Cosmological constraints on the standard model and its extensions

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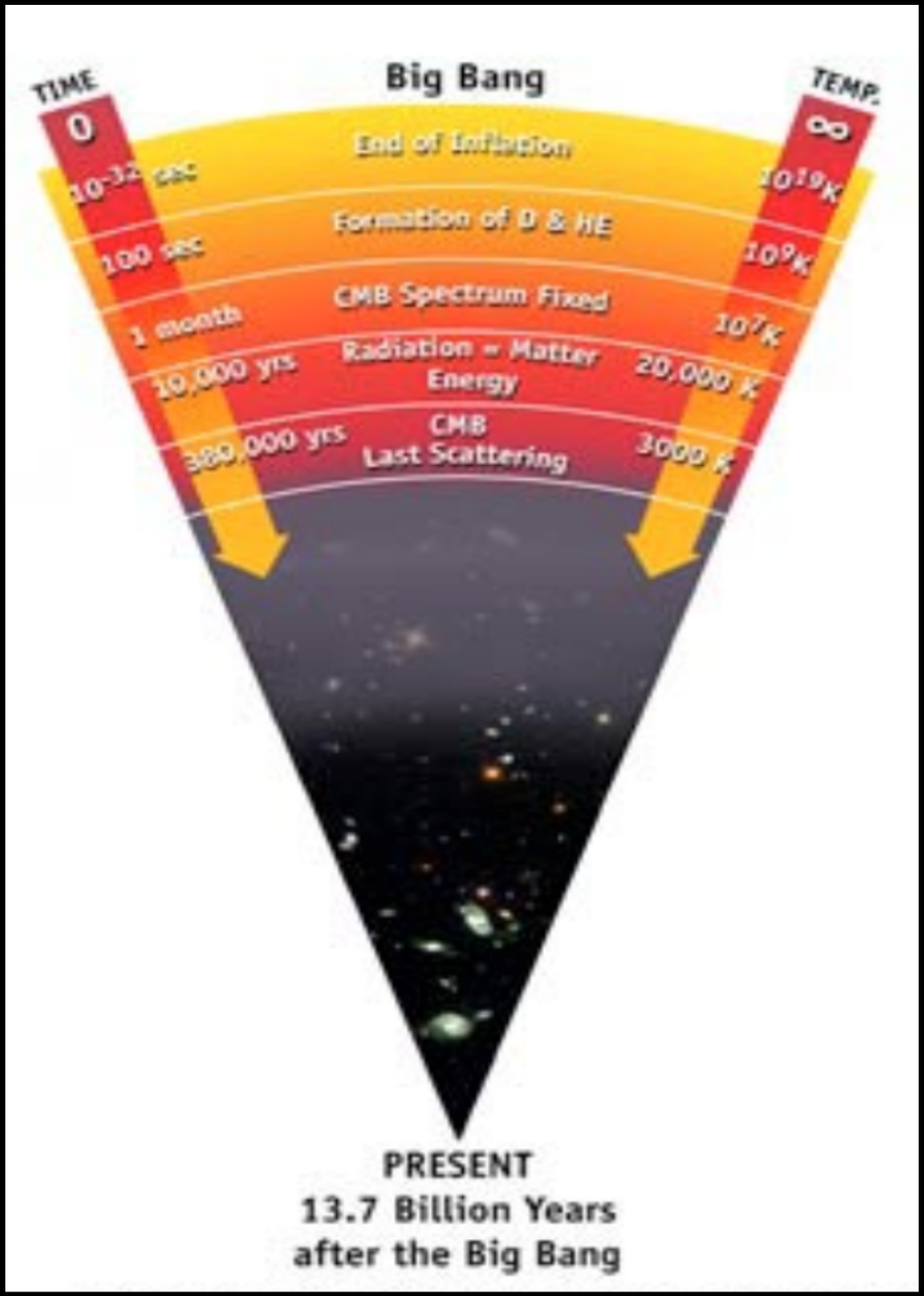
Introduction to cosmology



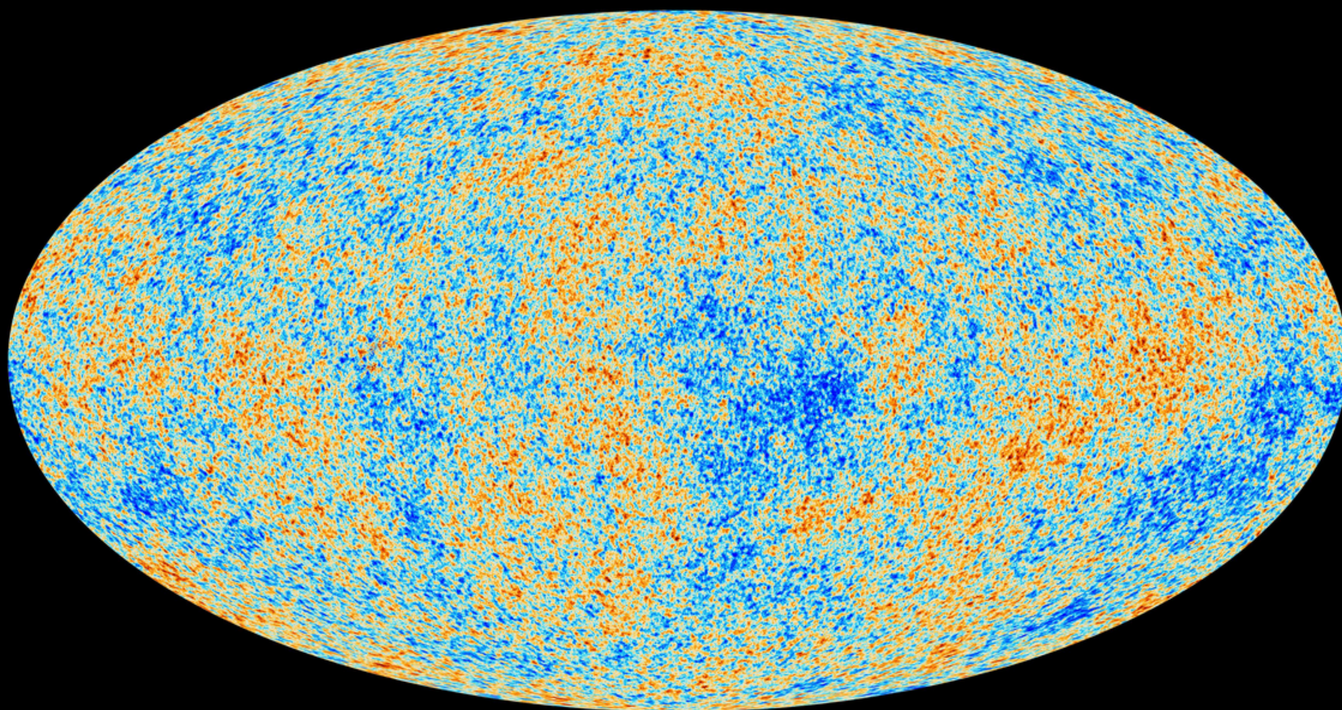
The Universe originates from a hot Big Bang.

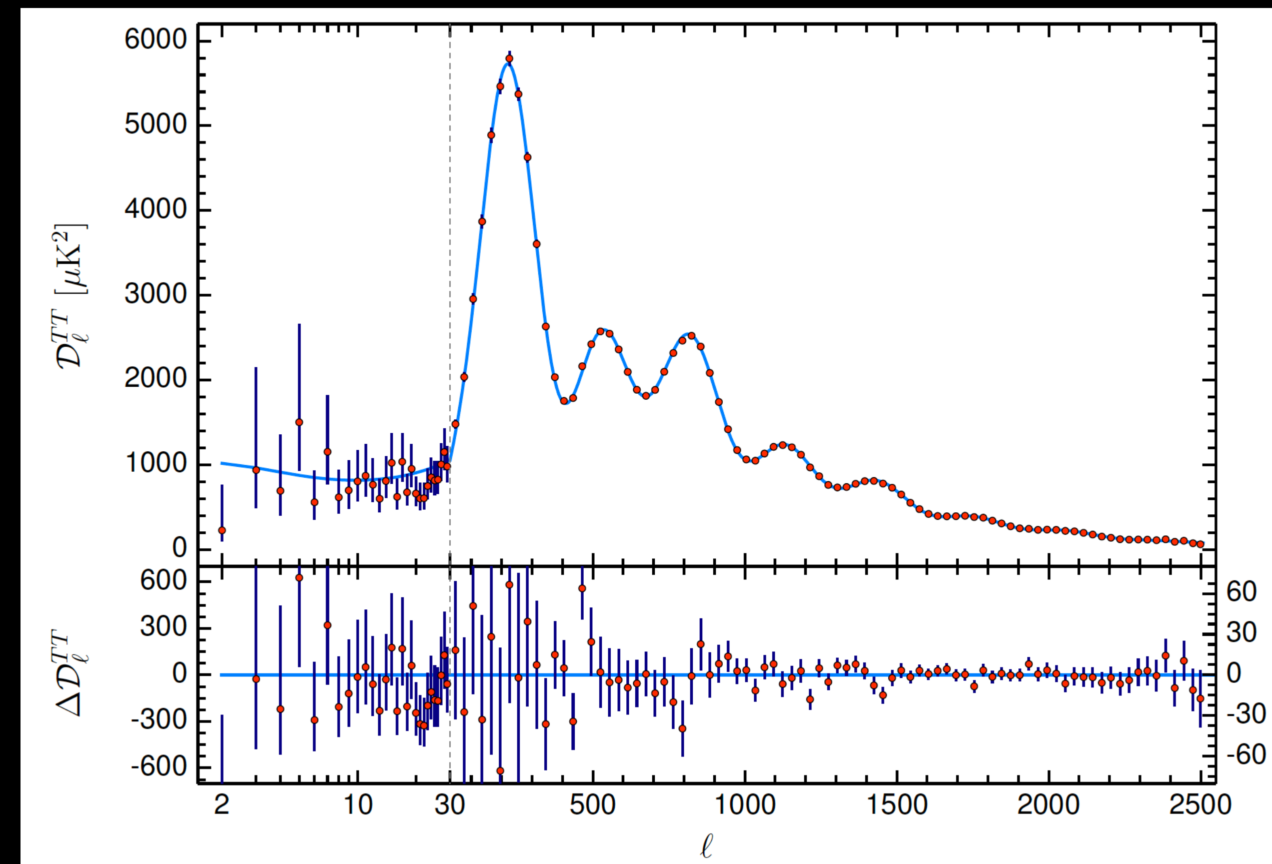
The primordial plasma in thermodynamic equilibrium cools with the expansion of the Universe. It passes through the phase of decoupling, in which the Universe becomes transparent to the motion of photons, and the phase of recombination, where electrons and protons combine into hydrogen atoms.

The Cosmic Microwave Background (CMB) is the radiation coming from the recombination, emitted about 13 billion years ago, just 400,000 years after the Big Bang.

The CMB provides an unexcelled probe of the early Universe and today it is a black body a temperature T=2.726K.

Introduction to CMB





Planck collaboration, 2018

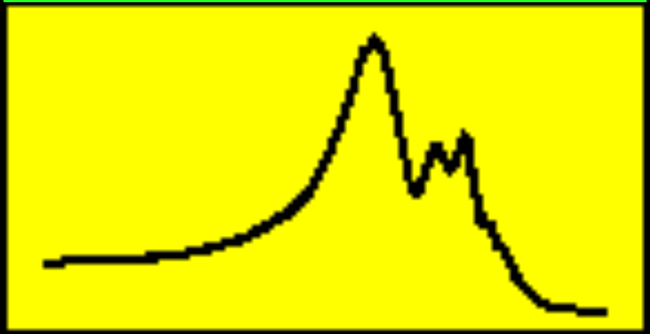
An important tool of research in cosmology is the angular power spectrum of CMB temperature anisotropies.

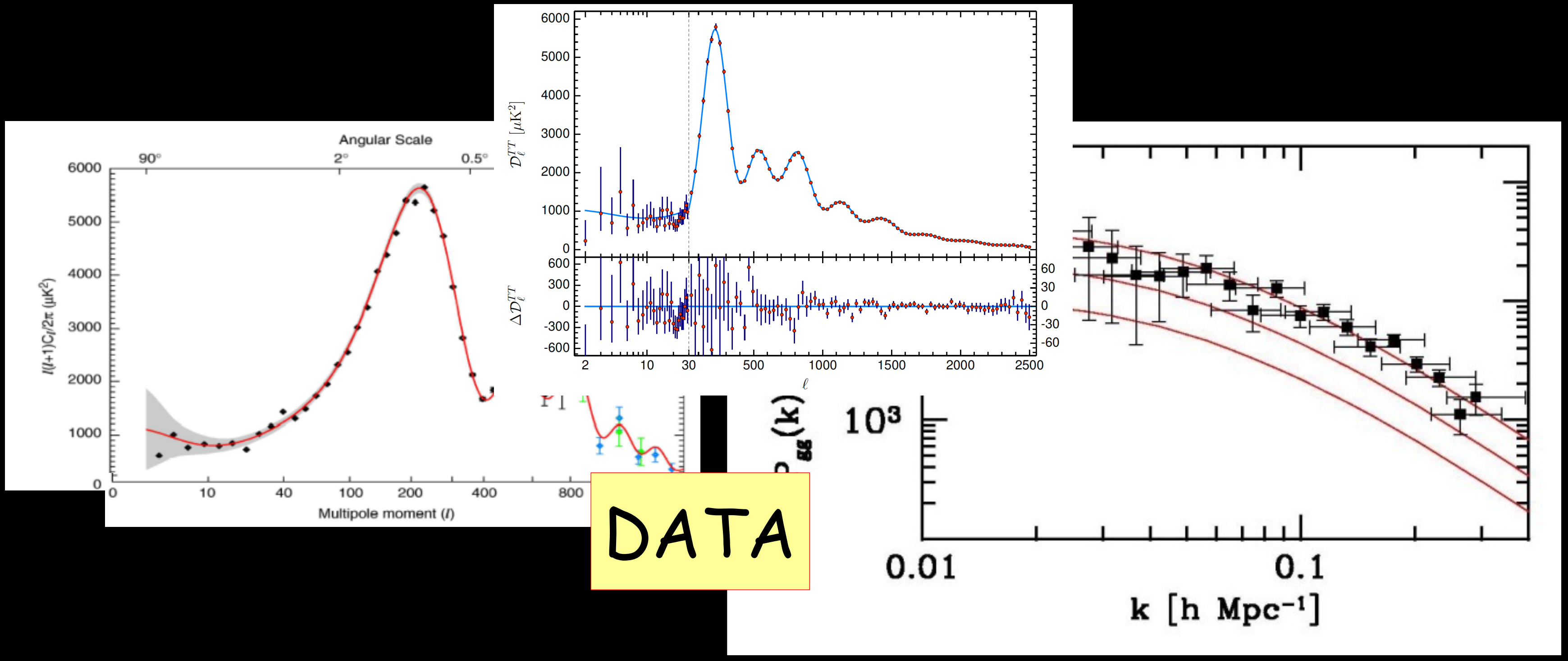
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

Introduction to CMB

Cosmological parameters:
$(\Omega_b h^2, \Omega_m h^2, h, n_s, \tau, \Sigma m_\nu)$

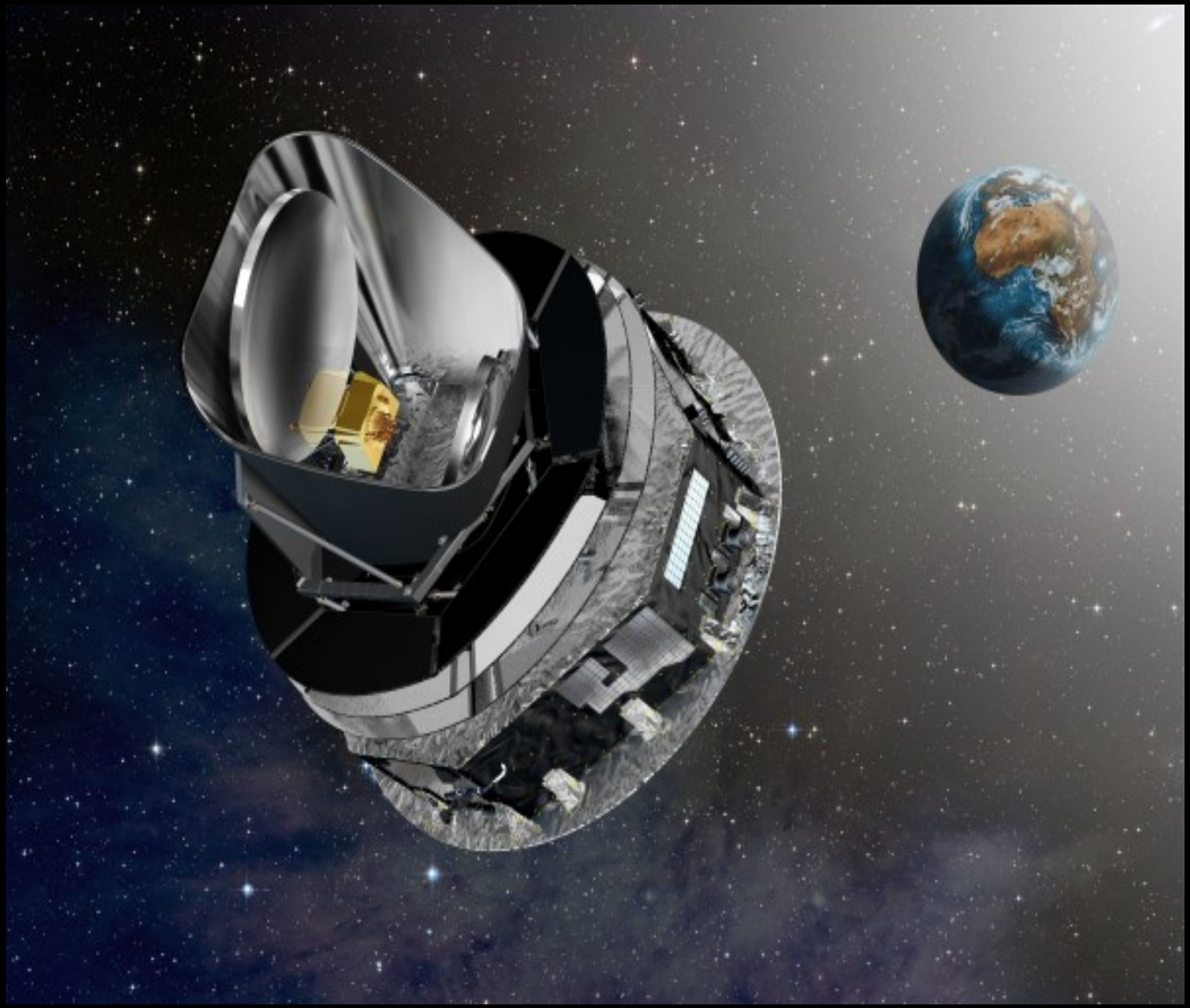
Theoretical model





PARAMETER CONSTRAINTS

Planck satellite experiment

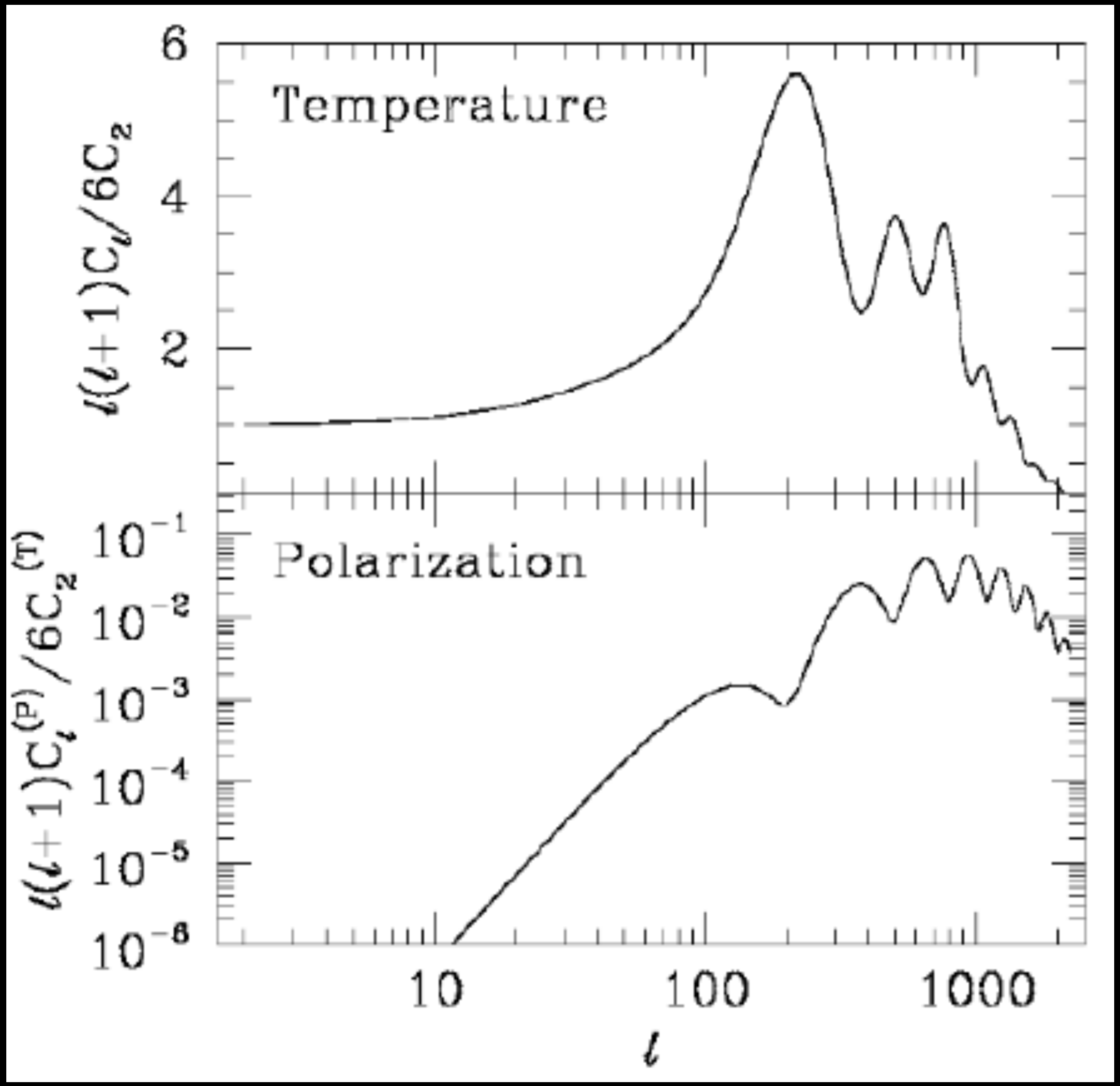


- Frequency range of 30GHz to 857GHz;
- Orbit around L2;
- Composed by 2 instruments:
  - LFI → 1.5 meters telescope; array of 22 differential receivers that measure the signal from the sky comparing with a black body at 4.5K.
  - HFI → array of 52 bolometers cooled to 0.1K.

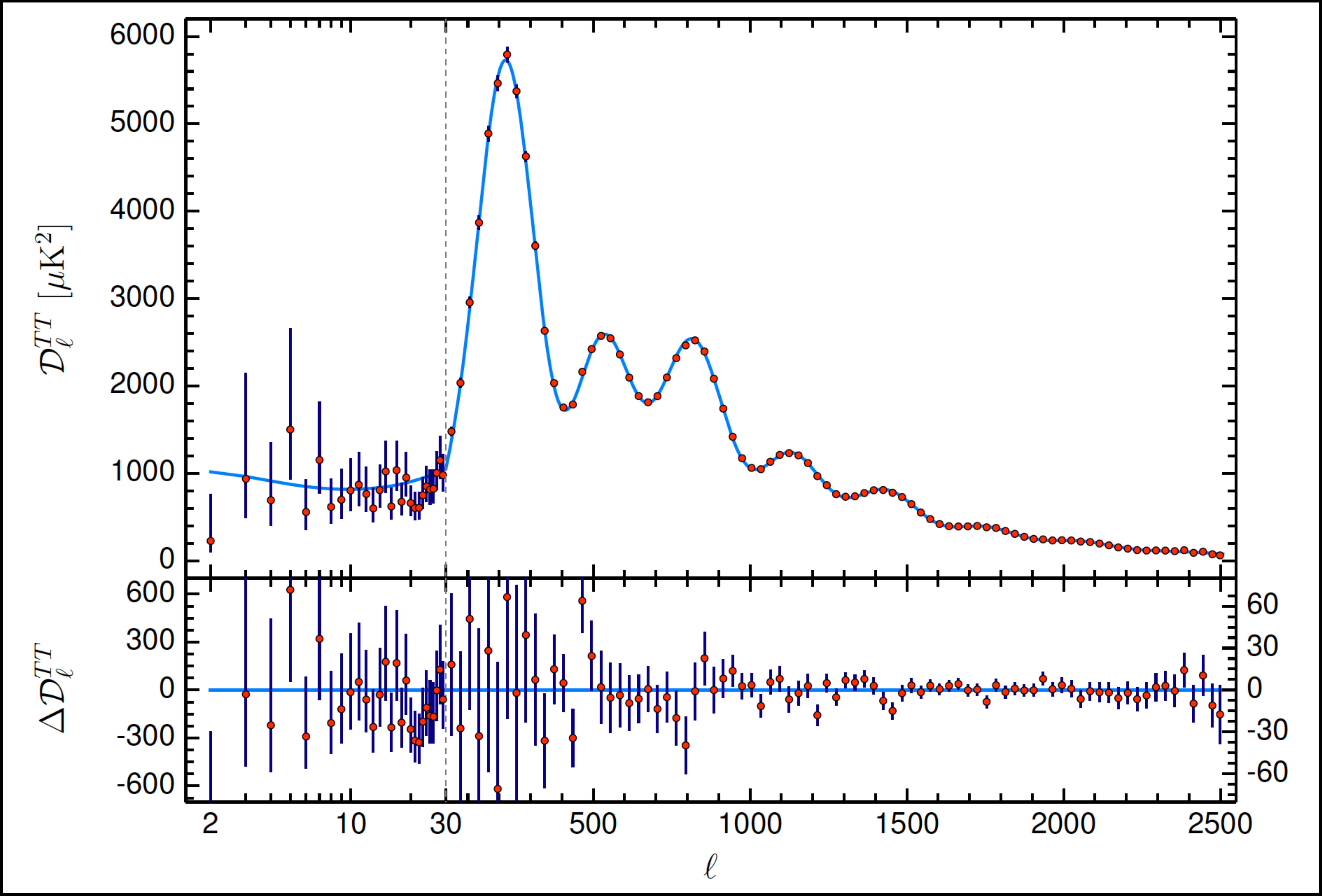
Planck satellite experiment

We can extract 4 independent angular spectra from the CMB:

- Temperature
- Cross Temperature Polarization
- Polarization type E (density fluctuations)
- Polarization type B (gravity waves)

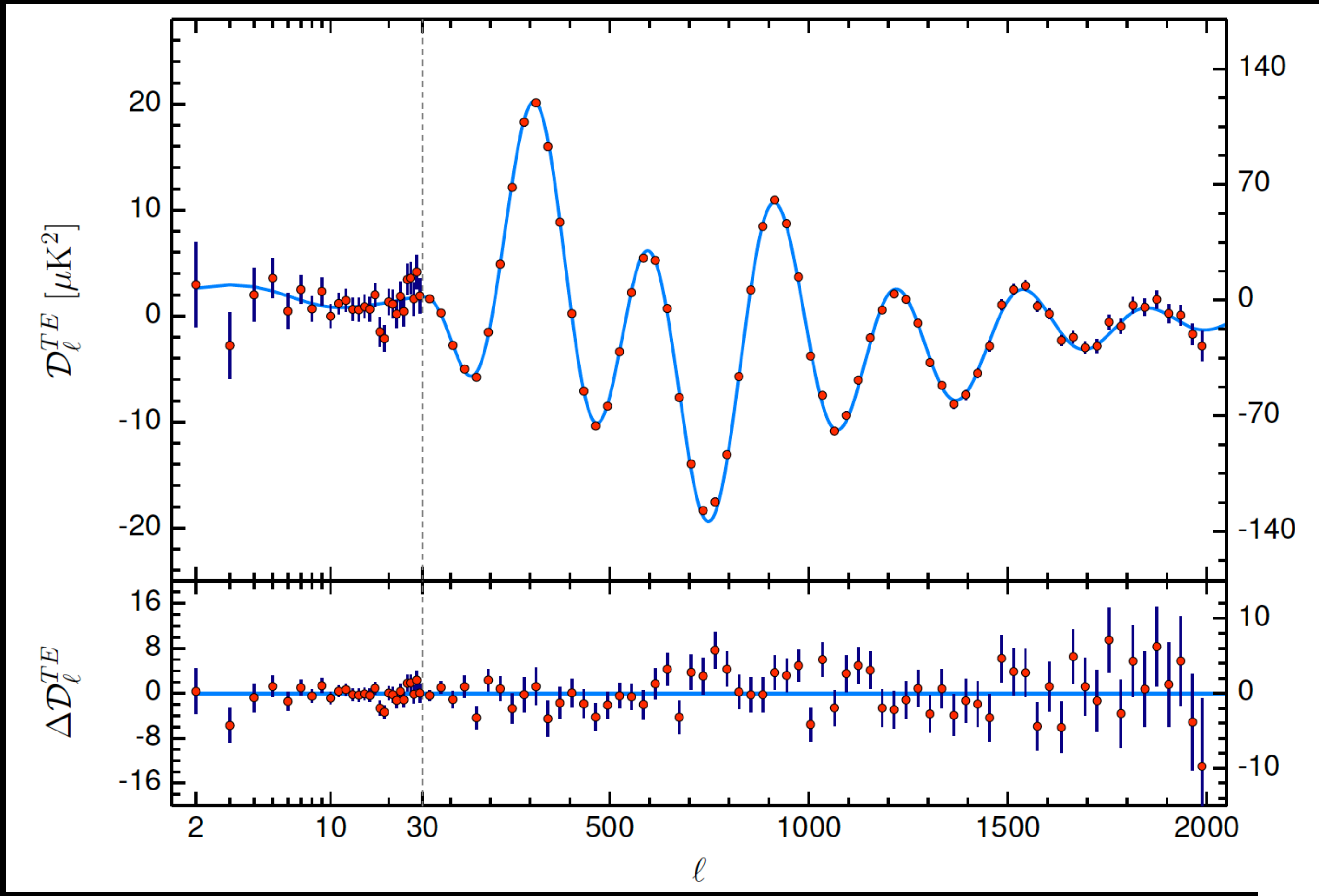


Planck satellite experiment



Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

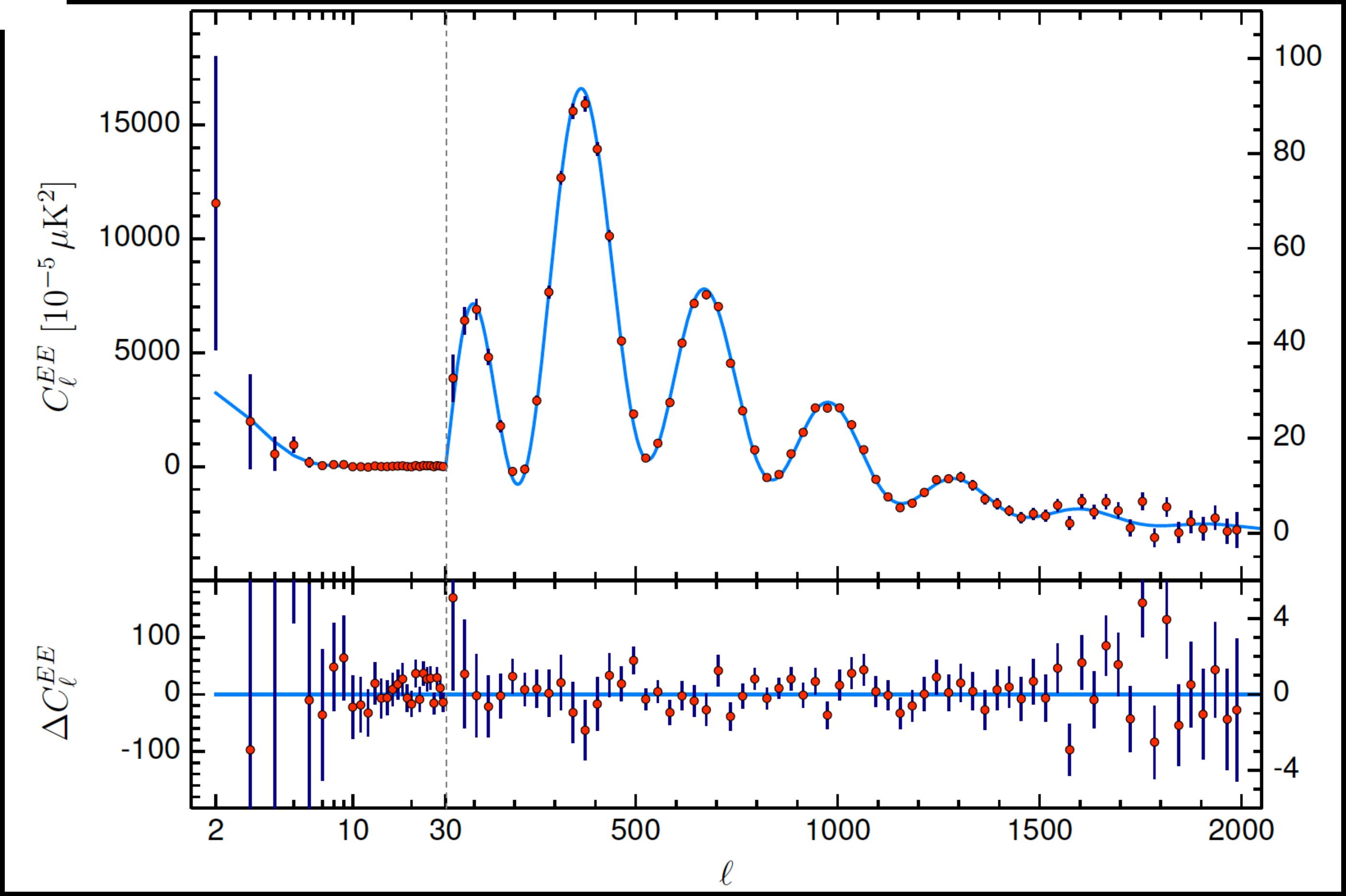
Planck satellite experiment



The theoretical spectra in light blues are computed from the best-fit base-LCDM theoretical spectrum fit to the Planck TT,TE,EE+lowE+lensing likelihood.

Residuals with respect to this theoretical model are shown in the lower panel in each plot.

Polarization spectra



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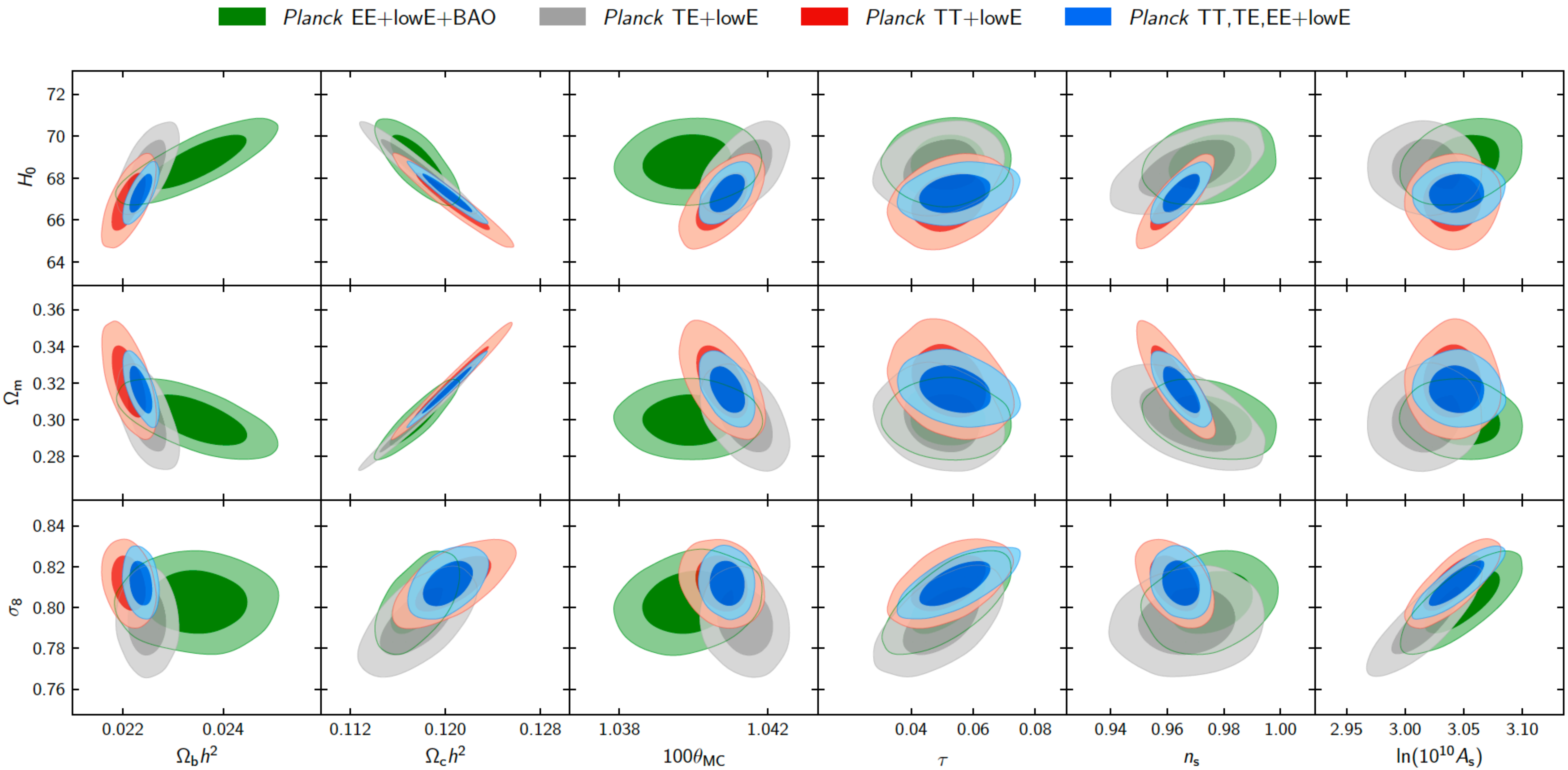
CMB constraints



Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

Constraints on parameters of the base-LCDM model from the separate Planck EE, TE, and TT high-l spectra combined with low-l polarization (lowE), and, in the case of EE also with BAO, compared to the joint result using Planck TT,TE,EE+lowE.

CMB constraints

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011

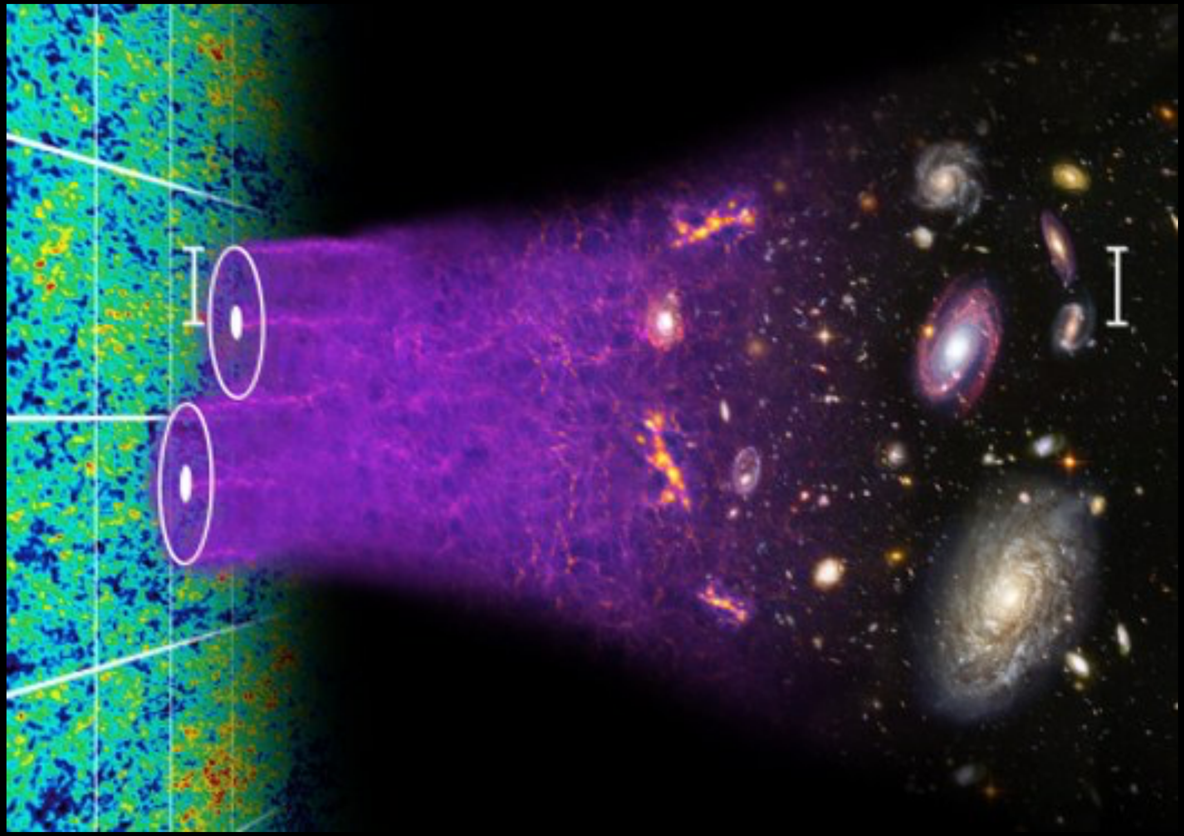
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

The precision measurements of the CMB polarization spectra have the potential to constrain cosmological parameters to higher accuracy than measurements of the temperature spectra because the acoustic peaks are narrower in polarization and unresolved foreground contributions at high multipoles are much lower in polarization than in temperature.

2018 Planck results are perfectly in agreement with the standard ΛCDM cosmological model.

BAO

Acoustic-scale distance measurements divided by the corresponding mean distance ratio from Planck TT,TE,EE+lowE+lensing in the base-LCDM model. The points, with their 1 error bars are as follows:



- green star, 6dFGS (Beutler et al. 2011, MNRAS, 416, 3017);
- magenta square, SDSS MGS (Ross et al. 2015, MNRAS, 449, 835);
- red triangles, BOSS DR12 (Alam et al. 2017, MNRAS, 470, 2617);
- small blue circles, WiggleZ (as analysed by Kazin et al. 2014, MNRAS, 441, 3524);
- large dark blue triangle, DES (DES Collaboration arXiv:1712.06209);
- cyan cross, DR14 LRG (Bautista et al. arXiv:1712.08064);
- red circle, SDSS quasars (Ata et al. arXiv:1705.06373);
- orange hexagon, BOSS Lyman-α (du Mas des Bourboux et al. arXiv:1708.02225).
- The green point with magenta dashed line is the 6dFGS and MGS joint analysis result of Carter et al. arXiv:1803.01746.

All ratios are for the averaged distance DV(z), except for DES and BOSS Lyman-α, where the ratio plotted is DM. The grey bands show the 68% and 95% confidence ranges allowed for the ratio DV(z)=rdrag by Planck TT,TE,EE+lowE+lensing.

BAO

Acoustic-scale distance measurements divided by the corresponding mean distance ratio from Planck TT,TE,EE+lowE+lensing in the base-LCDM model. The points, with their 1 error bars are as follows:

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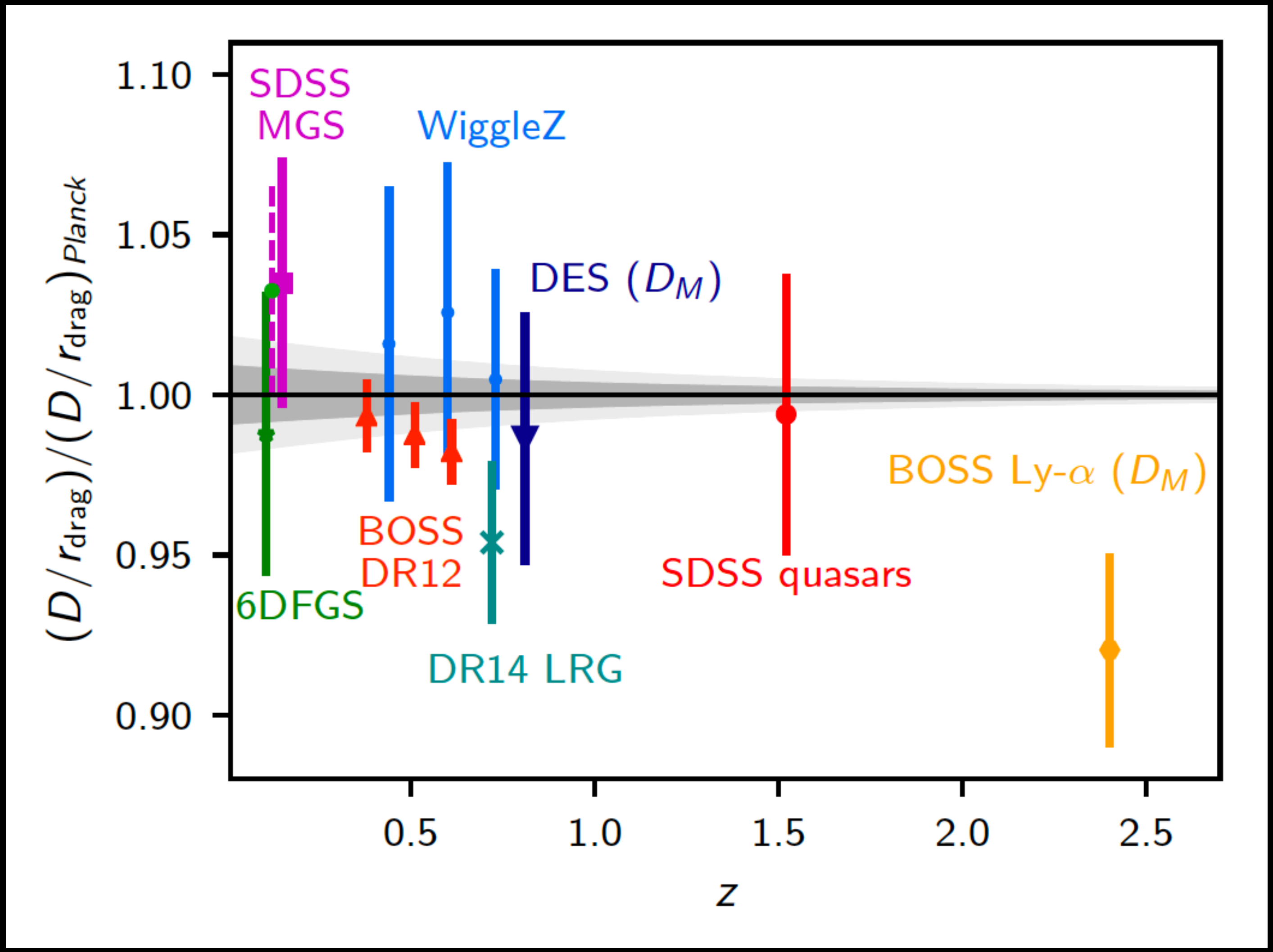

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However, anomalies and tensions between Planck and other cosmological probes are present well above the 3 standard deviations. These discrepancies, already hinted in previous Planck data releases, have persisted and strengthened despite several years of accurate analyses.

Recently, the Royal Astronomical Society awarded Planck their Group Achievement Award with the citation "(Planck) has now ushered in an era of tension cosmology.", clearly indicating that these tensions have reached such a level of statistical significance that the understanding of their physical nature is of utmost importance for modern cosmology.

If not due to systematics, the current anomalies could represent a crisis for the standard cosmological model and their experimental confirmation can bring a revolution in our current ideas of the structure and evolution of the Universe.

The most famous anomalies and tensions are:

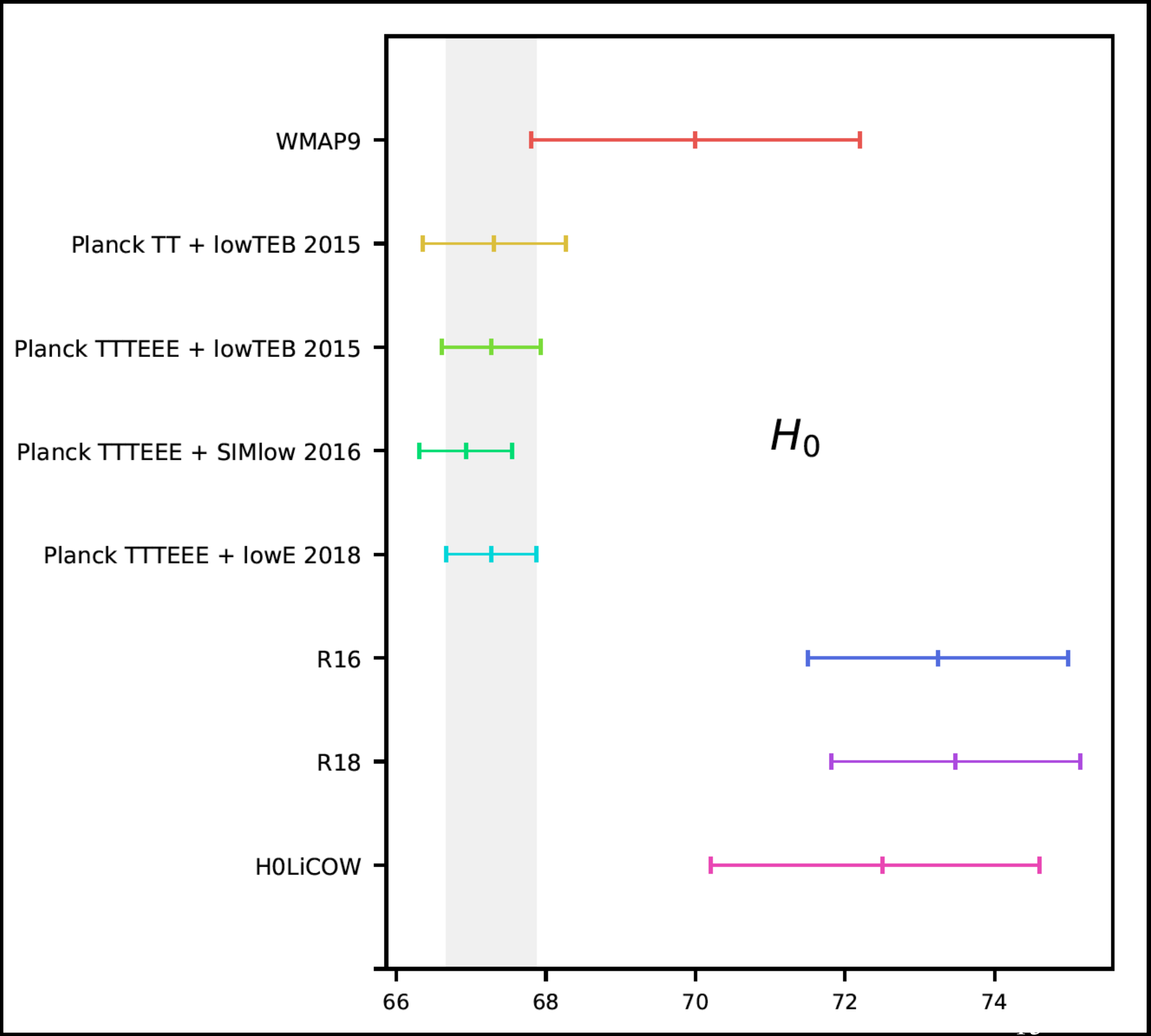
- H0 with local measurements
- S8 with cosmic shear data
- A_{lens} internal anomaly
- Curvature of the universe

Since the Planck constraints are model dependent, we can try to expand the cosmological scenario and see which extensions work in solving the tensions between the cosmological probes.

The H0 tension

We have two different blocks giving estimates of the Hubble constant in tension with each other:

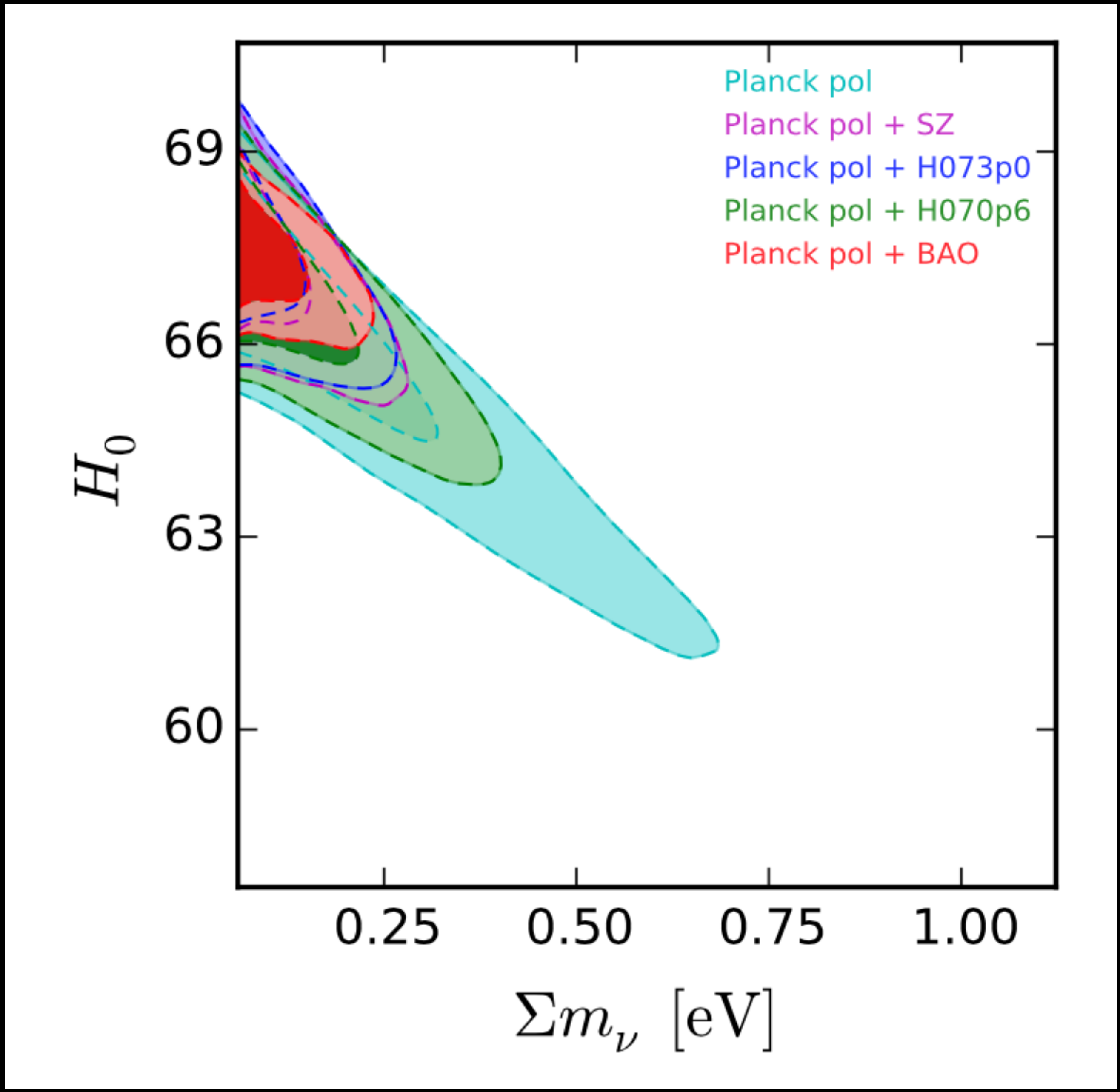
- CMB: WMAP, Planck, ground based telescopes.
- Local measurements and Strong lensing: HST, SH0ES, H0LiCOW.



Di Valentino et al. in preparation

The H0 value is very important for the determination of the total neutrino mass, that together with the neutrino effective number is a quantity the can be constrained by the CMB data, in combination with other cosmological probes.

In fact, there exist a very important negative correlation between the Hubble constant and the sum of the neutrino masses.



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

The H0 tension at more than 3σ

CMB: in this case the cosmological constraints are obtained by assuming a cosmological model and are therefore model dependent. Moreover these bounds are also affected by the degeneracy between the parameters that induce similar effects on the observables. Therefore the Planck constraints can change when modifying the assumptions of the underlying cosmological model.

$$H0 = 67.27 \pm 0.60 \text{ Km/s/Mpc in } \Lambda\text{CDM}$$

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

Local measurements: the 2016 estimate of the Hubble constant is based on the combination of three different geometric distance calibrations of Cepheids,

$$H0 = 73.24 \pm 1.74 \text{ Km/s/Mpc}$$

Riess et al. Astrophys.J. 826, no. 1, 56 (2016)

Or the 2018 parallax measurements of 7 long-period (> 10 days) Milky Way Cepheids using astrometry from spatial scanning of WFC3 on HST.

$$H0 = 73.48 \pm 1.66 \text{ Km/s/Mpc}$$

Riess et al. Astrophys.J. 855, 136 (2018)

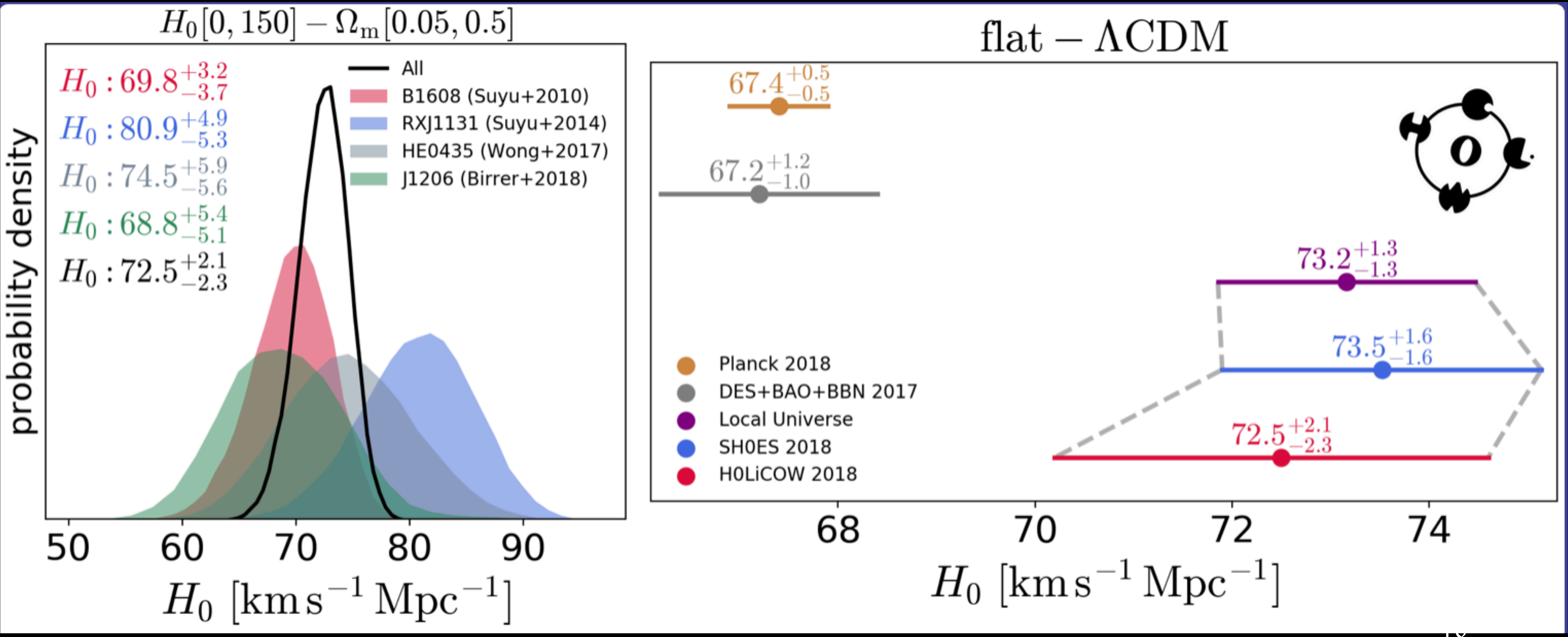
The H0 tension at more than 4σ

CMB: H0 = 67.27 ± 0.60 Km/s/Mpc in ΛCDM

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

Local measurements: H0 = 73.48 ± 1.66 Km/s/Mpc

Riess et al. Astrophys.J. 855, 136 (2018)



https://shsuyu.github.io/H0LiCOW/site/

Strong Lensing: H0 = $72.5^{+2.1}_{-2.3}$ Km/s/Mpc

Birrer et al. Mon.Not.Roy.Astron.Soc. 484 (2019) 4726

The H0 tension at more than 4σ

Table 5. Best Estimates of H_0 Including Systematics

Anchor(s)	Value [km s^{-1} Mpc^{-1}]	Δ Planck*+ ΛCDM (σ)
LMC	74.22 ± 1.82	3.6
Two anchors		
LMC + NGC 4258	73.40 ± 1.55	3.7
LMC + MW	74.47 ± 1.45	4.6
NGC 4258 + MW	73.94 ± 1.58	3.9
Three anchors (preferred)		
NGC 4258 + MW + LMC	$\mathbf{74.03 \pm 1.42}$	4.4

NOTE—* : $H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1} (Planck Collaboration et al. 2018)

Riess et al. arXiv:1903.07603 [astro-ph.CO]

Recently has been improved the H0 measurements using Hubble Space Telescope observations of 70 long-period Cepheids in the Large Magellanic Cloud.

The tension becomes of 4.4σ between local measurements of H0 and the value predicted from Planck in ΛCDM.

The Dark energy equation of state

Changing the dark energy equation of state w, we are changing the expansion rate of the Universe:

$$H^2 = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_{\rm de} (1+z)^{3(1+w)} + \Omega_k (1+z)^2 \right]$$

w introduces a geometrical degeneracy with the Hubble constant that will be unconstrained using the CMB data only, resulting in agreement with Riess+18.

We have in 2018 $w = -1.58^{+0.52}_{-0.41}$ with H0 > 69.9 km/s/Mpc at 95% cl.

Planck data prefer a phantom dark energy, with an energy component with w < –1, for which the density increases with time in an expanding universe that will end in a Big Rip. A phantom dark energy violates the energy condition ρ ≥ |p|, that means that the matter could move faster than light and a comoving observer measure a negative energy density, and the Hamiltonian could have vacuum instabilities due to a negative kinetic energy.

Anyway, there exist models that expect an effective energy density with a phantom equation of state without showing the problems before.

The Neutrino effective number

When the rate of the weak interaction reactions, which keep neutrinos in equilibrium with the primordial plasma, becomes smaller than the expansion rate of the Universe, neutrinos decouple at a temperature of about:

$$T_{dec} \approx 1 MeV$$

After neutrinos decoupling, photons are heated by electrons-positrons annihilation. After the end of this process, the ratio between the temperatures of photons and neutrinos will be fixed, despite the temperature decreases with the expansion of the Universe. We expect today a Cosmic Neutrino Background (CNB) at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

With a number density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

The Neutrino effective number

The relativistic neutrinos contribute to the present energy density of the Universe:

$$\rho_{rad} = \rho_\gamma + \rho_\nu = g_\gamma \left(\frac{\pi^2}{30}\right) T_\gamma^4 + g_\nu \left(\frac{\pi^2}{30}\right)\left(\frac{7}{8}\right) T_\nu^4$$

$$\rho_{rad} = \left(1 + \left(\frac{7}{8}\right)\left(\frac{4}{11}\right)^{\frac{4}{3}} \left(\frac{g_\nu}{g_\gamma}\right)\right) \rho_\gamma$$

We can introduce the effective number of relativistic degrees of freedom:

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

The expected value is Neff = 3.046, if we assume standard electroweak interactions and three active massless neutrinos. The 0.046 takes into account effects for the non-instantaneous neutrino decoupling and neutrino flavour oscillations (Mangano et al. hep-ph/0506164).

The Neutrino effective number

If we measure a Neff>3.046, we are in presence of extra radiation.
This extra radiation, essentially, increases the expansion rate H:

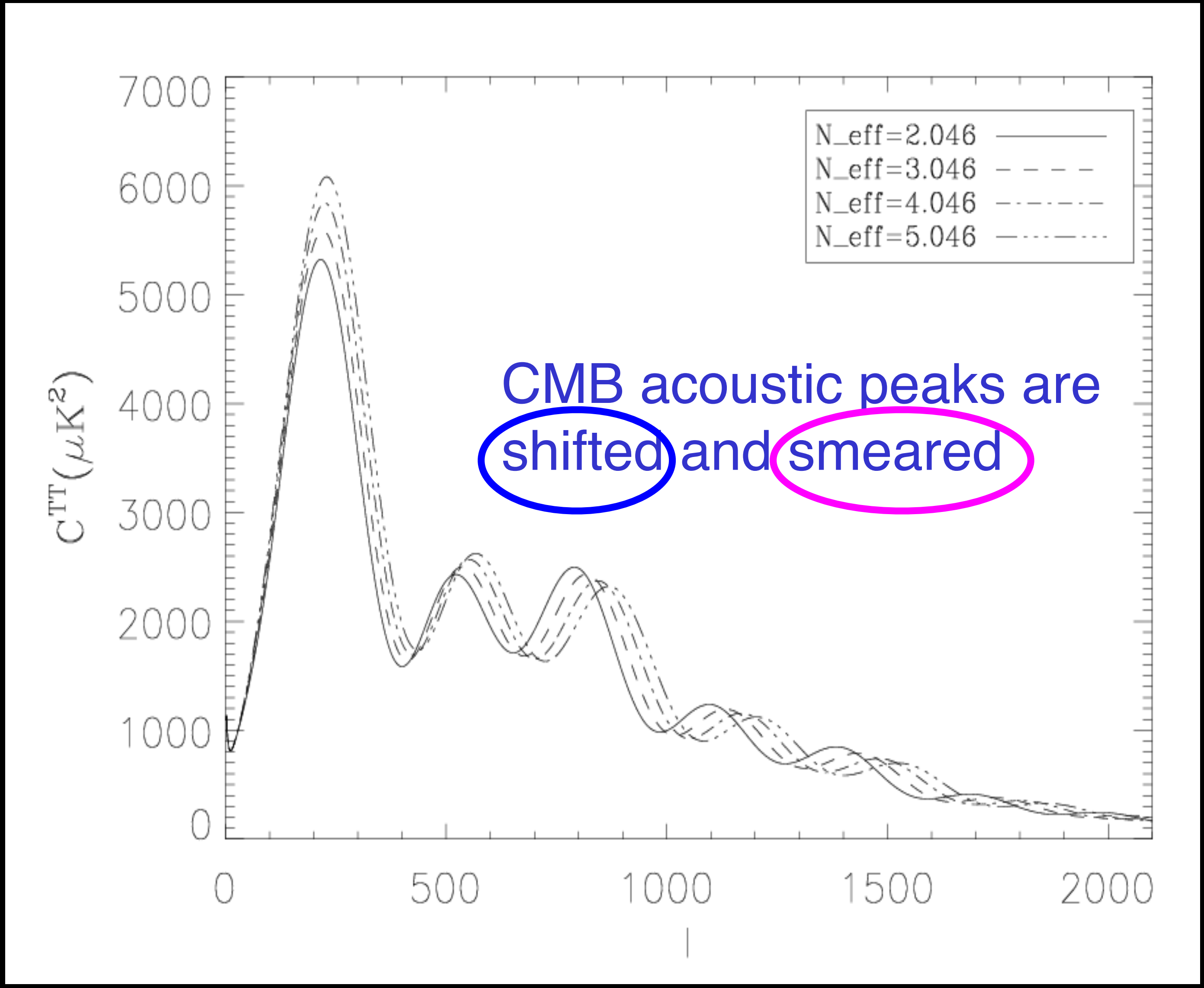
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

and it decreases the sound horizon at recombination,

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

and the diffusion distance (damping scale):

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



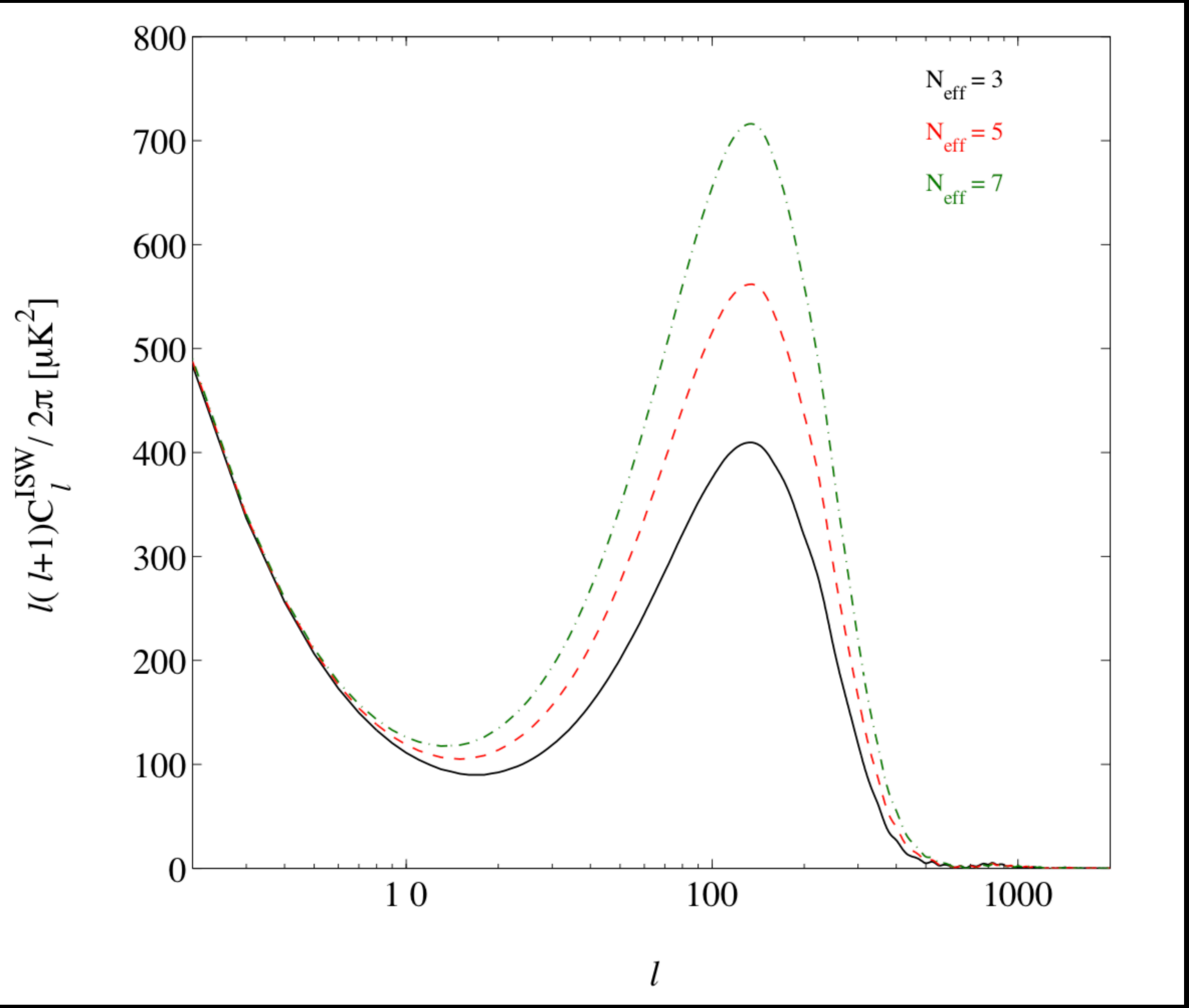
The Neutrino effective number

Varying N_{eff} changes the time of the matter radiation equivalence: a higher radiation content due to the presence of additional relativistic species leads to a delay in z_{eq}:

$$1 + z_{\rm eq} = \frac{\Omega_m}{\Omega_r} = \frac{\Omega_m h^2}{\Omega_\gamma h^2} \frac{1}{(1 + 0.2271 N_{\rm eff})}$$

This implies that at the time of decoupling the radiation is still a subdominant component and the gravitational potential is still slowly decreasing.

This shows up as an enhancement of the early Integrated Sachs Wolfe (ISW) effect that increases the CMB perturbation peaks at l ~ 200.



Archidiacono et al. Adv.High Energy Phys. 2013 (2013) 191047

The Neutrino effective number

If we compare the Planck 2015 constraint on Neff at 68% cl

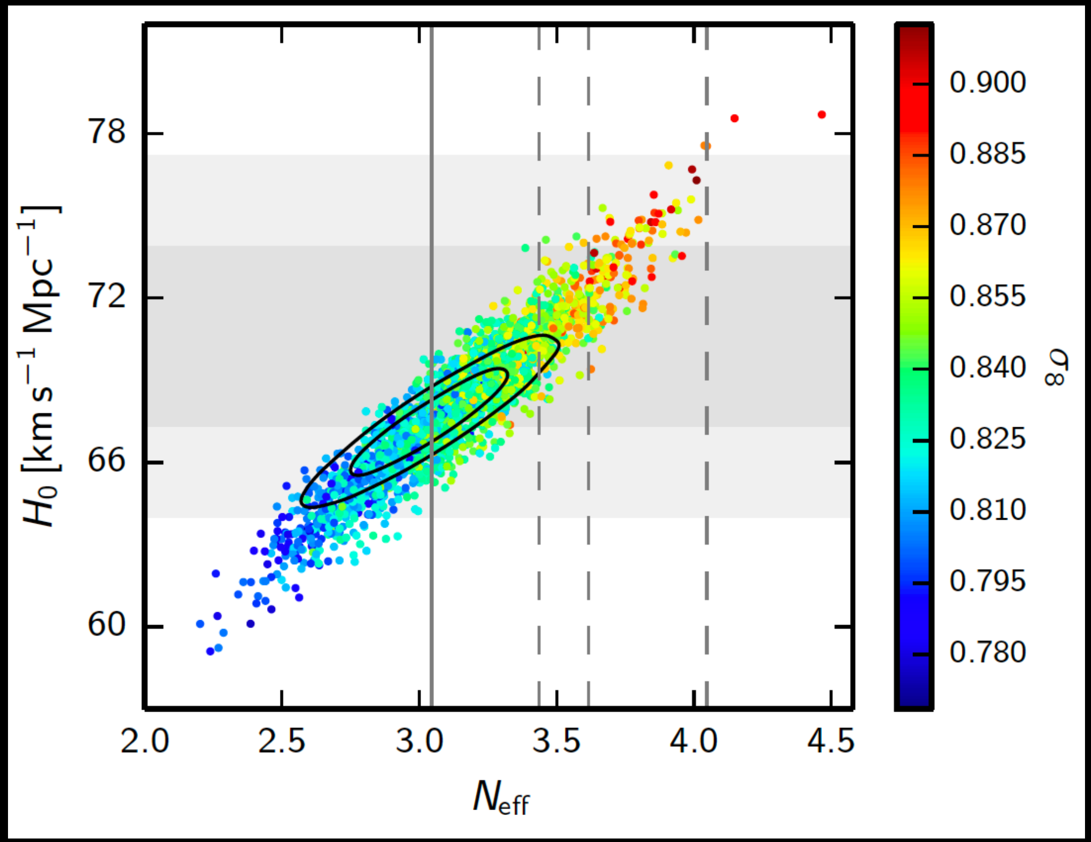
$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP},$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO},$$

with the new Planck 2018 bound,

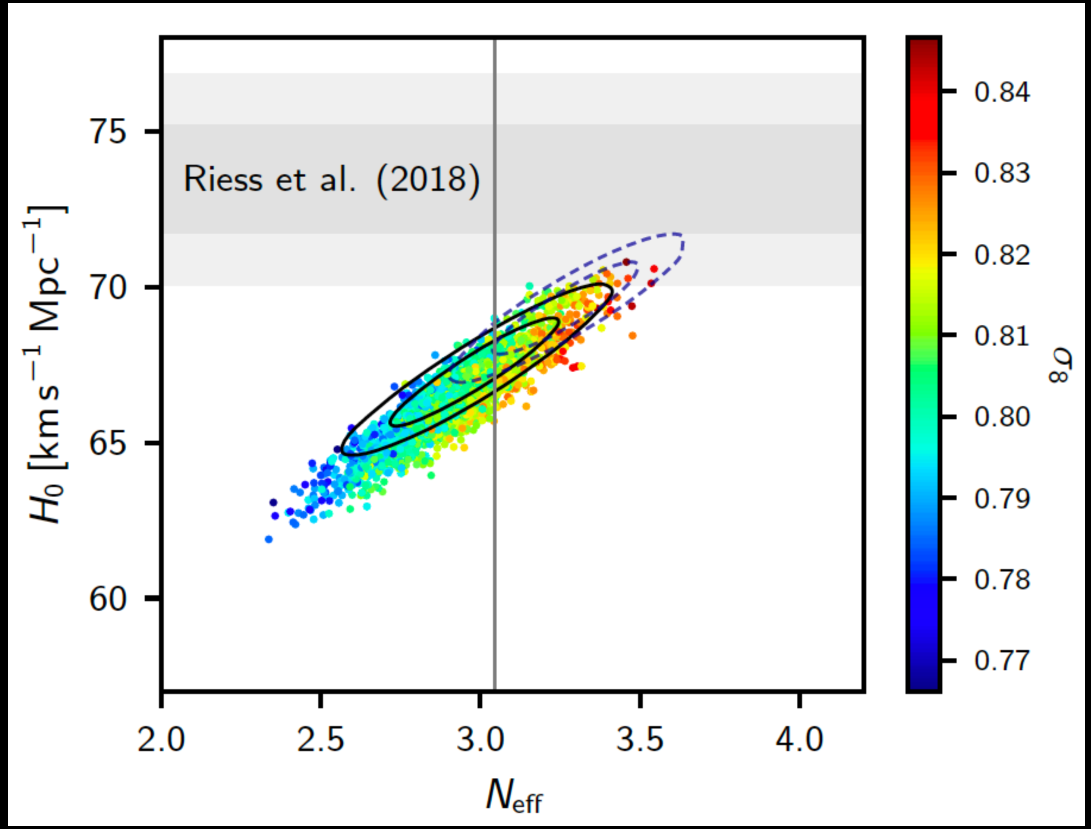
$$N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

we see that the neutrino effective number is now very well constrained.

The main reason for this good accuracy is due to the lack of the early integrated Sachs Wolfe effect in polarization data. The inclusion of polarization helps in determining the amplitude of the eISW and Neff. H0 passes from 68.0 ± 2.8 Km/s/Mpc (2015) to 66.4 ± 1.4 Km/s/Mpc (2018), and the tension with Riess+18 increases from 1.7σ to 3.2σ also varying Neff.

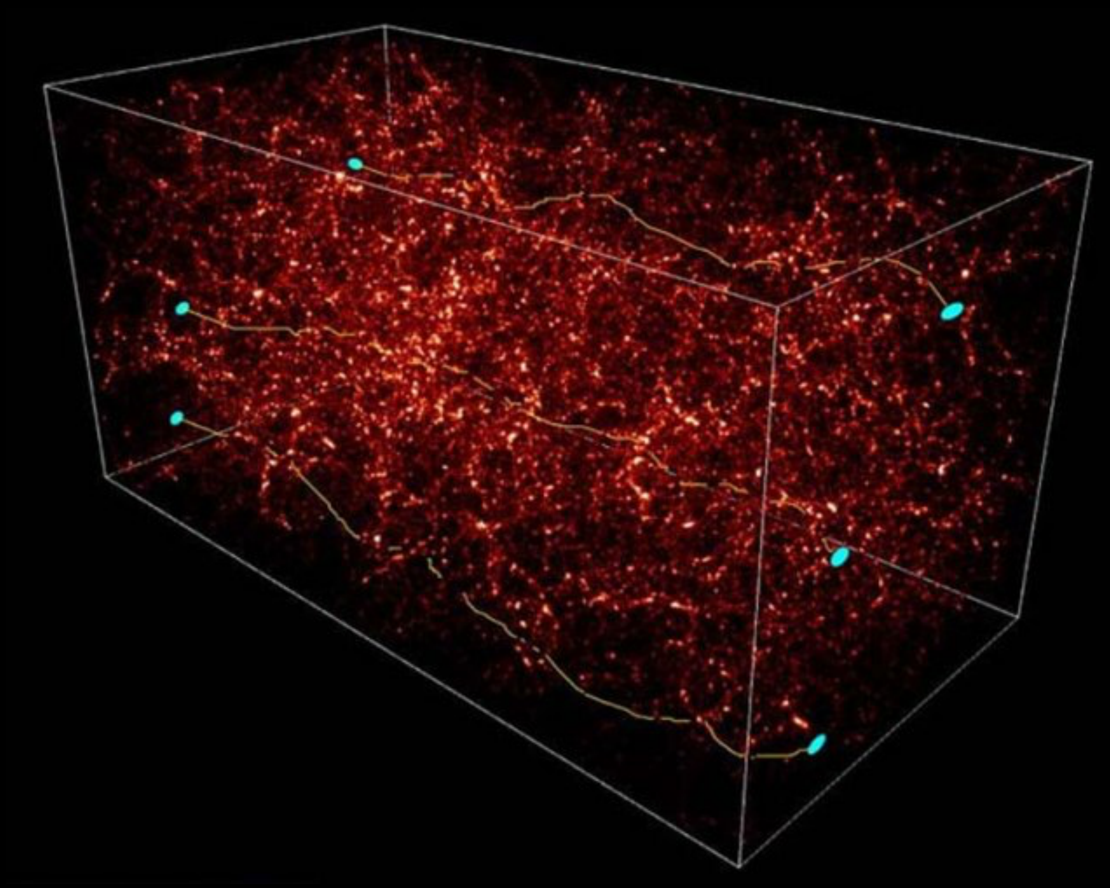


Planck collaboration, 2015



Planck collaboration, 2018

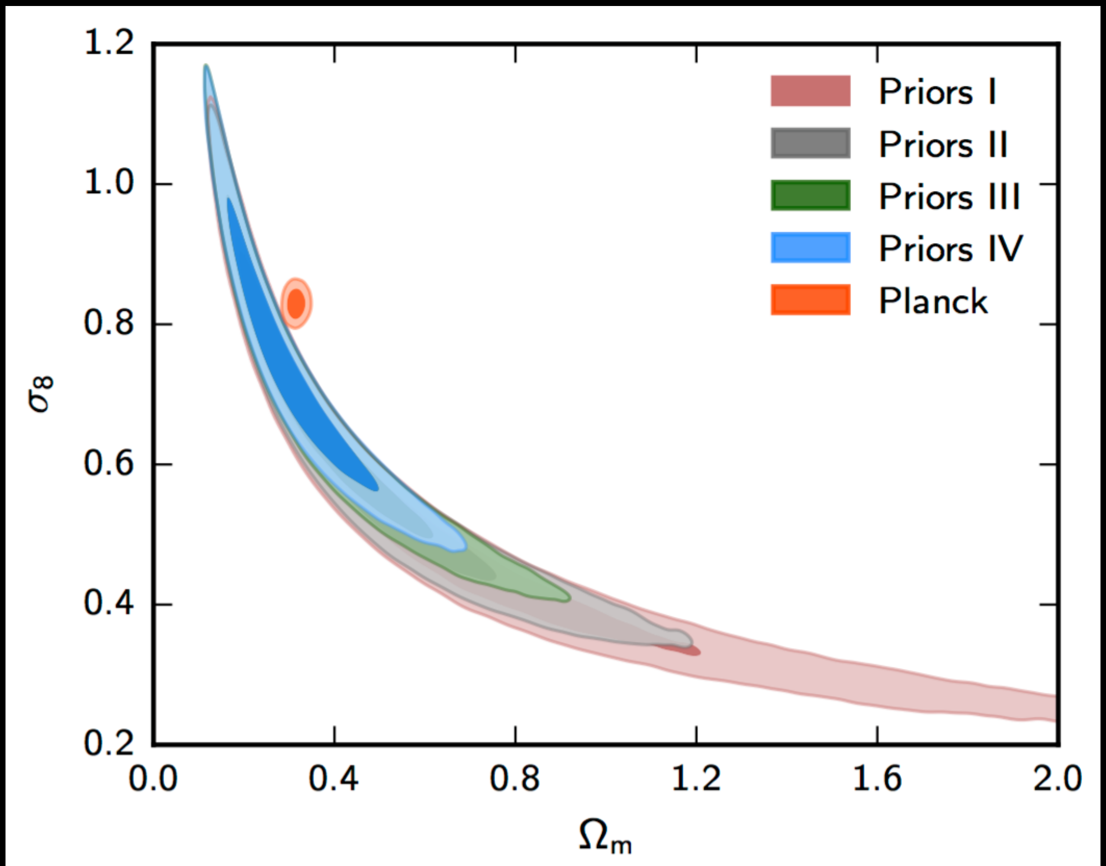
S8 tension



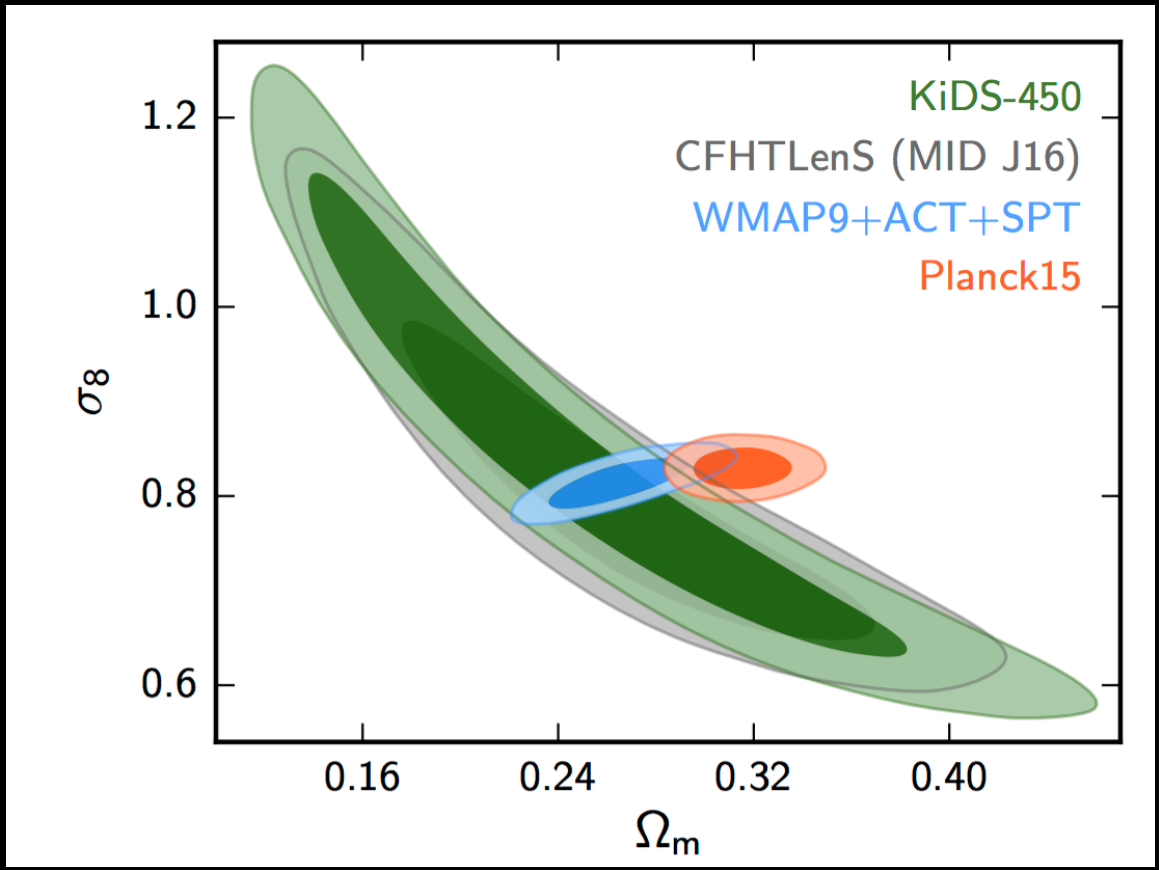
$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

The S8 tension at about 2.4 sigma level is present between the Planck data in the ΛCDM scenario and the cosmic shear data.

S8 tension



Joudaki et al, arXiv:1601.05786



Hildebrandt et al., arXiv:1606.05338.

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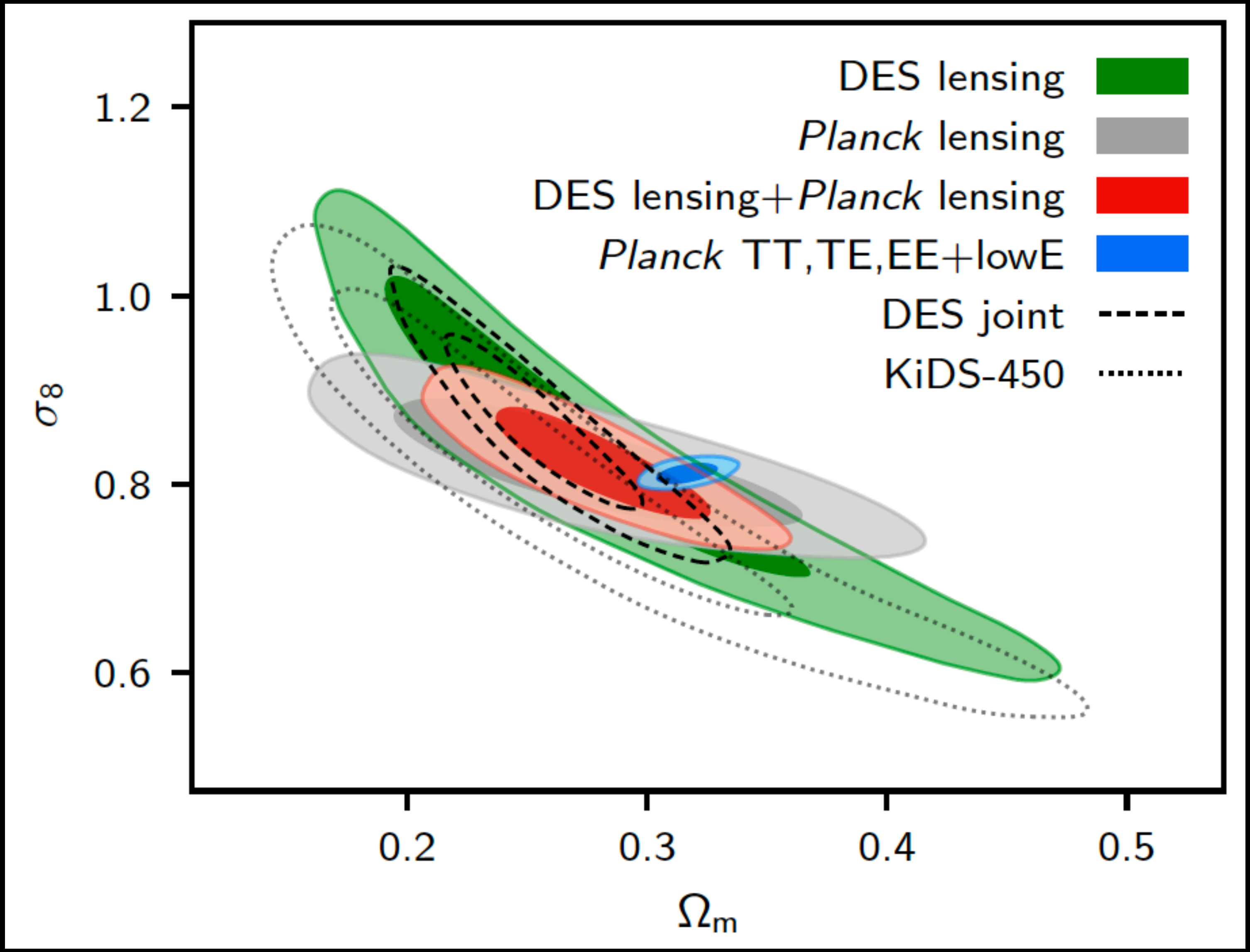
The S8 tension at about 2.4 sigma level is present between the Planck data in the ΛCDM scenario and the cosmic shear data from the CFHTLenS survey and KiDS-450.

S8 tension

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



While there is no tension with DES galaxy lensing, a tension at about 2.5 sigma level is present for the DES results that include galaxy clustering.

Sum of active neutrino masses

If the total neutrino mass is of the order of 1 eV, neutrinos are radiation at the time of equality, and non-relativistic matter today.

We expect the transition to the non-relativistic regime after the time of the photon decoupling.

⇨ When neutrinos are relativistic, will contribute to the radiation content of the universe, through the effective number of relativistic degrees of freedom Neff.

⇨ When they become non-relativistic, will only cluster at scales larger than their free streaming scale, suppressing therefore structure formation at small scales, and affecting the large scale structures.

Sum of active neutrino masses

Because the shape of the CMB spectrum is related mainly to the physical evolution before recombination, the effect of the neutrino mass, can appear through a modified background evolution and some secondary anisotropy corrections.

Varying their total mass we vary:

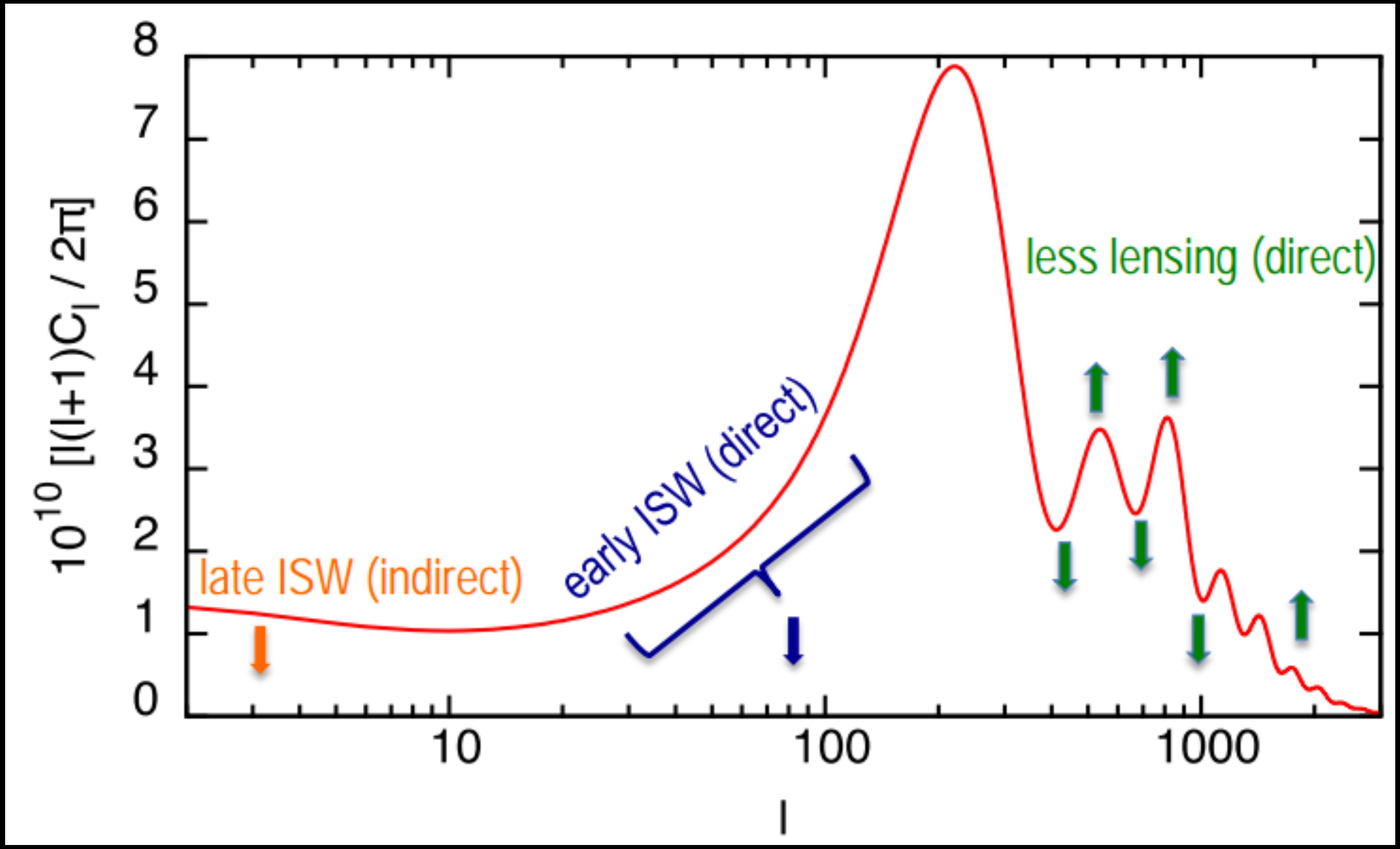
- The redshift of the matter-to-radiation equality zeq;
- The amount of matter density today.

$$\omega_M = \omega_b + \omega_{CDM} + (\Sigma\, m_\nu) / 93.14\ \mathrm{eV}$$

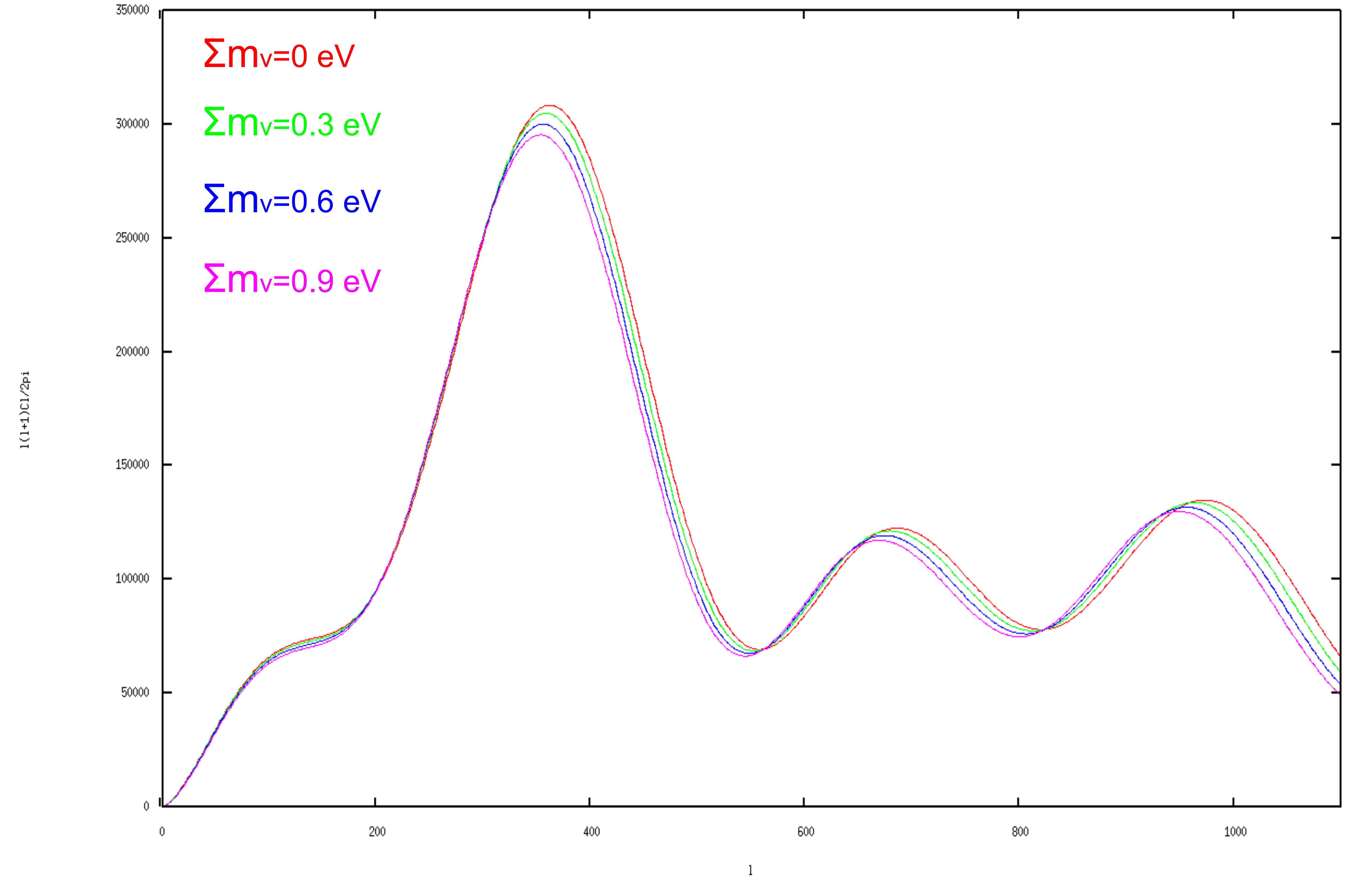
Sum of active neutrino masses

The impact on the CMB will be:

- The changing of the position and amplitude of the peaks;
- The slope of the low-l tail of the spectrum, due to the late ISW effect;
- The damping of the high-l tail, due to the lensing effect.



Sum of active neutrino masses



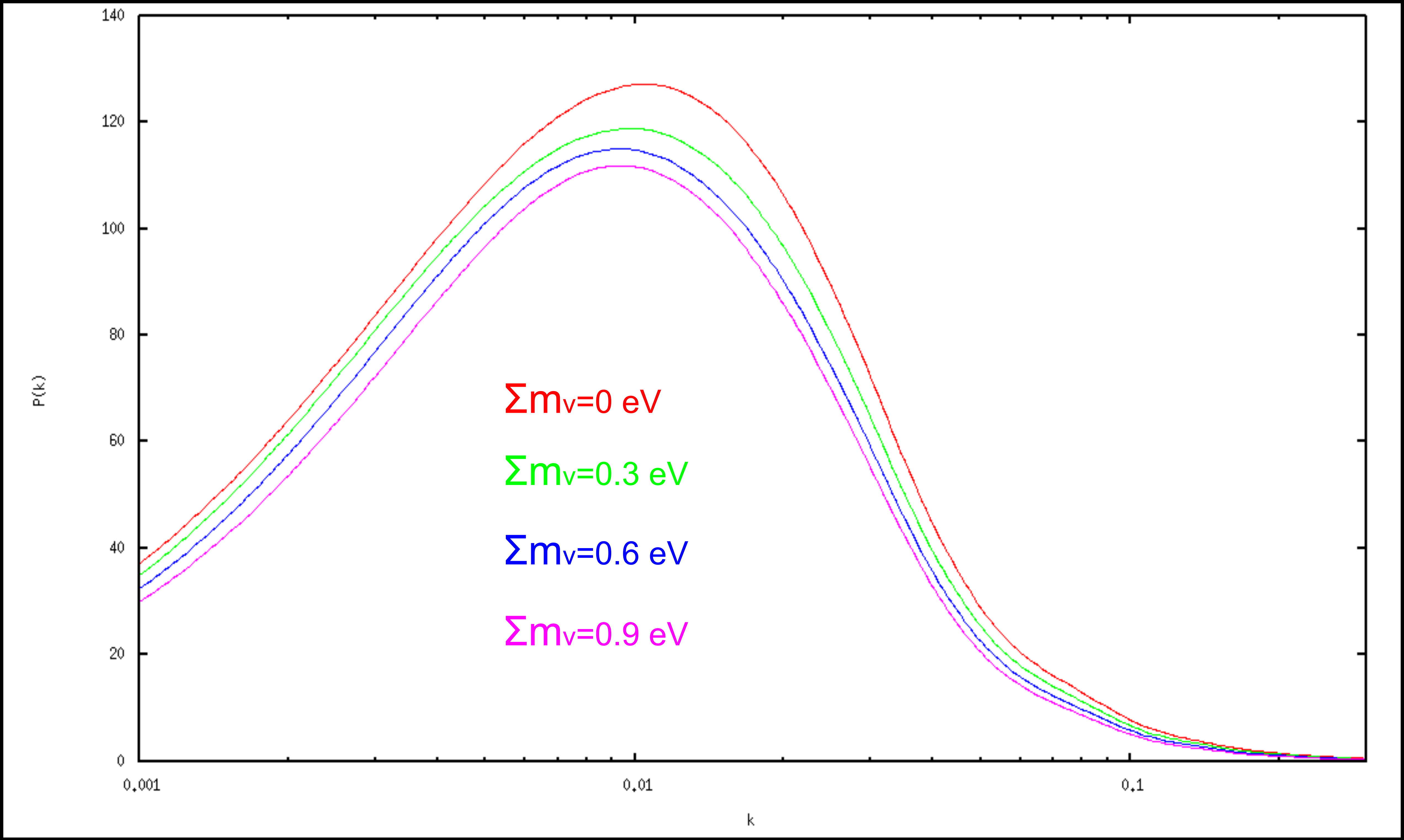
Sum of active neutrino masses

The shape of the matter power spectrum is the key observable for constraining the neutrino masses with cosmological methods.

This is defined as the two-point correlation function of the non-relativistic matter fluctuation in Fourier space:

$$P(k,z) = \langle|\delta_{\mathrm{m}}(k,z)|^2\rangle \quad \Rightarrow \quad \delta_{\mathrm{m}} = \frac{\sum_i \bar{\rho}_i \, \delta_i}{\sum_i \bar{\rho}_i}$$

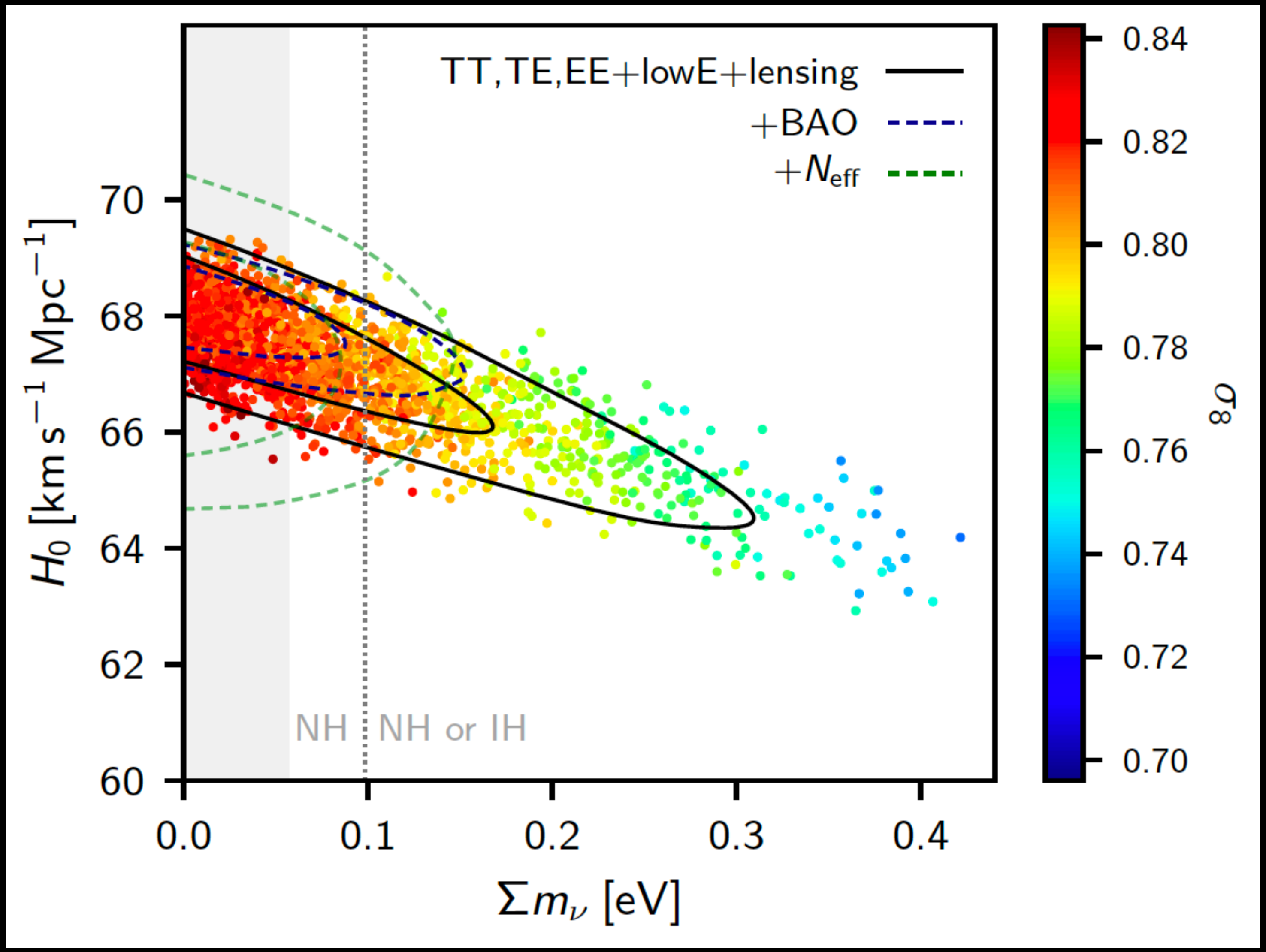
Sum of active neutrino masses



Imposing a flat Universe

Total neutrino mass

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

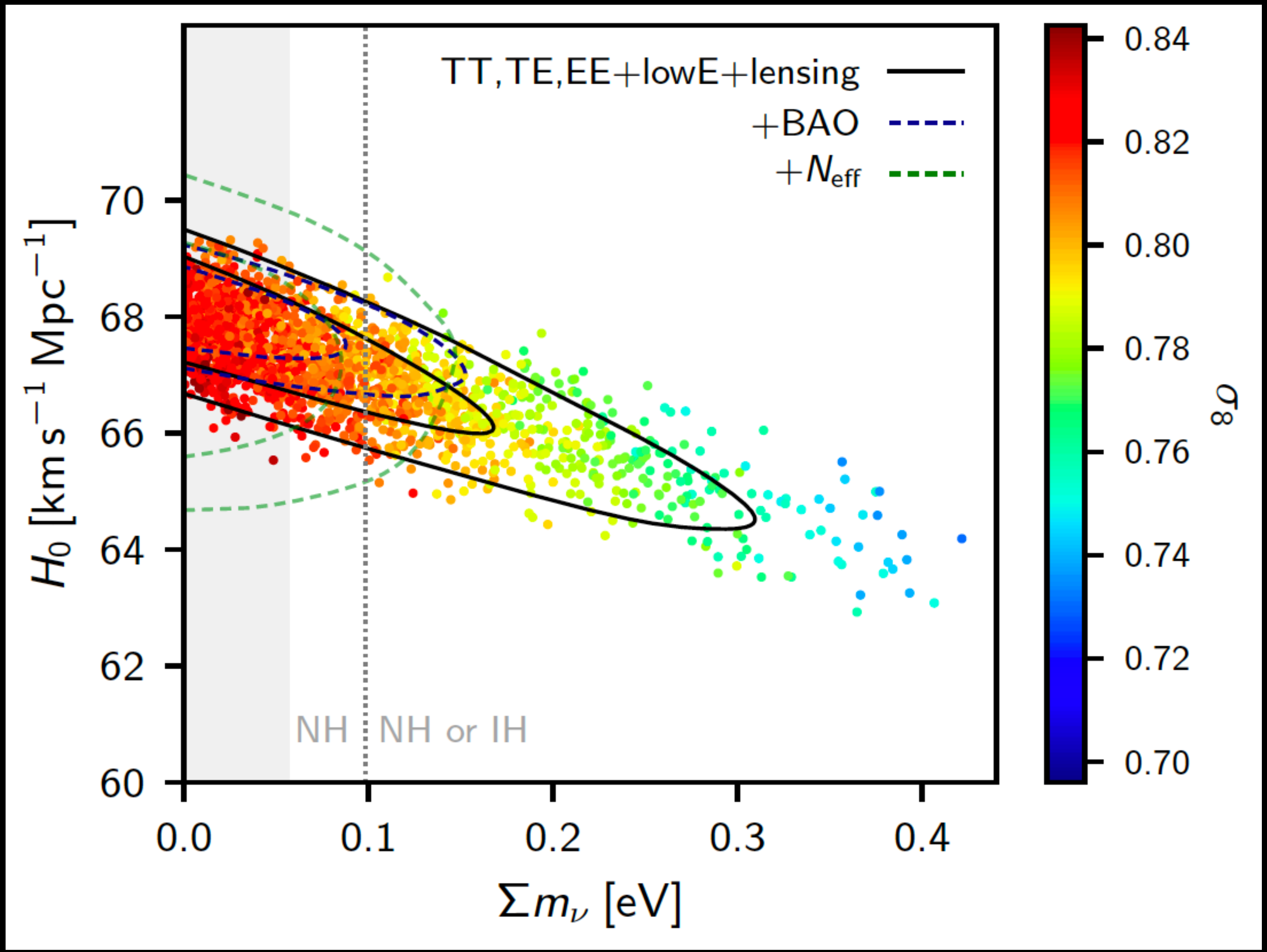


$$\sum m_\nu < 0.24 \text{ eV} \quad (95\,\%, \text{ TT,TE,EE+lowE+lensing}).$$

From Planck 2018 we have a very important upper limit on the total neutrino mass. However, the inclusion of additional low redshift probes is mandatory in order to sharpen the CMB neutrino bounds.

Total neutrino mass

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%, \textit{Planck}\text{ TT,TE,EE+lowE+lensing+BAO}).$$

The most stringent bound is obtained when adding the BAO data that are directly sensitive to the free-streaming nature of neutrinos. Moreover, the geometrical information they provide helps breaking degeneracies among cosmological parameters.

CMB constraints on the neutrino effective number and the total neutrino mass

$$\left.\begin{aligned} N_{\rm eff} &= 2.96^{+0.34}_{-0.33}, \\ \sum m_\nu &< 0.12\ \text{eV}, \end{aligned}\right\} \quad 95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE+lensing+BAO.}$$

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

When varying also N_{eff}, the bounds on the total neutrino mass doesn't change and the neutrino effective number is totally consistent with its standard value 3.046. The bounds remain very close to the bounds we have in 7-parameter models, showing that the data clearly differentiate between the physical effects generated by the addition of these two parameters.

Anyway, there is still the possibility to have some relic components.

The sterile neutrino

The main candidate is a sterile neutrino.
With the CMB we can only constrain the effective sterile neutrino mass, but fixing the model, we can infer also the physical mass of the particle.
The relationship between N_{eff} and m_{eff} is model dependent.

- ★ Thermally distributed

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

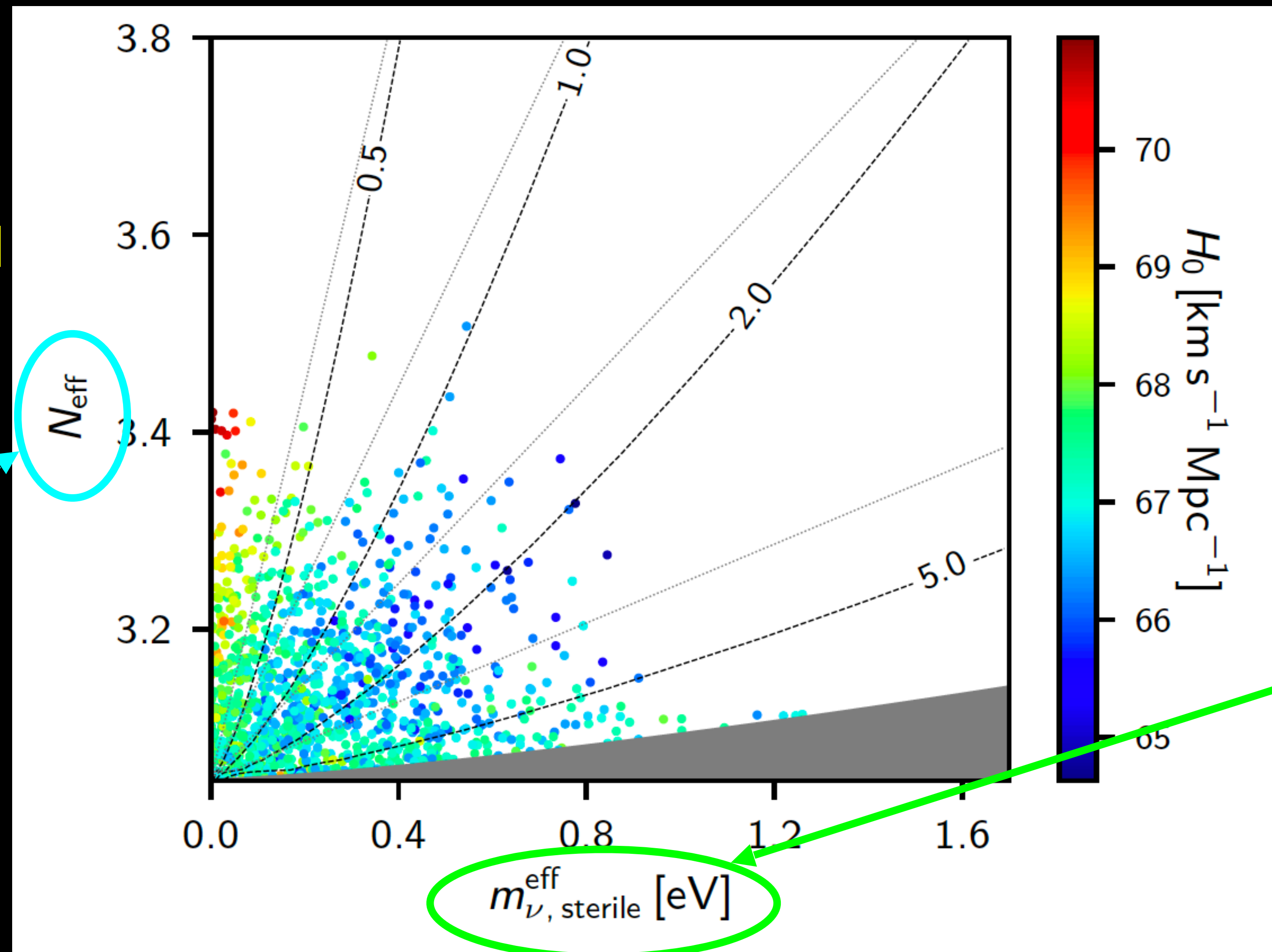
- ★ Produced via the mechanism described by Dodelson & Widrow, 1994, PRL, 72,17.

$$m_{\rm sterile}^{\rm DW} = (\Delta N_{\rm eff})^{-1} m_{\nu,\,\rm sterile}^{\rm eff}$$

For low ΔN_{eff} the physical mass can therefore become large and in that case the particles behave as cold dark matter.
For this reason in Planck are excluded all the sterile neutrino mass <10eV.

The sterile neutrino

Planck 2018, Aghanim et al.,
arXiv:1807.06209 [astro-ph.CO]



Contribution of the sterile neutrino when it is massless.

Contribution of the sterile neutrino when it is massive.

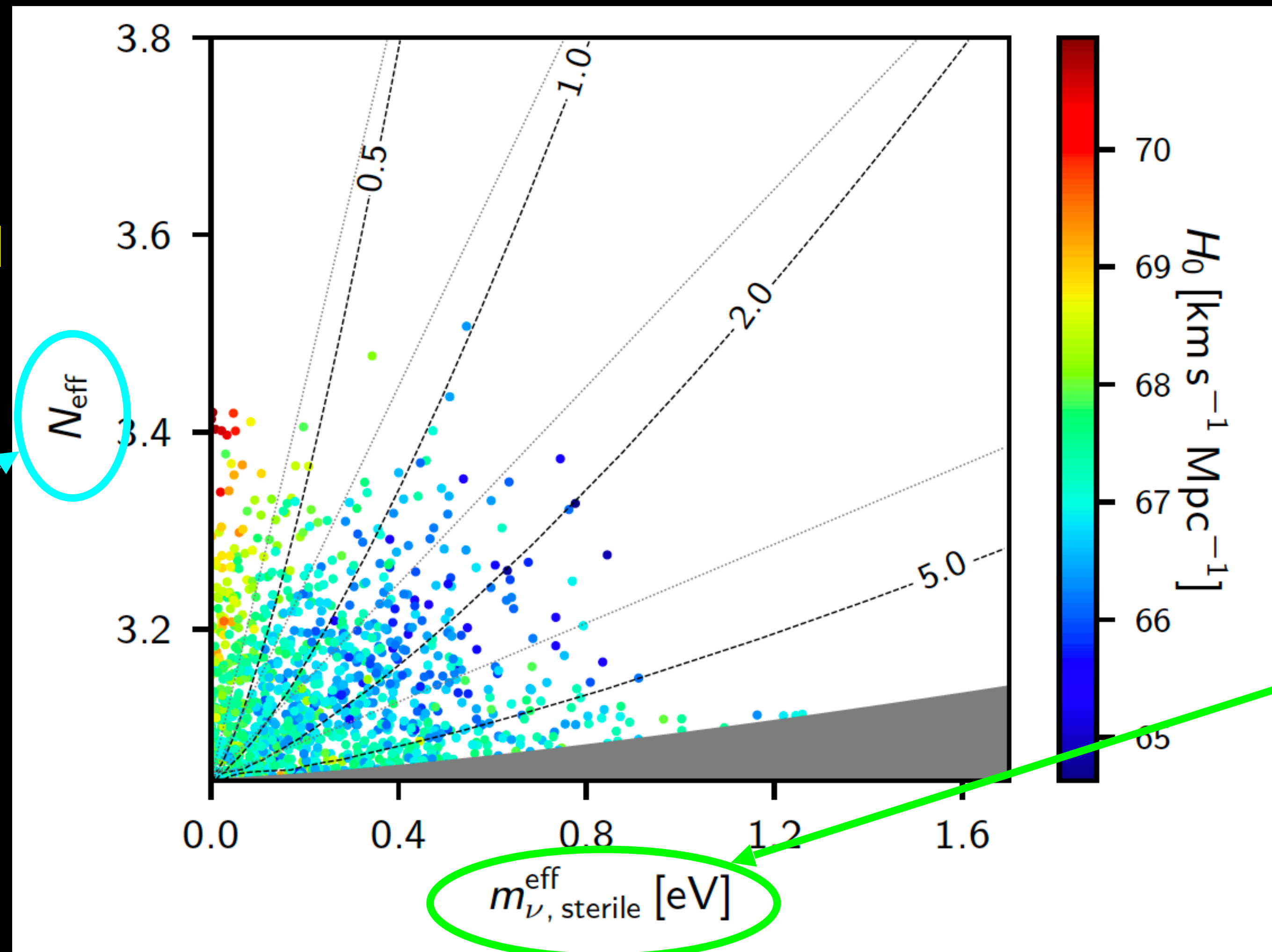
$$\left.\begin{array}{r} N_{\rm eff} < 3.29, \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.65\ {\rm eV}, \end{array}\right\} \begin{array}{l} 95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE} \\ \text{+lensing+BAO,} \end{array}$$

The physical mass for thermally-produced sterile neutrinos is constant along the grey lines labelled by the mass in eV, while the equivalent result for sterile neutrinos produced via the Dodelson-Widrow mechanism is shown by the adjacent thinner lines. The dark grey shaded region shows the part of parameter space excluded by the default prior $m_{\rm thermal}$ sterile < 10 eV.

The sterile neutrino

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

Contribution of the sterile neutrino when it is massless.



Contribution of the sterile neutrino when it is massive.

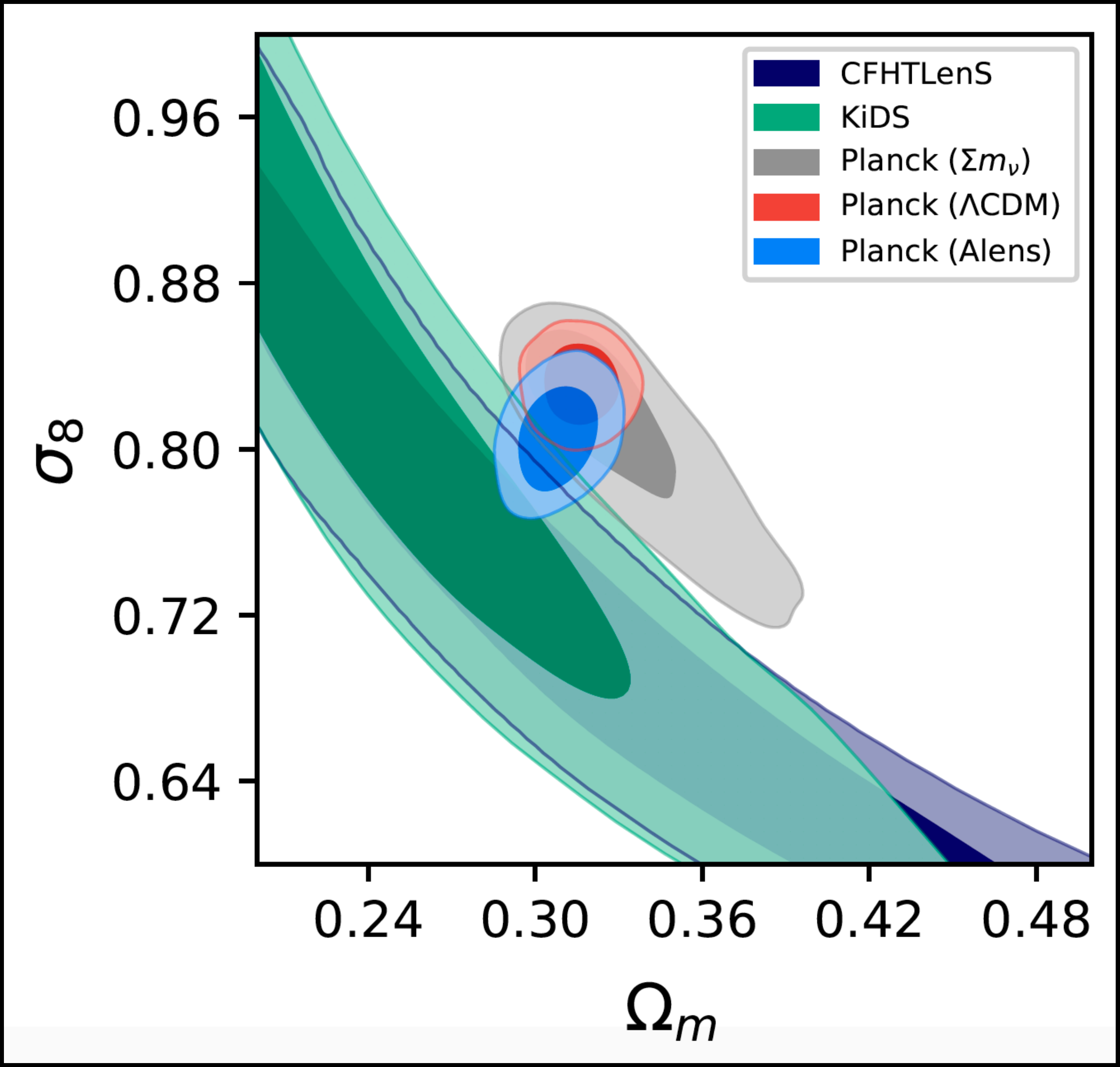
$$\left. \begin{array}{l} N_{eff} < 3.29, \\ m^{eff}_{\nu,\,sterile} < 0.65 \text{ eV}, \end{array} \right\} \begin{array}{l} 95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE} \\ \text{+lensing+BAO,} \end{array}$$

One thermalized sterile neutrino with $\Delta N_{eff} = 1$ is excluded at about 6σ irrespective of its mass. The presence of a light thermalized sterile neutrino is in strong contradiction with cosmological data, and that the production of sterile neutrinos possibly explaining the neutrino short baseline (SBL) anomaly would need to be suppressed by some non-standard interactions (Archidiacono et al. 2016, JCAP, 1608, 067; Chu et al. 2015, JCAP, 1510, 011), low-temperature reheating (de Salas et al. 2015, Phys. Rev., D92, 123534), or another special mechanism.

The S8 tension

The CMB and cosmic shear datasets, in tension in the standard LCDM model, are still in tension adding massive neutrinos.

In fact, adding the massive neutrinos there is a shift towards lower values of the clustering parameter σ_8, but the direction of the degeneracy is parallel to the bounds from the cosmic shear data.



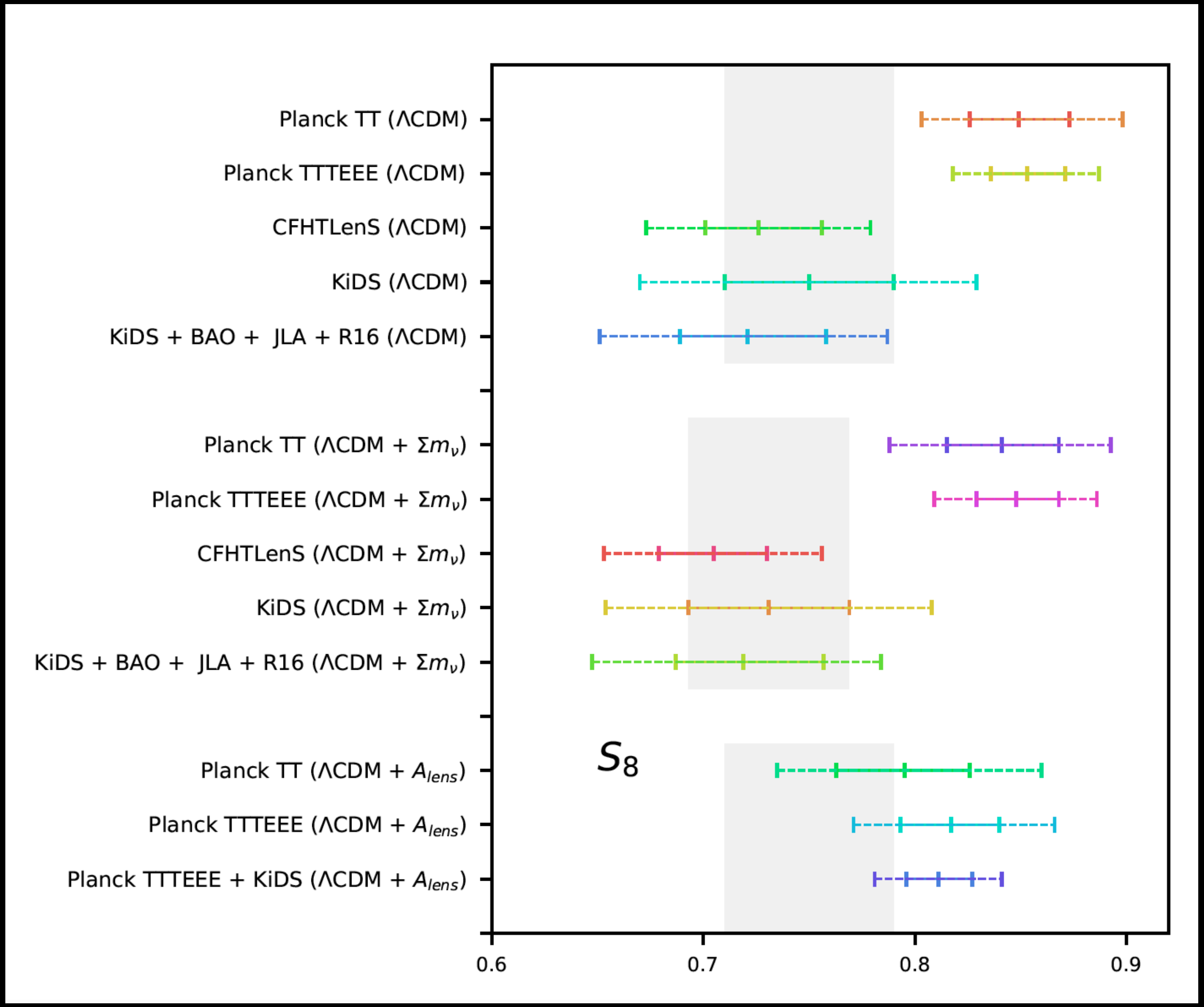
Di Valentino and Bridle, Symmetry 10 (2018) no.11, 585

The S8 tension

The CMB and cosmic shear datasets, in tension in the standard LCDM model, are still in tension adding massive neutrinos.

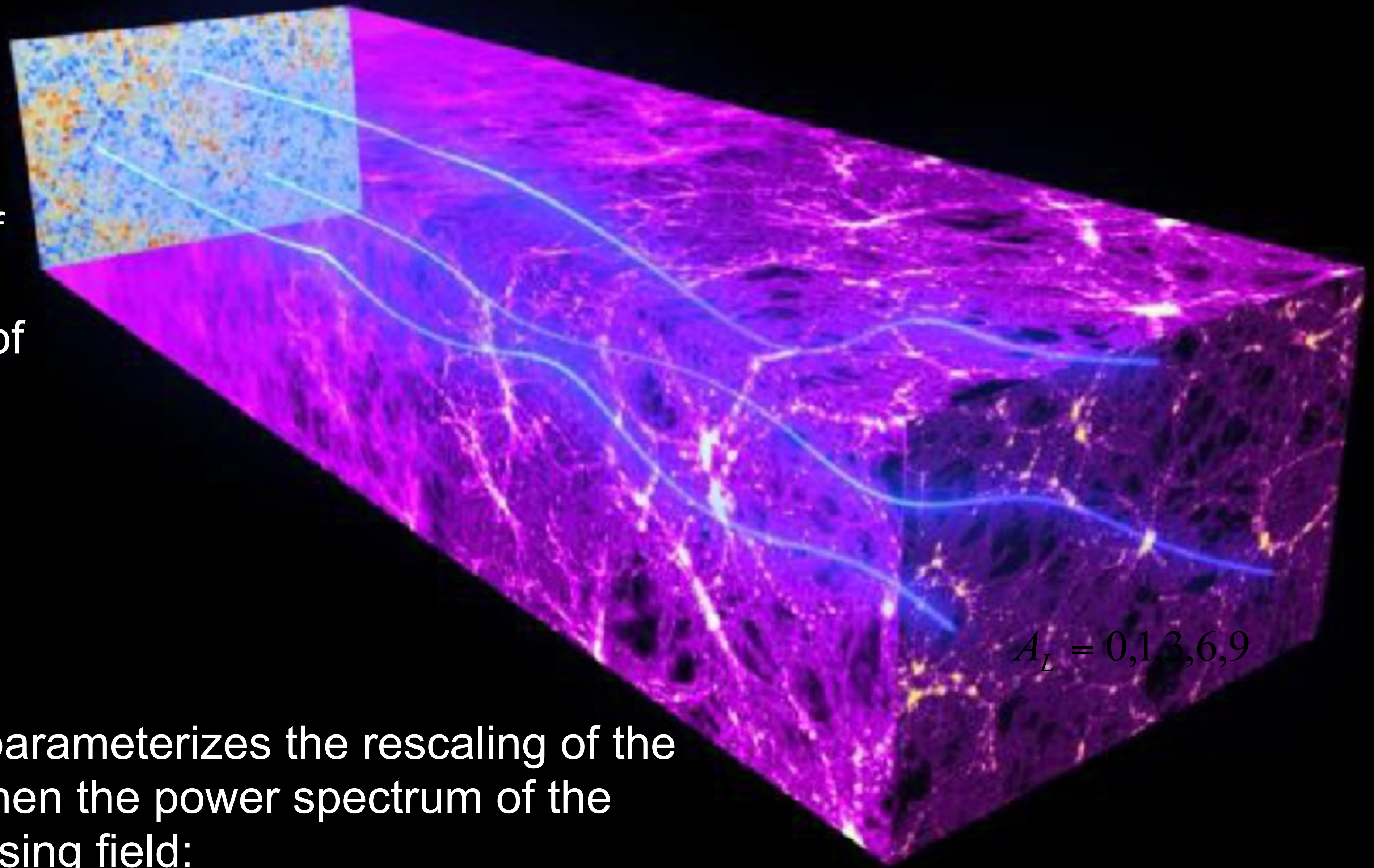
When the total neutrino mass is varying, we see a shift of the S8 parameter not only for the Planck bounds, but also for the cosmic shear ones, so the tension is the same as in the LCDM model.

A possibility for relieving the tension is the inclusion of the additional scaling parameter on the CMB lensing amplitude A_{lens}. We find that this can put in agreement the Planck 2015 with the cosmic shear data.



Di Valentino and Bridle, Symmetry 10 (2018) no.11, 585

The lensing amplitude



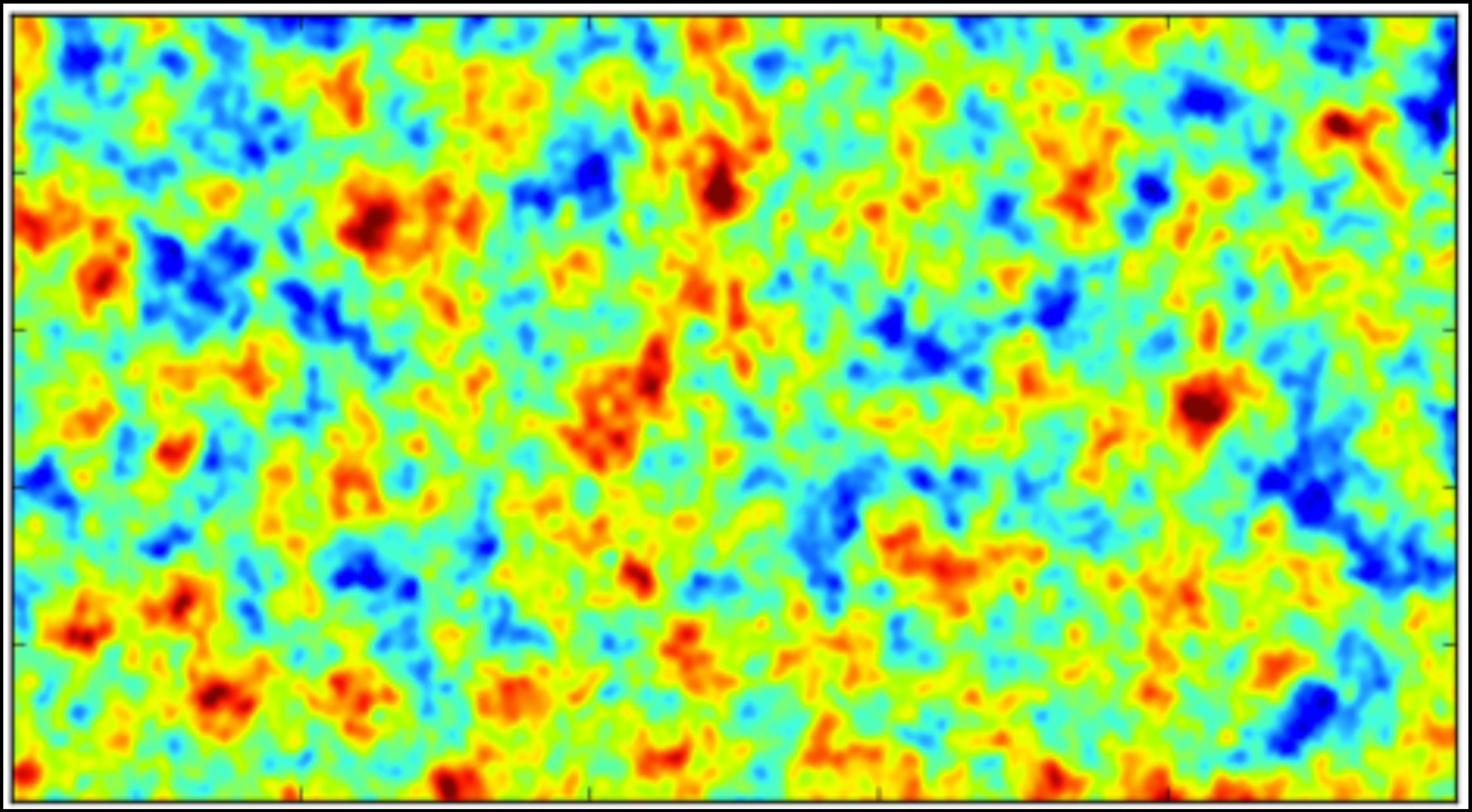
The gravitational effects of intervening dark matter fluctuations bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB.

The lensing amplitude A_L parameterizes the rescaling of the lensing potential ϕ(*n*), then the power spectrum of the lensing field:

$$C_\ell^{\phi\phi} \rightarrow A_\mathrm{L} C_\ell^{\phi\phi}$$

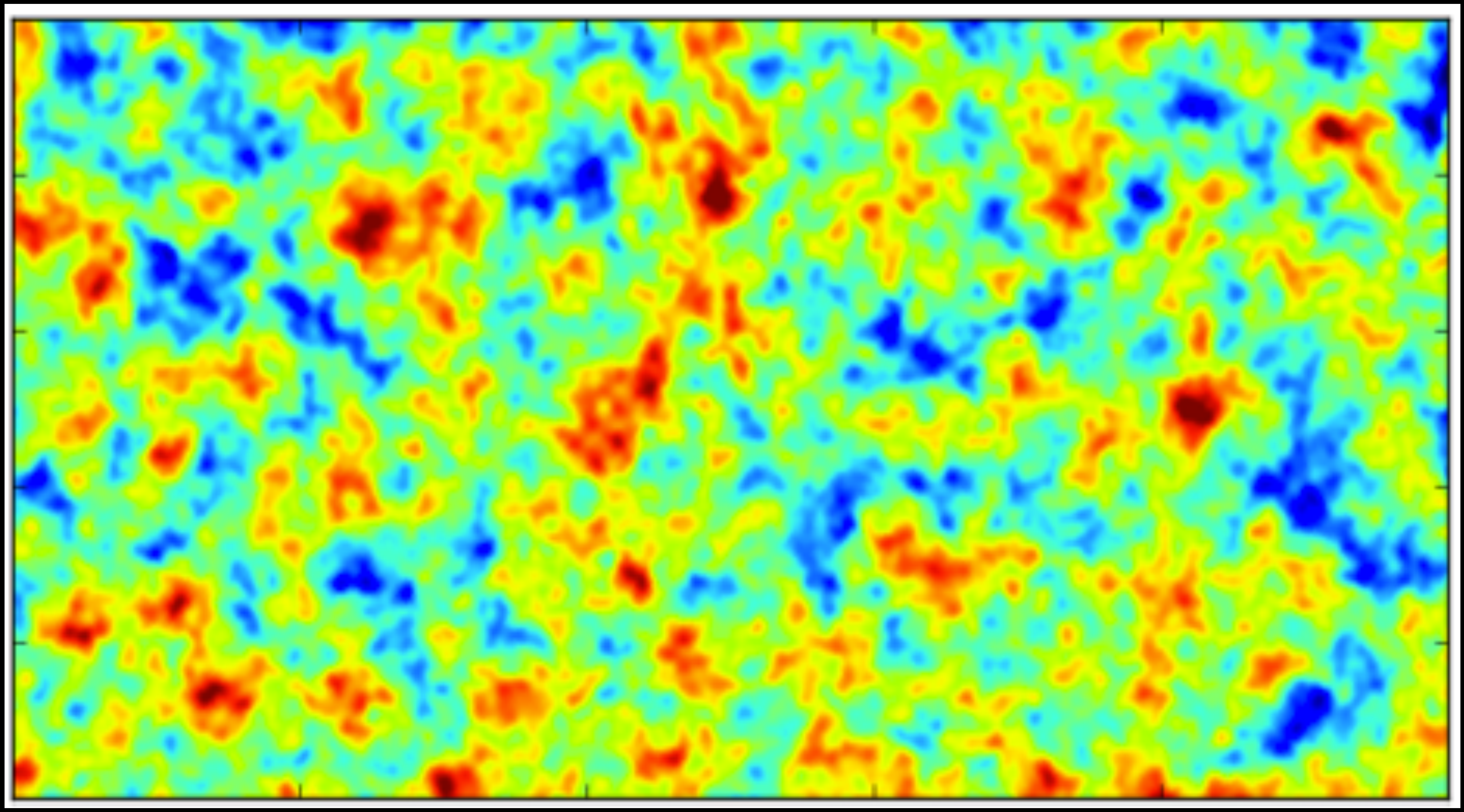
The gravitational lensing deflects the photon path by a quantity defined by the gradient of the lensing potential ϕ(*n*), integrated along the line of sight *n*, remapping the temperature field.

The CMB lensing



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

The CMB lensing



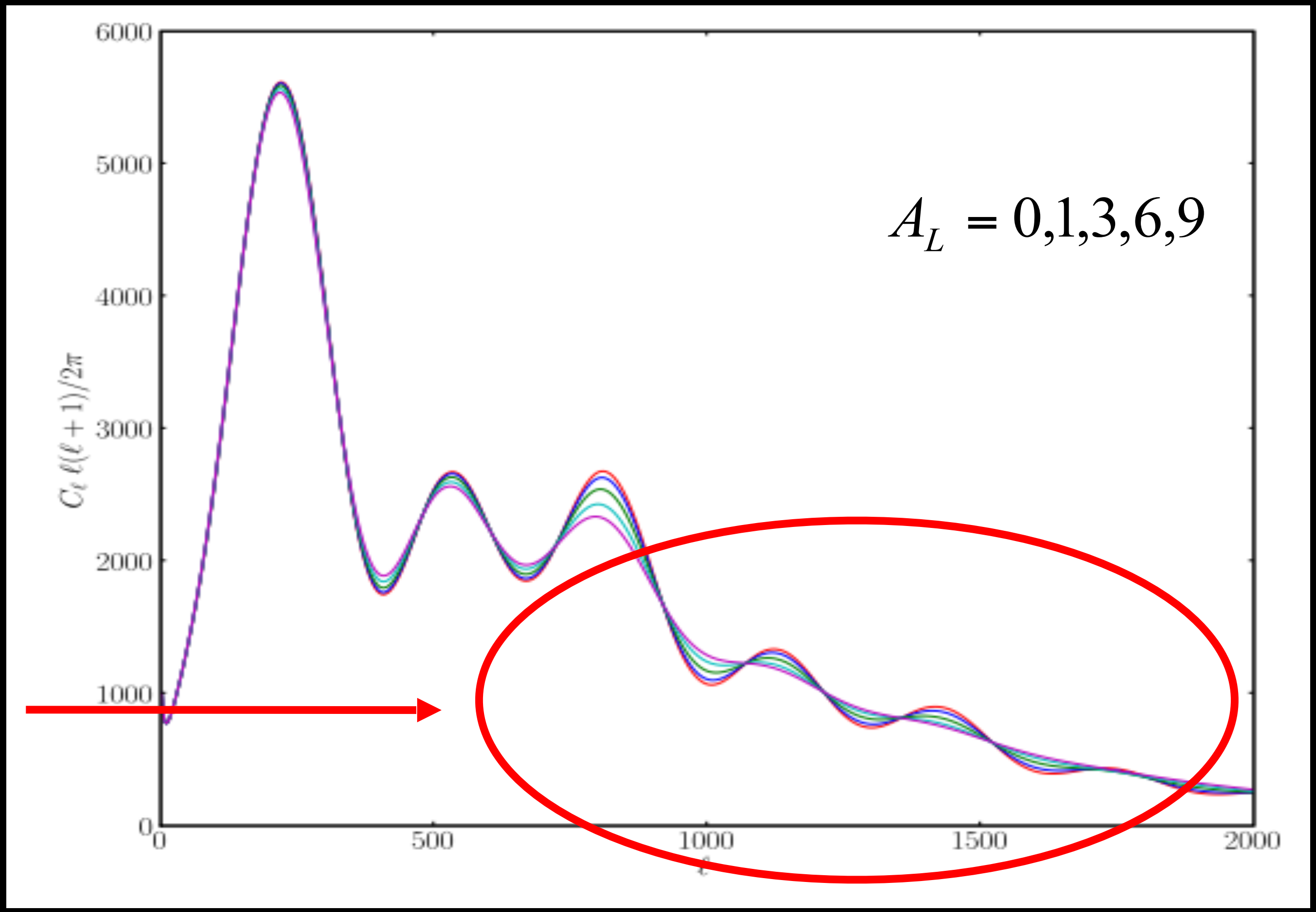
A simulated patch of CMB sky – **after dark matter lensing**

The lensing amplitude

Its effect on the power spectrum is the smoothing of the acoustic peaks, increasing AL.

Interesting consistency checks is if the amplitude of the smoothing effect in the CMB power spectra matches the theoretical expectation AL = 1 and whether the amplitude of the smoothing is consistent with that measured by the lensing reconstruction.

If AL =1 then the theory is correct, otherwise we have a new physics or systematics.



Calabrese et al., Phys. Rev. D, 77, 123531

The lensing amplitude

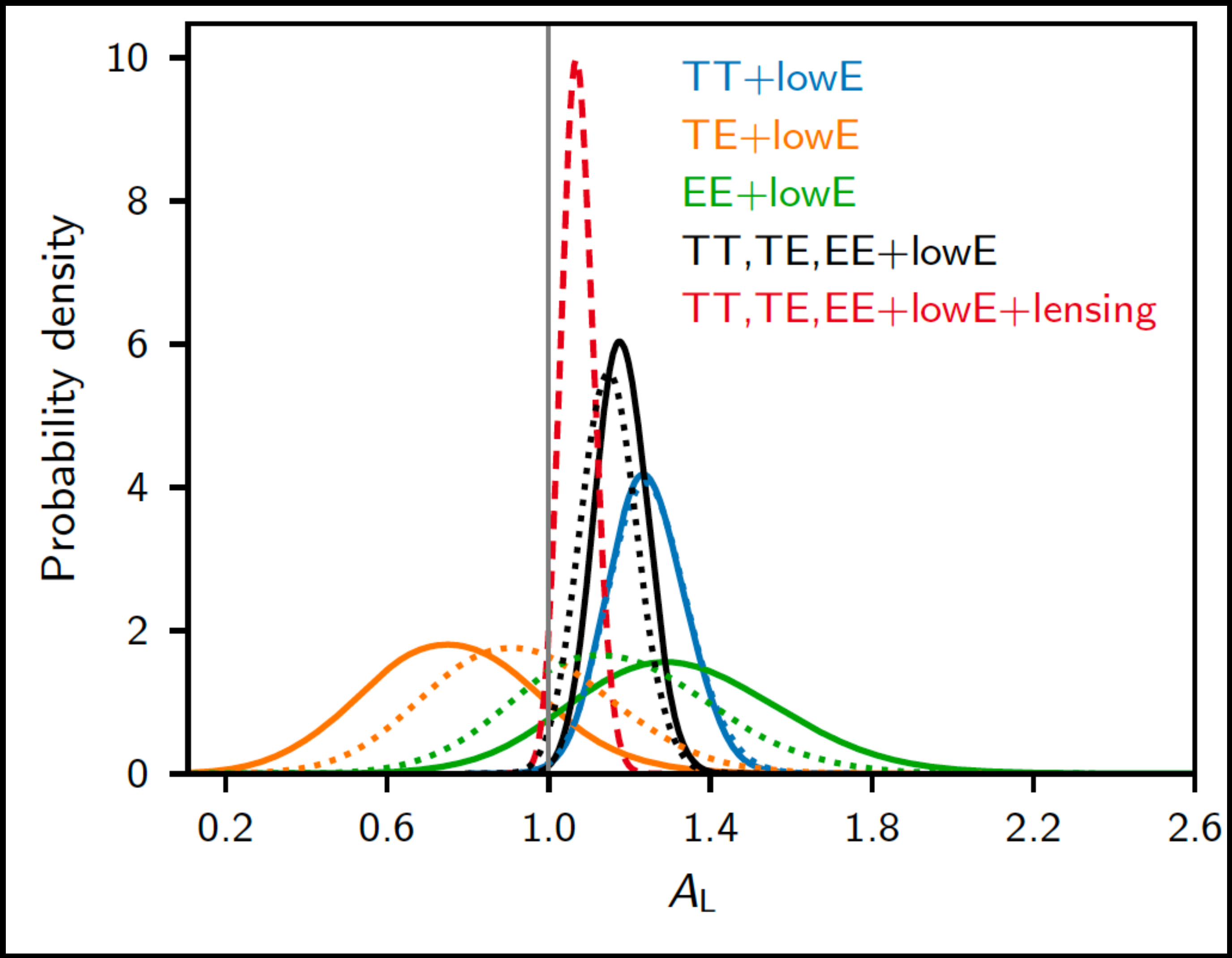
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for LCDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with AL = 1.

However, the distributions of AL inferred from the CMB power spectra alone indicate a preference for AL > 1.

The joint combined likelihood shifts the value preferred by the TT data downwards towards AL = 1, but the error also shrinks, increasing the significance of AL> 1 to 2.8σ.

The preference for high AL is not just a volume effect in the full parameter space, with the best fit improved by $\Delta\chi^2$~9 when adding AL for TT+lowE and 10 for TTTEEE+lowE.

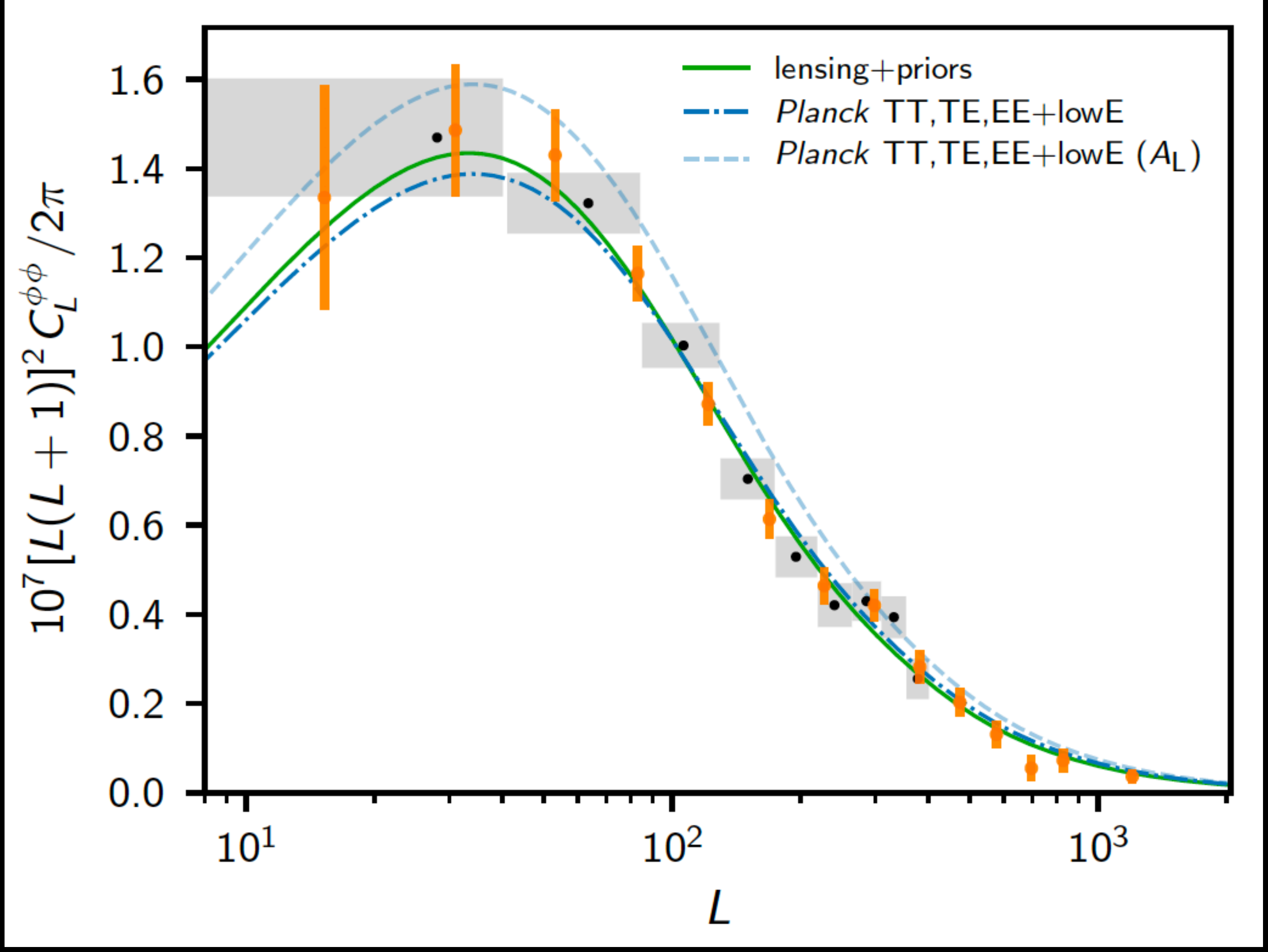
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE}),$$

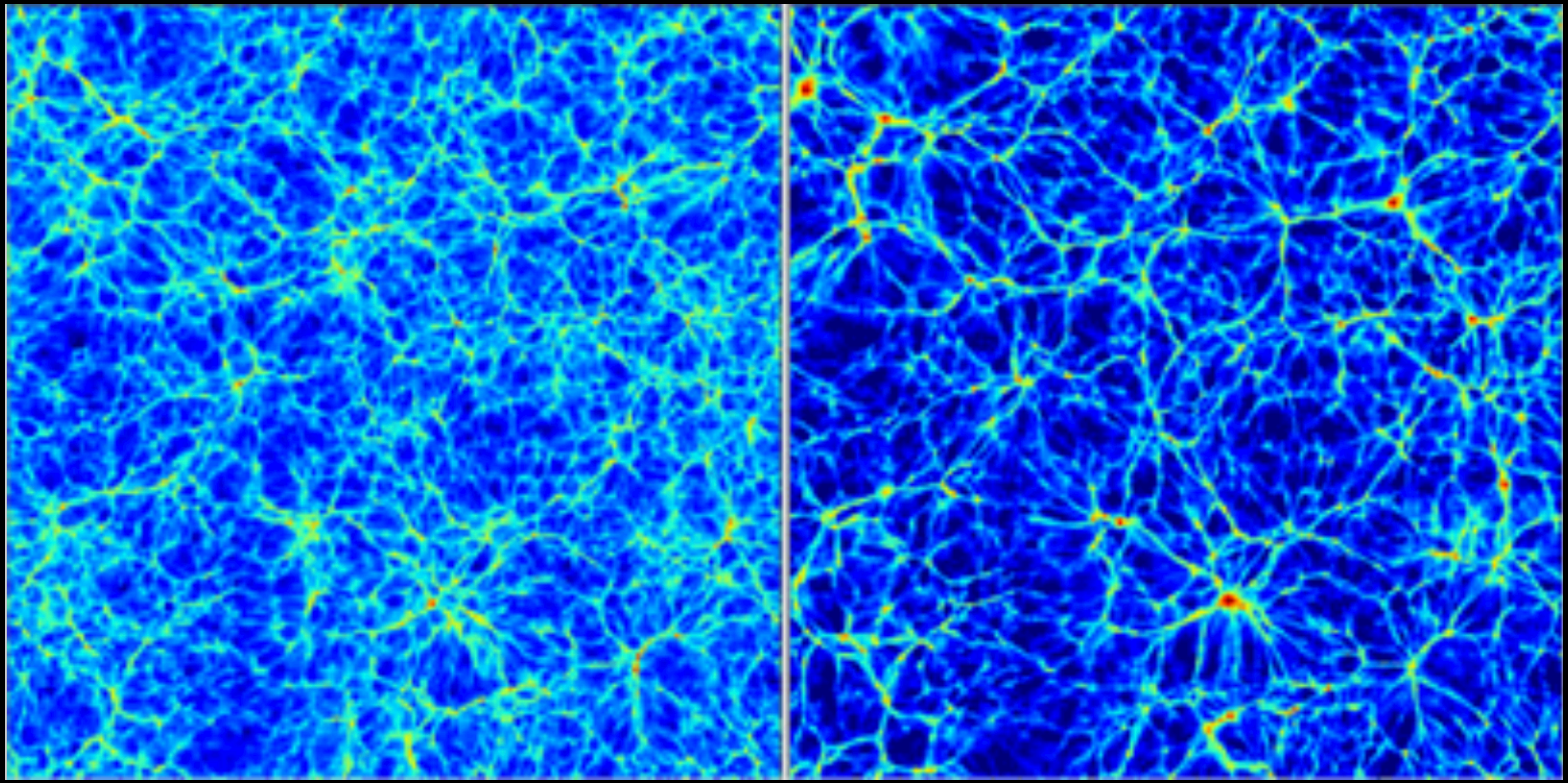
Lensing reconstruction

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



CMB lensing-potential power spectrum, as measured by Planck. The solid line shows the best CDM fit to the conservative points alone, and the dot-dashed line shows the prediction from the best fit to the Planck CMB power spectra alone. The dashed line shows the prediction from the best fit to the CMB power spectra when the lensing amplitude AL is also varied (AL = 1.19 for the best-fit model), and this is clearly inconsistent with the lensing reconstruction, since it lies above almost all of the measured data points.

Massive neutrinos



Massive neutrinos practically do not form structure!

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

A_L affects the total neutrino mass constraints

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

The Planck data shows a preference for A_{lens}>1 and the reason is unknown: systematics or new physics?

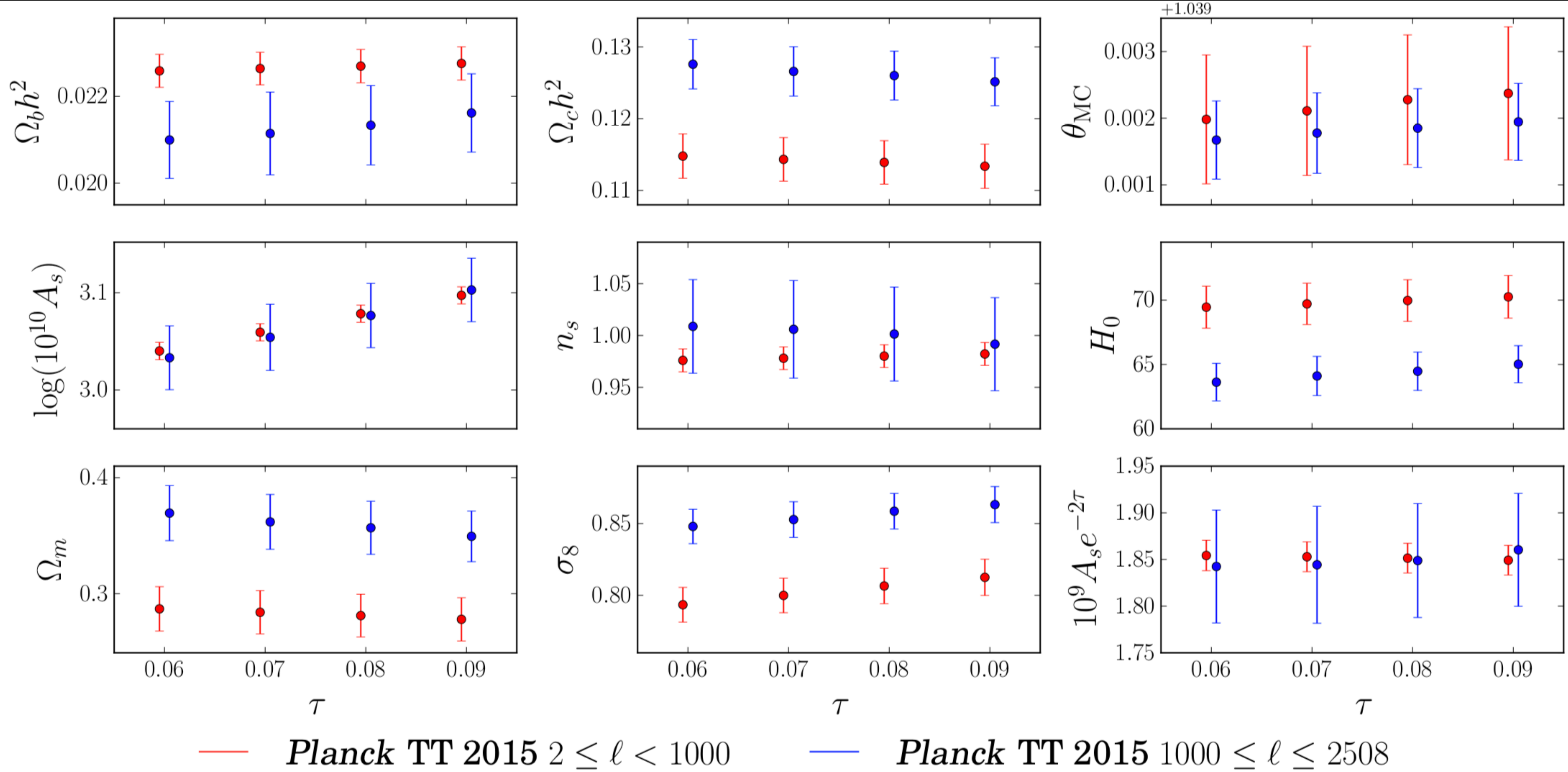
In any case, to be conservative, we need to take into account this wrong amount of lensing for constraining those parameters that modify the damping tail.

For example, when A_{lens} is free to vary, because of their correlation, the bounds on the total neutrino mass are strongly weakened, up to a factor of ~2.

As a consequence, in these cases there is no more the preference for the normal ordering we have in the LCDM scenario.

Capozzi et al., Phys. Rev. D **95**, 096014 (2017), arXiv:1703.04471

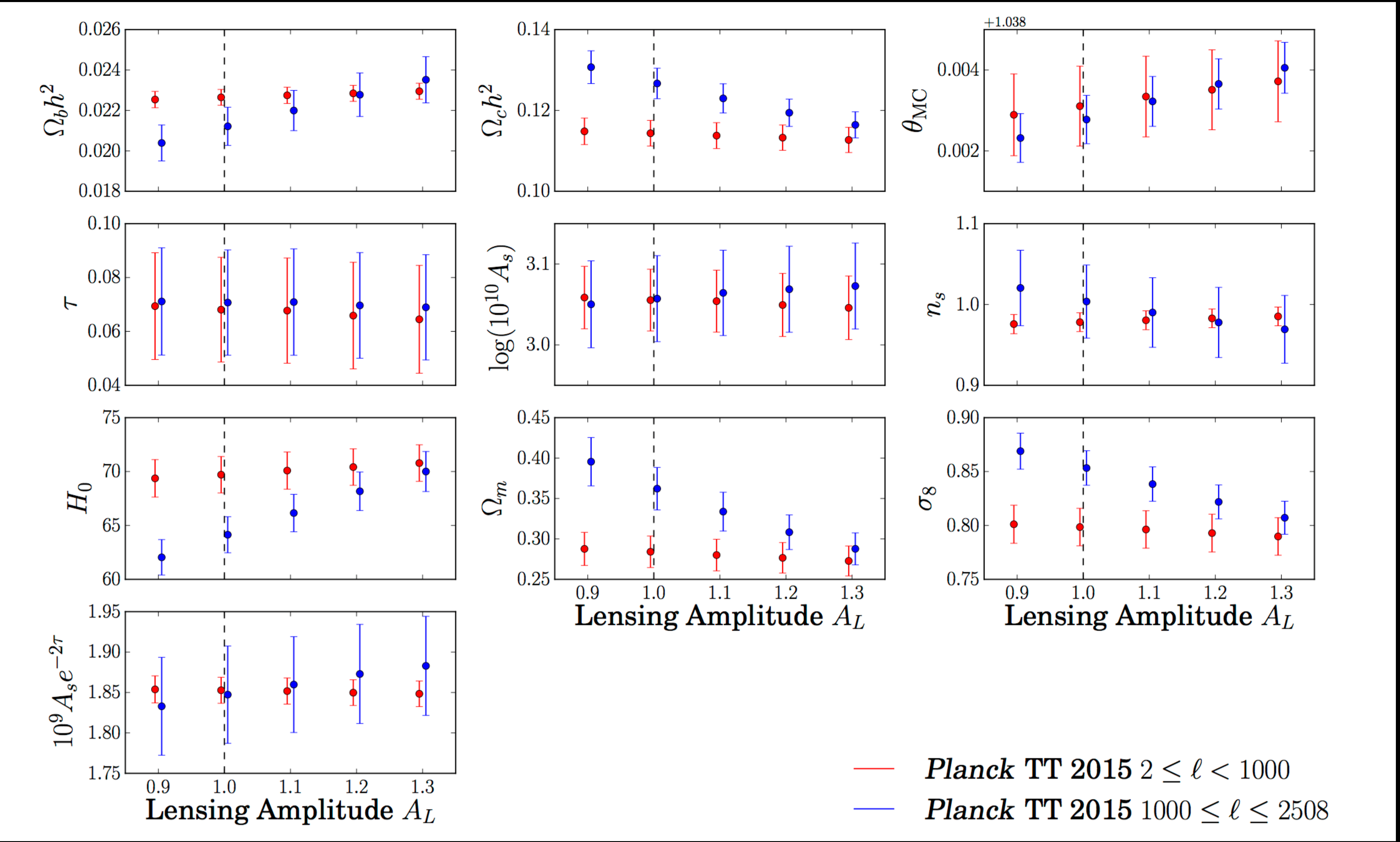
Internal inconsistency



Marginalized 68.3% confidence ΛCDM parameter constraints from fits to the l < 1000 and l ≥ 1000 Planck TT 2015 spectra, fixing τ at different values. Tension at the > 2σ level is apparent in $\Omega_c h^2$ and derived parameters, including H0, Ωm, and σ8.

Addison et al., Astrophys.J. 818 (2016) no.2, 132

Internal inconsistency solved with AL

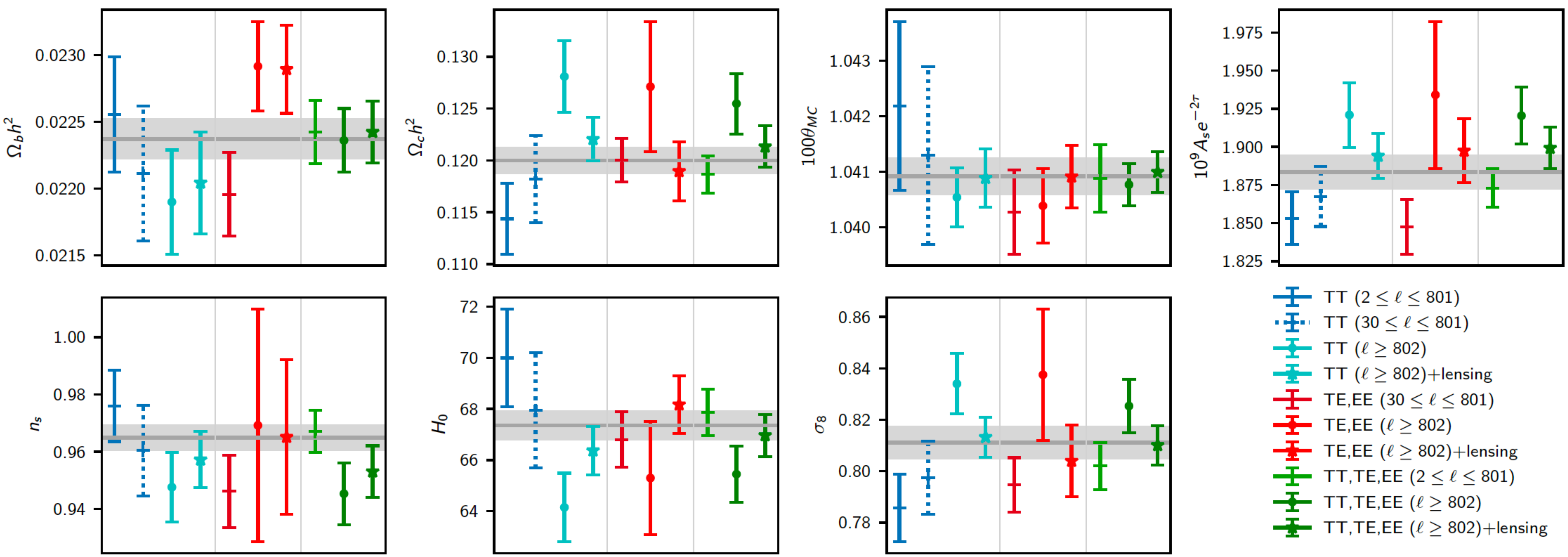


Marginalized 68.3% confidence ΛCDM parameter constraints from fits to the l < 1000 and l ≥ 1000 Planck TT 2015 spectra, fixing AL at different values. Increasing AL smooths out the high order acoustic peaks, improving the agreement between the two multipole ranges.

Addison et al., Astrophys.J. 818 (2016) no.2, 132

Internal inconsistency 2018

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



LCDM 68% marginalized parameter constraints for l=[2-801] (points marked with a cross), l>802 (points marked with a circle), and l>802 + lensing (points marked with a star). Correcting for the lensing, all the results from high multipoles are in better consistency with the results from lower multipoles.

Dotted error bars are the results from l=[30-801], without the large-scaleTT likelihood, showing that l< 30 pulls the low-multipole parameters further from the joint result.

Curvature

The ΛCDM model assumes that the universe is specially flat. The combination of the Planck temperature and polarization power spectra give

$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\,\%, \textit{Planck}\ \mathrm{TT,TE,EE+lowE}),$$

a detection of curvature at well over 2σ.

This is not entirely a volume effect, since the best-fit $\Delta\chi^2$ changes by -11 compared to base ΛCDM when adding the one additional curvature parameter.

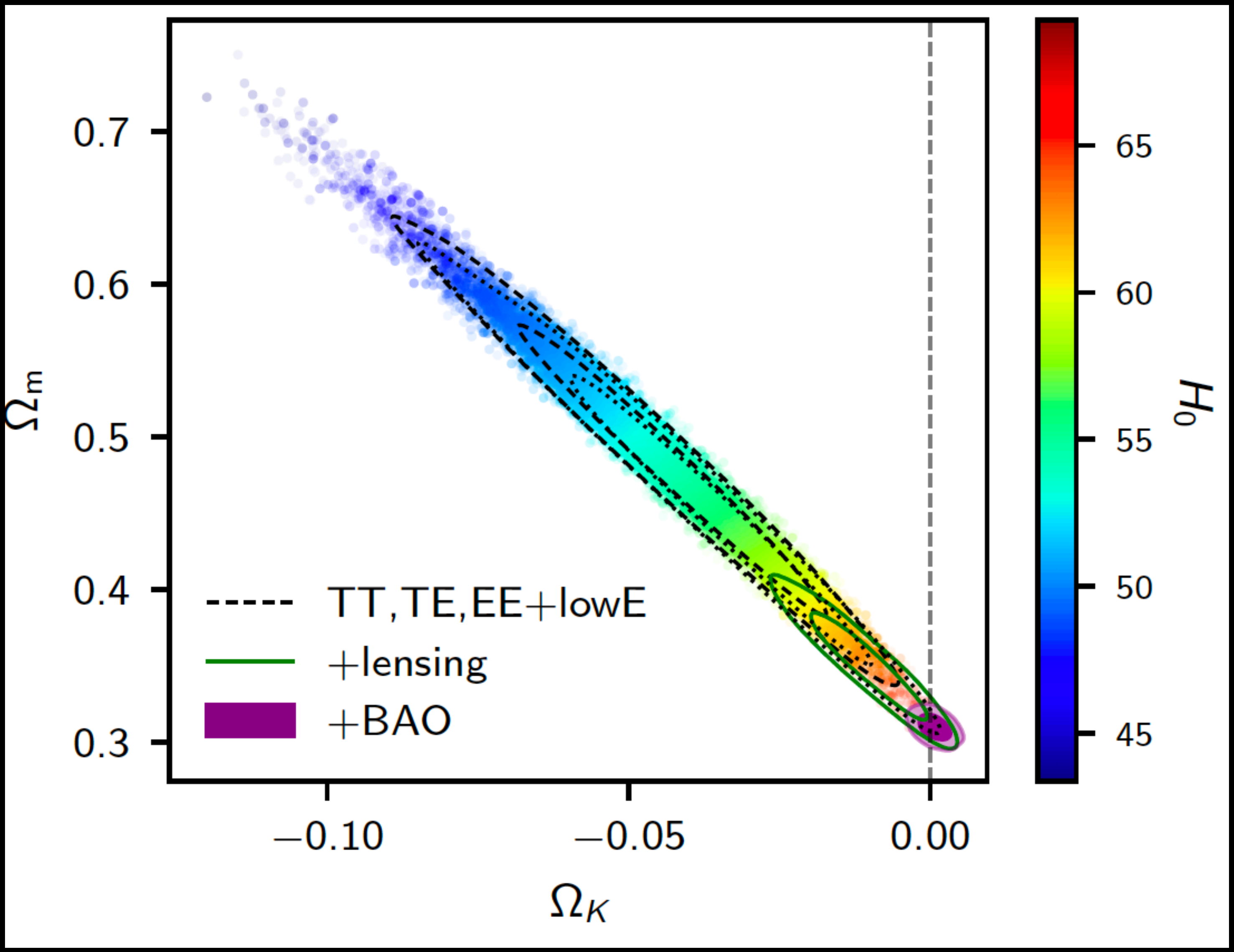
The reasons for the pull towards negative values of Ω_K are essentially the same as those that lead to the preference for $A_L > 1$, although slightly exacerbated in the case of curvature, since the low multipoles also fit the low-temperature likelihood slightly better if $\Omega_K < 0$.

Closed models predict substantially higher lensing amplitudes than in ΛCDM, so combining with the lensing reconstruction (which is consistent with a flat model) pulls parameters back into consistency with a spatially flat universe to well within 2σ:

$$\Omega_K = -0.0106 \pm 0.0065 \quad (68\,\%, \mathrm{TT,TE,EE+lowE} + \mathrm{lensing}).$$

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

Curvature



Adding BAO data, filled contours, convincingly breaks the geometric degeneracy giving a joint constraint very consistent with a flat universe.

$$\Omega_K = 0.0007 \pm 0.0019 \quad \text{(68 %, TT,TE,EE+lowE +lensing+BAO).}$$

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

What happens if we vary all the parameters together?

Measuring the CMB

In the past twenty years, measurements of the CMB anisotropy angular power spectrum have witnessed one of the most impressive technological advances in experimental physics.

Following the first detection of CMB temperature anisotropies at large angular scales by the COBE satellite in 1992, passing through balloon-borne experiments such as BOOMERanG, MAXIMA, the WMAP satellite, and ground-based experiments as DASI, ACT and SPT, we have now a cosmic-variance limited measurements made by the Planck experiment.

Despite this impressive progress on the experimental side, the constraints on cosmological parameters are still presented under the assumption of a simple ΛCDM model, based on the variation of just 6 cosmological parameters.

While this model still provides a good fit to the data, it is the same model used, for example, in the analysis of the BOOMERanG 1998 data, i.e. twenty years ago.

While this ”minimal” approach is justified by the good fit to the data that the ΛCDM provides, some of the assumptions or simplifications made in the 6 parameters approach are indeed not anymore fully justified and risk an oversimplification of the physics that drives the evolution of the Universe.

Beyond six parameters: extending ΛCDM

- The total neutrino mass is fixed arbitrary to 0.06eV. However, we know that neutrinos must have masses and that current cosmological datasets are sensitive to variations in the absolute neutrino mass scale of order ~ 100 meV.
- The cosmological constant offers difficulties in any theoretical interpretation. Therefore it seems reasonable to incorporate in the analysis a possible dynamical dark energy component. This is certainly plausible, and indeed fixing the dark energy equation of state to –1 is not favoured by any theoretical argument. Moreover, while both matter and radiation evolve rapidly, Lambda is assumed not to change with time, so its recent appearance in the standard cosmological model implies an extreme fine-tuning of initial conditions. This fine-tuning is known as the coincidence problem.
- Most inflationary models predict a sizable contribution of gravitational waves. Given the progress made in the search for B-mode polarization, it is an opportune moment to allow any such contribution to be directly constrained by the data, without assuming a null contribution as in the 6-parameter model.
- A similar argument can be made for the running of the scalar spectral index.
- The effective number of relativistic degrees of freedom could be easily different from the standard expected value of 3.046.
- We need to take into account the anomalous value for the lensing amplitude A_{lens}. While this parameter is purely phenomenological, one should clearly consider it and check if the cosmology obtained is consistent with other datasets.

Beyond six parameters: extending ΛCDM

Cosmological constraints are usually derived under the assumption of a 6 parameters ΛCDM theoretical framework or simple one-parameter extensions.

In Di Valentino, Melchiorri and Silk, Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646 we presented, for the first time, cosmological constraints in a significantly extended scenario, varying up to 12 cosmological parameters simultaneously, including:

- the sum of neutrino masses,
- the dark energy equation of state,
- the gravitational waves background,
- the running of the spectral index of primordial perturbations,
- the neutrino effective number,
- the angular power spectrum lensing amplitude, A_{lens}.

Constraints at 95% cl.

Beyond six parameters: extending ΛCDM

6 parameters in ΛCDM

12 parameters space

Model Dataset	$\Omega_b h^2$	$\Omega_c h^2$	H_0 [km/s/Mpc]	τ	n_s	[illegible]	$\frac{dn_s}{dlnk}$	r	w	$\Sigma m_\nu [eV]$	$N_{\rm eff}$	$A_{\rm lens}$
Λ CDM Planck TT+LowP	$0.02222^{+0.00046}_{-0.00044}$	$0.1198^{+0.0042}_{-0.0043}$	$67.3^{+2.0}$ [illegible]	[illegible]	[illegible]	[illegible] $^{+0.028}_{-0.028}$	-	-	-	-	-	-
Λ CDM Planck	$0.02226^{+0.00031}_{-0.00029}$	$0.1198^{+0.0028}_{-0.0028}$	67.3 [illegible]	[illegible] $^{+0.034}_{-0.035}$	$0.9646^{+0.0092}_{-0.0092}$	$0.831^{+0.026}_{-0.026}$	-	-	-	-	-	-
Λ CDM Planck+ BAO	$0.02229^{+0.00028}_{-0.00027}$	$0.1193^{+0.0021}_{-0.0020}$	$67.52^{+0.93}_{-0.93}$	$0.082^{+0.031}_{-0.032}$	$0.9662^{+0.0078}_{-0.0079}$	$0.832^{+0.025}_{-0.025}$	-	-	-	-	-	-
e CDM Planck TT+LowP	$0.0245^{+0.0024}_{-0.0022}$	$0.127^{+0.017}_{-0.016}$	> 43	$0.073^{+0.051}_{-0.051}$	$1.06^{+0.10}_{-0.098}$	$0.56^{+0.35}_{-0.27}$	$-0.004^{+0.042}_{-0.041}$	< 0.383	$-0.53^{+0.61}_{-0.96}$	< 1.30	$4.66^{+2.3}_{-2.1}$	$2.50^{+2.3}_{-1.7}$
e CDM Planck	$0.02239^{+0.00060}_{-0.00056}$	$0.1186^{+0.0071}_{-0.0068}$	> 51.2	$0.058^{+0.040}_{-0.043}$	$0.967^{+0.025}_{-0.025}$	$0.81^{+0.24}_{-0.26}$	$-0.003^{+0.020}_{-0.019}$	< 0.183	$-1.32^{+0.98}_{-0.85}$	< 0.959	$3.08^{+0.57}_{-0.51}$	$1.21^{+0.27}_{-0.24}$
e CDM Planck+BAO	$0.02251^{+0.00056}_{-0.00052}$	$0.1185^{+0.0069}_{-0.0069}$	$68.4^{+4.3}_{-4.1}$	$0.058^{+0.041}_{-0.043}$	$0.972^{+0.024}_{-0.024}$	$0.781^{+0.065}_{-0.063}$	$-0.004^{+0.018}_{-0.018}$	< 0.187	$-1.04^{+0.20}_{-0.21}$	< 0.534	$3.11^{+0.52}_{-0.48}$	$1.20^{+0.19}_{-0.19}$
e CDM Planck+lensing	$0.02214^{+0.00053}_{-0.00052}$	$0.1176^{+0.0069}_{-0.0066}$	> 54.5	$0.058^{+0.040}$ [illegible]	[illegible]	[illegible] $^{+0.21}_{-0.24}$	$-0.005^{+0.018}_{-0.018}$	< 0.178	$-1.45^{+0.96}_{-0.83}$	< 0.661	$2.93^{+0.51}_{-0.48}$	$1.04^{+0.16}_{-0.15}$
e CDM Planck+HST	$0.02239^{+0.00059}_{-0.00057}$	$0.1187^{+0.0072}_{-0.0070}$	74.4 [illegible]	[illegible]	[illegible] $_{-0.025}$	$0.81^{+0.10}_{-0.11}$	$-0.003^{+0.020}_{-0.019}$	< 0.186	$-1.32^{+0.29}_{-0.31}$	< 0.957	$3.09^{+0.58}_{-0.55}$	$1.18^{+0.19}_{-0.18}$
e CDM Planck+JLA	$0.02242^{+0.00058}_{-0.00056}$	$0.1188^{+0.0071}_{-0.0067}$	$67.4^{[illegible]}_{-4.2}$	$0.058^{+0.040}_{-0.043}$	$0.968^{+0.025}_{-0.025}$	$0.759^{+0.088}_{-0.089}$	$-0.004^{+0.020}_{-0.019}$	< 0.183	$-1.06^{+0.13}_{-0.14}$	< 0.854	$3.10^{+0.57}_{-0.54}$	$1.20^{+0.19}_{-0.17}$
e CDM Planck+WL	$0.02251^{+0.00056}_{-0.00055}$	$0.1188^{+0.0073}_{-0.0069}$	> 54.2	< 0.0835	$0.972^{+0.024}_{-0.024}$	$0.82^{+0.22}_{-0.25}$	$0.000^{+0.020}_{-0.019}$	< 0.197	$-1.41^{+0.98}_{-0.79}$	< 0.974	$3.16^{+0.58}_{-0.56}$	$1.24^{+0.23}_{-0.22}$
e CDM Planck+BAO-RSD	$0.02253^{+0.00052}_{-0.00050}$	$0.1184^{+0.0069}_{-0.0067}$	$68.6^{+4.2}_{-3.9}$	$0.056^{+0.038}_{-0.042}$	$0.972^{+0.023}_{-0.023}$	$0.774^{+0.055}_{-0.058}$	$-0.004^{+0.018}_{-0.018}$	< 0.188	$-1.05^{+0.17}_{-0.19}$	< 0.626	$3.12^{+0.51}_{-0.48}$	$1.22^{+0.18}_{-0.17}$
e CDM Planck+BKP	$0.02237^{+0.00057}_{-0.00056}$	$0.1186^{+0.0072}_{-0.0069}$	> 52.3	$0.058^{+0.039}_{-0.044}$	$0.966^{+0.026}_{-0.026}$	$0.81^{+0.23}_{-0.25}$	$-0.003^{+0.019}_{-0.018}$	< 0.101	$-1.31^{+0.96}_{-0.89}$	< 0.876	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

In this Table we show for comparison the constraints obtained assuming the standard, 6 parameters in ΛCDM, and in our extended 12 parameters space.

Di Valentino, Melchiorri and Silk, Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646

Constraints at 95% cl.

Beyond six parameters: extending ΛCDM

Model Dataset	$\Omega_b h^2$	$\Omega_c h^2$	H_0 [km/s/Mpc]	τ	n_s	σ_8	$\frac{dn_s}{dlnk}$	r	w	$\Sigma m_\nu [eV]$	$N_{\rm eff}$	$A_{\rm lens}$
Λ CDM Planck TT+LowP	$0.02222^{+0.00046}_{-0.00044}$	$0.1198^{+0.0042}_{-0.0043}$	$67.3^{+2.0}_{-1.8}$	$0.077^{+0.038}_{-0.036}$	$0.966^{+0.012}_{-0.012}$	$0.829^{+0.028}_{-0.028}$	-	-	-	-	-	-
Λ CDM Planck	$0.02226^{+0.00031}_{-0.00029}$	$0.1198^{+0.0028}_{-0.0028}$	$67.3^{+1.3}_{-1.3}$	$0.079^{+0.034}_{-0.035}$	$0.9646^{+0.0092}_{-0.0092}$	$0.831^{+0.026}_{-0.026}$	-	-	-	-	-	-
Λ CDM Planck+ BAO	$0.02229^{+0.00028}_{-0.00027}$	$0.1193^{+0.0021}_{-0.0020}$	$67.52^{+0.93}_{-0.93}$	$0.082^{+0.031}_{-0.032}$	$0.9662^{+0.0078}_{-0.0079}$	$0.832^{+0.025}_{-0.025}$	-	-	-	-	-	-
e CDM Planck TT+LowP	$0.0245^{+0.0024}_{-0.0022}$	$0.127^{+0.017}_{-0.016}$	> 43	$0.073^{+0.051}_{-0.051}$	$1.06^{+0.10}_{-0.098}$	$0.56^{+0.35}_{-0.27}$	$-0.004^{+0.042}_{-0.041}$	< 0.383	$-0.53^{+0.61}_{-0.96}$	< 1.30	$4.66^{+2.3}_{-2.1}$	$2.50^{+2.3}_{-1.7}$
e CDM Planck	$0.02239^{+0.00060}_{-0.00056}$	$0.1186^{+0.0071}_{-0.0068}$	> 51.2	$0.058^{+0.040}_{-0.043}$	$0.967^{+0.025}_{-0.025}$	$0.81^{+0.24}_{-0.26}$	$-0.003^{+0.020}_{-0.019}$	< 0.183	$-1.32^{+0.98}_{-0.85}$	< 0.959	$3.08^{+0.57}_{-0.51}$	$1.21^{+0.27}_{-0.24}$
e CDM Planck+BAO	$0.02251^{+0.00056}_{-0.00052}$	$0.1185^{+0.0069}_{-0.0069}$	$68.4^{+4.3}_{-4.1}$	$0.058^{+0.041}_{-0.043}$	$0.972^{+0.024}_{-0.024}$	$0.781^{+0.065}_{-0.063}$	$-0.004^{+0.018}_{-0.018}$	< 0.187	$-1.04^{+0.20}_{-0.21}$	[illegible]	[illegible]	$1.20^{+0.19}_{-0.19}$
e CDM Planck+lensing	$0.02214^{+0.00053}_{-0.00052}$	$0.1176^{+0.0069}_{-0.0066}$	> 54.5	$0.058^{+0.040}_{-0.043}$	$0.959^{+0.024}_{-0.024}$	$0.85^{+0.21}_{-0.24}$	$-0.005^{+0.018}_{-0.018}$	$< 0.$ [illegible]	[illegible]	[illegible]	[illegible]	$1.04^{+0.16}_{-0.15}$
e CDM Planck+HST	$0.02239^{+0.00059}_{-0.00057}$	$0.1187^{+0.0072}_{-0.0070}$	$74.4^{+5.1}_{-5.1}$	$0.057^{+0.040}_{-0.045}$	$0.966^{+0.025}_{-0.025}$	$0.81^{+0.10}_{-0.11}$	$-0.003^{+0.020}_{-0.019}$	< 0.1 [illegible]	[illegible]	< 0.957	$3.09^{+0.58}_{-0.55}$	$1.18^{+0.19}_{-0.18}$
e CDM Planck+JLA	$0.02242^{+0.00058}_{-0.00056}$	$0.1188^{+0.0071}_{-0.0067}$	$67.4^{+4.4}_{-4.2}$	$0.058^{+0.040}_{-0.043}$	$0.968^{+0.025}_{-0.025}$	$0.759^{+0.088}_{-0.089}$	$-0.004^{+0.020}_{-0.019}$	< 0.183	$-1.06^{+0.13}_{-0.14}$	< 0.854	$3.10^{+0.57}_{-0.54}$	$1.20^{+0.19}_{-0.17}$
e CDM Planck+WL	$0.02251^{+0.00056}_{-0.00055}$	$0.1188^{+0.0073}_{-0.0069}$	> 54.2	< 0.0835	$0.972^{+0.024}_{-0.024}$	$0.82^{+0.22}_{-0.25}$	$0.000^{+0.020}_{-0.019}$	< 0.197	$-1.41^{+0.98}_{-0.79}$	< 0.974	$3.16^{+0.58}_{-0.56}$	$1.24^{+0.23}_{-0.22}$
e CDM Planck+BAO-RSD	$0.02253^{+0.00052}_{-0.00050}$	$0.1184^{+0.0069}_{-0.0067}$	$68.6^{+4.2}_{-3.9}$	$0.056^{+0.038}_{-0.042}$	$0.972^{+0.023}_{-0.023}$	$0.774^{+0.055}_{-0.058}$	$-0.004^{+0.018}_{-0.018}$	< 0.188	$-1.05^{+0.17}_{-0.19}$	< 0.626	$3.12^{+0.51}_{-0.48}$	$1.22^{+0.18}_{-0.17}$
e CDM Planck+BKP	$0.02237^{+0.00057}_{-0.00056}$	$0.1186^{+0.0072}_{-0.0069}$	> 52.3	$0.058^{+0.039}_{-0.044}$	$0.966^{+0.026}_{-0.026}$	$0.81^{+0.23}_{-0.25}$	$-0.003^{+0.019}_{-0.018}$	< 0.101	$-1.31^{+0.96}_{-0.89}$	< 0.876	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

Extensions

The significant increase in the number of parameters produces, as expected, a relaxation in the constraints on the 6 ΛCDM parameters. We find impressive that despite the increase in the number of the parameters, some of the constraints on key parameters are relaxed but not significantly altered. The cold dark matter ansatz remains robust and the baryon density is compatible with BBN predictions.

Di Valentino, Melchiorri and Silk, Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646

Constraints at 95% cl.

Beyond six parameters: extending ΛCDM

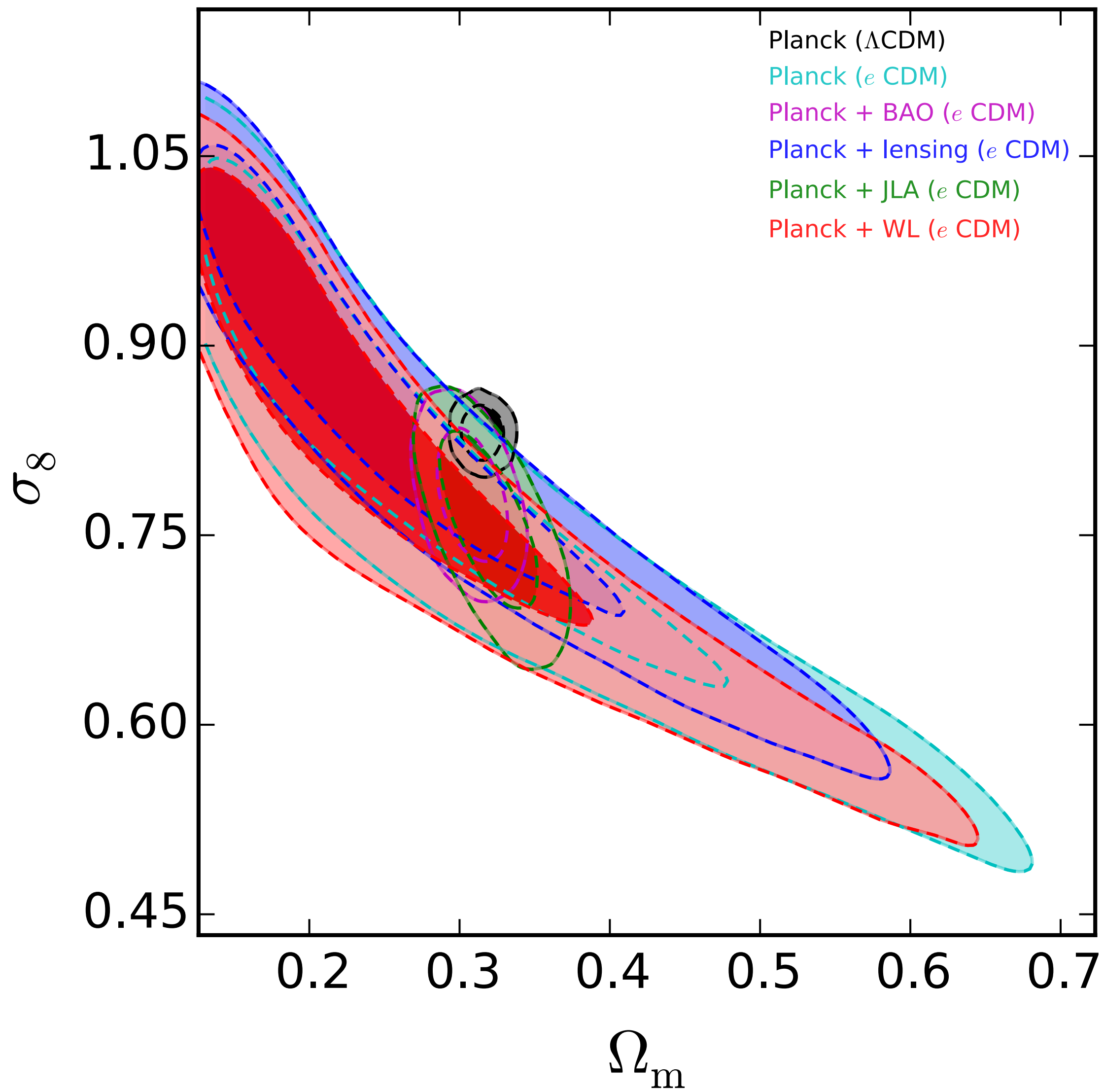
Model Dataset	$\Omega_b h^2$	$\Omega_c h^2$	H_0 [km/s/Mpc]	τ	n_s	σ_8	$\frac{dn_s}{dlnk}$	r	w	$\Sigma m_\nu [eV]$	$N_{\rm eff}$	$A_{\rm lens}$
Λ CDM Planck TT+LowP	$0.02222^{+0.00046}_{-0.00044}$	$0.1198^{+0.0042}_{-0.0043}$	$67.3^{+2.0}_{-1.8}$	$0.077^{+0.038}_{-0.036}$	$0.966^{+0.012}_{-0.012}$	$0.829^{+0.028}_{-0.028}$	-	-	-	-	-	-
Λ CDM Planck	$0.02226^{+0.00031}_{-0.00029}$	$0.1198^{+0.0028}_{-0.0028}$	$67.3^{+1.3}_{-1.3}$	$0.079^{+0.034}_{-0.035}$	$0.9646^{+0.0092}_{-0.0092}$	$0.831^{+0.026}_{-0.026}$	-	-	-	-	-	-
Λ CDM Planck+ BAO	$0.02229^{+0.00028}_{-0.00027}$	$0.1193^{+0.0021}_{-0.0020}$	$67.52^{+0.93}_{-0.93}$	$0.082^{+0.031}_{-0.032}$	$0.9662^{+0.0078}_{-0.0079}$	$0.832^{+0.025}_{-0.025}$	-	-	-	-	-	-
e CDM Planck TT+LowP	$0.0245^{+0.0024}_{-0.0022}$	$0.127^{+0.017}_{-0.016}$	> 43	$0.073^{+0.051}_{-0.051}$	$1.06^{+0.10}_{-0.098}$	$0.56^{+0.35}_{-0.27}$	$-0.004^{+0.042}_{-0.041}$	< 0.383	$-0.53^{+0.61}_{-0.96}$	< 1.30	$4.66^{+2.3}_{-2.1}$	$2.50^{+2.3}_{-1.7}$
e CDM Planck	$0.02239^{+0.00060}_{-0.00056}$	$0.1186^{+0.0071}_{-0.0068}$	> 51.2	$0.058^{+0.040}_{-0.043}$	$0.967^{+0.025}_{-0.025}$	$0.81^{+0.24}_{-0.26}$	$-0.003^{+0.020}_{-0.019}$	< 0.183	$-1.32^{+0.98}_{-0.85}$	< 0.959	$3.08^{+0.57}_{-0.51}$	$1.21^{+0.27}_{-0.24}$
e CDM Planck+BAO	$0.02251^{+0.00056}_{-0.00052}$	$0.1185^{+0.0069}_{-0.0069}$	$68.4^{+4.3}_{-4.1}$	$0.058^{+0.041}_{-0.043}$	$0.972^{+0.024}_{-0.024}$	$0.781^{+0.065}_{-0.063}$	$-0.004^{+0.018}_{-0.018}$	< 0.187	$-1.04^{+0.20}_{-0.21}$	< 0.534	$3.11^{+0.52}_{-0.48}$	$1.20^{+0.19}_{-0.19}$
e CDM Planck+lensing	$0.02214^{+0.00053}_{-0.00052}$	$0.1176^{+0.0069}_{-0.0066}$	> 54.5	$0.058^{+0.040}_{-0.043}$	$0.959^{+0.024}_{-0.024}$	$0.85^{+0.21}_{-0.24}$	$-0.005^{+0.018}_{-0.018}$	< 0.178	$-1.45^{+0.96}_{-0.83}$	< 0.661	$2.93^{+0.51}_{-0.48}$	$1.04^{+0.16}_{-0.15}$
e CDM Planck+HST	$0.02239^{+0.00059}_{-0.00057}$	$0.1187^{+0.0072}_{-0.0070}$	$74.4^{+5.1}_{-5.1}$	$0.057^{+0.040}_{-0.045}$	$0.966^{+0.025}_{-0.025}$	$0.81^{+0.10}_{-0.11}$	$-0.003^{+0.020}_{-0.019}$	< 0.186	$-1.32^{+0.29}_{-0.31}$	< 0.957	$3.09^{+0.58}_{-0.55}$	$1.18^{+0.19}_{-0.18}$
e CDM Planck+JLA	$0.02242^{+0.00058}_{-0.00056}$	$0.1188^{+0.0071}_{-0.0067}$	$67.4^{+4.4}_{-4.2}$	$0.058^{+0.040}_{-0.043}$	$0.968^{+0.025}_{-0.025}$	$0.759^{+0.088}_{-0.089}$	$-0.004^{+0.020}_{-0.019}$	< 0.183	$-1.06^{+0.13}_{-0.14}$	< 0.854	$3.10^{+0.57}_{-0.54}$	$1.20^{+0.19}_{-0.17}$
e CDM Planck+WL	$0.02251^{+0.00056}_{-0.00055}$	$0.1188^{+0.0073}_{-0.0069}$	> 54.2	< 0.0835	$0.972^{+0.024}_{-0.024}$	$0.82^{+0.22}_{-0.25}$	$0.000^{+0.020}_{-0.019}$	< 0.197	$-1.41^{+0.98}_{-0.79}$	< 0.974	$3.16^{+0.58}_{-0.56}$	$1.24^{+0.23}_{-0.22}$
e CDM Planck+BAO-RSD	$0.02253^{+0.00052}_{-0.00050}$	$0.1184^{+0.0069}_{-0.0067}$	$68.6^{+4.2}_{-3.9}$	$0.056^{+0.038}_{-0.042}$	$0.972^{+0.023}_{-0.023}$	$0.774^{+0.055}_{-0.058}$	$-0.004^{+0.018}_{-0.018}$	< 0.188	$-1.05^{+0.17}_{-0.19}$	< 0.626	$3.12^{+0.51}_{-0.48}$	$1.22^{+0.18}_{-0.17}$
e CDM Planck+BKP	$0.02237^{+0.00057}_{-0.00056}$	$0.1186^{+0.0072}_{-0.0069}$	> 52.3	$0.058^{+0.039}_{-0.044}$	$0.966^{+0.026}_{-0.026}$	$0.81^{+0.23}_{-0.25}$	$-0.003^{+0.019}_{-0.018}$	< 0.101	$-1.31^{+0.96}_{-0.89}$	< 0.876	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

We find a relaxed value for the Hubble constant, with respect to the one derived under the assumption of ΛCDM. The main reason for this relaxation is the inclusion in the analysis of the dark energy equation of state w, that introduces a geometrical degeneracy with the matter density and the Hubble constant. In this way, we can solve the existing tensions with the direct measurements.

Di Valentino, Melchiorri and Silk, Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646

Constraints at 95% cl.

Beyond six parameters: extending ΛCDM



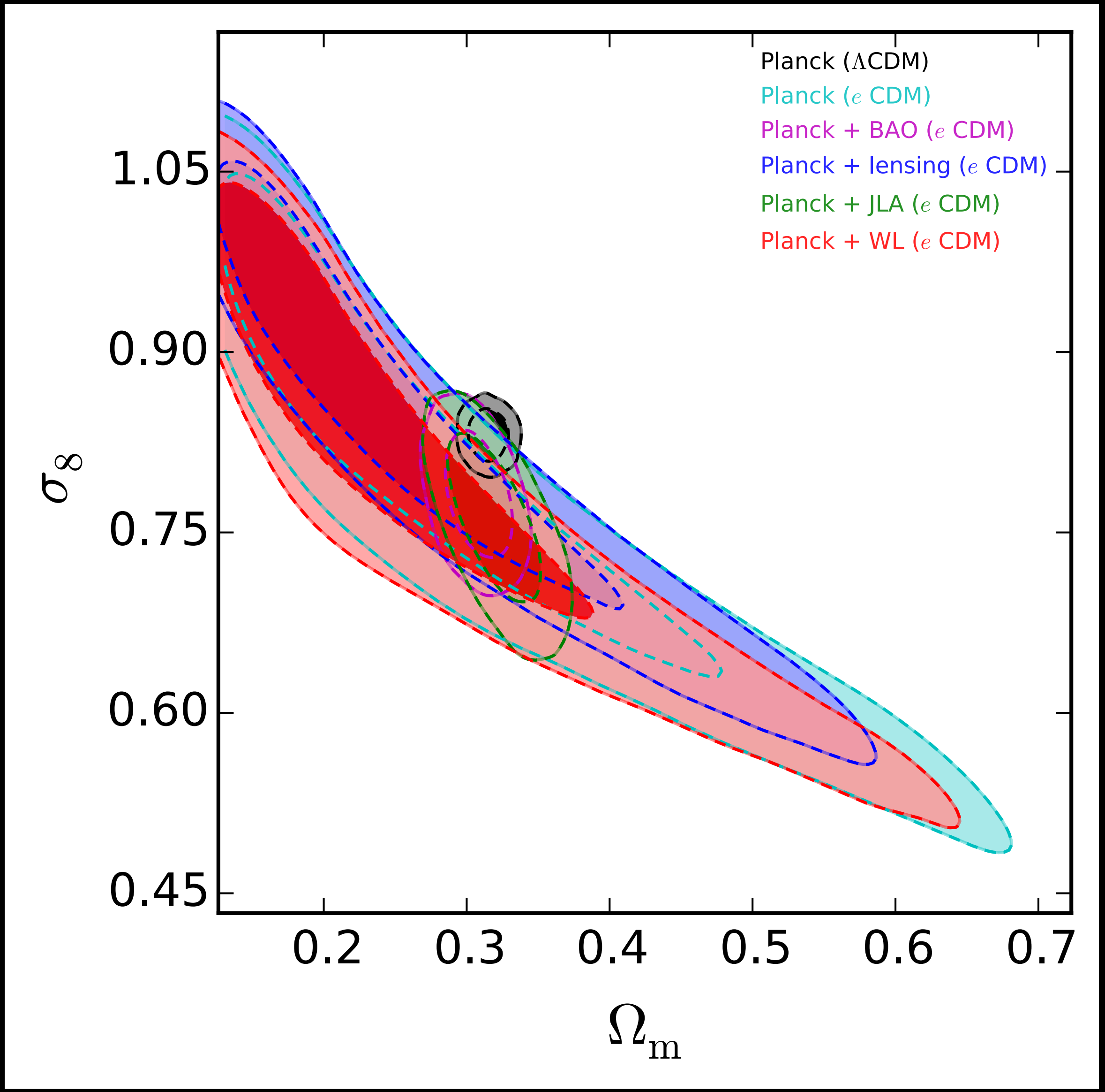
	n_s	σ_8	$\frac{dn_s}{dlnk}$	r	w	$\Sigma m_\nu[eV]$	$N_{\rm eff}$	$A_{\rm lens}$
Plai	$0.966^{+0.012}_{-0.012}$	$0.829^{+0.028}_{-0.028}$	-	-	-	-	-	-
	$0.9646^{+0.0092}_{-0.0092}$	$0.831^{+0.026}_{-0.026}$	-	-	-	-	-	-
P	$0.9662^{+0.0078}_{-0.0079}$	$0.832^{+0.025}_{-0.025}$	-	-	-	-	-	-
Plai	$1.06^{+0.10}_{-0.098}$	$0.56^{+0.35}_{-0.27}$	$-0.004^{+0.042}_{-0.041}$	< 0.383	$-0.53^{+0.61}_{-0.96}$	< 1.30	$4.66^{+2.3}_{-2.1}$	$2.50^{+2.3}_{-1.7}$
	$0.967^{+0.025}_{-0.025}$	$0.81^{+0.24}_{-0.26}$	$-0.003^{+0.020}_{-0.019}$	< 0.183	$-1.32^{+0.98}_{-0.85}$	< 0.959	$3.08^{+0.57}_{-0.51}$	$1.21^{+0.27}_{-0.24}$
P	$0.972^{+0.024}_{-0.024}$	$0.781^{+0.065}_{-0.063}$	$-0.004^{+0.018}_{-0.018}$	< 0.187	$-1.04^{+0.20}_{-0.21}$	< 0.534	$3.11^{+0.52}_{-0.48}$	$1.20^{+0.19}_{-0.19}$
Pl	$0.959^{+0.024}_{-0.024}$	$0.85^{+0.21}_{-0.24}$	$-0.005^{+0.018}_{-0.018}$	< 0.178	$-1.45^{+0.96}_{-0.83}$	< 0.661	$2.93^{+0.51}_{-0.48}$	$1.04^{+0.16}_{-0.15}$
P	$0.966^{+0.025}_{-0.025}$	$0.81^{+0.10}_{-0.11}$	$-0.003^{+0.020}_{-0.019}$	< 0.186	$-1.32^{+0.29}_{-0.31}$	< 0.957	$3.09^{+0.58}_{-0.55}$	$1.18^{+0.19}_{-0.18}$
P	$0.968^{+0.025}_{-0.025}$	$0.759^{+0.088}_{-0.089}$	$-0.004^{+0.020}_{-0.019}$	< 0.183	$-1.06^{+0.13}_{-0.14}$	< 0.854	$3.10^{+0.57}_{-0.54}$	$1.20^{+0.19}_{-0.17}$
I	$0.972^{+0.024}_{-0.024}$	$0.82^{+0.22}_{-0.25}$	$0.000^{+0.020}_{-0.019}$	< 0.197	$-1.41^{+0.98}_{-0.79}$	< 0.974	$3.16^{+0.58}_{-0.56}$	$1.24^{+0.23}_{-0.22}$
Plar	$0.972^{+0.023}_{-0.023}$	$0.774^{+0.055}_{-0.058}$	$-0.004^{+0.018}_{-0.018}$	< 0.188	$-1.05^{+0.17}_{-0.19}$	< 0.626	$3.12^{+0.51}_{-0.48}$	$1.22^{+0.18}_{-0.17}$
P	$0.966^{+0.026}_{-0.026}$	$0.81^{+0.23}_{-0.25}$	$-0.003^{+0.019}_{-0.018}$	< 0.101	$-1.31^{+0.96}_{-0.89}$	< 0.876	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

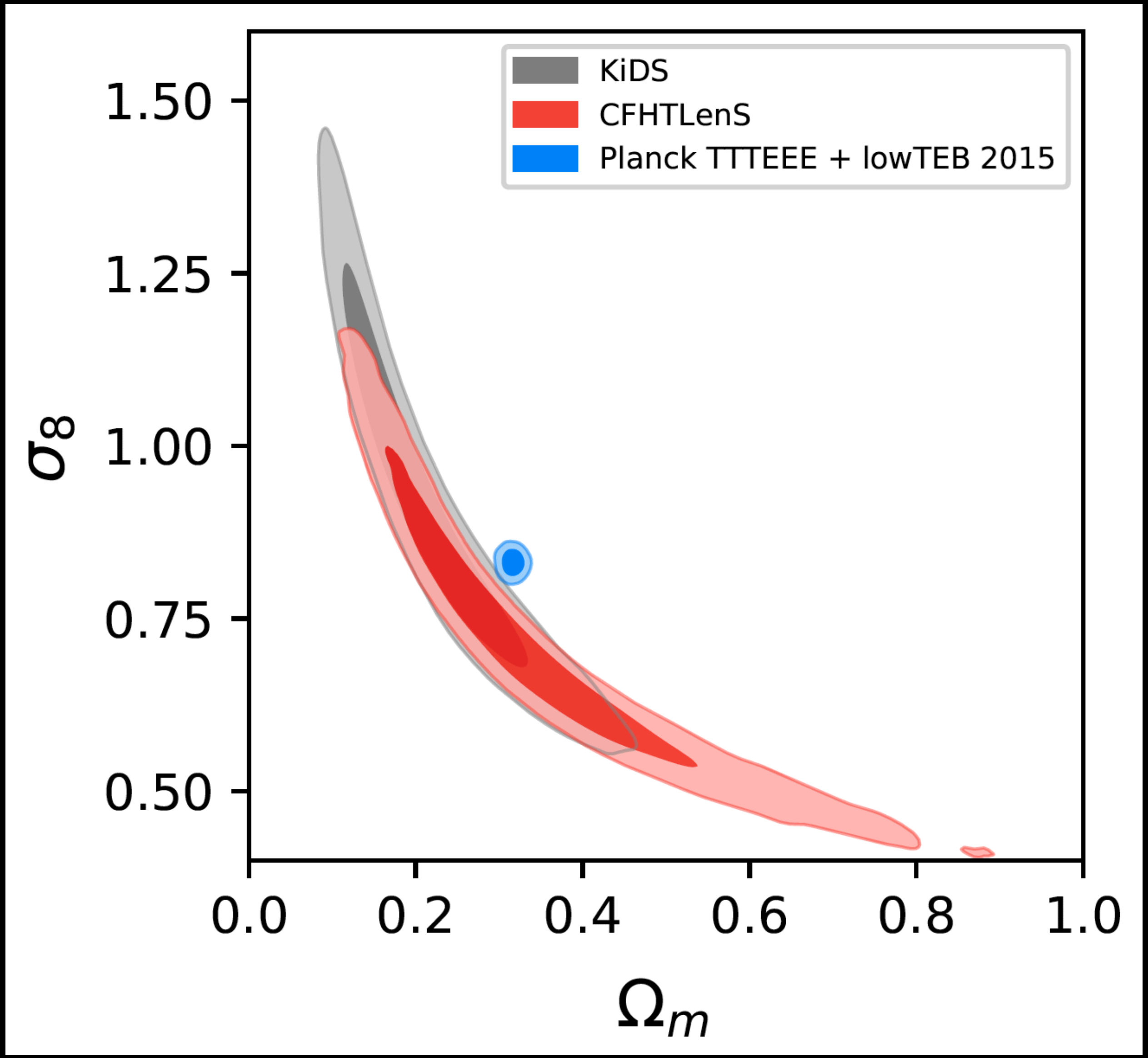
We find a relaxed and lower value for the clustering parameter, respect to the one derived under the assumption of ΛCDM.

Di Valentino, Melchiorri and Silk, Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646

Beyond six parameters: extending ΛCDM

Di Valentino et al. in preparation





$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

In this way, we can solve the existing S8 tensions at 2.4σ with the CFHTlenS and KiDS-450 cosmic shear surveys.

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Constraints at 95% cl.

Beyond six parameters: extending ΛCDM

Model Dataset	$\Omega_b h^2$	$\Omega_c h^2$	H_0 [km/s/Mpc]	τ	n_s	σ_8	$\frac{dn_s}{dlnk}$	r	w	$\Sigma m_\nu [eV]$	$N_{\rm eff}$	$A_{\rm lens}$
Λ CDM Planck TT+LowP	$0.02222^{+0.00046}_{-0.00044}$	$0.1198^{+0.0042}_{-0.0043}$	$67.3^{+2.0}_{-1.8}$	$0.077^{+0.038}_{-0.036}$	$0.966^{+0.012}_{-0.012}$	$0.829^{+0.028}_{-0.028}$	-	-	-	-	-	-
Λ CDM Planck	$0.02226^{+0.00031}_{-0.00029}$	$0.1198^{+0.0028}_{-0.0028}$	$67.3^{+1.3}_{-1.3}$	$0.079^{+0.034}_{-0.035}$	$0.9646^{+0.0092}_{-0.0092}$	$0.831^{+0.026}_{-0.026}$	-	-	-	-	-	-
Λ CDM Planck+ BAO	$0.02229^{+0.00028}_{-0.00027}$	$0.1193^{+0.0021}_{-0.0020}$	$67.52^{+0.93}_{-0.93}$	$0.082^{+0.031}_{-0.032}$	$0.9662^{+0.0078}_{-0.0079}$	$0.832^{+0.025}_{-0.025}$	-	-	-	-	-	-
e CDM Planck TT+LowP	$0.0245^{+0.0024}_{-0.0022}$	$0.127^{+0.017}_{-0.016}$	> 43	$0.073^{+0.051}_{-0.051}$	$1.06^{+0.10}_{-0.098}$	$0.56^{+0.35}_{-0.27}$	$-0.004^{+0.042}_{-0.041}$	< 0.383	$-0.53^{+0.61}_{-0.96}$	< 1.30	$4.66^{+2.3}_{-2.1}$	$2.50^{+2.3}_{-1.7}$
e CDM Planck	$0.02239^{+0.00060}_{-0.00056}$	$0.1186^{+0.0071}_{-0.0068}$	> 51.2	$0.058^{+0.040}_{-0.043}$	$0.967^{+0.025}_{-0.025}$	$0.81^{+0.24}_{-0.26}$	$-0.003^{+0.020}_{-0.019}$	< 0.183	$-1.32^{+0.98}_{-0.85}$	< 0.959	$3.08^{+0.57}_{-0.51}$	$1.21^{+0.27}_{-0.24}$
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e CDM Planck+lensing	$0.02214^{+0.00053}_{-0.00052}$	$0.1176^{+0.0069}_{-0.0066}$	> 54.5	$0.058^{+0.040}_{-0.043}$	$0.959^{+0.024}_{-0.024}$	$0.85^{+0.21}_{-0.24}$	$-0.005^{+0.018}_{-0.018}$	< 0.178	$-1.45^{+0.96}_{-0.83}$	< 0.661	$2.93^{+0.51}_{-0.48}$	$1.04^{+0.16}_{-0.15}$
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e CDM Planck+WL	$0.02251^{+0.00056}_{-0.00055}$	$0.1188^{+0.0073}_{-0.0069}$	> 54.2	< 0.0835	$0.972^{+0.024}_{-0.024}$	$0.82^{+0.22}_{-0.25}$	$0.000^{+0.020}_{-0.019}$	< 0.197	$-1.41^{+0.98}_{-0.79}$	< 0.974	$3.16^{+0.58}_{-0.56}$	$1.24^{+0.23}_{-0.22}$
e CDM Planck+BAO-RSD	$0.02253^{+0.00052}_{-0.00050}$	$0.1184^{+0.0069}_{-0.0067}$	$68.6^{+4.2}_{-3.9}$	$0.056^{+0.038}_{-0.042}$	$0.972^{+0.023}_{-0.023}$	$0.774^{+0.055}_{-0.058}$	$-0.004^{+0.018}_{-0.018}$	< 0.188	$-1.05^{+0.17}_{-0.19}$	< 0.626	$3.12^{+0.51}_{-0.48}$	$1.22^{+0.18}_{-0.17}$
e CDM Planck+BKP	$0.02237^{+0.00057}_{-0.00056}$	$0.1186^{+0.0072}_{-0.0069}$	> 52.3	$0.058^{+0.039}_{-0.044}$	$0.966^{+0.026}_{-0.026}$	$0.81^{+0.23}_{-0.25}$	$-0.003^{+0.019}_{-0.018}$	< 0.101	$-1.31^{+0.96}_{-0.89}$	< 0.876	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

The only notable exception is the angular power spectrum lensing amplitude, $A_{\rm lens}$ that is larger than the expected value at more than two standard deviations even when combining the Planck data with BAO and supernovae type Ia external datasets.

Di Valentino, Melchiorri and Silk, Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646

Constraints at 95% cl.

Beyond six parameters: extending ΛCDM

Model Dataset	$\Omega_b h^2$	$\Omega_c h^2$	H_0 [km/s/Mpc]	τ	n_s	σ_8	$\frac{dn_s}{dlnk}$	r	w	$\Sigma m_\nu [eV]$	$N_{\rm eff}$	$A_{\rm lens}$
Λ CDM Planck TT+LowP	$0.02222^{+0.00046}_{-0.00044}$	$0.1198^{+0.0042}_{-0.0043}$	$67.3^{+2.0}_{-1.8}$	$0.077^{+0.038}_{-0.036}$	$0.966^{+0.012}_{-0.012}$	$0.829^{+0.028}_{-0.028}$	-	-	-	-	-	-
Λ CDM Planck	$0.02226^{+0.00031}_{-0.00029}$	$0.1198^{+0.0028}_{-0.0028}$	$67.3^{+1.3}_{-1.3}$	$0.079^{+0.034}_{-0.035}$	$0.9646^{+0.0092}_{-0.0092}$	$0.831^{+0.026}_{-0.026}$	-	-	-	-	-	-
Λ CDM Planck+ BAO	$0.02229^{+0.00028}_{-0.00027}$	$0.1193^{+0.0021}_{-0.0020}$	$67.52^{+0.93}_{-0.93}$	$0.082^{+0.031}_{-0.032}$	$0.9662^{+0.0078}_{-0.0079}$	$0.832^{+0.025}_{-0.025}$	-	-	-	-	-	-
e CDM Planck TT+LowP	$0.0245^{+0.0024}_{-0.0022}$	$0.127^{+0.017}_{-0.016}$	> 43	$0.073^{+0.051}_{-0.051}$	$1.06^{+0.10}_{-0.098}$	$0.56^{+0.35}_{-0.27}$	$-0.004^{+0.042}_{-0.041}$	< 0.383	$-0.53^{+0.61}_{-0.96}$	< 1.30	$4.66^{+2.3}_{-2.1}$	$2.50^{+2.3}_{-1.7}$
e CDM Planck	$0.02239^{+0.00060}_{-0.00056}$	$0.1186^{+0.0071}_{-0.0068}$	> 51.2	$0.058^{+0.040}_{-0.043}$	$0.967^{+0.025}_{-0.025}$	$0.81^{+0.24}_{-0.26}$	$-0.003^{+0.020}_{-0.019}$	< 0.183	$-1.32^{+0.98}_{-0.85}$	< 0.959	$3.08^{+0.57}_{-0.51}$	$1.21^{+0.27}_{-0.24}$
e CDM Planck+BAO	$0.02251^{+0.00056}_{-0.00052}$	$0.1185^{+0.0069}_{-0.0069}$	$68.4^{+4.3}_{-4.1}$	$0.058^{+0.041}_{-0.043}$	$0.972^{+0.024}_{-0.024}$	$0.781^{+0.065}_{-0.063}$	$-0.004^{+0.018}_{-0.018}$	< 0.187	$-1.04^{+0.20}_{-0.21}$	< 0.534	$3.11^{+0.52}_{-0.48}$	$1.20^{+0.19}_{-0.19}$
e CDM Planck+lensing	$0.02214^{+0.00053}_{-0.00052}$	$0.1176^{+0.0069}_{-0.0066}$	> 54.5	$0.058^{+0.040}_{-0.043}$	$0.959^{+0.024}_{-0.024}$	$0.85^{+0.21}_{-0.24}$	$-0.005^{+0.018}_{-0.018}$	< 0.178	$-1.45^{+0.96}_{-0.83}$	< 0.661	$2.93^{+0.51}_{-0.48}$	$1.04^{+0.16}_{-0.15}$
e CDM Planck+HST	$0.02239^{+0.00059}_{-0.00057}$	$0.1187^{+0.0072}_{-0.0070}$	$74.4^{+5.1}_{-5.1}$	$0.057^{+0.040}_{-0.045}$	$0.966^{+0.025}_{-0.025}$	$0.81^{+0.10}_{-0.11}$	$-0.003^{+0.020}_{-0.019}$	< 0.186	$-1.32^{+0.29}_{-0.31}$	< 0.957	$3.09^{+0.58}_{-0.55}$	$1.18^{+0.19}_{-0.18}$
e CDM Planck+JLA	$0.02242^{+0.00058}_{-0.00056}$	$0.1188^{+0.0071}_{-0.0067}$	$67.4^{+4.4}_{-4.2}$	$0.058^{+0.040}_{-0.043}$	$0.968^{+0.025}_{-0.025}$	$0.759^{+0.088}_{-0.089}$	$-0.004^{+0.020}_{-0.019}$	< 0.183	$-1.06^{+0.13}_{-0.14}$	< 0.854	$3.10^{+0.57}_{-0.54}$	$1.20^{+0.19}_{-0.17}$
e CDM Planck+WL	$0.02251^{+0.00056}_{-0.00055}$	$0.1188^{+0.0073}_{-0.0069}$	> 54.2	< 0.0835	$0.972^{+0.024}_{-0.024}$	$0.82^{+0.22}_{-0.25}$	$0.000^{+0.020}_{-0.019}$	< 0.197	$-1.41^{+0.98}_{-0.79}$	< 0.974	$3.16^{+0.58}_{-0.56}$	$1.24^{+0.23}_{-0.22}$
e CDM Planck+BAO-RSD	$0.02253^{+0.00052}_{-0.00050}$	$0.1184^{+0.0069}_{-0.0067}$	$68.6^{+4.2}_{-3.9}$	$0.056^{+0.038}_{-0.042}$	$0.972^{+0.023}_{-0.023}$	$0.774^{+0.055}_{-0.058}$	$-0.004^{+0.018}_{-0.018}$	< 0.188	$-1.05^{+0.17}_{-0.19}$	< 0.626	$3.12^{+0.51}_{-0.48}$	$1.22^{+0.18}_{-0.17}$
e CDM Planck+BKP	$0.02237^{+0.00057}_{-0.00056}$	$0.1186^{+0.0072}_{-0.0069}$	> 52.3	$0.058^{+0.039}_{-0.044}$	$0.966^{+0.026}_{-0.026}$	$0.81^{+0.23}_{-0.25}$	$-0.003^{+0.019}_{-0.018}$	< 0.101	$-1.31^{+0.96}_{-0.89}$	< 0.876	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

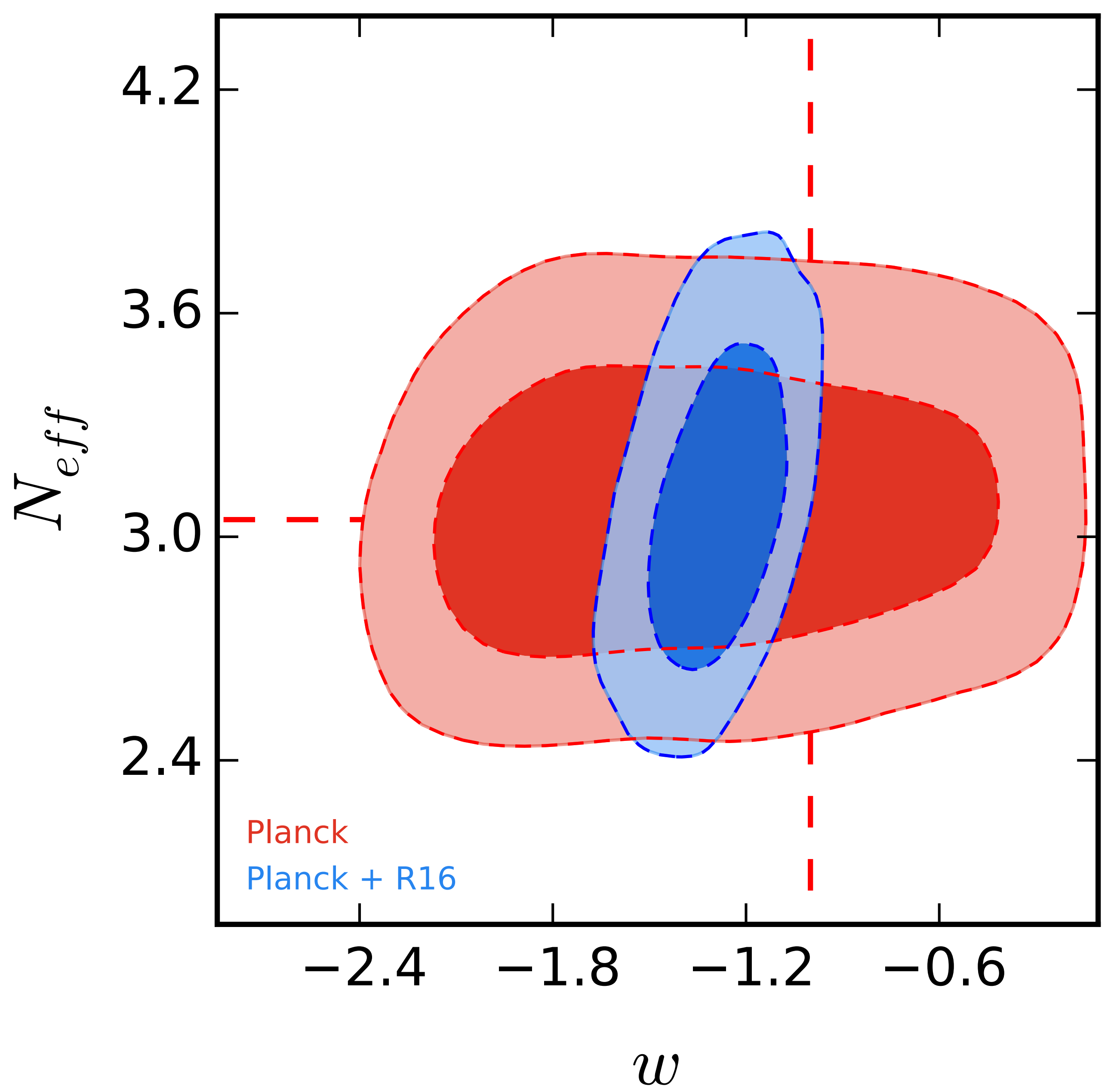
We see no evidence for "new physics": we just have (weaker) upper limits on the neutrino mass, the running of the spectral index is compatible with zero, the dark energy equation of state is compatible with w = −1, and the neutrino effective number is remarkably close to the standard value Neff = 3.046.

Di Valentino, Melchiorri and Silk, Phys.Rev. D92 (2015) no.12, 121302, arXiv:1507.06646

Constraints at 68% cl.

Towards a new concordance model

	Planck	Planck + R16
$\Omega_b h^2$	0.02239 ± 0.00030	0.02239 ± 0.00029
$\Omega_c h^2$	0.1186 ± 0.0035	0.1187 ± 0.0036
τ	0.058 ± 0.021	$0.058^{+0.021}_{-0.023}$
n_S	0.967 ± 0.013	0.967 ± 0.013
$log(10^{10} A_S)$	3.048 ± 0.043	$3.048^{+0.043}_{-0.048}$
H_0	> 67.1	73.5 ± 1.9
σ_8	$0.81^{+0.16}_{-0.12}$	$0.804^{+0.056}_{-0.044}$
$\sum m_\nu$ [eV]	< 0.53	< 0.512
w	$-1.32^{+0.47}_{-0.67}$	$-1.29^{+0.15}_{-0.12}$
$N_{\rm eff}$	$3.08^{+0.26}_{-0.30}$	$3.09^{+0.26}_{-0.31}$
$A_{\rm lens}$	$1.21^{+0.09}_{-0.14}$	$1.18^{+0.09}_{-0.11}$
$\frac{dn_S}{d\ln k}$	-0.0034 ± 0.0098	$-0.003^{+0.010}_{-0.011}$
r	< 0.0911	< 0.0934



Since now datasets are fully compatible, we combined the Planck data with R16 (H0=73.24 +/- 1.74 Km/s/Mpc), and we found a phantom-like dark energy component with an equation of state w<–1 at about two standard deviations. On the other hand, the neutrino effective number is fully compatible with standard expectations.

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

Conclusions:

2018 Planck results are perfectly in agreement with the standard ΛCDM cosmological model.
However, anomalies and tensions between Planck and other cosmological probes are present well above the 3 standard deviations that can bias the cosmological constraints.
Probably small, unresolved systematics can be easily present in all the datasets.

If we perform a combined analysis of Planck and R16 in an extended parameter space, varying simultaneously 12 cosmological parameters, since in this scenario a higher value of H0 is naturally allowed, we found that the tension is reduced with N_{eff} in very good agreement with the standard expectations, $H_0 = 73.5 \pm 2.9$ km/s/Mpc at 68% c.l., and w<-1 at about 2 sigma. Moreover, this extended scenario is also fully compatible with cosmic shear data.

We still don't have a new concordance model, but we can consider the very extended scenario as the more conservative one for deriving the cosmological constraints.

The new generation of experiments will be decisive in solving all these issues.

Thank you!

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