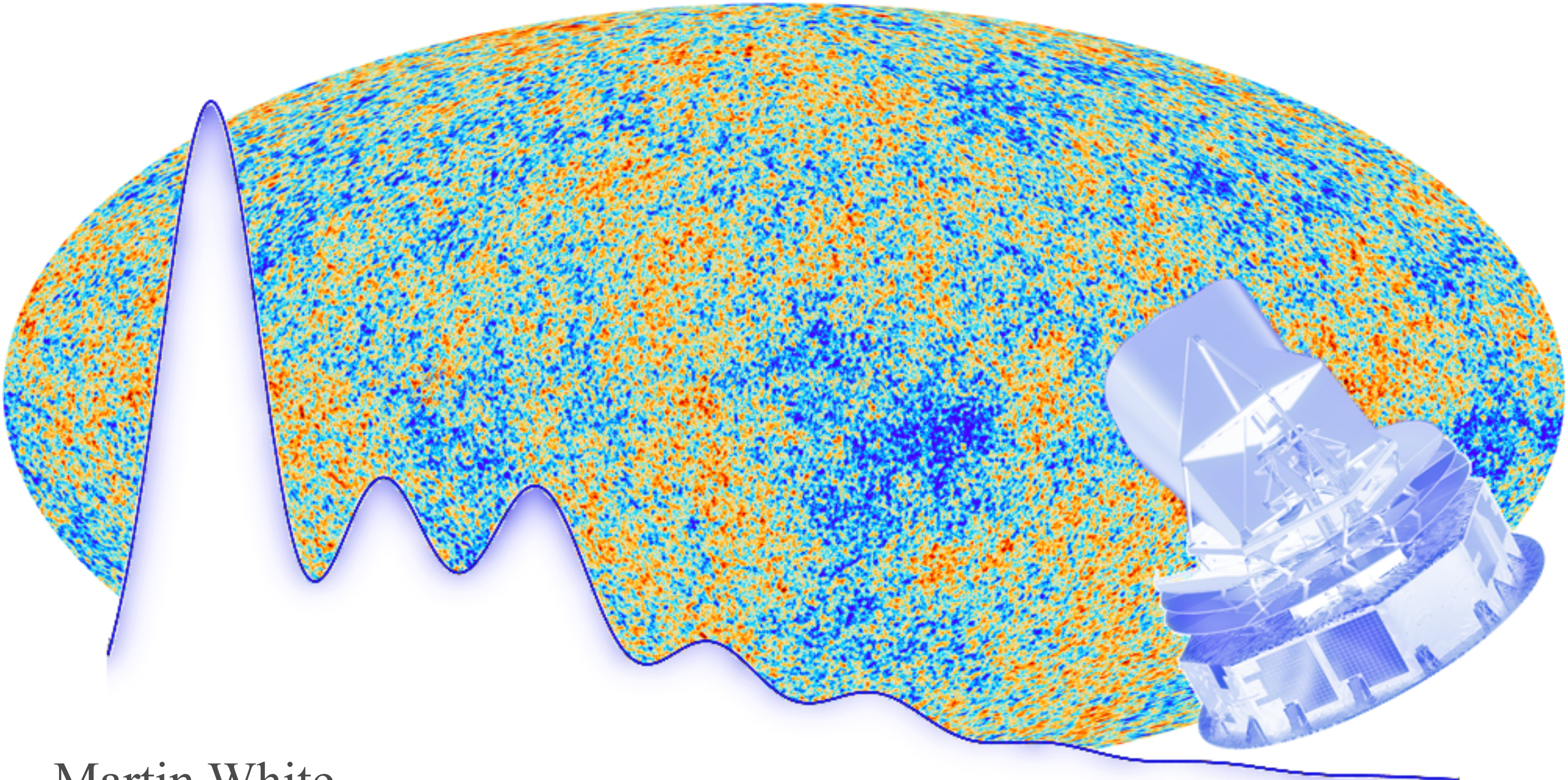
# Cosmological Results from Planck 2015



Martin White
**on behalf of the Planck collaboration**



Fig. courtesy V. Pettorino

**The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada**

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

# Outline

- What is the CMB?
- What is Planck?
- What has changed (& what hasn’t).
  - Cosmological parameters.
  - CMB lensing.
  - Comparison with other datasets.
- More cool stuff!
- Conclusions.

# The cosmic microwave background

- The entire Universe is filled with radiation in the form of a 2.7K black-body.
- This radiation is a relic of the hot, dense, early phase of the Universe (the hot-big bang).
- The light travels to us from a “surface of last scattering” at z~1100 (when the Universe was $10^{-3}$ times smaller than today and only 380,000yr old).
  - At this *z* the Universe was finally cold enough for protons to capture electrons to form neutral Hydrogen.
  - Optical depth to photon scattering quickly drops from $\tau \gg 1$ to $\tau \ll 1$.
- The radiation is almost the same intensity in all directions, but contains tiny fluctuations in intensity (or temperature) at the level of $10^{-4}$: CMB anisotropy.

# The cartoon: sound waves in the early Universe

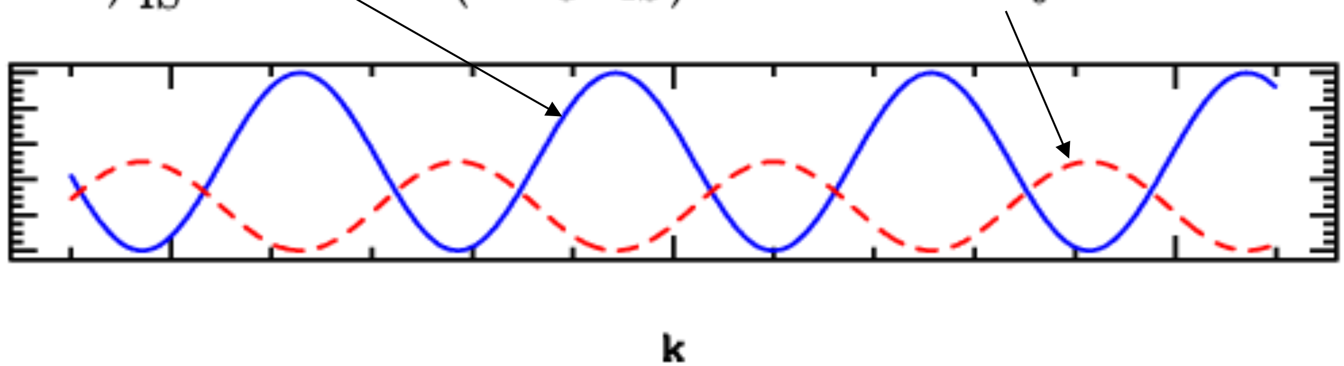
- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering.
  - Short m.f.p. allows fluid approximation.
- Initial fluctuations in density and gravitational potential drive acoustic waves in the b$\gamma$ fluid: compressions and rarefactions.
- These show up as temperature fluctuations in the CMB

$$\Delta T \sim \delta\rho_\gamma^{1/4} \sim A(k)\cos(kc_s t) \qquad \text{[harmonic wave]}$$

# The cartoon

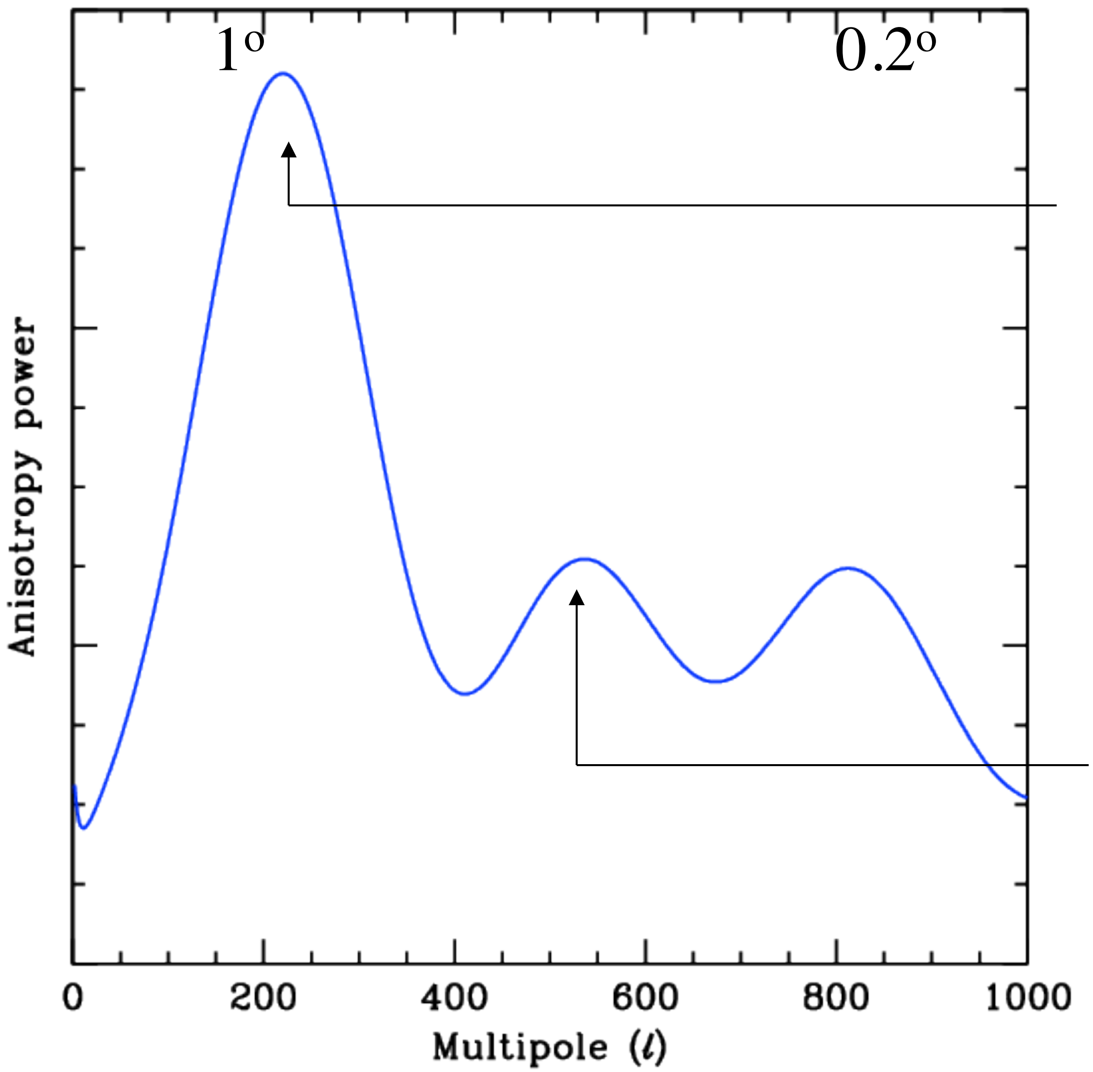
- A sudden "recombination" decouples the radiation and matter, giving us a snapshot of the fluid at "last scattering".

$$(\Delta T)^2_{\rm ls} \sim \cos^2(k c_s t_{\rm ls}) + \text{velocity terms}$$




- These fluctuations are then projected on the sky with $\lambda$~$d_{ls}\theta$ or $l$~$k\ d_{ls}$
- (We usually work in "angular Fourier space", and decompose $\Delta T(\theta,\phi)=\Sigma\ a_{lm}\ Y_{lm}(\theta,\phi)$ then use the $a_{lm}$).

# Angular power spectrum!

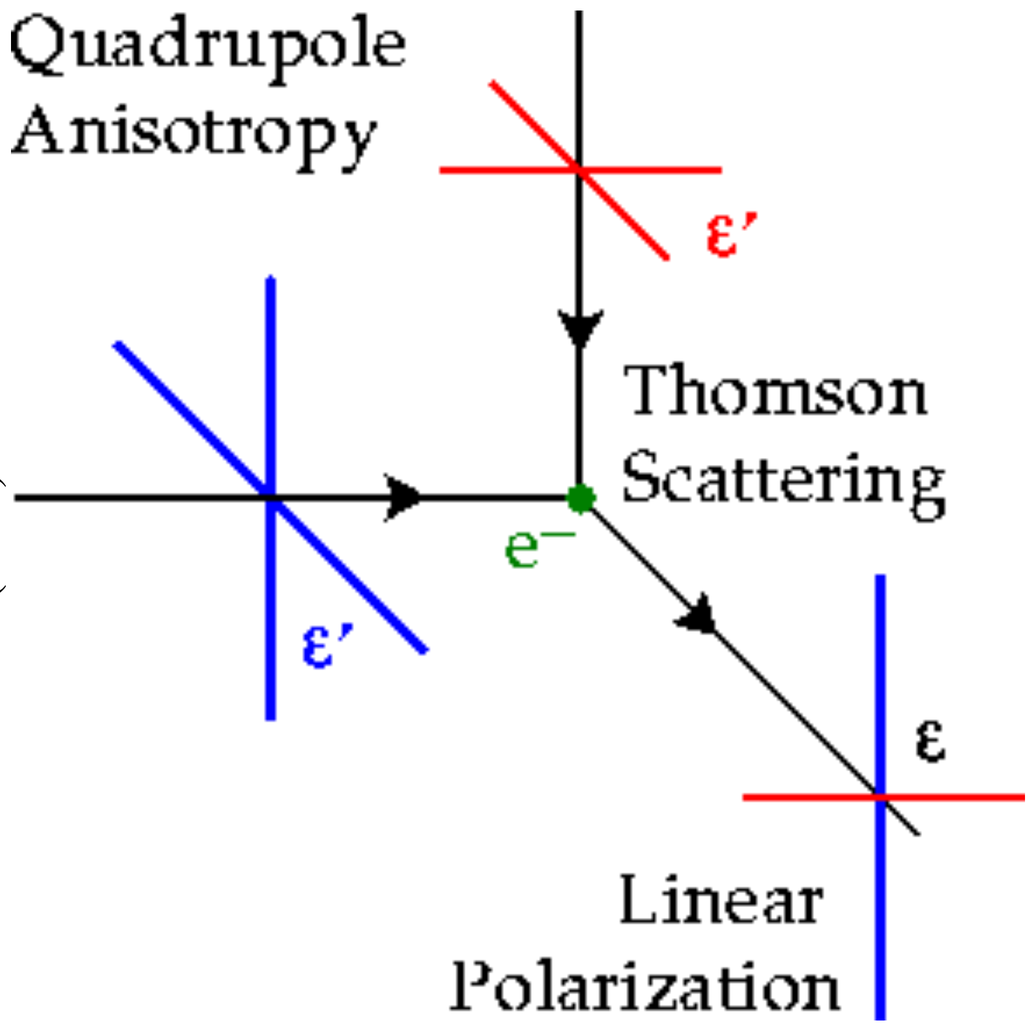



First "compression", at $kc_s t_{ls}=\pi$. Density maximum.

First "rarefaction" peak at $kc_s t_{ls}=2\pi$

→ Smaller scales

# Anisotropy generates (linear) polarization




Hu & White (1997)

A quadrupole anisotropy generates linear poln. Normally we define polarization patterns in terms of their parity and (confusingly!) refer to them as E & B modes. Density perturbations can generate only E-mode polarization, but primordial gravity waves (or vorticity) can generate both E- and B-modes.

# CMB encodes valuable information

- The CMB spectrum depends upon the initial spectrum of perturbations (inflation?) and the conditions in the photon-baryon fluid prior to last scattering.
- The rich structure in the spectrum, and the dependence on many cosmological parameters, provides a gold-mine of information *if* the signal can be accurately measured *and* compared to precise theoretical predictions.
- Scattering of an anisotropic temperature field generates (linear) polarization, which allows access to even more information.
- We can also get information about the low z Universe by looking at CMB lensing and BAO.

# Planck mission

- Planck was a 3rd generation space mission (COBE, WMAP)
  - Like WMAP, Planck observed at “$L_2$”.
- It was part of ESA’s “Cosmic Visions” program.
- It was the first sub-mm mission to map the entire sky with mJy sensitivity and resolution better than 10 arcmins.
  - 74 detectors covering 25GHz-1000GHz, resolution 30’-5’.
- Planck measured temperature anisotropy with accuracy set by fundamental astrophysical limits.

# *PLANCK*

## *Looking back to the dawn of time*

Planck Telescope
1.5x1.9m off-axis
Gregorian
T = 50 K

LFI Radiometers
30-70 GHz, T = 20 K

HFI Bolometers
100-857 GHz, T = 0.1 K

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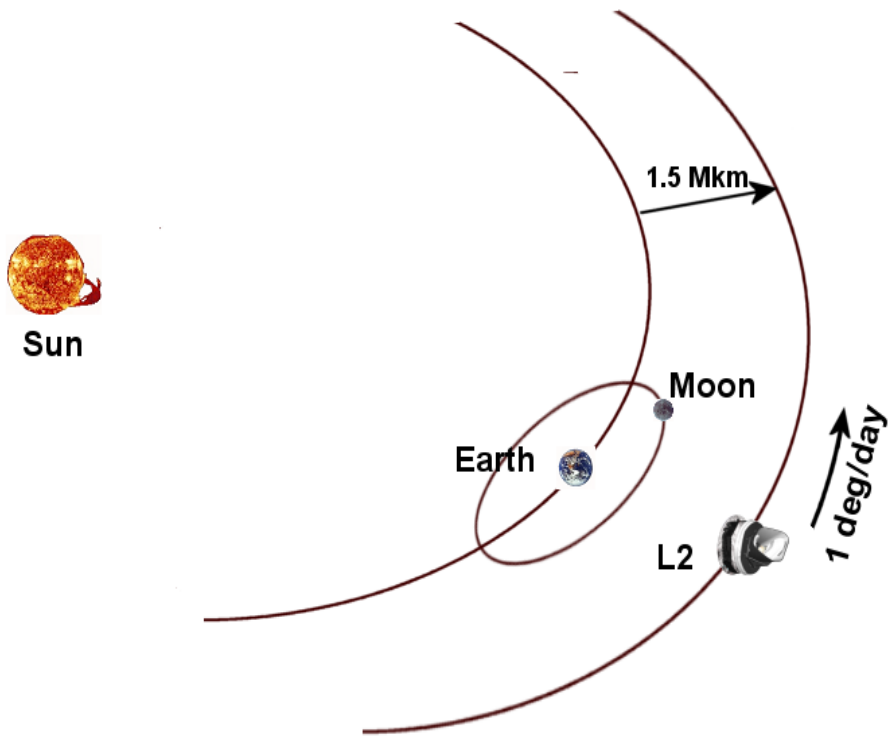
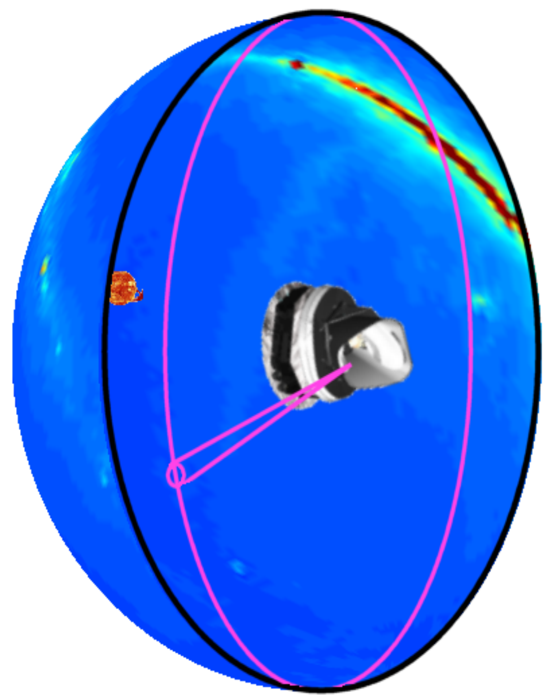
# The orbit

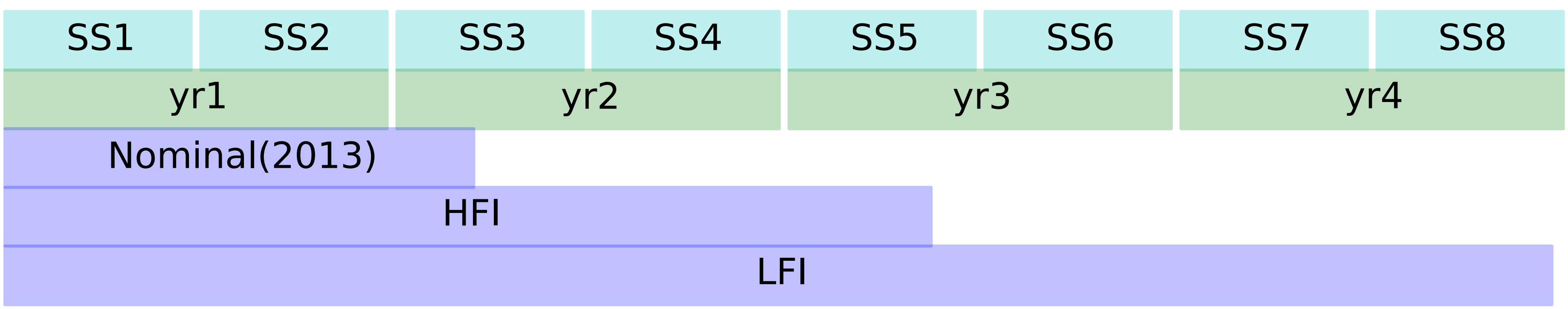
Planck made a map of the full sky every ~6 months.



# Current data release: 2015

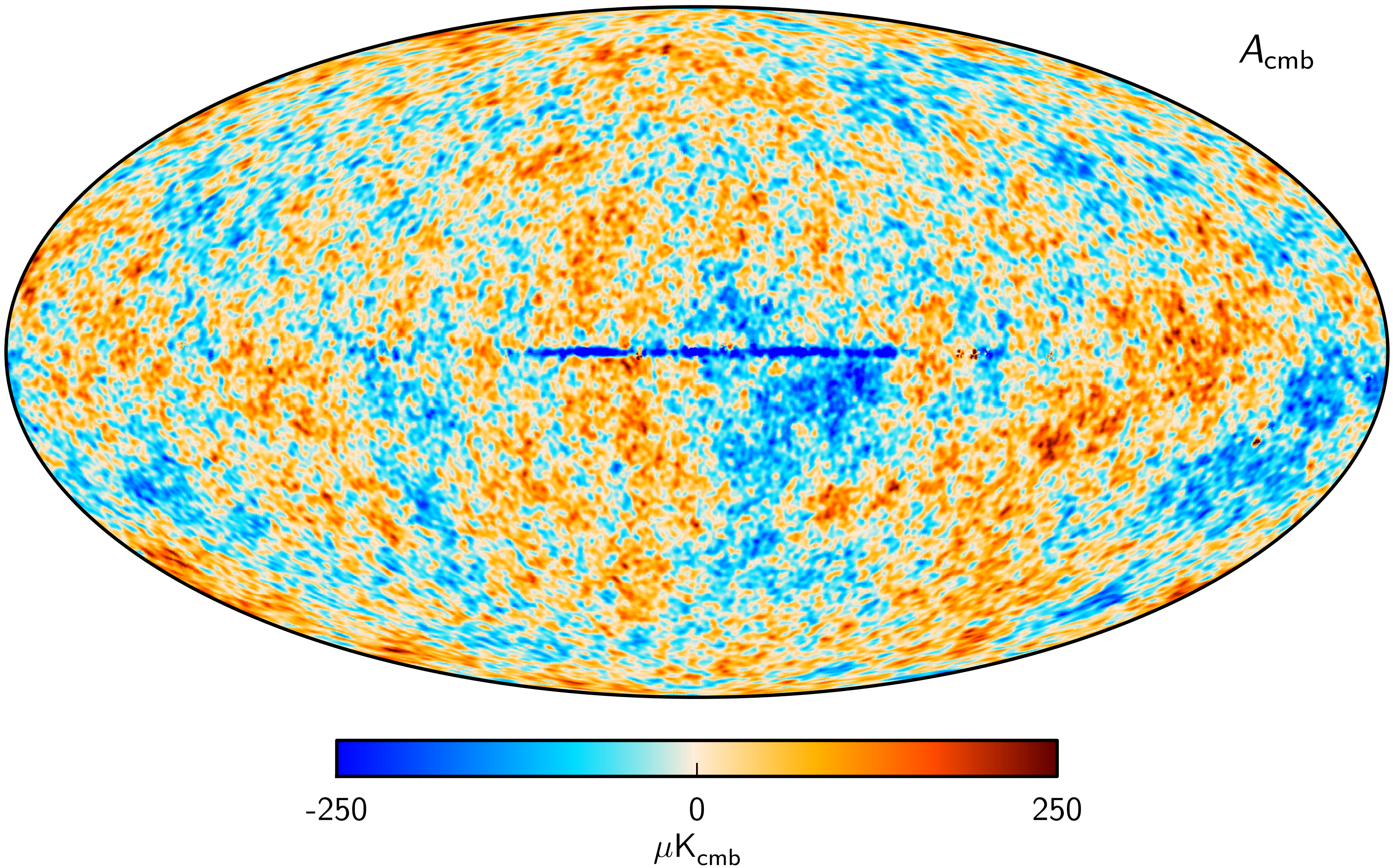
- This is our second data release
  - Full mission data (12 Aug 2009 – 23 Oct 2013).
- In addition to better S/N, the new release takes advantage of multiple full-sky redundancies
  - Planck scans the sky differently in “even” and “odd” sky surveys.
  - Scan changed between SS4 and SS5.
- There will be one more data release, next year.



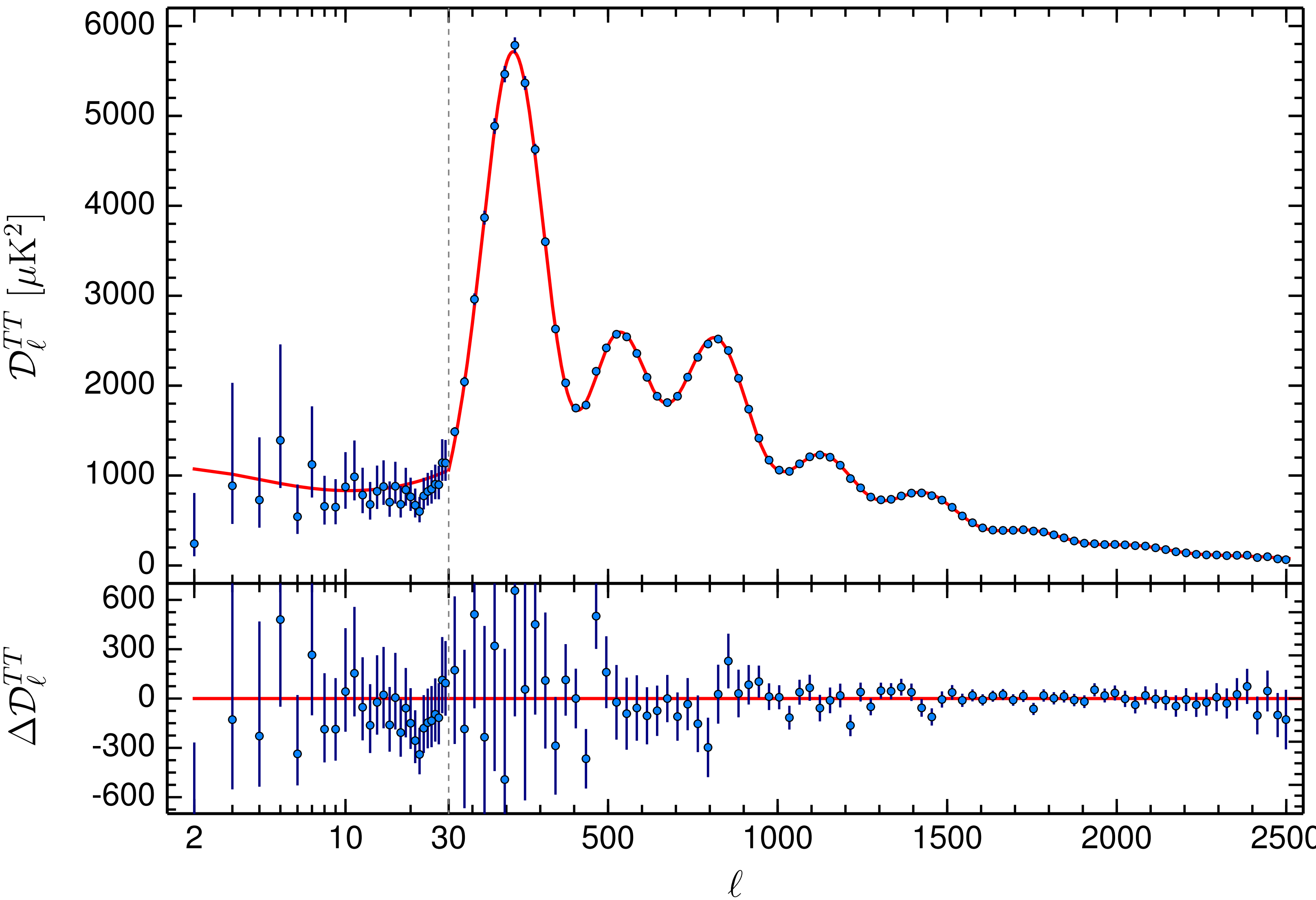
# Current data release: 2015

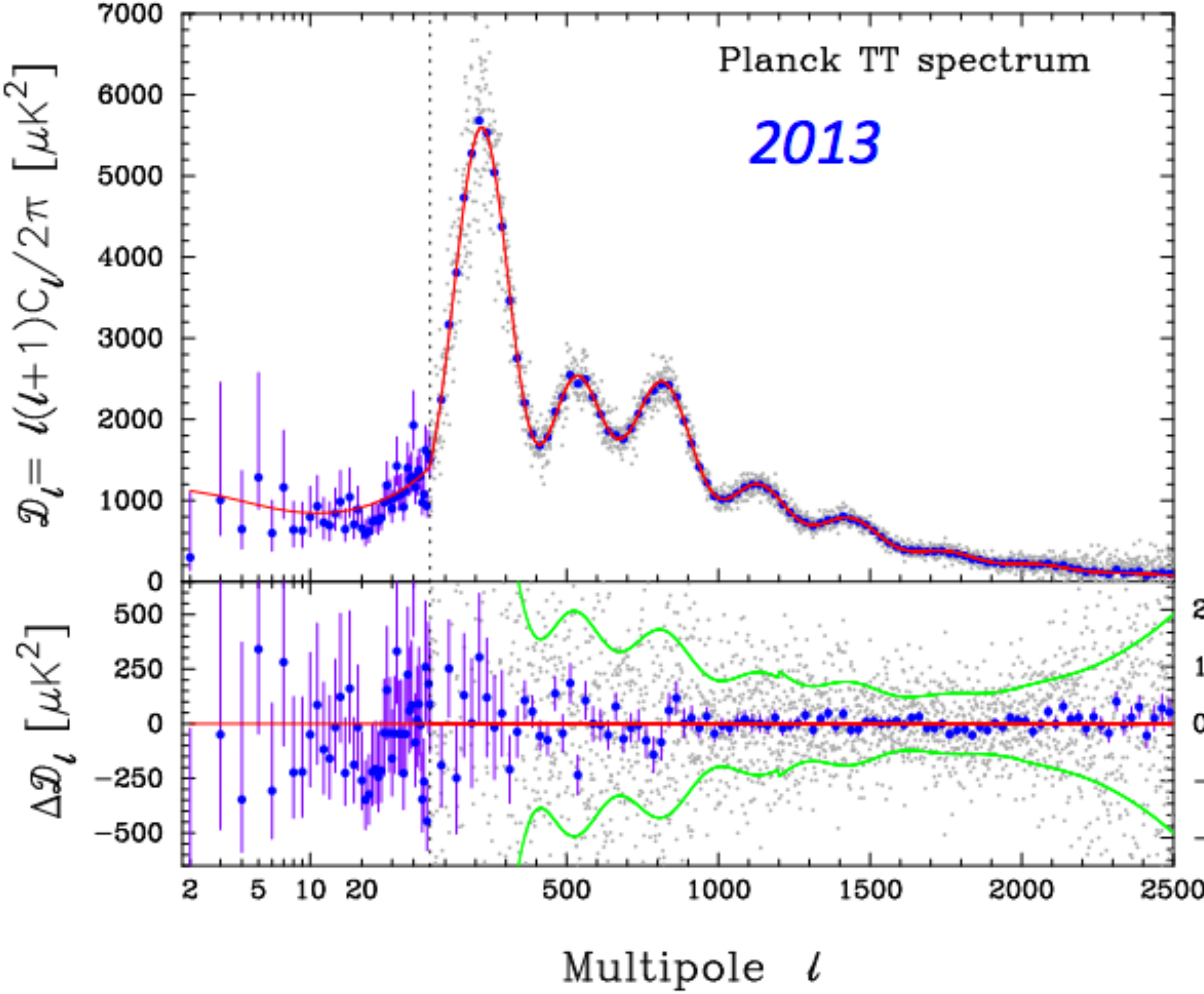
- What has changed:
  - More data (29/49 months vs. 15.5) enabling further checks.
  - Improved systematics removal, calibration and beams.
  - More simulations (10x) used to assess uncertainties.
  - More sky used, improved foreground model (incl. dust at all freq.).
  - Lensing now 40$\sigma$ (and best modes have S/N~1 per mode)!
  - Polarization!!!
- What has not changed (much):
  - $\Lambda$CDM still a good fit.
  - The Universe is still very flat
  - Parameters and major cosmological inferences from 2013.

# CMB map

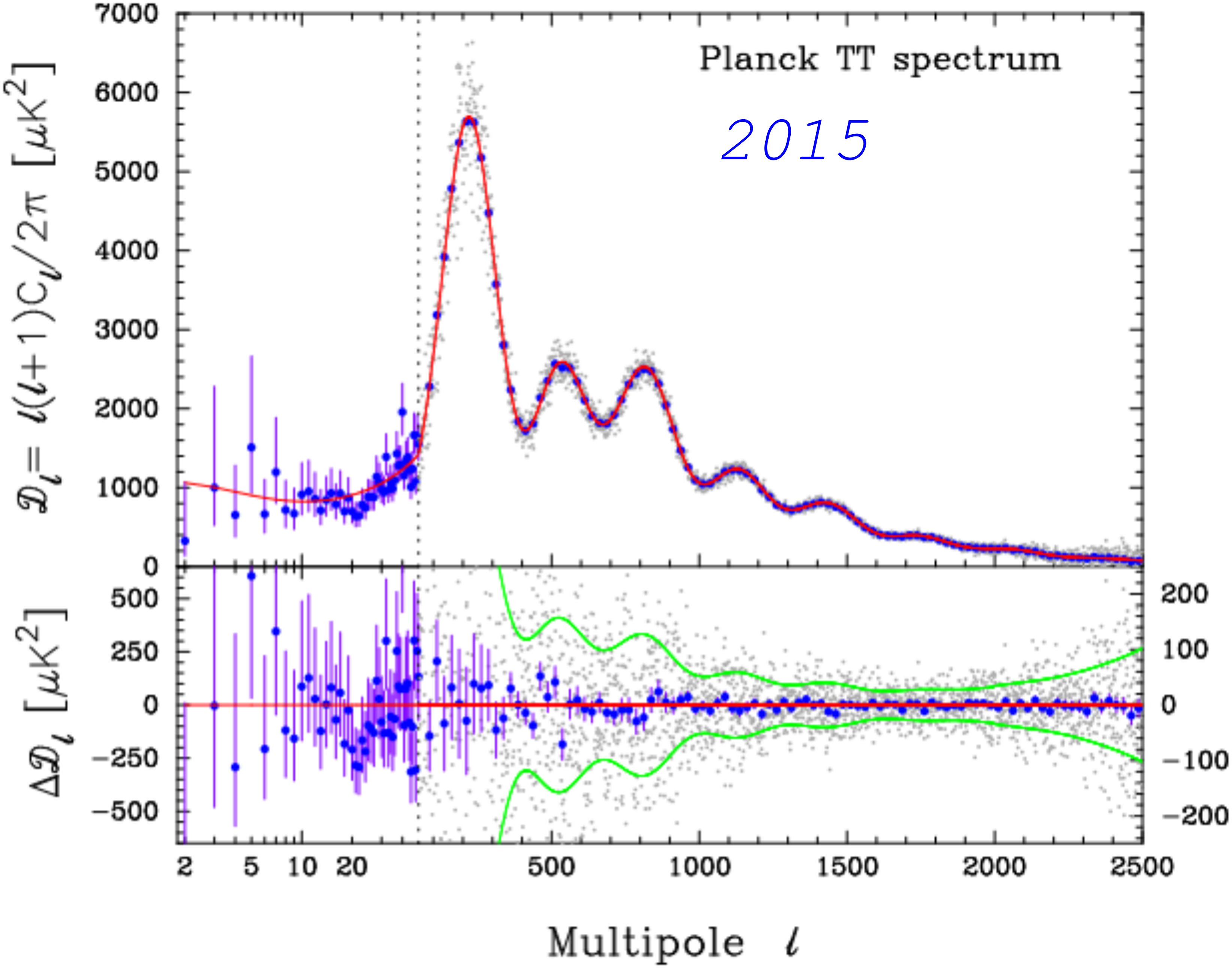


# The angular power spectrum



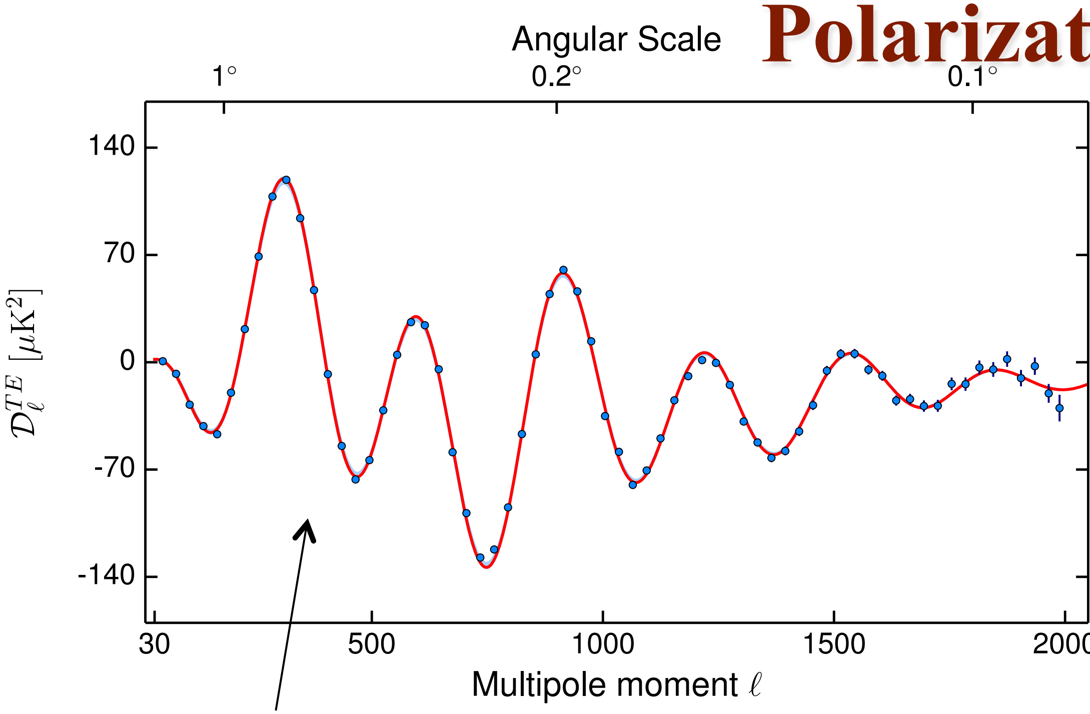


Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole $\ell$



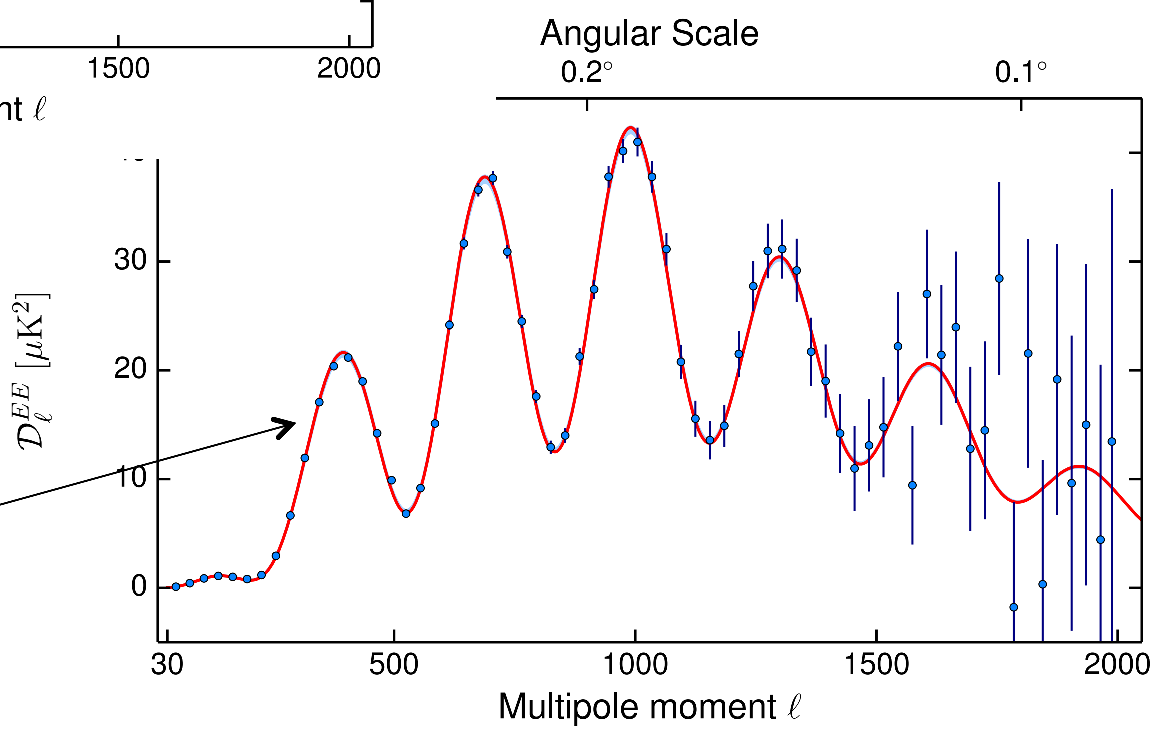
Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500
Multipole $\ell$

# Polarization




The red line is not fit to the polarization data – it is a prediction of the model based on the temperature spectrum!

Temperature-Polarization cross-spectrum




Polarization auto-spectrum

# Data compression!

- A gold-mine of information *if* the signal can be accurately measured *and* compared to precise theoretical predictions.
- We find that a simple, 6 parameter model fits the data extremely well.
  - Data compression: trillions of bits of data are compressed to billions of measurements at 9 frequencies, then tens of millions of pixels are compressed to thousands of multipoles which are compressed to 6 cosmological parameters!
  - With no evidence for a 7$^{th}$.
- For the "base model" the CMB determines all of the parameters, on its own, with exceptional accuracy.
  - If we include polarization, best determined parameter is 0.03%.
  - Many parameters are determined to better than 1%.

# Base ΛCDM model

| Parameter | Temperature + lensing | All + lensing |
|---|---|---|
| $\omega_b$ | 0.02226 ± 0.00023 | 0.02226 ± 0.00016 |
| $\omega_c$ | 0.1186 ± 0.0020 | 0.1193 ± 0.0014* |
| $100\theta_{MC}$ | 1.04103 ± 0.00046 | 1.04087 ± 0.00032 |
| $\tau$ | 0.066 ± 0.016 | 0.063 ± 0.014 |
| $10^9 A_s e^{-2\tau}$ | 1.874 ± 0.013 | 1.878 ± 0.011 |
| $n_s$ | 0.9677 ± 0.0060 | 0.9653 ± 0.0048 |
| $H_0$ (km/s/Mpc) | 67.81 ± 0.92 | 67.5 ± 0.64 |
| $\sigma_8$ | 0.8149 ± 0.0093 | 0.8150 ± 0.0087 |

And my favorite derived parameter: $z_{rec}$ = 1090.00±0.29

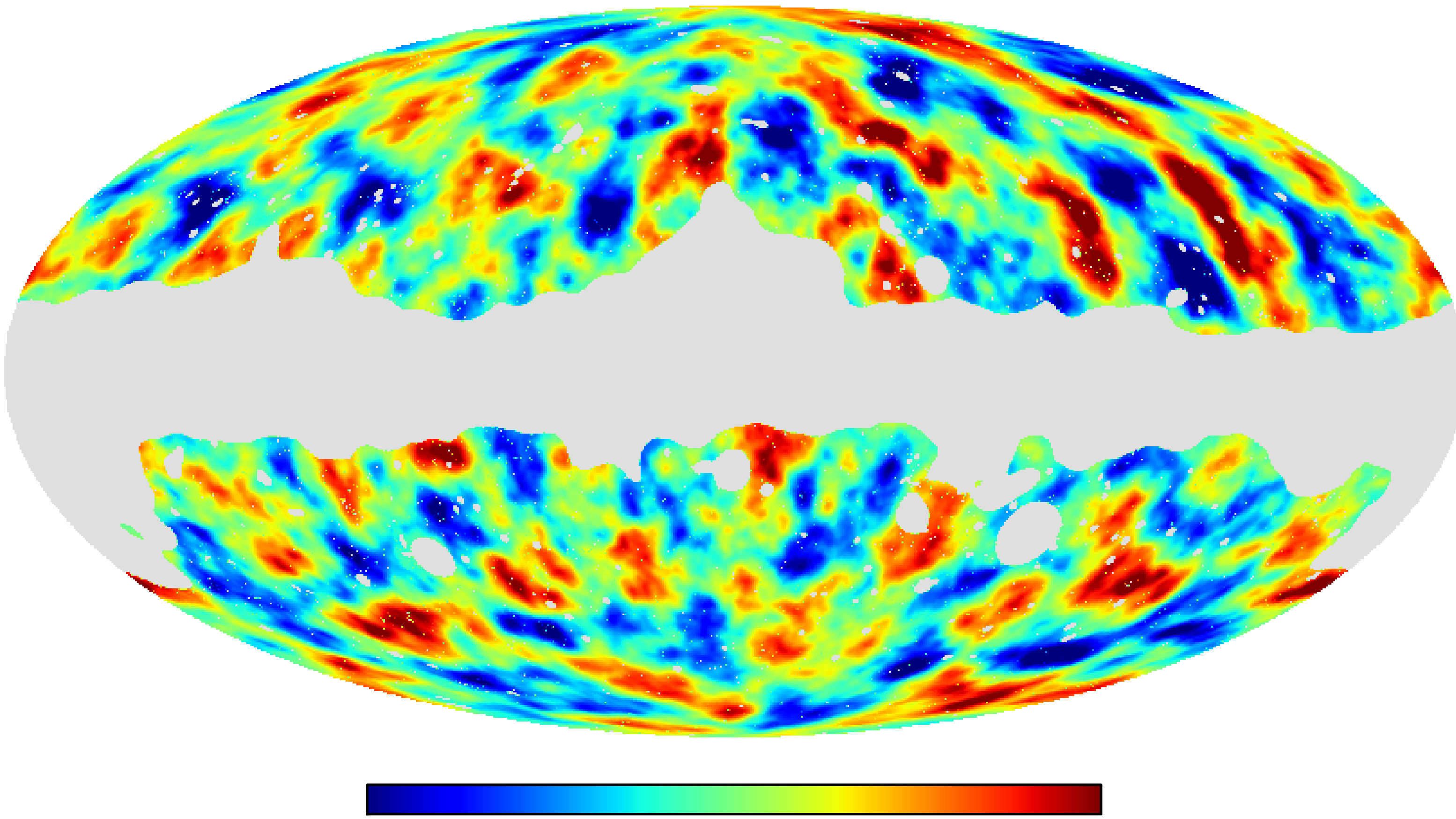
# Changes in parameters: standard model

- Uncertainties reduced by 2-3x on key parameters.
- Photometric calibration increased by 0.8%.
  - Uncertainty now 0.1%. Excellent agreement on orbital dipole between WMAP, LFI & HFI!
- Thomson $\tau$ lower by ~1$\sigma$ (so $z_{re}$ decreased ~1$\sigma$)
  - but calibration increased power so $\sigma_8$ hardly changed
- $n_s$ increased by ~0.7$\sigma$
- $\omega_b$ increased by ~0.6$\sigma$ *and* error decreased.
- Limits on isocurvature modes, $\Omega_K$, $m_\nu$, $\Delta N_{eff}$, $f_{NL}$, DM annihilation etc. all tighter. No deviations detected.

# CMB lensing

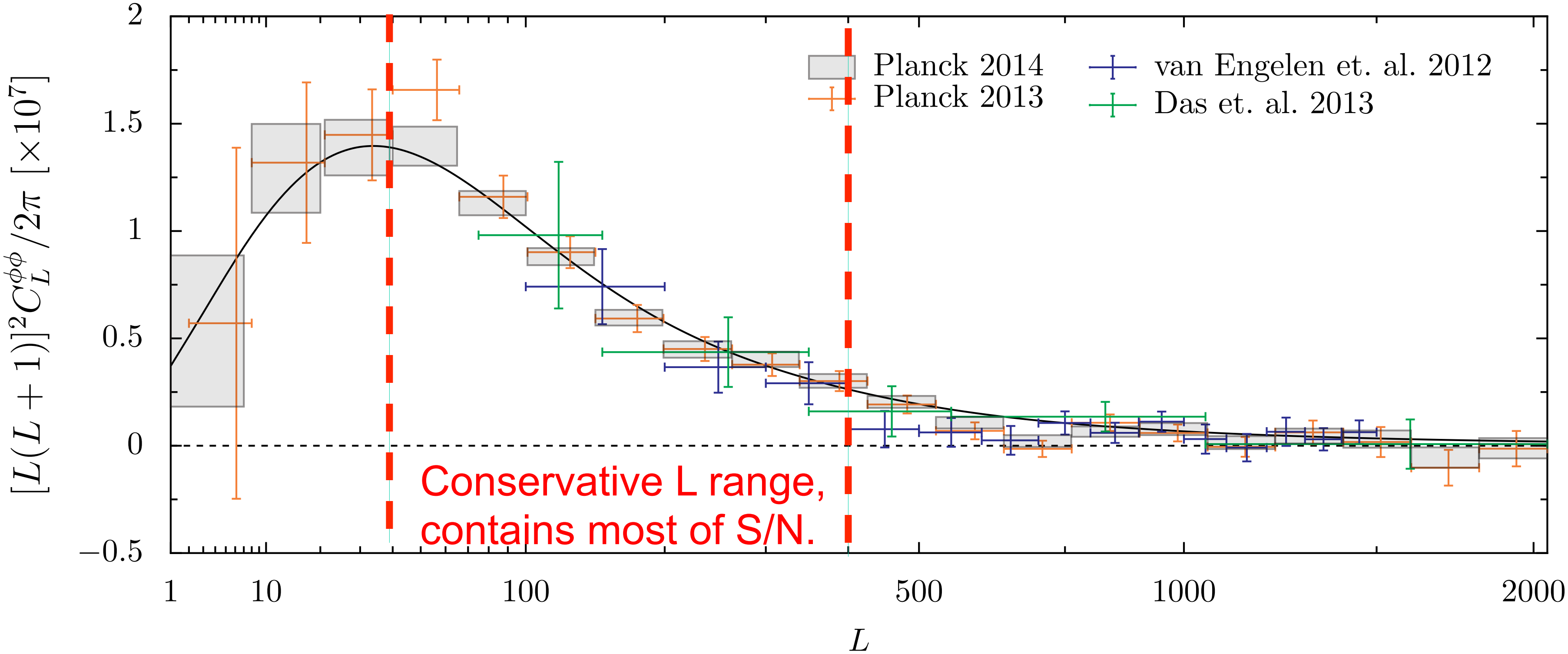
- Photons from the CMB are deflected on their way to us by the potentials due to large-scale structure.
- The typical deflection is 2-3 arcmin but deflections are coherent over degrees.
  - Signal dominated by structures of tens of Mpc at z~2.
- Gives sensitivity to the “low z” Universe.
  - Allows us to break some degeneracies from purely within the Planck dataset.
  - Provides a cross-check on the paradigm: are the structures we infer at z~2 consistent with the “initial conditions” measured at z~1,000?
- Provides a map, over the whole sky, of the (projected) mass back to the surface of last-scattering (98% of the way to the horizon).

# Lensing potential




Lensing now measured at 40$\sigma$.
Better than predicted by anisotropy!

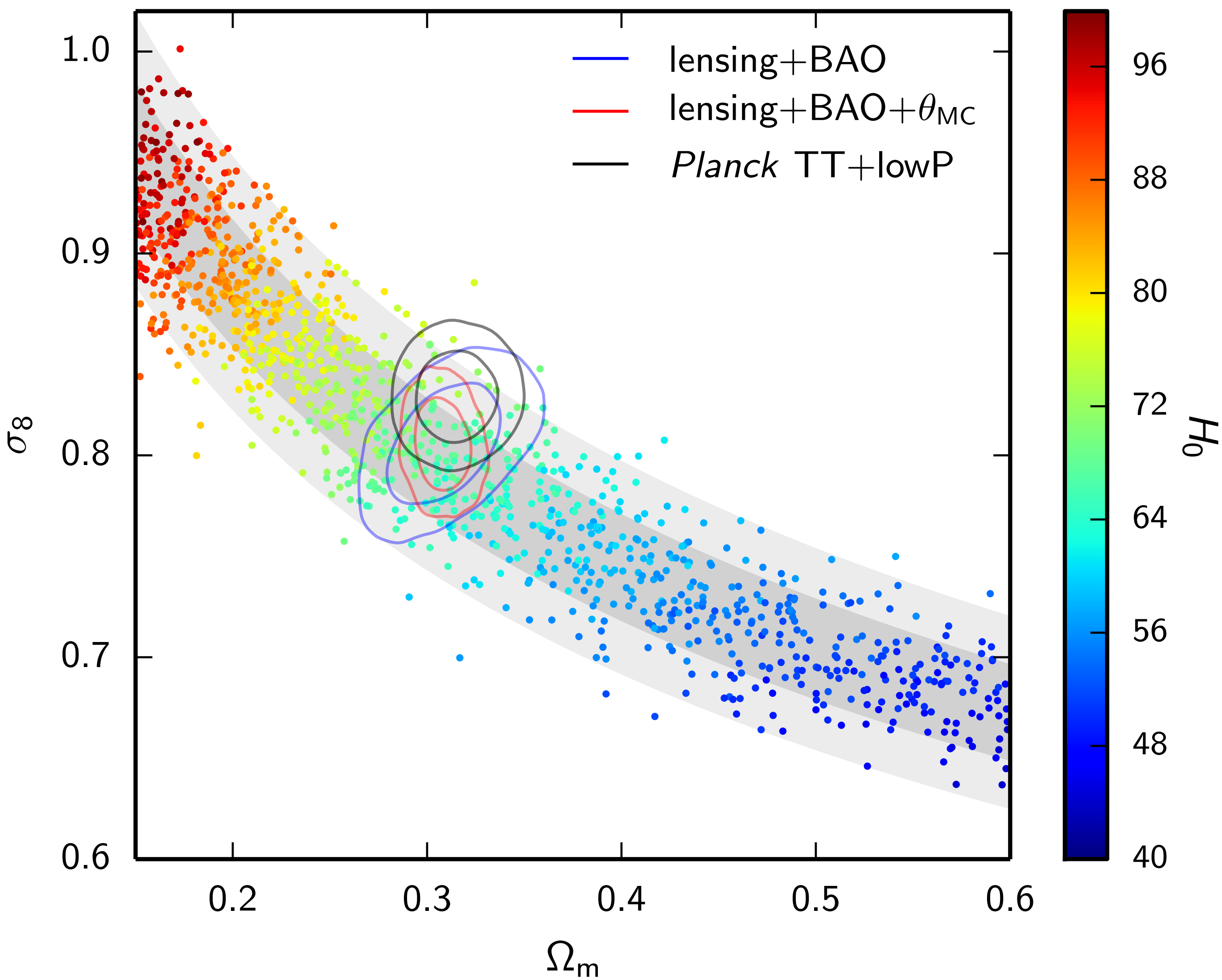
# Lensing power spectrum




Constrains $\sigma_8 \Omega_m^{1/4}$ to 3.5%!

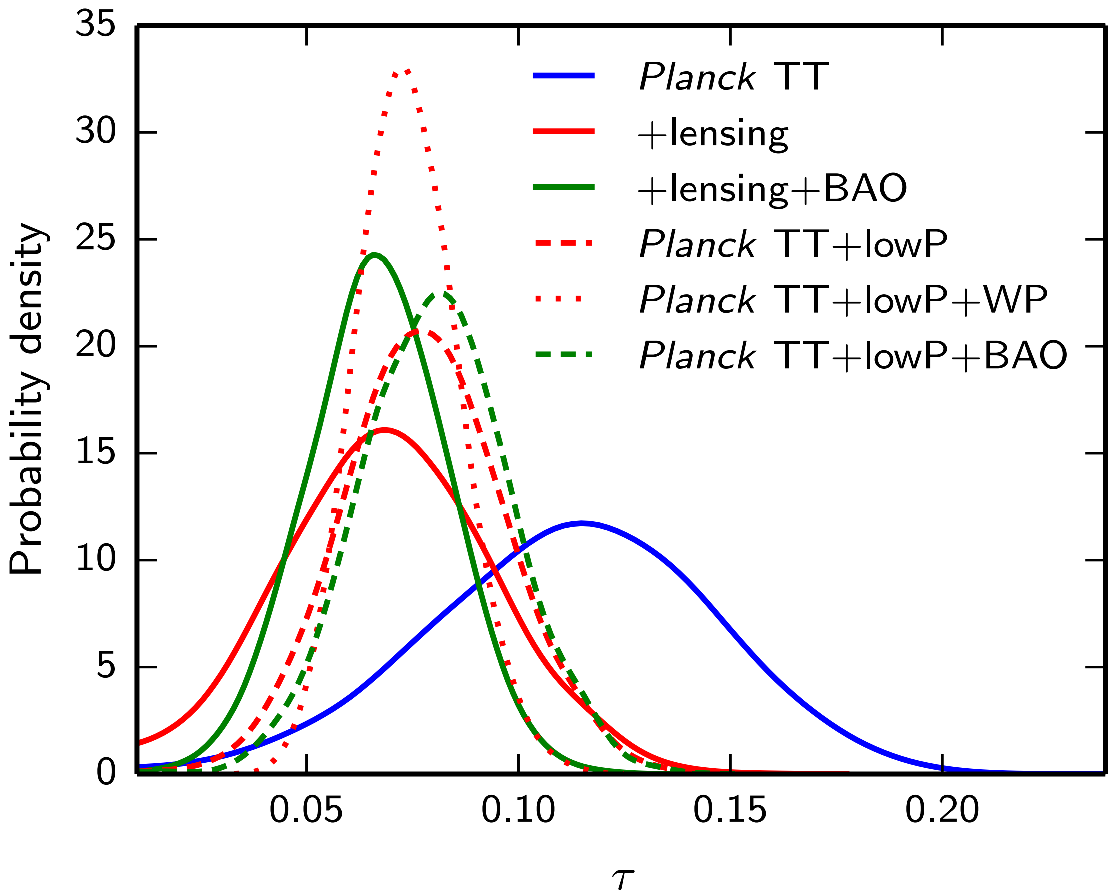
# Independent check on the amplitude of matter fluctuations in the Universe: $\sigma_8$

Lensing allows an independent check on the normalization. Consistent with primary anisotropy results. Higher than some probes had found.



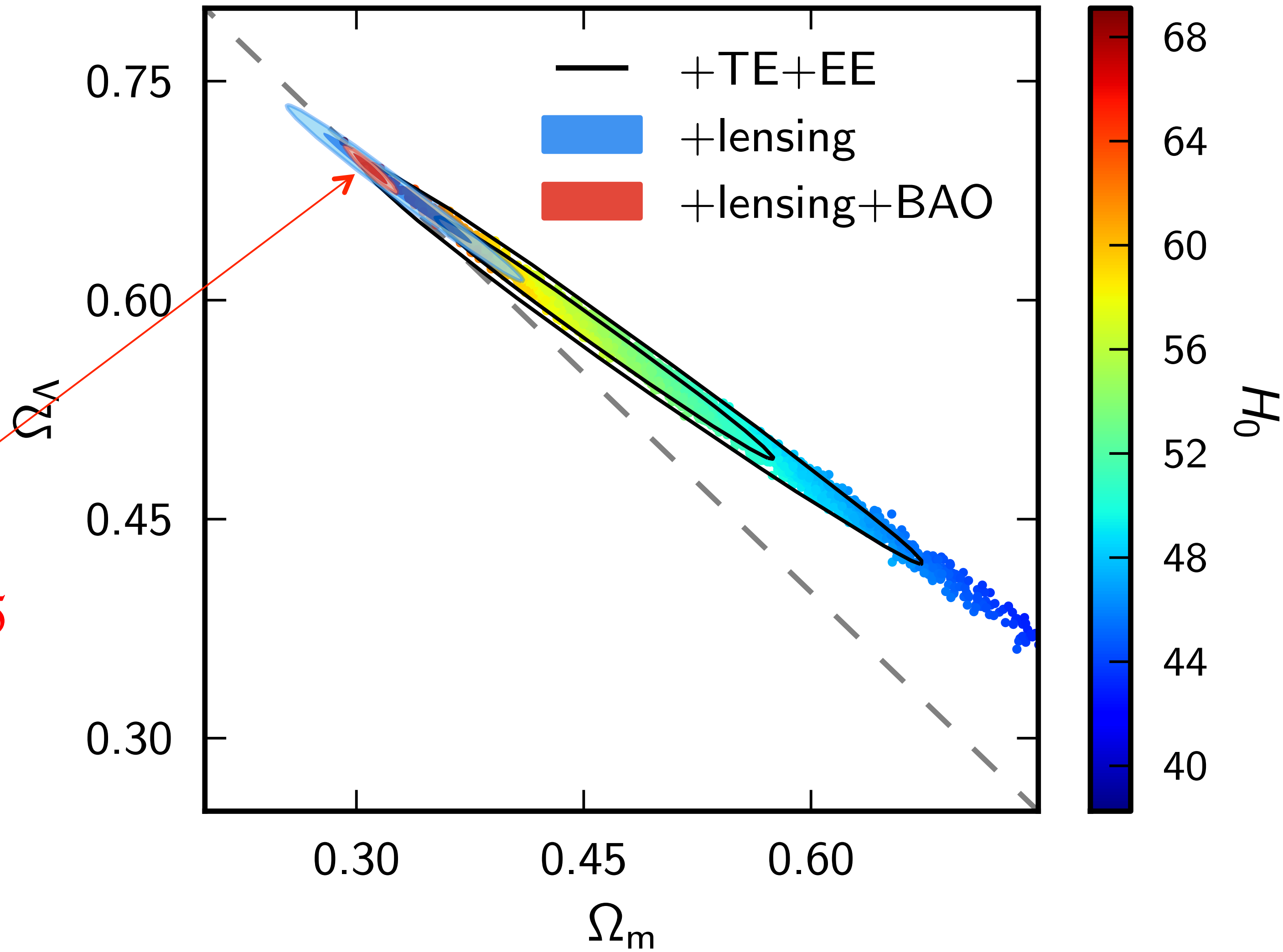
# Optical depth to Thomson scattering

New Planck results (or WMAP results "cleaned" with Planck 353GHz data) point to a later epoch of reionization.



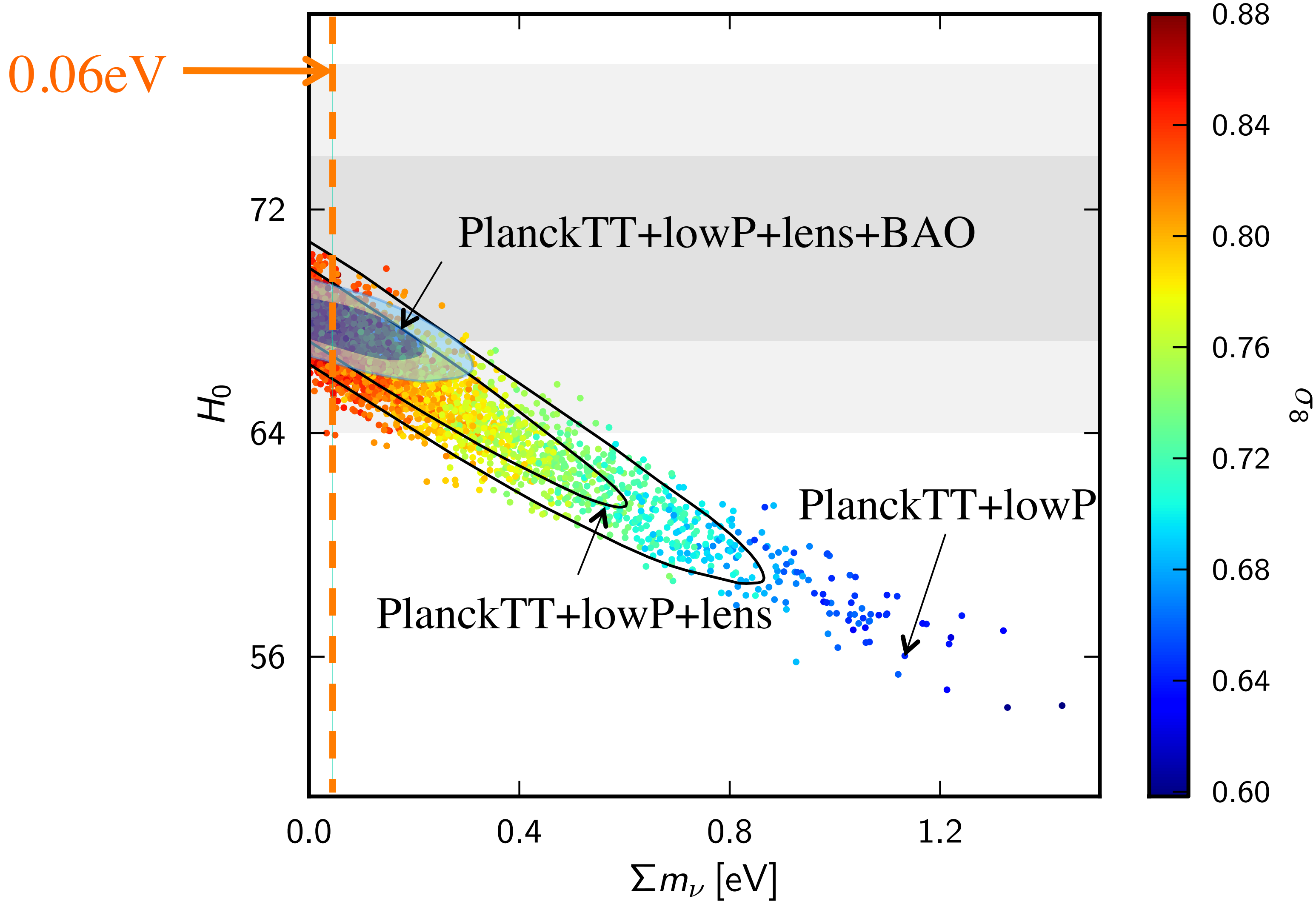

This is easier to accommodate into our view of how reionization occurred based on galaxy counts at early times.

# Still flat after all these years …




$\Omega_k$=0.000±0.005 (95%)

# Constraints on neutrinos now tighter



# Constraints on Inflation

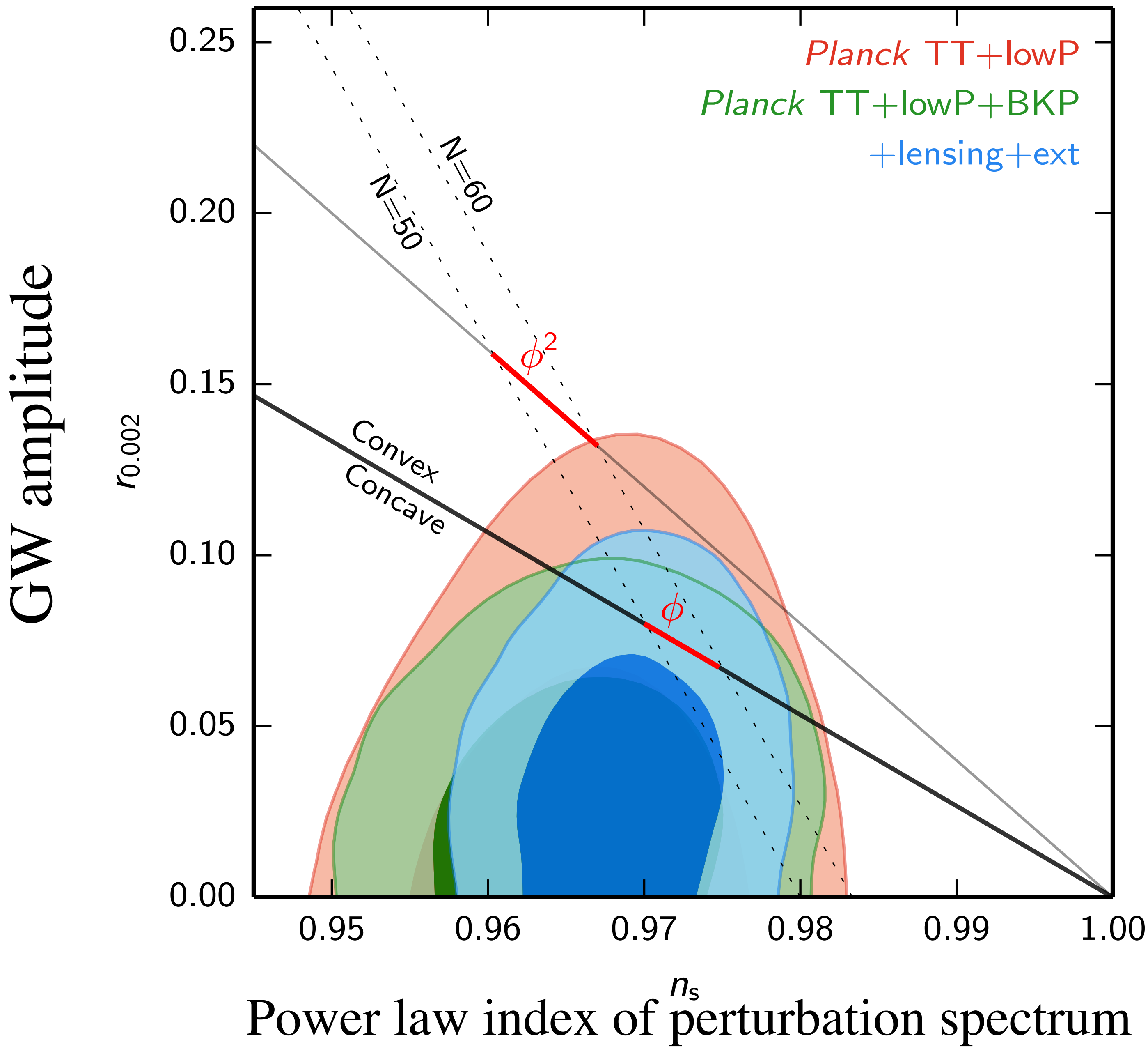
- Planck 2013 had a huge impact on inflationary model building …
- With Planck 2015
  - Constraints on non-Gaussianity get tighter, and new different types are considered explicitly.
  - Constraints on isocurvature modes get tighter.
  - Running of spectral index zero within ~1$\sigma$.
  - Further, tighter constraints on features in primordial power spectrum.
- Joint analysis of Planck+BICEP2/Keck array data gives limits on primordial gravitational wave signal in good agreement with Planck alone.

# Planck and inflation: scorecard

The simplest models of inflation predict …

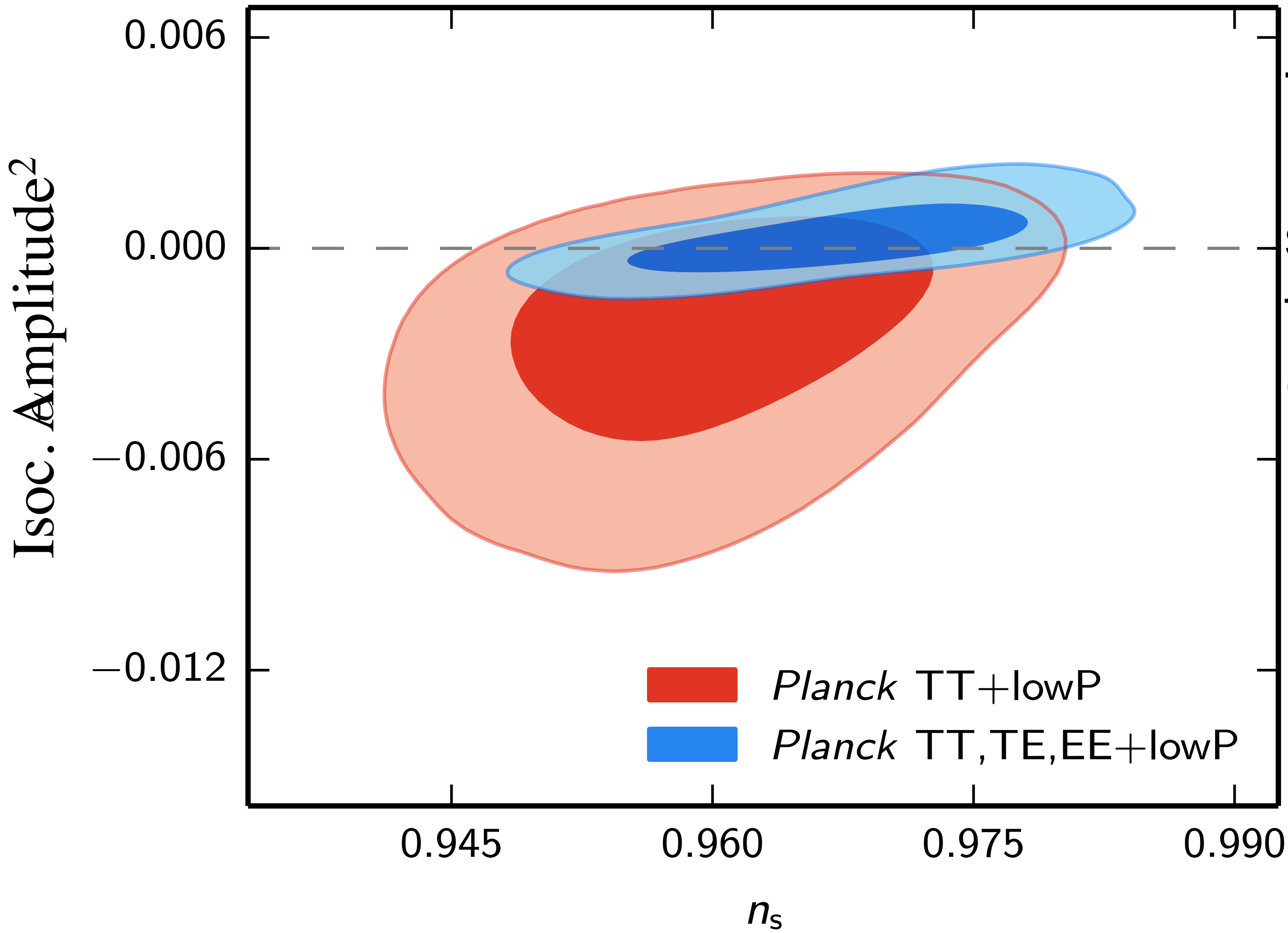
| | |
|---|---|
| A spatially flat Universe | $\Omega_K$=0.000 ± 0.0025 |
| with *nearly* scale-invariant (red) spectrum of density perturbations | 0.968 ± 0.006 |
| which is almost a power-law | $dn_s/d\ln k$ = -0.0065 ± 0.0076 |
| dominated by scalar perturbations | $r_{0.002}$<0.09 (95%) |
| which are Gaussian | $f_{NL}$ = 2.5 ± 5.7 |
| and adiabatic | $\beta_{iso}$ < 3% (95%) |
| with negligible topological defects | $f_{10}$ < 0.04 ($G\mu/c^2 < 10^{-7} - 10^{-6}$) |

# Inflation



Planck TT+lowP
Planck TT+lowP+BKP
+lensing+ext
N=60
N=50
$\phi^2$
$\phi$
Convex
Concave
0.25
0.20
0.15
0.10
0.05
0.00
0.95
0.96
0.97
0.98
0.99
1.00
$r_{0.002}$
$n_s$
GW amplitude
Power law index of perturbation spectrum

# Polarization quite constraining for some extensions to standard model: e.g. fully correlated matter isocurvature




The perturbations we see are almost fully adiabatic ($\delta p \sim \delta\rho$).

Informative for inflationary model building!

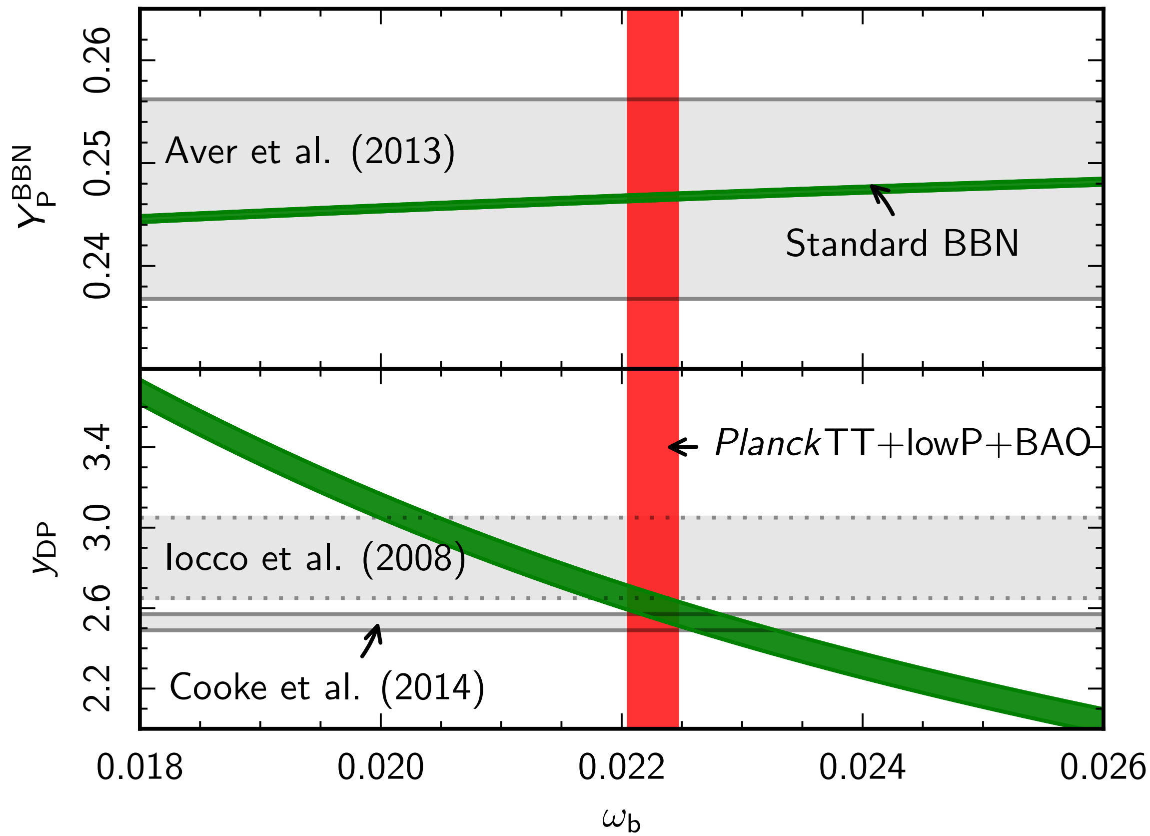
# Consistency with other data

- The Planck data are consistent with the predictions of the simplest $\Lambda$CDM models.
- Within the framework of such models we can compare to a wide variety of other astrophysical/cosmological datasets.
  - Primordial nucleosynthesis
  - Baryon Acoustic Oscillations (distance scale).
  - Direct measures of $H_0$.
  - Redshift-space distortions.
  - Type Ia SNe.
  - Cosmic shear.
  - Counts of rich clusters of galaxies.
  - etc

Tensions remain.

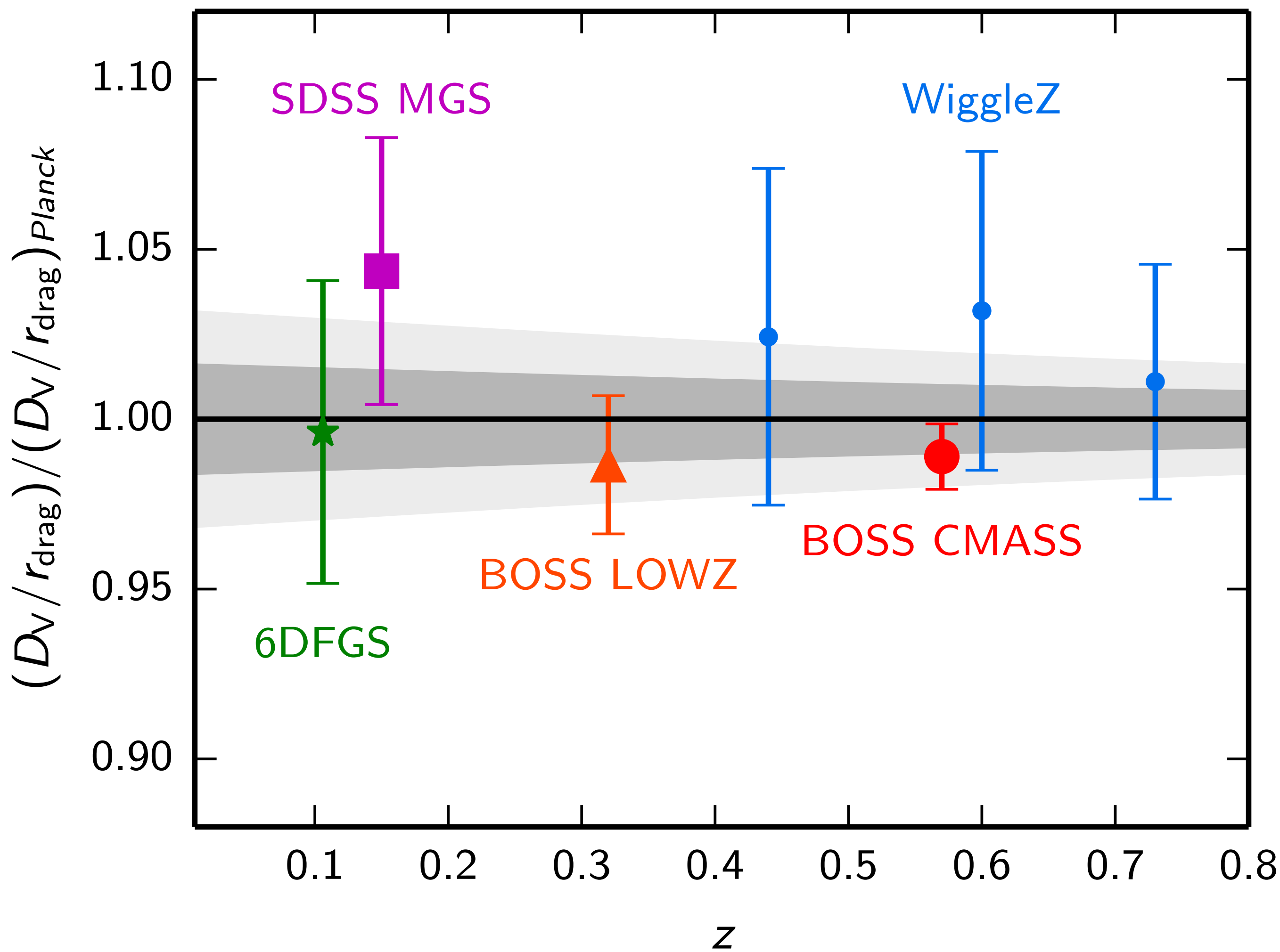
# Physics is Universal!

Baryon density measured by BBN and CMB are in excellent agreement … comparison uses all known laws of physics!




[And we also have a measurement of the Hydrogen 2s➔1s transition which is 5x better than the lab measurement, and in fantastic agreement with the theoretical calculation!]

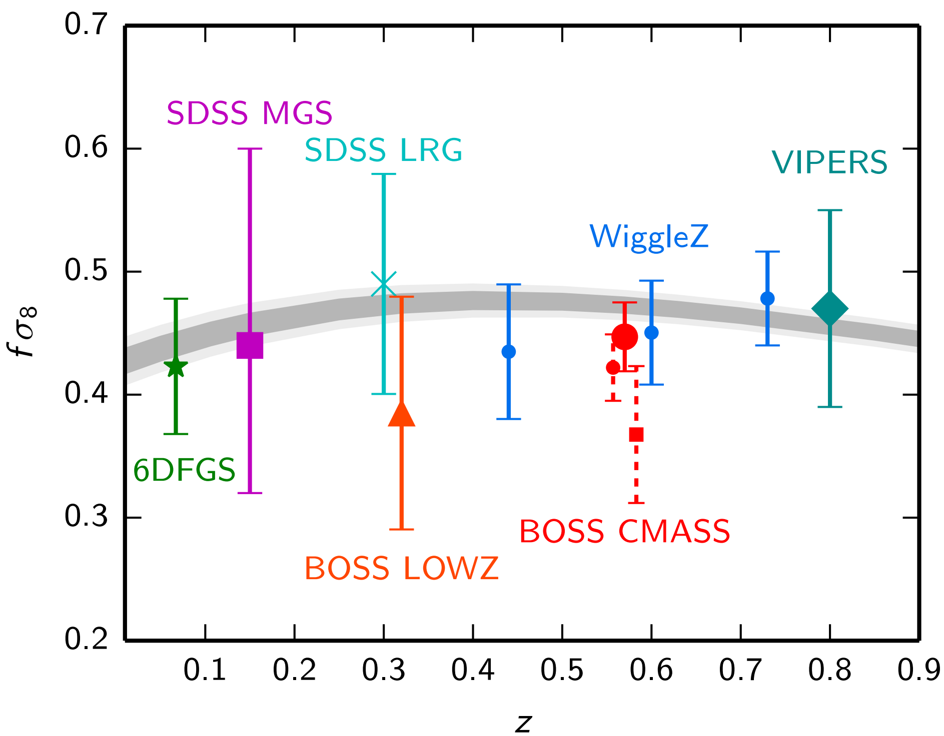
# Distance scale comparison: BAO

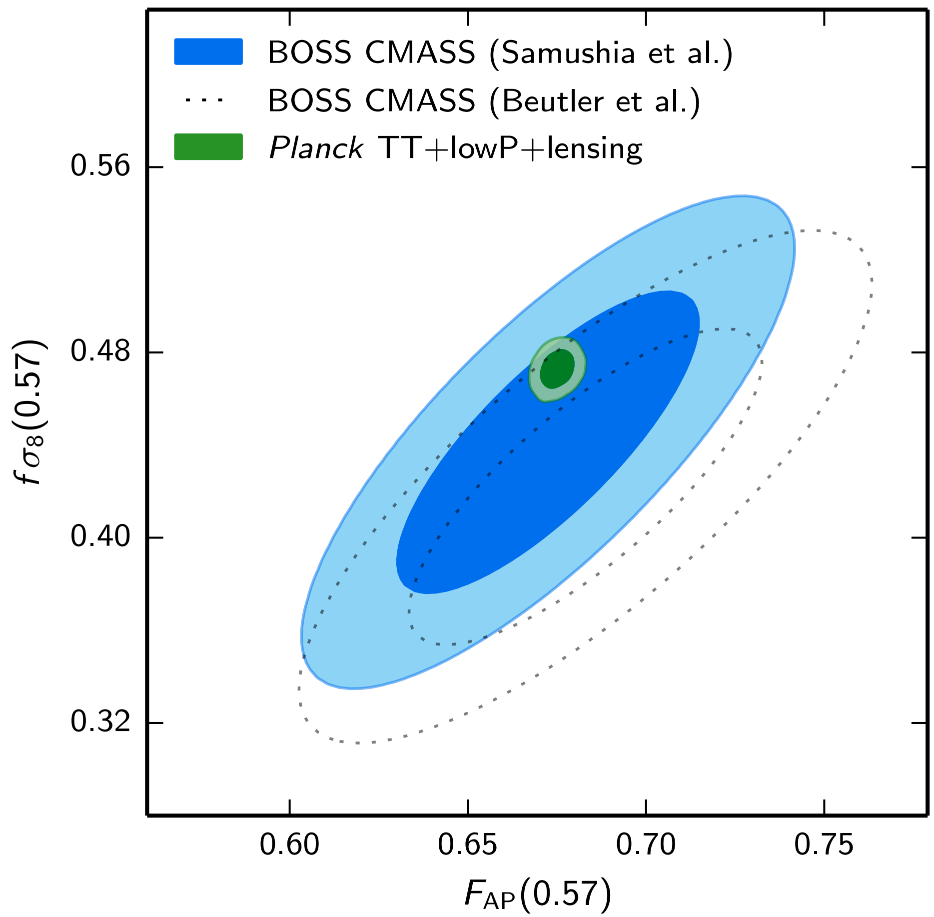



Acoustic oscillations at z~1100 and z<1 tell the same story about the distance scale: ΛCDM!

# And RSD

We can measure the rate-of-growth of large-scale structure at z<1 from galaxy redshift surveys and compare to ΛCDM predictions constrained from Planck…



# Just plain cool …

- In 2013 we detected the motion of the Earth in the aberration of the measured CMB anisotropy.
  - Observed at >4σ in 2013 data.

- In this data release we detect the impact of fluctuations in the 2K neutrino background!
- Evidence for ν background strong ($N_{eff}$=0 ruled out @ >10σ)
- Now have exquisite detection of free-streaming of this component (measures of $c_{eff}^2$ and $c_{vis}^2$).
  - Sound speed (squared) should be, and is, 1/3!

# Conclusions

- The Planck mission has been stunningly successful.
- Impressive confirmation of the standard cosmological model.
  - Precise constraints on model and parameters.
  - Tight limits on deviations from base model.
  - Some indications of internal and external tensions, but with only modest statistical significance.
- New analysis should improve data quality even more for the next release!

# The End