AN OVERVIEW OF COSMOLOGICAL DATA

WIN2017, IRVINE

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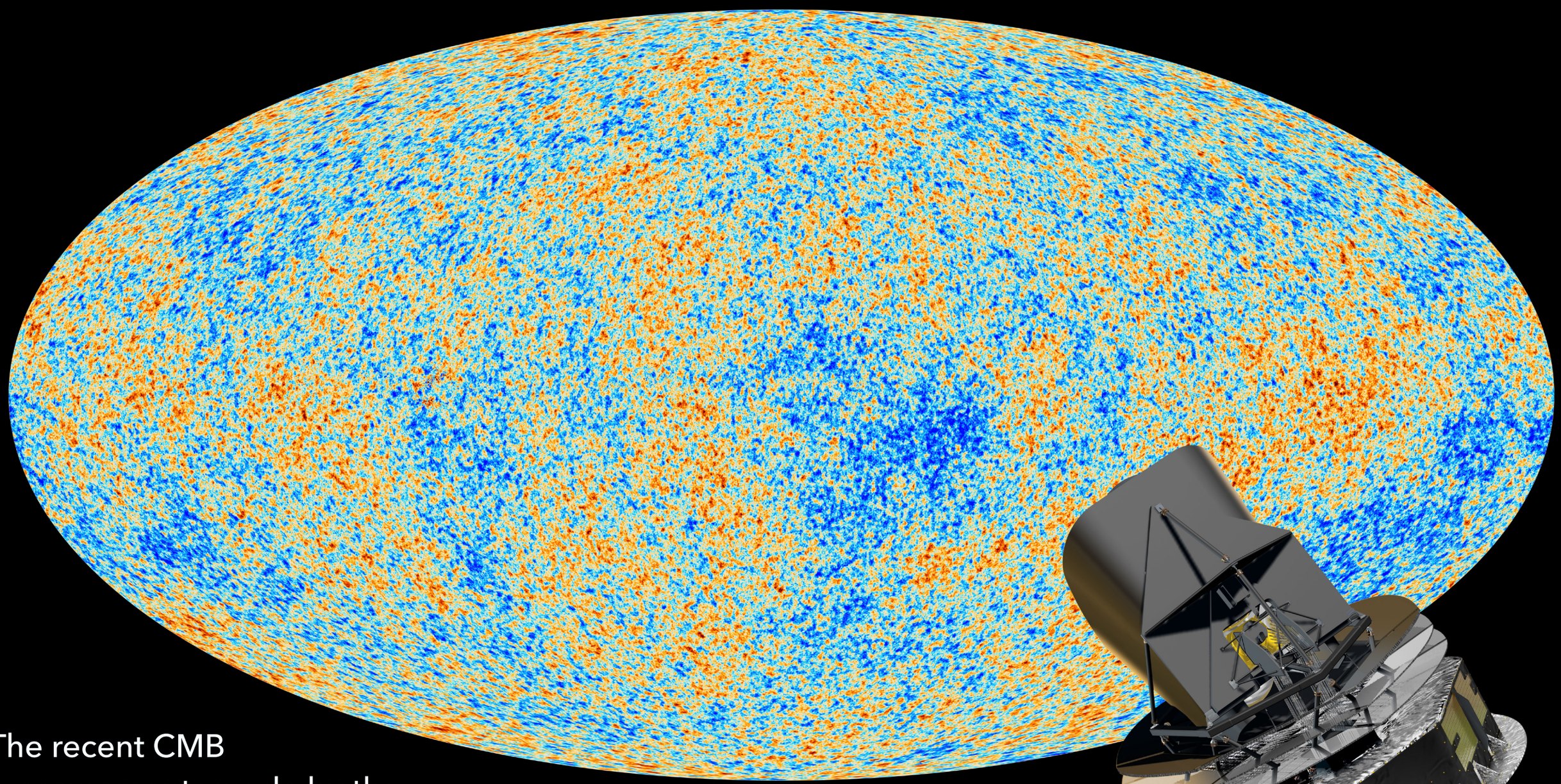
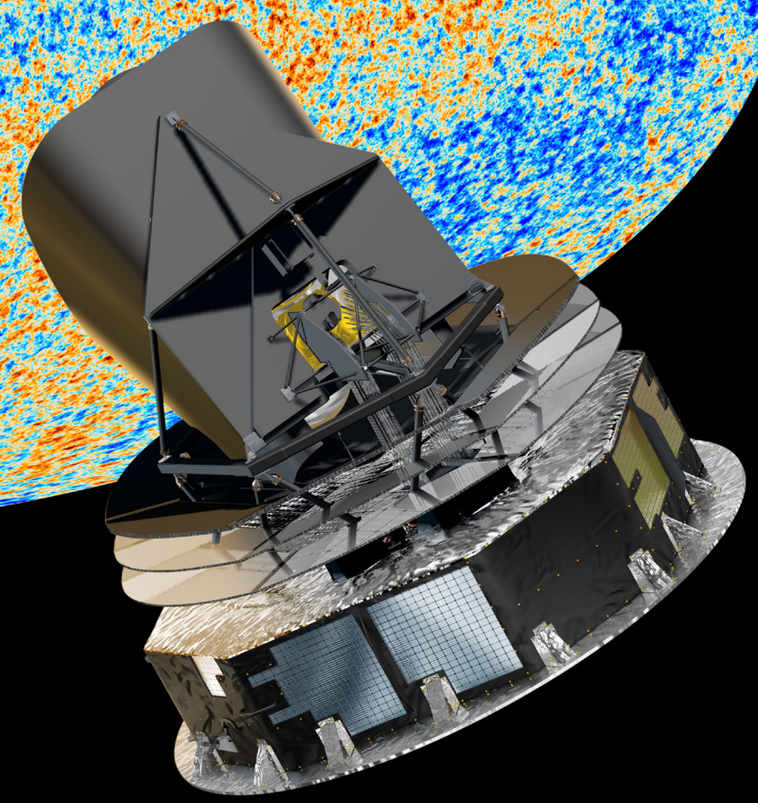
ALESSANDRO MELCHIORRI
UNIVERSITY OF ROME “SAPIENZA”

A PERFECT (LCDM) UNIVERSE ?





The recent CMB measurements made by the Planck satellite are in perfect agreement with the expectations of the LCDM model.

Planck collaboration, arXiv:1502.01589

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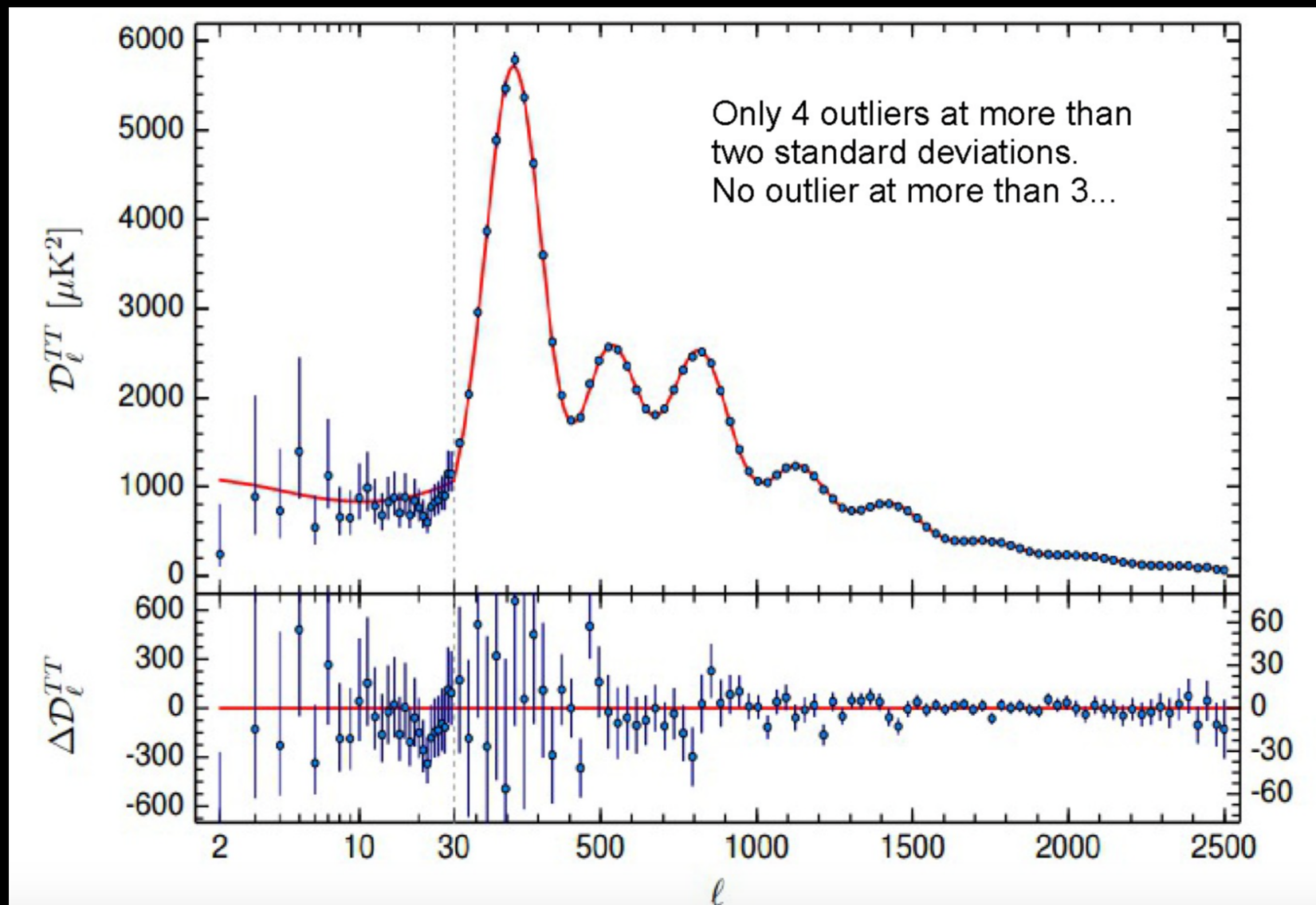

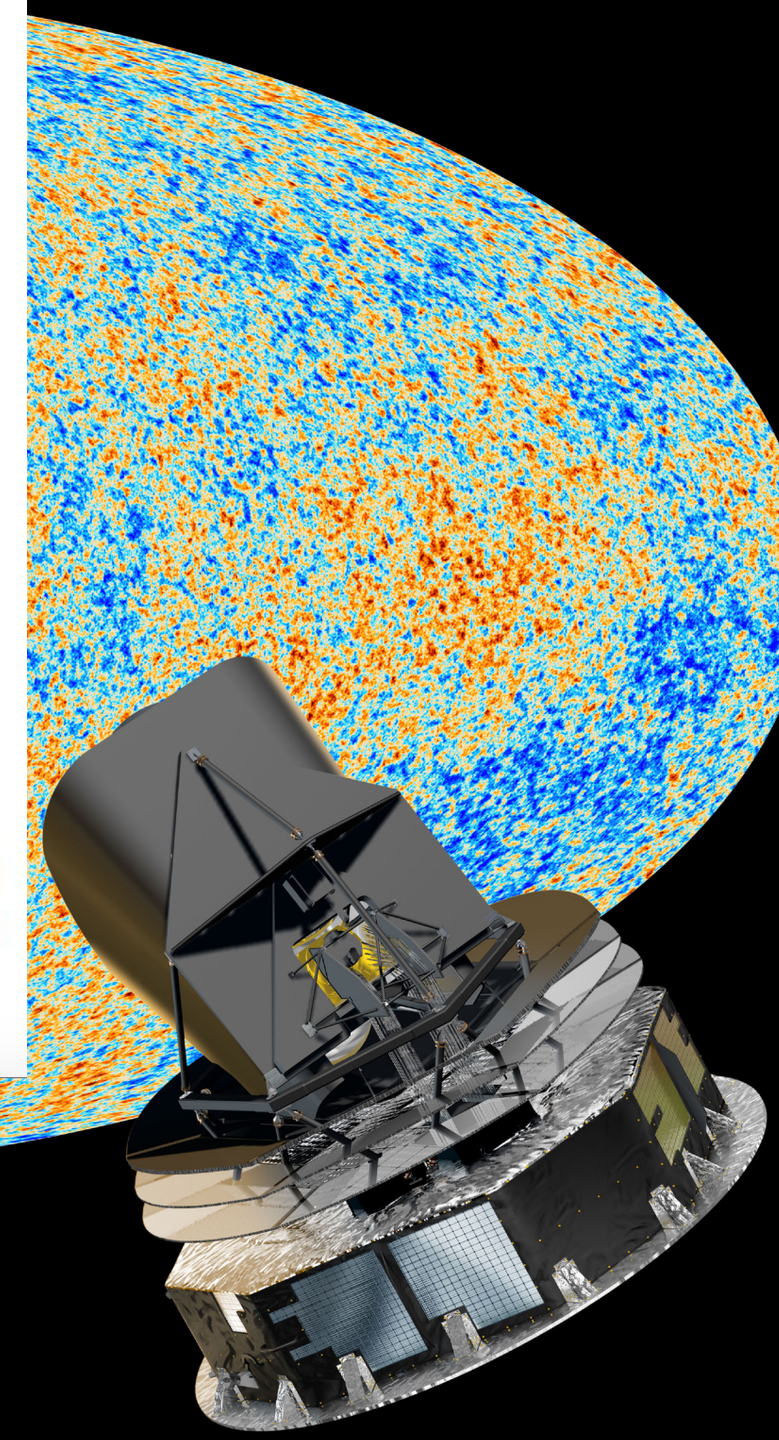

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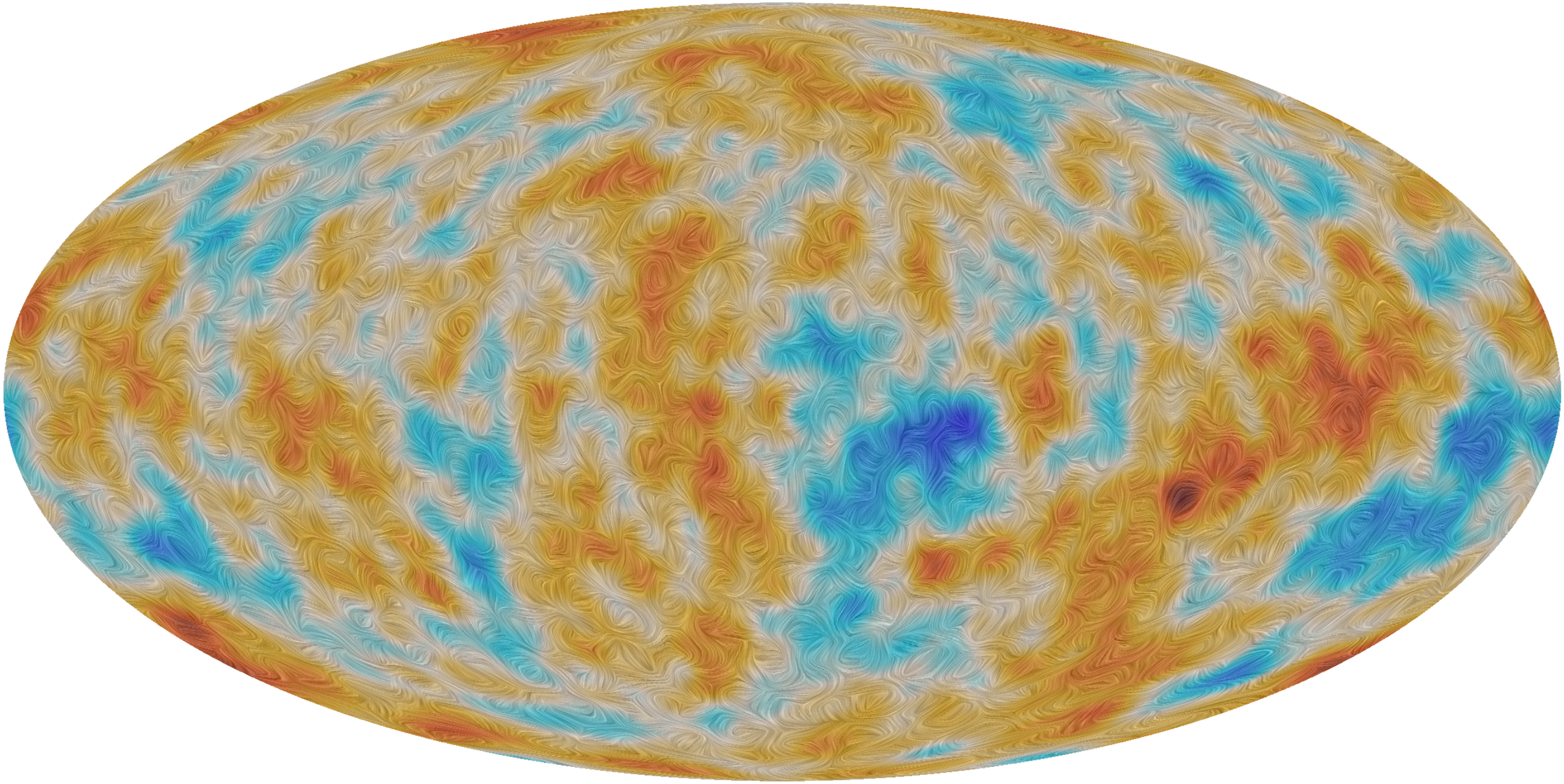
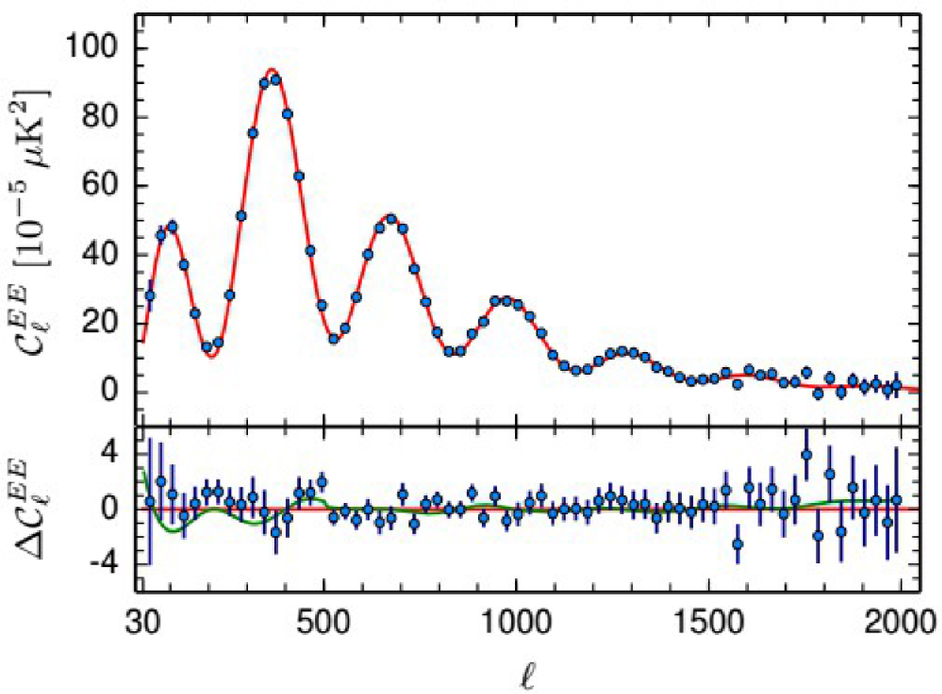


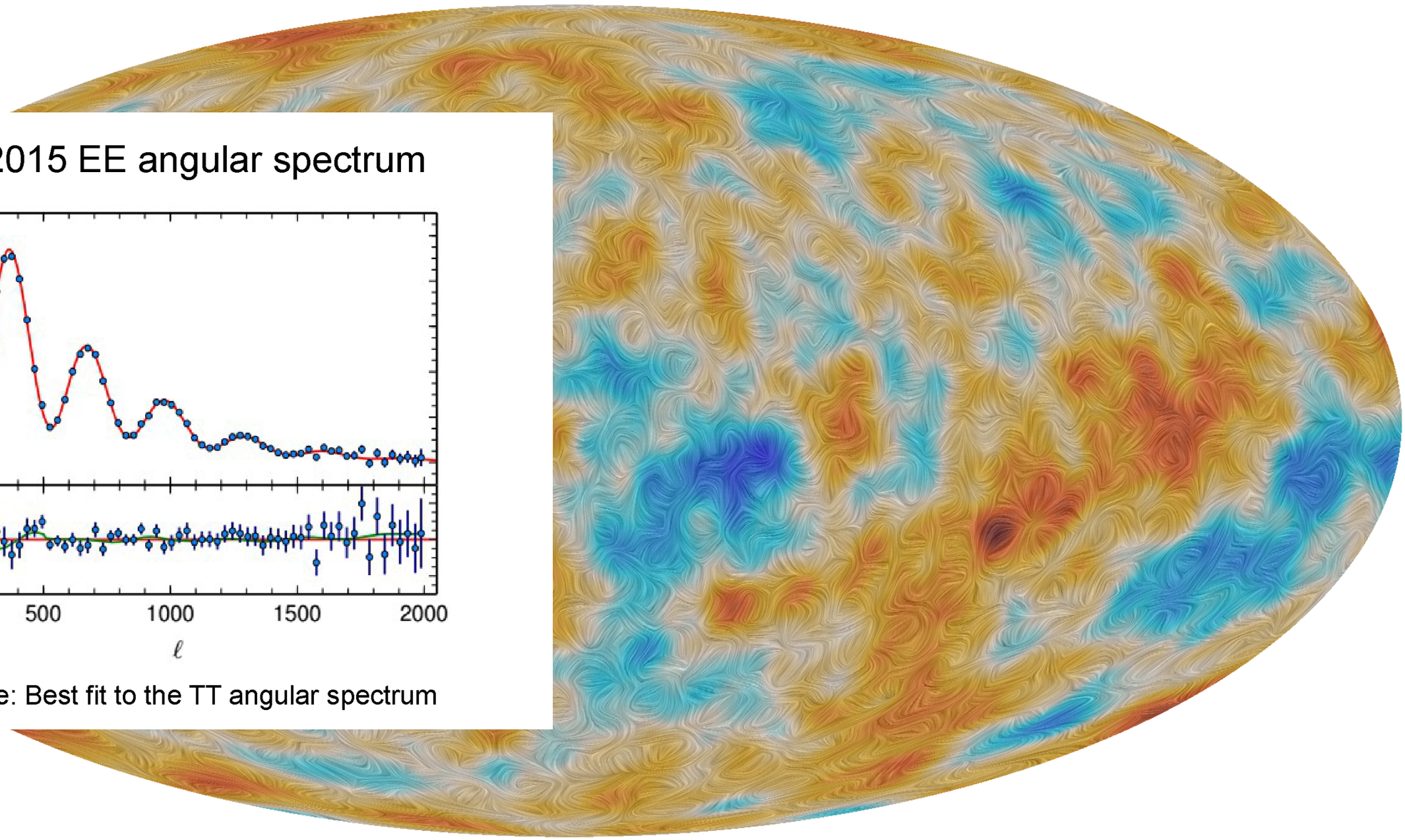
Planck CMB polarization map filtered at 5 degrees

A PERFECT (LCDM) UNIVERSE ?

Planck 2015 EE angular spectrum



Red Line: Best fit to the TT angular spectrum



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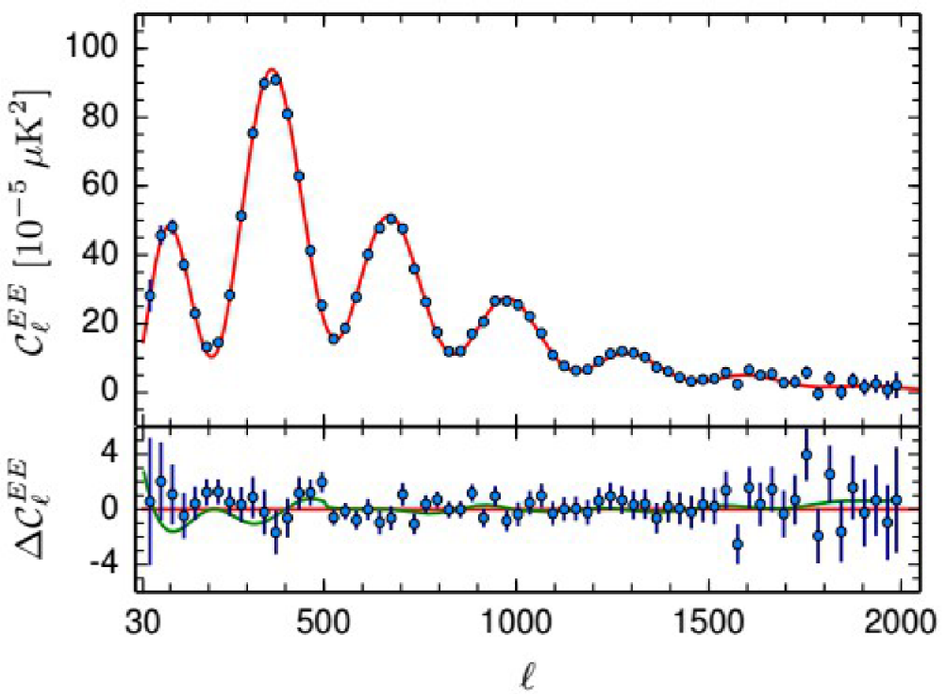
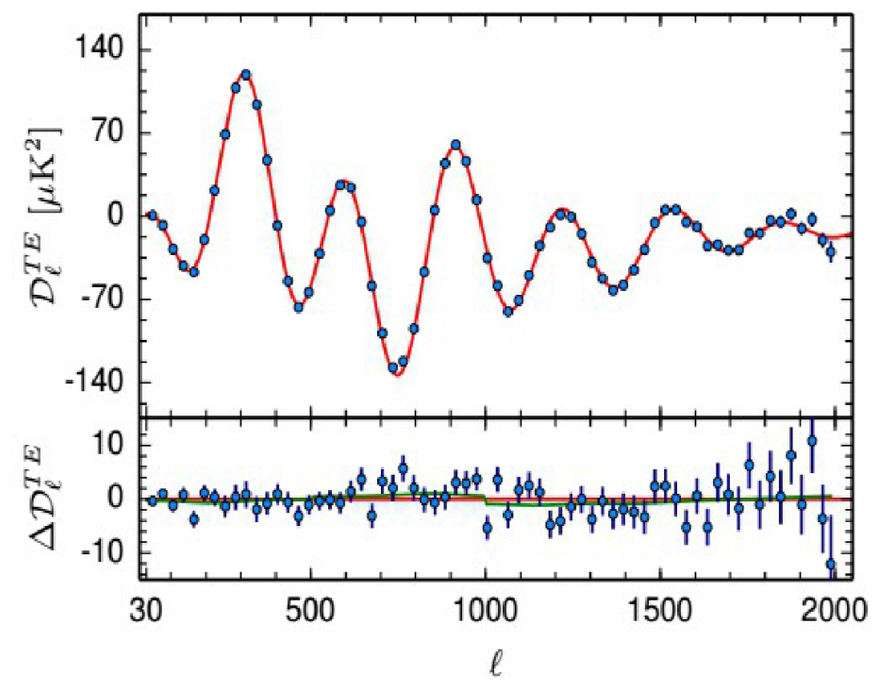


Red Line: Best fit to the TT angular spectrum

Planck 2015 TE angular spectrum



Red Line: Best fit to the TT angular spectrum

Planck CMB polarization map filtered at 5 degrees

CONSTRAINTS ON NEUTRINO MASSES FROM PLANCK CMB ANGULAR SPECTRA

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

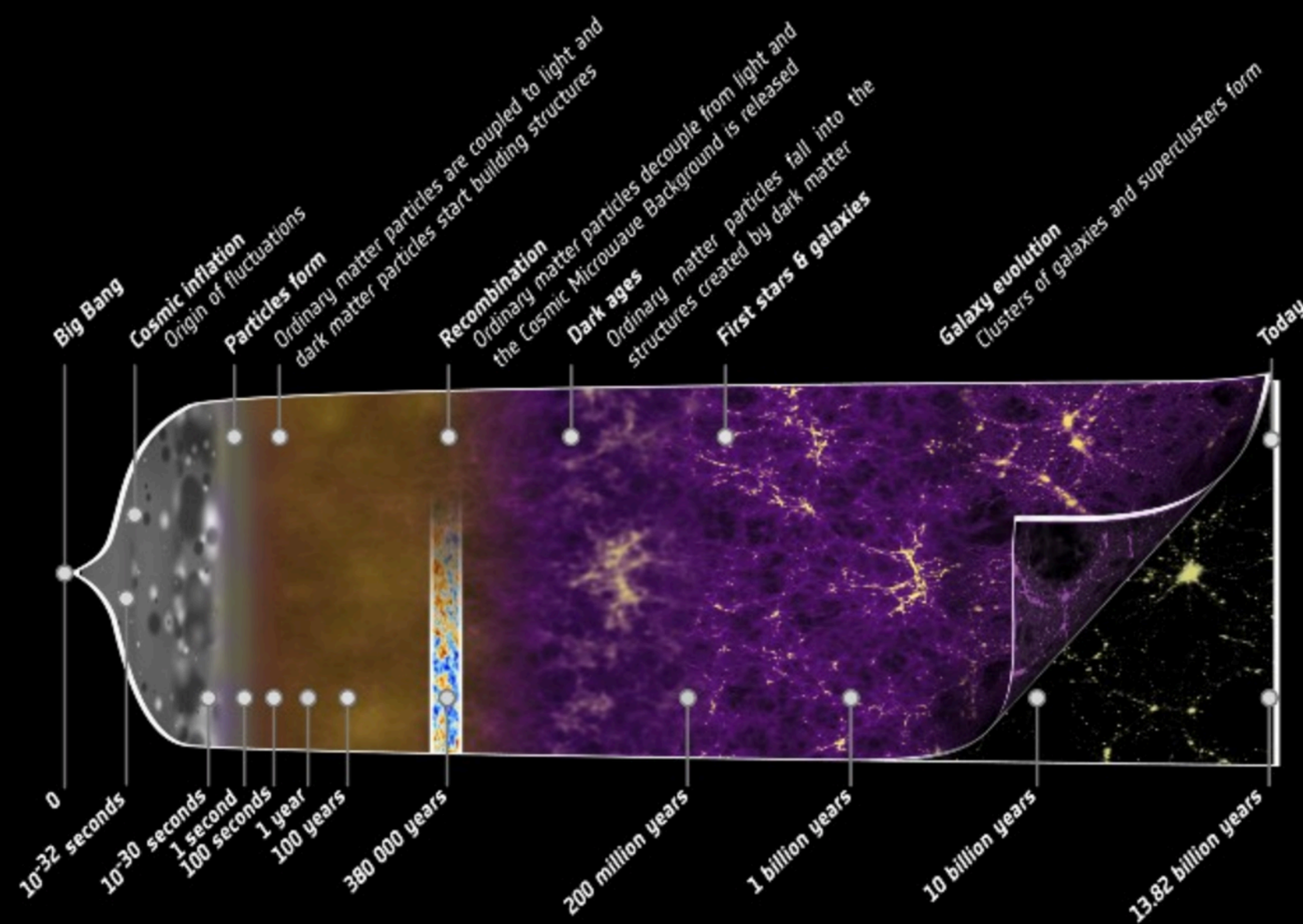
$$\sum m_\nu < 0.492 \ \ eV$$

Ade et al., A&A 594, A13 (2016)
Planck 2015 constraint

$$\sum m_\nu < 0.340 \ \ eV$$

Ade et al., A&A 596, A107 (2016)
Better measurement of large angular scale polarisation improves significantly the previous constraint.

NEUTRINO MASS AND THE CMB

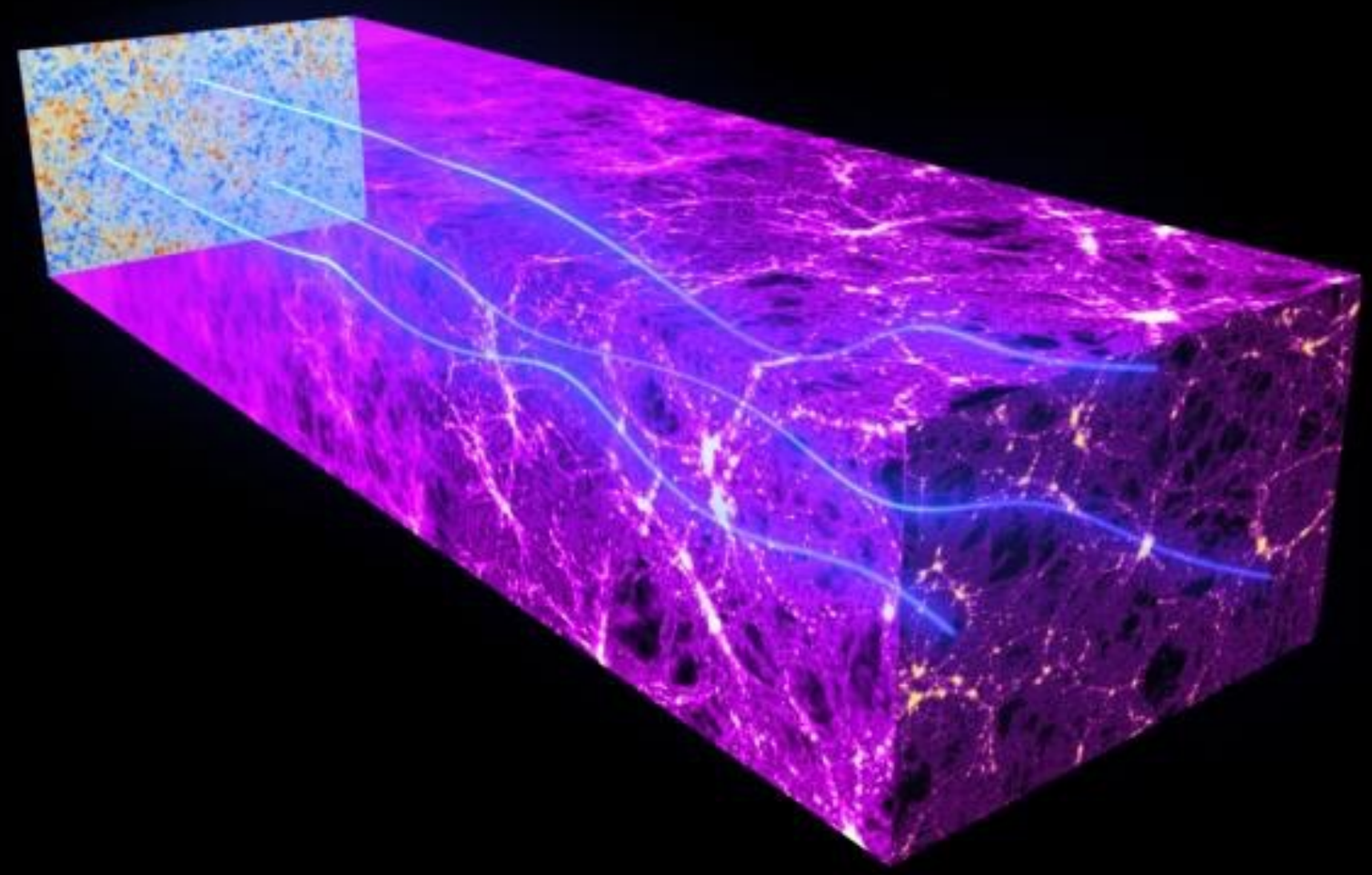


Primary CMB anisotropies form at recombination, at redshift z=1300 when the CMB was at a temperature of T~0.3 eV. A neutrino with a mass of ~(0.34/3)~0.11 eV is still relativistic at that epoch.

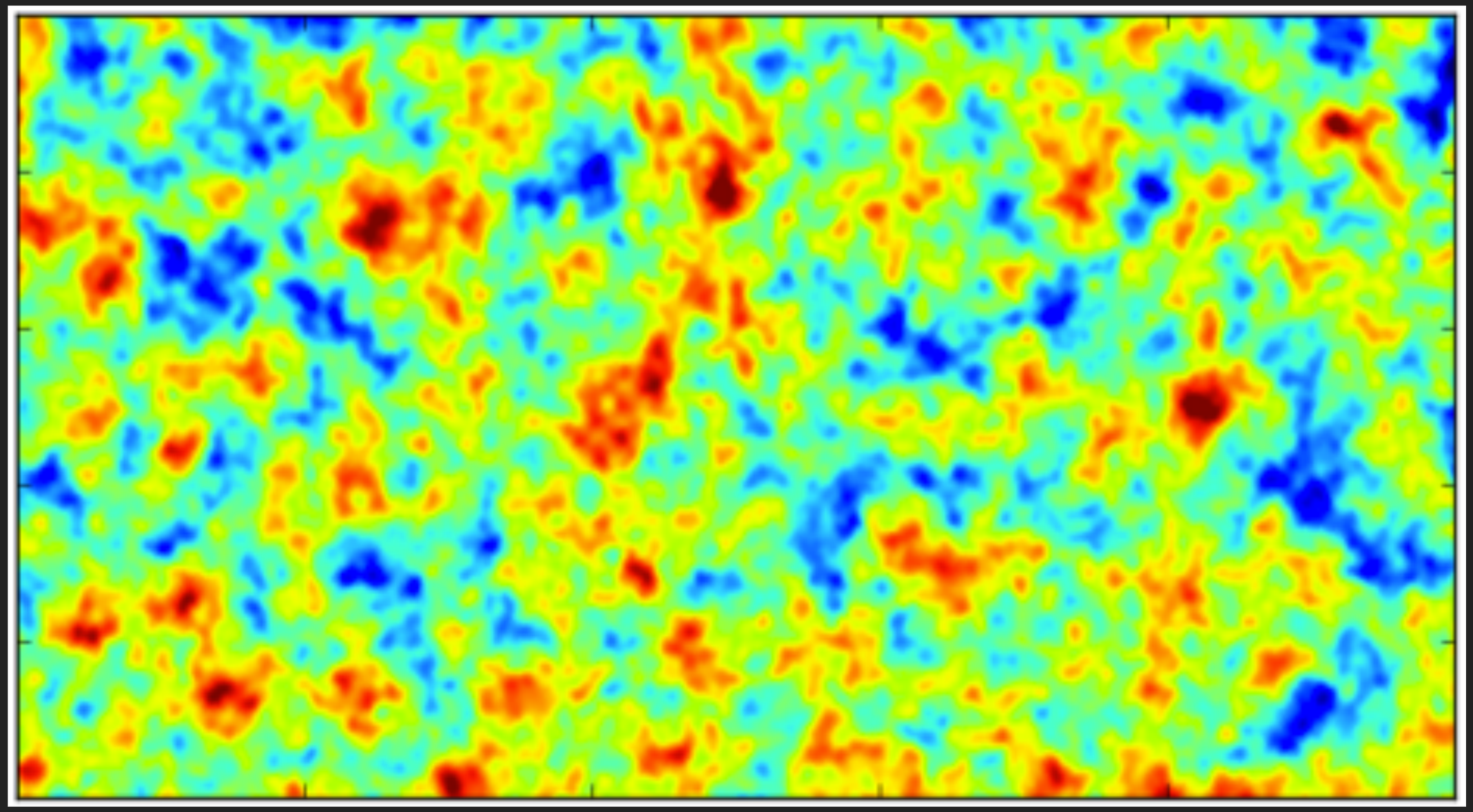
How I can place with CMB data this incredibly good upper limit ?

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.

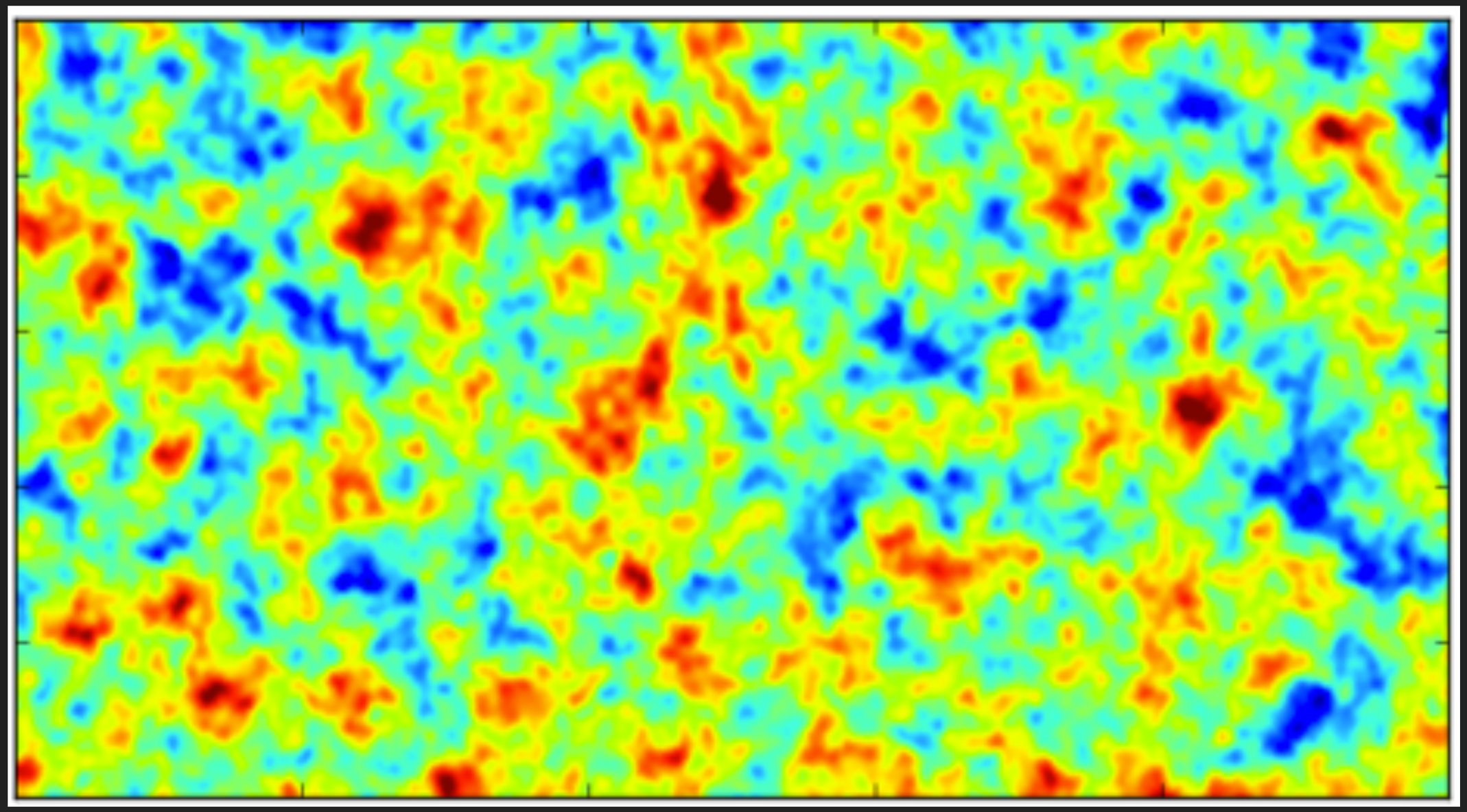


CMB LENSING



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

CMB LENSING



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

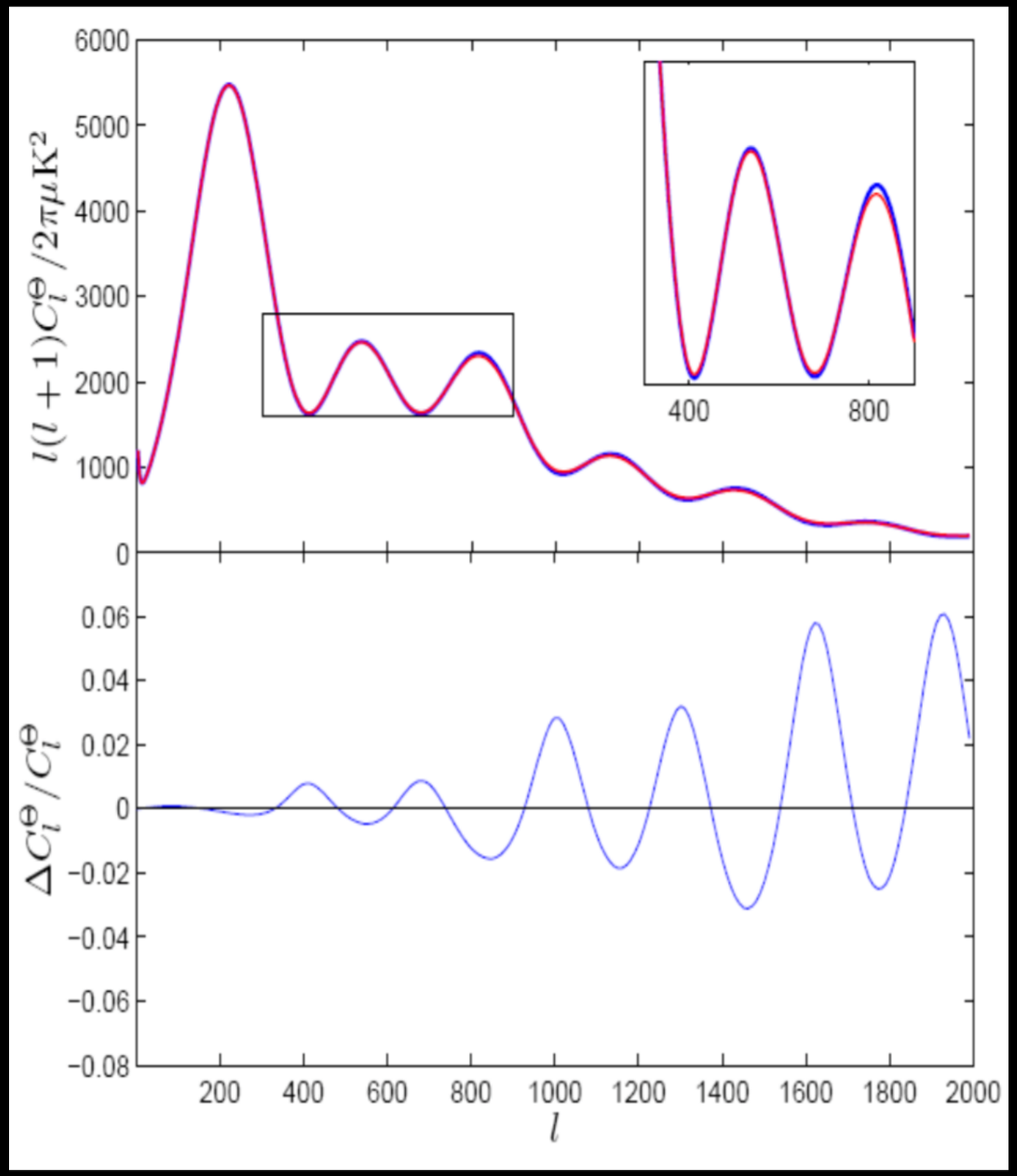
CMB LENSING

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

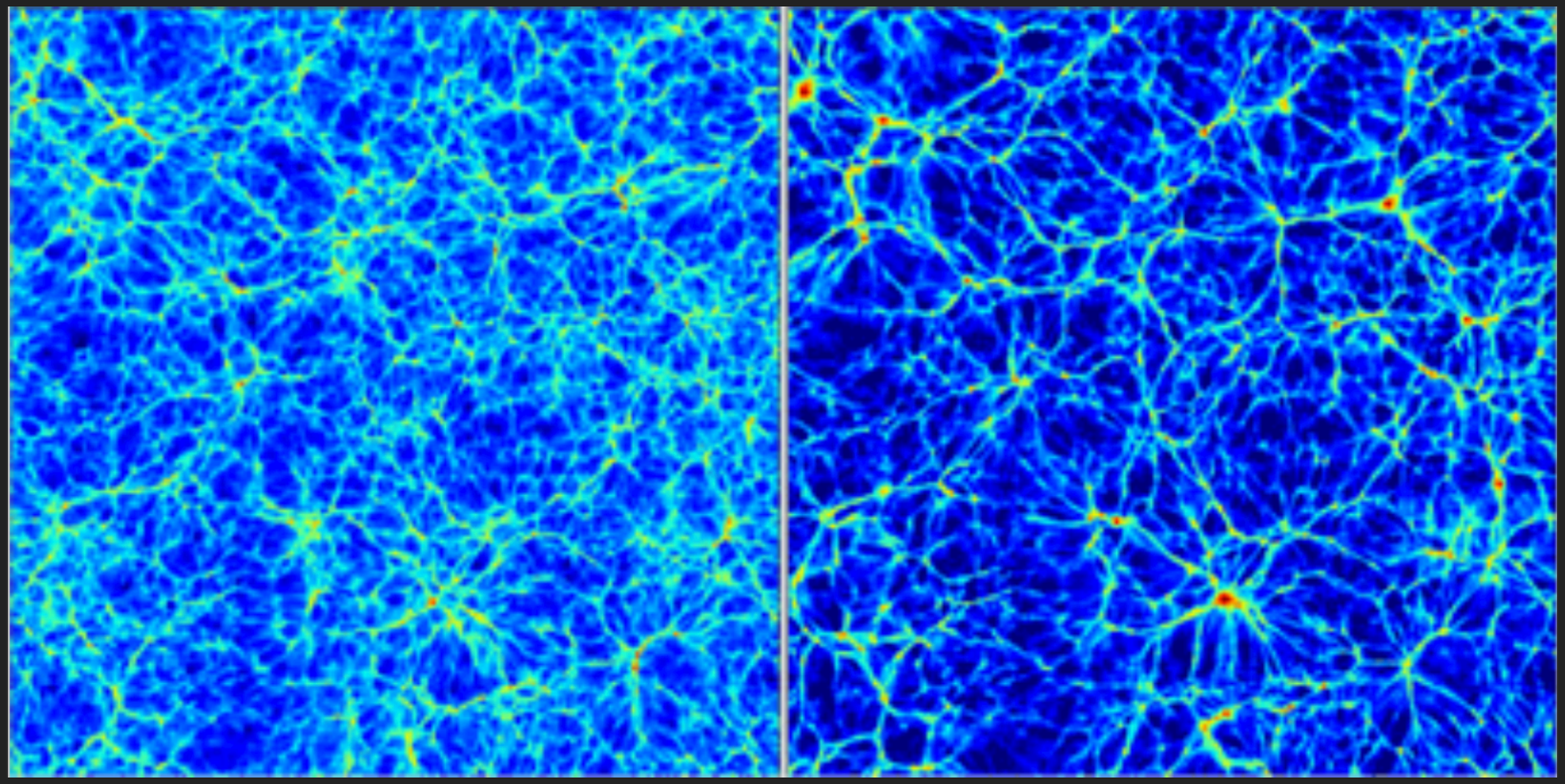
This affects the CMB anisotropy angular spectrum by smearing the high l peaks.

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

Planck is sensitive to these tiny variations !



CMB LENSING



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

More massive is the neutrino less structure we have -> less CMB lensing.

CONSTRAINTS ON NEUTRINO MASSES FROM PLANCK CMB ANGULAR SPECTRA

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

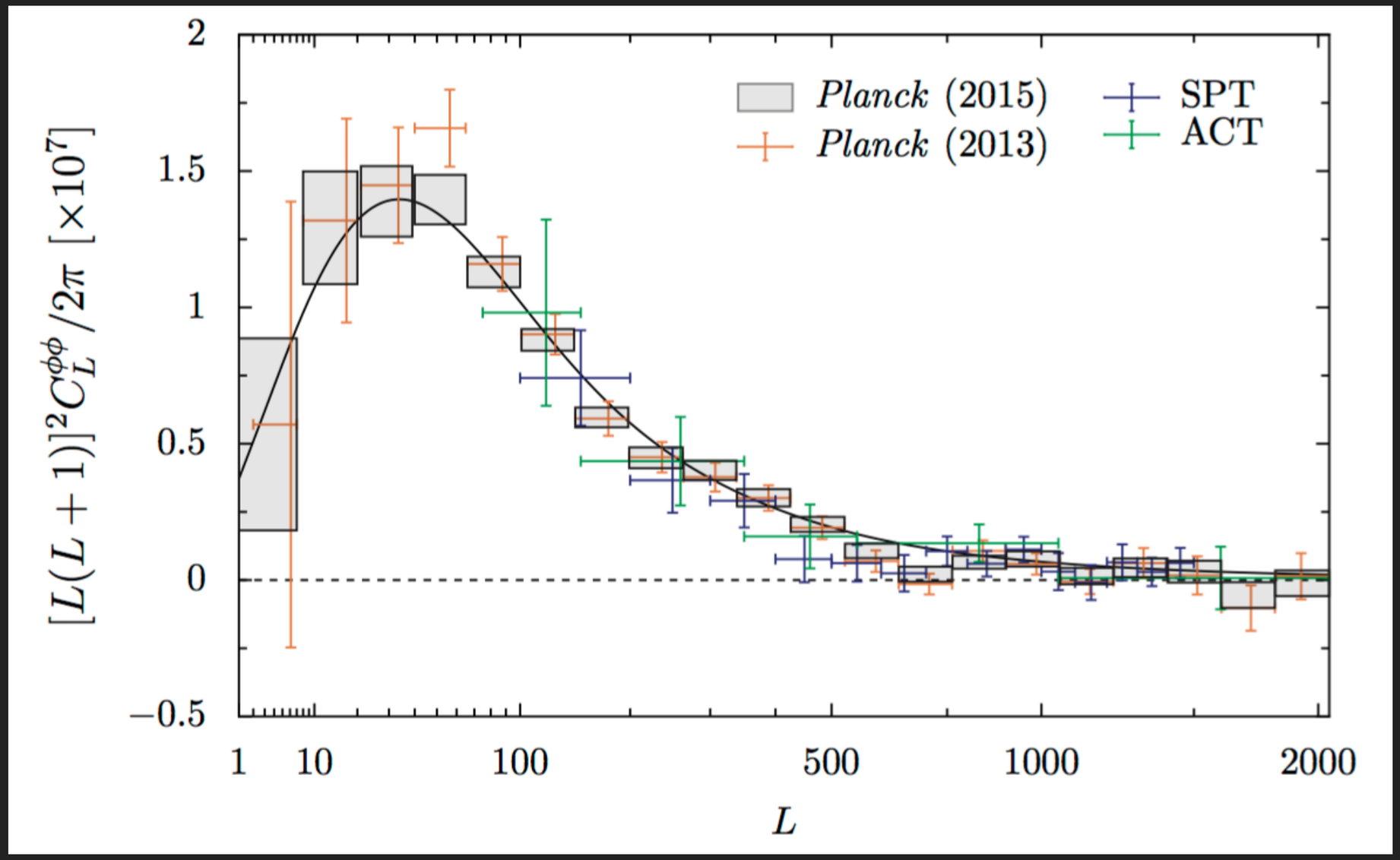
$$\sum m_\nu < 0.492 \ \ eV$$

$$\sum m_\nu < 0.340 \ \ eV$$

These limits are completely due to CMB lensing !

Such strong limits indicate that we have a clear detection of the lensing signal in the CMB spectra (more lensing less neutrino mass) !

CMB LENSING 2



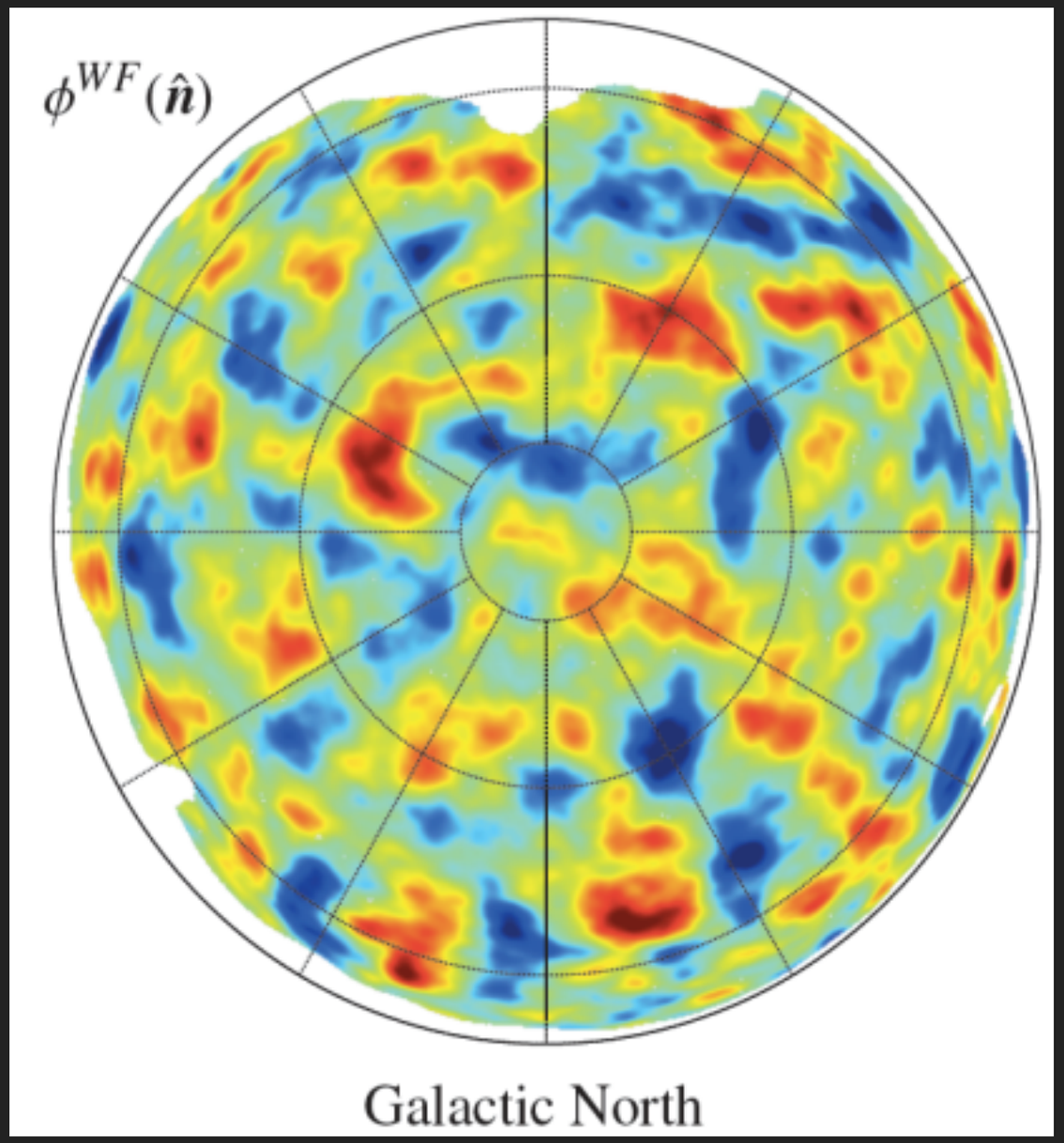
Planck collaboration, arXiv:1502.01589

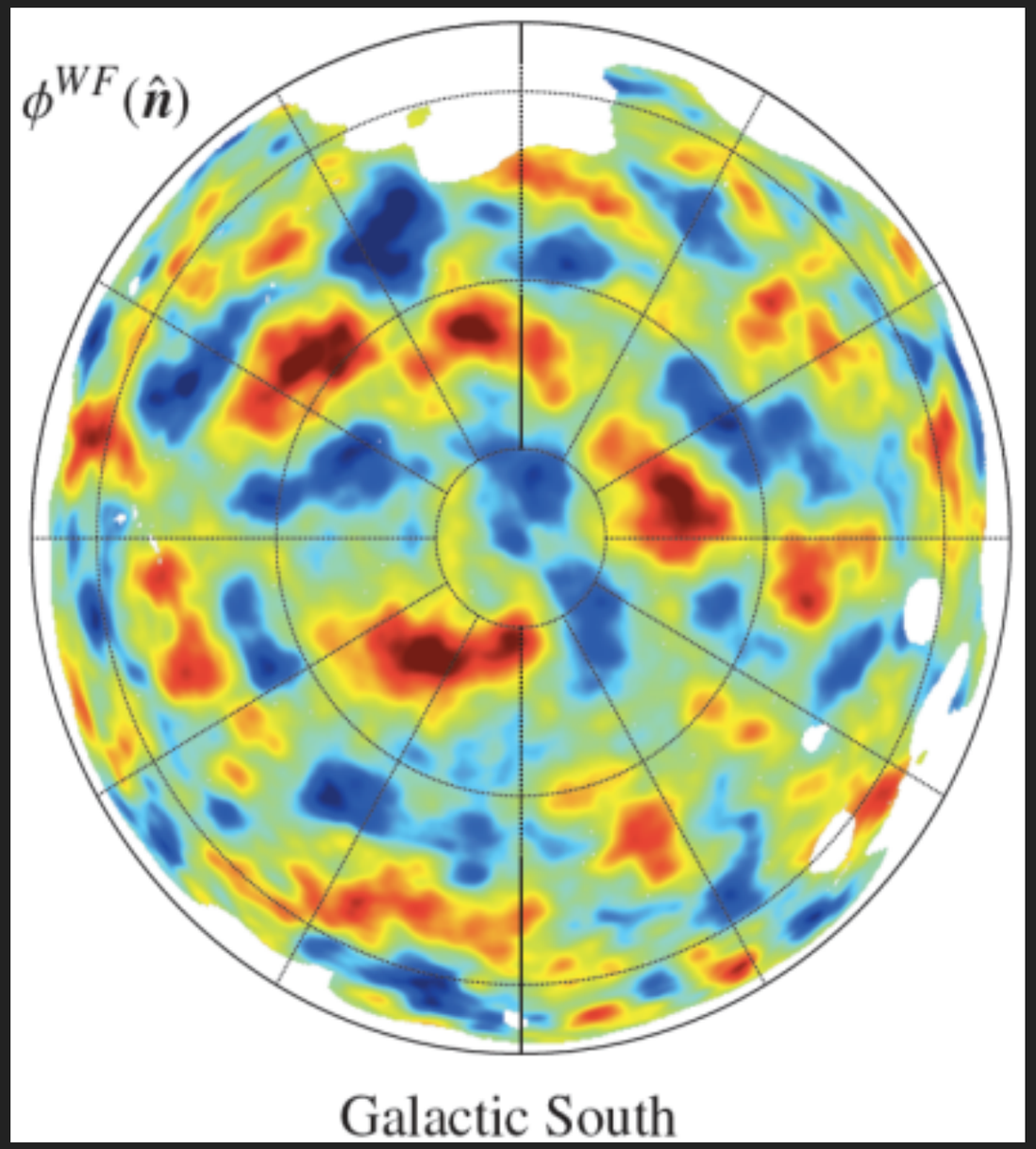
CMB Lensing can be measured also in a different way.

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 2015 release)

$$\sum m_\nu < 0.188 \ \ eV$$

Planck TT+TE+EE

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Planck TT+TE+EE+lensing (TTTT)

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Planck TT+TE+EE+lensing (TTTT)

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

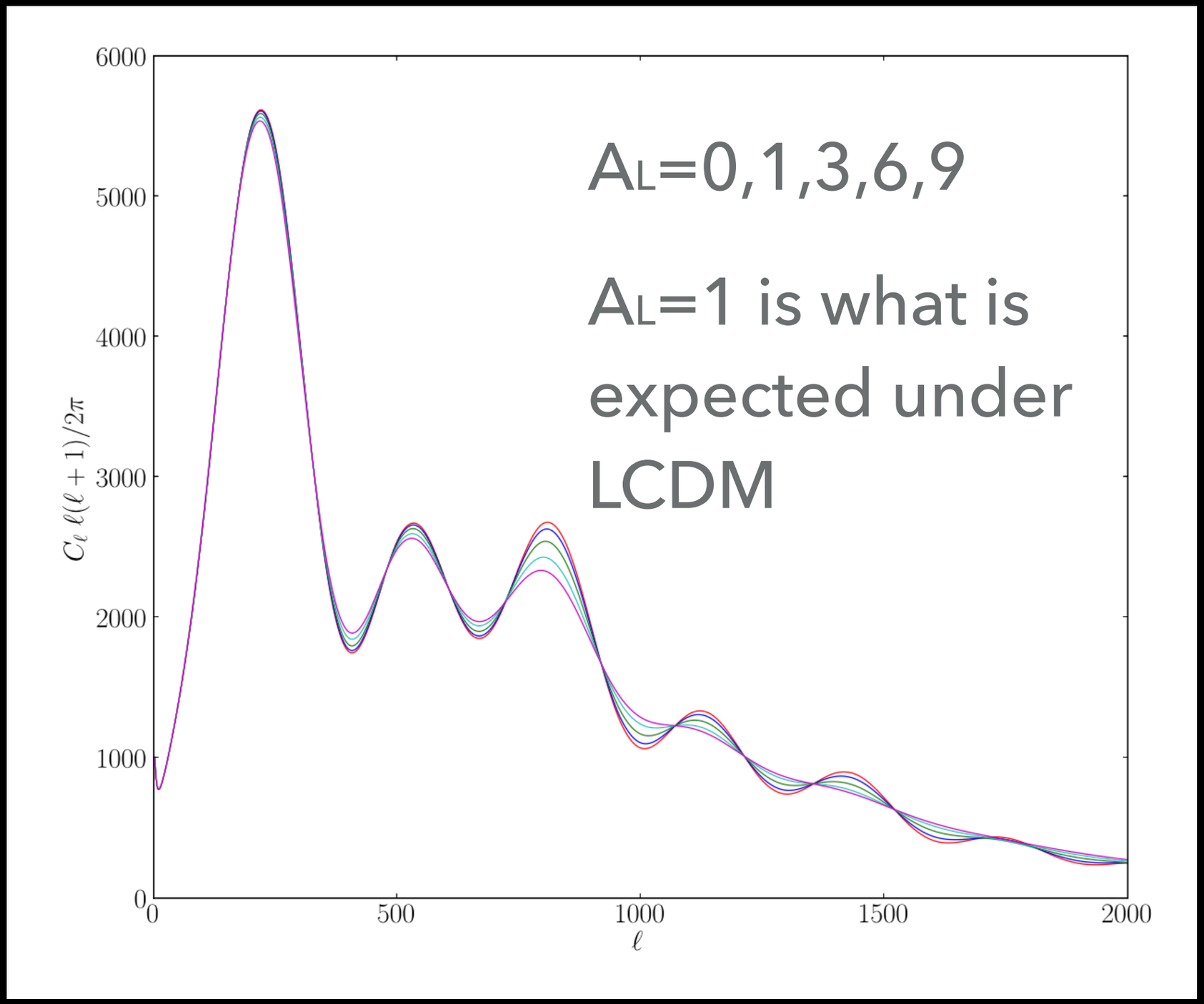
How this can be possible ?

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.



THE A_L PROBLEM

The most recent Planck analysis (arXiv:1605.02985) prefers A_L>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
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$2.97^{+0.58}_{-0.53}$	$2.99^{+0.41}_{-0.39}$	$2.91^{+0.39}_{-0.37}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.242^{+0.039}_{-0.040}$	$0.250^{+0.026}_{-0.027}$	$0.244^{+0.026}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.014}_{-0.014}$	$-0.003^{+0.014}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.111	< 0.0987	< 0.111
w	$-1.54^{+0.62}_{-0.50}$	$-1.57^{+0.61}_{-0.49}$	$-1.55^{+0.58}_{-0.48}$	$-1.59^{+0.58}_{-0.46}$
$A_{\rm L}$	$1.22^{+0.21}_{-0.20}$	$1.23^{+0.20}_{-0.18}$	$1.15^{+0.16}_{-0.15}$	$1.15^{+0.13}_{-0.12}$

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.

95% c.l. constraints on neutrino mass from Planck TTTEEE (2015):

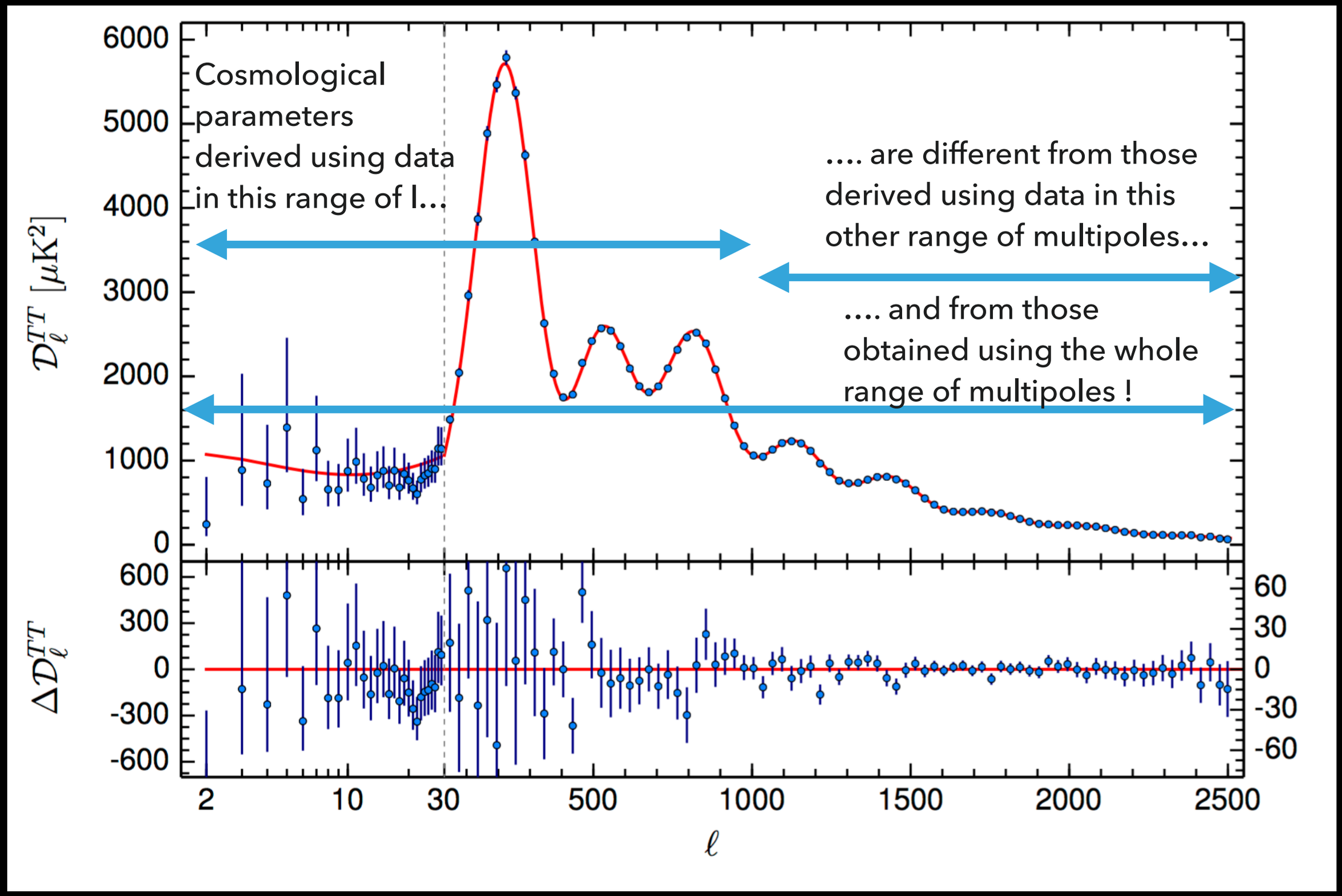
$$\sum m_\nu < 0.492 \ \ eV$$

LCDM

$$\sum m_\nu < 0.825 \ \ eV$$

LCDM+AL

ANOMALIES IN TT SPECTRA ?



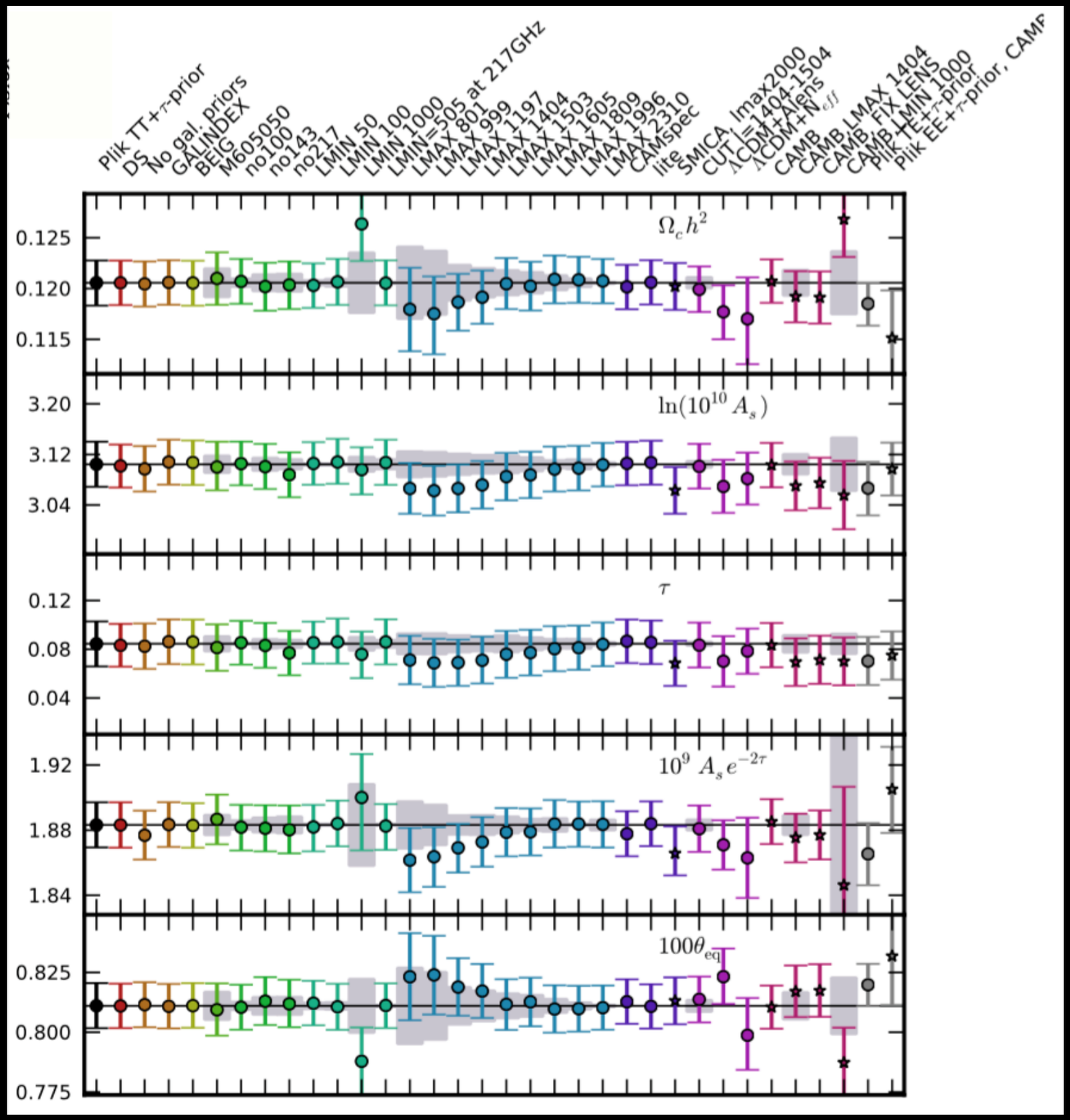
(LCDM and a prior on the optical depth τ=0.07±0.02 are assumed)

ANOMALIES IN TT SPECTRA ?

If we estimate LCDM parameters in the multipole range 2<l<1000 Planck temperature data gives slightly different values (1-2σ) than what we get when analyzing the whole range (2<l<2300).

(Planck 2015 paper IX, arXiv: 1507.02704, figure 35, but see also discussion by Addison et al, arXiv: 1511.00055)

From where it comes ?



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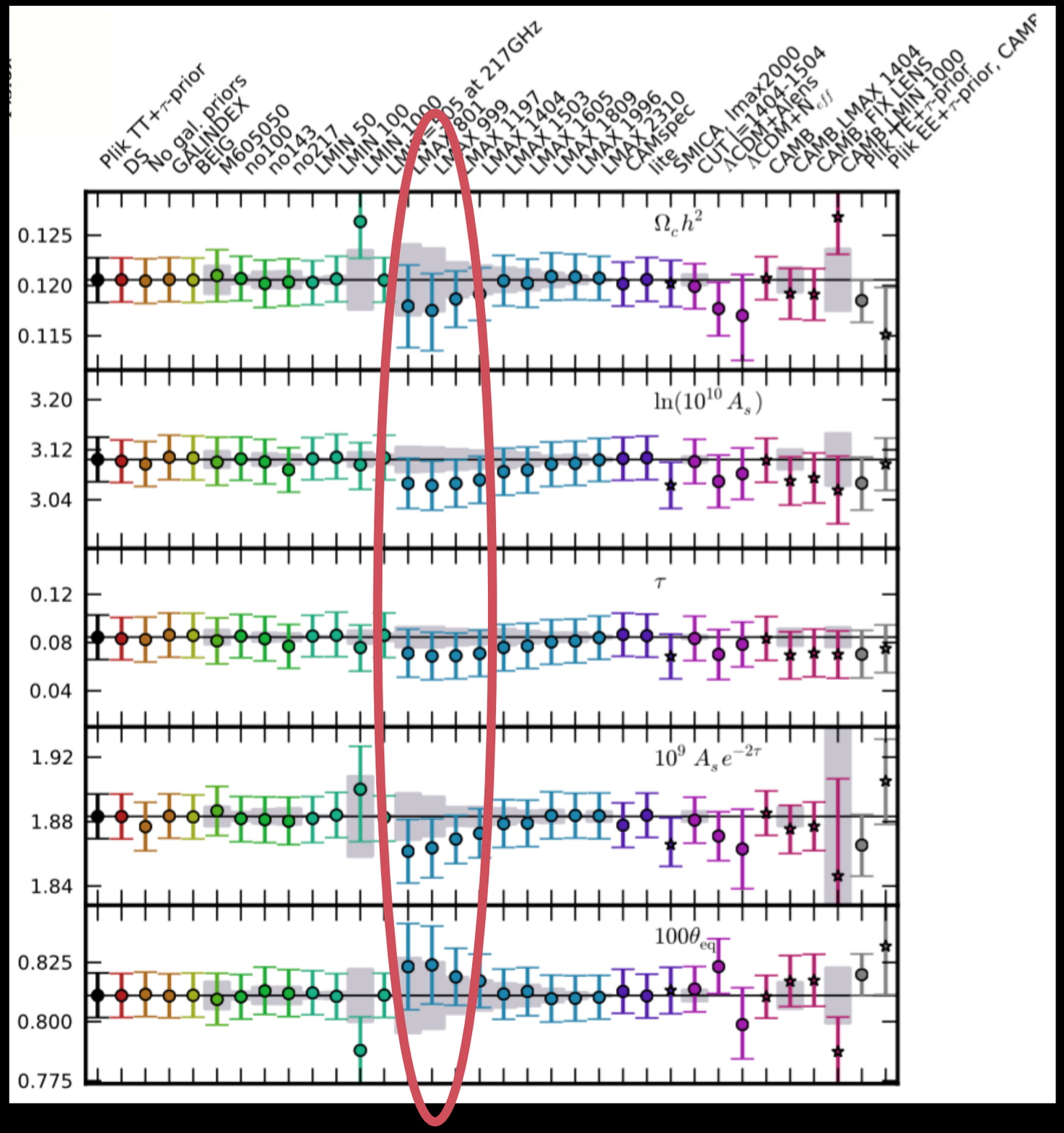
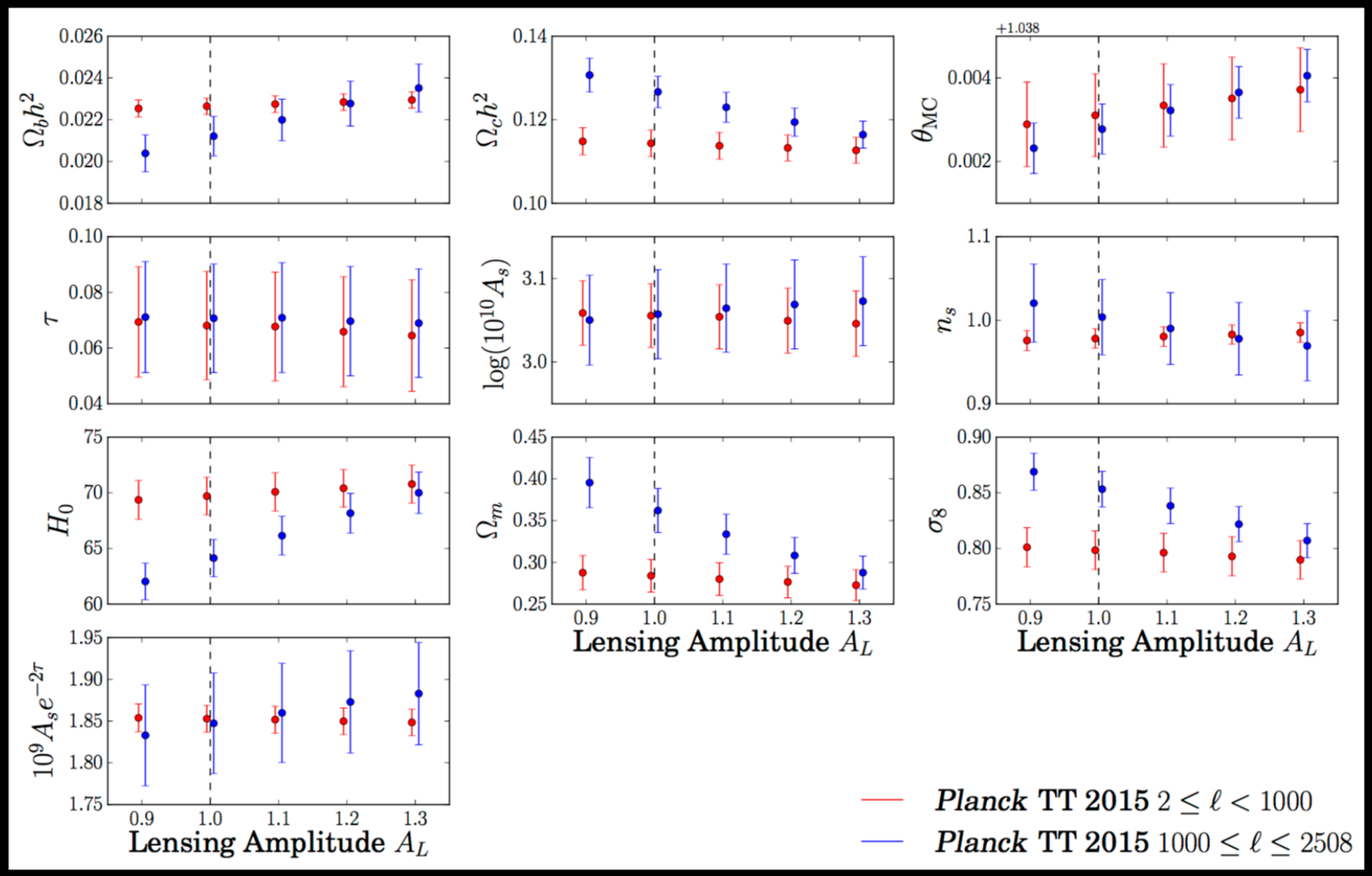


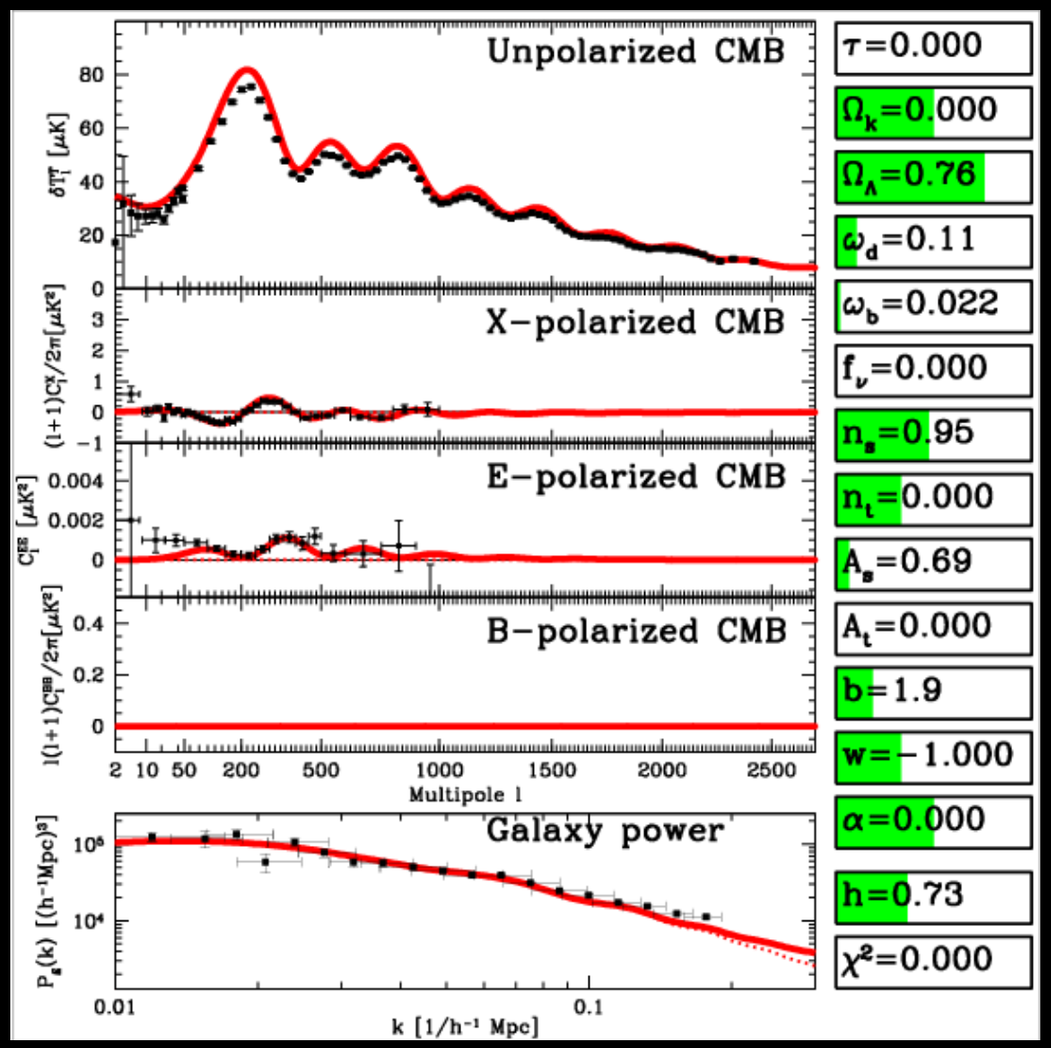
ANOMALIES ARE SOLVED BY A_L

When A_L~1.2 we have the same parameters constraints from 2<l<1000 and 1000<l<2508 !



Addison et al, arXiv:1511.00055

TENSION ON OPTICAL DEPTH



Reionization affects both temperature and polarisation spectra.

Both low-l polarisation bump and small scale temperature anisotropies (thanks to lensing) can bound the reionization optical depth.

Using only TT data in LCDM we get:

$$\tau=0.099\pm0.024$$

Using only EE data we get:

$$\tau=0.055\pm0.009$$

i.e. we notice a tension at the level of ~1.7σ

Using only TT data and varying A_L we get:

$$\tau=0.059\pm0.021$$

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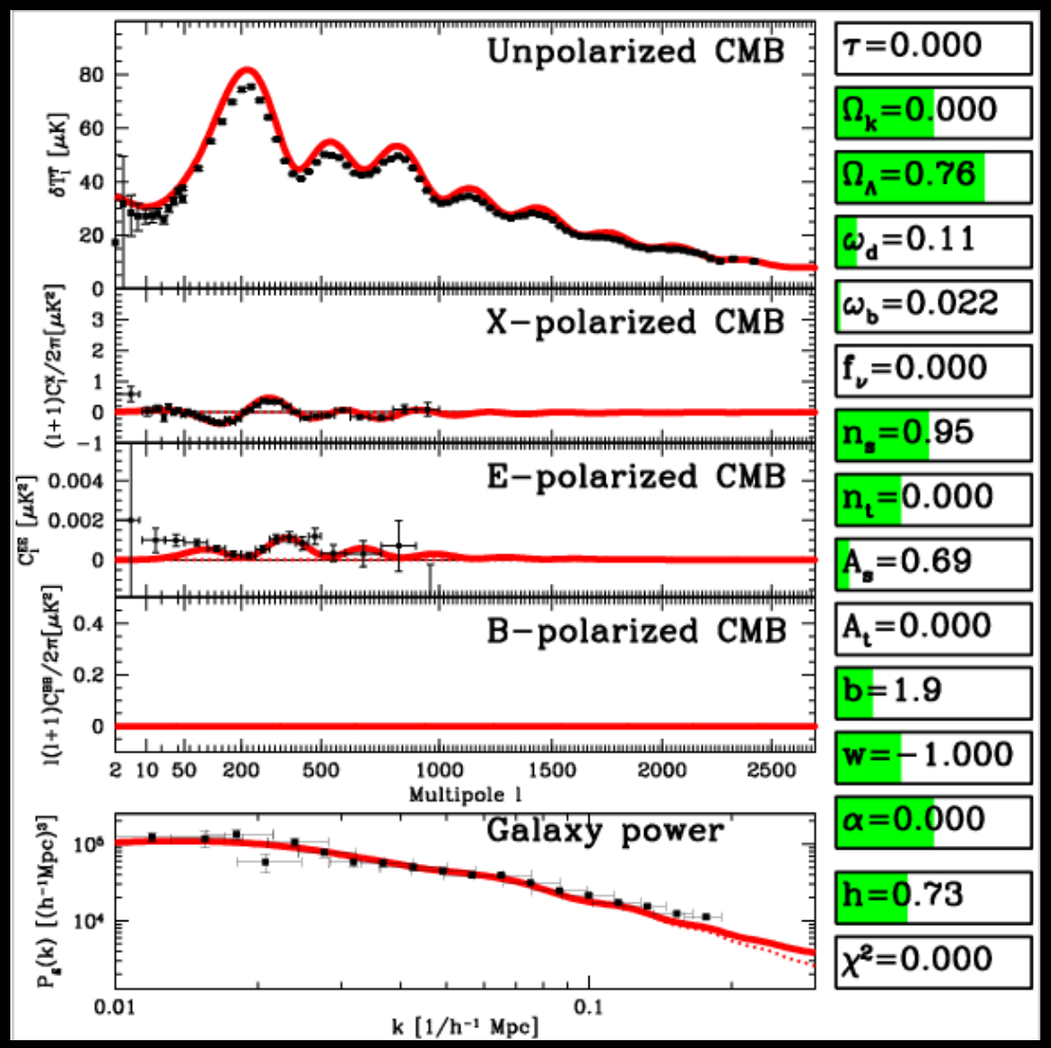

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THE AL ANOMALY, MG ?

What it can be ? values of $A_L<1$ can hint for unaccounted neutrino mass, but $A_L>1$ can be produced only by having more lensing than CDM ! "modified gravity" could perhaps produce this (see Di Valentino, AM, Silk, PRD 2016) but is rather exotic.

$$k^2\Psi = -4\pi G a^2 \mu(k,a)\rho\Delta$$

Poisson eq.

$$\eta(k,a) = \frac{\Phi}{\Psi}$$

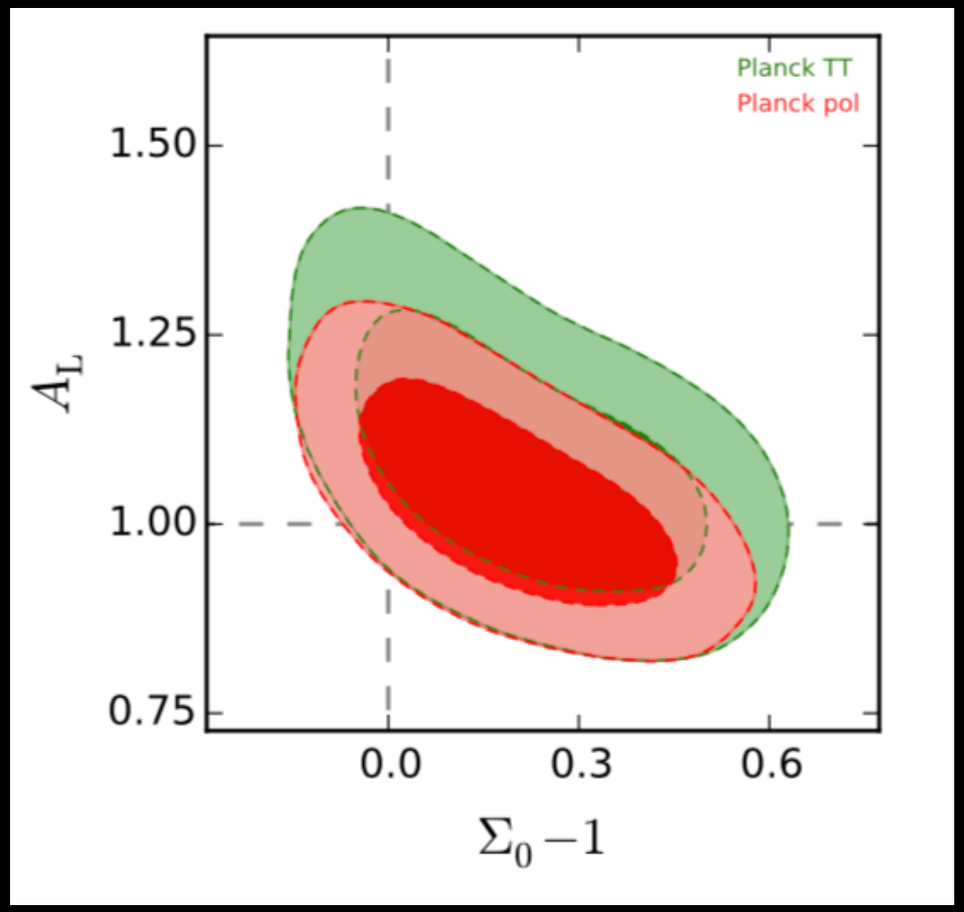
Cosmic Shear

$$\begin{aligned}\mu(k,a) &= 1 + E_{11}\Omega_{\rm DE}(a)\\ \eta(k,a) &= 1 + E_{22}\Omega_{\rm DE}(a)\end{aligned}$$

We use this prescription.

$$\Sigma = \frac{\mu}{2}(1+\eta)$$

If this parameter is different from one then we need MG.



Degeneracy between A_L and Σ.

Di Valentino, AM, Silk, Phys. Rev. D 93, 023513 (2016)

THE A_L ANOMALY:CIP ?

Compensated Isocurvature Perturbations, J. B. Munoz wt al., Phys. Rev. D **93**, 043008 (2016)

$$\mathcal{S}_{mr} \equiv \delta(n_m/n_r)\,/\,(n_m/n_r)$$

$$\mathcal{S}_{m\gamma} = \frac{\Omega_c}{\Omega_m}\mathcal{S}_{c\gamma} + \frac{\Omega_b}{\Omega_m}\mathcal{S}_{b\gamma}$$

Primordial density Isocurvature perturbations

$$\mathcal{S}_{c\gamma} = -\frac{\Omega_b}{\Omega_c}\mathcal{S}_{b\gamma}$$

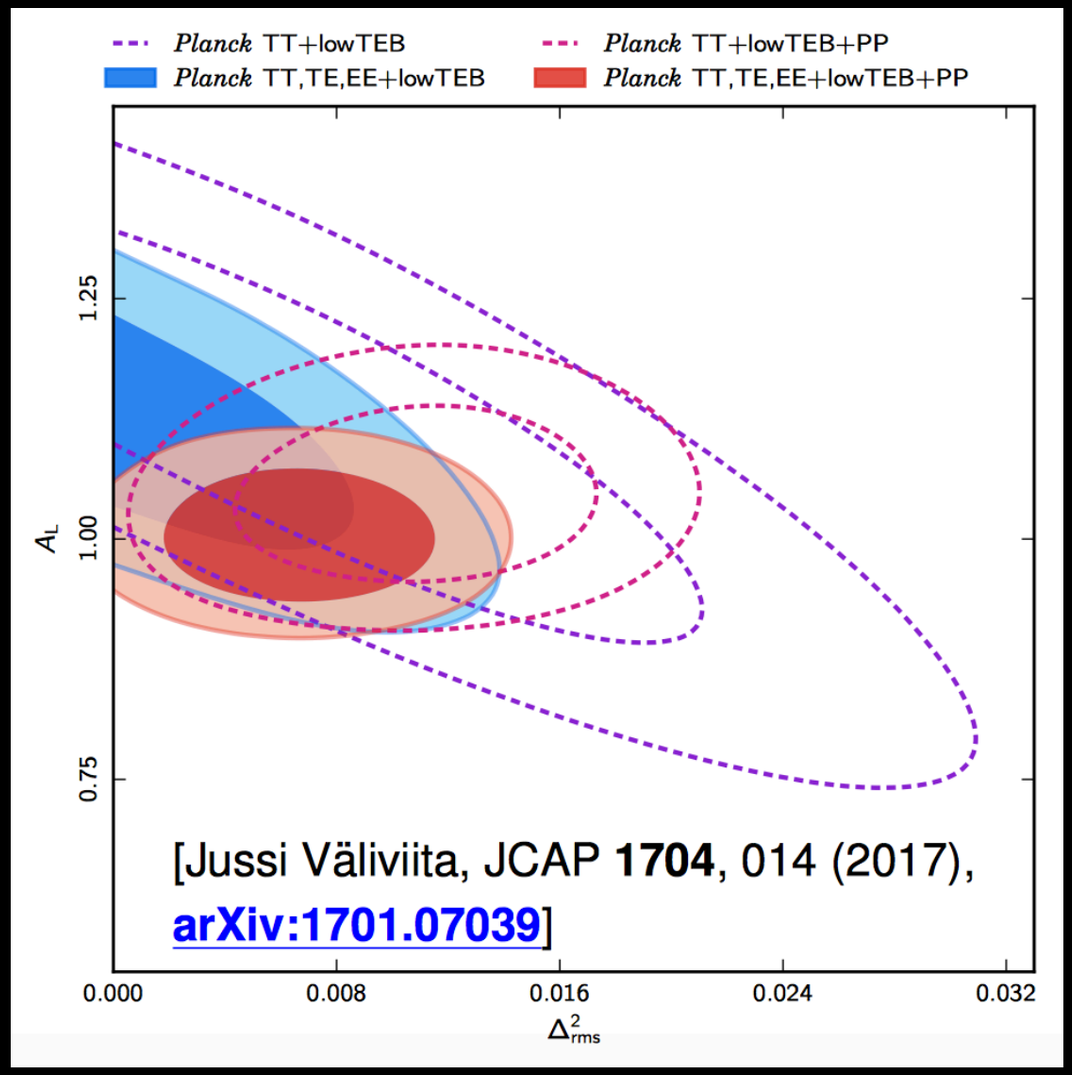
CIP (S_{mr}=0)

Until last scattering we have:

$$\delta\rho_c(t_{\rm primordial}, \mathbf{x}) \approx -\delta\rho_b(t_{\rm primordial}, \mathbf{x})$$

CIP can be described as a small anisotropy (a large scale modulation) of baryon and CDM densities:

$$\Omega_{\rm b}(\hat{n}) = [1+\Delta(\hat{n})]\bar{\Omega}_{\rm b} \qquad \Omega_{\rm c}(\hat{n}) = \bar{\Omega}_{\rm c} - \Delta(\hat{n})\bar{\Omega}_{\rm b}$$

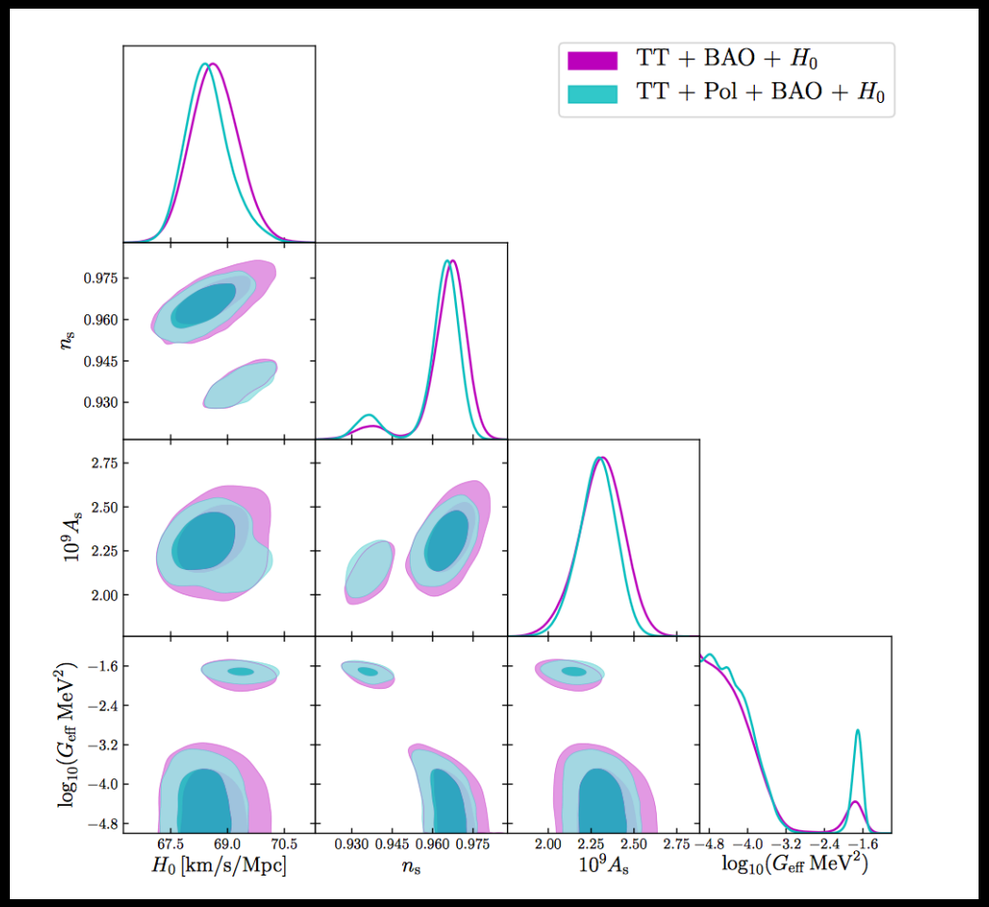


If D is a gaussian variable CIP produce a modulation of Cl's:

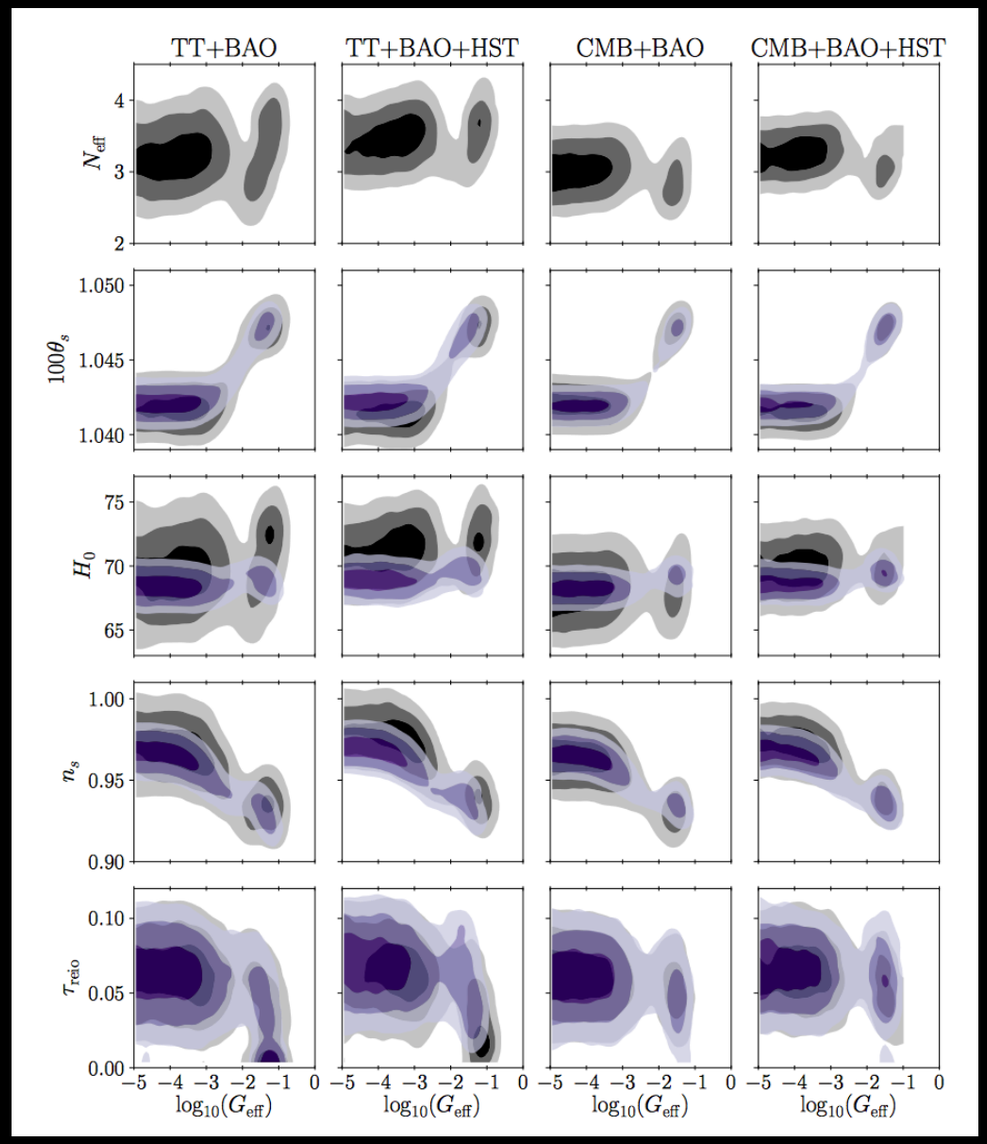
$$C_\ell^{\rm obs}(\bar{\Omega}_{\rm b}, \bar{\Omega}_{\rm c}, \tau, H_0, n_{\rm S}, A_{\rm S}) = \frac{1}{\sqrt{2\pi\Delta^2_{\rm rms}}}\int C_\ell(\Omega_{\rm b}(\Delta), \Omega_{\rm c}(\Delta), \tau, H_0, n_{\rm S}, A_{\rm S})\, e^{-\Delta^2/(2\Delta^2_{\rm rms})} d\Delta$$

THE AL ANOMALY:INTERACTING NEUTRINOS ?

Recent works have demonstrated than when considering a Fermi-like four-fermion interaction between massless neutrinos, characterized by an effective coupling constant Geff, a value of Geff>0 is compatible with the data.



Lancaster et al, arXiv:1704.06657



Oldengott et al, arXiv:1706.02123

Is this connected to AL ?

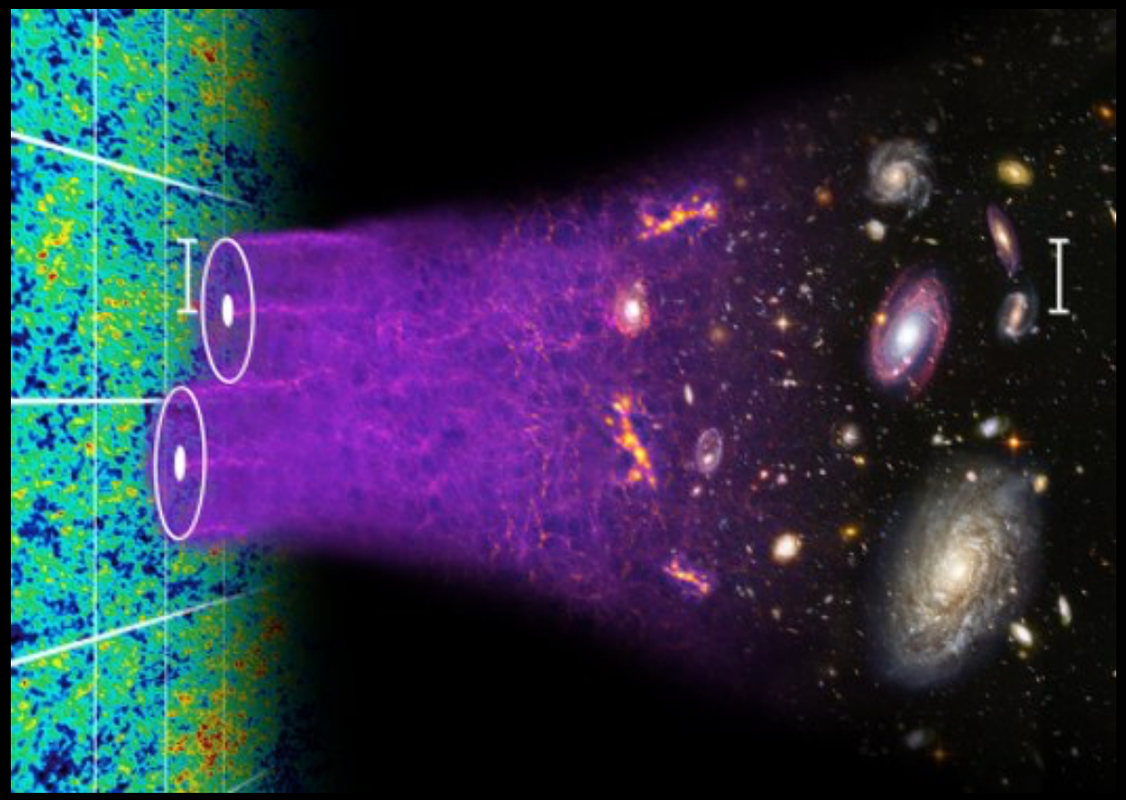
In any case new physics is certainly well compatible with current CMB data.

PLANCK CONSTRAINTS ON NEUTRINO MASSES

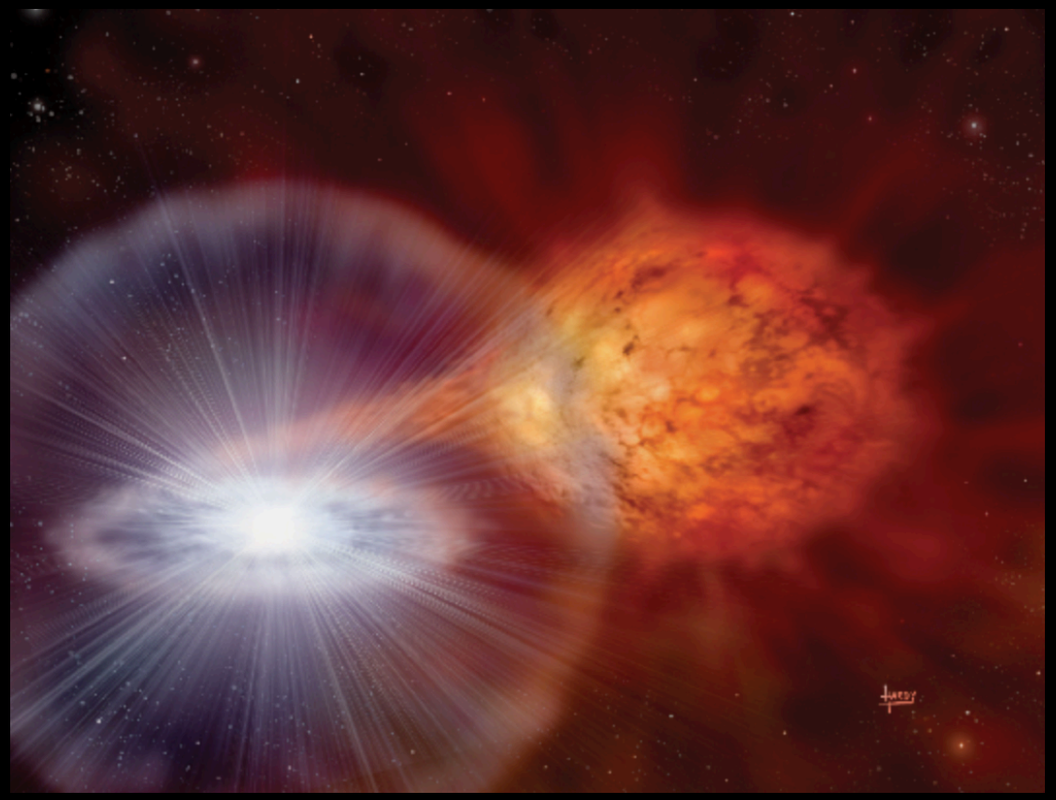
Summarizing:

- Planck data is in spectacular agreement with the LCDM model.
- However small (~2.5 standard deviations) hints for anomalies are present.
- These anomalies could significantly affect current Planck constraints on neutrino masses.
- Until the nature of these anomalies (new physics ? systematics ?) is clear we should be very conservative when considering cosmological constraints on neutrino masses.

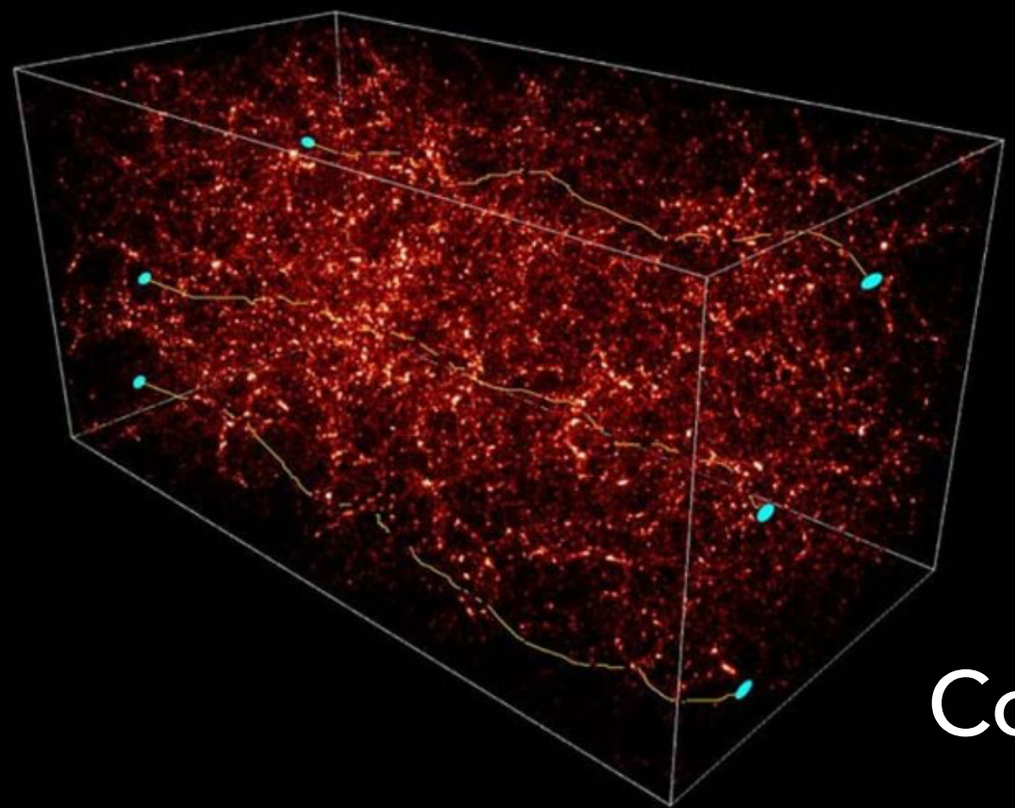
WHAT ABOUT EXTERNAL DATASETS ?



BAO



SN-Ia



Cosmic Shear

BAO

BAO data are in very good agreement with the PLANCK constraints obtained under LCDM...

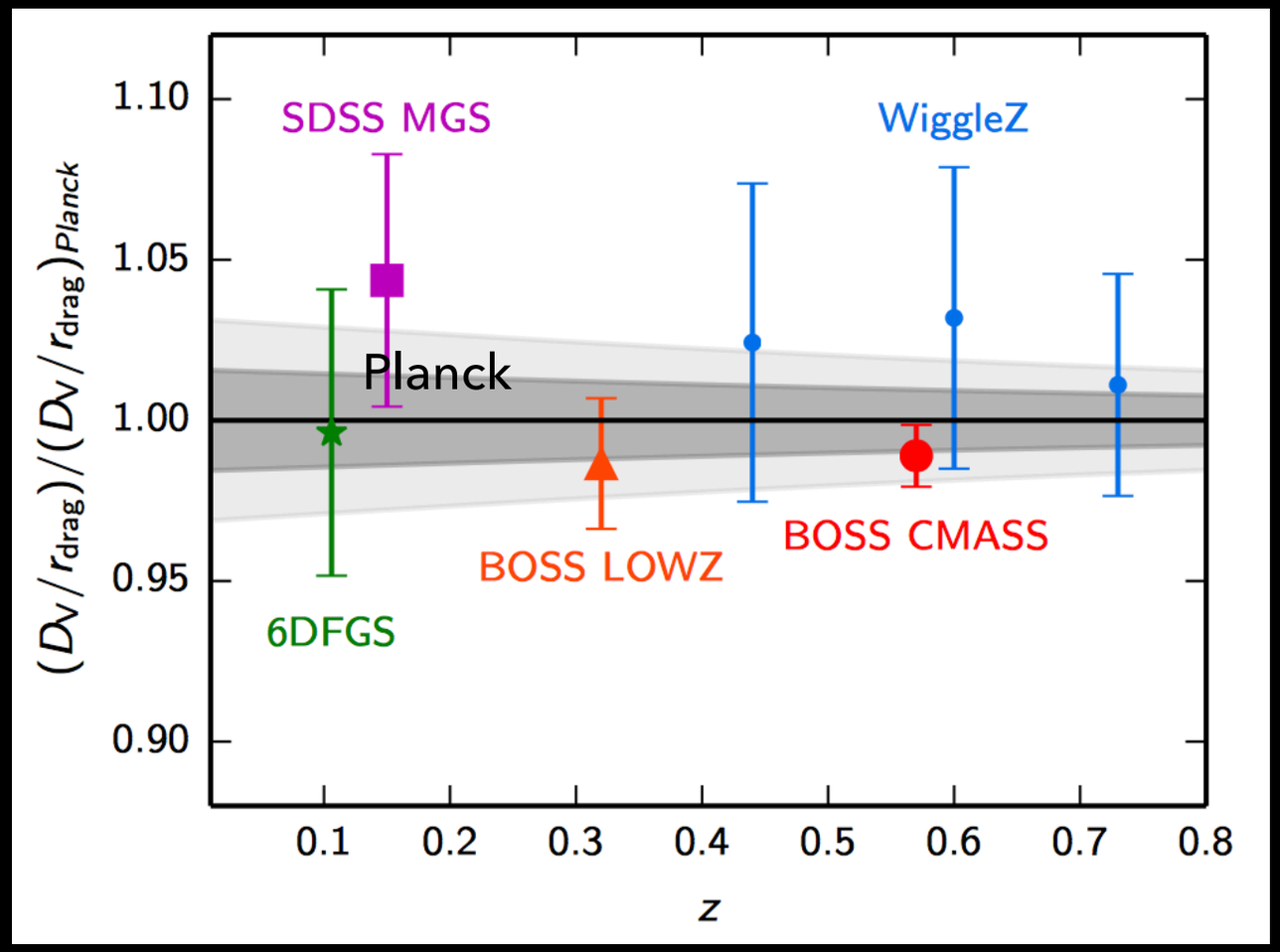
Constraints at 68% c.l. from Planck TT+Lensing+BAO

$$\sum m_\nu < 0.145 \ \ eV$$

..but when we include AL...

Constraints at 68% c.l. from Planck TT+Lensing+BAO varying AL:

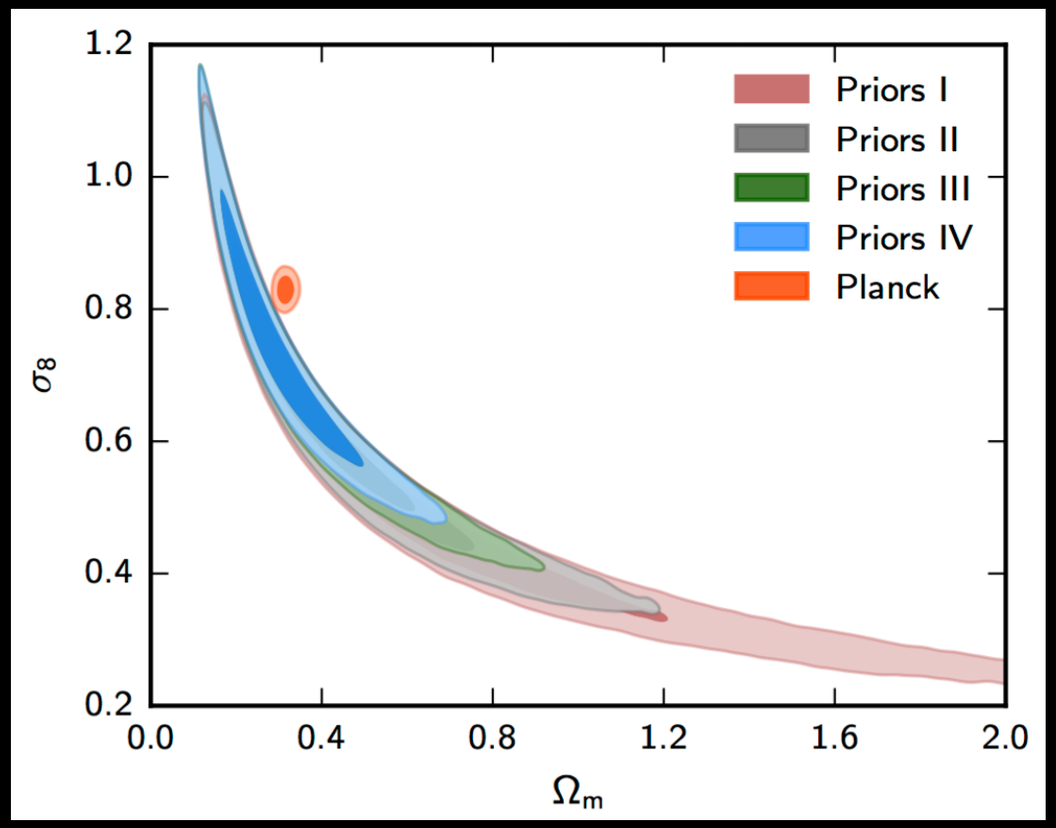
$$\sum m_\nu = 0.21^{+0.10}_{-0.15} \ \ eV$$



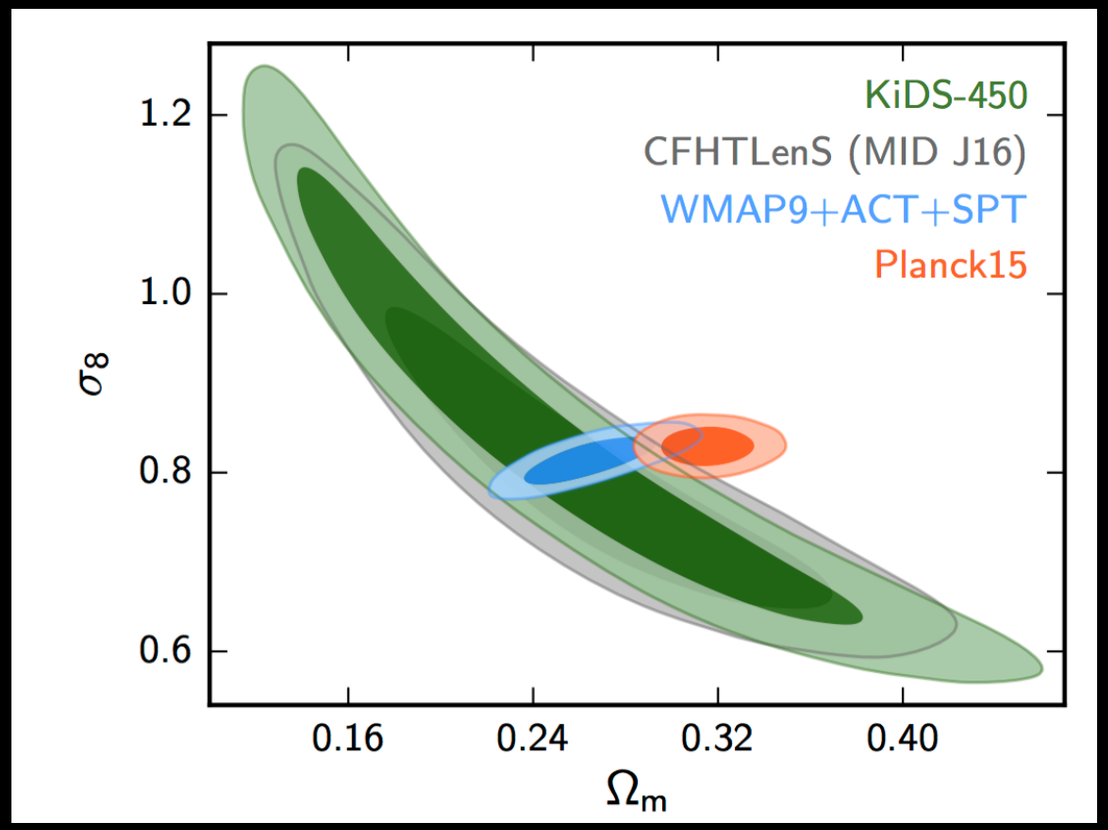
We get a bound on the neutrino mass that is weaker by a factor 2 and even a mild detection for a neutrino mass !

TENSION I

A clear tension (2.4 σ) is present between Planck and cosmic shear data from CFHTLenS and KiDS-450 on the σ_8 vs Ω_m plane. This comparison assumes LCDM.



Joudaki et al, arXiv:1601.05786



Hildebrandt et al, arXiv:1606.05338

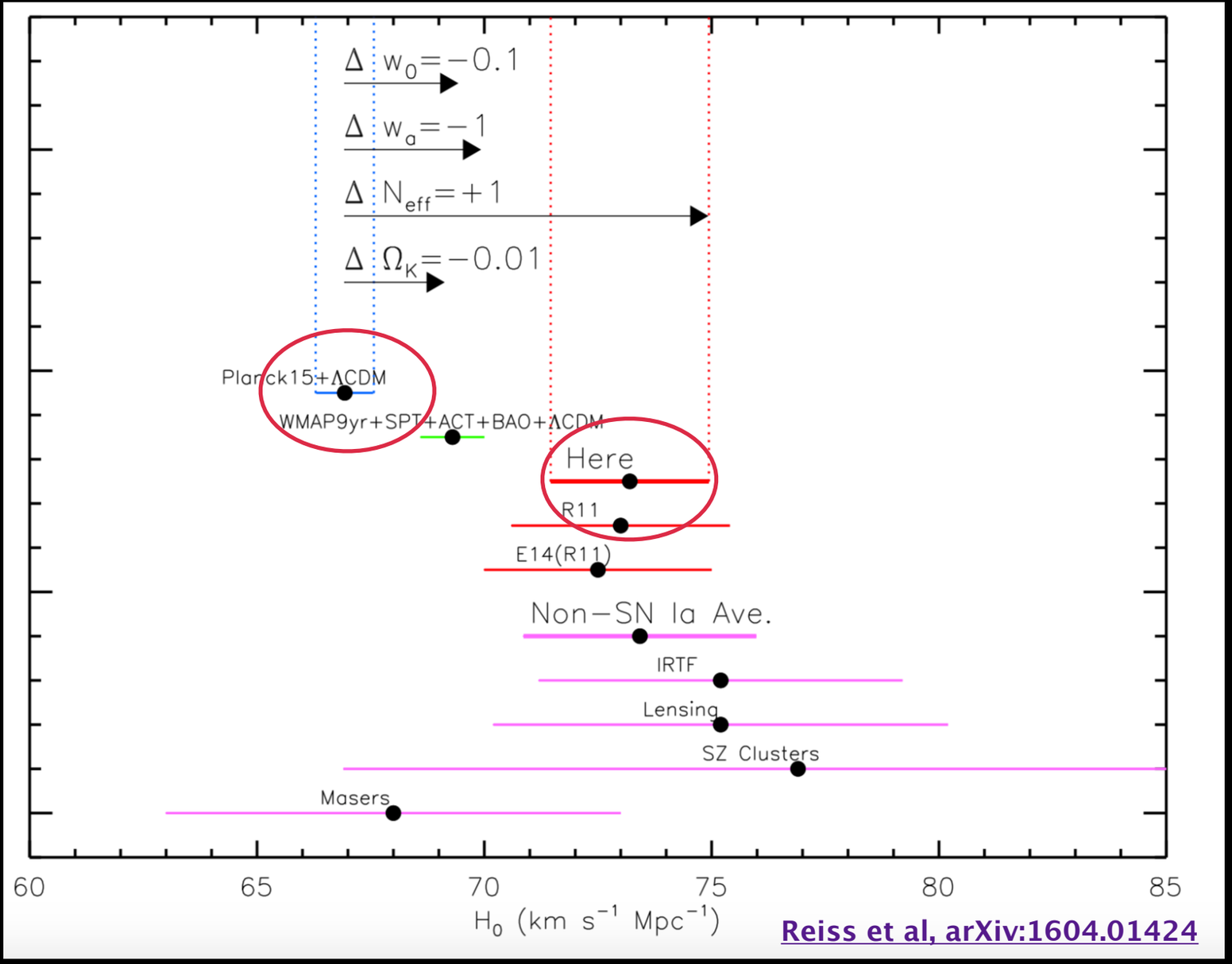
TENSION II

The recent Riess et al. 2016 (R16) determination of the Hubble constant:

$$H_0 = 73.24 \pm 1.74 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

is more than 3σ away from the value determined by Planck assuming LCDM:

$$H_0 = 66.93 \pm 0.62 \text{ km/s/Mpc}$$



Reiss et al, arXiv:1604.01424

LCDM

The LCDM model is extremely successful but it is based on just 6 parameters (flat universe + cosmological constant):

Ω_{cdm} : energy density in cold dark matter

Ω_b : energy density in baryons

n_s : spectral index of density perturbations

A_s : amplitude of density perturbations

H_0 : Hubble constant

τ : reionization optical depth

Can we describe structure formation with just 6 parameters ?

EXTENDED LCDM

It makes sense to extend LCDM including 6 more parameters:

Σm_ν : Sum of neutrino masses

w : Dark energy equation of state

r : Contribution of GW

n' : running of the spectral index

N_{eff} : neutrino effective number (dark radiation)

A_L : lensing amplitude

What happens when we extend LCDM ? can we solve the tensions ? do we have hints for neutrino mass ?

Enrico Fermi:"I remember my friend Johnny von Neumann used to say, 'with four parameters I can fit an elephant and with five I can make him wiggle his trunk.‘”

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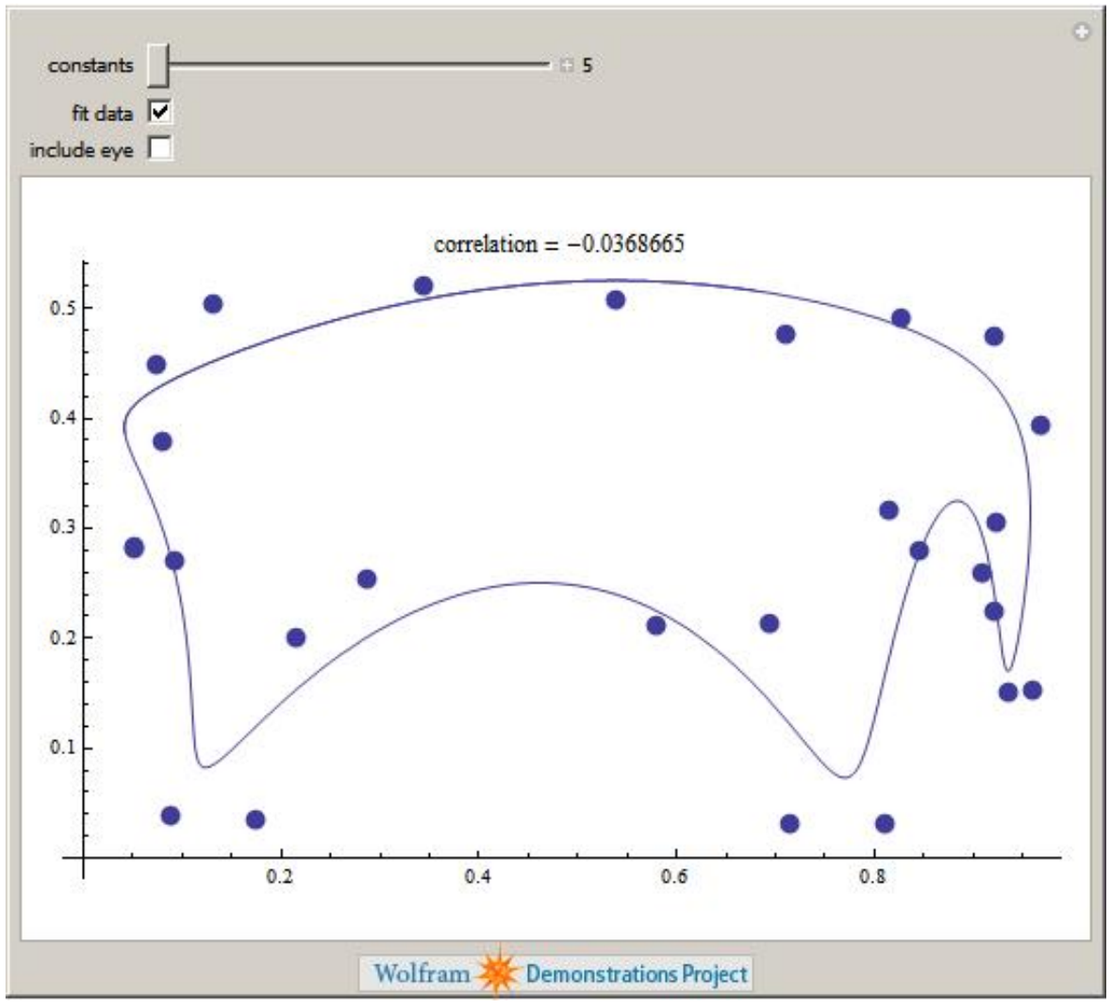

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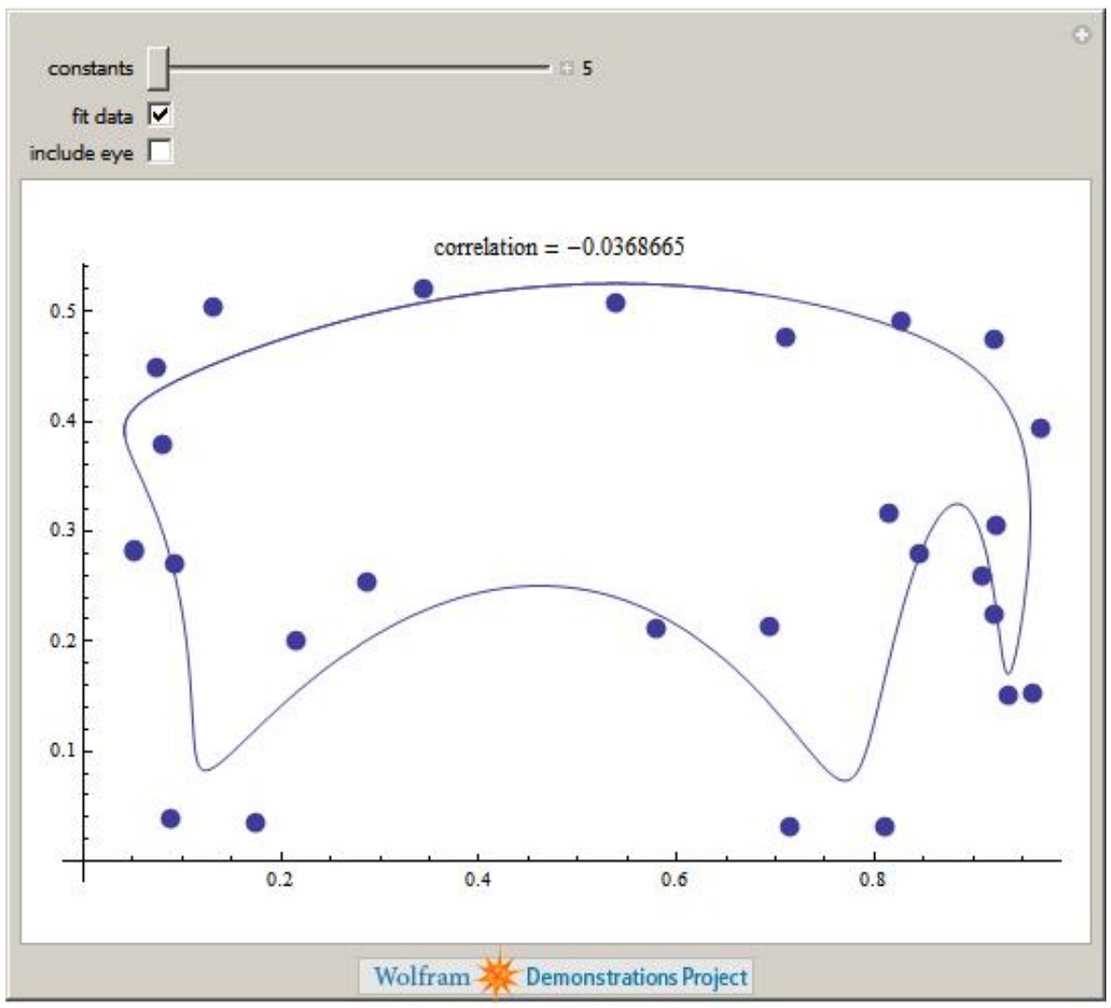

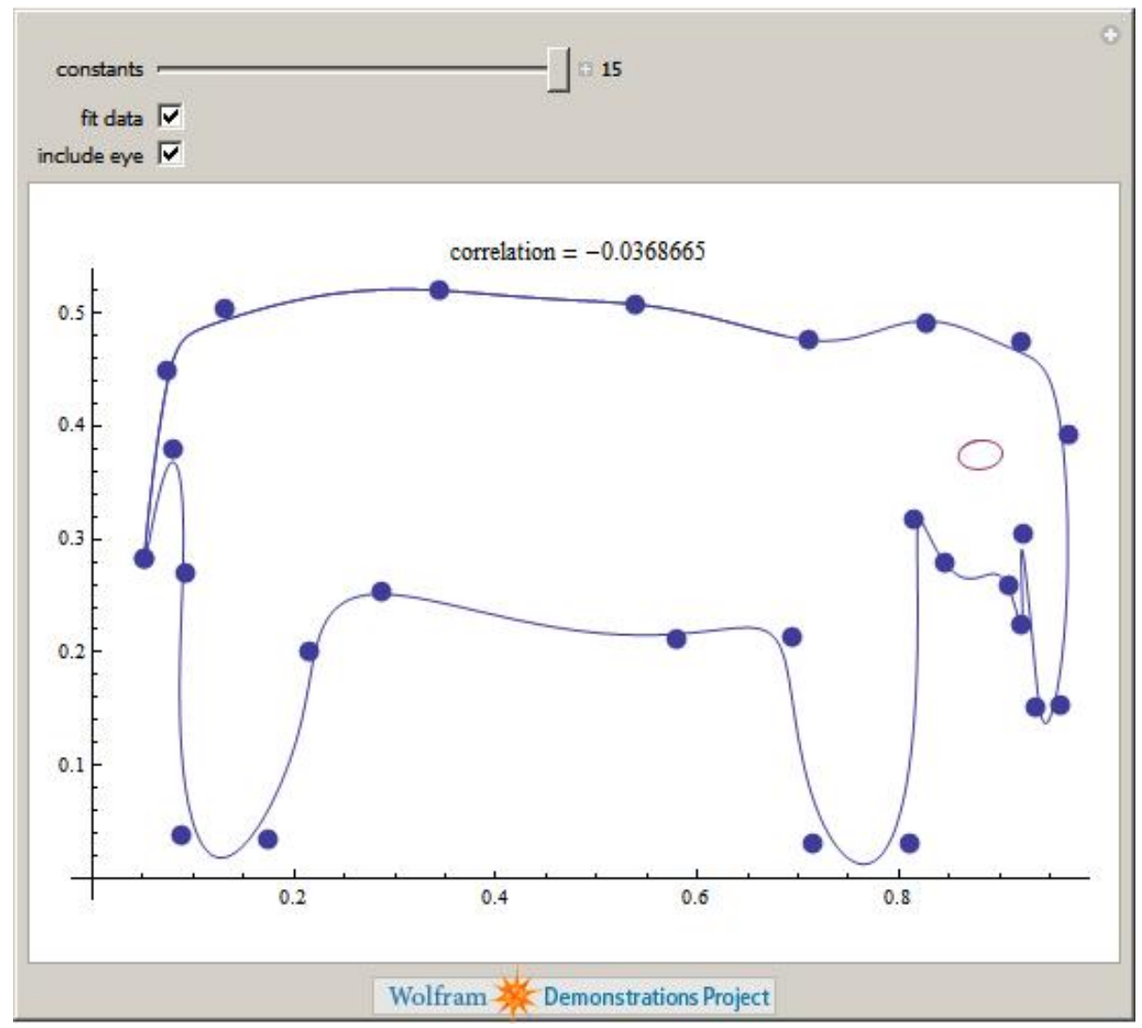

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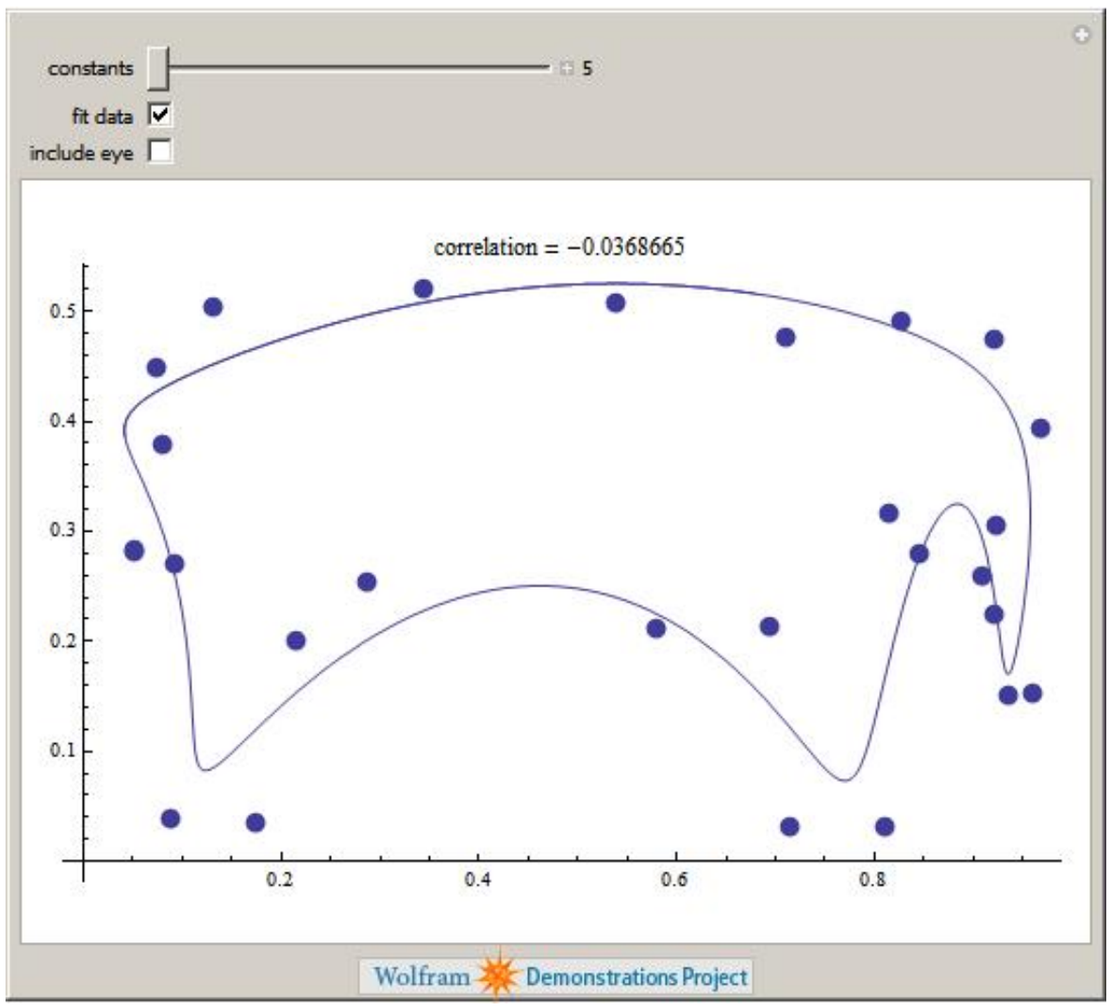
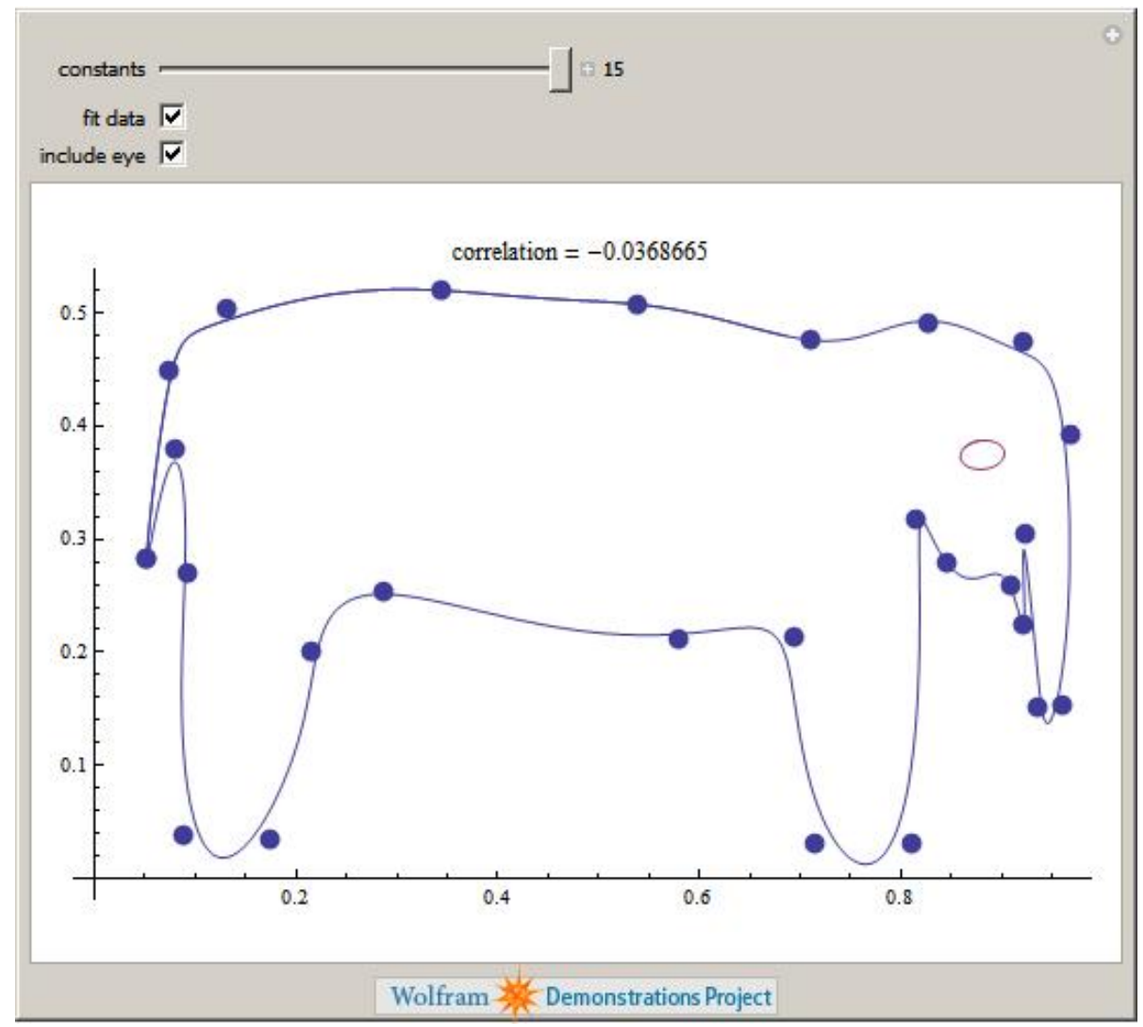
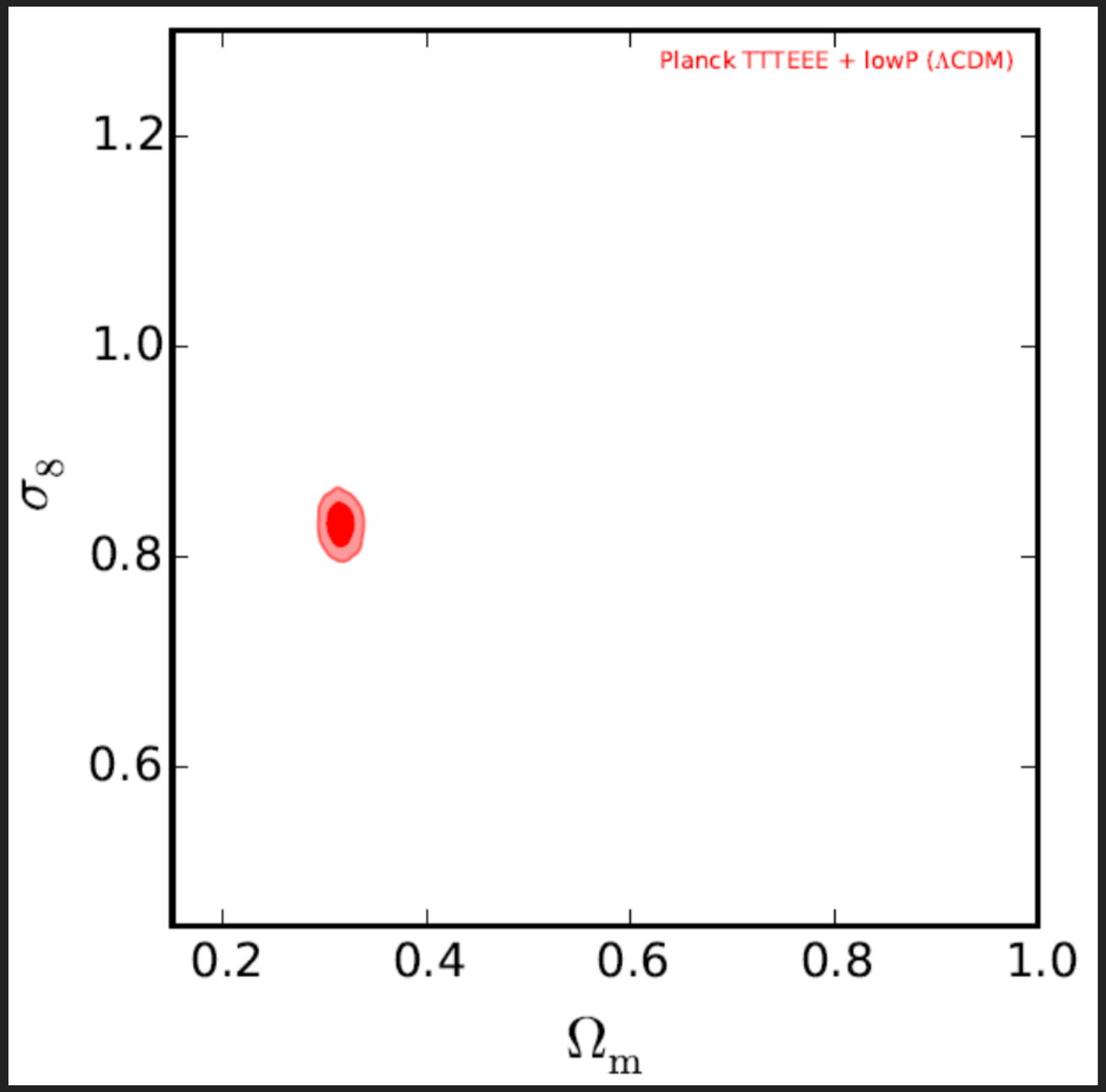




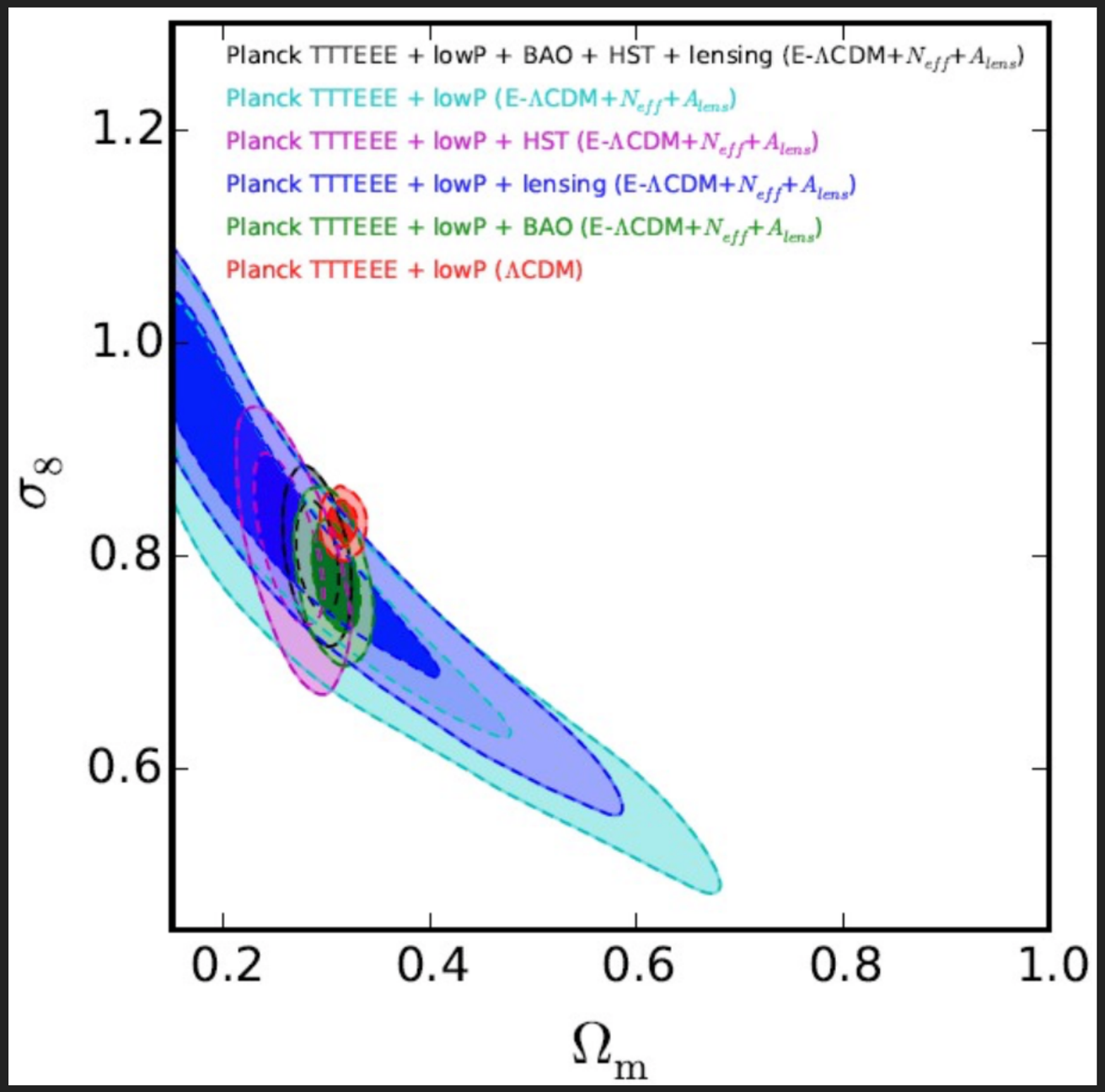
Not true ! you need at least 15 parameters to fit a 2D elephant.

EXTENDED LCDM



Di Valentino, AM, Silk, Phys. Rev. D 92, 121302 (2015)

EXTENDED LCDM

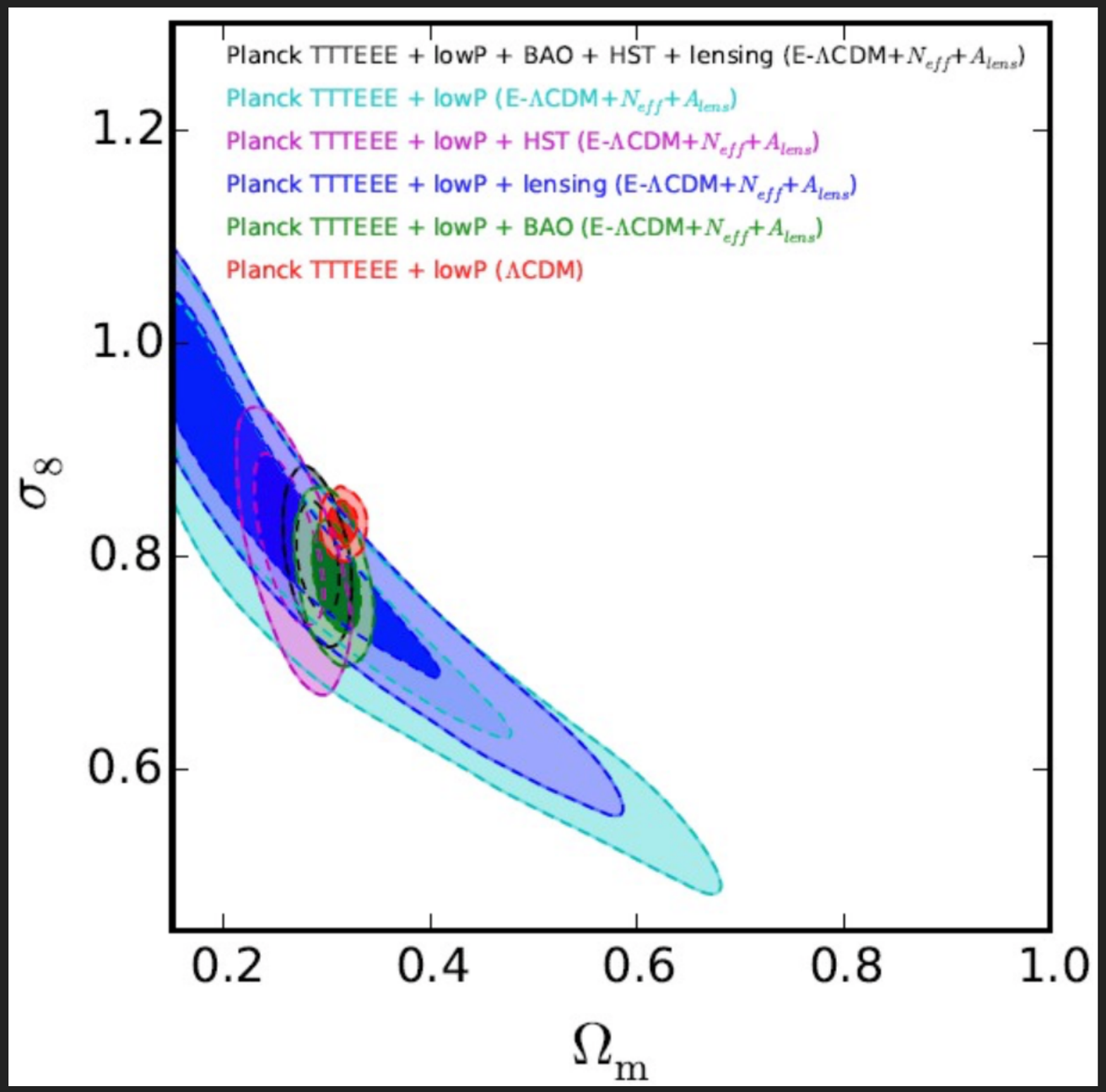


Di Valentino, AM, Silk, Phys. Rev. D 92, 121302 (2015)

EXTENDED LCDM

In an extended parameter space the Planck constraint goes down and spread over the Ω_m vs σ_8 plane.

Planck is now consistent with CFHTLenS.



Di Valentino, AM, Silk, Phys. Rev. D 92, 121302 (2015)

EXTENDED LCDM

68% c.l.

	Planck	Planck + R16	Planck +R16+BAO	Planck +R16+JLA	Planck +R16+ WL	Planck +R16+lensing
$\Omega_b h^2$	0.02239 ± 0.00030	0.02239 ± 0.00029	$0.02258^{+0.00026}_{-0.00032}$	0.02270 ± 0.00025	0.02252 ± 0.00029	0.02214 ± 0.00027
$\Omega_c h^2$	0.1186 ± 0.0035	0.1187 ± 0.0036	$0.1209^{+0.0032}_{-0.0036}$	0.1218 ± 0.0034	$0.1189^{+0.0035}_{-0.0041}$	0.1176 ± 0.0035
τ	0.058 ± 0.021	$0.058^{+0.021}_{-0.023}$	0.058 ± 0.021	0.059 ± 0.021	0.050 ± 0.020	0.057 ± 0.021
n_S	0.967 ± 0.013	0.967 ± 0.013	0.976 ± 0.12	0.981 ± 0.011	0.973 ± 0.013	0.959 ± 0.012
$log(10^{10} A_S)$	3.048 ± 0.043	$3.048^{+0.043}_{-0.048}$	3.053 ± 0.043	3.056 ± 0.043	3.030 ± 0.040	3.042 ± 0.044
H_0	> 67.1	73.5 ± 1.9	71.3 ± 1.6	70.9 ± 1.5	73.4 ± 2.0	73.7 ± 1.9
σ_8	$0.81^{+0.16}_{-0.12}$	$0.804^{+0.056}_{-0.044}$	0.788 ± 0.036	$0.785^{+0.056}_{-0.037}$	$0.788^{+0.050}_{-0.044}$	0.826 ± 0.039
$\sum m_\nu$ [eV]	< 0.53	< 0.512	$0.35^{+0.16}_{-0.25}$	< 0.384	$0.41^{+0.13}_{-0.39}$	$0.32^{+0.14}_{-0.24}$
w	$-1.32^{+0.47}_{-0.67}$	$-1.29^{+0.15}_{-0.12}$	$-1.14^{+0.12}_{-0.10}$	$-1.079^{+0.072}_{-0.057}$	$-1.25^{+0.14}_{-0.11}$	$-1.33^{+0.14}_{-0.12}$
$N_{\rm eff}$	$3.08^{+0.26}_{-0.30}$	$3.09^{+0.26}_{-0.31}$	$3.26^{+0.24}_{-0.28}$	$3.37^{+0.24}_{-0.28}$	$3.17^{+0.25}_{-0.33}$	2.94 ± 0.25
$A_{\rm lens}$	$1.21^{+0.09}_{-0.14}$	$1.18^{+0.09}_{-0.11}$	1.210 ± 0.095	$1.22^{+0.09}_{-0.11}$	$1.23^{+0.09}_{-0.10}$	$1.034^{+0.060}_{-0.067}$
$\frac{dn_S}{d\,ln\,k}$	-0.0034 ± 0.0098	$-0.003^{+0.010}_{-0.011}$	-0.0003 ± 0.0091	$0.001^{+0.009}_{-0.011}$	-0.0001 ± 0.0099	-0.0055 ± 0.0091
r	< 0.0911	< 0.0934	< 0.0974	< 0.0943	< 0.103	< 0.0843

Di Valentino, AM, Silk, arXiv:1606.00634
Phys.Lett. B761 (2016) 242-246

EXTENDED LCDM

68% c.l.

	Planck	Planck + R16	Planck +R16+BAO	Planck +R16+JLA	Planck +R16+ WL	Planck +R16+lensing
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r	< 0.0911					

When we move to 12 parameters tensions and anomalies between datasets are mostly solved.

Constraints on neutrino masses are weaker and we have even a mild detection (but don't believe too much on it) in some cases !

Di Valentino, AM, Silk, arXiv:1606.00634
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r	< 0.0911	< 0.0934	< 0.0974	< 0.0943	< 0.103	< 0.0843

But we found ~2 sigma indications for w<-1 and A_L>1 in many cases ! new physics or systematics could be there and this affects bounds on neutrino masses !

Di Valentino, AM, Silk, arXiv:1606.00634
Phys.Lett. B761 (2016) 242-246

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68% c.l.

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$\frac{dn_S}{d\ln k}$	-0.0034 ± 0.0098					
r	< 0.0911	< 0.0934	< 0.0974	< 0.0943	< 0.103	< 0.0843

No indication for extra relativistic particles !

Di Valentino, AM, Silk, arXiv:1606.00634
Phys.Lett. B761 (2016) 242-246

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 ?

DOES COSMOLOGY PREFER NORMAL NEUTRINO HIERARCHY ?

Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo, Phys. Rev. D 95, 096014 (2017)

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	-0.1
8	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

TABLE III: Values of $\Delta\chi^2_{\mathrm{IO-NO}}$ from the global analysis of oscillation and non oscillation data (numbered according to the adopted cosmological datasets as in Table II), to be compared with the value 3.6 from oscillation data only [Eq. (9)]. An overall preference emerges for NO, at the level of 1.9–2.1σ.

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

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12	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

No preference from conservative cosmological bounds that include Alens in the analysis. Some mild preference from the less conservative cases.

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4			< 0.44	< 0.48	0.6
5			< 0.45	< 0.47	0.3
6			< 0.18	< 0.20	1.6
7			< 1.08	< 1.08	-0.1
8	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

No preference from conservative cosmological bounds that include Alens in the analysis. Some mild preference from the less conservative cases.

TABLE

cosmolo

for NO,

scillation data (numbered according to the adopted

on data only [Eq. (9)]. An overall preference emerges

Some indication (about 2 standard deviations) when you include non-cosmological data (see Marrone's talk).

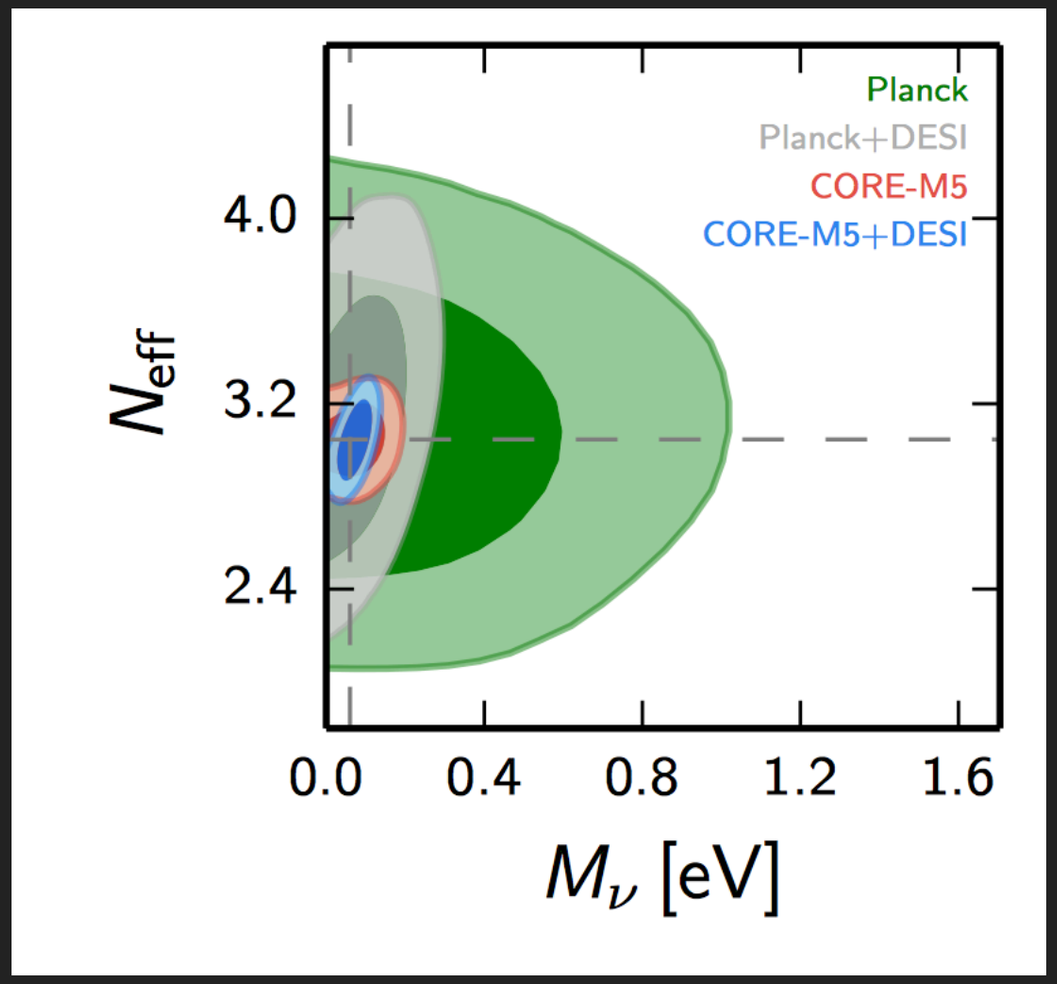
#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

FUTURE DATA

Future CMB data will be able to clearly shedding light on these anomalies.

Considering a cosmic variance limited CMB experiment (as the proposed and unfortunately dead CORE satellite or the Stage-IV experiment), CMB bounds can be improved by a factor 5.

There is an impressive activity in ground based and balloon borne experiments (see talks by Madhavacheril, Chinone and Reichardt).



Di Valentino et al, CORE collaboration arXiv:1612.00021

Abazajan et al, S-4 collaboration, arXiv:1610.02743

CONCLUSIONS

- The Planck result is a spectacular success for cosmology !
- While the agreement is nearly perfect, we do see anomalies in the CMB data at about 2 standard deviations.
- Moreover, not all cosmological datasets are in agreement when LCDM is assumed.
- 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 !