MASSIVE NEUTRINOS IN COSMOLOGY

Martina Gerbino

Oskar Klein Centre
for Cosmoparticle Physics
Stockholm University

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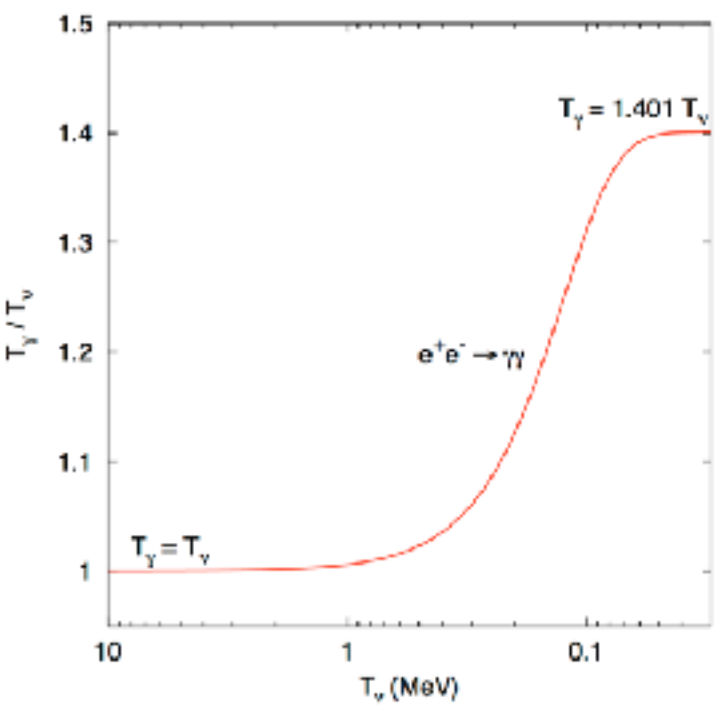
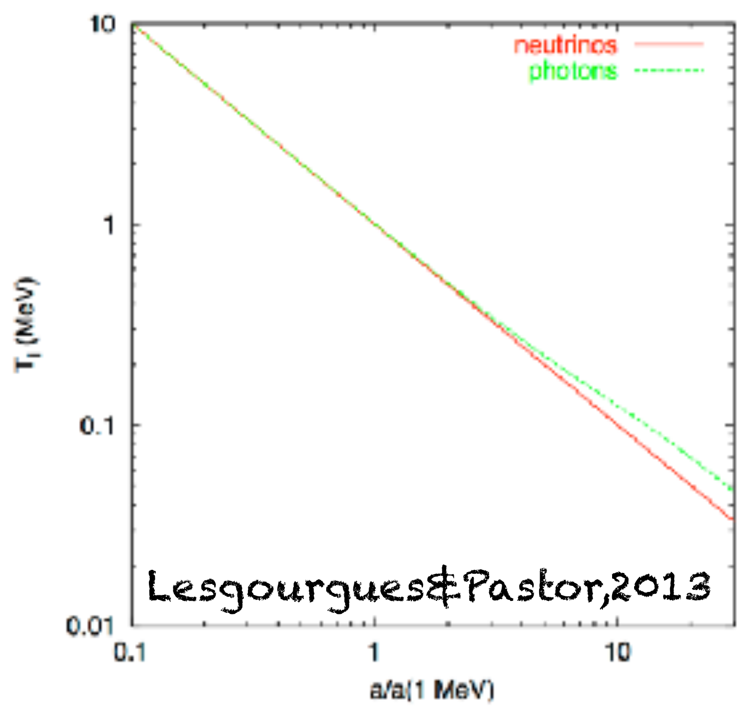
Some basic facts

- 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 ($T_\nu \neq T$, $T_\nu \propto 1/a$):

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





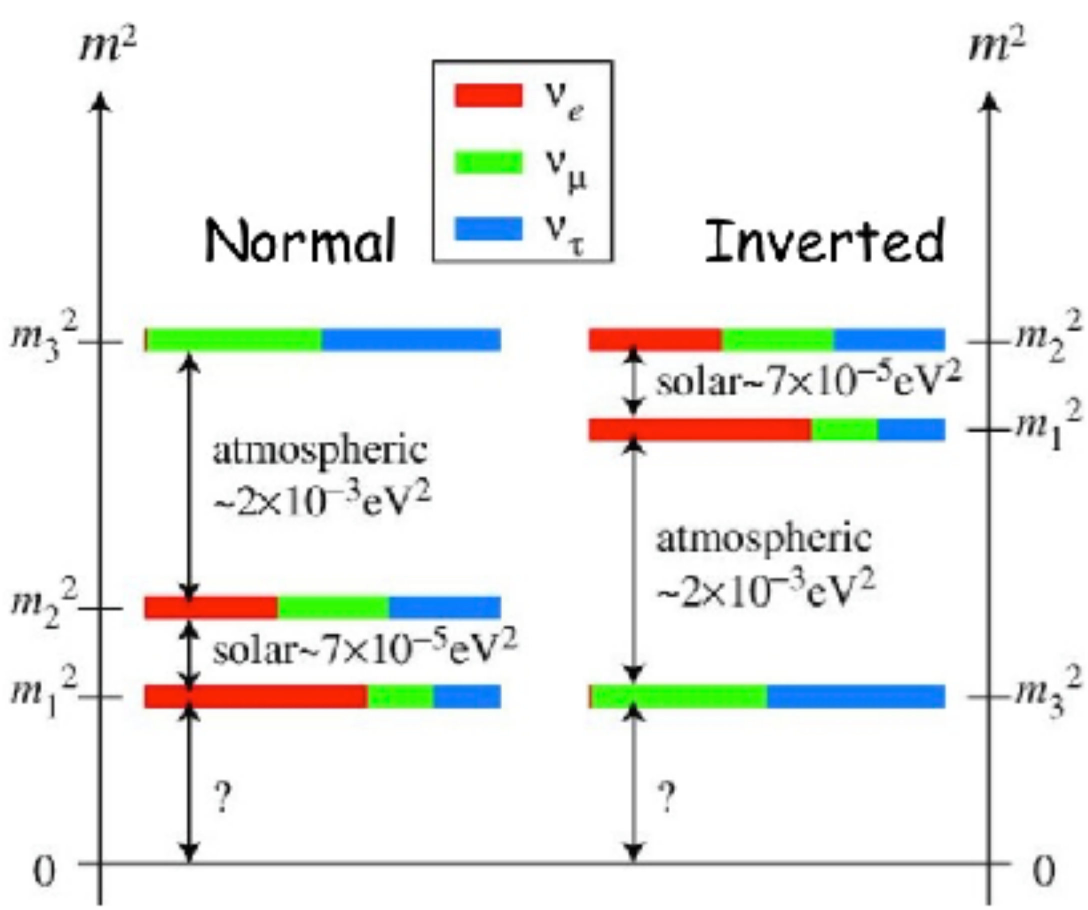
- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species

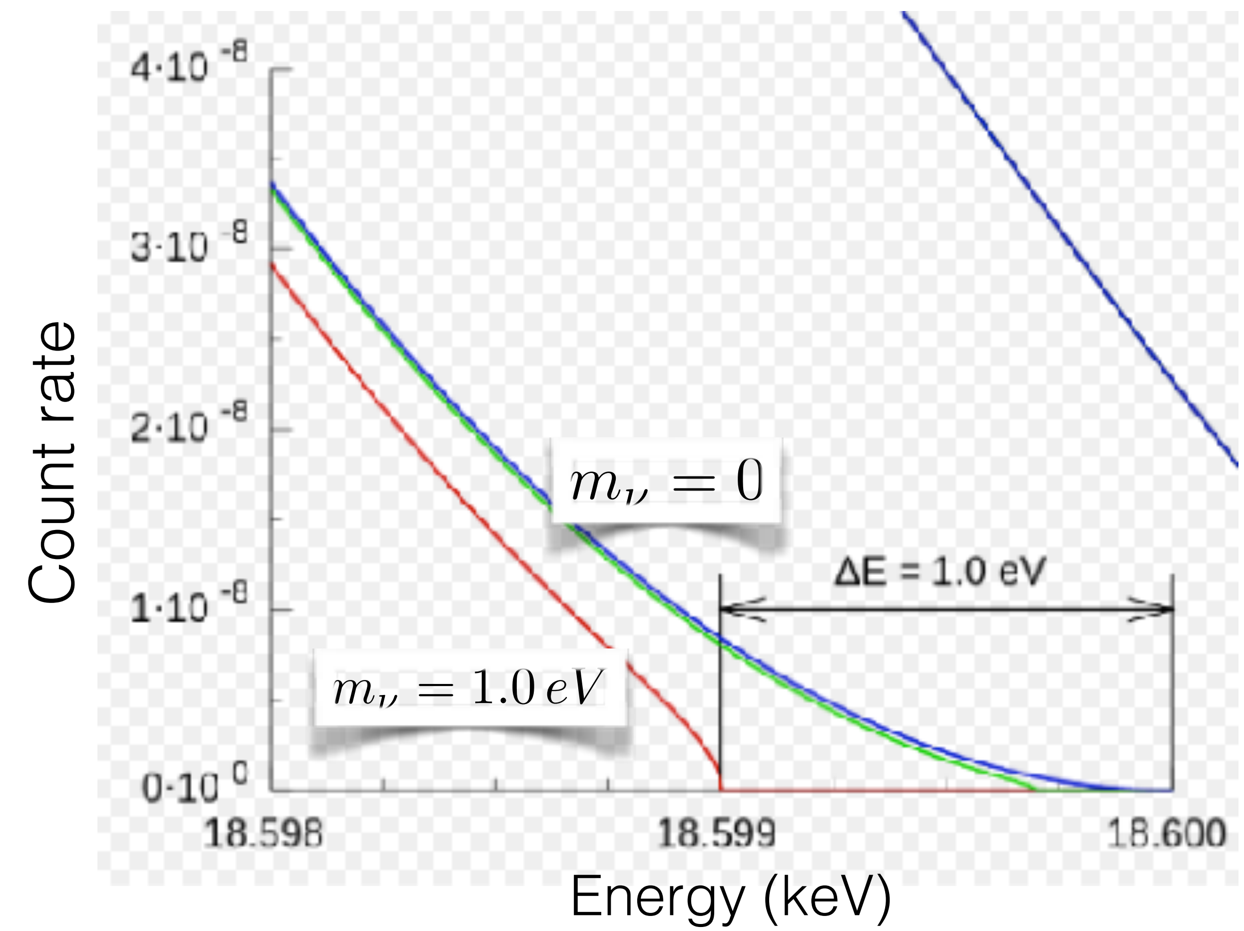
What we know, from the outside

How do they behave?

Neutrinos oscillate, so they are massive

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





Lower bound
from oscillation experiments

Upper bound
from kinematic measurements

Neutrino phenomenology

Neutrinos were relativistic in the early Universe

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

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

$$N_{\rm eff} = \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm st}} = 3.046$$

Dolgov, 1997
Mangano+,2005
deSalas&Pastor,2016

Neff could account for any 'extra' radiation component

Neutrino phenomenology

Neutrinos are non-relativistic today

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

so they contribute to the matter content

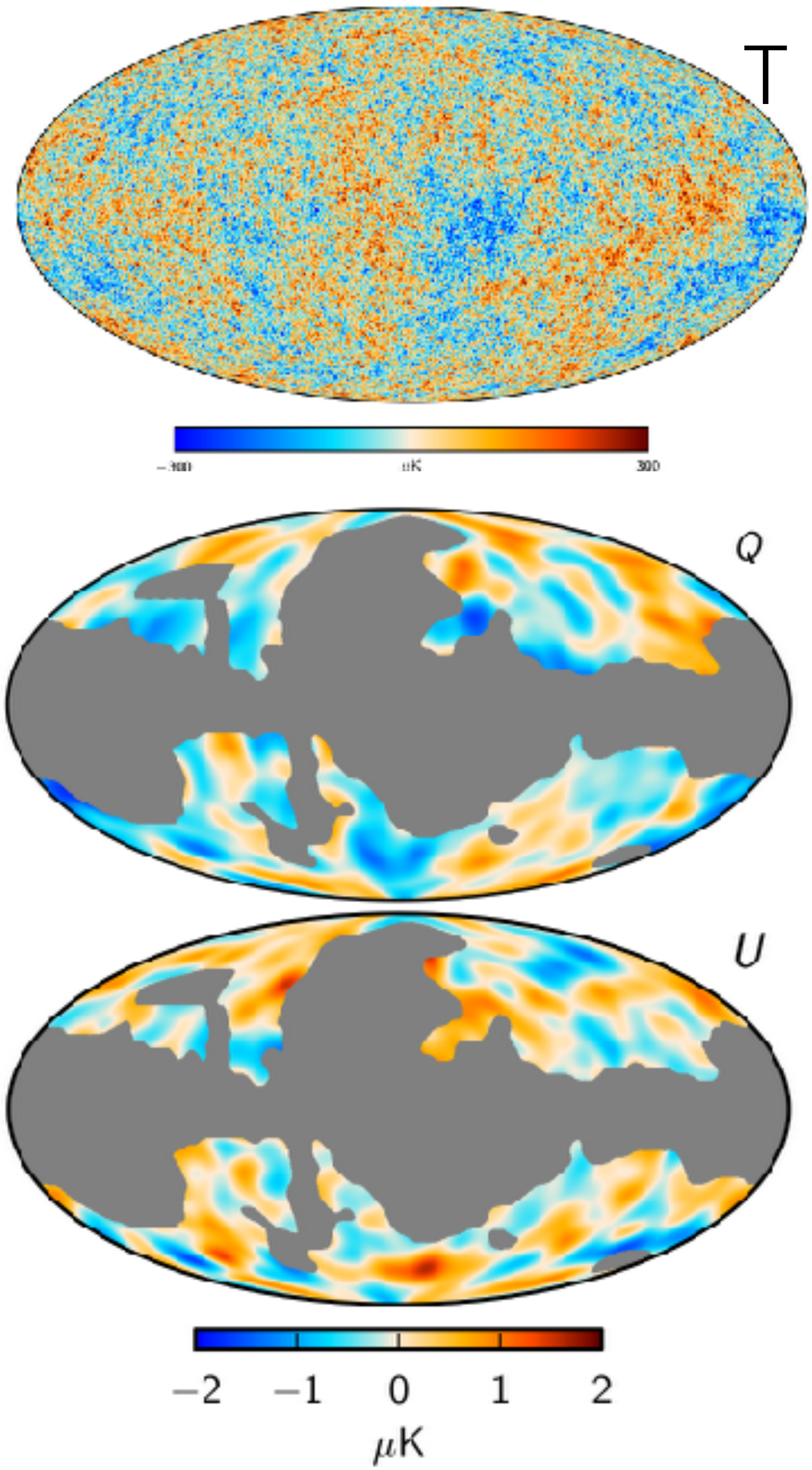
$$\Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2 \text{ eV}}$$

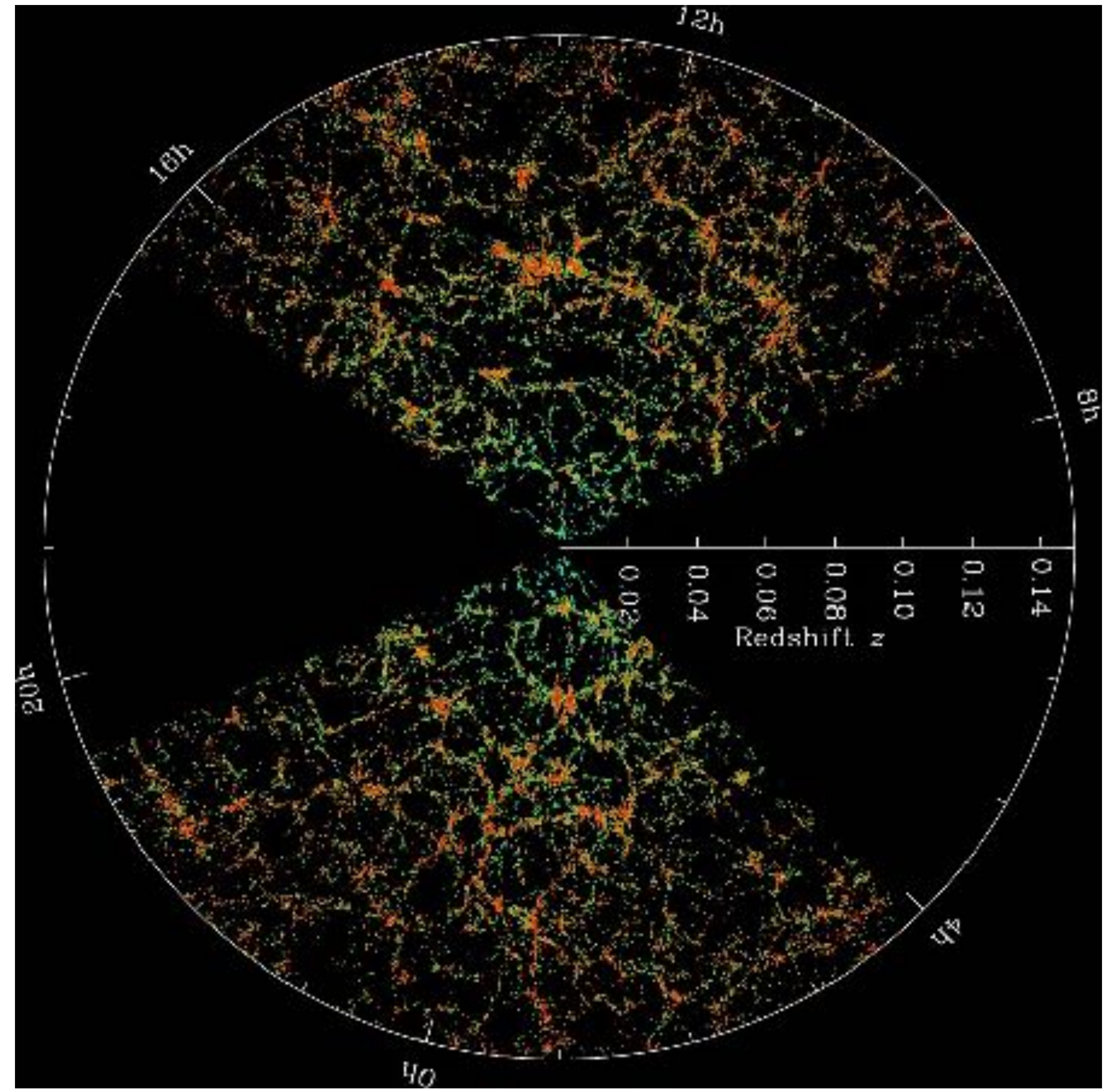
$$\rho_c = \frac{3H^2}{8\pi G}$$

What we want to know from cosmology is (at least)

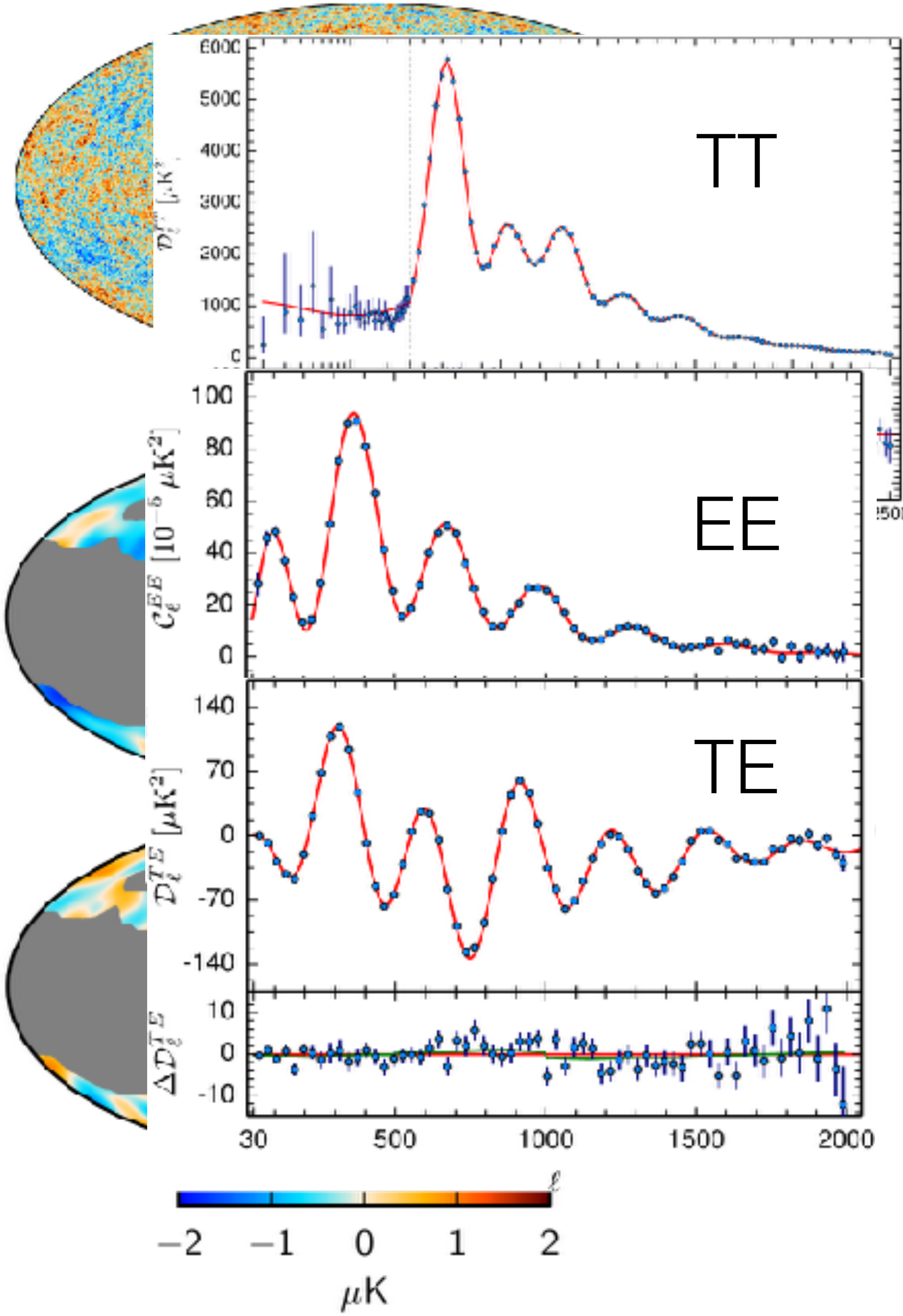
- how many (constraints on Neff)
- how much (constraints on Mnu)

What we observe

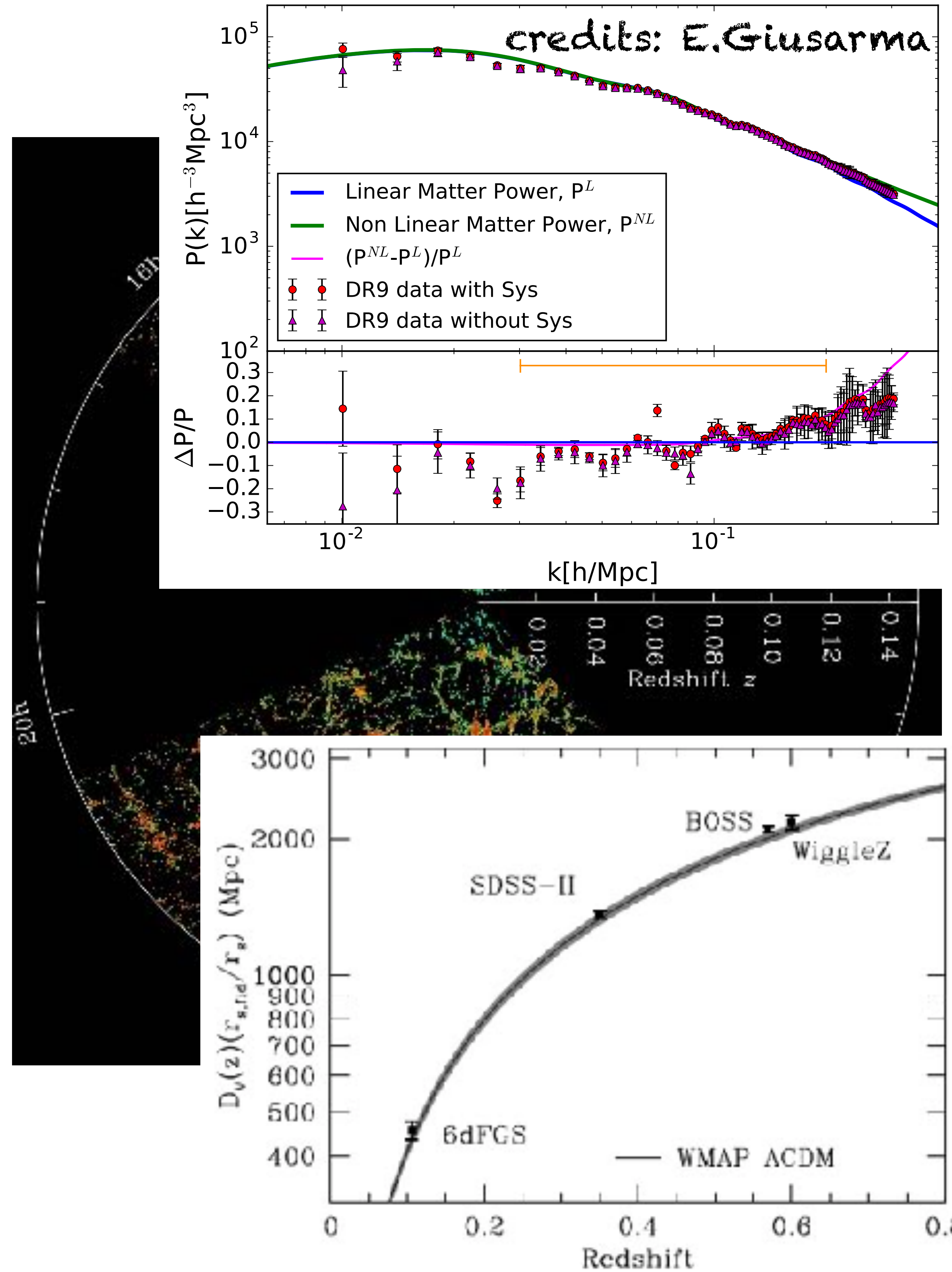




What we compute

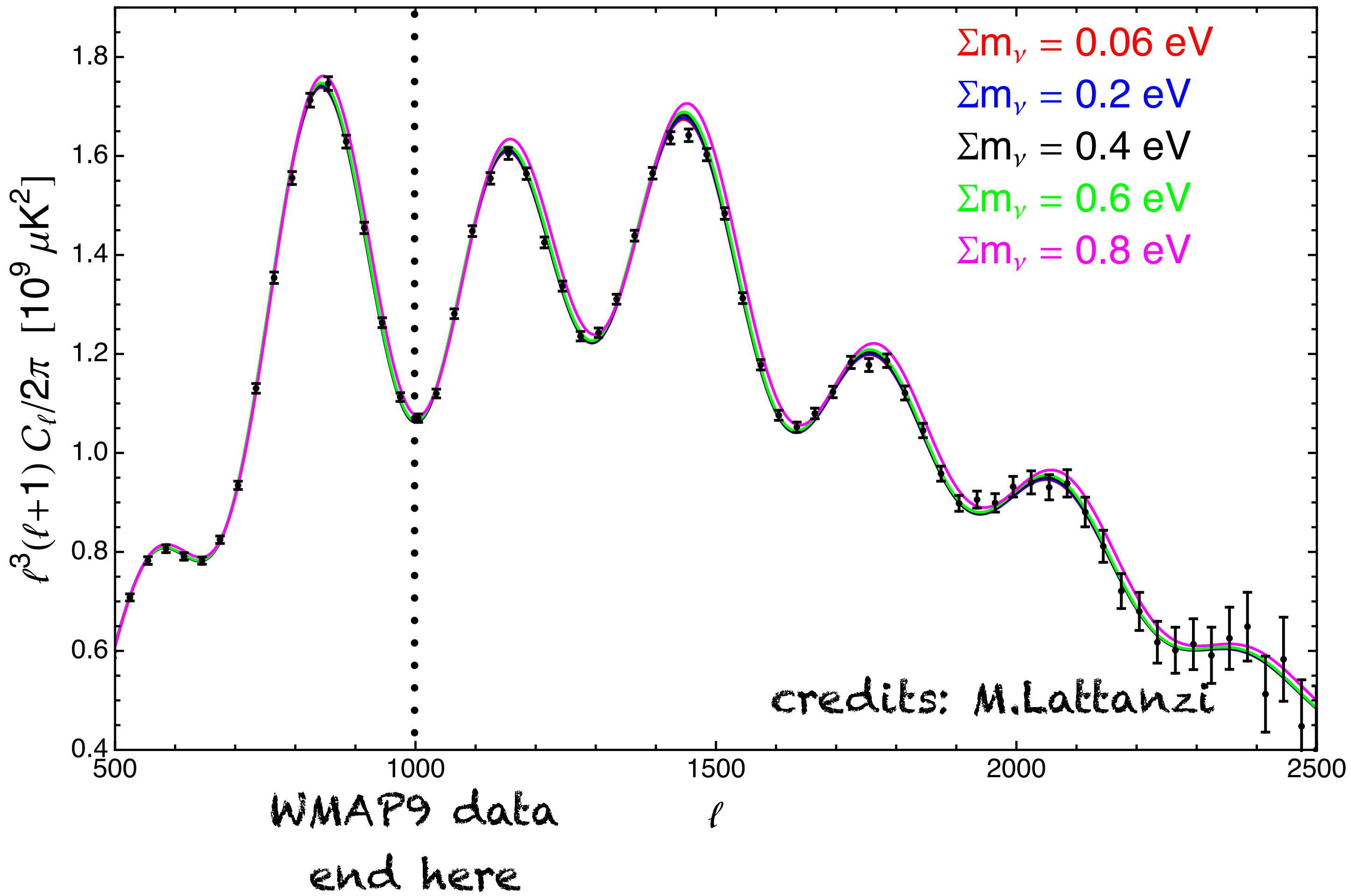


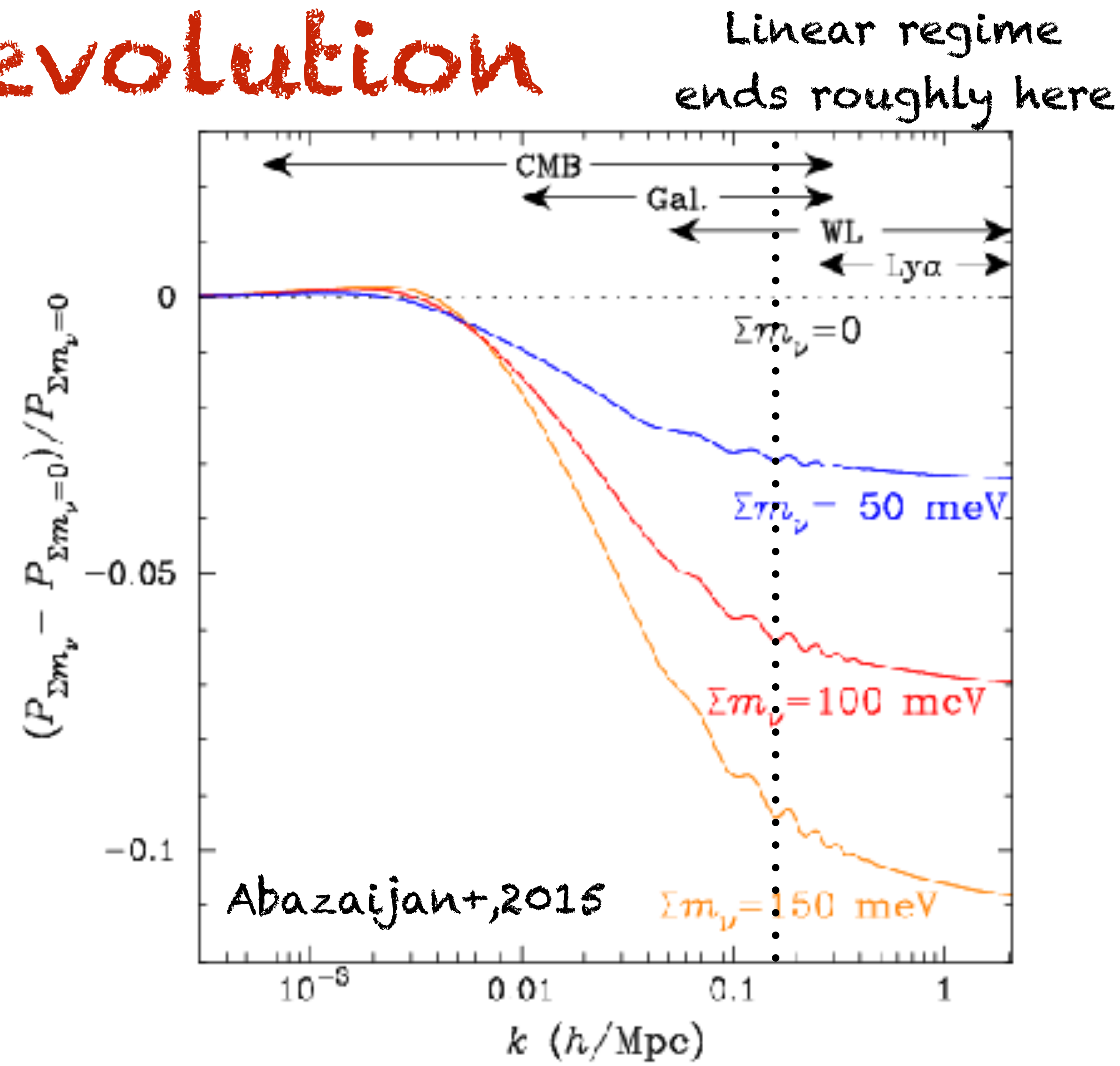
Planck collaboration



SDSS-BOSS collaboration

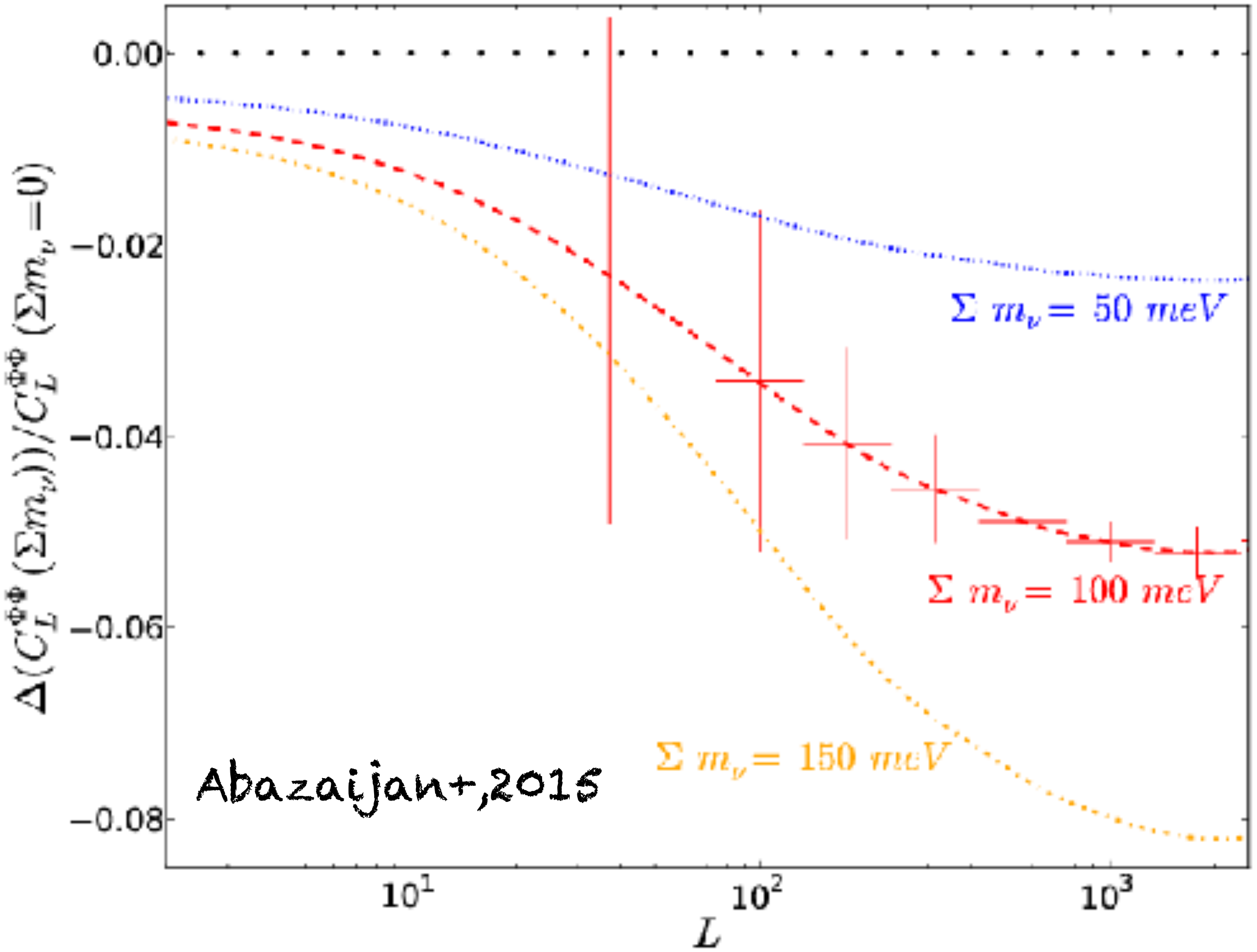
Massive neutrinos alter background and perturbation evolution





- Background: matter-radiation equality shifted, angular diameter distance modified
- Perturbations: early ISW at intermediate scales and power suppression at small scales

Massive neutrinos alter background and perturbations



Gravitational Lensing potential (also lensed BB) will be crucial in the future

In addition, complement CMB and LSS with other late-time observables: local Hubble, deionisation optical depth, cluster science, ...

Joint constraints on Mnu - present

Planck TT+lowP+BAO:	Mnu<0.2eV
Planck TT+lowP+Pk:	Mnu<0.3eV
Planck TT+lowP+BAO+Pk:	Mnu<0.25eV

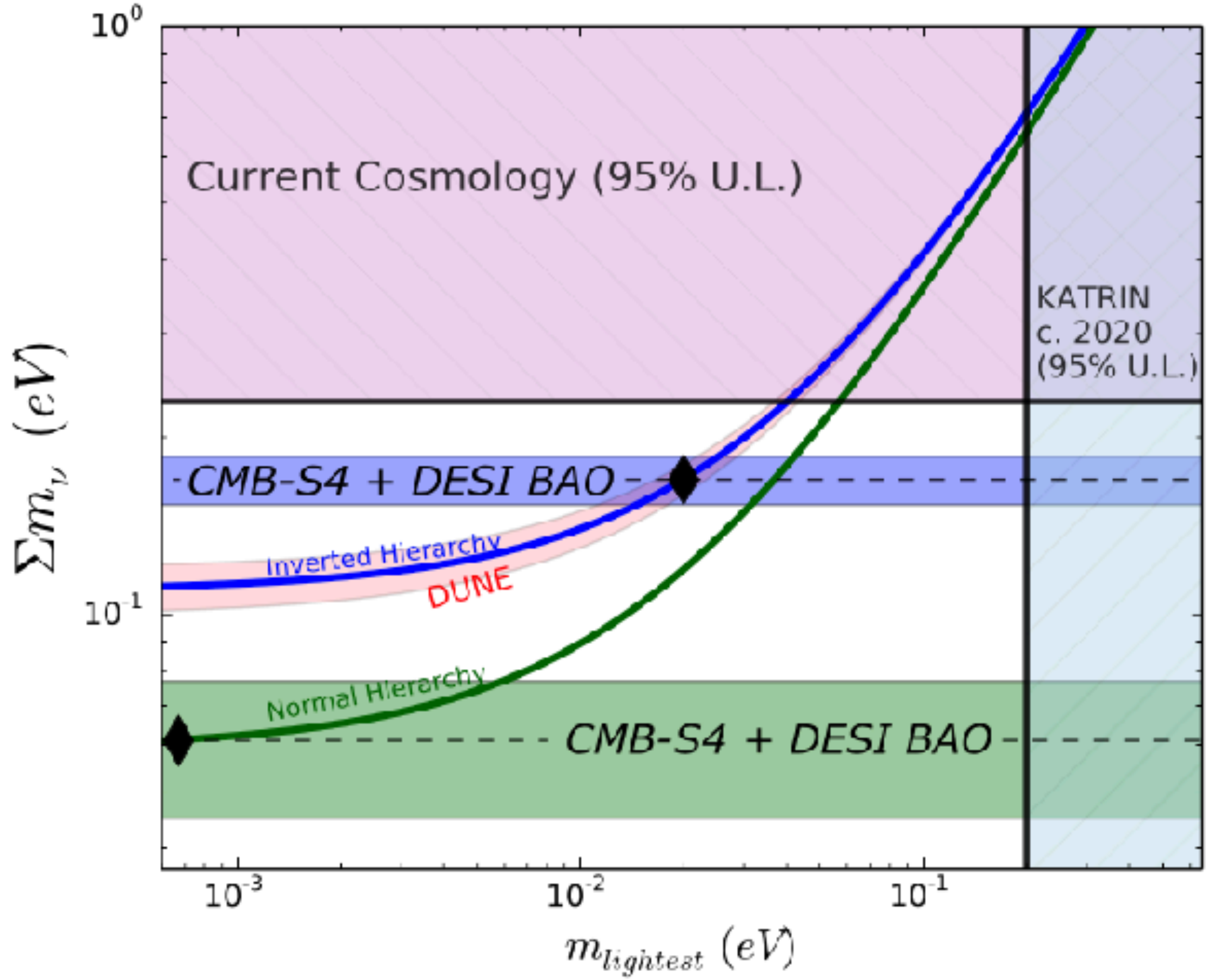
95% CL

~30% improvement with a better measurement of the optical depth and/or use of CMB small scale polarisation:
wait for Planck legacy release!

Take home message: tight and robust bounds

Vagnozzi,Giusarma,Mena,Freese,MG,Ho,Lattanzi 2017

Joint constraints on Mnu - future



CMB-S4 Science Book

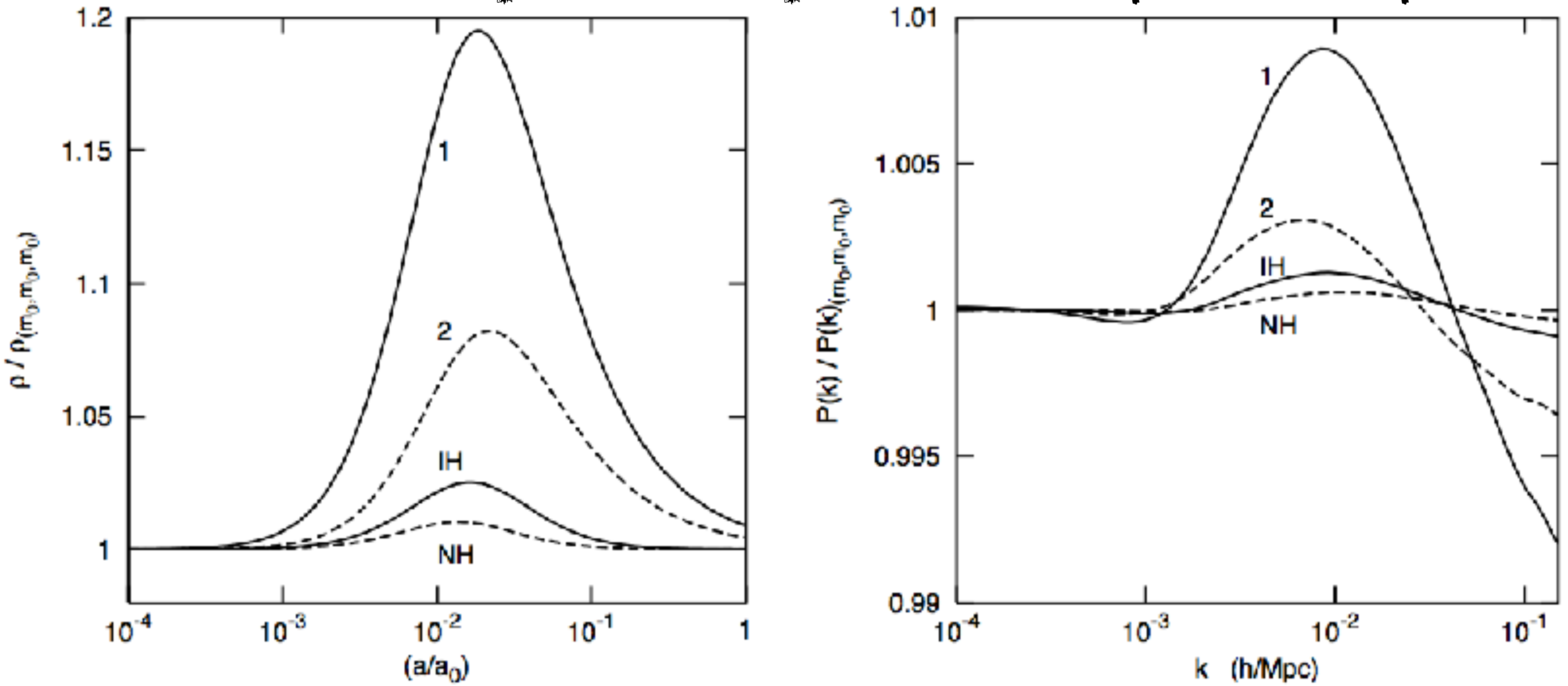
~3sigma detection

in the minimal mass scenario with S4 surveys

Sensitivity to the hierarchy

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

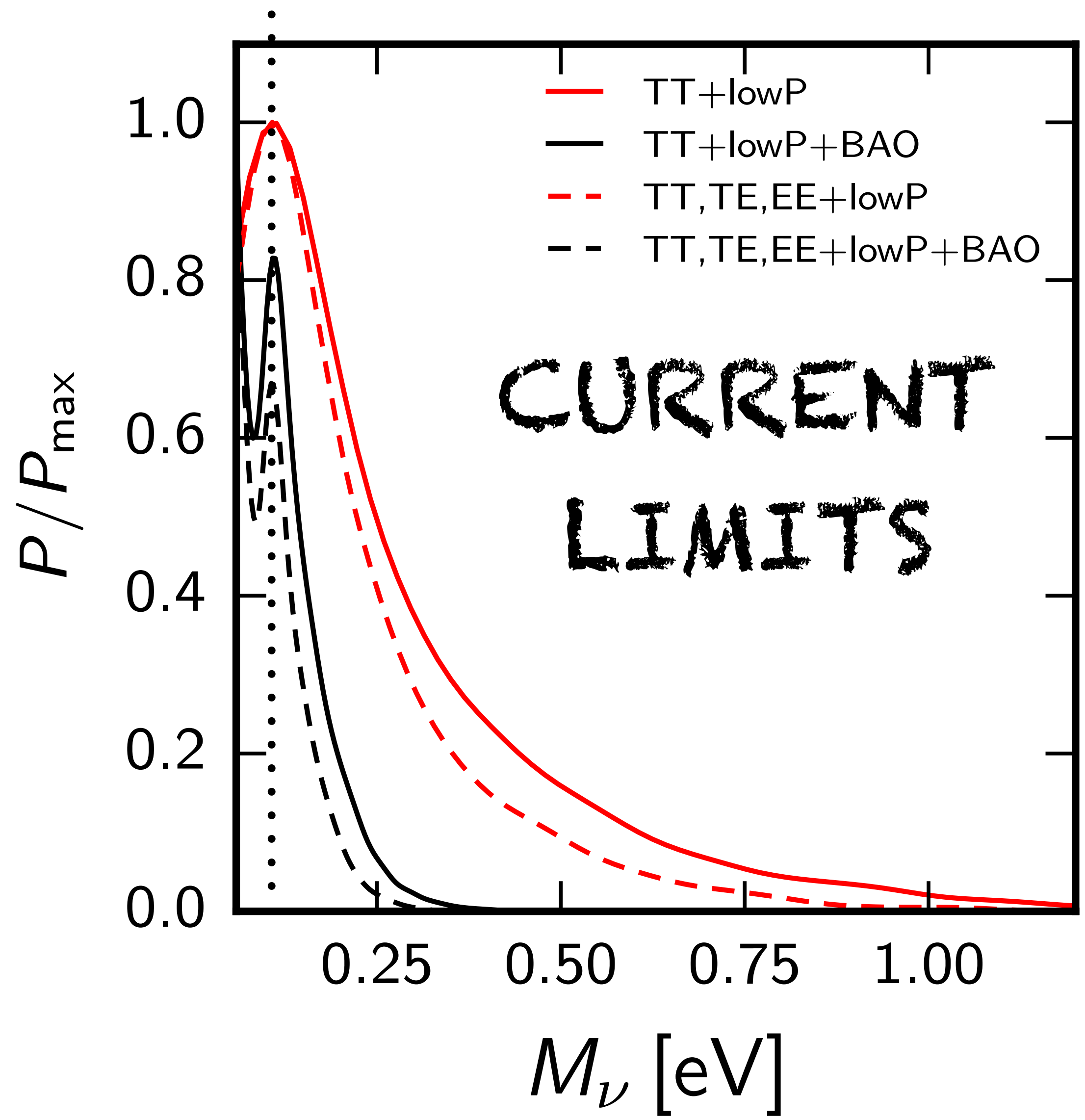
Total nu energy density　　Matter power spectrum

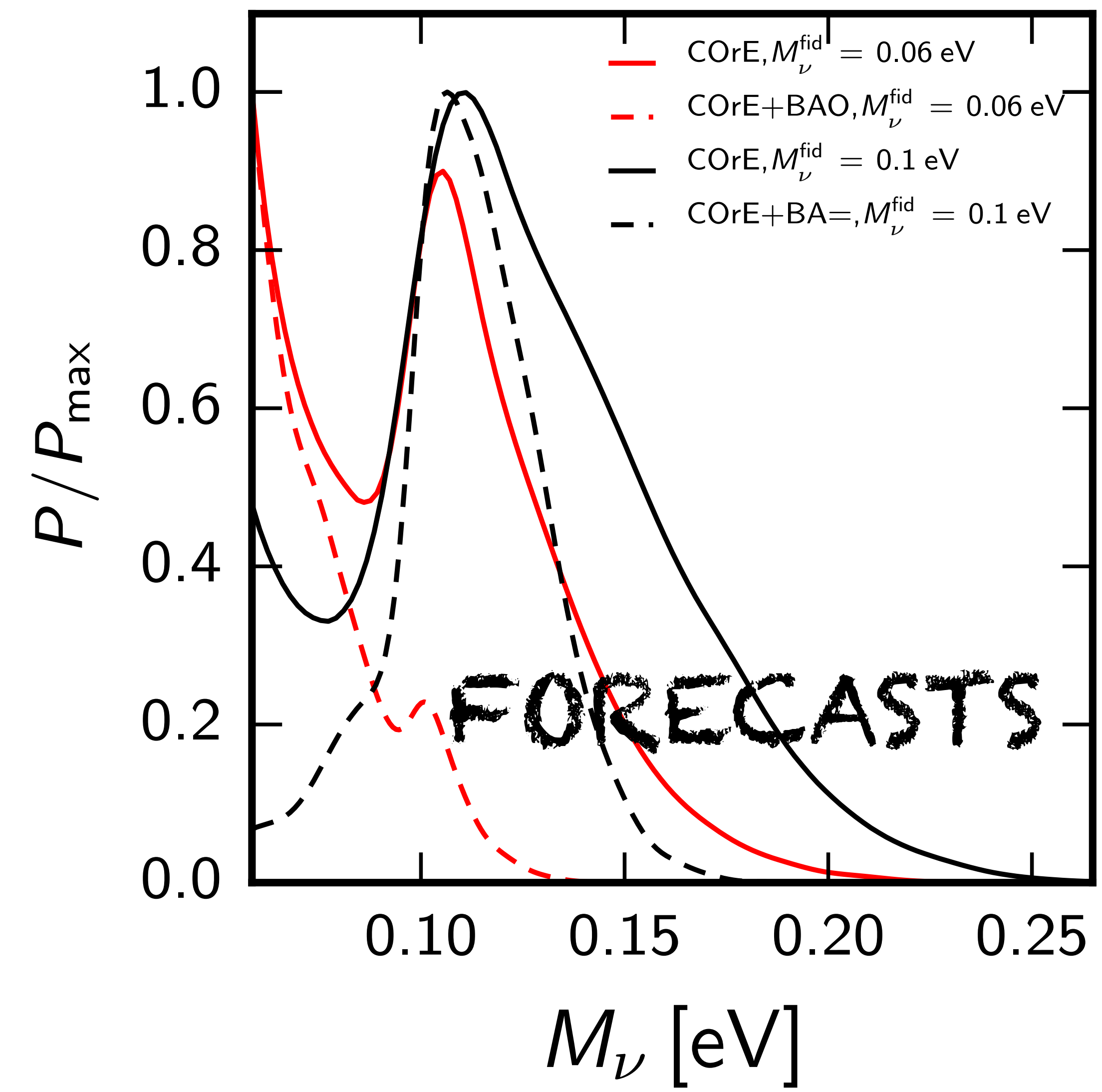


Lesgourgues&Pastor, 2006

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

Sensitivity to the hierarchy





Gerbino,Lattanzi,Mena,Freese 2016

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

.... 3:2

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

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

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

See also Hannestad&Schwetz,2016

CONCLUSIONS

Determine CnB properties from its peculiar effects on cosmological observables

Strong (and nowadays robust) constraints from cosmology

Sensitivity to the hierarchy in the very low-mass regime only (volume effects)

BACKUP SLIDES

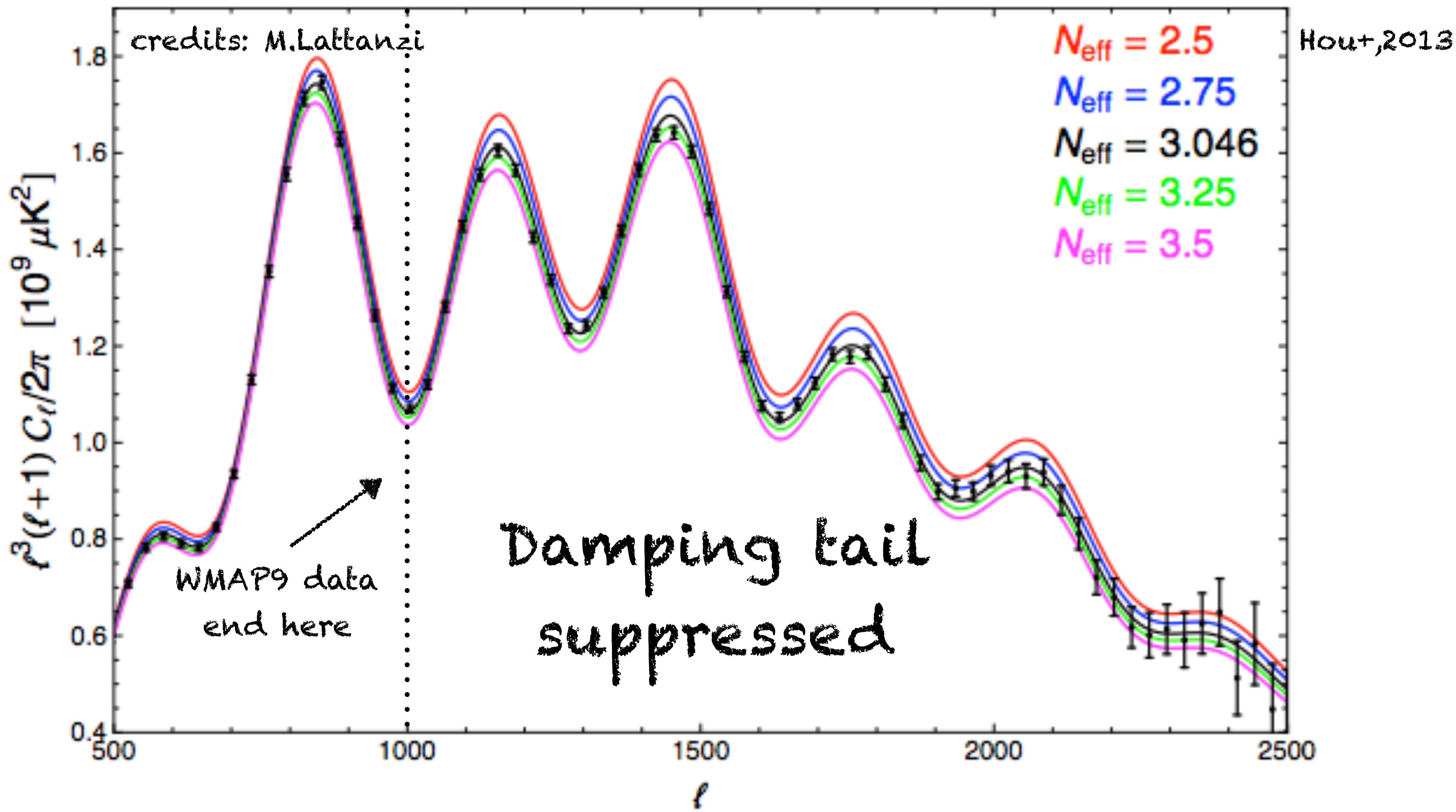
Neff modifies the expansion rate

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

$r_d^2 \propto 1/H$ (random walk)

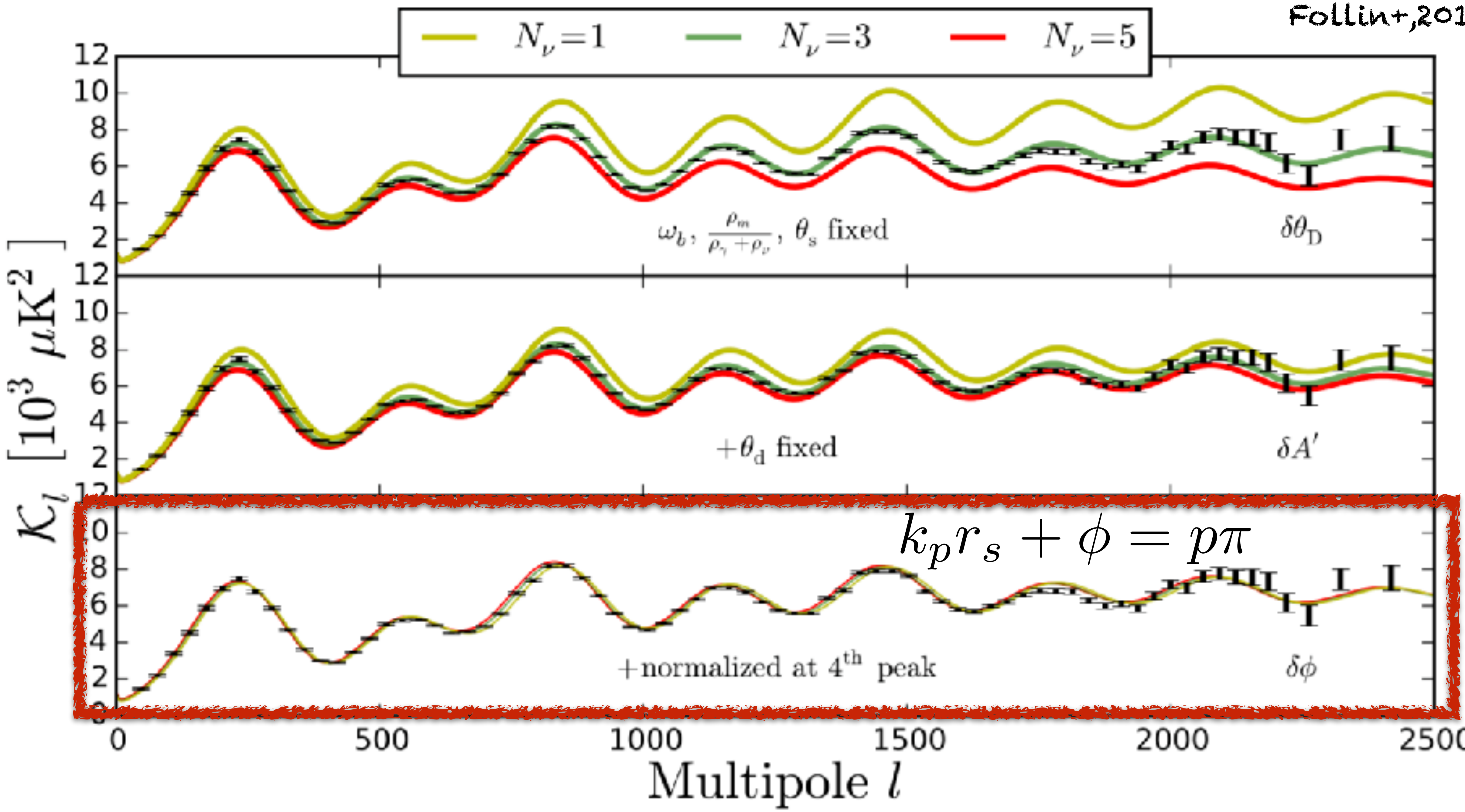
$D_A \propto 1/H$

$\theta_d = r_d / D_A \propto H^{1/2}$



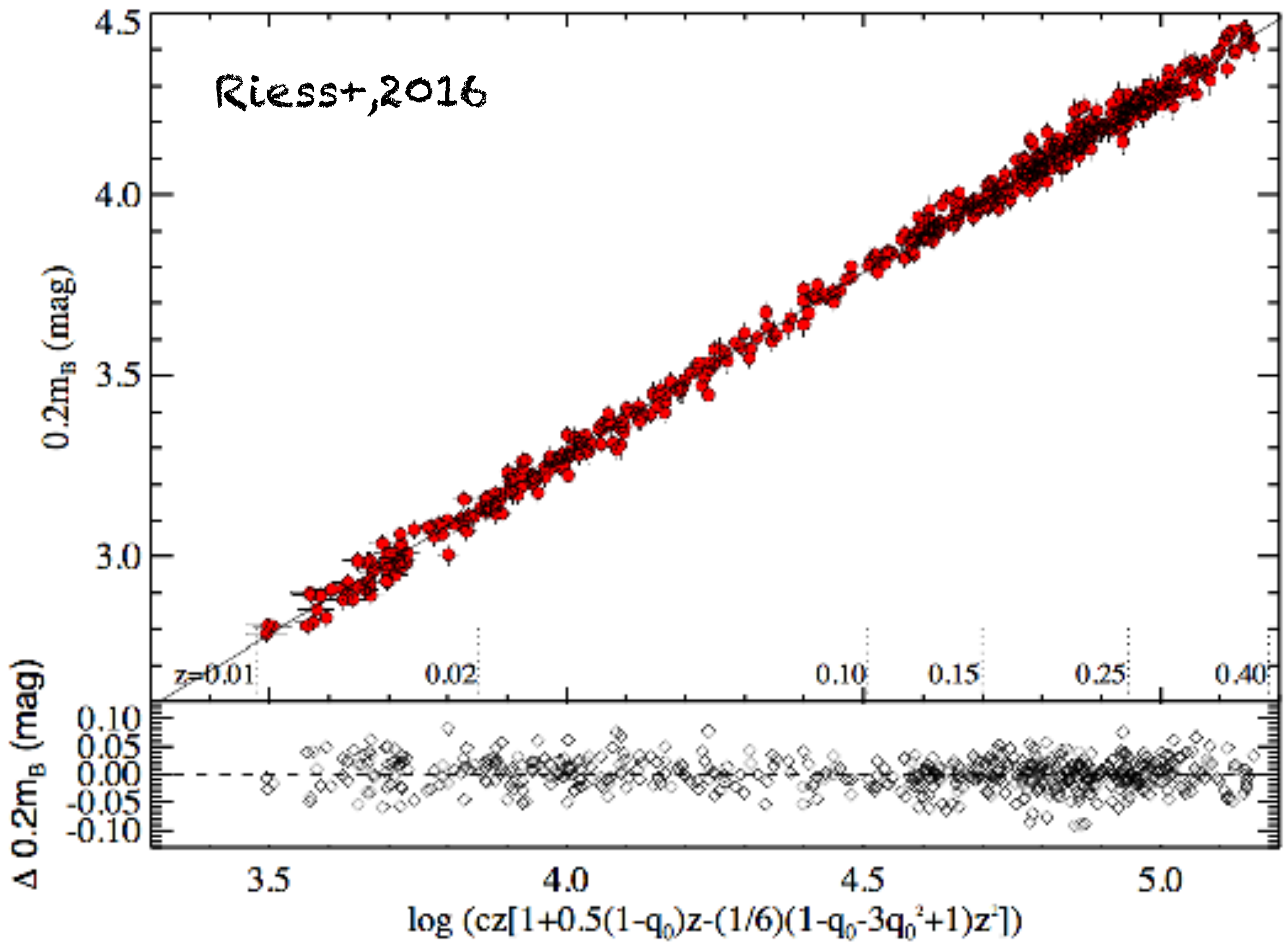
Neff modifies the expansion rate

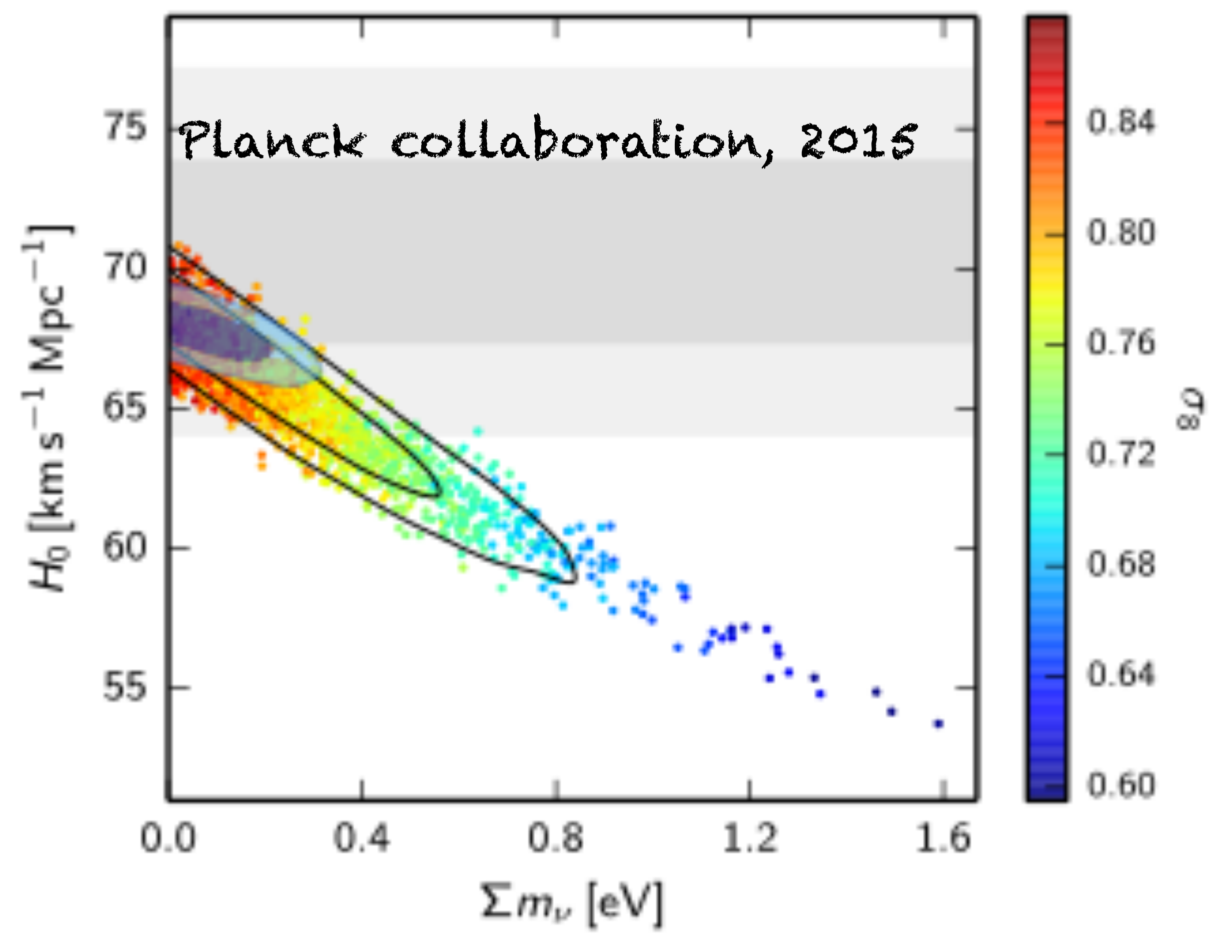
Follin+,2015



Phase shift driven by alteration of gravitational potentials due to neutrino free streaming

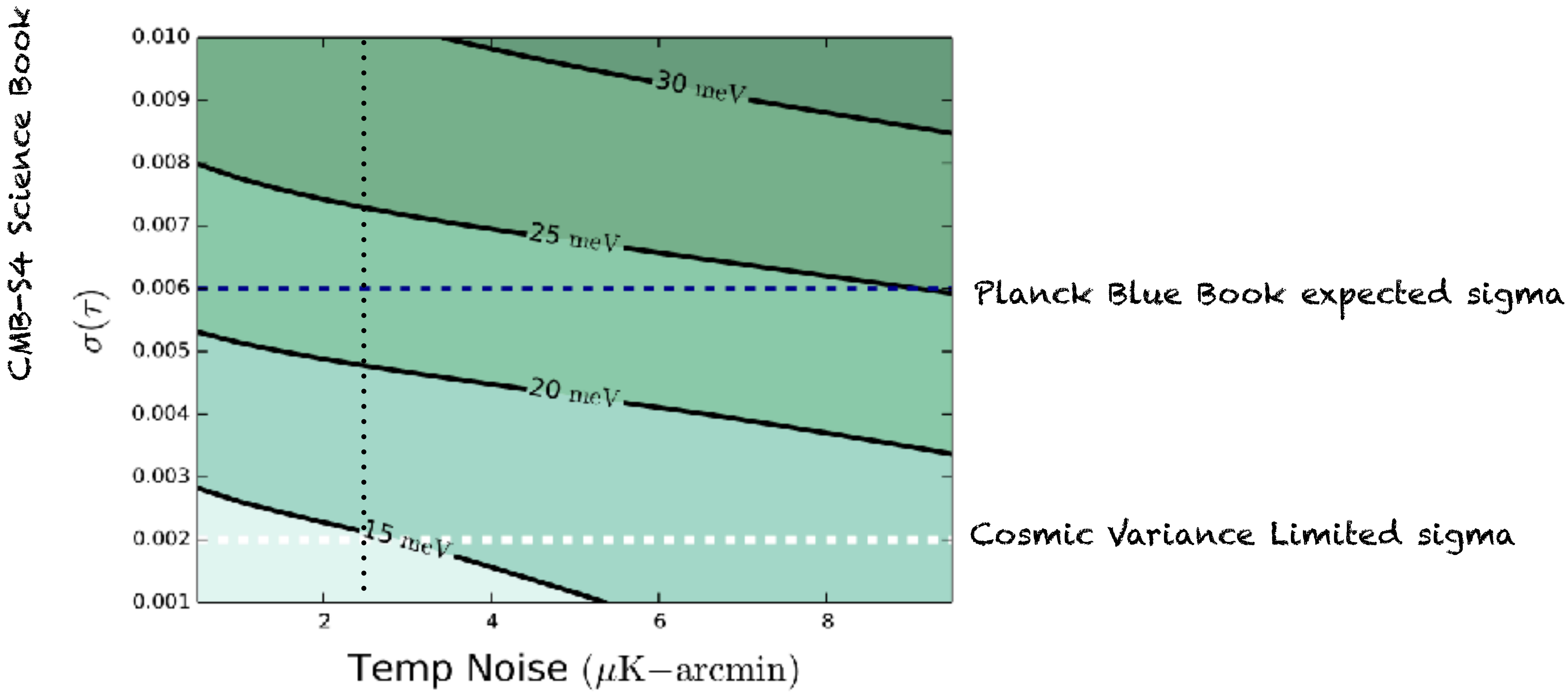
The Hubble constant





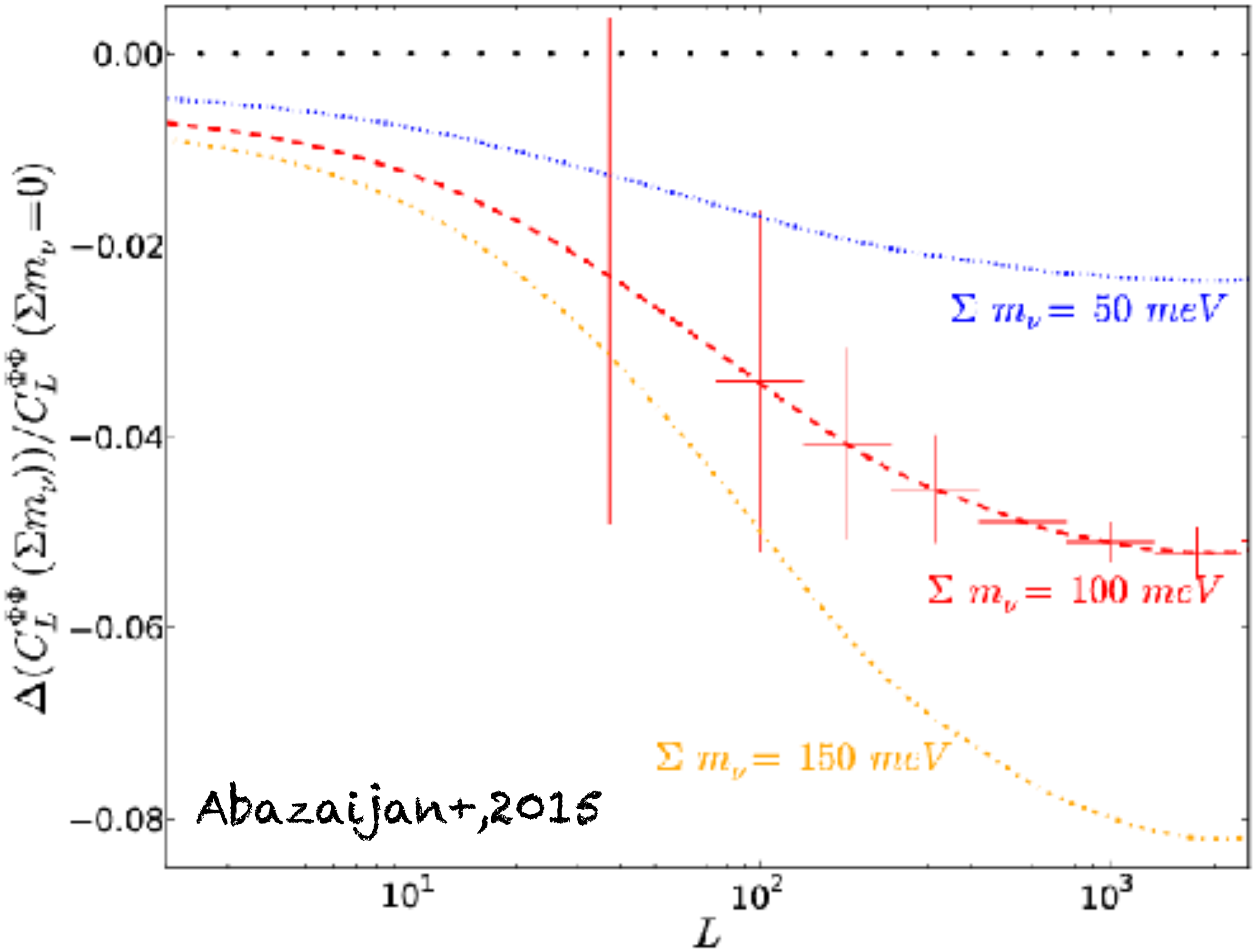
Compensate a change in the distance
to the last scattering surface
by modifying the Hubble constant

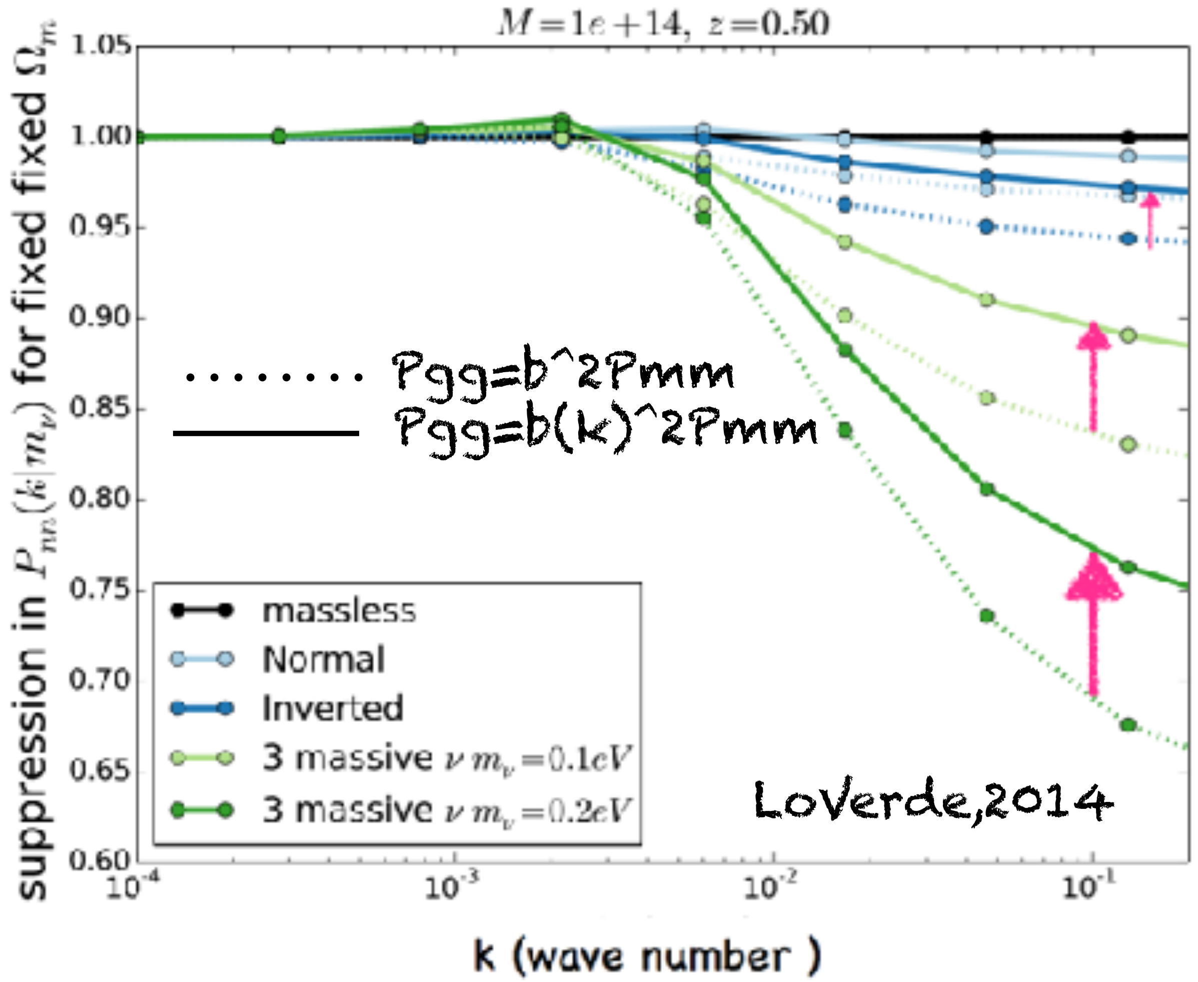
The reionisation optical depth



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

Massive neutrinos alter perturbation evolution





Gravitational Lensing potential (also lensed BB)

Scale-dependent bias in matter power spectrum

see also Costanzi+,2014

The proposed method

Mnu + other cosmological parameters

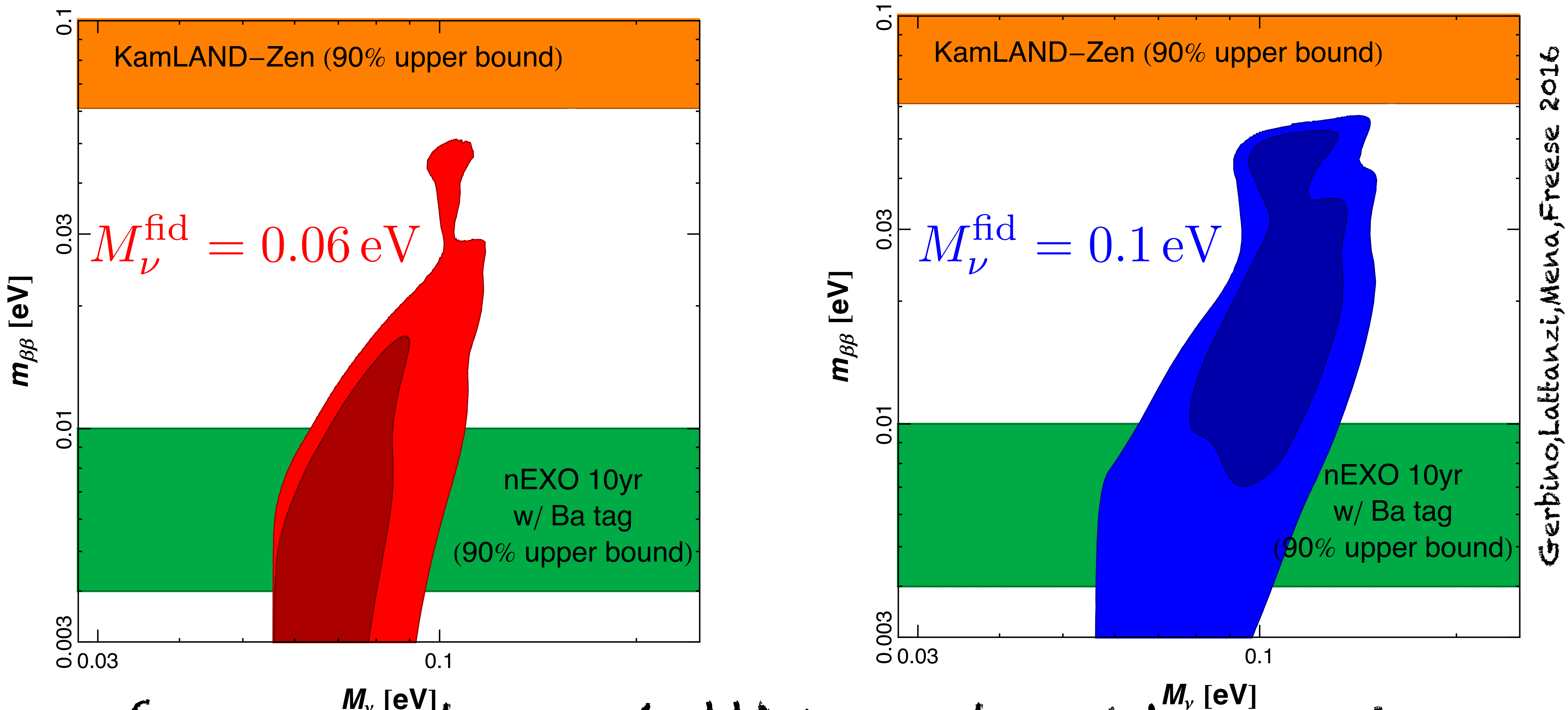
+ h → Hyper-parameter h flat in [0,1]

h<0.5	h>0.5
NORMAL HIERARCHY	**INVERTED HIERARCHY**
$m_{\nu,1} = m_{\rm light}$	$m_{\nu,3} = m_{\rm light}$
$m_{\nu,2} = \sqrt{m_1^2 + \Delta m_{12}^2}$	$m_{\nu,1} = \sqrt{m_3^2 + \Delta m_{13}^2}$
$m_{\nu,3} = \sqrt{m_1^2 + \Delta m_{13}^2}$	$m_{\nu,2} = \sqrt{m_1^2 + \Delta m_{12}^2}$

Advantages:

- neutrinos modelled with exact mass spectrum
- information from oscillations taken into account
- quantifies sensitivity to the hierarchy
- takes into account uncertainties related to the hierarchy

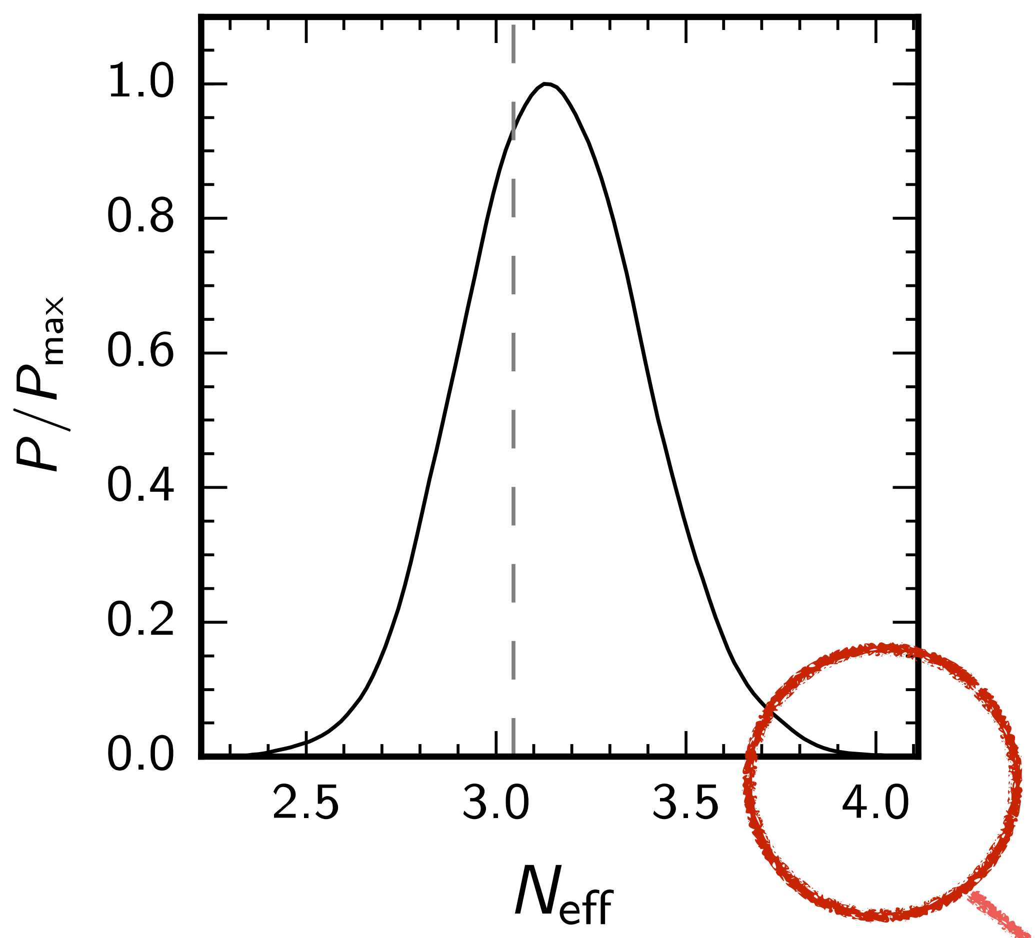
Sensitivity to the hierarchy

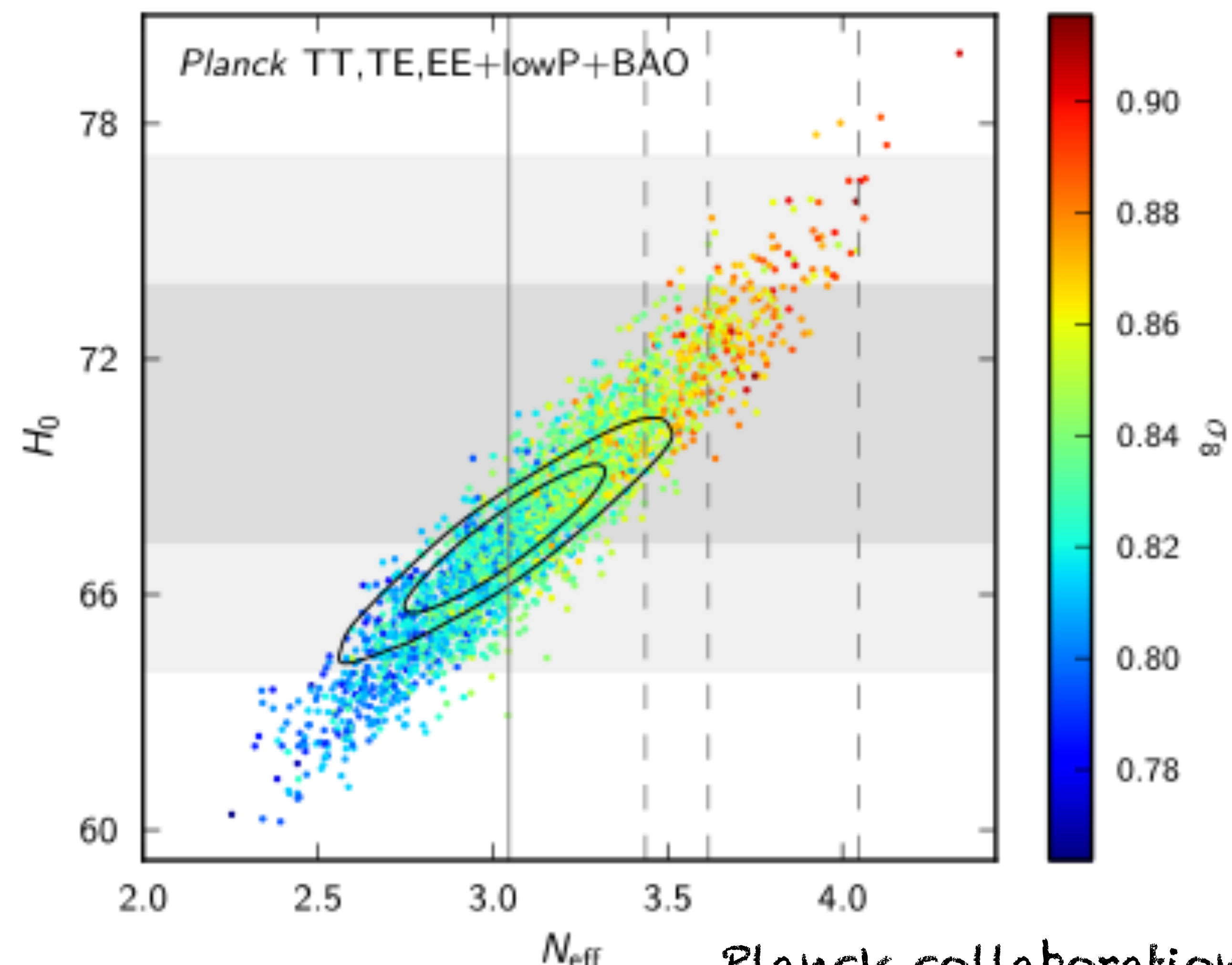


If Mnu=0.1eV, sigma(mbb)~10meV could guarantee 0n2b measurement

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_{eff} = 3.13 ± 0.32 (PlanckTT+lowP)

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

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

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

$N_{\rm eff} = 4$

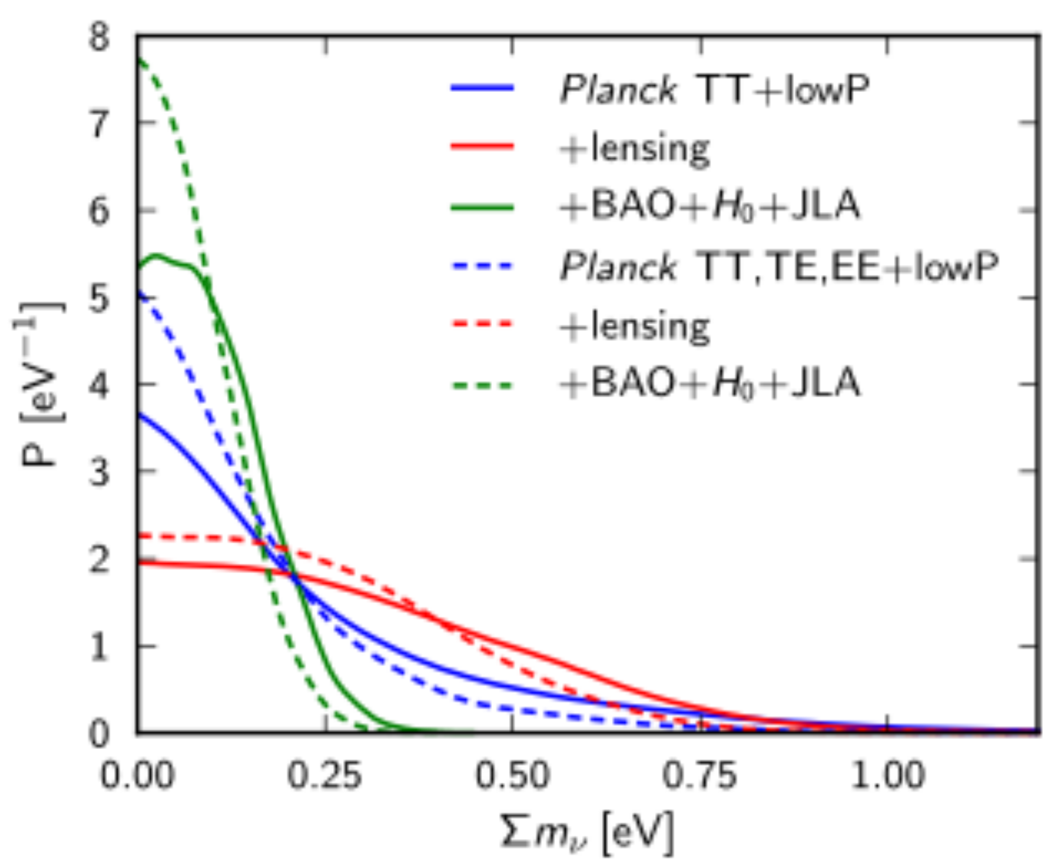
(one extra thermalized) excluded at more than 3σ

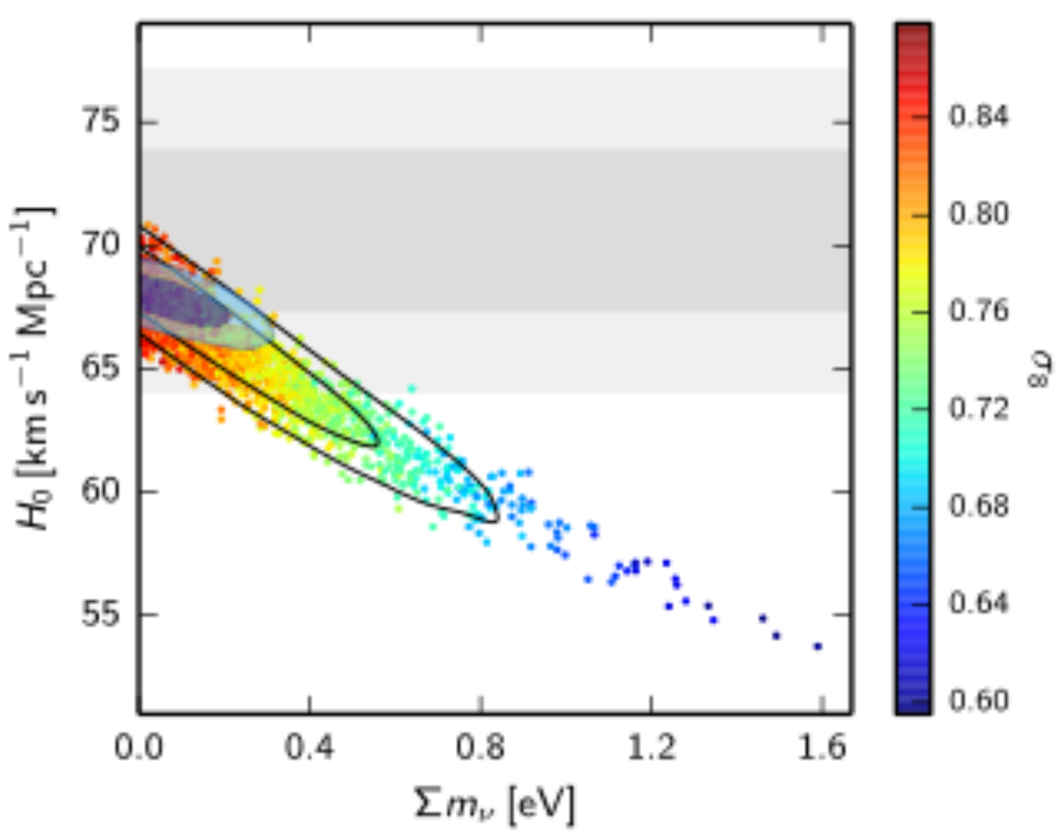
Limits on Mnu from Planck 2015

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

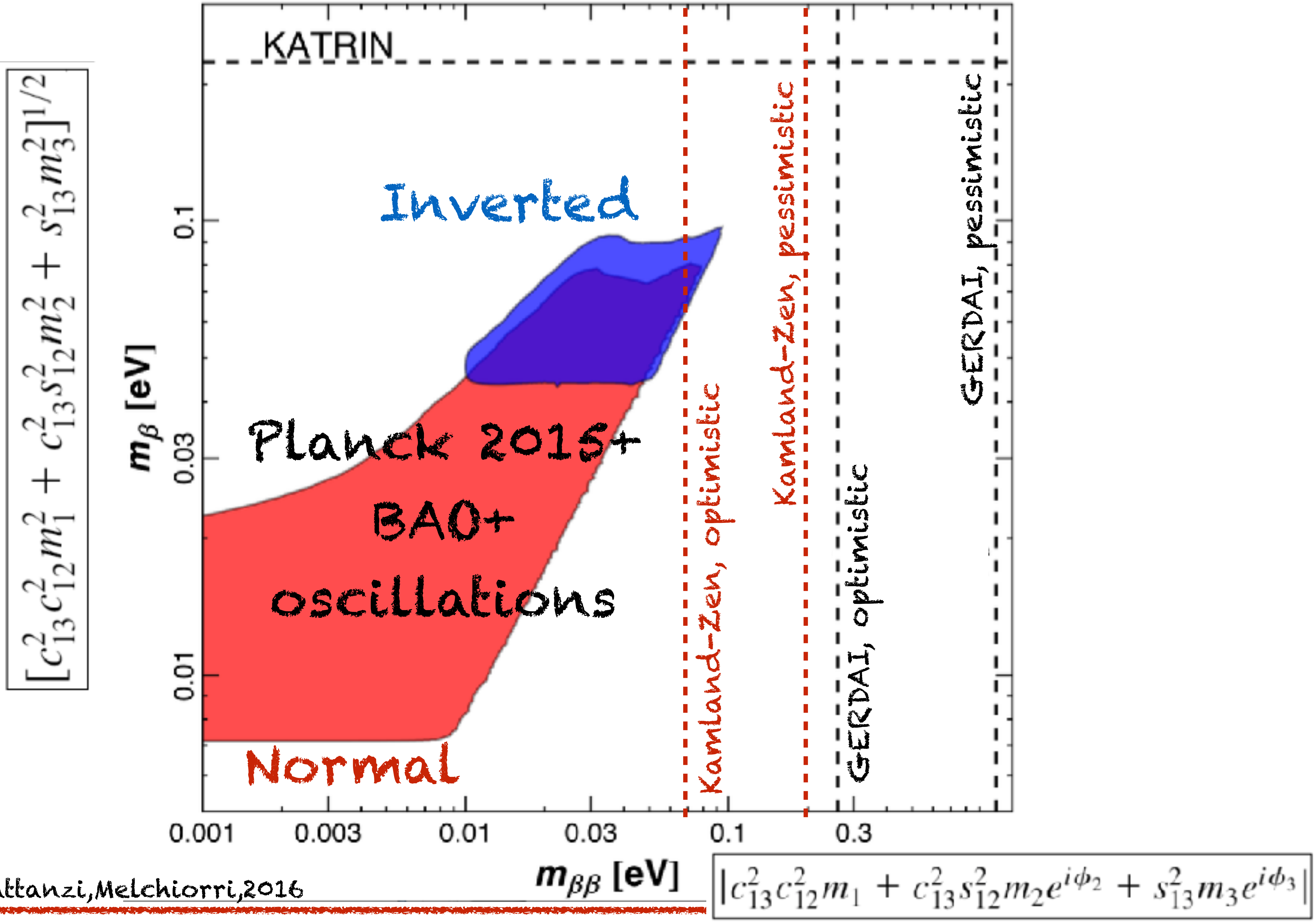
>10x better than current kinematic measurements

Planck collaboration,2015



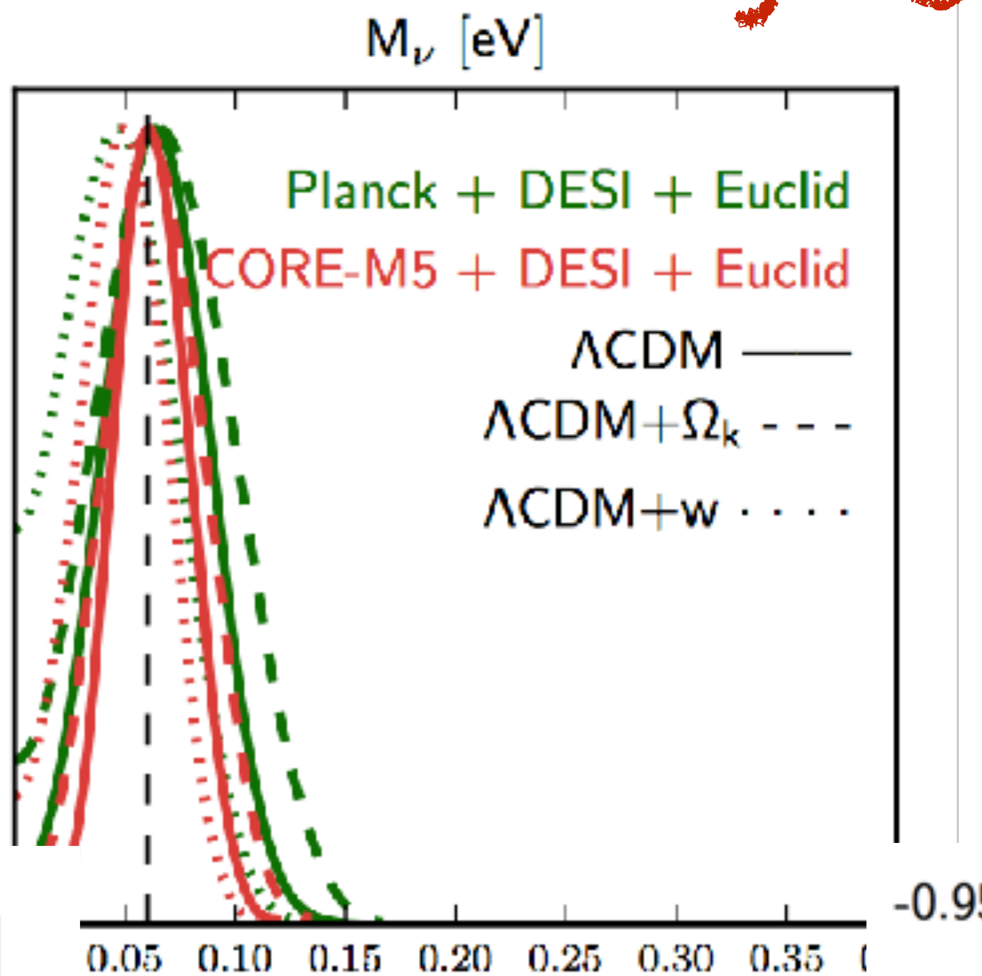


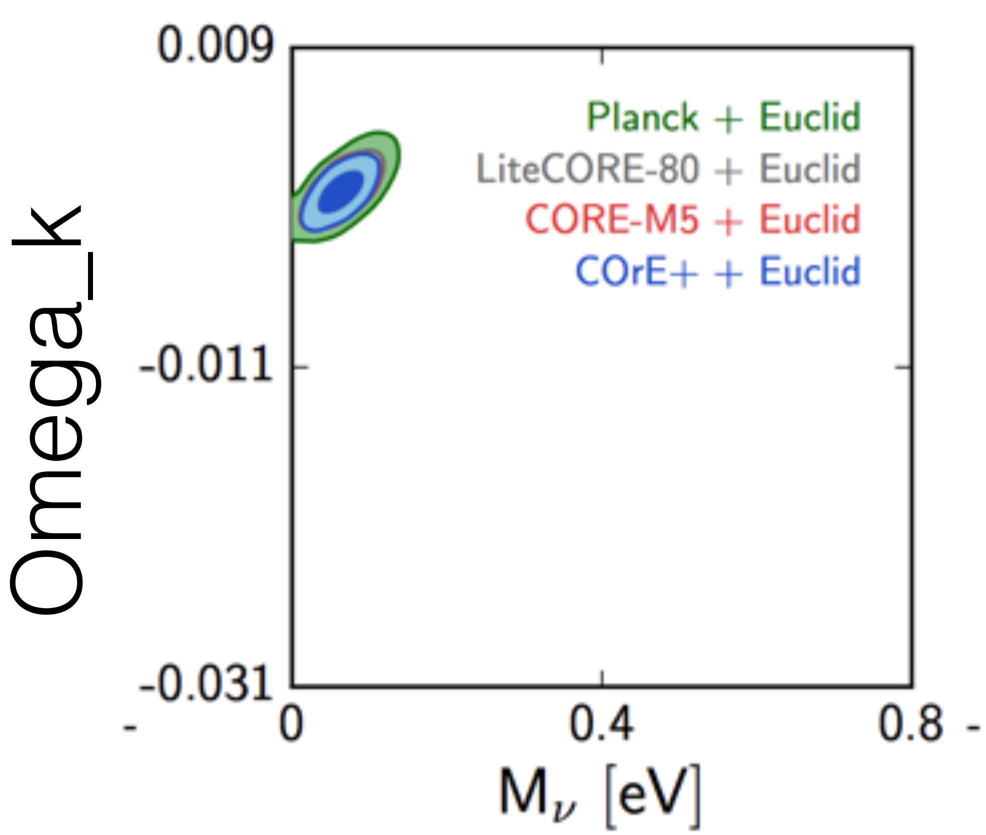
State of the art (cosmo+lab)

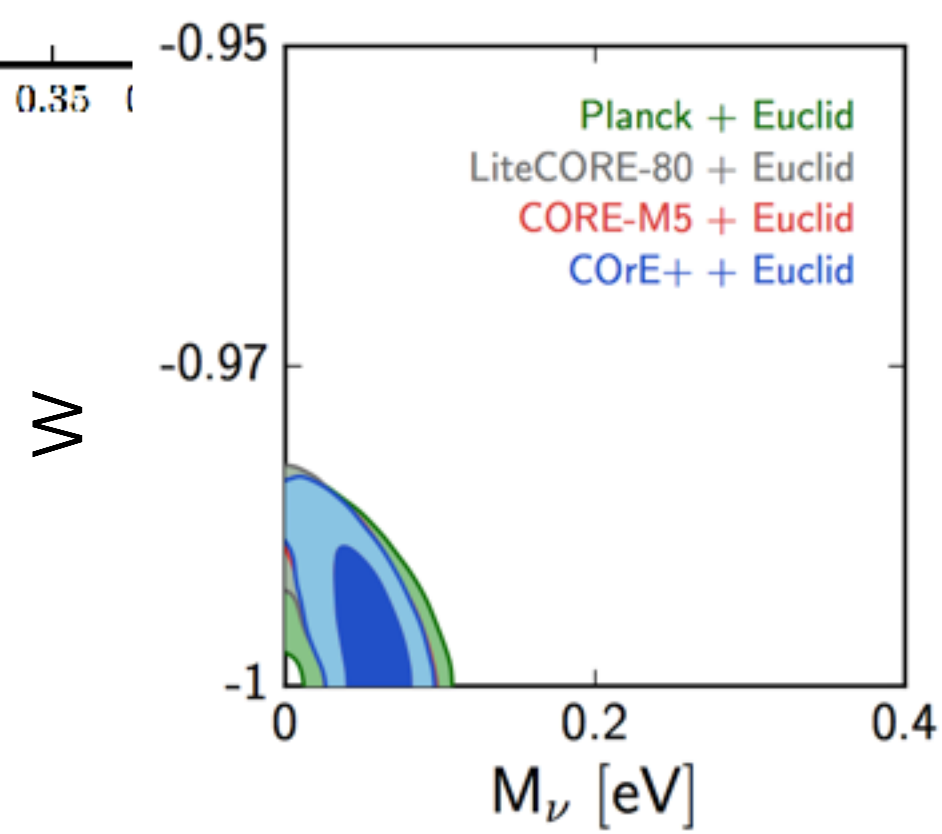


Gerbino,Lattanzi,Melchiorri,2016

Robustness wrt the underlying cosmology







CORE collaboration (DiValentino et al),2016