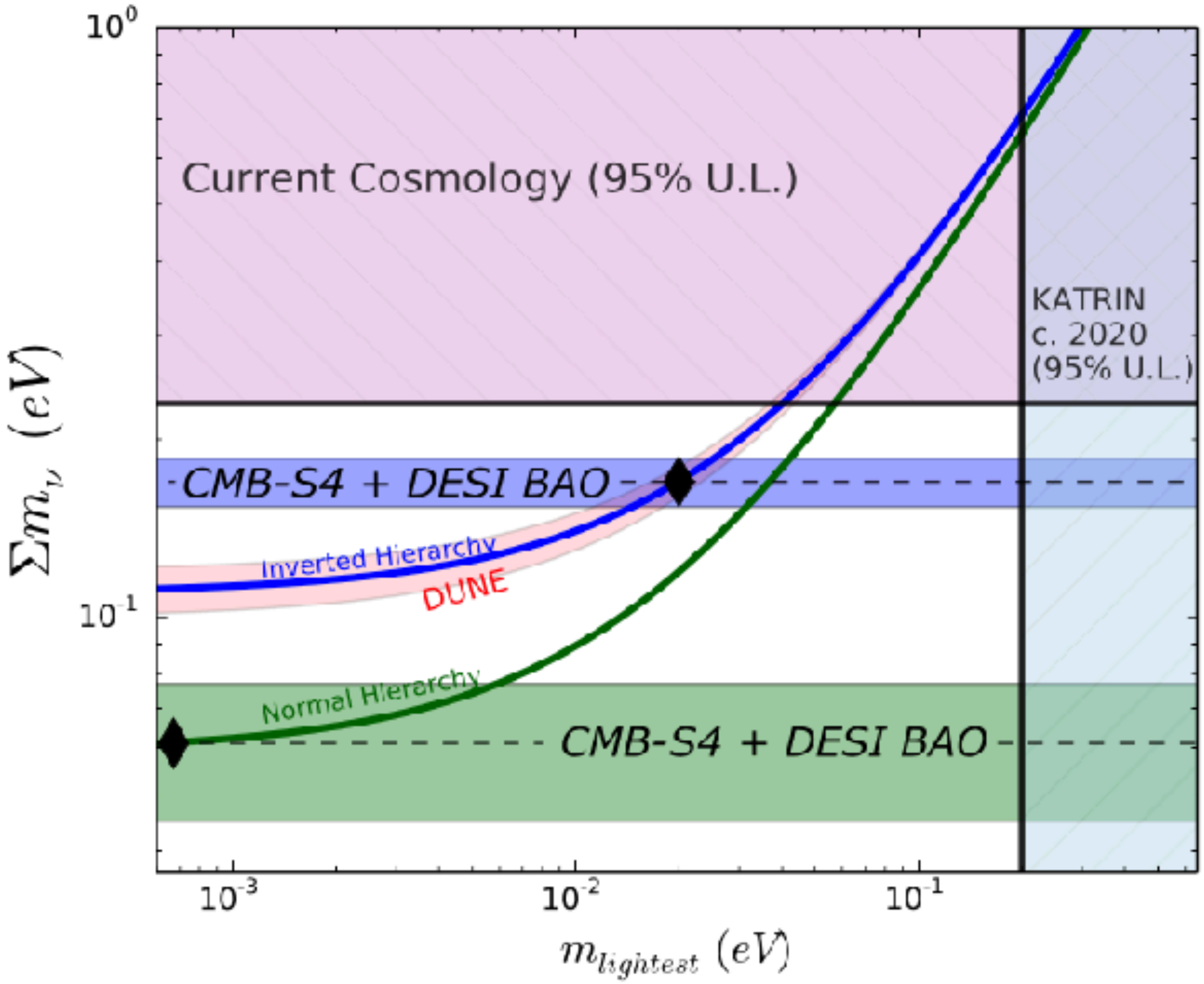
Complementarity with laboratory searches



Complementarity with laboratory searches



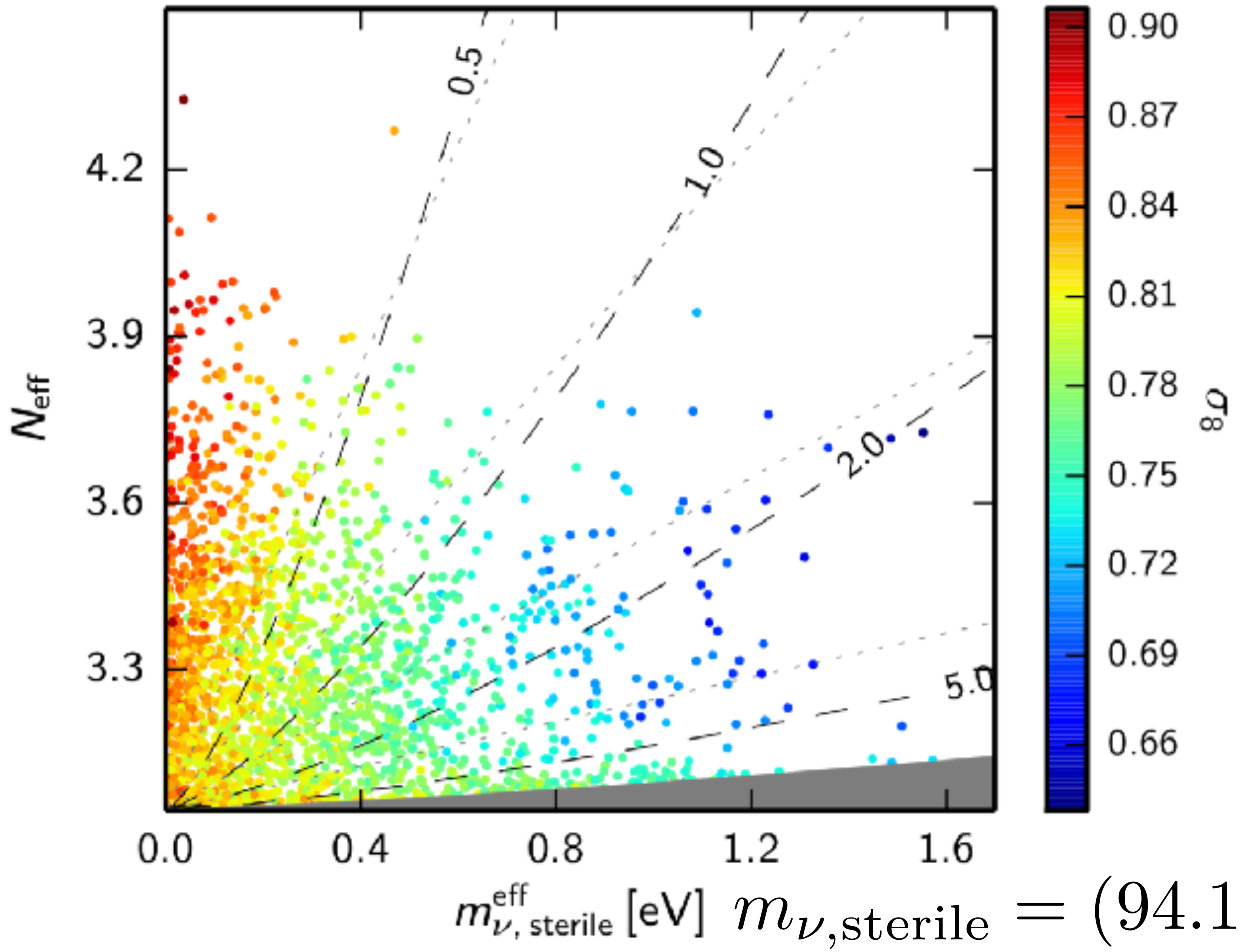
Joint constraints on Mnu - future



CMB-S4 Science Book

~3sigma detection
in the minimal mass scenario with S4 surveys

Current limits on sterile neutrinos



Planck+lensing +BAO 95%CL

$$N_{\rm eff} < 3.7$$

$$m_{\nu,\rm sterile}^{\rm eff} < 0.38$$

Planck collaboration, XIII

$$m_{\nu,\rm sterile} = (94.1\,\Omega_{\nu,\rm sterile}\,h^2)\,\rm eV$$

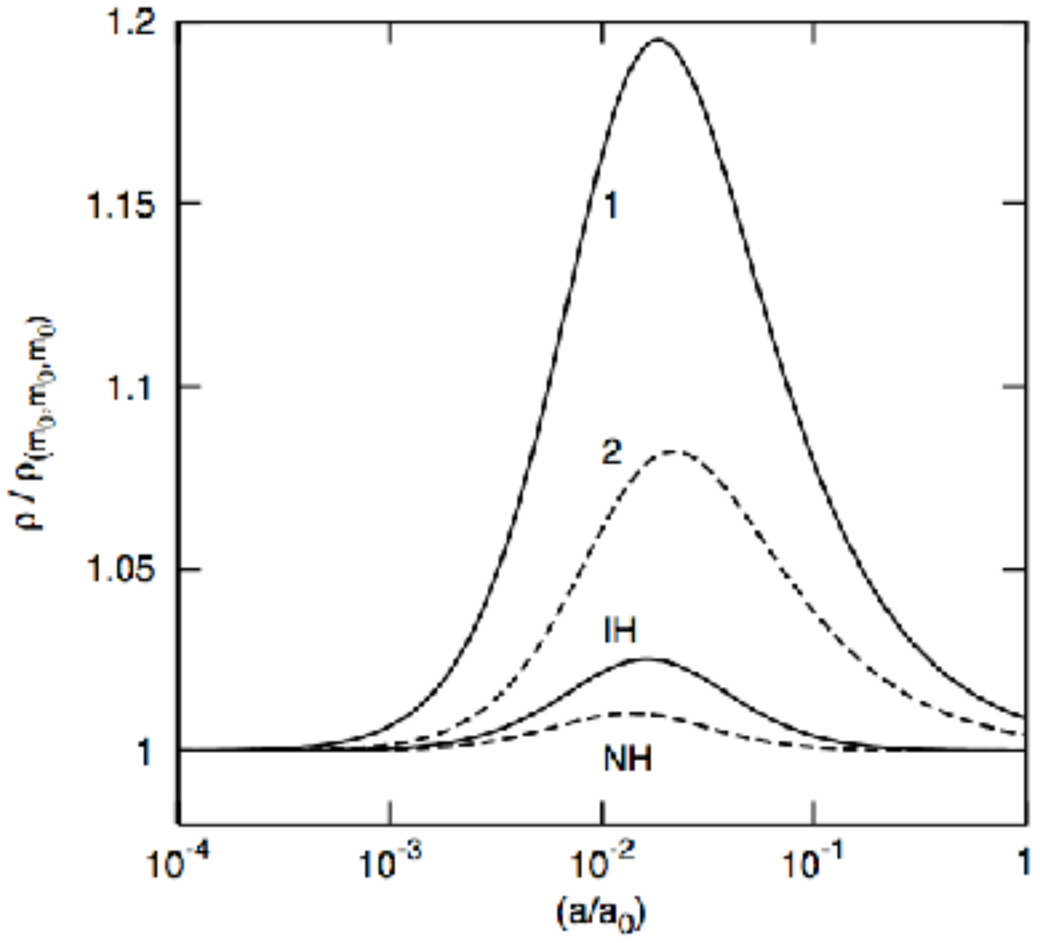
$$m_{\nu,\rm sterile} = (\Delta N_{\rm eff})^{3/4} m_{\rm sterile}^{\rm thermal}$$ **thermally distributed (dashed)**

$$m_{\nu,\rm sterile} = \Delta N_{\rm eff}\, m_{\rm sterile}^{\rm DW}$$ **Dodelson-Widrow (dotted)**

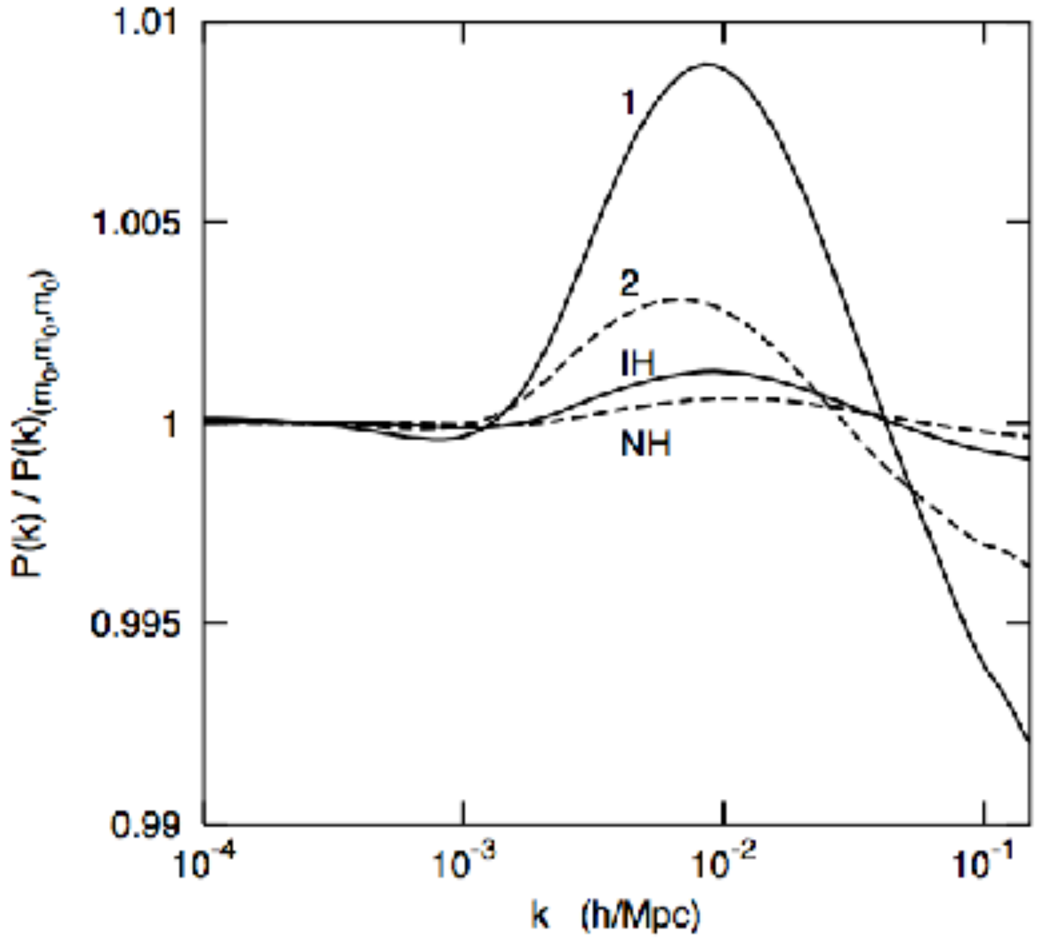
Sensitivity to the hierarchy

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

Total nu energy density



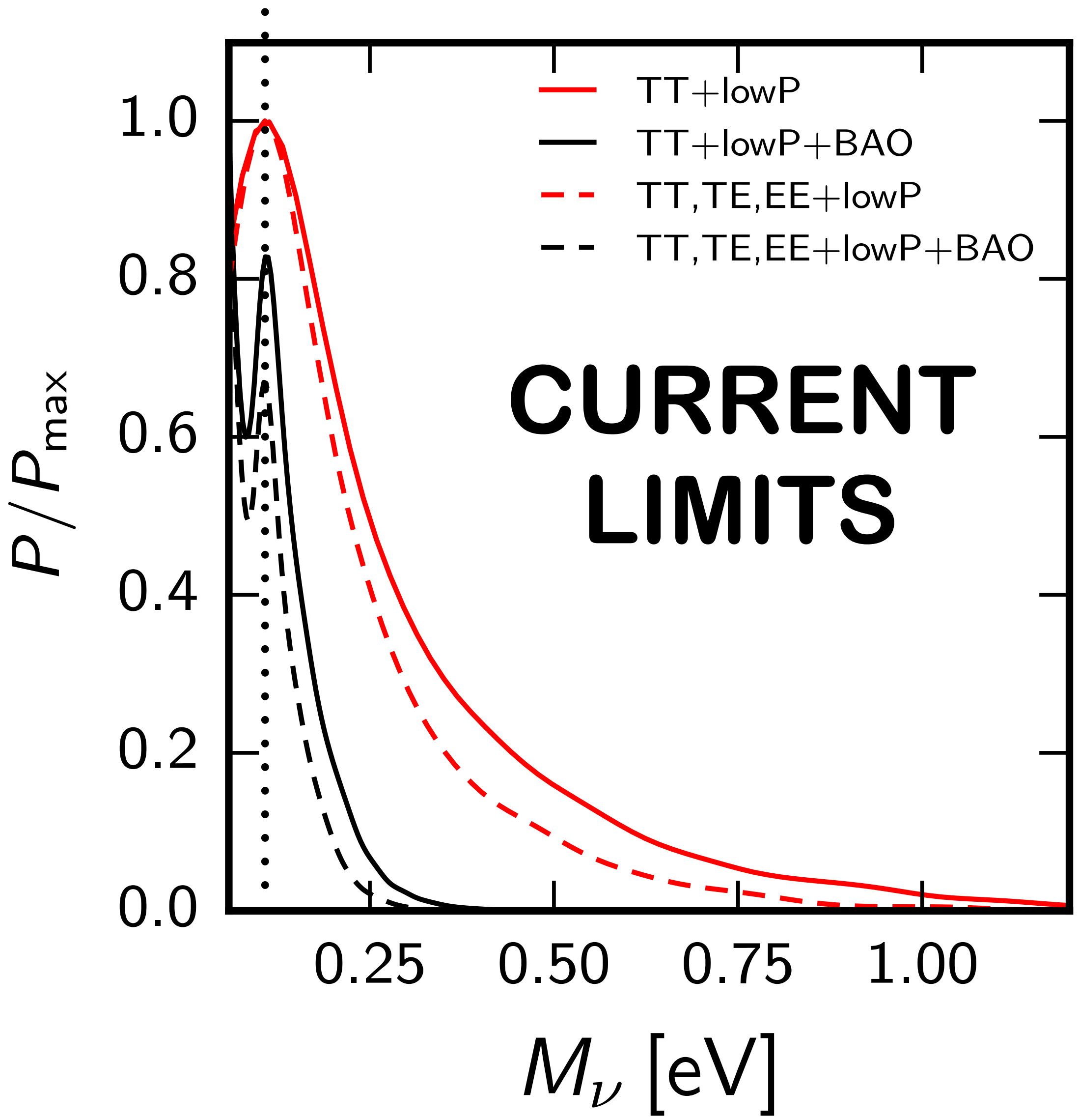
Matter power spectrum



Lesgourgues&Pastor, 2006

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

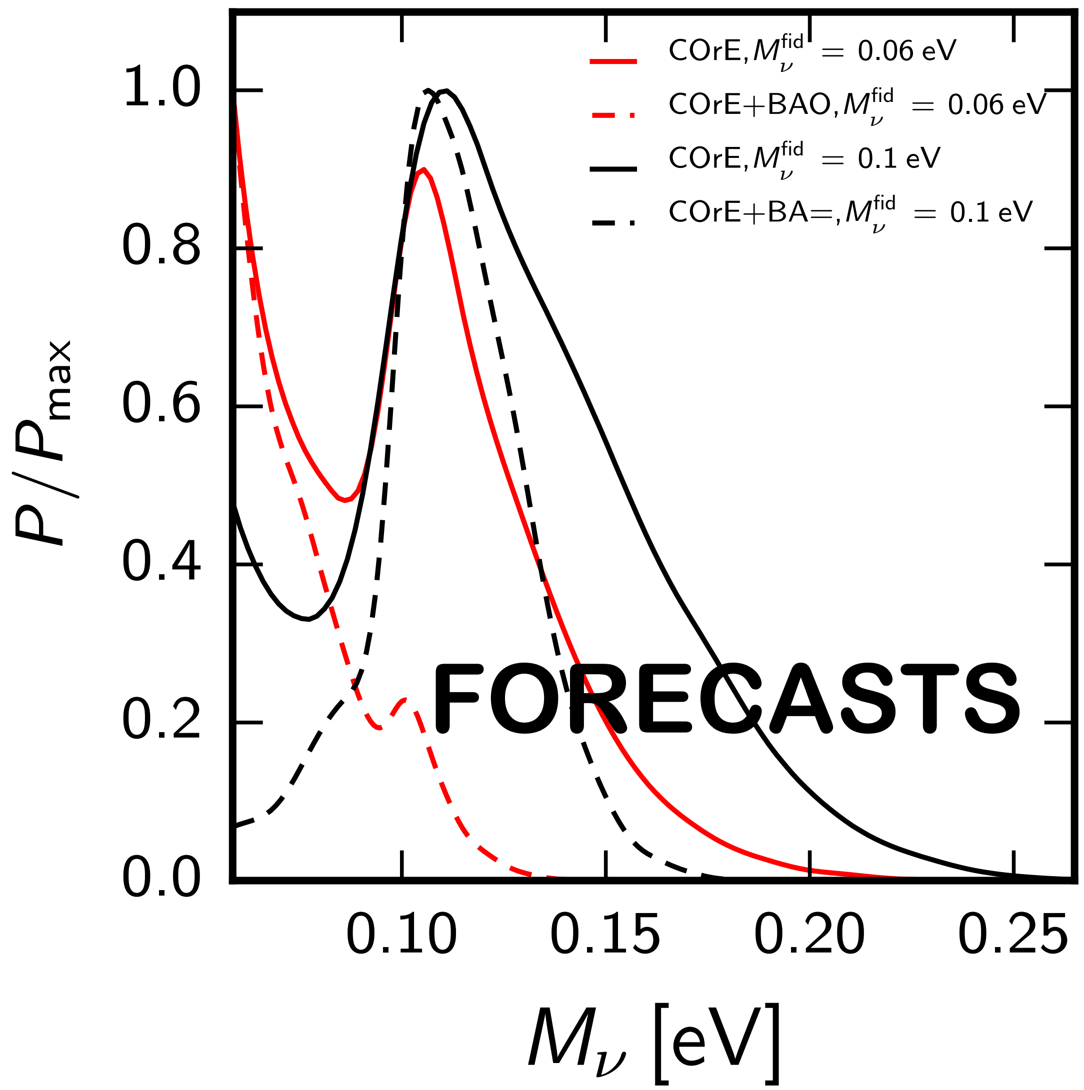
Sensitivity to the hierarchy



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

.... **3:2**

See also Hannestad&Schwetz,2016



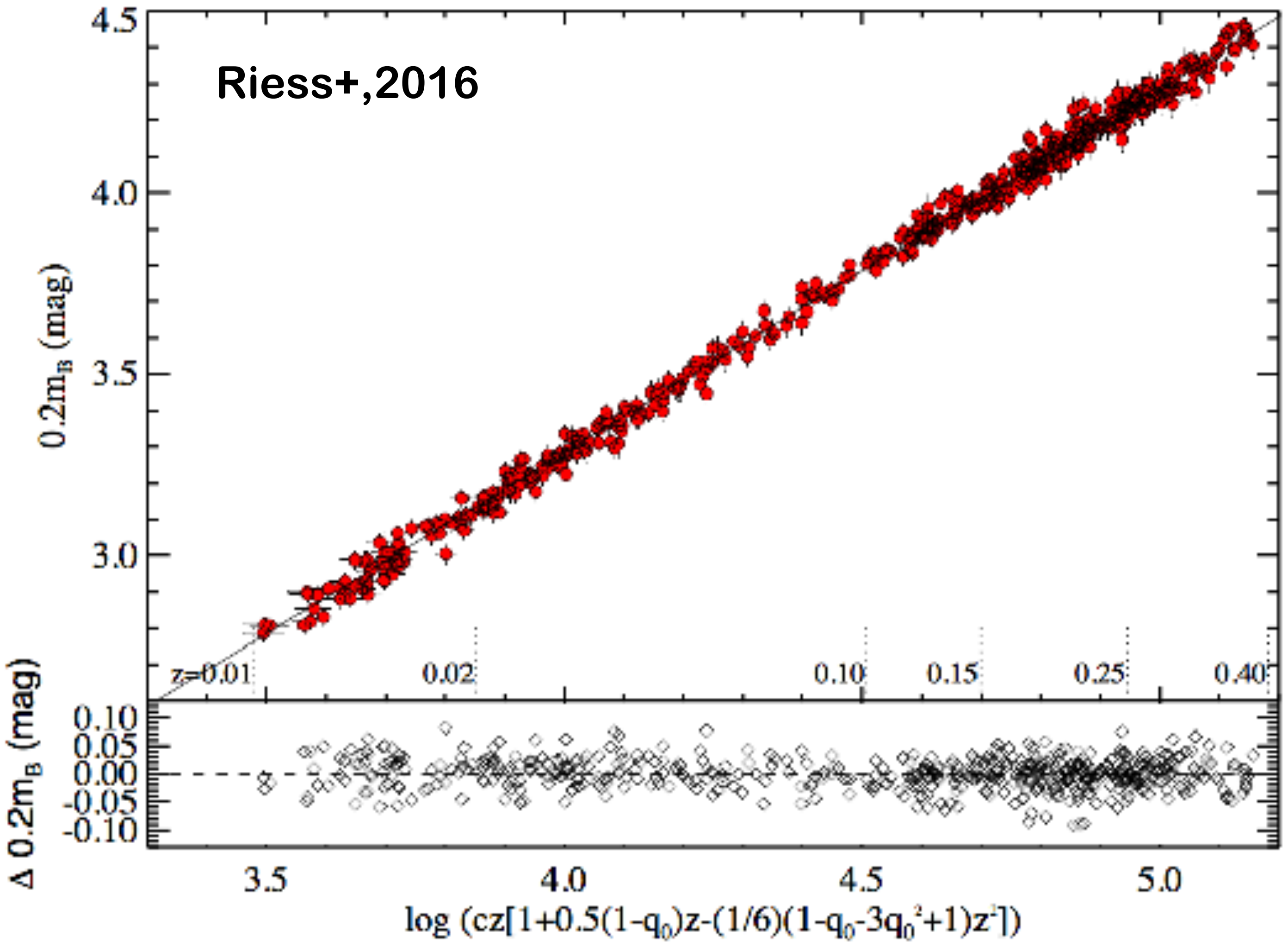
Gerbino,Lattanzi,Mena,Freese 2016

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

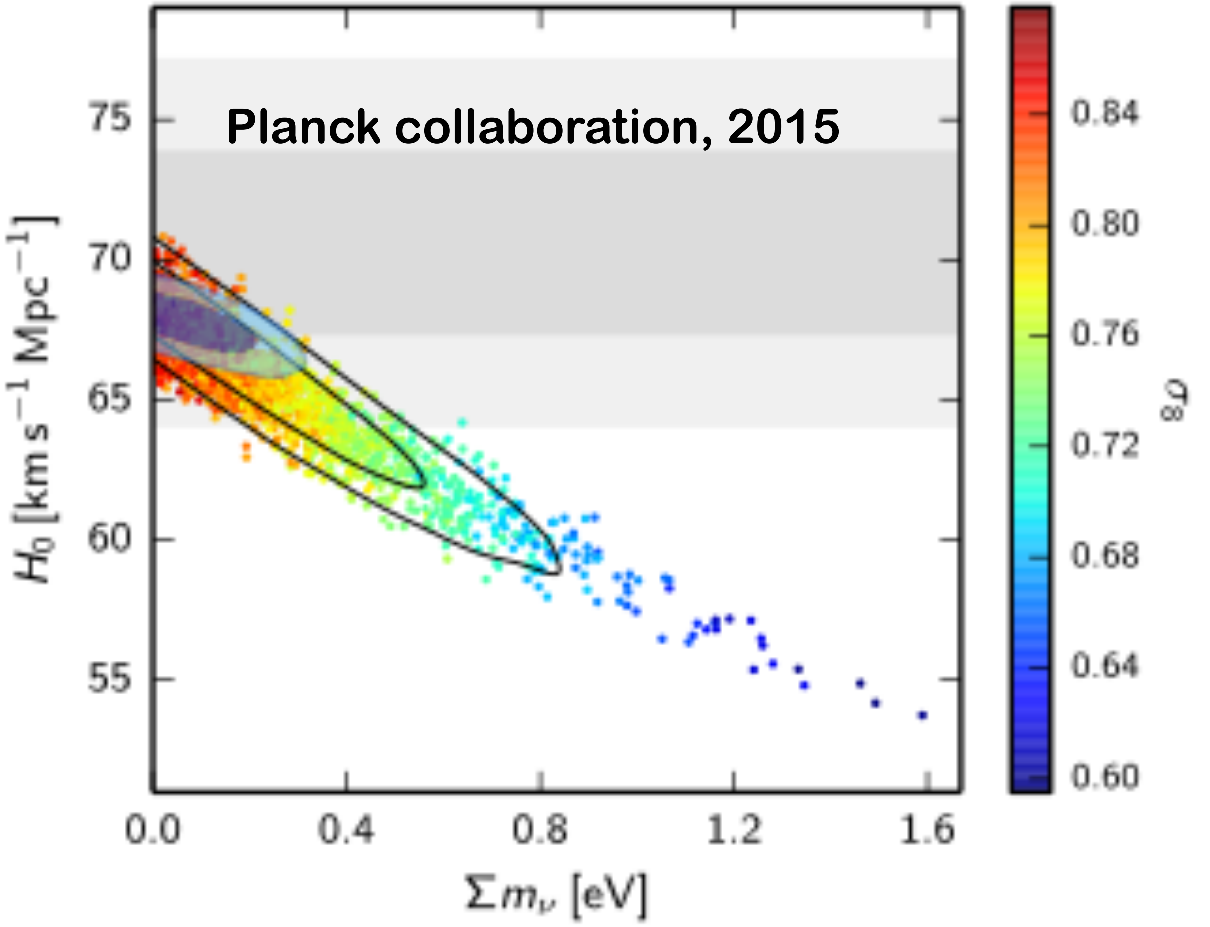
.... **0.06eV mass -> 9:1**

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

The Hubble constant



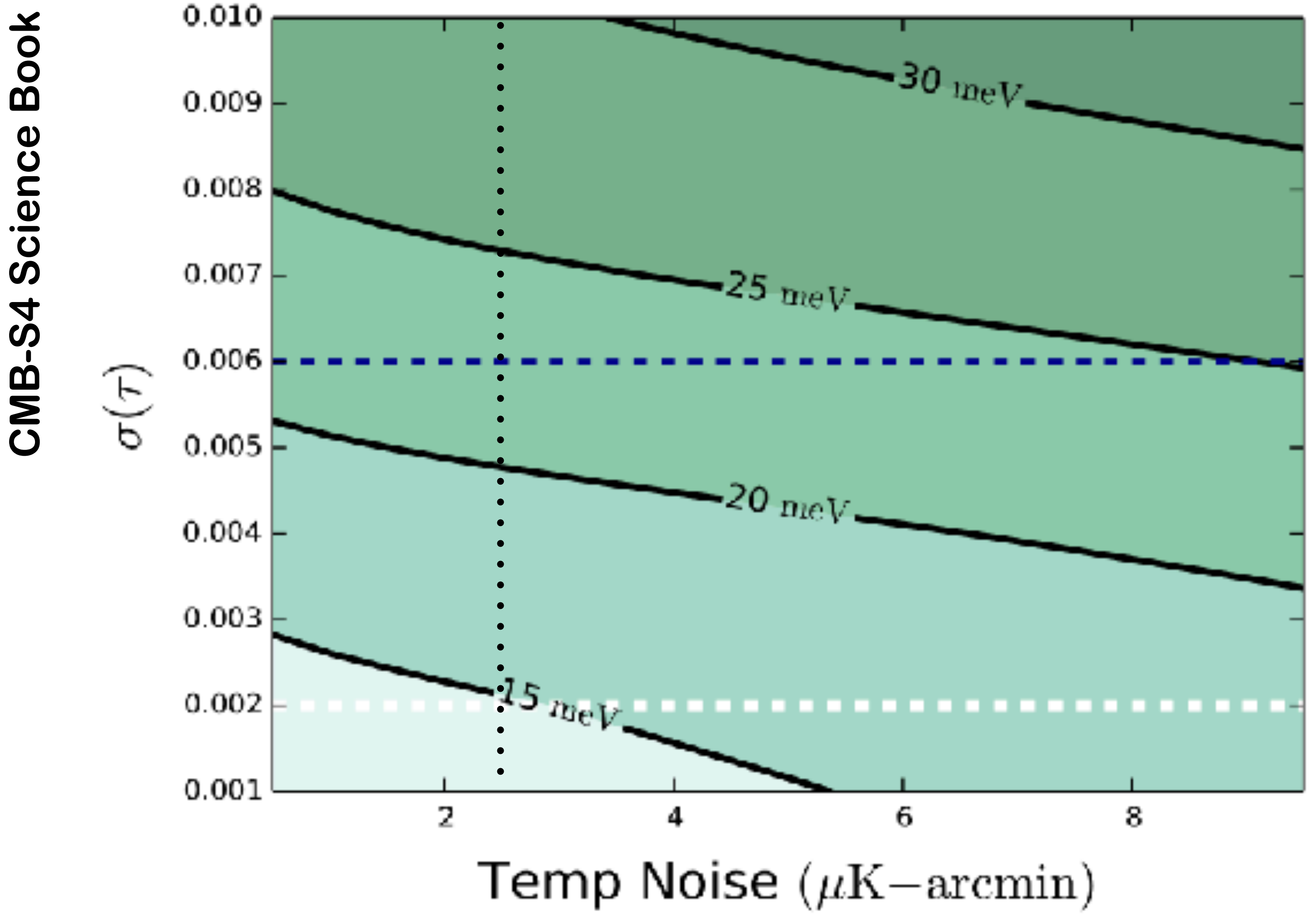
Riess+,2016



Planck collaboration, 2015

Compensate a change in the distance to the last scattering surface by modifying the Hubble constant

The reionisation optical depth

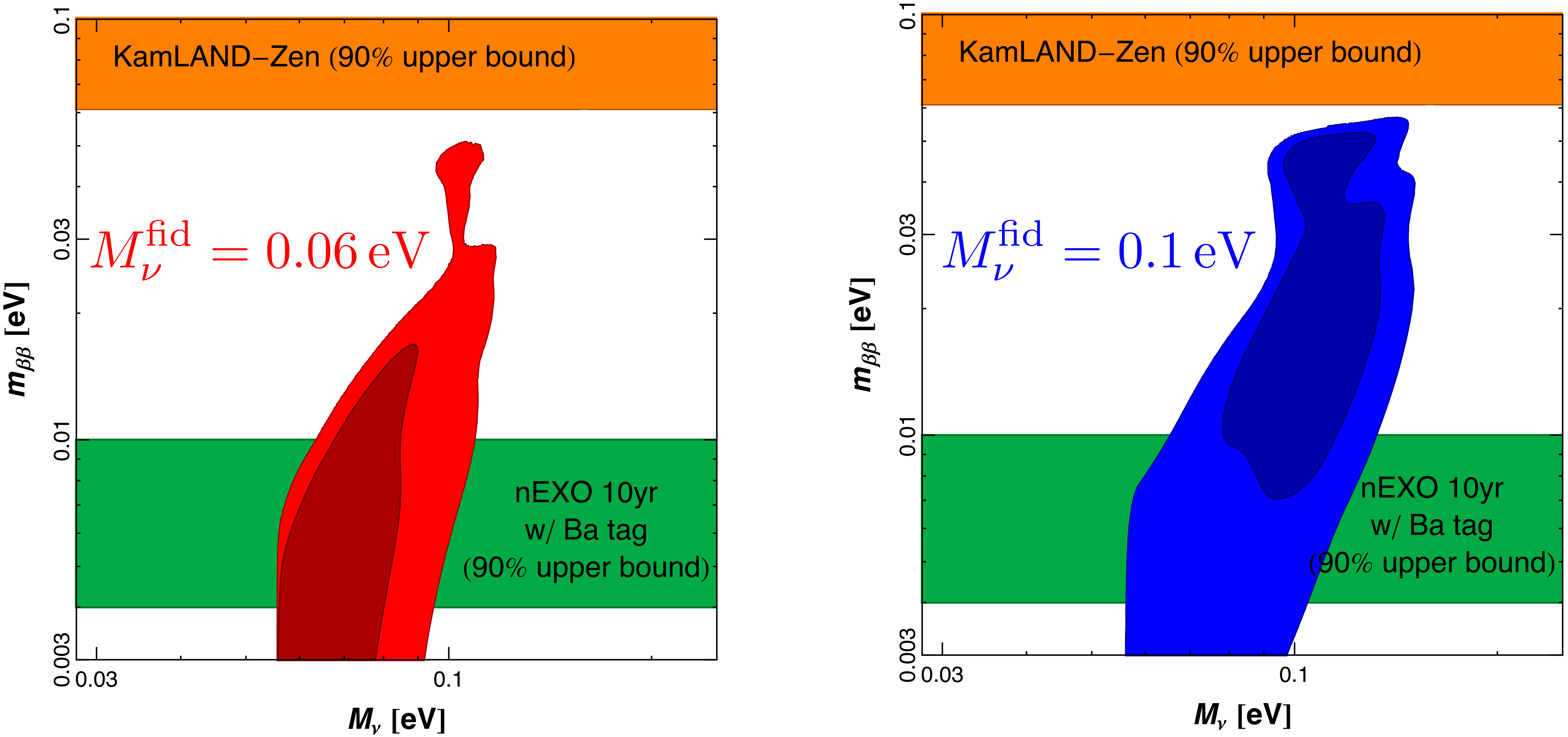


Planck Blue Book expected sigma

Cosmic Variance Limited sigma

- Better determination of tau benefits parameter estimation in general
- Degeneracy between the optical depth and neutrino mass

Sensitivity to the hierarchy

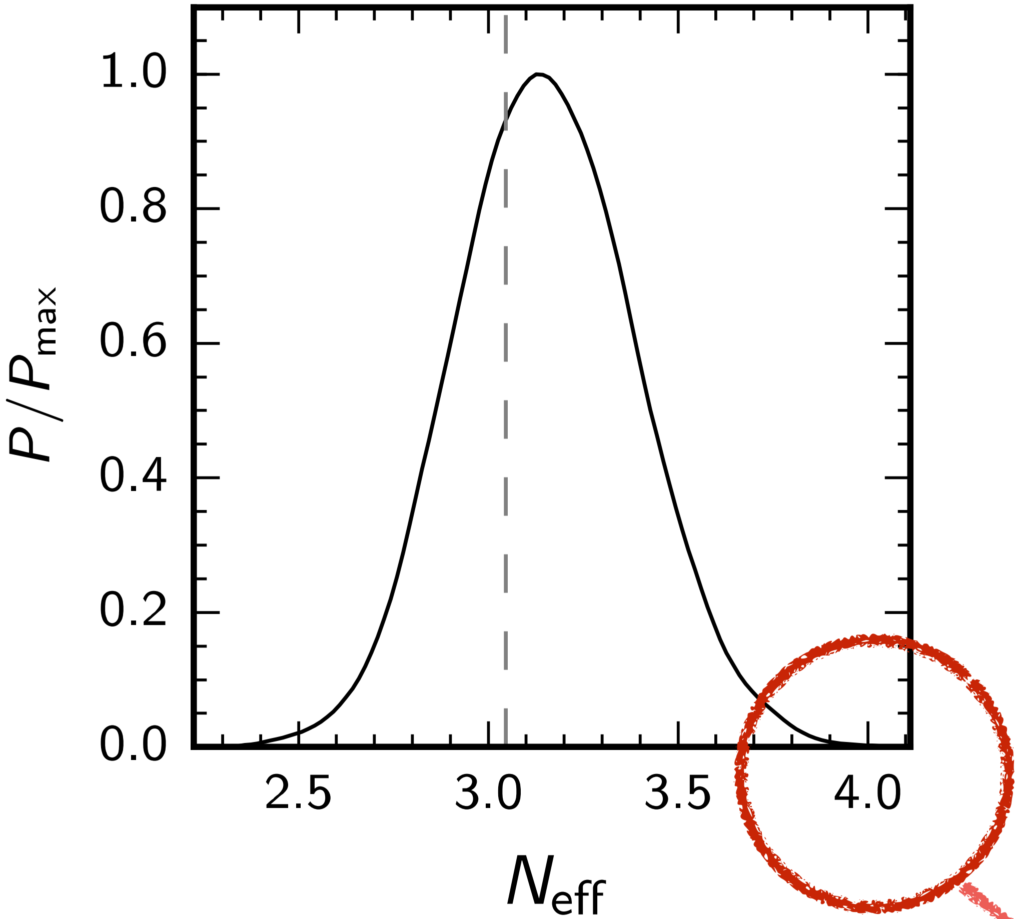


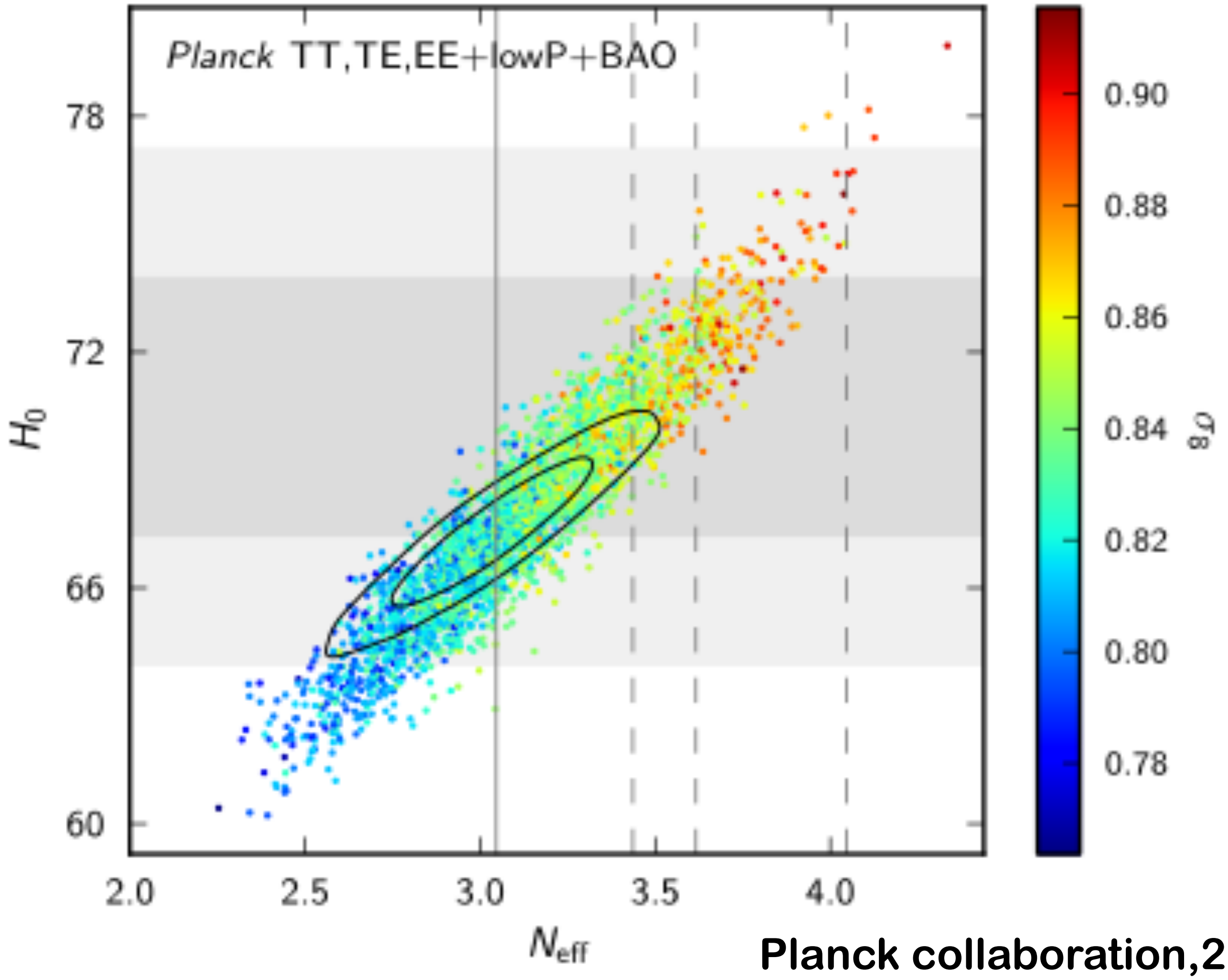
Gerbino,Lattanzi,Mena,Freese 2016

If Mnu=0.1eV, sigma(mbb)~10meV could guarantee 0n2b measurement

0n2b could in turn helps unravel the hierarchy (wip, extending the results in Gerbino+2015 in the hierarchical bayesian context)

Limits on Neff from Planck 2015





Planck collaboration,2015

$N_{\rm eff}$ = 3.13 ± 0.32 (PlanckTT+lowP)

$N_{\rm eff}$ = 3.15 ± 0.23 (PlanckTT+lowP+BAO)

$N_{\rm eff}$ = 2.99 ± 0.20 (PlanckTT,TE,EE+lowP)

$N_{\rm eff}$ = 3.04 ± 0.18 (PlanckTT,TE,EE+lowP+BAO)

$$N_{\rm eff} = 4$$

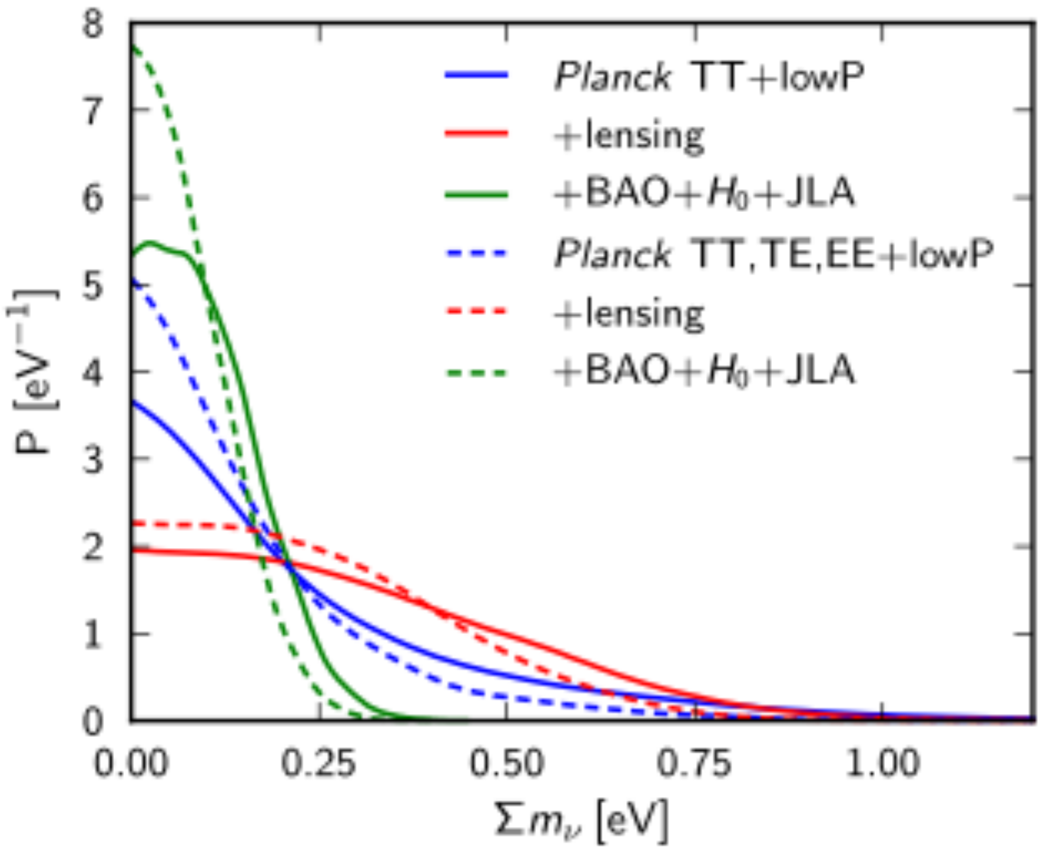
(one extra thermalized) excluded at more than

$$3\sigma$$

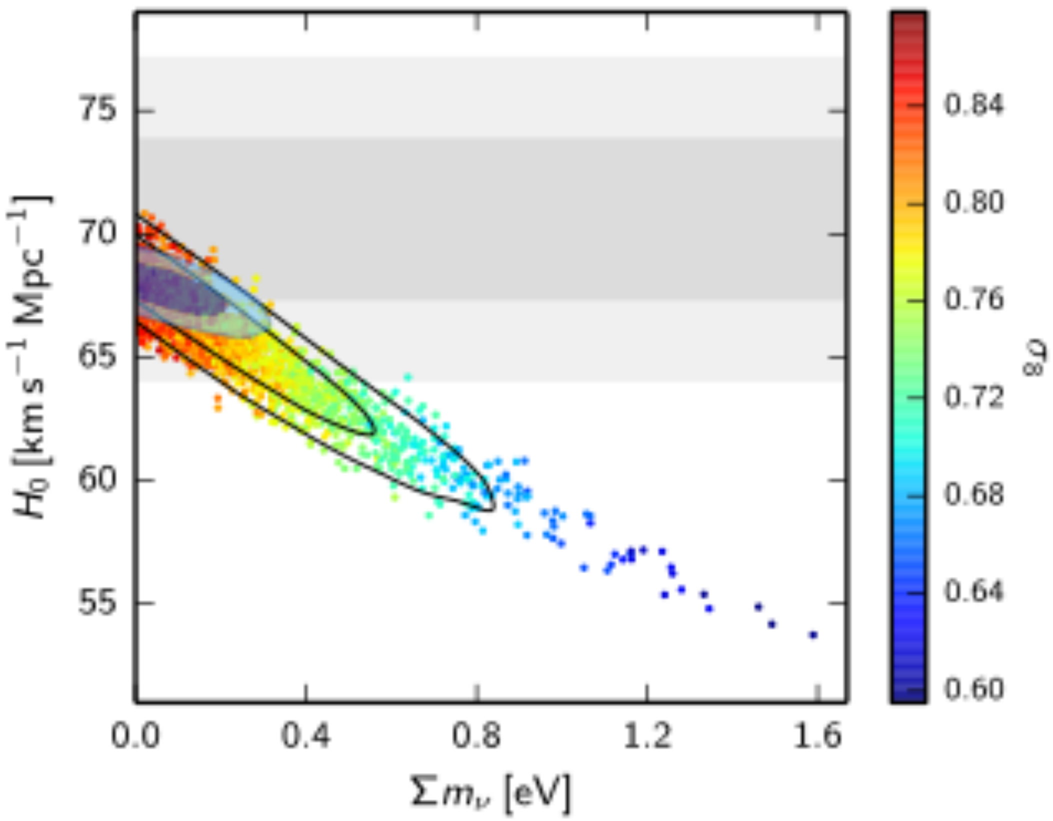
Limits on Mnu from Planck 2015

95%CL	2013	2015	2015 + PlanckTE,EE
PlanckTT+lowP	<0.93 eV	<0.72 eV (23%)	<0.49 eV (48%)
PlanckTT+lowP+lensing	<1.1 eV	<0.68 eV (38%)	<0.59 eV (47%)
PlanckTT+lowP+BAO	<0.25 eV	<0.21 eV (16%)	<0.17 eV (36%)
PlanckTT+lowP+ext		<0.20 eV	<0.15 eV
PlanckTT+lowP+lensing+ext		<0.23 eV	<0.19 eV

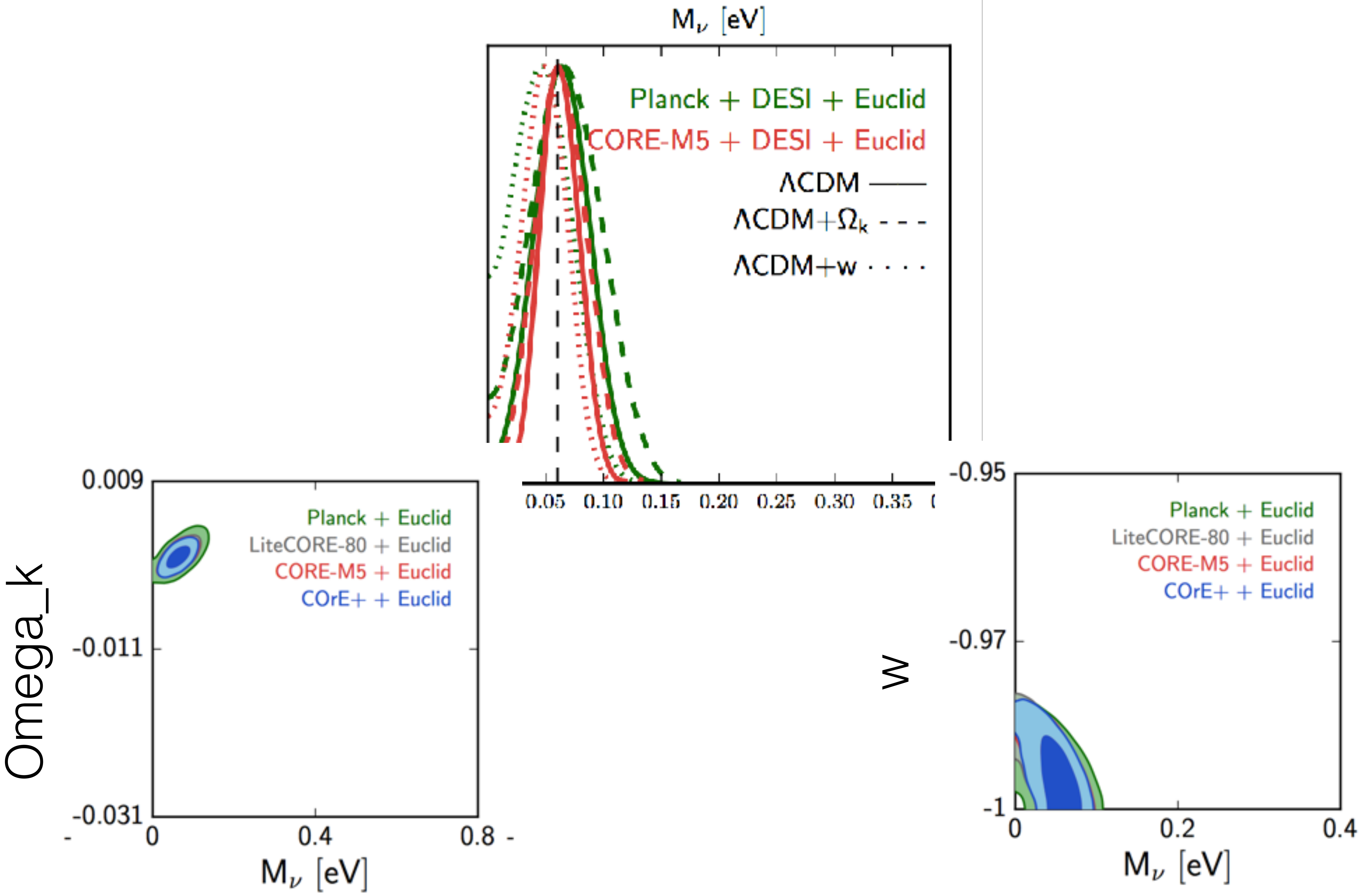
>10x better than current kinematic measurements



Planck collaboration,2015

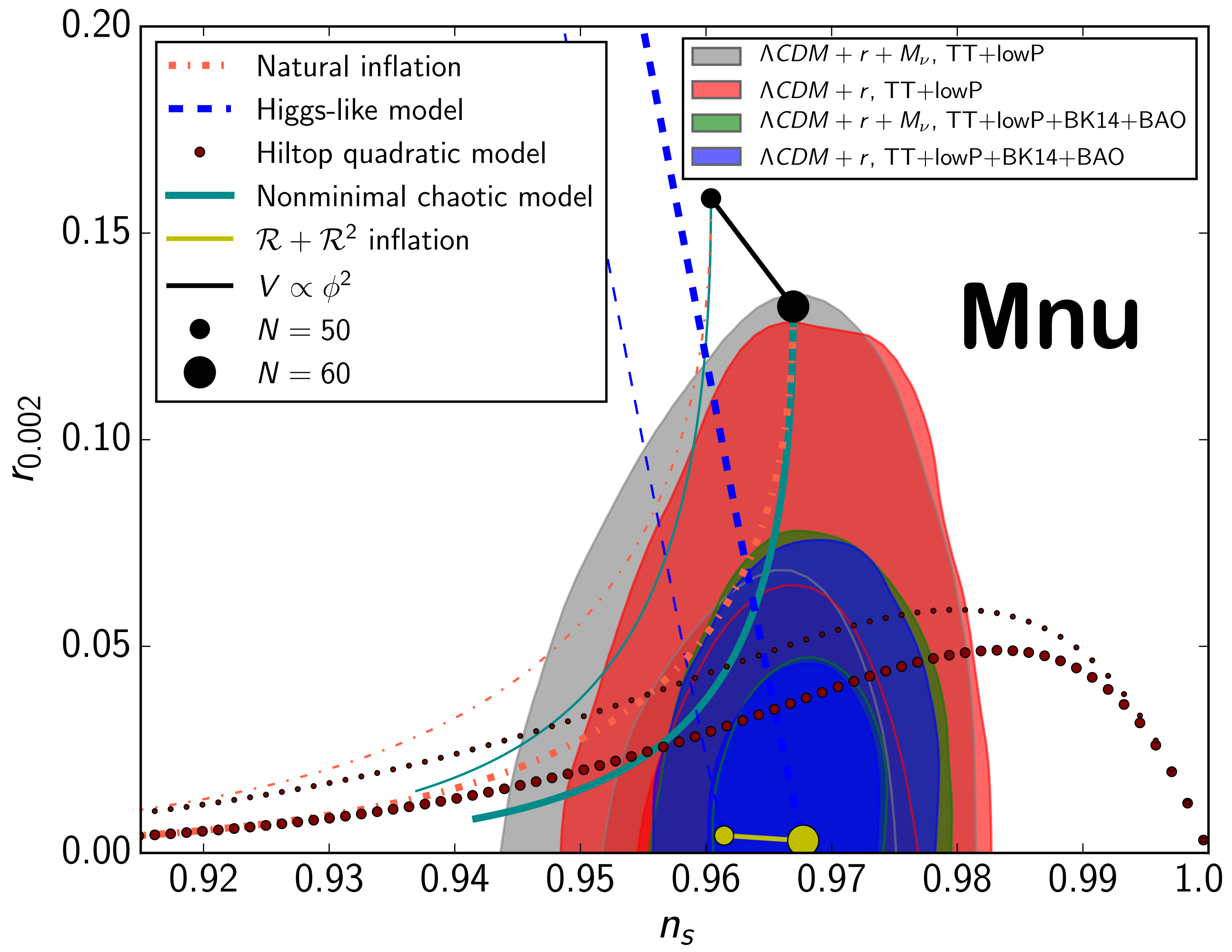


Robustness wrt the underlying cosmology



CORE collaboration (DiValentino et al),2016

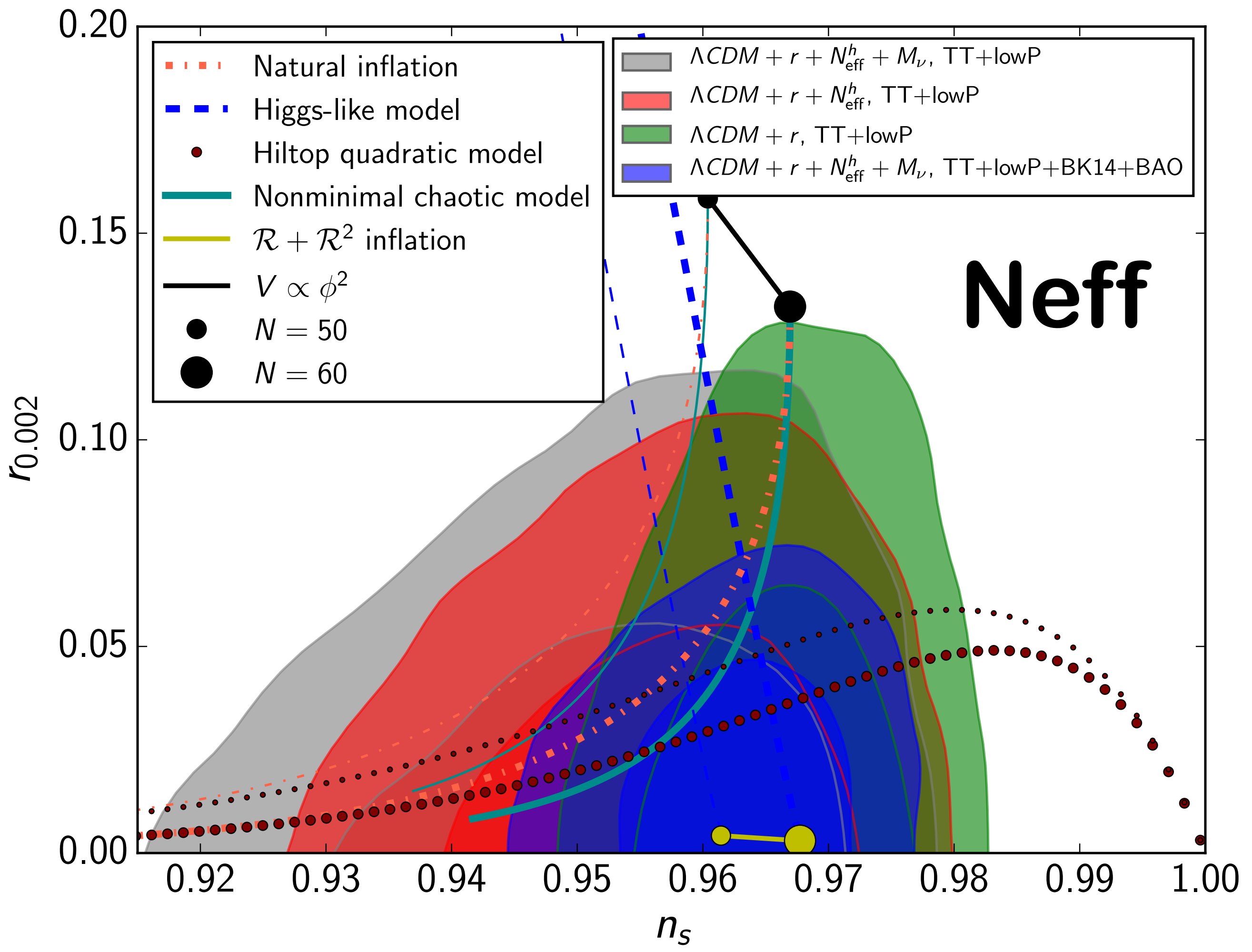
Neutrino unknown: when neutrinos are nuisance



- When accounting for uncertainties in Mnu or Neff, some models are still in agreement with data
- With BAO, more stable contours

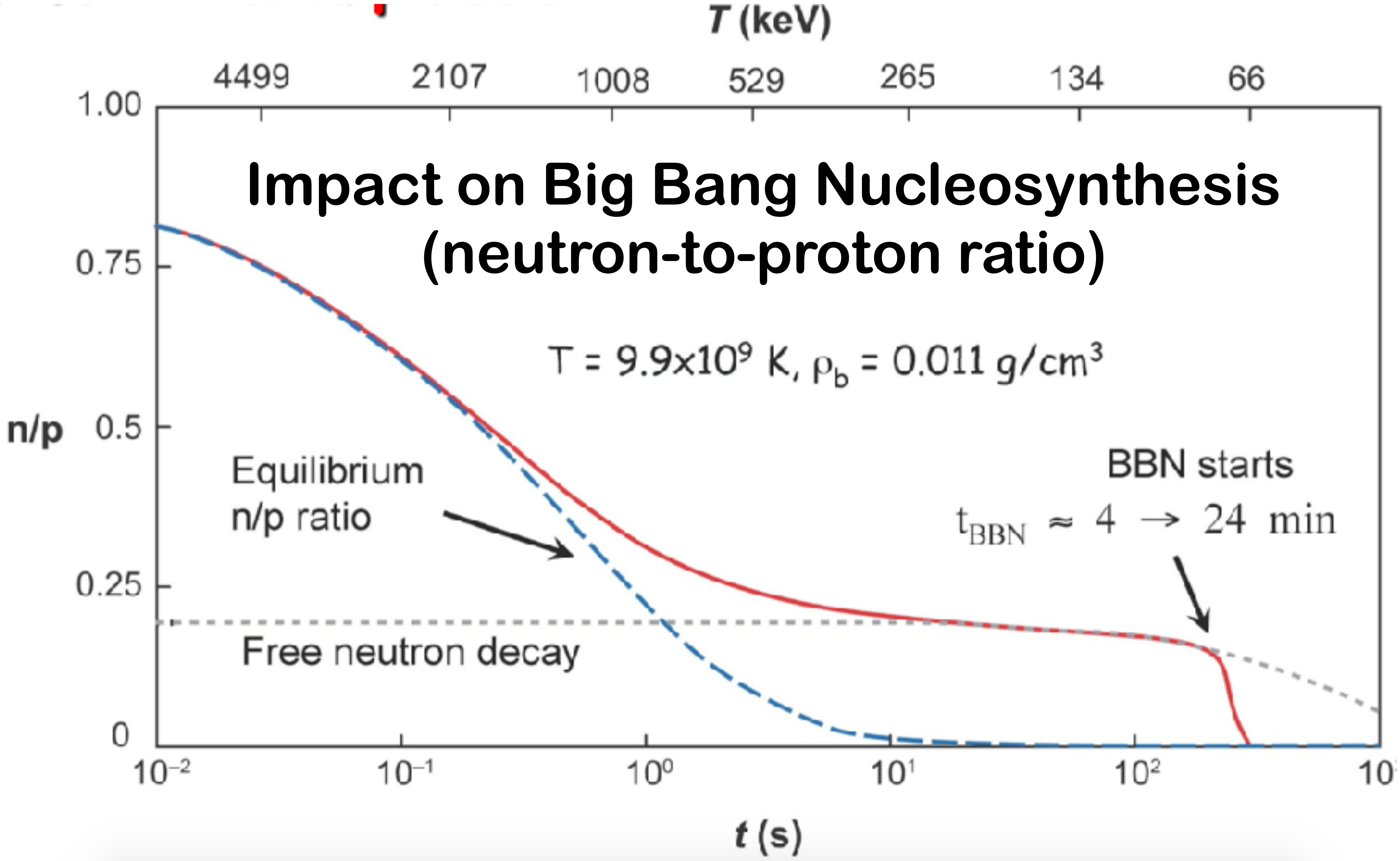
- Better constraints on neutrino properties will improve constraints on inflation
- Need for taking into account neutrino uncertainties to better assess consistency of inflationary models

Gerbino,Freese+,in prep



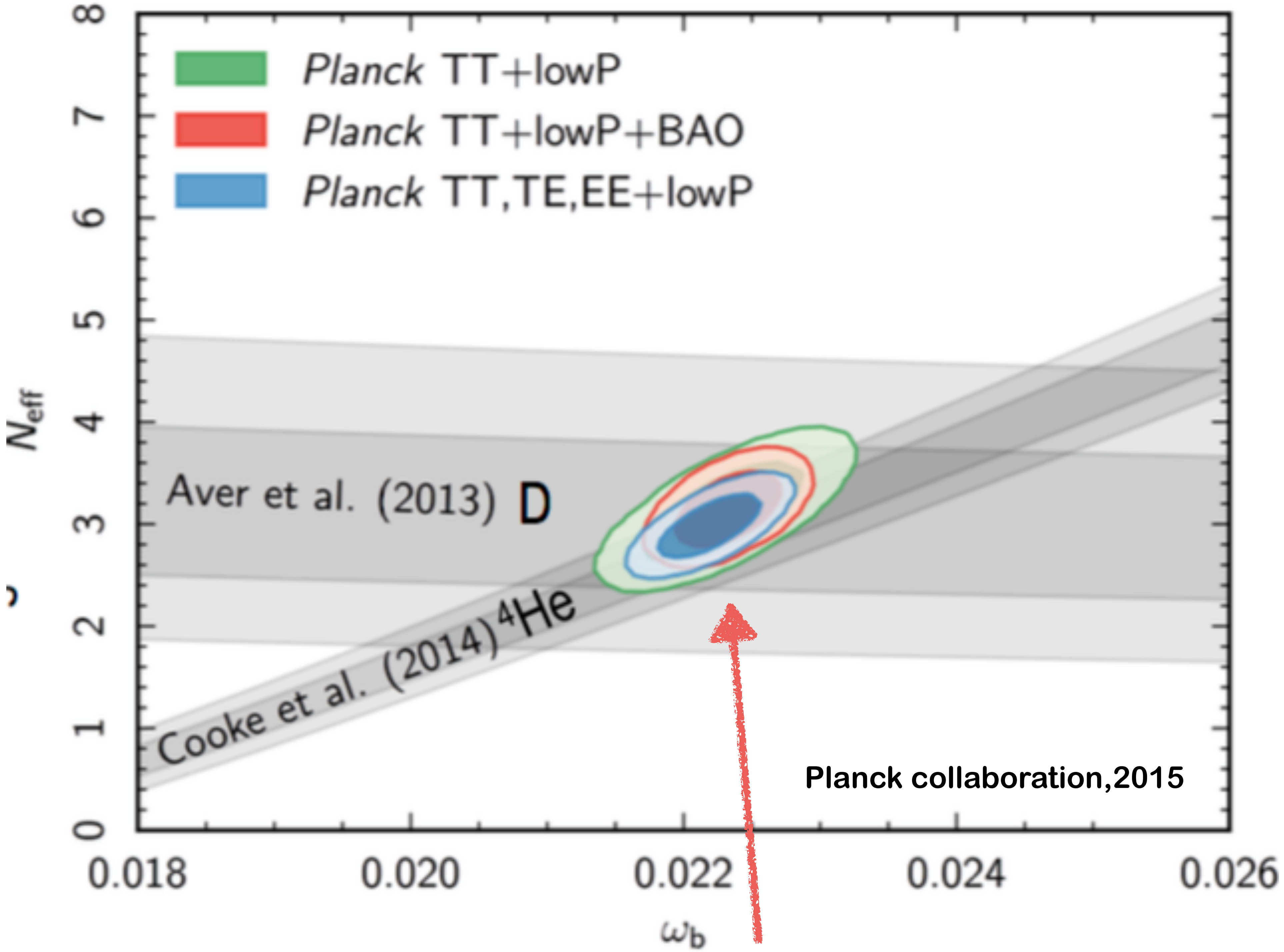
Neff modifies the expansion rate

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



Impact on Big Bang Nucleosynthesis (neutron-to-proton ratio)

Limits on Neff from Planck 2015



Planck collaboration,2015

Agreement between cosmological (2D contours) and astrophysical (bands) measurements

Gravitational lensing provides new probes for neutrino masses