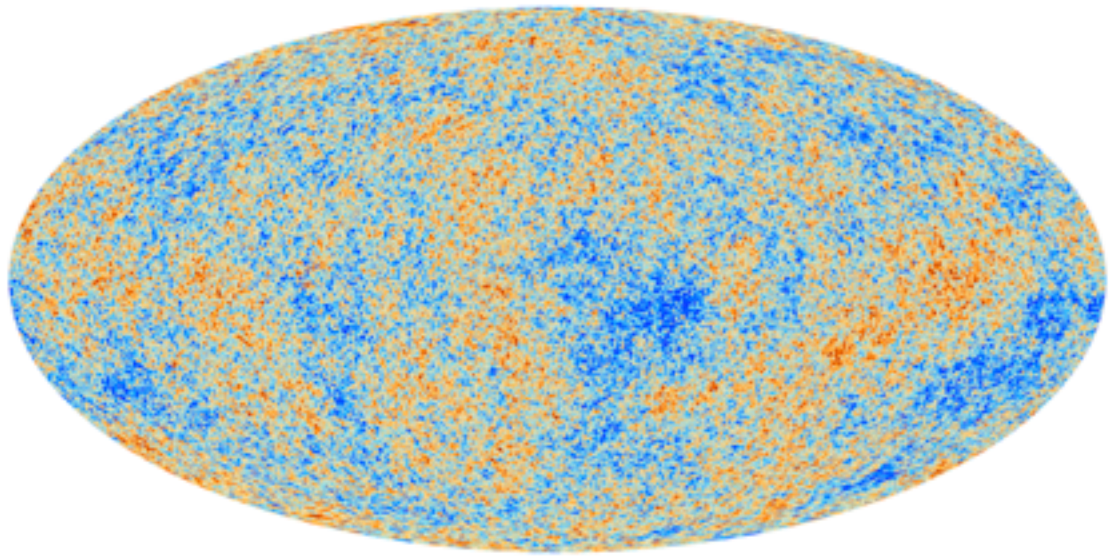
Particle Physics from Planck for 'Pedestrians'



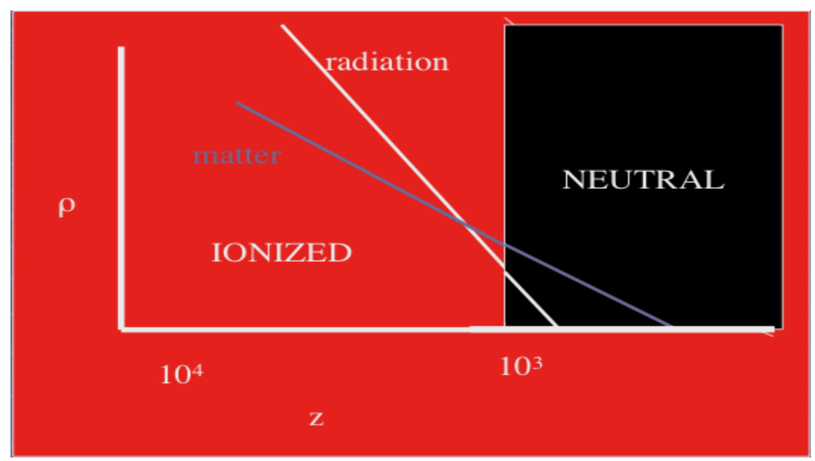
Jo Dunkley

Oxford Astrophysics

Oxford, June 20

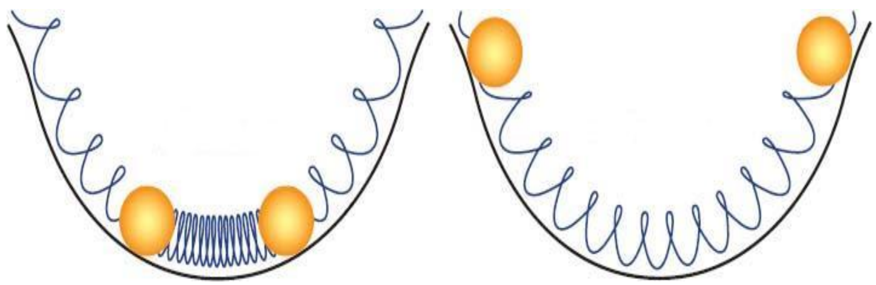
History of early universe

Inflation?	$T \sim 10^{15}$ GeV	$t \sim 10^{-35}$ s
CDM decoupling?	$T \sim 10$ GeV?	$t \sim 10^{-8}$ s
Quark-hadron transition	$T \sim$ GeV	$t \sim 10^{-6}$ s
Neutrino Decoupling	$T \sim 1$MeV	$t \sim 1$s
Big Bang Nucleosynthesis	$T \sim 100$ keV	$t \sim 10$ min
Matter-Radiation Equality	$T \sim 0.8$eV	$t \sim 60000$ yr
Recombination	$T \sim 0.3$eV	$t \sim 380000$ yr



Seeds of structure

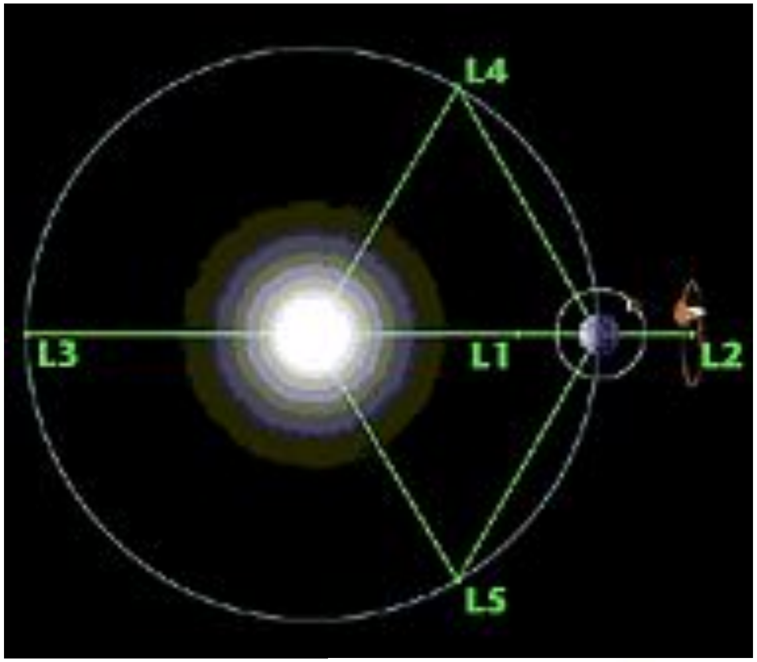
1. Inflation (?) imprints quantum fluctuations.
2. Space expands, regions enter into causal contact and start to evolve.
3. Coupled baryons and photons produce oscillations in plasma.

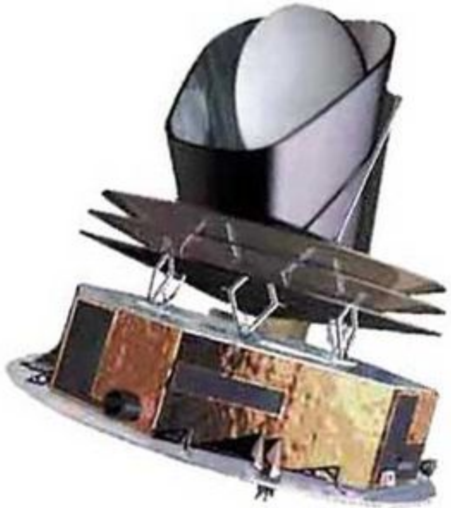


After 380,000 years the fluctuations have evolved, and we see a snapshot of them as anisotropies.

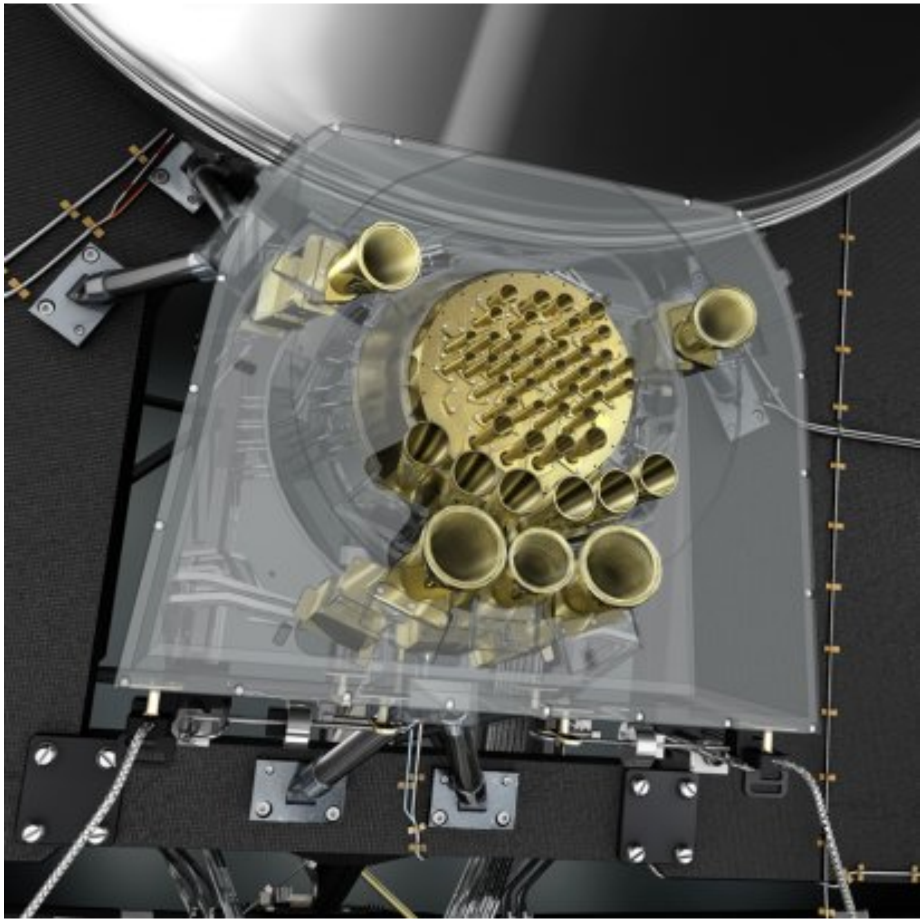
Linearity means we can use the anisotropies to infer the initial fluctuations and the contents of the Universe.

Planck launched 2009



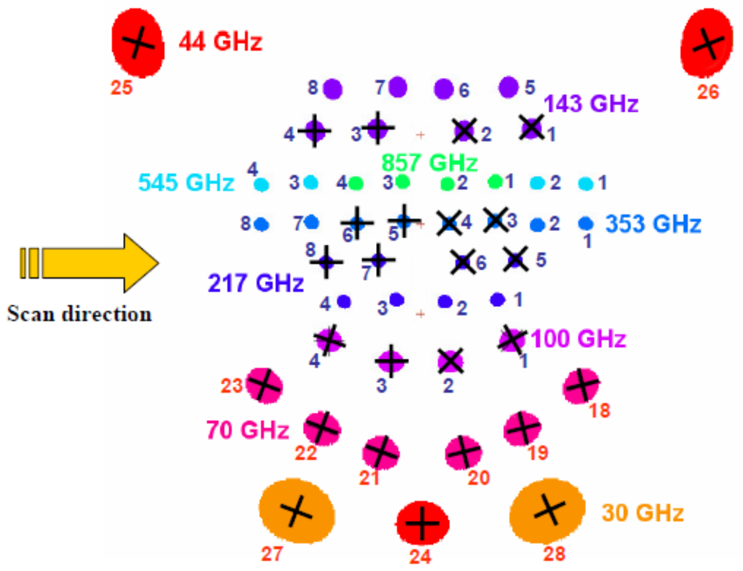


The Planck instruments

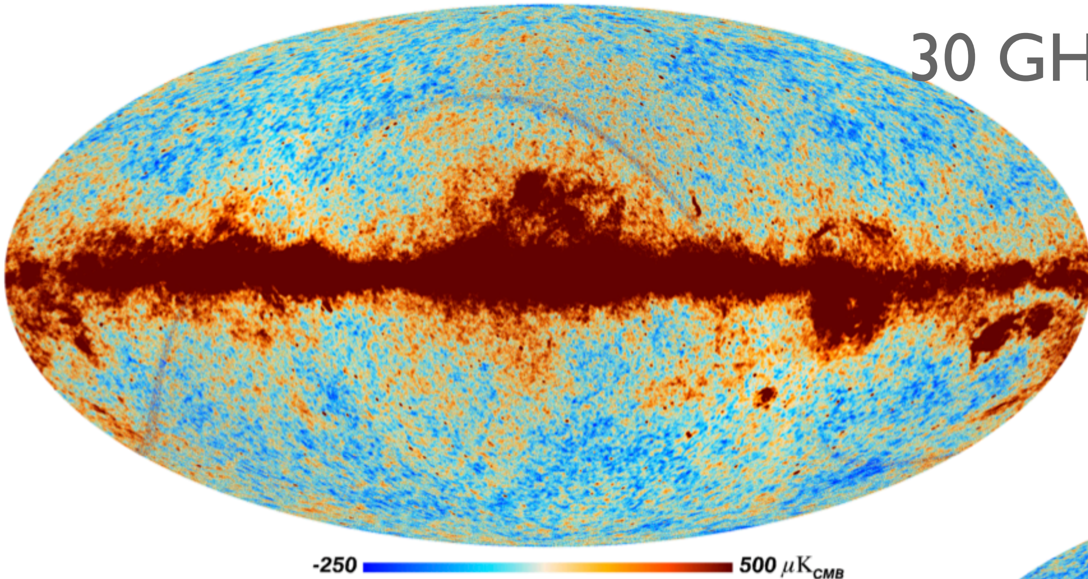


Low Frequency Instrument (LFI) – 33-70 GHz
High Frequency Instrument (HFI) – 100-857 GHz.

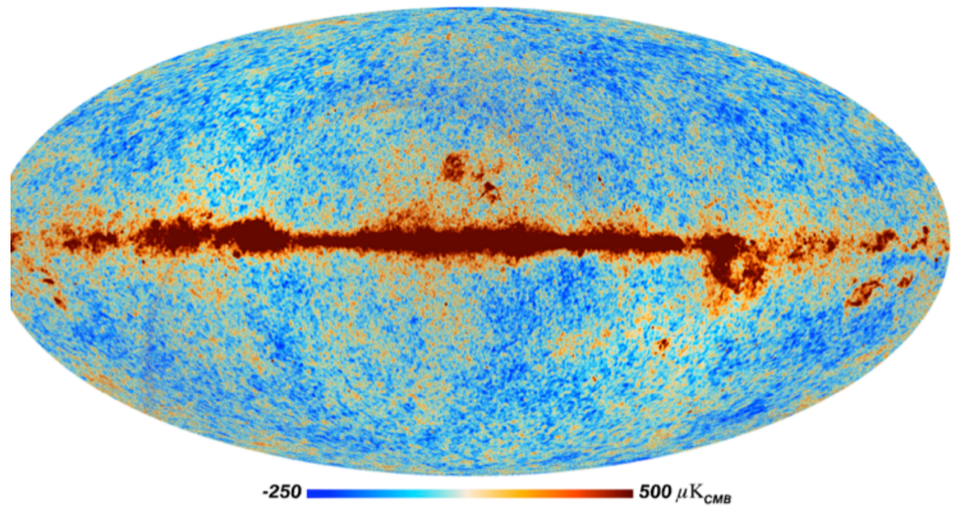
HFI actively cooled to 0.1K so took data until Jan 2012. LFI still observing.
Bigger mirror: few arcmin resolution



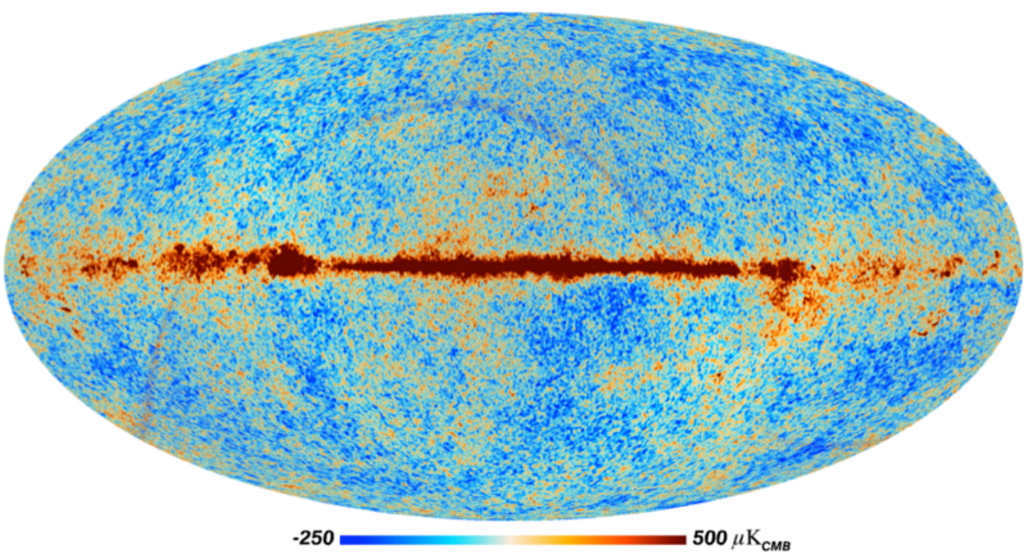
30 GHz

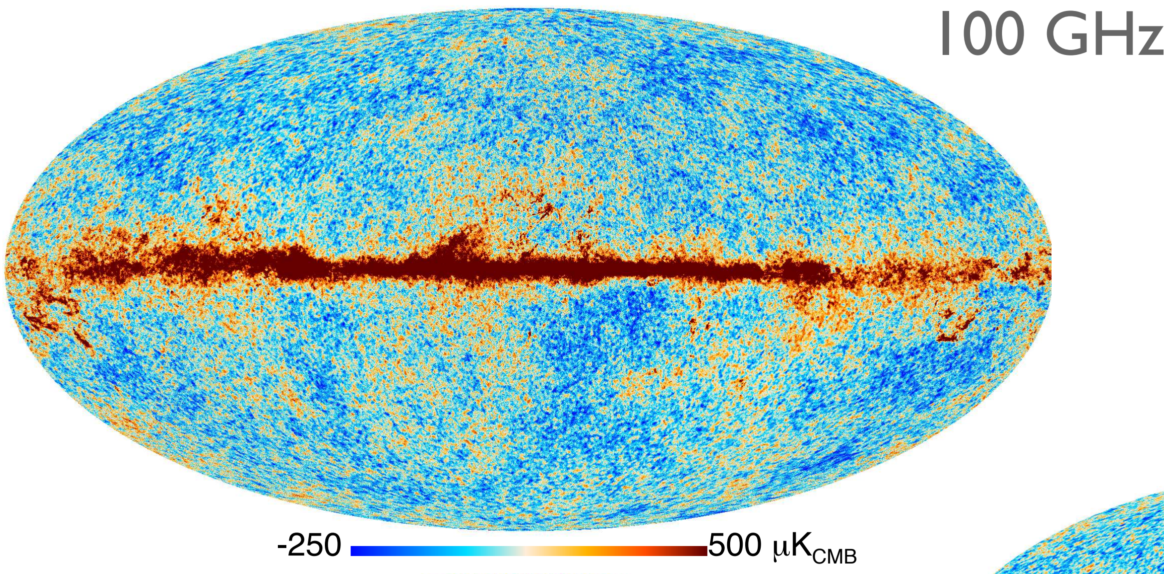


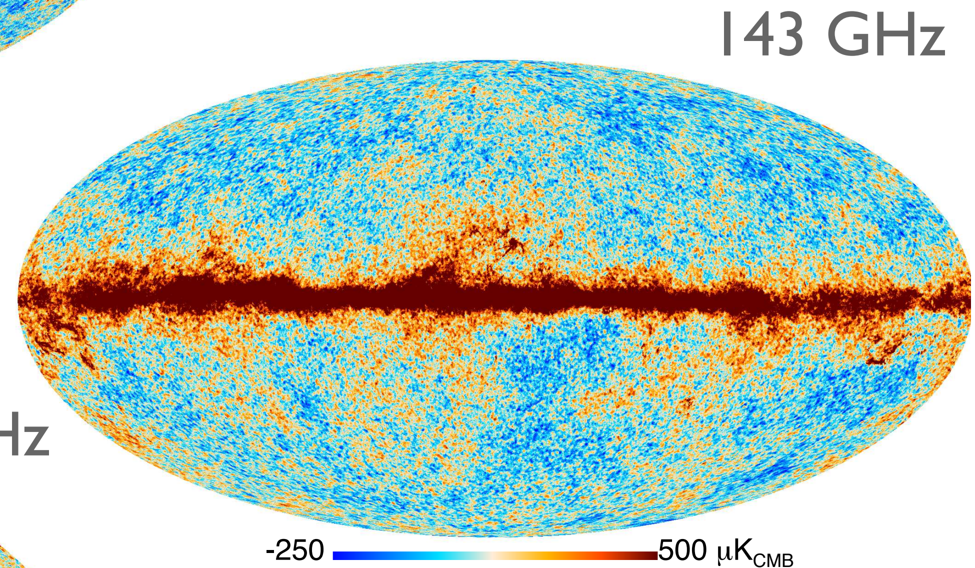
44 GHz

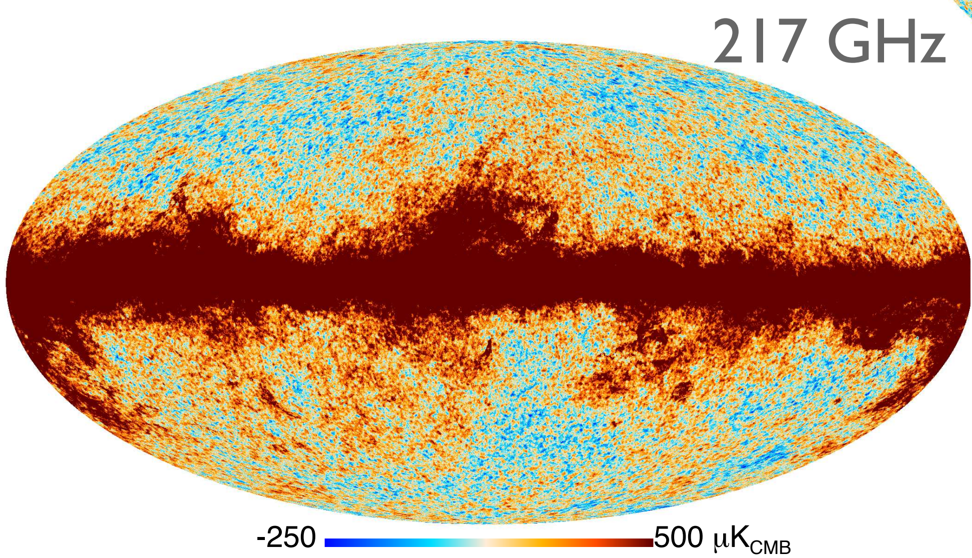


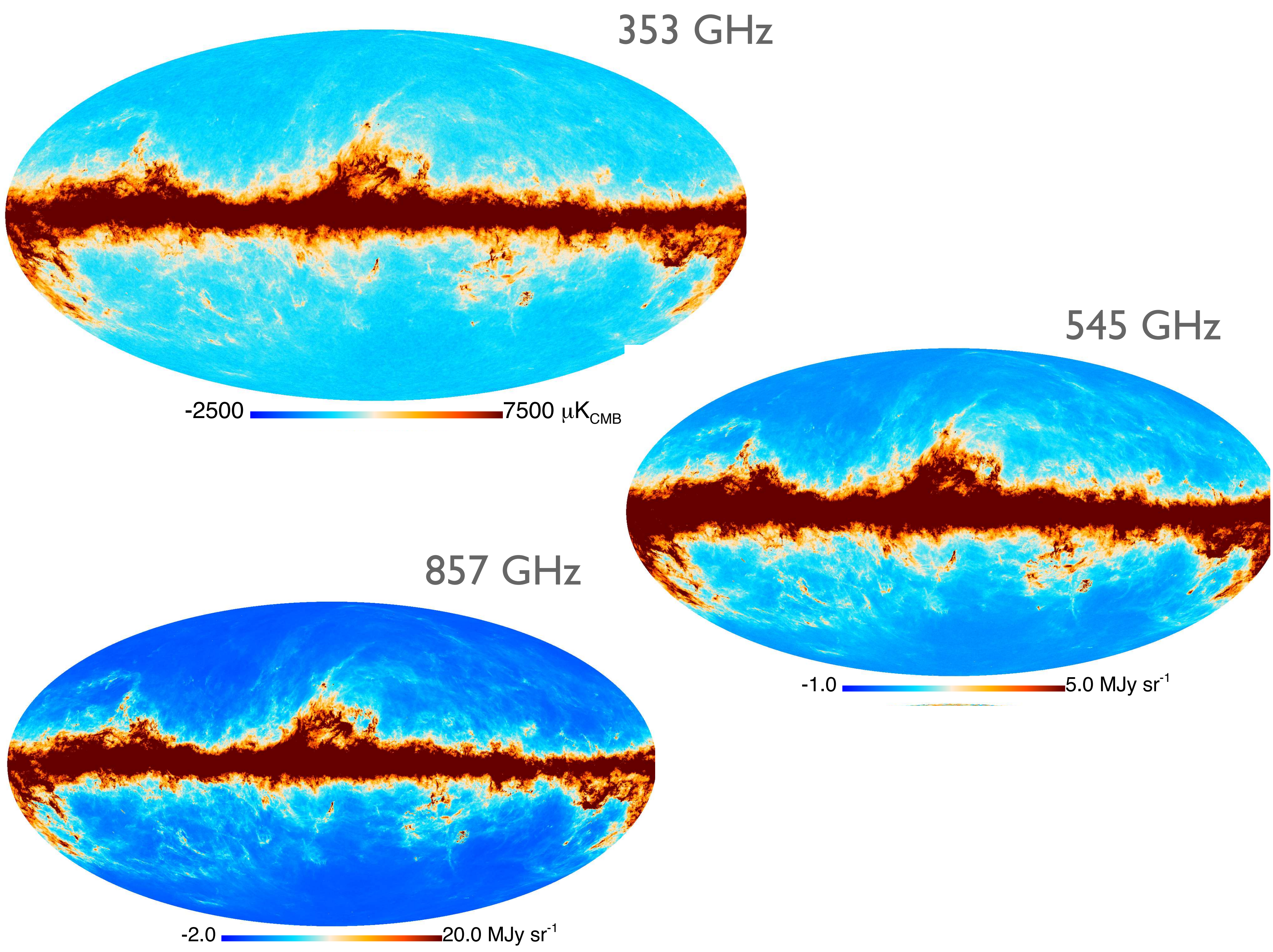
70 GHz

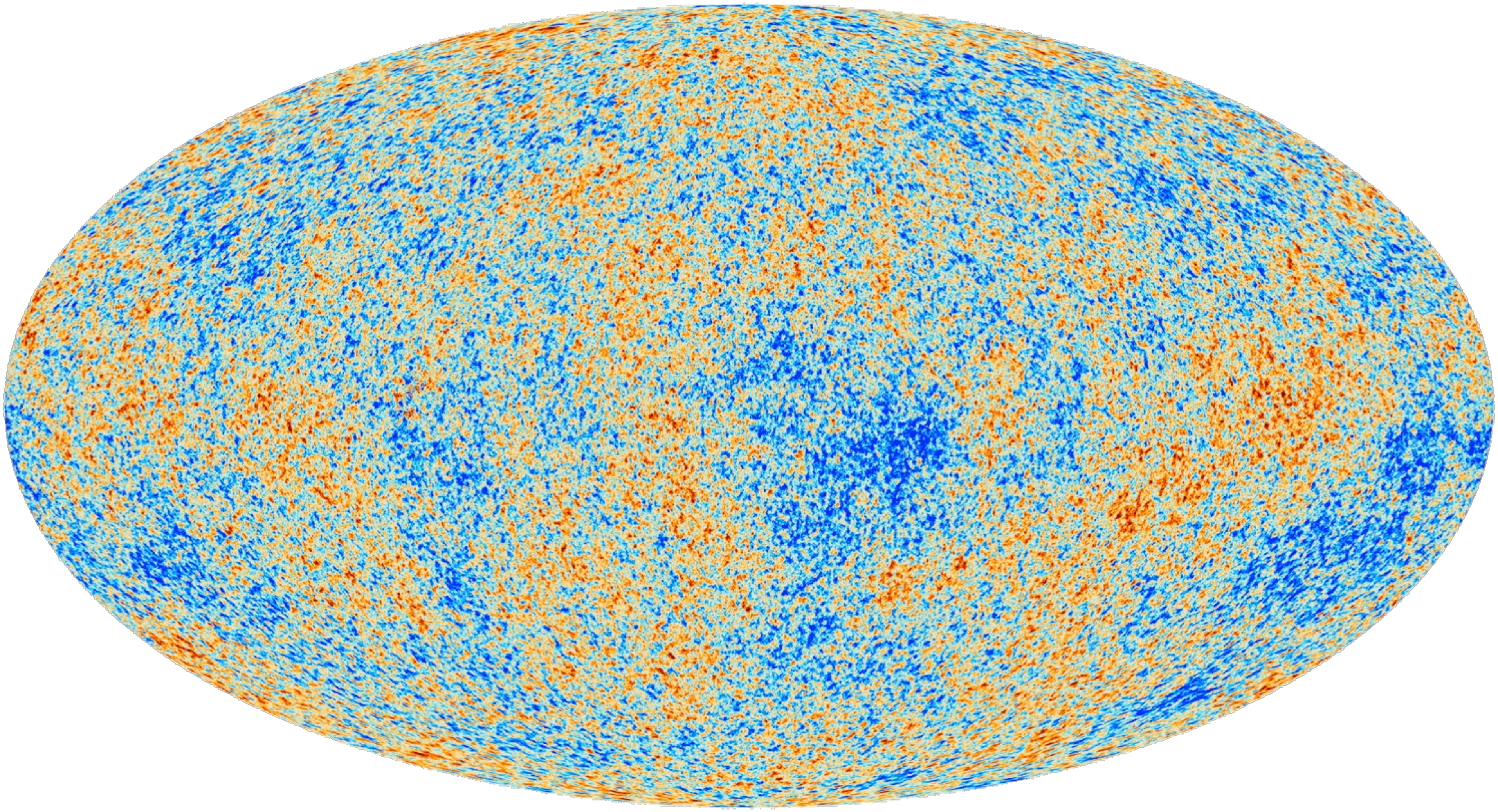


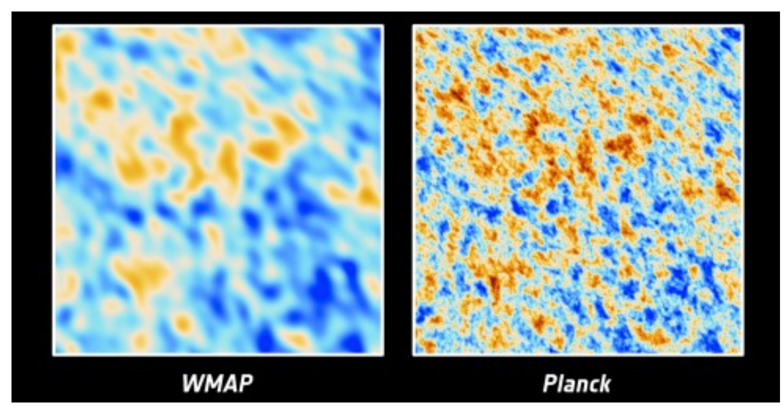

100 GHz
-250
500 μK_CMB


143 GHz
-250
500 μK_CMB

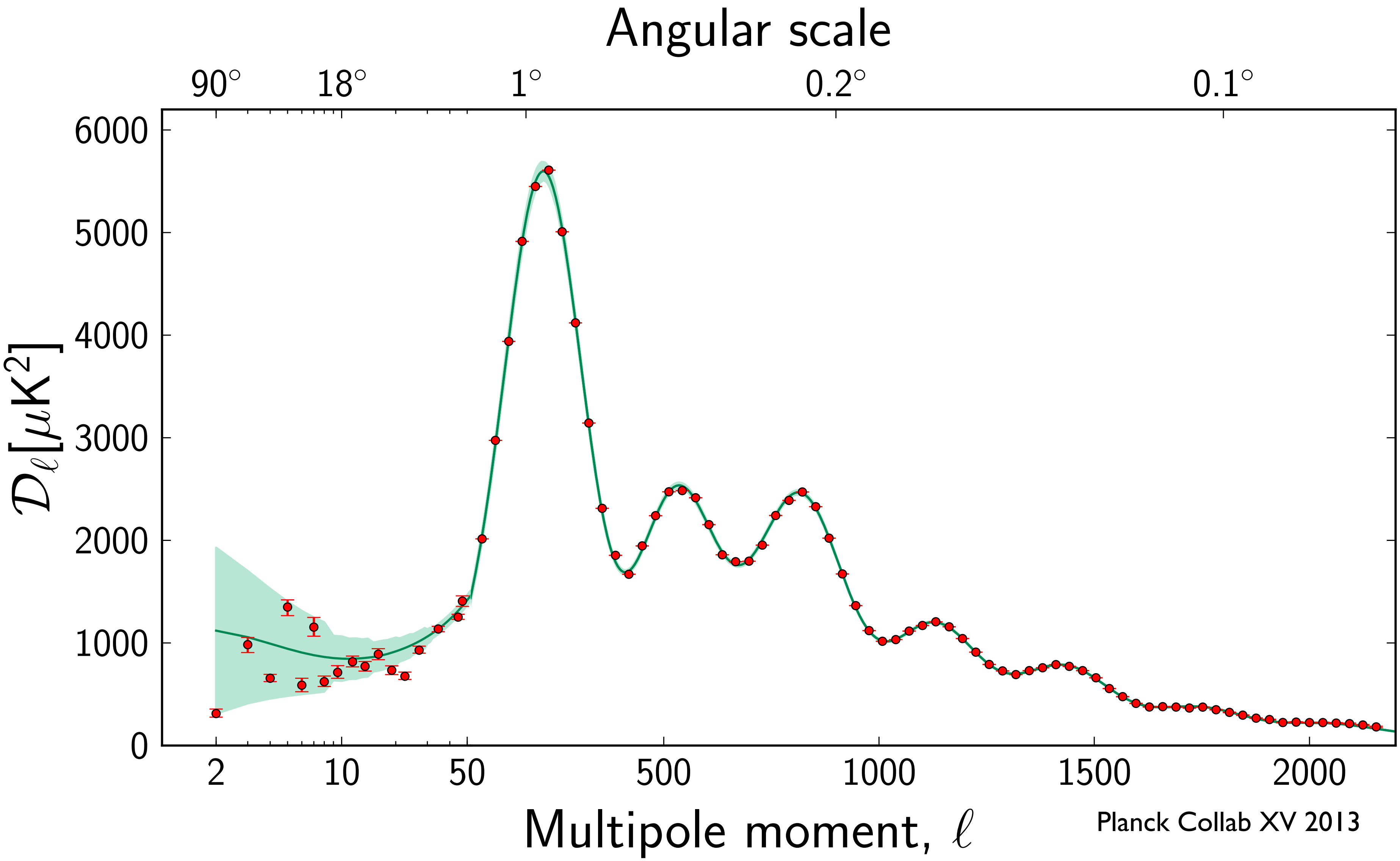

217 GHz
-250
500 μK_CMB


353 GHz
-2500
7500 μK$_{CMB}$
545 GHz
-1.0
5.0 MJy sr^{-1}
857 GHz
-2.0
20.0 MJy sr^{-1}



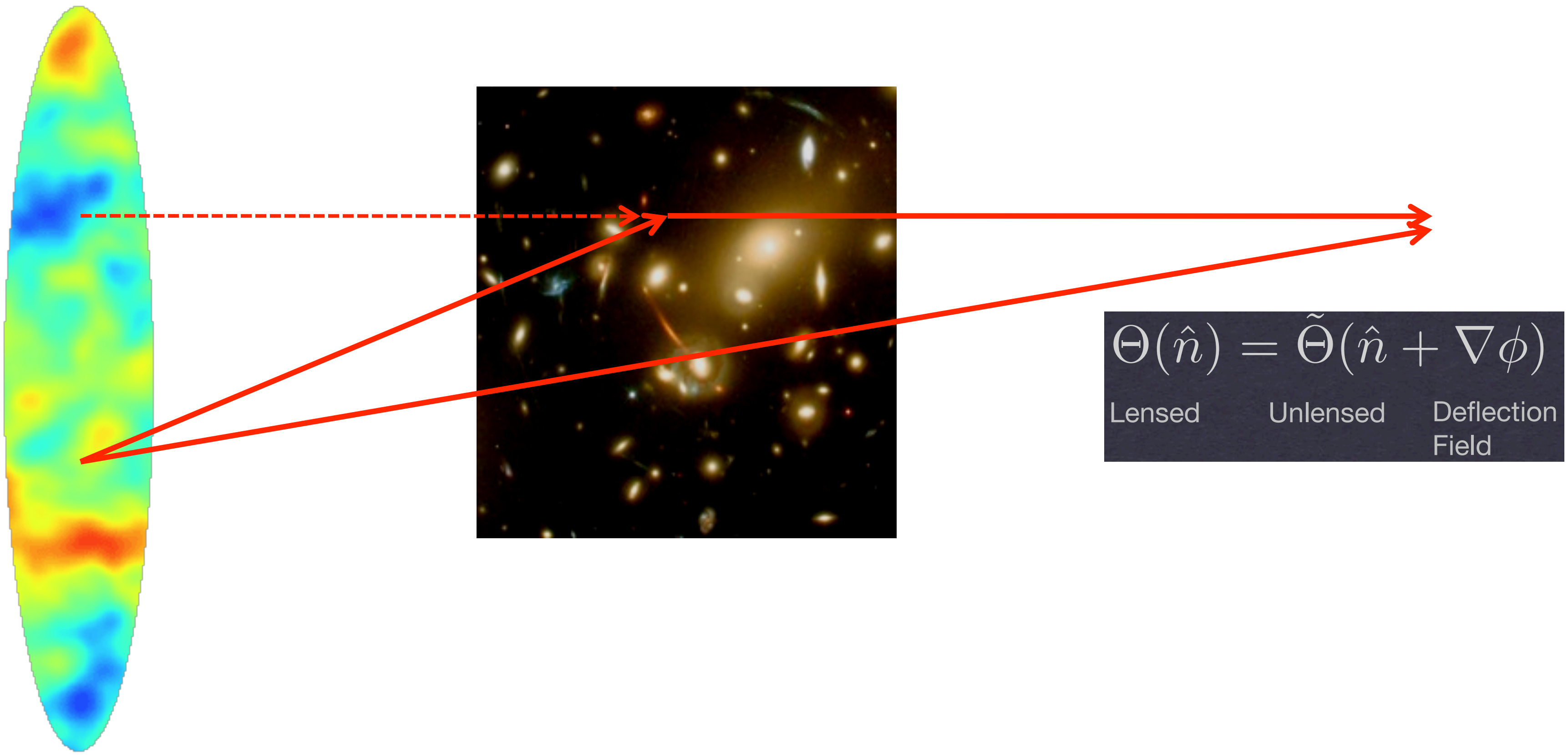

WMAP
Planck

Planck



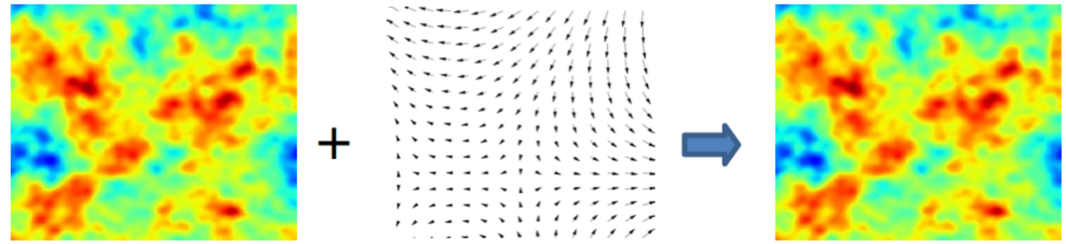
Angular scale
90°
18°
1°
0.2°
0.1°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
Multipole moment, ℓ
Planck Collab XV 2013

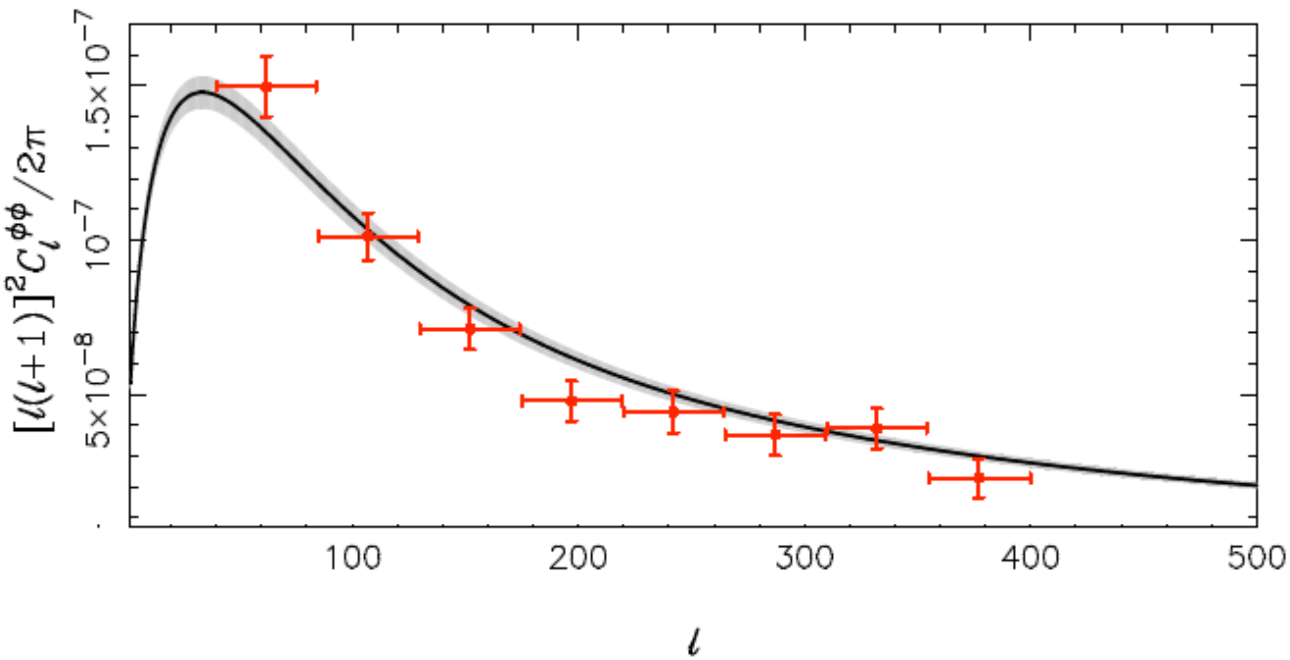
Lensing of the CMB



Integrated mass fluctuations along the line of sight
Deflection is a couple of arcminutes, but coherent on degree scales.

CMB lensing





$$\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} \mathrm{d}\eta \, \underbrace{W^2(\eta)}_{\text{geometry}} \, \underbrace{P\left(k = \frac{\ell+1/2}{d_A(\eta)},\right.}_{\text{matter}}$$

What questions can we ask of the data?

Does ΛCDM still work?

Is inflation the right paradigm?

Which inflation model?

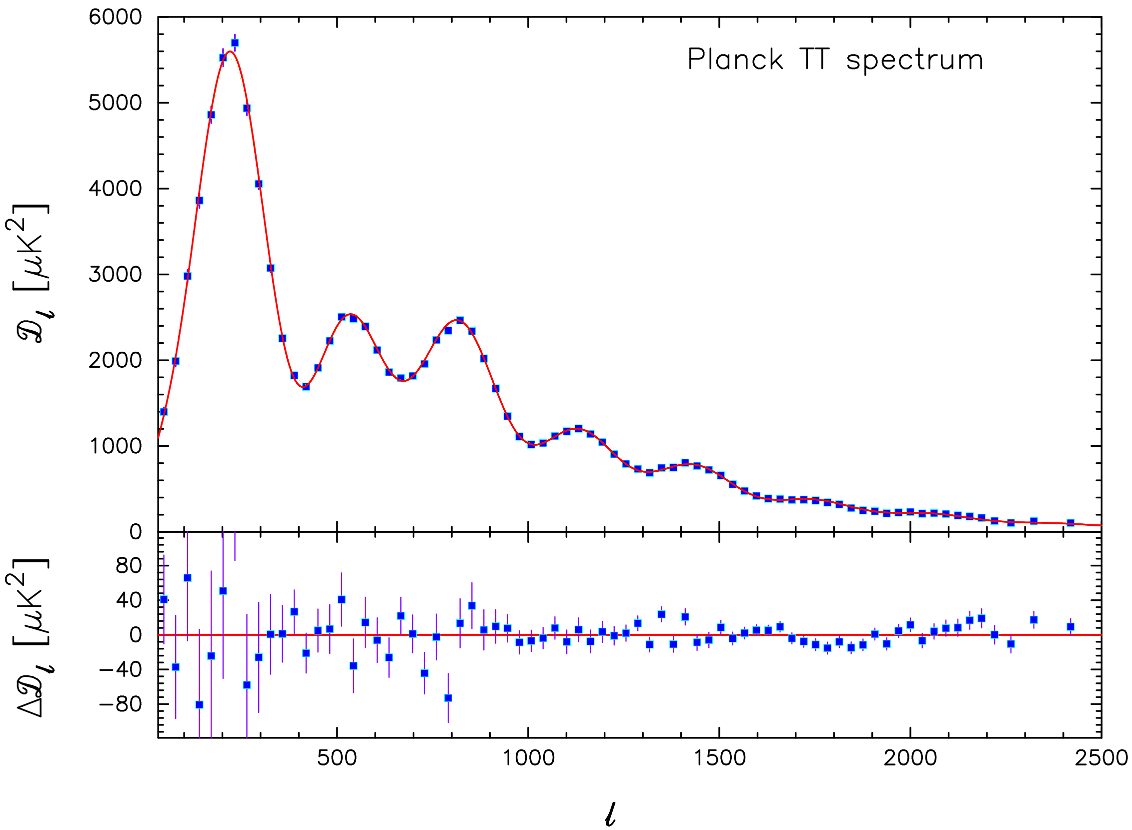
Is Dark Energy a constant, or a dynamical component?

*What are the masses of the neutrinos?

*Are there extra relativistic species?

Are there other high energy signatures?

Are there 'other' signatures?



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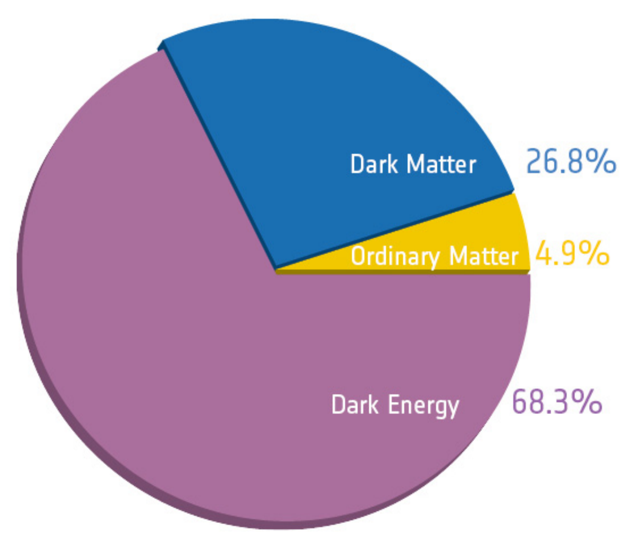
ΛCDM: flat 6-parameters



Planck +WP

$\Omega_b h^2$ = 0.0221 ± 0.0003

$\boxed{\Omega_c h^2 \quad = 0.120 \pm 0.003}$

n_s = 0.960 ± 0.007

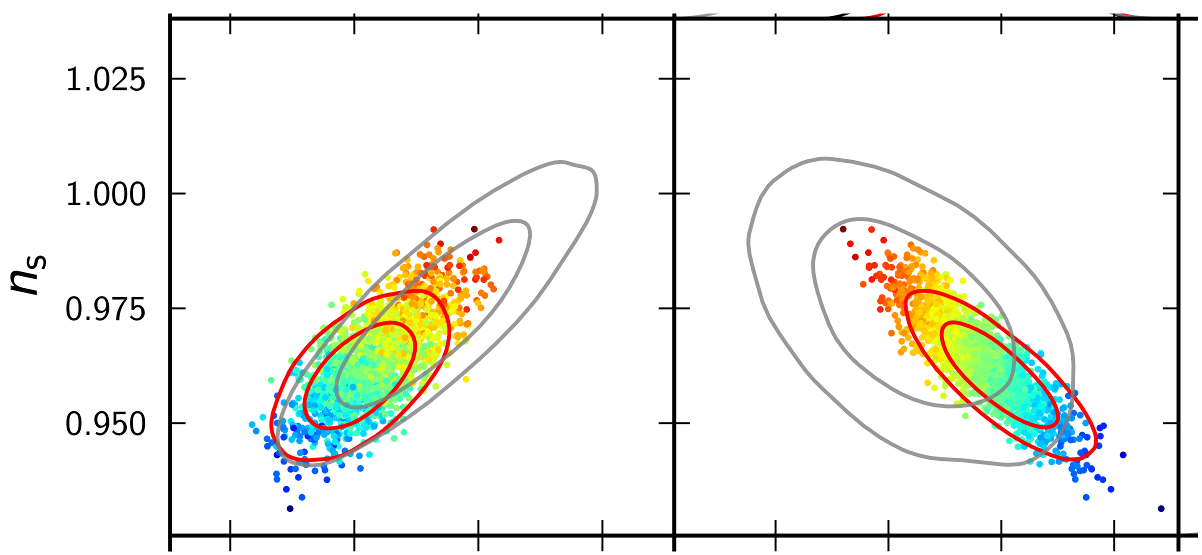
$10^9 A_s$ = 2.20 ± 0.06

τ = 0.089 ± 0.014

H_0 = 67.3 ± 1.2

Ω_Λ = 0.685 ± 0.017

σ_8 = 0.83 ± 0.01



High mass → low cross section → high relic density

Neutrinos: cosmological effects

- Neutrinos thermally decouple when weak interaction rate < expansion rate of universe ~ 1 MeV.
- Photons have higher temperature from e+e- annihilation.
- If massive, become non-relativistic
  - z=6000 (3eV)
  - z=30 (0.05eV)

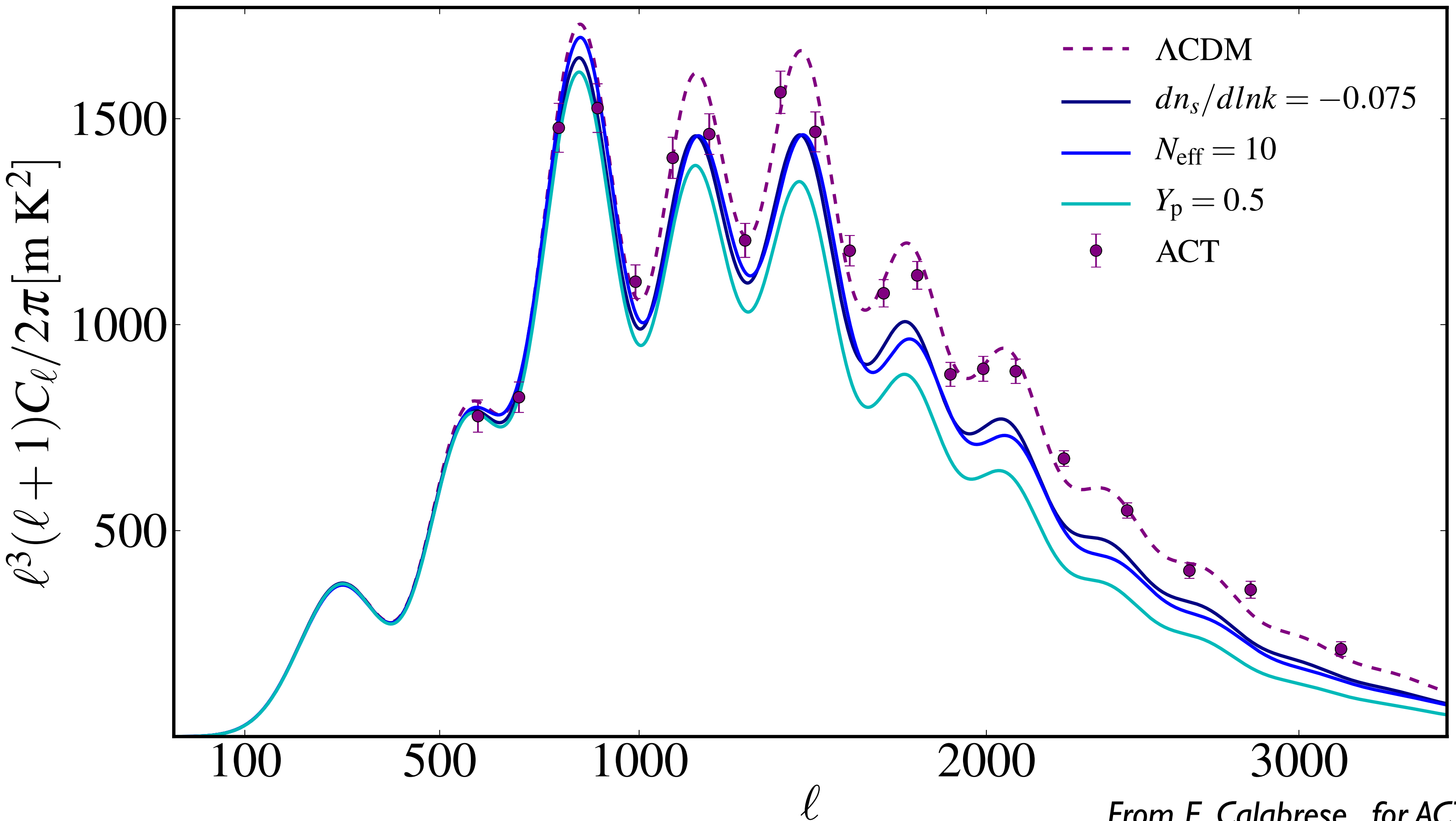
$$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3}$$

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

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94 eV}$$

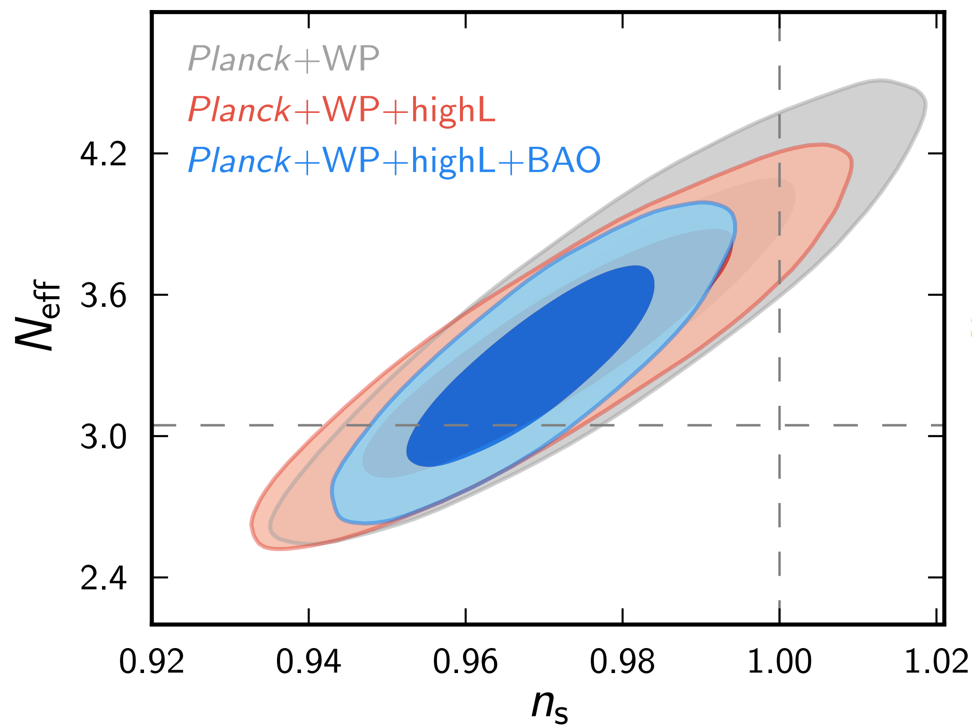
Standard model: N=3.046
Effect of electron-positron annihilation (0.034)
Finite temperature QED (0.01)

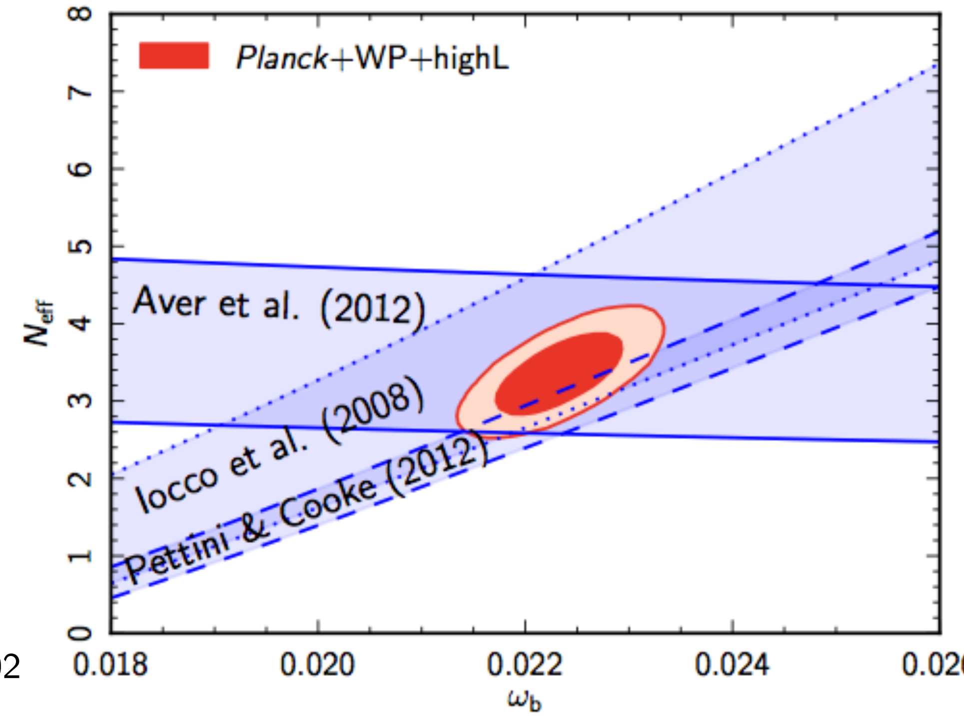
Effect on small scales



From E. Calabrese, for ACT

Relativistic species





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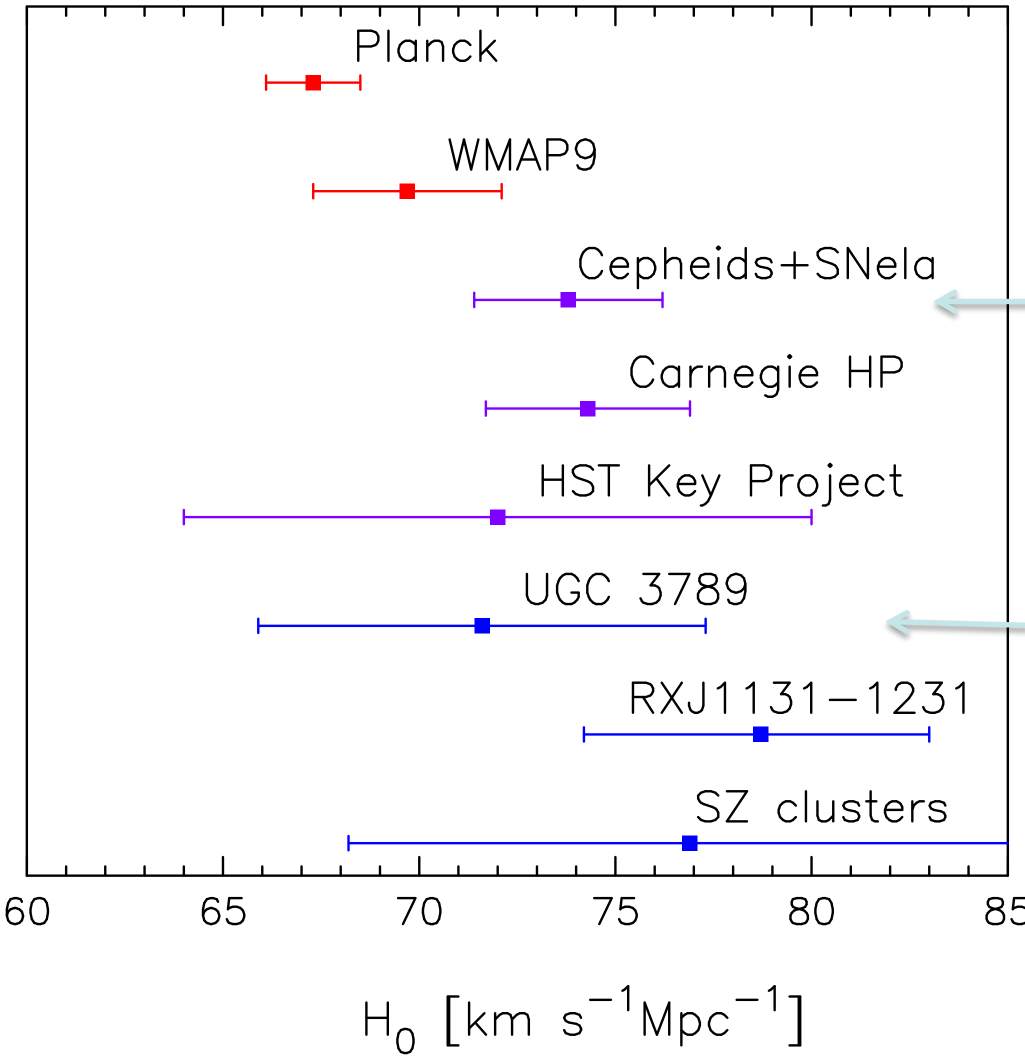
More species, longer radiation domination; suppress early acoustic oscillations in primary CMB; have anisotropic stress

$N_{\mathrm{eff}} = 3.36 \pm 0.34$ (68%, Planck+WP+highL)
$N_{\mathrm{eff}} = 3.30 \pm 0.27$ (+BAO)

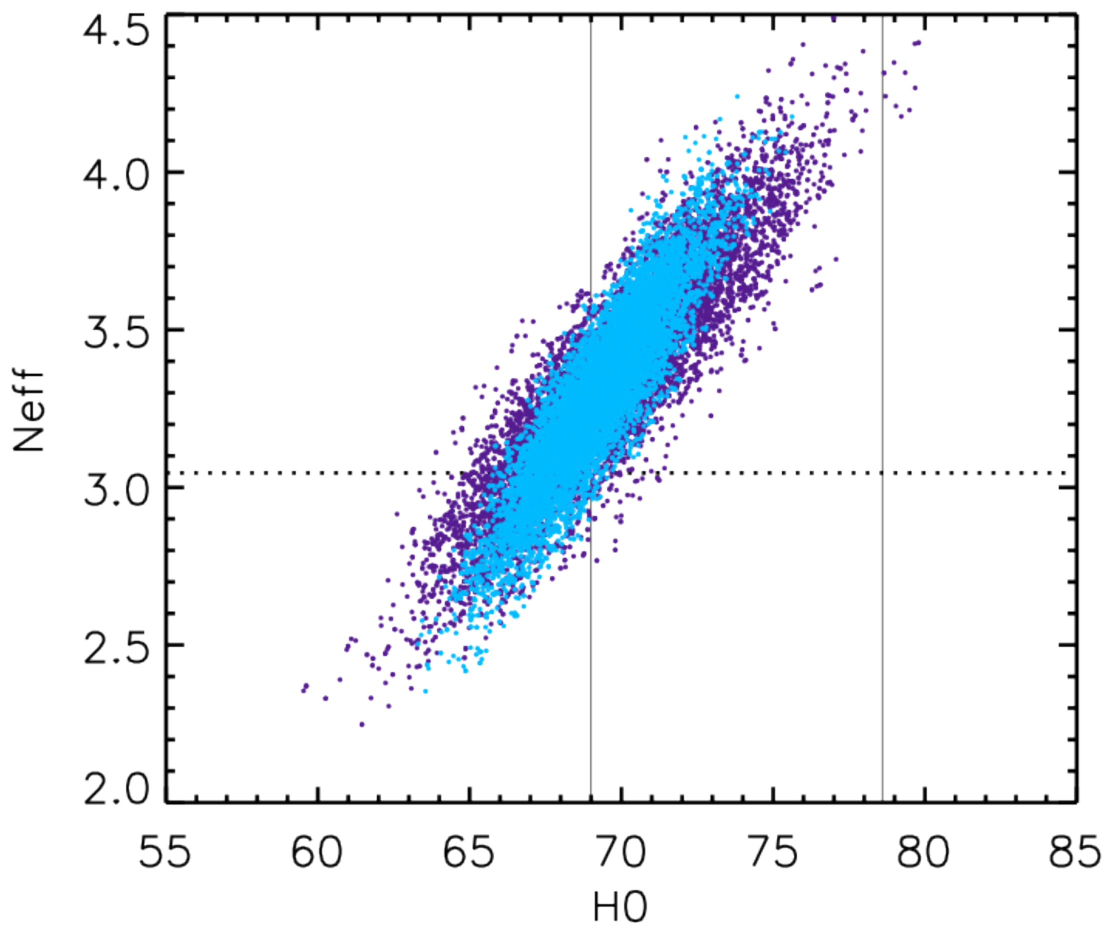
Hubble constant: a 2.5σ tension for N=3



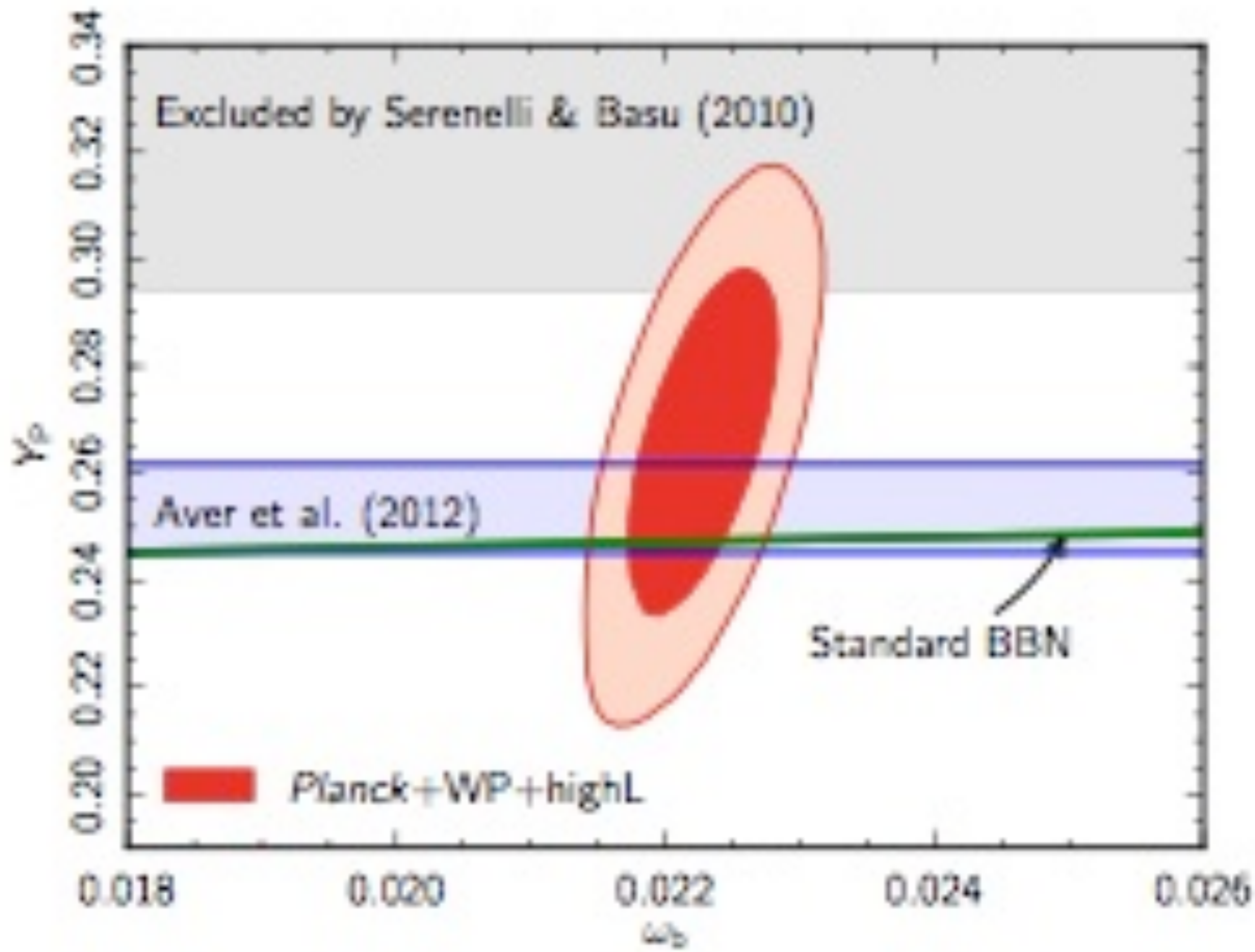
Uses three 1st-rung calibrators: 71.3 – 75.7

UGC, at 50 Mpc: now H_0=68.9+-7.1

How does N>3 relieve tension?



Primordial helium

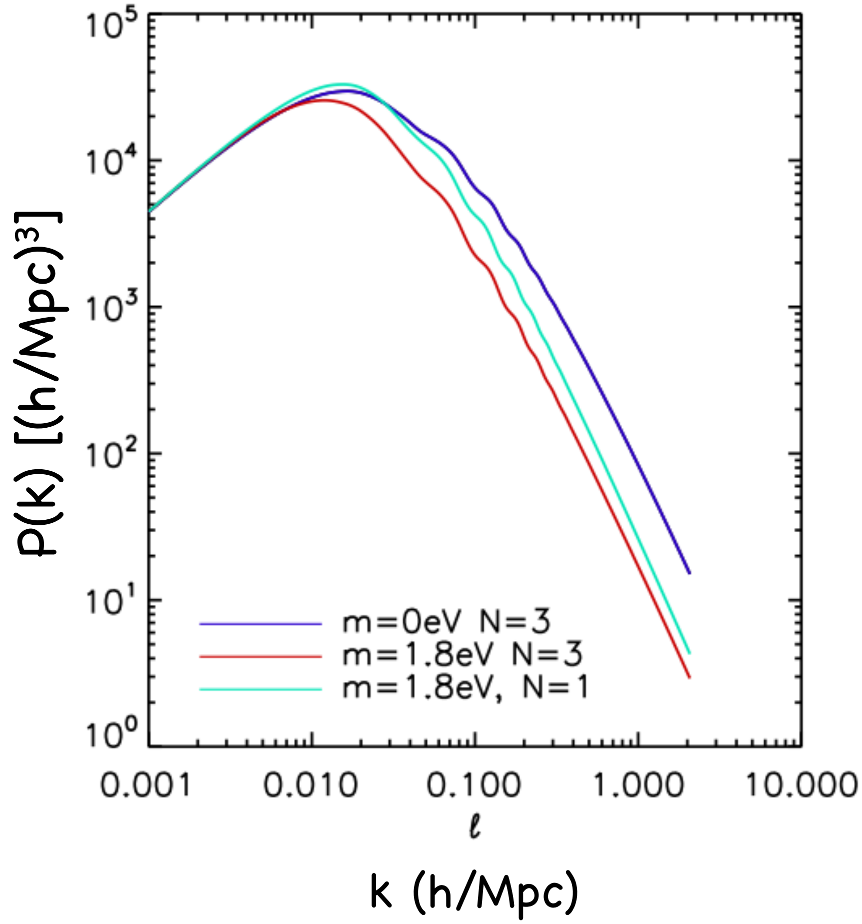


Effect of massive neutrinos (CMB+LSS)

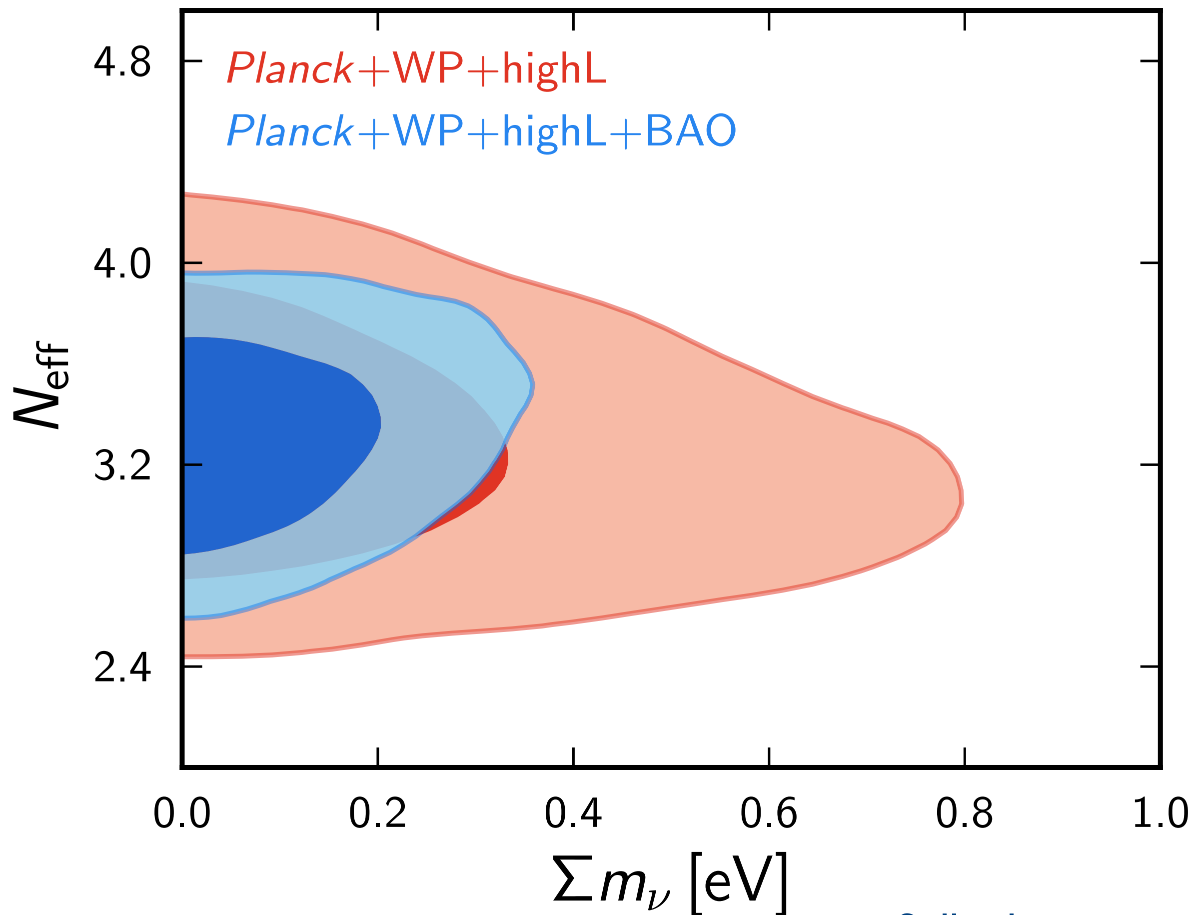
1. **Background:** Neutrinos act like radiation while relativistic.

2. **Perturbations:**
   - Neutrinos free-stream when relativistic, and reduce damping of photon-baryon oscillations for these scales.
   - 1.5eV total mass ~ time of CMB
   - smears out matter clustering on scales where relativistic.
   - if N_mass<3, each neutrino becomes non-relativistic sooner.

$$k_{nr} = 0.026\left(\frac{m_\nu}{1eV}\right)^{1/2} \Omega_m^{\;1/2} h\mathrm{Mpc}^{-1}$$



Sum of neutrino masses

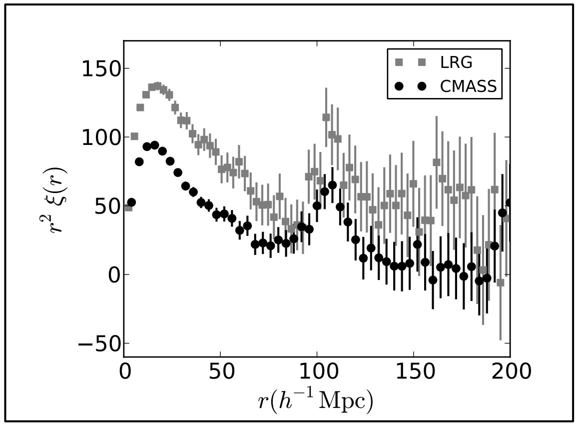


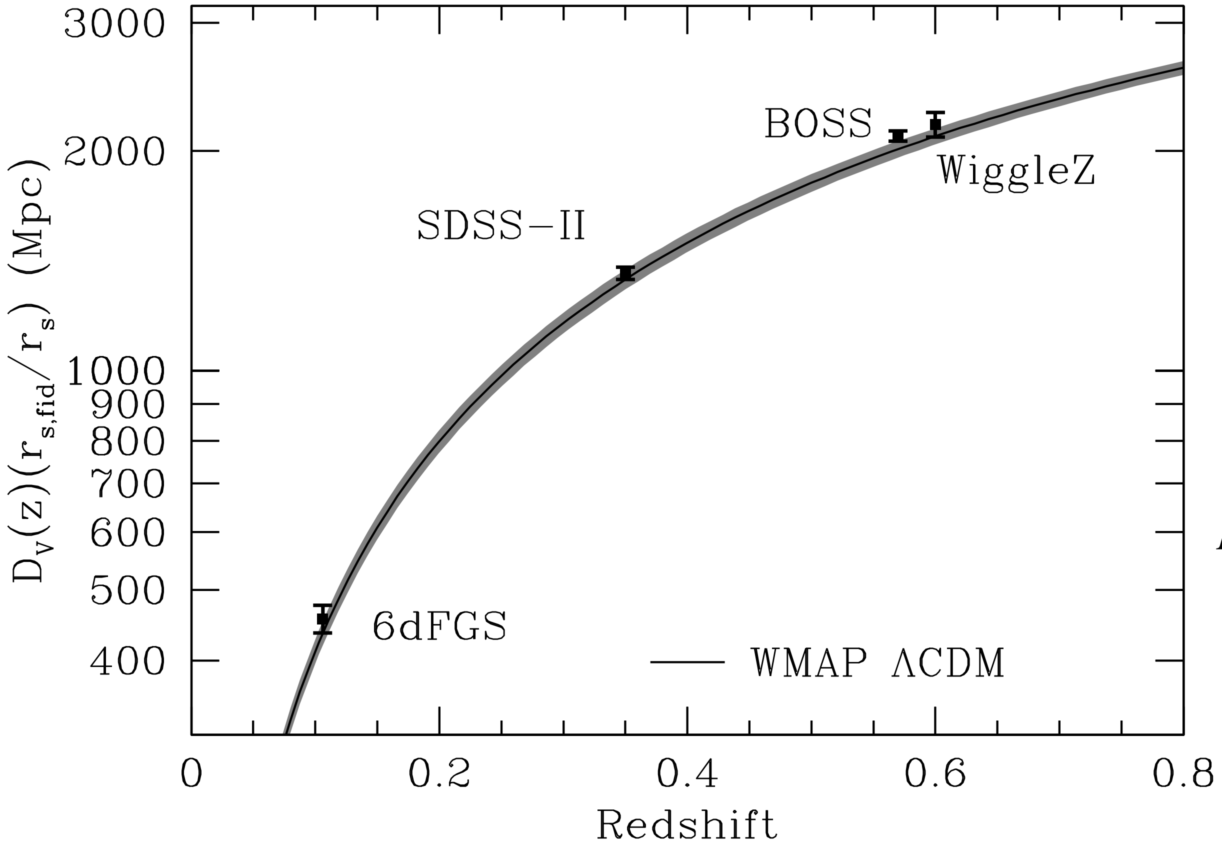
Σm_ν < 0.66 eV (95%, Planck+WP +highL)
Σm_ν < 0.23 eV (+BAO)

But, adding Planck lensing spectrum increases limit to <0.85; preferring slightly higher masses.

- Still relativistic at recombination
- Improved limit also driven by lensing effect in power spectrum
- More mass; more suppression of lensing

Baryon Acoustic Oscillations





BOSS,
Anderson et al 2012

$$D_V(z) = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

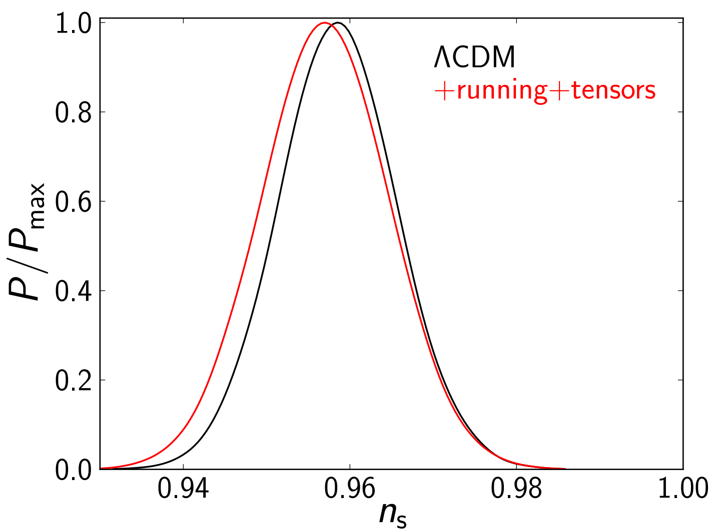
r_s is the comoving sound horizon at the baryon drag epoch
D_V combines the angular diameter distance and the Hubble parameter

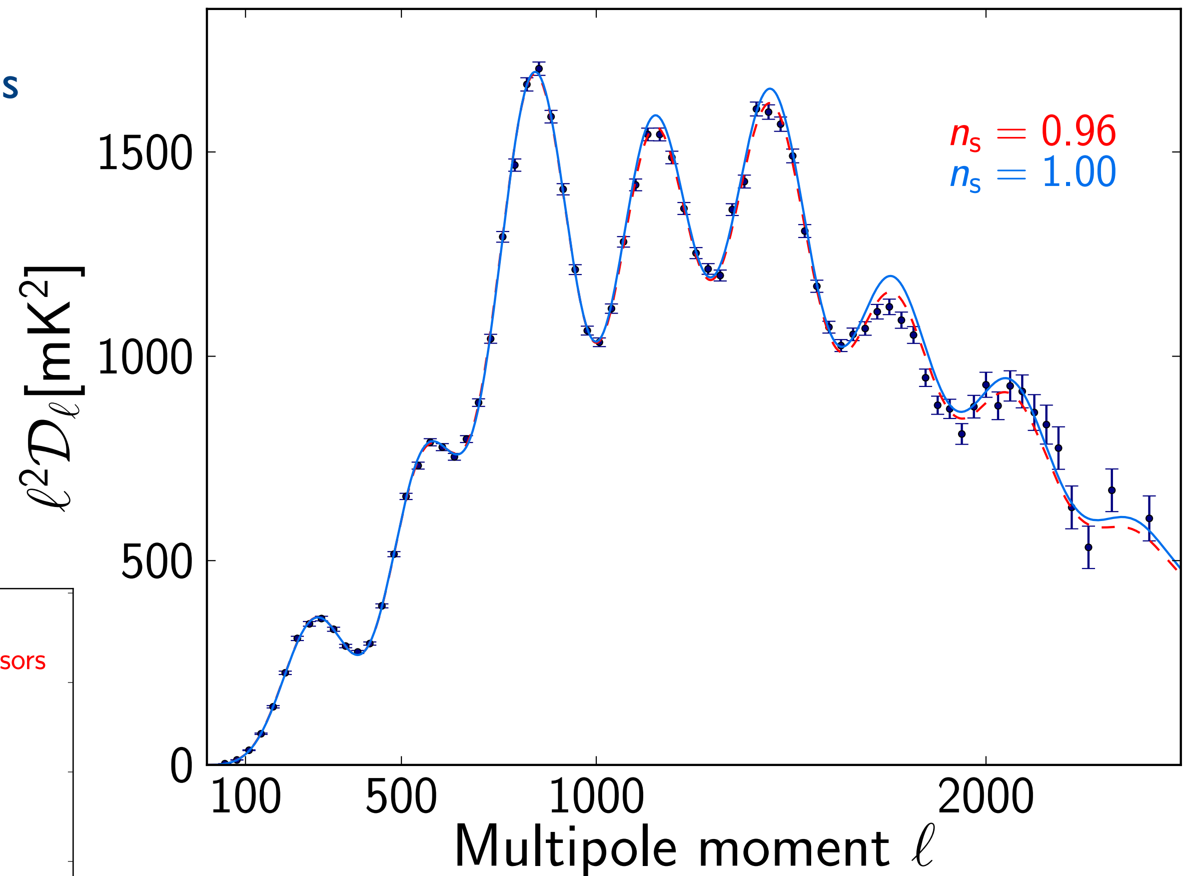
Inflation: scalar spectral index n<1

Harrison-Zel'dovich generates too much power on small scales

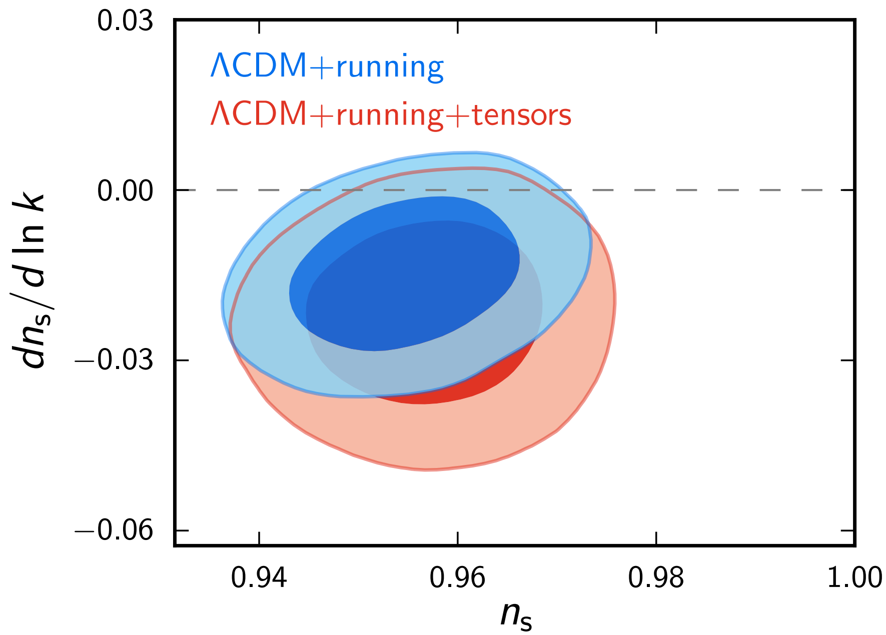
Ruled out at >5σ

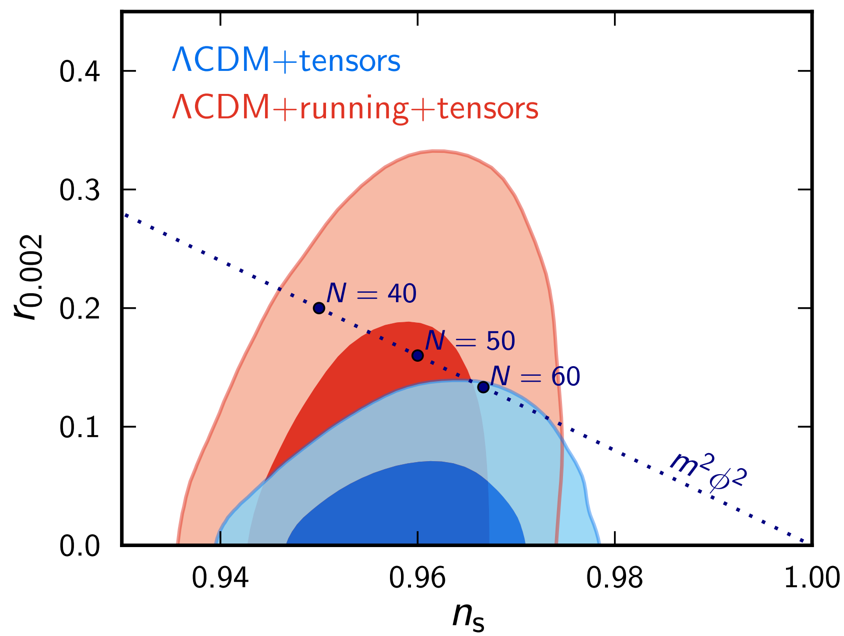
$n_s = 0.960 \pm 0.007$





Inflation: running and tensors





$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_0)\left(\frac{k}{k_0}\right)^{n_s(k_0)-1+\frac{1}{2}\ln(k/k_0)dn_s/d\ln k}$$

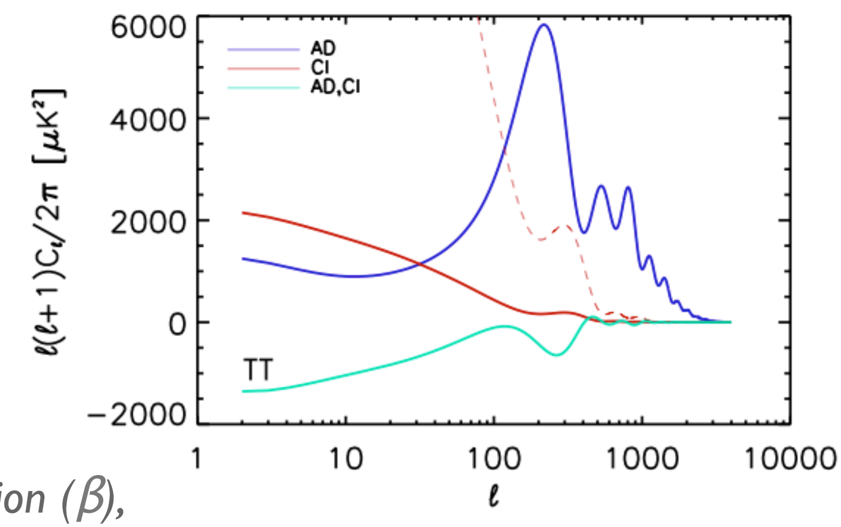
$m^2\Phi^2$ model starts to be disfavored
Constraint on r comes from large-scale TT

$dn_s/d\ln k = -0.015 \pm 0.009$ (68%, Planck+WP+highL)

r<0.11 (95%, Planck+WP+highL)

Inflation: no evidence for isocurvature

$$\mathcal{S}_{c,\gamma} \equiv \frac{\delta\rho_c}{\rho_c} - \frac{3\delta\rho_\gamma}{4\rho_\gamma}$$



Upper limits on fractional primordial contribution (β), or fractional contribution to CMB power (α):

Model	$\beta_{\rm iso}(k_{\rm low})$	$\beta_{\rm iso}(k_{\rm mid})$	$\beta_{\rm iso}(k_{\rm high})$	$\alpha_{\mathcal{RR}}^{(2,2500)}$	$\alpha_{\mathcal{II}}^{(2,2500)}$	$\alpha_{\mathcal{RI}}^{(2,2500)}$
General model:						
CDM isocurvature	0.075	0.39	0.60	[0.98:1.07]	0.039	[-0.093:0.014]
ND isocurvature	0.27	0.27	0.32	[0.99:1.09]	0.093	[-0.18:0]
NV isocurvature	0.18	0.14	0.17	[0.96:1.05]	0.068	[-0.090:0.026]
Special CDM isocurvature cases:						
Uncorrelated, $n_{\mathcal{II}} = 1$, ("axion")	0.036	0.039	0.040	[0.98:1]	0.016	–
Fully correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$, ("curvaton")	0.0025	0.0025	0.0025	[0.97:1]	0.0011	[0:0.028]
Fully anti-correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$	0.0087	0.0087	0.0087	[1:1.06]	0.0046	[-0.067:0]

Planck Collab XXII 2013

Summary

- The Planck satellite has measured 7 acoustic peaks of the CMB power spectrum, and the lensing power spectrum

- Places strong (percent-level) constraints on ΛCDM model (CDM density error halved); in excellent agreement with data.

- Constrains neutrino physics: mnu<0.66 eV (0.23), and N=3.3+-0.3

- Detection of n<1 at ~ 5 sigma; robust to extensions. No non-Gaussianity or non-adiabaticity. All consistent with inflation.

- Upcoming CMB data could get to errors on N of 0.1, and errors on mnu of 0.1 and later 0.05 (using lensing).

esa

planck

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NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

INAF ISTITUTO NAZIONALE DI ASTROFISICA

CSIC

National Research Council of Italy

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

Aalto University

APC

ioa

KICC Kavli Institute for Cosmology Cambridge

CAVENDISH ASTROPHYSICS

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY PRIFYSGOL CAERDYD

irfu cea saclay

cea

CESR

CITA–ICAT

cnrs IN2P3 Les deux infinis

ipac Infrared Processing and Analysis Center

HELSINKI INSTITUTE OF PHYSICS

INSTITUTO DE ASTROFISICA DE CANARIAS IAC

IFCA Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG

ISDC

JPL

LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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