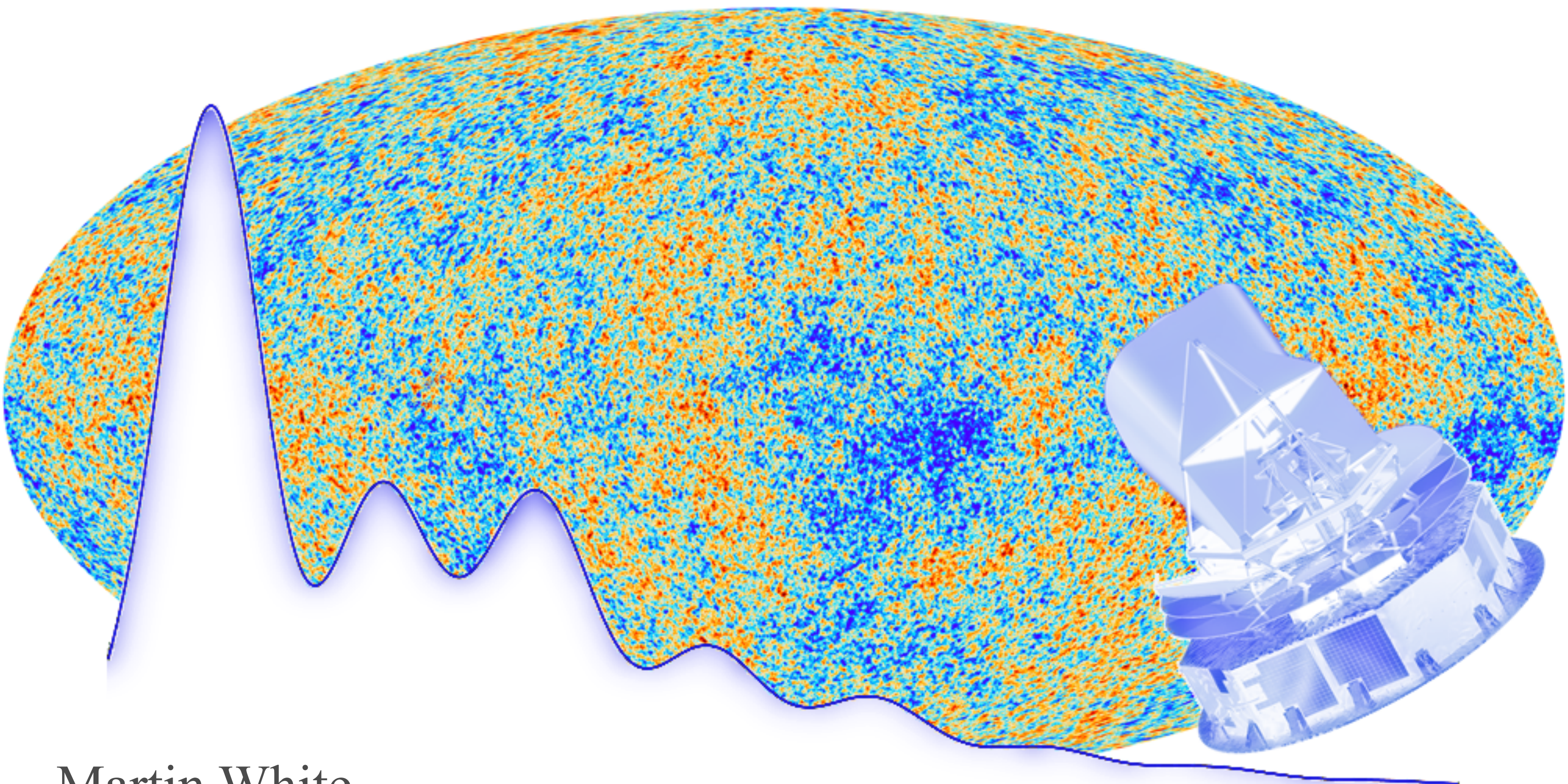
Echoes of Gravity



Martin White
on behalf of the Planck
(and BOSS) collaboration(s).

Figs. 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 do I mean by Echoes of Gravity?
- What is Planck?
- Planck (and BOSS) update(s).
  - Cosmological parameters.
  - CMB lensing.
  - Connecting high-z to low-z.
  - Comparison with other datasets.
- "Just plain 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 $\tau >> 1$ to $\tau << 1$.
- 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

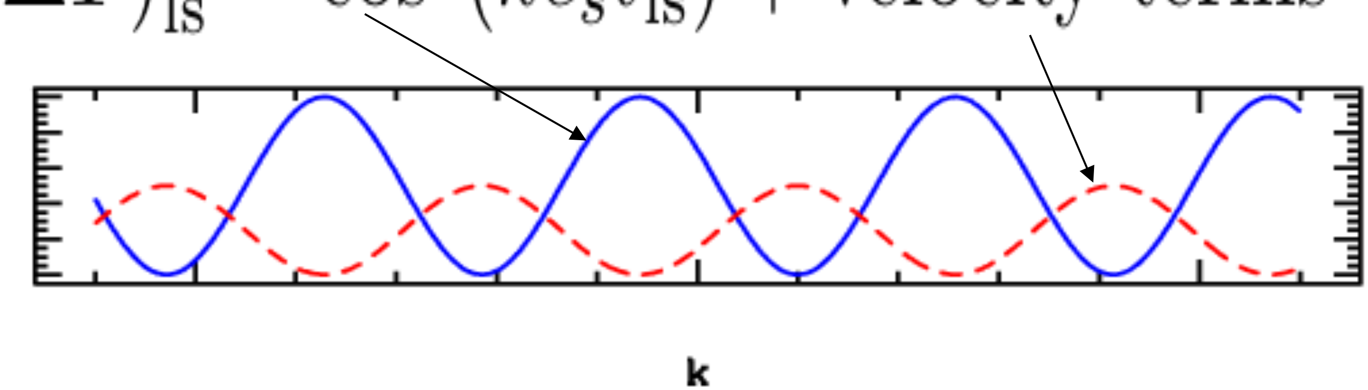
- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering.
  - Short m.f.p. allows fluid approximation.
- Initial fluctuations in density and gravitational potential drive acoustic waves in the bγ fluid: compressions and rarefactions.
- These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

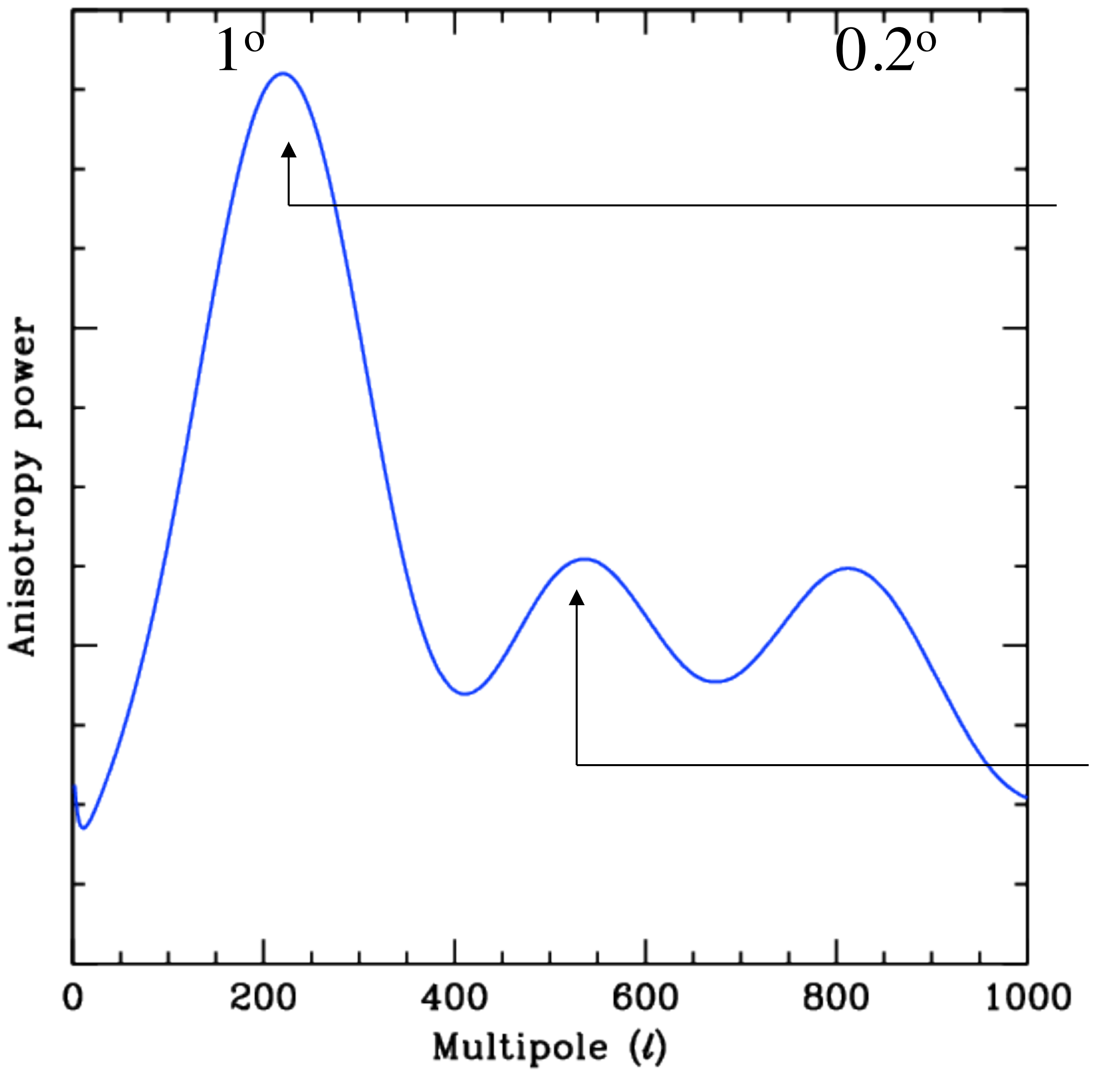
- A sudden "recombination" decouples the radiation and matter, giving us a snapshot of the fluid at "last scattering".

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



- These fluctuations are then projected on the sky with $\lambda \sim d_{ls}\theta$ or $l \sim k\, d_{ls}$
- (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!

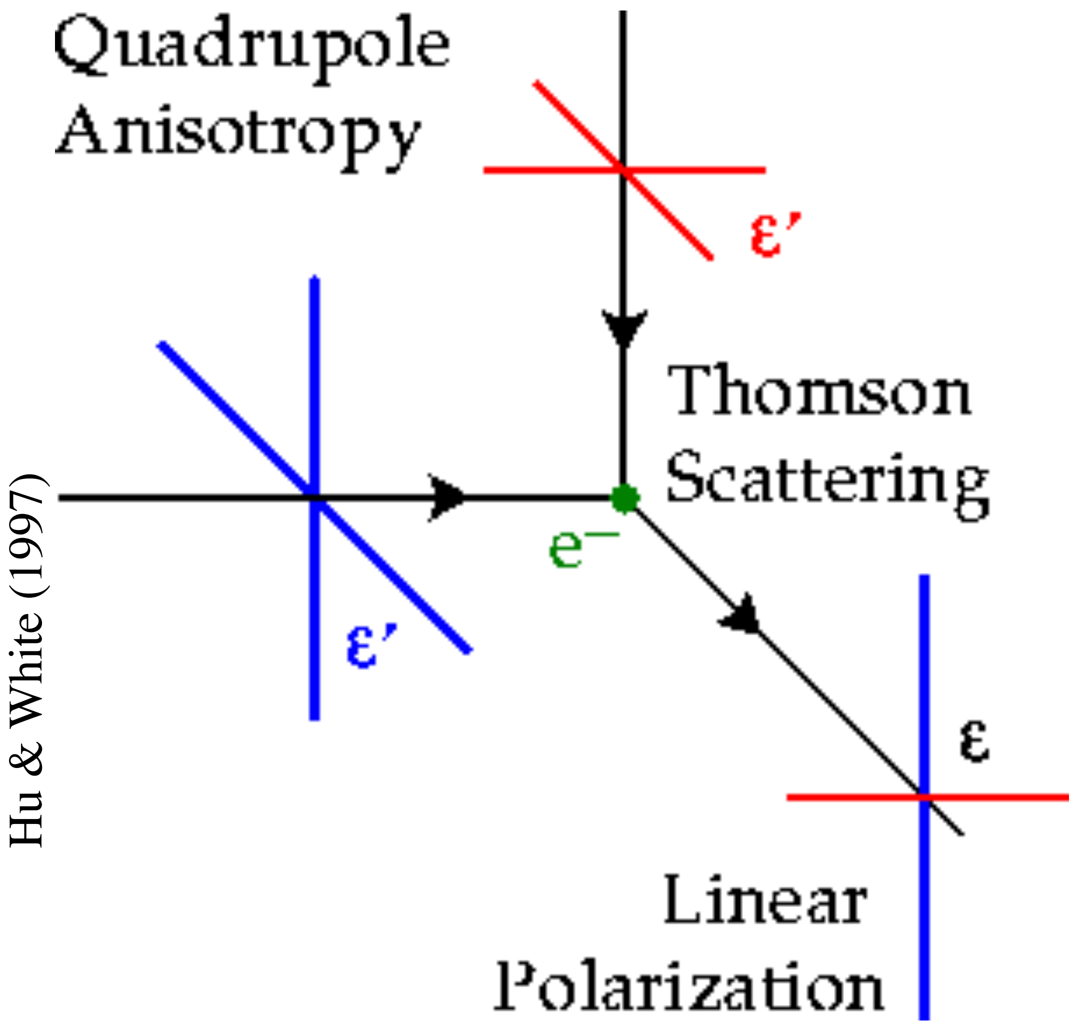


First "compression", at $kc_s t_{ls}=\pi$. Density maximum.

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

→ Smaller scales

Anisotropy generates (linear) polarization



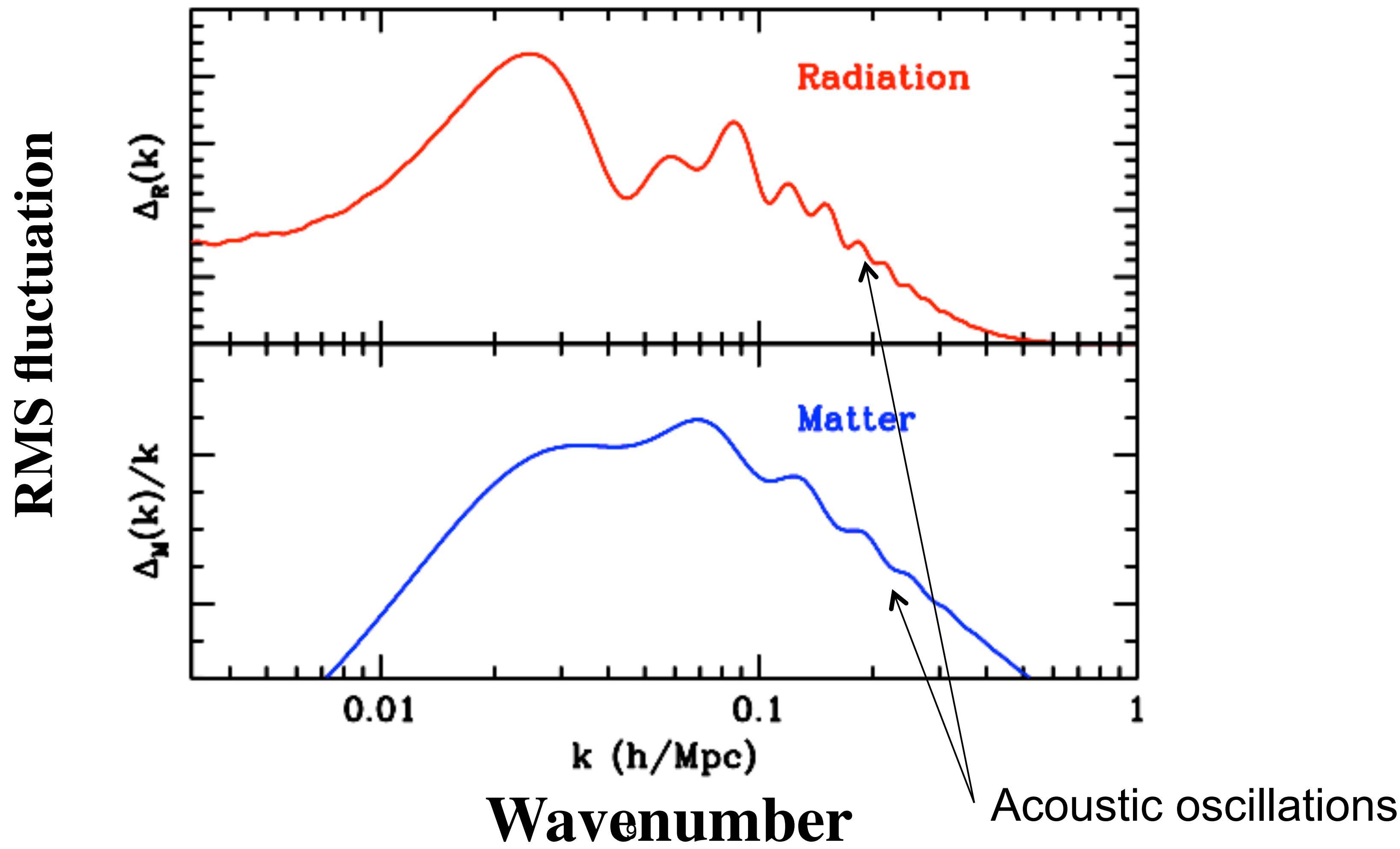
A quadrupole anisotropy generates linear poln.

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.

Baryon Acoustic Oscillations

The oscillations in the photon-baryon fluid also imprint a feature in the late-time clustering of matter … with the same characteristic length scale! Allows a "standard ruler" test of the expansion history!



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.
- 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.
  - Breaks a key degeneracy (angular size-distance).
  - Checks our model predictions/extrapolations in time.

The magic of CMB …

The CMB contains a gold-mine of information

- *if* it can be accurately measured
- *and* compared to precise theoretical predictions
- in a statistically reliable
- and computationally tractable way

There are very few situations in cosmology, astrophysics or indeed physics where all of these conditions are met.

It is the intersection of these qualities that makes CMB such a powerful cosmological probe!

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.

esa

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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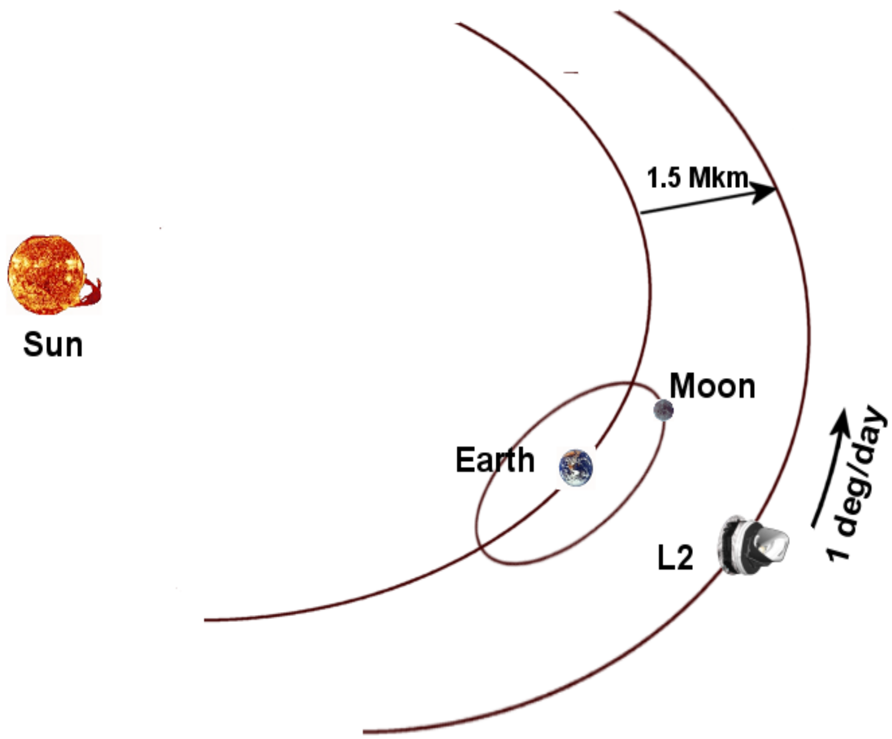
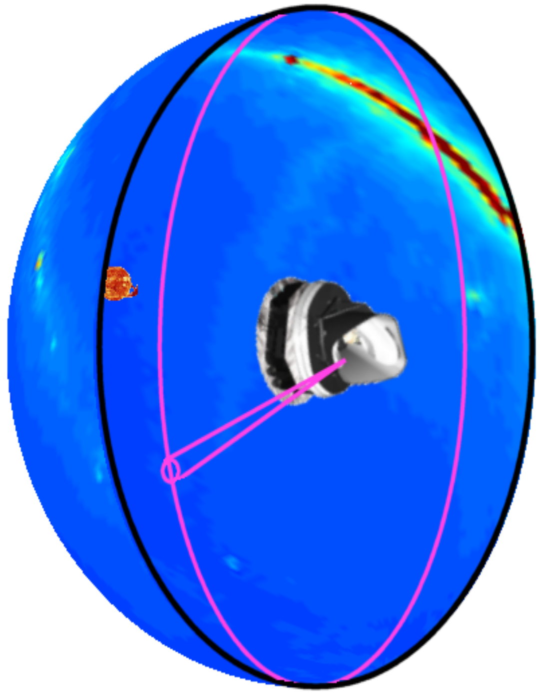
The orbit

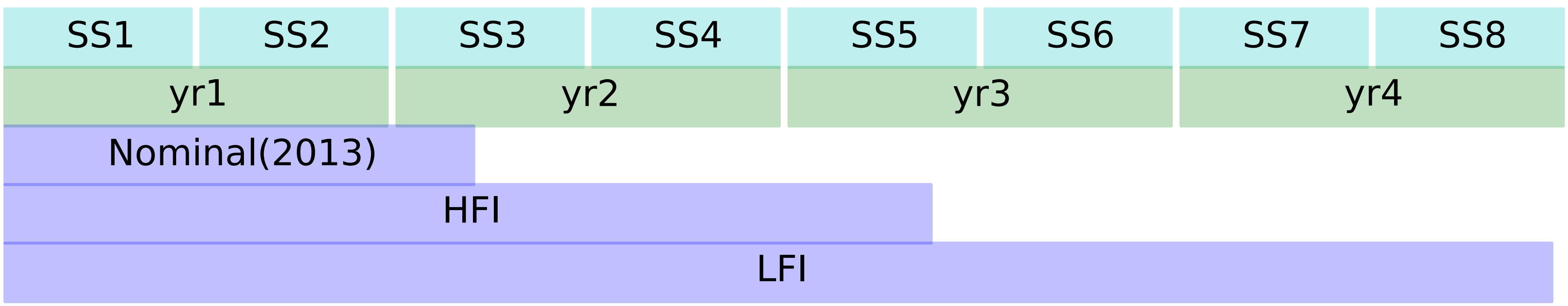
Planck made a map of the full sky every ~6 months.



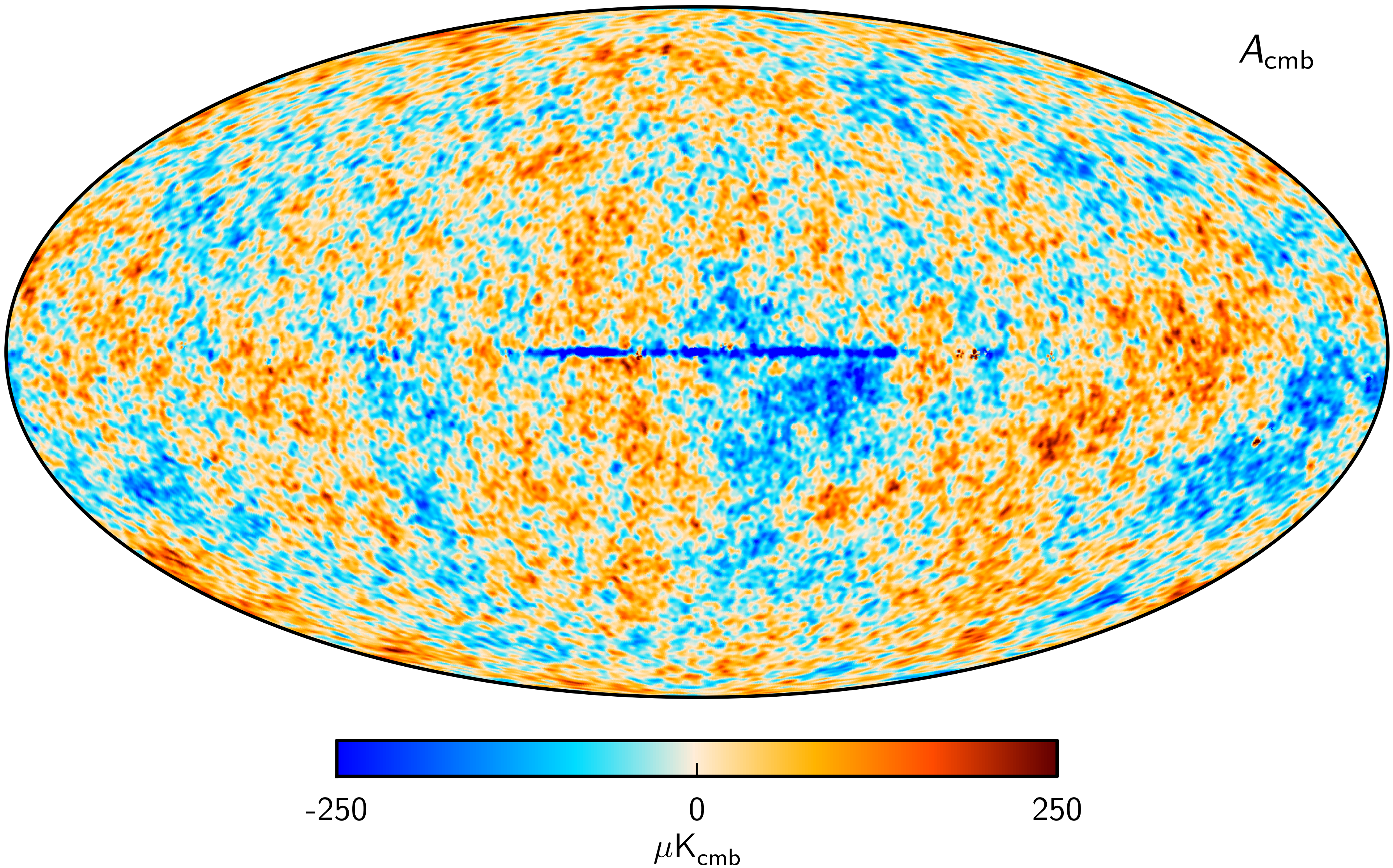


Current data release

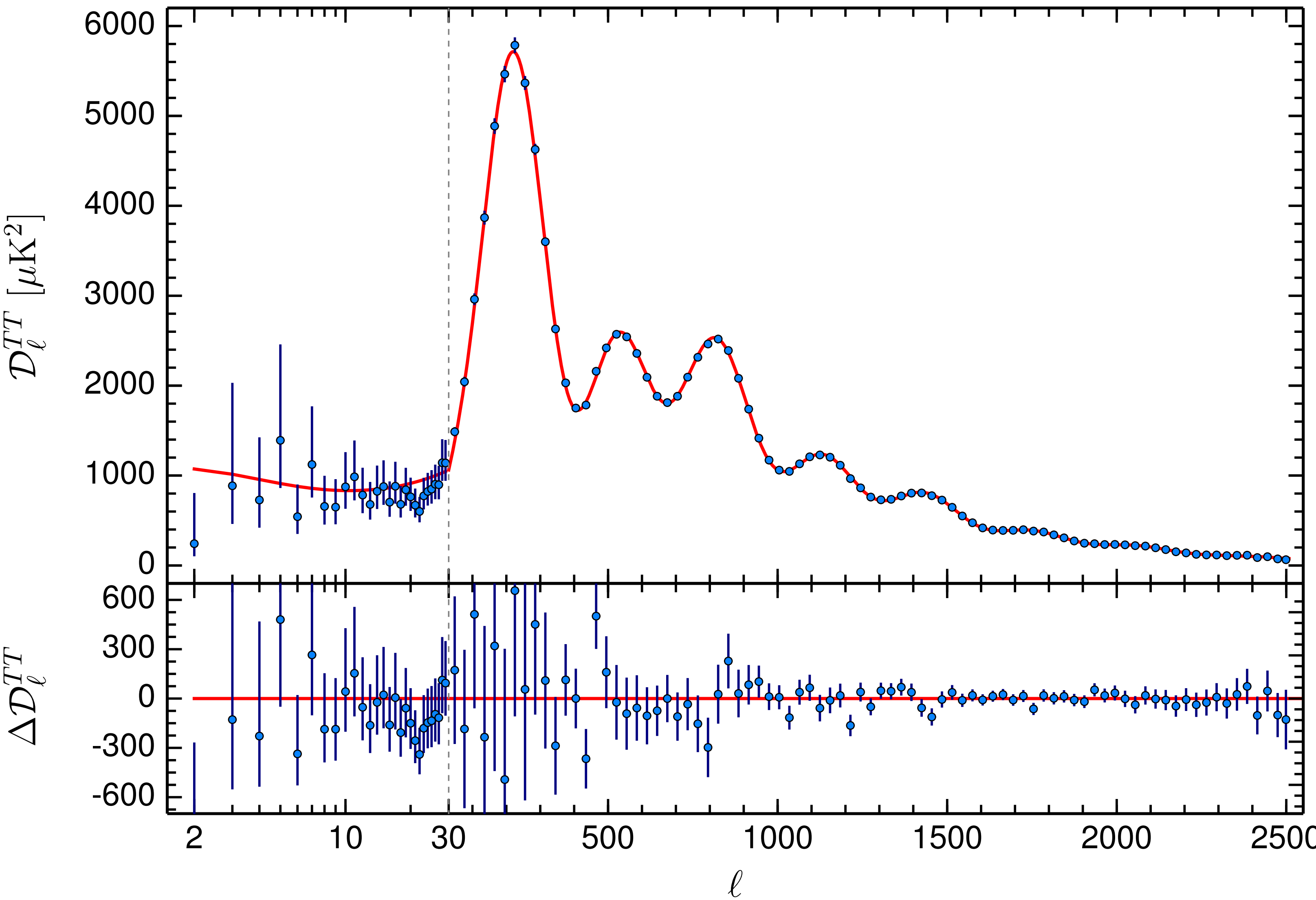
- We have had two public data releases
  - Full mission data (12 Aug 2009 – 23 Oct 2013).
- In addition to better S/N, the last release takes advantage of multiple full-sky redundancies
  - Planck scans the sky differently in “even” and “odd” sky surveys.
  - Scan changed between SS4 and SS5.
- There will be one more data release, early next (calendar) year.



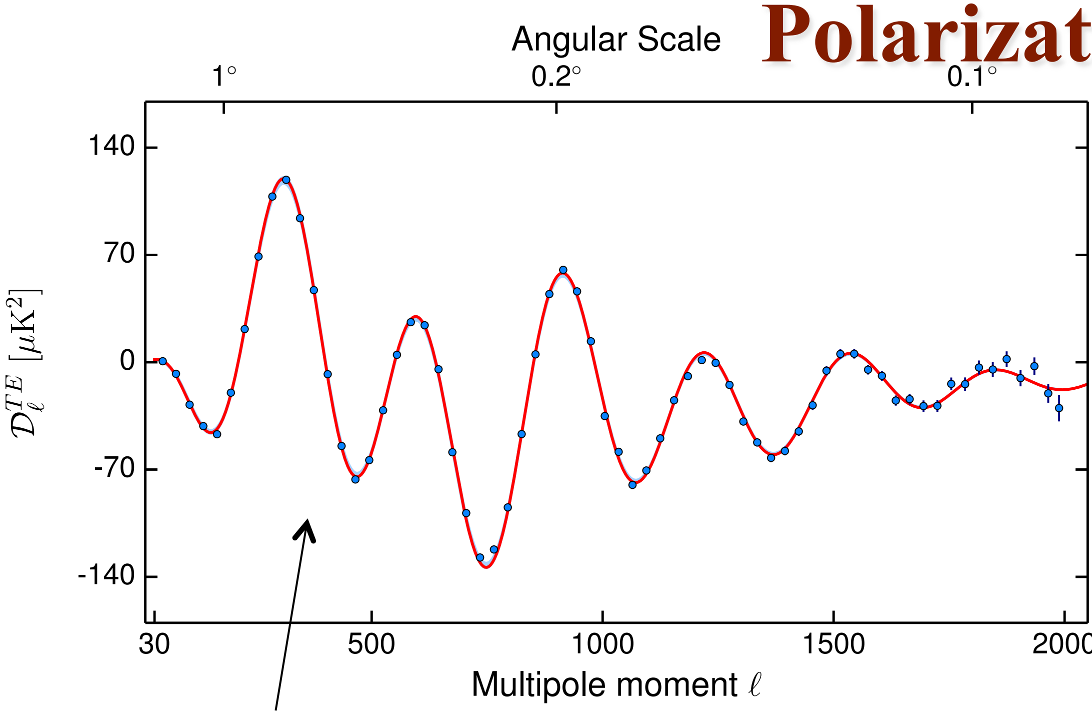
CMB map



The angular power spectrum



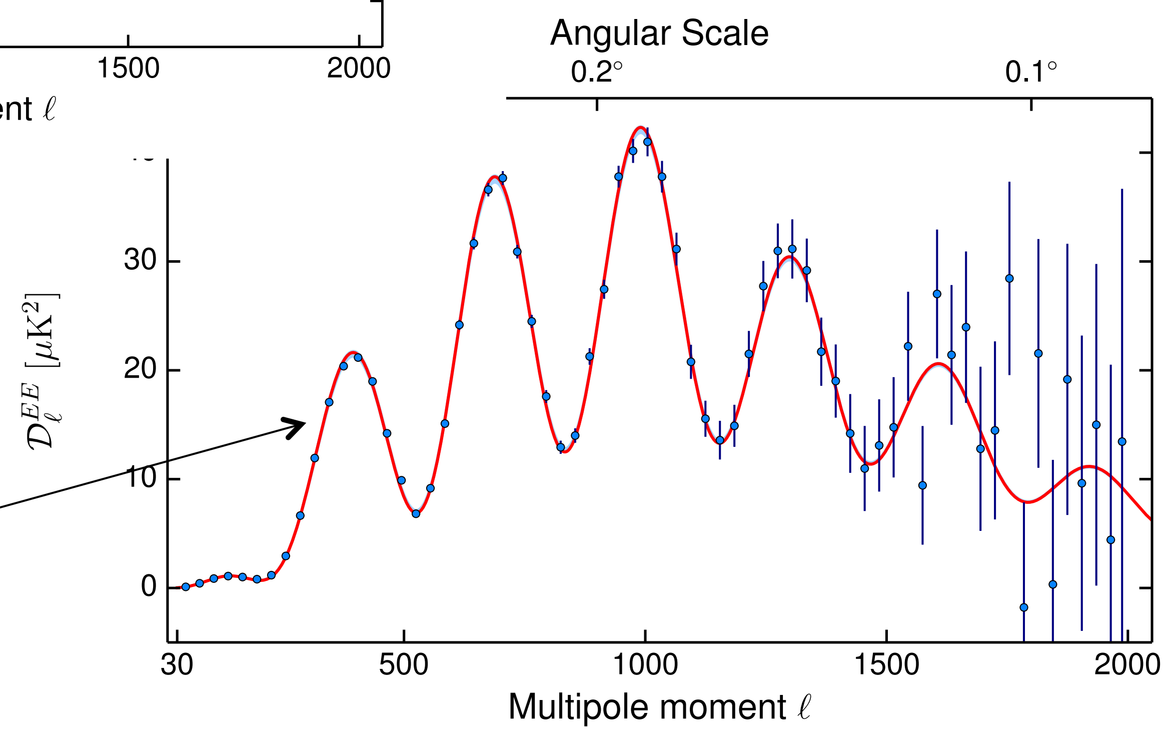
Polarization



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!

- 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%.

Planck base ΛCDM model

Parameter	Description	Value
ω_b	Baryon density	0.02218 ± 0.00015
ω_c	Cold dark matter density	0.1205 ± 0.0014
$100\theta_{MC}$	Angular size of acoustic scale	1.04069 ± 0.00031
τ	Optical depth to Thomson scattering	0.056 ± 0.009
$10^9 A_s e^{-2\tau}$	Observed fluctuation amplitude	1.886 ± 0.012
n_s	Slope of primordial power spectrum (spectral index)	0.9619 ± 0.0045
H_0 (km/s/Mpc)	Expansion rate of Universe	66.9 ± 0.62
σ_8	Amplitude of fluctuations in matter today	0.8174 ± 0.0081

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

Changes in parameters: standard model

(PIP LI describes the physics behind these changes)

- 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 τ lower (so z_{re} decreased!)
- n_s increased by ~0.7σ
- ω_b increased by ~0.6σ *and* error decreased.
- Limits on isocurvature modes, Ω_K, m_ν, ΔN_{eff}, f_{NL}, DM annihilation etc. all tighter. No deviations detected.

Planck 2016 intermediate results. LI.
Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters

ABSTRACT

The six parameters of the standard ΛCDM model have best-fit values derived from the *Planck* temperature power spectrum that are shifted somewhat from the best-fit values derived from WMAP data. These shifts are driven by features in the *Planck* temperature power spectrum at angular scales that had never before been measured to cosmic-variance level precision. We investigate these shifts to determine whether they are within the range of expectation and to understand their origin in the data. Taking our parameter set to be the optical depth of the reionized intergalactic medium τ, the baryon density ω_b, the matter density ω_m, the angular size of the sound horizon θ_*, the spectral index of the primordial power spectrum, n_s, and $A_s e^{-2\tau}$ (where A_s is the amplitude of the primordial power spectrum), we examine the change in best-fit values between a WMAP-like large angular-scale data set (with multipole moment $\ell < 800$ in the *Planck* temperature power spectrum) and an all angular-scale

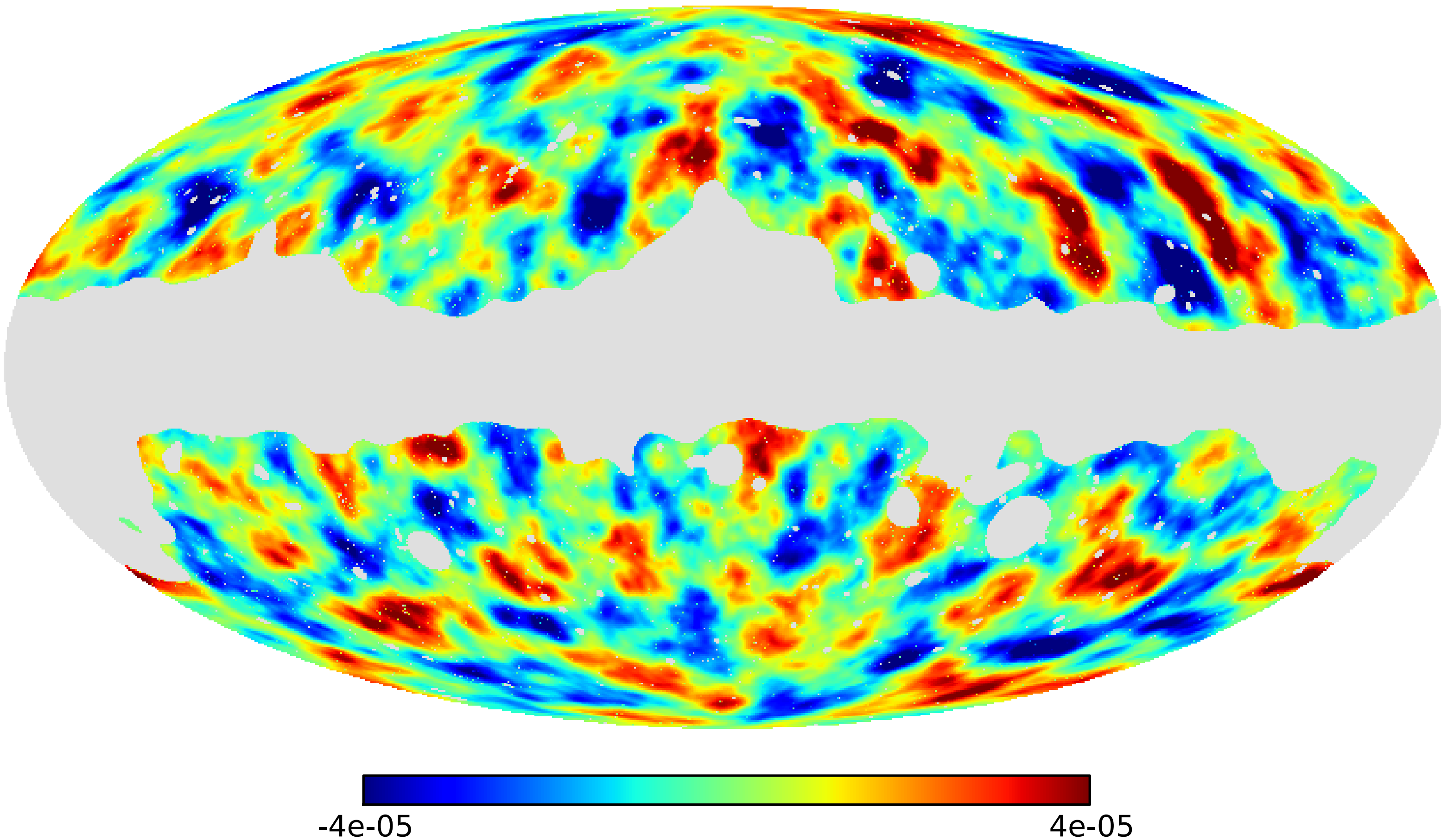
Parameter shifts: PTE 15%.

"… current CMB data sets give an internally consistent picture of the ΛCDM model"

CMB lensing

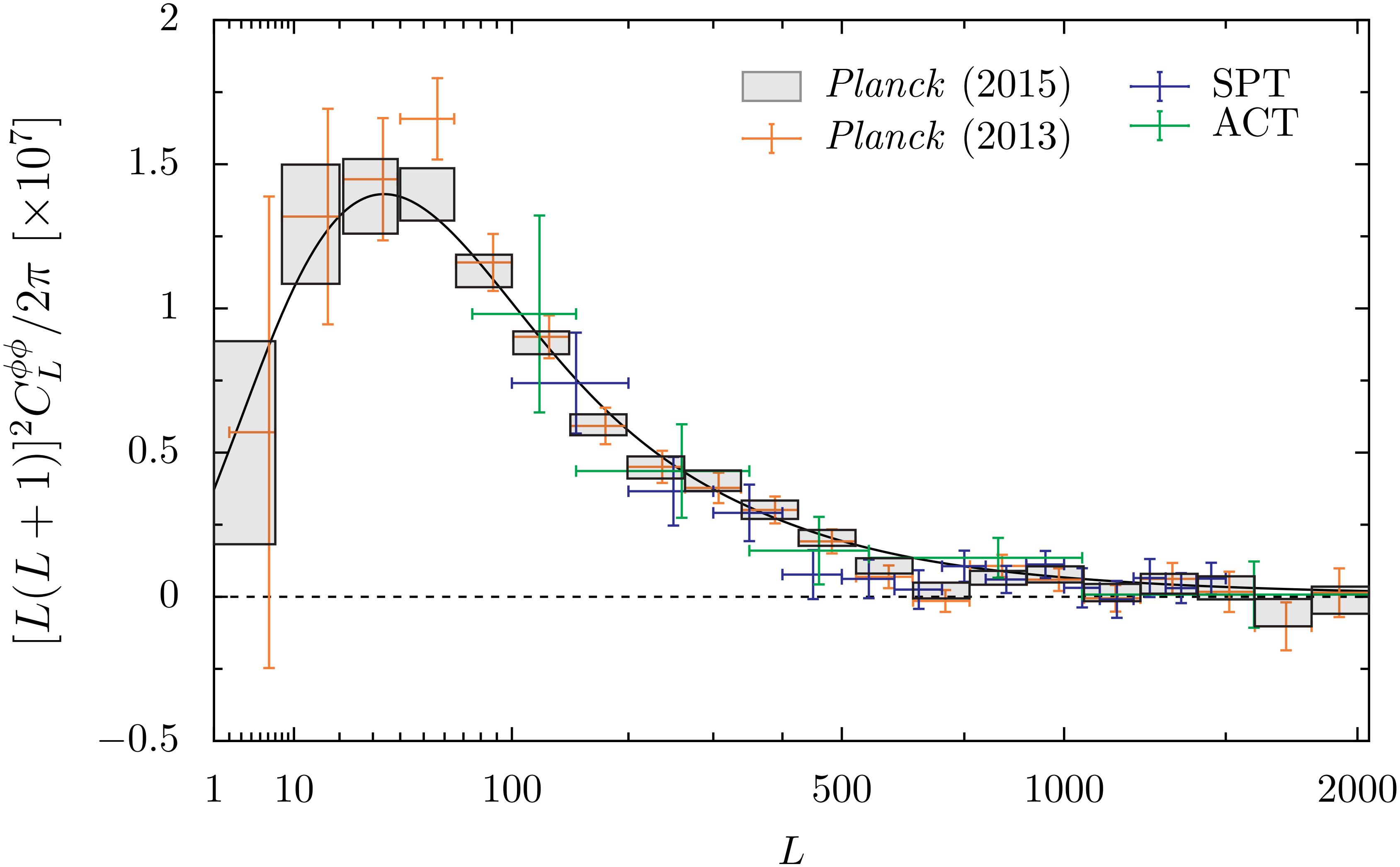
- Photons from the CMB are deflected on their way to us by the potentials due to large-scale structure.
- The typical deflection is 2-3 arcmin but deflections are coherent over degrees.
  - Signal dominated by structures of tens of Mpc at z~2.
- Gives sensitivity to the “low z” Universe.
  - Allows us 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 40σ.
Better than predicted by anisotropy!

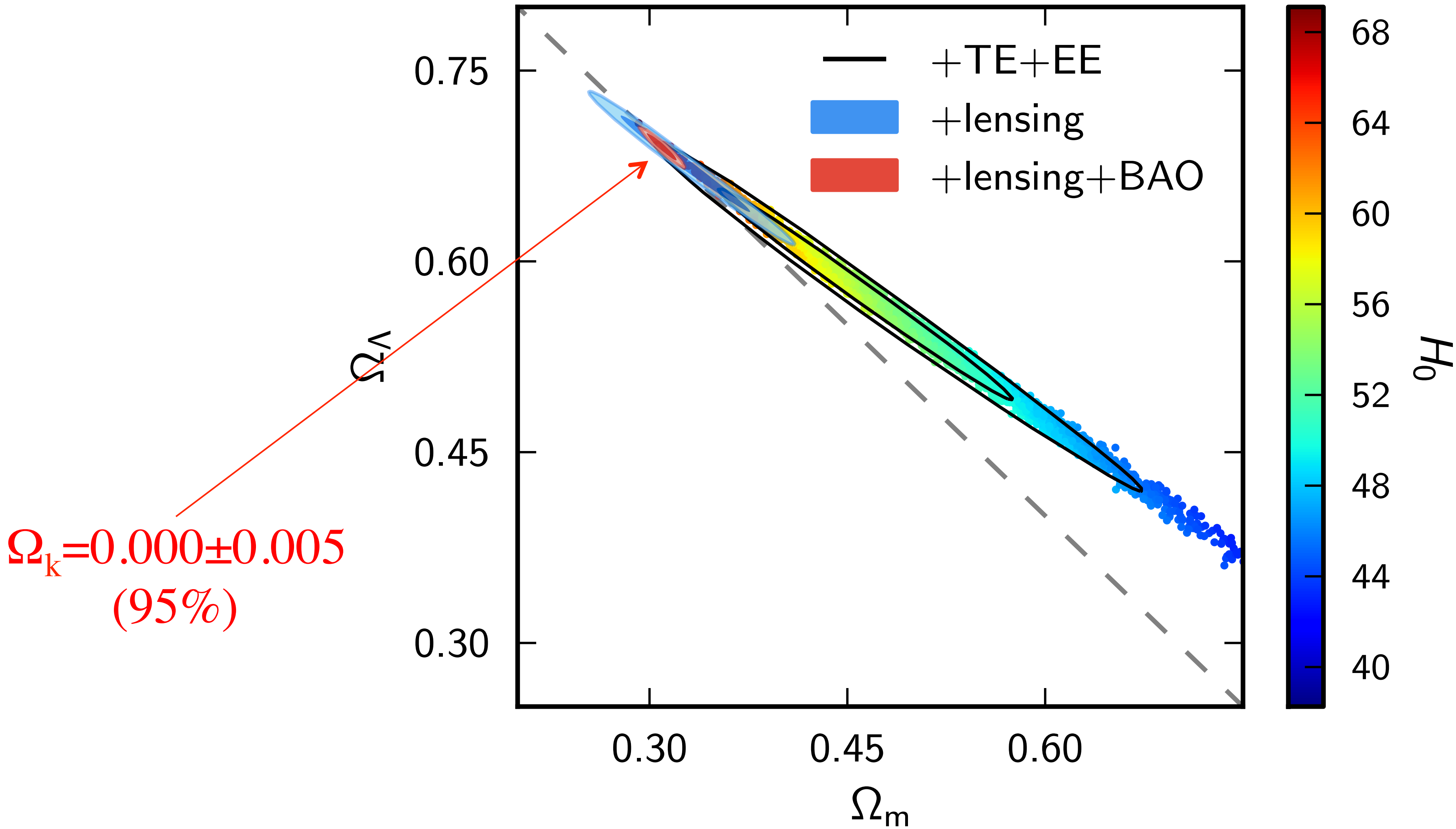
Lensing power spectrum



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

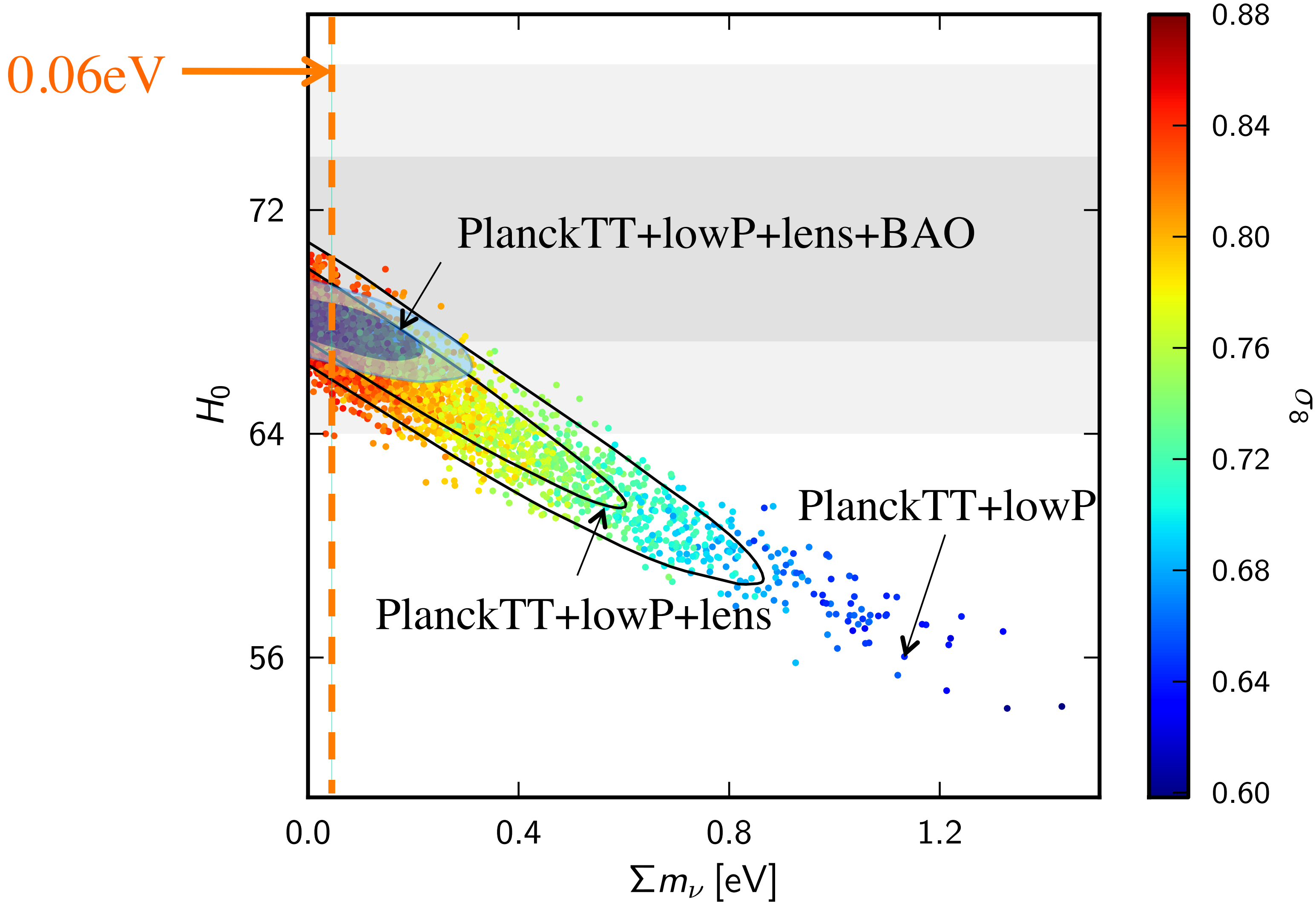
Still flat after all these years …

Cosmic sound at late times tells the same story as at early times
… and that story is (flat) ΛCDM!



Constraints on neutrinos now tighter

$\Sigma m_\nu < 0.17$ eV (95%)



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 ~1σ.
  - 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.

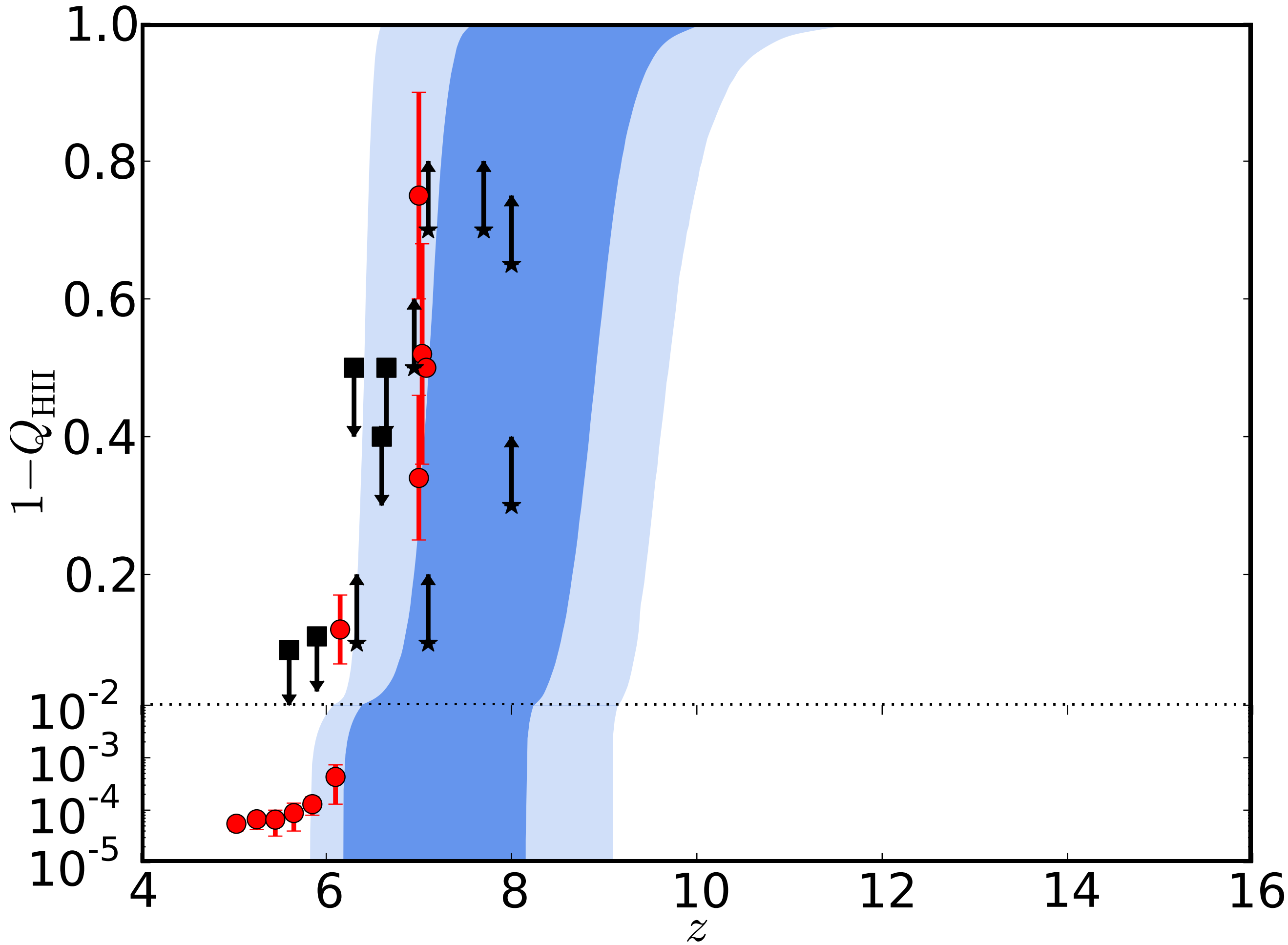
Planck and inflation: scorecard

The simplest models of inflation predict …

A spatially flat Universe	Ω_K=0.000 ± 0.0025
with *nearly* scale-invariant (red) spectrum of density perturbations	0.962 ± 0.005
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 ~ 0
and adiabatic	β_{iso} < 3% (95%)
with negligible topological defects	f_{10} < 0.04 ($G\mu/c^2 < 10^{-7} - 10^{-6}$)

Optical depth to Thomson scattering

New Planck results point to "*late and fast*" reionization.



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

A consistent model is emerging …

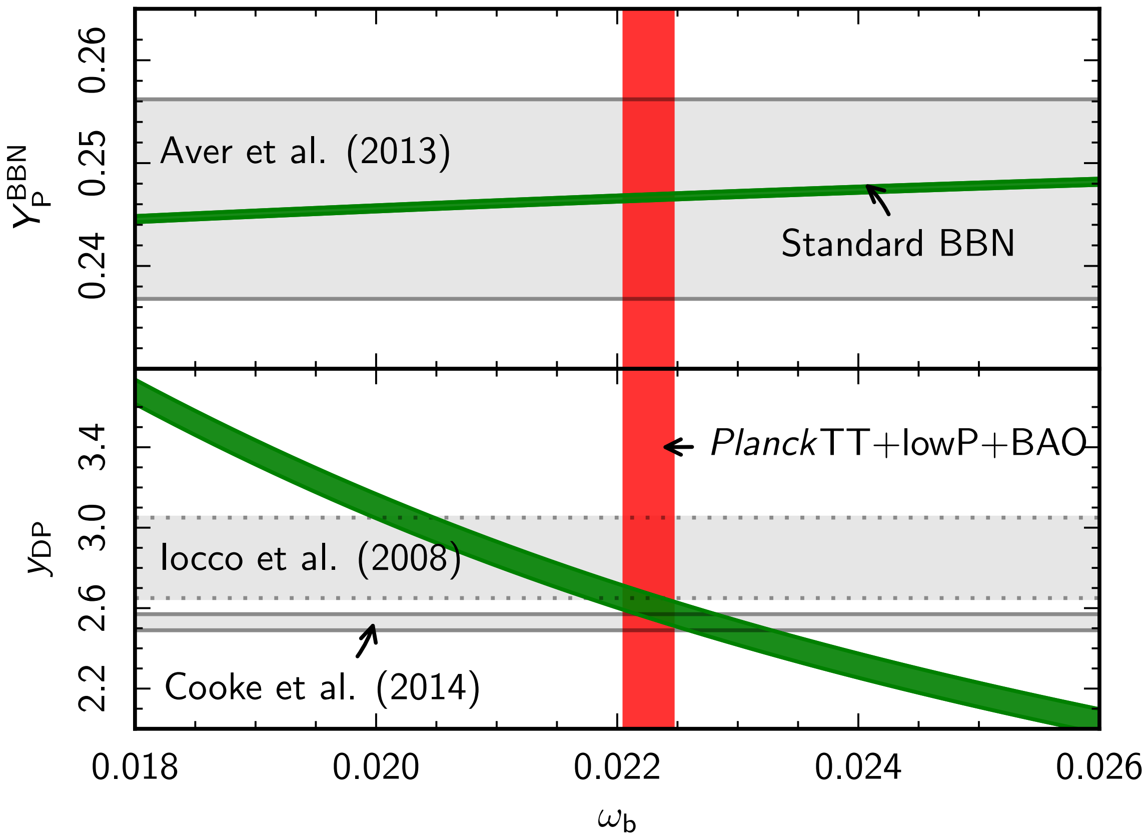
Consistency with other data

- The Planck data are consistent with the predictions of the simplest ΛCDM 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. (← Cosmic shear; Counts of rich clusters of galaxies)

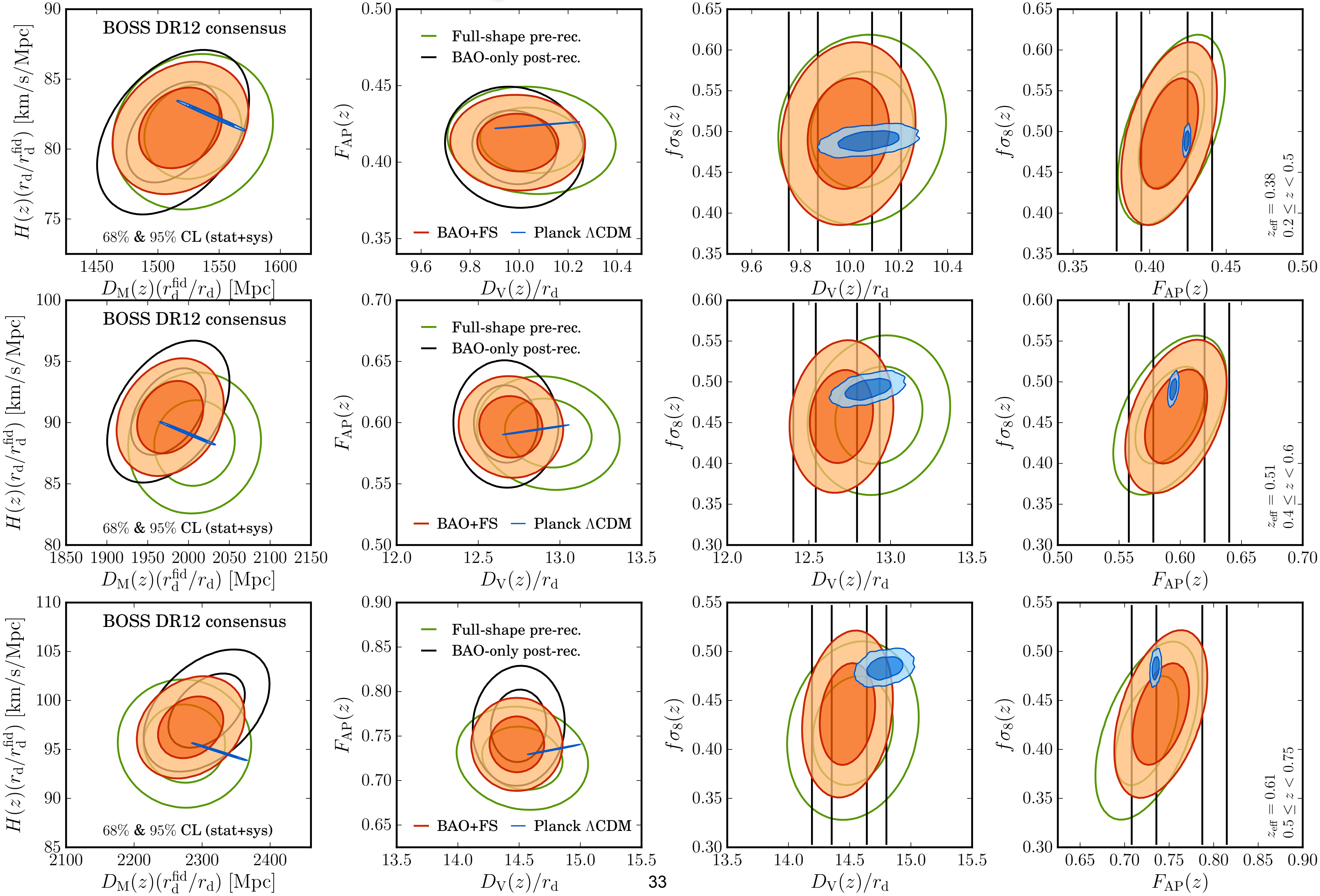
Physics is Universal!

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!]

At low z: BOSS final results



Just plain cool …

- In 2013 Planck 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.
- (The BOSS survey finished early and performed flawlessly.)
- The two experiments provide a rigorous test of our models using the physics of harmonic oscillators!
  - Established acoustic physics as the "gold standard" probe.
- Final analyses of Planck is still underway.
  - We expect science to flow from these data for many years.
- 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 last (official) Planck release!

The End