Cosmological parameters and constraints on inflation from Planck

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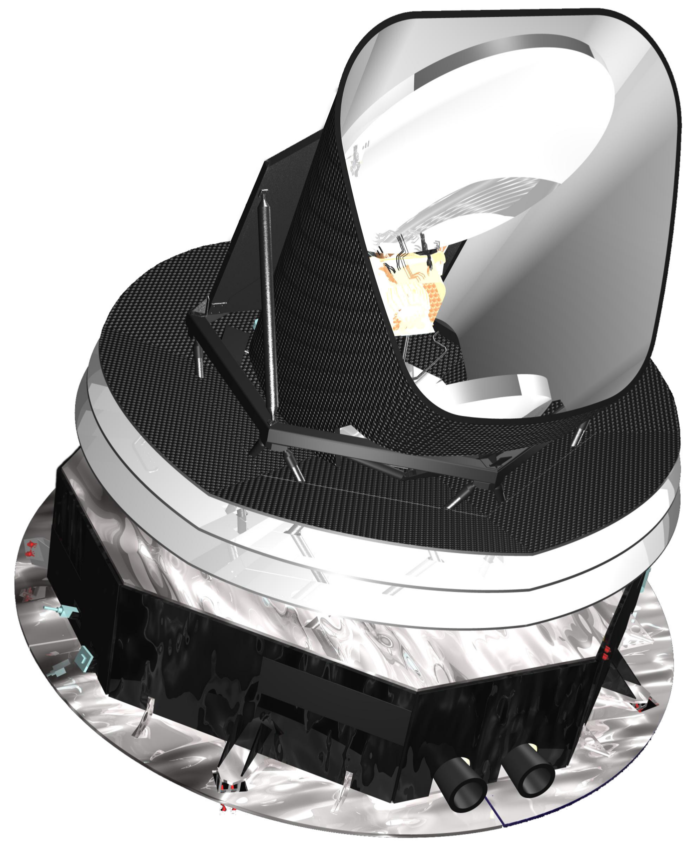
The Cosmic Microwave Background (CMB)

- A snapshot of the early universe from the time of “last scattering”, 380,000 years after the big bang
- The universe is very simple this young, so any lumps seen then must have been there at the Big Bang (unless there are cosmic strings; see paper XXV…)

Simplified description of the Universe often suffices…

- We have distributions of:
  - Matter (Normal and “dark”)
  - Radiation (set by T_{CMB})
  - Dark Energy
- “Optical depth τ, due to reionization”
  - I.e. how much CMB gets “lost” on its way to us
- Initial gaussian, adiabatic, “growing” perturbations described by
  - Amplitude
  - Scale dependence (“spectral index”, n_s)

Planck



http://www.esa.int/Our_Activities/Space_Science/Planck (ESA)

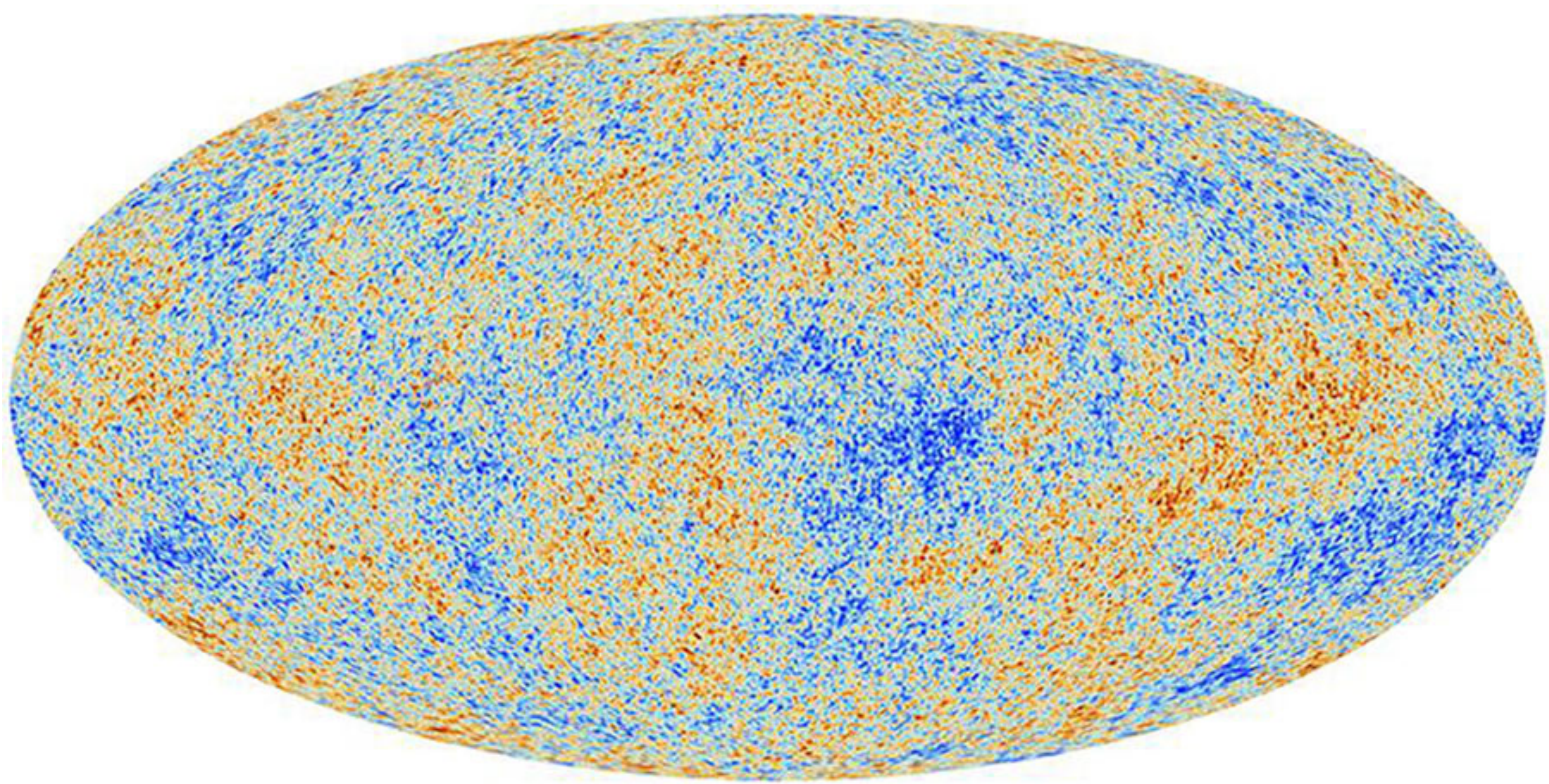
http://www.rssd.esa.int/index.php?project=Planck

The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 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.

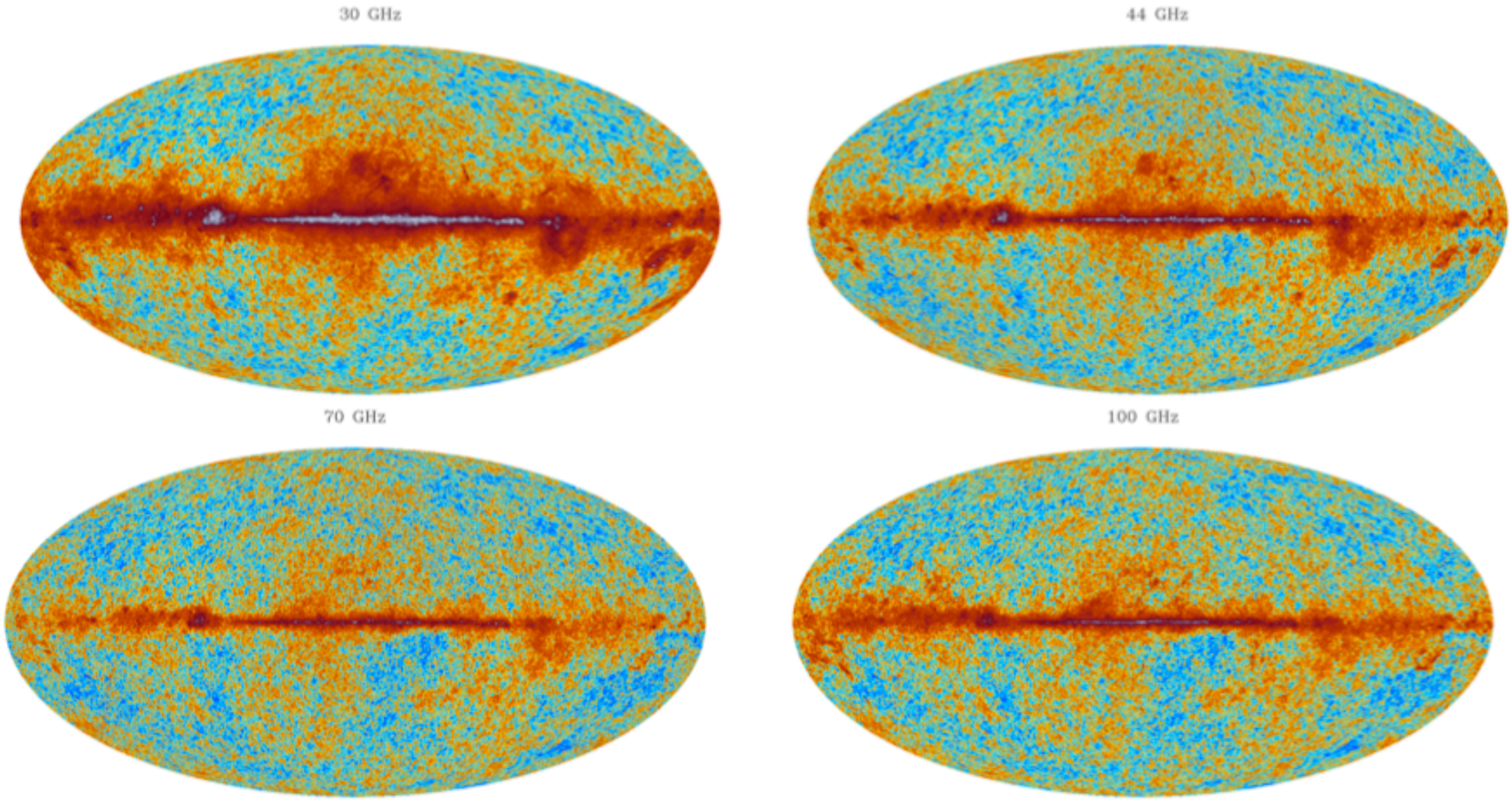
- Planck 2013 results. XV. CMB power spectra and likelihood
- Planck 2013 results. XVI. Cosmological parameters
- Planck 2013 results. XVII. Gravitational lensing by large-scale structure
- Planck 2013 results. XXII. Constraints on inflation

Planck CMB map



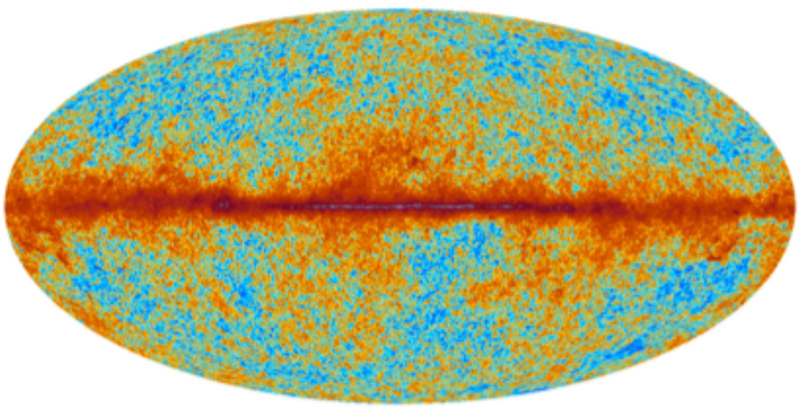
(ESA)

Actually, what we really see is…

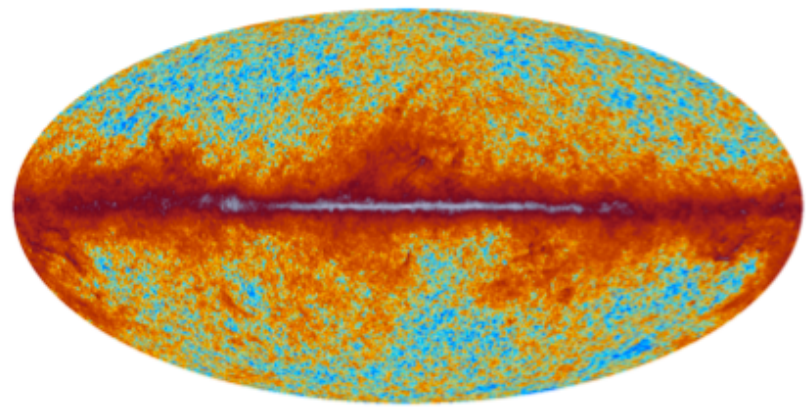


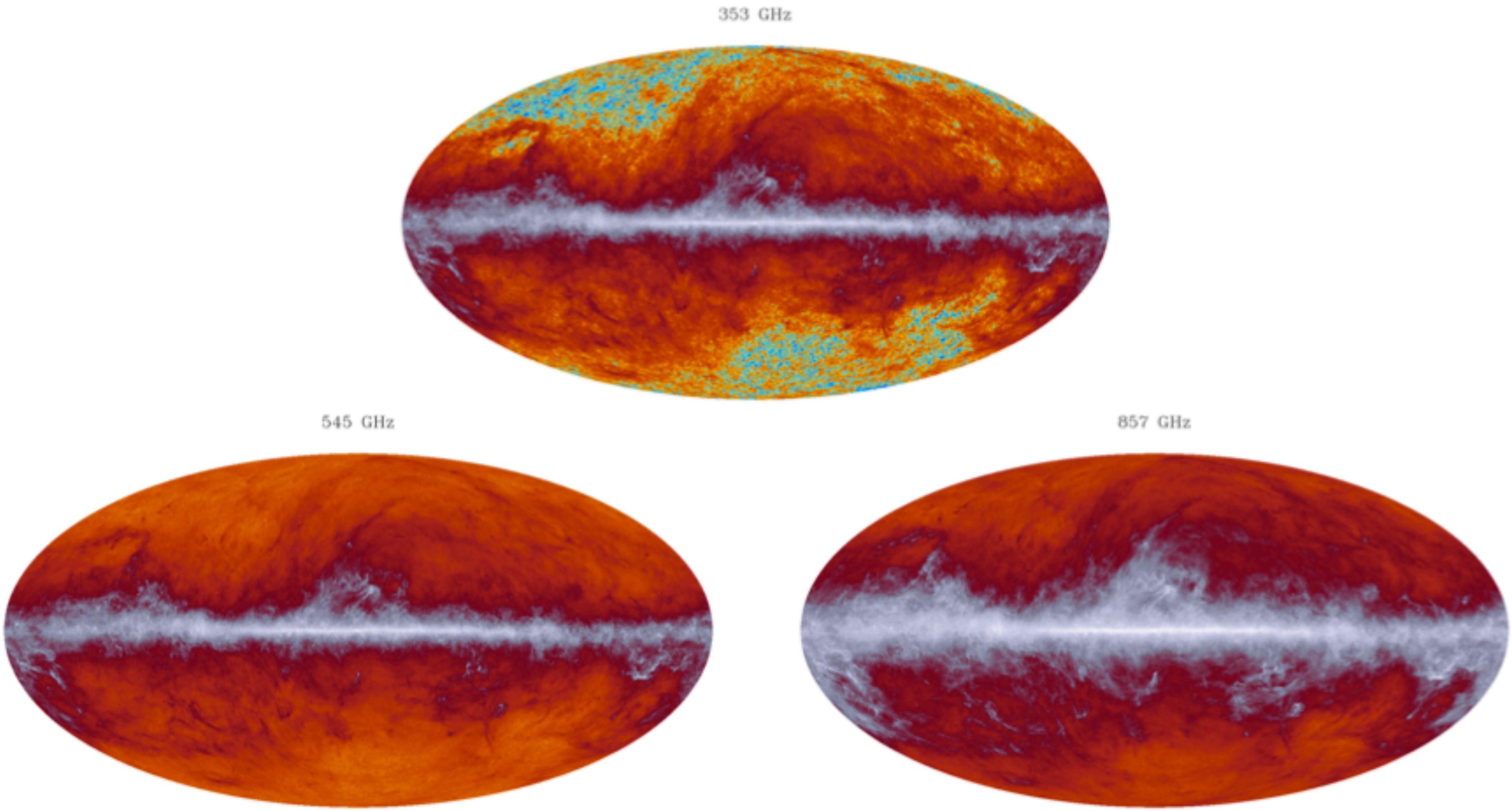
Planck 2013 results. I. Overview of products and scientific results

143 GHz



217 GHz




353 GHz
545 GHz
857 GHz

How to analyze?

- Low-l (multipoles $2 <= l <= 49$)
  - Use a "Gibbs sampler" on low-res maps
    - More or less equivalent to a pixel-based approach, also handles foregrounds and is faster to use
    - Uses 91% of the sky
- High-l (multipoles $50 <= l <= 2500$)
  - …

At high-l we have to deal with *unresolved* foregrounds…

- "Point Sources"
  - Synchroton and dust emission from galaxies

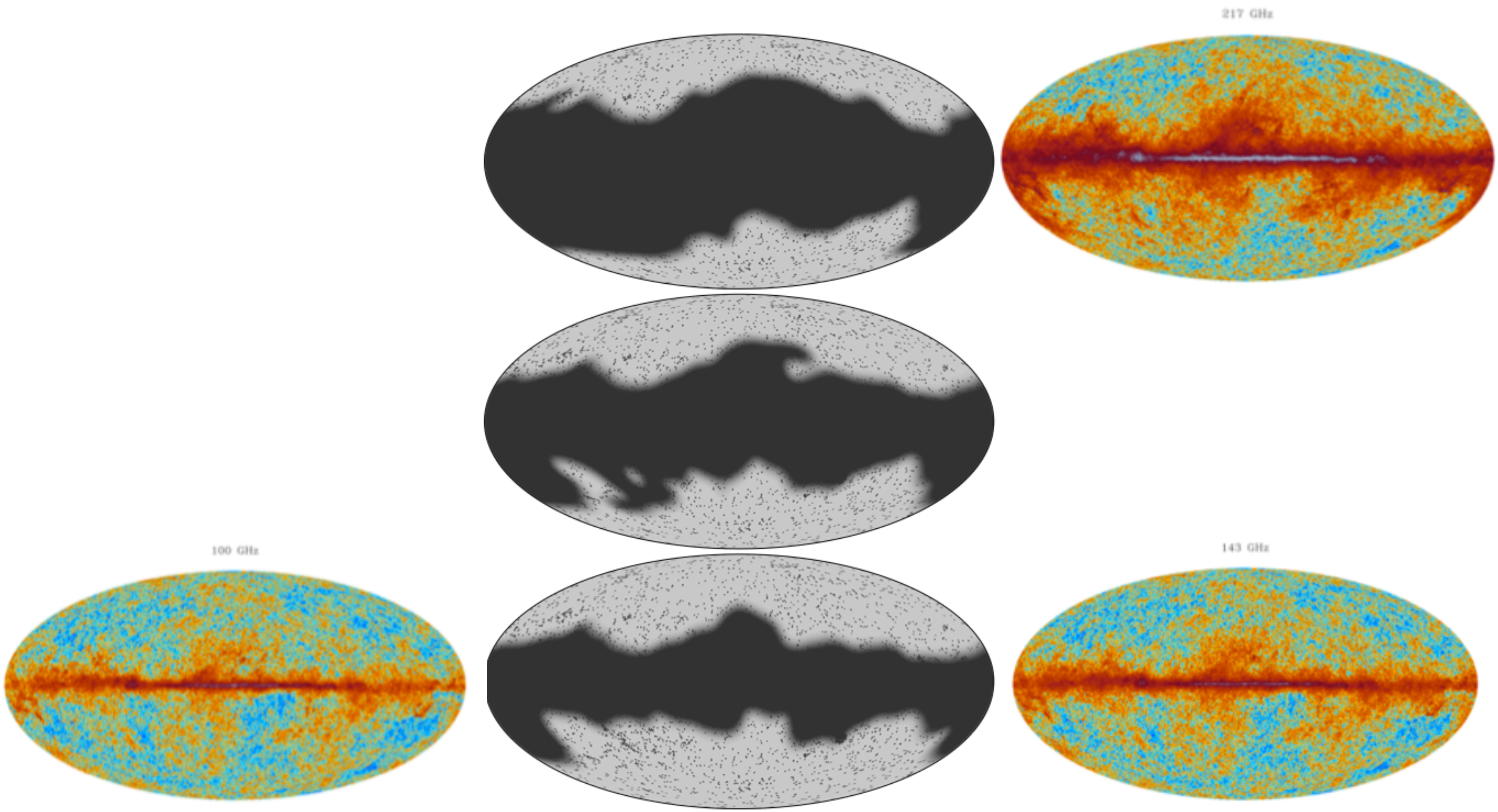
- SZ (Sunyaev-Zeldovich) Effect
  - Hot gas in clusters of galaxies interacts with CMB on its way to us

- CIB (Cosmic Infrared Background)
  - Structured Emission from dusty galaxies

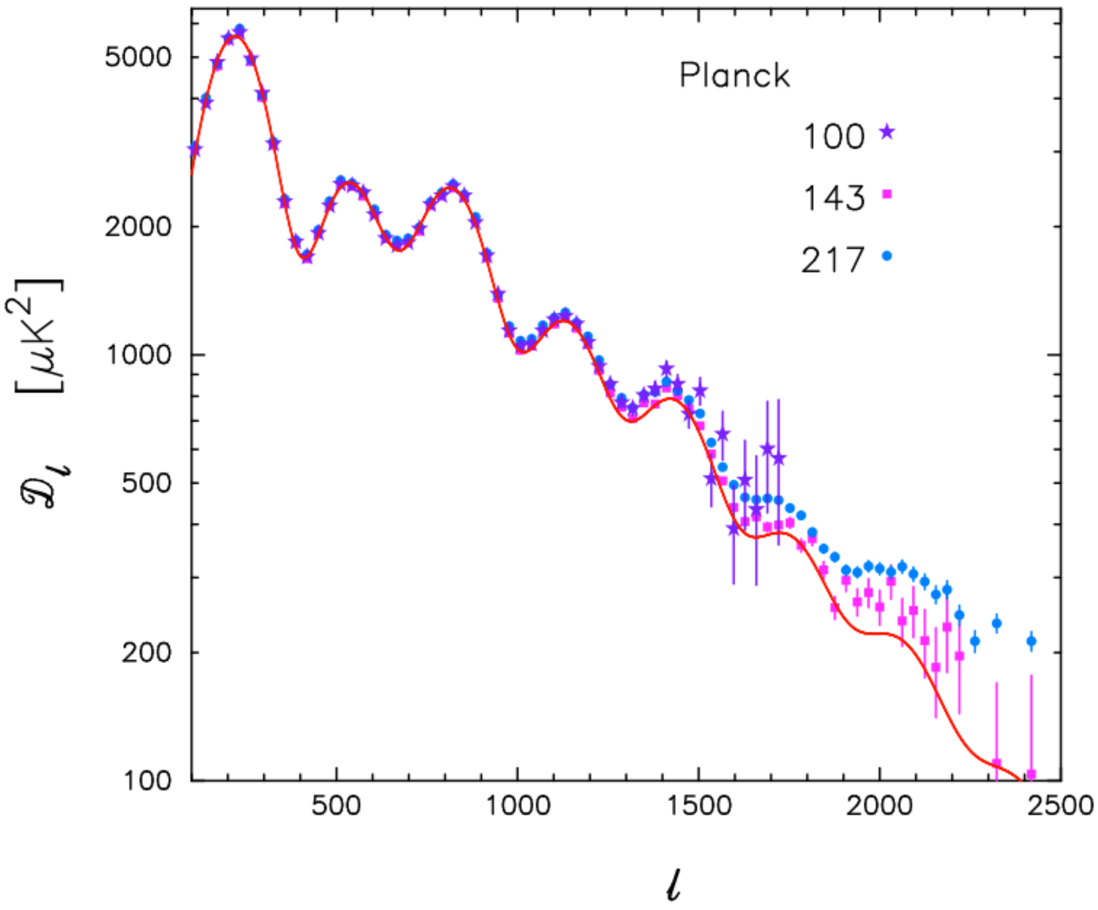
…and instrumental systematics

- Relative calibration factors
- Beam errors

In fact we use the just cleanest channels and apply big masks…

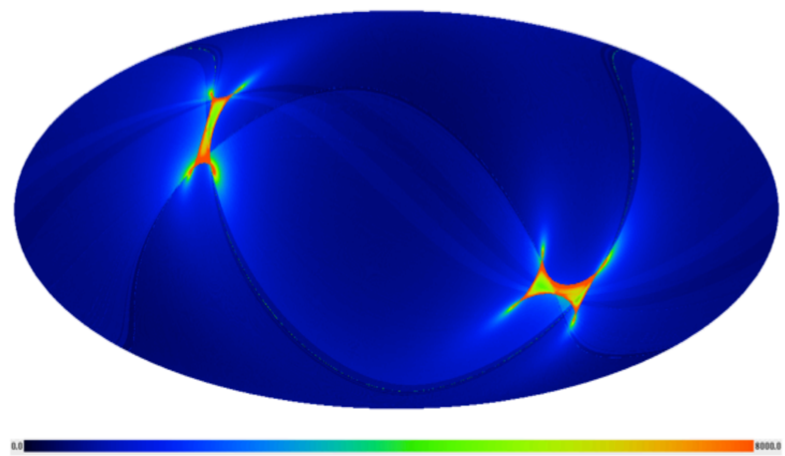


We use "pseudo" power spectra…

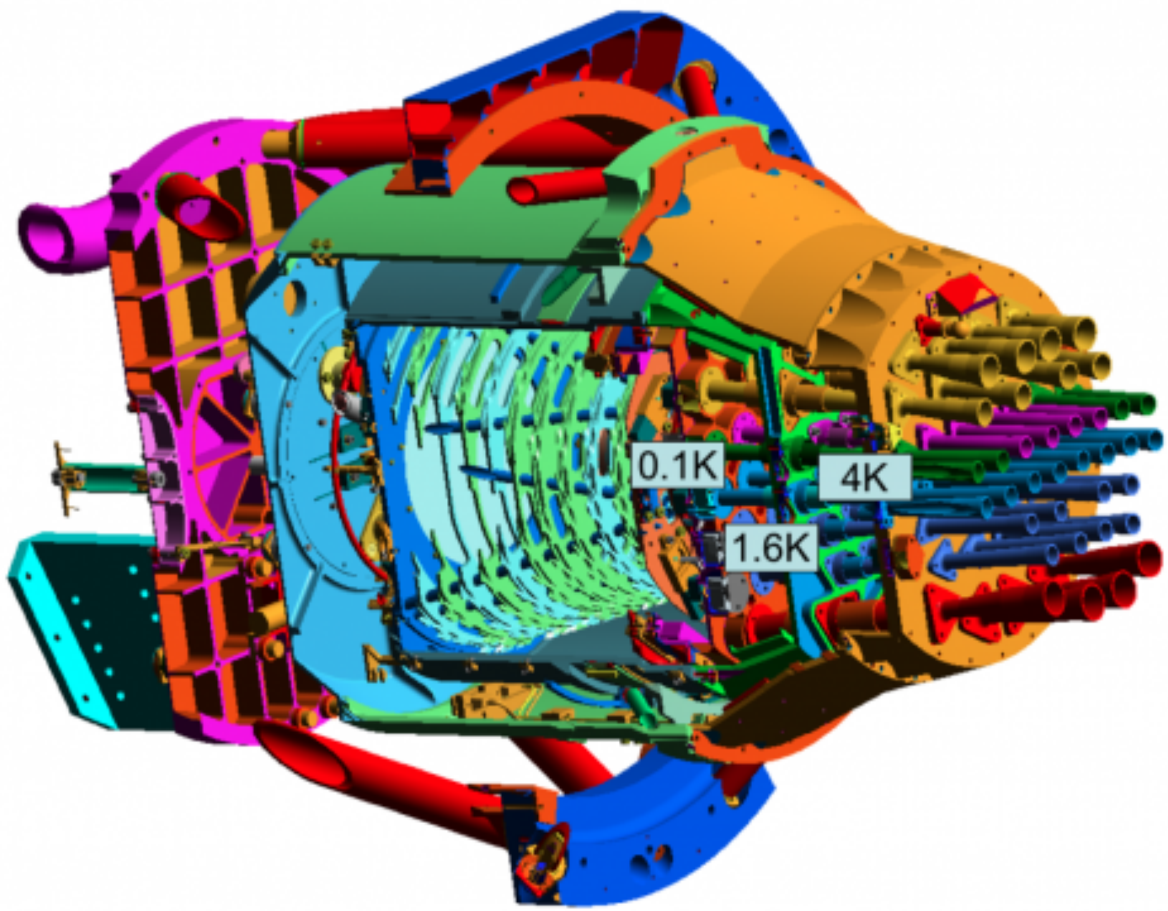


But these don’t come from the frequency maps!

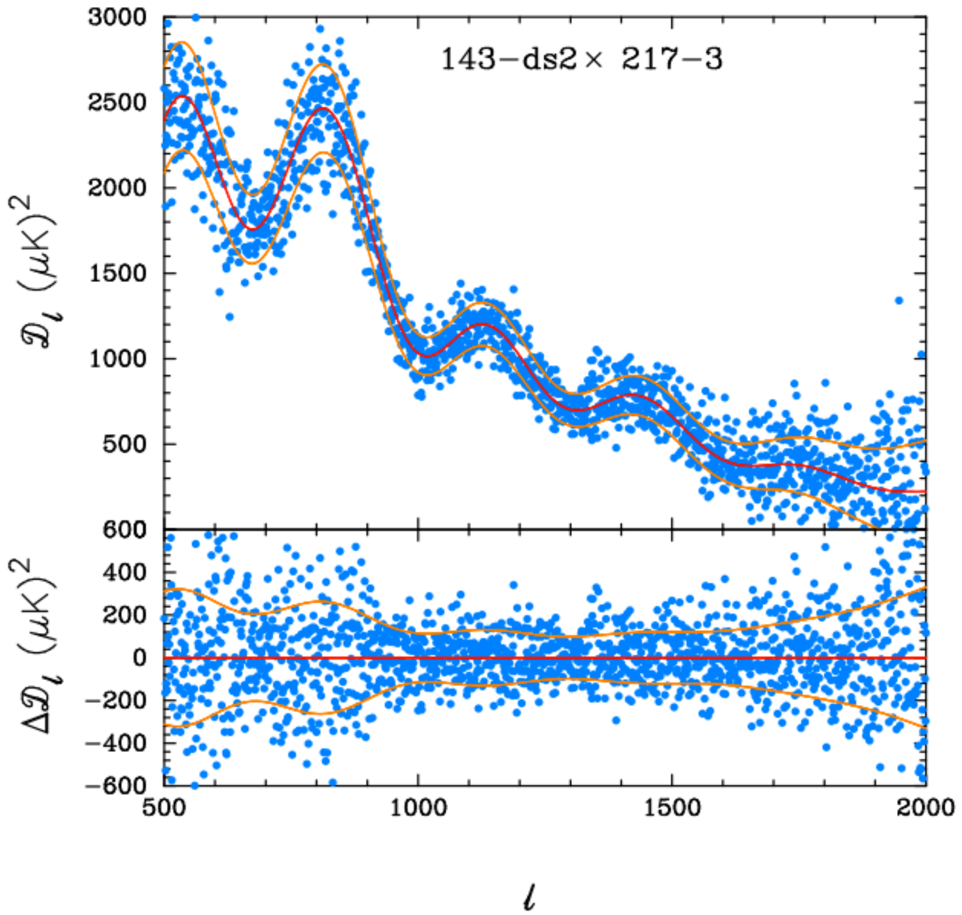
- One would see the noise contribution
  - And have to model it just right to trust subtracting it out!



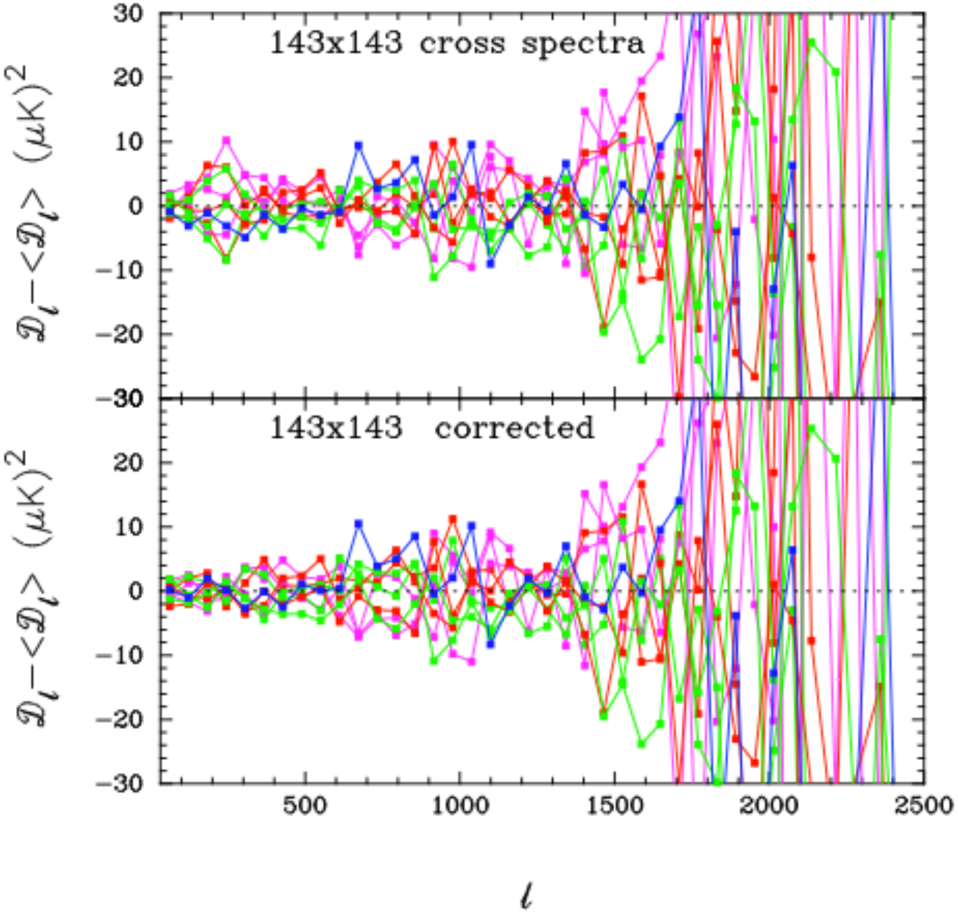
Planck actually makes multiple maps at each frequency…



We can make many "fine-grained" cross spectra, e.g. …



And take weighted averages of them…

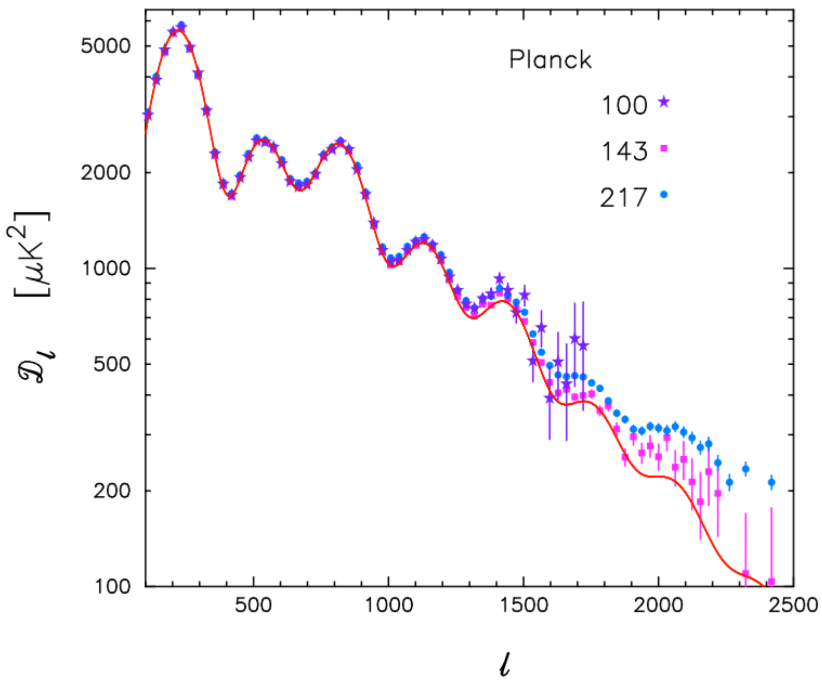


Left with four effective spectra…

- 100x100: 50<=/<=1200
- 143x143: 50<=/<=2000
- 217x217: 500<=/<=2500
- 143x217: 500<=/<=2500

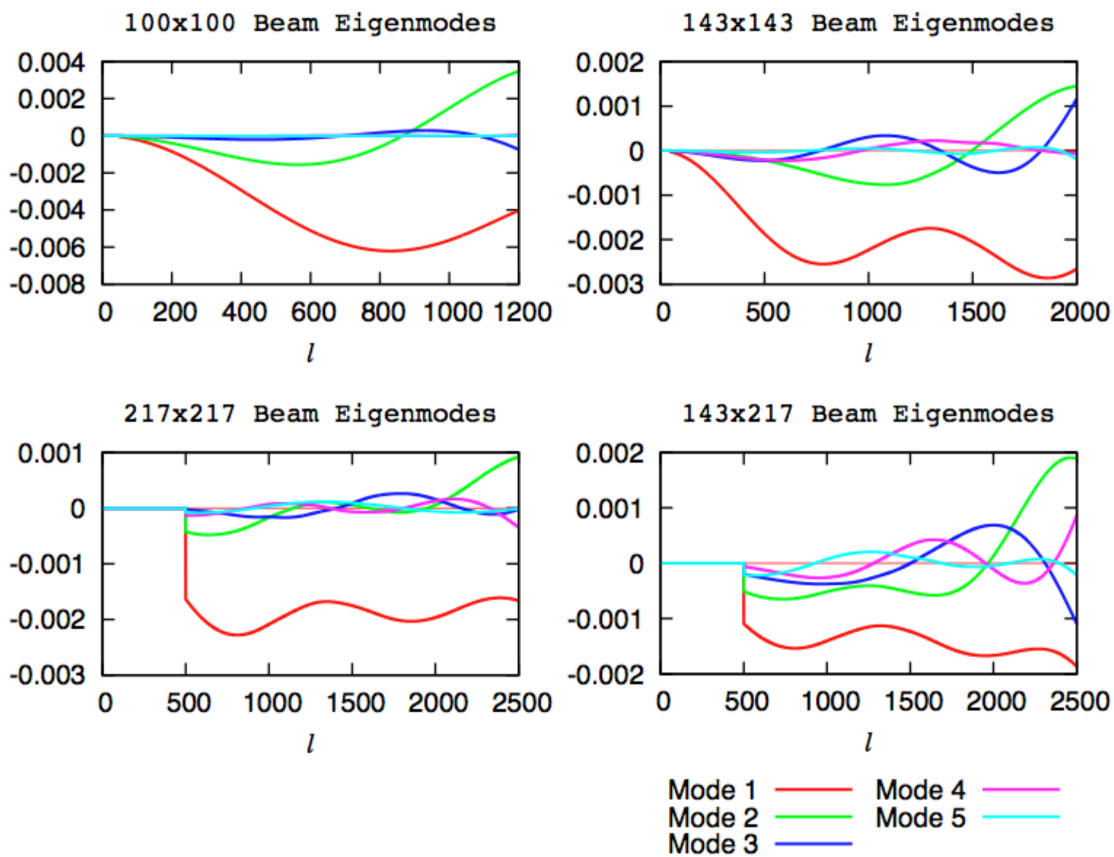
Unresolved components

- Model them at the power spectrum level
  - Simple templates in *l*
  - Various coefficients to describe amplitudes and (cross-) correlations



Beam errors

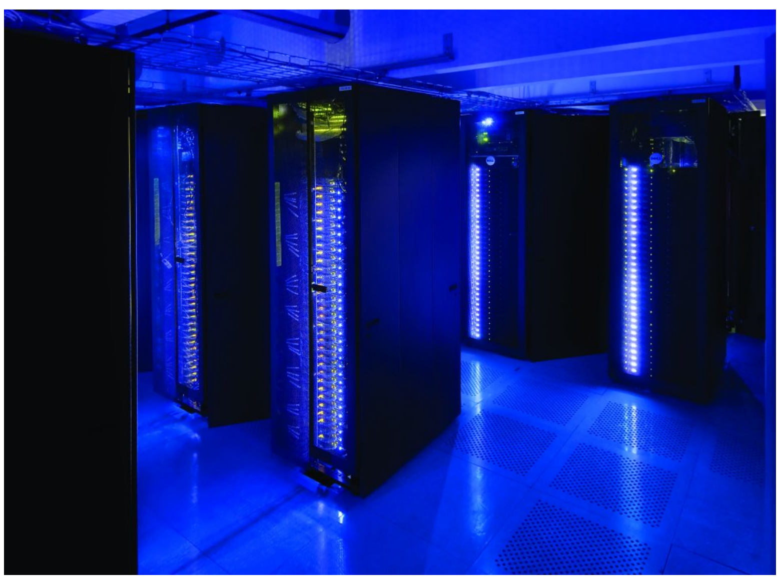
- We parameterize uncertainties in our understanding of the beams with "beam eigenmodes"



- Different theories lead to different predictions about what the CMB map should statistically look like
- Gives us a way to figure out what the universe is like

Compare theories to data using Bayes' Theorem:

$$P(\text{theory}|\text{data}) = \frac{P(\text{data}|\text{theory})\, P(\text{theory})}{P(\text{data})}$$



Planck alone

- Seven peaks give us the acoustic scale really well:
  - $\theta_* = (1.04148 \pm 0.00066) \times 10^{-2}$
    $= 0.596724^\circ \pm 0.00038^\circ$.
- Turns out the following is also really well constrained:
  - $\Omega_\mathrm{m}h^3 = 0.0959 \pm 0.0006$
- 2% constraint on H_0:
  - $H_0 = (67.4 \pm 1.4)\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

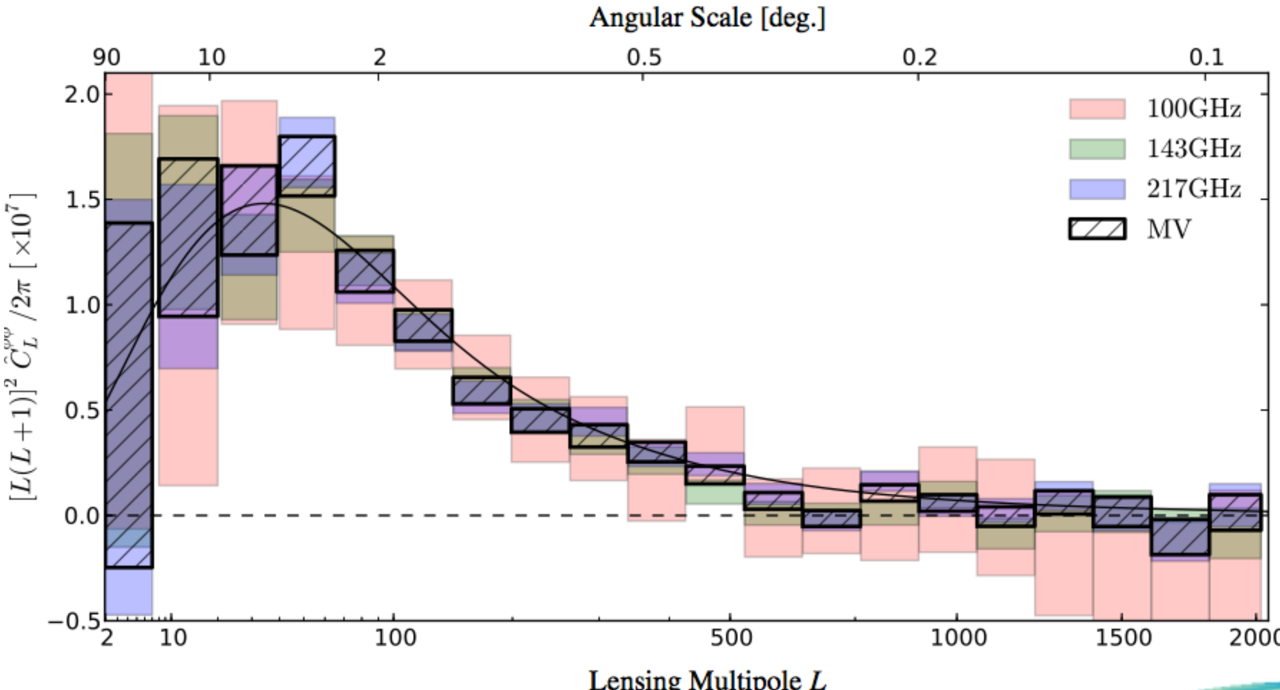
Also add in other data sets

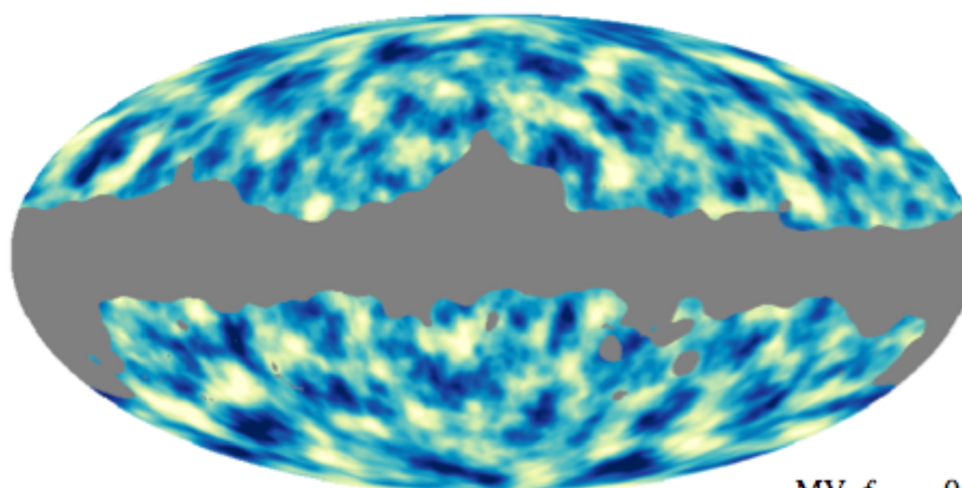
- CMB
  - WMAP polarization data (helps for tau)
  - High-l experiments, ACT & SPT, looking at small regions of the sky at high-resolution
- Non-CMB

Planck 2013 Results. XVII Gravitational lensing by large-scale structure.

  - Planck lensing map (DM distribution deduced from CMB deflections)
  - BAO ("baryon acoustic oscillation") measurements
    - wiggles in the matter power spectrum
  - (SN and HST)

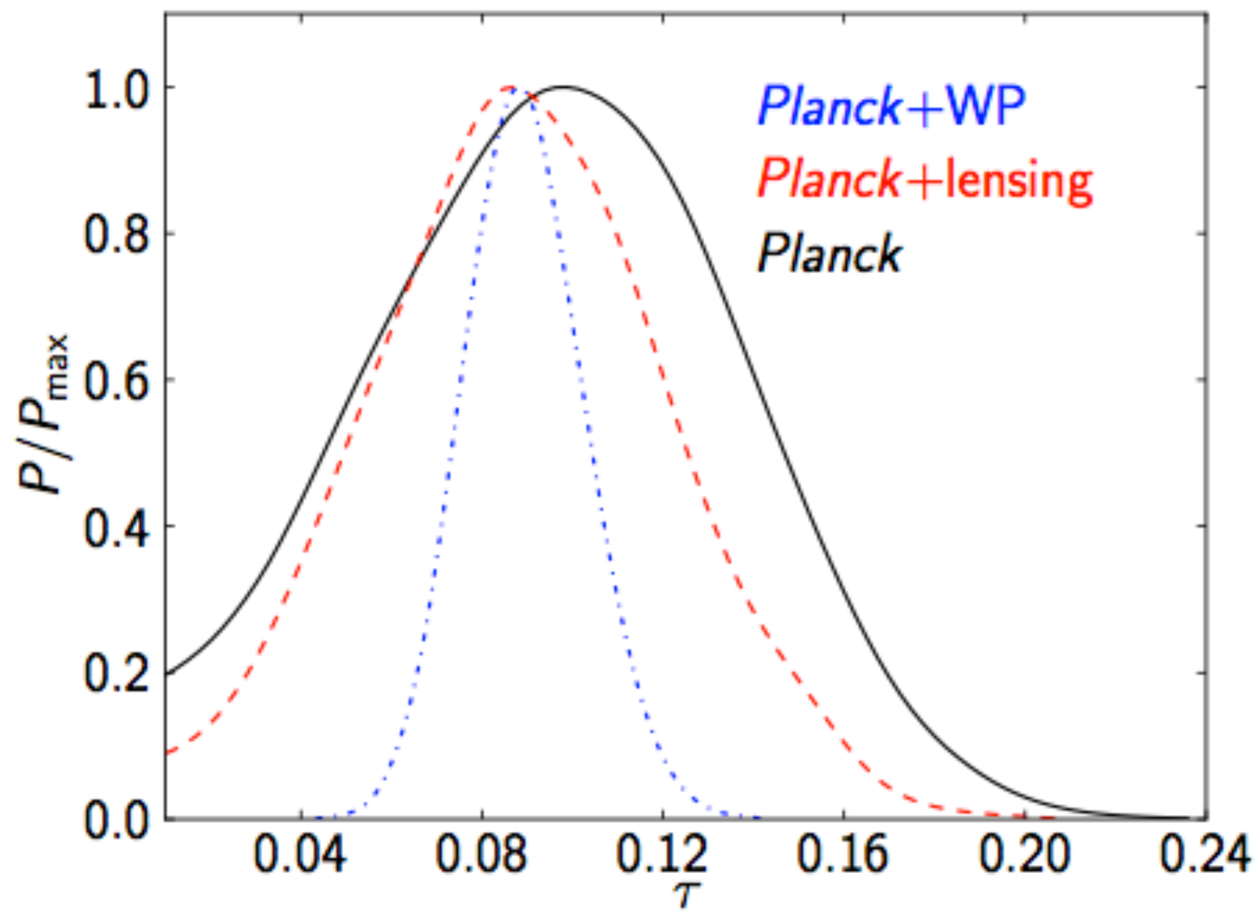
Planck Lensing (1)



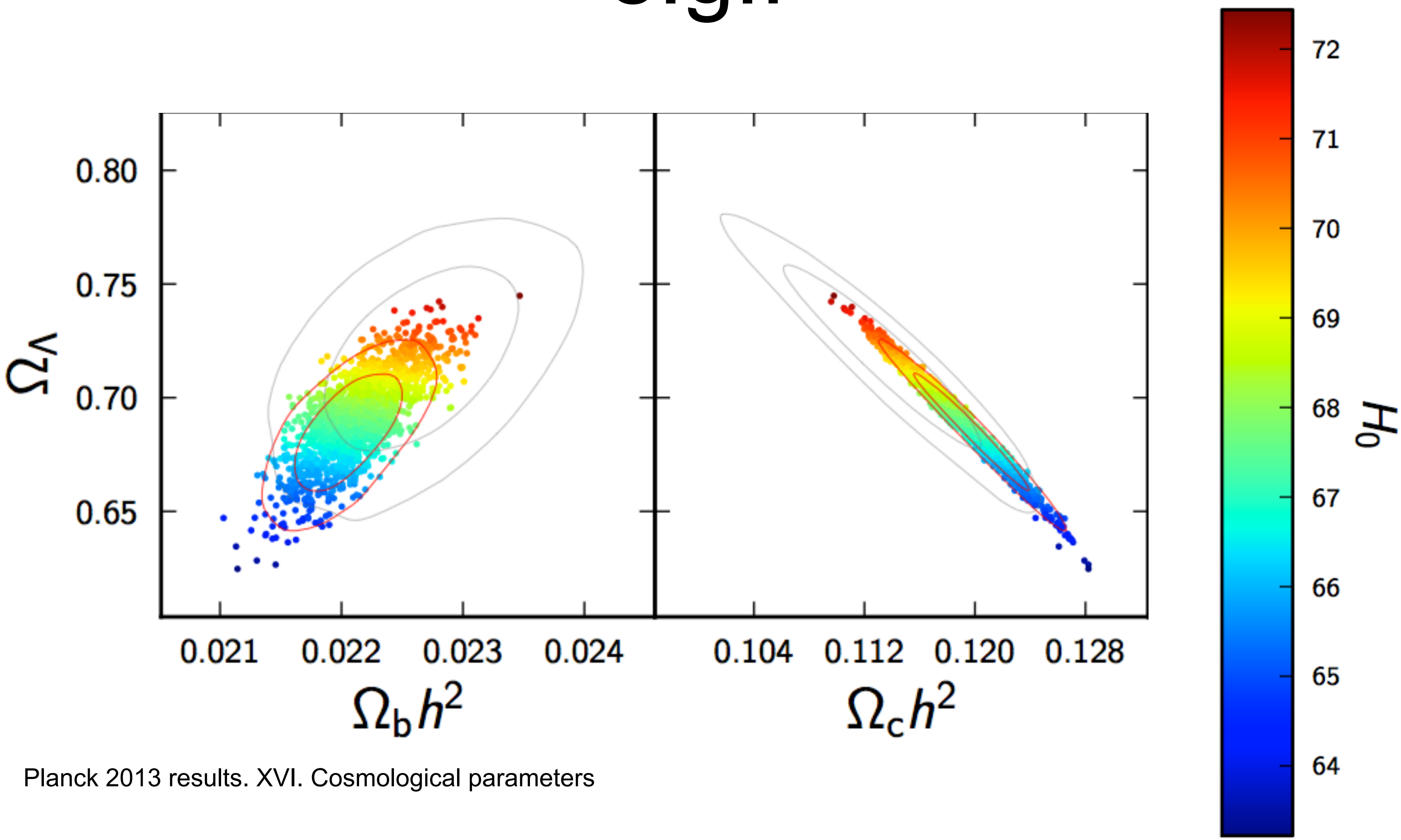


MV, $f_{\rm sky}$ = 0.70

Planck Lensing (2)

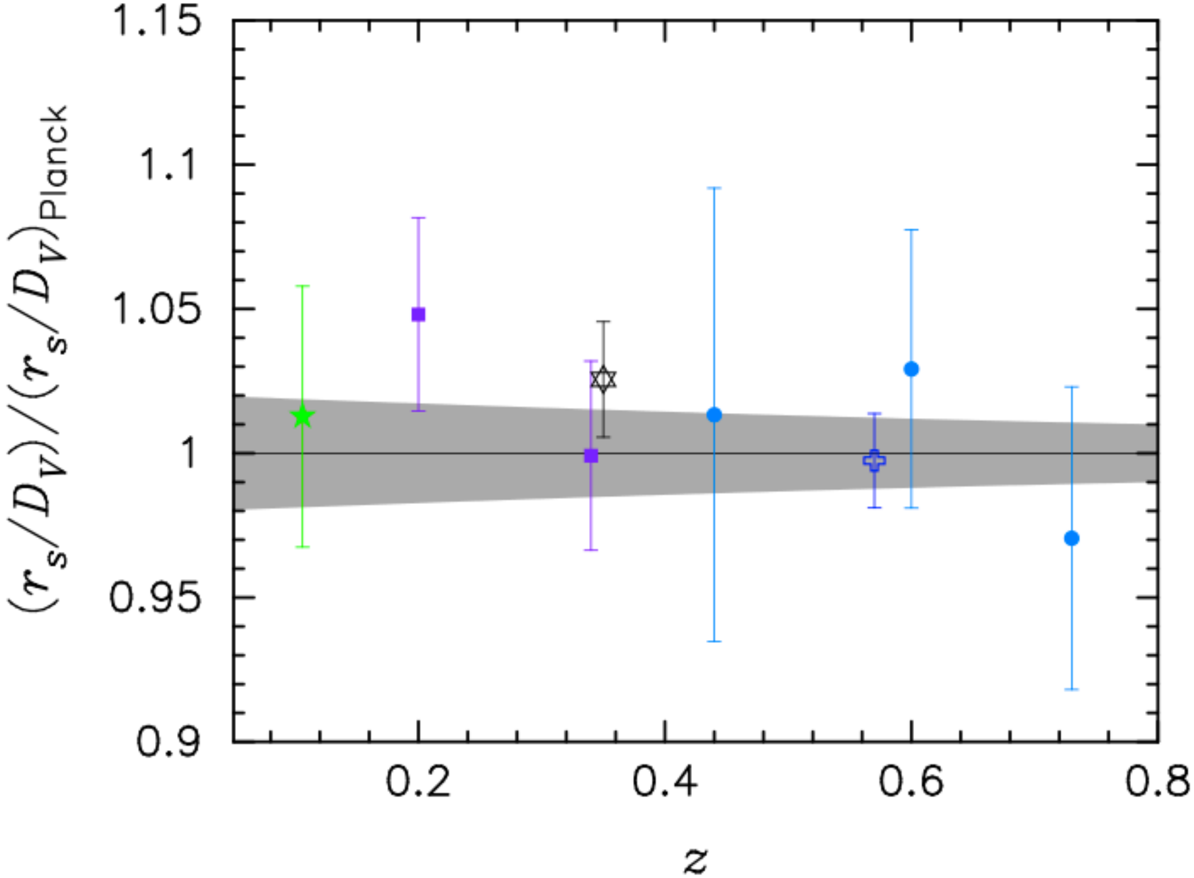


Get nice parameter constraints, e.g.:

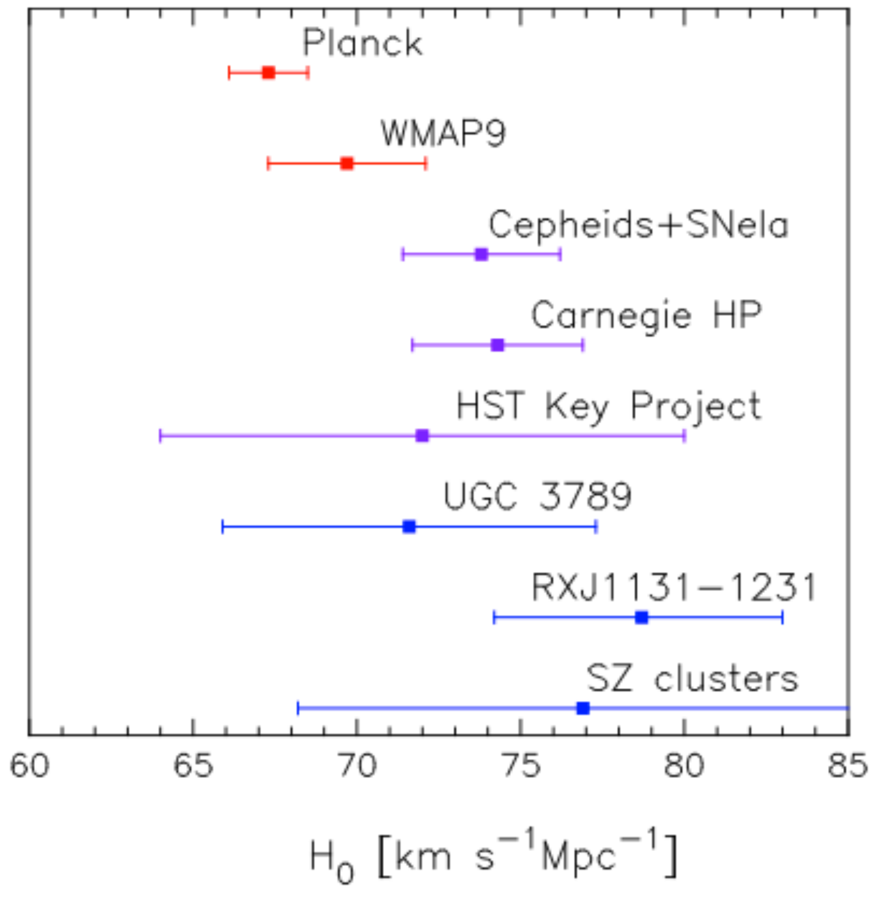


Planck 2013 results. XVI. Cosmological parameters

BAO



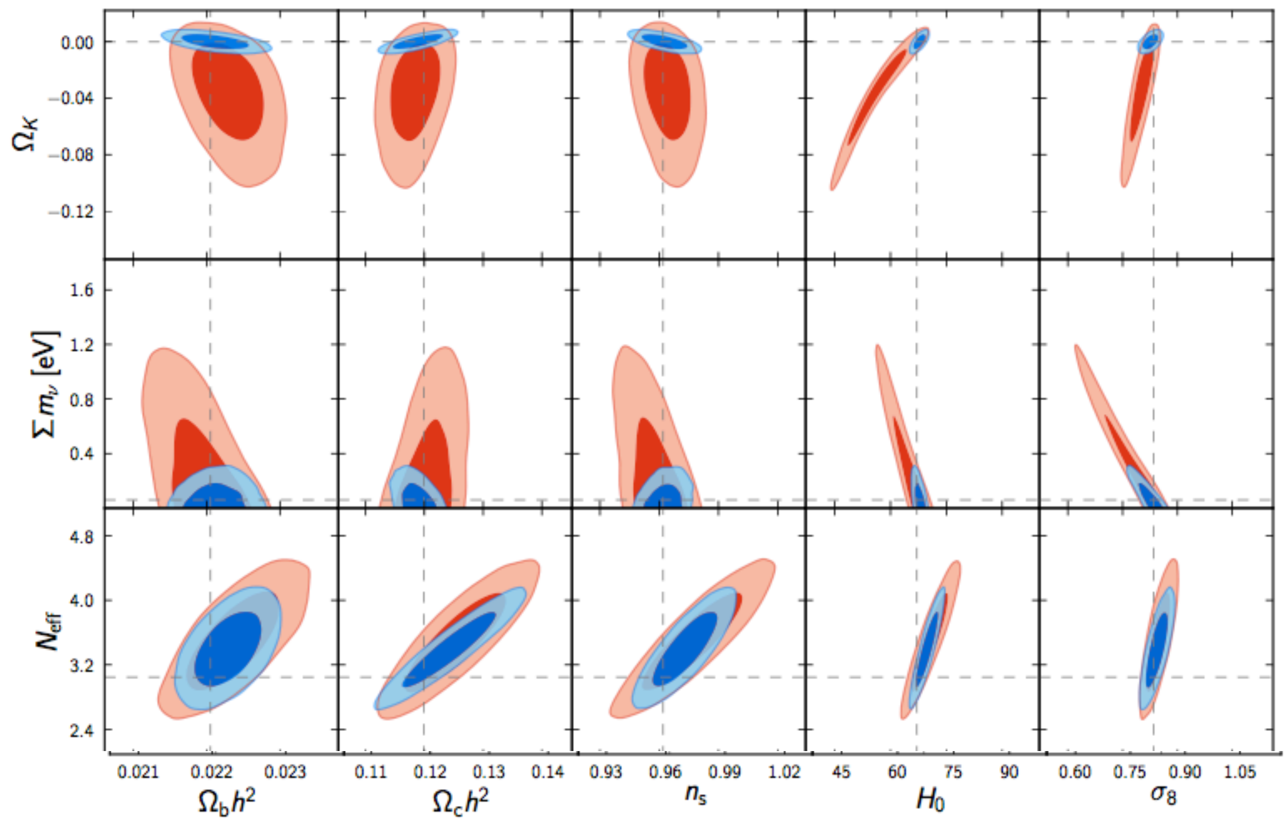
HST



Planck
WMAP9
Cepheids+SNeIa
Carnegie HP
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
H_0 [km s^{-1}Mpc^{-1}]

But what of plausible extensions? Nothing!

- Curvature, neutrino masses, varying number of neutrinos…



- Helium fraction, running, tensors, dark energy…

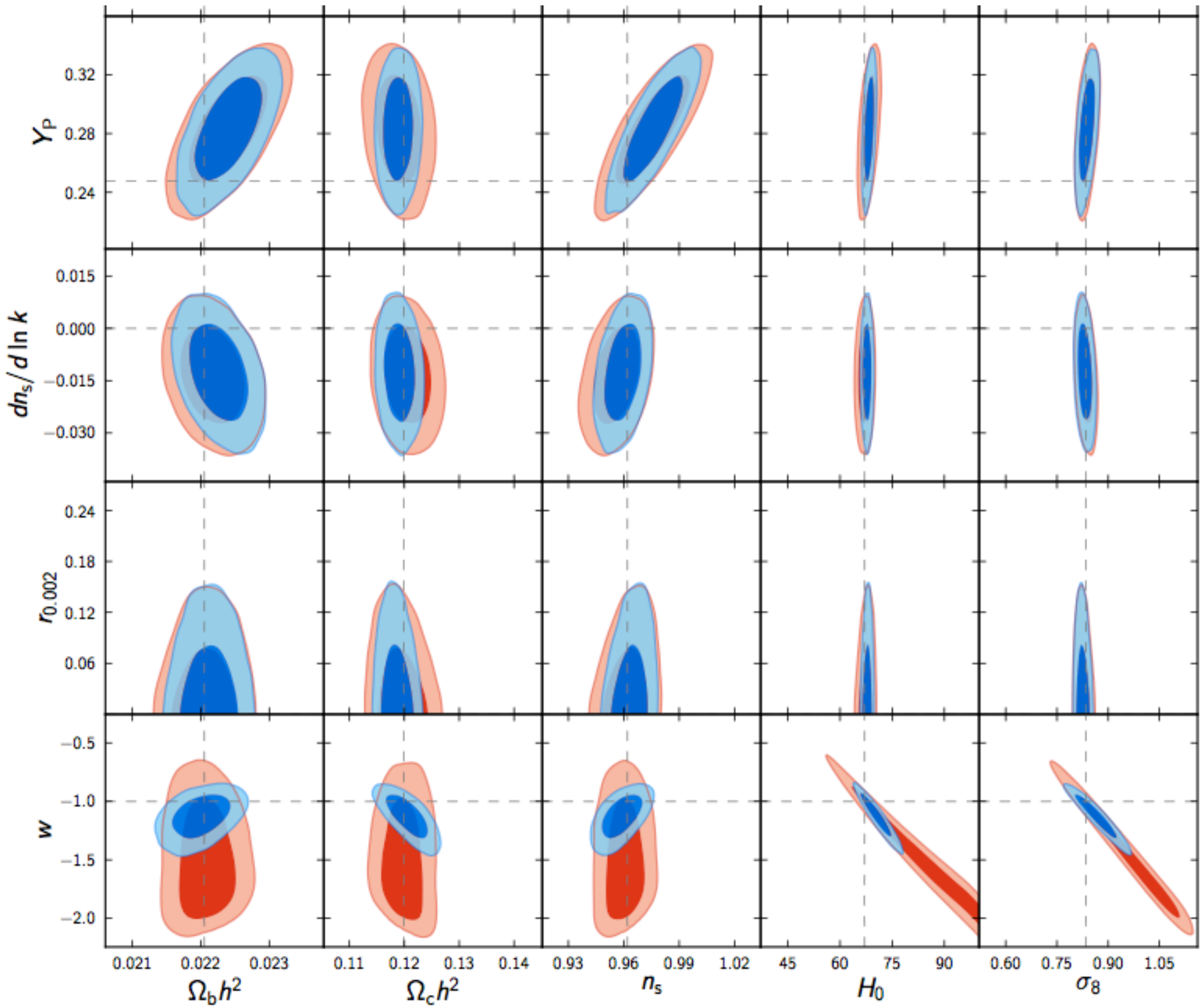
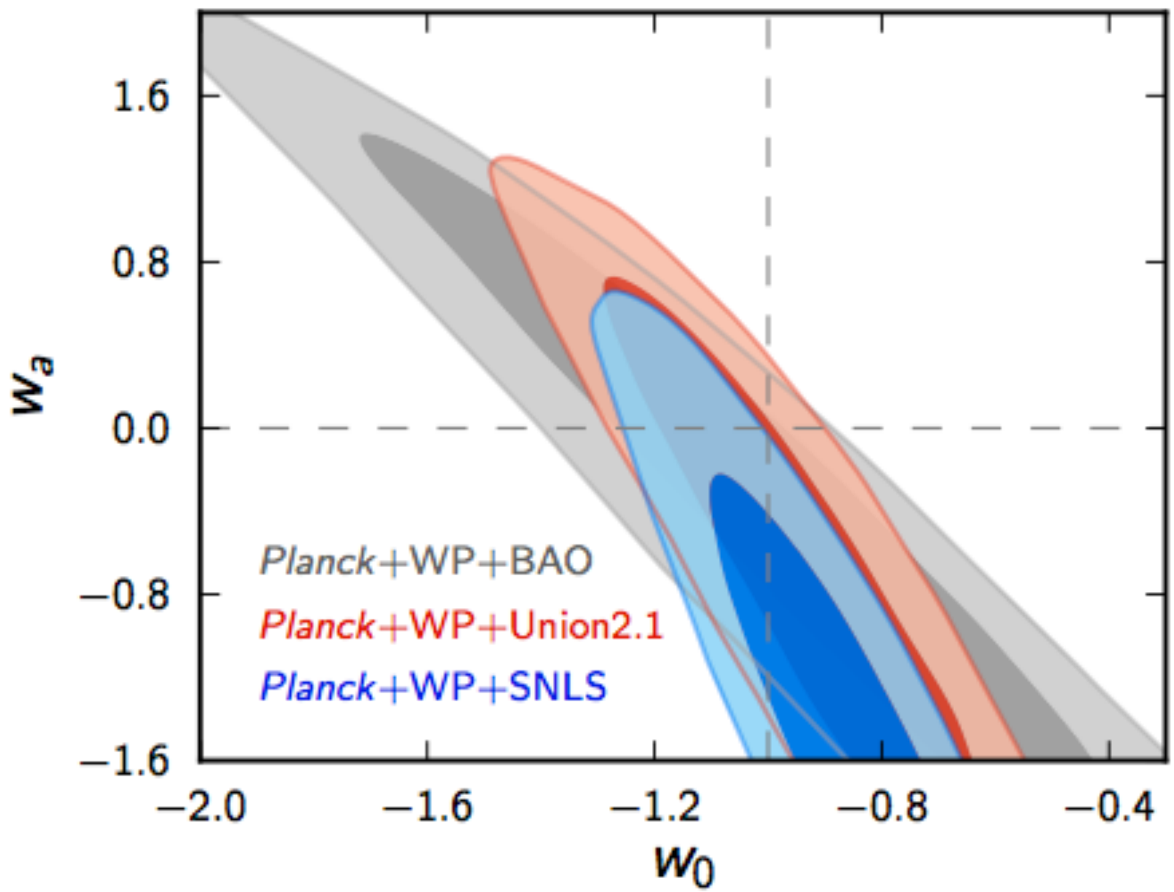


Illustration of effects of tensions on extended models:



- Check out our full “grid” of models and data combinations online:
  - http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive

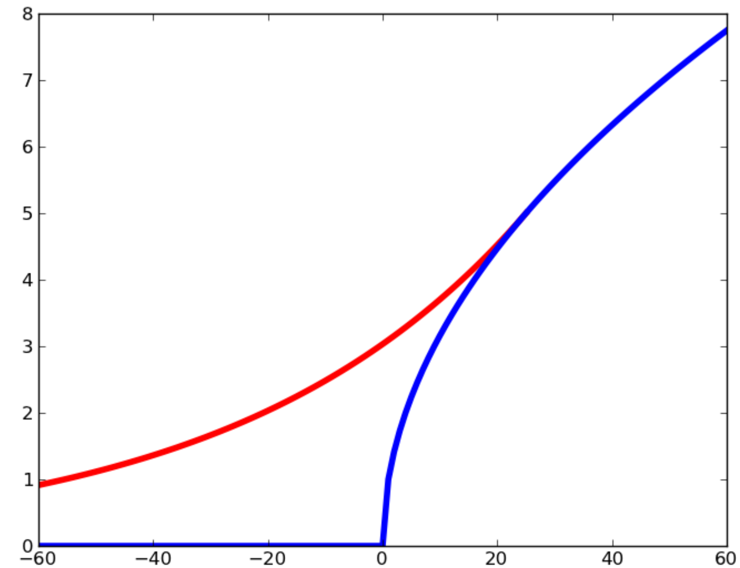
Still questions about LCDM…

- What is the dark matter?
- What is the dark energy?

- Why is the Universe neither totally chaotic nor perfectly uniform? (The Horizon Problem…)

Therefore, inflation! (perhaps…)

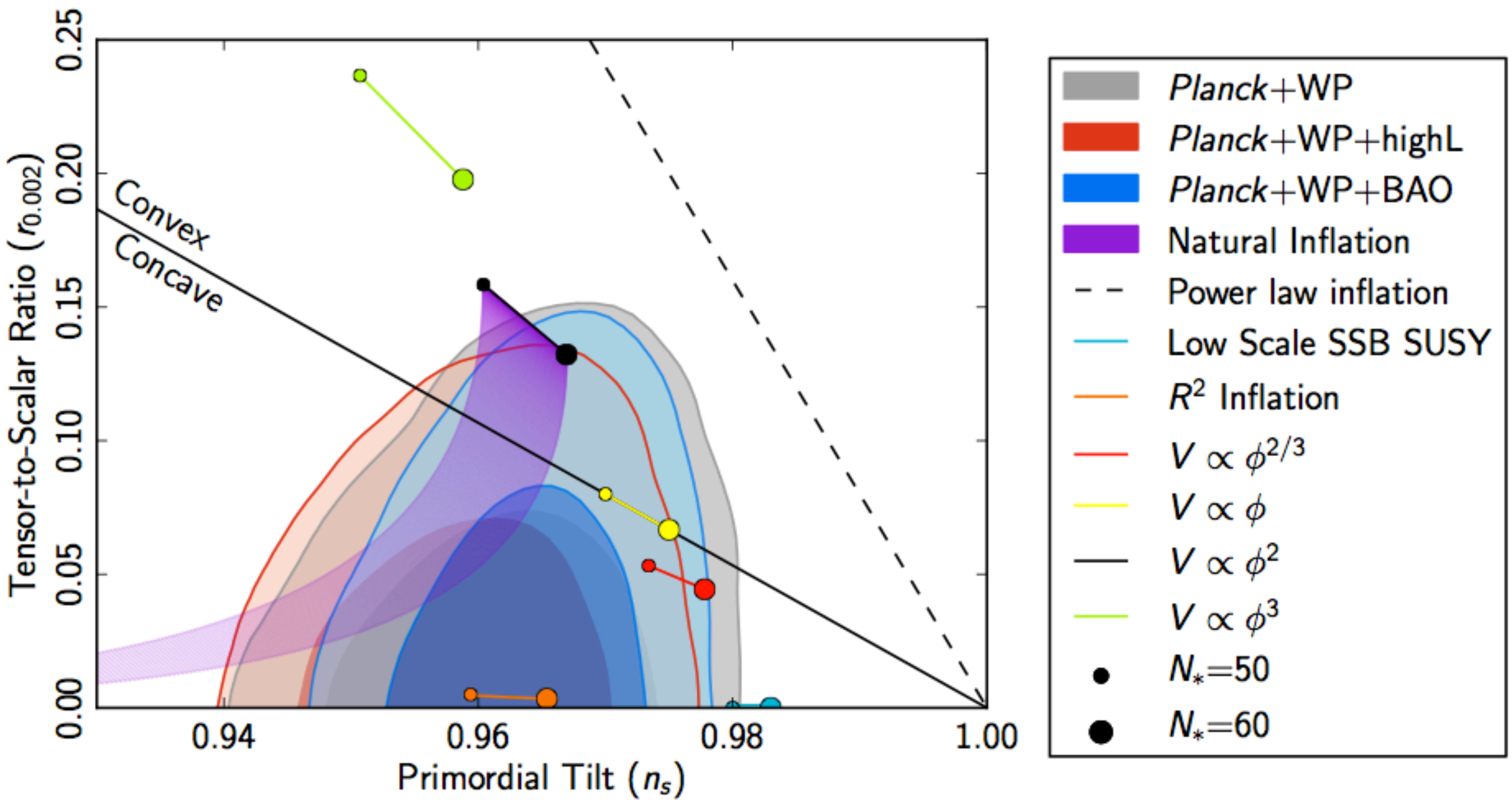
- Gives us more time…



- And quantum fluctuations stretch and grow into the “primordial” fluctuations in the hot big bang epoch

Details of the inflaton potential affect the perturbations…

- Puts pressure on large-field models



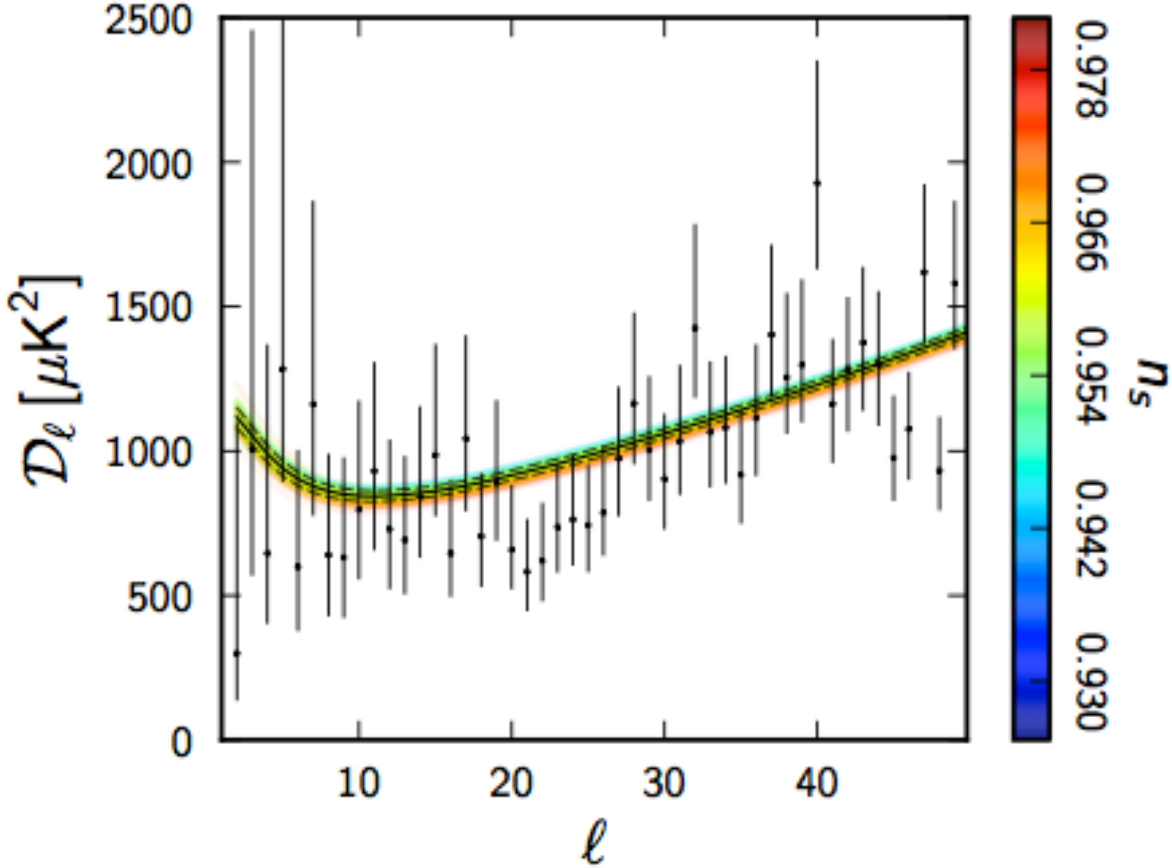
Nb. more complicated scenarios are possible

- Multifield inflation,
- non-canonical kinetic terms,
- non-standard vacuum,
- …

There are *some* “curiosities”…

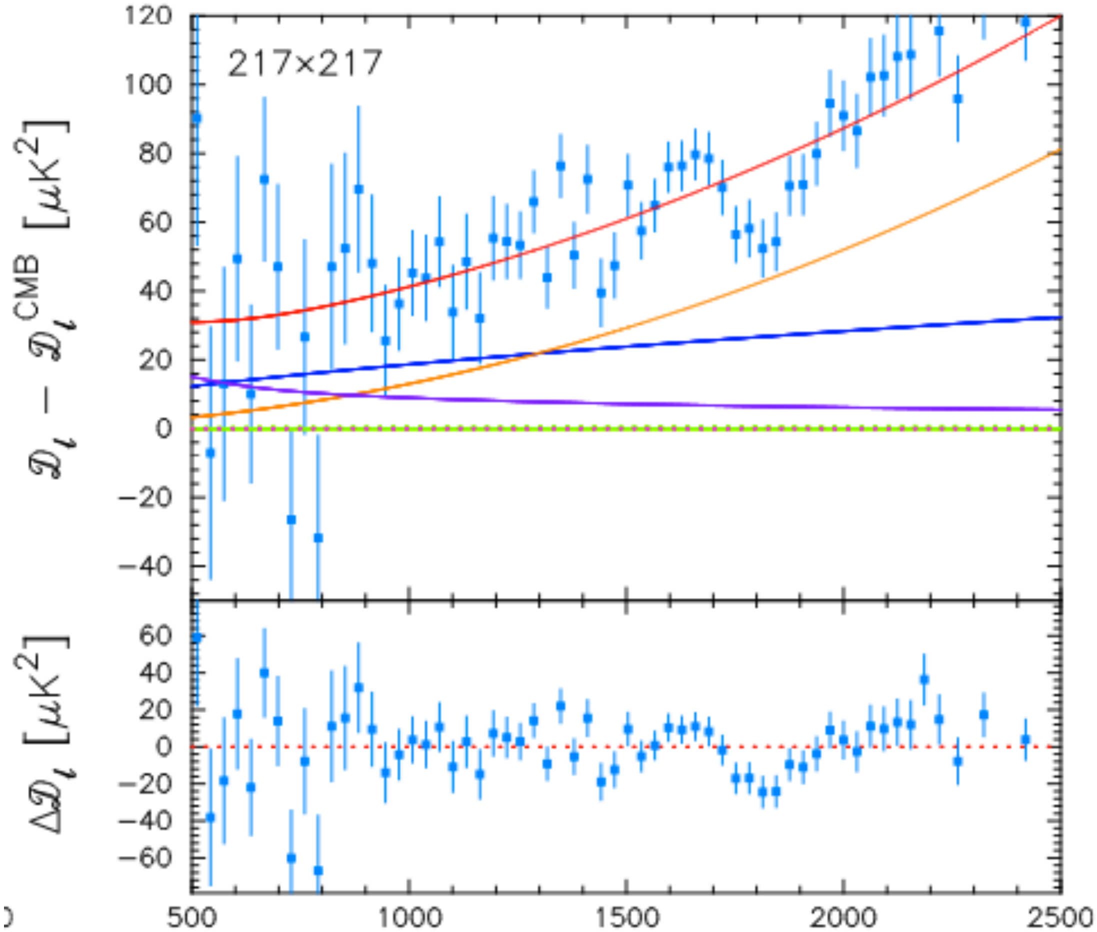
- Features in the power spectra
  - low-l dip
  - High-l dip
- Power asymmetries

Low-l dip…



2500
2000
1500
1000
500
0
10
20
30
40
ℓ
$\mathcal{D}_\ell\,[\mu\mathrm{K}^2]$
0.978
0.966
0.954
0.942
0.930
n_s

High-l dip…

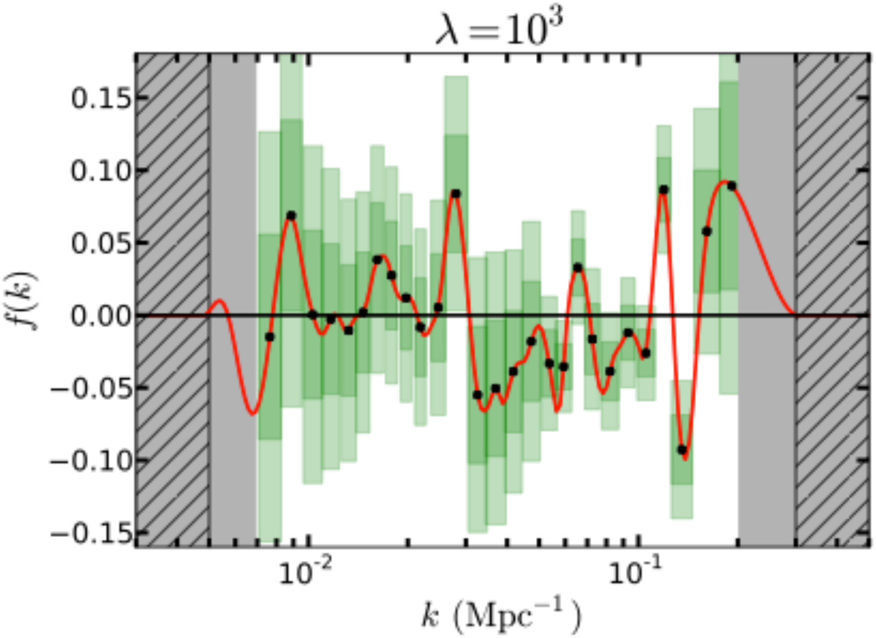


217×217
$\mathcal{D}_\ell - \mathcal{D}_\ell^{\rm CMB}$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
120
100
80
60
40
20
0
−20
−40
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500

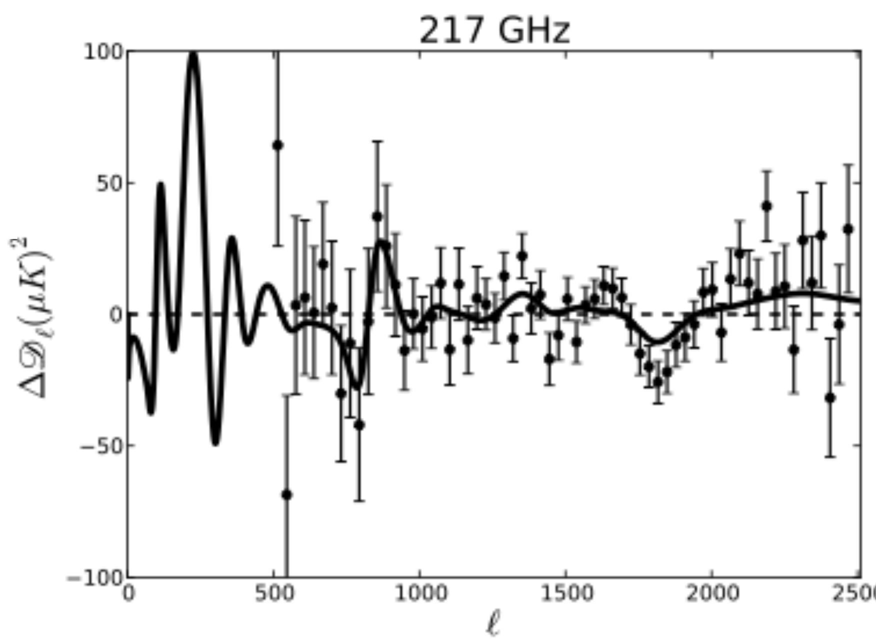
Some constraints on model-inspired modified power spectra…

Model	$-2\Delta \ln \mathcal{L}_{\max}$	$\ln B_{0X}$	Parameter	Best fit value
Wiggles	-9.0	1.5	α_w	0.0294
			ω	28.90
			φ	$0.075\,\pi$
Step-inflation	-11.7	0.3	$\mathcal{A}_f$	0.102
			$\ln(\eta_f/\mathrm{Mpc})$	8.214
			$\ln x_d$	4.47
Cutoff	-2.9	0.3	$\ln\left(k_c/\mathrm{Mpc}^{-1}\right)$	-8.493
			λ_c	0.474

Power-spectrum reconstruction…



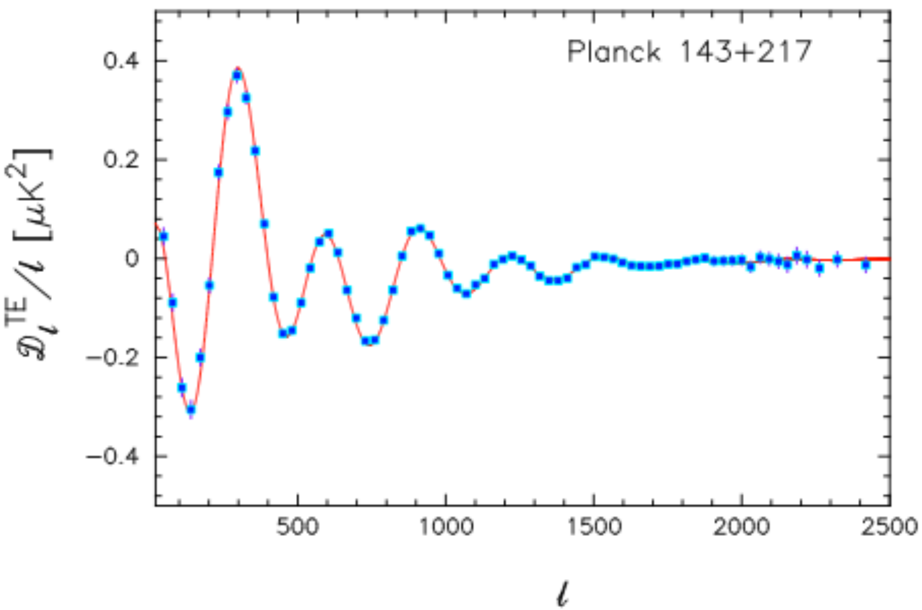
Planck 2013 results. XXII. Constraints on inflation

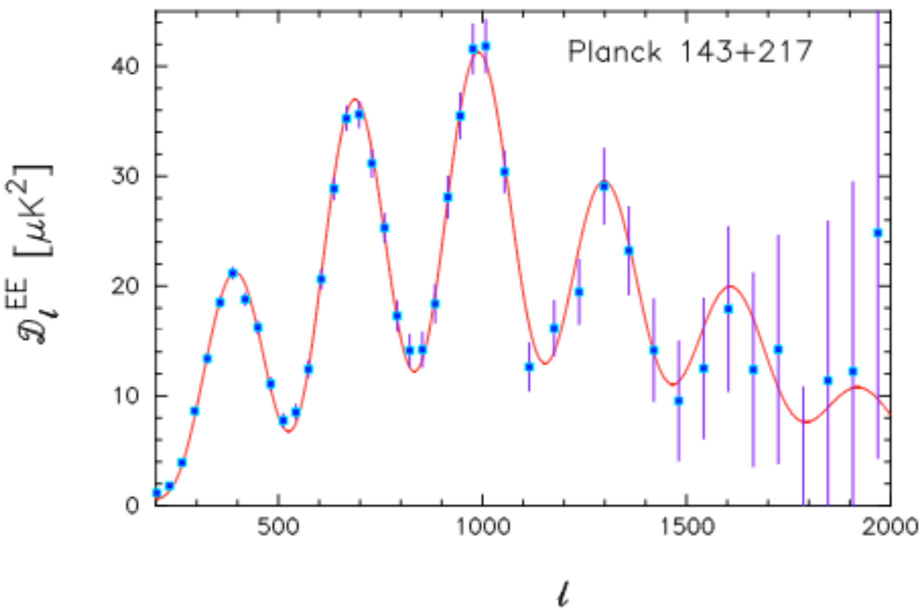


What's coming…

- Full temperature data, more aggressive analysis
  - Should help understand the power spectra features
- Polarization maps
  - At high-l, complement the temperature power spectra; not much foreground contamination!

"Teaser" plot…


Planck 143+217
$\mathcal{D}_\ell^{TE}/\ell\ [\mu K^2]$
0.4
0.2
0
−0.2
−0.4
500
1000
1500
2000
2500
ℓ


Planck 143+217
$\mathcal{D}_\ell^{EE}\ [\mu K^2]$
40
30
20
10
0
500
1000
1500
2000
ℓ

- Moreover, tensor fluctuations imprint a distinct “B-mode” pattern into the polarization maps at low-l
- Hard to disentangle from systematics but if convincingly found or bounded will rule in or out many inflationary and other models

Conclusions

- Six-parameter LCDM fits the high-l data as well as any other plausible model
- Some “curiosities” that merit further investigation
- Stay tuned!