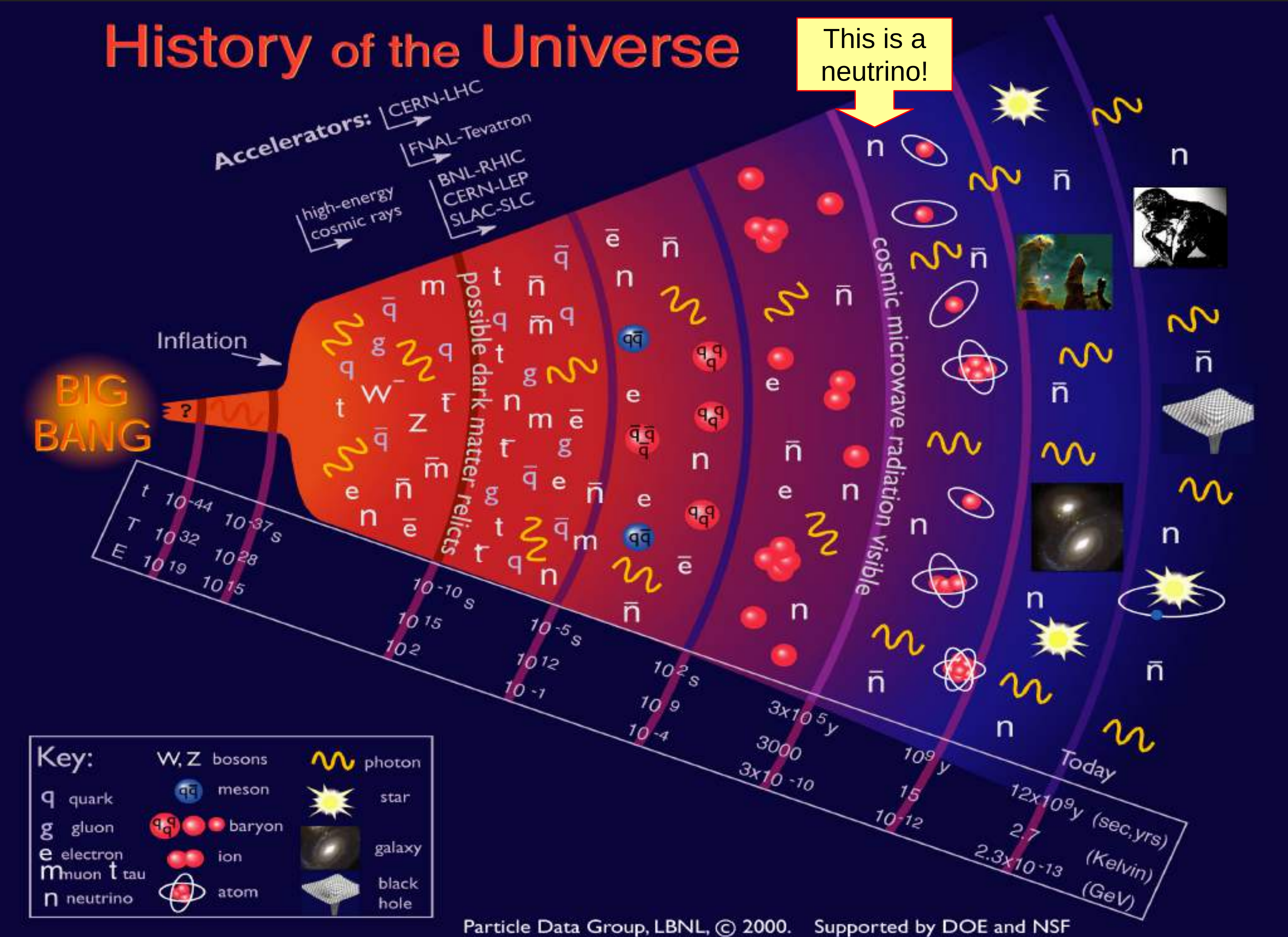
COSMIC NEUTRINO BACKGROUND: STATUS, PERSPECTIVES, AND POTENTIAL RESOLUTION OF CURRENT TENSIONS

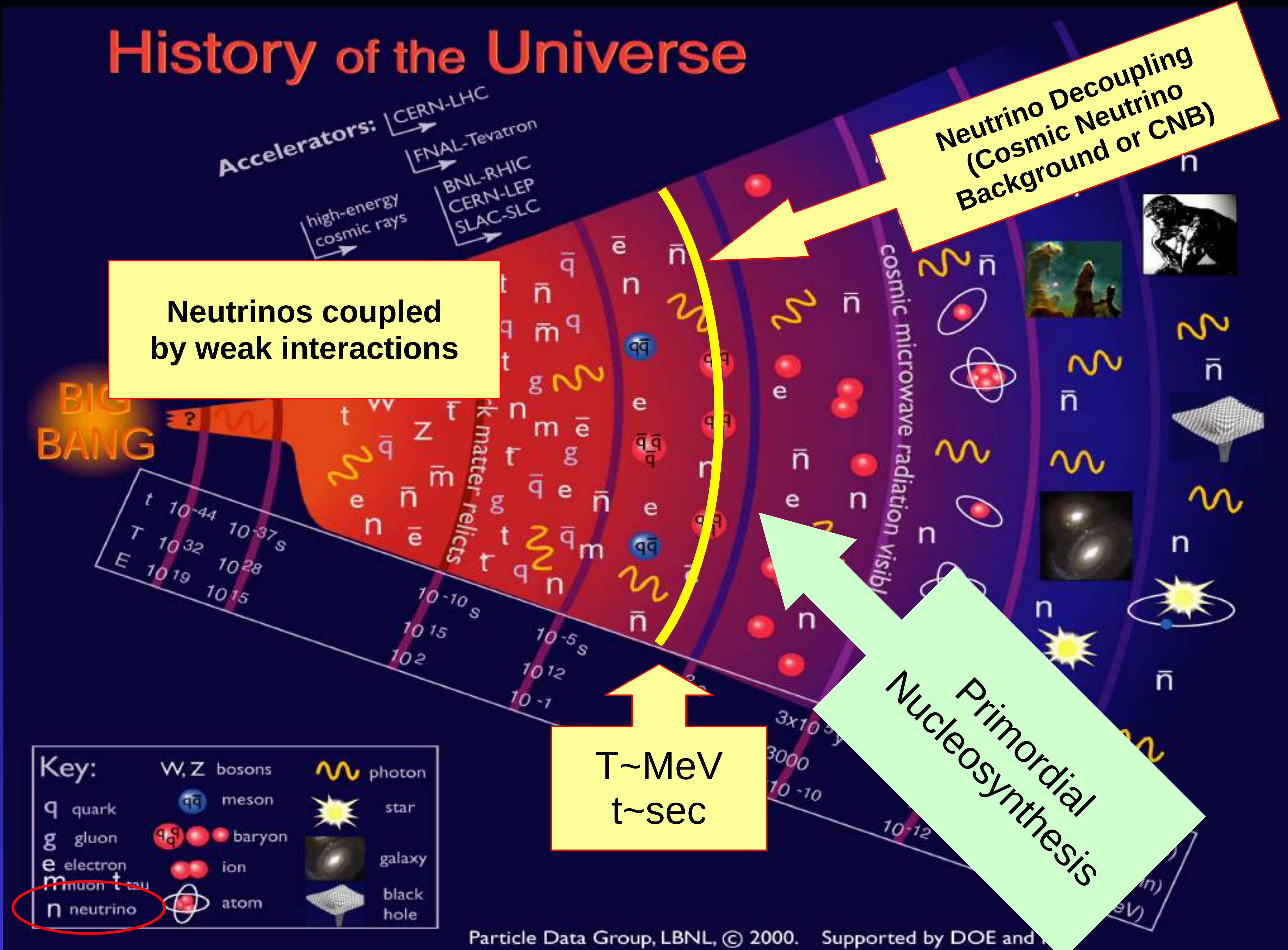
COSMOVERSE@LISBON

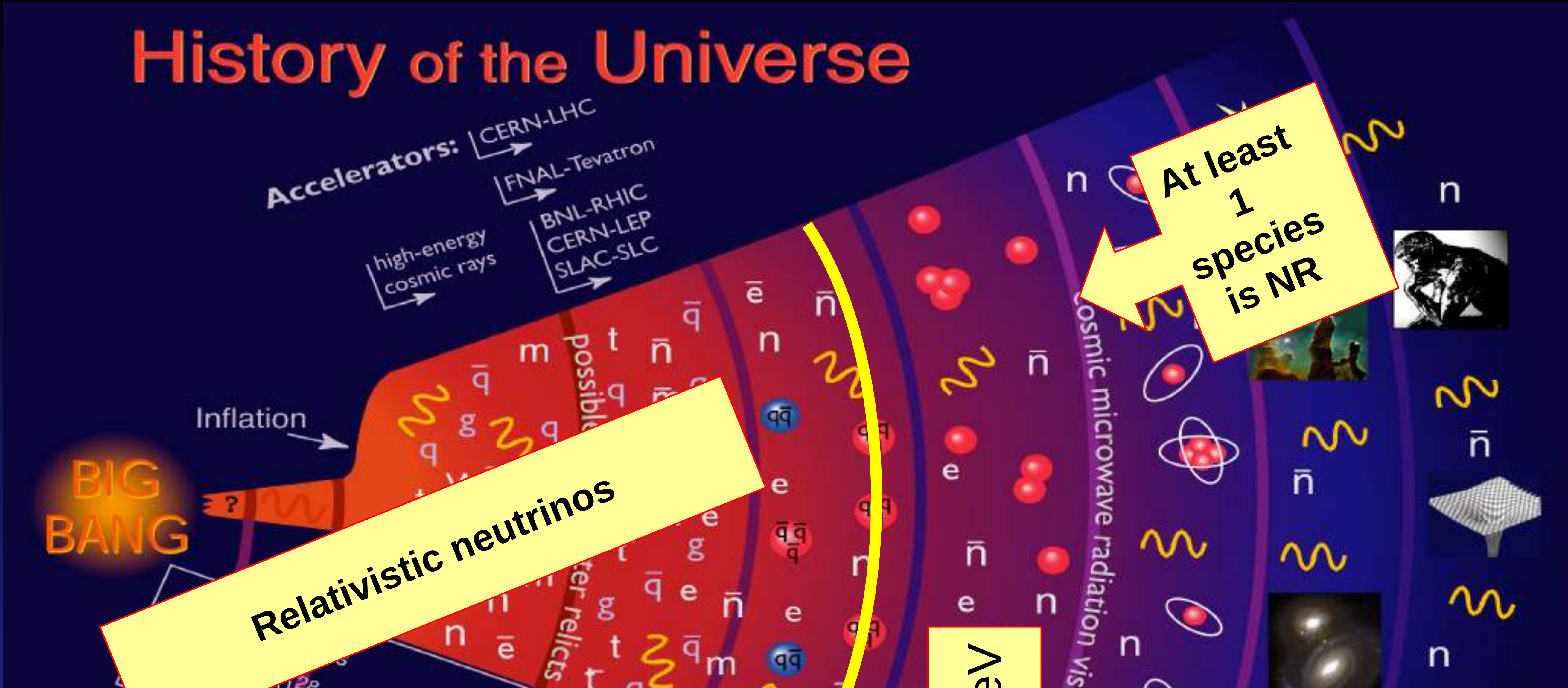
30 MAY -2 JUNE 2023

ALESSANDRO MELCHIORRI

UNIVERSITY OF ROME “SAPIENZA”


History of the Universe
This is a neutrino!
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Neutrino Decoupling (Cosmic Neutrino Background or CNB)
Neutrinos coupled by weak interactions
BIG BANG
cosmic microwave radiation visibl
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
m muon
t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and



Neutrino cosmology is interesting because Relic neutrinos are very abundant:

- The CNB contributes to radiation at early times and to matter at late times (info on the number of neutrinos and their masses)
- Cosmological observables can be used to test non-standard neutrino properties

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

COSMIC NEUTRINO BACKGROUND

THE COSMIC NEUTRINO BACKGROUND (CNB) IS AN IMPORTANT COMPONENT OF THE EARLY UNIVERSE AND HAS SIGNIFICANT IMPLICATIONS FOR COSMOLOGY.

IN THE EARLY STAGES OF THE UNIVERSE, WHEN IT WAS HOT AND DENSE, NEUTRINOS WERE IN THERMAL EQUILIBRIUM WITH OTHER PARTICLES. THE PRESENCE OF THE CNB INFLUENCES THE EXPANSION RATE AND DYNAMICS OF THE EARLY UNIVERSE.

$$\Omega_r = \left[1 + \frac{7}{4} N_{eff} \left(\frac{4}{11} \right)^{4/3} \right] \Omega_\gamma$$

STANDARD 3 NEUTRINOS

FRAMEWORK IMPLIES:

$$N_{eff} = 3.046$$

Relativistic neutrinos

COSMIC NEUTRINO BACKGROUND

$N_{eff} > 3.046$

Extra relativistic particles (axions, sterile neutrinos, EDE, etc …).

$N_{eff} = 3.046$

standard 3 neutrinos framework

$N_{eff} < 3.046$

Non-standard neutrino decoupling ?

(Inflationary reheating at low energies,.. etc)

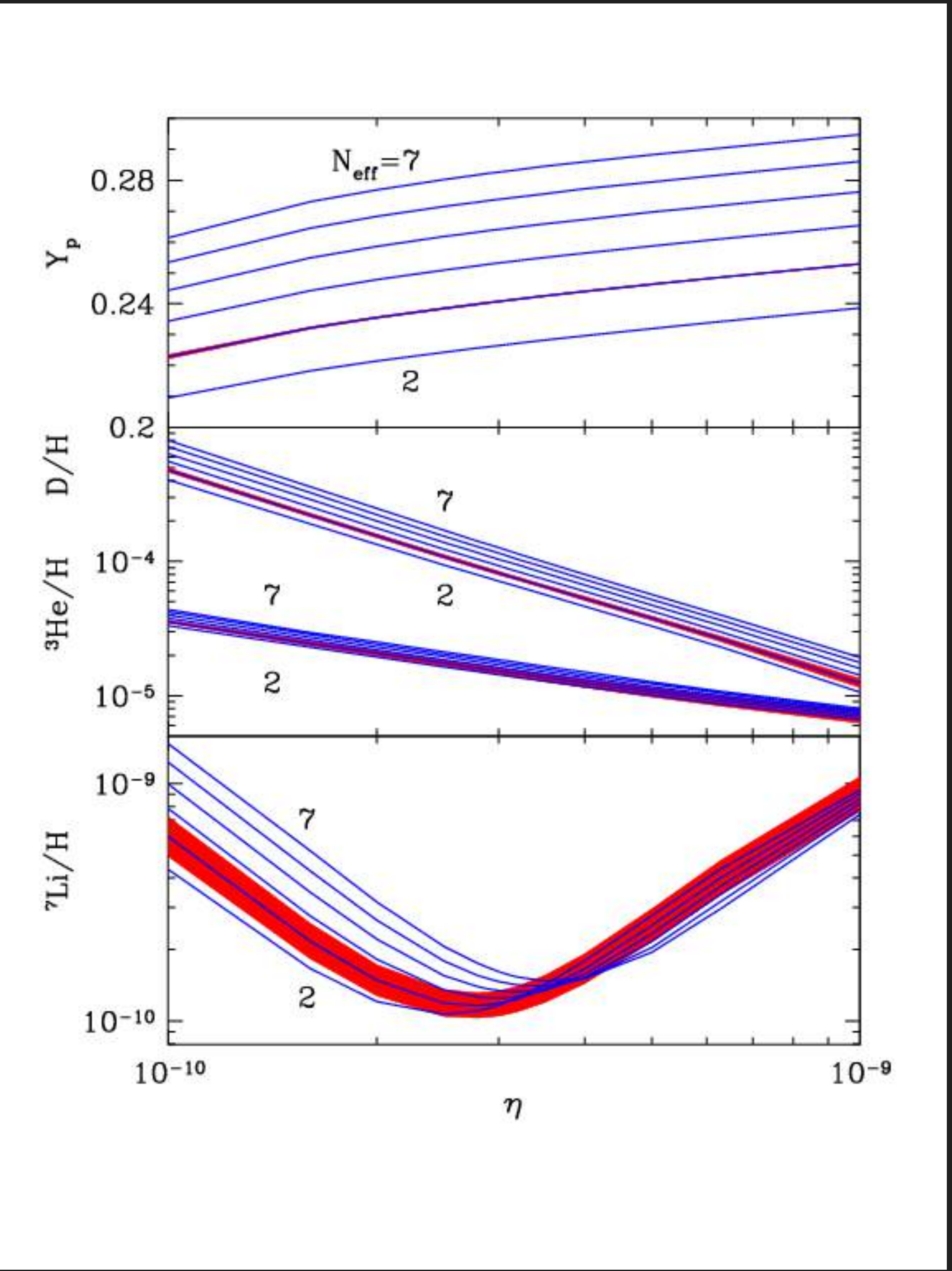
COSMIC NEUTRINO BACKGROUND

THE PRESENCE OF THE CNB INFLUENCES THE EXPANSION RATE AND DYNAMICS OF THE EARLY UNIVERSE. THIS AFFECTS VARIOUS COSMOLOGICAL PROCESSES, SUCH AS NUCLEOSYNTHESIS.

PRIMORDIAL HELIUM+DEUTERIUM MEASUREMENTS CAN CONSTRAIN CNB.

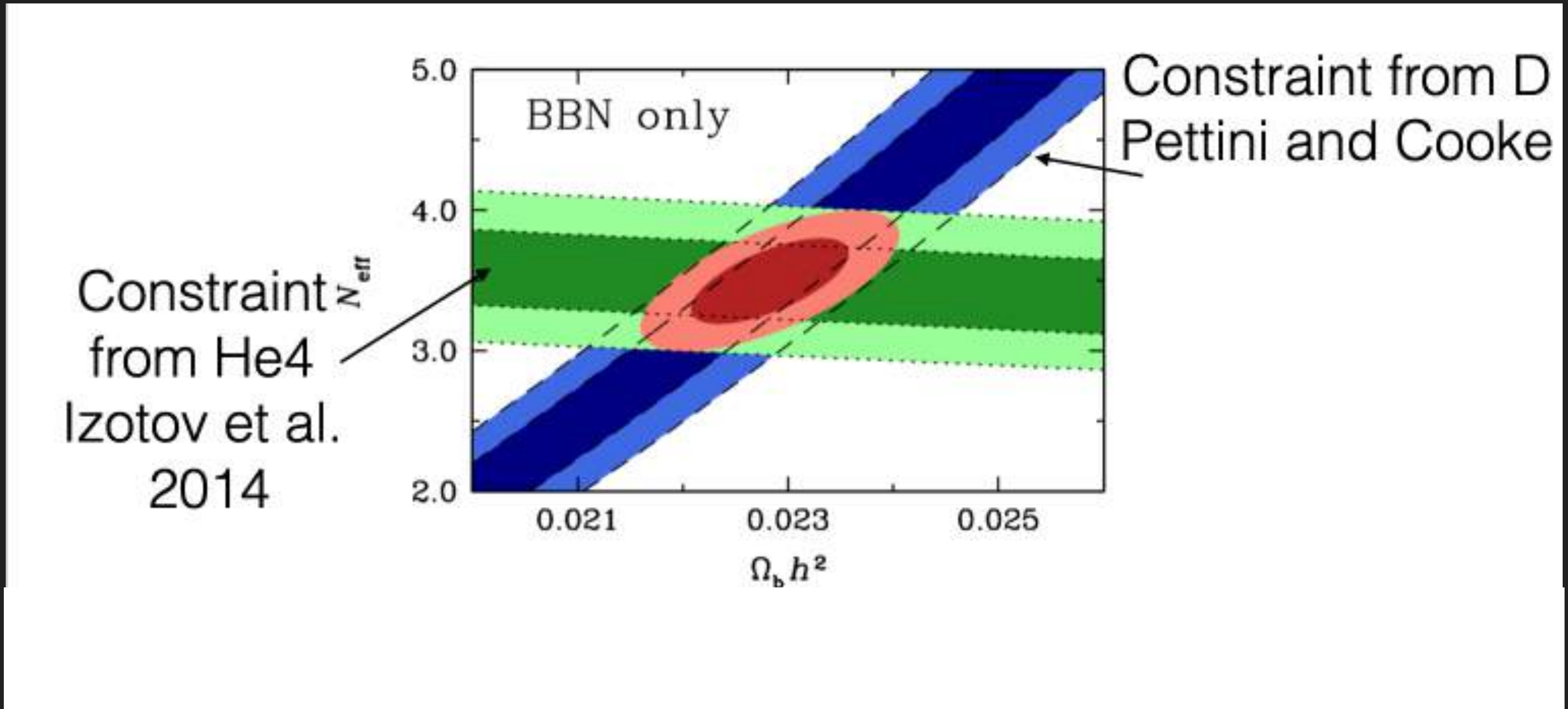
EXTRA NEUTRINOS INCREASE THE HUBBLE RATE AND SHIFT TO LOWER AGES THE EPOCH OF FREEZE-OUT.

MORE NEUTRONS AT THE BEGINNING OF BBN-> MORE HELIUM.



COSMIC NEUTRINO BACKGROUND

PRIMORDIAL HELIUM+DEUTERIUM MEASUREMENTS CAN CONSTRAIN CNB.

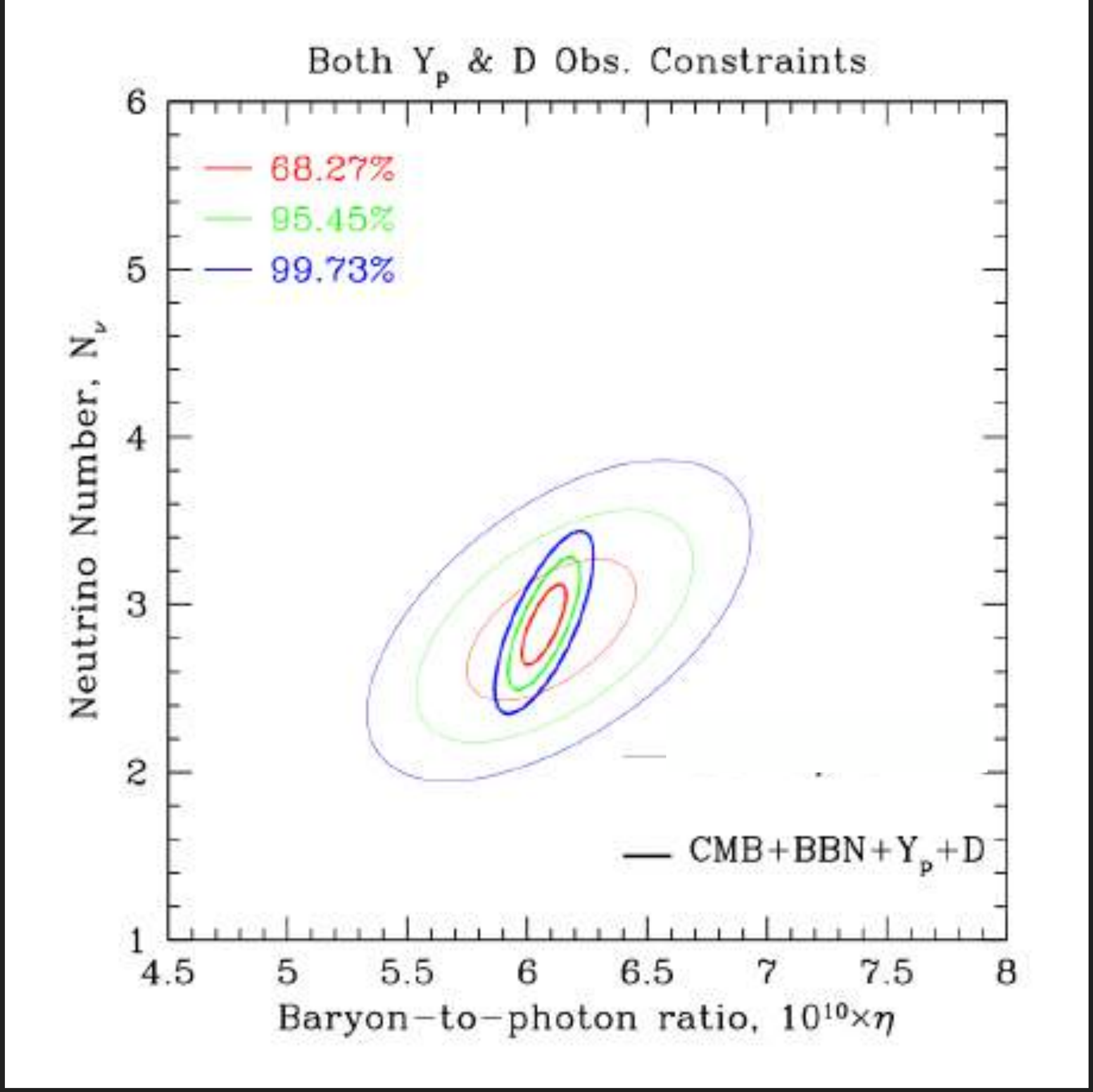


CNB DETECTED AT MORE THAN 17 STANDARD DEVIATIONS !!!

$$N_{eff} = 3.50 \pm 0.20$$

COSMIC NEUTRINO BACKGROUND

PRIMORDIAL HELIUM+DEUTERIUM MEASUREMENTS CAN CONSTRAIN CNB.



AVER ET AL. 2015

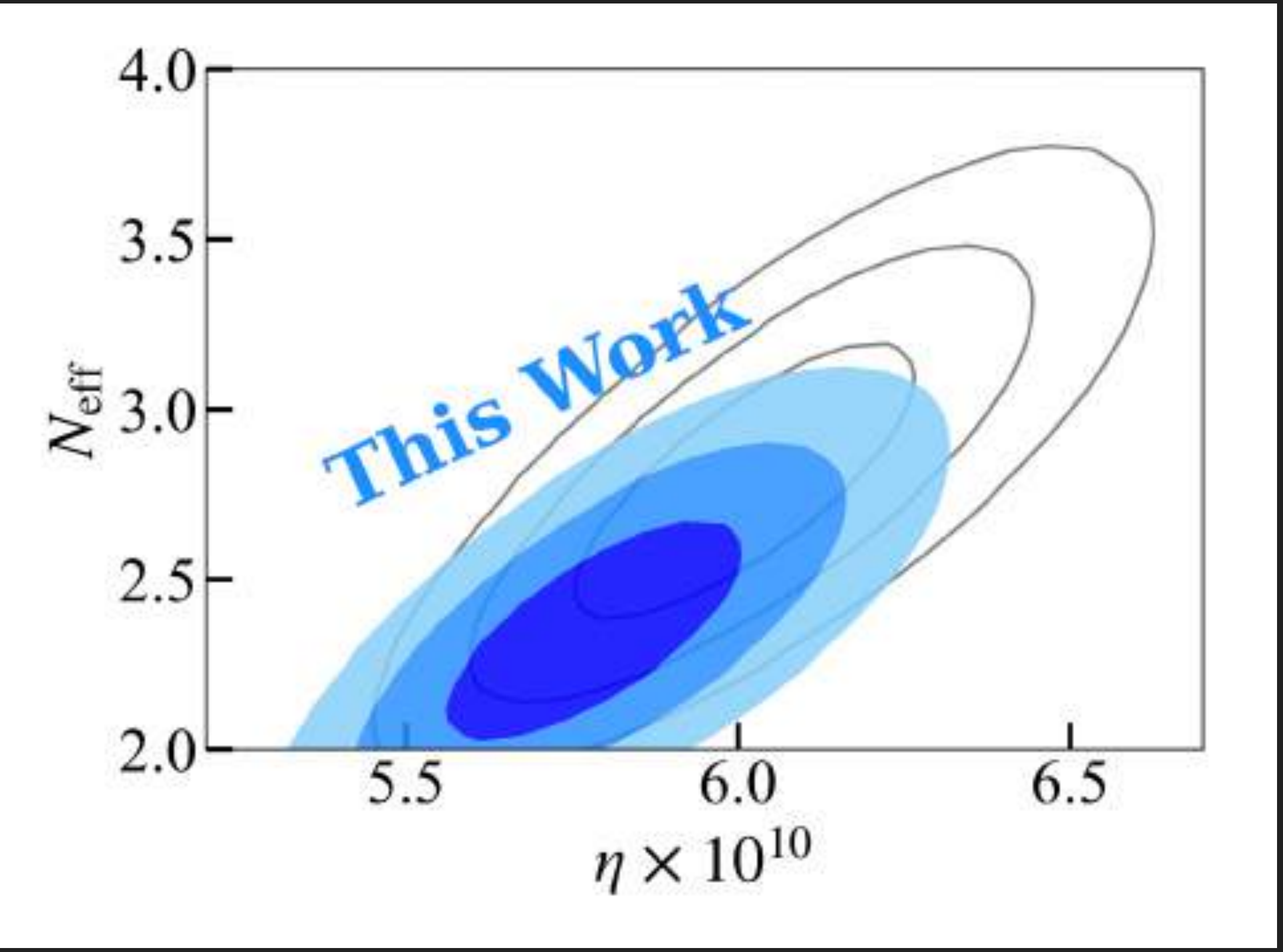
CYBURT ET AL. 2015

$$N_{eff} = 2.85 \pm 0.28$$

CNB DETECTED AT MORE THAN 10 STANDARD DEVIATIONS !!

COSMIC NEUTRINO BACKGROUND

PRIMORDIAL HELIUM+DEUTERIUM MEASUREMENTS CAN CONSTRAIN CNB.



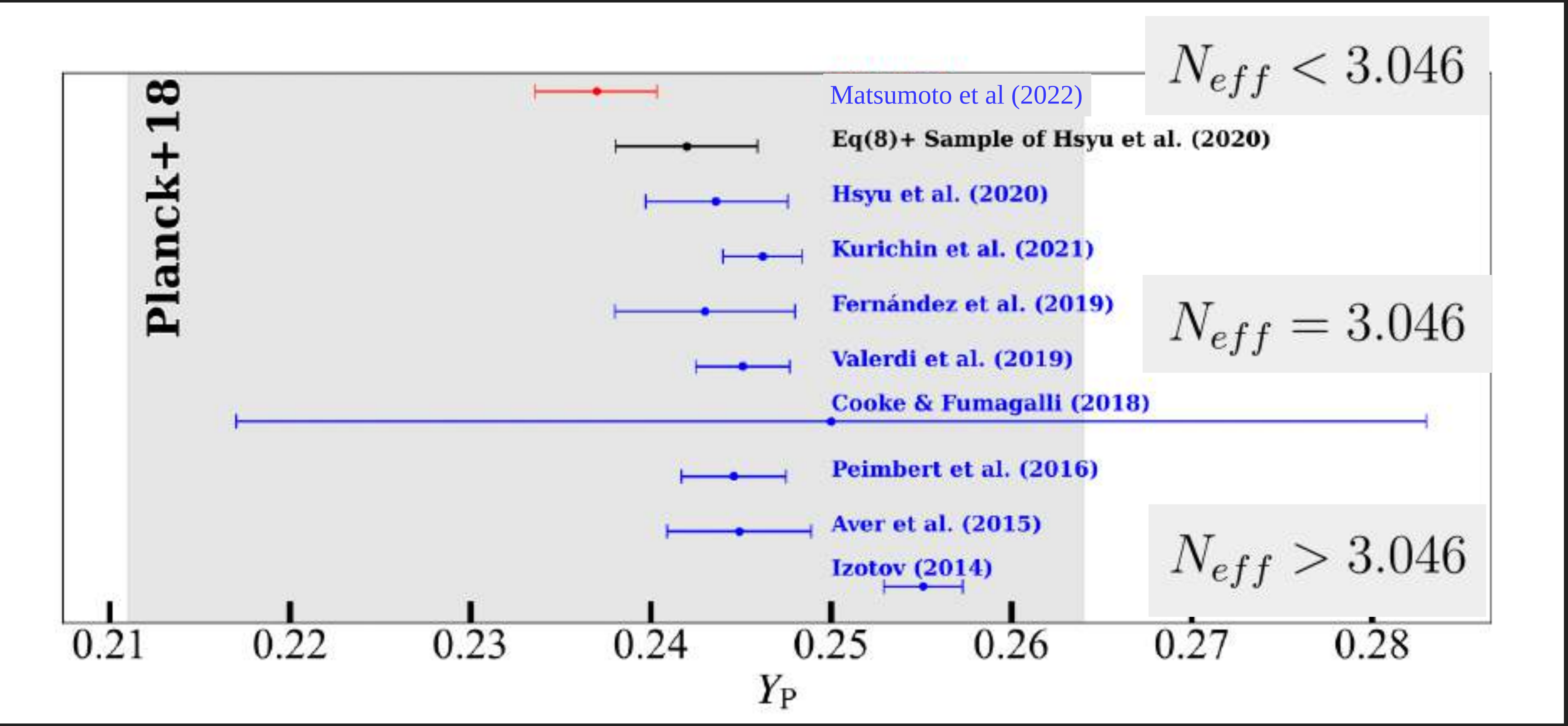
MATSUMOTO ET AL 2022

$$N_{eff} = 2.37^{+0.19}_{-0.24}$$

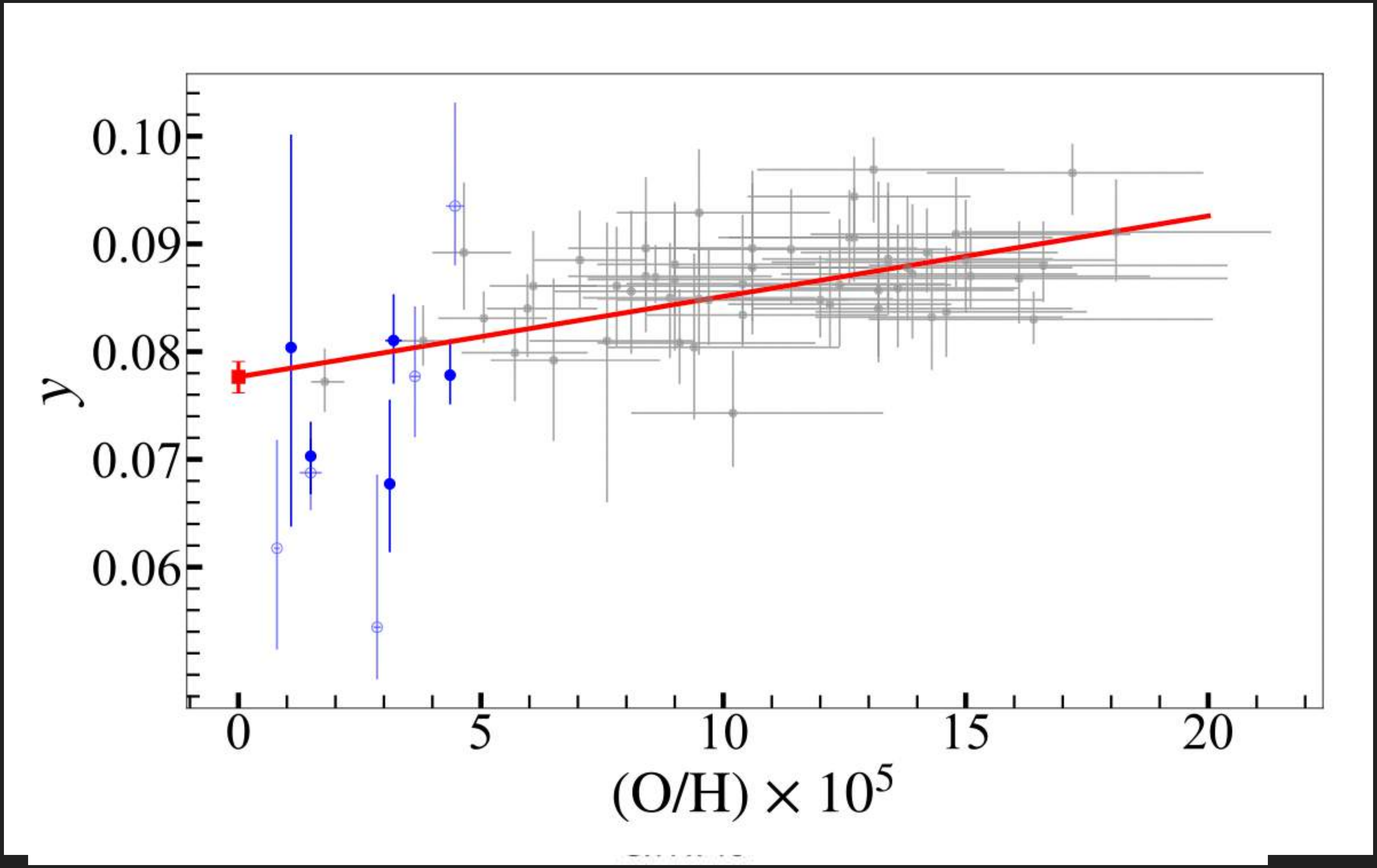
CNB DETECTED AT MORE THAN 9 STANDARD DEVIATIONS !

COSMIC NEUTRINO BACKGROUND

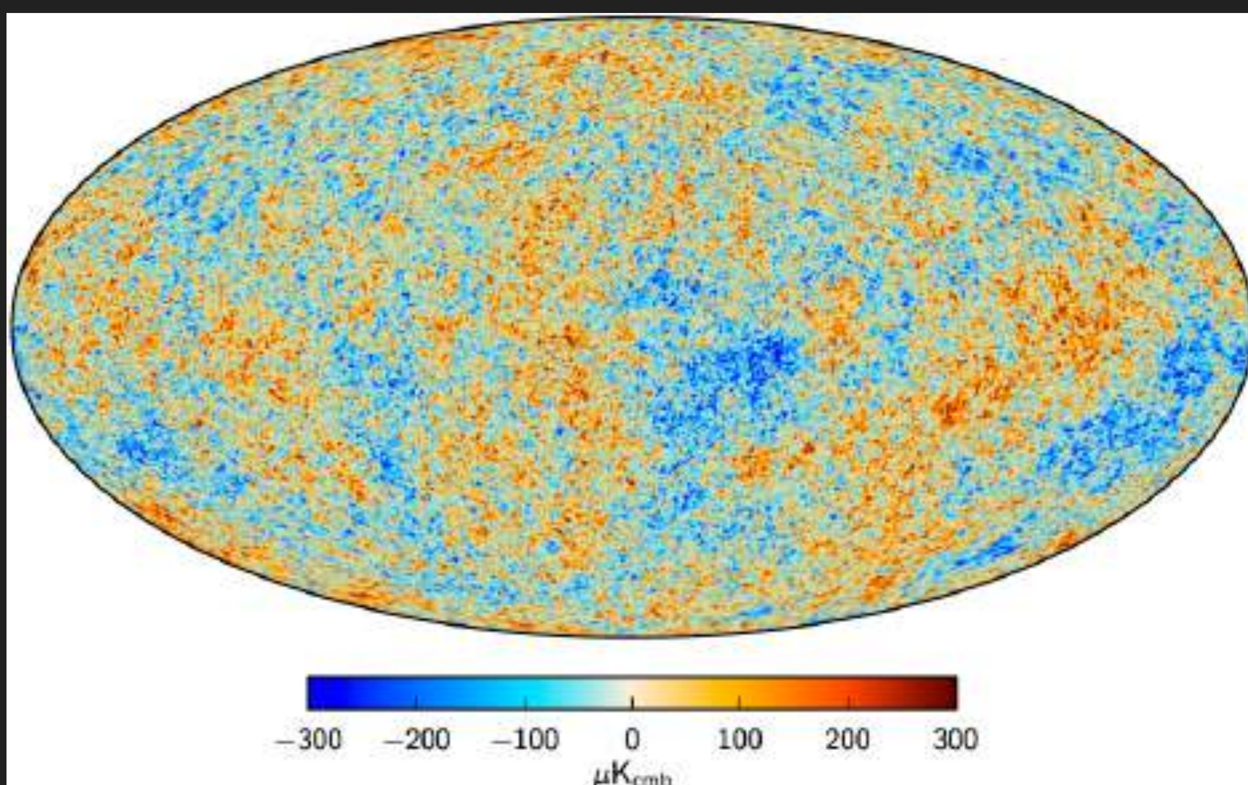
CURRENT EXPERIMENTAL UNCERTAINTIES IN THE PRIMORDIAL HE4 ABUNDANCE ARE IN TENSION…

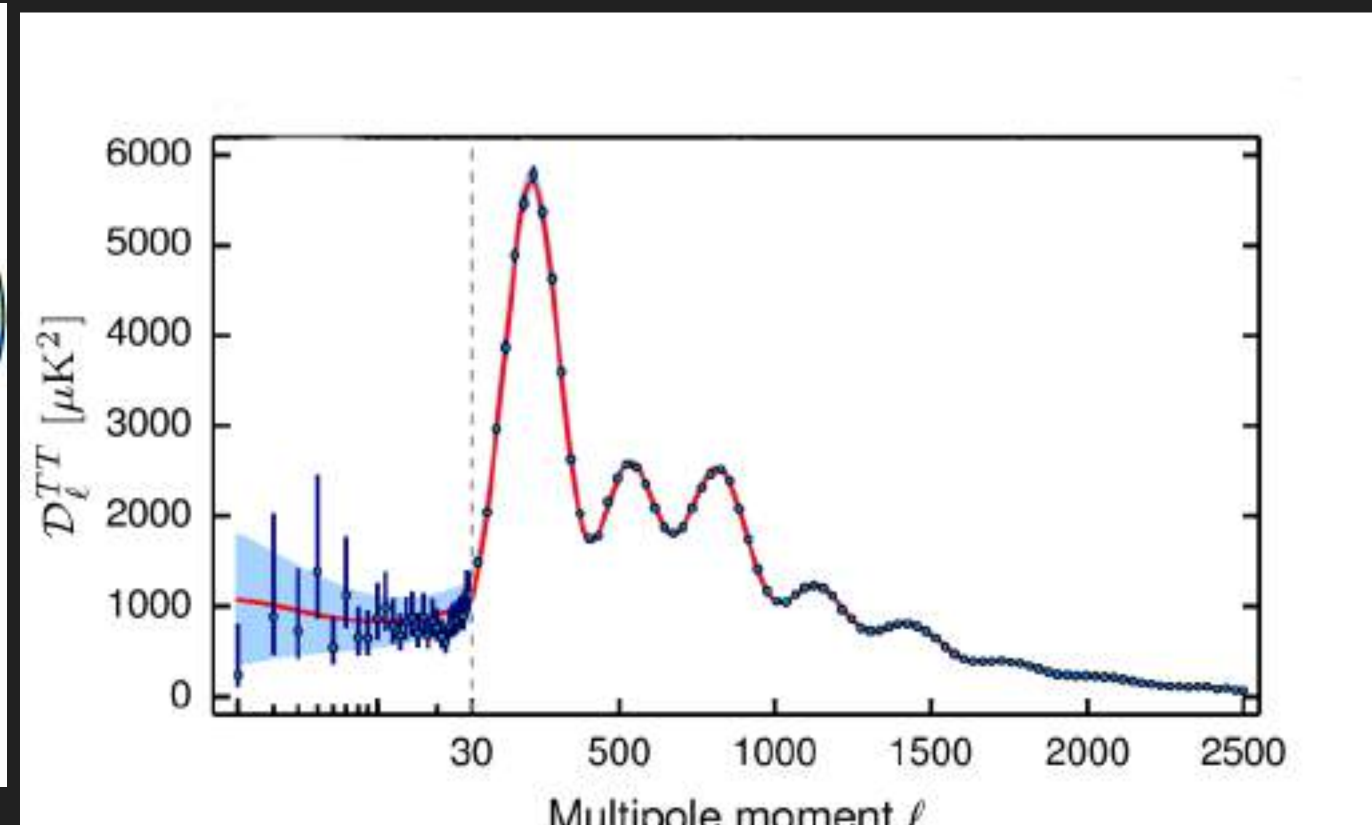


HELIUM 4 MEASUREMENTS



CNB FROM CMB

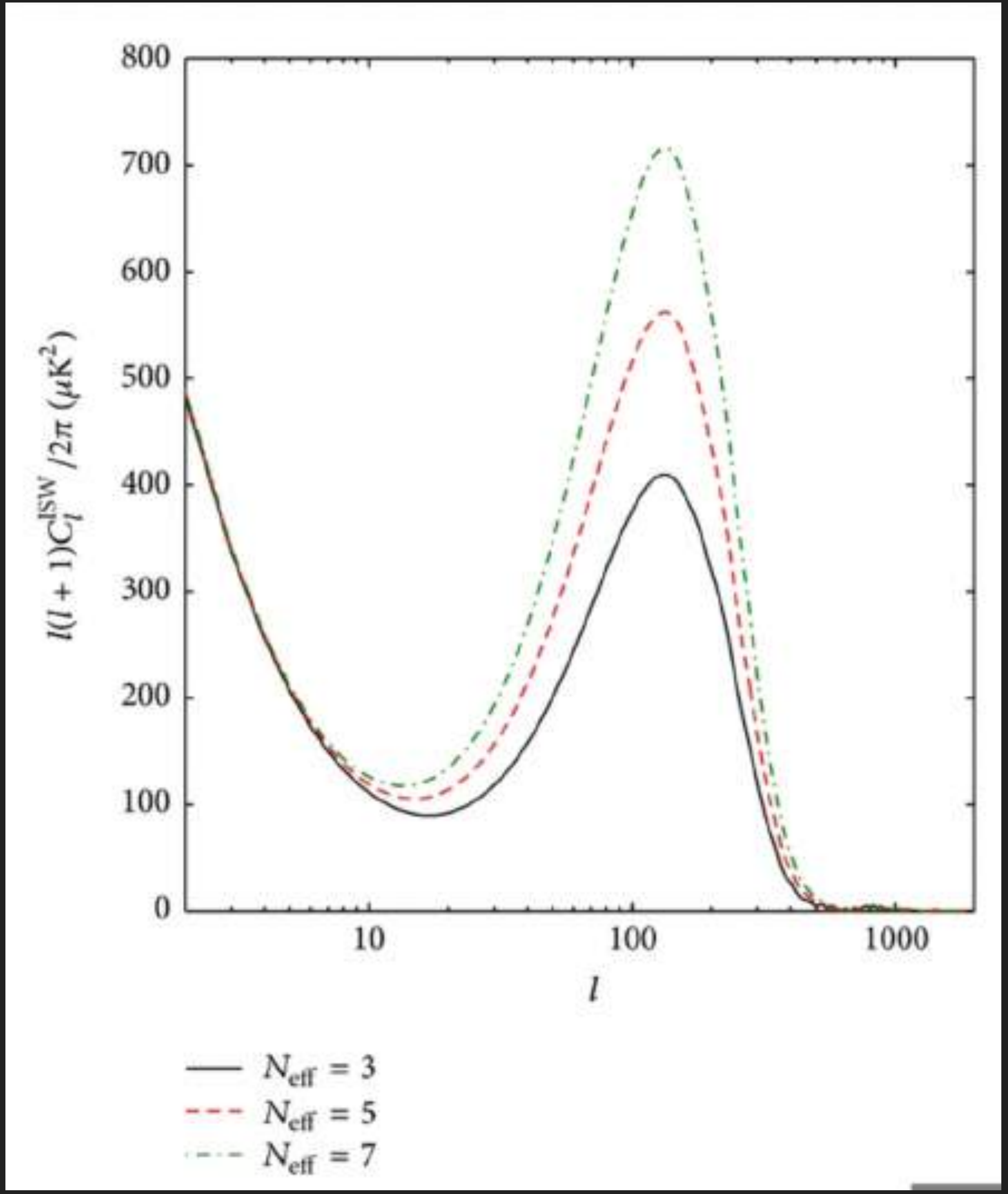

−300 −200 −100 0 100 200 300
μK_cmb


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
30
500
1000
1500
2000
2500
Multipole moment ℓ

CMB VS CNB

First effect:

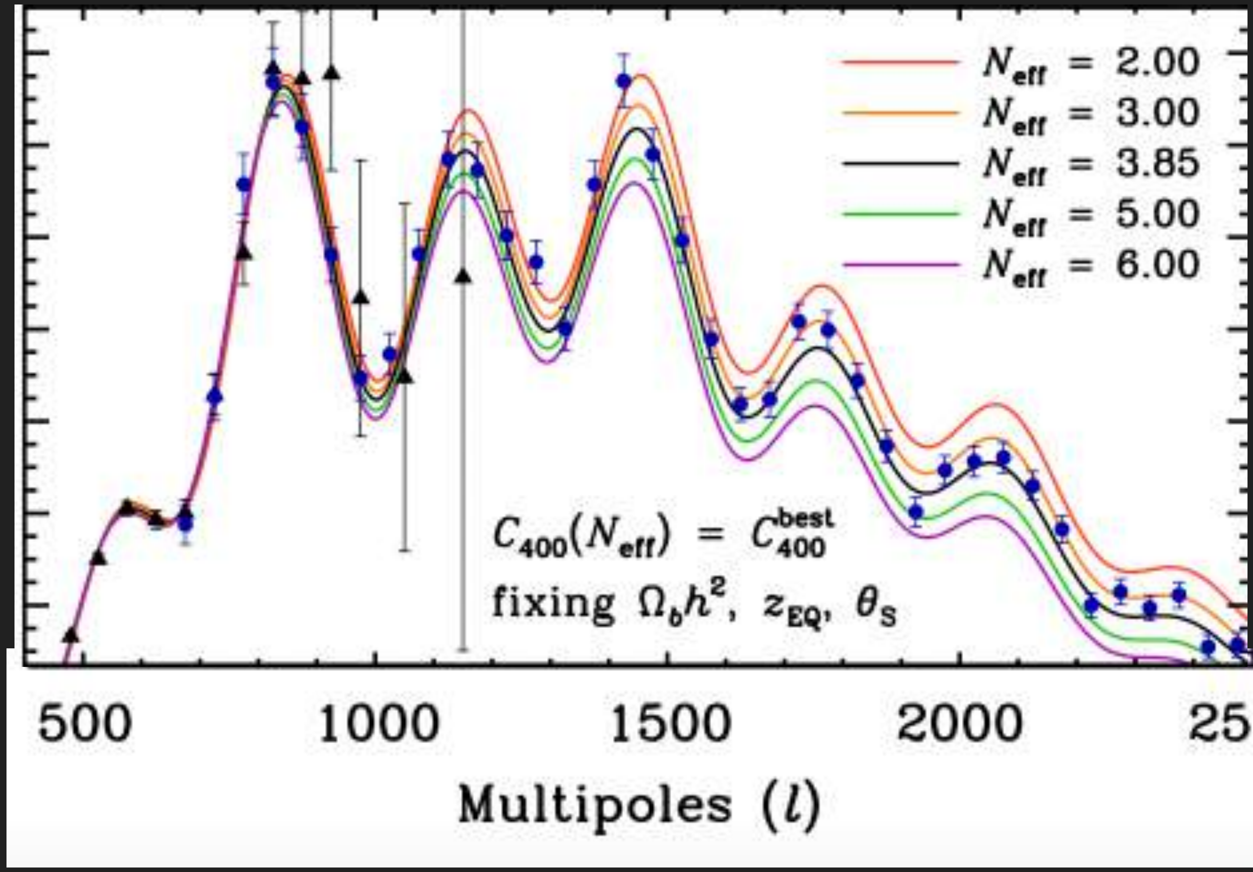
Neff changes the amount of radiation at recombination. This changes the Early Integrated Sachs Wolfe effect.



CMB VS CNB

Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the damping scale at recombination:

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$



increasing N_{eff} should decrease the damping scale and the result should be an increase in the small angular scale anisotropy.
However you have to keep fixed the sound horizon angular scale:

$$\theta_S = r_s / D_A$$

$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}.$$

that varies more rapidly than the damping scale and the result is a increase in $\theta_d = r_d / D_A$
and a decrease in the small angular scale anisotropy.
We expect degeneracies with the Hubble constant and the Helium abundance.
(see e.g. Hou, Keisler, Knox et al. 2013, Lesgourgues and Pastor 2006).

CMB VS CNB

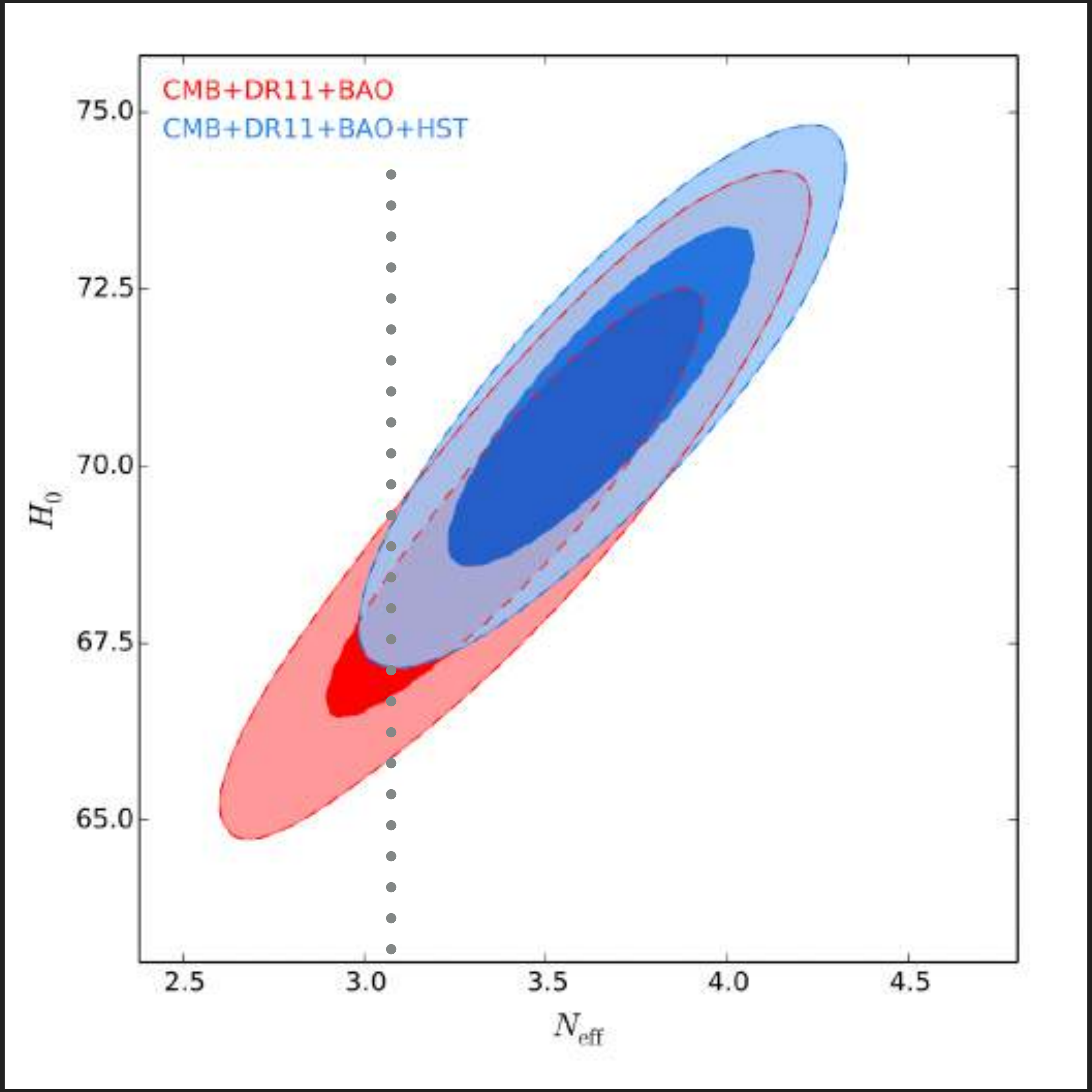
A brief history of bounds (at 95\%) on Neff

$N_{eff} \leq 13$	Hannestad 2000 (Boomerang data)
$N_{eff} > 2.7$	Komatsu et al. 2013 (WMAP7 data)
$N_{eff} = 4.08^{+0.71}_{-0.68}$	Archidiacono et al. 2013 (WMAP7+ACT+SPT data)
$N_{eff} = 3.51^{+0.81}_{-0.74}$	Planck +WP 2013
$N_{eff} = 3.73^{+0.51}_{-0.51}$	Giusarma et al 2014 (Planck+WP+DR11+HST)

EXTRA NEUTRINOS BACK THEN…

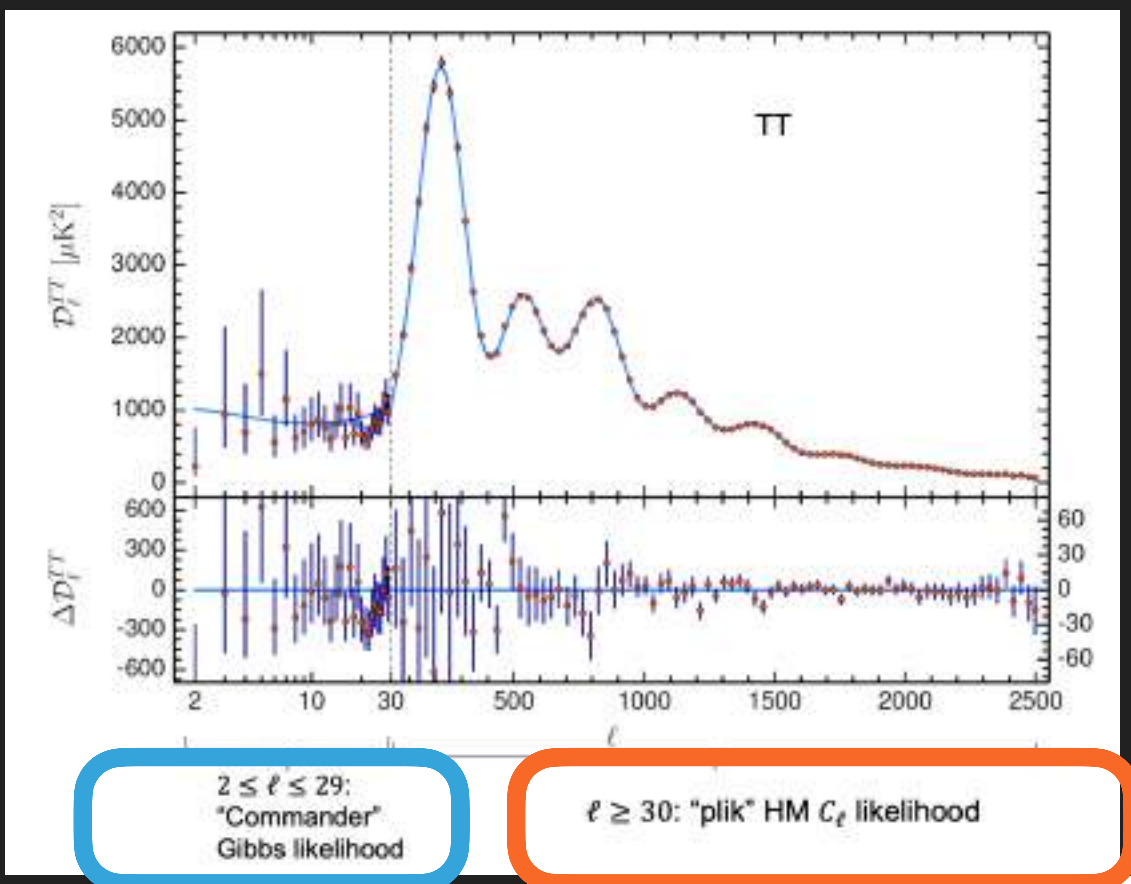
The Planck 2013 data release utilized the WMAP data for the large-scale polarization.

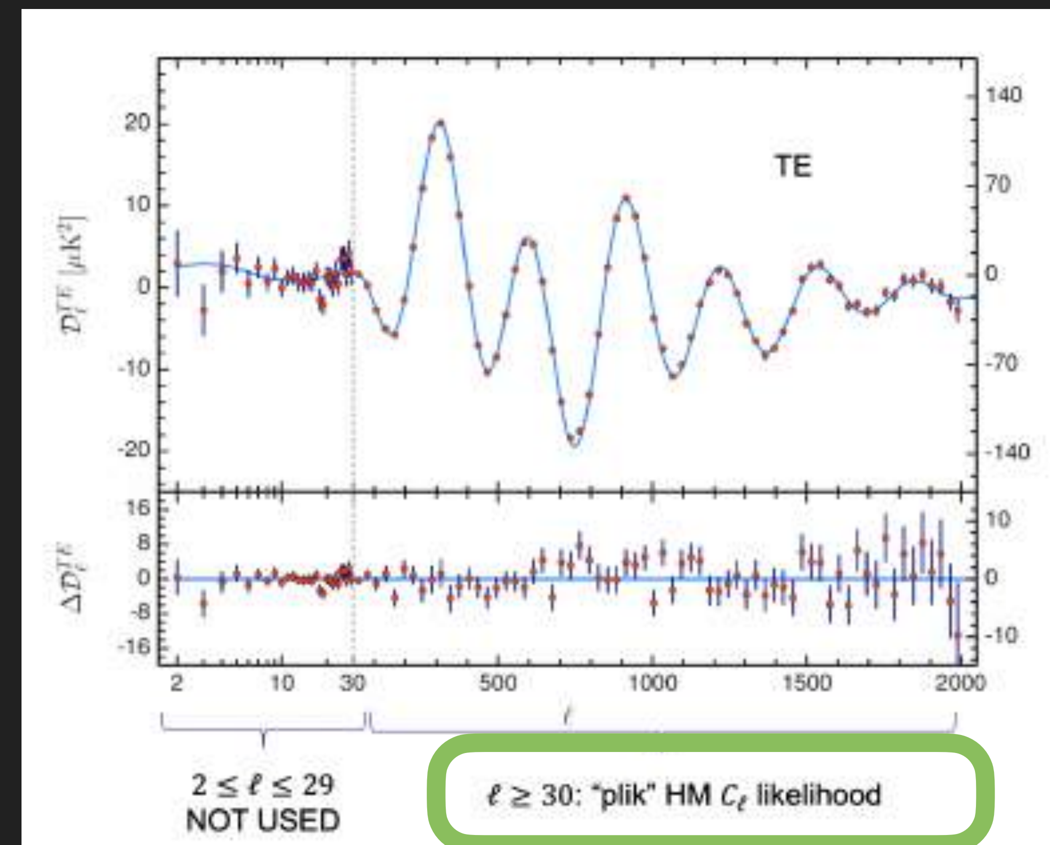
This dataset supported a higher value for Neff, which helped address the Hubble tension observed at that time (approximately 2-3 sigmas).

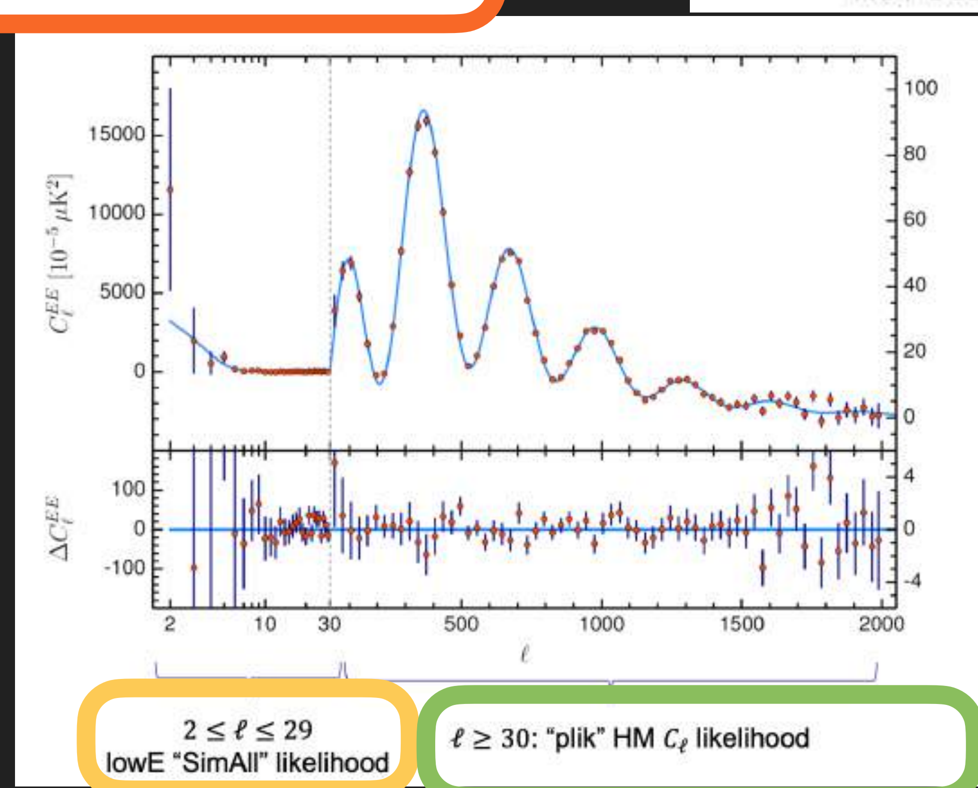


Giusarma et al, 2014

PLANCK 2018 SPECTRA







WHERE IS THE HUBBLE TENSION?

LOW L TT

HIGH L TT

LOW L EE

HIGH L TEEE

WHERE IS THE HUBBLE TENSION?

LOW L TT

HIGH L TT

LOW L EE

HIGH L TEEE

If you consider only temperature data, an extra neutrino could offer an optimal solution to the Hubble tension!

$$N_{eff} = 4.53 \pm 0.71$$

$$H_0 = 81.8^{+8.7}_{-7.3}$$

WHERE IS THE HUBBLE TENSION?

LOW L TT

HIGH L TT

LOW L EE

HIGH L TEEE

If you consider only temperature data, an extra neutrino could offer an optimal solution to the Hubble tension!

$$N_{eff} = 3.00 \pm 0.28$$

$$H_0 = 66.5 \pm 2.3$$

WHERE IS THE HUBBLE TENSION?

LOW L TT

HIGH L TT

LOW L EE

HIGH L TEEE

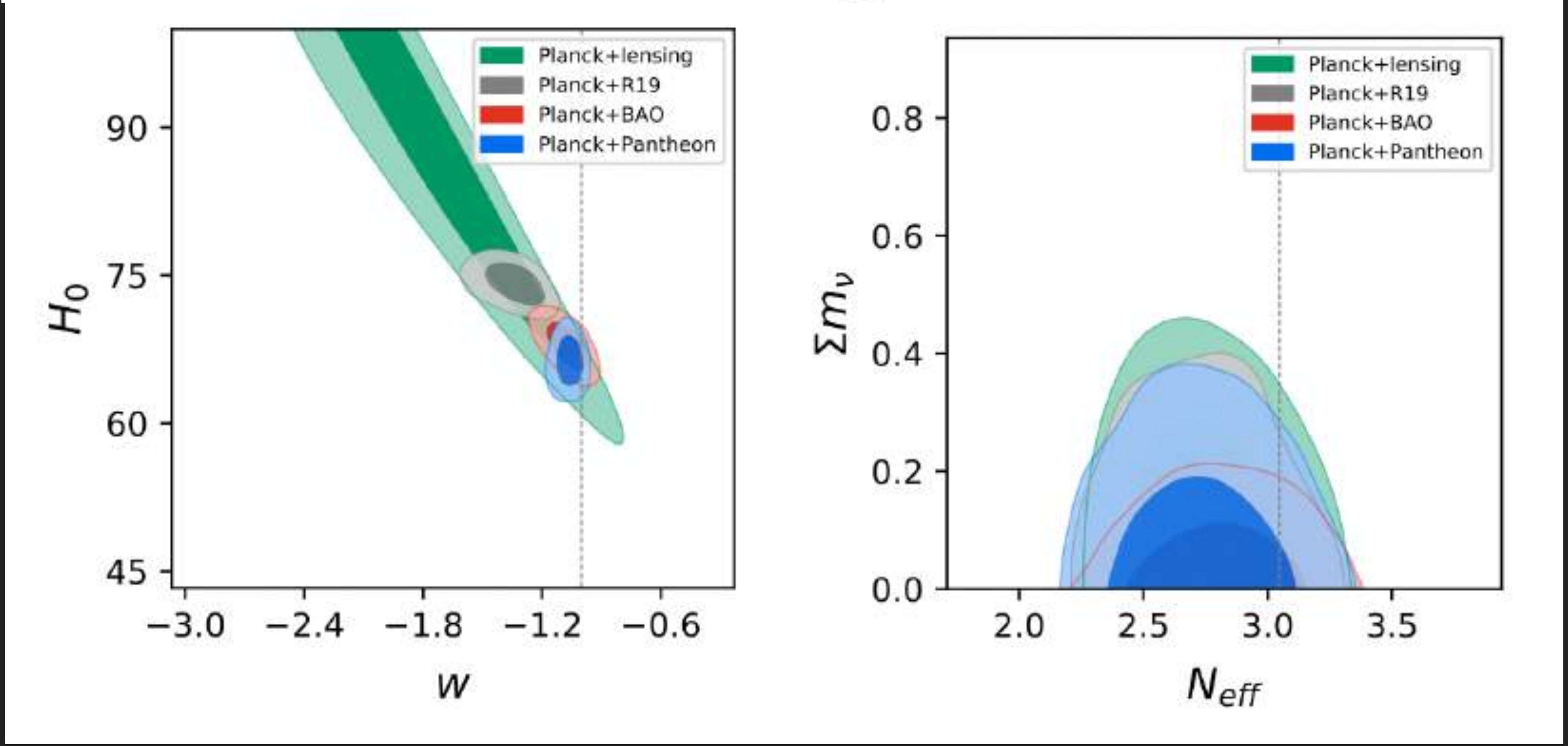
However, when polarization is taken into account, degeneracies are resolved, and the situation changes.

$$N_{eff} = 2.92 \pm 0.19$$

$$H_0 = 66.4^{+1.4}_{-1.4}$$

EXTRA RADIATION DO NOT SOLVE THE HUBBLE TENSION.

A 10 parameters model, ΛCDM$+w+\alpha_S+N_{eff}+\Sigma m_\nu$, is assumed in the analysis.



Even when you include extra parameters additional radiation do not solve the Hubble tension because of polarisation data (Di Valentino, Melchiorri and Silk, JCAP 2020)

WHY CMB POLARISATION KILLS EXTRA NEUTRINOS ?

1- TE breaks degeneracies between parameters (no EISW in polarisation).

2- Low L polarisation is far lower than previously thought-> Lower optical depth.

Planck 2013 (+wmap)	Planck 2015 (Low E from LFI)	Planck 2018
$\tau = 0.089^{+0.012}_{-0.014}$	$\tau = 0.079 \pm 0.017$	$\tau = 0.0544^{+0.070}_{-0.081}$

>2.2 sigmas shift in the optical depth during the 3 data releases !!!

WHY CMB POLARISATION KILLS EXTRA NEUTRINOS ?

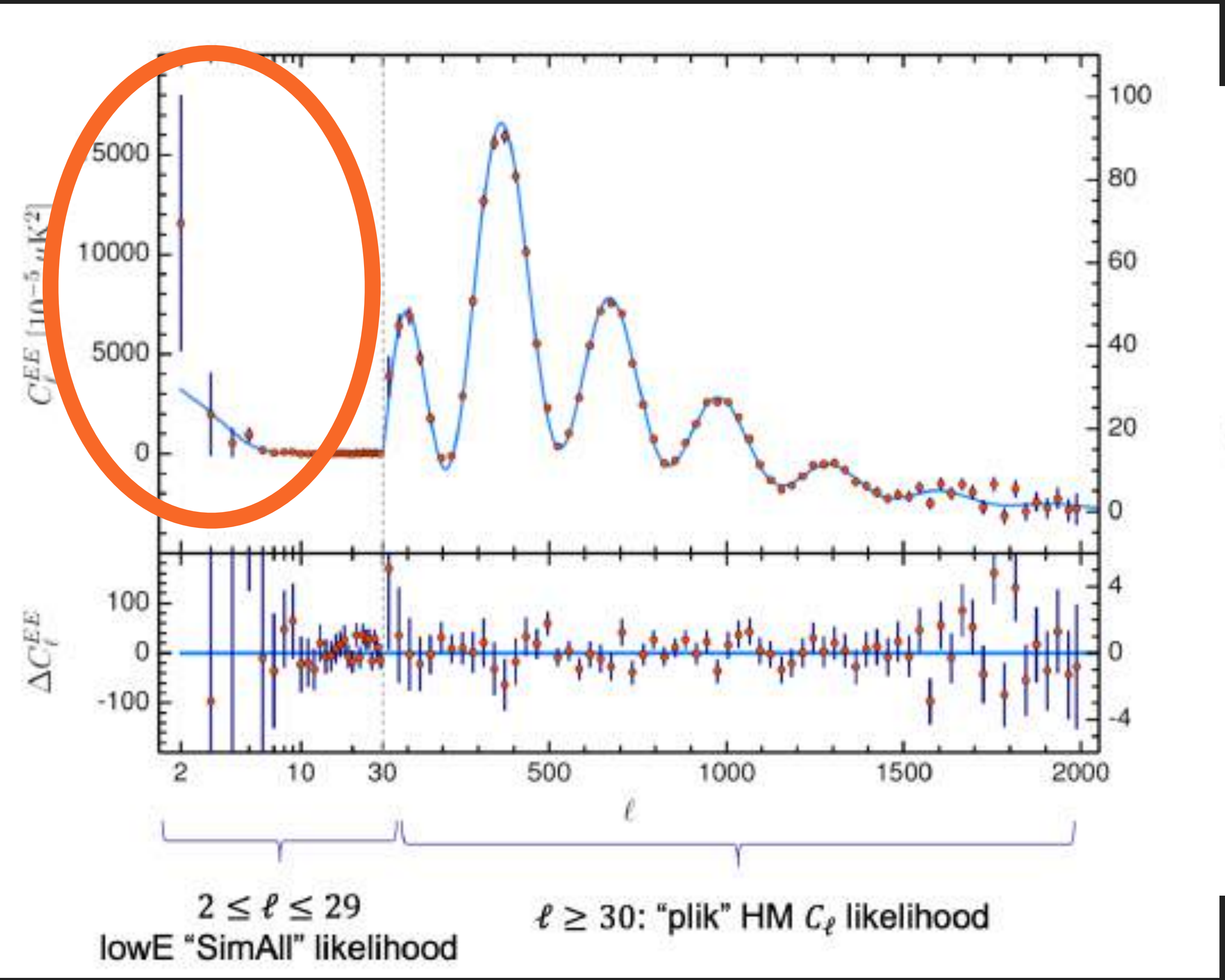
Planck temperature only data.

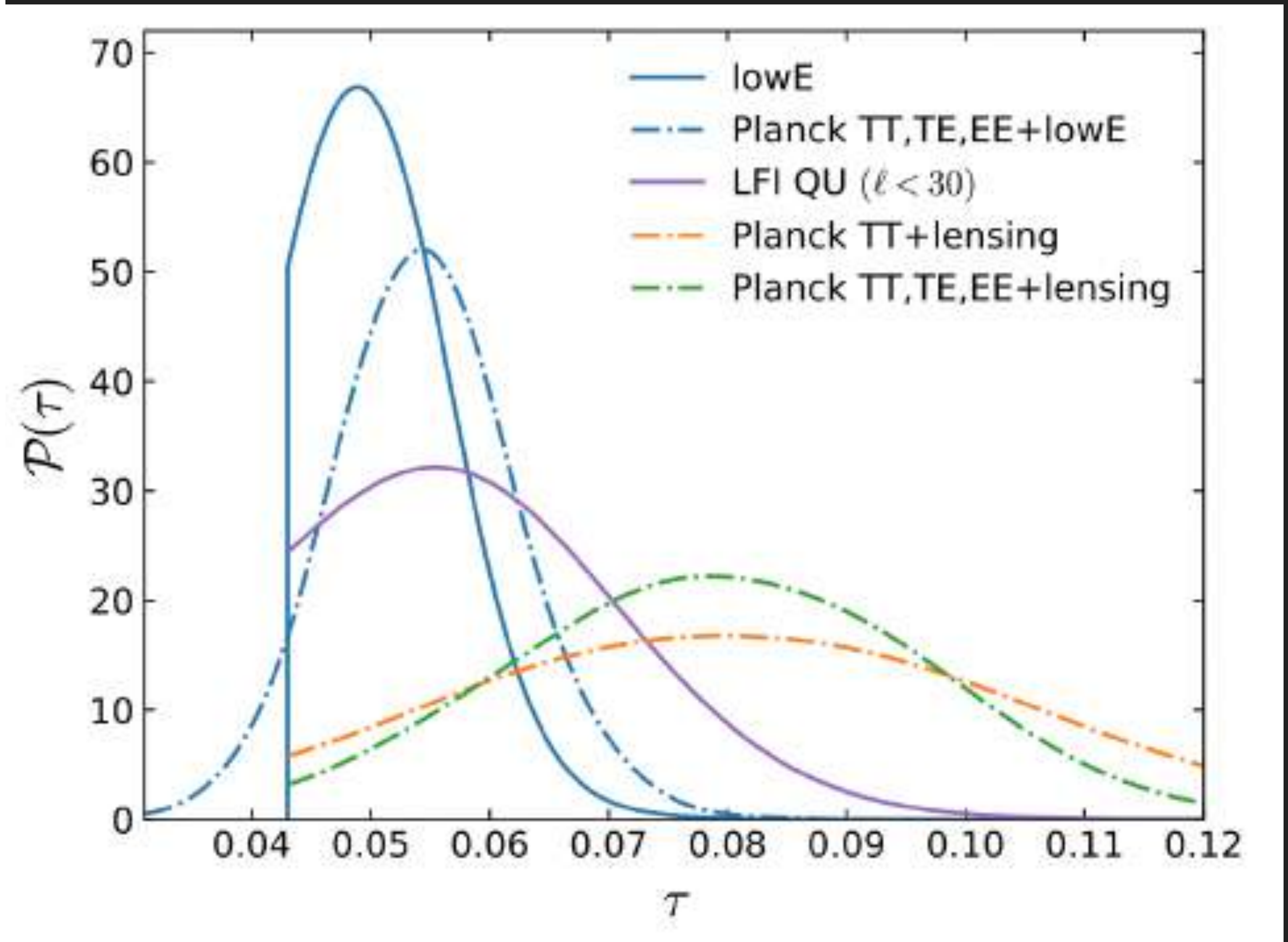
Parameter	ΛCDM	ΛCDM (HZ)	ΛCDM $+N_{\rm eff}$	ΛCDM $+N_{\rm eff}$ (HZ)
$\Omega_b h^2$	0.02222 ± 0.00023	0.02300 ± 0.00020	0.02230 ± 0.00037	0.02294 ± 0.00019
$\Omega_c h^2$	0.1198 ± 0.0022	0.1100 ± 0.0011	0.1205 ± 0.0041	0.1248 ± 0.0034
θ_c	1.04085 ± 0.00048	1.04217 ± 0.00041	1.04082 ± 0.00056	1.04055 ± 0.00052
τ	0.077 ± 0.019	$0.139^{+0.019}_{-0.017}$	0.080 ± 0.022	0.110 ± 0.019
n_s	0.9655 ± 0.0062	1	0.969 ± 0.016	1
$\ln(10^{10} A_s)$	3.088 ± 0.036	$3.189^{+0.039}_{-0.033}$	3.096 ± 0.047	$3.166^{+0.039}_{-0.035}$
$H_0/{\rm km\,s^{-1}\,Mpc^{-1}}$	67.29 ± 0.98	72.01 ± 0.51	68.0 ± 2.8	73.51 ± 0.64
σ_8	0.829 ± 0.014	0.842 ± 0.016	0.834 ± 0.023	0.868 ± 0.017
$N_{\rm eff}$	3.046	3.046	3.12 ± 0.31	3.69 ± 0.14
$\Sigma m_\nu [eV]$	0.06	0.06	0.06	0.06
$d \ln n_s / d \ln k$	0	0	0	0
$A_{\rm lens}$	1	1	1	1
w	-1	-1	-1	-1
$\bar{\chi}^2_{\rm eff}$	11281.95	11307.88	11282.90	11286.19

When you consider just TT data a fourth neutrino can solve the Hubble tension but you need also n=1. This is disfavoured by a lower value of the optical depth.

Di Valentino, Melchiorri, Fantaye, Heavens, PRD 2018

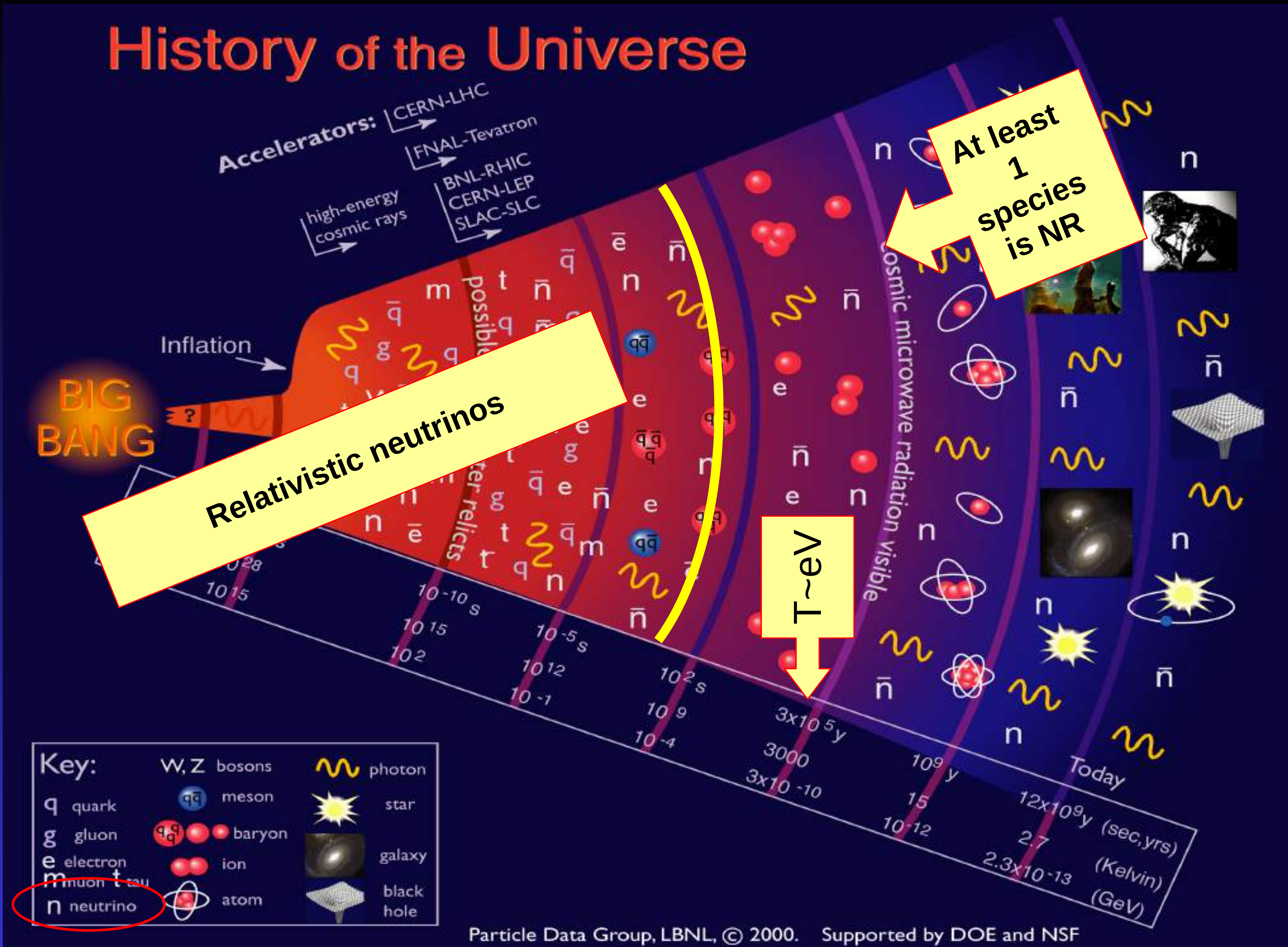
HOW MUCH SHOULD WE TRUST LOWE FROM PLANCK ?





4 datapoints!!!! optical depth could be even lower without prior >0.04 !

4 DATA POINTS KILL 4 NEUTRINOS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Cosmic microwave radiation visible
Relativistic neutrinos
At least 1 species is NR
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10 12
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3x10 5 y
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W, Z bosons
meson
baryon
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atom
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star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Energy density from neutrinos (after decoupling)

If they are relativistic:

$$\rho_\nu = \frac{7\pi^2}{120} N_{eff} \left(\frac{4}{11}\right)^{4/3} T_\gamma^4$$

$$\Omega_\nu h^2 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\, \Omega_\gamma h^2$$

$$\Omega_\nu h^2 = 0.58\times 10^{-5} N_{eff}$$

$(T_\gamma = 2.726\, K)$

If they are not relativistic:

$$\rho_\nu = \sum n_i m_i$$

$$n_i = \frac{6\zeta(3)}{11\pi^2} T_\gamma^3$$

$\rightarrow$

$$\Omega_\nu h^2 = \frac{\sum m_i}{93.2\, eV}$$

$(T_\gamma = 2.726\, K)$

CONSTRAINTS ON NEUTRINO MASSES FROM PLANCK CMB ANGULAR SPECTRA

Constraints at 95% c.l., LCDM model is assumed.

$\Sigma m_\nu < 0.492 eV$	Planck 2013
$\Sigma m_\nu < 0.340 eV$	Planck 2015
$\Sigma m_\nu < 0.257 eV$	Planck 2018

DOES COSMOLOGY PREFER NORMAL NEUTRINO HIERARCHY ?

arXiv.org > astro-ph > arXiv:1703.03425

Strong Bayesian Evidence for the Normal Neutrino Hierarchy

Fergus Simpson, Raul Jimenez, Carlos Pena-Garay, Licia Verde

(Submitted on 9 Mar 2017 (v1), last revised 4 Jun 2017 (this version, v2))

The configuration of the three neutrino masses can take two forms, known as the normal and inverted hierarchies. We compute the Bayesian evidence associated with these two hierarchies. Previous studies found a mild preference for the normal hierarchy, and this was driven by the asymmetric manner in which cosmological data has confined the available parameter space. Here we identify the presence of a second asymmetry, which is imposed by data from neutrino oscillations. By combining constraints on the squared-mass splittings with the limit on the sum of neutrino masses of $\Sigma m_\nu < 0.13$ eV and using a minimally informative prior on the masses, we infer odds of 42:1 in favour of the normal hierarchy, which is classified as "strong" in the Jeffreys' scale. We explore how these odds may evolve in light of higher precision cosmological data, and discuss the implications of this finding with regards to the nature of neutrinos. Finally the individual masses are inferred to be $m_1 = 3.80^{+26.2}_{-3.73}$ meV, $m_2 = 8.8^{+18}_{-1.2}$ meV, $m_3 = 50.4^{+5.8}_{-1.2}$ meV (95% credible intervals).

arXiv.org > astro-ph > arXiv:1703.04585

Comment on "Strong Evidence for the Normal Neutrino Hierarchy"

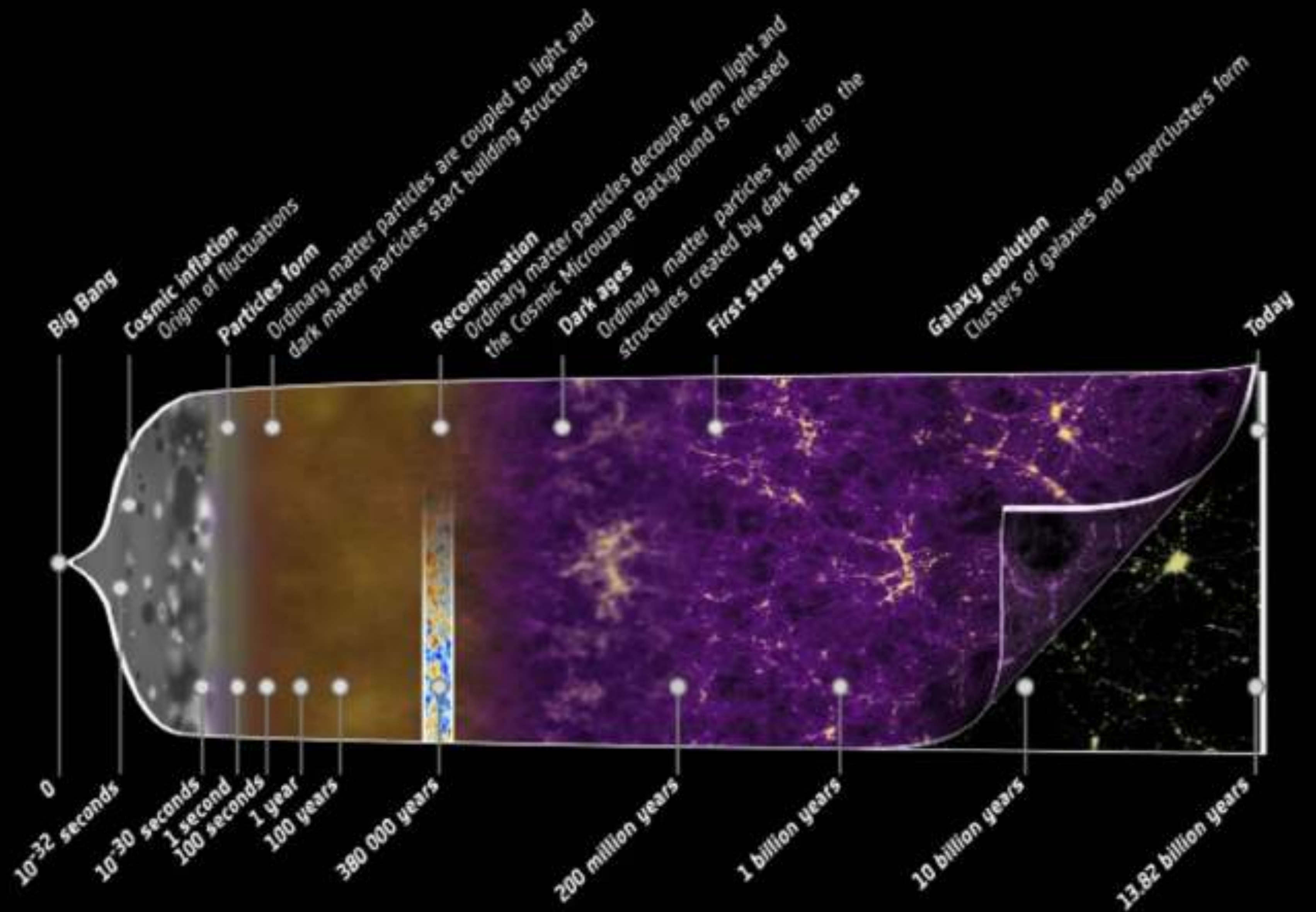
T. Schwetz, K. Freese, M. Gerbino, E. Giusarma, S. Hannestad, M. Lattanzi, O. Mena, S. Vagnozzi

(Submitted on 14 Mar 2017)

In the preprint arxiv:1703.03425 "strong evidence" for the normal neutrino mass ordering is claimed. The authors obtain Bayesian odds of 42:1 in favour of the normal ordering. Their conclusion is based on adopting a flat logarithmic prior for the three neutrino masses. Such an assumption favours a hierarchical spectrum for the masses, which is much easier to accommodate for the normal mass ordering, and hence their prior assumption makes the inverted ordering much less likely a priori. We argue that the claimed "evidence" for normal ordering is almost entirely driven by the adopted prior and not due to the data itself.

DOES COSMOLOGY PREFER NORMAL NEUTRINO HIERARCHY ?

NEUTRINO MASS AND THE CMB

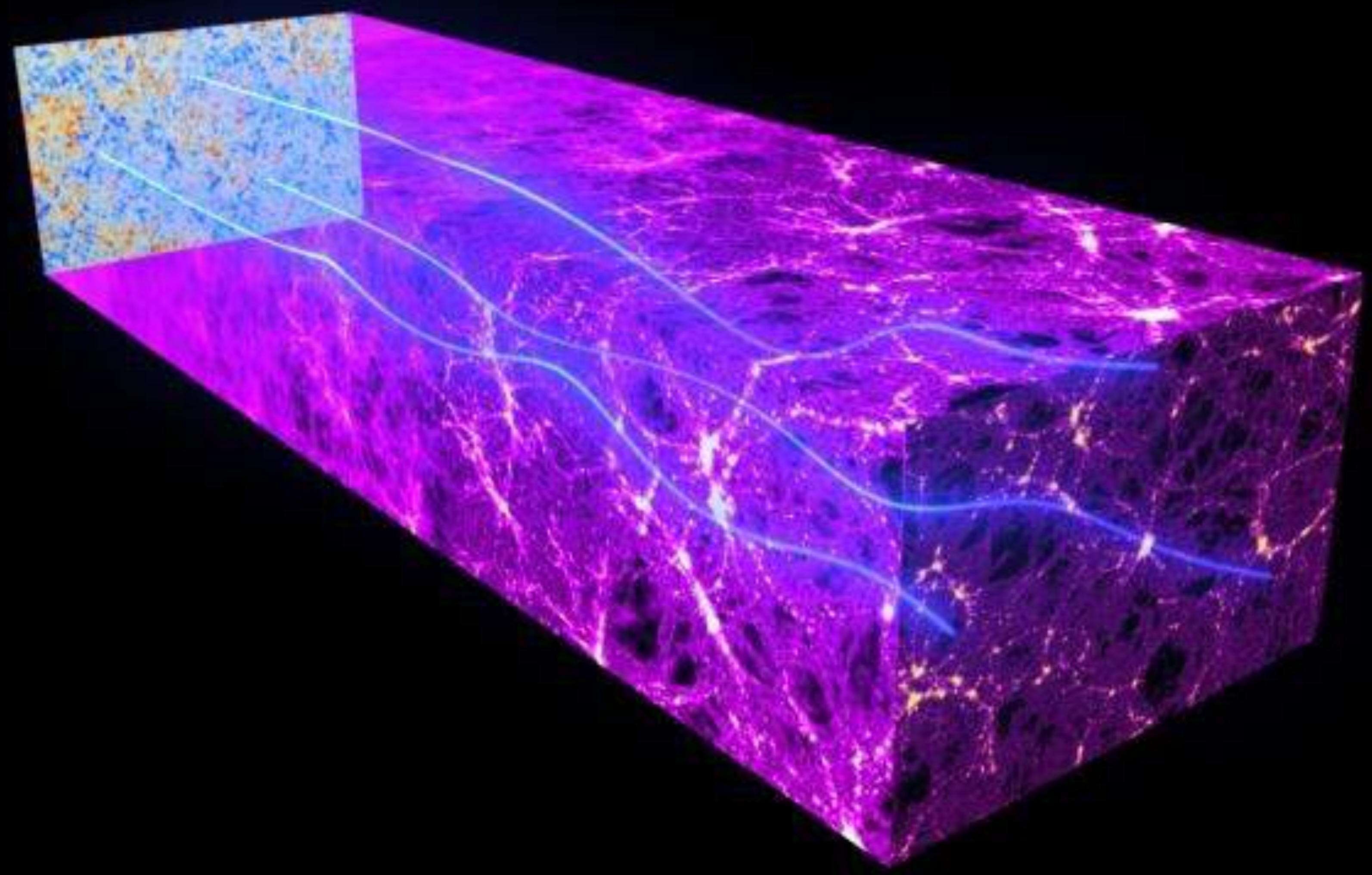


Primary CMB anisotropies form at recombination, at redshift z=1300 when the CMB was at a temperature of T~0.3 eV. A neutrino with a mass of ~0.1 eV is still relativistic at that epoch.

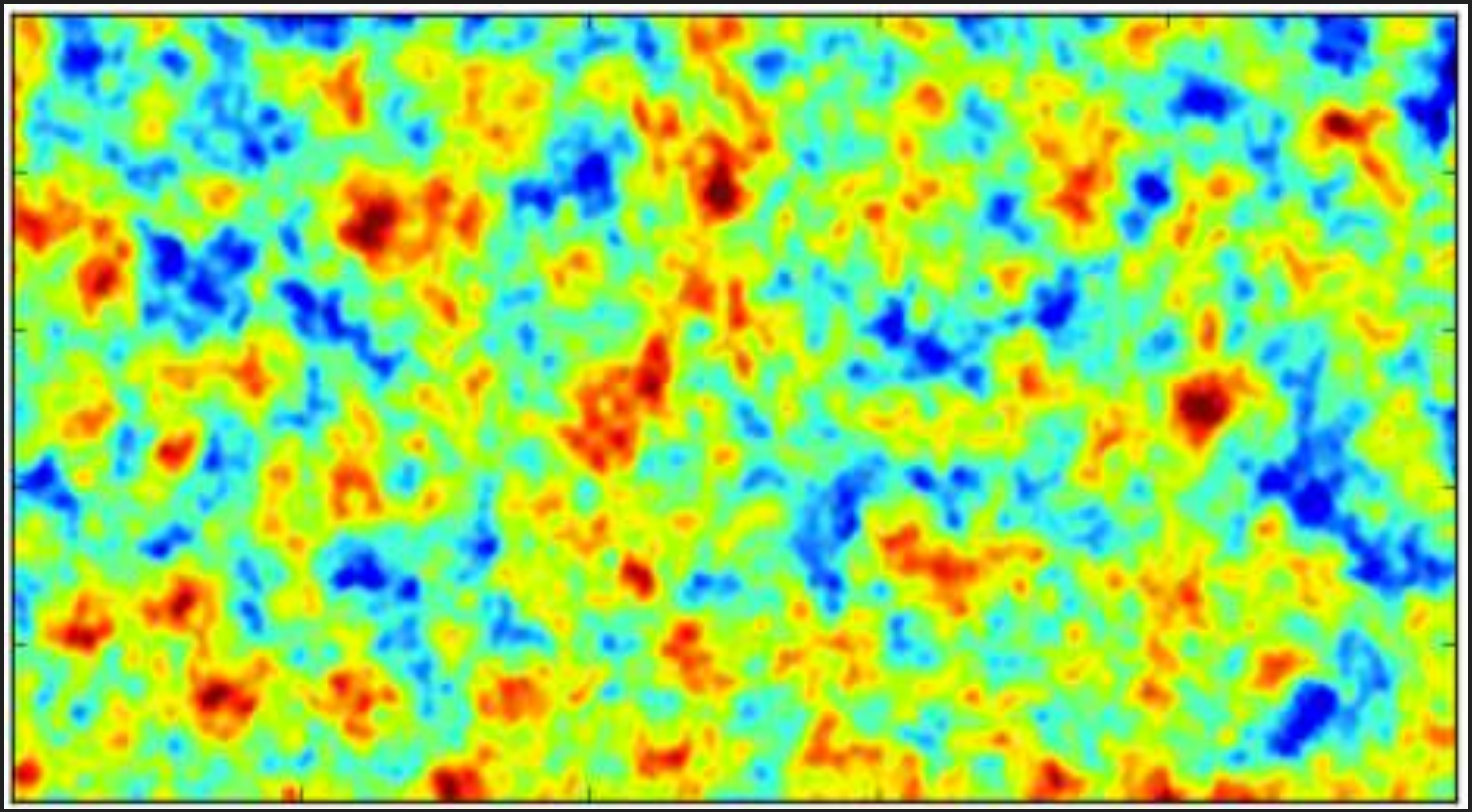
How I can place with CMB data this incredibly good upper limit ?

CMB LENSING

The gravitational effects of intervening dark matter fluctuations bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB.

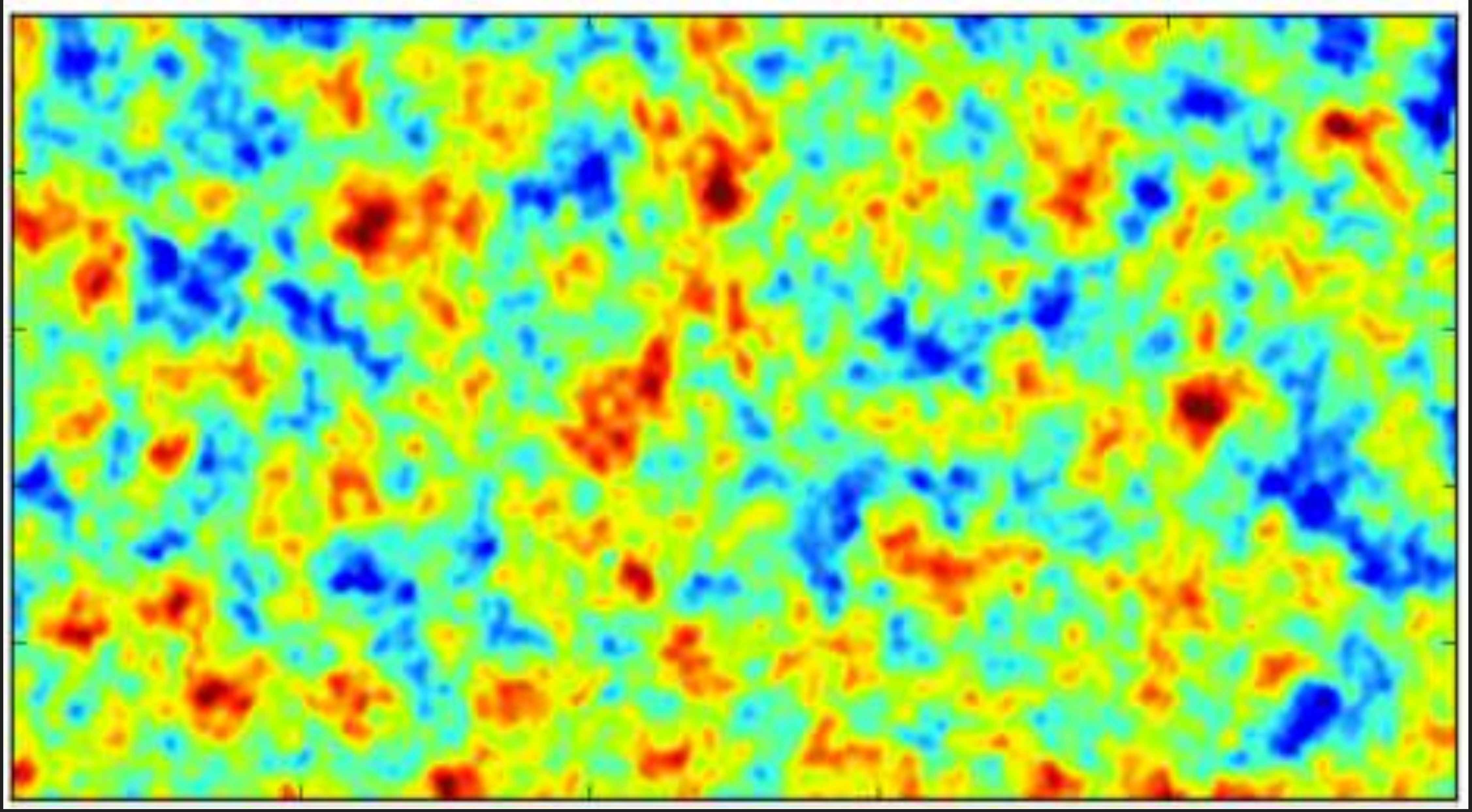


CMB LENSING



A simulated patch of CMB sky – **before dark matter lensing**

CMB LENSING



A simulated patch of CMB sky – **after dark matter lensing**

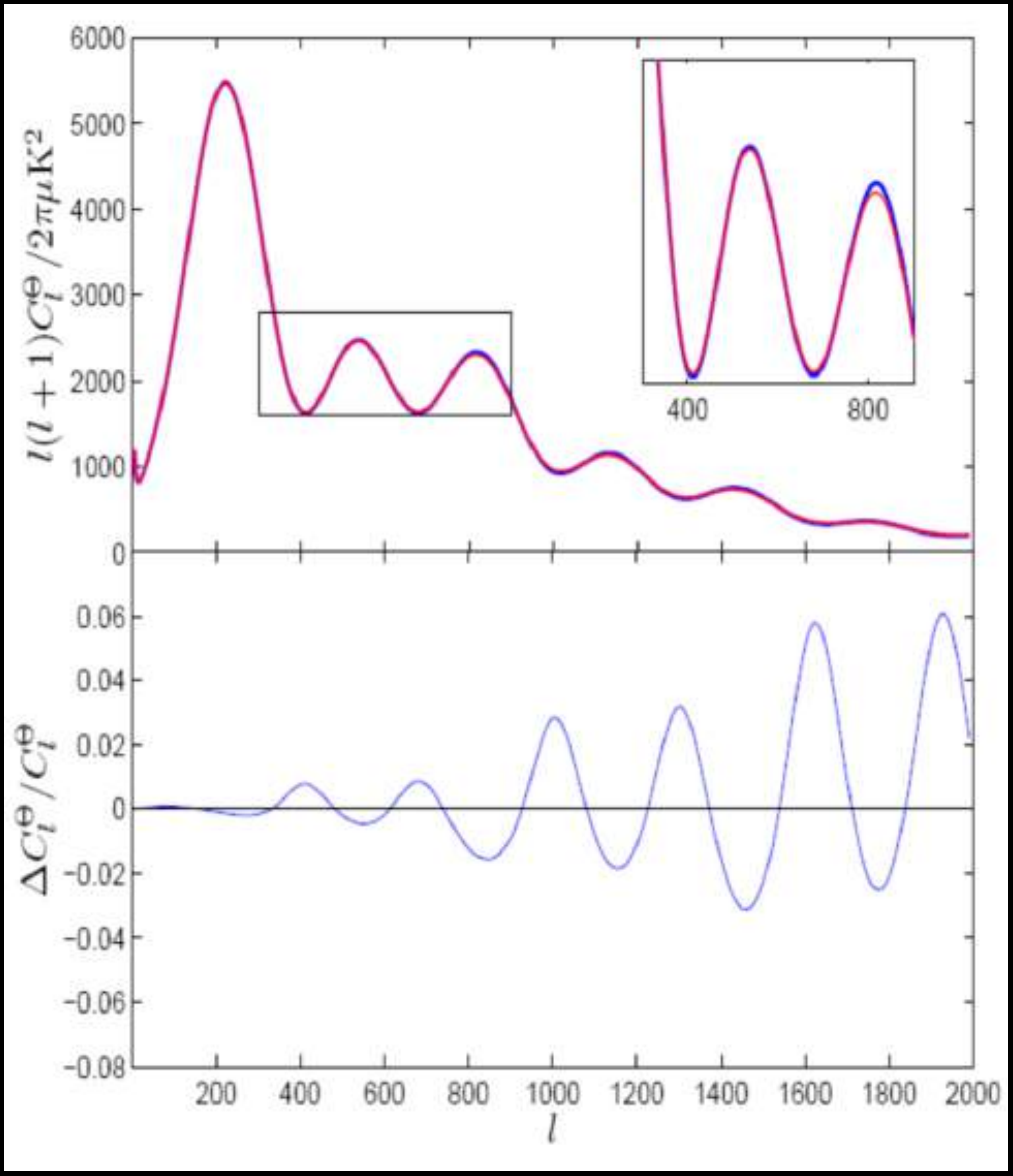
CMB LENSING

CMB photons emitted at z=1100 are deflected by the gravitational lensing effect of massive cosmic structures.

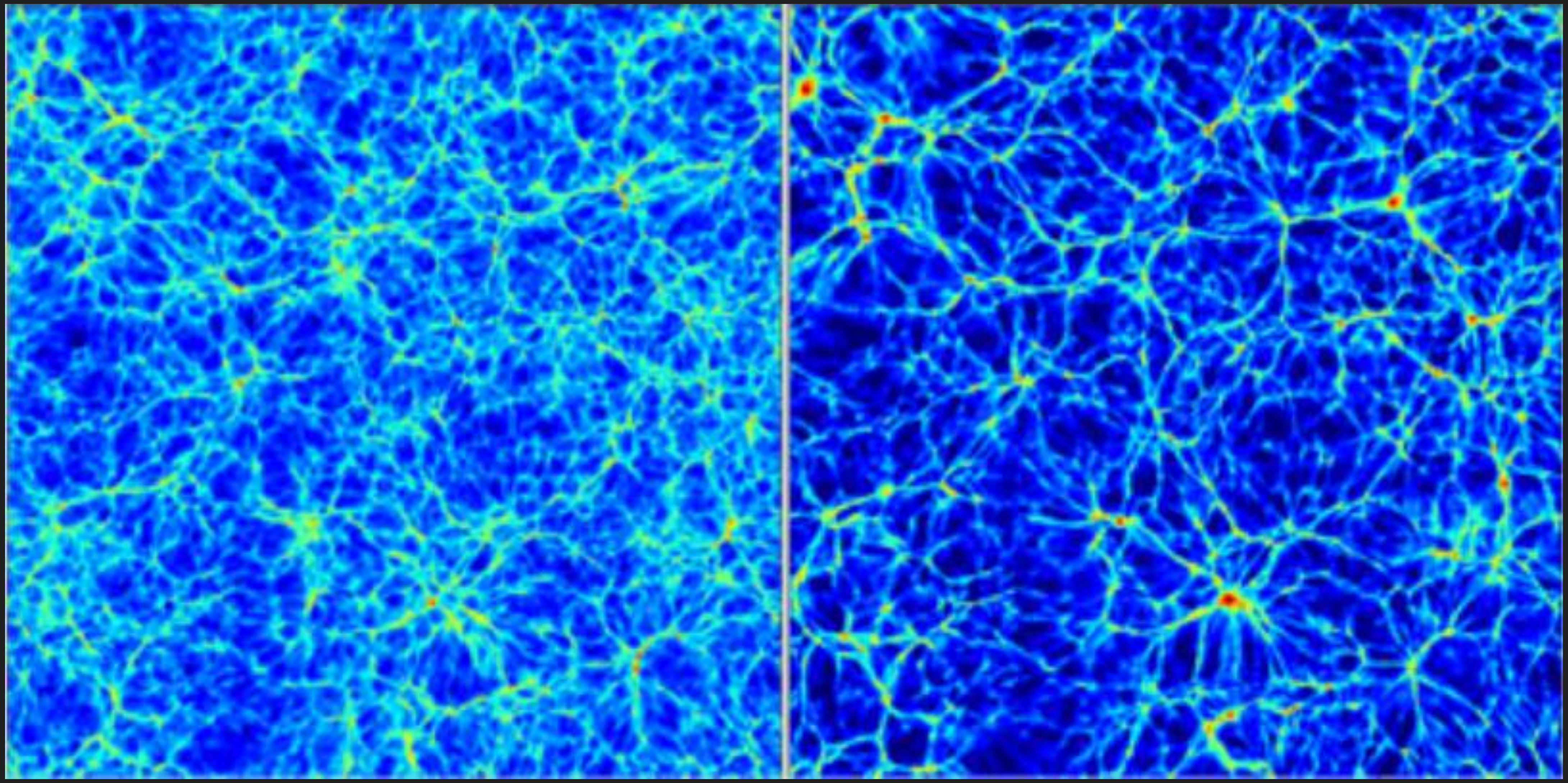
This affects the CMB anisotropy angular spectrum by smearing the high l peaks.

The shape of the spectrum changes by ~5% at l=1500.

Planck is sensitive to these tiny variations !



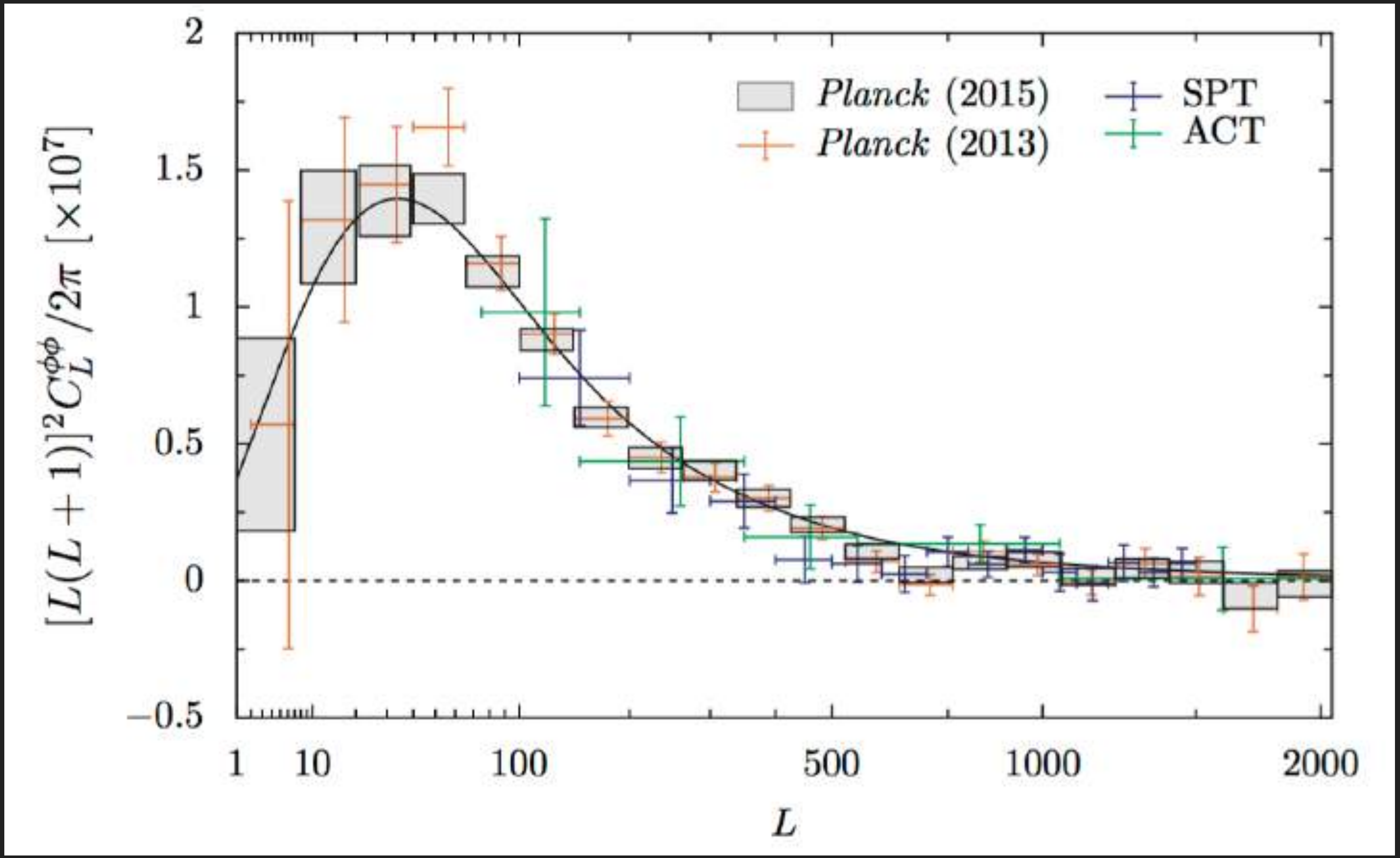
CMB LENSING



Massive neutrinos (1 eV) practically do not form structure !

More massive is the neutrino -> Higher omega -> less structure -> less CMB lensing.

CMB LENSING 2



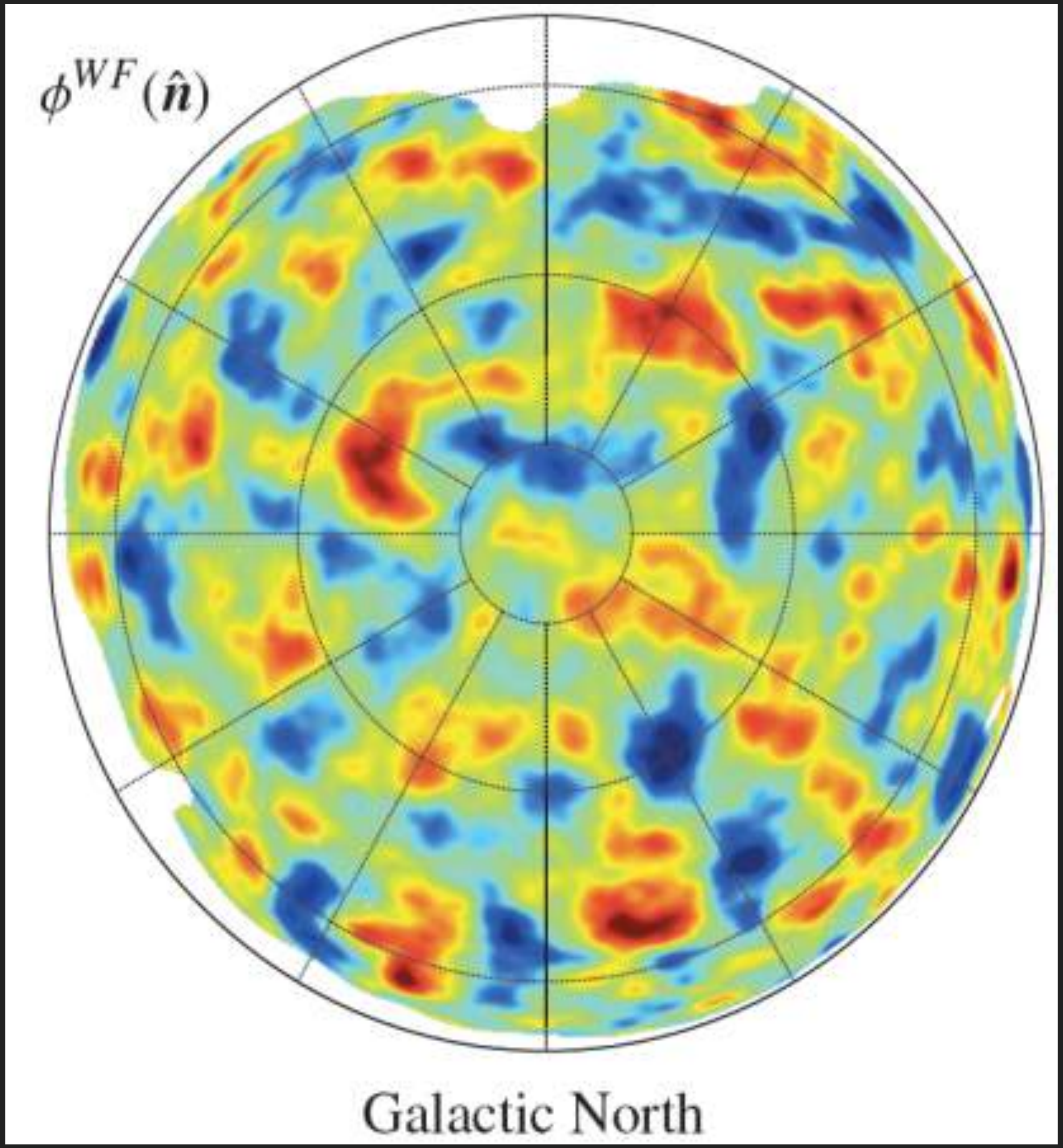
Planck collaboration, arXiv:1502.01589

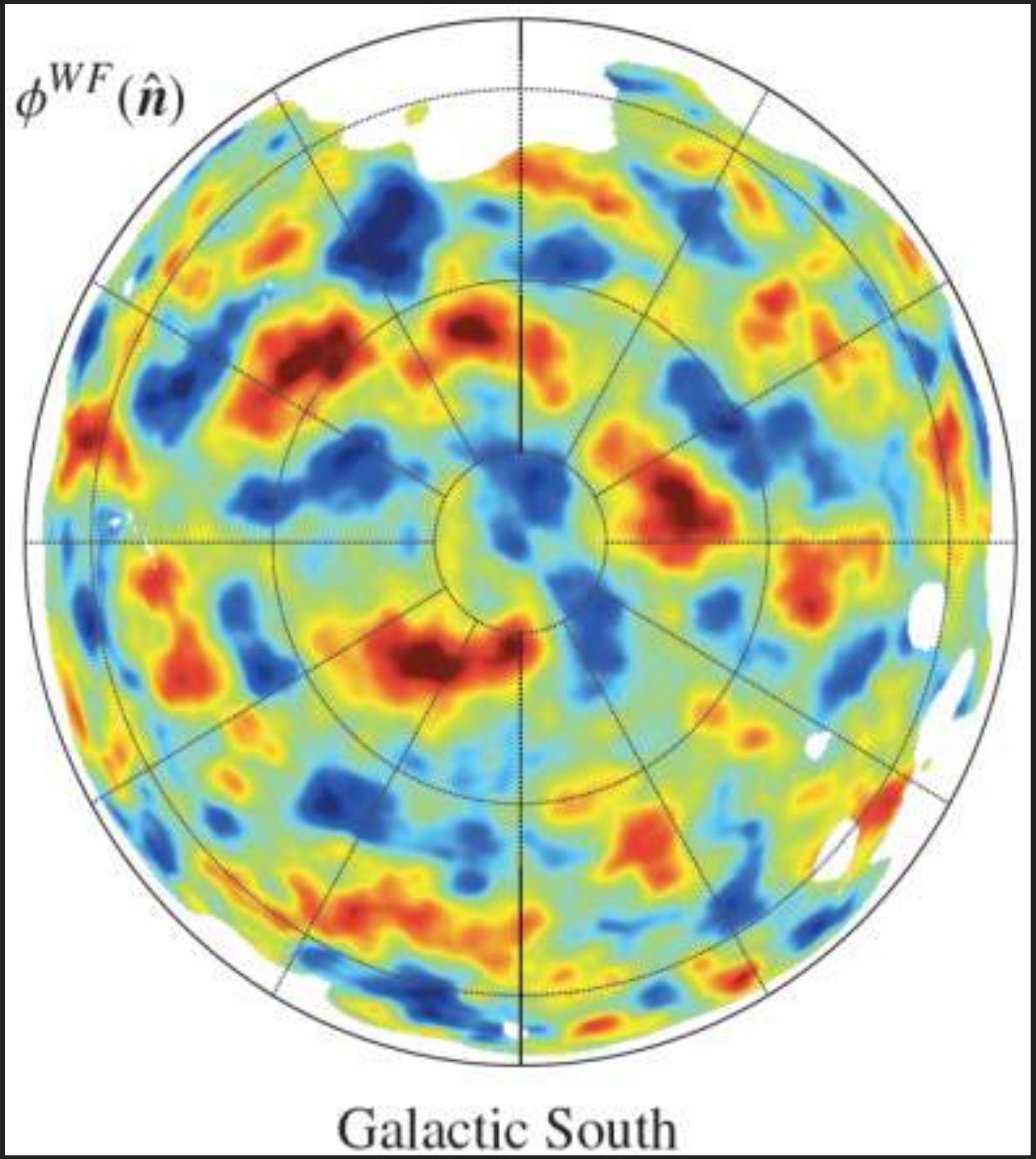
CMB Lensing can be measured also in a different way.

This different method is based on the trispectrum (TTTT) of the CMB maps. This results in a 40σ measurement of lensing.

CMB LENSING 2

Thanks to trispectrum measurements it is possible to map the dark matter distribution !





Planck collaboration, arXiv:1502.01589

CMB LENSING

Constraints at 68% c.l. (Planck 2018 release)

$$\Sigma m_\nu < 0.107 eV$$

Planck TT+TE+EE

$$\Sigma m_\nu < 0.180 eV$$

Planck TT+TE+EE+lensing (TTTT)

When we include the lensing dataset from TTTT the constraint on the neutrino mass gets weaker !

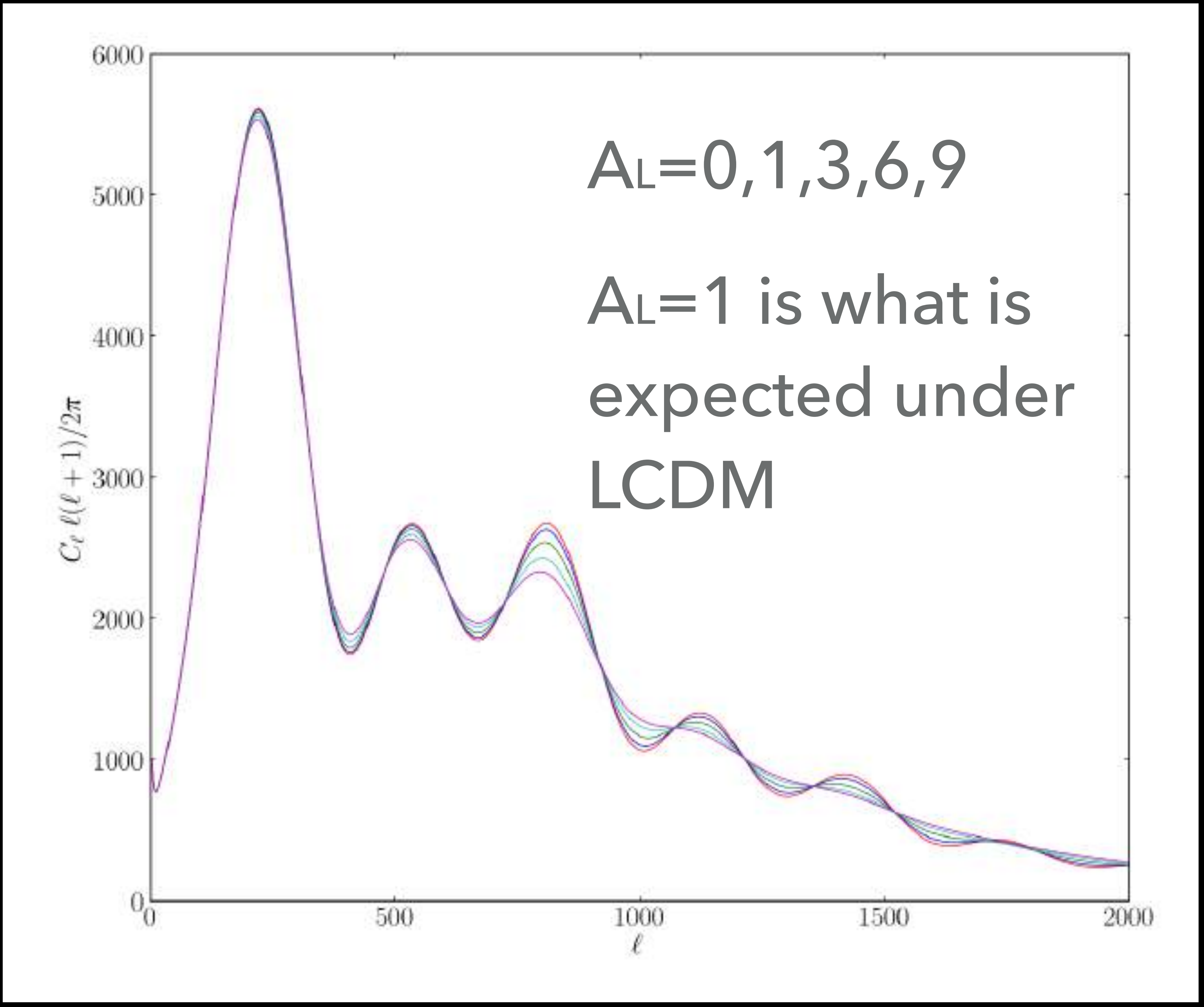
How this can be possible ?

CMB LENSING

Let's parametrize the amount of lensing in the CMB angular spectra by an effective parameter A_L.

A_L=1 means that we have lensing as expected in LCDM.

A_L>1 we have too much lensing.



A_L=0,1,3,6,9

A_L=1 is what is expected under LCDM

THE AL PROBLEM

The Planck analysis (arXiv:1605.02985) prefers AL>1 at 2.5 standard deviations.

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_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_L	$1.22^{+0.21}_{-0.20}$	$1.23^{+0.20}_{-0.18}$	$1.15^{+0.16}_{-0.15}$	$1.15^{+0.13}_{-0.12}$

We have too much lensing in the CMB angular spectra ! This reflects in a stronger bound on the neutrino mass (less lensing, higher neutrino mass). When the lensing from TTTT is included we force lensing to have the standard value and the constraints on the neutrino mass are weaker.

68% c.l. constraints on neutrino mass from Planck TTTEEE (2018):

$$\Sigma m_\nu < 0.107 eV$$

LCDM

$$\Sigma m_\nu < 0.51 eV$$

LCDM+AL

IS A_L>1 CONNECTED WITH LOWE ?

No indication for Alens>1 at more than 2 standard deviation if you exclude LowE ! Not at more than 1 sigma if you also exclude LowL.

Constraints at 95% C.L.

$A_{lens} = 1.24 \pm 0.18$	Planck TT+lowL+LowE
$A_{lens} = 1.23 \pm 0.23$	Planck TT+lowL
$A_{lens} = 1.13 \pm 0.26$	Planck TT
$A_{lens} = 1.18 \pm 0.13$	Planck TTTEEE+lowL+LowE
$A_{lens} = 1.17 \pm 0.19$	Planck TTTEE+lowL
$A_{lens} = 1.09 \pm 0.22$	Planck TTTEEE

WHAT ABOUT OTHER DATASETS?

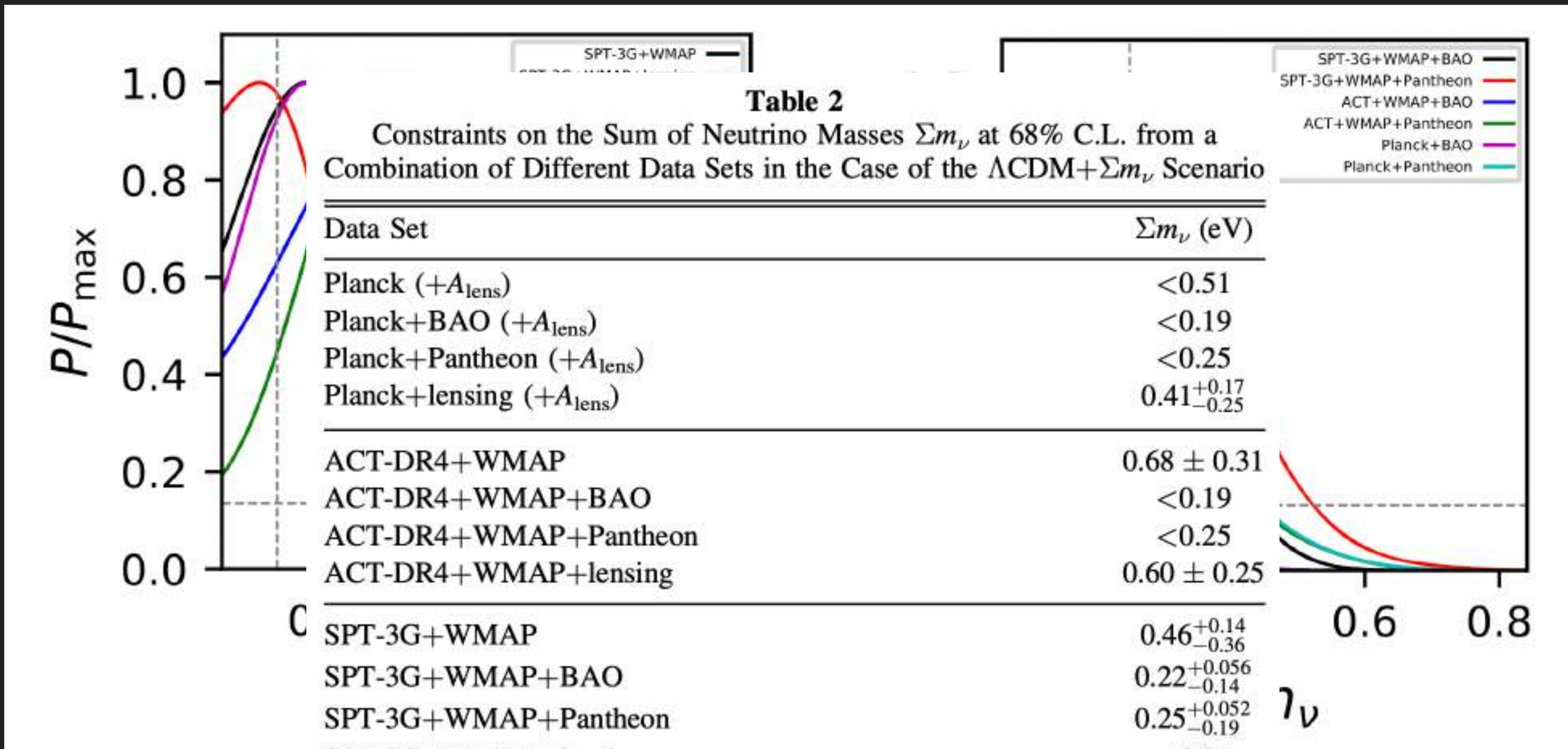


Table 2
Constraints on the Sum of Neutrino Masses Σm_ν at 68% C.L. from a Combination of Different Data Sets in the Case of the ΛCDM+Σm_ν Scenario

Data Set	Σm_ν (eV)
Planck (+$A_{\rm lens}$)	<0.51
Planck+BAO (+$A_{\rm lens}$)	<0.19
Planck+Pantheon (+$A_{\rm lens}$)	<0.25
Planck+lensing (+$A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$
ACT-DR4+WMAP	0.68 ± 0.31
ACT-DR4+WMAP+BAO	<0.19
ACT-DR4+WMAP+Pantheon	<0.25
ACT-DR4+WMAP+lensing	0.60 ± 0.25
SPT-3G+WMAP	$0.46^{+0.14}_{-0.36}$
SPT-3G+WMAP+BAO	$0.22^{+0.056}_{-0.14}$
SPT-3G+WMAP+Pantheon	$0.25^{+0.052}_{-0.19}$
SPT-3G+WMAP+lensing	<0.37

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No dataset excludes masses above 0.3 eV !

WHAT ABOUT OTHER DATASETS?

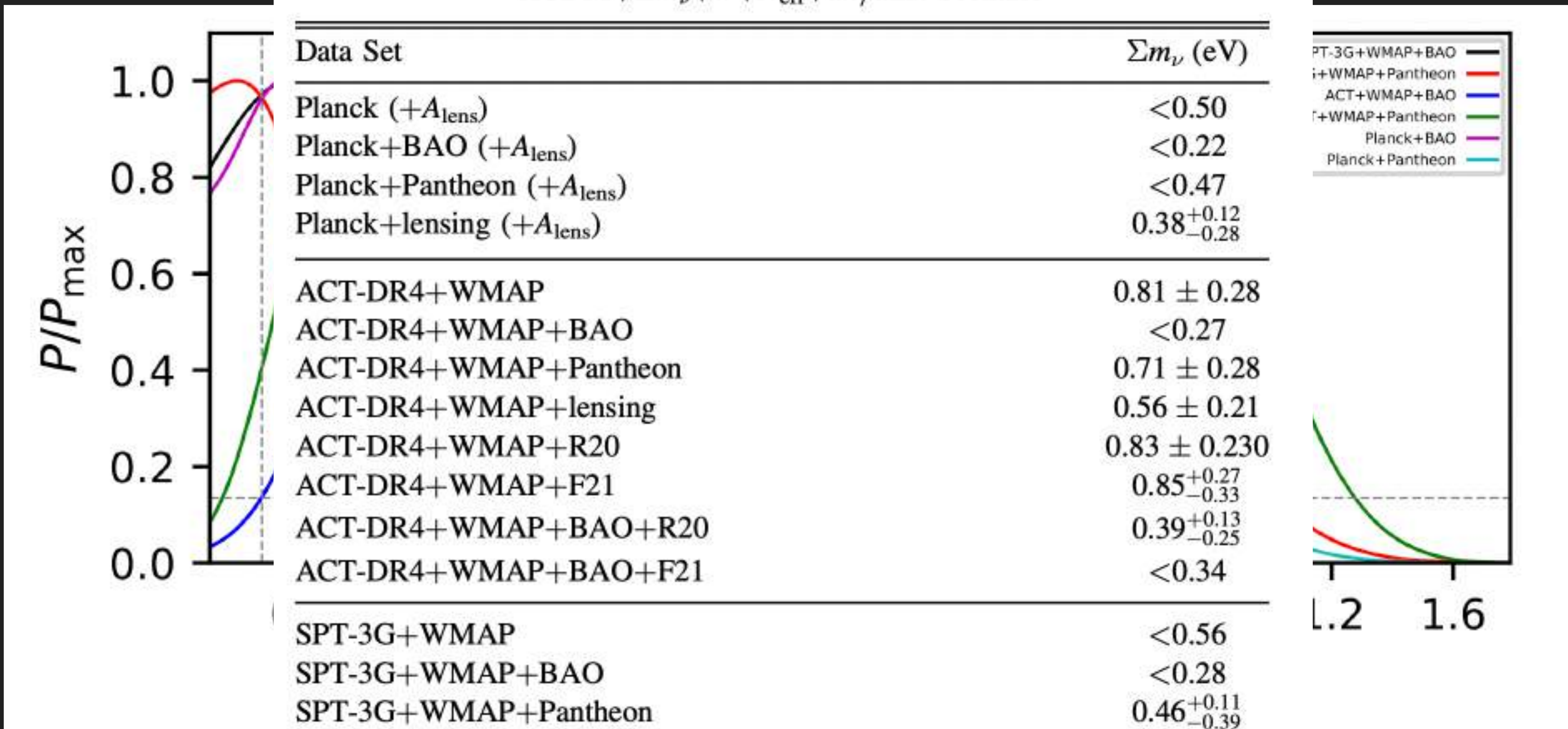


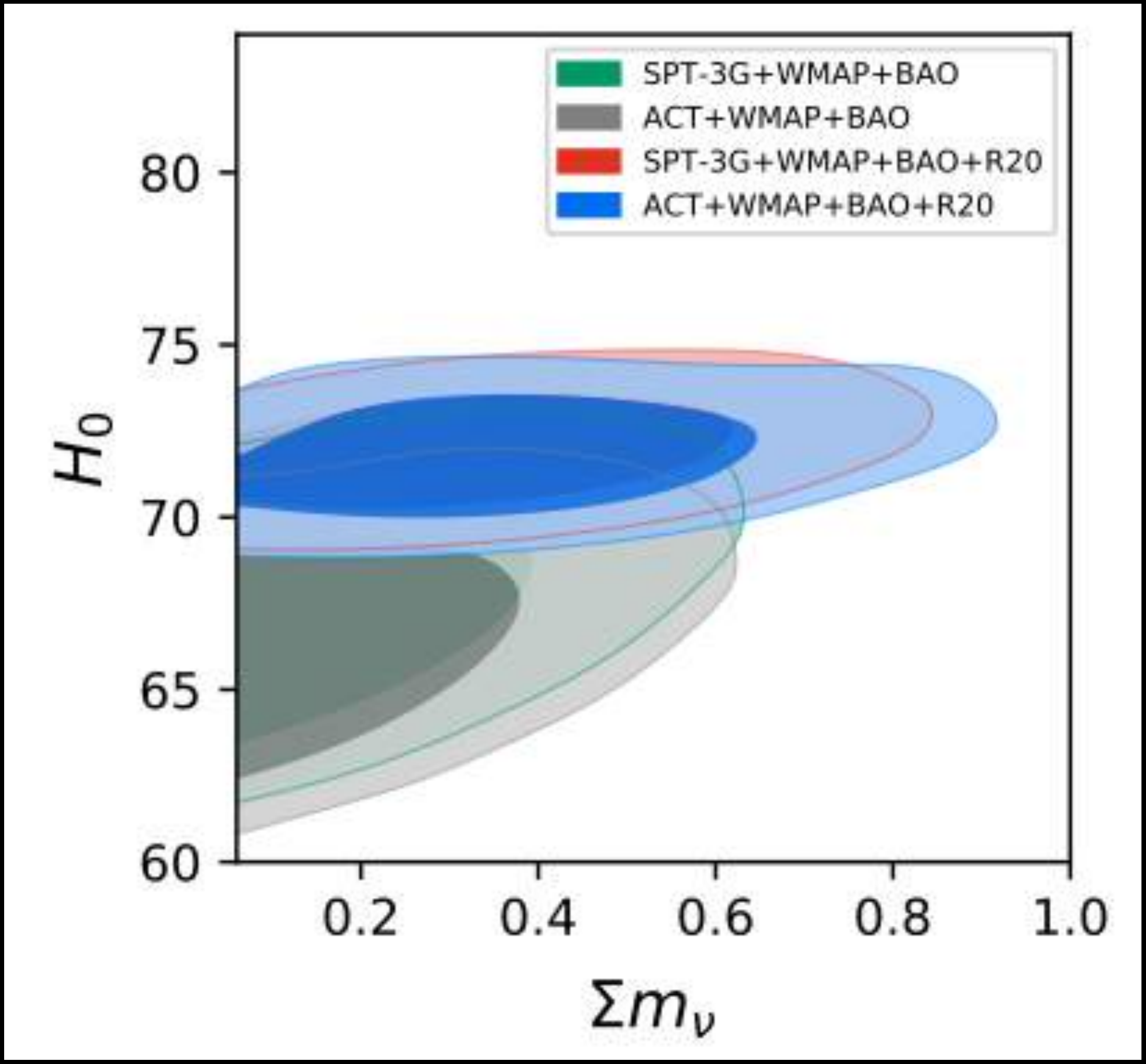
Table 3
Constraints on the Sum of Neutrino Masses Σm_ν at 68% C.L. from a Combination of Different Data Sets in the Case of the ΛCDM+Σm_ν+w+$N_{\rm eff}$+$dn/d\ln k$ Scenario

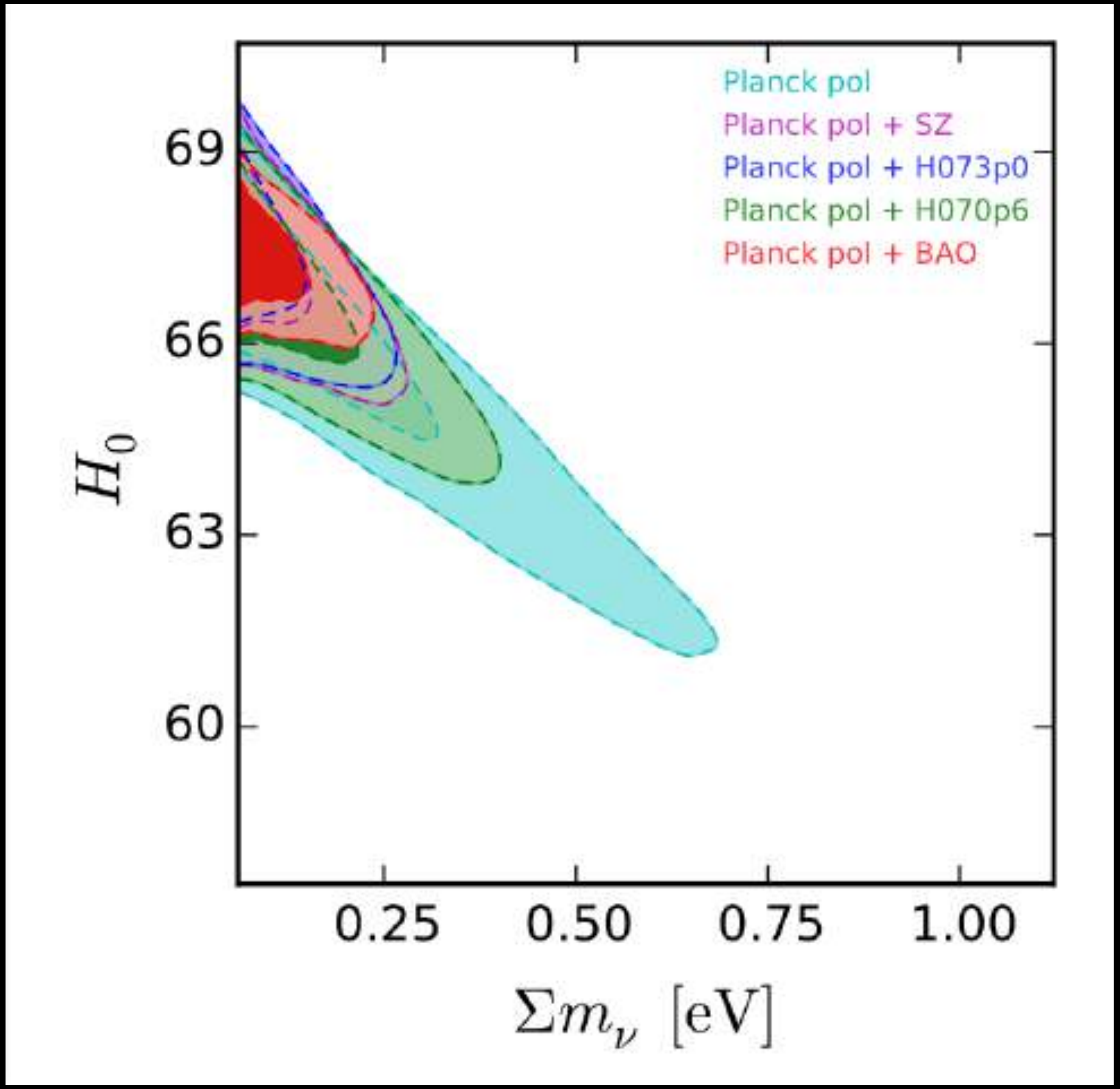
Data Set	Σm_ν (eV)
Planck (+$A_{\rm lens}$)	<0.50
Planck+BAO (+$A_{\rm lens}$)	<0.22
Planck+Pantheon (+$A_{\rm lens}$)	<0.47
Planck+lensing (+$A_{\rm lens}$)	$0.38^{+0.12}_{-0.28}$
ACT-DR4+WMAP	0.81 ± 0.28
ACT-DR4+WMAP+BAO	<0.27
ACT-DR4+WMAP+Pantheon	0.71 ± 0.28
ACT-DR4+WMAP+lensing	0.56 ± 0.21
ACT-DR4+WMAP+R20	0.83 ± 0.230
ACT-DR4+WMAP+F21	$0.85^{+0.27}_{-0.33}$
ACT-DR4+WMAP+BAO+R20	$0.39^{+0.13}_{-0.25}$
ACT-DR4+WMAP+BAO+F21	<0.34
SPT-3G+WMAP	<0.56
SPT-3G+WMAP+BAO	<0.28
SPT-3G+WMAP+Pantheon	$0.46^{+0.11}_{-0.39}$
SPT-3G+WMAP+lensing	<0.39
SPT-3G+WMAP+R20	$0.49^{+0.12}_{-0.42}$
SPT-3G+WMAP+F21	<0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	<0.32

ilk, ApJ letters 2022

10 parameters

standard ΛCDM





Di Valentino and Melchiorri, 2022 *ApJL* **931** L18

Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

When CMB and BAO data are considered in these extended cosmologies, they provide constraints on the Σmν vs H0 plane that clearly show a correlation between these two parameters, that is exactly the opposite of what is obtained under standard ΛCDM.

CONCLUSIONS

- There is now strong evidence for the CNB from CMB and BBN data.
- There is clearly the possibility of systematics in the data. An extra background of relativistic particles is possible (as lower Neff).
- When only TT CMB data is considered a fourth neutrino and a HZ spectrum offer a solution to the Hubble tension.
- Planck polarization data (especially at large scales) are in tension with TT data. This can prevent a solution to the Hubble tension.
- In this scenario, a conservative approach when considering cosmological bounds on neutrino masses should be taken. It is clearly too early to claim that NO is ruled out by cosmology (even if this could be the case…)
- Plenty of future CMB experiments in construction and/or already taking data !