Cosmic Sound: Near and Far

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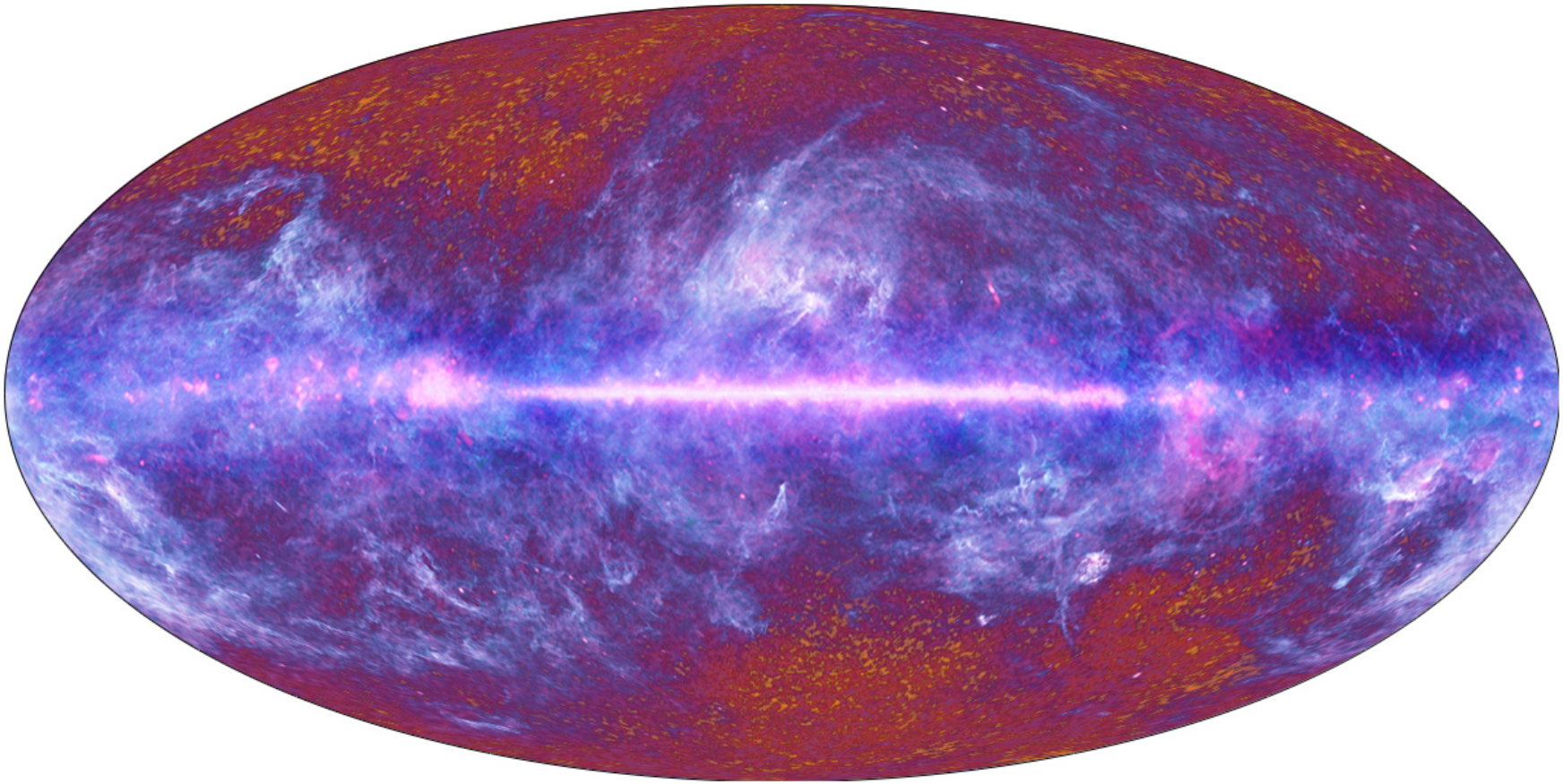
for the Planck and BOSS teams



Outline

- The standard cosmological model and the CMB.
- Planck: mission.
- Planck: cosmological parameters
- Planck: CMB lensing.
- Planck: constraints on inflation
- Planck: comparison with other datasets.
- BOSS: breaking degeneracies and measuring distances.
- Conclusions.

The cosmic microwave background

- The entire Universe is filled with radiation in the form of a 2.7K black-body.
  - n_γ = 411 cm^{-3}, ρ_γ = 4.64 10^{34} g/cm^3 = 0.260 eV/cm^3
- 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

- 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.

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

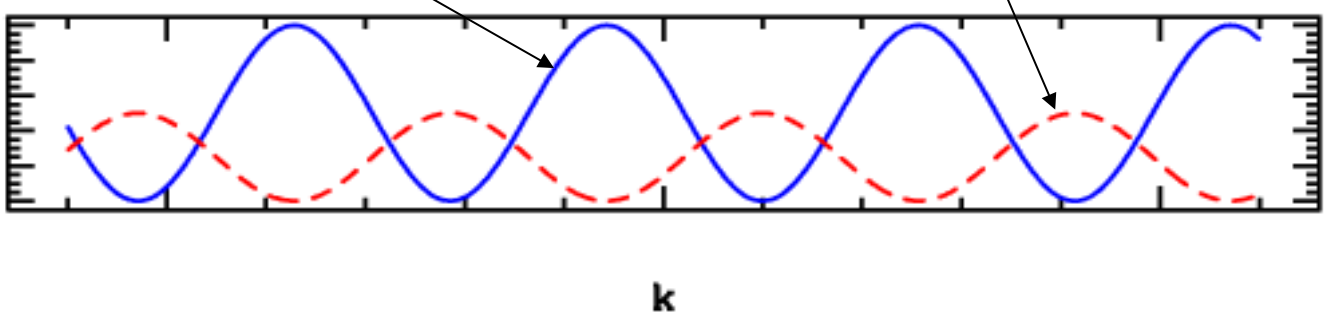
- These show up as temperature fluctuations in the CMB

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

The cartoon

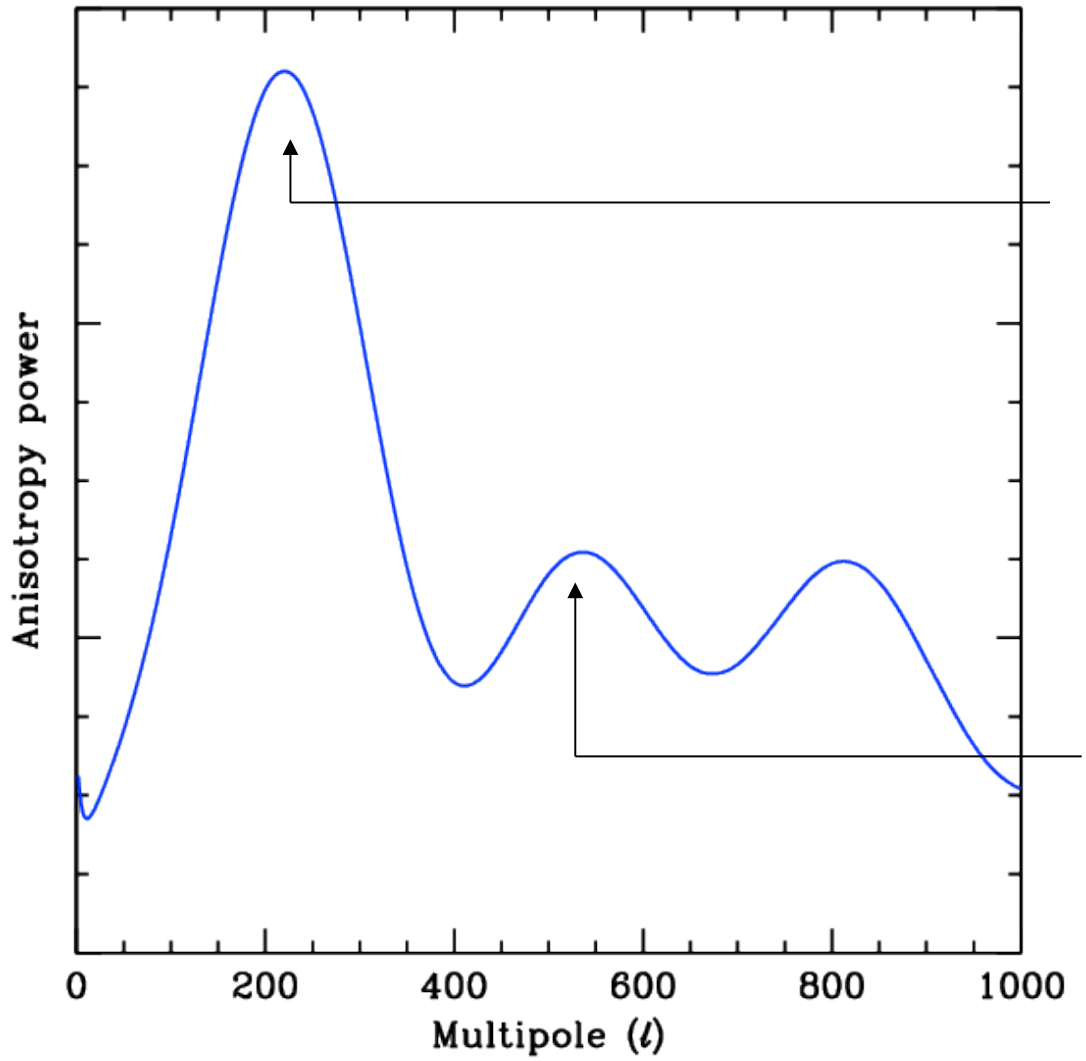
- A sudden "recombination" decouples the radiation and matter, giving us a snapshot of the fluid at "last scattering".

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



- 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!



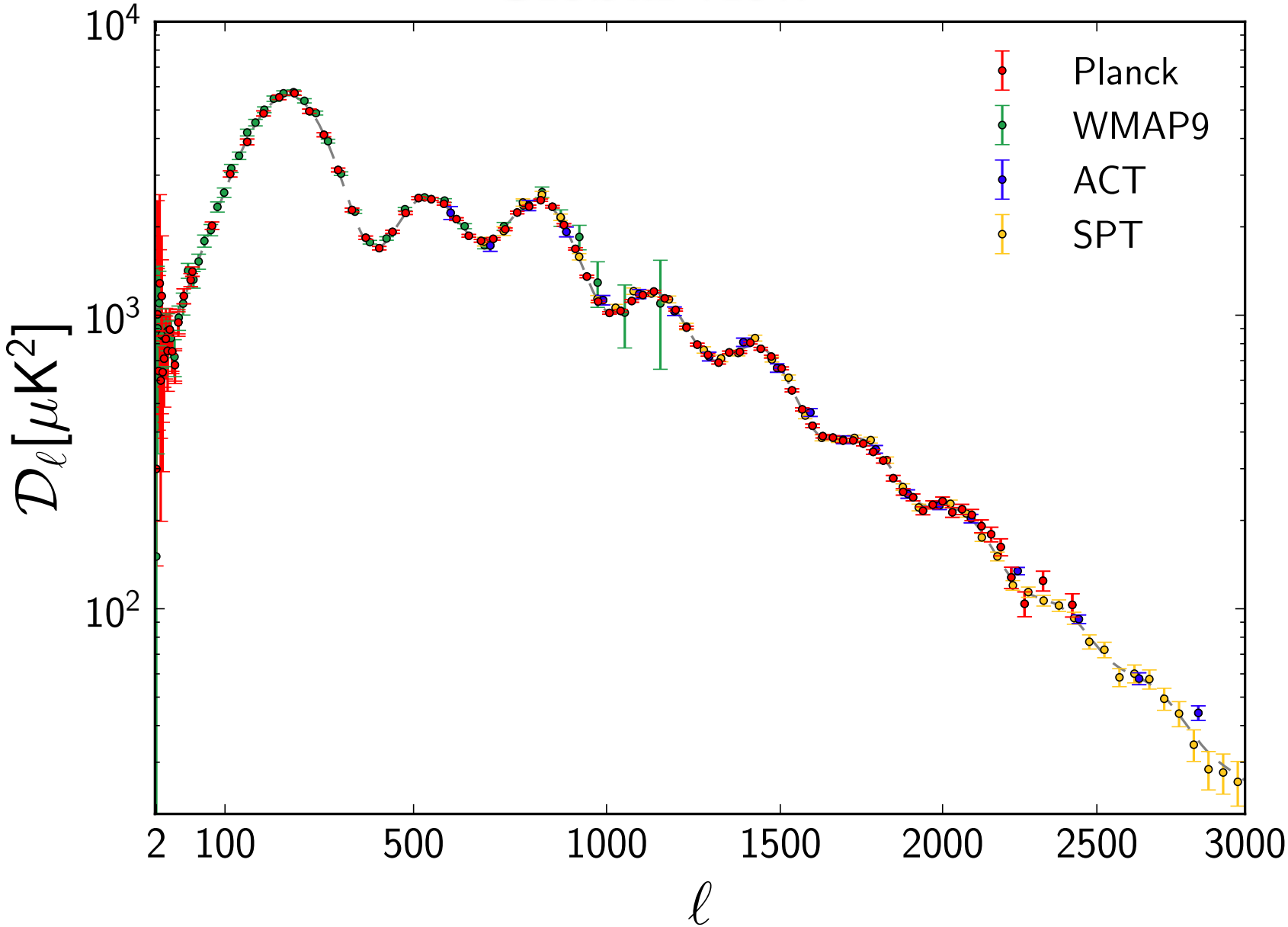
First "compression", at $kc_s t_{ls}=\pi$. Density maxm, velocity null.

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

→ Smaller scales

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

Global view


Planck
WMAP9
ACT
SPT
10^4
10^3
10^2
$\mathcal{D}_\ell [\mu K^2]$
2
100
500
1000
1500
2000
2500
3000
ℓ

CMB encodes valuable information

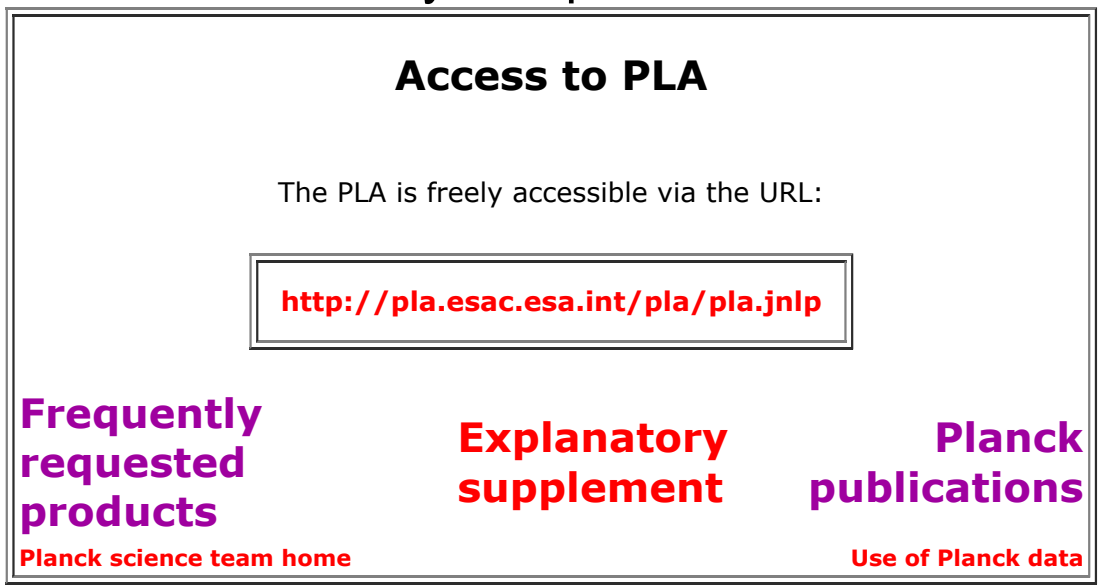
- The CMB spectrum depends upon the initial spectrum of perturbations (inflation?) and the conditions in the photon-baryon fluid prior to last scattering.
- The rich structure in the spectrum, and the dependence on many cosmological parameters, provides a gold-mine of information if signal can be accurately 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 $z \sim 10^3$.
- The most precise inferences come from comparing the observations to detailed theoretical predictions …

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.

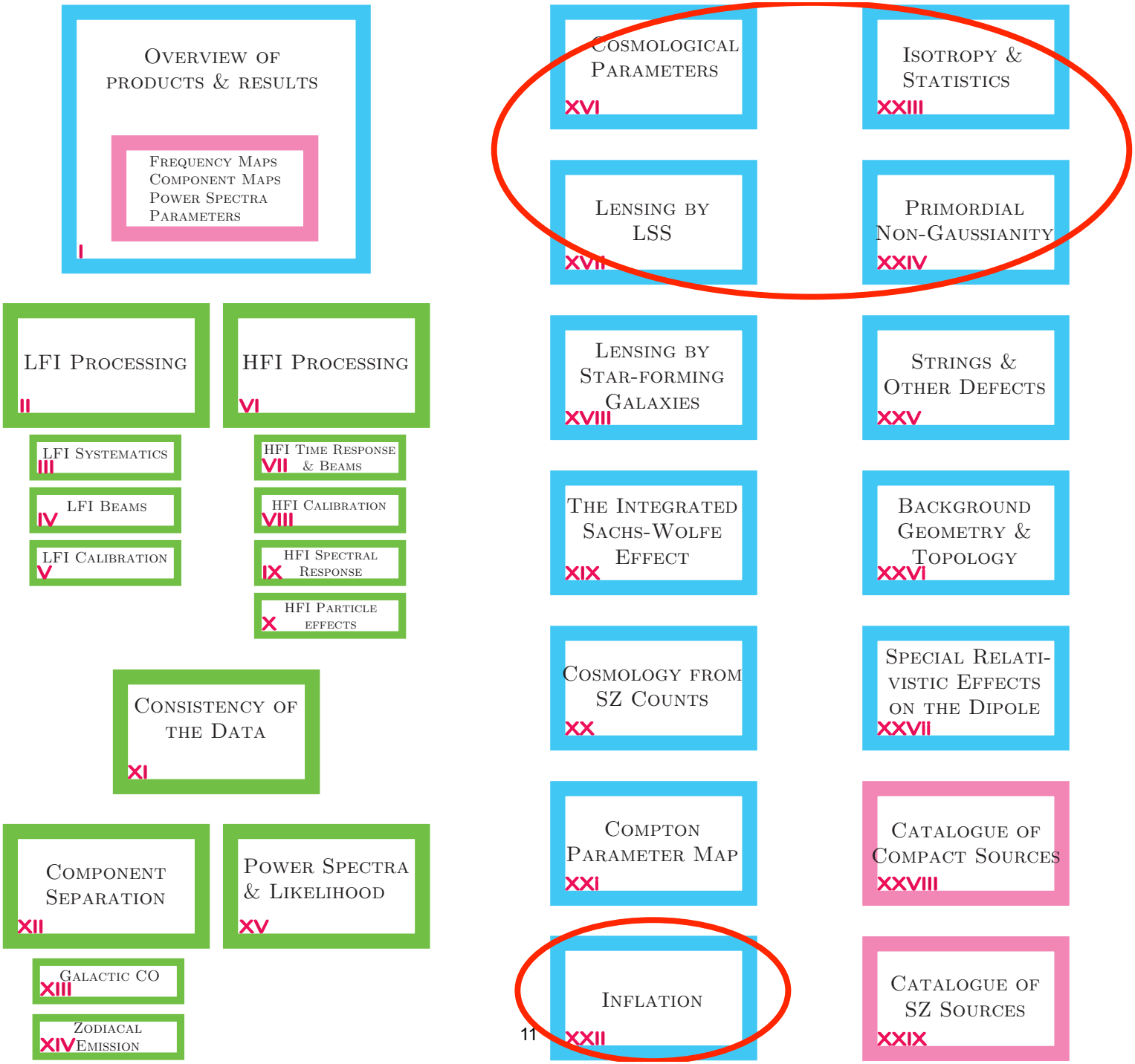
Current data release

- 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.



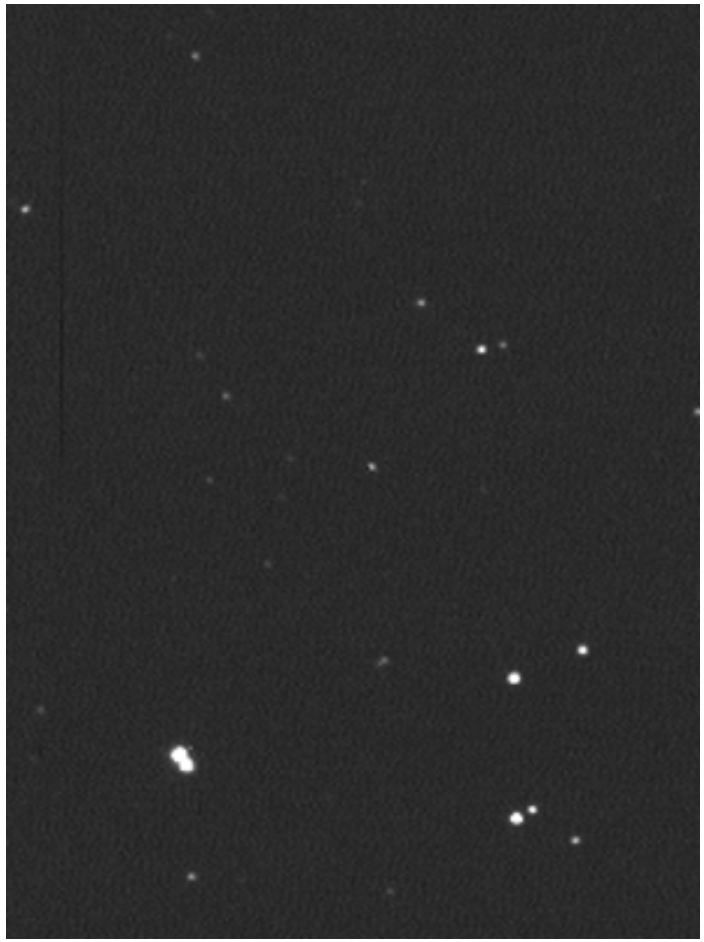
The PLA interface also inter-operates with the astronomical catalogues served by the Centre de Donnees de Strasbourg (CDS), via the interactive software Aladin. Data can be transferred seamlessly from the PLA to Aladin. Additional tabular data manipulation functionality is available via the Topcat tool. 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.

Close on 1,000 pages ...



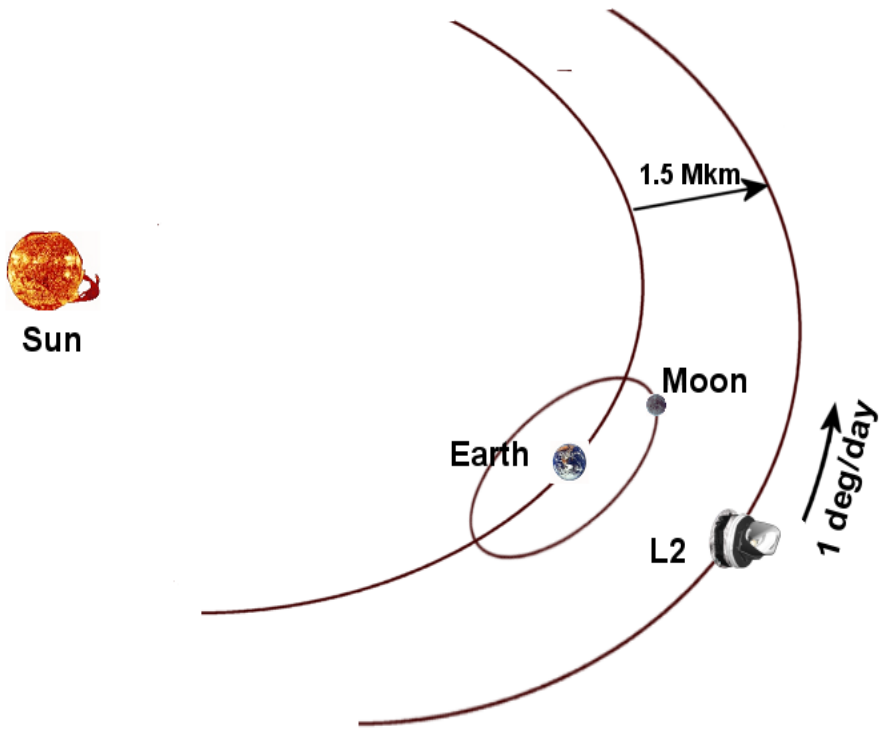
A picture-perfect launch!

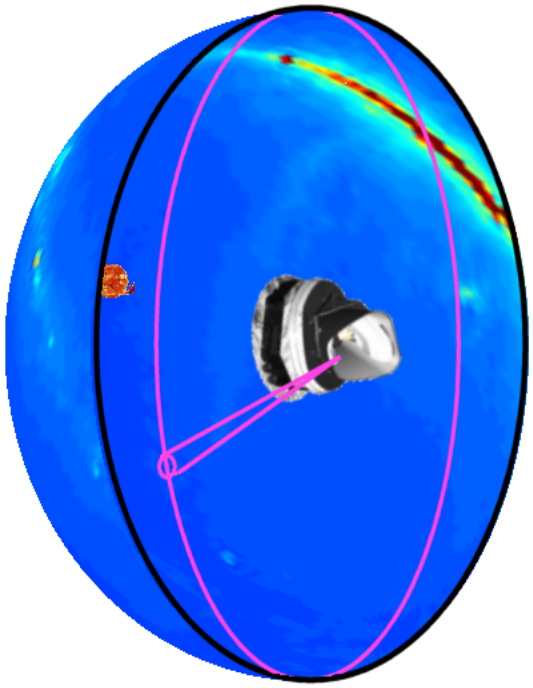
Ariane 5 lifts off with Herschel and Planck on board on 14 May 2009 at 15:12:02 CEST.

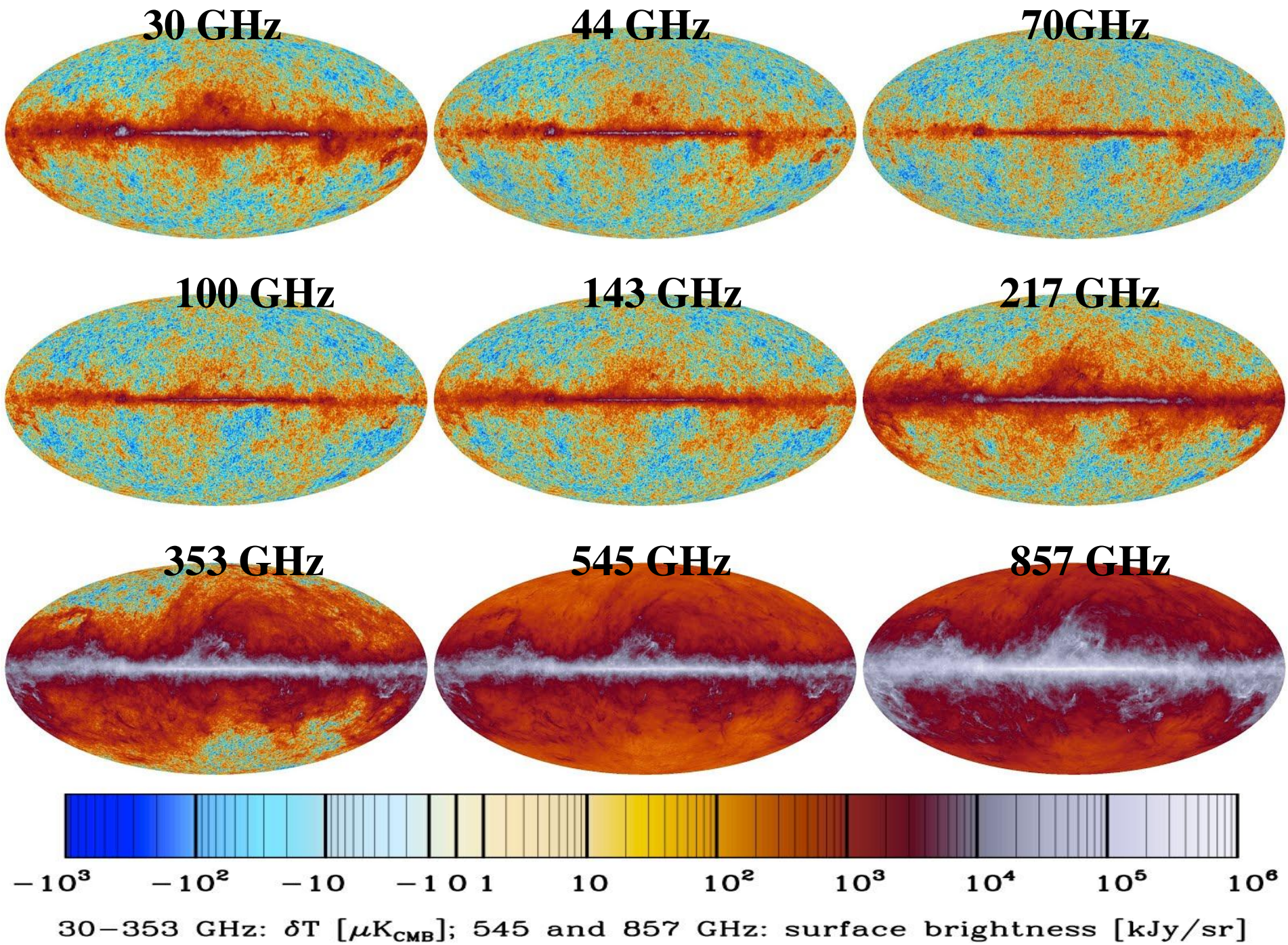


The orbit

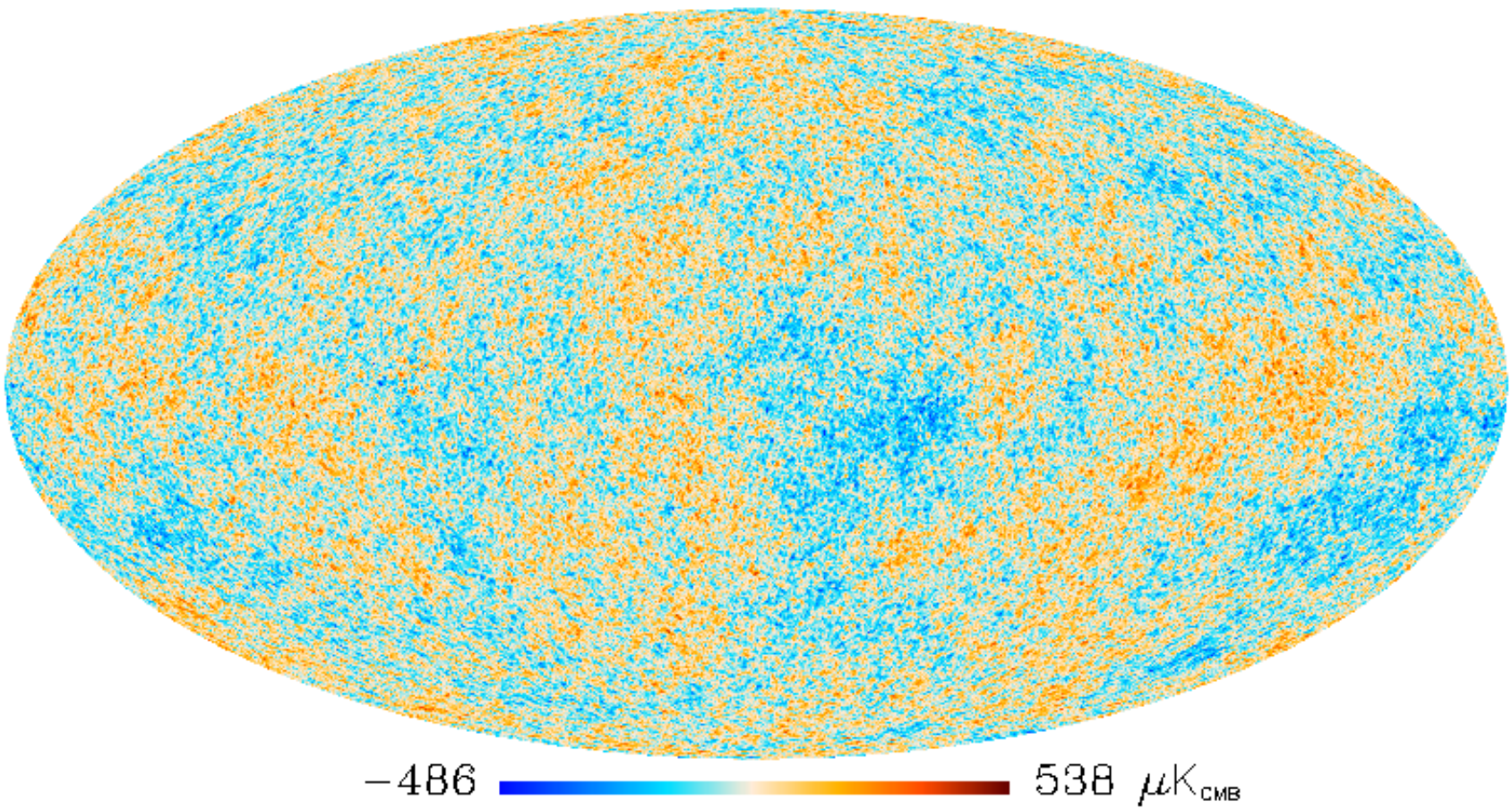
Planck makes a map of the full sky every ~6 months.



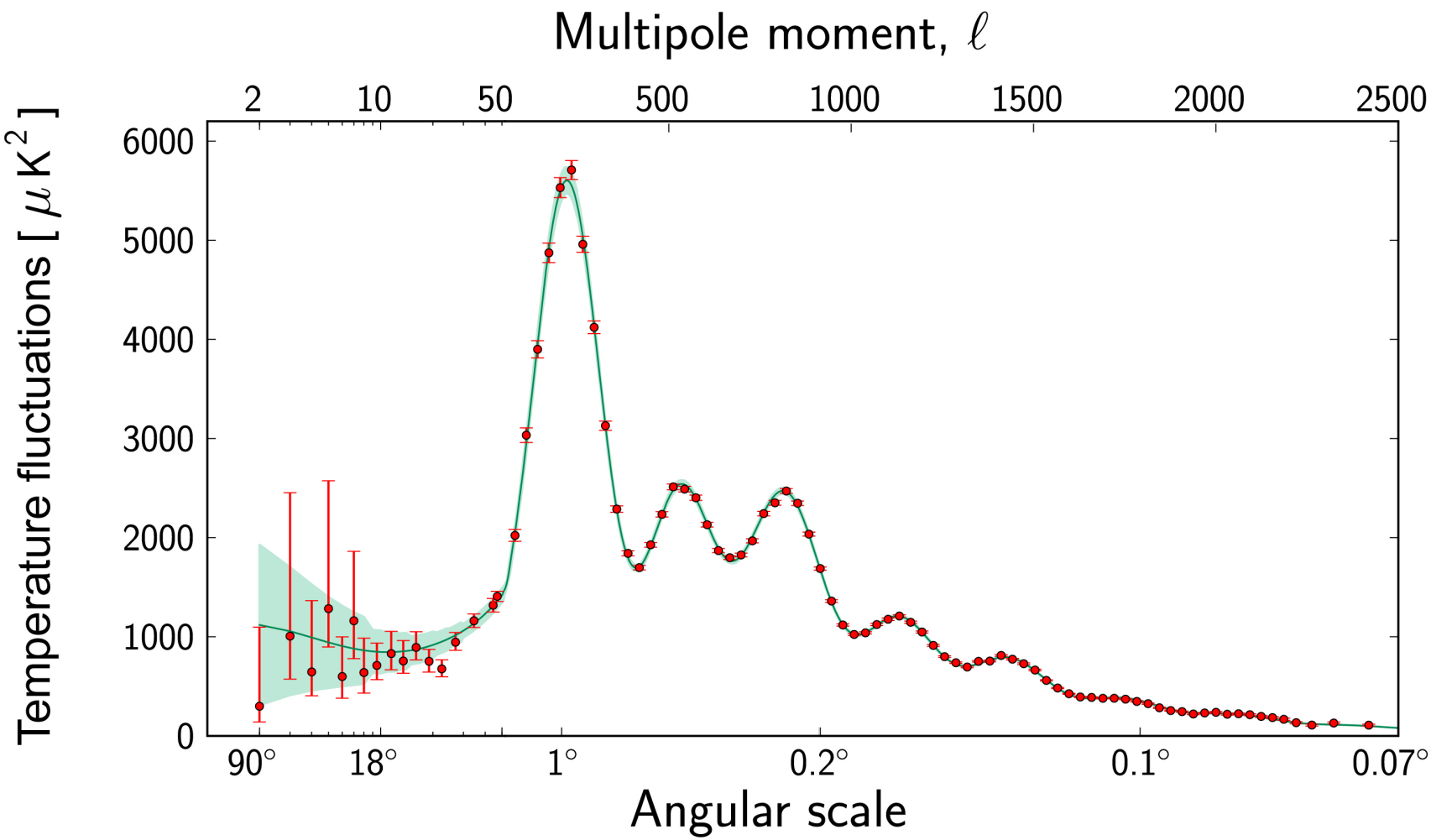



30 GHz
44 GHz
70GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

Foreground cleaned CMB map



The angular power spectrum

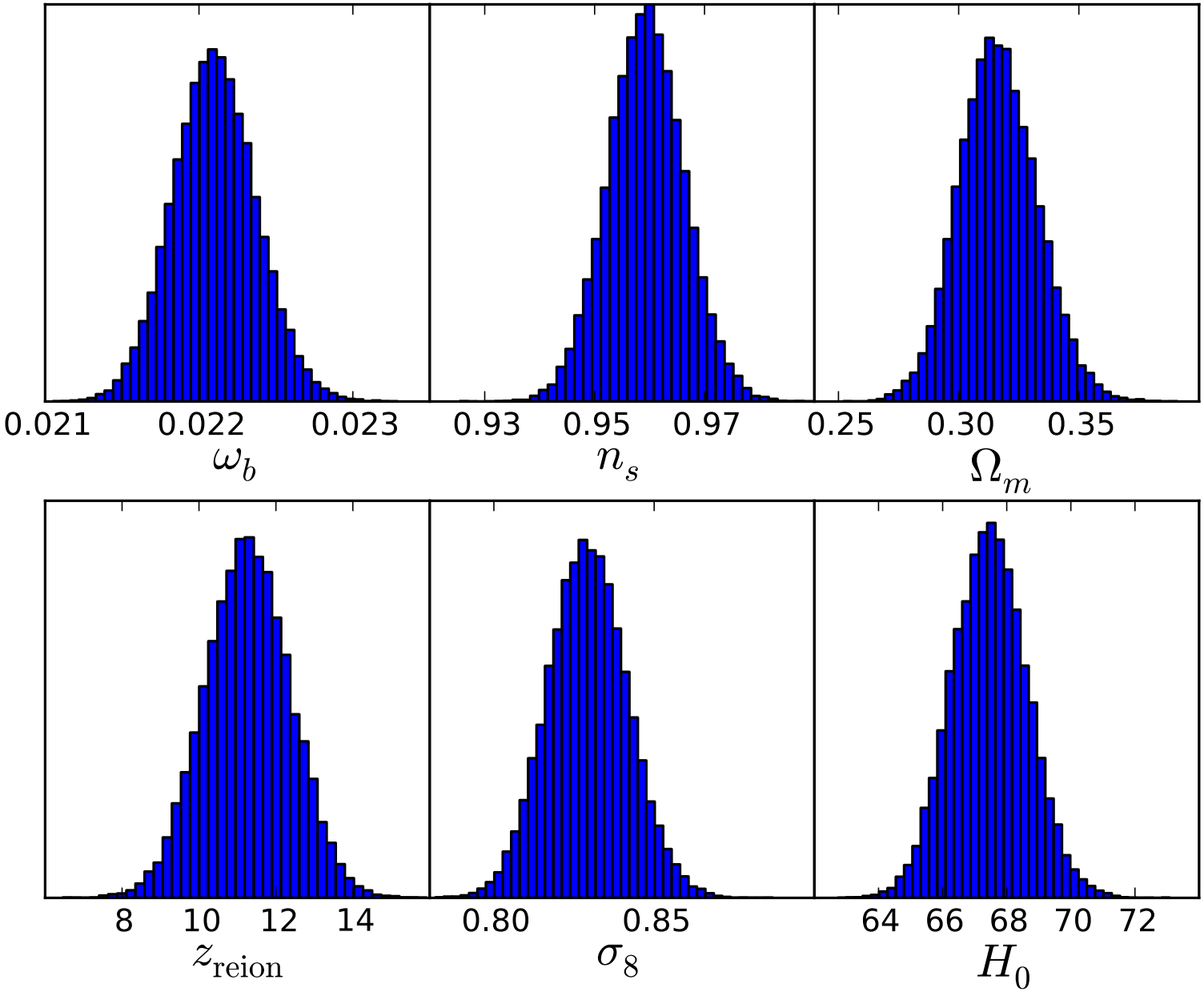


Parameter constraints: standard model

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 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10}A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 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 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

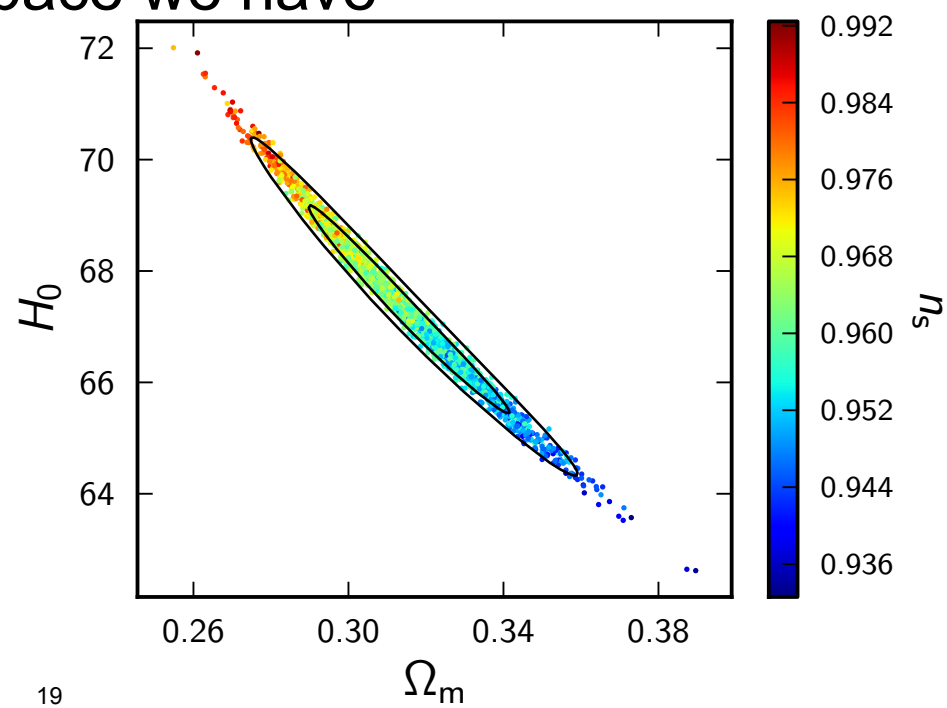
Parameter constraints

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



The acoustic scale

- The angular size of the acoustic scale is now determined to 0.07% (second best known number in cosmology!)
  - θ=1.19355 ± 0.00078 degrees (68% CL).
- In ΛCDM 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 Ω_m = low H_0



Reason … and implications
(for the experts)

- 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 ρ_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 $\rho_m+\rho_{DE} = H_0^2$: so need to lower H_0.

- Note that since ρ_{crit} has gone down *and* Ω_{DE} has gone down, ρ_{DE} has gone down ~20%.

So why raise Ω_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 ρ_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".

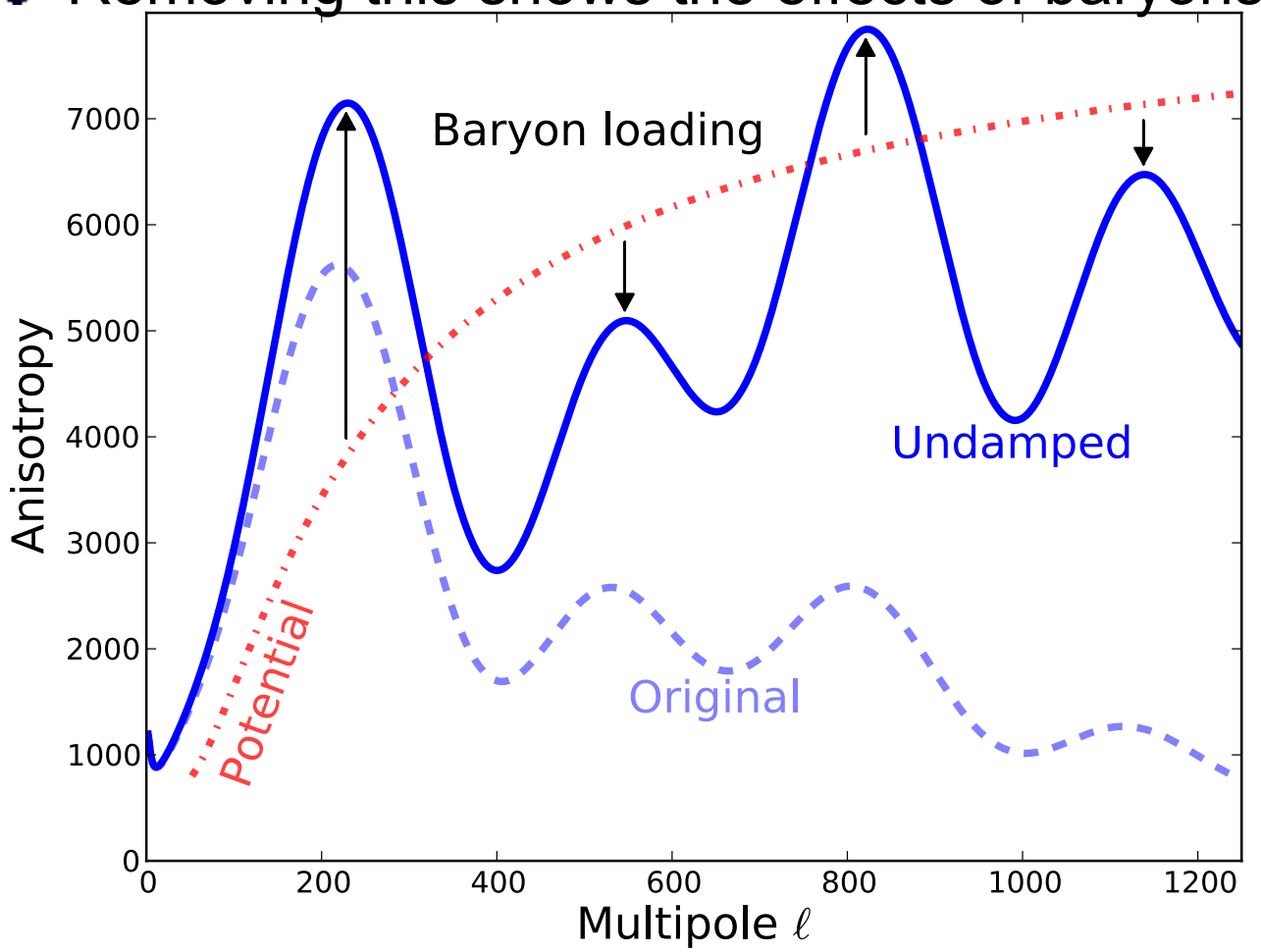
Baryon loading and the potential envelope

- 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 $b\gamma$ 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!

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 ($\Theta+\Psi+R\Psi$).

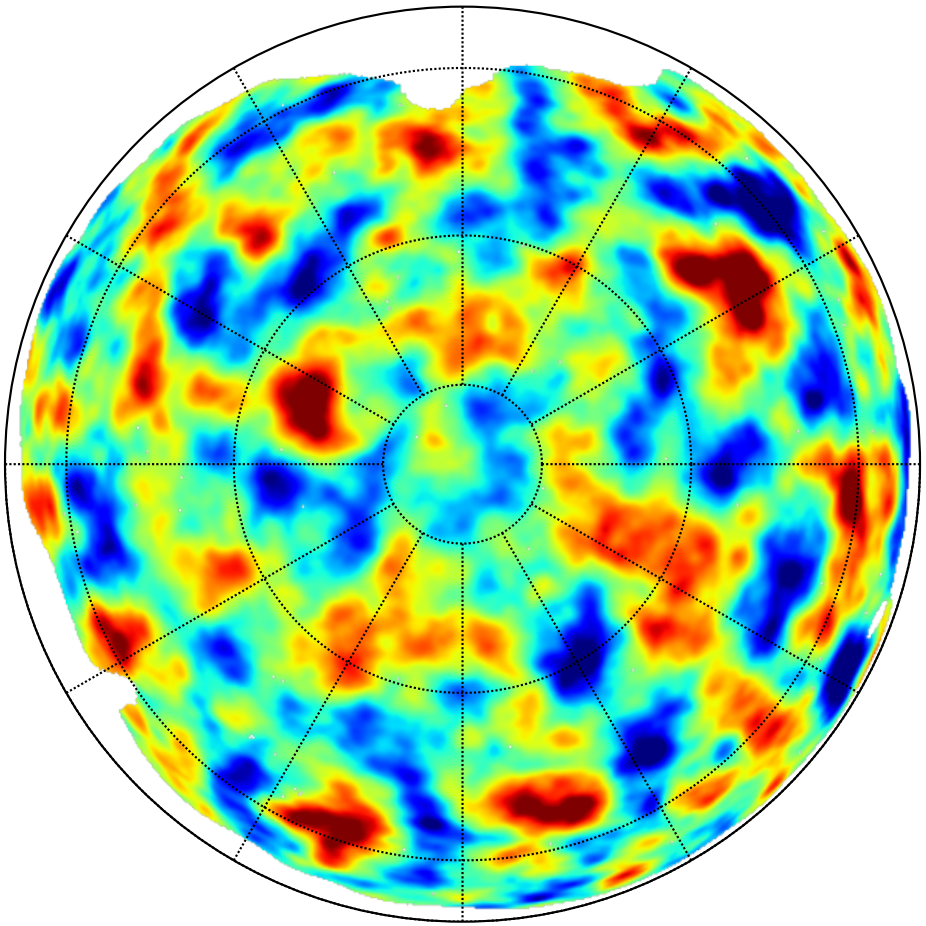
DM stabilizes the potentials: more DM = less boost.

CMB lensing

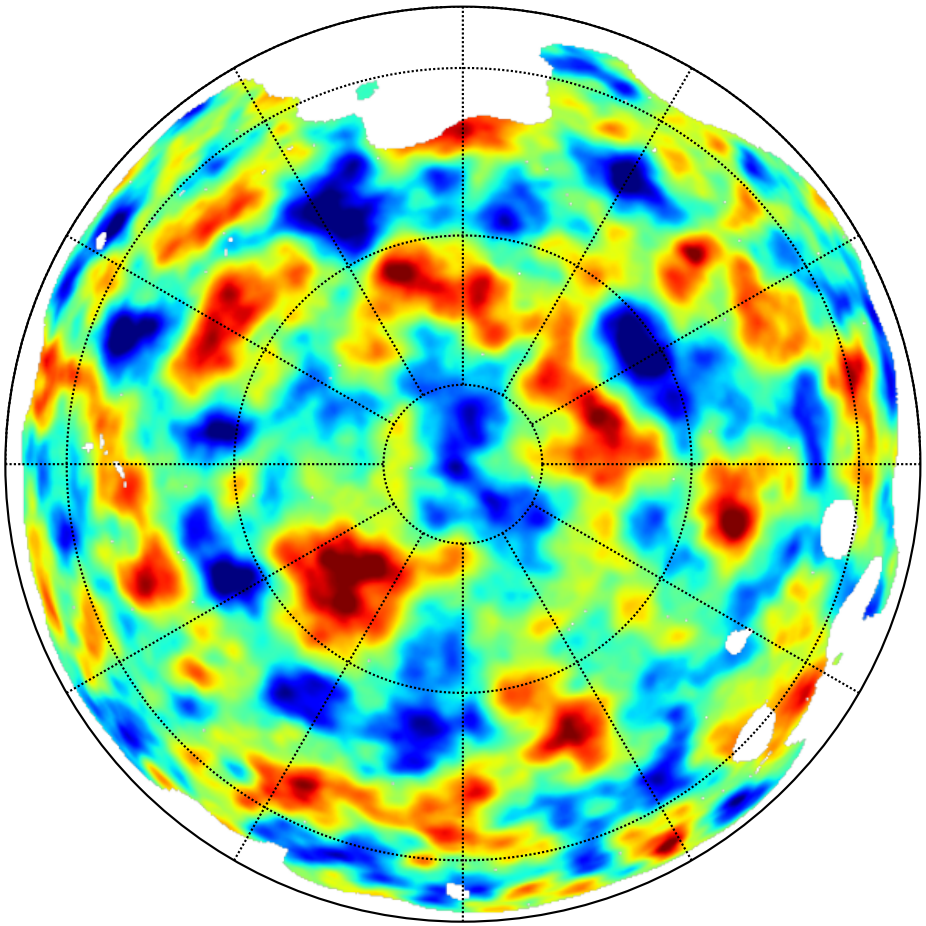
- Photons from the CMB are deflected on their way to us by the potentials due to large-scale structure.
- The typical deflection is 2-3 arcmin.
- The deflections are coherent over degrees.
- First considered in 1987, first measured in 2004.
- Lensing:
  - Blurs acoustic peaks (more lensing = smoother 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.

Projected potential

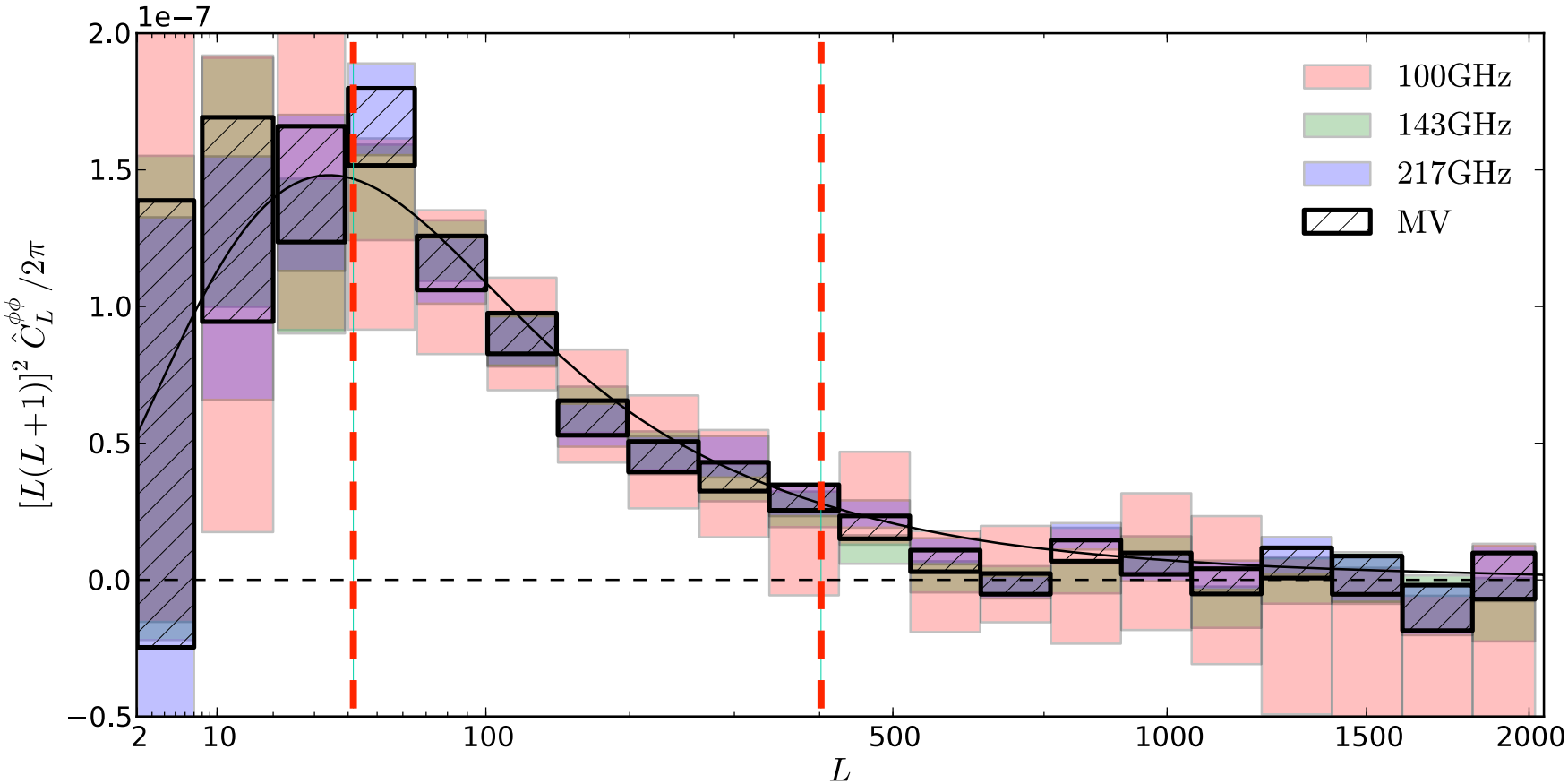
North



South



Lensing potential power spectrum



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

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.

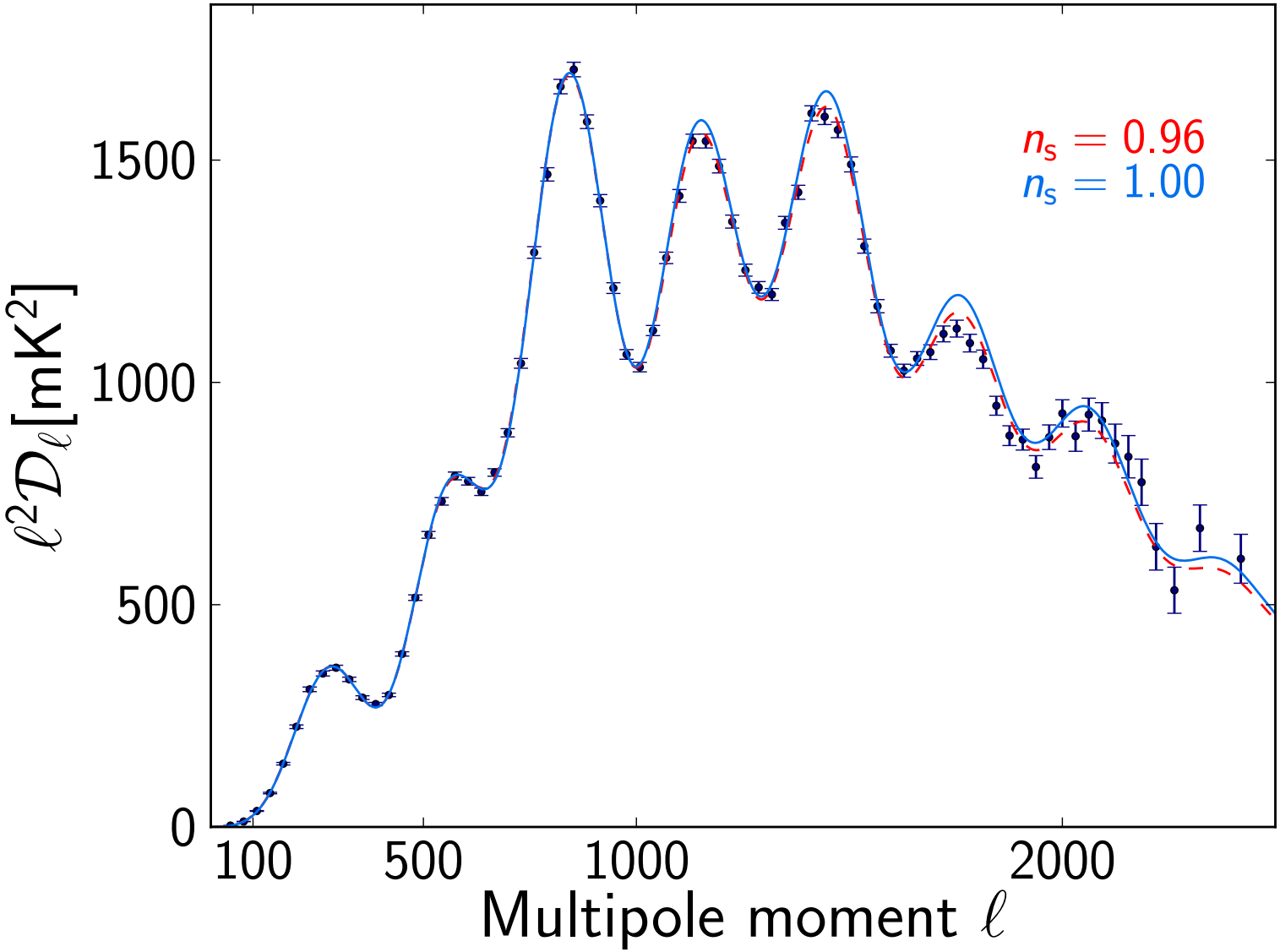
Inflation

- In the very early Universe we believe there was a period of quasi-exponential expansion which
  - Allowed the observed Universe today to be big, and smooth, and free of relics from phase transitions in the early Universe and …
  - Generated an *almost* scale-invariant spectrum of density perturbations in the early Universe by amplifying quantum fluctuations on very small scales.
  - … and possibly long-wavelength gravitational waves and isocurvature modes and non-Gaussianity and …
- Generally we suppose inflation was driven by the "inflaton", which is a scalar field with a very flat potential.
  - $H^2 = (d\ln a/dt)^2 \sim \rho \sim (d\phi/dt)^2 + V(\phi) \sim V(\phi) \sim$ const.
- The amplitude of the perturbations generated by inflation depends on the amplitude of $V(\phi)$ when $k \sim H$.
  - If ϕ rolls "down" the potential, expect smaller amplitude at higher k.

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 ~3σ preference for n_s<1.
- With Planck this becomes 6σ.
  - 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 4th, 5th and 6th peaks breaks r-n_s degen.
  - Adding polarization helps because τ modulates large- to small-scale power.

Not scale invariant!



Inflation

- Planck prefers the “simplest” inflationary models.
  - Favors potentials with V’’<0.
  - 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 … or from string theory …

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).

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!

* effective/emergent?

Higgs inflation!

- Could the "standard model Higgs" be the inflaton?
- Yes, if it is non-minimally coupled to gravity!

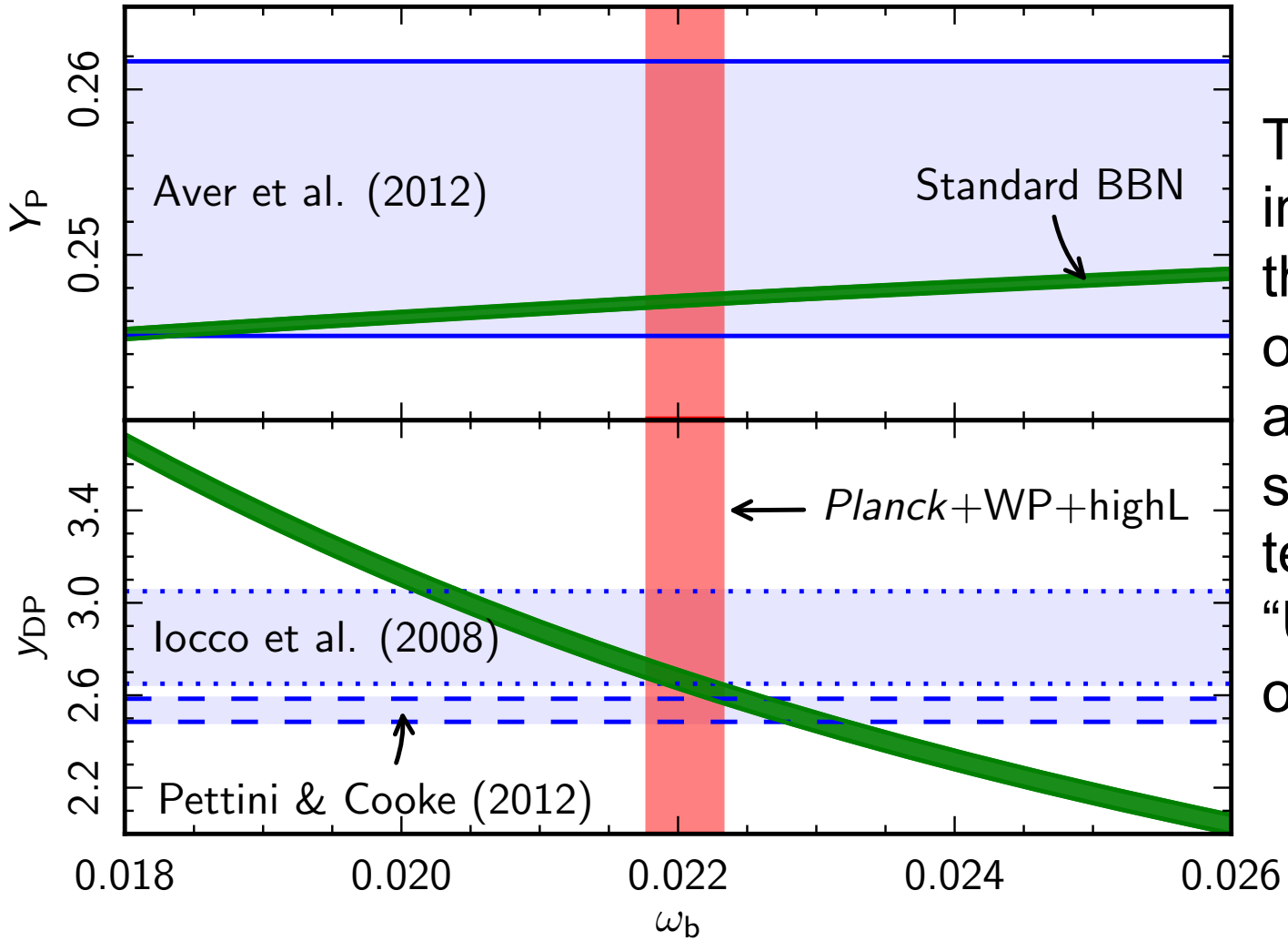
$$S = \int d^4x\sqrt{-g}\left[R - \xi h^\dagger h R - \lambda\left(h^\dagger h - v^2\right)^2 + \cdots\right]$$

- Can focus on just "radial" motion, since "orbital" motion is damped by expansion of Universe. Call this ϕ.
- Redefine *g* as $(1+\xi\phi^2)g$ and work through the derivatives in R etc. and you find a "normal" scalar field with potential
  - $V(\phi) \sim (\phi^2 - v^2)^2 / [1+\xi\phi^2]^2$
- For $h > M_p/\sqrt{\xi}$ can have slow-roll inflation.
- For a wide range of couplings etc. find
  - $n_s \sim 0.96\text{-}0.97$ and $r \sim 0.003\text{-}0.004$
  - Right in the sweet spot for Planck!

Consistency with other data

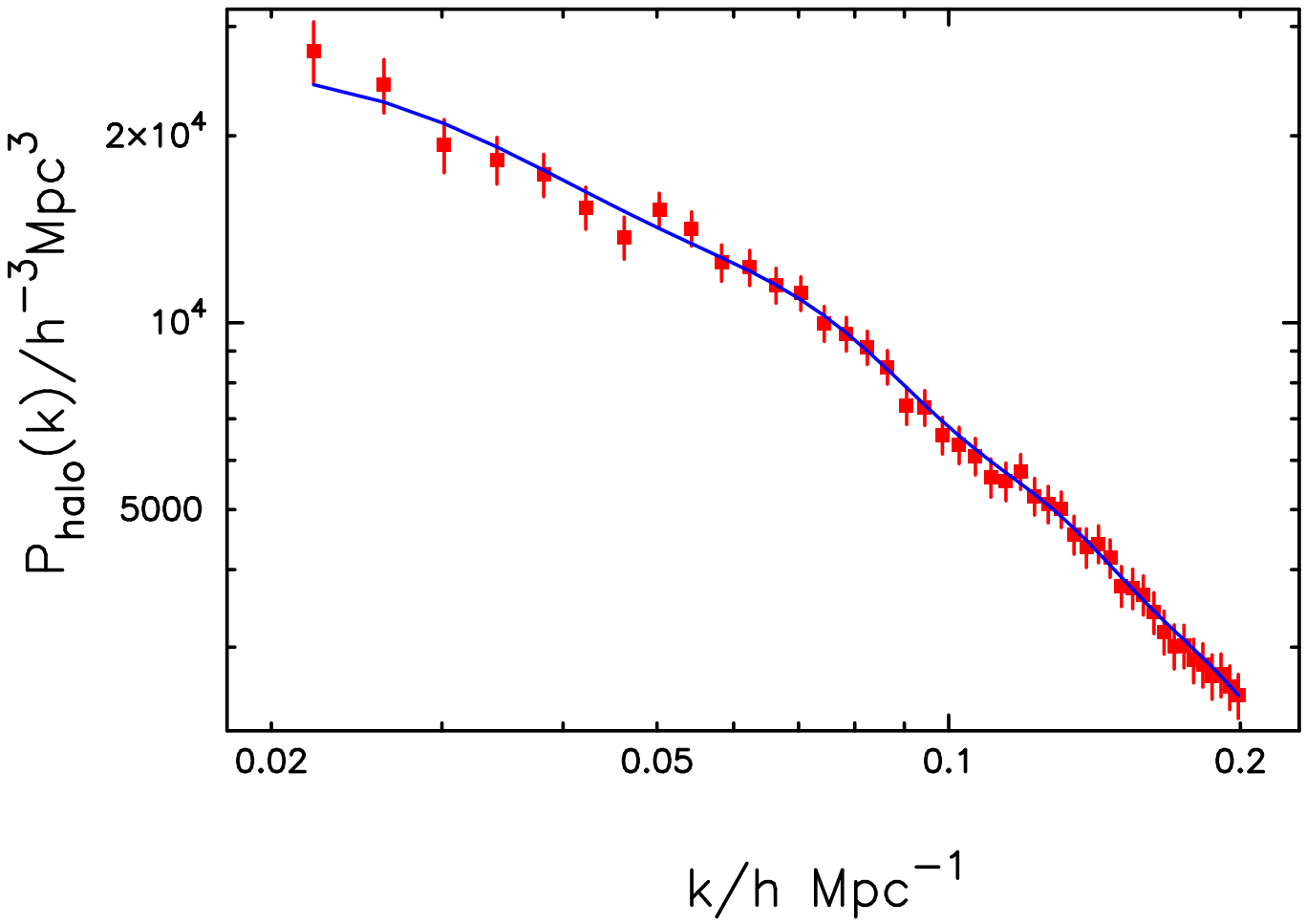
- The Planck data are consistent with the predictions of the simplest ΛCDM models.
- Within the framework of such models we can compare to a wide variety of other astrophysical/cosmological datasets.
  - Primordial nucleosynthesis
  - Large-scale structure (shape of power spectrum).
  - Baryon Acoustic Oscillations (distance scale).
  - Direct measures of H_0.
  - Redshift-space distortions. ☑
  - Type Ia SNe. ☑☐
  - Cosmic shear. ☒☑
  - Counts of rich clusters of galaxies. ☒☐☑

Excellent agreement with BBN!



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

Power spectrum shape comparison



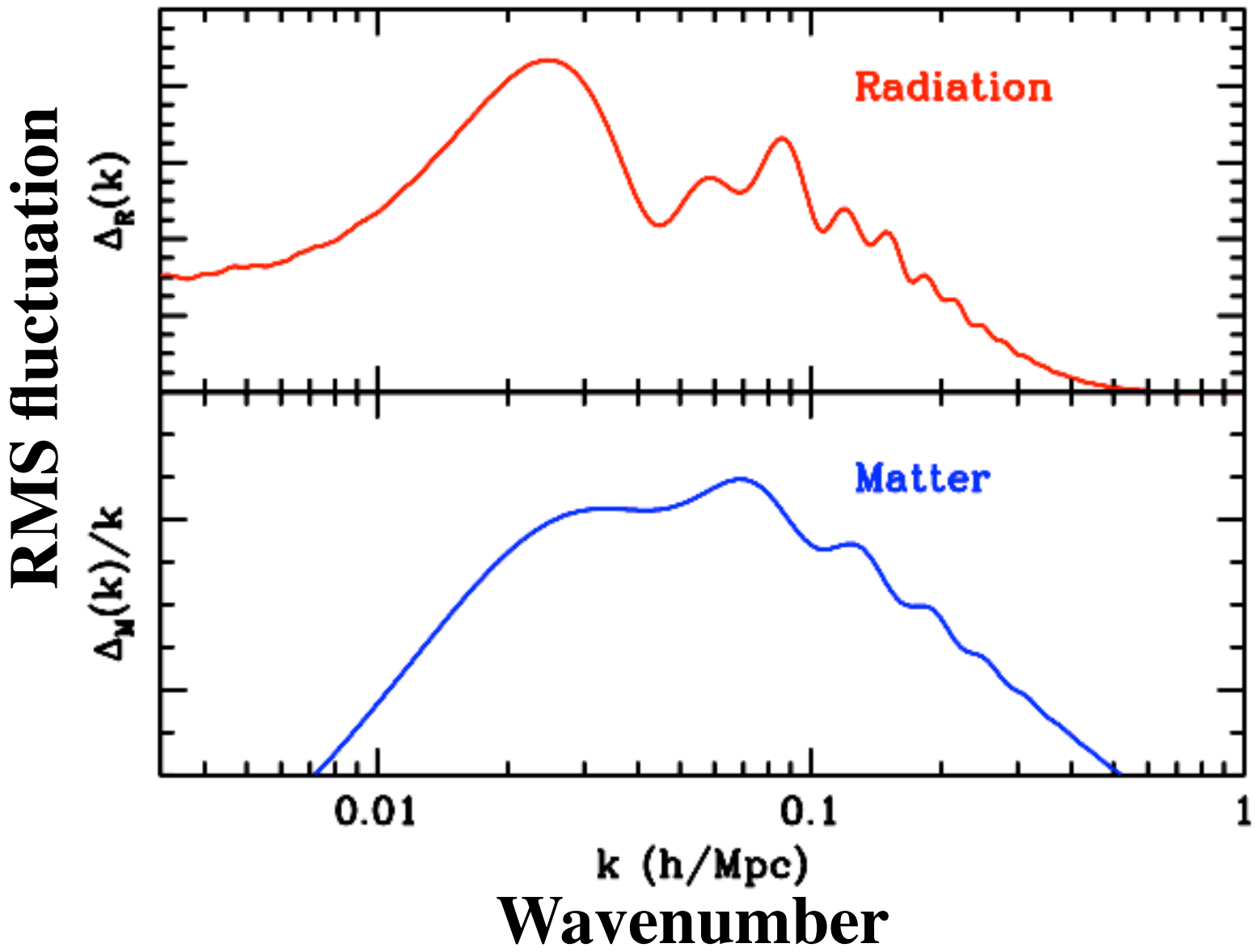
The predicted power spectrum is in excellent agreement with that seen in the SDSS (Reid++).

The shape is well constrained by the CMB.

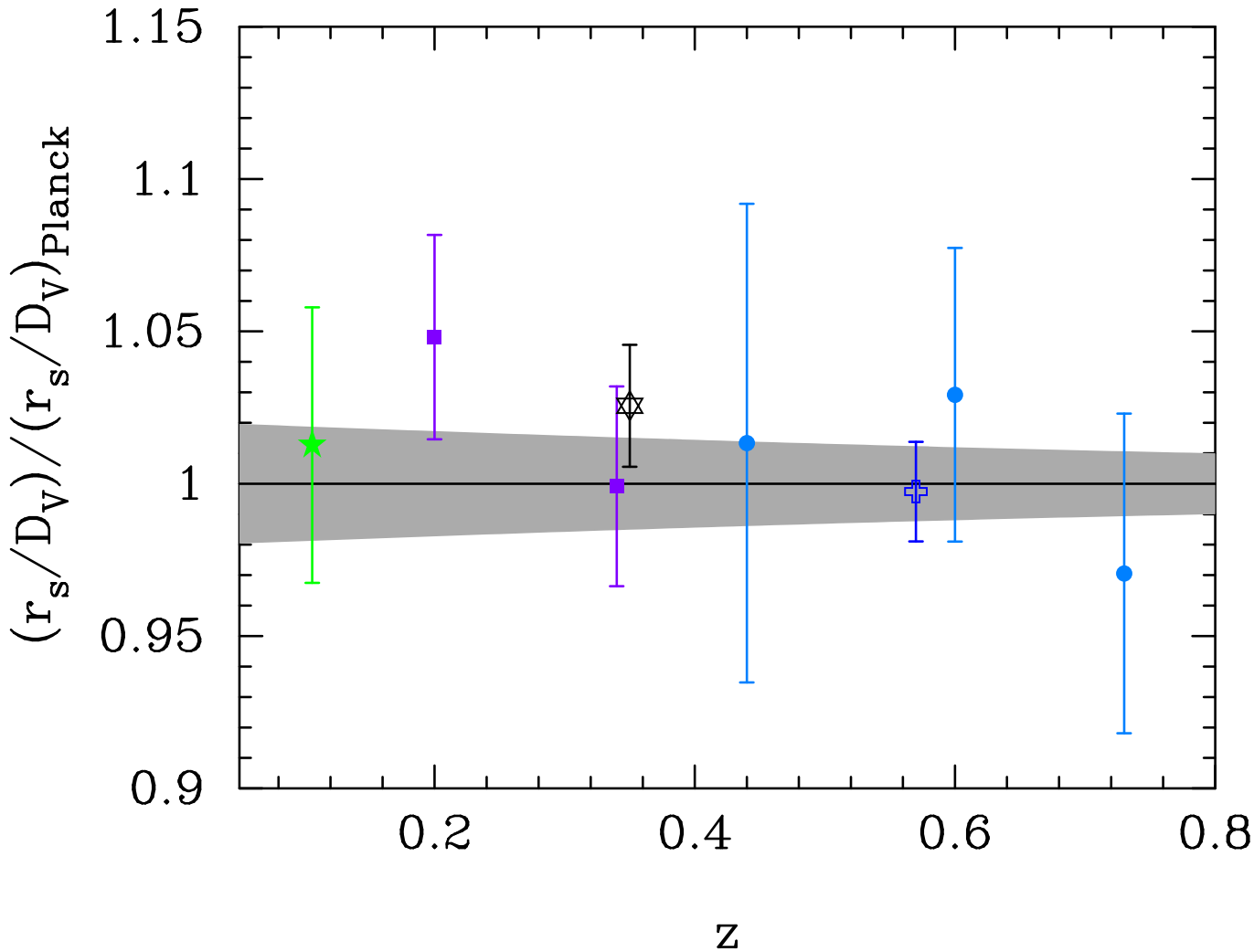
Baryon oscillations in *P(k)*

- We now have convincing evidence for acoustic oscillations in the baryon-photon fluid in the infant Universe.
- Since the baryons contribute ~15% of the total matter density, the total gravitational potential is affected by the acoustic oscillations with scale set by *s*.
- This leads to small oscillations in the matter power spectrum $P(k)$.
  - No longer order unity, like in the CMB, now suppressed by $\Omega_b/\Omega_m \sim 0.1$

Baryon (acoustic) oscillations



Distance scale comparison: BAO

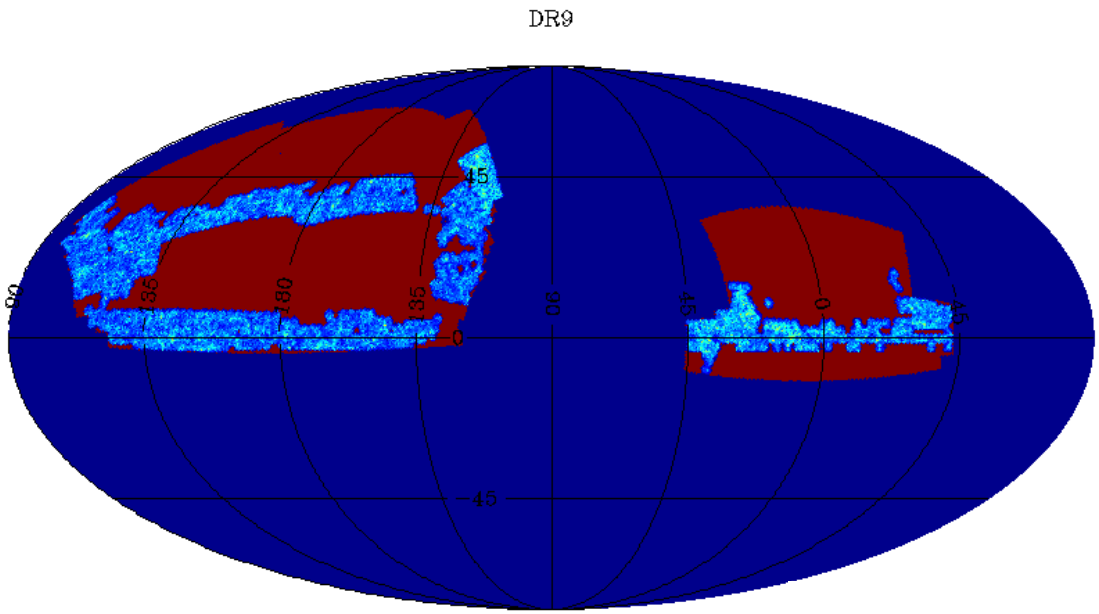


Acoustic oscillations at z~1100 and z<1 tell the same story about the distance scale: ΛCDM!

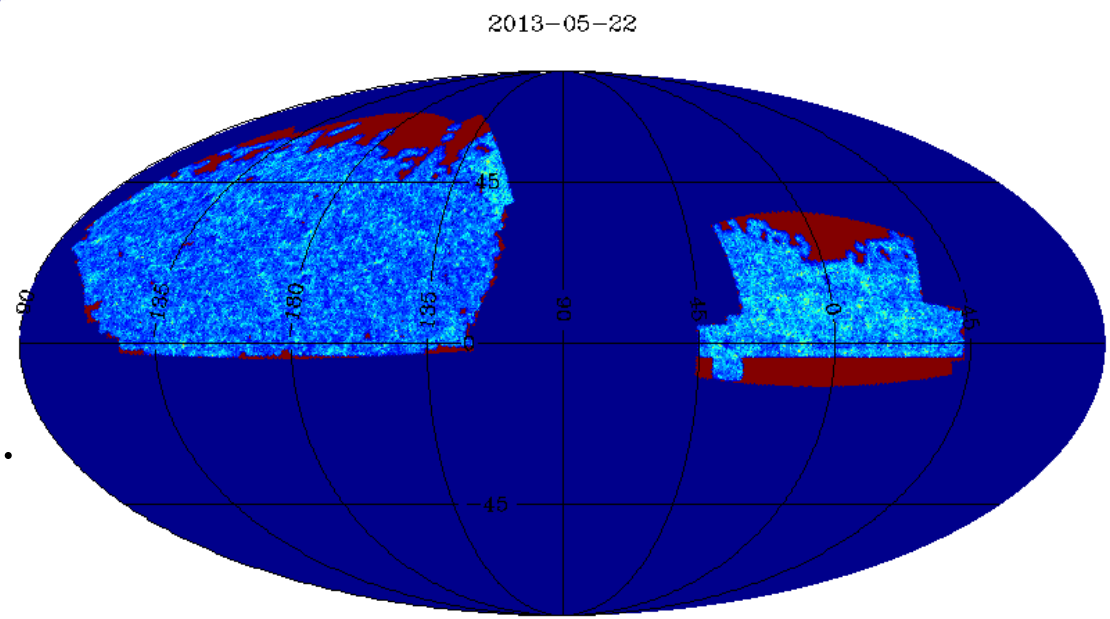
Precision cosmology

- With the Planck data, very few degeneracies remain.
- Biggest remaining: the angular diameter distance/ acoustic size degeneracy.
  - Only weakly broken by non-acoustic/higher-order effects, often in a model-dependent manner.
- Adding BAO data essentially breaks this last degeneracy by allowing comparison of $z \sim 10^3$ with $z<1$.
- For constraints on curvature, m_ν or DE, adding BAO data dramatically improves constraints:
  - $\Omega_k = -0.0010 \pm 0.0065$ (95%)
  - $\Sigma m_\nu < 0.23$ eV (95%)
  - $w_0 = -1.04 \pm 0.7$ (95%), $w_a < 1.32$ (95%)

BOSS progress-to-date

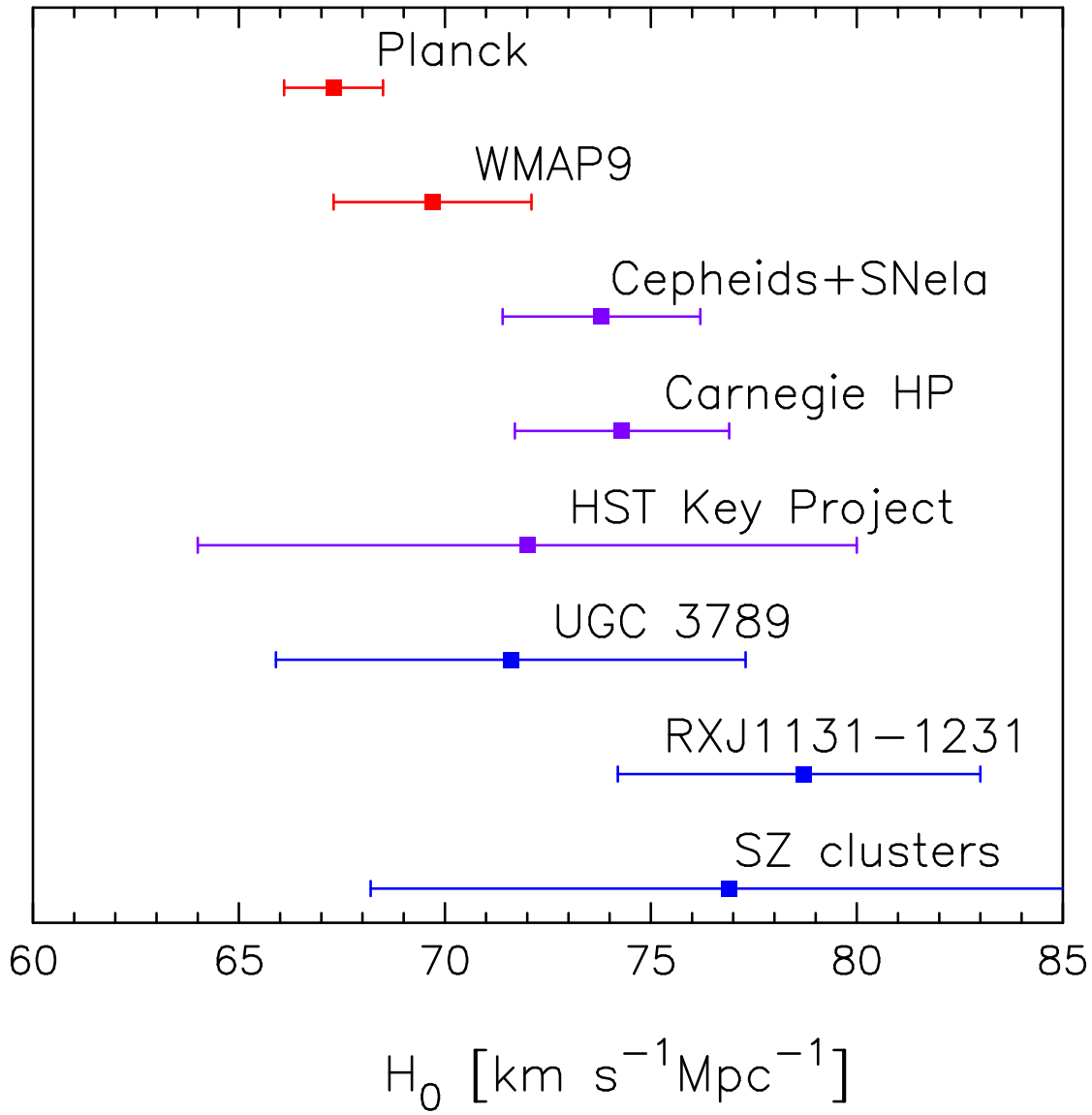


BOSS DR9:
3,275 sq. deg. and
264,283 galaxies.



BOSS DR11:
8,500 sq. deg. and
1,277,503 galaxies.

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 Ω_m.

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 >4σ !!
  - 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.
    - 6σ deviation from scale-invariance, 0.07% measurement of θ_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!

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

The End