The cosmological data set analysis with Neutrinos and Sterile Neutrinos

From Planck 2015 data release

The 19th Paris Cosmology Colloquium 2015

In honor of Héctor J. De Vega

July 22nd 2015

Alessandro Melchiorri
University of Rome Sapienza

Planck Collaboration 400+ names

Planck 2015 results. I. Overview of products and scientific results

Planck Collaboration: R. Adam[97], P. A. R. Ade[114], N. Aghanim[79], Y. Akrami[83,134], M. I. R. Alves[79], M. Arnaud[95], F. Arroja[87,101], J. Aumont[79], C. Baccigalupi[113], M. Ballardini[66,68,40], A. J. Banday[129,12], R. B. Barreiro[86], J. G. Bartlett[1,88], N. Bartolo[41,87], S. Basak[113], P. Battaglia[124], E. Battaner[132,133], R. Battye[89], K. Benabed[80,126], A. Benoît[77], A. Benoit-Lévy[30,80,126], J.-P. Bernard[129,12], M. Bersanelli[44,67], B. Bertincourt[79], P. Bielewicz[129,12,113], A. Bonaldi[89], L. Bonavera[86], J. R. Bond[11], J. Borrill[17,119], F. R. Bouchet[80,117], F. Boulanger[79,110], M. Bucher[1], C. Burigana[66,42,68], R. C. Butler[66], E. Calabrese[122], J.-F. Cardoso[96,1,80], P. Carvalho[82,90], B. Casaponsa[86], G. Castex[1], A. Catalano[97,93], A. Challinor[82,90,15], A. Chamballu[95,19,79], R.-R. Chary[76], H. C. Chiang[34,9], J. Chluba[29,90], P. R. Christensen[107,48], S. Church[121], M. Clemens[63], D. L. Clements[75], S. Colombi[80,126], L. P. L. Colombo[28,88], C. Combet[97], B. Comis[97], D. Contreras[27], F. Couchot[91], A. Coulais[93], B. P. Crill[88,108], M. Cruz[24], A. Curto[8,86], F. Cuttaia[66], L. Danese[113], R. D. Davies[89], R. J. Davis[89], P. de Bernardis[43], A. de Rosa[66], G. de Zotti[63,113], J. Delabrouille[1], J.-M. Delouis[80,126], F.-X. Désert[72], E. Di Valentino[43], C. Dickinson[89], J. M. Diego[86], K. Dolag[131,102], H. Dole[79,78], S. Donzelli[67], O. Doré[88,14], M. Douspis[79], A. Ducout[80,75], J. Dunkley[122], X. Dupac[52], G. Efstathiou[82], P. R. M. Eisenhardt[88], F. Elsner[30,80,126], T. A. Enßlin[102], H. K. Eriksen[83], E. Falgarone[93], Y. Fantaye[83], M. Farhang[11,111], S. Feeney[75], J. Fergusson[15], R. Fernandez-Cobos[86], F. Feroz[8], F. Finelli[66,68], E. Florido[132], O. Forni[129,12], M. Frailis[65], A. A. Fraisse[34], C. Franceschet[44], E. Franceschi[66], A. Frejsel[107], A. Frolov[116], S. Galeotta[65], S. Galli[80], K. Ganga[1], C. Gauthier[1,101], R. T. Génova-Santos[85], M. Gerbino[43], T. Ghosh[79], M. Giard[129,12], Y. Giraud-Héraud[1], E. Giusarma[43], E. Gjerløw[83], J. González-Nuevo[86,113], K. M. Górski[88,136], K. J. B. Grainge[8,90], S. Gratton[90,82], A. Gregorio[45,65,71], A. Gruppuso[66], J. E. Gudmundsson[34], J. Hamann[125,123], W. Handley[90,8], F. K. Hansen[83], D. Hanson[104,88,11], D. L. Harrison[82,90], A. Heavens[75], G. Helou[14], S. Henrot-Versillé[91], C. Hernández-Monteagudo[16,102], D. Herranz[86], S. R. Hildebrandt[88,14], E. Hivon[80,126], M. Hobson[8], W. A. Holmes[88], A. Hornstrup[20], W. Hovest[102], Z. Huang[11], K. M. Huffenberger[32], G. Hurier[79], S. Ilić[129,12,79], A. H. Jaffe[75], T. R. Jaffe[129,12], T. Jin[8], W. C. Jones[34], M. Juvela[33], A. Karakci[1], E. Keihänen[33], R. Keskitalo[17], K. Kiiveri[33,60], J. Kim[102], T. S. Kisner[99], R. Kneissl[50,10], J. Knoche[102], N. Krachmalnicoff[44], M. Kunz[21,79,4], H. Kurki-Suonio[33,60], F. Lacasa[79,61], G. Lagache[7,79], A. Lähteenmäki[2,60], J.-M. Lamarre[93], M. Langer[79], A. Lasenby[8,90], M. Lattanzi[42], C. R. Lawrence[88] *, M. Le Jeune[1], J. P. Leahy[89], E. Lellouch[94], R. Leonardi[52], J. León-Tavares[84,55,3], J. Lesgourgues[125,112,92], F. Levrier[93], A. Lewis[31], M. Liguori[41,87], P. B. Lilje[83], M. Linden-Vørnle[20], V. Lindholm[33,60], H. Liu[107,48], M. López-Caniego[52,86], P. M. Lubin[38], Y.-Z. Ma[27,89], J. F. Macías-Pérez[97], G. Maggio[65], D. S. Y. Mak[28], N. Mandolesi[66,6,42], A. Mangilli[80], A. Marchini[69], A. Marcos-Caballero[86], D. Marinucci[47], D. J. Marshall[95], P. G. Martin[11], M. Martinelli[134], E. Martínez-González[86], S. Masi[43], S. Matarrese[41,87,57], P. Mazzotta[46], J. D. McEwen[105], P. McGehee[76], S. Mei[56,128,14], P. R. Meinhold[38], A. Melchiorri[43,69], J.-B. Melin[19], L. Mendes[52], A. Mennella[44,67], M. Migliaccio[82,90], K. Mikkelsen[83], S. Mitra[74,88], M.-A. Miville-Deschênes[79,11], D. Molinari[86,66], A. Moneti[80], L. Montier[129,12], R. Moreno[94], G. Morgante[66], D. Mortlock[75], A. Moss[115], S. Mottet[80], M. Müenchmeyer[80], D. Munshi[114], J. A. Murphy[106], A. Narimani[27], P. Naselsky[107,48], A. Nastasi[79], F. Nati[34], P. Natoli[42,5,66], M. Negrello[63], C. B. Netterfield[25], H. U. Nørgaard-Nielsen[20], F. Noviello[89], D. Novikov[100], I. Novikov[107,100], M. Olamaie[8], N. Oppermann[11], E. Orlando[135], C. A. Oxborrow[20], F. Paci[113], L. Pagano[43,69], F. Pajot[79], R. Paladini[76], S. Pandolfi[22], D. Paoletti[66,68], B. Partridge[59], F. Pasian[65], G. Patanchon[1], T. J. Pearson[14,76], M. Peel[89], H. V. Peiris[30], V.-M. Pelkonen[76], O. Perdereau[91], L. Perotto[97], Y. C. Perrott[8], F. Perrotta[113], V. Pettorino[58], F. Piacentini[43], M. Piat[1], E. Pierpaoli[28], D. Pietrobon[88], S. Plaszczynski[91], D. Pogosyan[35], E. Pointecouteau[129,12], G. Polenta[5,64], L. Popa[81], G. W. Pratt[95], G. Prézeau[14,88], S. Prunet[80,126], J.-L. Puget[79], J. P. Rachen[26,102], B. Racine[1], W. T. Reach[130], R. Rebolo[85,18,49], M. Reinecke[102], M. Remazeilles[89,79,1], C. Renault[97], A. Renzi[47,70], I. Ristorcelli[129,12], G. Rocha[88,14], M. Roman[1], E. Romelli[45,65], C. Rosset[1], M. Rossetti[44,67], A. Rotti[74], G. Roudier[1,93,88], B. Rouillé d'Orfeuil[91], M. Rowan-Robinson[75], J. A. Rubiño-Martín[85,49], B. Ruiz-Granados[132], C. Rumsey[8], B. Rusholme[76], N. Said[43], V. Salvatelli[43,7], L. Salvati[43], M. Sandri[66], H. S. Sanghera[82,90], D. Santos[97], R. D. E. Saunders[8,90], A. Sauvé[129,12], M. Savelainen[33,60], G. Savini[109], B. M. Schaefer[127], M. P. Schammel[8], D. Scott[27], M. D. Seiffert[88,14], P. Serra[79], E. P. S. Shellard[15], T. W. Shimwell[8], M. Shiraishi[41,87], K. Smith[34], T. Souradeep[74], L. D. Spencer[114], M. Spinelli[91], S. A. Stanford[37], D. Stern[88], V. Stolyarov[8,90,120], R. Stompor[1], A. W. Strong[103], R. Sudiwala[114], R. Sunyaev[102,118], P. Sutter[80], D. Sutton[82,90], A.-S. Suur-Uski[33,60], J.-F. Sygnet[80], J. A. Tauber[53], D. Tavagnacco[65,45], L. Terenzi[54,66], D. Texier[51], L. Toffolatti[23,86,66], M. Tomasi[44,67], M. Tornikoski[3], M. Tristram[91], A. Troja[44], T. Trombetti[66], M. Tucci[21], J. Tuovinen[13], M. Türler[73], G. Umana[62], L. Valenziano[66], J. Valiviita[33,60], B. Van Tent[98], T. Vassallo[65], M. Vidal[89], M. Viel[65,71], P. Vielva[86], F. Villa[66], L. A. Wade[88], B. Walter[59], B. D. Wandelt[80,126,39], R. Watson[89], I. K. Wehus[88], N. Welikala[122], J. Weller[131], M. White[36], S. D. M. White[102], A. Wilkinson[89], D. Yvon[19], A. Zacchei[65], J. P. Zibin[27], and A. Zonca[38]

Planck 2013 Core-Team

(a fraction of it)

Planck 2015 Core-Team

(again, a fraction of it)

PLANCK 2013: High Impact !

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Top Cited Articles during 2014

1. 1739 core citations in 2014
   Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
   ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 24 pp.
   Published in **Phys.Lett. B716 (2012) 1-29**
   CERN-PH-EP-2012-218
   DOI: 10.1016/j.physletb.2012.08.020
   e-Print: **arXiv:1207.7214 [hep-ex]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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2. 1715 core citations in 2014
   Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
   CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012. 42 pp.
   Published in **Phys.Lett. B716 (2012) 30-61**
   CMS-HIG-12-028, CERN-PH-EP-2012-220
   DOI: 10.1016/j.physletb.2012.08.021
   e-Print: **arXiv:1207.7235 [hep-ex]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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3. 1664 core citations in 2014
   Planck 2013 results. XVI. Cosmological parameters
   Planck Collaboration (P.A.R. Ade (Cardiff U.) *et al.*). Mar 20, 2013. 67 pp.
   Published in **Astron.Astrophys. 571 (2014) A16**
   DOI: 10.1051/0004-6361/201321591
   e-Print: arXiv:1303.5076 **[astro-ph.CO]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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Planck 2015 release (papers)

I. Overview of products and results (*this paper*)
II. Low Frequency Instrument data processing
III. LFI systematic uncertainties
IV. LFI beams and window functions
V. LFI calibration
VI. LFI maps
VII. High Frequency Instrument data processing: Time-ordered information and beam processing
VIII. High Frequency Instrument data processing: Calibration and maps
IX. Diffuse component separation: CMB maps
X. Diffuse component separation: Foreground maps
XI. CMB power spectra, likelihood, and consistency of cosmological parameters
XII. Simulations
XIII. Cosmological parameters
XIV. Dark energy and modified gravity
XV. Gravitational lensing
XVI. Isotropy and statistics of the CMB
XVII. Primordial non-Gaussianity
XVIII. Background geometry and topology of the Universe
XIX. Constraints on primordial magnetic fields
XX. Constraints on inflation
XXI. The integrated Sachs-Wolfe effect
XXII. A map of the thermal Sunyaev-Zeldovich effect
XXIII. The thermal Sunyaev-Zeldovich effect–cosmic infrared background correlation
XXIV. Cosmology from Sunyaev-Zeldovich cluster counts
XXV. Diffuse, low-frequency Galactic foregrounds
XXVI. The Second Planck Catalogue of Compact Sources
XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich Sources
XXVIII. The Planck Catalogue of Galactic Cold Clumps

Planck 2015: still very high impact !

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Visualizza risultati: 25 risultati | lista unica

HEP 38 record trovati 1 - 25 ▶ salta al record: 1 La ricerca ha impiegato 1.01 secon

1. **Planck 2015 results. XIII. Cosmological parameters**
(398) Planck Collaboration (P.A.R. Ade (Cardiff U.) *et al.*). Feb 5, 2015.
e-Print: arXiv:1502.01589 [astro-ph.CO] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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2. **Planck 2015 results. XX. Constraints on inflation**
(182) Planck Collaboration (P.A.R. Ade (Cardiff U.) *et al.*). Feb 7, 2015. 64 pp.
e-Print: arXiv:1502.02114 [astro-ph.CO] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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3. **Joint Analysis of BICEP2/*Keck Array* and *Planck* Data**
(148) BICEP2 and Planck Collaborations (P. A. R. Ade (Cardiff U.) *et al.*). Feb 2, 2015. 17 pp.
Published in **Phys.Rev.Lett. 114 (2015) 10, 101301**
DOI: 10.1103/PhysRevLett.114.101301
e-Print: arXiv:1502.00612 [astro-ph.CO] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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4. **Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV**
(124) CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.*). Dec 30, 2014. 75 pp.
Published in **Eur.Phys.J. C75 (2015) 5, 212**
CMS-HIG-14-009, CERN-PH-EP-2014-288
DOI: 10.1140/epjc/s10052-015-3351-7
e-Print: arXiv:1412.8662 [hep-ex] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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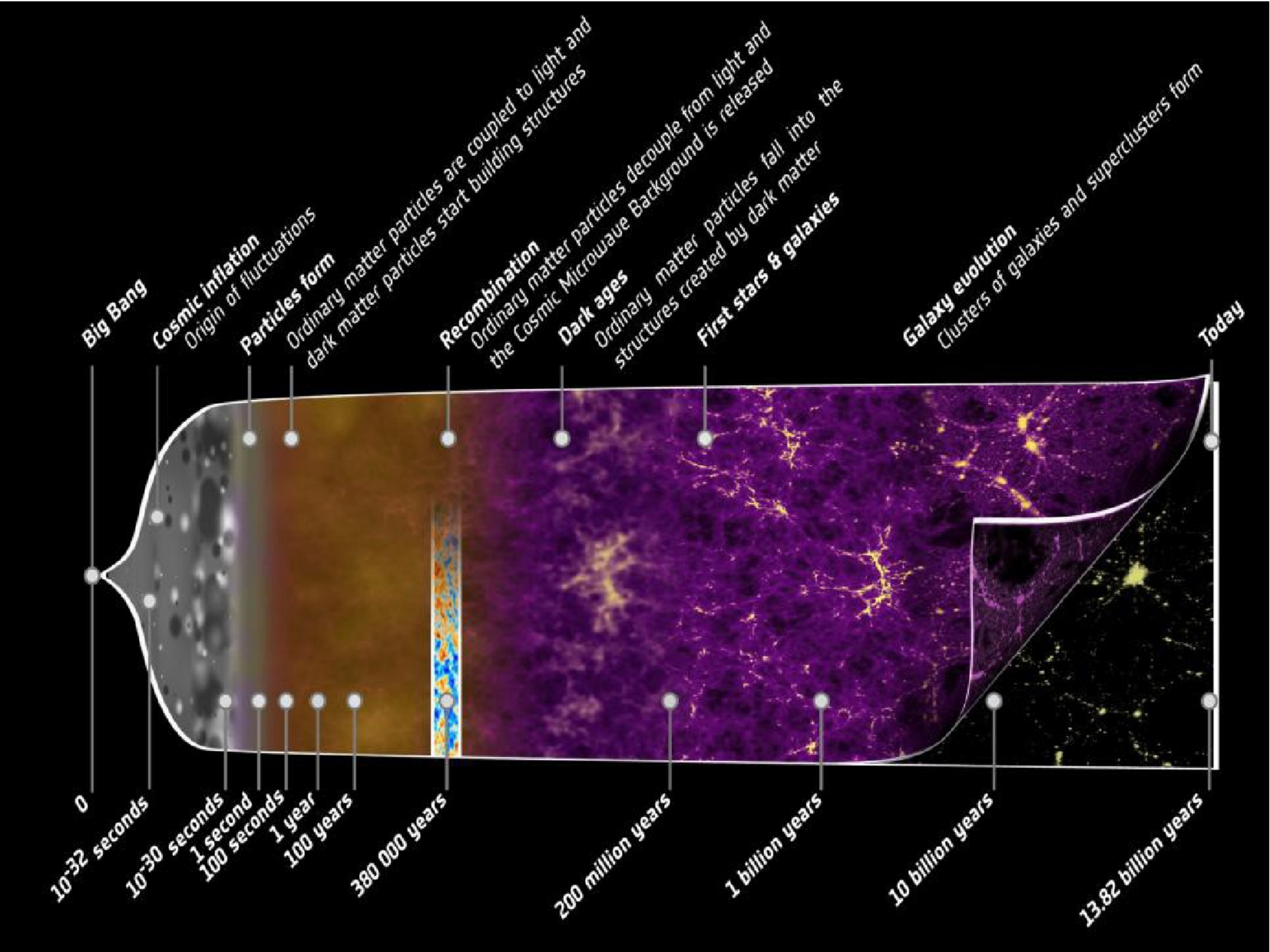
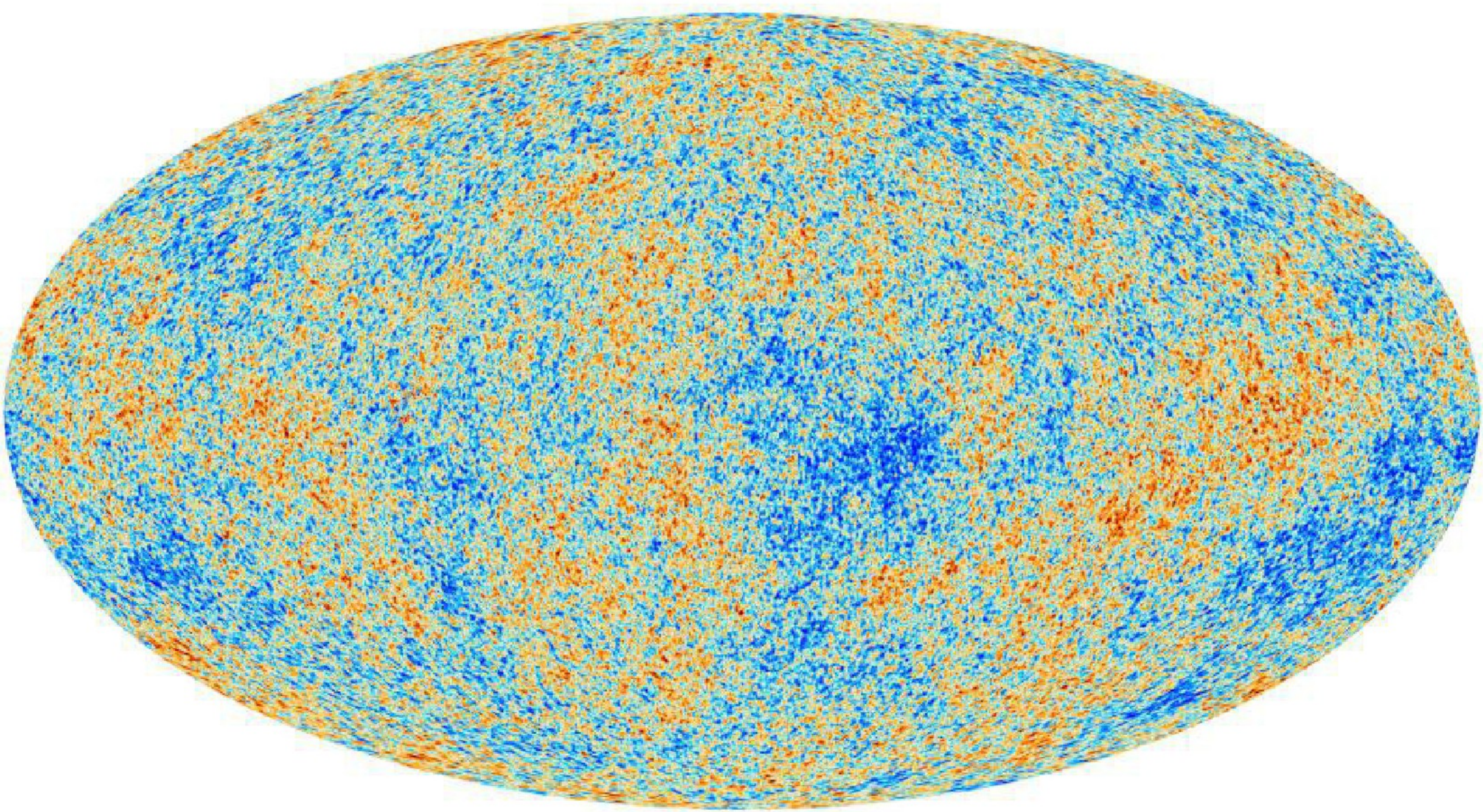
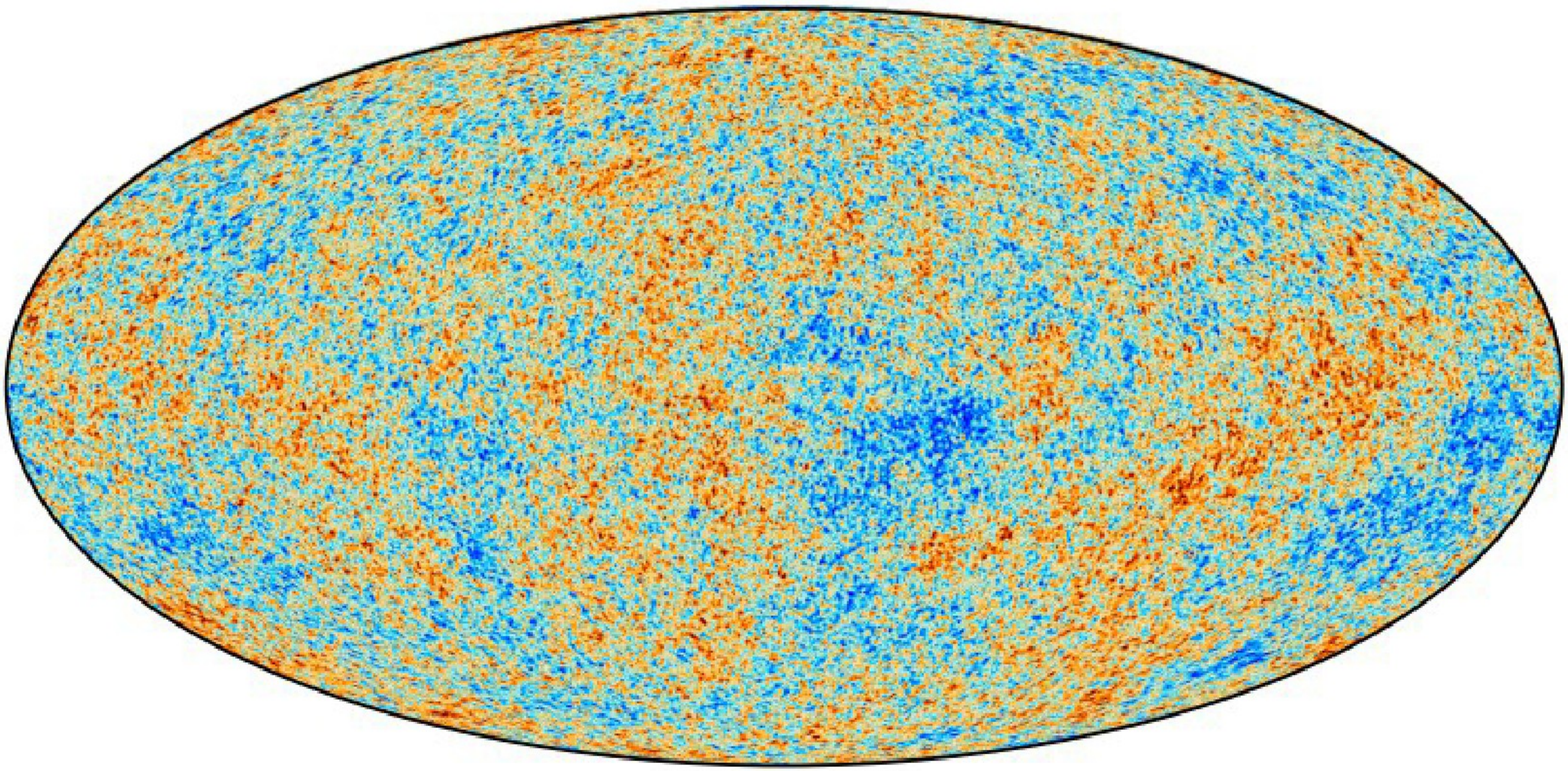

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Planck 2013 CMB Temperature map



Planck 2015 CMB Temperature map

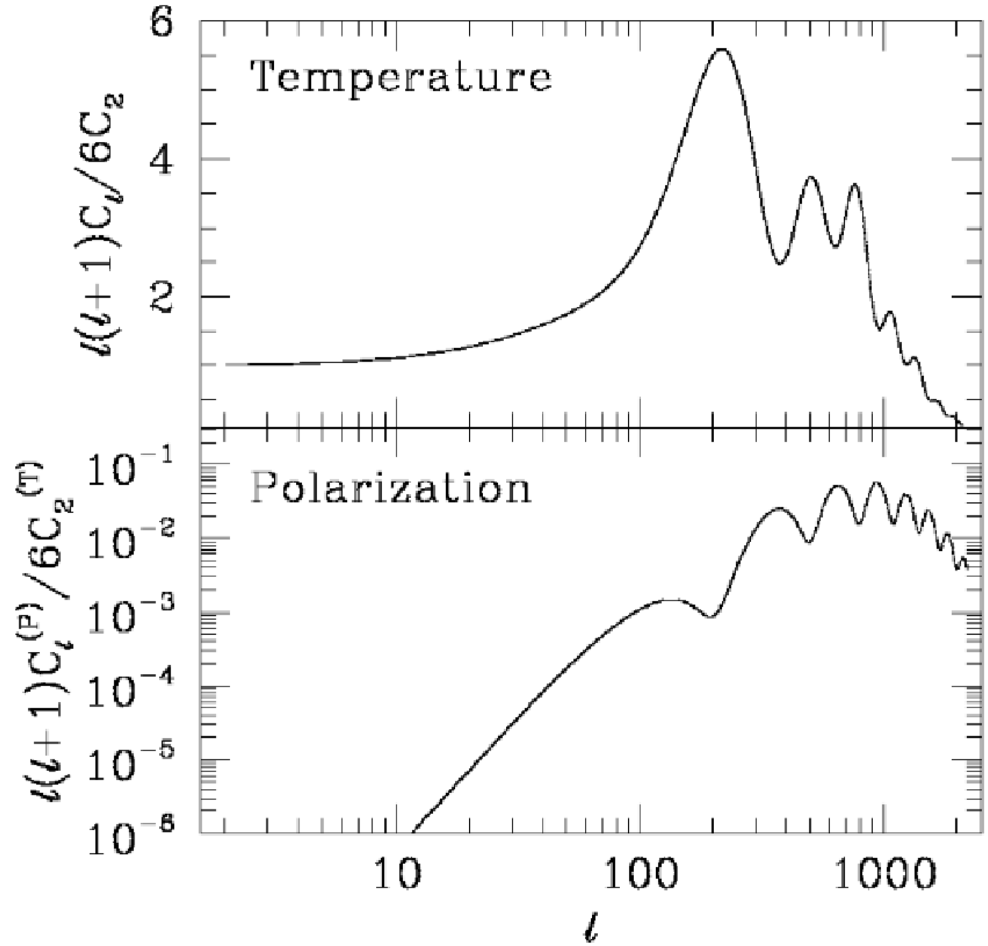


The CMB Angular Power Spectrum

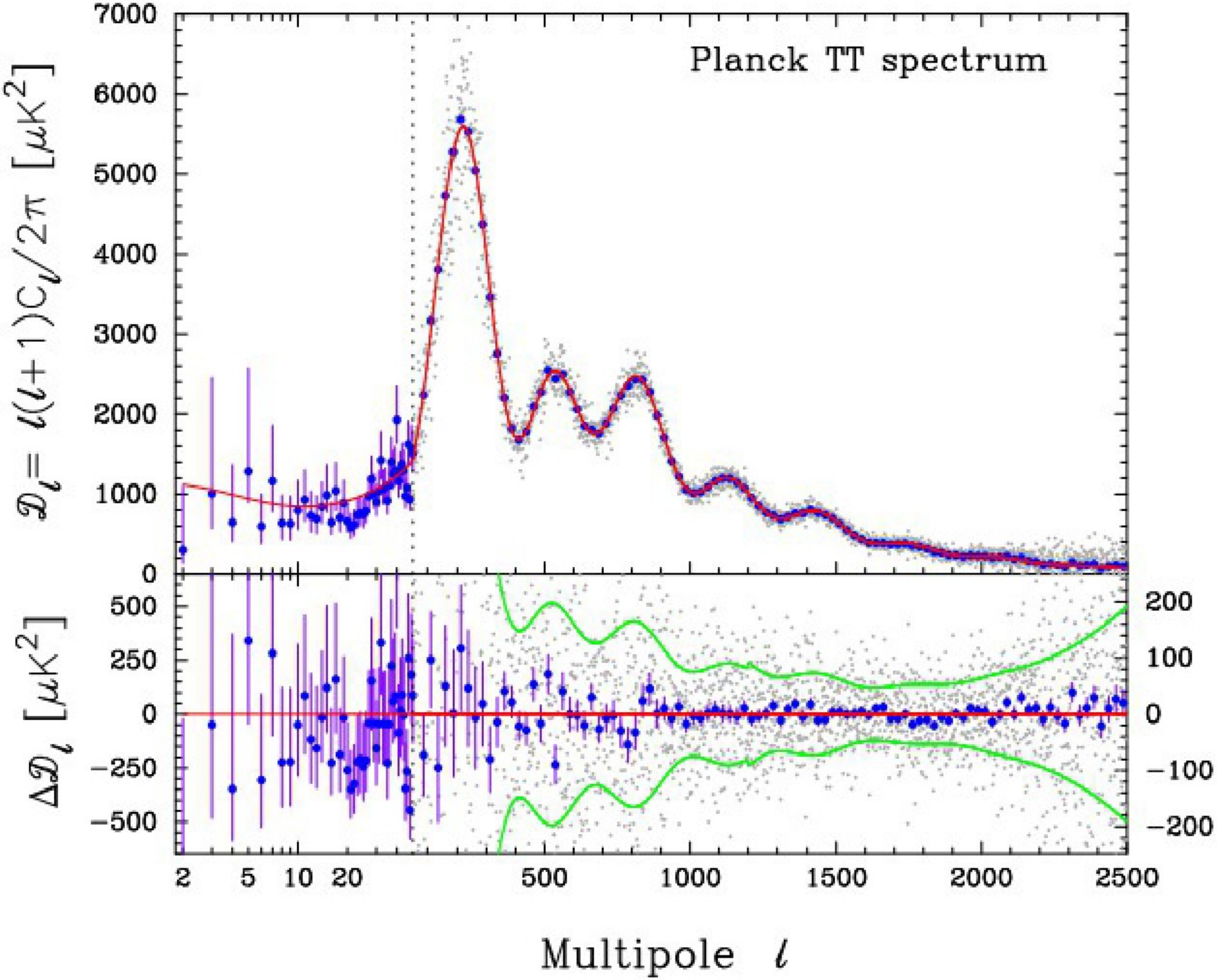
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)\,C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

R.m.s. of $\Delta T / T$ has $l(l+1)C_l / 2\pi$ power per decade in l:

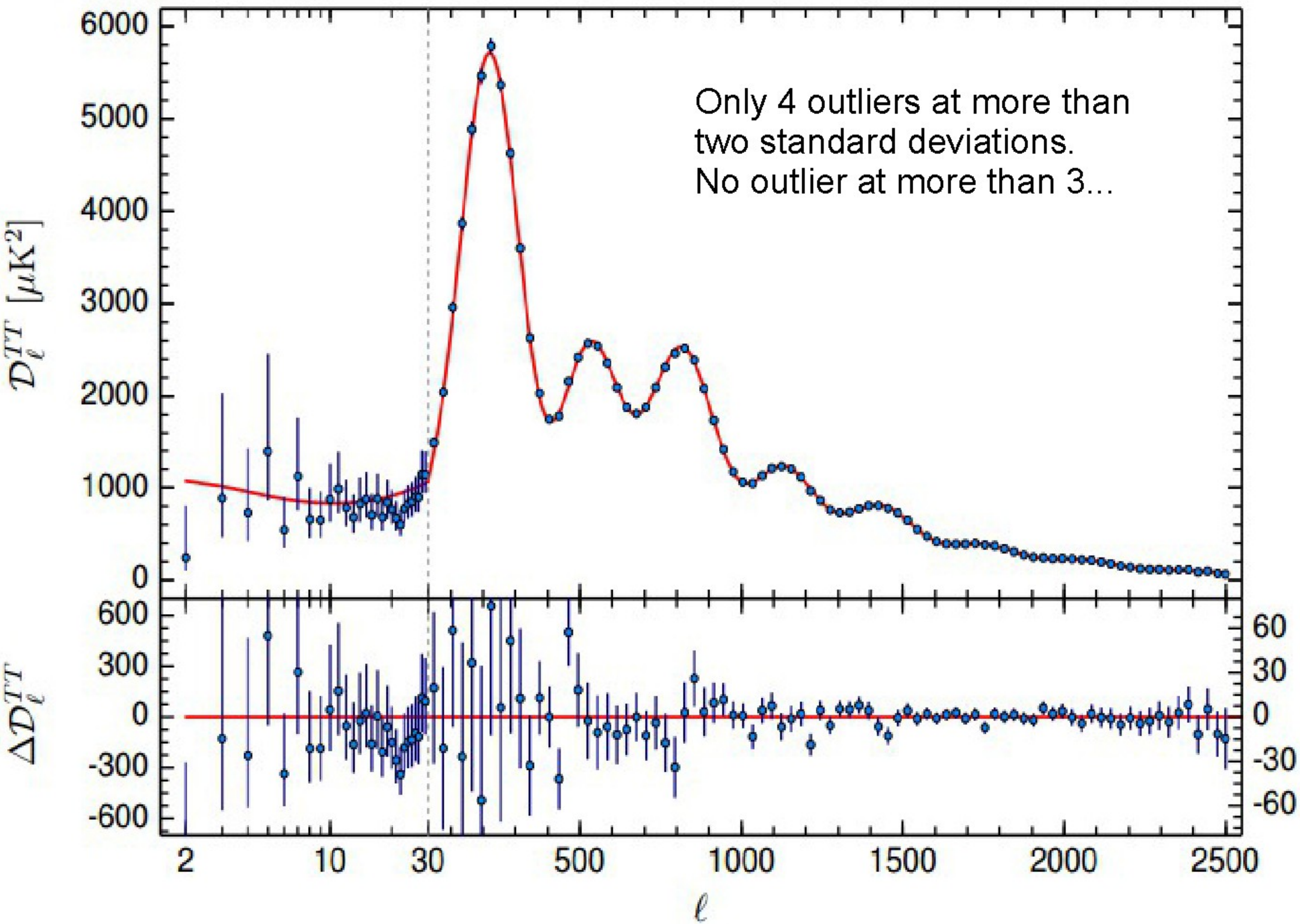
$$\left\langle (\Delta T / T)^2 \right\rangle_{rms} = \sum_l \frac{(2l+1)}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d\ln l$$



Planck 2013 Temperature Angular Spectrum



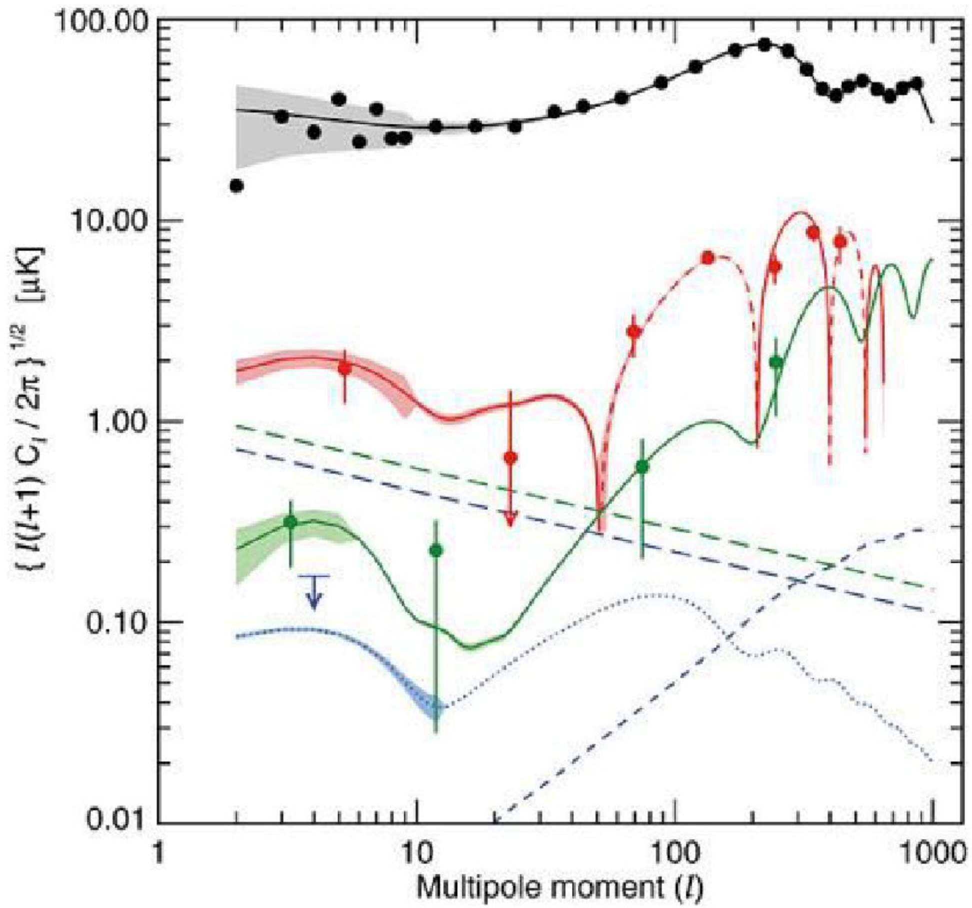
Planck 2015 Temperature Angular Spectrum



The CMB Angular Power Spectrum

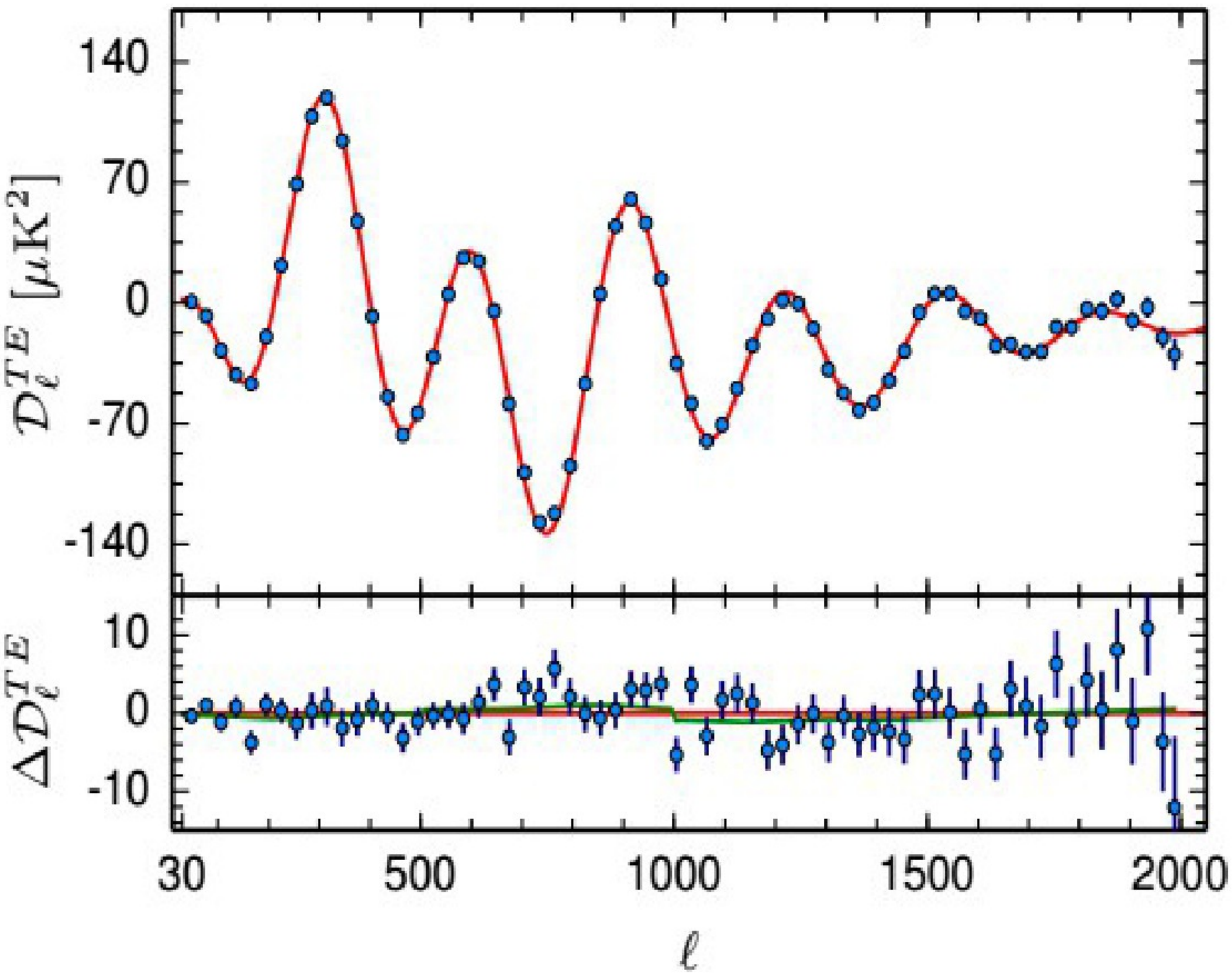
We can extract 4 independent angular spectra from the CMB:

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



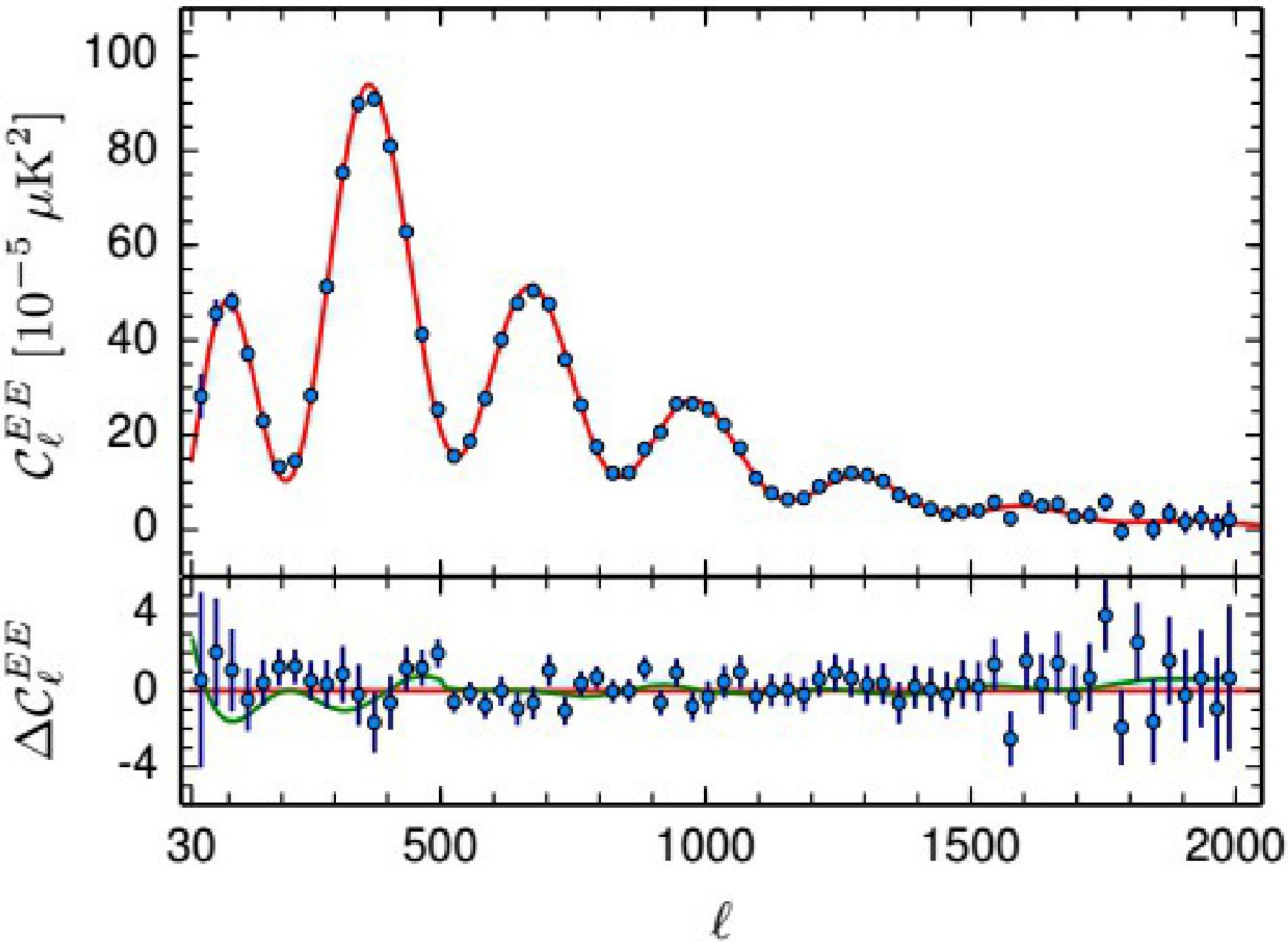
Planck 2013 release was only temperature ps.
Planck 2015 now includes polarization !

Planck 2015 TE angular spectrum



Red Line: Best fit to the TT angular spectrum

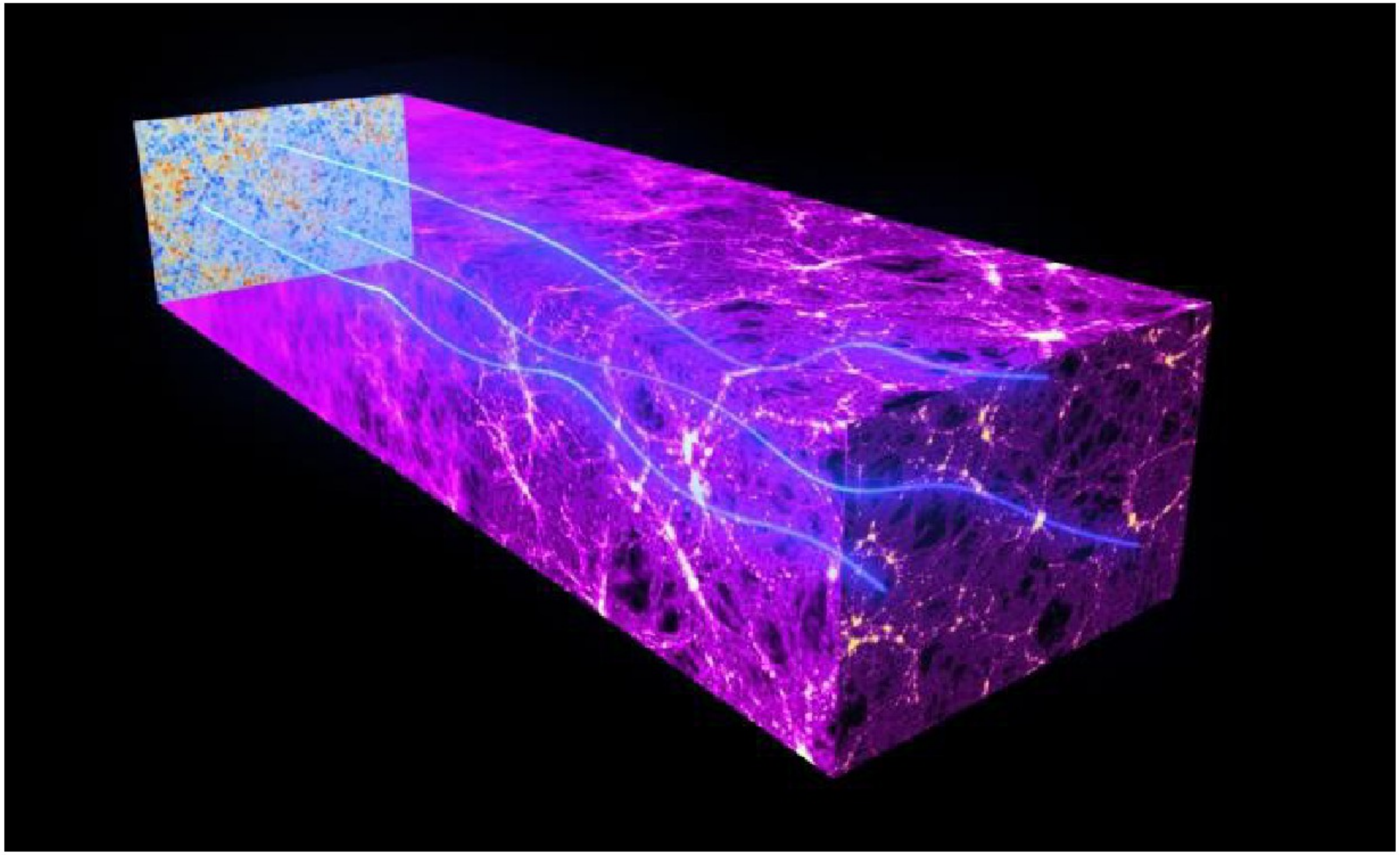
Planck 2015 EE angular spectrum



Red Line: Best fit to the TT angular spectrum

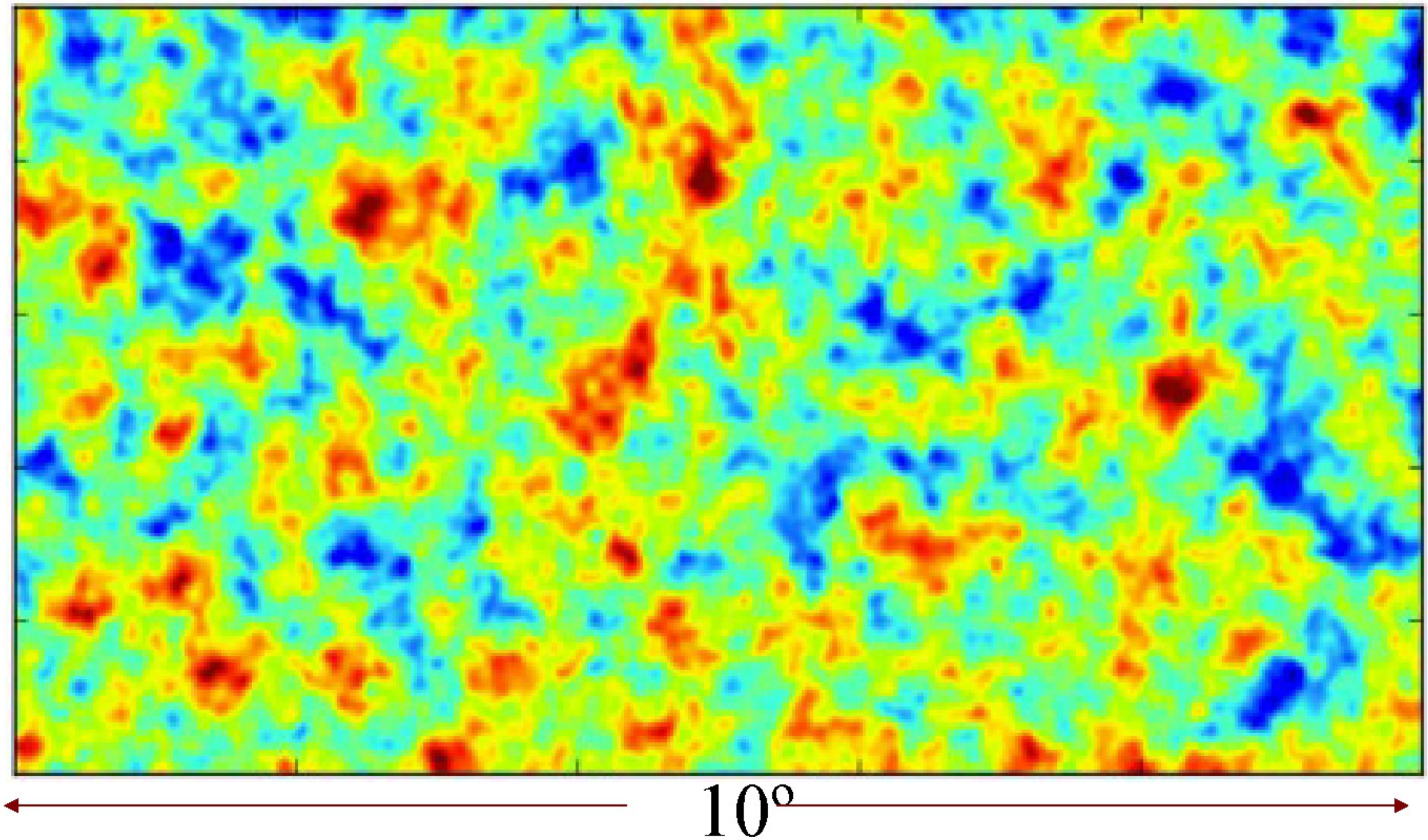
Gravitational Lensing

The gravitational effects of intervening matter 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



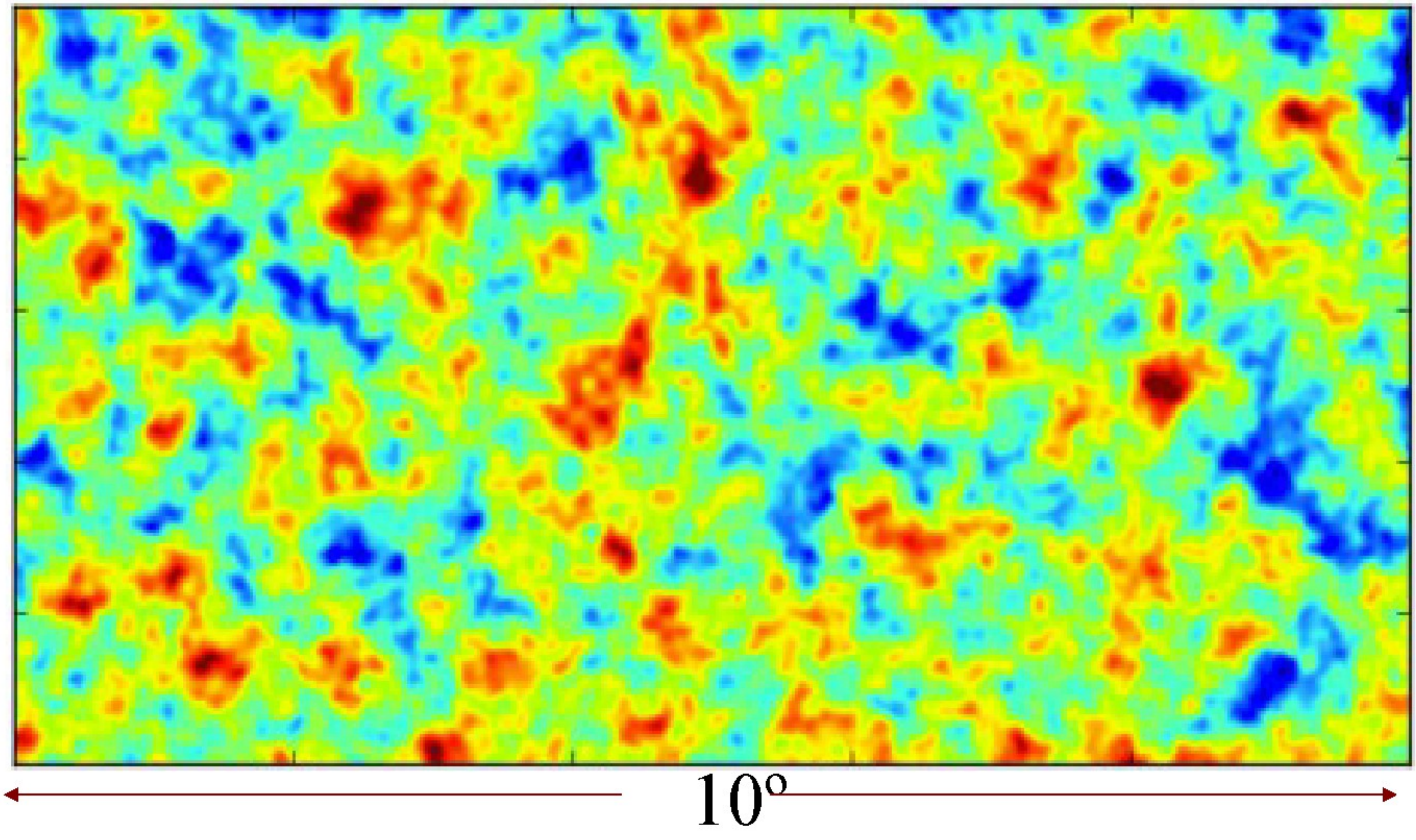
Gravitational Lensing

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

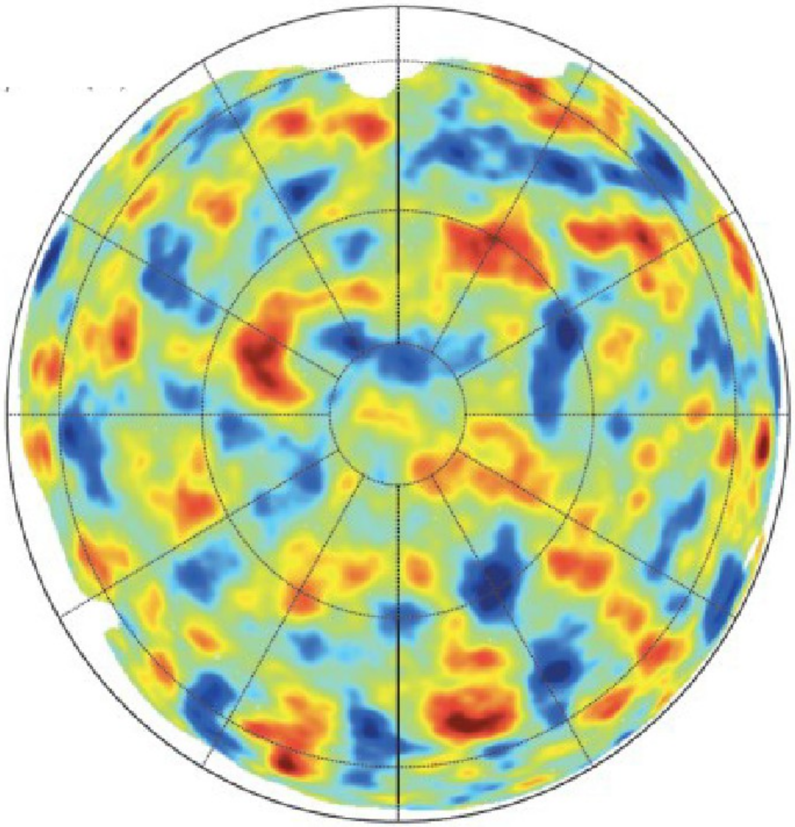


Gravitational Lensing

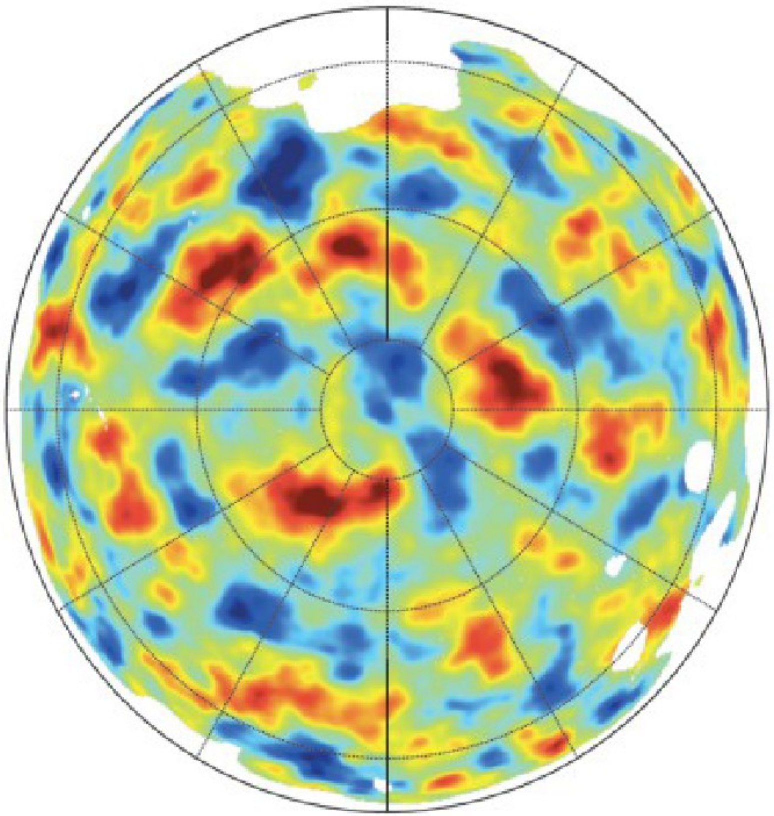
A simulated patch of CMB sky – **after lensing**



Planck dark matter distribution throught CMB lensing

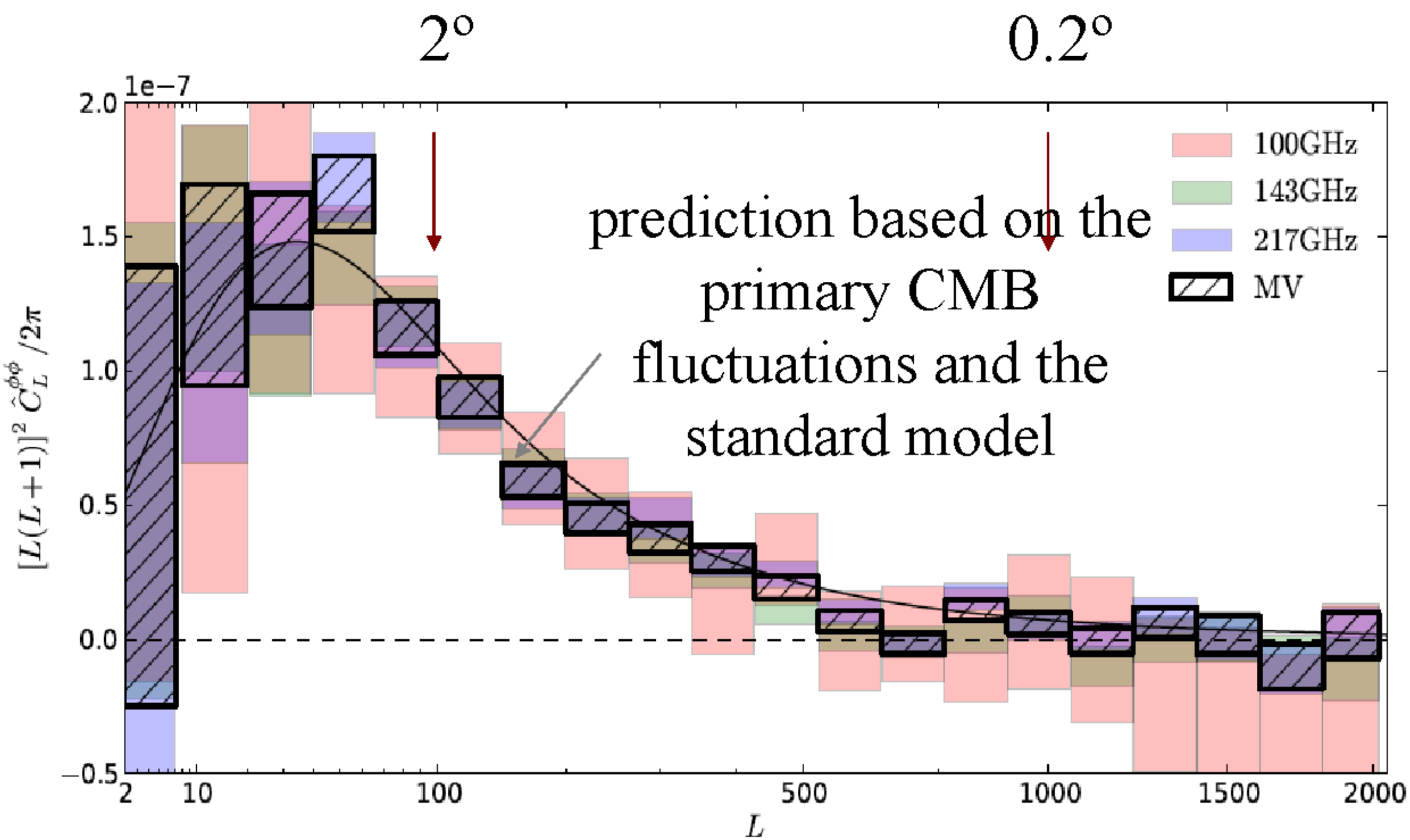


Galactic North



Galactic South

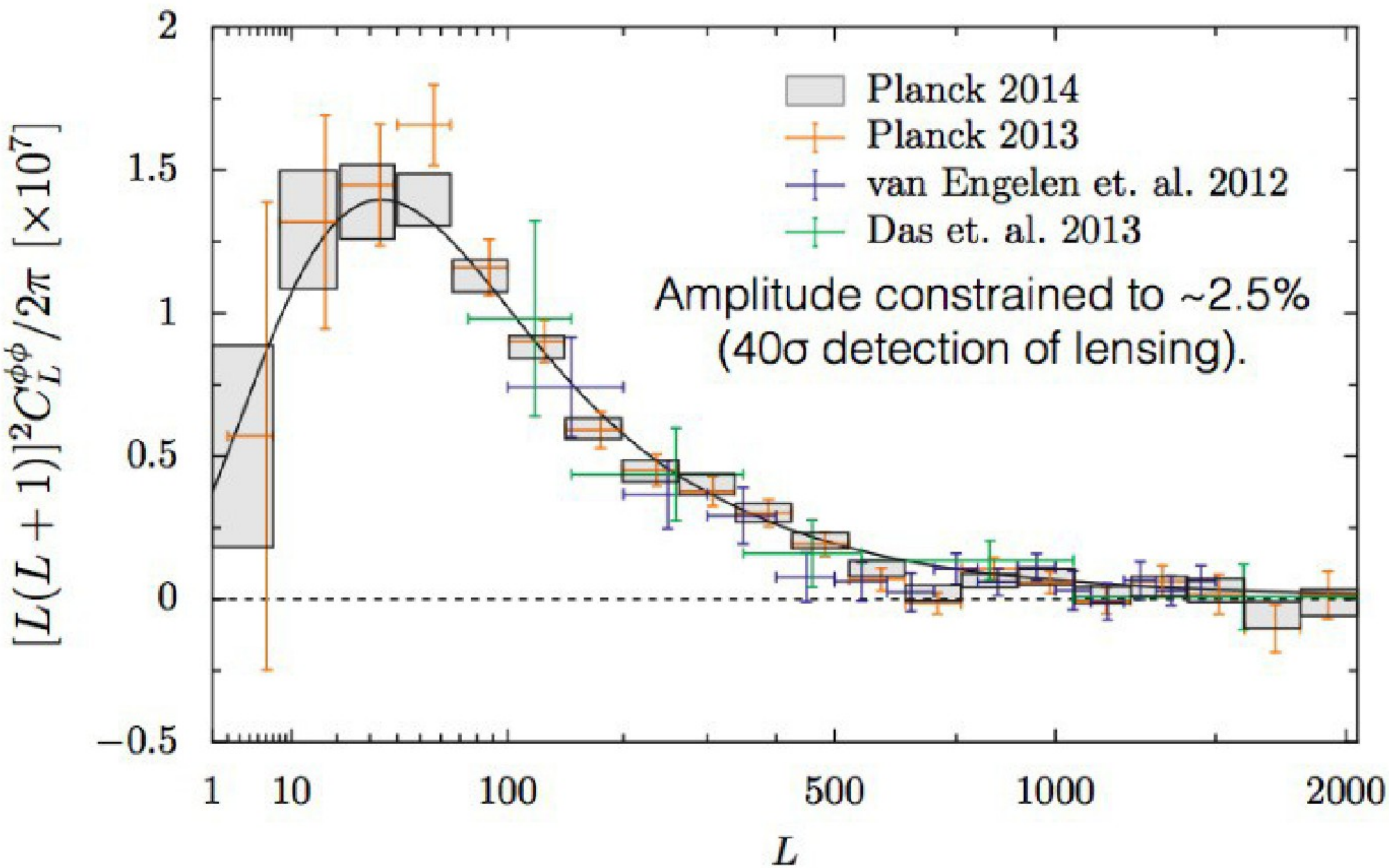
PLANCK LENSING 2013 Power Spectrum
Measured from the Trispectrum (4-point correlation)



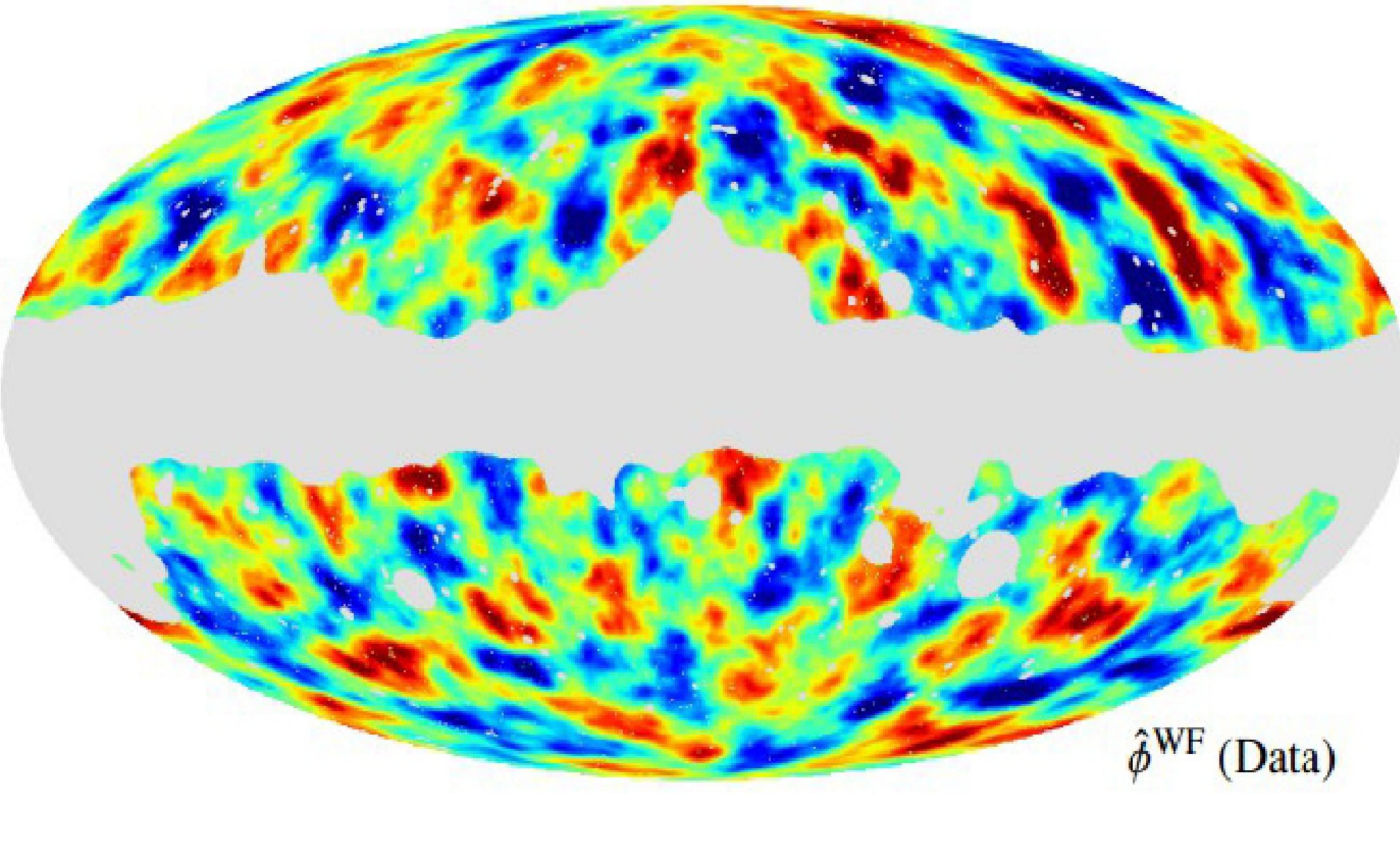
It is a 25 sigma effect!!

This spectrum helps in constraining parameters

Planck 2015 Lensing Power spectrum



Planck 2015 Lensing Map



Constraints on Cosmological Parameters

(assuming LCDM)

The standard cosmological model

- Assumes General Relativity, Inflation, Adiabatic and Scalar Perturbations, flat universe.

- Friedmann-Robertson-Walker (or Friedmann-Lemaitre) metric. Hubble Constant (+1)

$$H_0 = 100\, h\ km / s / Mpc$$

- 3 Energy components: Baryons, Cold Dark Matter, Cosmological Constant (+3). Flat Universe (-1).

$$\omega_b = \Omega_b h^2 \quad \omega_{CDM} = \Omega_{CDM} h^2$$

- Initial conditions for perturbations given by Inflation: Adiabatic, nearly scale invariant initial power spectrum, only scalar perturbations. Two free parameters (+2): Amplitude and Spectral index.

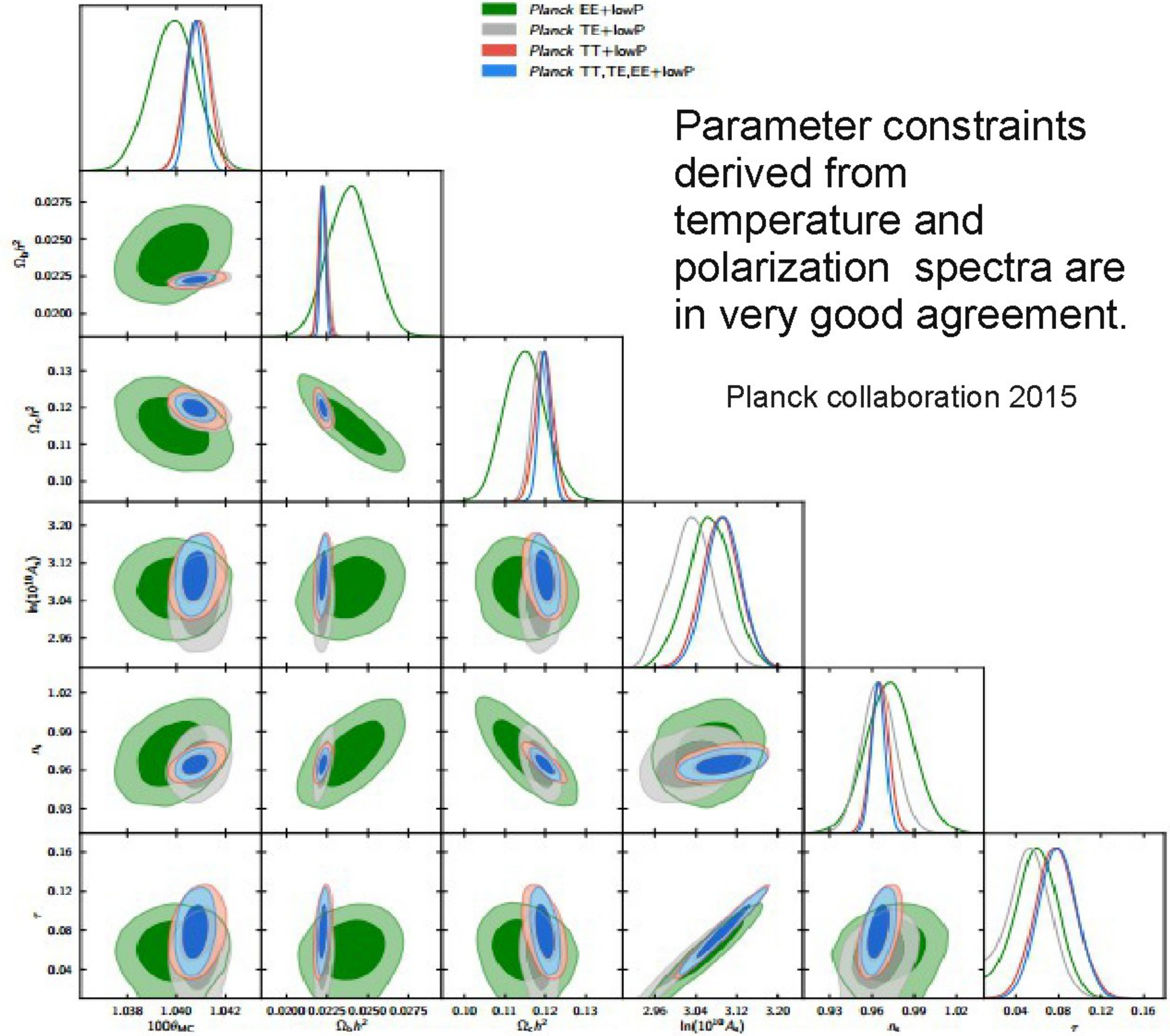
$$P(k) \approx A_S \left(\frac{k}{k_0} \right)^{n_S}$$

Pivot scale is usually fixed to:

$$k_0 = 0.002\ hMpc^{-1}$$

- Late universe reionization characterized with a single parameter(+1) : optical depth τ or reionization redshift z_r.

Total: 1+3-1+2+1= 6 parameters.



Parameter constraints derived from temperature and polarization spectra are in very good agreement.

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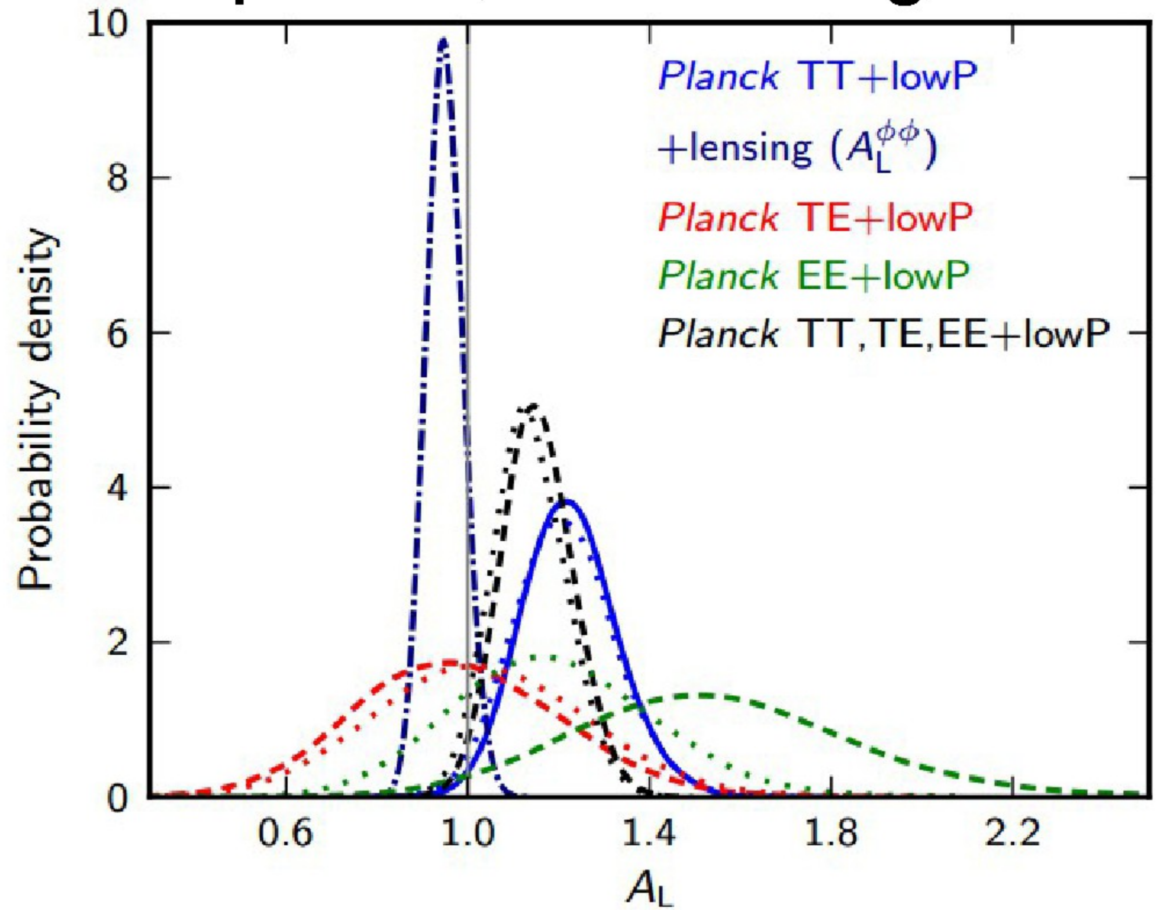
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

2015 Planck results are perfecly in agreement with the standard ΛCDM cosmological model.

Lensing constribution in TT, TE angular spectra, still too high



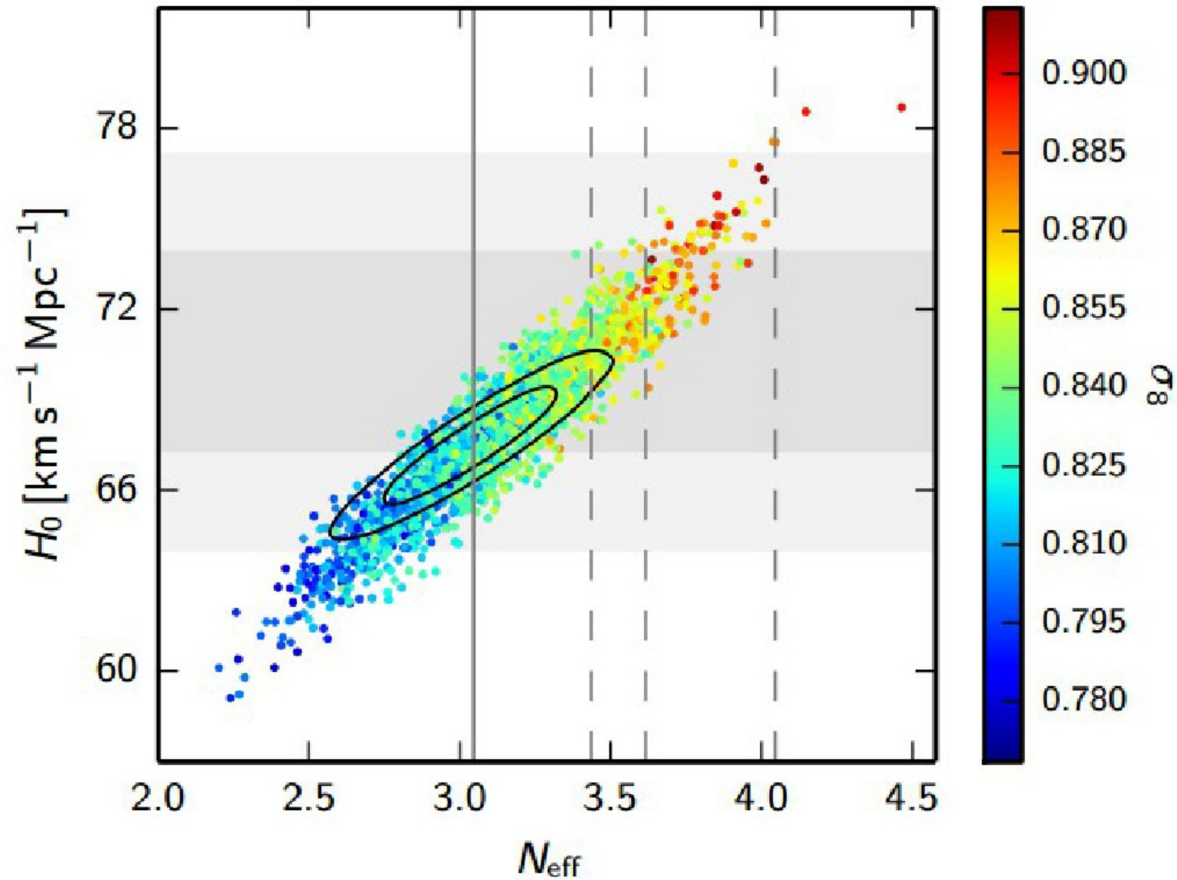
$$A_L = 1.22 \pm 0.10 \quad (68\%, \textit{Planck}\ \mathrm{TT+lowP})$$

$$A_L^{\phi\phi} = 0.95 \pm 0.04 \quad (68\%, \textit{Planck}\ \mathrm{TT+lowP+lensing}).$$

Is clearly a systematic in
TT data since
we don't see this
in the TTTT lensing

Planck collaboration 2015

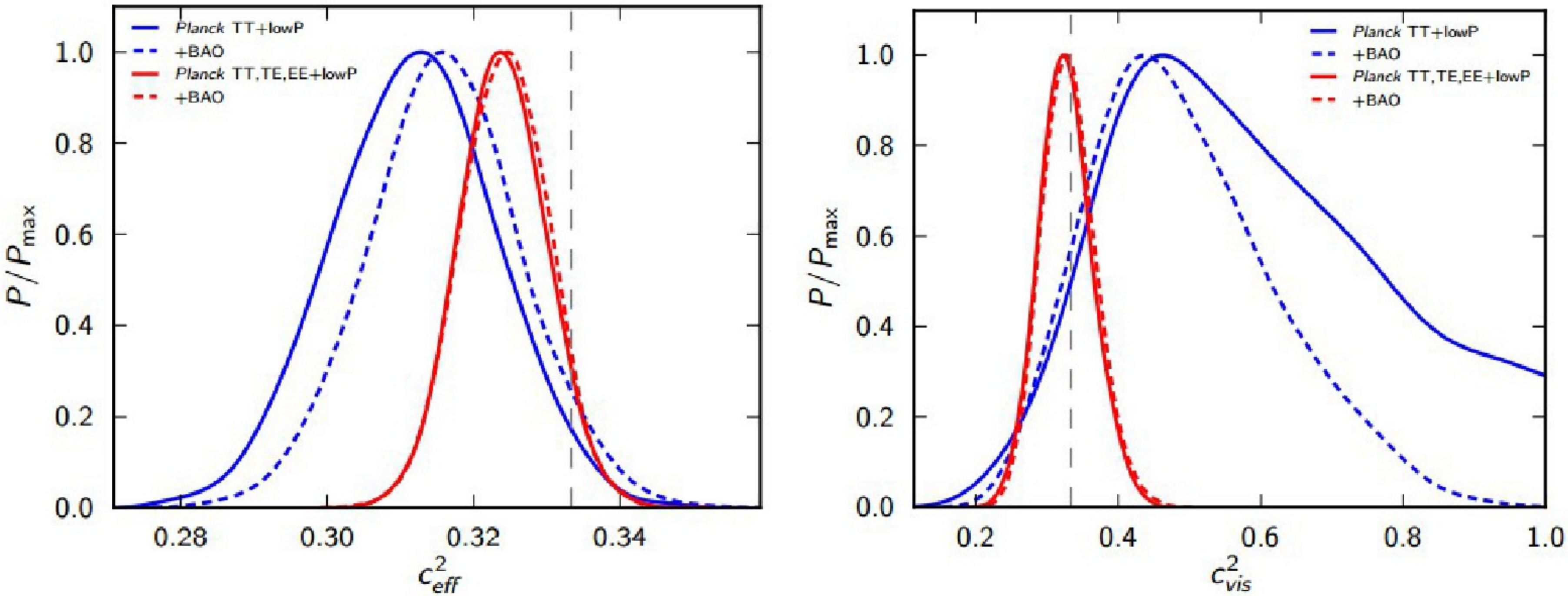
Neutrino cosmology...



$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP};$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO};$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \text{TT, TE, EE+lowP};$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \text{TT, TE, EE+lowP+BAO}.$$

Planck collaboration 2015

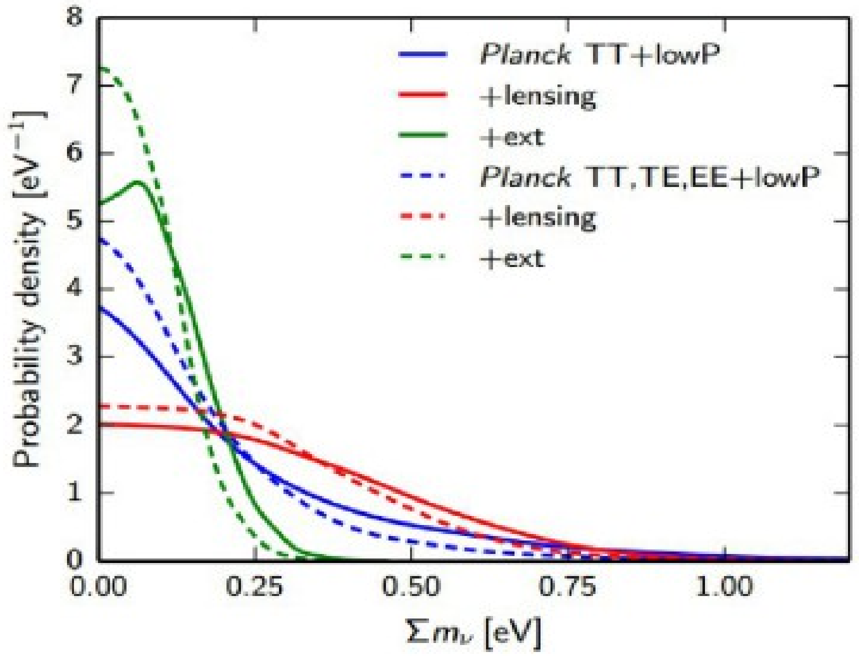
Perturbations in the neutrino background



$$\left.\begin{aligned} c^2_{\rm eff} &= 0.3242 \pm 0.0059 \\ c^2_{\rm vis} &= 0.331 \pm 0.037 \end{aligned}\right\} \textit{Planck}\ \text{TT,TE,EE+lowP+BAO.}$$

Planck collaboration 2015

3 standard Massive Neutrinos



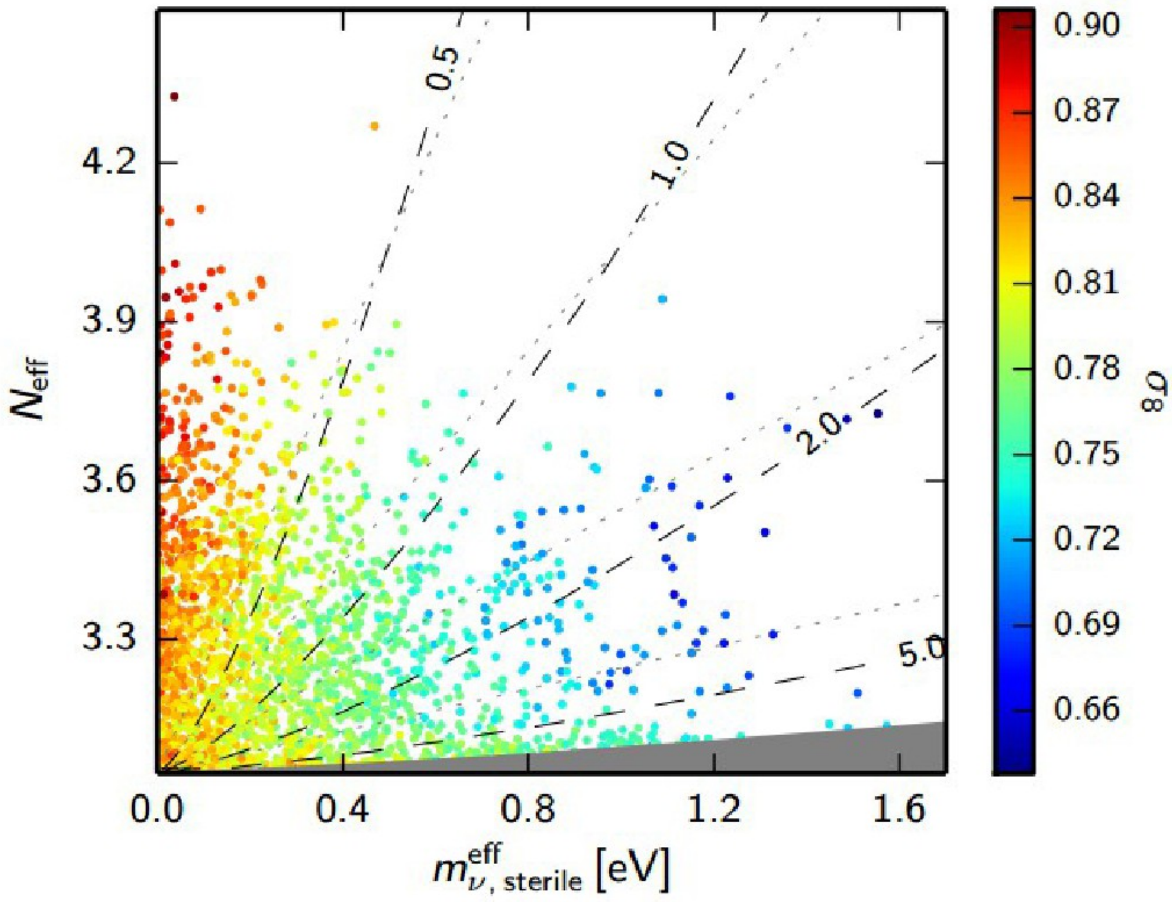
$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$

$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$

$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$

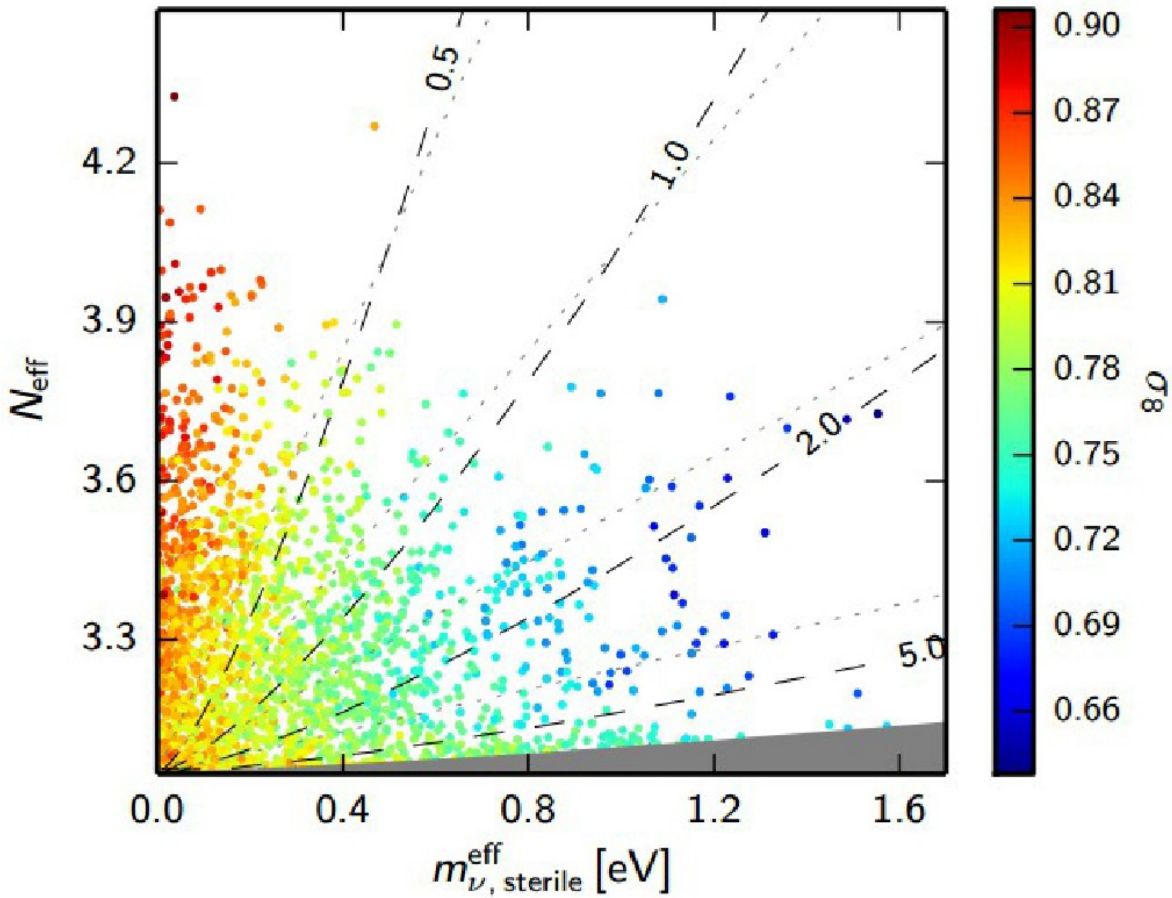
$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

Massive Sterile Neutrinos



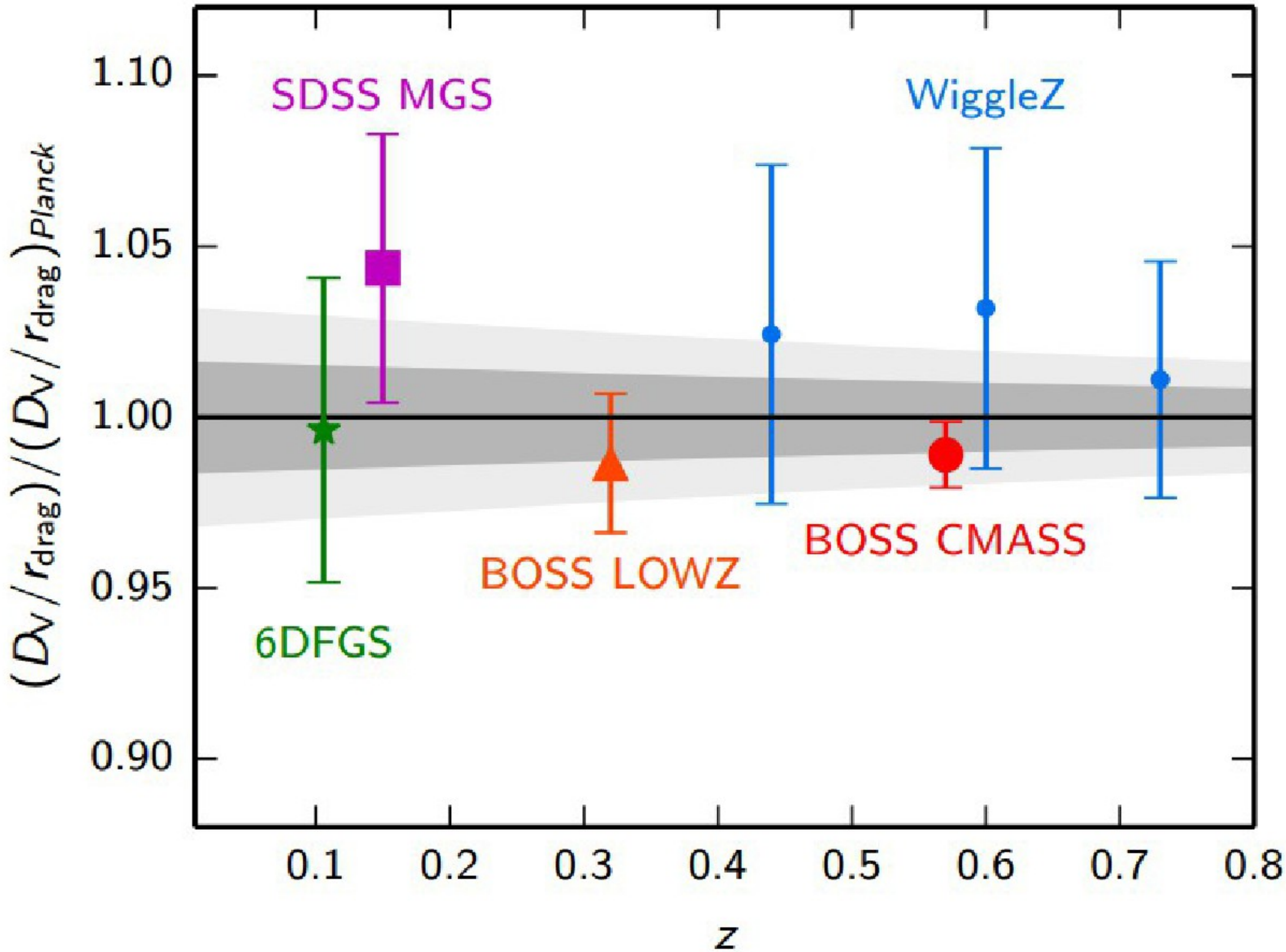
$$\left.\begin{aligned} N_{eff} &< 3.7 \\ m^{eff}_{\nu,\,sterile} &< 0.38 \text{ eV} \end{aligned}\right\} \quad 95\%, \textit{Planck} \text{ TT+lowP+lensing+BAO.}$$

Massive Sterile Neutrinos

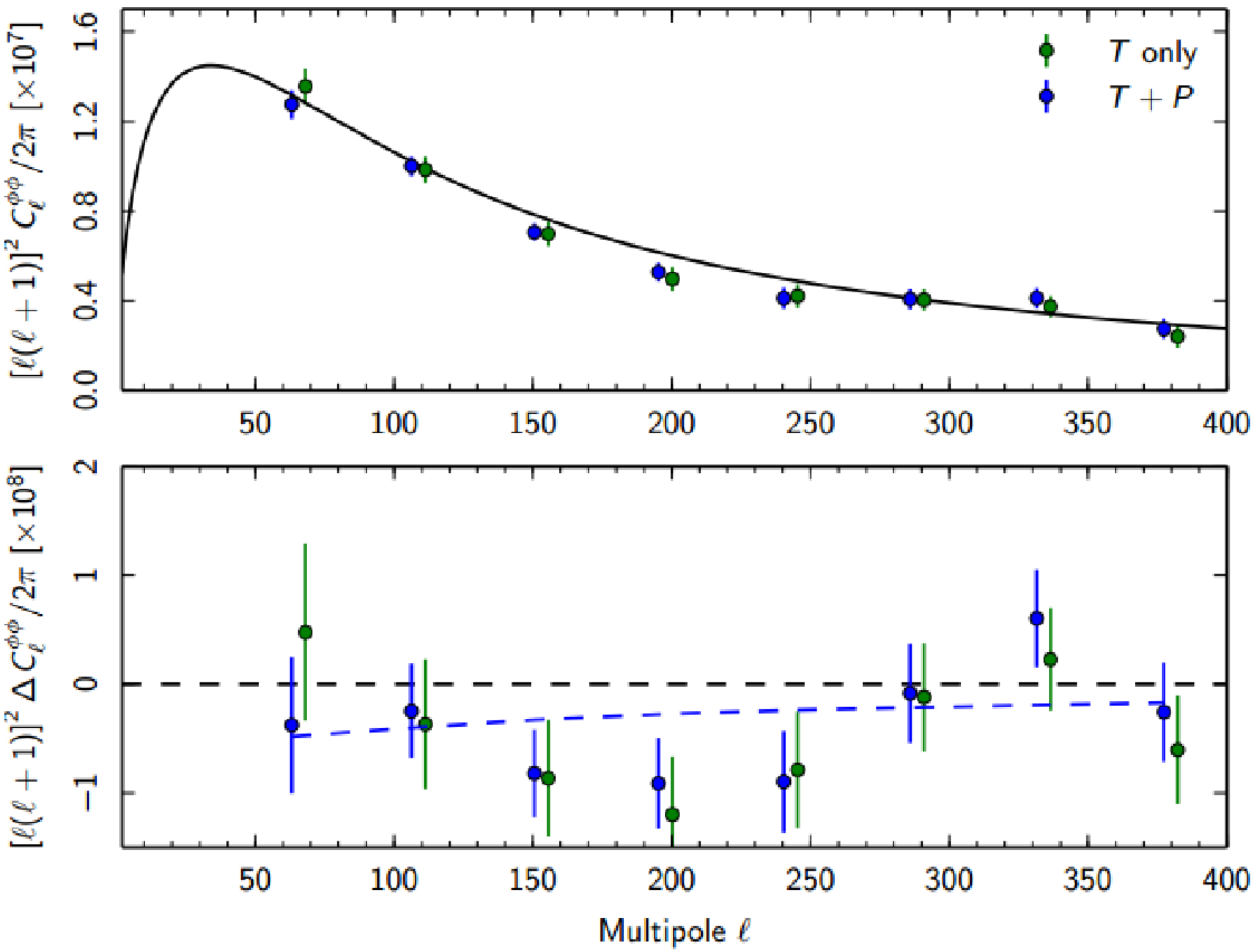


$$\left.\begin{aligned} N_{\rm eff} &< 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.38\ \text{eV} \end{aligned}\right\}\quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO}.$$

Consistency with other datasets...


SDSS MGS
WiggleZ
BOSS LOWZ
BOSS CMASS
6DFGS
1.10
1.05
1.00
0.95
0.90
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$(D_V/r_{drag})/(D_V/r_{drag})_{Planck}$
z

Small tension between Planck TT best fit (assuming LCDM) and CMB lensing dataset



Planck cosmology still in tension with:

- HST value of the Hubble constant
- Weak lensing data from CFHTlens survey
- SZ clusters counts
- Redshift space distortions

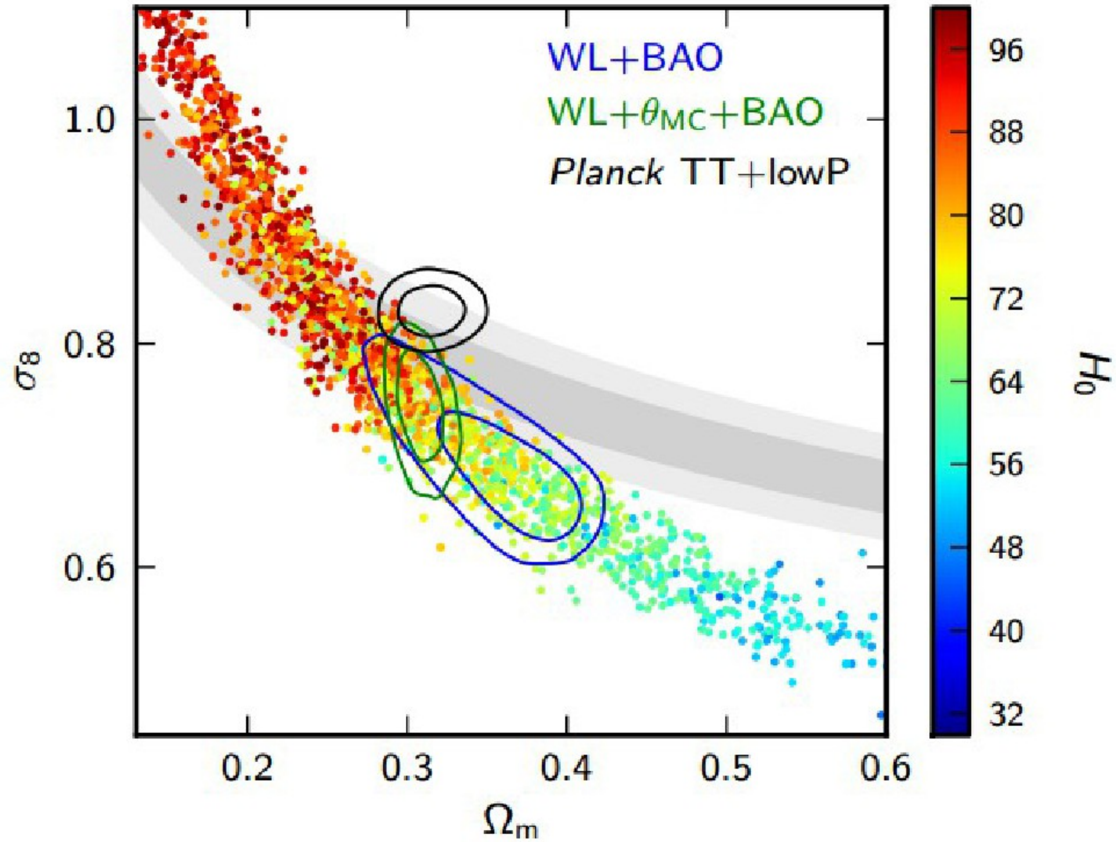
- HST value of the Hubble constant:
  $H_0 = (73.8 \pm 2.4)$ km $s^{-1}Mpc^{-1}$

Possible solution:

- In the paper we use the R11 Cepheid data reanalysed by Efstathiou (2014) using the revised geometric maser distance to NGC 4258 of Humphreys et al. (2013) as a distance anchor, finding a "conservative" H_0 prior:
  $H_0 = (70.6 \pm 3.3)$ km $s^{-1}Mpc^{-1}$
  which is within 1σ of the Planck TT estimate

$$H_0 = (69.7 \pm 2.1)\ \mathrm{km\,s^{-1}Mpc^{-1}}, \qquad \mathrm{WMAP9},$$
$$H_0 = (68.0 \pm 0.7)\ \mathrm{km\,s^{-1}Mpc^{-1}}, \qquad \mathrm{WMAP9{+}BAO}.$$

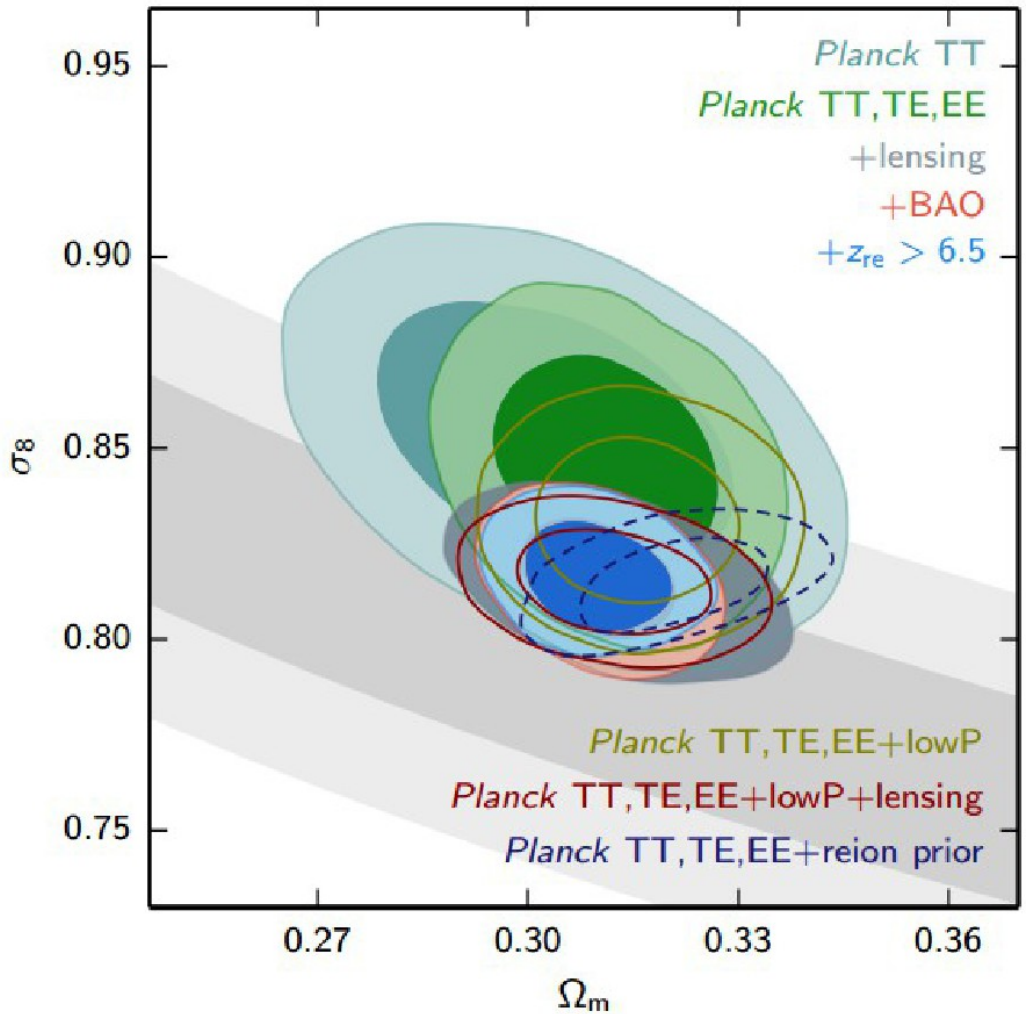
- Weak lensing data from CFHTlens survey.



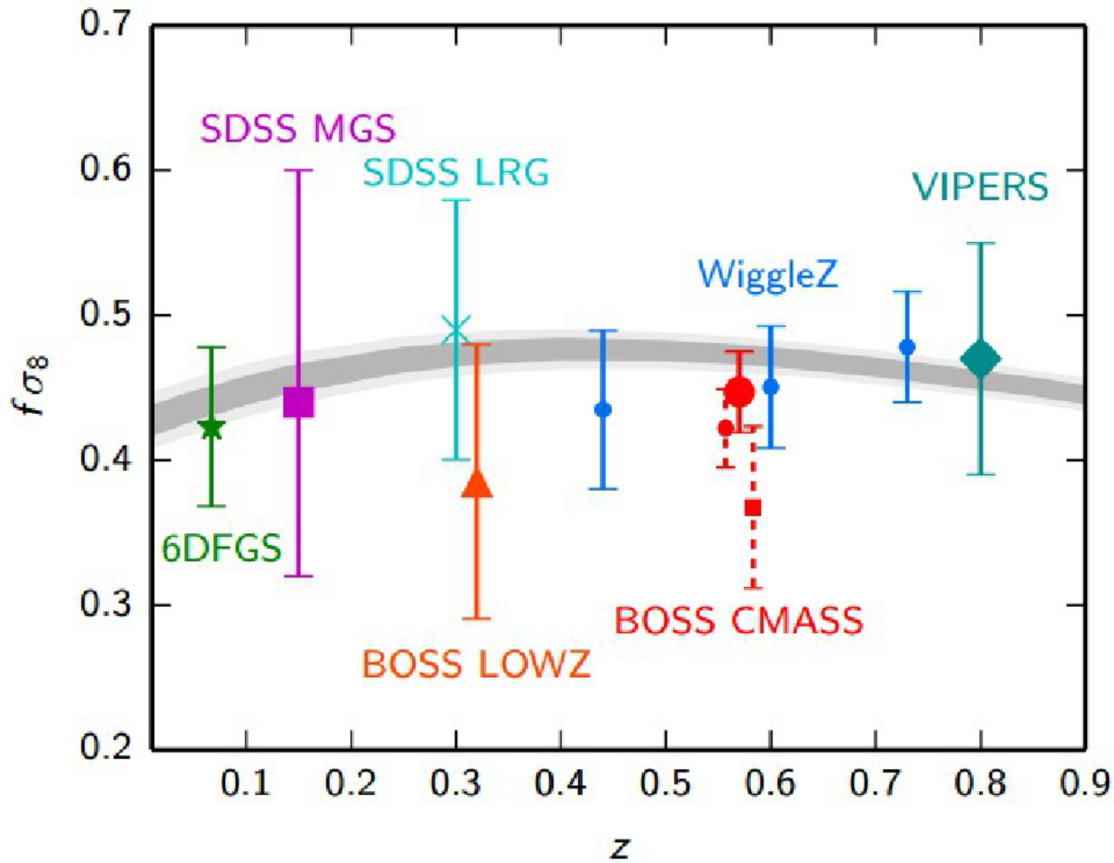
The grey band show the constraint from Planck CMB lensing.

SZ clusters counts

The Planck catalog consist of 439 clusters detected via their Sunyaev-Zeldovich (SZ) signal and prefers smaller value than Planck CMB for σ_8.



• Redshift space distortions



Constraints on the growth rate of fluctuations from various redshift surveys in the base ΛCDM model. The large red circle is BOSS CMASS, as analysed by Samushia et al. 2014, while the points with dashed red error bars correspond to alternative analyses of BOSS CMASS from Beutler et al. (2014b, small circle) and Chuang et al. (2013, small square). The BOSS CMASS points are based on the same data set and are therefore not independent. The grey bands show the range allowed by Planck TT+lowP+lensing in the base ΛCDM model.

Extending LCDM: going beyond 6 parameters

(in collaboration with Eleonora Di Valentino and Joe Silk).

When we analyze current datasets we often limit ourselves to the 6 parameters of LCDM or to 1-2 parameter extensions to it.

Given the high quality of the new data we should extend the parameter space and analyze the data considering at the same time:

- Variation in the dark energy equation of state w

- Neutrino mass.

- Neutrino effective number

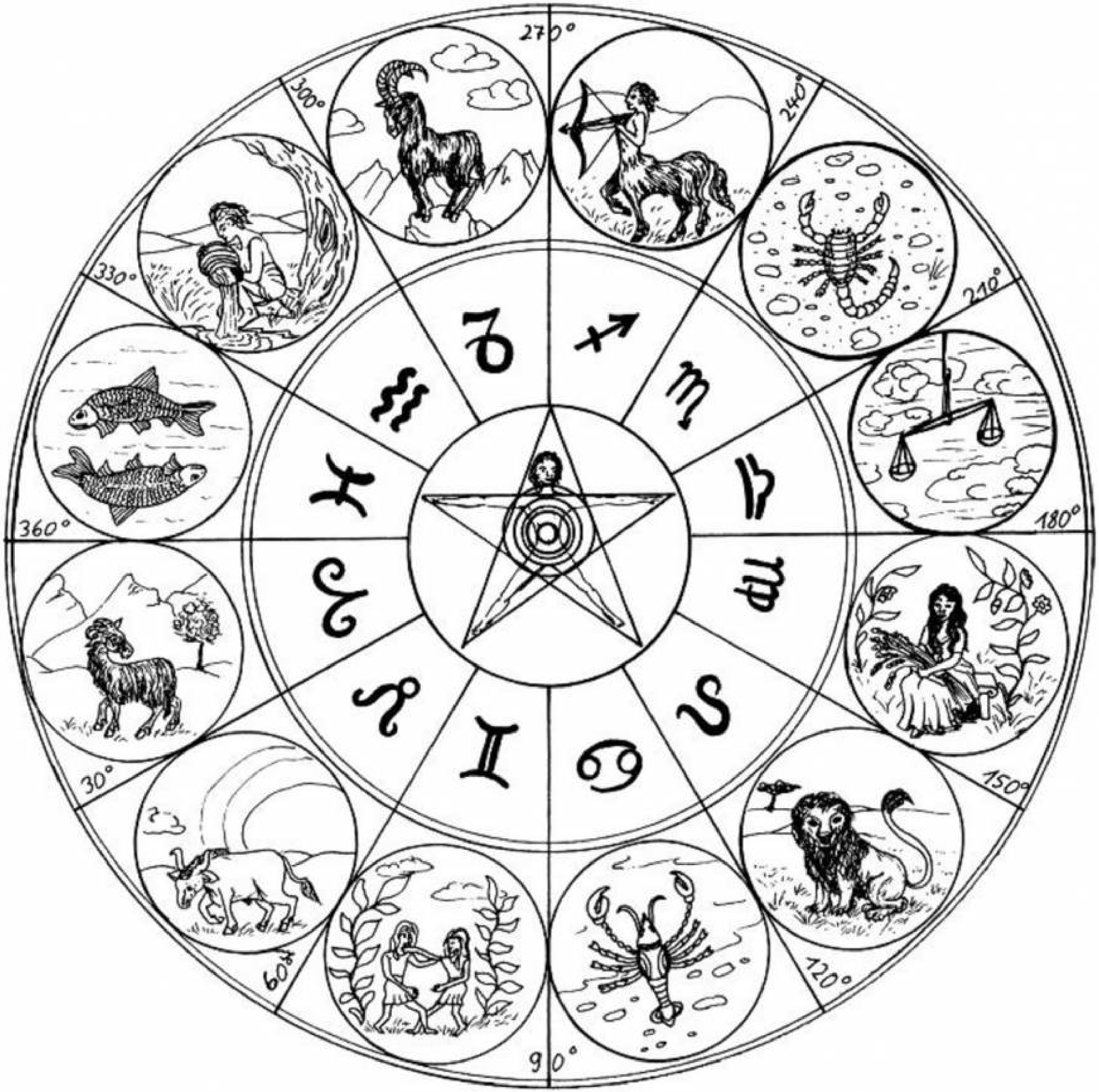
- Gravitational waves (tensor component)

- Running of the primordial spectral index.

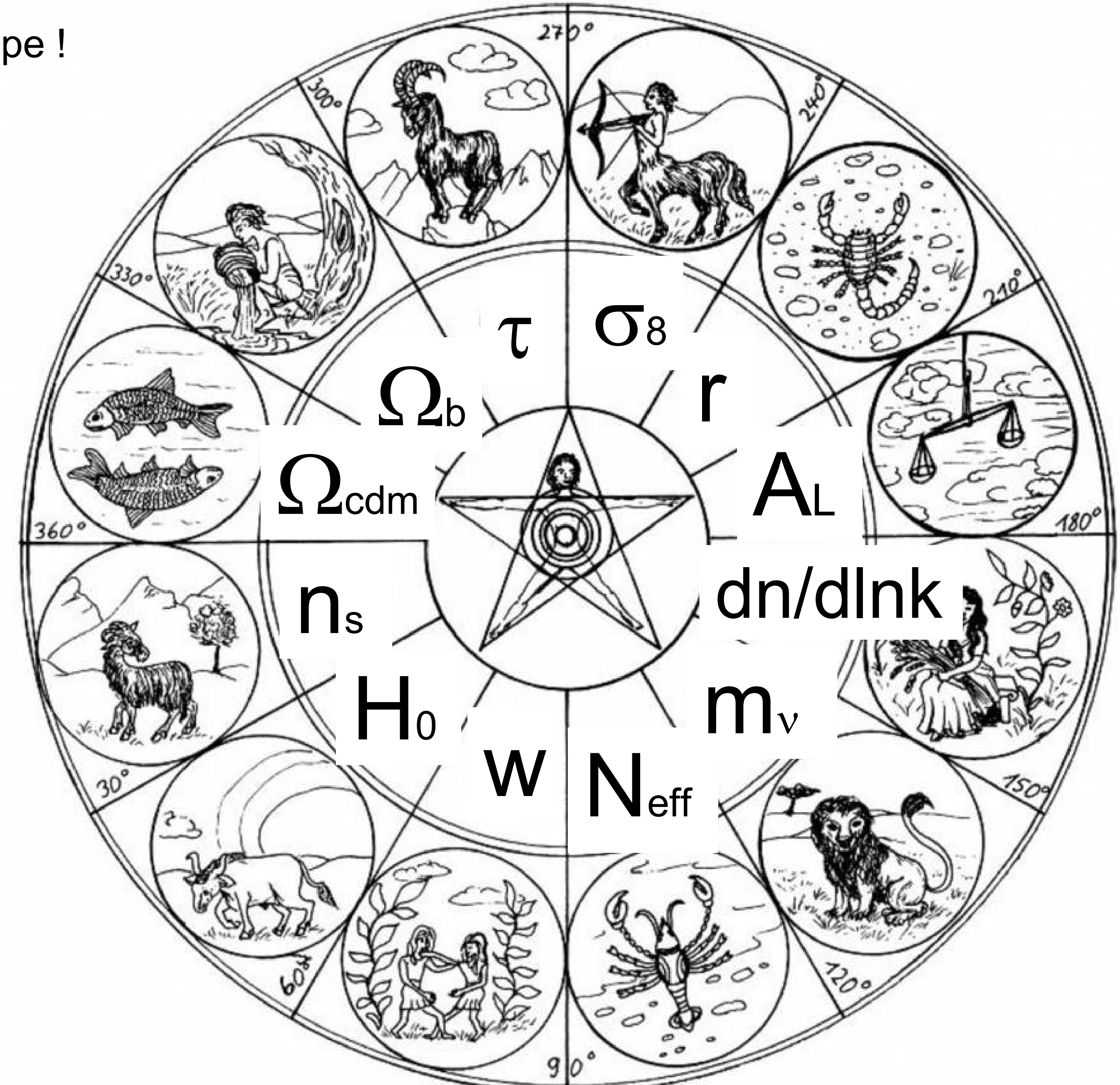
- Lensing amplitude in the CMB angular spectra.

i.e. we should, at least, vary 12 cosmological parameters instead of just 6 !

Horo-scope

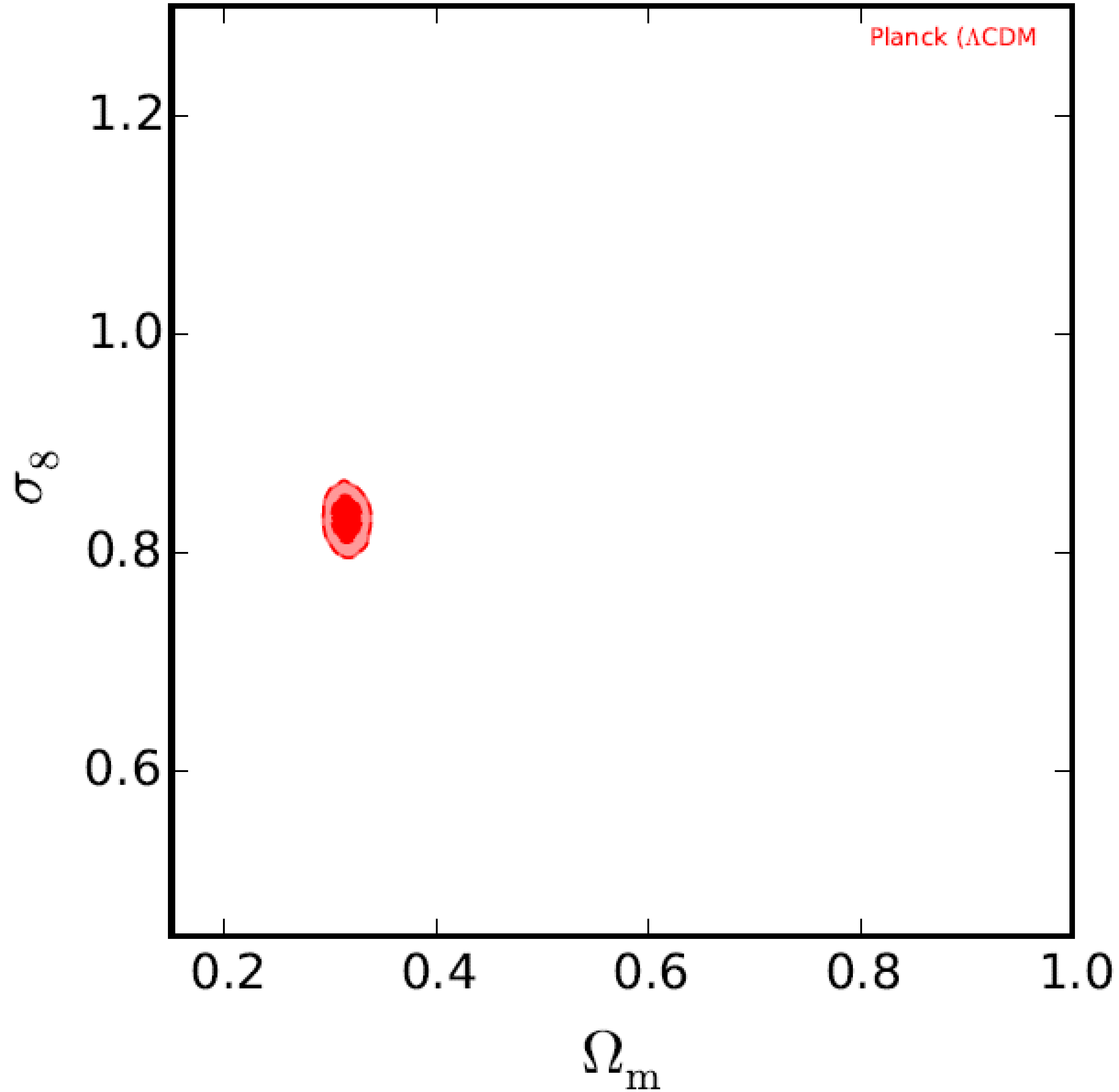


Cosmo-scope !

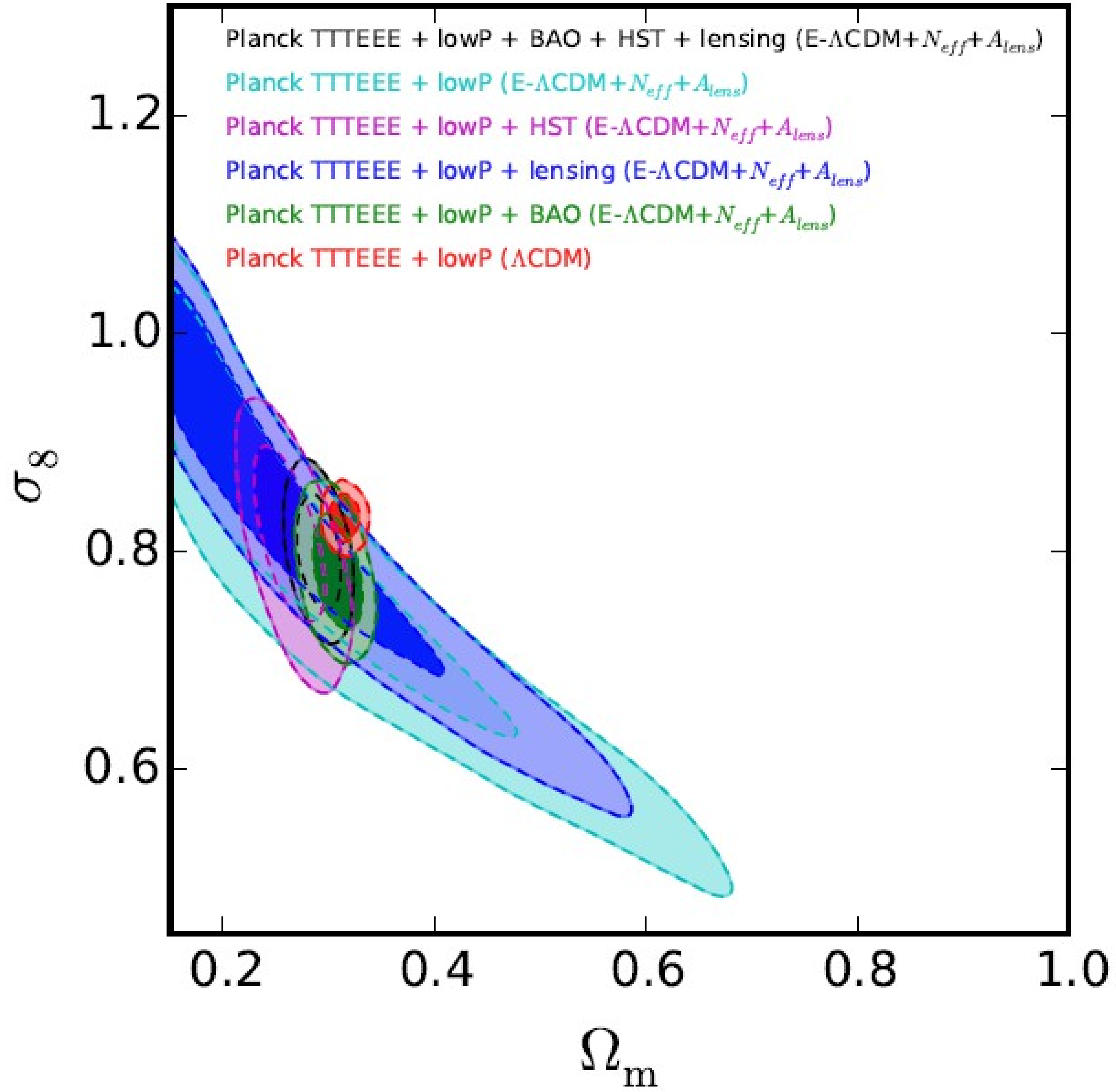


270°
240°
210°
180°
150°
120°
90°
60°
30°
360°
330°
300°
τ
σ_8
r
A_L
$dn/d\ln k$
m_ν
N_{eff}
w
H_0
n_s
Ω_{cdm}
Ω_b

Constraints from Planck assuming 6 parameters LCDM



Constraints from Planck assuming 12 parameters eCDM



Limits at 95 % c.l.

Model Dataset	$\Omega_b h^2$	$\Omega_c h^2$	H_0	τ	n_s	σ_8	$\frac{dn_s}{d\ln k}$	r	w	$\Sigma m_\nu [eV]$	$N_{\rm eff}$	$A_{\rm lens}$
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	$0.02239^{+0.00060}_{-0.00056}$	$0.1186^{+0.0071}_{-0.0068}$	> 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	$3.07^{+0.57}_{-0.55}$	$1.20^{+0.24}_{-0.22}$

Di Valentino, Melchiorri, Silk 2015 in prep.

Conclusions

- Planck 2015 provides excellent support to LCDM

- Polarization data significantly improves statistical errors on parameters.

- Lower optical depth respect to WMAP9 results (because of dust).

- Effective neutrino number strongly constrained and compatible with 3 standard relativistic neutrinos (at recombination !).

- Neutrino mass strongly constrained.

But …

LCDM relies on just 6 parameters, if we move to a more realistic “12” Parameters model:

- Lensing anomaly starts to be quite serious.
- Neutrino mass is weakly constrained (up to a factor 3 larger errors).
- optical depth is even lower.
- Neutrino effective number is only marginally affected.

… we need to move to larger parameter space !