Cosmic sound: near and far

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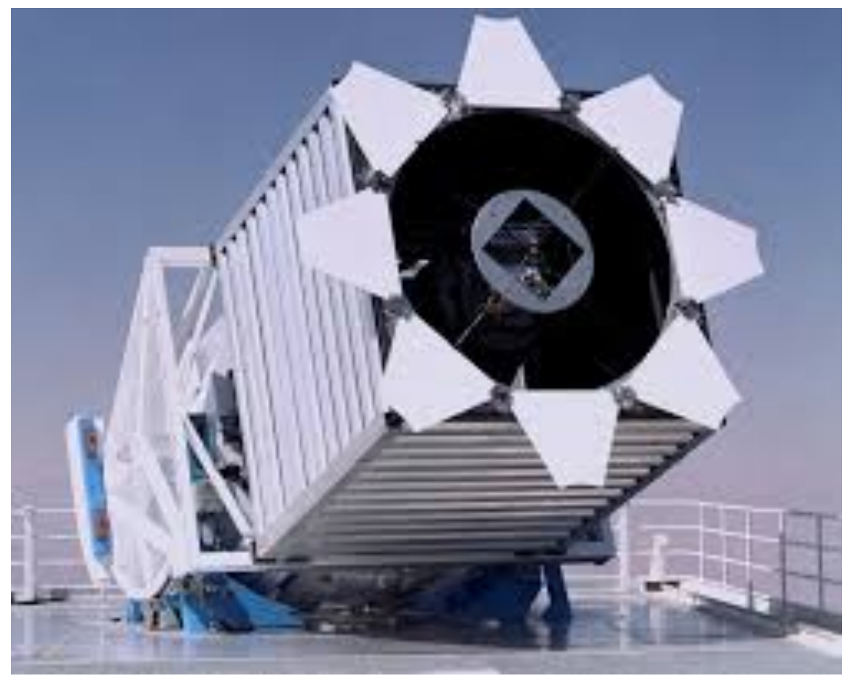
<u>for the Planck & BOSS teams</u>

Planck



BOSS

Outline

- The standard cosmological model and the CMB.
  - Acoustic oscillations in the infant Universe.
- Planck: mission.
- Planck: cosmological parameters
- Planck: comparison with other datasets.
- Acoustic oscillations in the matter.
- BOSS: cosmic sound “nearby”
- Conclusions.

Standard cosmological model

- The Universe is well described by
  - A spatially flat, Friedmann metric
  - whose dynamics are governed by General Relativity
  - and whose constituents are dominated by
    - radiation (ν and γ) at early times and
    - cold dark matter (CDM) and Λ at later times.
- The FRW metric has one free, scalar function of time known as the scale factor: *a(t)*.
  - We often use an alternate convention, redshift, where $a=(1+z)^{-1}$.
  - The log-derivative of *a(t)* is known as the Hubble parameter: $H = d\ln(a)/dt$
  - Within GR: $H^2 \sim \rho_{tot}$.

The cosmic microwave background

- The entire Universe is filled with radiation in the form of a 2.7K black-body.
  - $n_\gamma = 411\ cm^{-3}$, $\rho_\gamma = 4.64\ 10^{34}\ g/cm^3 = 0.260\ eV/cm^3$
- 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 $z\sim1100$ (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.

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

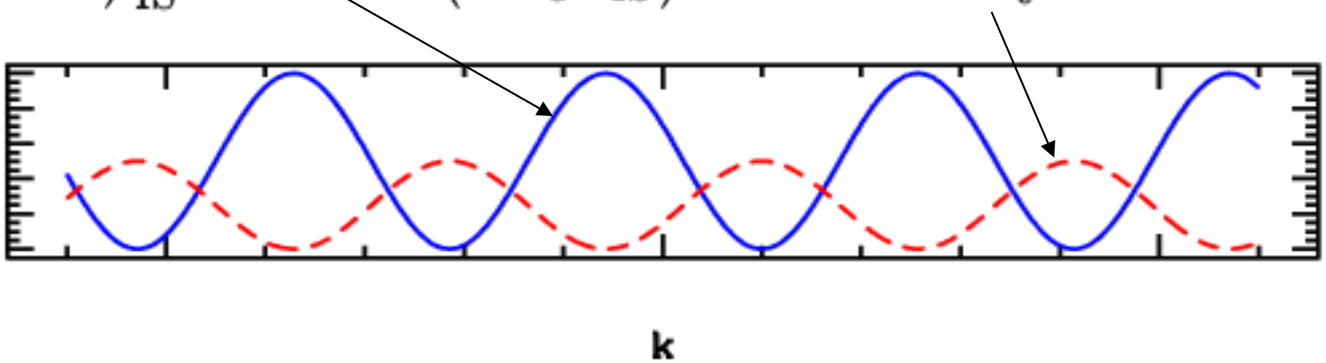
- These show up as temperature fluctuations in the CMB

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

The cartoon

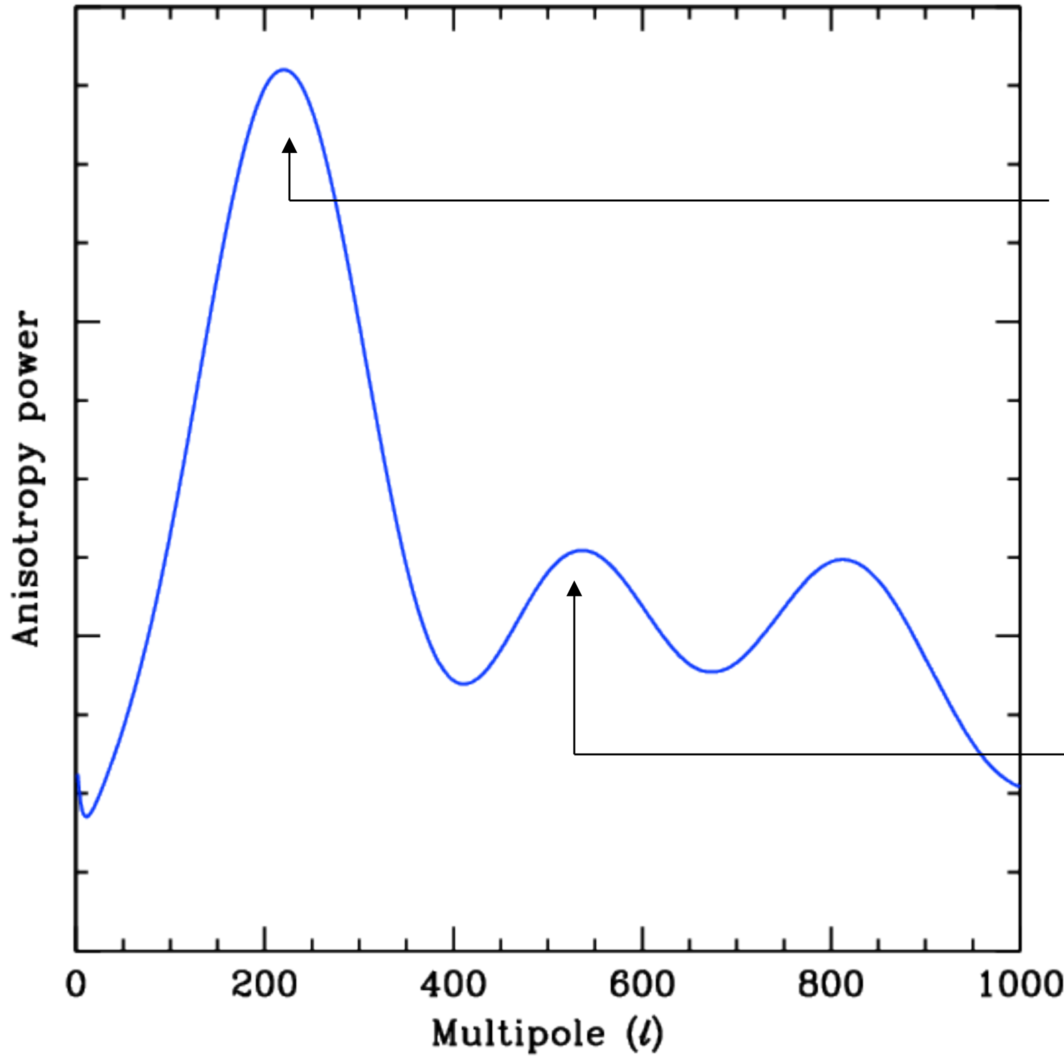
- A sudden "recombination" decouples the radiation and matter, giving us a snapshot of the fluid at "last scattering".

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



- 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!



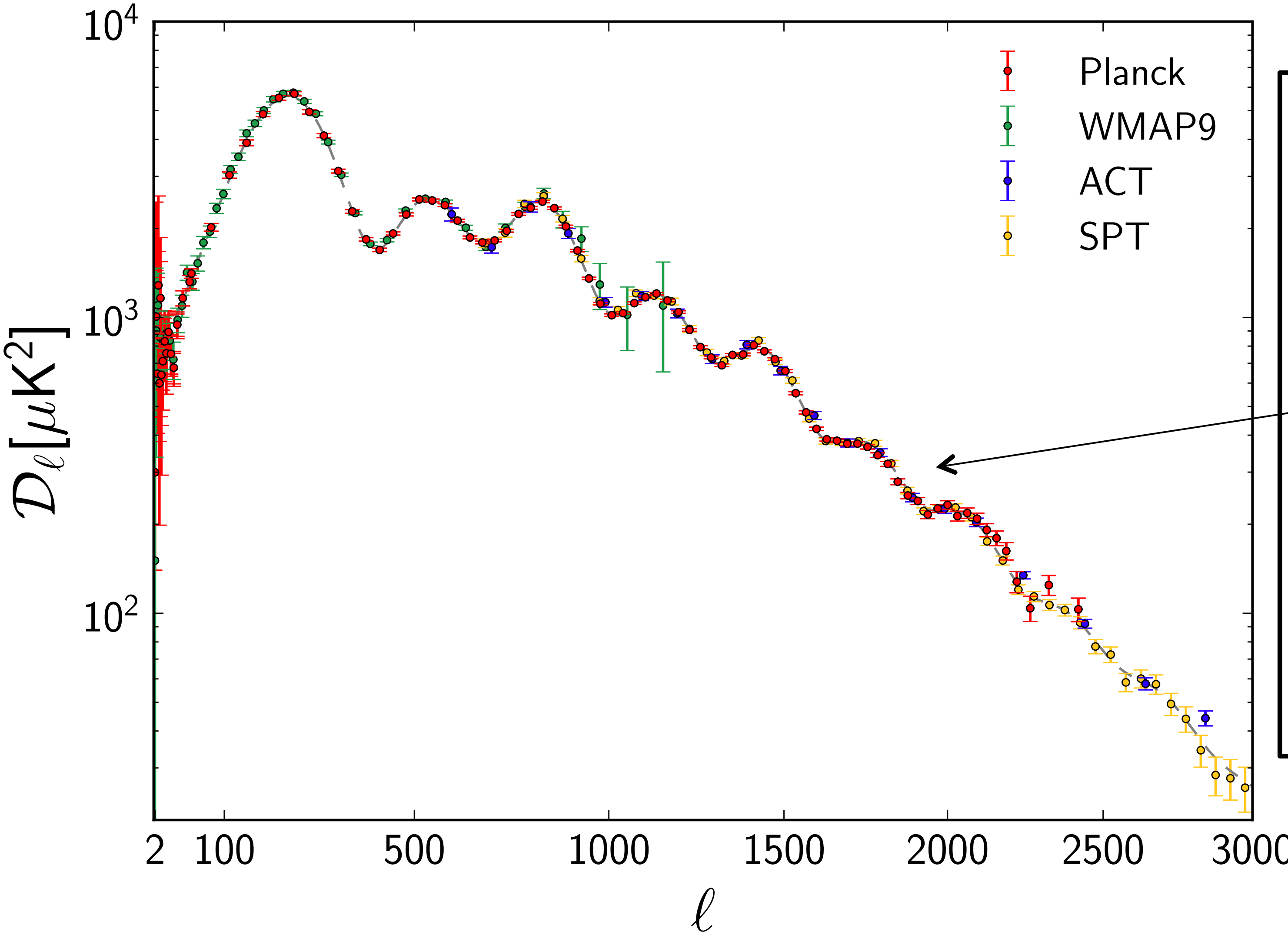
First "compression", at $kc_s t_{ls}=\pi$. Density maxm, velocity null.

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



Coupling is "tight" but not perfect. Photon diffusion damps power at small scales (Silk damping).

CMB encodes valuable information

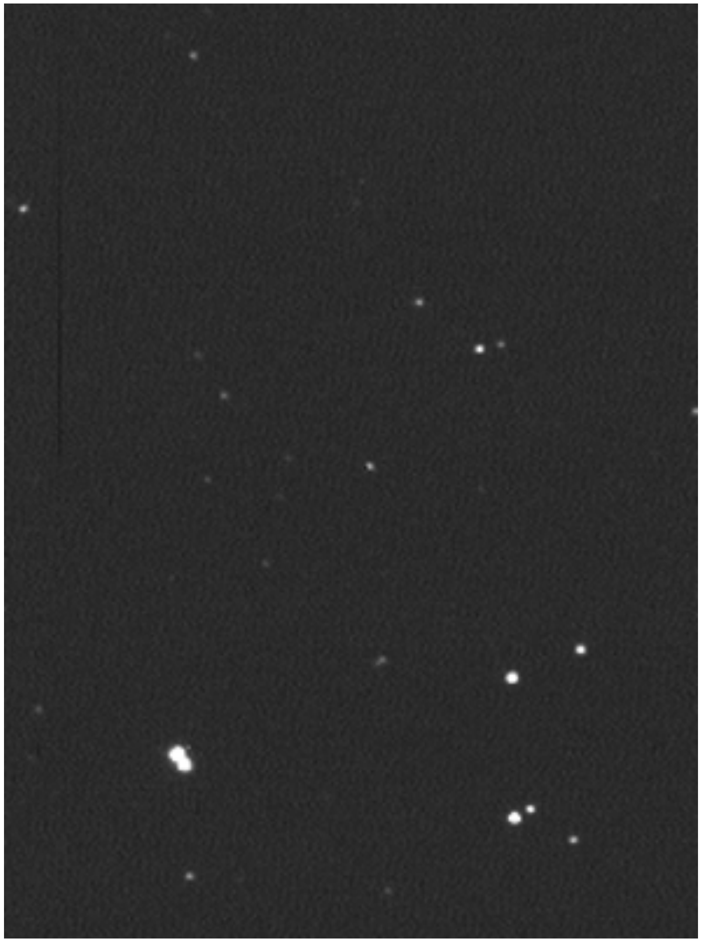
- The CMB spectrum depends upon the initial spectrum of perturbations (inflation?) and the conditions in the photon-baryon fluid prior to last scattering.
- The rich structure in the spectrum, and the dependence on many cosmological parameters, provides a gold-mine of information if signal can be accurately 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 $l=10^3$.

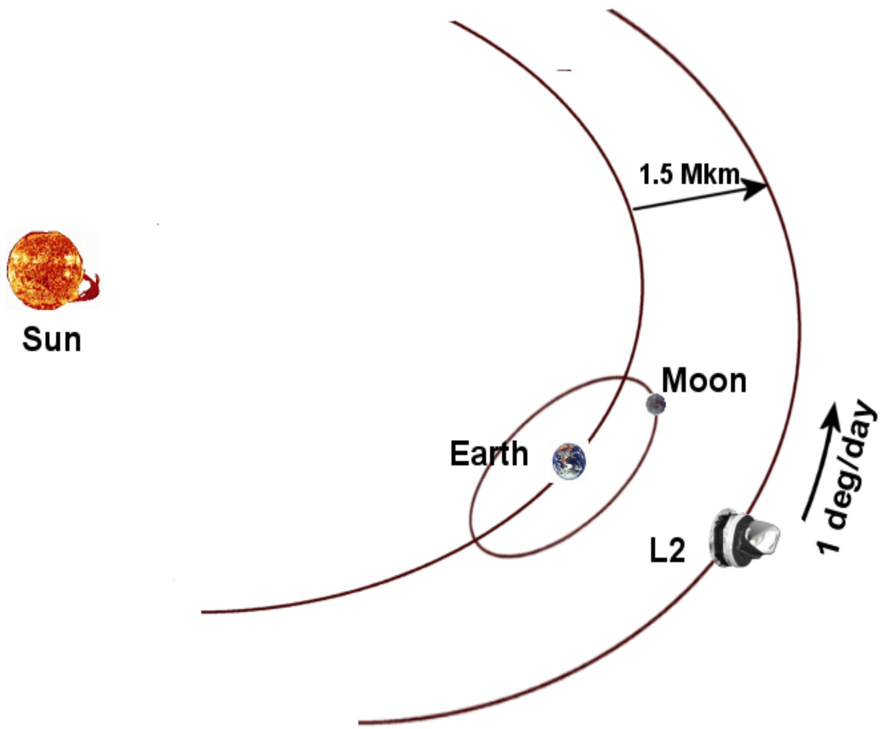
A picture-perfect launch!

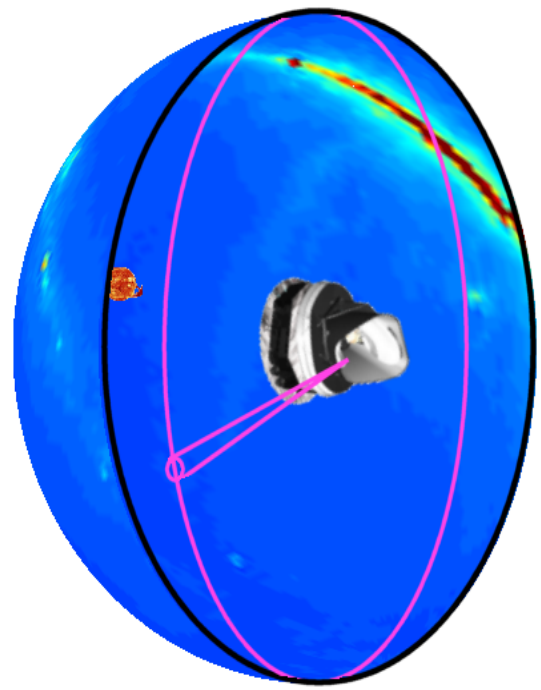
Ariane 5 lifts off with Herschel and Planck on board on 14 May 2009 at 15:12:02 CEST.



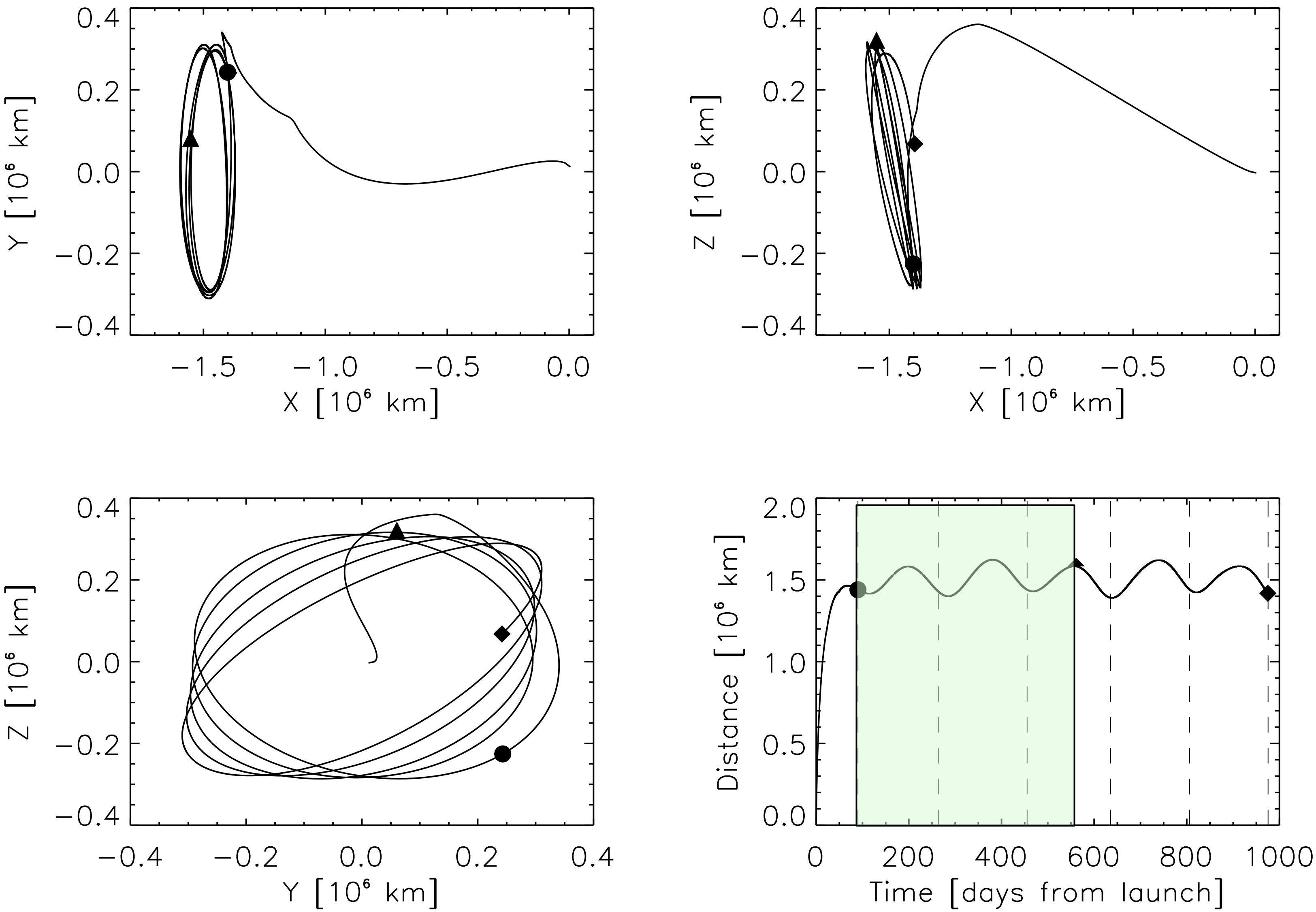
The orbit

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

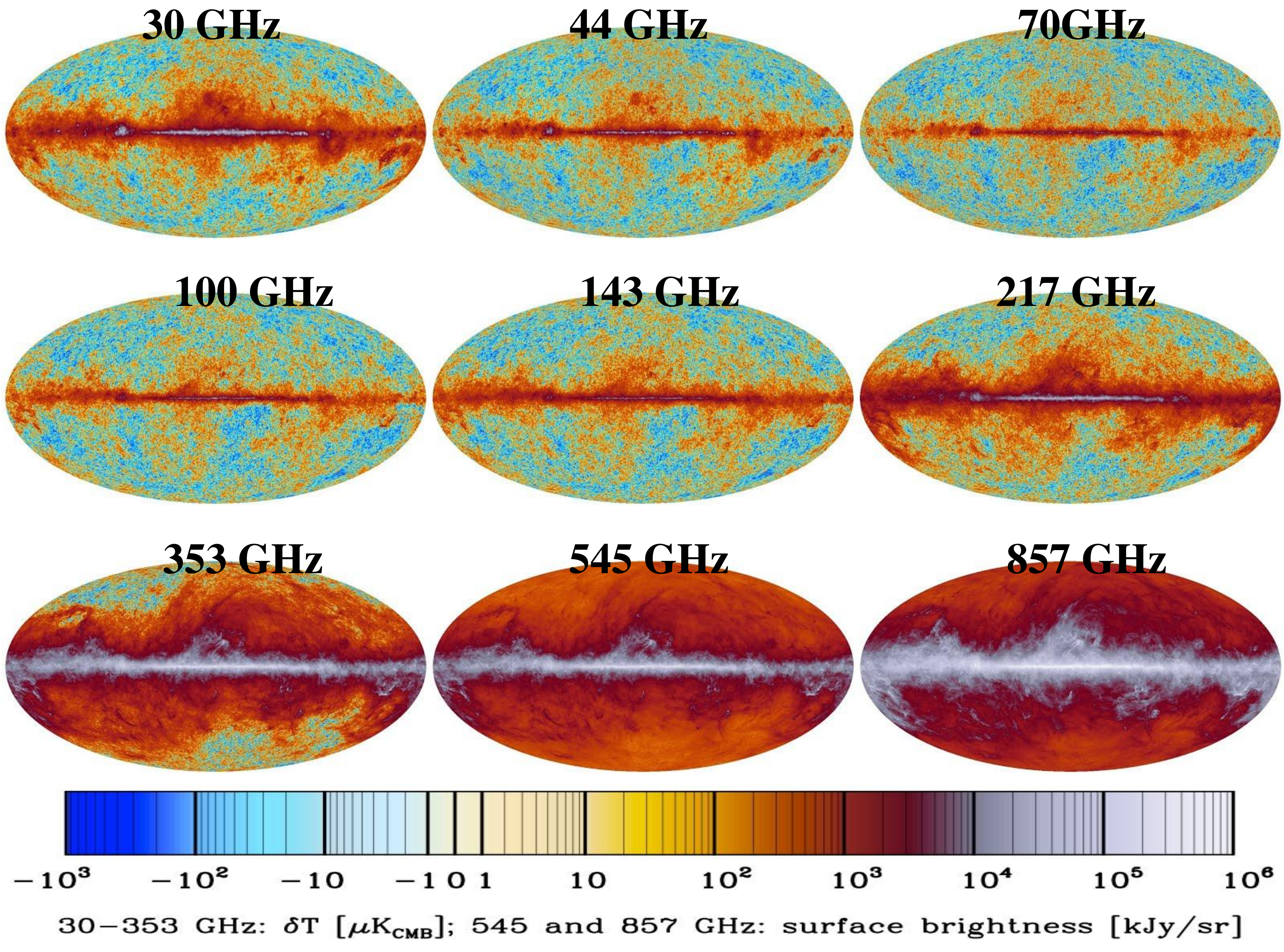




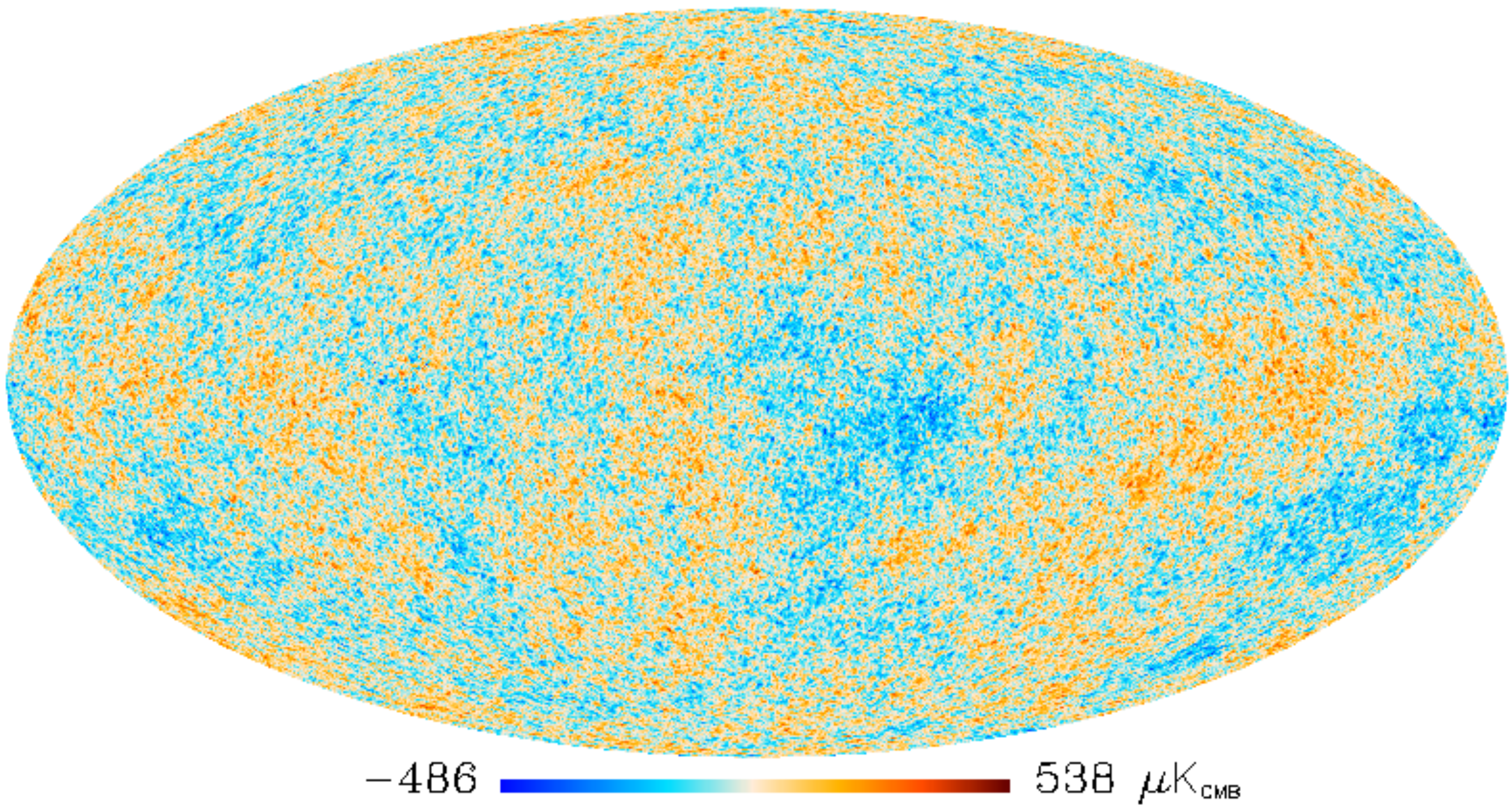
Orbit



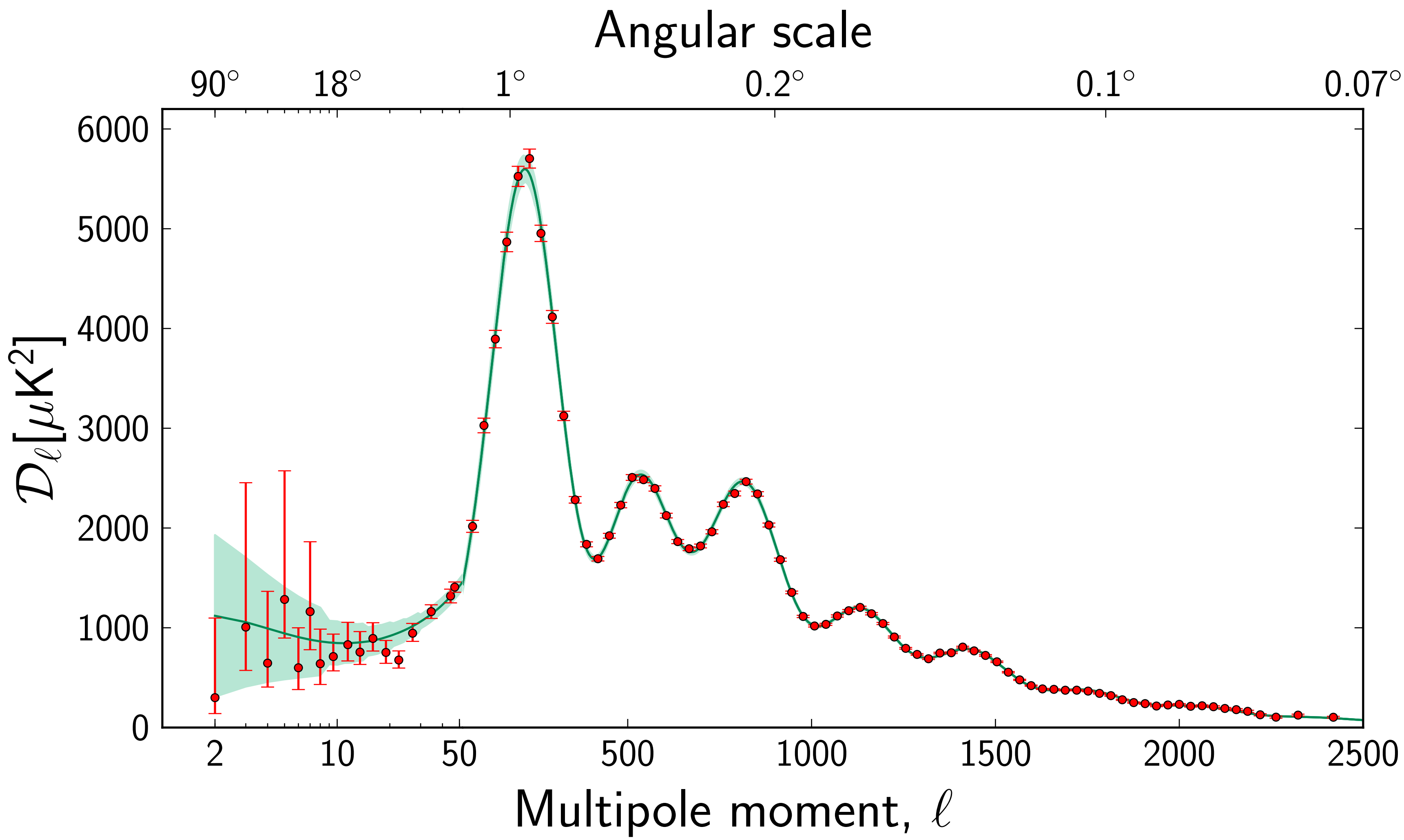
0.4
0.2
0.0
−0.2
−0.4
Y [10⁶ km]
−1.5
−1.0
−0.5
0.0
X [10⁶ km]
Z [10⁶ km]
Y [10⁶ km]
2.0
1.5
1.0
0.5
Distance [10⁶ km]
0
200
400
600
800
1000
Time [days from launch]


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



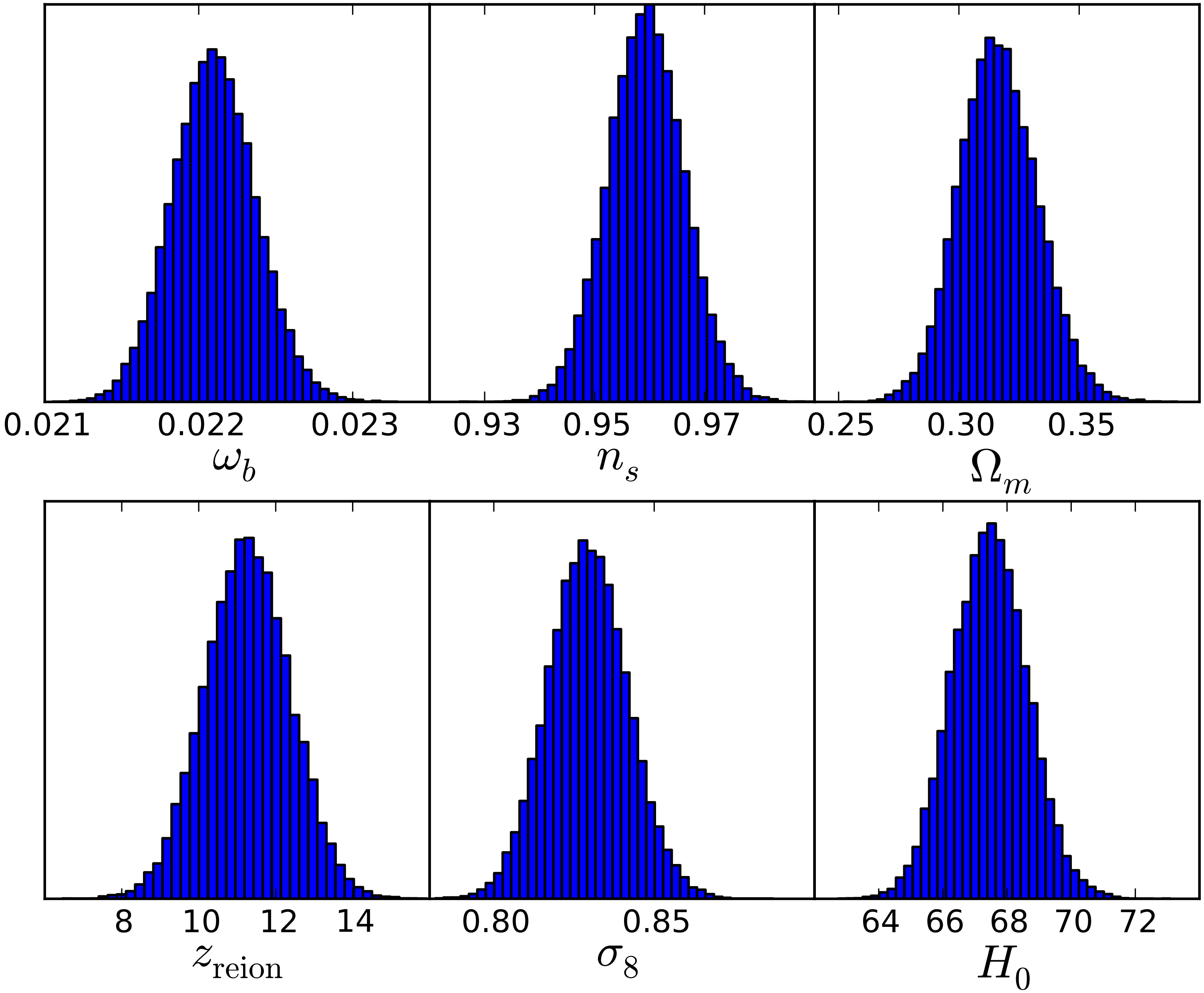
The angular power spectrum



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

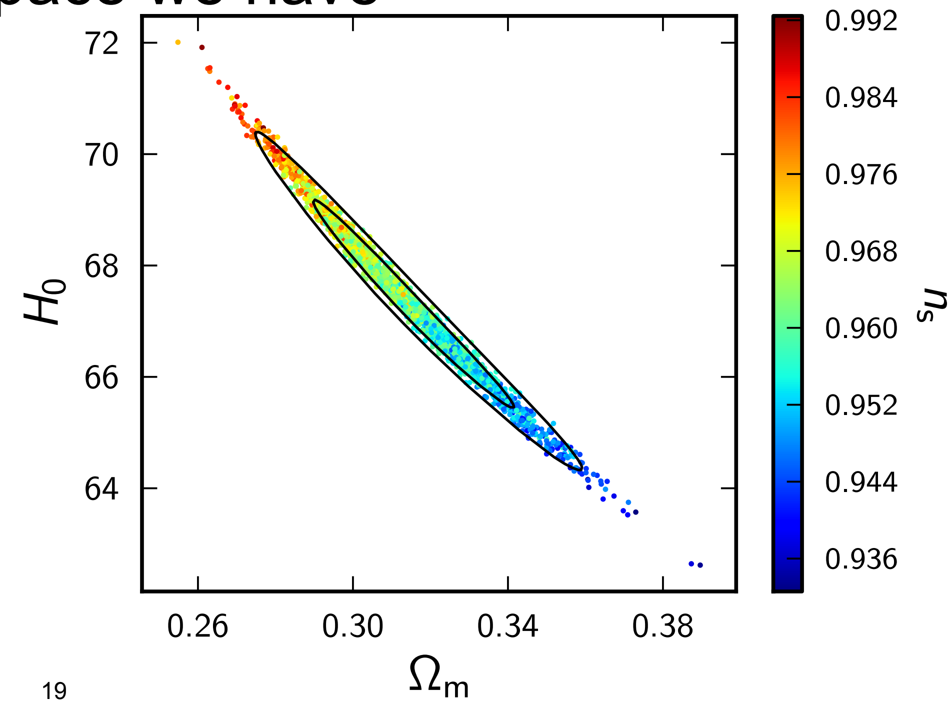
Parameter constraints



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)

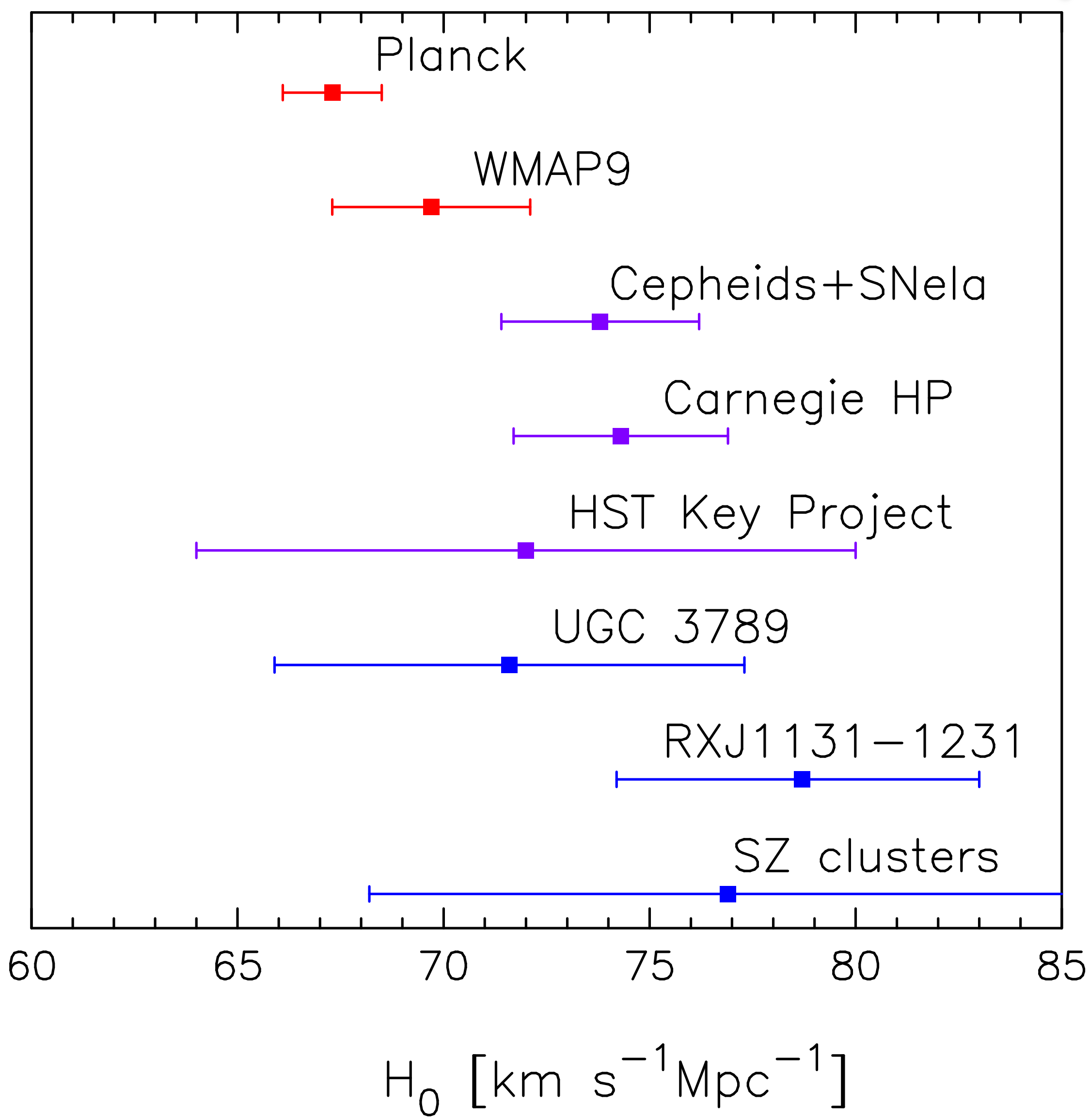
- The acoustic scale is a ratio: r_s/d_{LS}

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

- 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 $\rho_m + \rho_{DE} = \rho_{crit} \sim H_0^2$: 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%.

The Hubble uncertainty principle



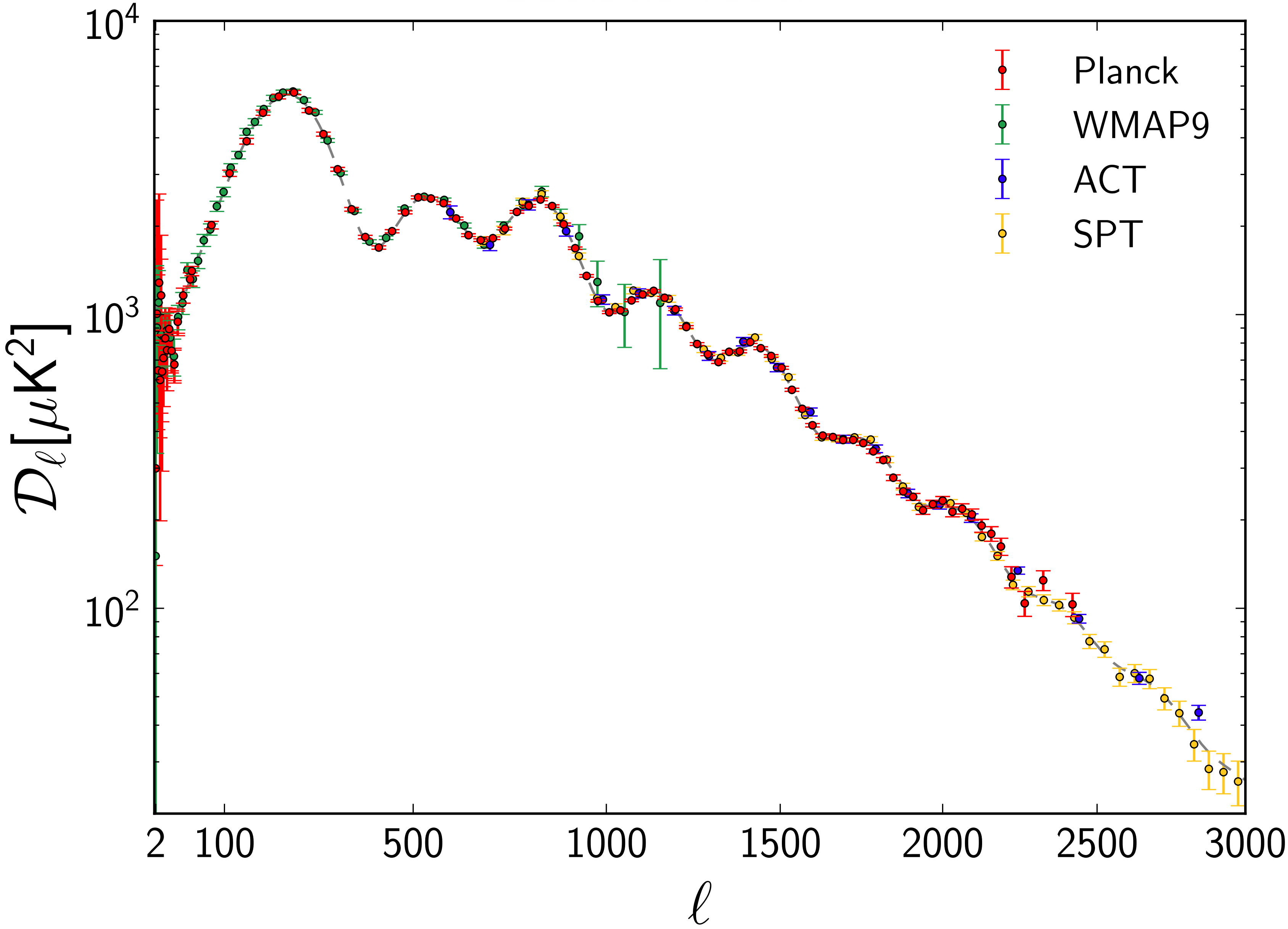
Within the ΛCDM model, the Planck data prefer a lower expansion rate (at late times) than that inferred from the traditional distance scale based on Type Ia SNe and local calibrators.

This is driven by Planck's preference for a higher Ω_m.

So why raise Ω_m?

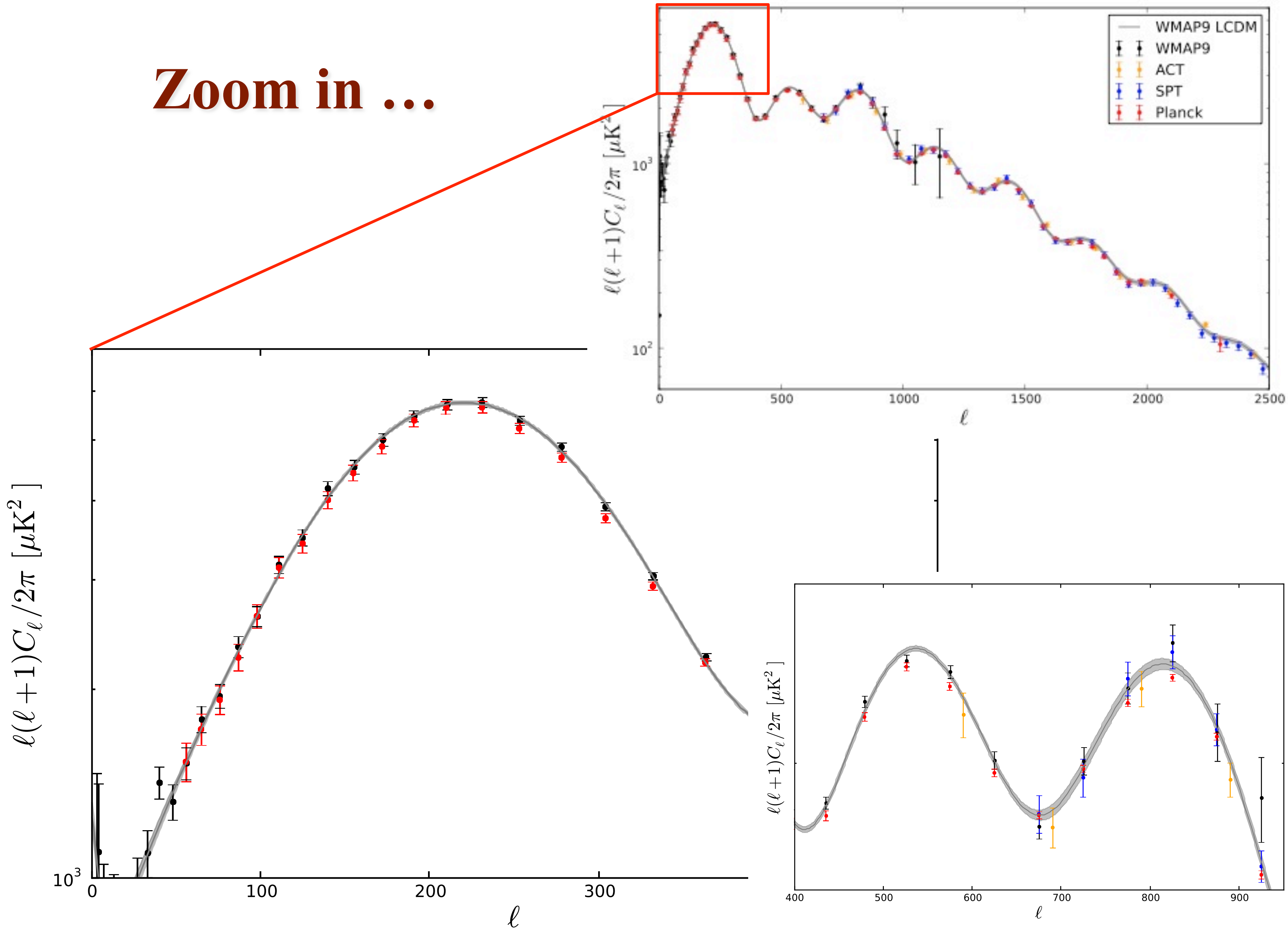
- Actually, it's kind of complicated …
  - … but the basic physical picture can be sketched out.
- Planck sees more power at high-*l*, and smoother peaks, than the "old" best-fit model predicts.
- Raising ρ_m will lower the first few peaks (c.f. those at higher-*l*) and increase the amount of gravitational 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".

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

Zoom in …


WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
ℓ
0
500
1000
1500
2000
2500
10^3
10^2
100
200
300
400
600
700
800
900

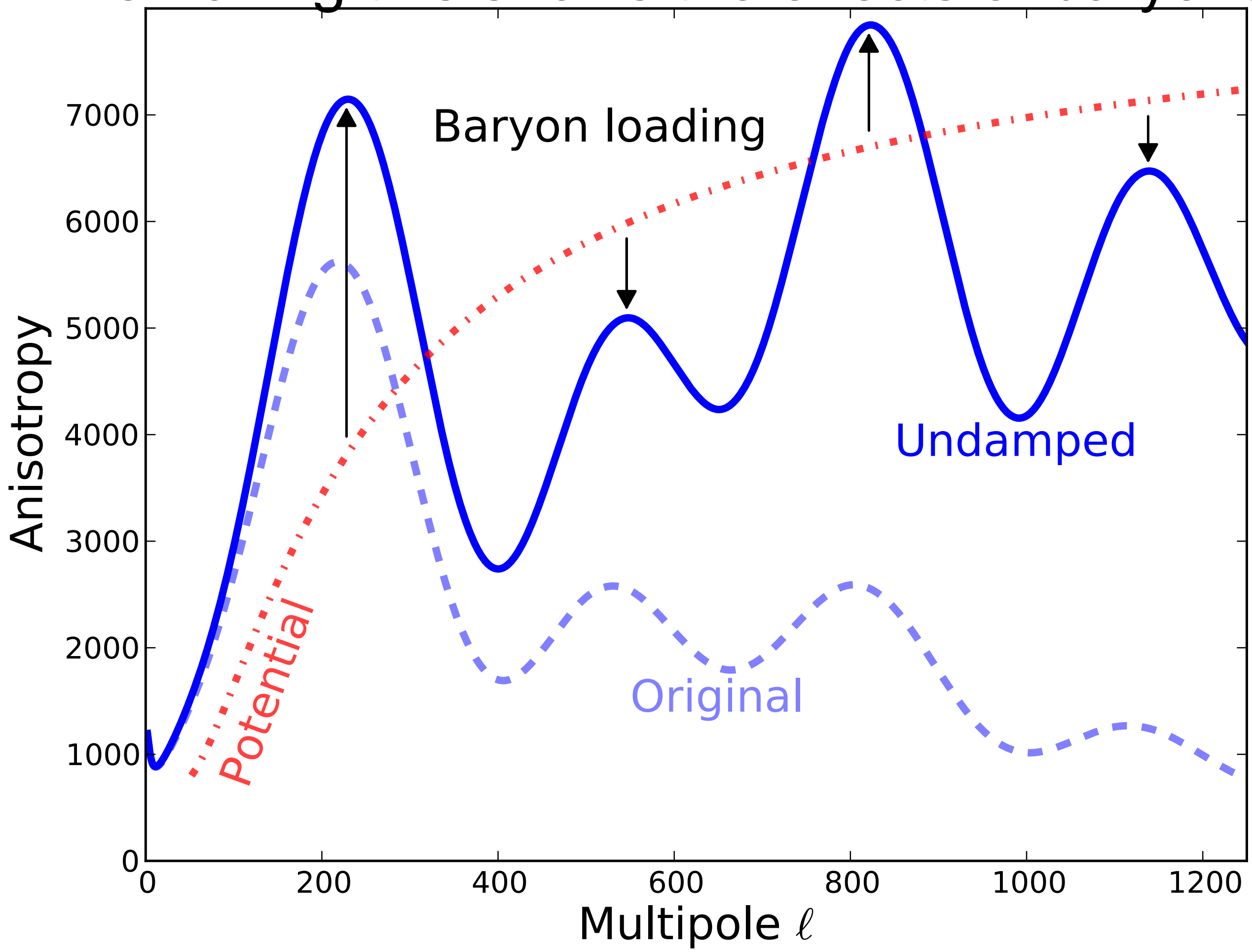
Baryon loading and the potential envelope

- 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.

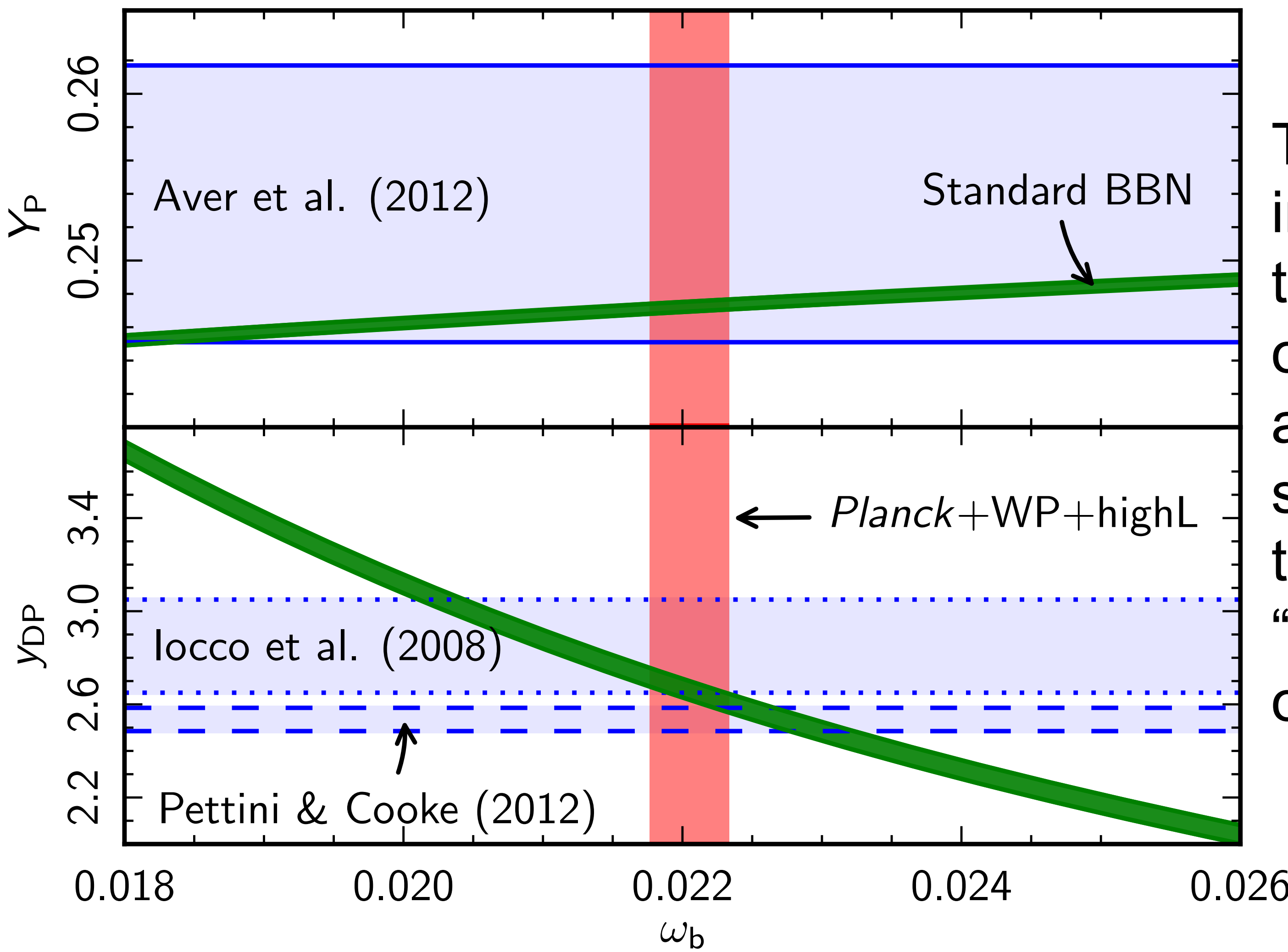
Boost by potential decay ($\Theta+\Psi+R\Psi$).

DM stabilizes the potentials: more DM = less boost.

Consistency with other data

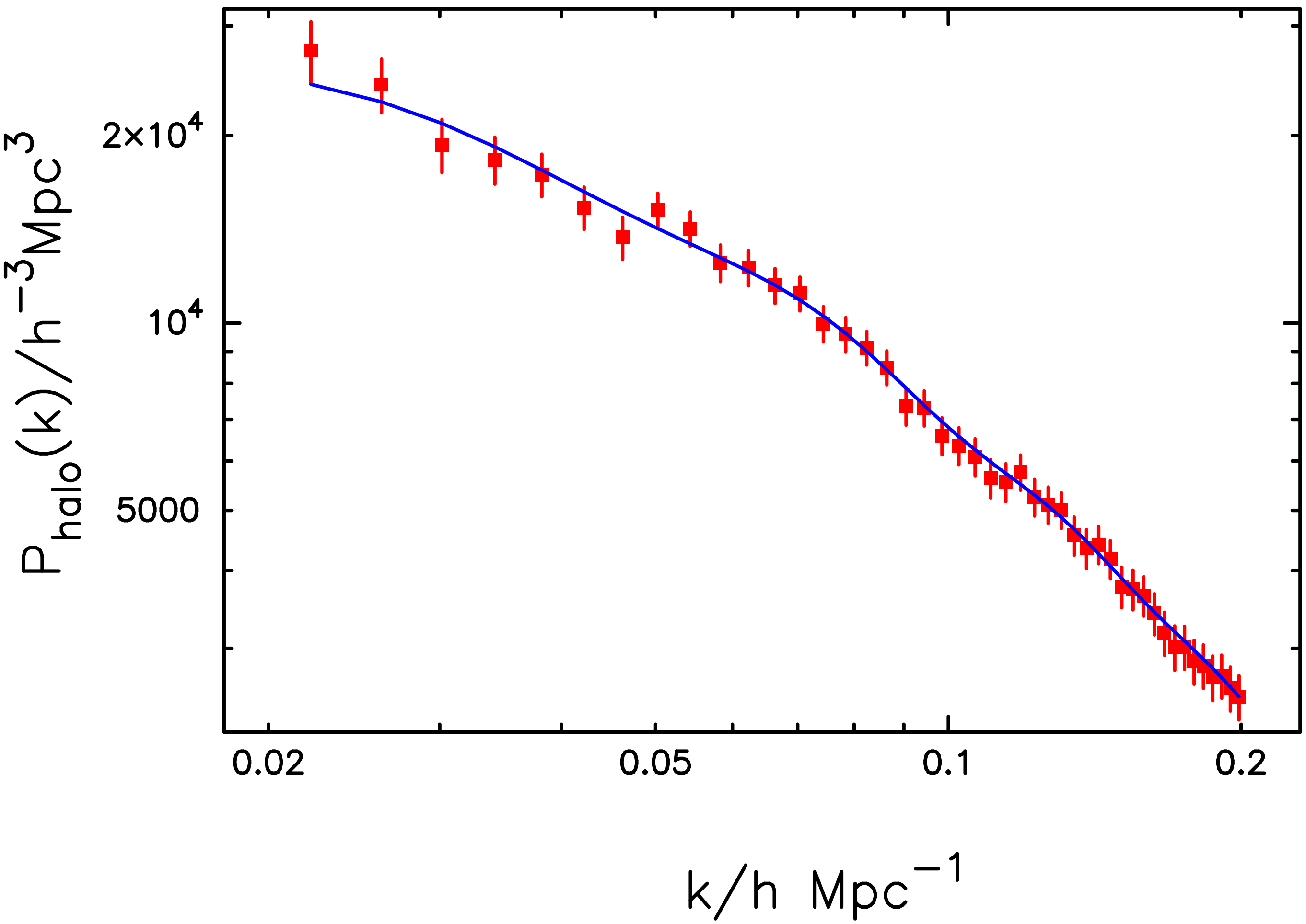
- The Planck data are consistent with the predictions of the simplest ΛCDM models.
- Within the framework of such models we can compare to a wide variety of other astrophysical/cosmological datasets.
  - Primordial nucleosynthesis
  - Large-scale structure (shape of power spectrum).
  - Baryon Acoustic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

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



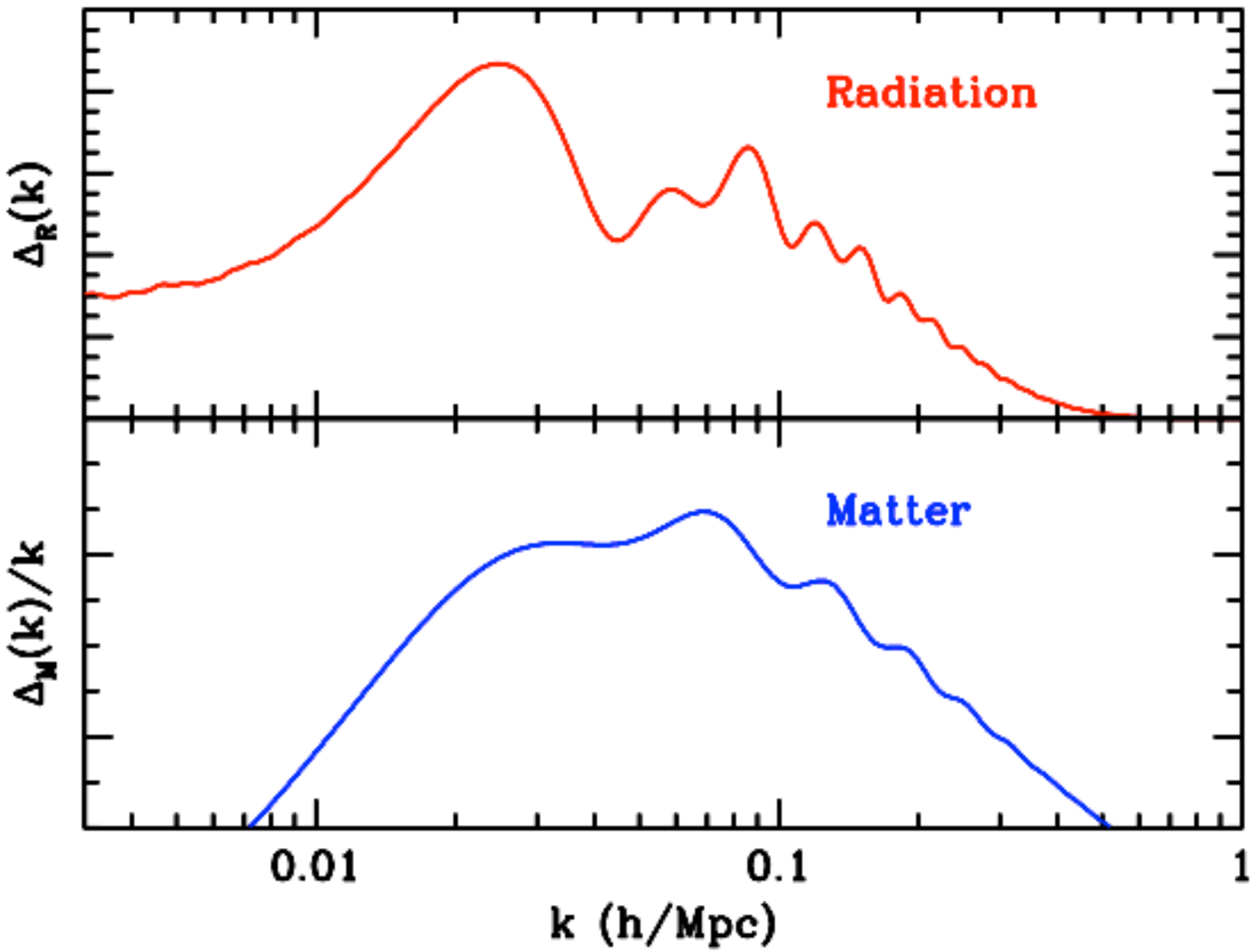
The predicted power spectrum is in excellent agreement with that seen in the SDSS (Reid++).

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

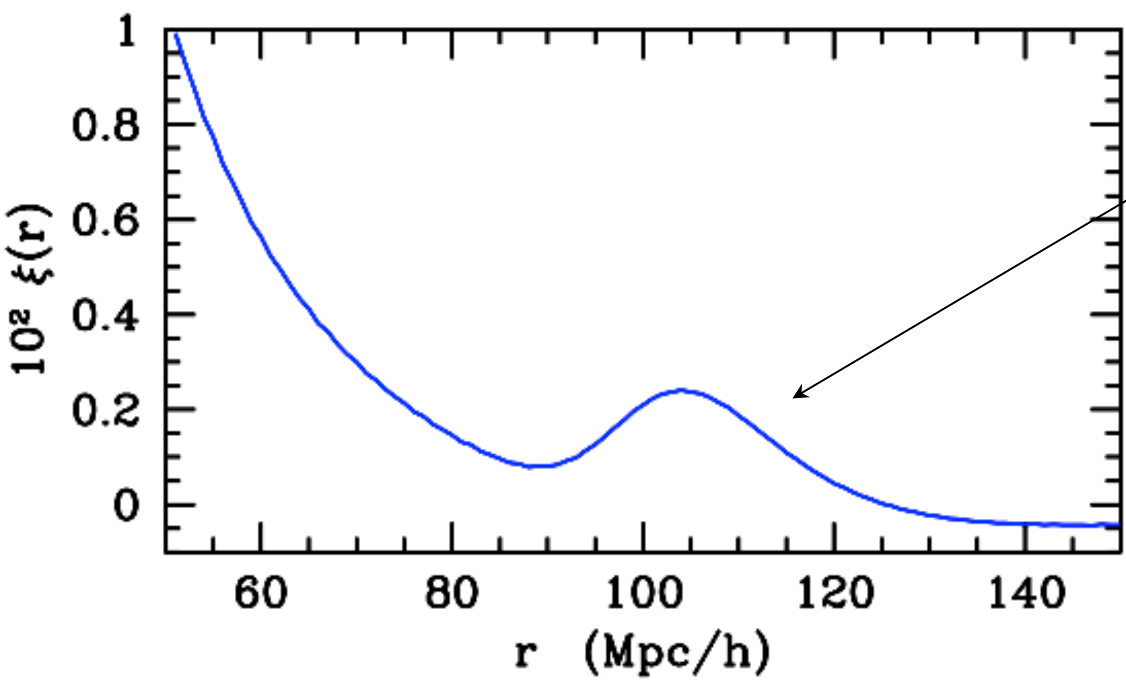


RMS fluctuation

Wavenumber

In configuration space

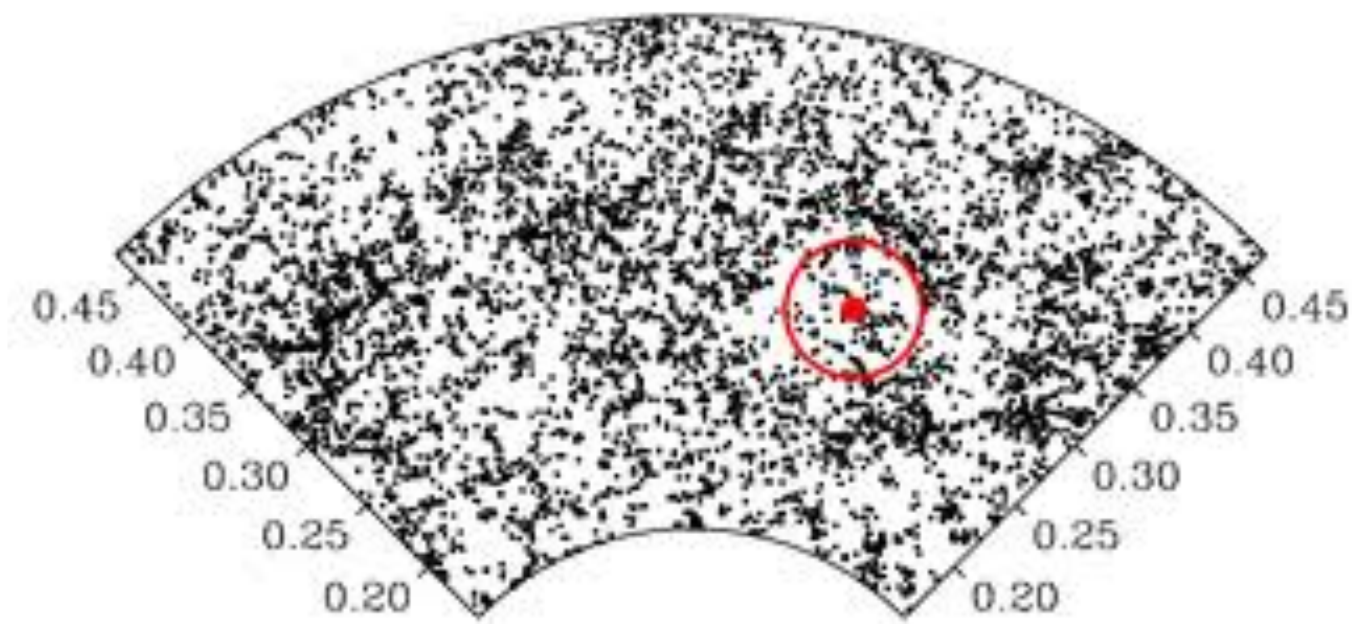
- In configuration space we measure not power spectra but correlation functions
  - $FT[\langle\delta_k^2\rangle] = \xi(r) = \langle\delta_x \delta_{x+r}\rangle$
- A harmonic sequence would be a δ-function in *r*, the shift in frequency and diffusion damping broaden the feature.



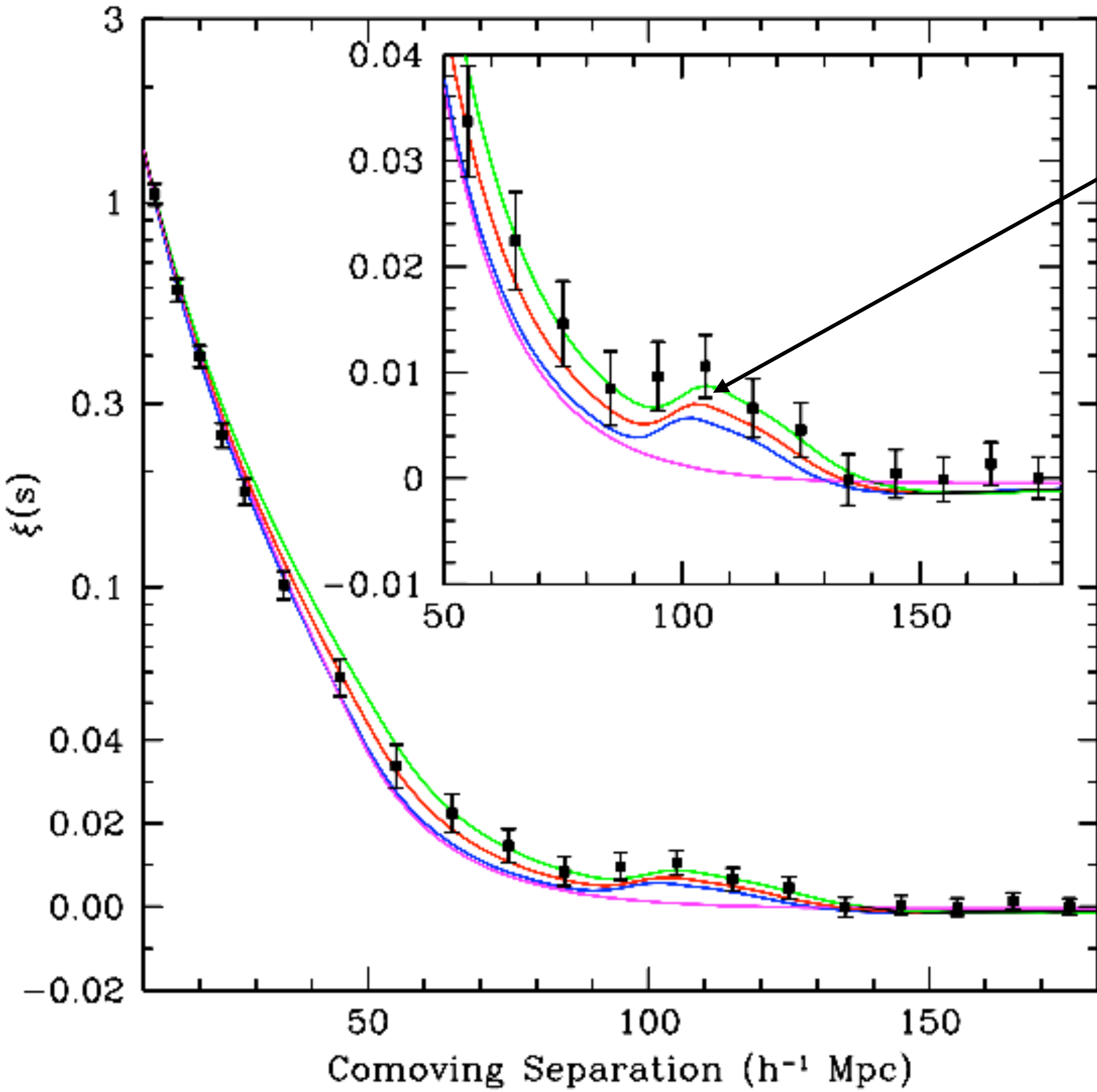
Acoustic feature at ~100 Mpc/*h* with width ~10 Mpc/*h* (Silk scale)

Acoustic signal in galaxy surveys

- If the probability of forming a galaxy increases in regions of increased matter density then the correlations we just computed should show up in the statistics of the galaxy distribution as well.
- The peak in $\xi(r)$ shows up as an excess of pairs of galaxies, above the broad-band expectation, at ~100Mpc/*h*.



Another prediction verified!!



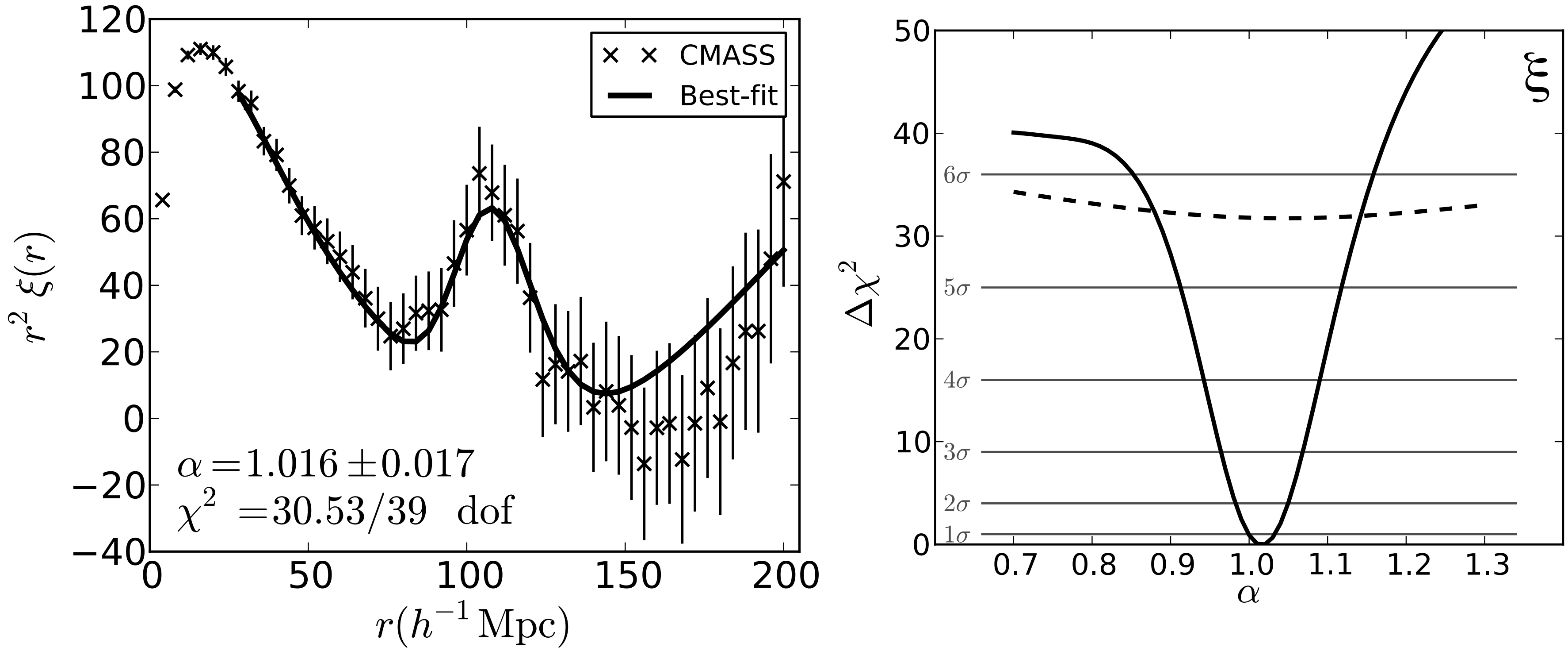
Eisenstein et al. (2005) detect oscillations in the SDSS LRG ξ(r) at z~0.35! Knowing ***s*** determines D(*z*=0.35).

About 10% of the way to the surface of last scattering!

Constraints argue for the existence of DE, but do not strongly constrain its properties.

BOSS BAO detection: Anderson++12

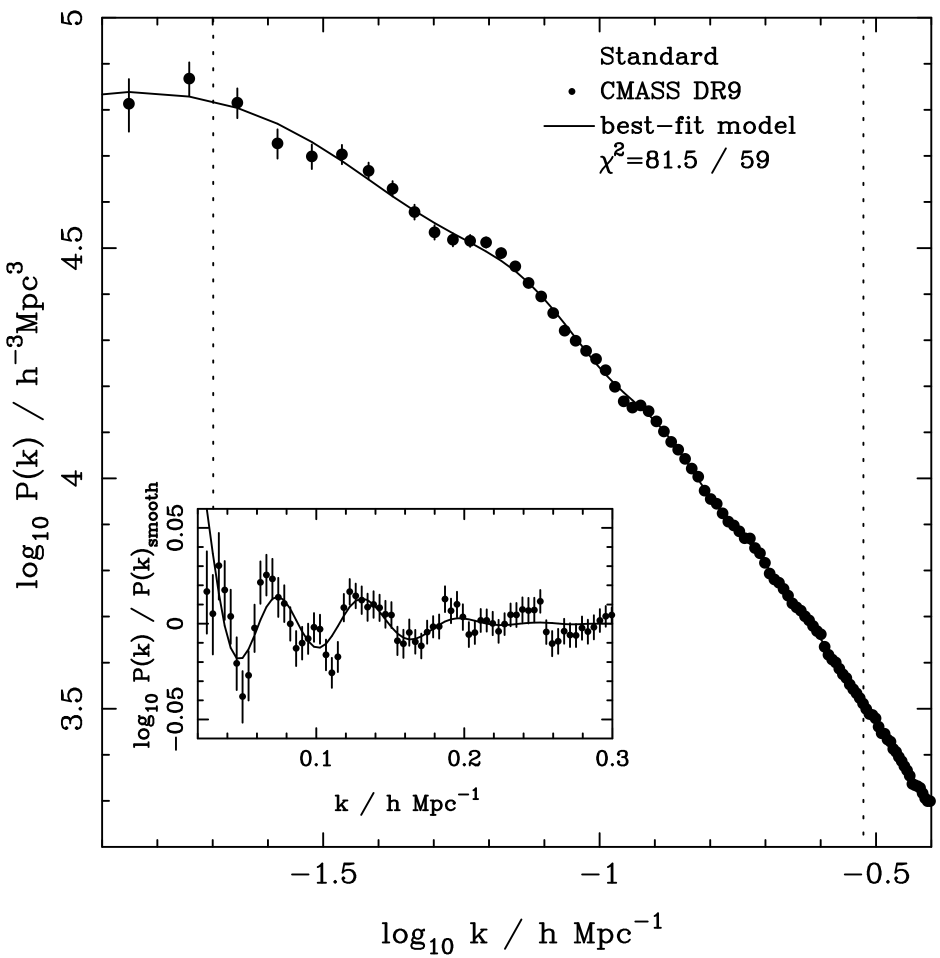
(BAO detected at >5σ in both ξ and P)

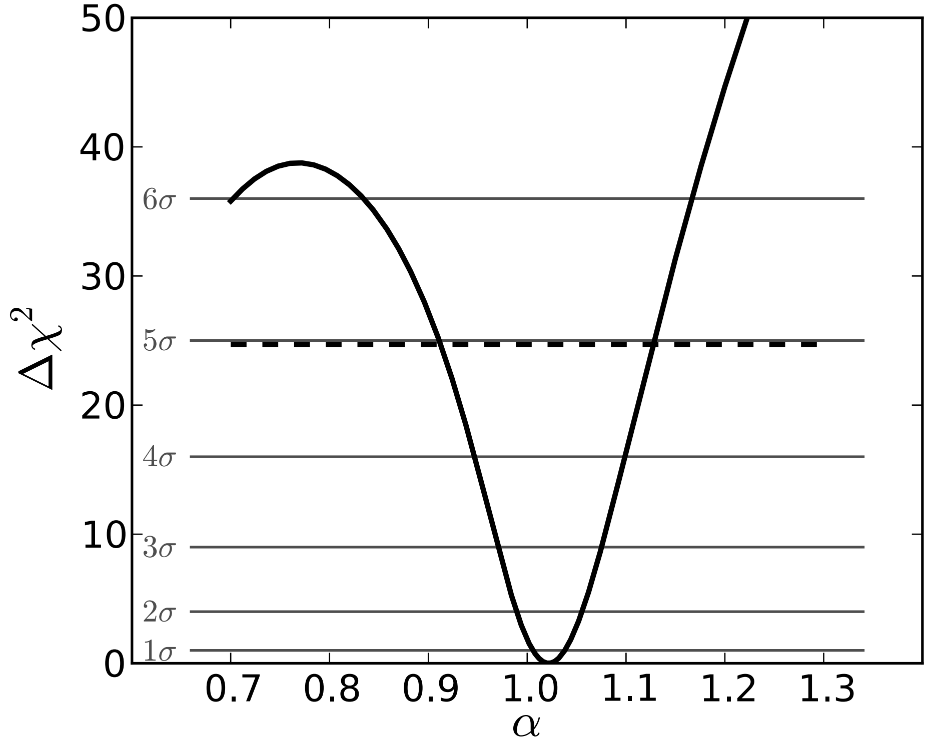


We scale a template by α so that $D_V/r_s = \alpha(D_V/r_s)_{\mathrm{fid}}$

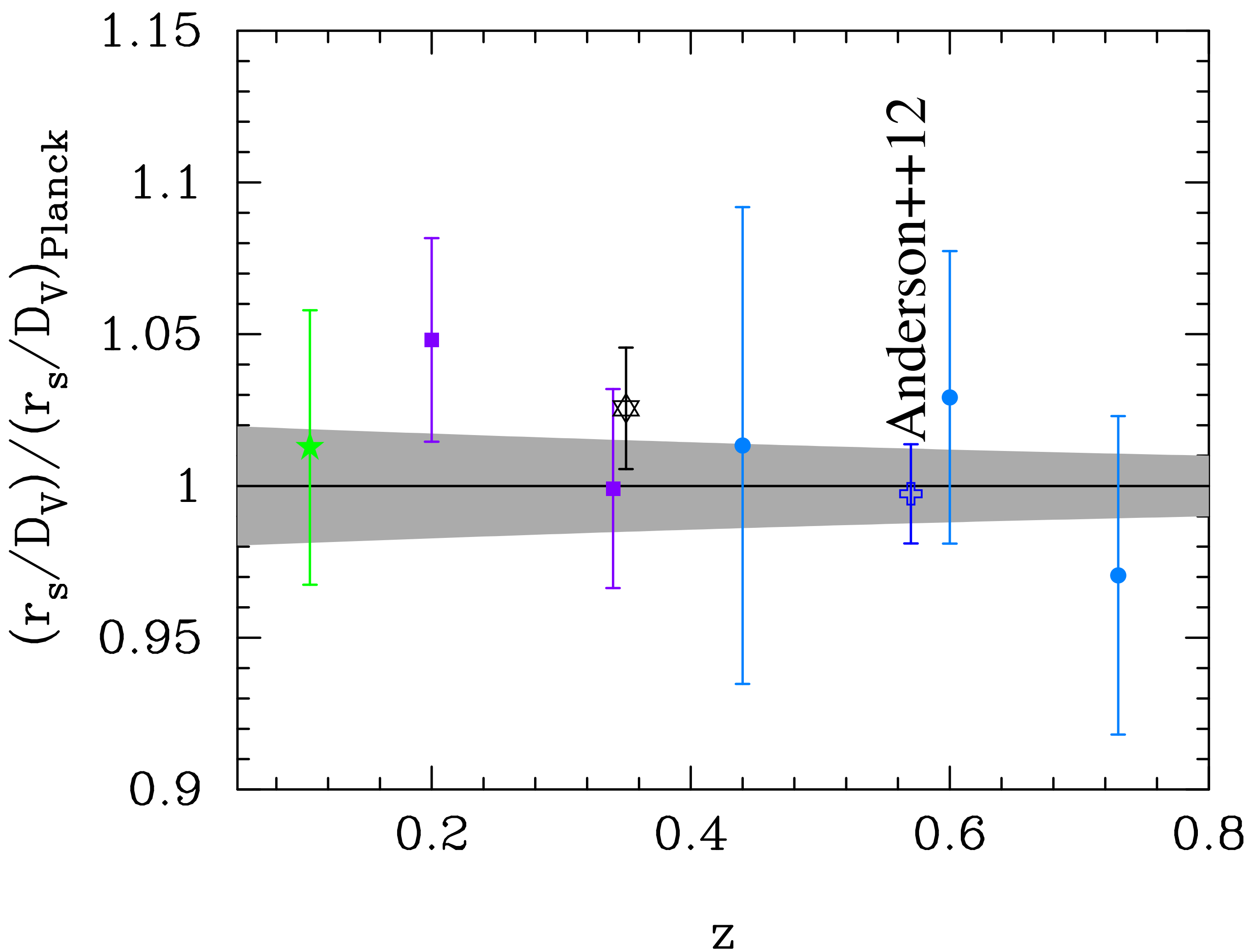
BAO detection: Anderson++12

(BAO detected at >5σ in both ξ and P)





Distance scale comparison: BAO



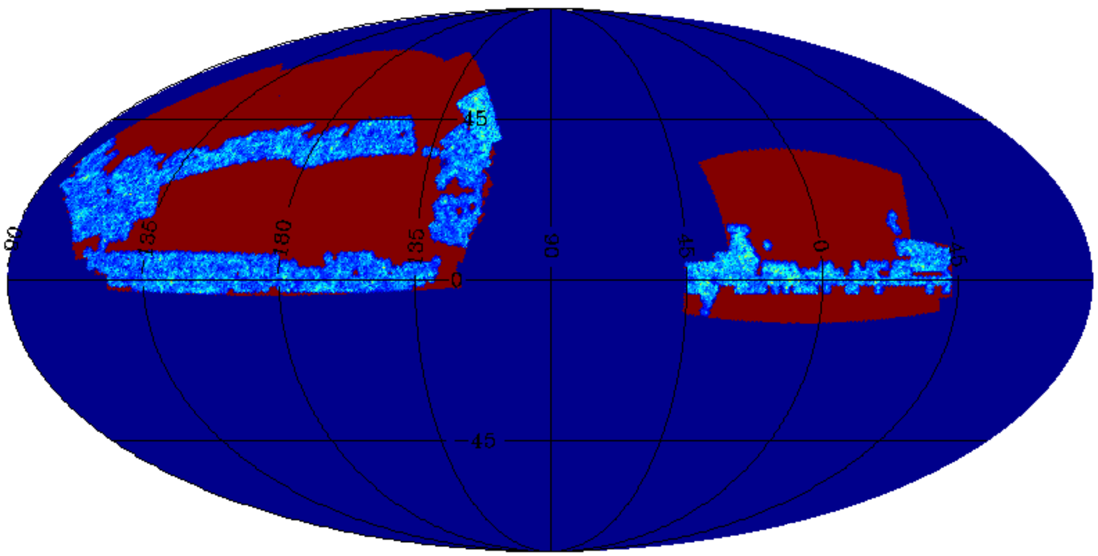
Acoustic oscillations at z~1100 and z<1 tell the same story about the distance scale: ΛCDM!

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%)

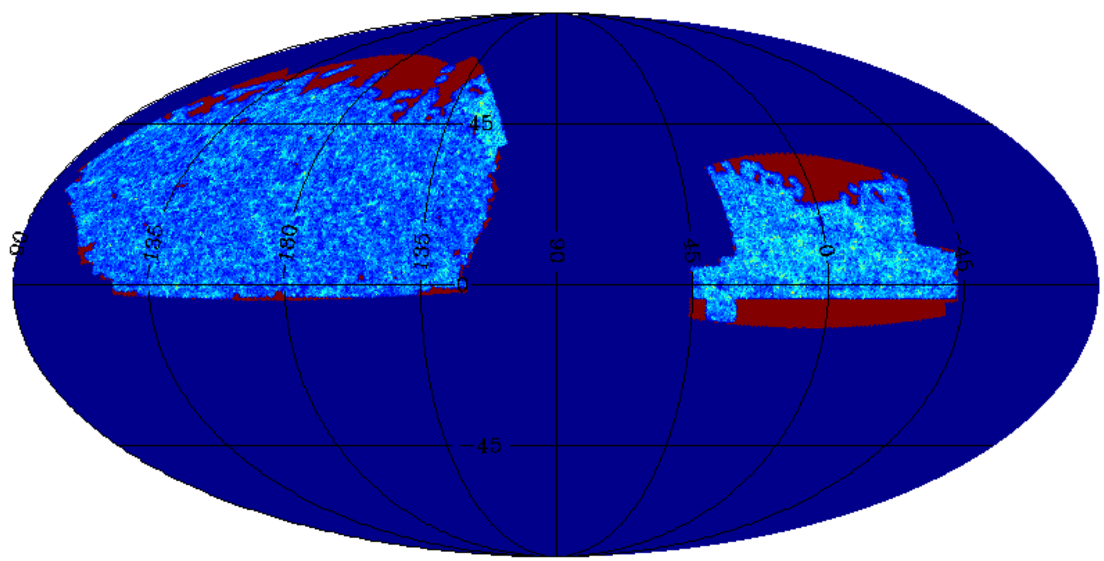
BOSS progress-to-date

DR9



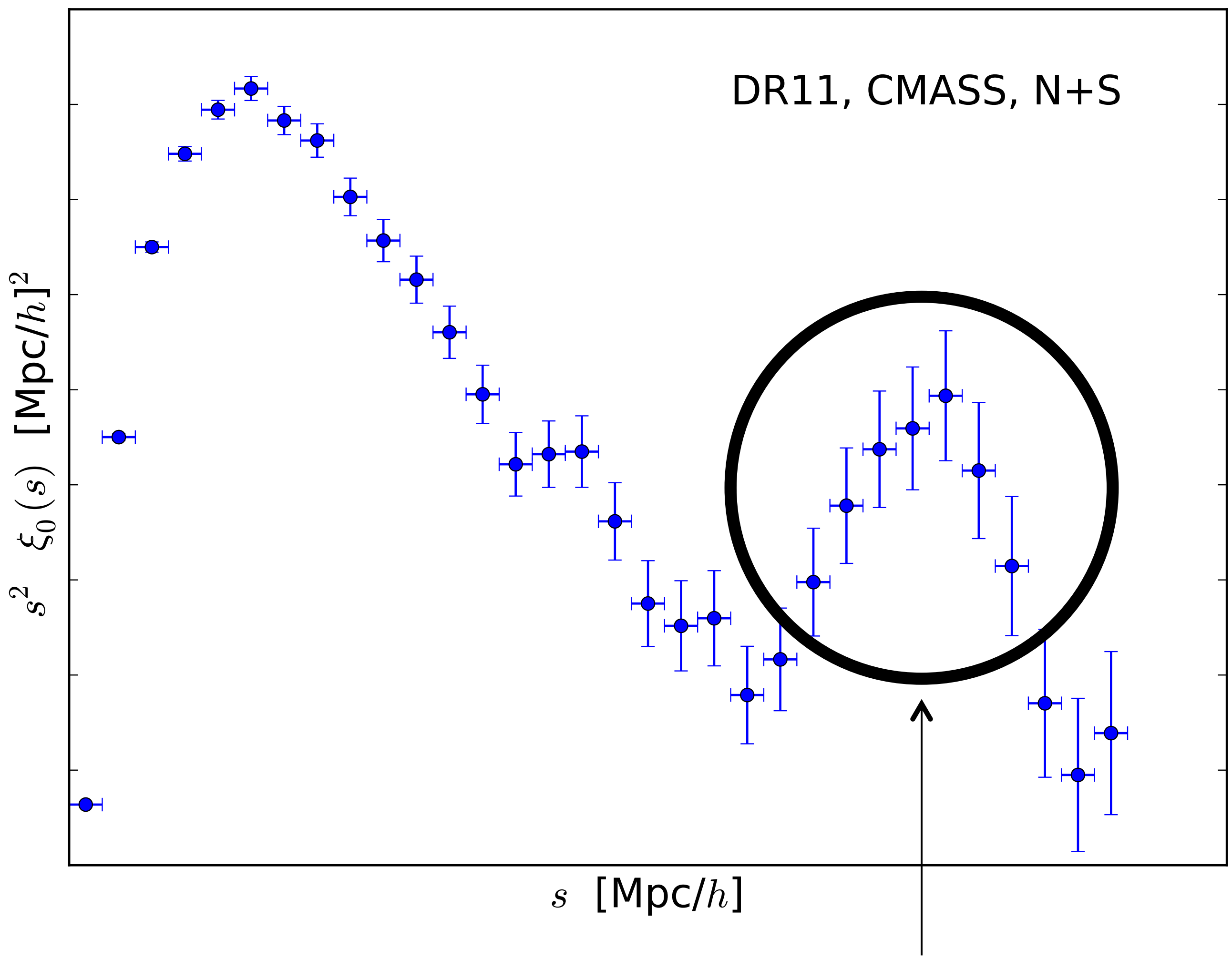
BOSS DR9:
3,275 sq. deg. and
264,283 galaxies.

2013-05-22



BOSS DR11:
8,500 sq. deg. and
1.2M galaxies.

BOSS DR11: approaching 1%



DR11 represents most of the data BOSS will gather, though this plot shows only the CMASS sample. Future releases will include various analysis improvements plus *z* evolution.

Don't even need the line to "guide the eye" anymore!

Conclusions

- The Planck mission has been stunningly successful.
- Impressive confirmation of the standard 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.
- The acoustic oscillation program also allows precision cosmology at lower *z*: BOSS is closing in on a percent-level constraint on distance out to z~0.7.
  - BOSS is ahead of schedule and should finish data taking next Spring.
  - All indications are we will achieve our primary science goals, in addition to many others we didn't think of when we began …

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~~ has the harmonic oscillator ever done for us?

Reg, spokesman for the People's Front of Judea

The End