Neutrino Cosmology (II)

Stanford, August 12th 2015

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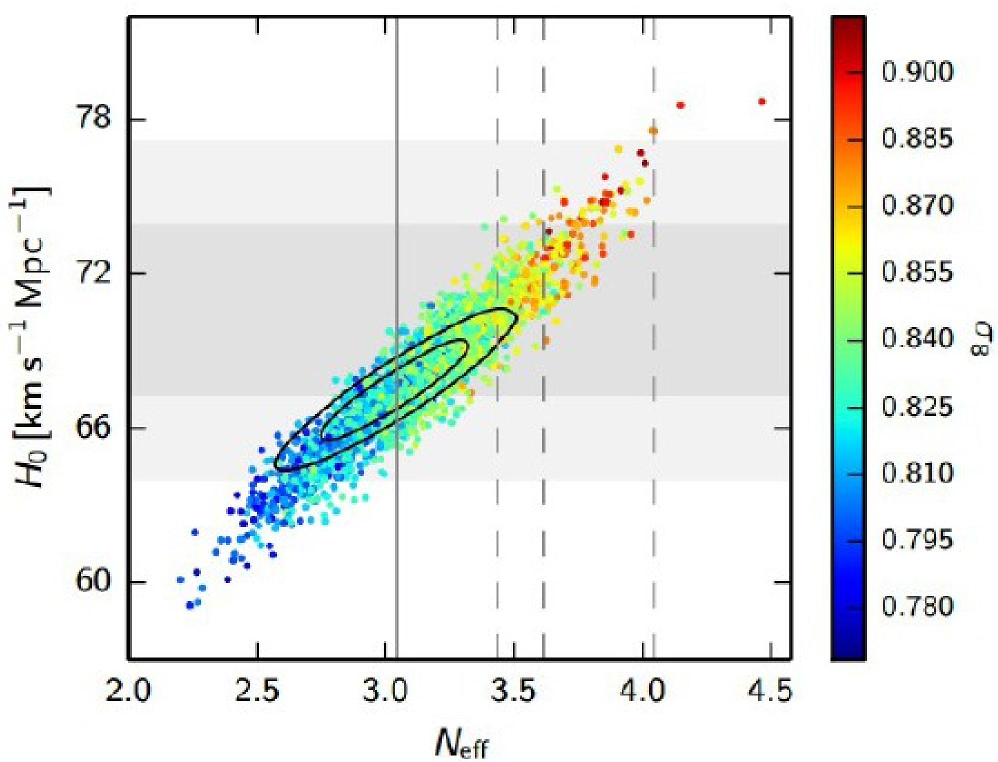
University of Rome “La Sapienza”

(Disclaimer: many thanks to Eleonora Di Valentino and Sergio Pastor for some of the slides)



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

Mechanisms for having $N_{eff}>3.046$

Non-standard decoupling (Mangano et al. 2006)

$N_{eff}\sim3.04-3.1$

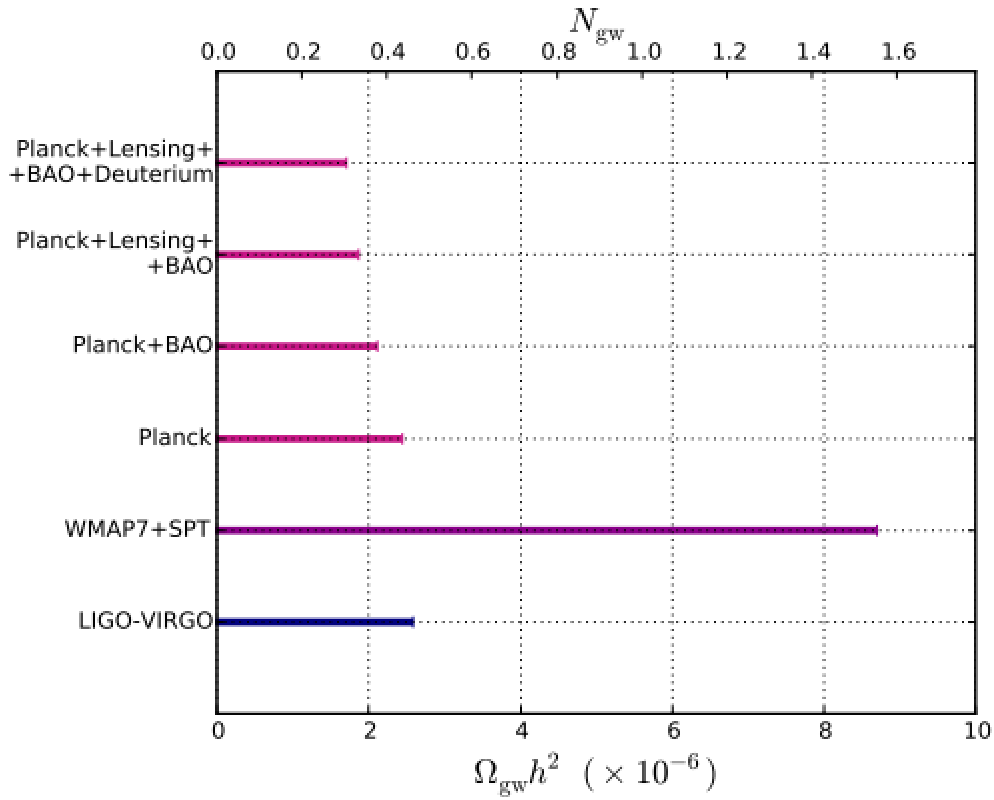
Thermal axions (see eg. Di Valentino et al. 2015)

Gravitational waves (Smith et al., 2006)

Extra dimensions

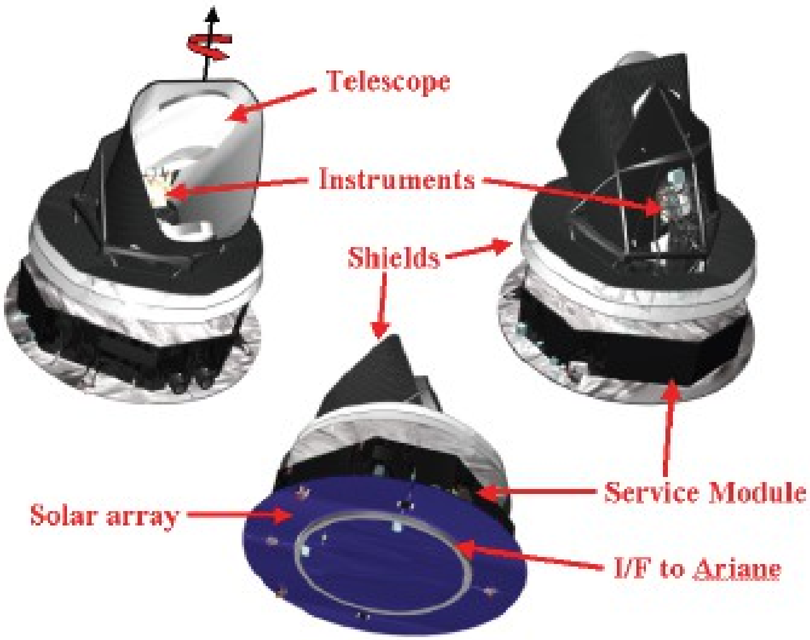
….

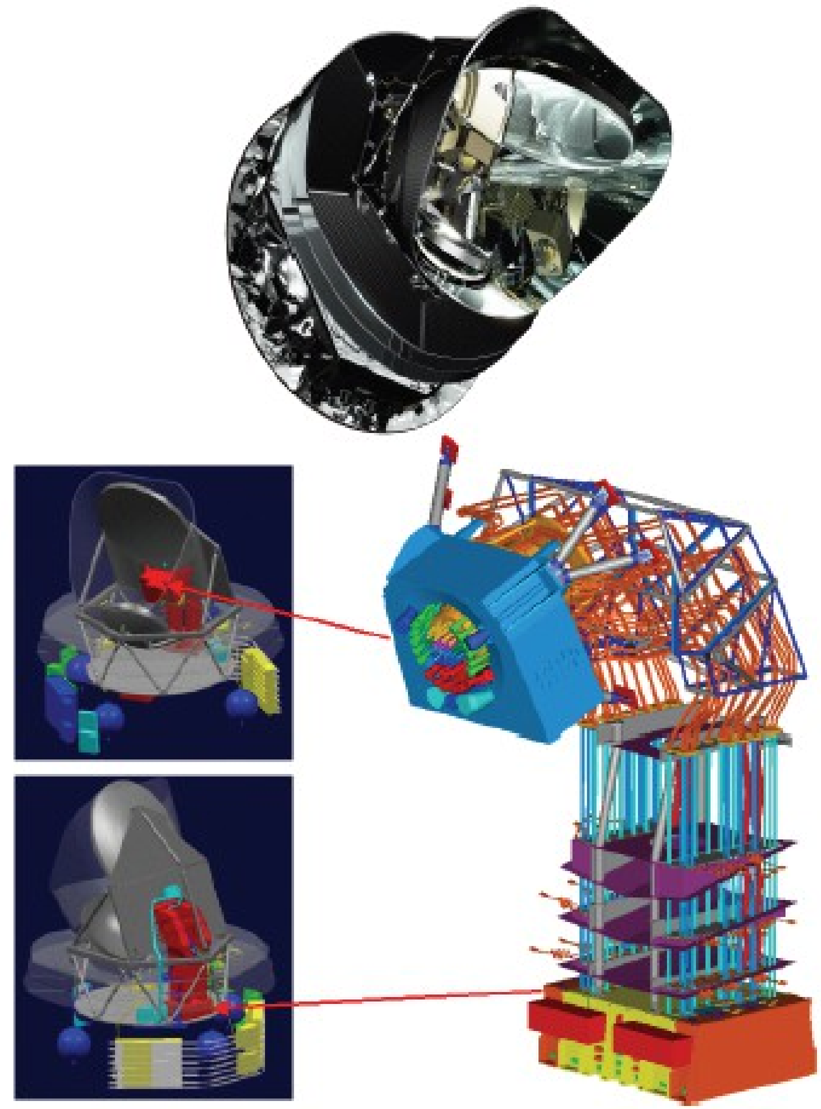
New constraints from Planck on GW



Pagano et al, arXiv:1508.02393

Planck in cartoons





Planck has two instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI) in a shared focal plane containing 74 channels and covering 8 degrees on the sky.

Planck being assembled

Planck in February 2009


Planck
Satellite launch
14/5/2009
esa

PLANCK'S LAST COMMAND

23 October 2013 ESA's Planck space telescope has been turned off after nearly 4.5 years soaking up the relic radiation from the Big Bang and studying the evolution of stars and galaxies throughout the Universe's history.

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
CERN Document Server ; ADS Abstract Service; Link to all figures including auxiliary figures; Interactions.org article

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
CERN Document Server ; ADS Abstract Service; Link to PRESSRELEASE; Interactions.org article

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
ADS Abstract Service

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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Ordinamento per: Le ultime all'inizio | disc. | numero citazioni

Visualizza risultati: 25 risultati | lista unica

HEP 12 record trovati La ricerca ha impiegato 25.19 secondi.

1. **Planck 2015 results. XIII. Cosmological parameters**
(535) 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**
(233) 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
ADS Abstract Service
Record dettagliato - Citato da 233 record 100+

3. **Joint Analysis of BICEP2/*Keck Array* and *Planck* Data**
(168) BICEP2 and Planck Collaborations (P. A. R. Ade (Cardiff U.) *et al.*). Feb 2, 2015. 17 pp.
Published in **Phys.Rev.Lett. 114 (2015) 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**
(162) 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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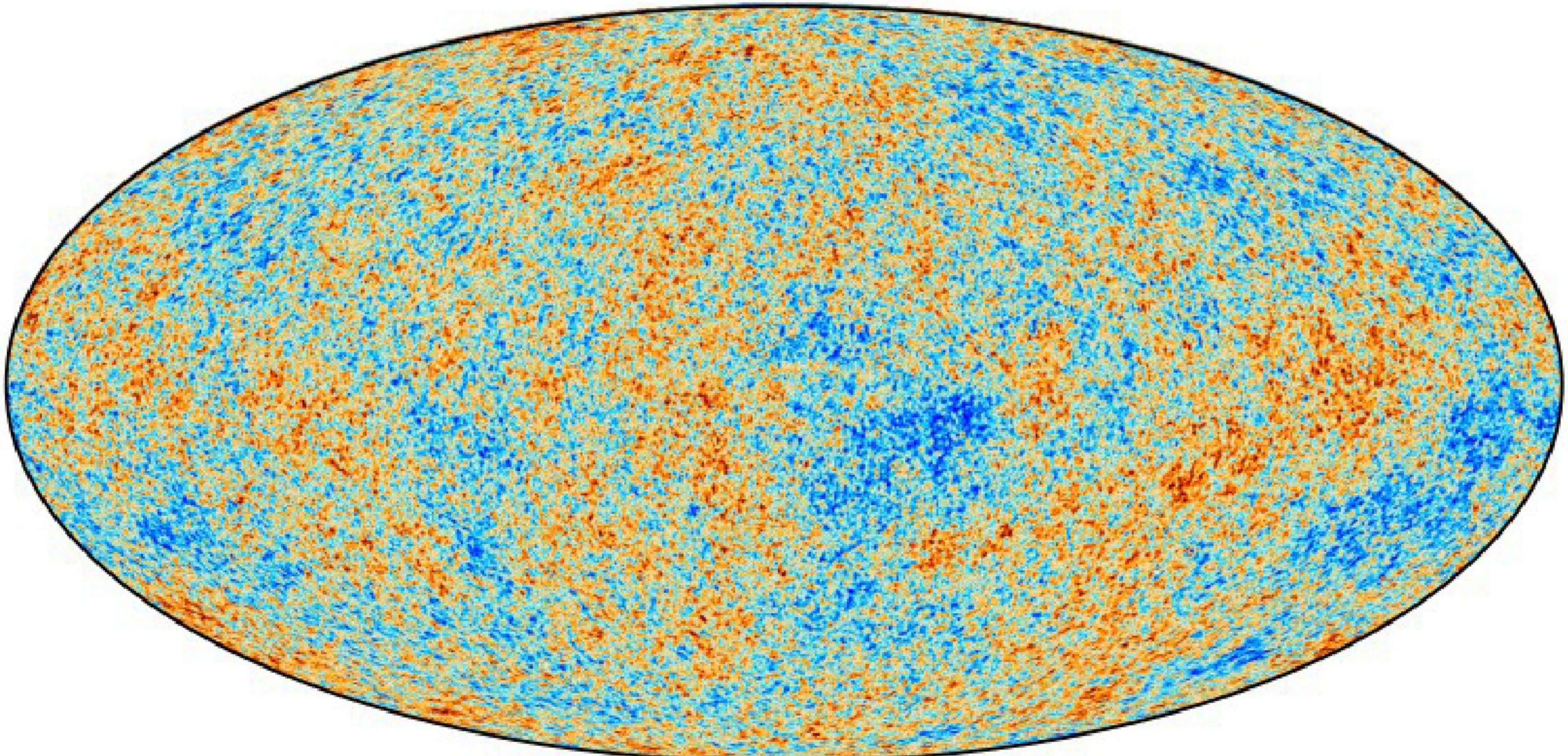
Planck 2015 CMB Temperature map

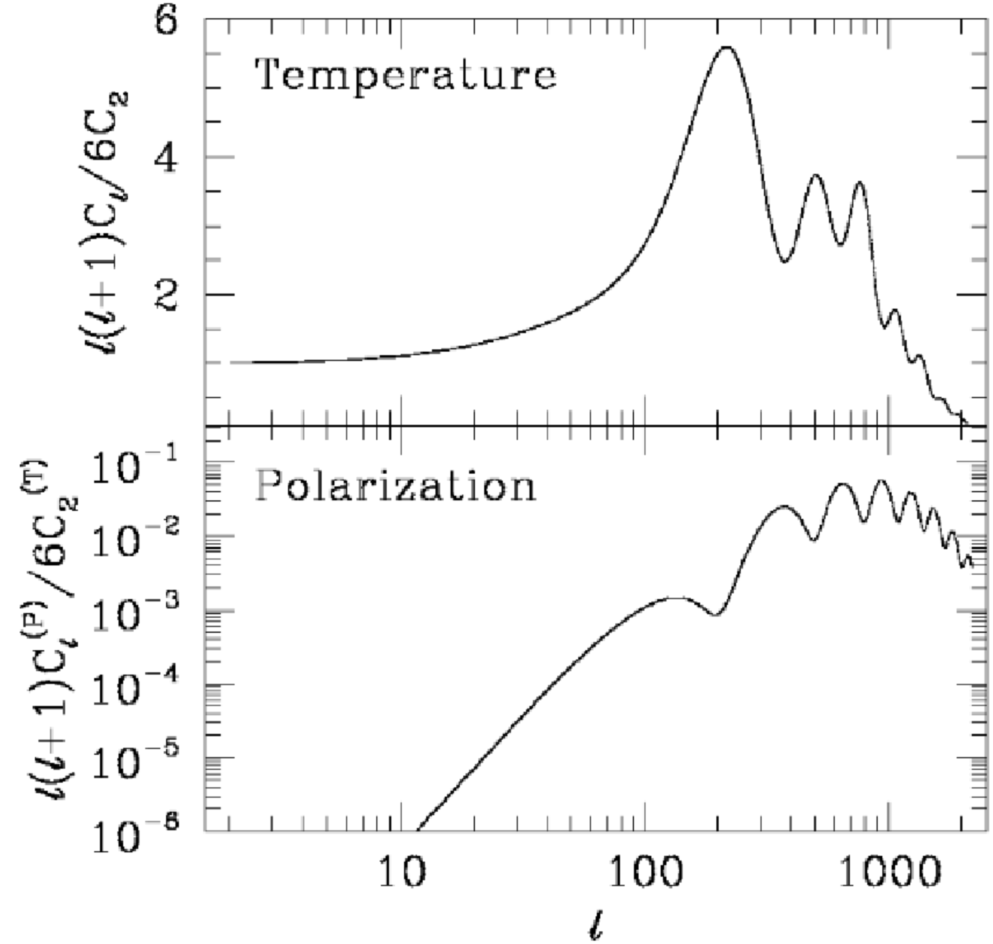


The CMB Angular Power Spectrum

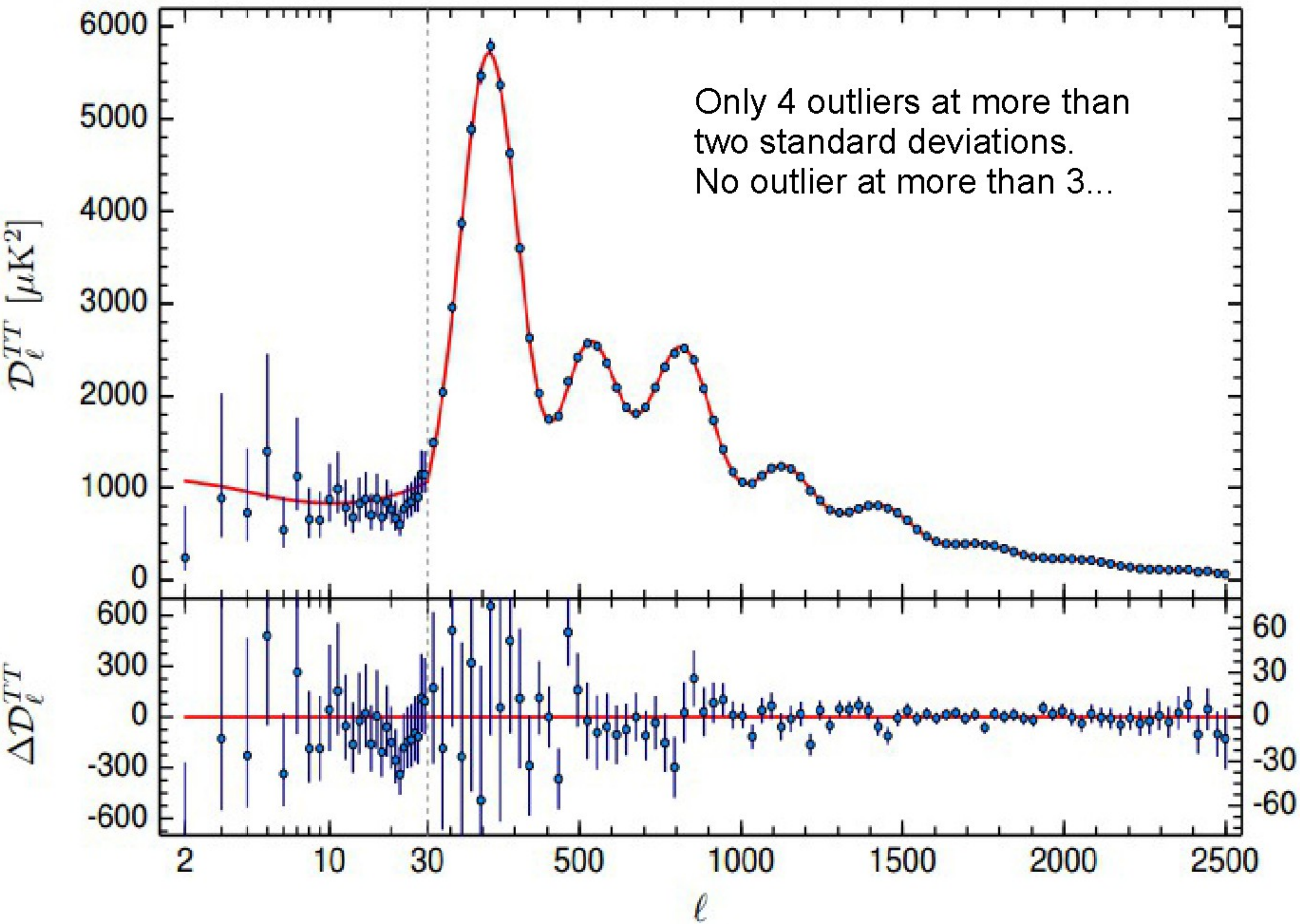
$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)\,C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$

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

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



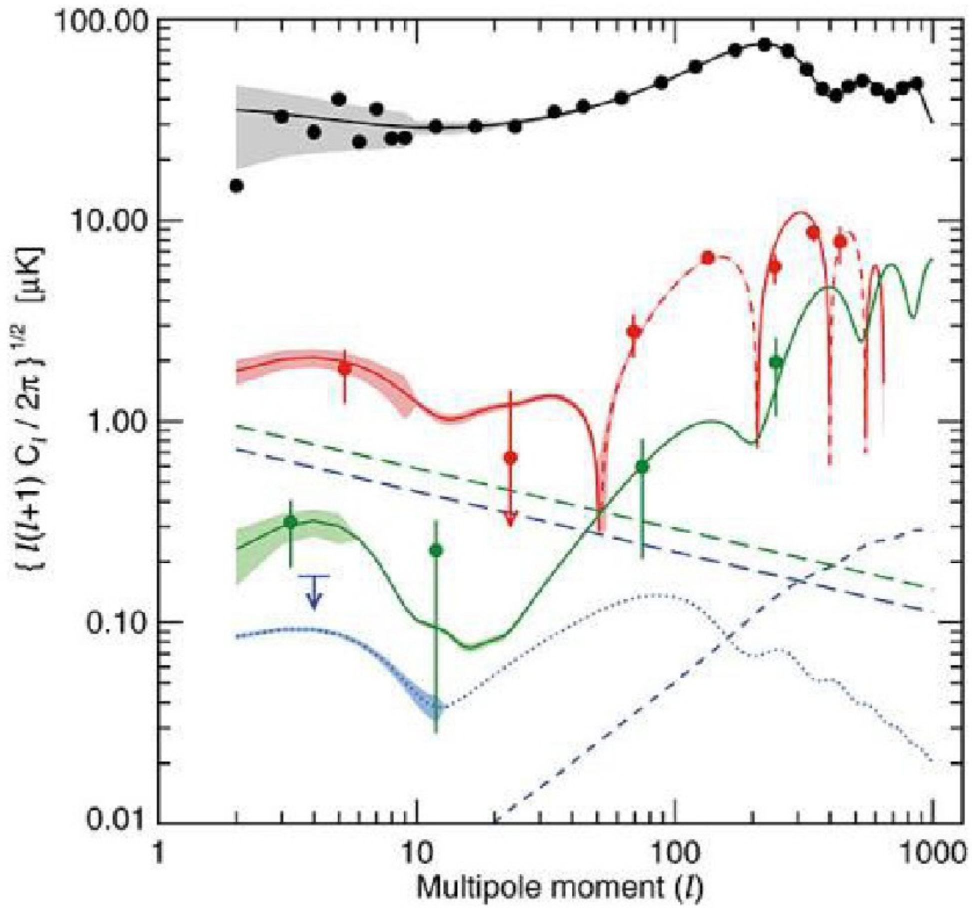
Planck 2015 Temperature Angular Spectrum



The CMB Angular Power Spectrum

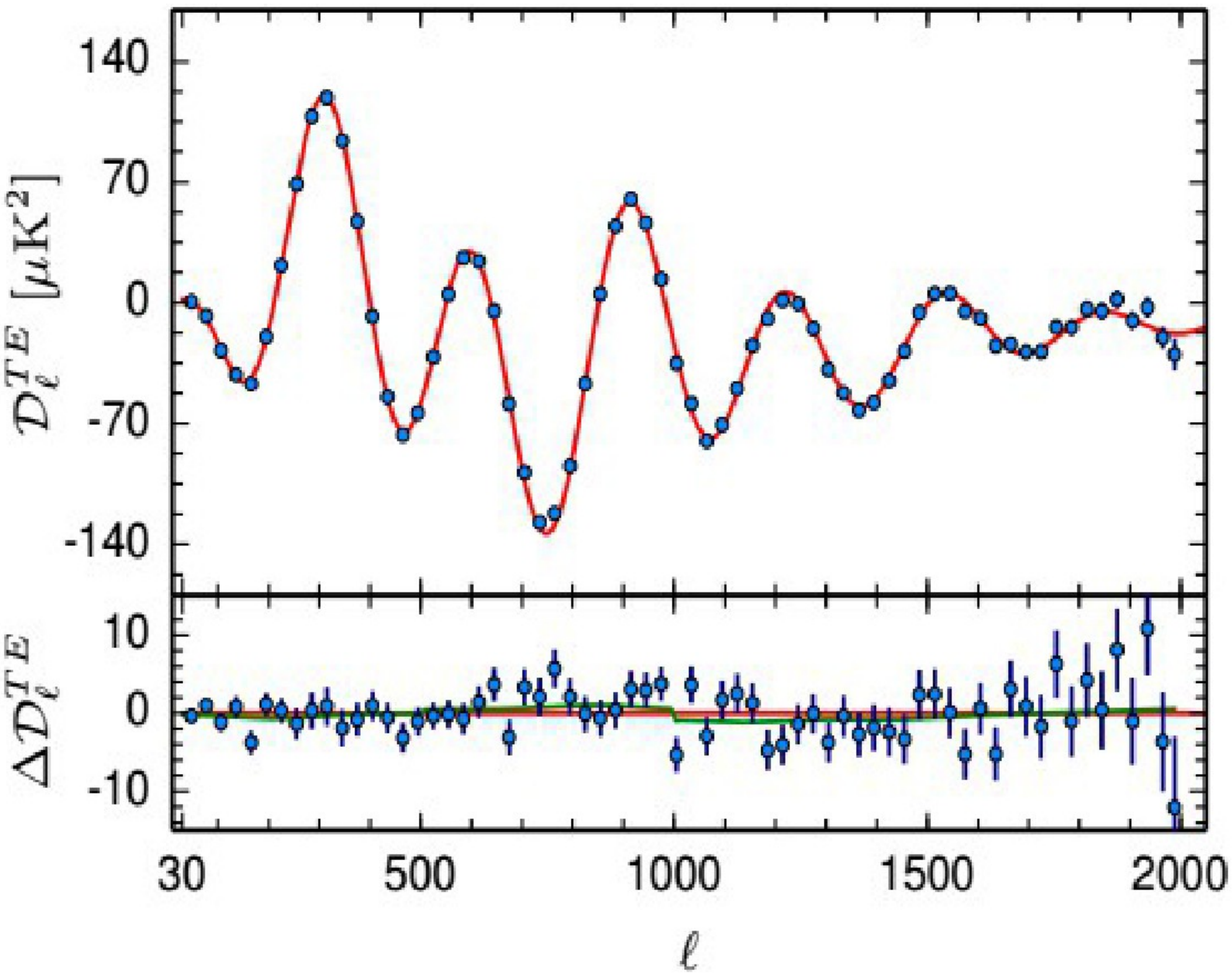
We can extract 4 independent angular spectra from the CMB:

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



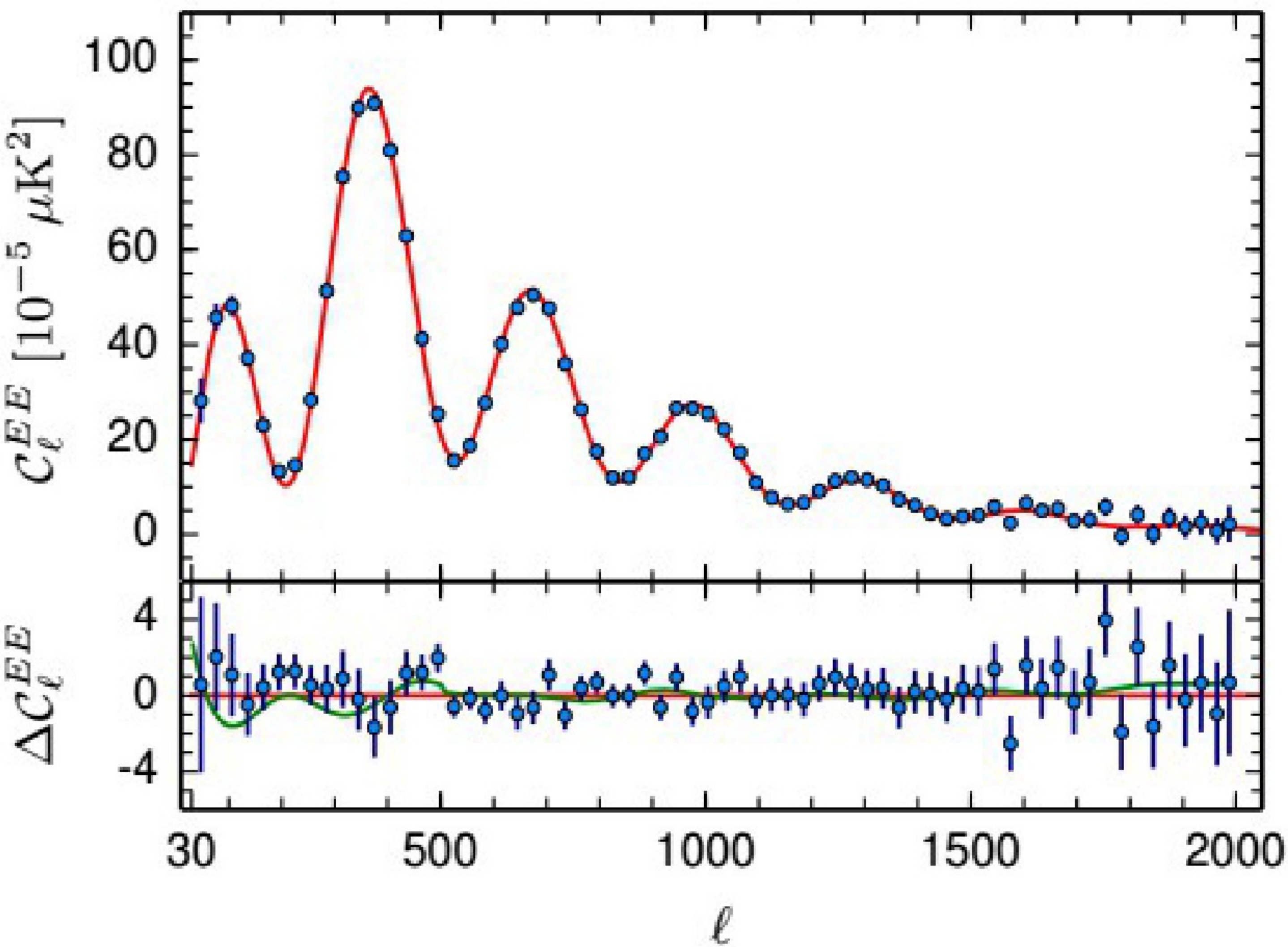
Planck 2013 release was only temperature ps.
Planck 2015 now includes polarization !

Planck 2015 TE angular spectrum



Red Line: Best fit to the TT angular spectrum

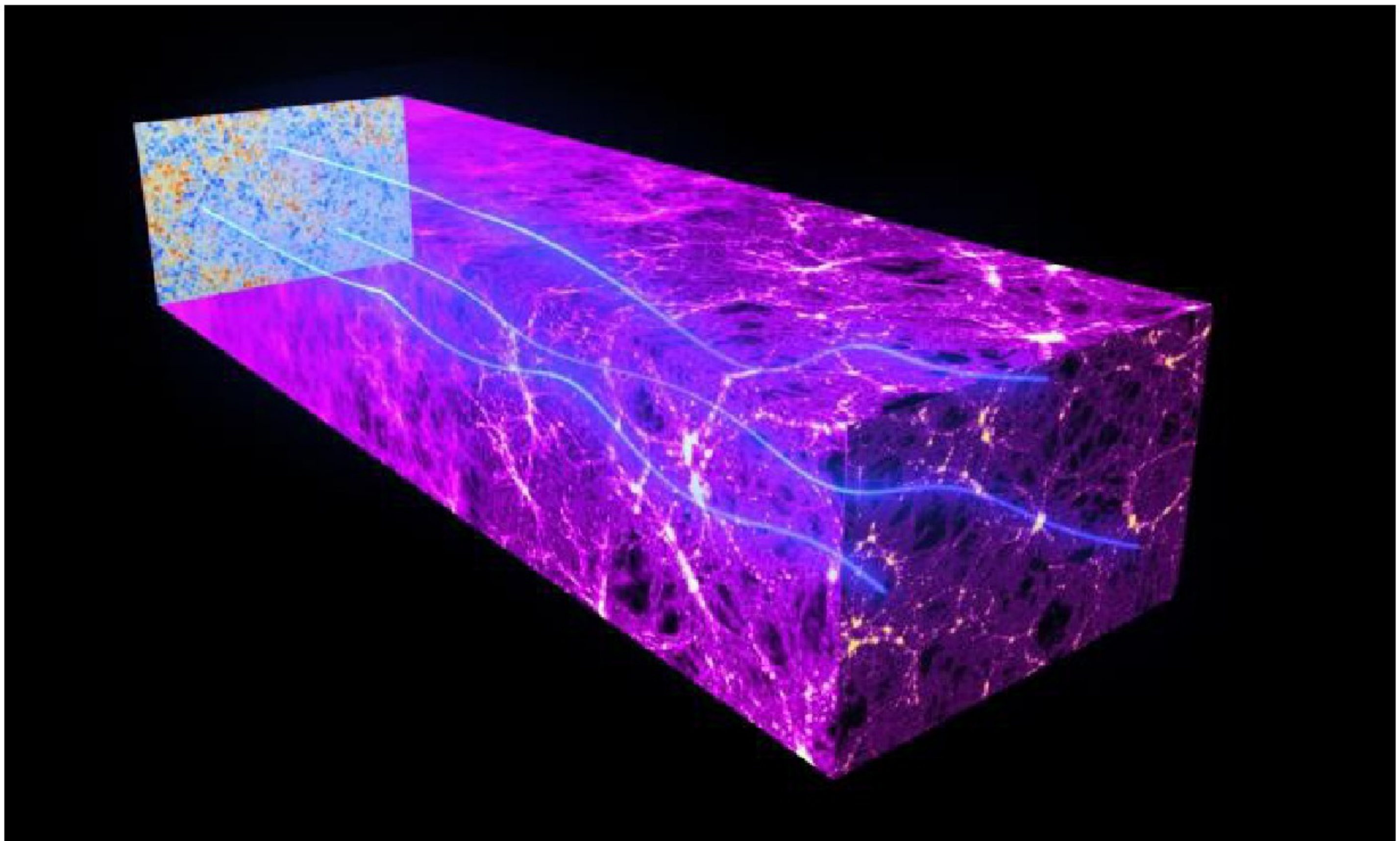
Planck 2015 EE angular spectrum



Red Line: Best fit to the TT angular spectrum

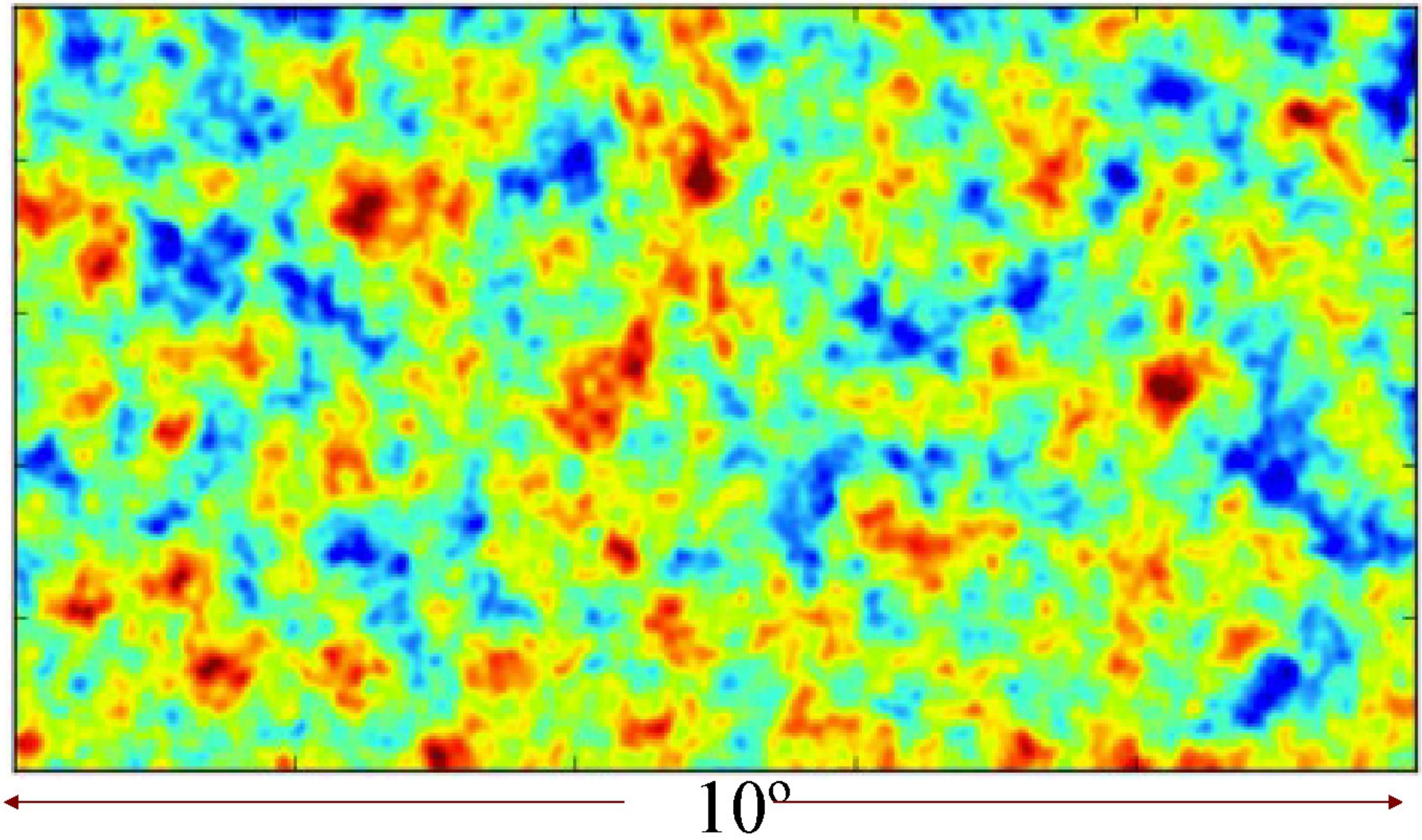
Gravitational Lensing

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



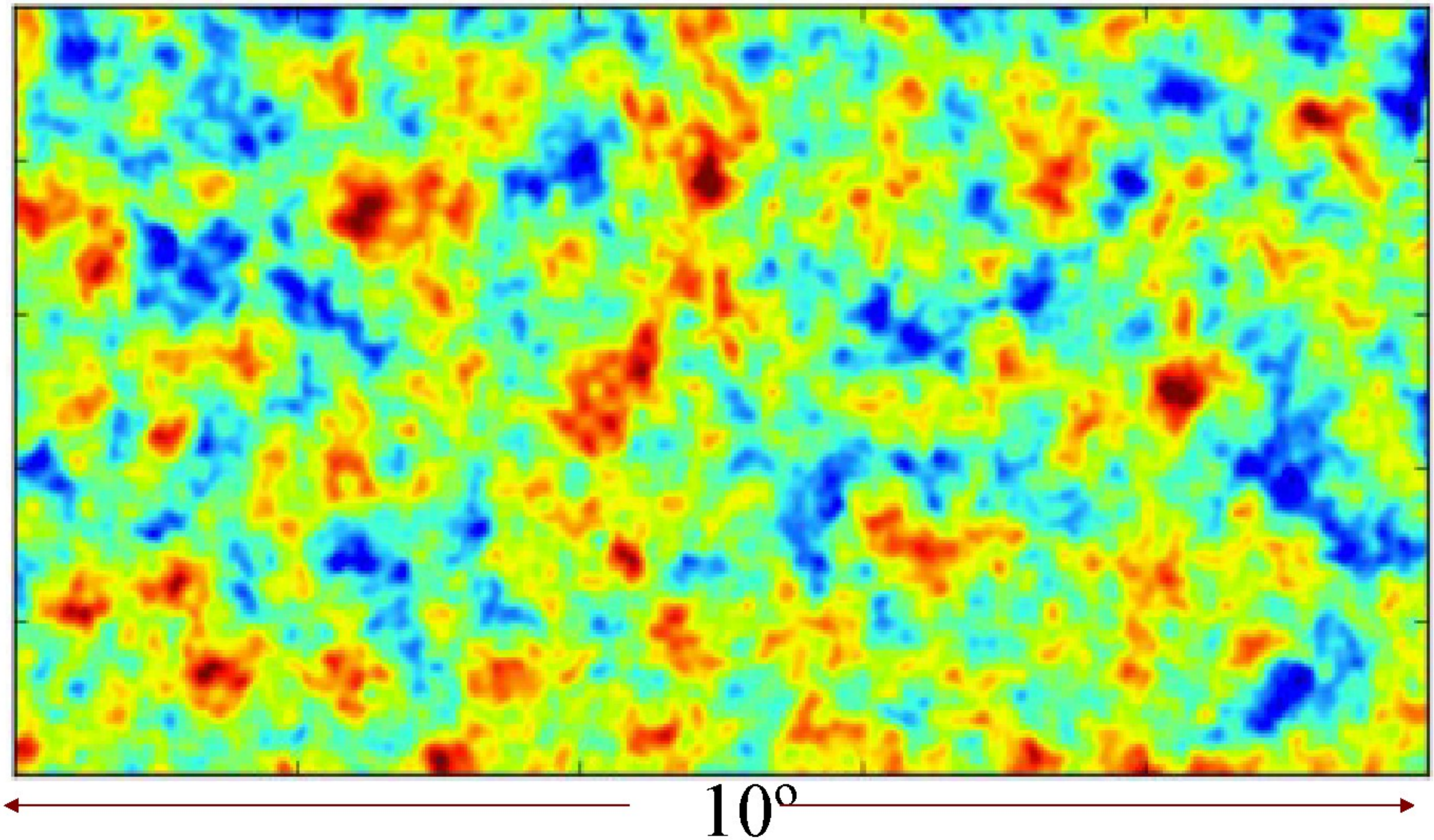
Gravitational Lensing

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

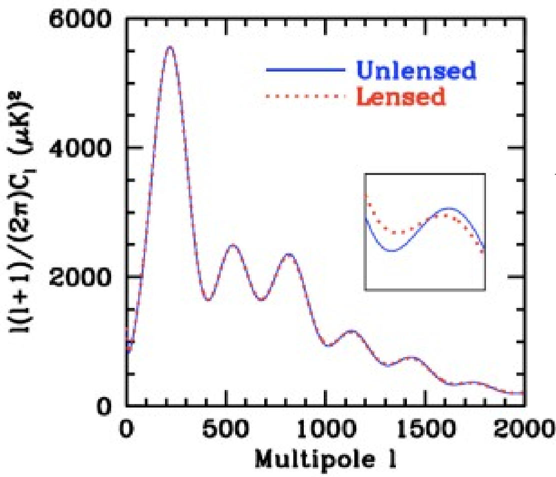


Gravitational Lensing

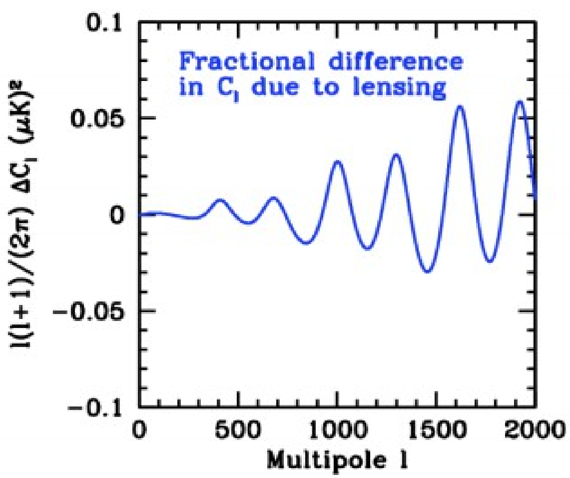
A simulated patch of CMB sky – **after lensing**



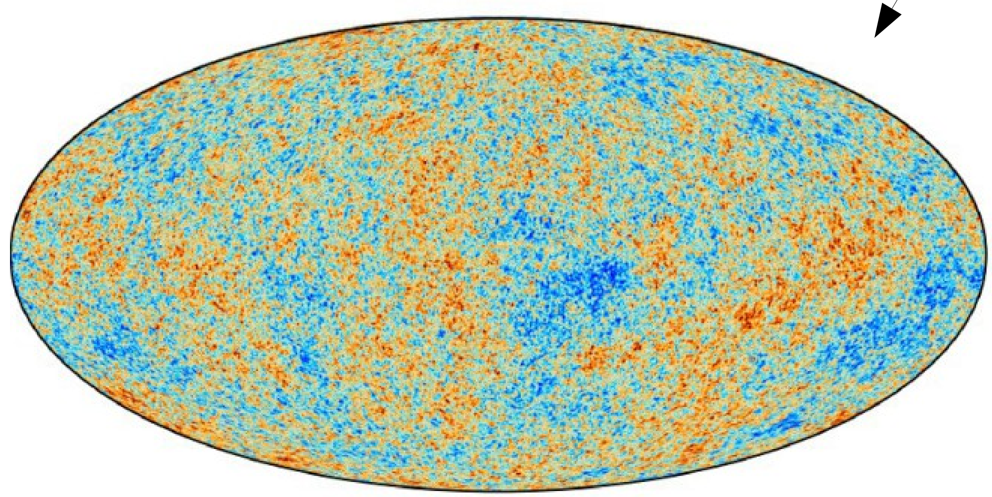
Extracting Lensing Signal from the CMB



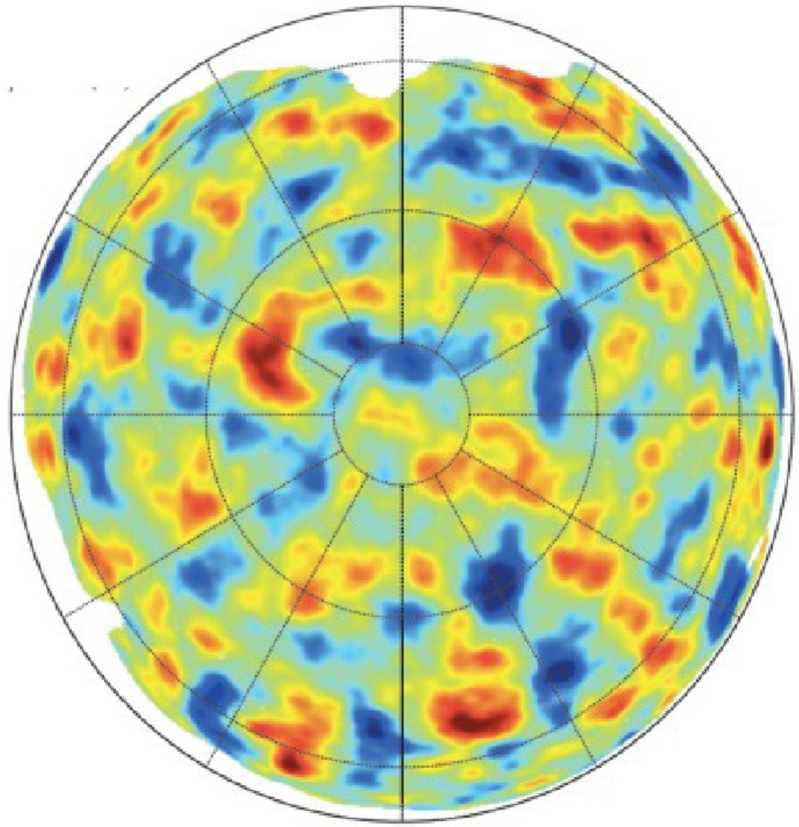
Extraction at Angular Spectrum Level
Effects on CMB angular spectrum.
More massive neutrinos → less lensing.



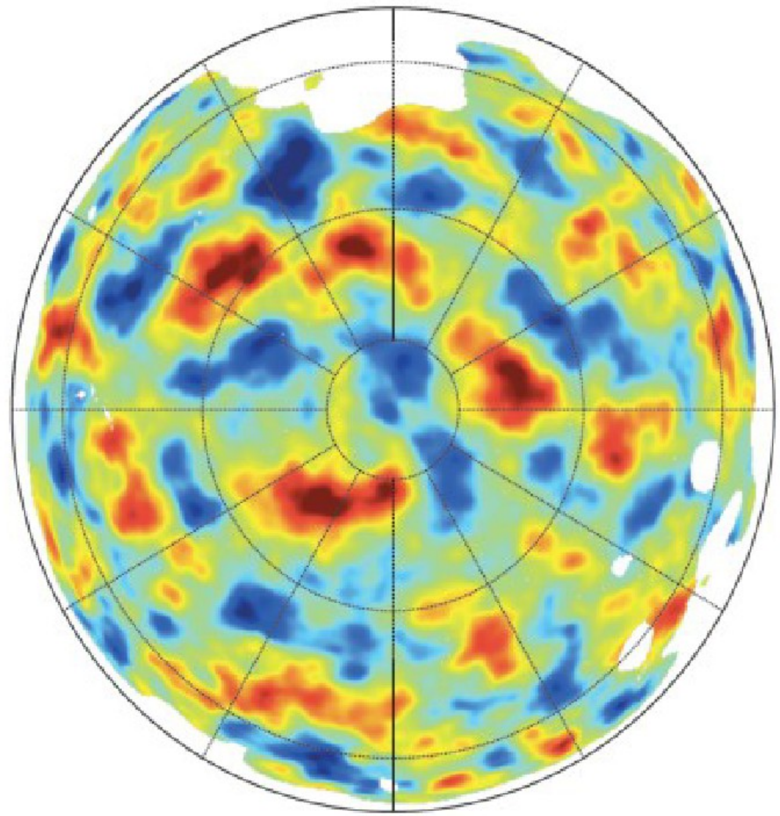
Extraction at map level.
Lensing introduce a correlation between Cl's.
This creates a non-zero trispectrum (4-point c.f.).



Planck dark matter distribution throught CMB lensing

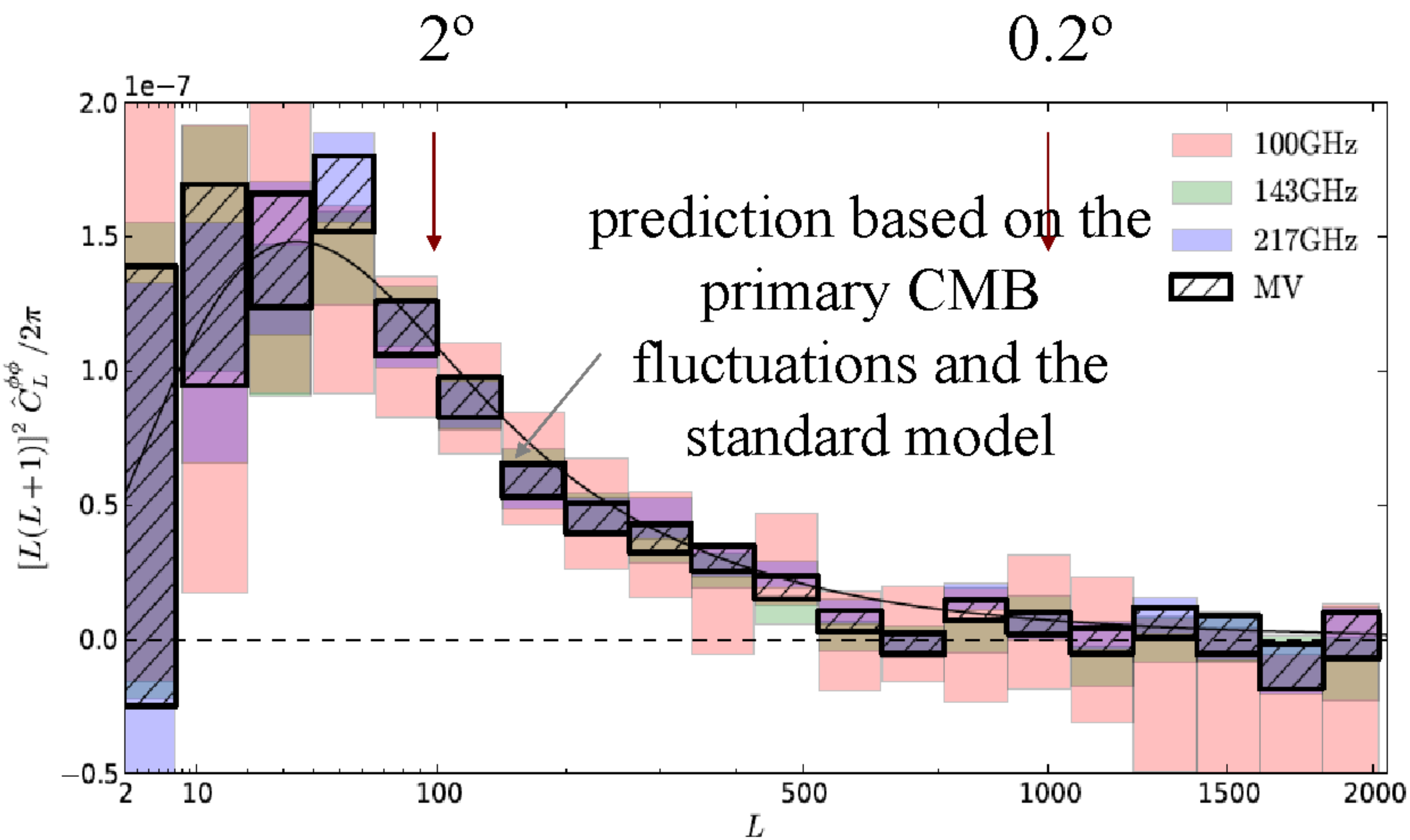


Galactic North



Galactic South

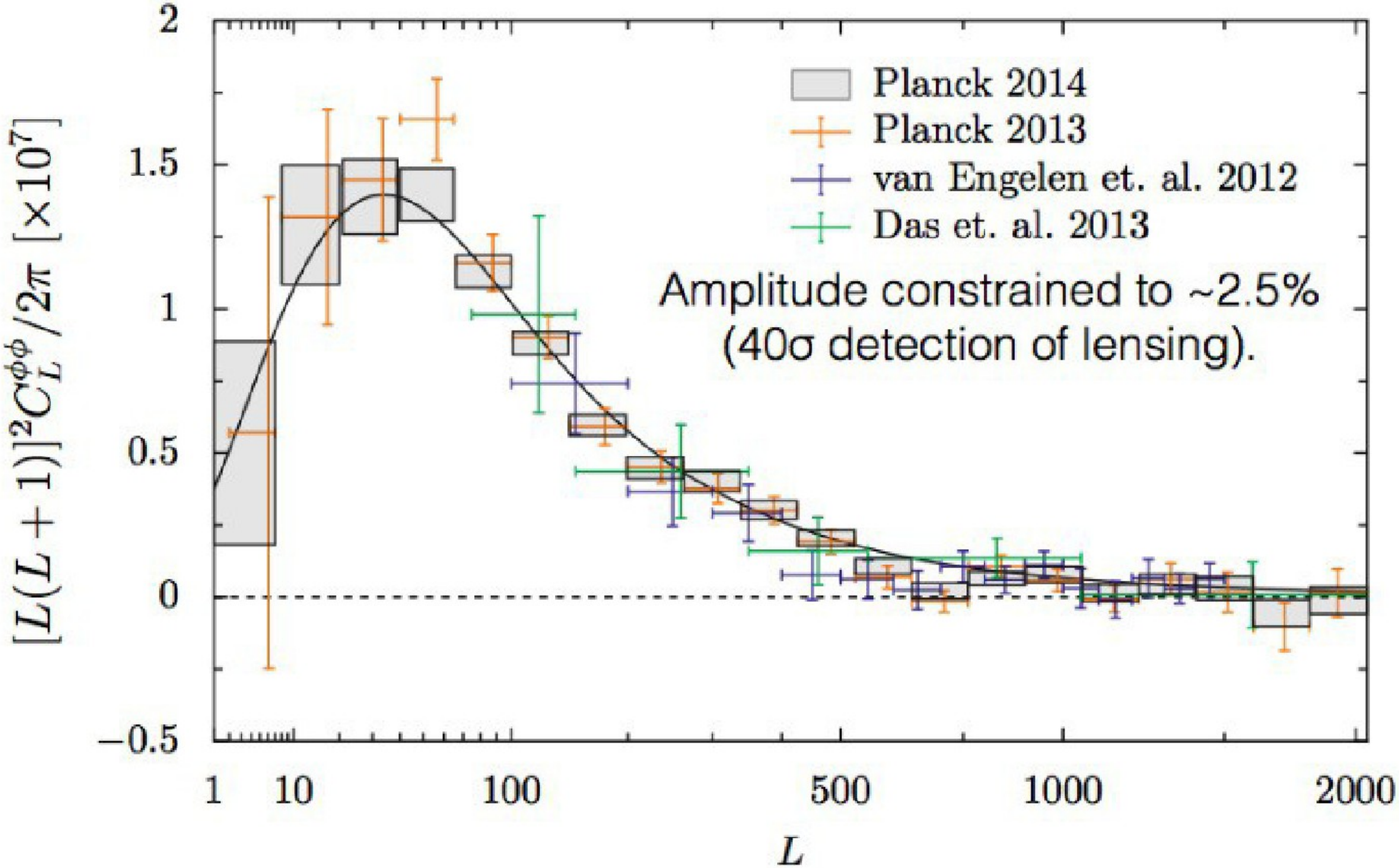
PLANCK LENSING 2013 Power Spectrum Measured from the Trispectrum (4-point correlation)



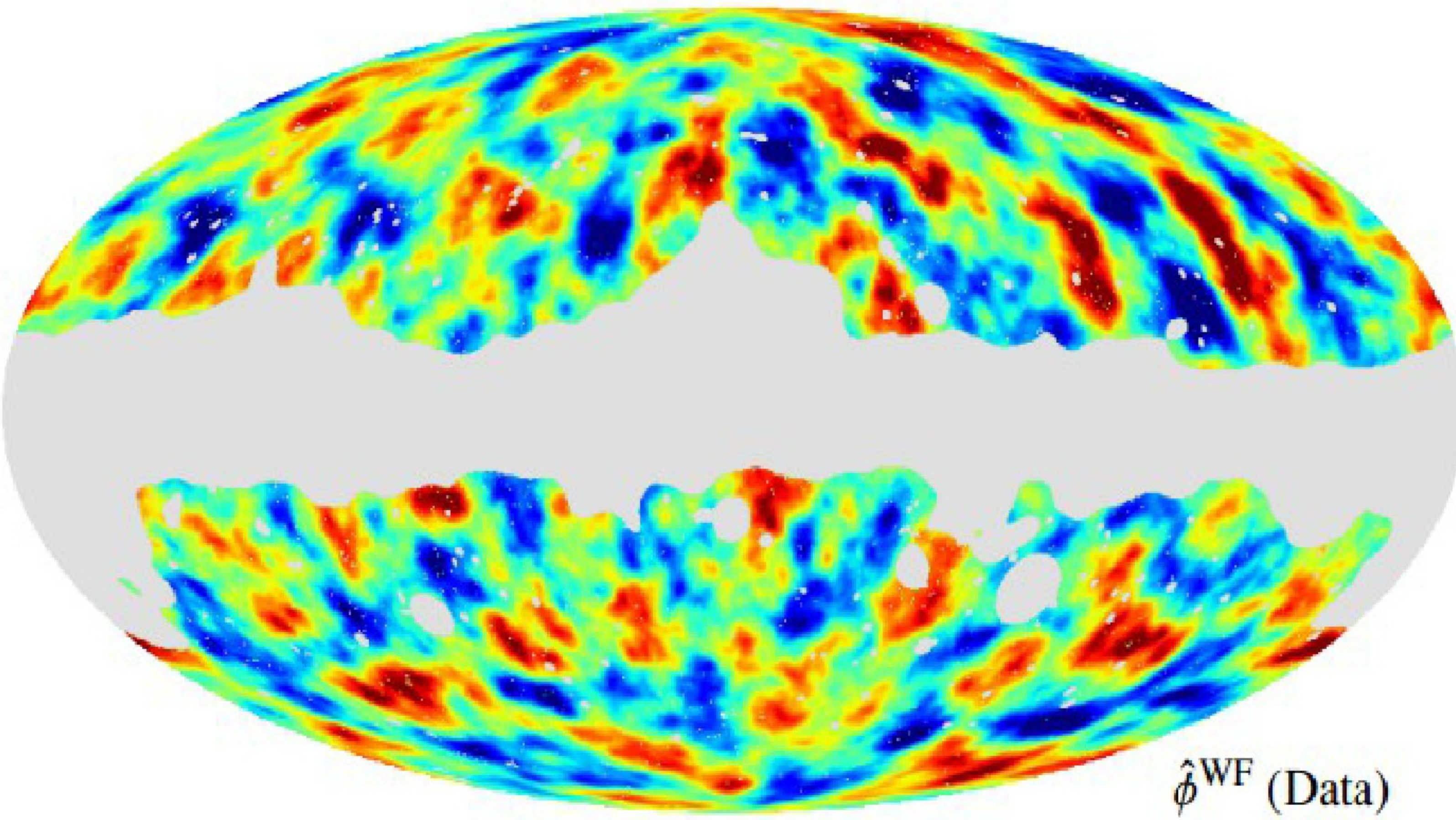
It is a 25 sigma effect!!

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.

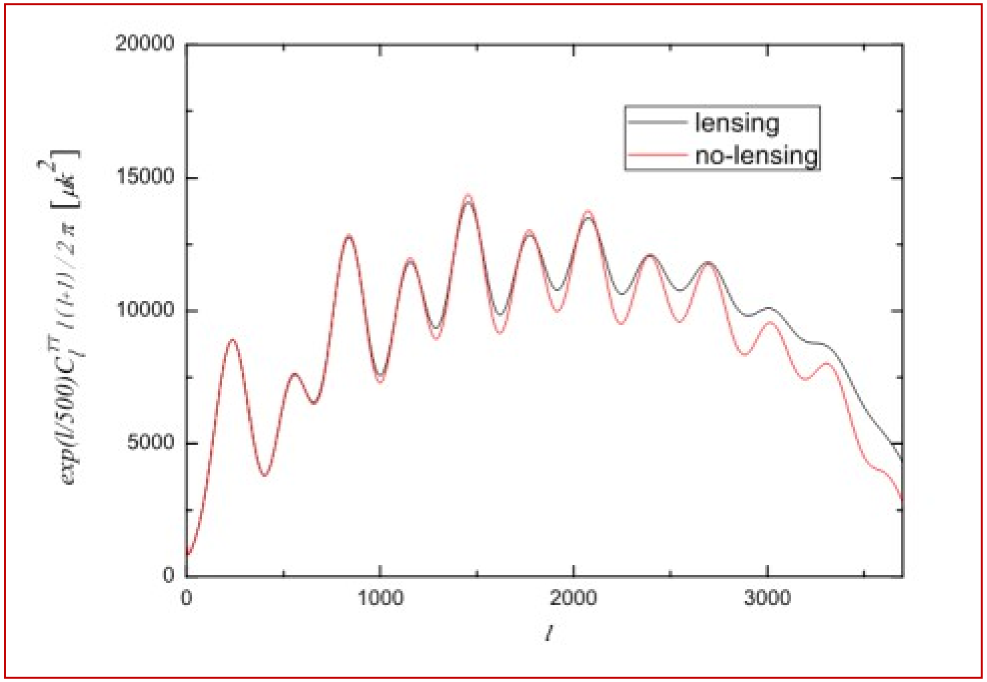
Total: 1+3-1+2+1= 6 parameters.

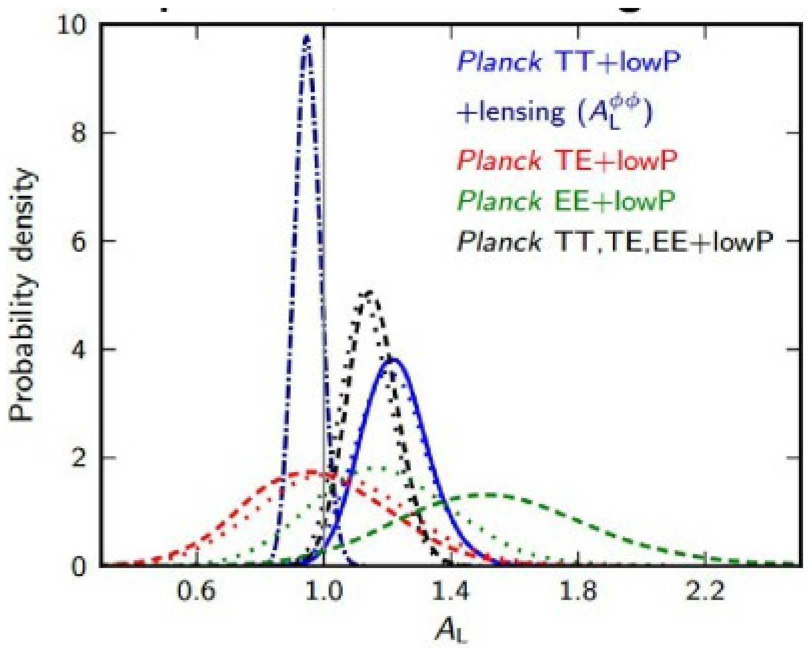
Planck collaboration 2015

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





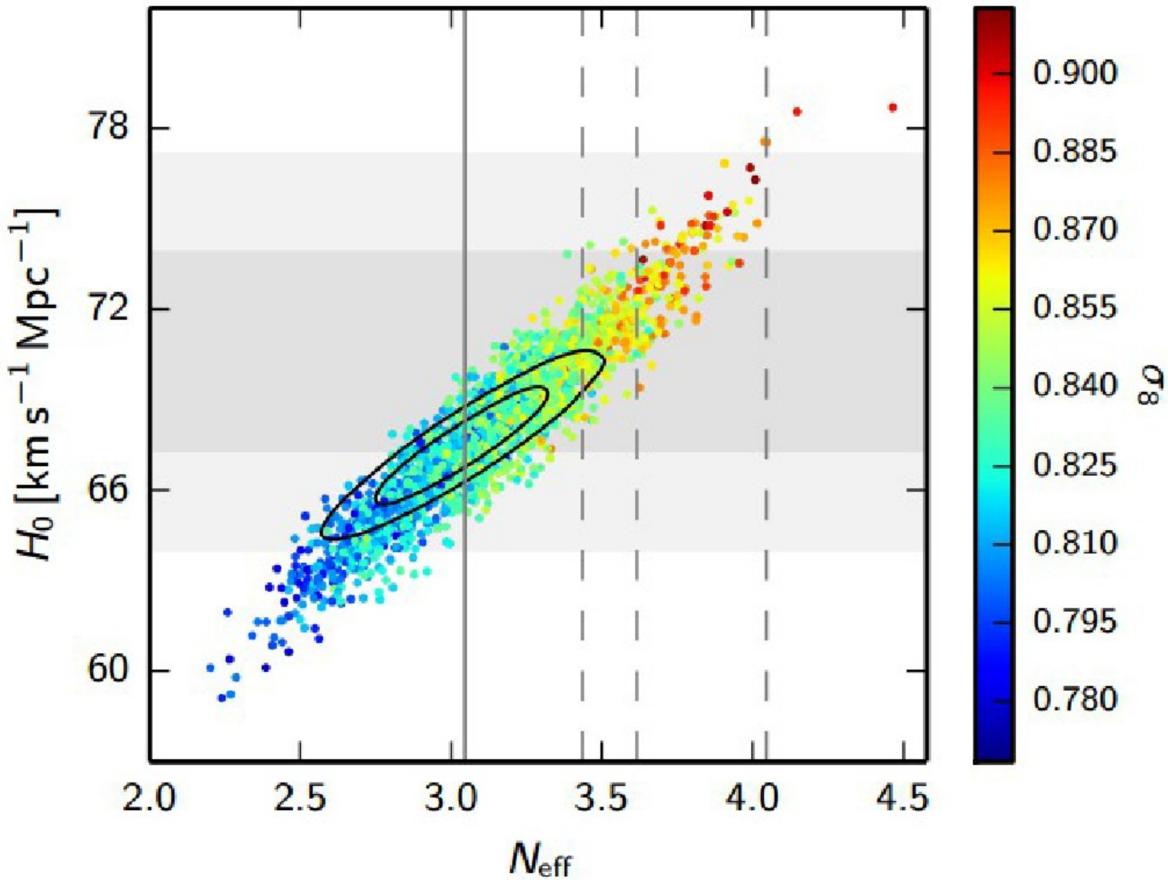
$$A_L = 1.22 \pm 0.10 \quad (68\%, \textit{Planck}\ \mathrm{TT{+}lowP})$$

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

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

Planck collaboration 2015

Neutrino cosmology...



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

Planck collaboration 2015

Neutrino Background Anisotropies

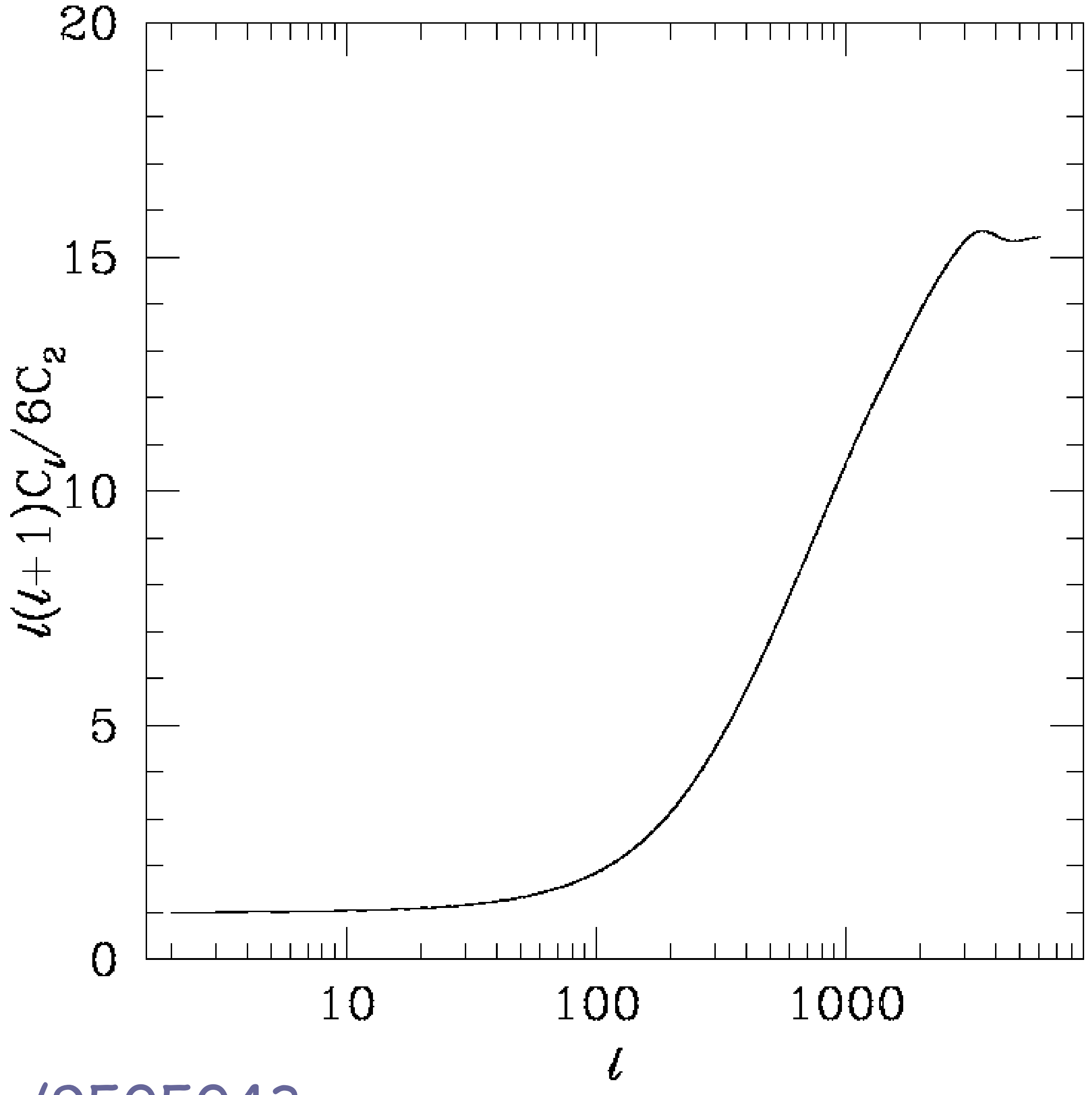
Massless neutrinos, like photons, have anisotropies which follow a Liouville differential equation:

$$\frac{\partial \iota}{\partial t} + \frac{\gamma_i}{a}\frac{\partial \iota}{\partial x^i} - 2\dot{h}_{jk}\gamma_j\gamma_k = 0$$

As in the case of photons, these anisotropies can be computed integrating a hierarchy of differential equations.

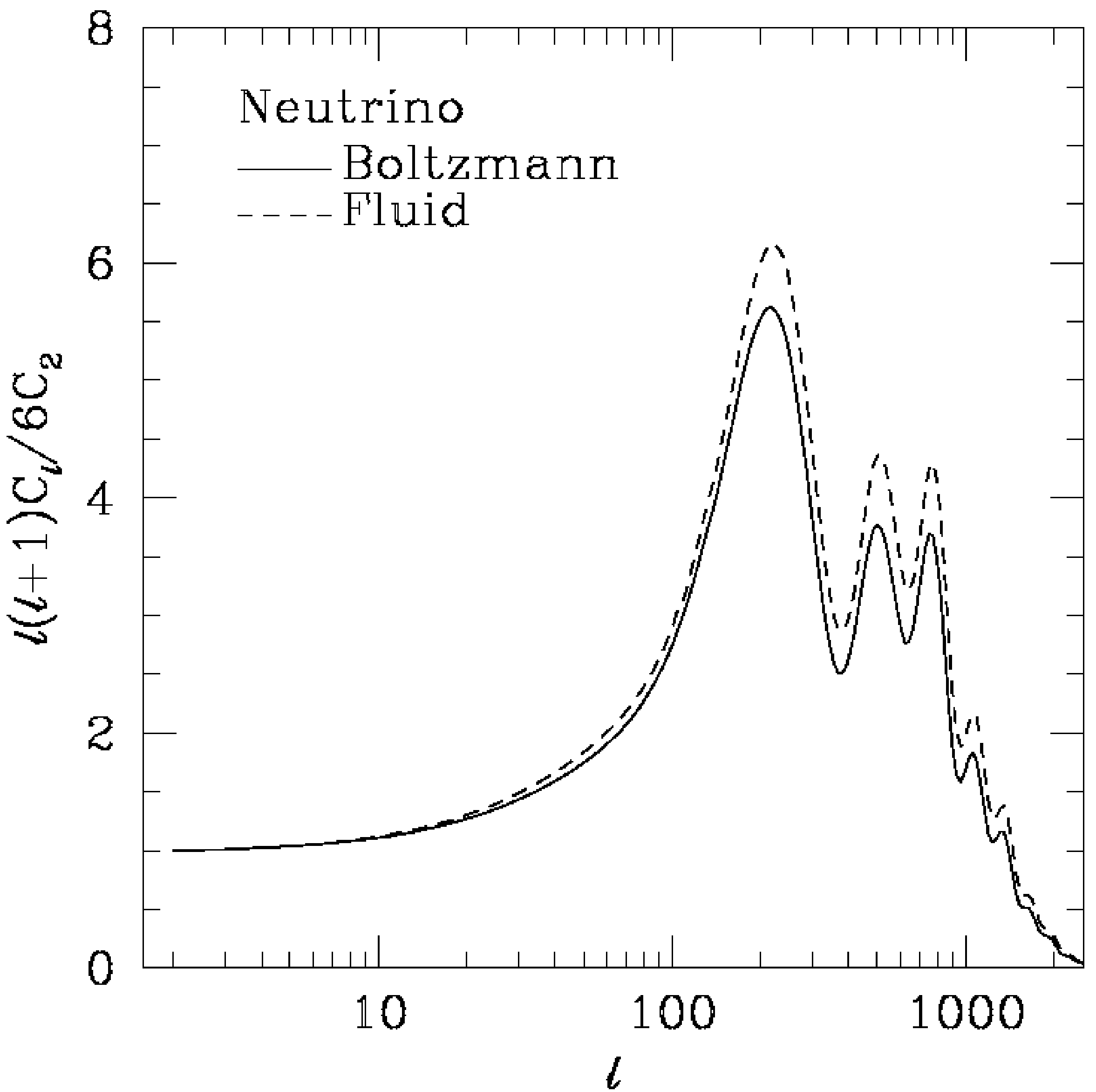
Neutrino Background Anisotropies

Can we see them ?

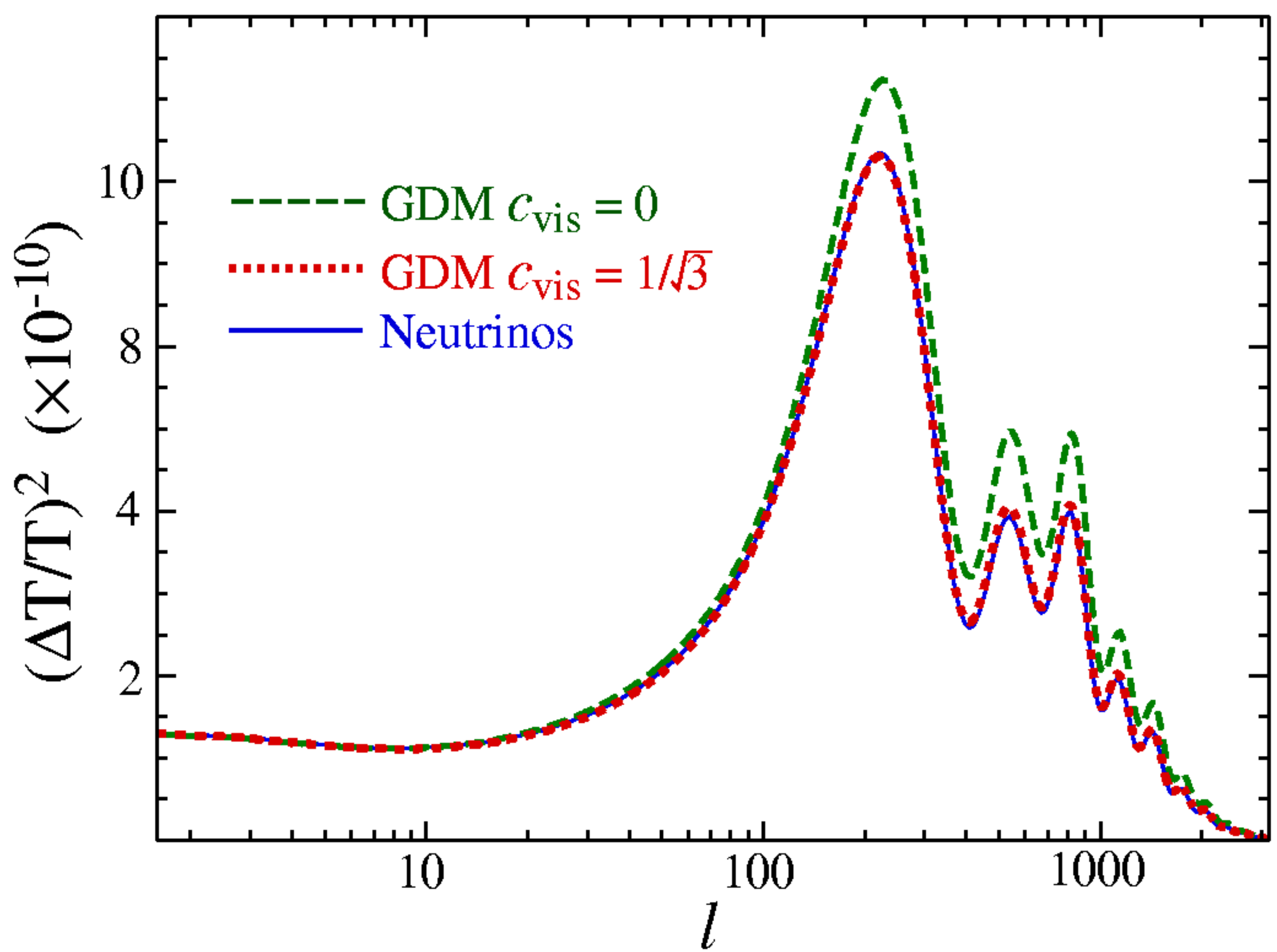


Hu et al., astro-ph/9505043

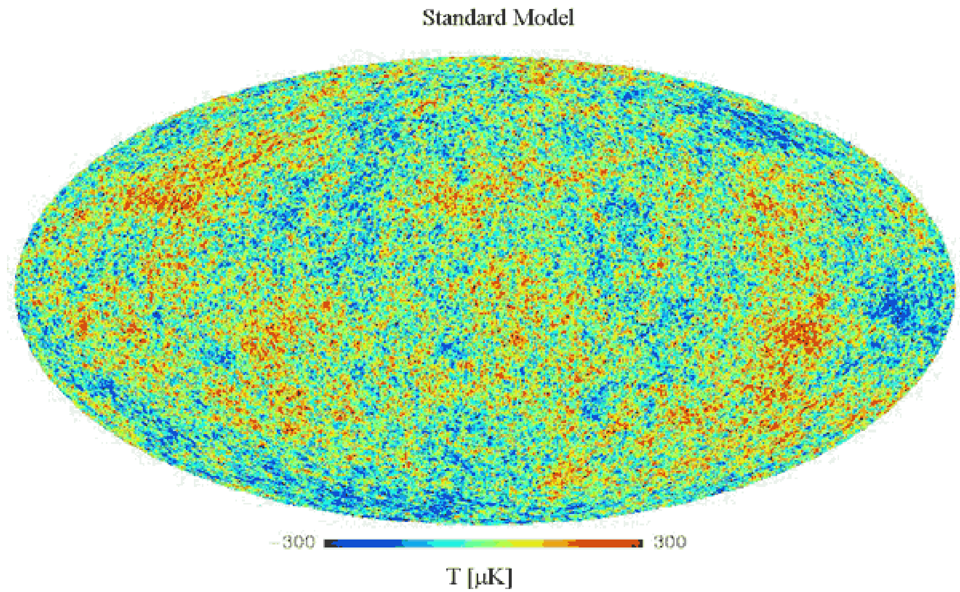
Not directly!
But we can see the effects on the CMB angular spectrum !
CMB photons see the NB anisotropies through gravity.



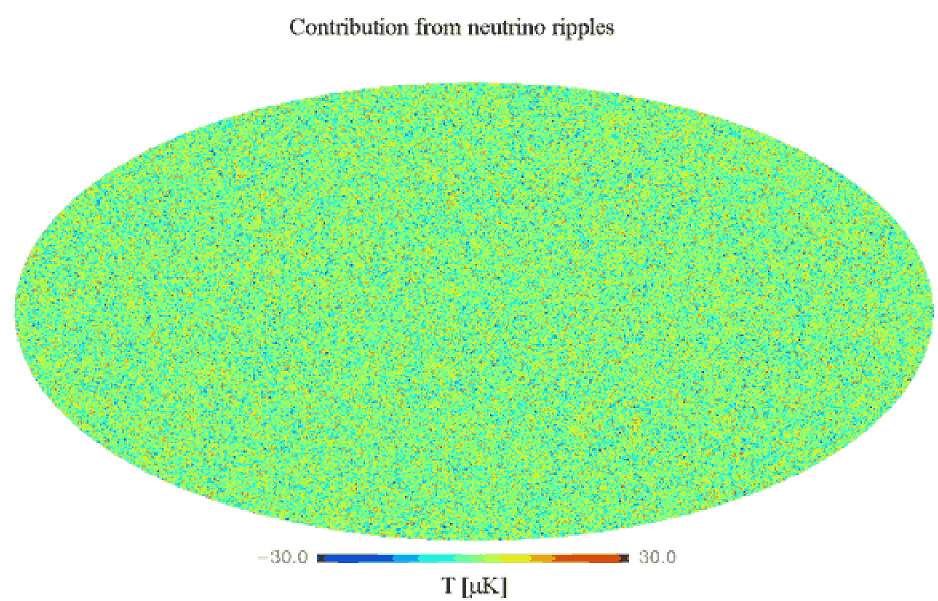
The Neutrino anisotropies can be parameterized through the "speed viscosity" c_{vis}. which controls the relationship between velocity/metric shear and anisotropic stress in the NB.



Hu, Eisenstein, Tegmark and White, 1999

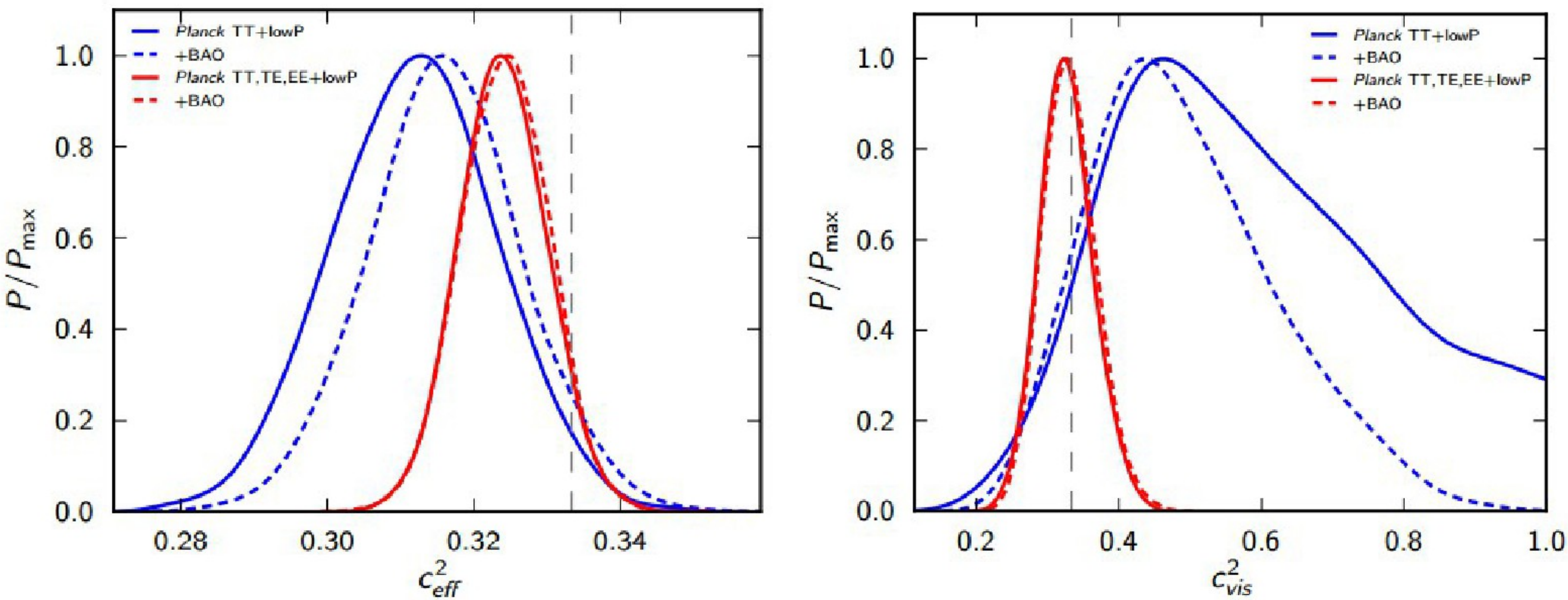


Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.



The net effect on the Microwave Background of the presence of neutrino ripples, interpreted as the signature of the existence of neutrino fluctuations as predicted in the Standard Model.

Perturbations in the neutrino background



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

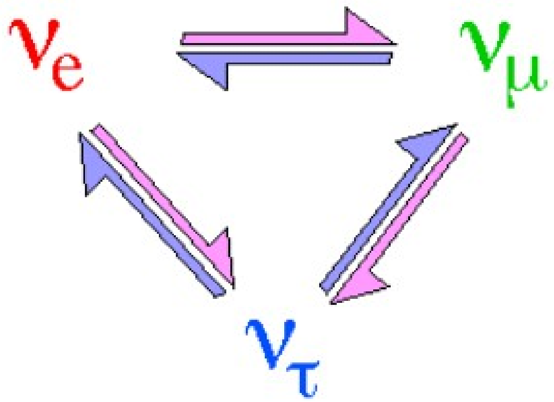
Planck collaboration 2015

C^2_{eff} is the neutrino sound speed in its own reference frame and c^2_{vis} parameterizes the anisotropic stress. For standard non-interacting massless neutrinos $c^2_{eff}=c^2_{vis}=1/3$. Any deviation from the expected values could provide a hint of non-standard physics in the neutrino sector. A vanishing value of c^2_{vis}, which means that the CNB is a perfect fluid and might imply an interaction between neutrinos and other species, is excluded at about 9σ when Planck polarization data are included!!!

Neutrino Masses

We know that flavour neutrino oscillations exists

From present evidences of oscillations from experiments measuring atmospheric, solar, reactor and accelerator neutrinos



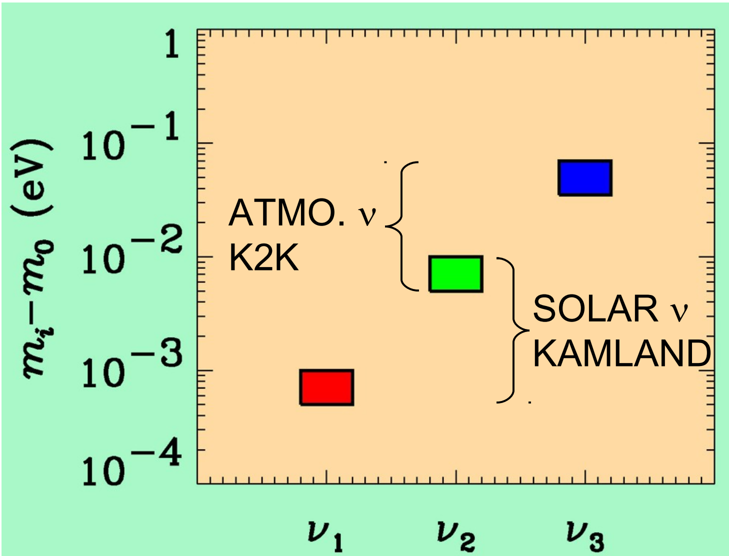
$$(e, \mu, \tau) \leftrightarrow (\nu_1, \nu_2, \nu_3)$$

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \nu_{iL}, \quad (\alpha = e, \mu, \tau)$$

$$\begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \end{array}$$

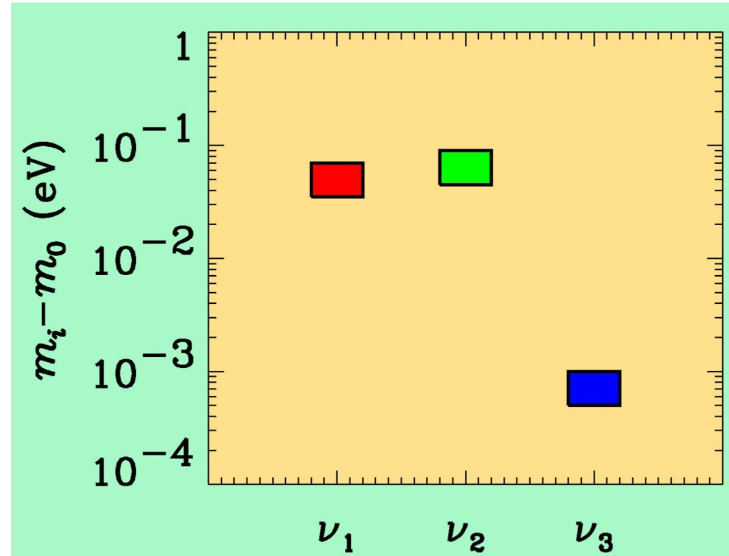
$$\times \, \mathrm{diag}(e^{i\alpha_1/2}, \; e^{i\,\alpha_2/2}, \; 1) \; .$$

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy

$$m_3 > m_2 > m_1$$



Inverted hierarchy

$$m_2 > m_1 > m_3$$

Moreover neutrino masses can also be degenerate

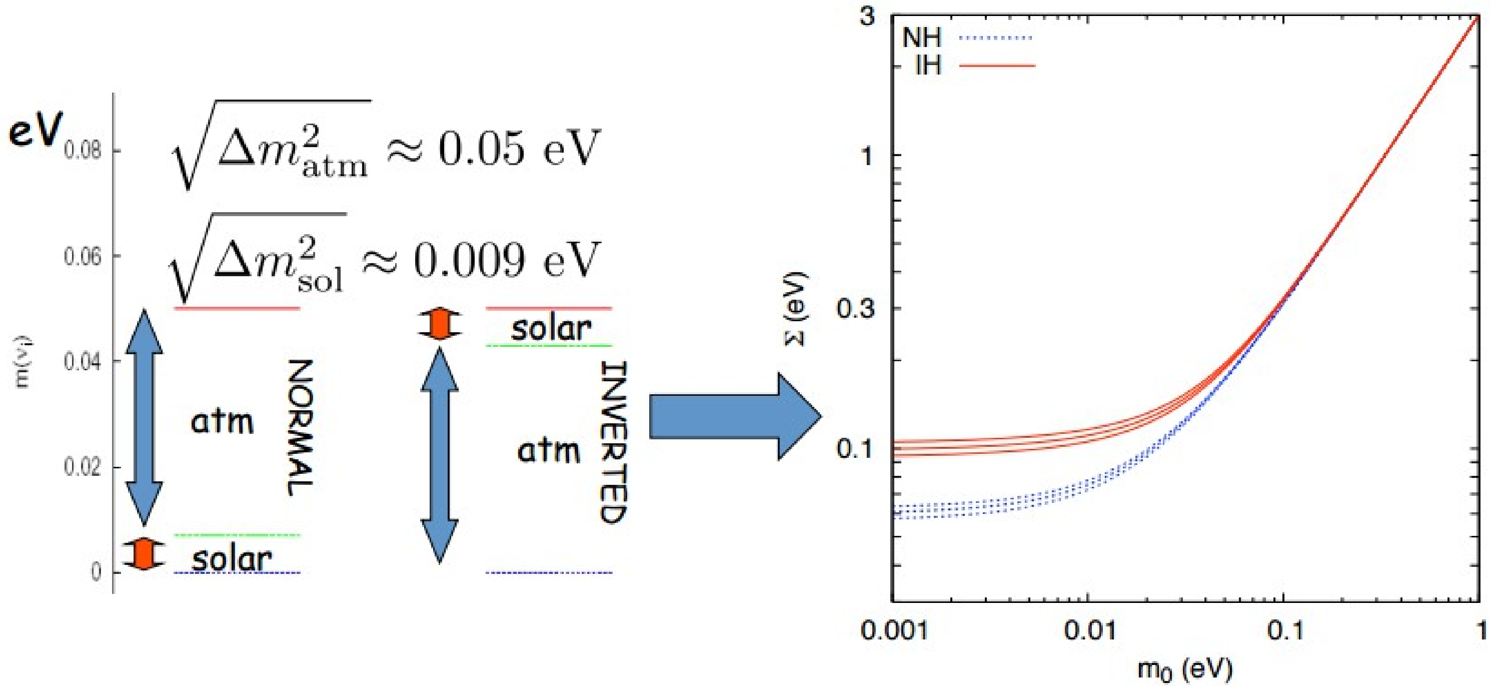
$$m_1, m_2, m_3 >> \delta m_{\text{atmospheric}}$$

Neutrino Absolute Mass Scale

Oscillation data do not fix the absolute mass scale.

$$\sqrt{\Delta m^2_{\rm atm}} \approx 0.05 \text{ eV}$$

$$\sqrt{\Delta m^2_{\rm sol}} \approx 0.009 \text{ eV}$$



$$0.06(0.1)\,\text{eV} \lesssim \sum_i m_i \lesssim 6\,\text{eV}$$

A large range of values (about 2 orders of magnitude) is still allowed by current experiments !

Energy density from neutrinos (after decoupling)

If they are relativistic:

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

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

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

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

If they are not relativistic:

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

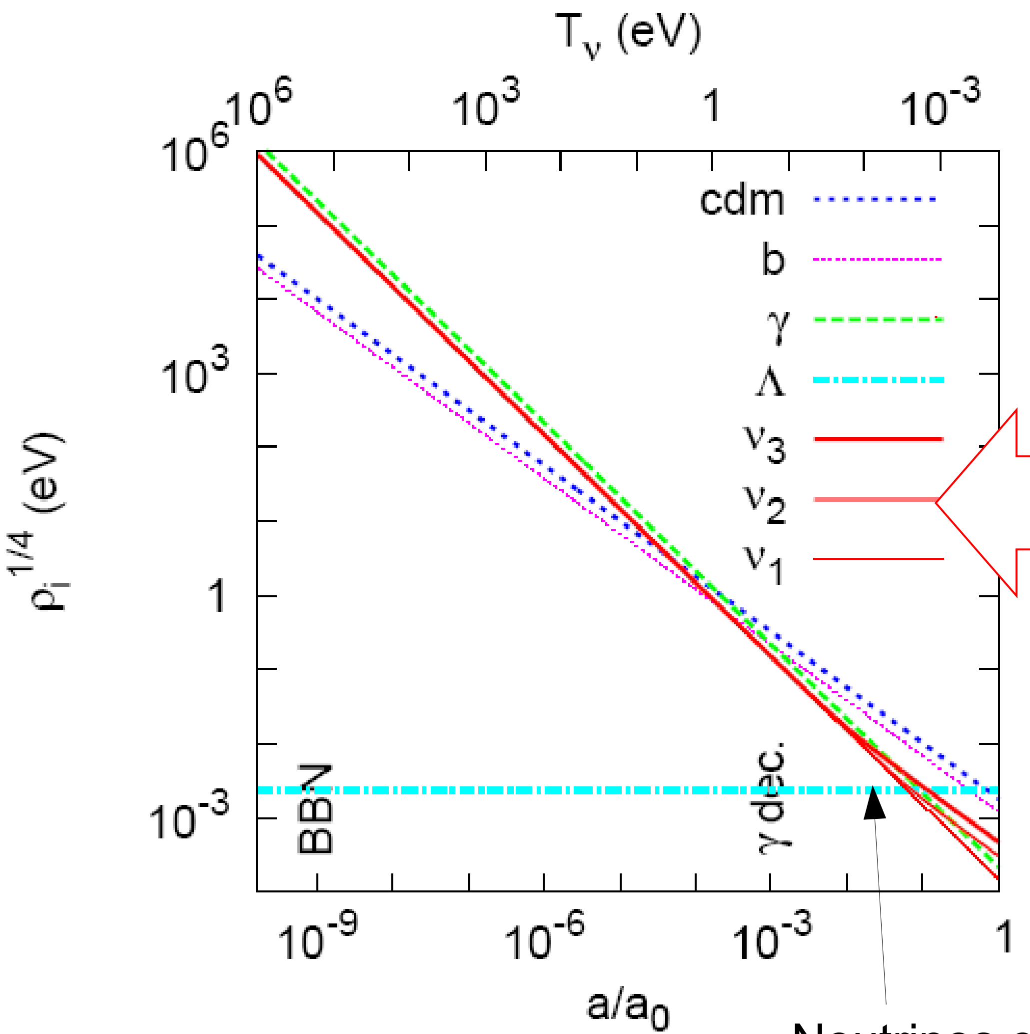
$$n_i = \frac{6\zeta(3)}{11\pi^2} T_\gamma^3$$

→

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

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

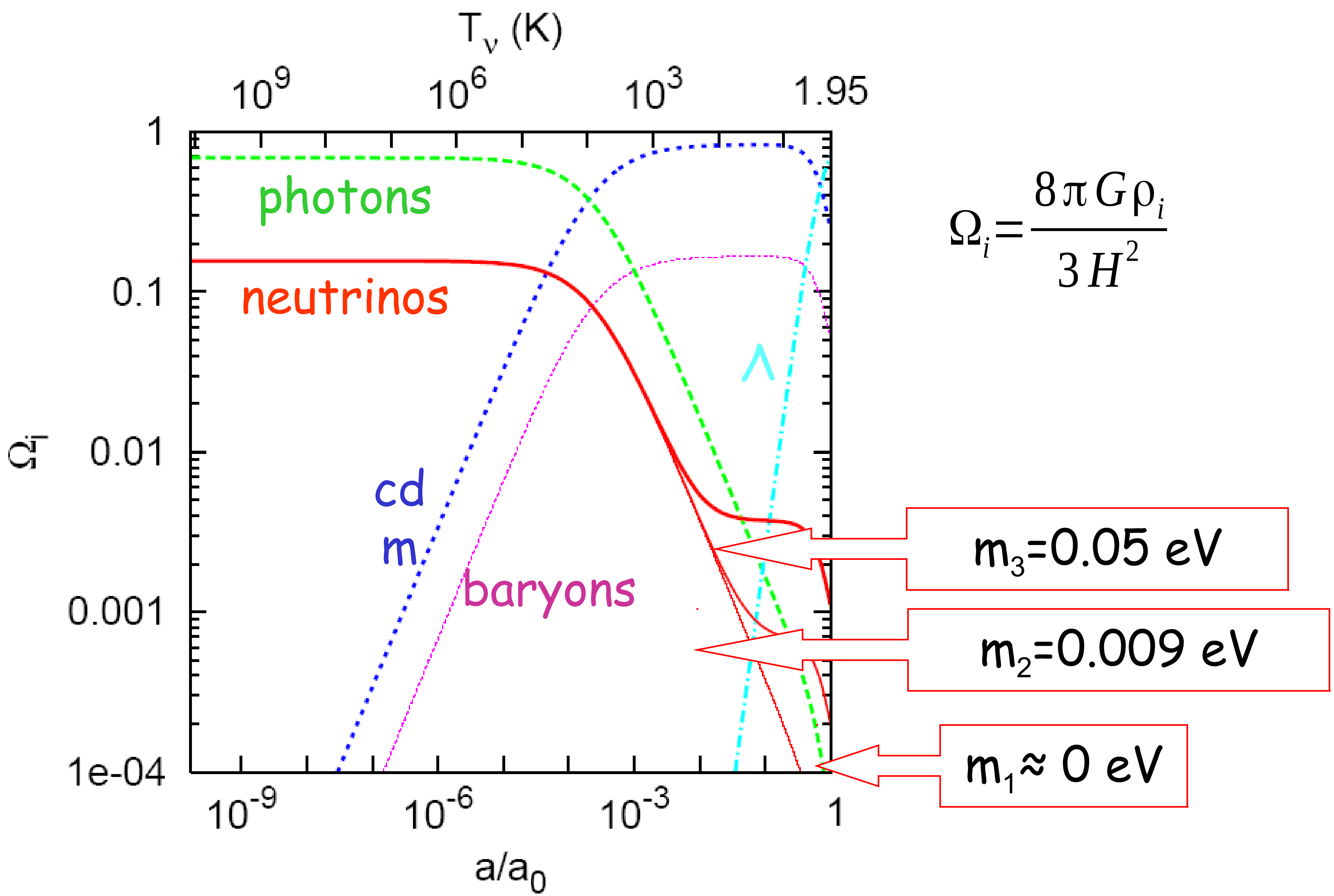
Evolution of the background densities: 1 MeV → now



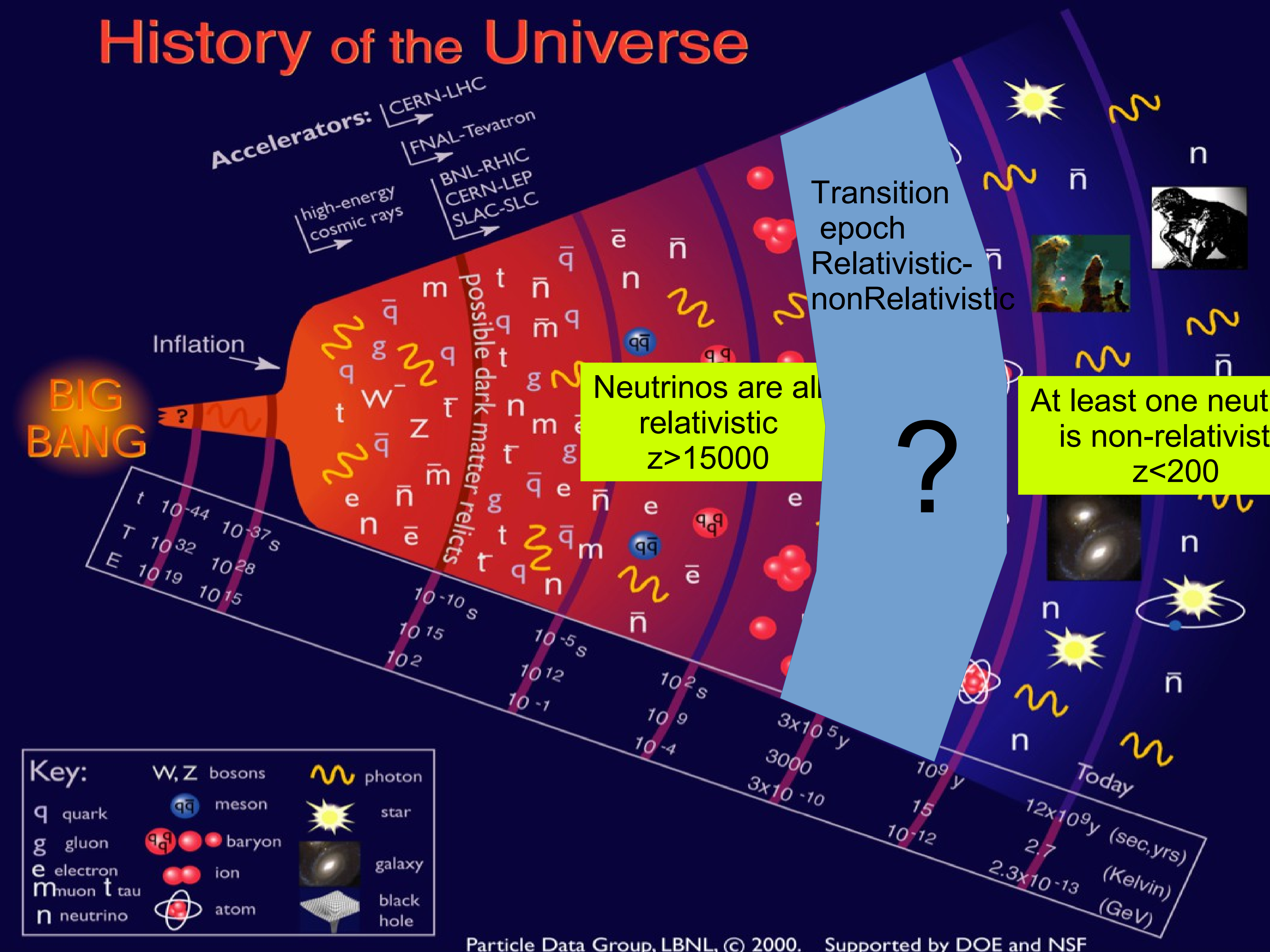
3 neutrino species with different masses

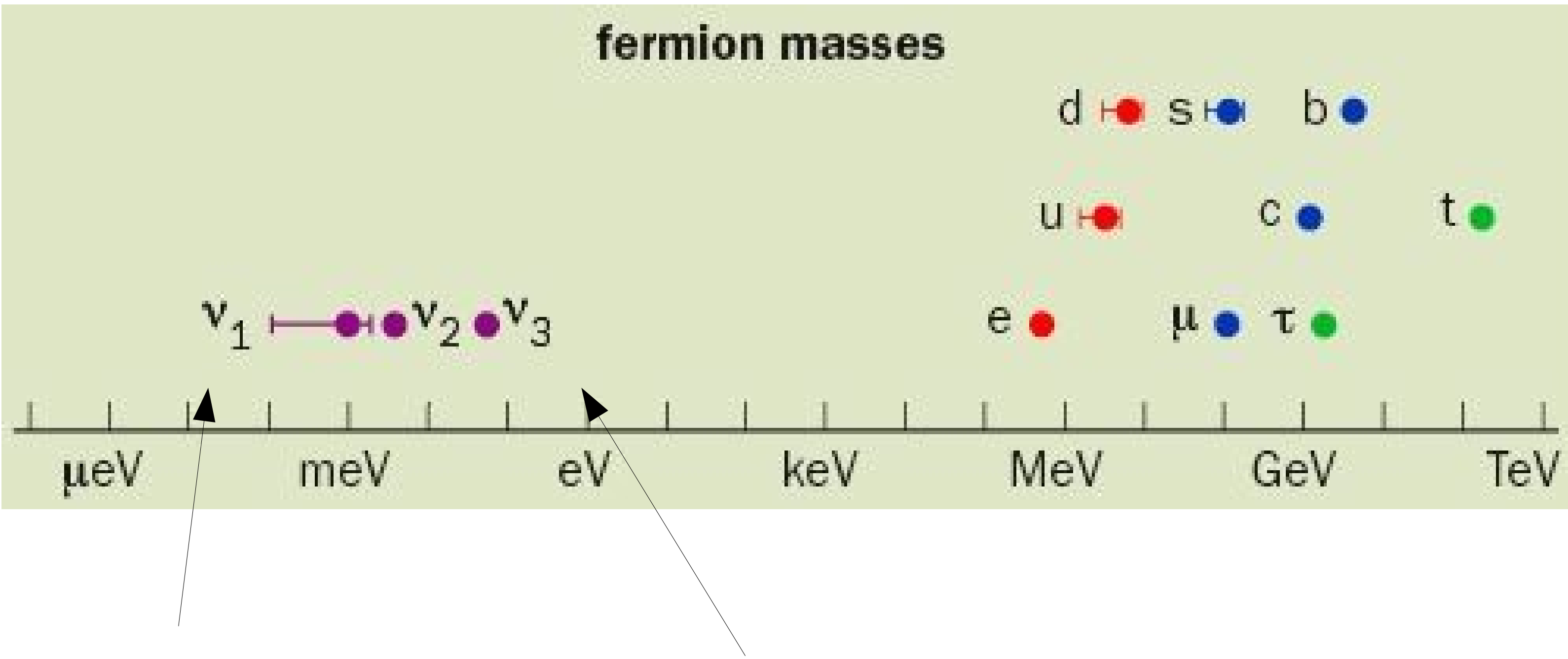
Neutrinos change from relativistic to non-relativistic

Evolution of the background densities: 1 MeV → now



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


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
Transition epoch
Relativistic-nonRelativistic
Neutrinos are all relativistic
z>15000
?
At least one neut
is non-relativist
z<200
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



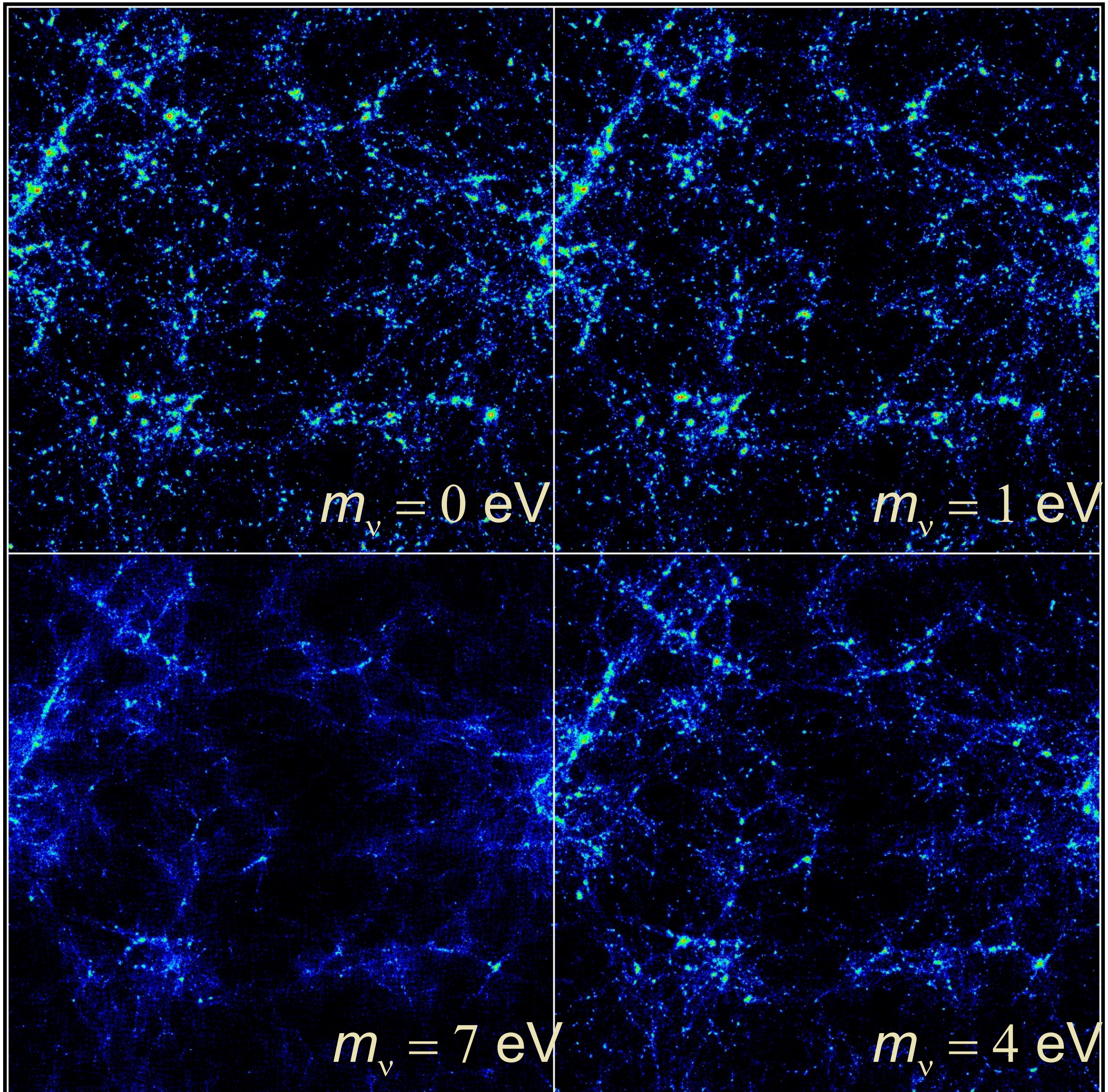
This mass range is very good for cosmologists !

Massive Neutrinos affect large scale structure !

- We can relate the neutrino abundance in the universe to the total mass:

$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{93.6\,eV}$$

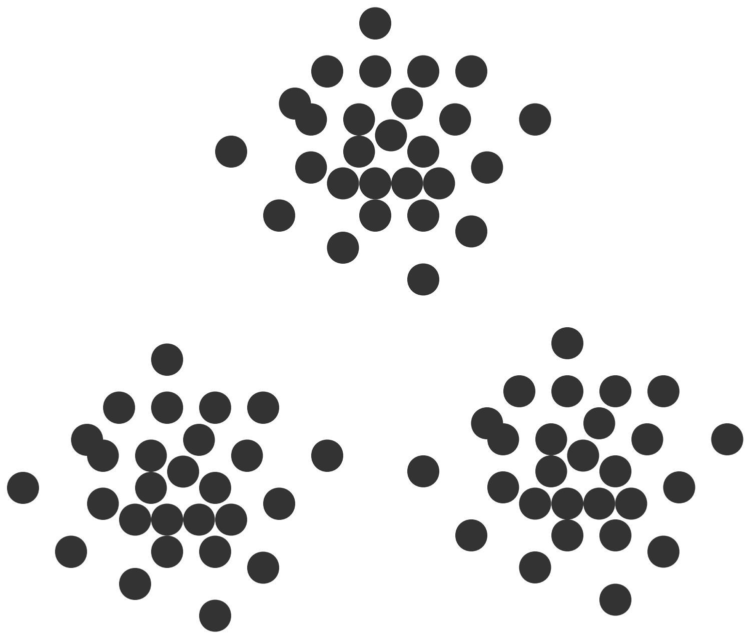
- Less clustering in universe with massive neutrinos.



Ma ’96

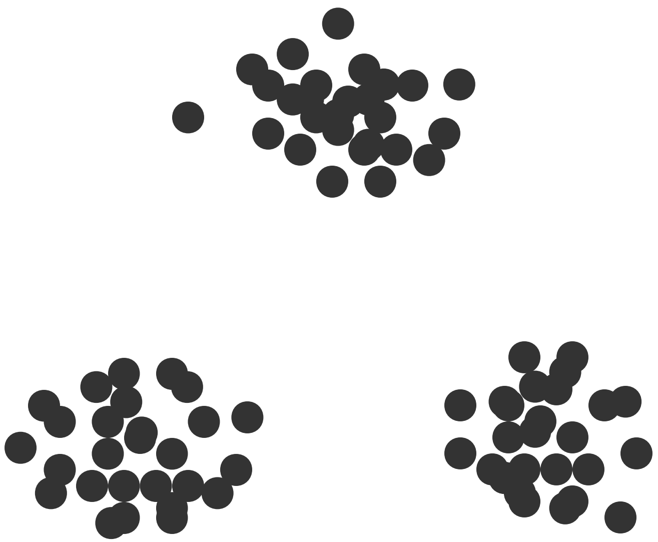
Structure formation after equality

baryons and CDM experience gravitational clustering



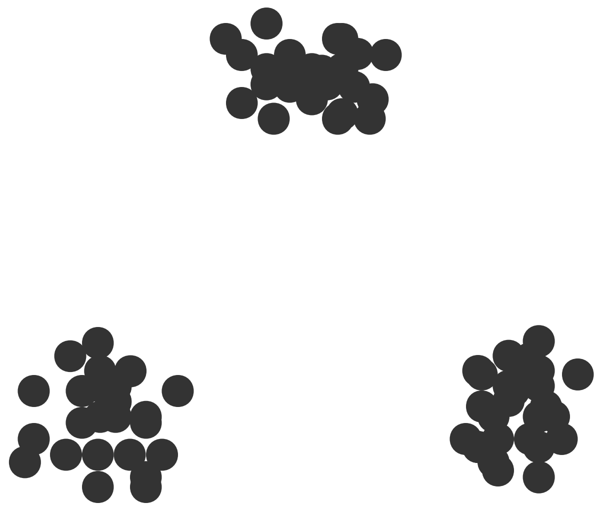
Structure formation after equality

baryons and
CDM
experience
gravitational
clustering



Structure formation after equality

baryons and CDM experience gravitational clustering

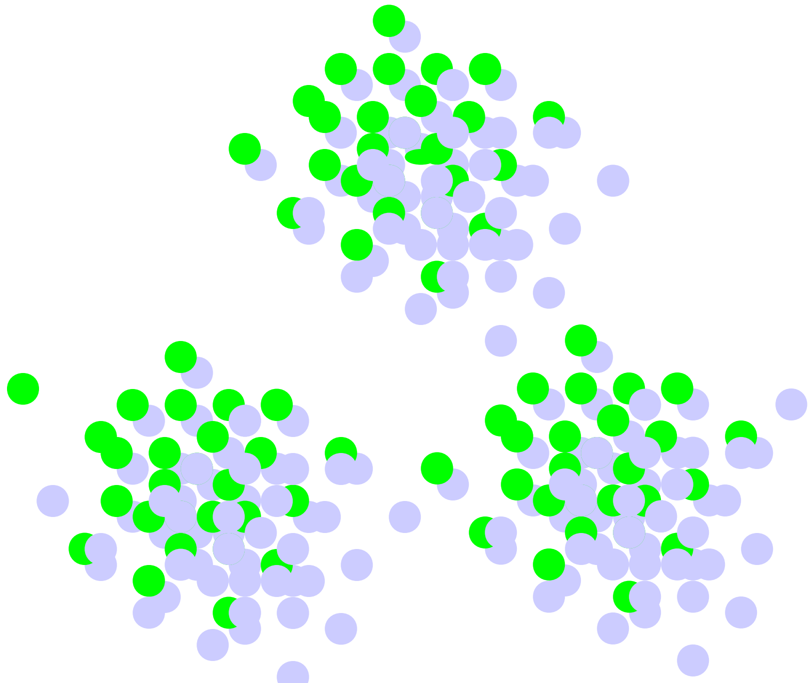


growth of $\delta\rho/\rho$ (k,t) fixed by « gravity vs. expansion » balance

$$\delta\rho/\rho \propto a$$

Structure formation after equality

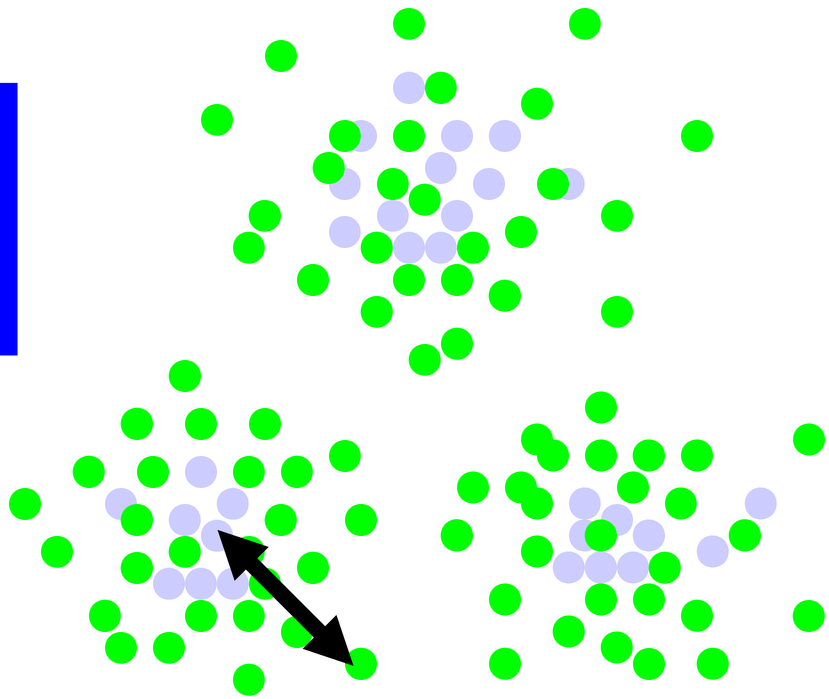
baryons and CDM experience gravitational clustering



neutrinos experience free-streaming with v = c or <p>/m

Structure formation after equality

baryons and CDM experience gravitational clustering

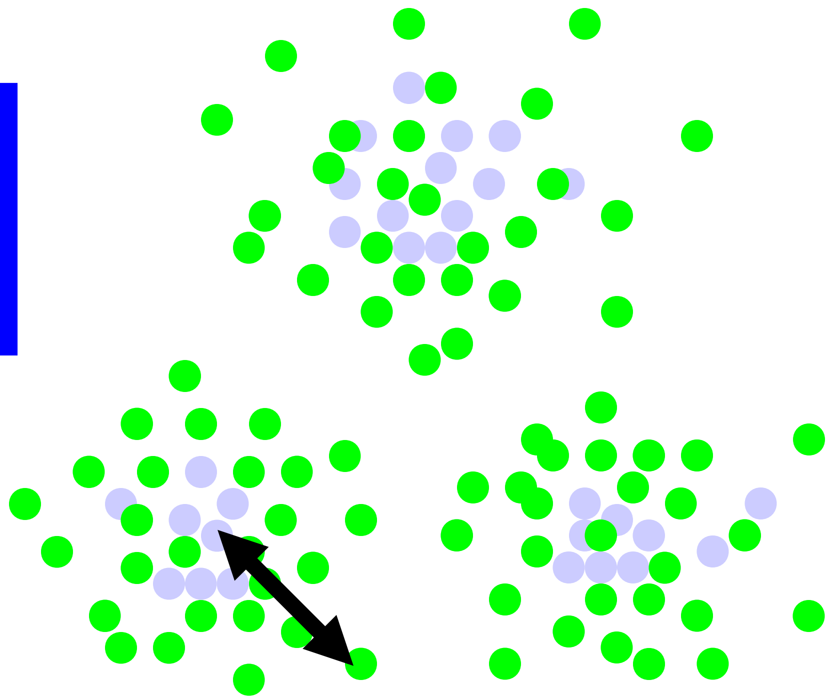


neutrinos experience free-streaming with v = c or <p>/m

neutrinos cannot cluster below a diffusion length

Structure formation after equality

baryons and CDM experience gravitational clustering



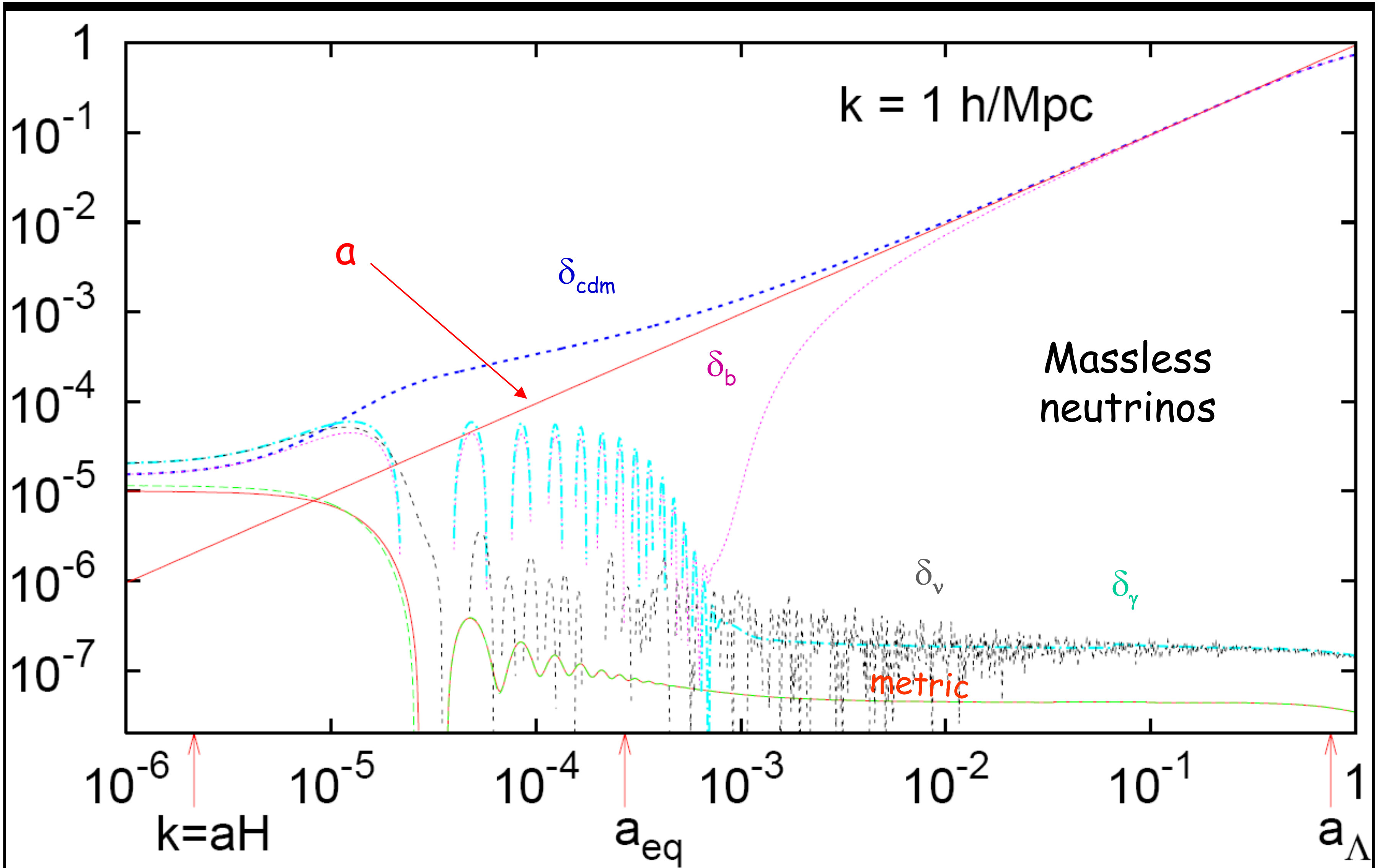
neutrinos experience free-streaming with $v = c$ or $\langle p \rangle / m$

for $(2\pi/k) < \lambda$,

free-streaming supresses growth of structures during MD

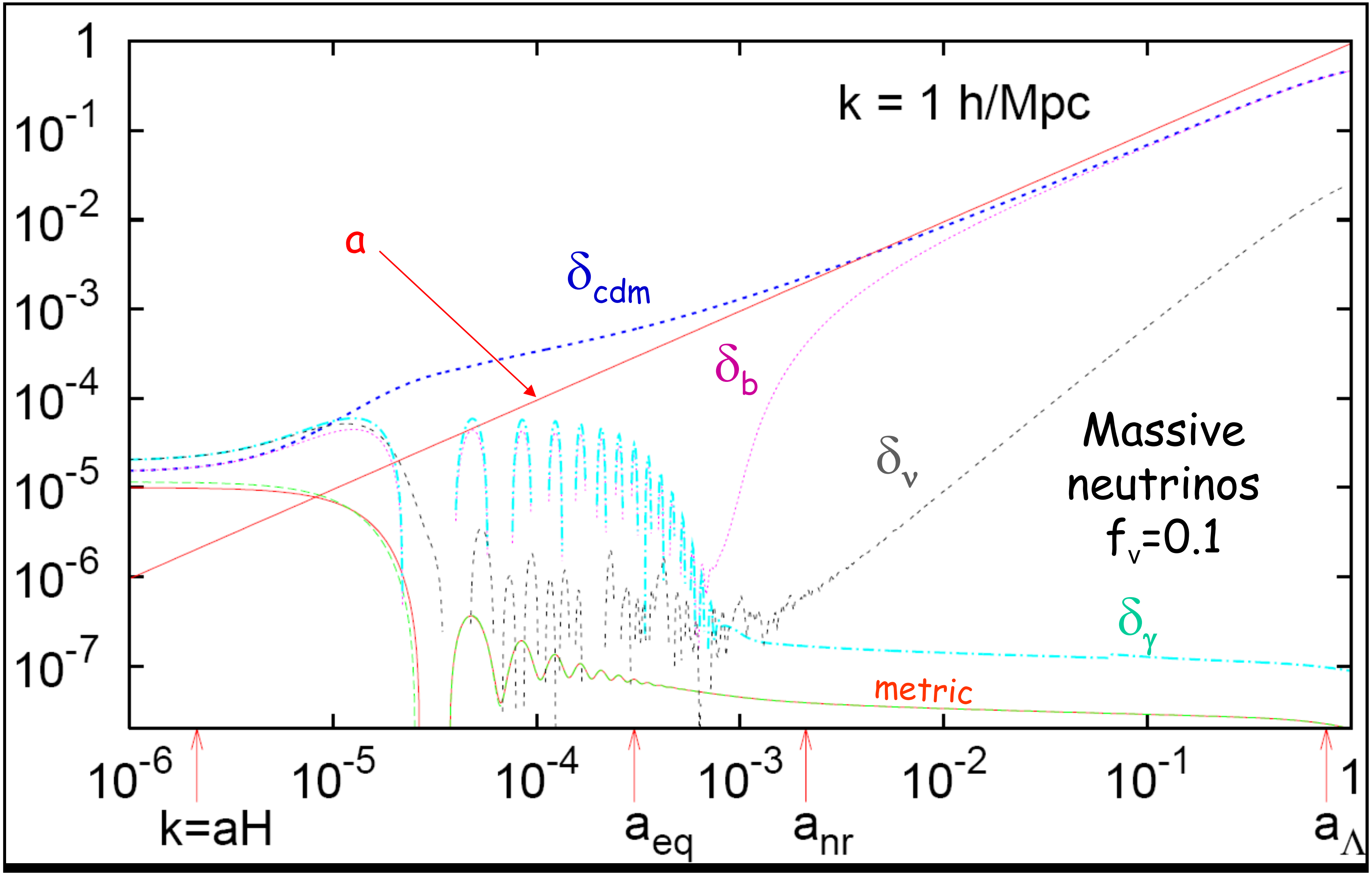
$\delta\rho/\rho \propto a^{1-3/5\, f\nu}$ with $f_\nu = \rho_\nu/\rho_m \approx (\Sigma m_\nu)/(15\ \mathrm{eV})$

Structure formation after equality



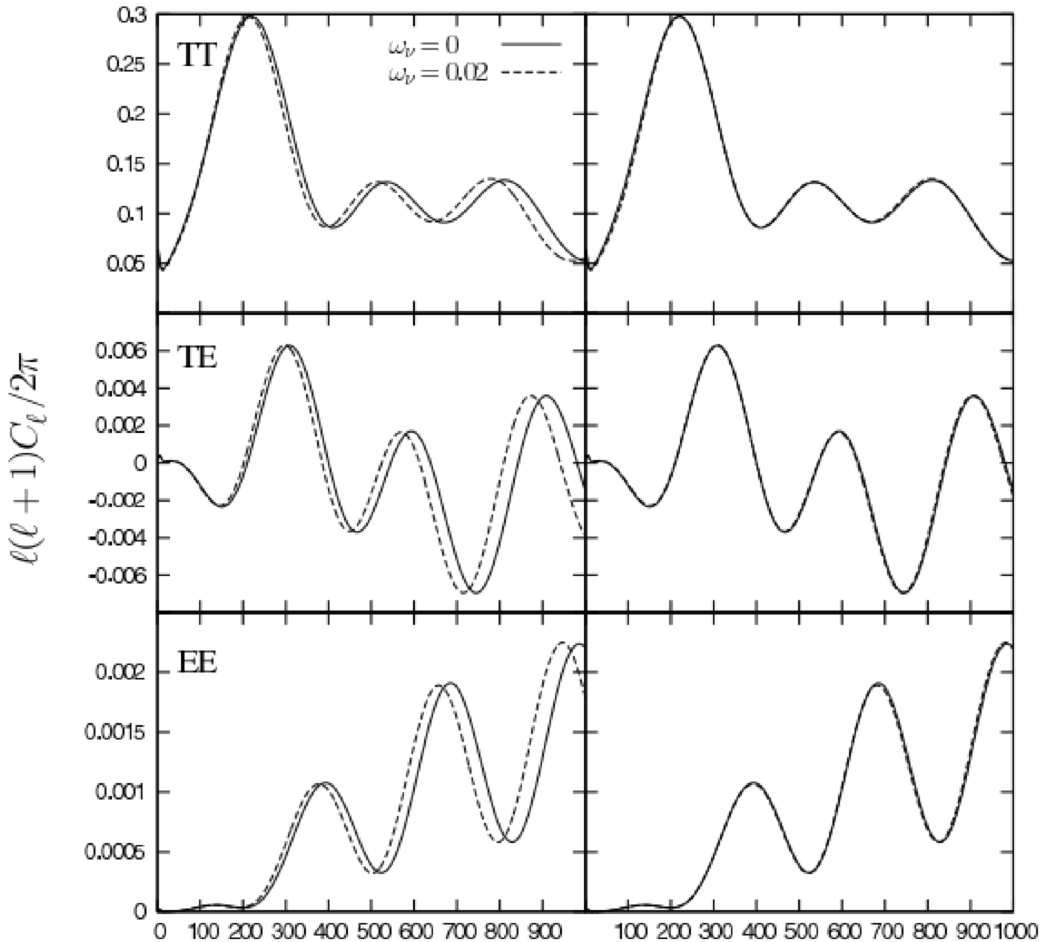
J.Lesgourgues & Sergio Pastor, Phys Rep 429 (2006) 307 [astro-ph/0603494]

Structure formation after equality



J.Lesgourgues & Sergio Pastor, Phys Rep 429 (2006) 307 [astro-ph/0603494]

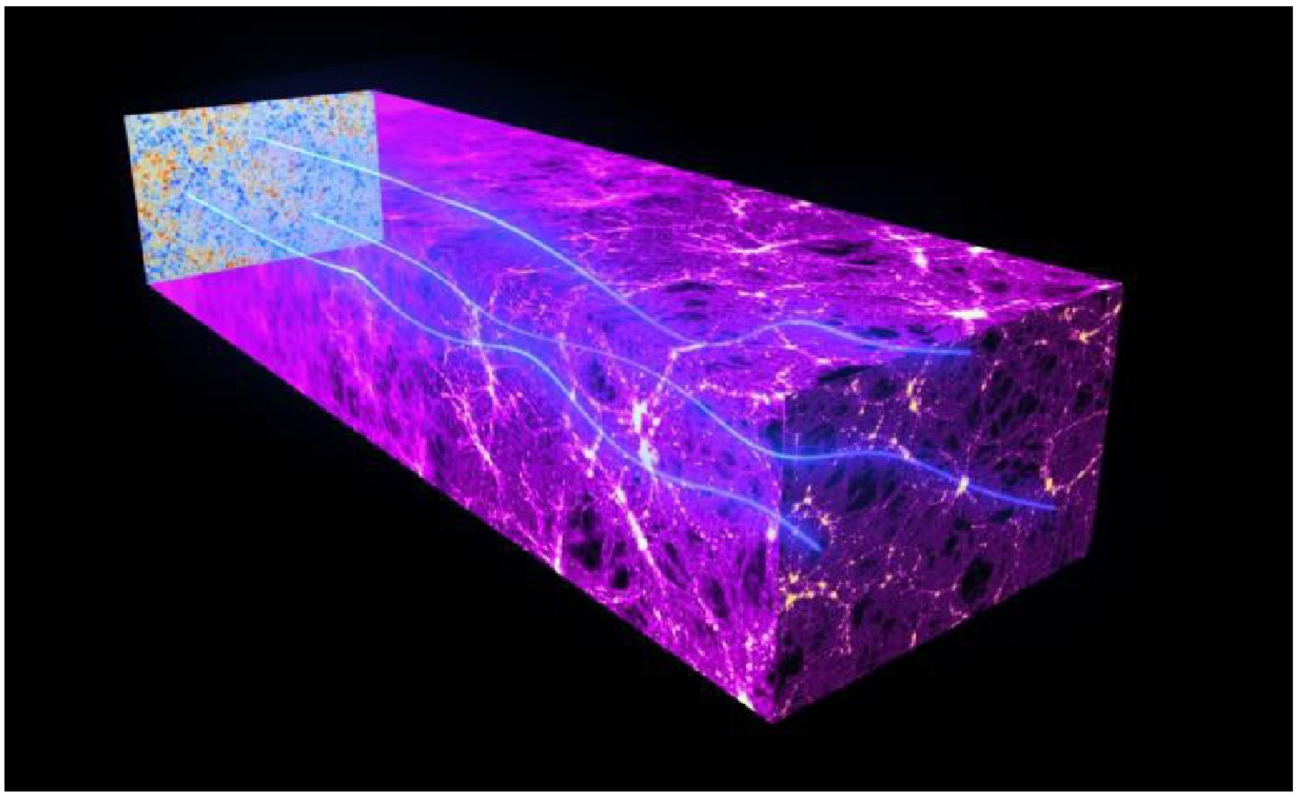
CMB bounds on neutrino masses



If neutrinos have a mass larger than m ~ 0.3 eV they are non-relativistic at recombination. At this point, increasing their mass increases the dark matter component at recombination. The change in the gravitational potential at early times with massive neutrinos leads to a slight changes in Cl below the first acoustic peak (see Ma & Bertshchinger 1998, Fukugita et al, 2006). In principle, CMB should constrain neutrino masses to m < 2 eV but constraints are actually much better because of lensing.

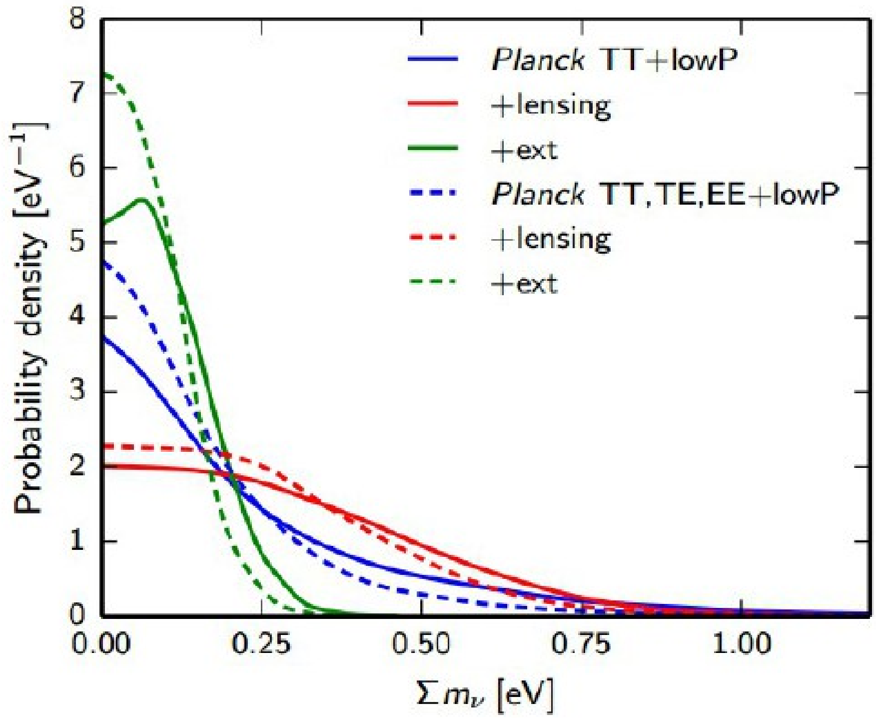
Gravitational Lensing

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



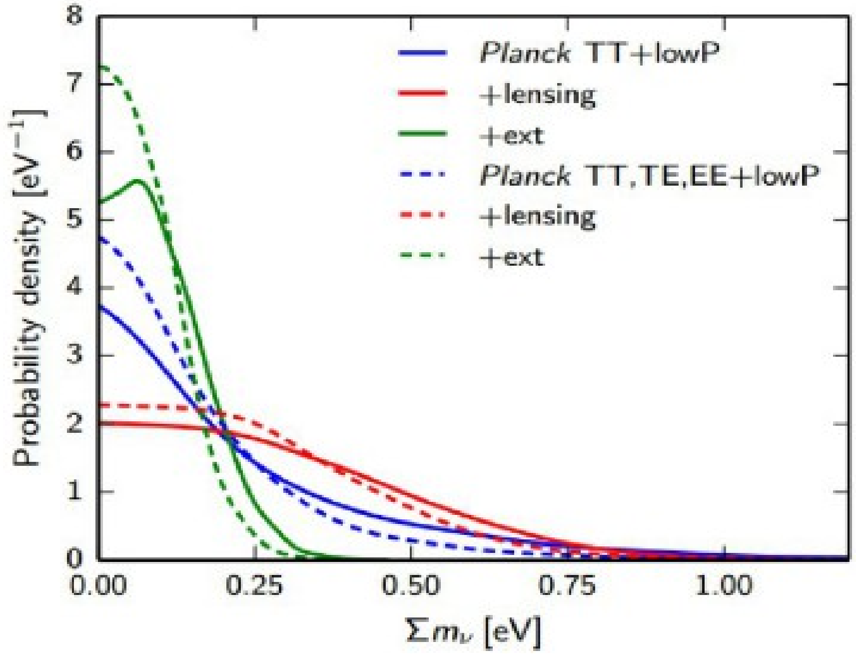
CMB anisotropy do not probe just recombination epoch !
CMB lensing probes structure formation around z~2 (broadly)

3 standard Massive Neutrinos



$$\left. \begin{array}{r} \sum m_\nu < 0.23 \text{ eV} \\ \Omega_\nu h^2 < 0.0025 \end{array} \right\} \quad 95\%, \textit{Planck} \text{ TT+lowP+lensing+ext.}$$

3 standard Massive Neutrinos



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

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

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

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

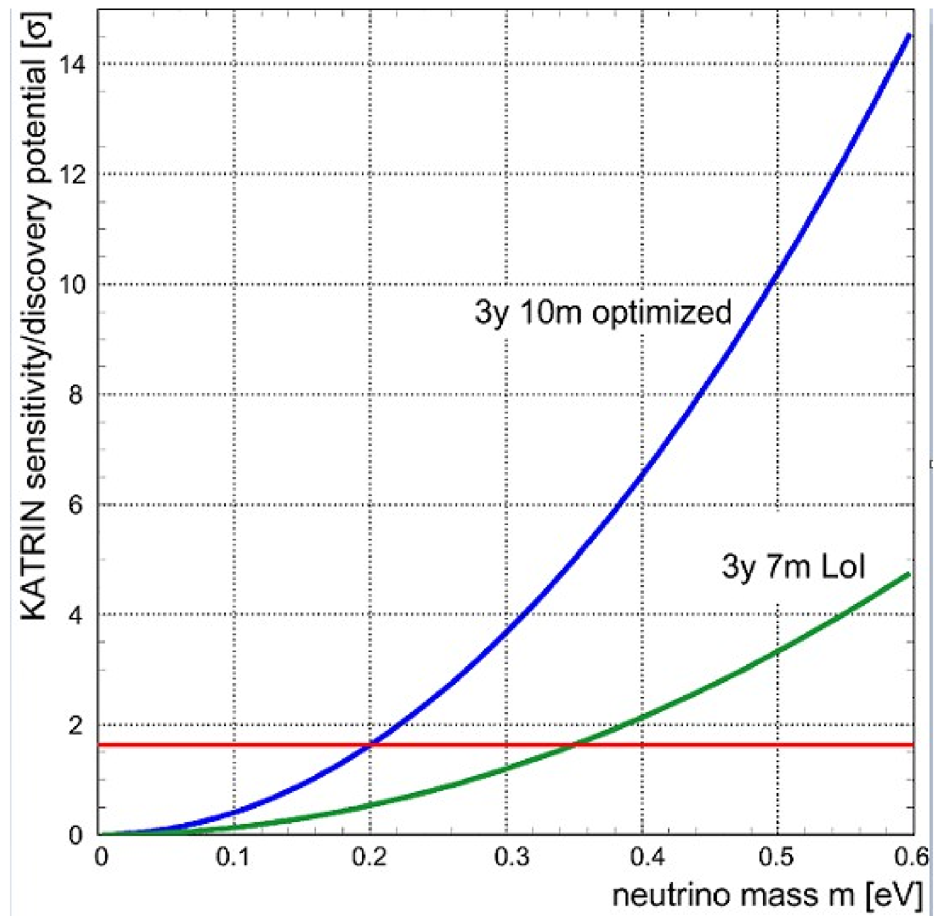
Implications of a <0.17 eV constraint at 95 % c.l. from Planck+BAO

Parameter	Present	
	Normal	Inverted
M_ν, ξ free	$[53 - 170]$	$[93 - 195]$
$M_\nu, \xi \equiv 1$	$[53 - 170]$	$[93 - 194]$
$m_{\beta\beta}, \xi$ free	< 36	$[16 - 59]$
$m_{\beta\beta}, \xi \equiv 1$	< 36	$[16 - 59]$
m_β, ξ free	$[6 - 50]$	$[46 - 71]$
$m_\beta, \xi \equiv 1$	$[6 - 50]$	$[46 - 71]$

Constraints in meV !!!!

Gerbino et al, arXiv:1507.08614

Prospects for direct detection for KATRIN....



Constraints on a massive sterile neutrino

We consider a particle that contributes to Neff when is relativistic and behaves with a mass:

$$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} \equiv (94.1\,\Omega_{\nu,\mathrm{sterile}} h^2)\ \mathrm{eV}$$

when is not relativistic.
This is a very general parametrization of a sterile neutrino.

If the sterile neutrino is thermally distributed we have:

$$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} = (T_{\mathrm{s}}/T_{\nu})^3 m_{\mathrm{sterile}}^{\mathrm{thermal}} = (\Delta N_{\mathrm{eff}})^{3/4} m_{\mathrm{sterile}}^{\mathrm{thermal}}$$

While for the Dodelson-Widrow case the relation is given by:

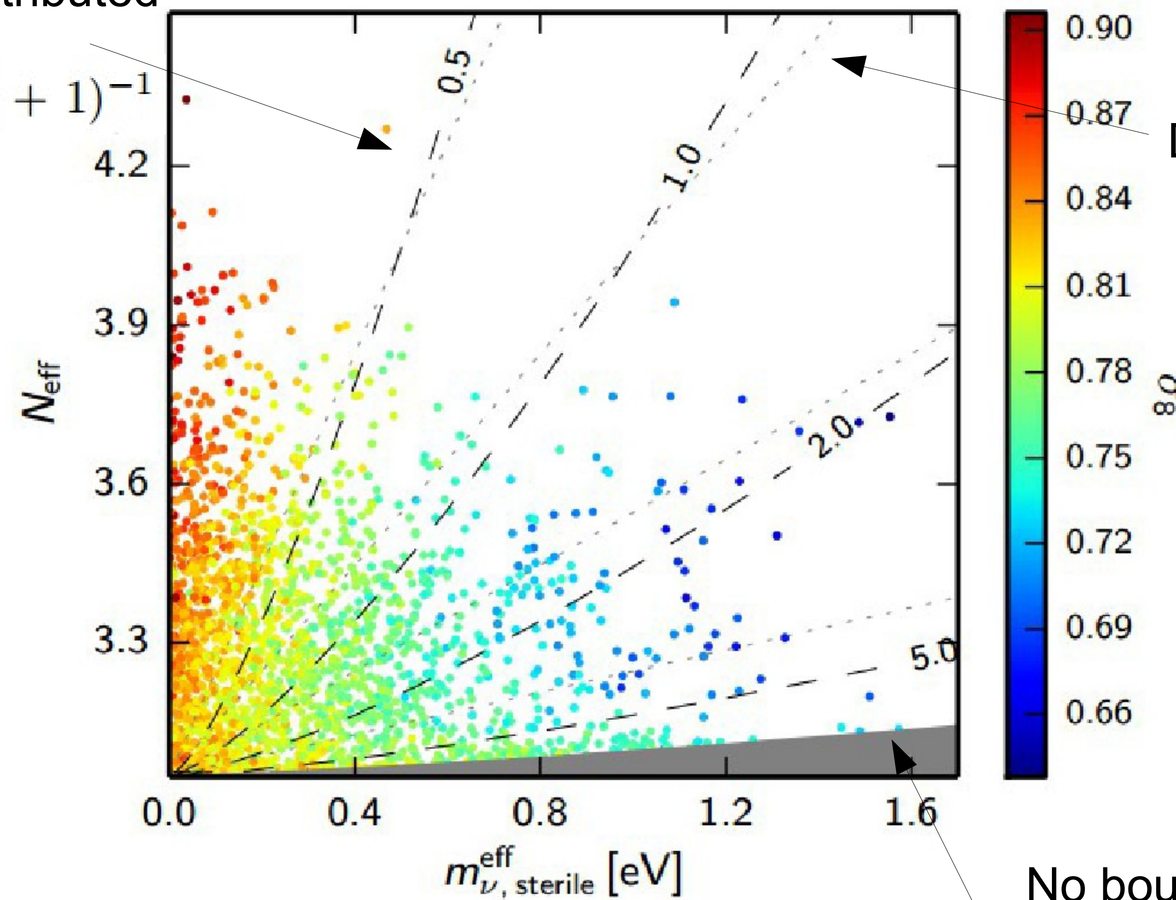
$$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} = \chi_{\mathrm{s}}\, m_{\mathrm{sterile}}^{\mathrm{DW}}$$

$$\Delta N_{\mathrm{eff}} = \chi_{\mathrm{s}}$$

Massive Sterile Neutrinos

Thermally distributed

$$f_s(E) = (e^{E/T_s} + 1)^{-1}$$



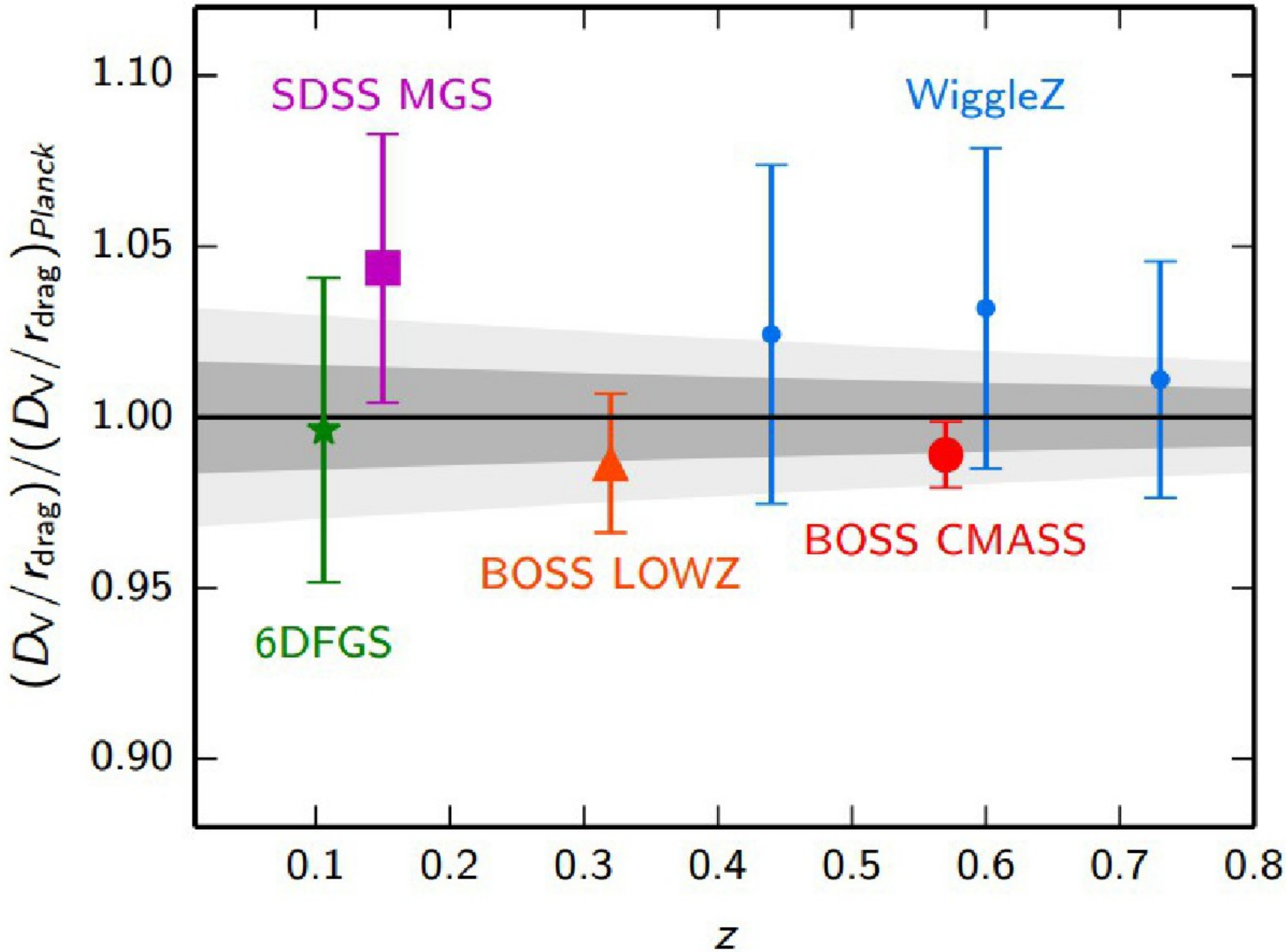
Dodelson-Widrow

$$f_s(E) = \chi_s/(e^{E/T_\nu} + 1)$$

No bound !
Sterile neutrino is cold dark matter (for the CMB)

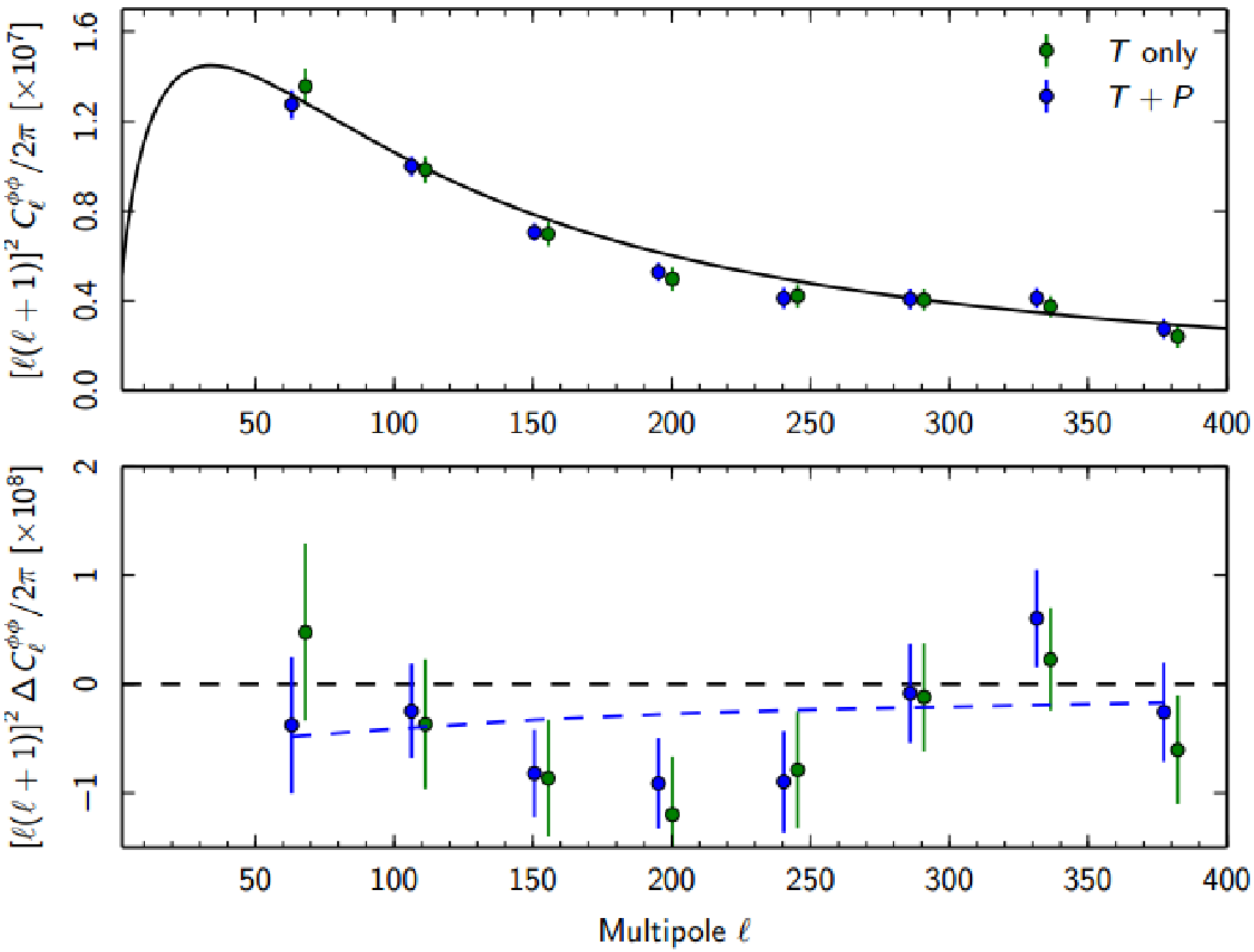
$$\left.\begin{aligned} N_{\rm eff} &< 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.38\ \rm eV \end{aligned}\right\} \quad 95\%,\ \textit{Planck}\ \rm TT{+}lowP{+}lensing{+}BAO.$$

Consistency with other datasets...



Acoustic-scale distance ratio $D_V(z)/r_{drag}$ in the base ΛCDM model divided by the mean distance ratio from Planck TT+lowP+lensing. The points with 1σ errors are as follows: green star (6dFGS, Beutler et al. 2011); square (SDSS MGS, Ross et al. 2014); red triangle and large circle (BOSS "LOWZ" and CMASS surveys, Anderson et al. 2014); and small blue circles (WiggleZ, as analysed by Kazin et al. 2014). The grey bands show the 68% and 95% confidence ranges allowed by Planck TT+lowP+lensing.

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:

$H_0 = (73.8 \pm 2.4)\ \mathrm{km\ s^{-1} Mpc^{-1}}$

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:

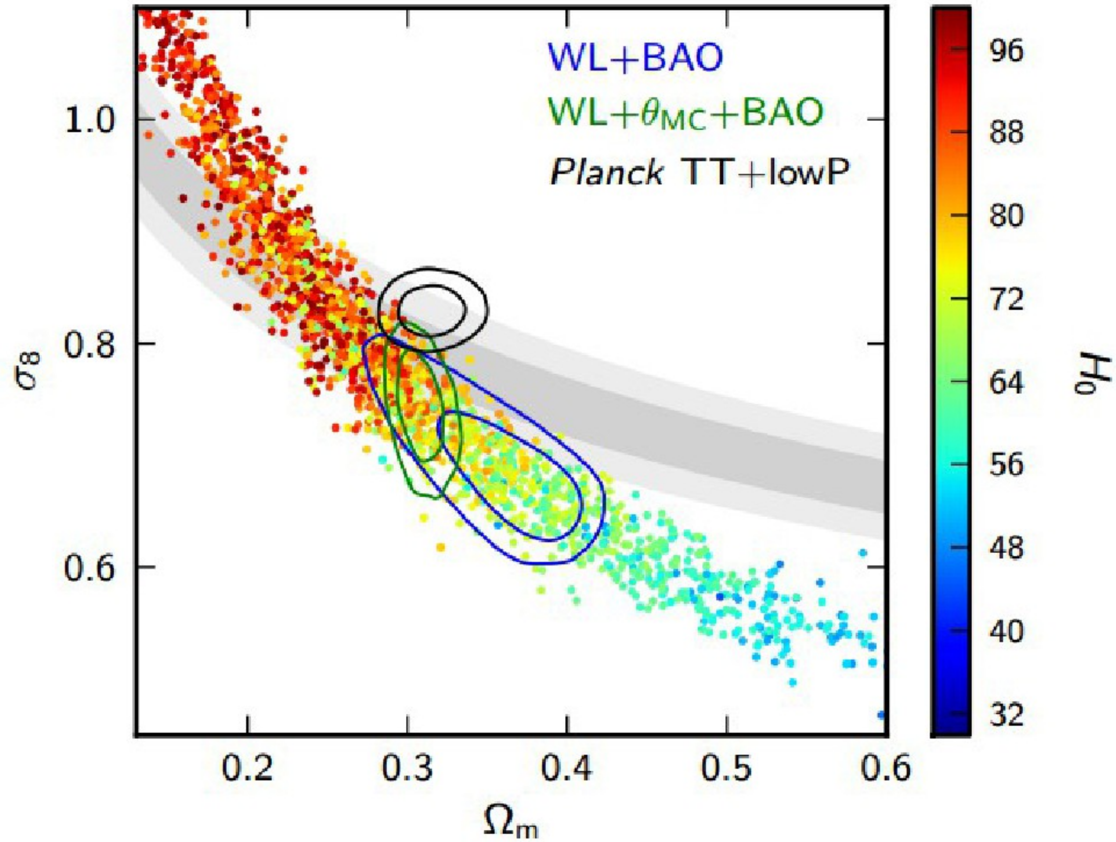
  $H_0 = (70.6 \pm 3.3)\ \mathrm{km\ s^{-1} Mpc^{-1}}$

  which is within 1σ of the Planck TT estimate

$$H_0 = (69.7 \pm 2.1)\ \mathrm{km\ s^{-1} Mpc^{-1}}, \quad \text{WMAP9},$$

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

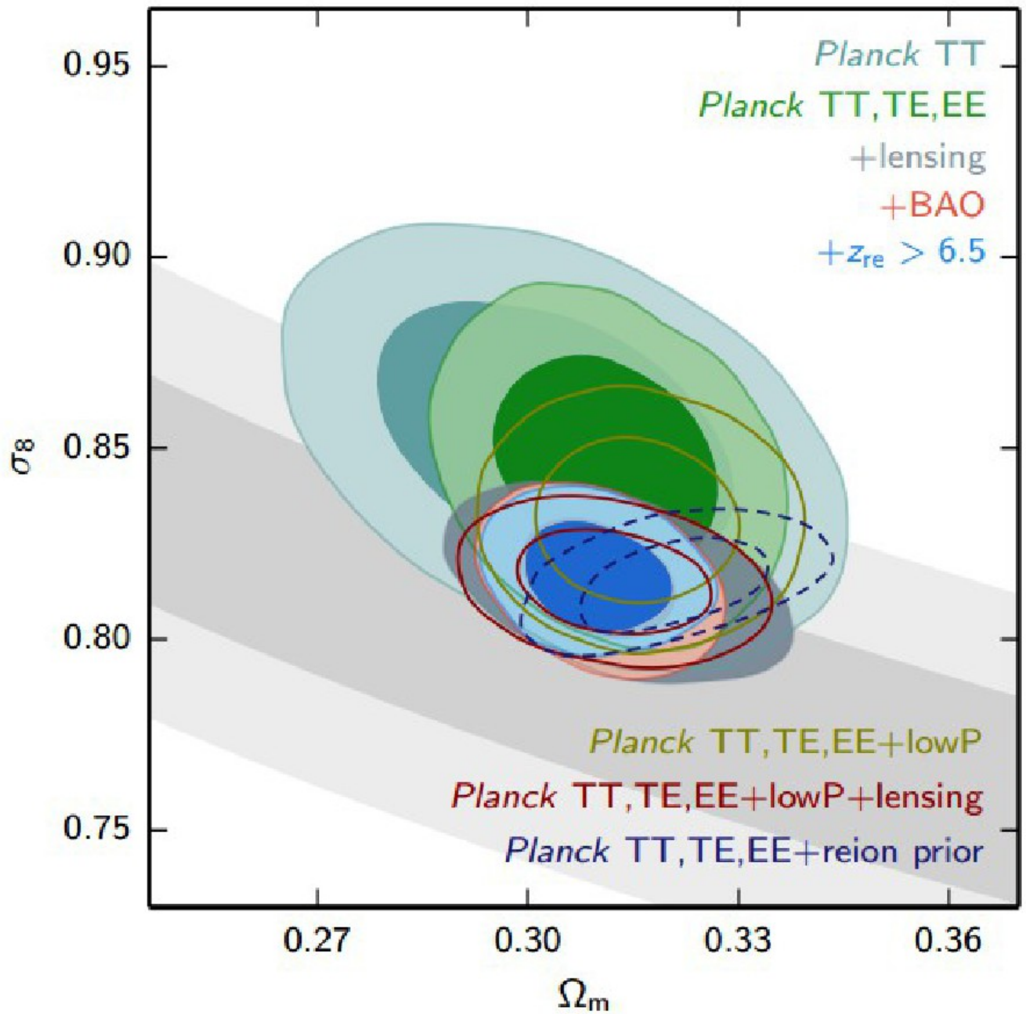
- Weak lensing data from CFHTlens survey.



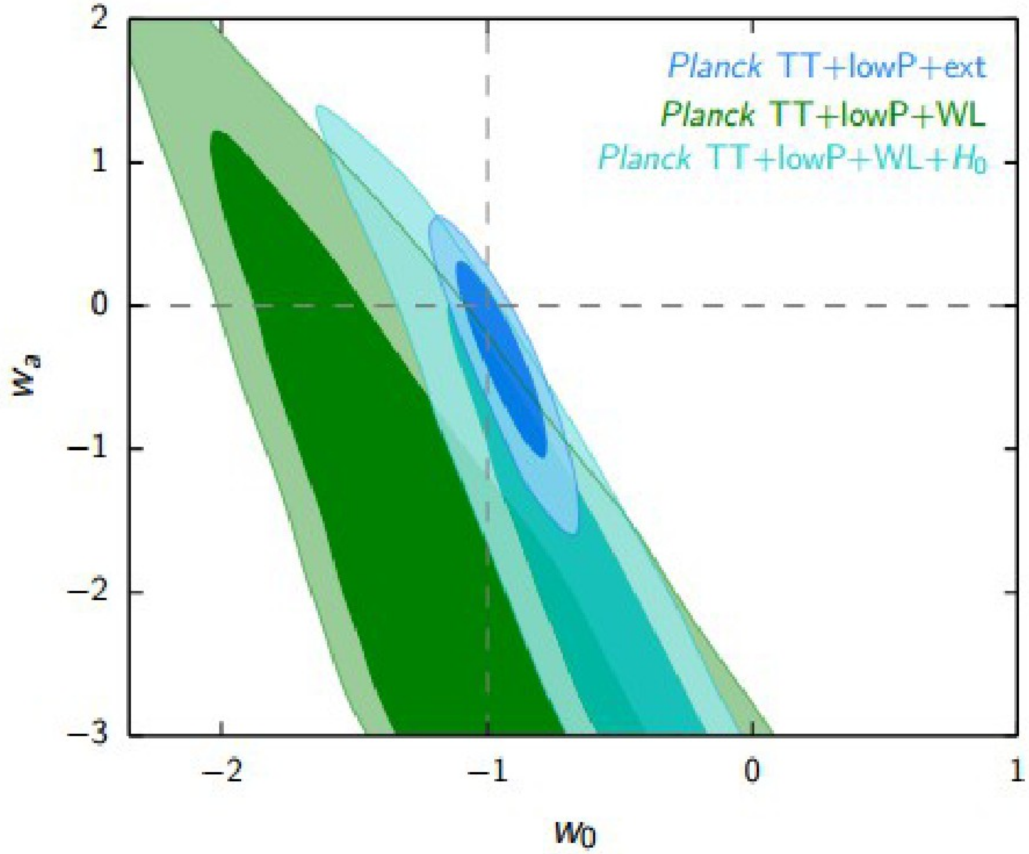
The grey band show the constraint from Planck CMB lensing.

- # 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.

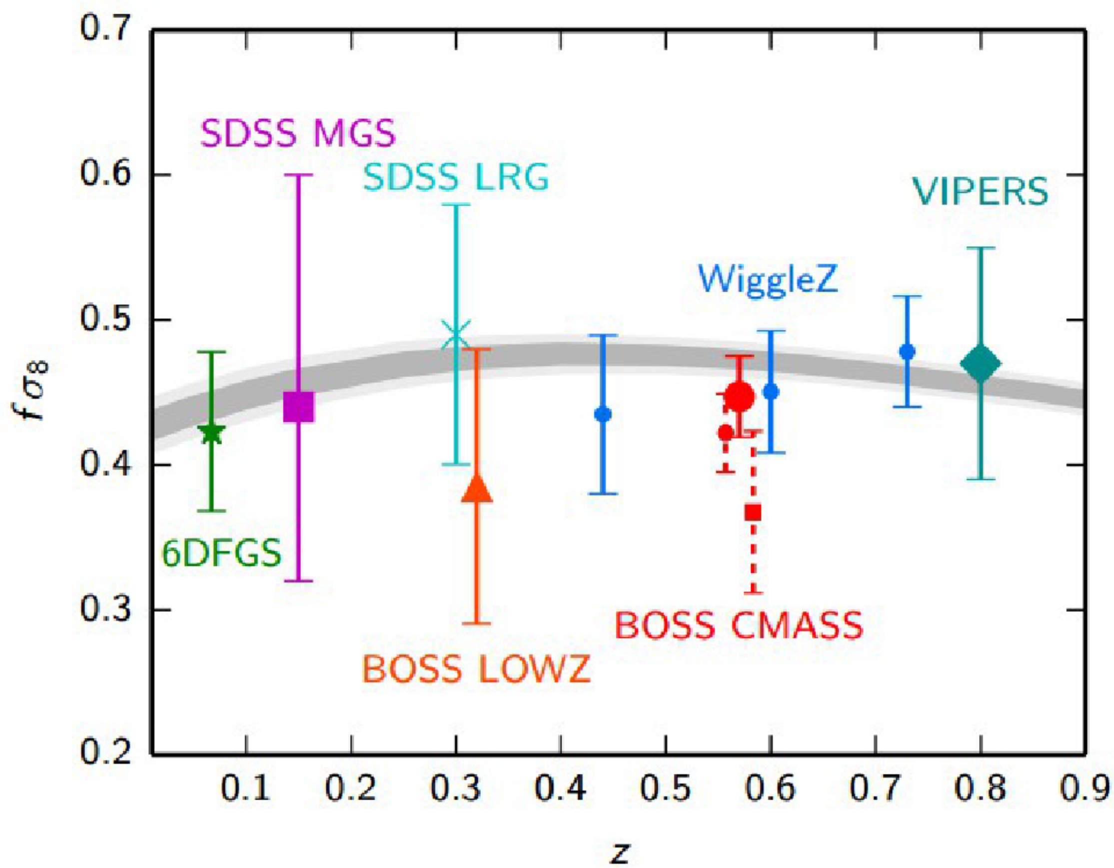


Planck+external datasets



Ext: BAO+JLA+H0 (Efstathiou)

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

Di Valentino, AM, Silk, arXiv:1507.06646

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

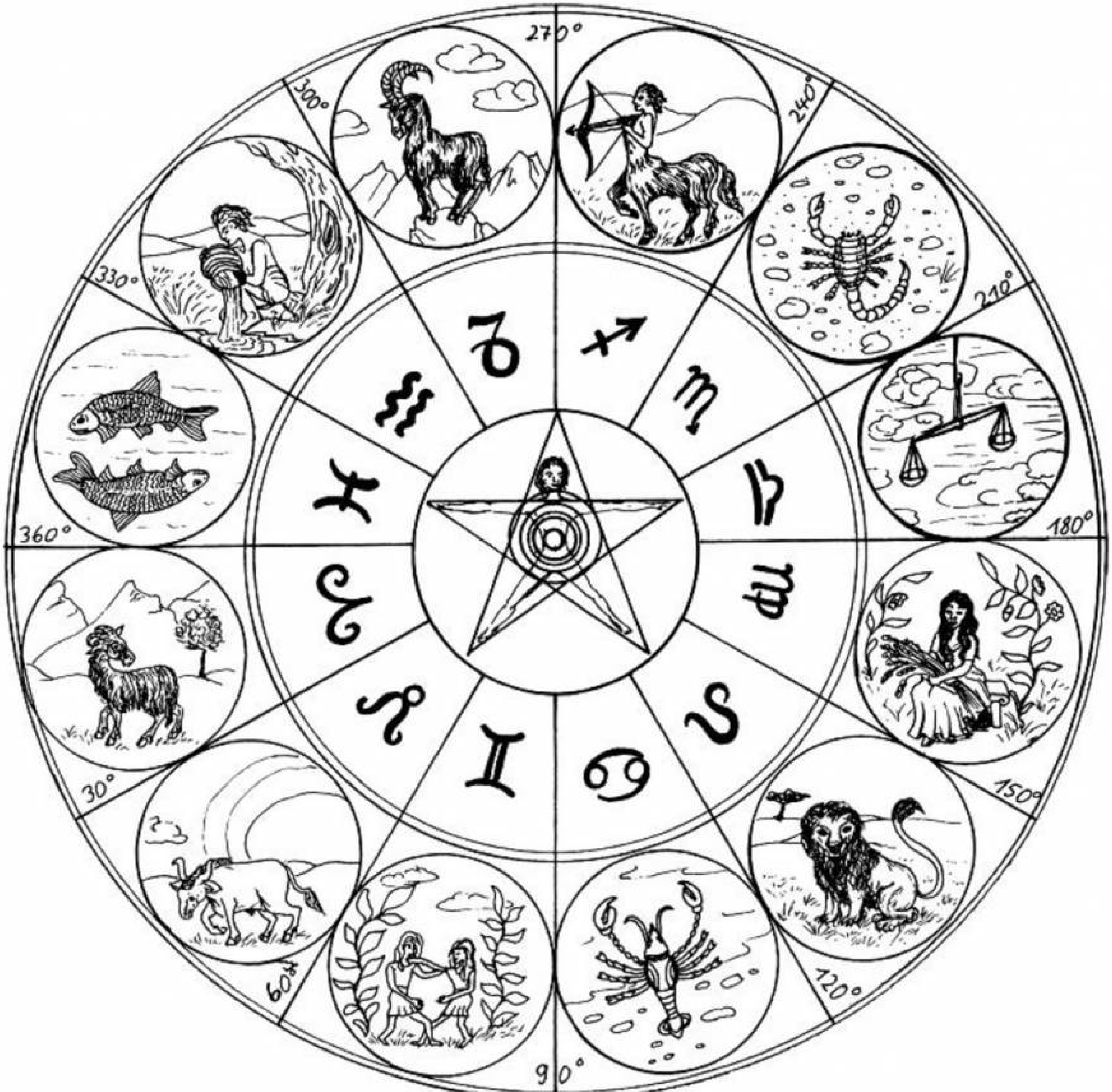
- Gravitational waves (tensor component)

- Running of the primordial spectral index.

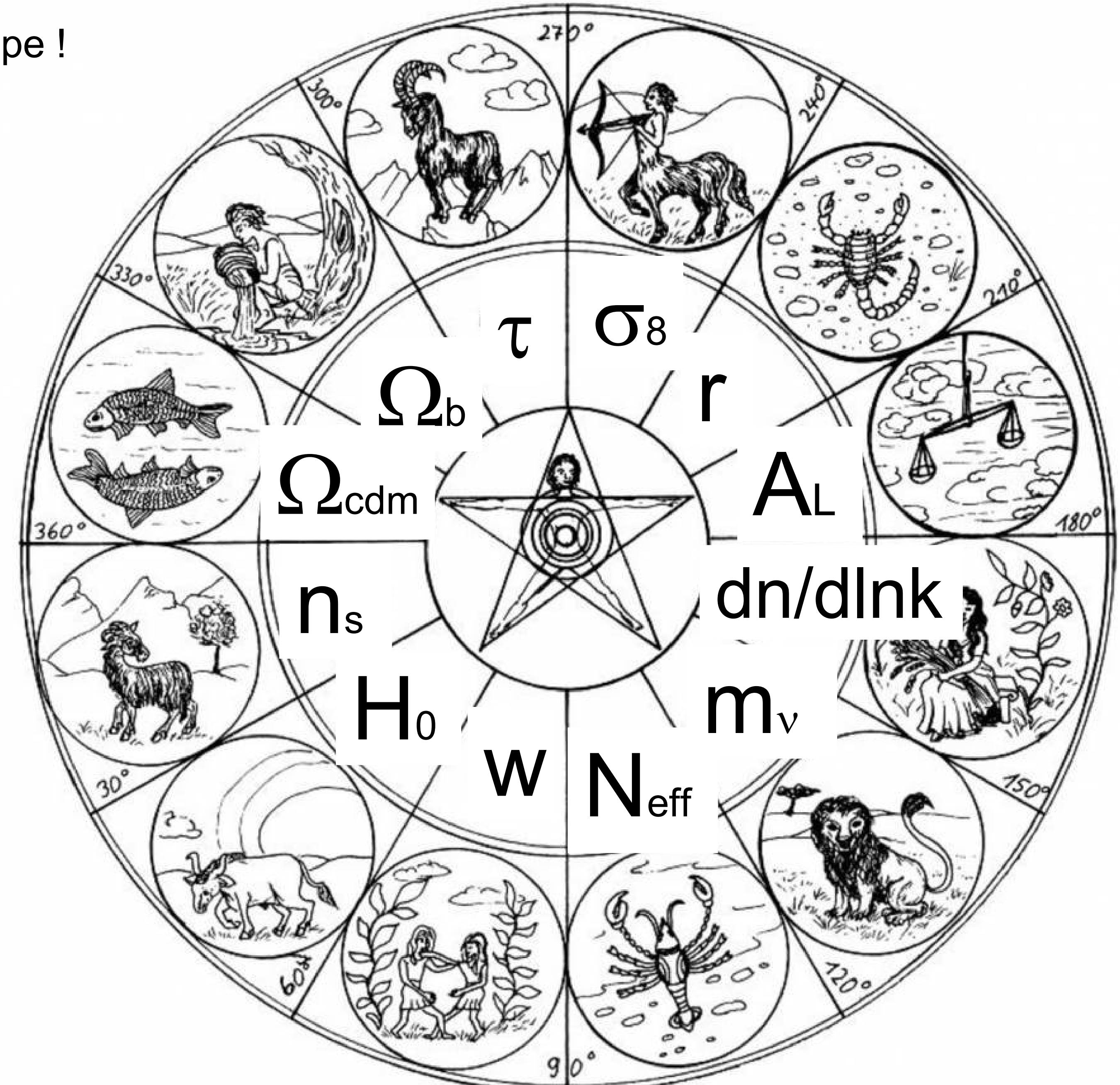
- Lensing amplitude in the CMB angular spectra.

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

Horo-scope

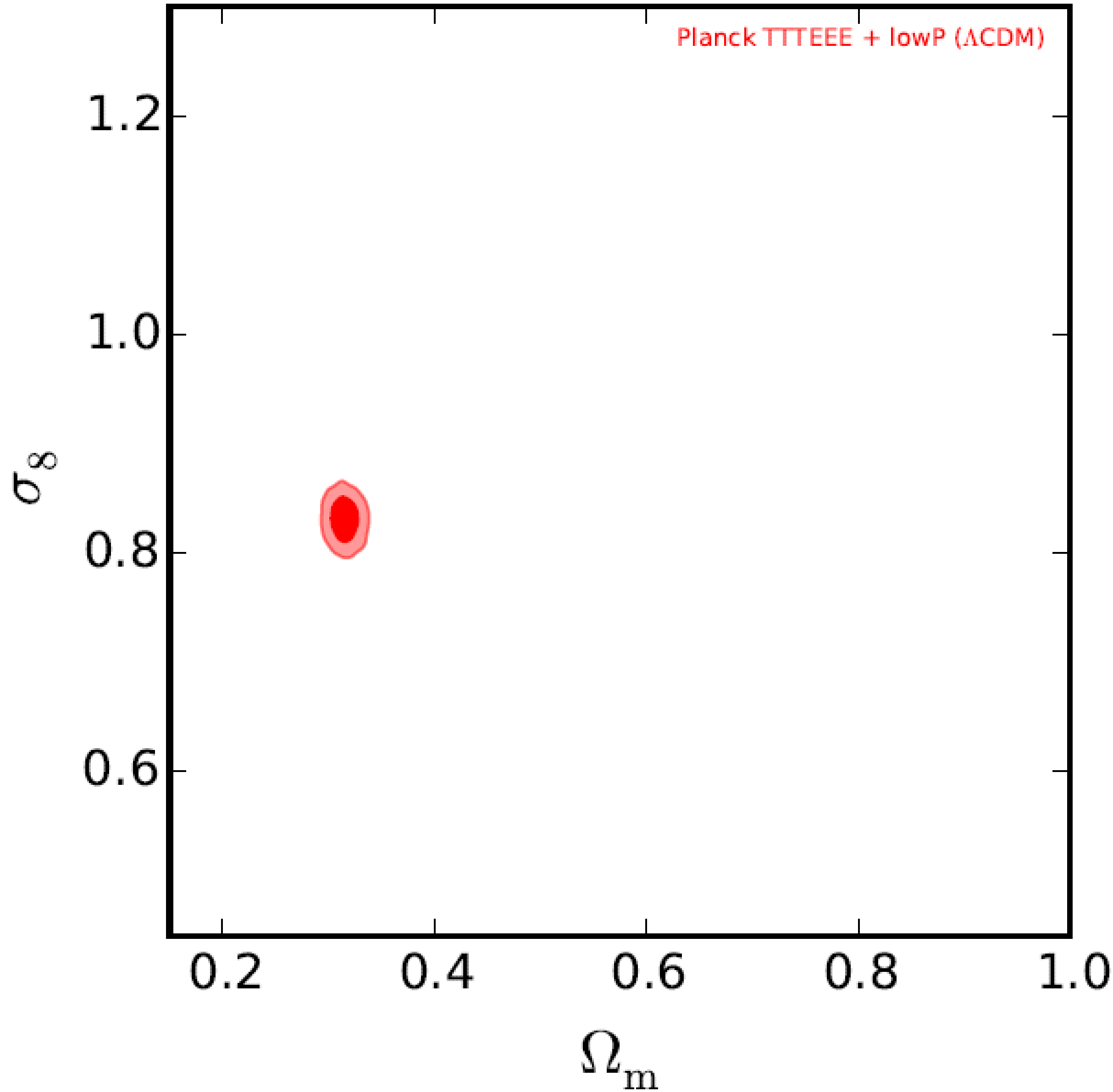


Cosmo-scope !

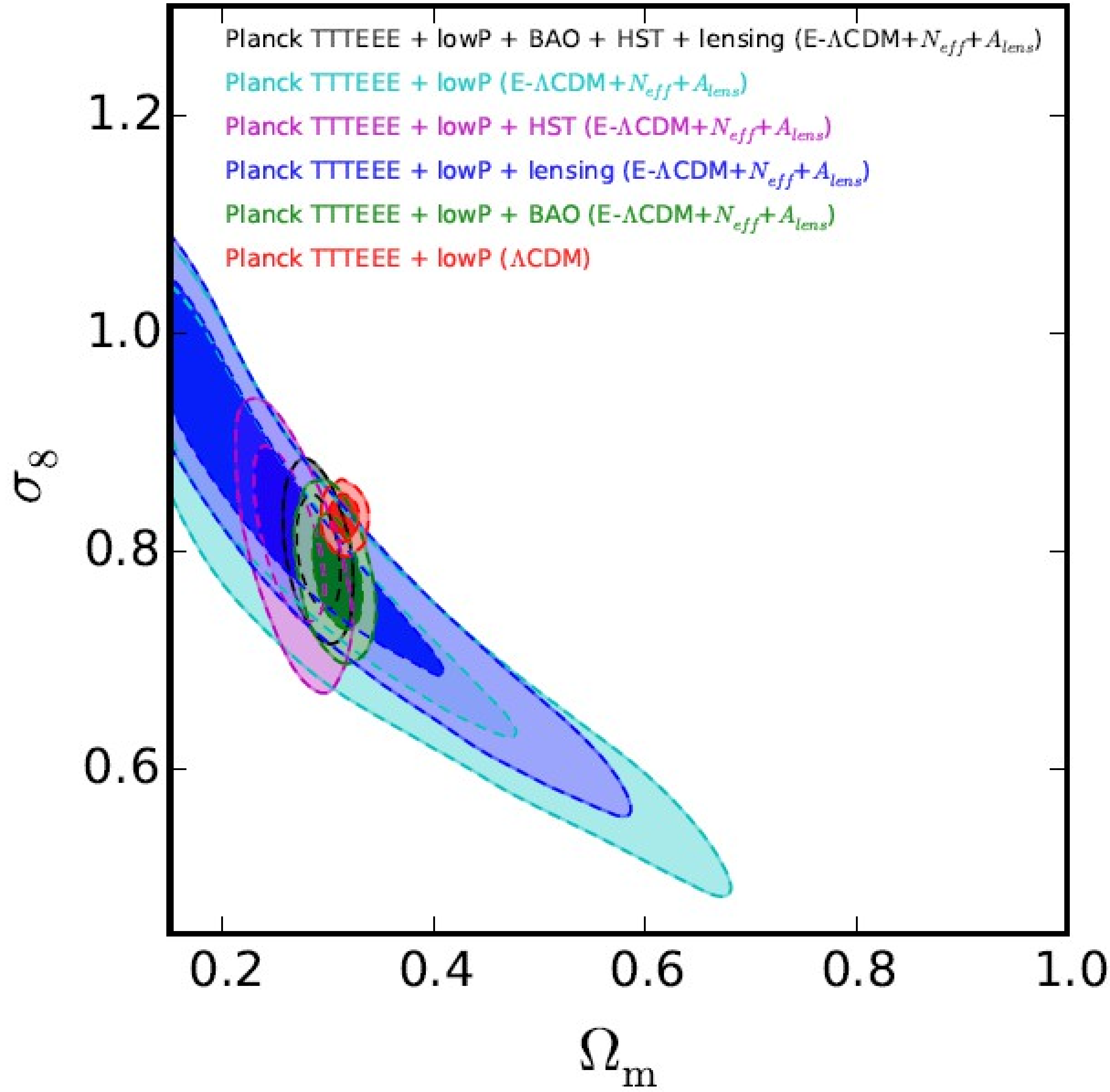


270°
240°
210°
180°
150°
120°
90°
60°
30°
360°
330°
300°
τ
σ_8
r
A_L
dn/dlnk
m_ν
N_{eff}
w
H_0
n_s
Ω_{cdm}
Ω_b

Constraints from Planck assuming 6 parameters LCDM



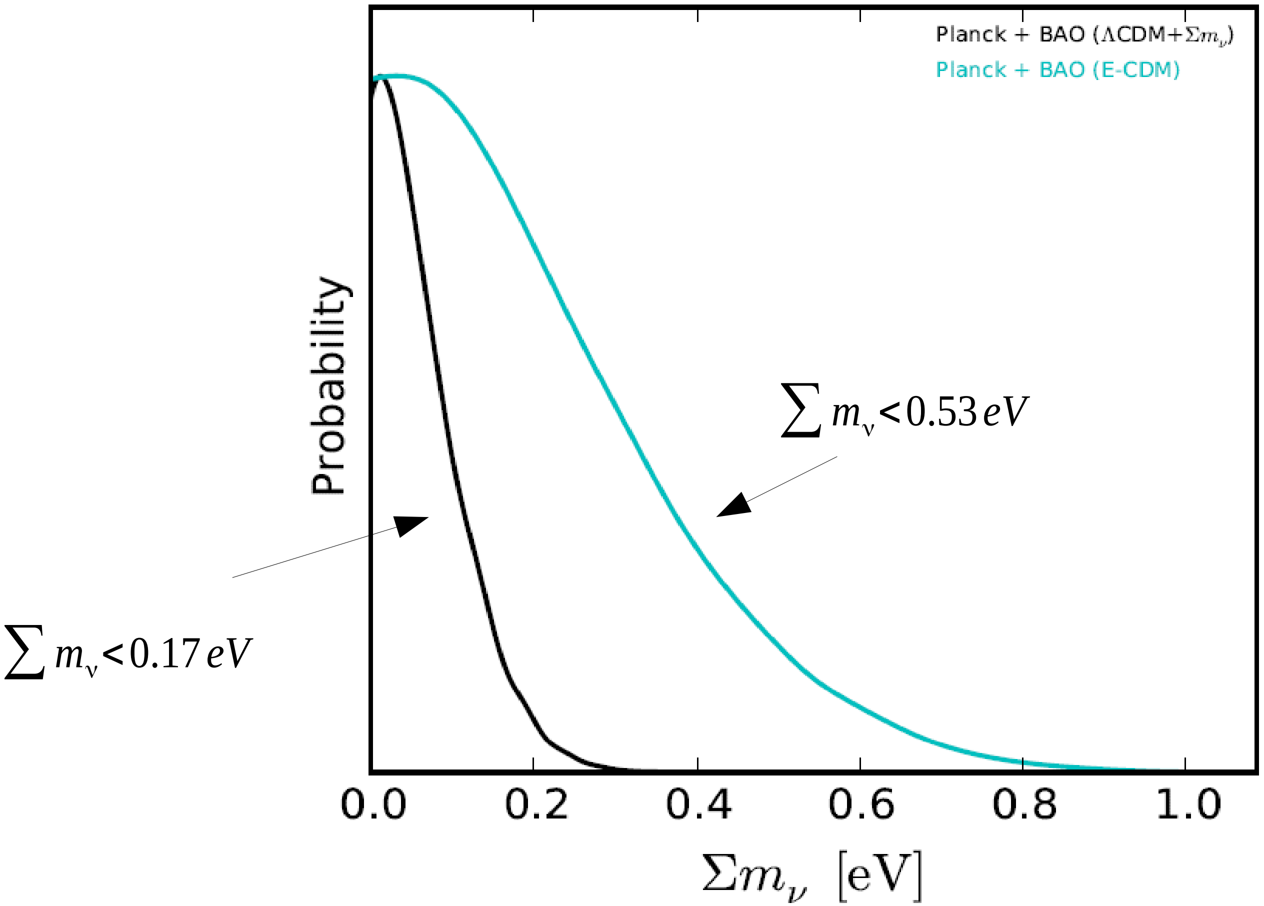
Constraints from Planck assuming 12 parameters eCDM



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, AM, Silk, arXiv:1507.06646



When moving from 6+1 to 12 parameters, the Planck+BAO 95% c.l. constraint on the sum of neutrino masses is relaxed by a factor ~3.

Conclusions

- The 6-parameters cosmological standard model has been further confirmed
By the Planck 2015 data release.

- We have strong implications for neutrino physics: neutrino effective number
and total neutrino mass are now strongly constrained.

- no evidence for extra radiation or extra sterile neutrino.

- no evidence for neutrino mass. If constraints under LCDM are true, it will
Be really difficult to detect a neutrino mass with planned beta and double beta
Decay experiments.

- Cosmological constraints are model dependent ! Increasing the number
of parameters could relax current neutrino constraints by a factor 3.

Future direct neutrino mass measurements will provide a wonderful test
for LCDM cosmology !