# First cosmology results from Planck

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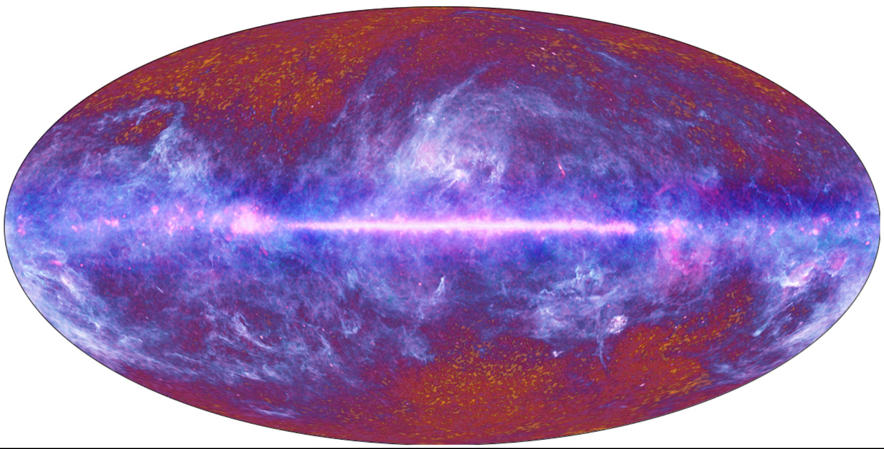
**for the Planck team**



## Outline

- The CMB.
- Planck: mission.
- Planck: cosmological parameters
- Planck: CMB lensing.
- Planck: constraints on inflation
- Planck: comparison with other datasets.
- Conclusions.

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## Our most valuable cosmological probe

- Existence of CMB
  - One of the pillars of the hot big-bang model.
- Measurement of the black-body spectrum
  - T = 2.725 ± 0.001 K, deviations < $10^{-4}$
  - Sets the temperature scale of the Universe
    - Only cosmological parameter known to 0.01%!
  - Rules out significant energy injection below z~$10^7$.
- Measurement of the anisotropy
  - Shrunk substantially the range of viable cosmological models.
  - Showed the fluctuations are of the form predicted by inflation and the large-scale structure of space-time is "simple".
  - Best measurement of most cosmological parameters



## The cartoon

- 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.

$$\frac{d}{d\tau}\left[m_{\rm eff}\frac{d\delta_b}{d\tau}\right]+\frac{k^2}{3}\delta_b=F[\Psi] \qquad m_{\rm eff}=1+3\rho_b/4\rho_\gamma$$

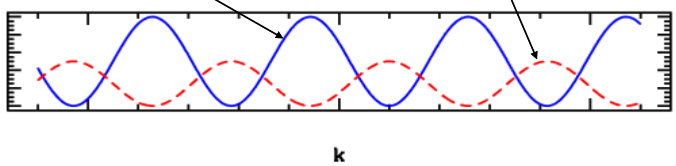
- These show up as temperature fluctuations in the CMB [harmonic wave]

$$\Delta T\sim\delta\rho_\gamma^{1/4}\sim A(k)\cos(kc_st)$$

## The cartoon

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

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




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

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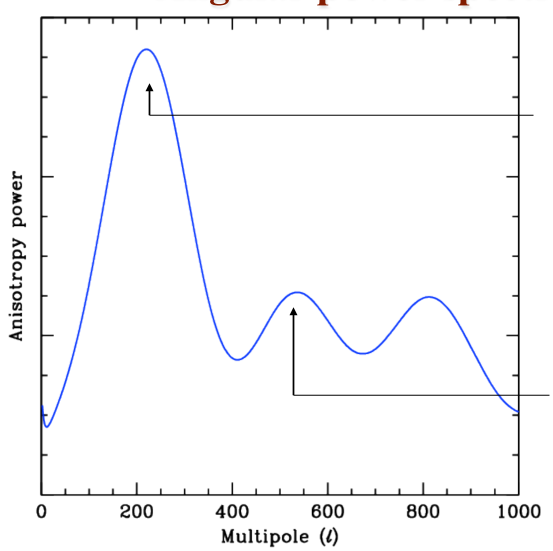
## Angular power spectrum!




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

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

Acoustic scale is set by the *sound horizon* at last scattering: $r_s \sim c_s t_{ls}$

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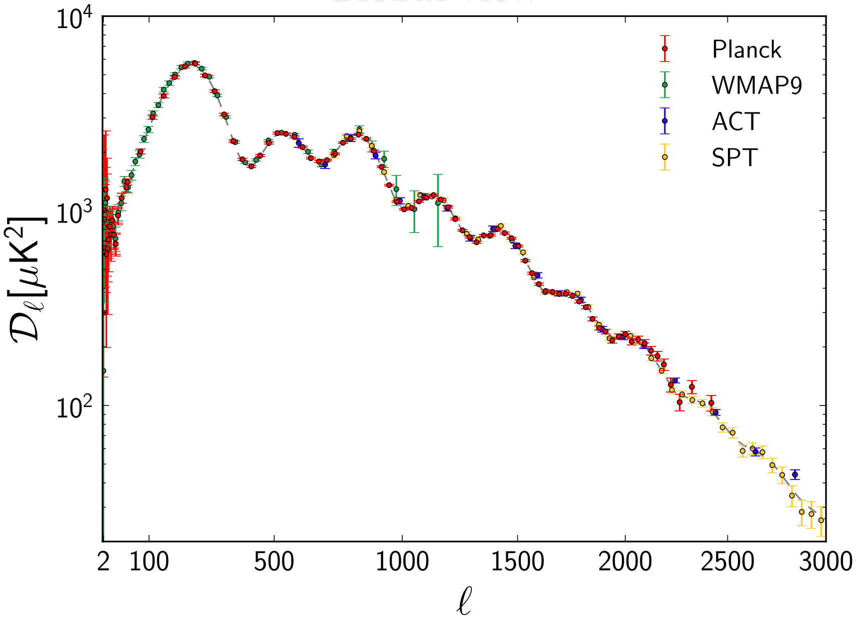
## Global view




## 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 signal can be accurately measured and compared to precise theoretical predictions.
- Basic inferences:
  - From the narrow first peak we know that whatever "rang the bell" was sharp and of short duration, not a continuous driving.
  - The fluctuations are dominated by large-scale density perturbations (not vorticity modes or gravity waves).
  - The universe was not "weird" at z~$10^3$.

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# Planck mission

- Planck is a 3rd generation space mission (COBE, WMAP)
  - Like WMAP, Planck observes at "$L_2$".
- It is part of ESA's "Cosmic Visions" program.
  - Launched in May 2009 along with the Herschel satellite.
  - Stably and continuously mapping the sky since 13 August 2009.
- It is 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'.
  - Sensitivity is ~25x better than WMAP and resolution ~3x better.
  - Expect 6x more modes and 12x lower noise per $arcmin^2$.
- Planck measures temperature anisotropy with accuracy set by fundamental astrophysical limits.
  - The CMB spectrum is a band limited function.
  - Planck is cosmic variance limited to $l=10^3$.

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# Current data release

- Highlights from our recent data release: temperature anisotropies during the nominal mission (12 Aug 2009 – 27 Nov 2010).
  - Products all available from Planck Legacy Archive (PLA).
- There will be two more data releases, one/year.
- These will cover additional sky and polarization.

**Access to PLA**

The PLA is freely accessible via the URL:

**http://pla.esac.esa.int/pla/pla.jnlp**

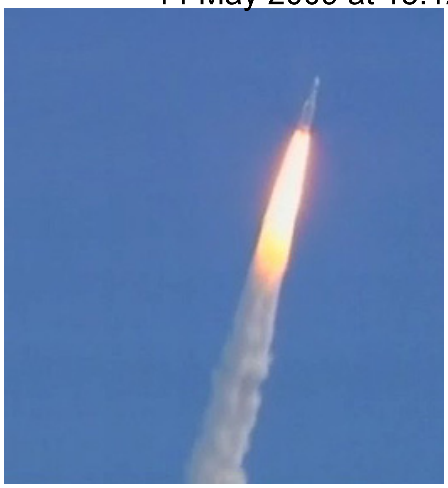
**Frequently requested products** | **Explanatory supplement** | **Planck publications**

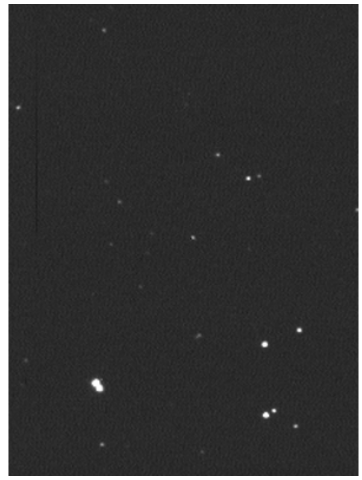
**Planck science team home** | **Use of Planck data**

The PLA interface also inter-operates with the astronomical catalogues served by the Centre de Donnees de Strasbourg (CDS), via the interactive software Aladin. Data can be transferred seamlessly from the PLA to Aladin. Additional tabular data manipulation functionality is available via the Topcat tool. Please note that users do not need to install Aladin and Topcat a-priori in order to use them; they will be called up automatically by the PLA interface when invoked.

## A picture-perfect launch!

Ariane 5 lifts off with Herschel and Planck on board on 14 May 2009 at 15:12:02 CEST.





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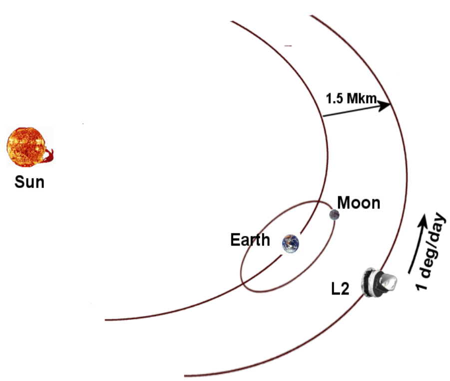
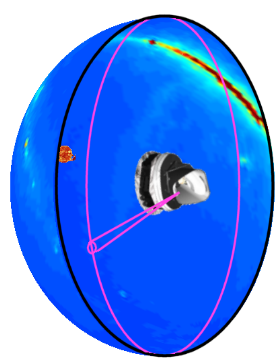
## The orbit

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



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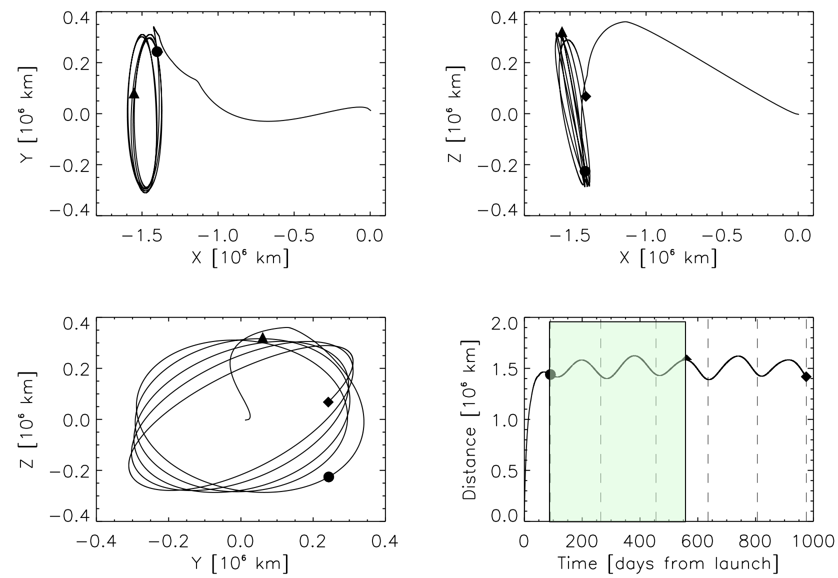
# Orbit


Y [10⁶ km]
X [10⁶ km]
Z [10⁶ km]
Distance [10⁶ km]
Time [days from launch]

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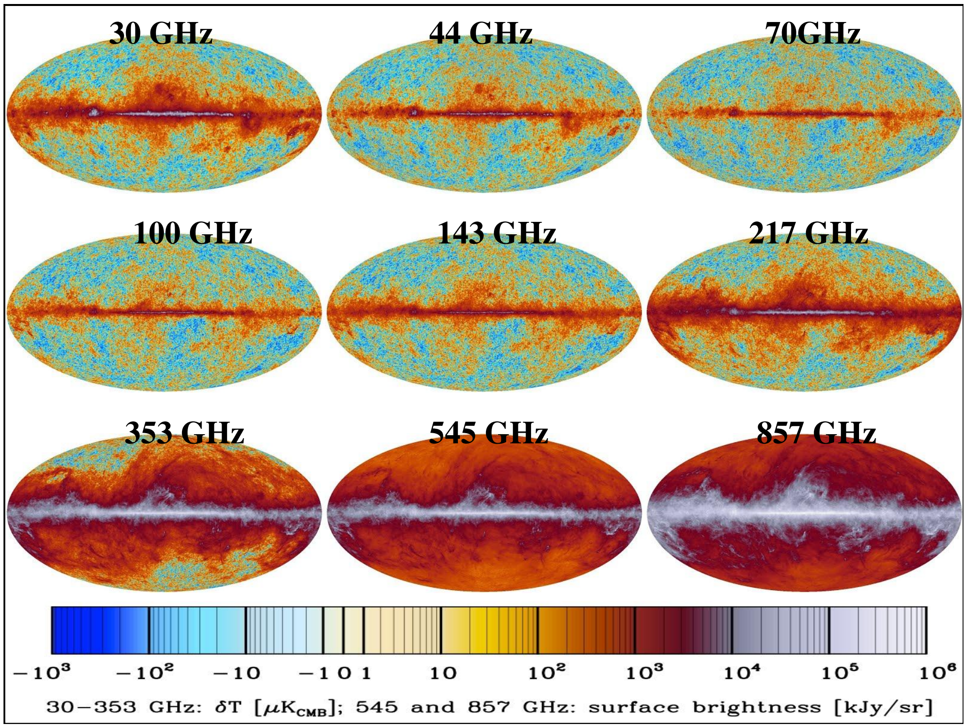
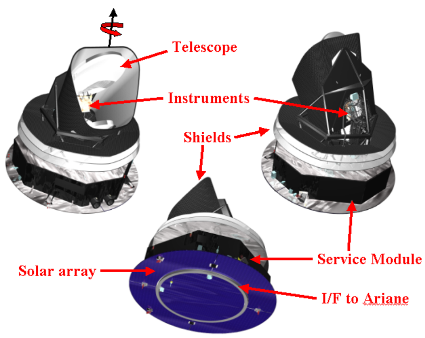
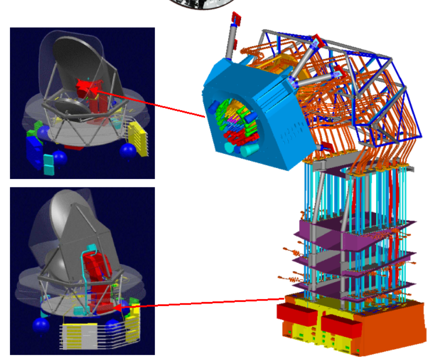

30 GHz
44 GHz
70GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

## 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.

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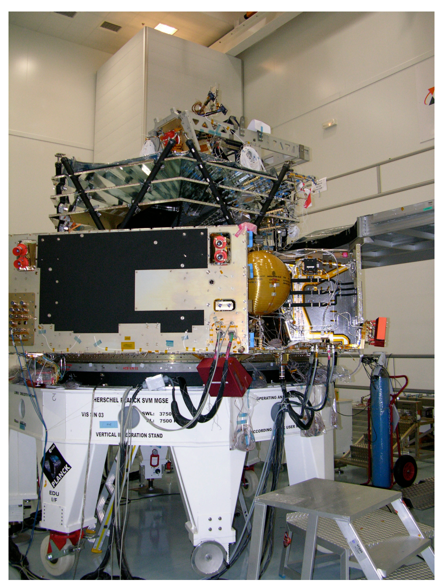
## Planck being assembled



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# Planck in February 2009

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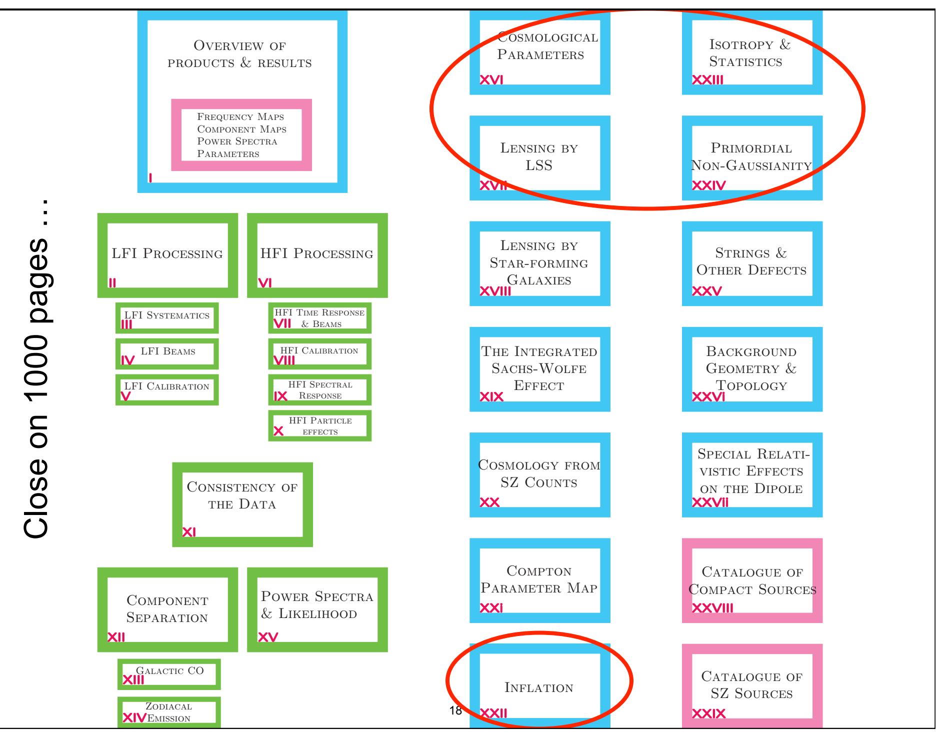


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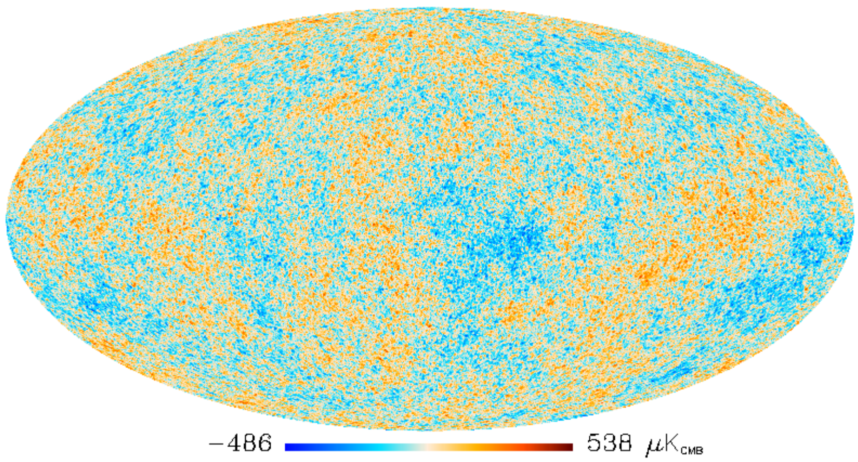
# Foreground cleaned CMB map

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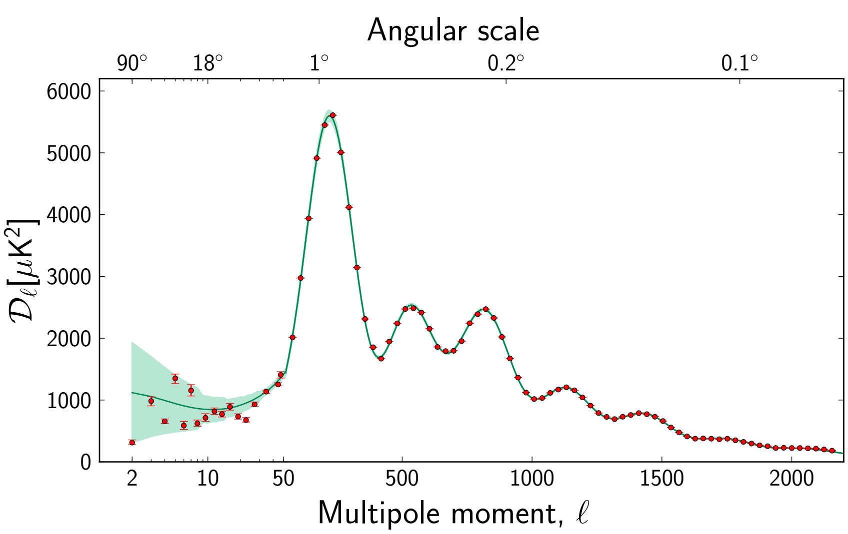
# The angular power spectrum

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# Parameter constraints: standard model

| Parameter | *Planck* Best fit | *Planck* 68% limits | *Planck*+lensing Best fit | *Planck*+lensing 68% limits | *Planck*+WP Best fit | *Planck*+WP 68% limits |
|---|---|---|---|---|---|---|
| $\Omega_b h^2$ | 0.022068 | $0.02207 \pm 0.00033$ | 0.022242 | $0.02217 \pm 0.00033$ | 0.022032 | $0.02205 \pm 0.00028$ |
| $\Omega_c h^2$ | 0.12029 | $0.1196 \pm 0.0031$ | 0.11805 | $0.1186 \pm 0.0031$ | 0.12038 | $0.1199 \pm 0.0027$ |
| $100\theta_{MC}$ | 1.04122 | $1.04132 \pm 0.00068$ | 1.04150 | $1.04141 \pm 0.00067$ | 1.04119 | $1.04131 \pm 0.00063$ |
| $\tau$ | 0.0925 | $0.097 \pm 0.038$ | 0.0949 | $0.089 \pm 0.032$ | 0.0925 | $0.089^{+0.012}_{-0.014}$ |
| $n_s$ | 0.9624 | $0.9616 \pm 0.0094$ | 0.9675 | $0.9635 \pm 0.0094$ | 0.9619 | $0.9603 \pm 0.0073$ |
| $\ln(10^{10} A_s)$ | 3.098 | $3.103 \pm 0.072$ | 3.098 | $3.085 \pm 0.057$ | 3.0980 | $3.089^{+0.024}_{-0.027}$ |
| $\Omega_\Lambda$ | 0.6825 | $0.686 \pm 0.020$ | 0.6964 | $0.693 \pm 0.019$ | 0.6817 | $0.685^{+0.018}_{-0.016}$ |
| $\Omega_m$ | 0.3175 | $0.314 \pm 0.020$ | 0.3036 | $0.307 \pm 0.019$ | 0.3183 | $0.315^{+0.016}_{-0.018}$ |
| $\sigma_8$ | 0.8344 | $0.834 \pm 0.027$ | 0.8285 | $0.823 \pm 0.018$ | 0.8347 | $0.829 \pm 0.012$ |
| $z_{re}$ | 11.35 | $11.4^{+4.0}_{-2.8}$ | 11.45 | $10.8^{+3.1}_{-2.5}$ | 11.37 | $11.1 \pm 1.1$ |
| $H_0$ | 67.11 | $67.4 \pm 1.4$ | 68.14 | $67.9 \pm 1.5$ | 67.04 | $67.3 \pm 1.2$ |
| $10^9 A_s$ | 2.215 | $2.23 \pm 0.16$ | 2.215 | $2.19^{+0.12}_{-0.14}$ | 2.215 | $2.196^{+0.051}_{-0.060}$ |
| $\Omega_m h^2$ | 0.14300 | $0.1423 \pm 0.0029$ | 0.14094 | $0.1414 \pm 0.0029$ | 0.14305 | $0.1426 \pm 0.0025$ |
| $\Omega_m h^3$ | 0.09597 | $0.09590 \pm 0.00059$ | 0.09603 | $0.09593 \pm 0.00058$ | 0.09591 | $0.09589 \pm 0.00057$ |
| $Y_P$ | 0.247710 | $0.24771 \pm 0.00014$ | 0.247785 | $0.24775 \pm 0.00014$ | 0.247695 | $0.24770 \pm 0.00012$ |
| Age/Gyr | 13.819 | $13.813 \pm 0.058$ | 13.784 | $13.796 \pm 0.058$ | 13.8242 | $13.817 \pm 0.048$ |
| $z_*$ | 1090.43 | $1090.37 \pm 0.65$ | 1090.01 | $1090.16 \pm 0.65$ | 1090.48 | $1090.43 \pm 0.54$ |
| $r_*$ | 144.58 | $144.75 \pm 0.66$ | 145.02 | $144.96 \pm 0.66$ | 144.58 | $144.71 \pm 0.60$ |
| $100\theta_*$ | 1.04139 | $1.04148 \pm 0.00066$ | 1.04164 | $1.04156 \pm 0.00066$ | 1.04136 | $1.04147 \pm 0.00062$ |
| $z_{drag}$ | 1059.32 | $1059.29 \pm 0.65$ | 1059.59 | $1059.43 \pm 0.64$ | 1059.25 | $1059.25 \pm 0.58$ |
| $r_{drag}$ | 147.34 | $147.53 \pm 0.64$ | 147.74 | $147.70 \pm 0.63$ | 147.36 | $147.49 \pm 0.59$ |
| $k_D$ | 0.14026 | $0.14007 \pm 0.00064$ | 0.13998 | $0.13996 \pm 0.00062$ | 0.14022 | $0.14009 \pm 0.00063$ |
| $100\theta_D$ | 0.161332 | $0.16137 \pm 0.00037$ | 0.161196 | $0.16129 \pm 0.00036$ | 0.161375 | $0.16140 \pm 0.00034$ |
| $z_{eq}$ | 3402 | $3386 \pm 69$ | 3352 | $3362 \pm 69$ | 3403 | $3391 \pm 60$ |
| $100\theta_{eq}$ | 0.8128 | $0.816 \pm 0.013$ | 0.8224 | $0.821 \pm 0.013$ | 0.8125 | $0.815 \pm 0.011$ |
| $r_{drag}/D_V(0.57)$ | 0.07130 | $0.0716 \pm 0.0011$ | 0.07207 | $0.0719 \pm 0.0011$ | 0.07126 | $0.07147 \pm 0.00091$ |

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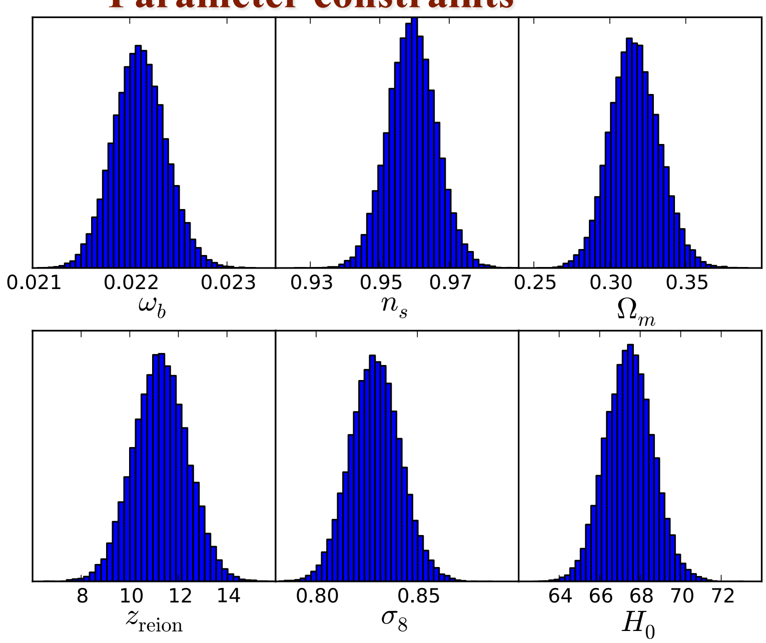
# Parameter constraints

The Planck data provide tight constraints on the six parameters describing the ΛCDM model, and thus on derived parameters.

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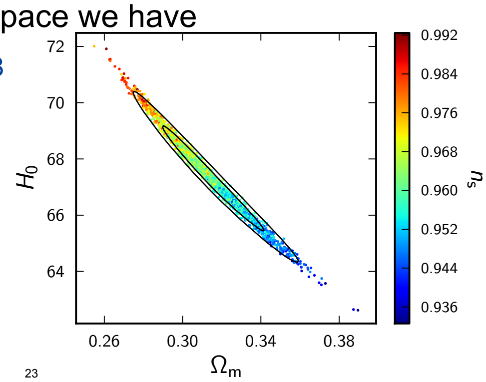
# The acoustic scale

- The angular size of the acoustic scale is now determined to better than 0.1%
  - $\theta$=1.19355 ± 0.00078 degrees (68% CL).
- In $\Lambda$CDM models this defines a 0.3% constraint
  - $\Omega_m h^{3.2} (\Omega_b h^2)^{-0.55} = 0.7218 \pm 0.0025$ (68%CL)
- Projecting onto a 2D subspace we have
  - $\Omega_m h^3 = 0.09595 \pm 0.00058$
  - High $\Omega_m$ = low $H_0$

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# Reason … and implications

- The acoustic scale is a ratio: $r_s/d_{LS}$

$$r_s = \int_0^{t_{LS}} c_s(1+z)\,dt = \int_{z_{LS}}^{\infty} \frac{c_s\,dz}{H(z)} \qquad d_{LS} = \int_0^{z_{LS}} \frac{dz}{H(z)}$$

- For $r_s$, dominated by high-z: $H(z) \sim \sqrt{(\rho_m+\rho_r)}$.
  - Increasing $\rho_m$ will decrease $r_s$. Decrease is softer than $\sqrt{\rho_m}$.
  - So $d_{LS}$ must also decrease, more softly than $\sqrt{\rho_m}$
- For $d_{LS}$, dominated by low-z: $H(z) \sim \sqrt{(\rho_m+\rho_{DE})}$.
- But $\rho_m+\rho_{DE} = \rho_{crit} \sim H_0^2$: so need to lower $H_0$.
- Note that since $\rho_{crit}$ has gone down *and* $\Omega_{DE}$ has gone down, $\rho_{DE}$ has gone down ~20%.

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## So why raise $\Omega_m$?

- Actually, it's kind of complicated …
  - … but the basic physical picture can be sketched out.
- Planck sees more power at high-*l*, and smoother peaks, than the "old" best-fit model predicts.
- Raising $\rho_m$ will lower the first few peaks (c.f. those at higher-*l*) and increase the amount of gravitational lensing.
- Increasing the overall normalization at the same time (and some other things) gives us more power at high-*l*, smoother peaks but overshoots the low-*l* data a bit.
  - WMAP got more of its constraint from lower *l*, so preferred a slightly higher $H_0$ (though it was moving to lower $H_0$ with time).
  - SPT+ACT didn't have the dynamic range to see these effects alone and inter-calibration with WMAP was "noisy".

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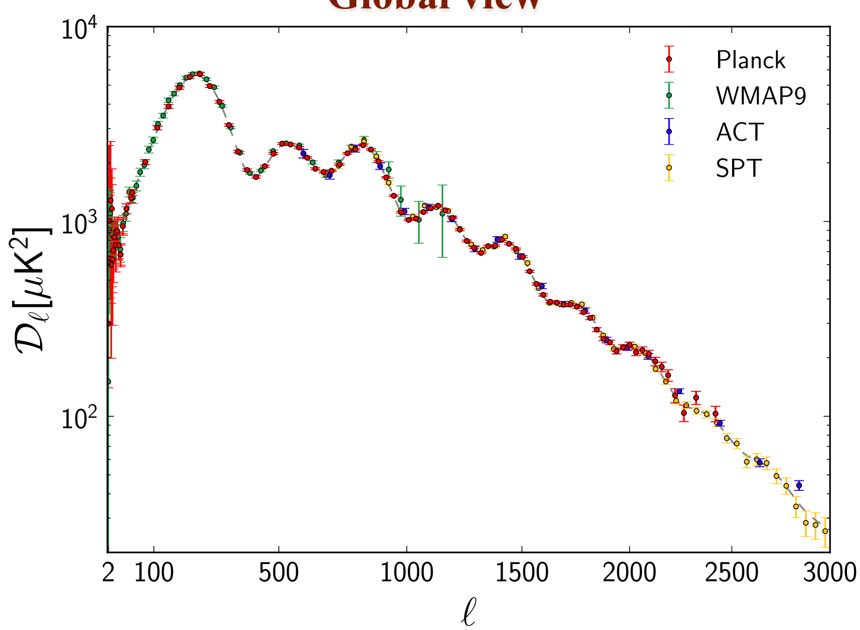
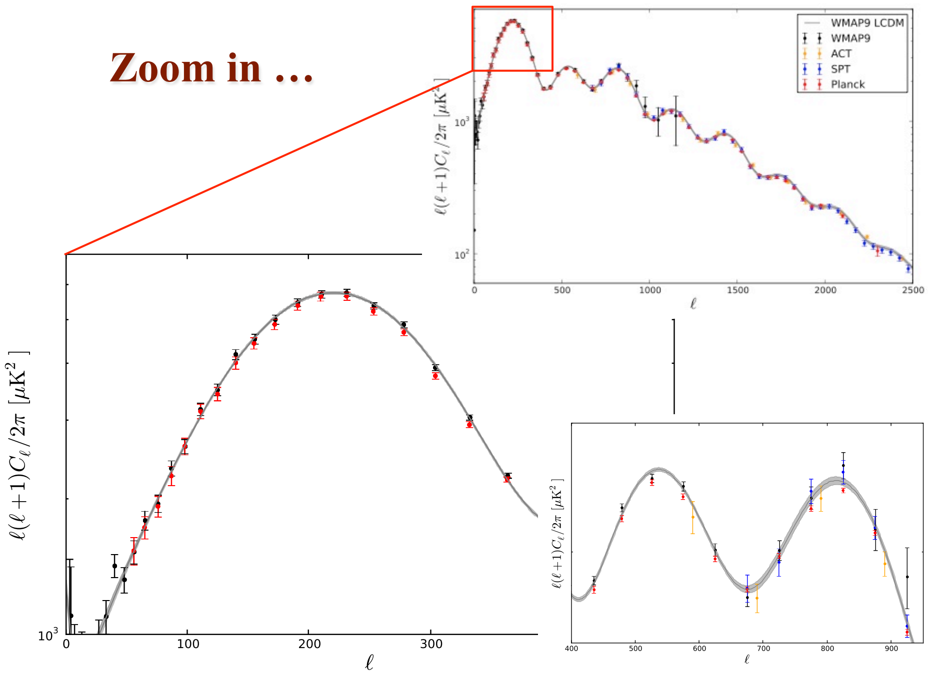
## Global view



## Zoom in …

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## Baryon loading and the potential envelope

- Baryons weight the photon-baryon fluid making it easier to fall into a potential well and harder to "bounce" out.
  - Baryon loading enhances the compressions and weakens the rarefactions, leading to an alternating height of the peaks.
- At earlier times the photon-baryon fluid contributes more to the total density of the universe. The effects of bγ self-gravity enhance the fluctuations on small scales.
  - Since the fluid has pressure, it is hard to compress and infall into potentials is slower than free-fall.
  - Because the (over-)density cannot grow fast enough, the potential is forced to decay by the expansion of the universe.
  - The photons are then left in a compressed state with no need to fight against the potential as they leave -- enhancing small-scale power. Since the decay is timed to the oscillation, this is like a resonant driving!

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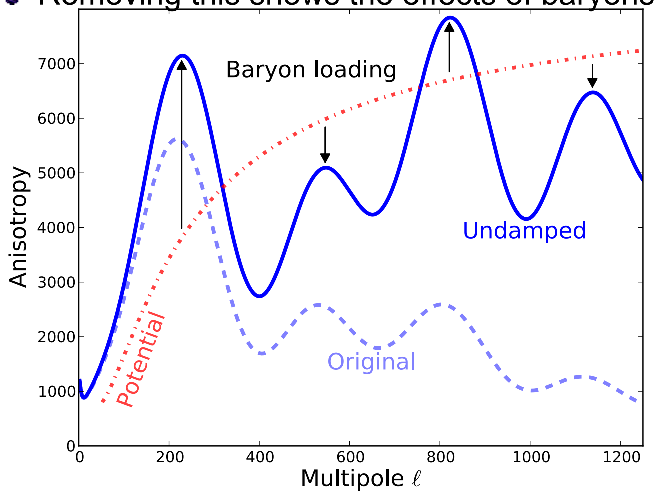
Hu & White (1996,1997)

## The matter density and the higher peaks

- The CMB anisotropies are damped at small angular scales by photon diffusion. Well understood!
- Removing this shows the effects of baryons/potential decay.




Peak modulation by baryon loading.

Boost by potential decay (Θ+Ψ+RΨ).

DM stabilizes the potentials: more DM = less boost.

## 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.
- The deflections are coherent over degrees.
- First considered in 1987, first measured in 2004.
- Lensing:
  - Blurs acoustic peaks (more lensing = smoother peaks).
  - Generates small-scale power.
  - Generates non-Gaussianity.
  - Mixes E- and B-mode polarization.
- ACT and SPT detect lensing at 4-6σ.
- Planck detects lensing at 25σ (see smearing effect at 10σ).
  - Integrated to LSS, but peak sensitivity z~2.
  - Structures of a few Mpc.

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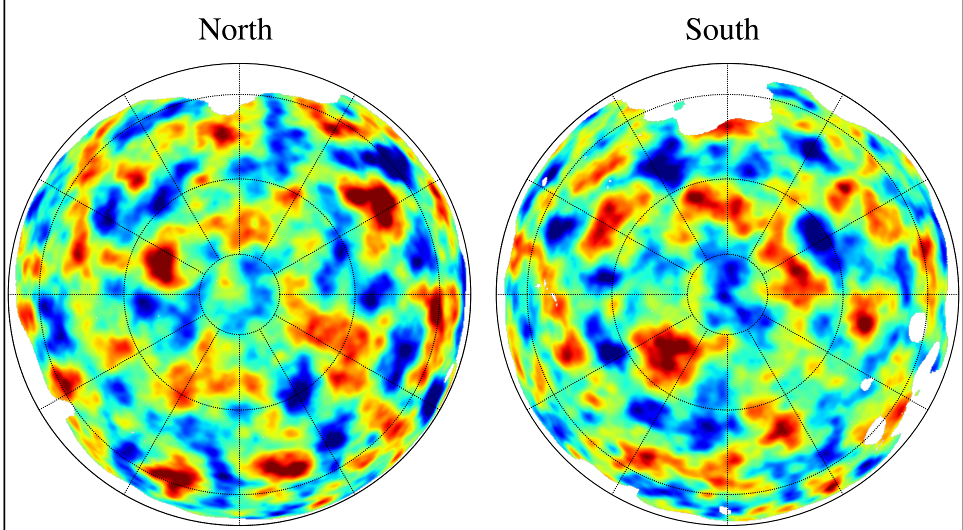
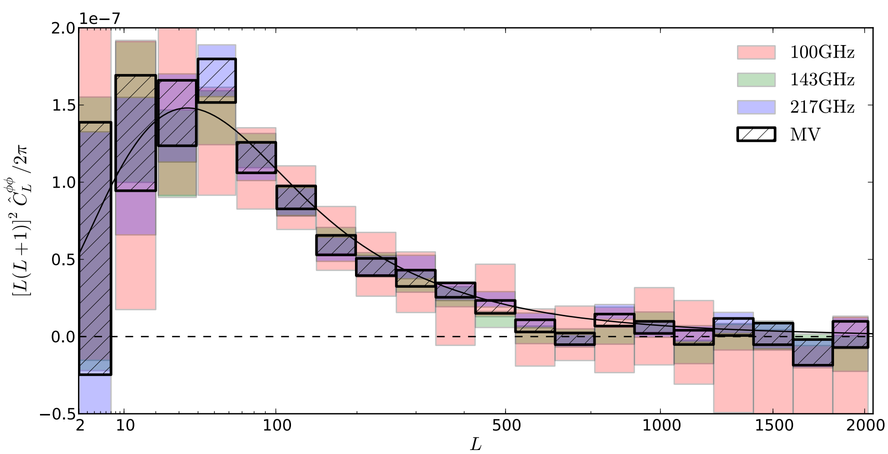
# Projected potential

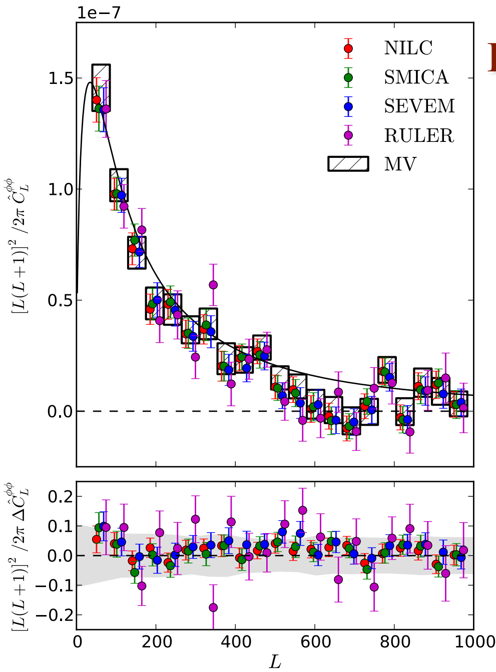





# Lensing potential power spectrum




Even the noisiest channel (100GHz) provides a 10σ detection of lensing, which is more significant than all previous detections!




## Robust to foregrounds

Gravitational lensing is a subtle effect, relying on both large- and small-scale measurements against a significant background.

Numerous cross-checks were done to asses robustness.

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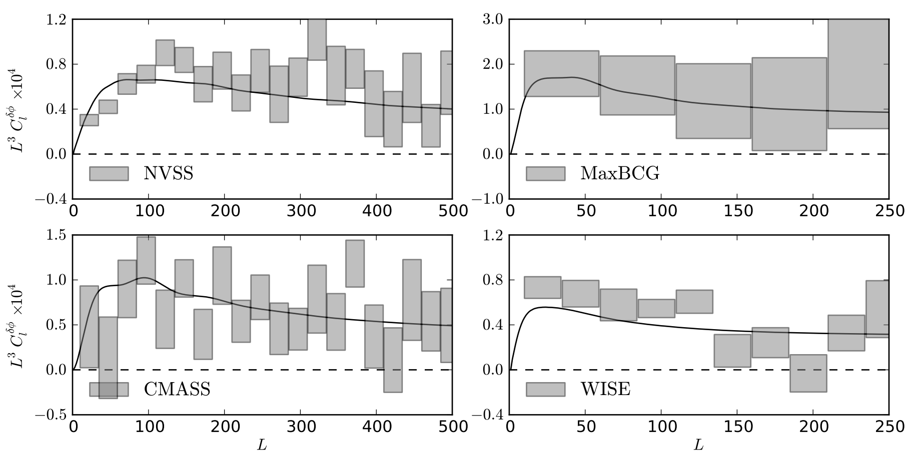
## Stronger in auto-correlation than cross-

- The Planck lensing map is such high S/N we now detect lensing more strongly within the Planck data than when cross-correlating with an external data set!



## Lensing and the amplitude

- As we are able to measure 7 acoustic peaks, we clearly see the impact of gravitational lensing.
  - Smearing of small-scale peaks.
  - Non-Gaussianity induced by photon deflections.
- This allows us to constrain the amplitude of the fluctuations even w/o polarization.
  - A valuable cross-check (galactic foregrounds).
  - Provides internal consistency check on $H_0$.
  - Allows us to constrain spatial curvature from CMB alone.

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## Departures from scale-invariance.

- With Planck we detect clear departures from a scale-invariant spectrum of potential fluctuations.
  - As predicted by inflation.
- Earlier experiments gave ~3$\sigma$ preference for $n_s$<1.
- With Planck this becomes 6$\sigma$.
  - Preference for $n_s$<1 now robust to expansion of model space.
  - Slightly sensitive to foreground model and parameter space, but conclusion robust.
  - Measurement of 4$^{th}$, 5$^{th}$ and 6$^{th}$ peaks breaks r-$n_s$ degen.
  - Adding polarization helps because $\tau$ modulates large- to small-scale power.

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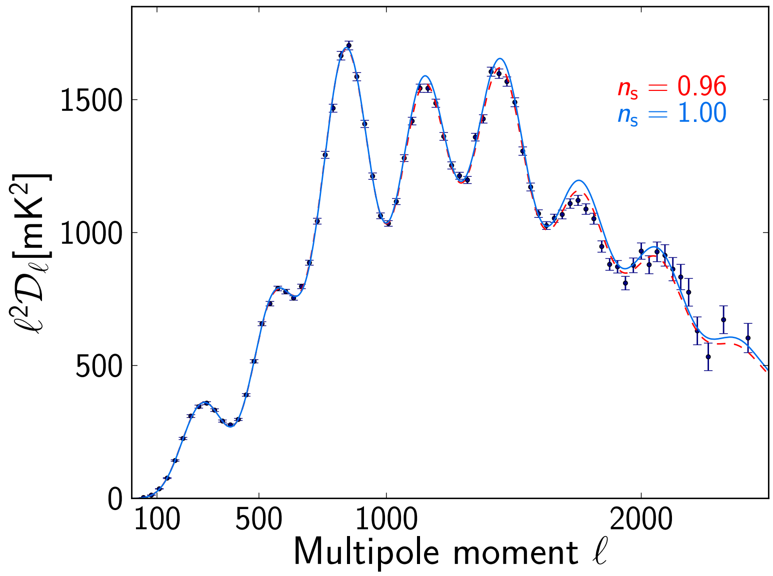
# Not scale invariant!

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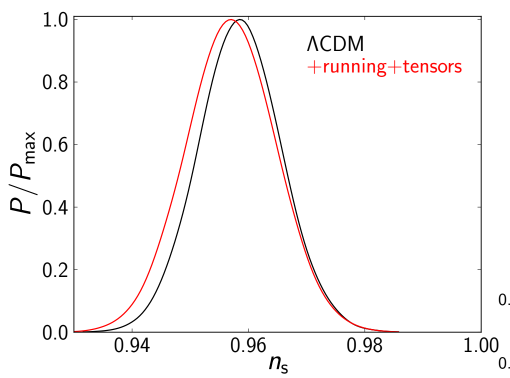
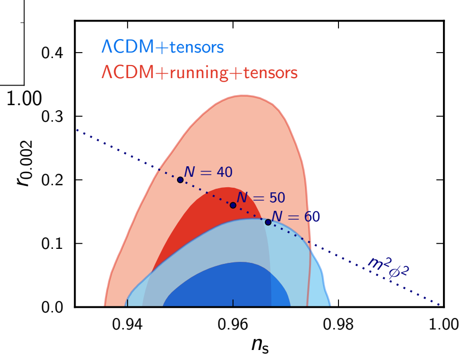
# Scale non-invariance

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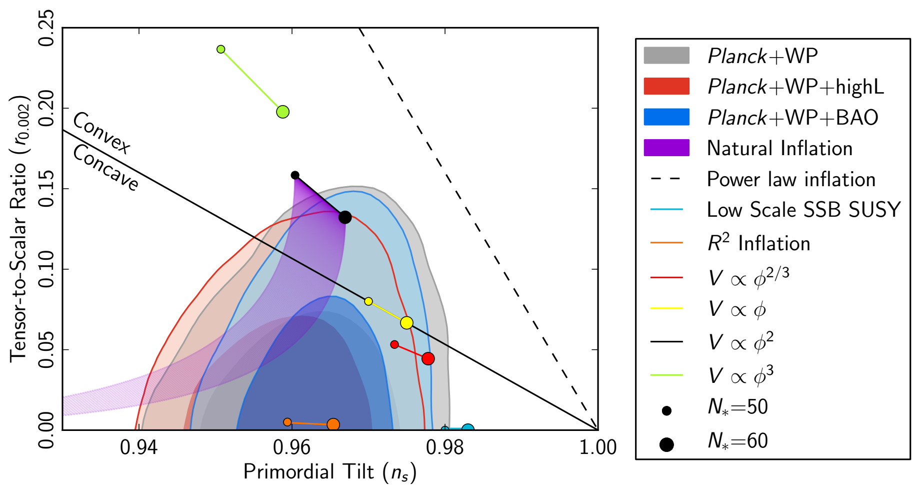
## A broader class of "simple" models

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## Inflation

- Planck prefers the simplest inflationary models.
  - Favors potentials with V''<0.
  - Rules out monomials of degree larger than 2 and $\phi^2$ is now at 95%CL boundary.
  - These models are (in some sense) the hardest to understand theoretically, because they are so minimal!
- No detectable:
  - Tensor modes.
  - Running (of the spectral index).
  - Isocurvature modes.
  - Non-Gaussianity.

Interesting models with modified couplings to gravity …

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## Isocurvature and Tensor modes

- Planck saturates the upper limit for tensor modes from temperature anisotropies!
  - Degeneracies broken by higher order acoustic peaks.
  - $r_{0.002}$<0.11 (95% CL, Planck TT + WP + BAO)
  - $E_{inf}$ < 1.9 x $10^{16}$ GeV, $H_{inf}$<7.3 x $10^{-6}$ $m_{Pl}$
- Planck detects no isocurvature modes.
  - Correlated/curvaton bound <0.0026 (95%CL).
  - Uncorrelated/axion bound <0.048 (95%CL).

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## Non-Gaussianity

| Type | Limit | Generated by… |
|---|---|---|
| Local | 2.7±5.8 | Curvaton, reheating, multifield, … |
| Equilateral | -42±75 | Non-canonical kinetic term or higher derivative (e.g. K-flation, DBI, ghost inflation, with $c_s$<<1). |
| Orthogonal | -25±39 | Non-canonical kinetic term or higher derivative ($c_s$<<1). |

(Other, specific shapes/cases are discussed in papers)

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## This suggests inflation has …

- A single, weakly coupled, neutral scalar field driving the expansion and generating curvature perturbations,
- with a standard kinetic term, that is
- slowly rolling down a featureless potential ...
- … and lies initially in the Bunch-Davies vacuum.
- Potentials with V''<0 are preferred.

Alternatives exist, but it is remarkable how well the simplest scenarios have withstood the test of time!

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## 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.
  - Large-scale structure (shape of power spectrum).
  - Baryon Acoustic Oscillations (distance scale).
  - Type Ia SNe (distance scale).
  - Direct measures of distance ladder (local distance scale).

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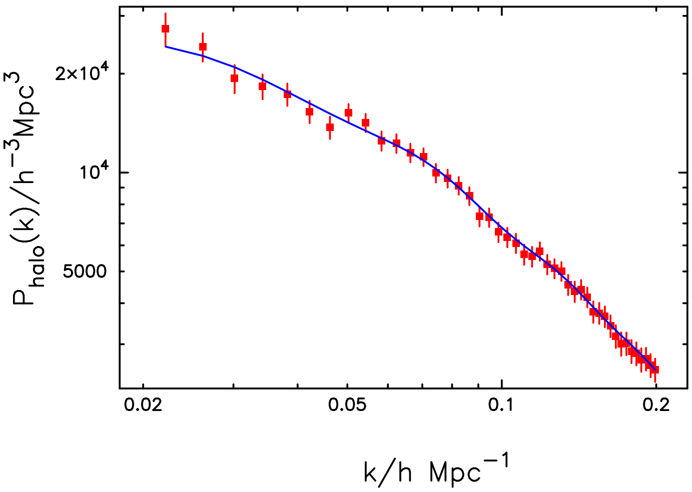
## Power spectrum shape comparison




The predicted power spectrum is in excellent agreement with that seen in the SDSS (Reid++).

The shape is well constrained by the CMB.

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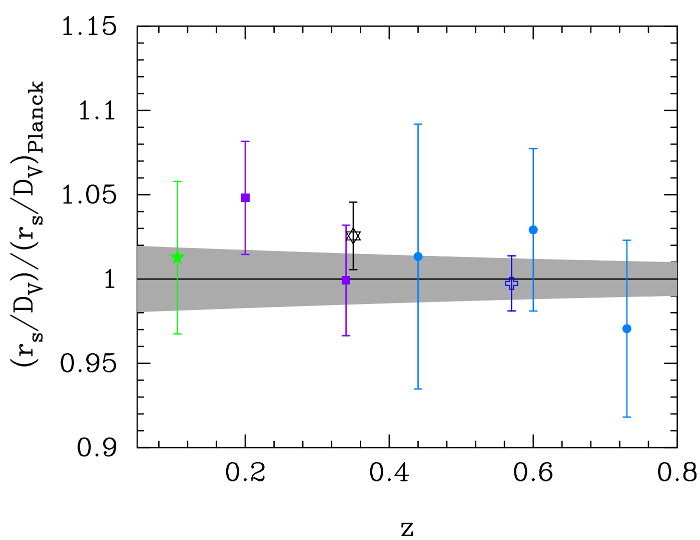
## Distance scale comparison: BAO




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

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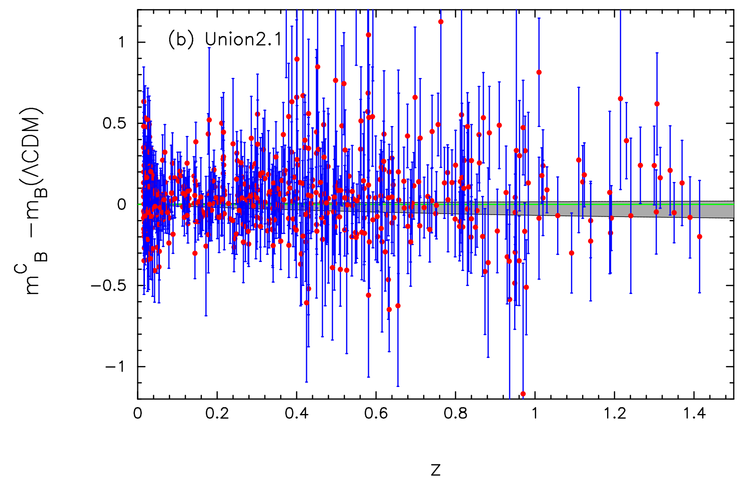
# Distance scale comparison: SNe

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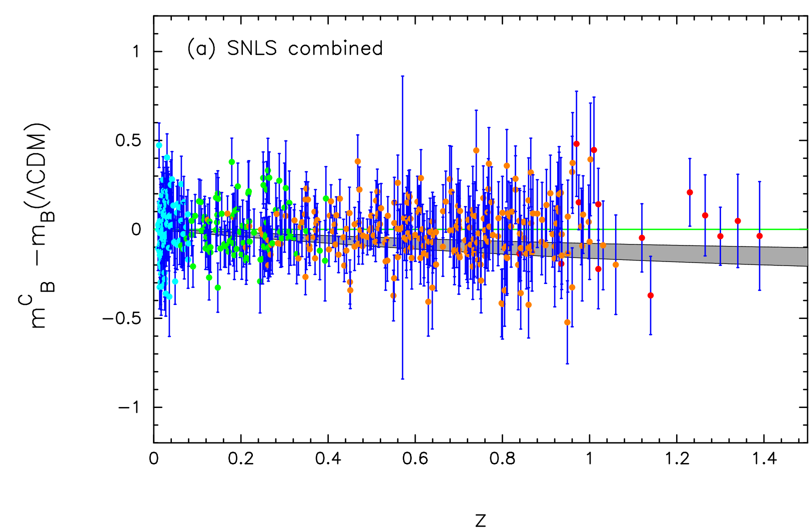
# Distance scale comparison: SNe

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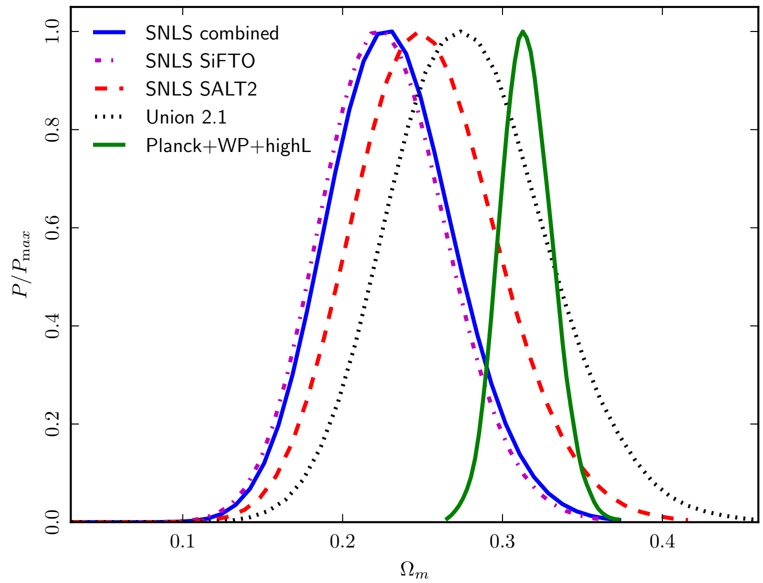
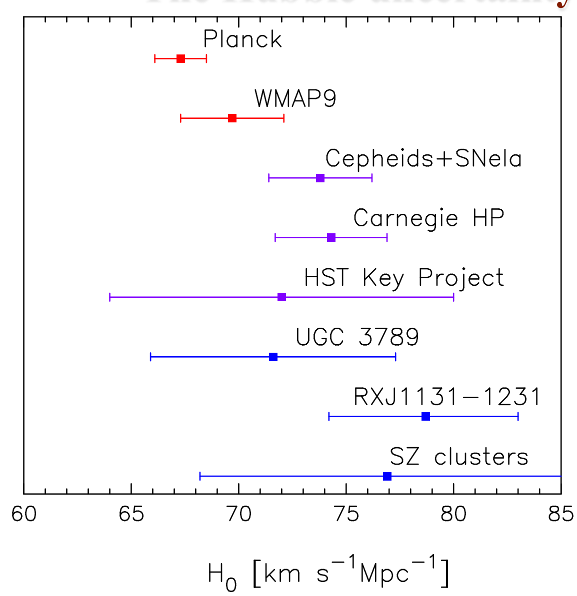
## Within ΛCDM: implications for $\Omega_m$ and $\Omega_\Lambda$




## The Hubble uncertainty principle




Within the ΛCDM model, the Planck data prefer a lower expansion rate (at late times) than that inferred from the traditional distance scale based on Type Ia SNe and local calibrators.

This is driven by Planck's preference for a higher $\Omega_m$.

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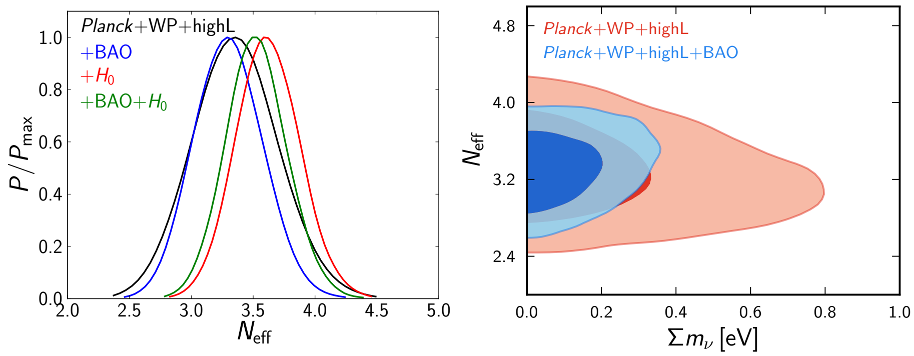
# Light degrees of freedom

We see no evidence for extra, relativistic degrees of freedom or massive neutrinos.
Our $m_\nu$ constraint is now driven largely by lensing!

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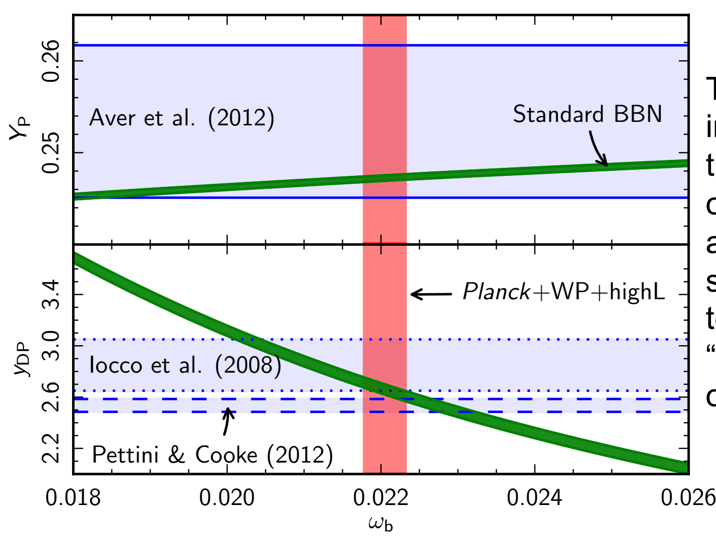
# Excellent agreement with BBN!




This test involves all of the known laws of physics: agreement is a stunning testament of "Universal" laws of nature!

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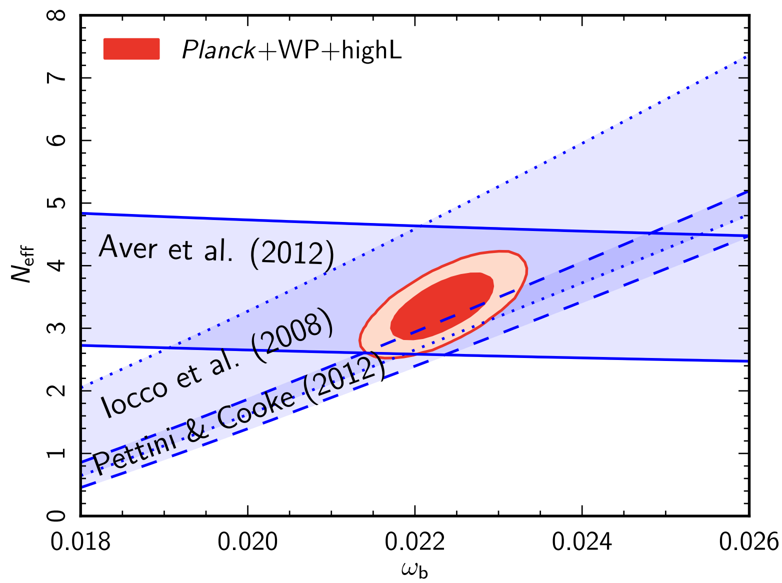
## Can open "theory" space up in various ways

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## Other data sets

- Cosmic shear.
  - The Planck results are in significant (3-4$\sigma$) tension with those derived from a tomographic 2D analysis of cosmic shear from the CFHTLenS experiment (154 deg$^2$, 5-band photometry).
  - Much better agreement with 3D lensing analysis.
- Abundance of clusters of galaxies
  - 3$\sigma$ tension with $\sigma_8\Omega_m^{0.3}$ constraints from Planck (and SPT) clusters, depending on mass calibration and correction for selection biases. [Some analyses of SZ and optical clusters are not in tension, others are in more tension.]

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## The CMB "prior"

- We now have very precise knowledge of the universe at z~1000.
- We have tightly constrained the physical densities of matter and baryons, the amplitude of the fluctuations in the linear phase over 3 decades in length scale and the shape of the primordial power spectrum.
- Our knowledge of physical conditions and large-scale structure at $z\sim10^3$ is better than our knowledge of such quantities at z~0!
- If dark energy is a recent phenomenon, then we can translate this knowledge reliably to intermediate redshifts which are currently at the observational frontier.
  - A calibrated, standard "fluctuation spectrum".
  - The key behind BAO and RSD measurements!

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## Planck science: more than "just" CMB

- Planck is the first sub-mm mission to map the entire sky at mJy sensitivity with angular resolution better than 10'.
- The science enabled by such a survey encompasses
  - Extragalactic sources
    - Radio sources, GPS, dusty galaxies, galaxy clusters.
  - QSO and Blazar astrophysics
  - Galactic and solar system science
    - Studies of the local ISM
      - Interstellar gas, dust, cold cores, late type stars, SNR.
    - The large-scale structure of the Milky Way
    - Planets, asteroids, comets, Zodiacal light.

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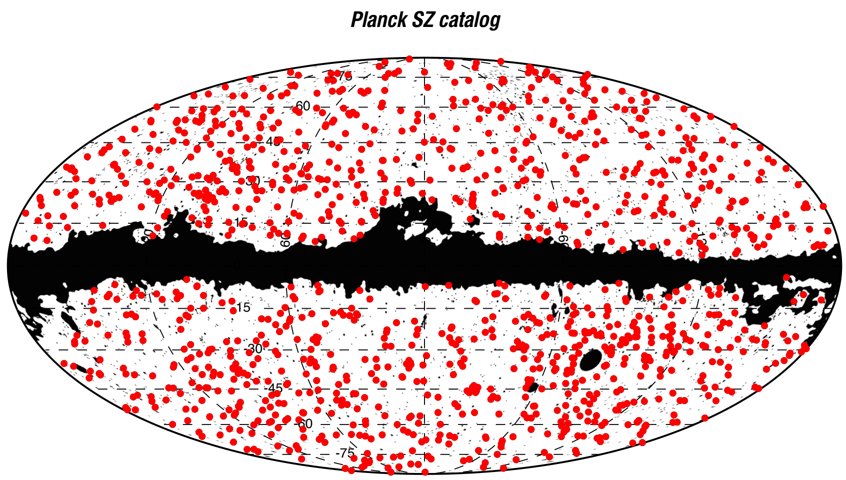
# Planck SZ catalog

- 1227 clusters and candidates across 83.7% of the sky
- 861 confirmed, 178 new.






# Eppur Si Muove

- In 1728, Bradley detected the Earth's motion using stellar aberration.
- In Planck our motion with respect to the Universal Rest Frame (CMB) has two effects.
  - Boosting and aberration.
  - To see either need full sky and high resolution!
- Boosting changes the power spectrum in forward direction c.f. backward direction.
- Aberration mixes multipole 1000 with 1001
- Expected effect is $10^{-3}$ of $10^{-5}$ = 10ppb
- We observe this at $>4\sigma$ !!
  - This also implies we are stable to <10ppb

# Conclusions

- The Planck mission has been stunningly successful.
- Impressive confirmation of the standard cosmological model.
  - Precise constraints on model and parameters.
    - 6$\sigma$ deviation from scale-invariance, <0.1% measurement of $\theta_s$.
    - Strong constraints on inflationary models.
  - Tight limits on deviations from base model.
  - Some indications of internal and external tensions, but with only modest statistical significance.
- More data to be analyzed and released!

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All right. But apart from the sanitation, the medicine, education, wine, public order, irrigation, roads, the fresh water system, and public health . . .

What have the Romans ever done for us?

Reg, spokesman for the People's Front of Judea

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# The End

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