Cosmological Results from Planck 2013

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Cosmology Reminder

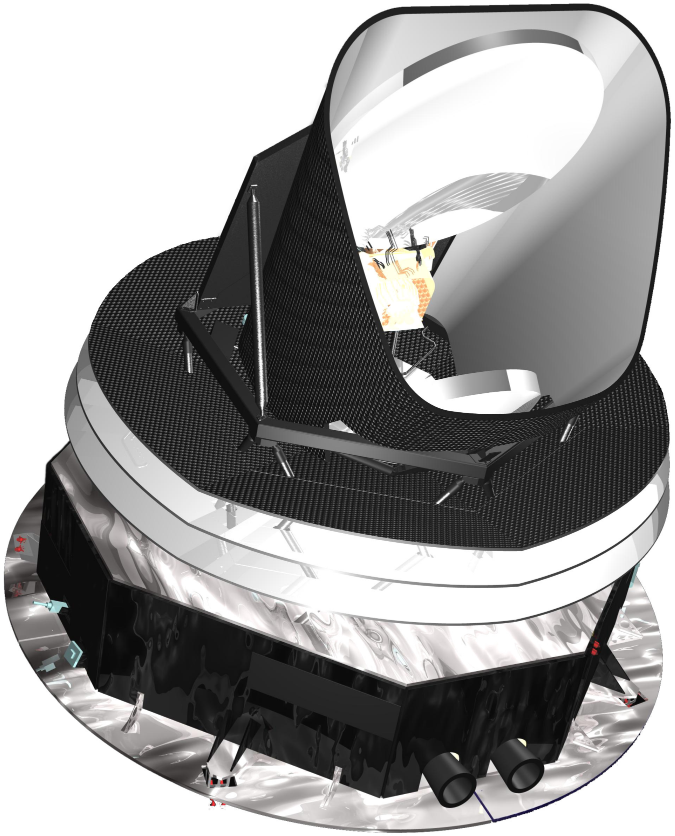
- Us, O(30) years old
- Earth, O(5 billion) years old
- The Big Bang itself, c. 13.8 billion years ago

- First stars form, few hundred million years after BB (these make heavier elements)
- Radiation “decouples”, c. 380,000 years after BB
  - After this time light can travel unimpeded through the universe to us, giving the cosmic microwave background
- Light elements formed by 3 minutes after BB

The Cosmic Microwave Background (CMB)

- A snapshot of the early universe from the time of “last scattering”, 380,000 years after the big bang
- A bit like taking a picture of clearing fog
  - Earlier, the fog is too thick to see anything
  - Later, the fog is too thin
- The universe is very simple this young, so any lumps seen then must have been there at the Big Bang
  - We can extrapolate forwards and backwards using linear theory

Planck



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

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

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HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

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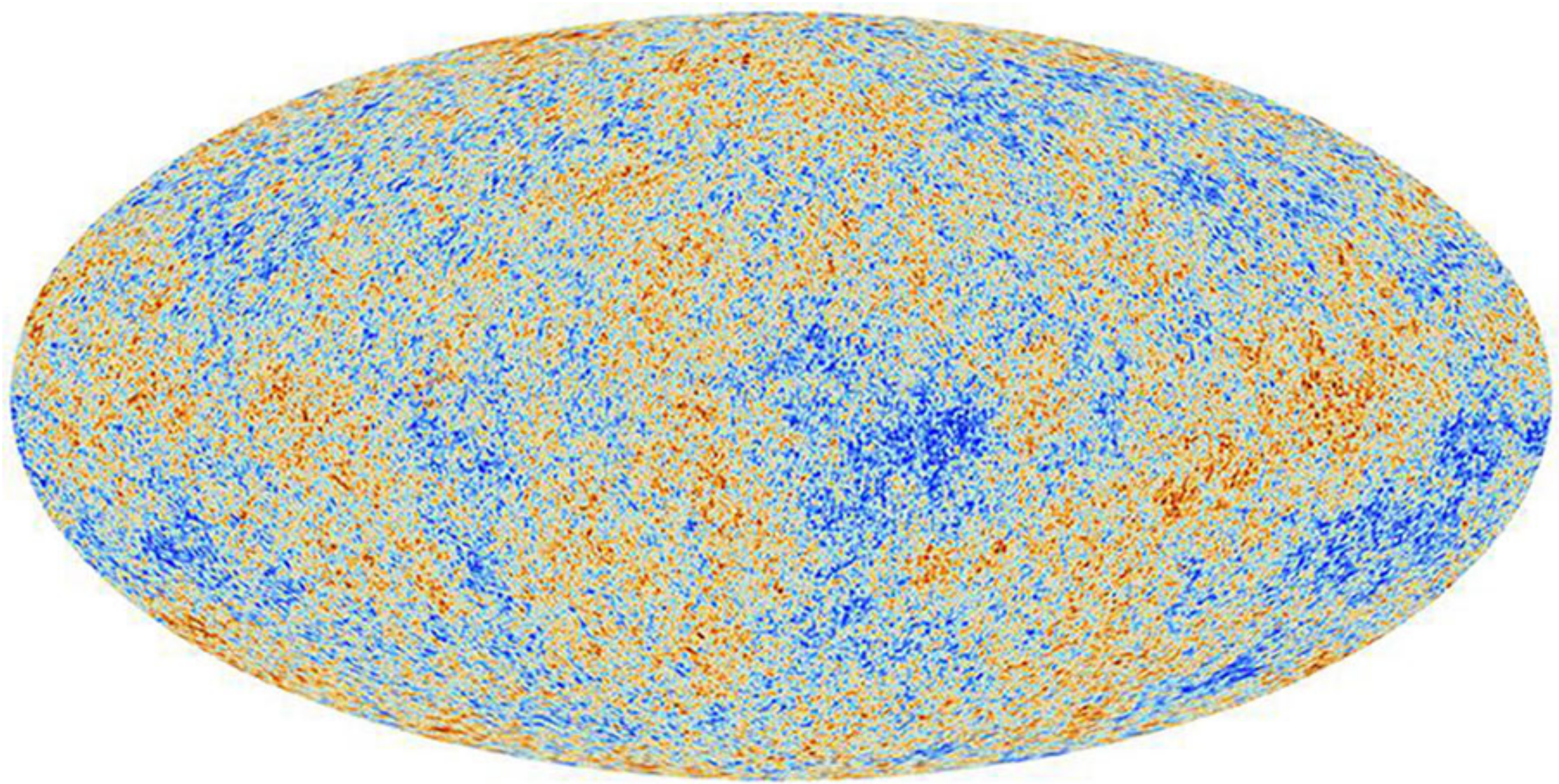
asdc
ASI Science Data Center

- 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

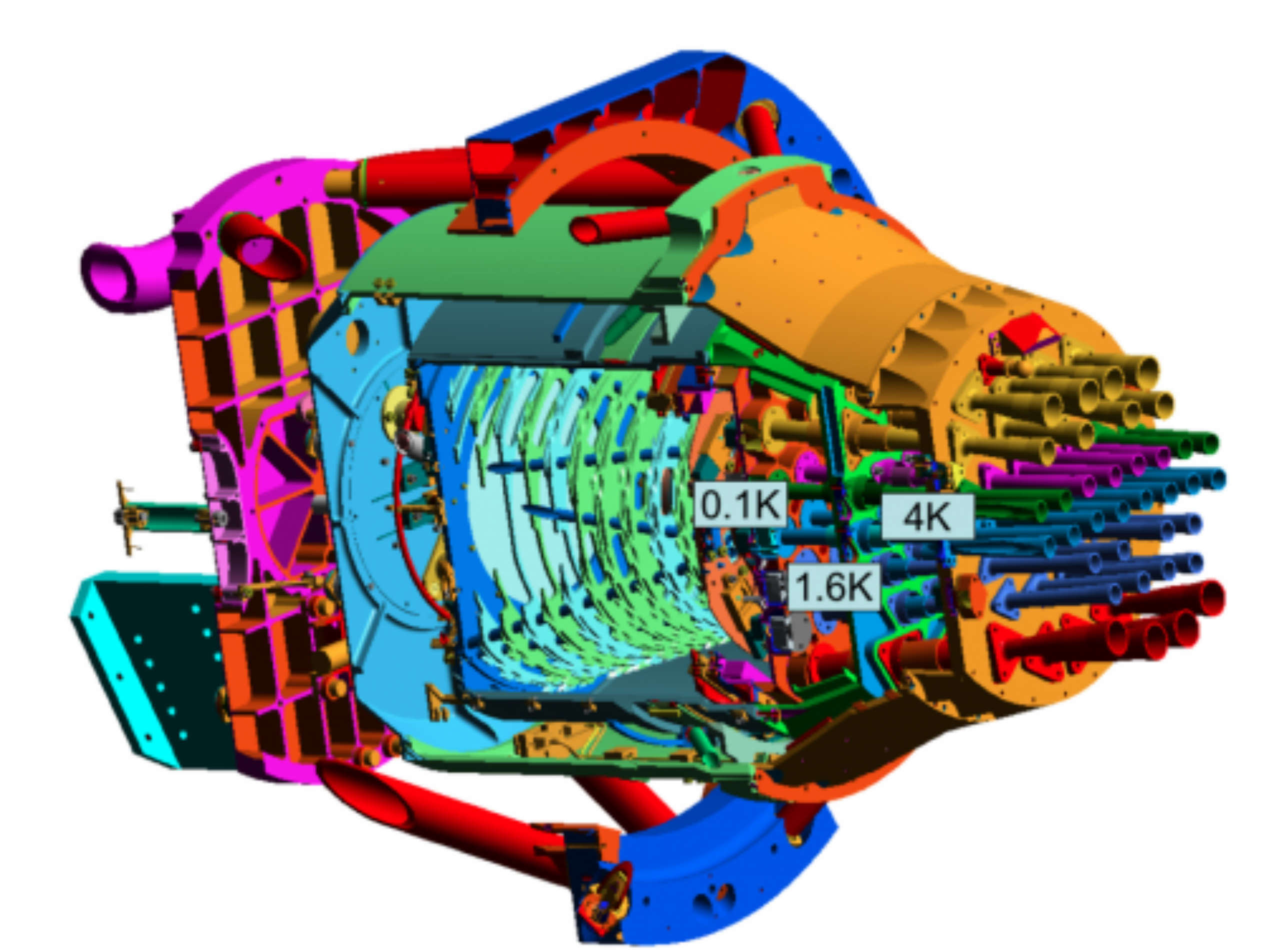


(ESA)

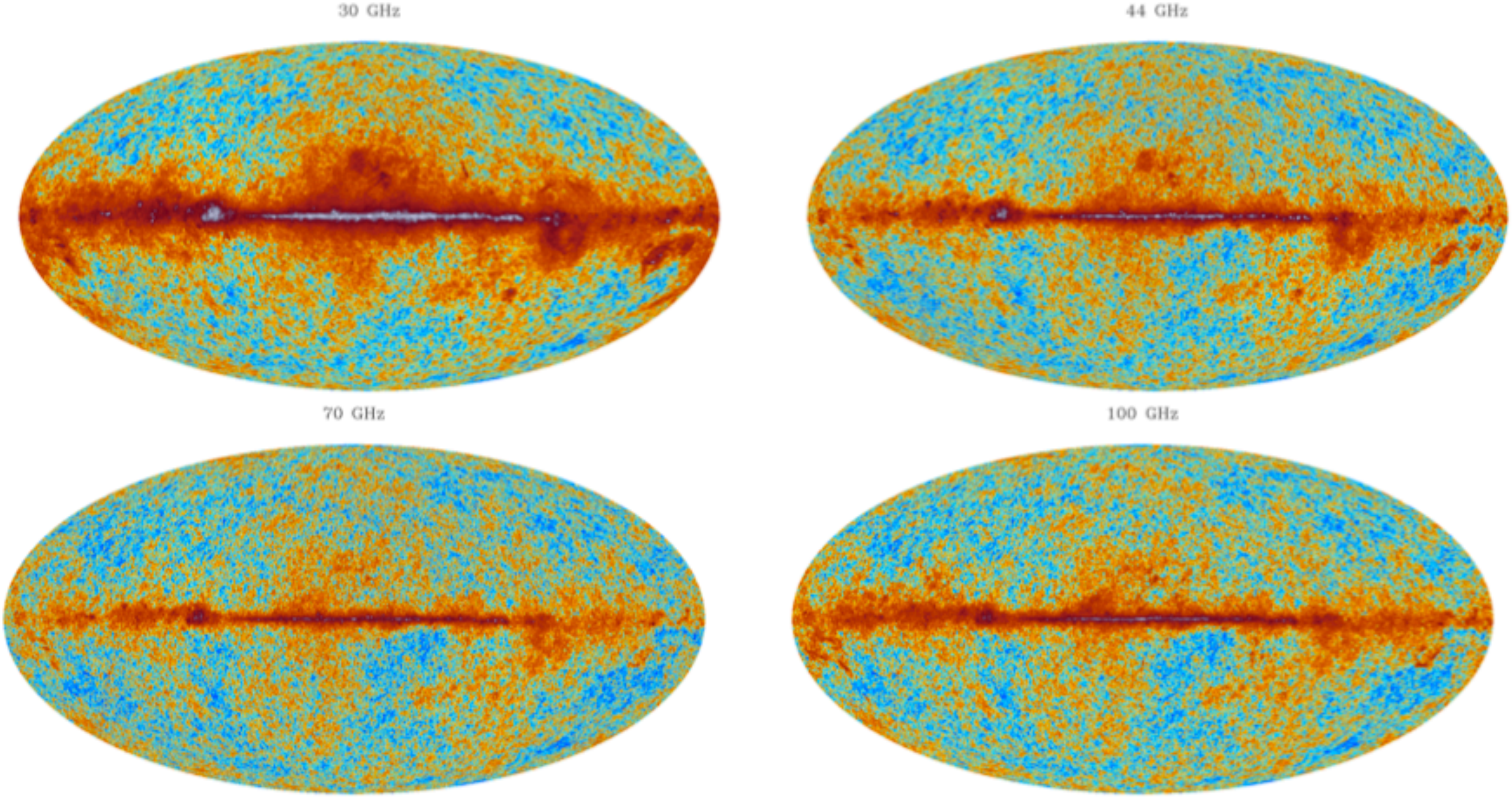
Cf. a projection of the Earth…

(Wikipedia)

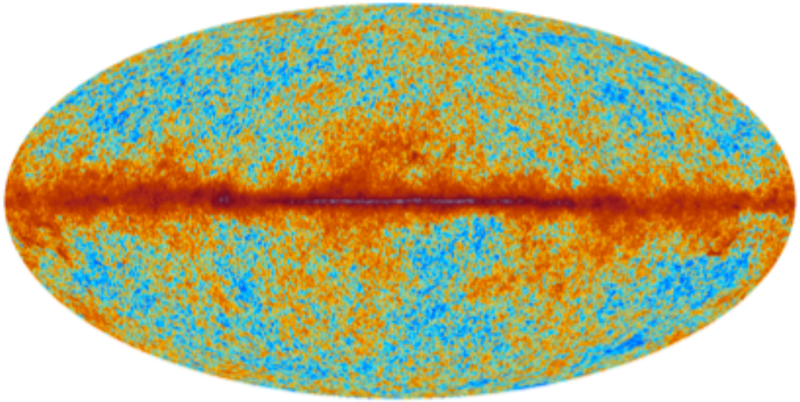
Planck actually makes multiple maps at each frequency…



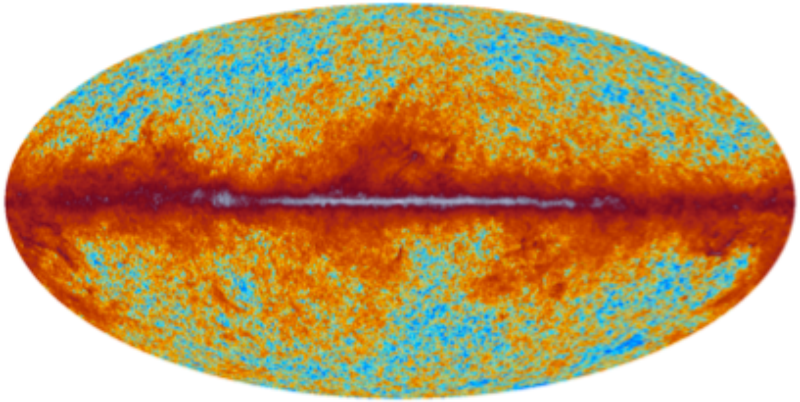
So more like…



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

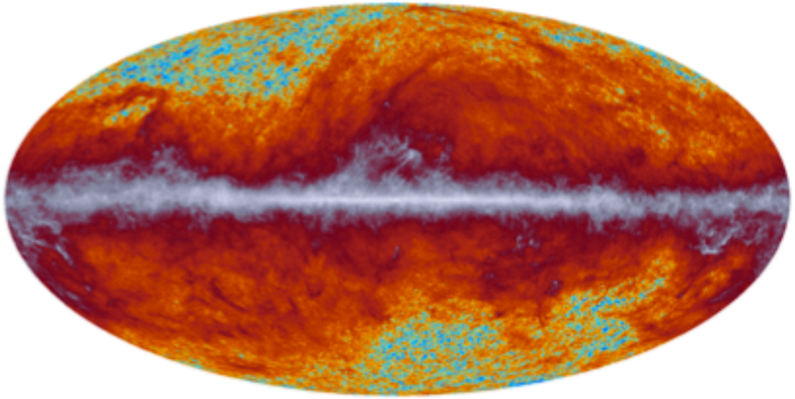


143 GHz

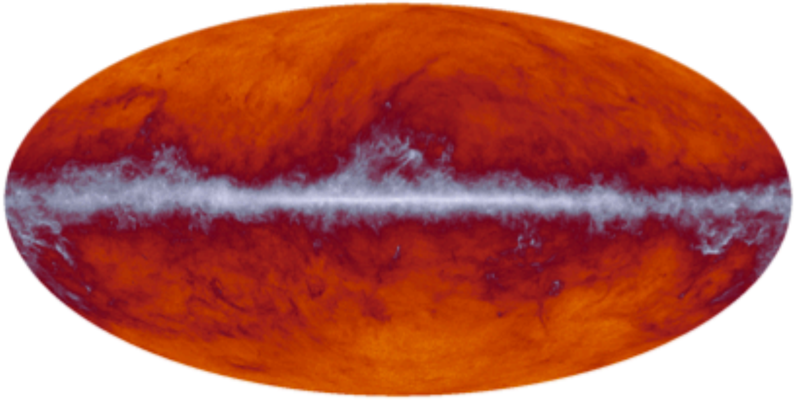


217 GHz

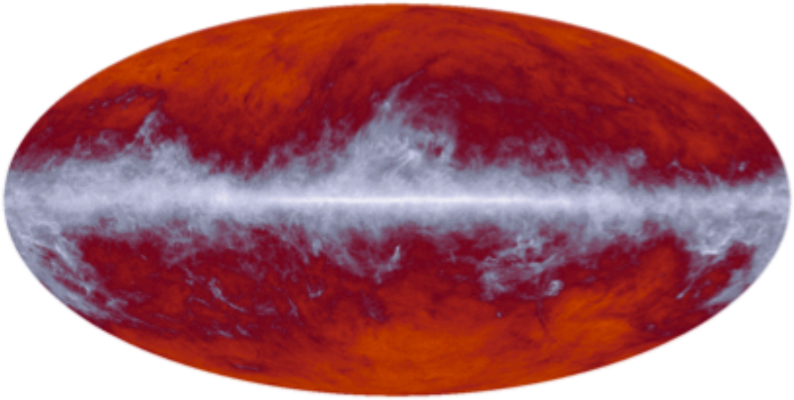
353 GHz



545 GHz



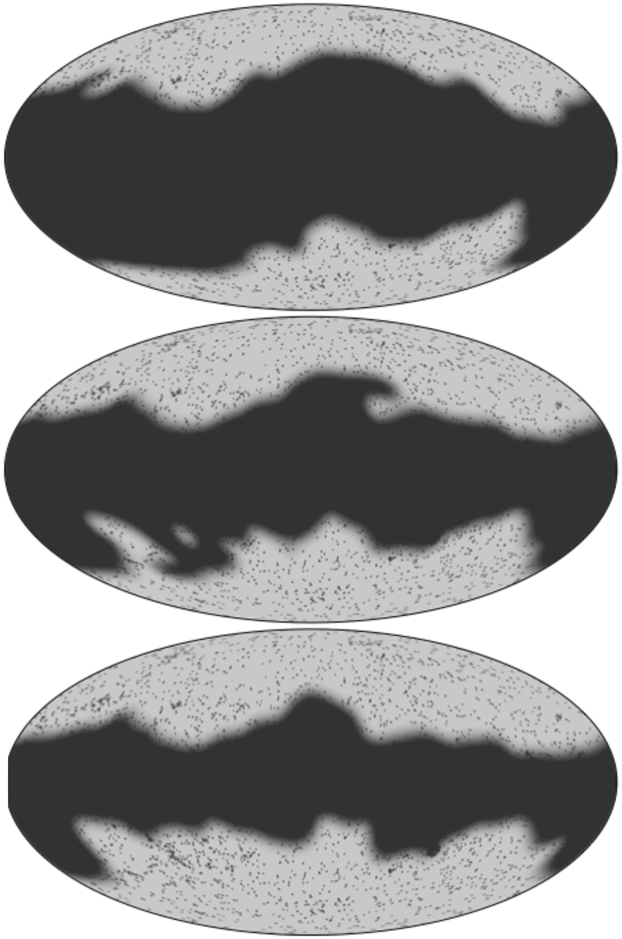
857 GHz

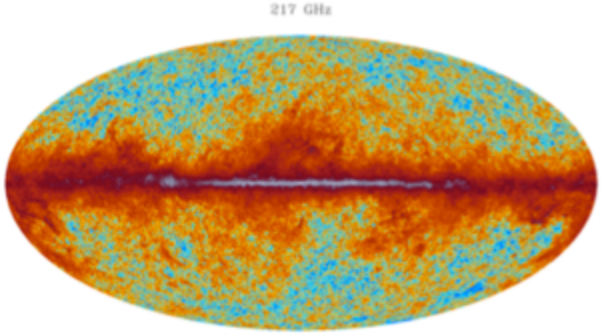


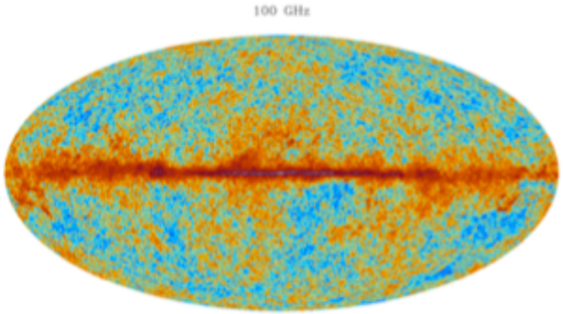
How to analyze?

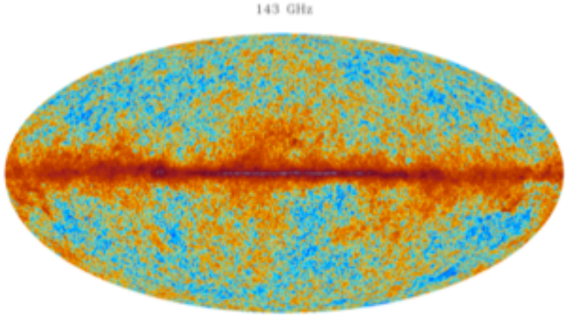
- For large scales or low-l (multipoles $2<=l<=49$)
  - – Use a “Gibbs sampler” on low-res maps
    - More or less equivalent to a pixel-based approach, also handles foregrounds and is faster to use
    - Uses 91% of the sky
- For small scales or high-l (multipoles $50<=l<=2500$)
  - – Power spectrum based method…

This uses just the cleanest channels and applies big masks…









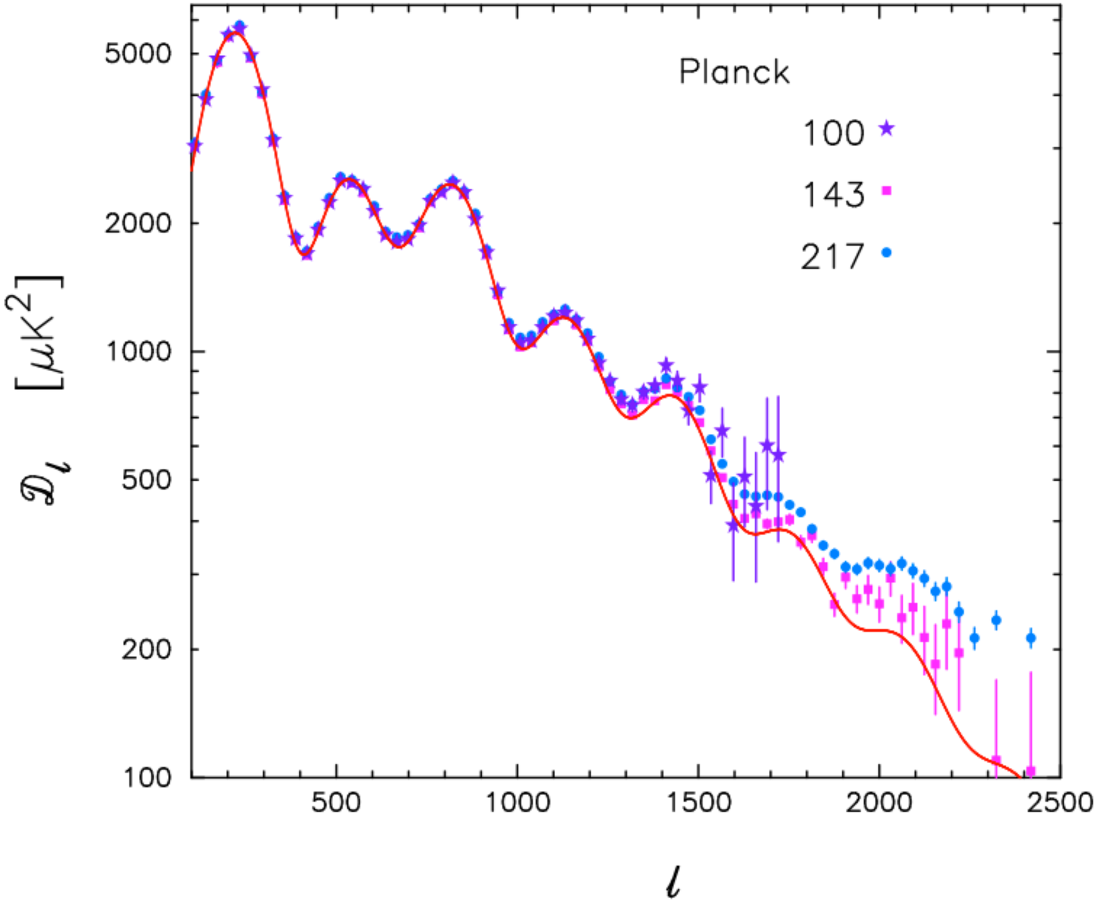
Also have to deal with *unresolved* foregrounds…

- “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

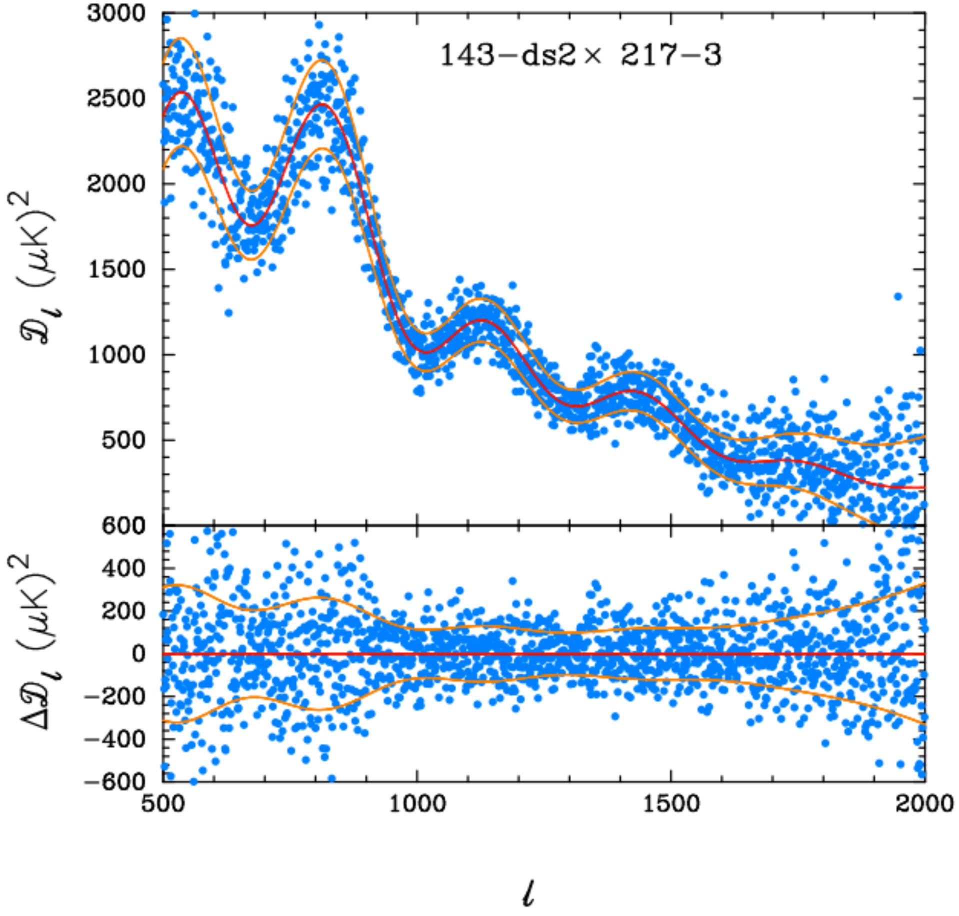
…and instrumental systematics

- Relative calibration factors
- Beam errors

We use “pseudo” power spectra…



…made out of averages of “fine-grained” cross spectra, e.g.



Left with four effective spectra…

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

- And a 7104x7104 covariance matrix!

Why are we so interested in the CMB?

- Different theories lead to different predictions about what the CMB map should statistically look like
  - i.e. they predict a theoretical power spectrum
- Gives us a way to figure out what the universe is like by comparing this to our observations

Indeed, a very simple 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})

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

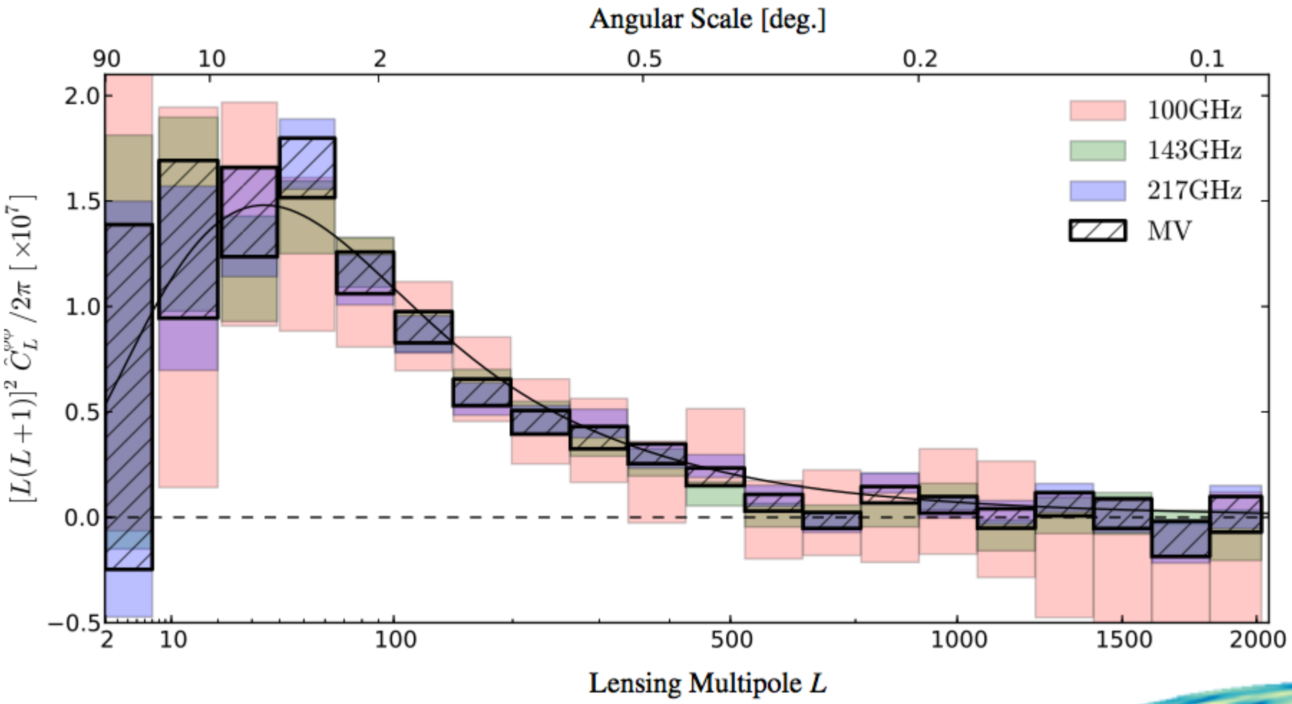
- Seven peaks give us the acoustic scale really well:
  - $\theta_* = (1.04148 \pm 0.00066) \times 10^{-2}$
    $= 0.596724^\circ \pm 0.00038^\circ$.
- Turns out the following is also really well constrained:
  - $\Omega_m h^3 = 0.0959 \pm 0.0006$
- 2% constraint on H_0:
  - $H_0 = (67.4 \pm 1.4)$ km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

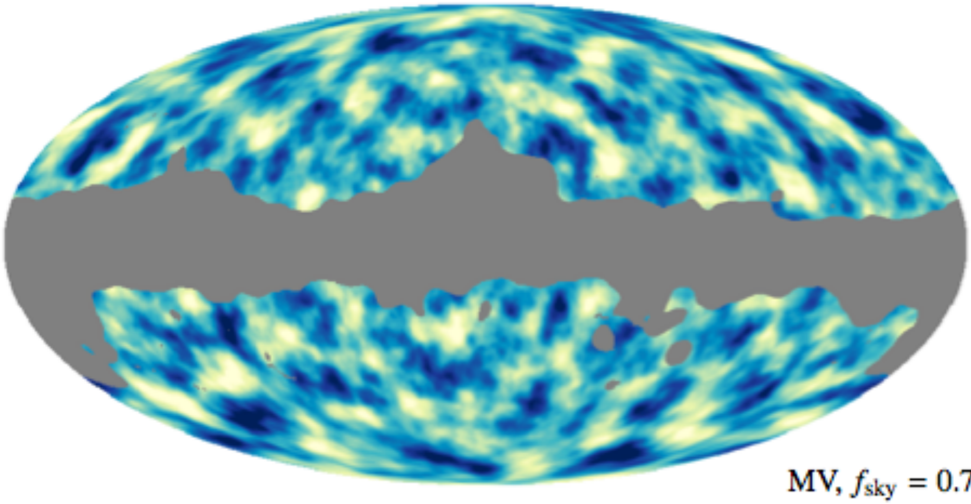
Also add in other data sets

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

- Nb., we’ve really tried to “push” the methodology and presentation,
  - Making choices, not combining everything
  - Looking at the behaviour of individual chi-squared’s when combining
  - Investigating residuals…
- Check out our full “grid” of models and data combinations online:
  - http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive

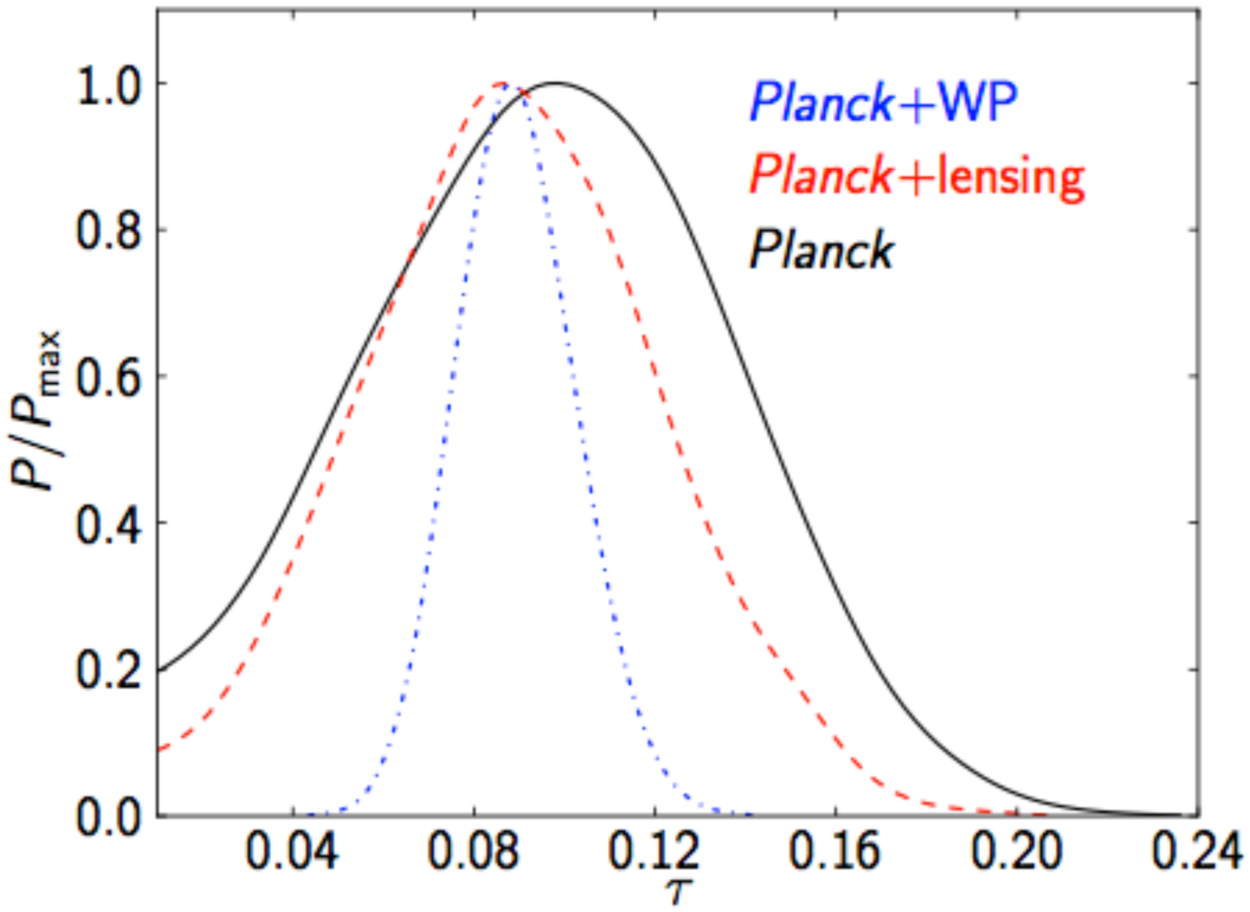
Planck Lensing (1)



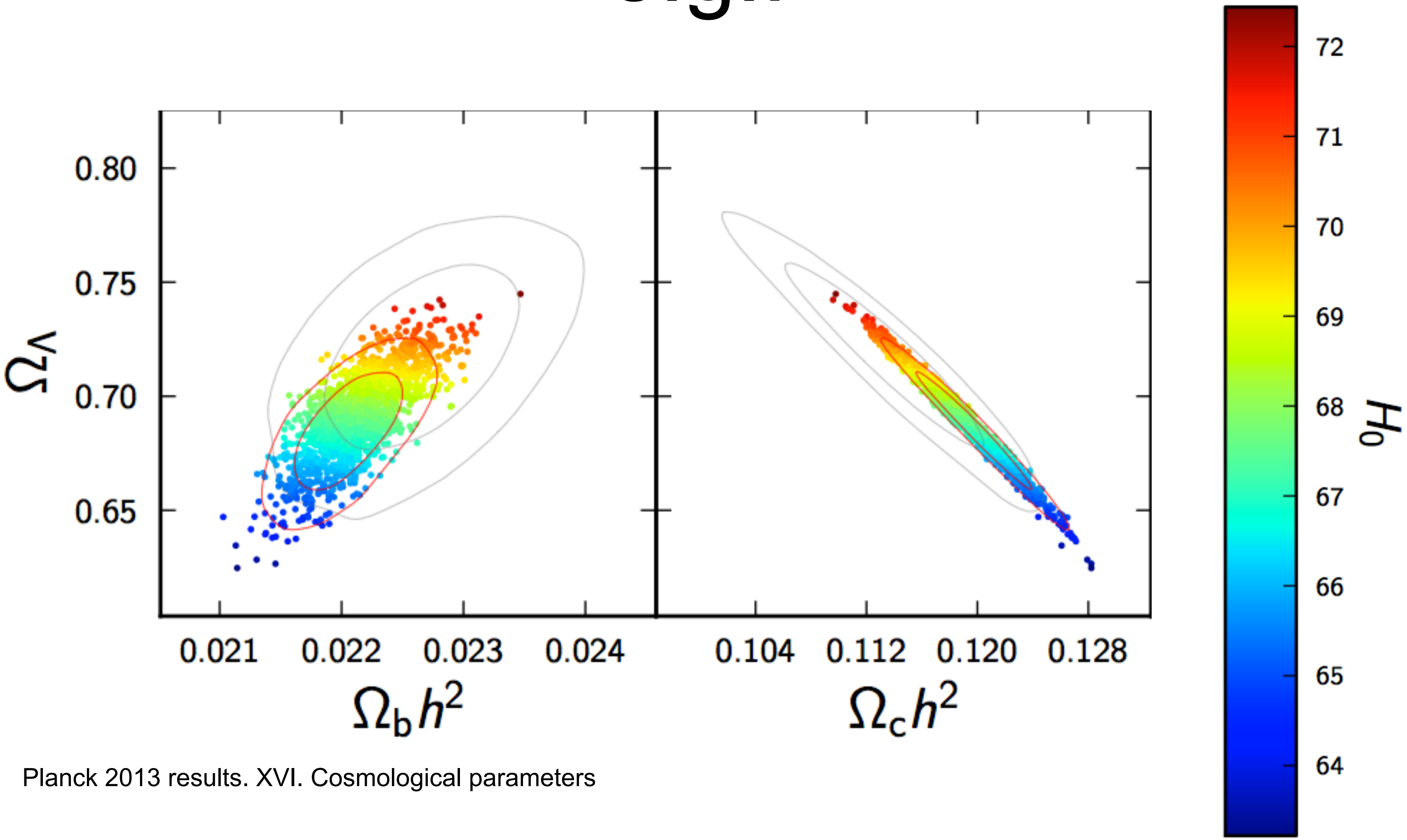


MV, $f_{\rm sky}$ = 0.70

Planck Lensing (2)

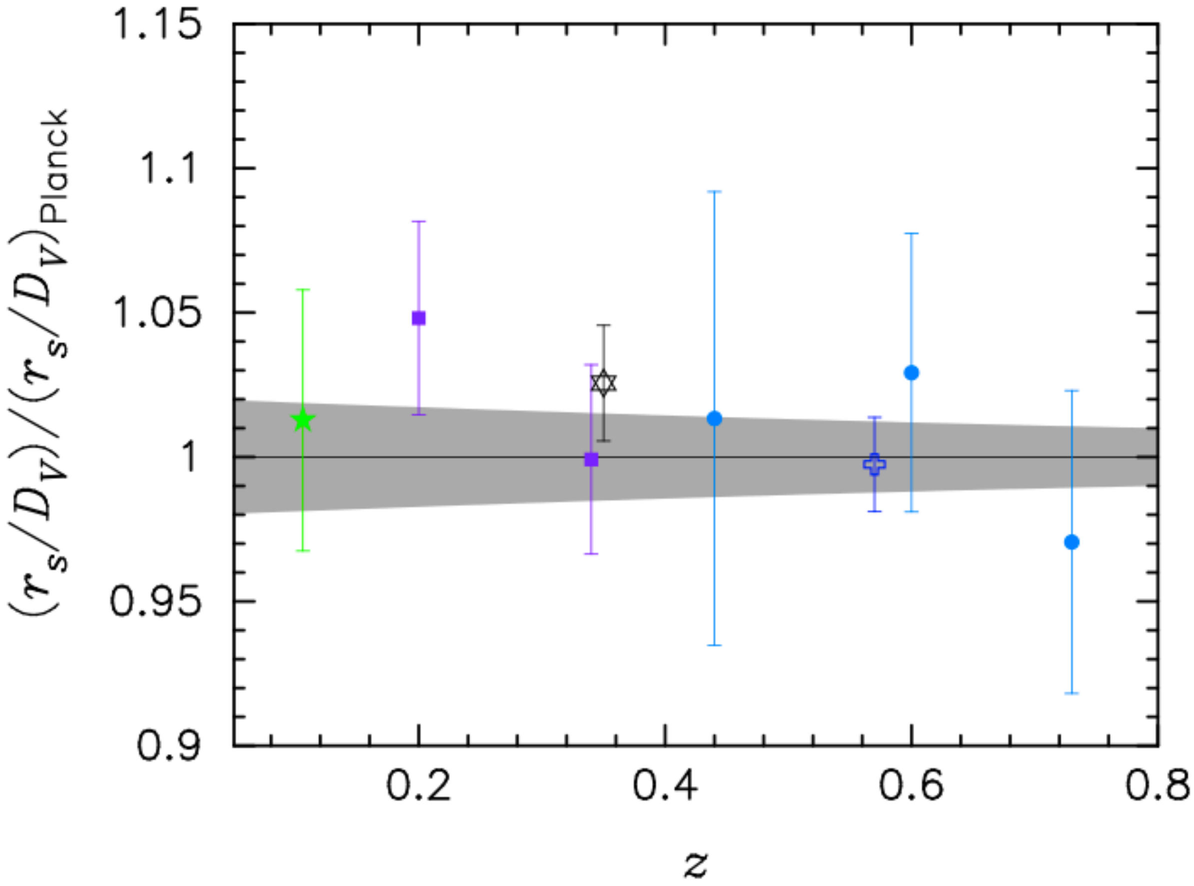


Get nice parameter constraints, e.g.:

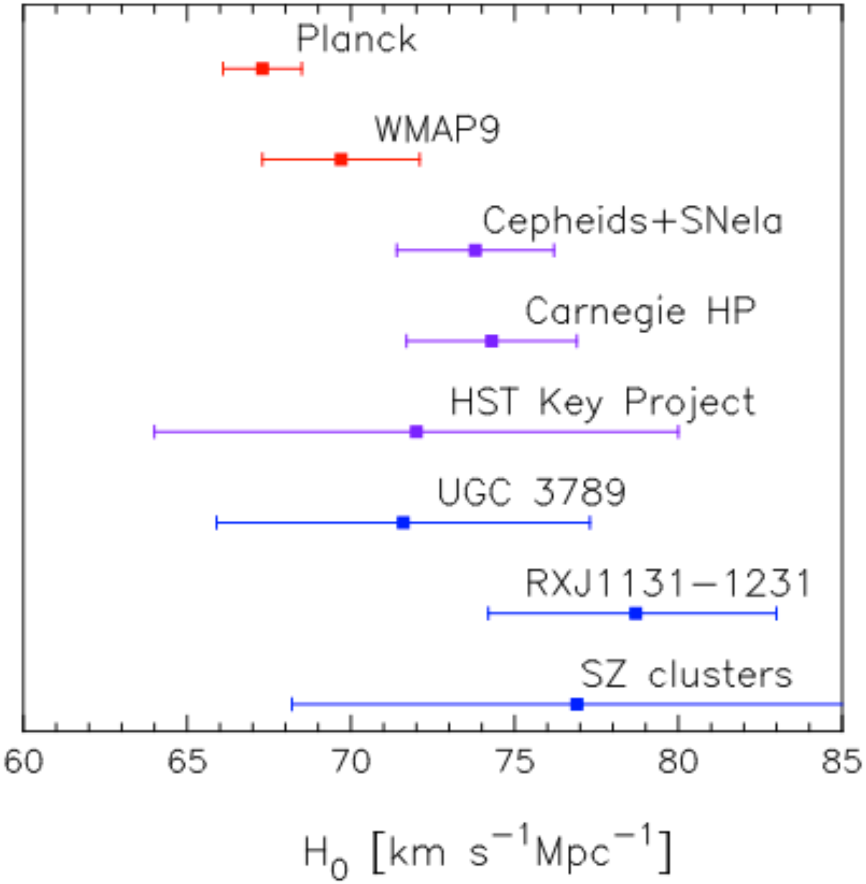


Planck 2013 results. XVI. Cosmological parameters

BAO

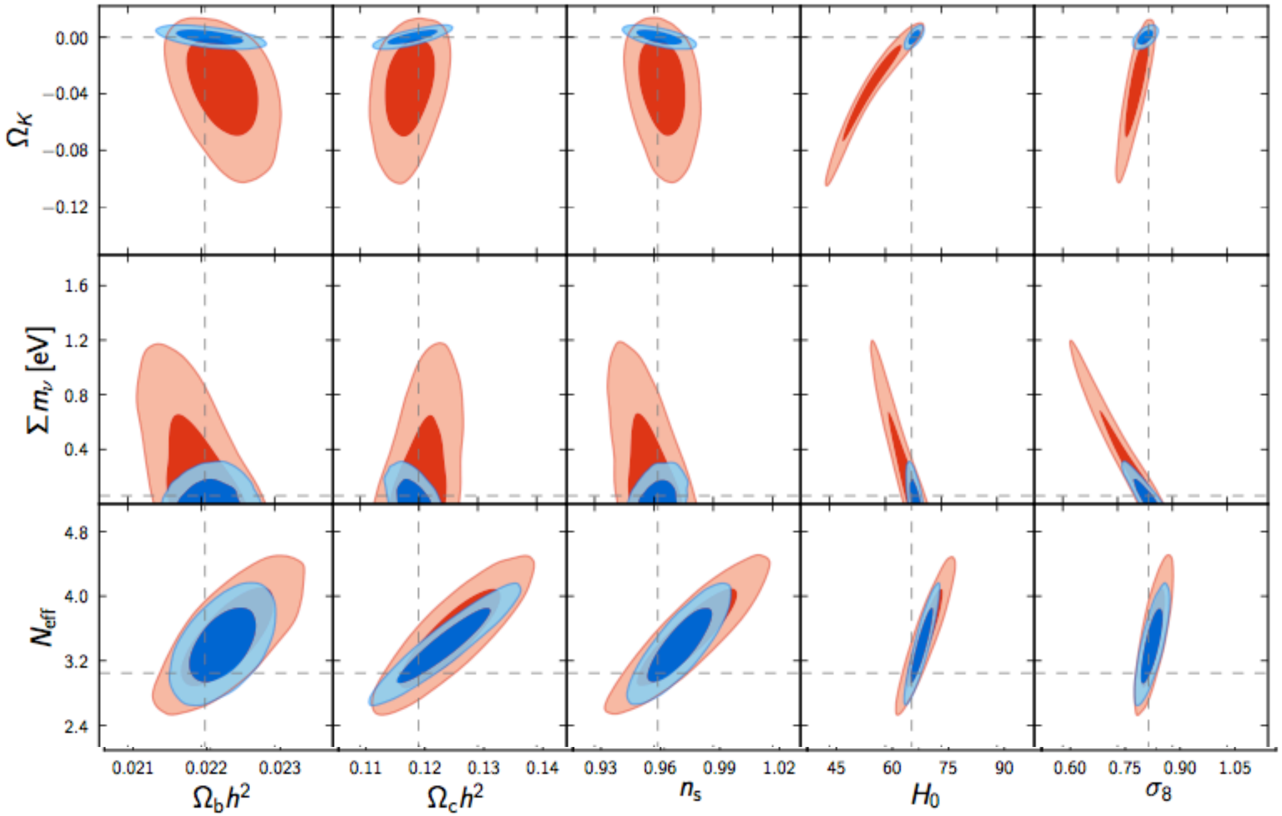


HST


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?…

- Curvature, neutrino masses, varying number of neutrinos…



- Helium fraction, running, tensors, dark energy…

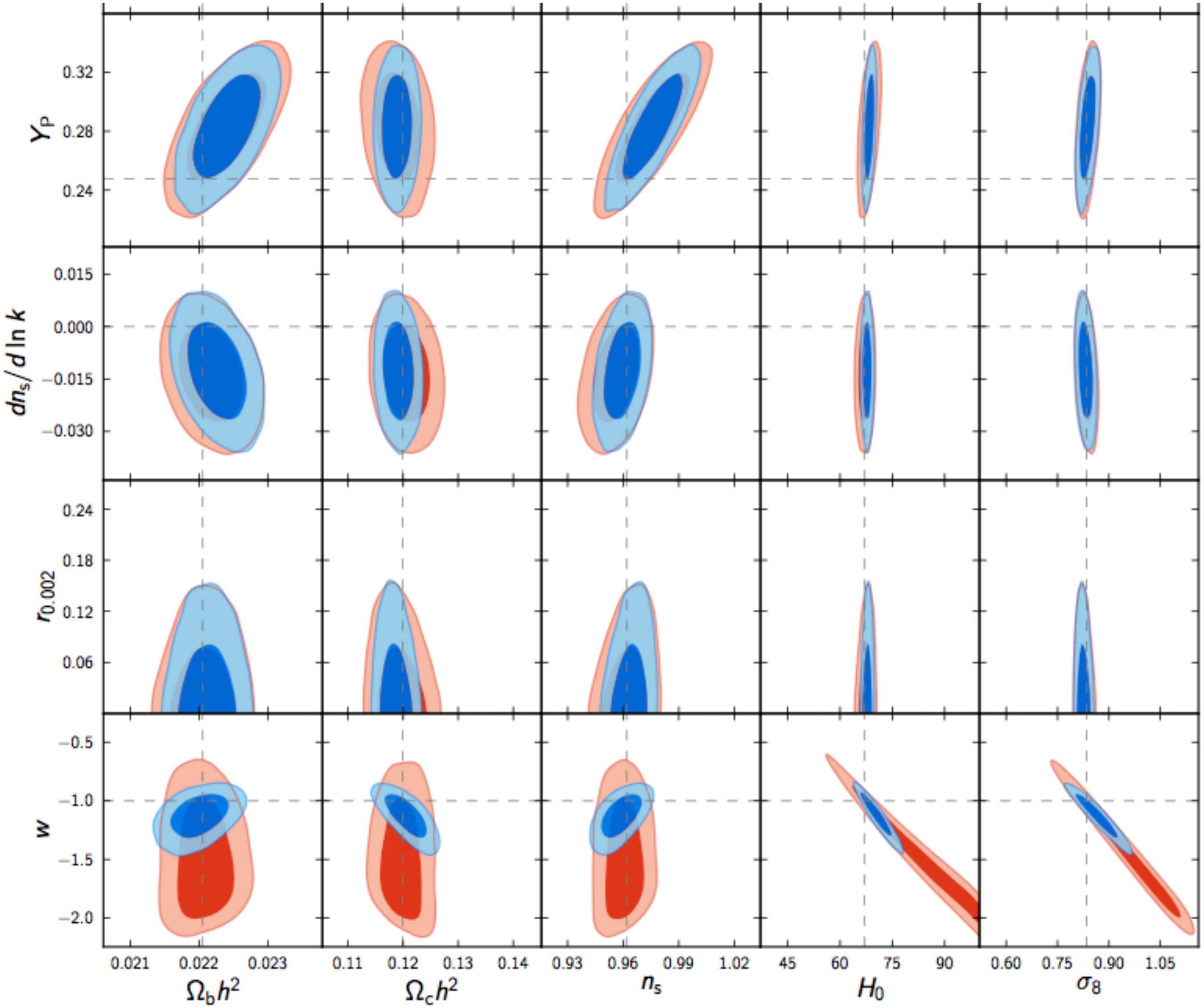
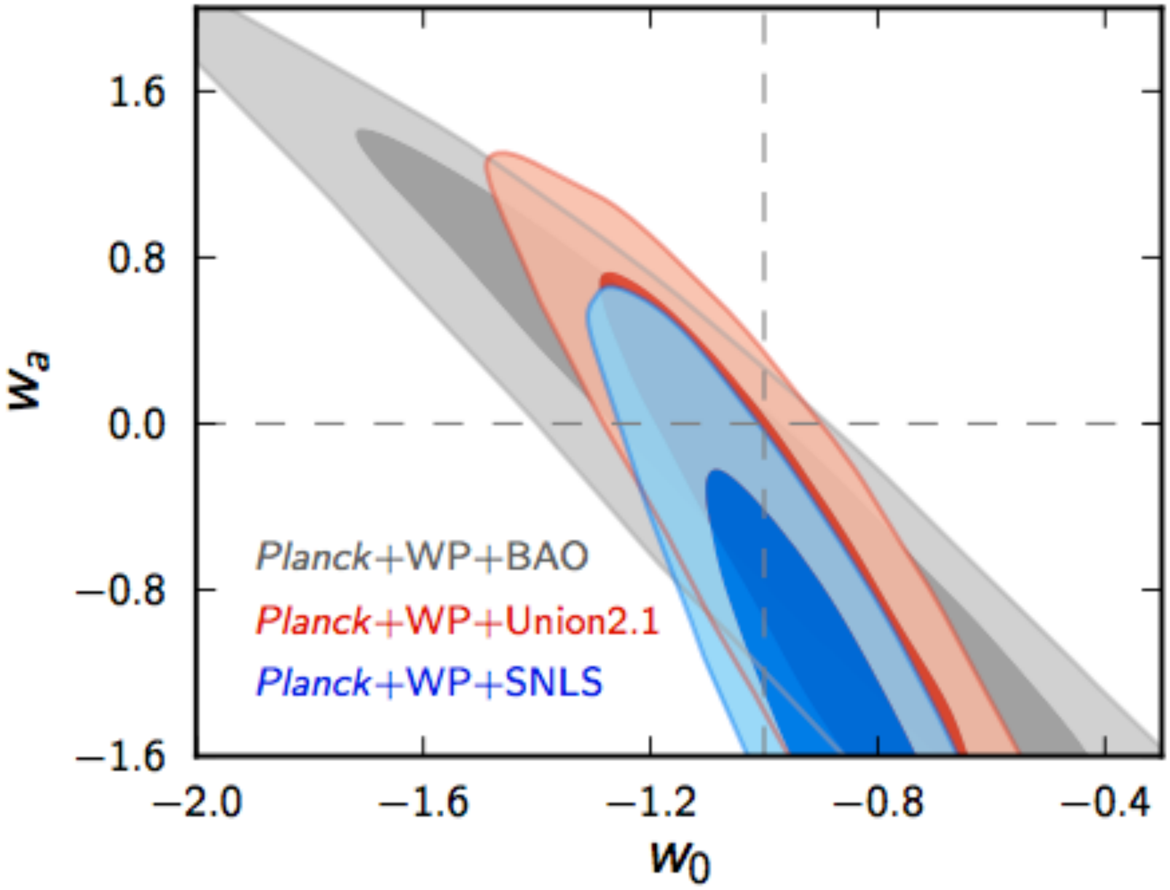


Illustration of effects of tensions on extended models:



Parameters Paper revisions

- *l=1800 "dip"* understood to be due to residual systematic from 4K line removal; marginalizing a feature out increases H_0 by 0.3 sigma
- Humphreys et al. (2013) new geometric maser distance to NGC4258 =>

  H_0=72±3 km/s/Mpc
- Betoule et al. (2013) =>

  Ω_m=0.295±0.034

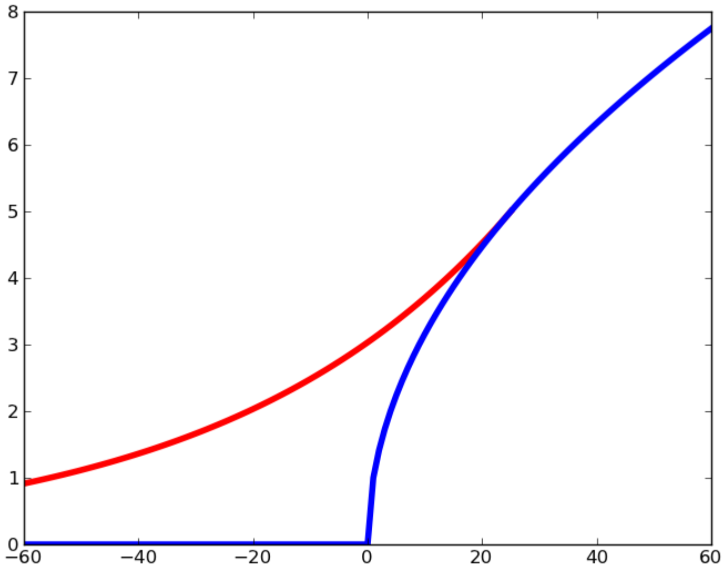
Still questions about LCDM…

- 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…)

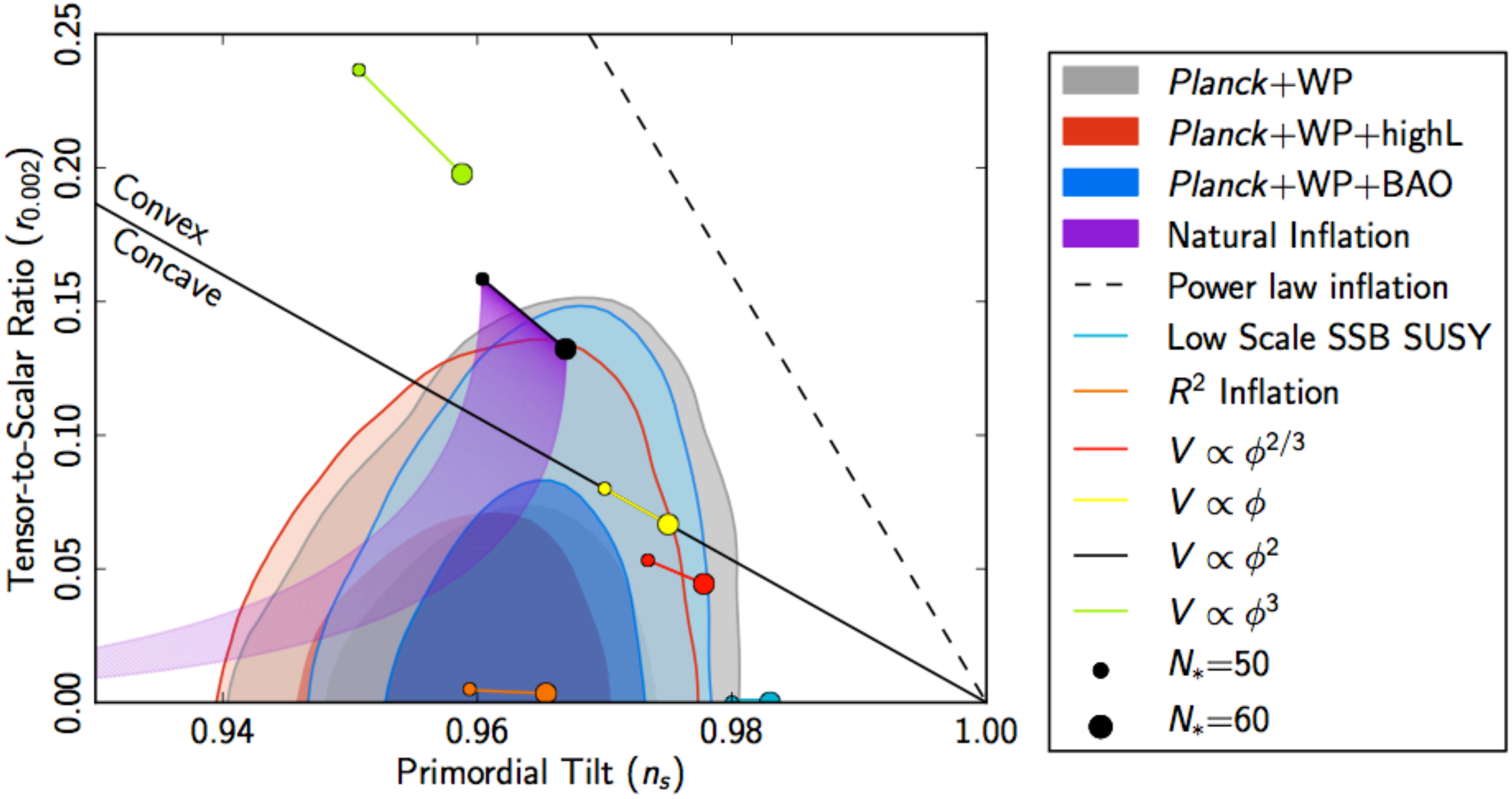
- Gives us more time…



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

Details of the inflaton potential affect the perturbations…

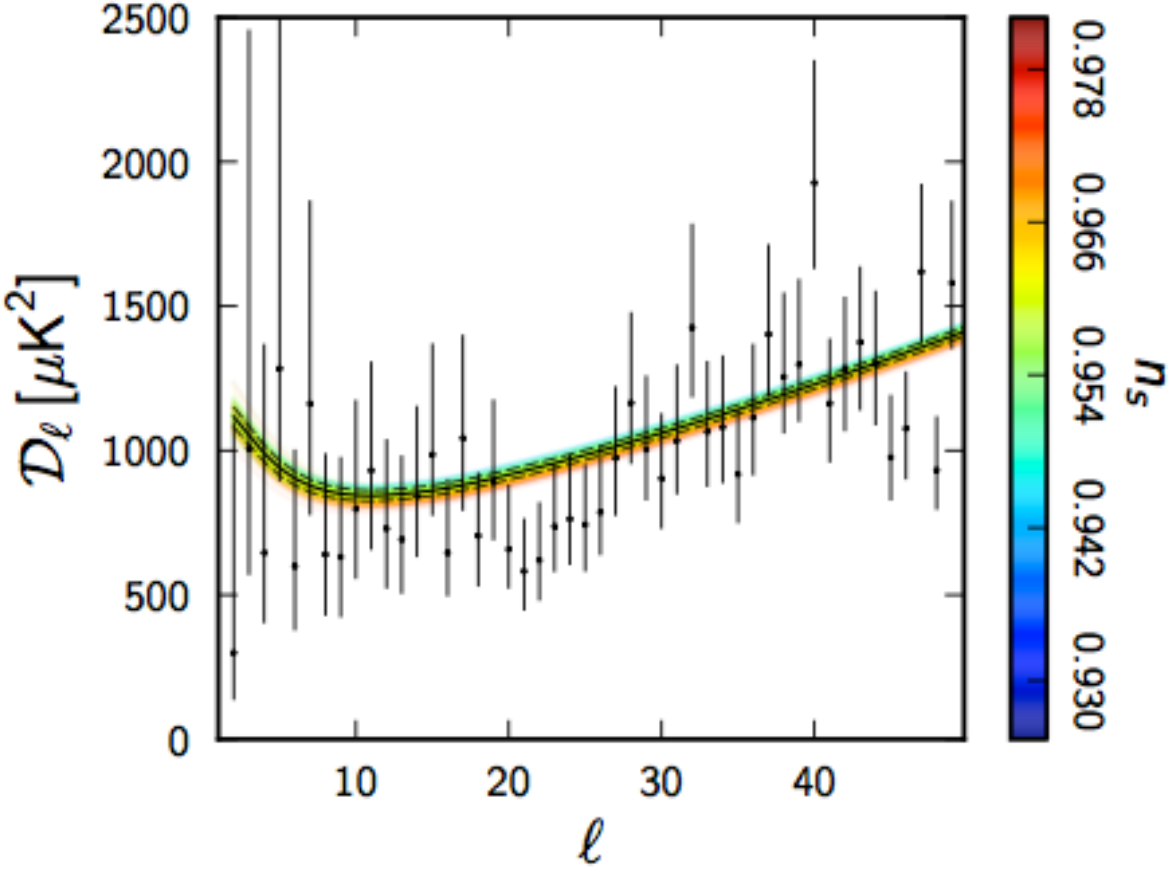
- Puts pressure on large-field models



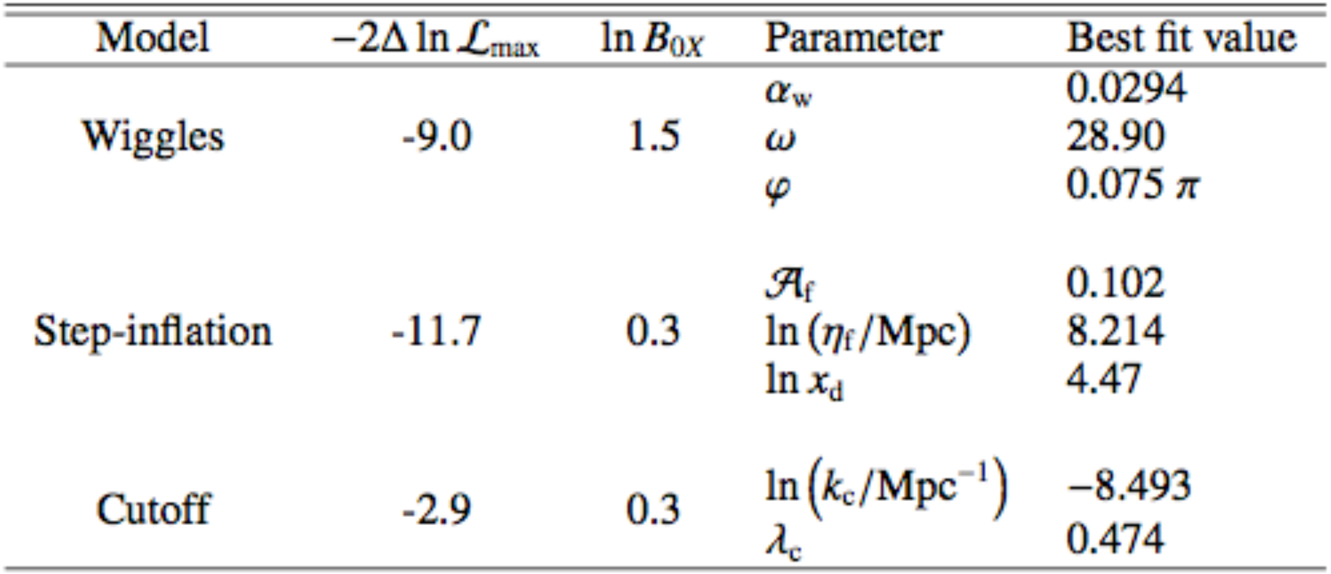
More complicated scenarios are possible

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

A Curiosity in the Power Spectrum: Low-/ dip…

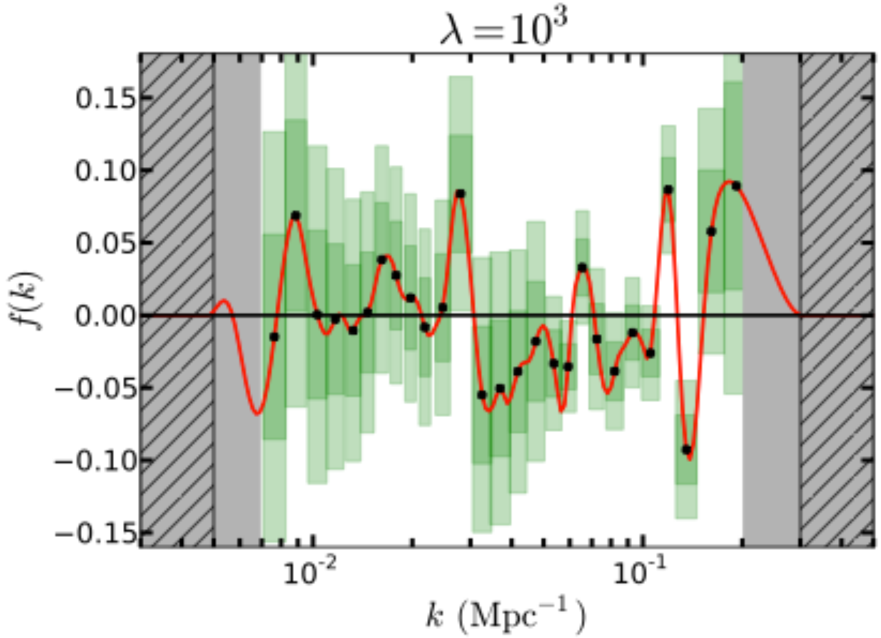


Some constraints on model-inspired modified power spectra…

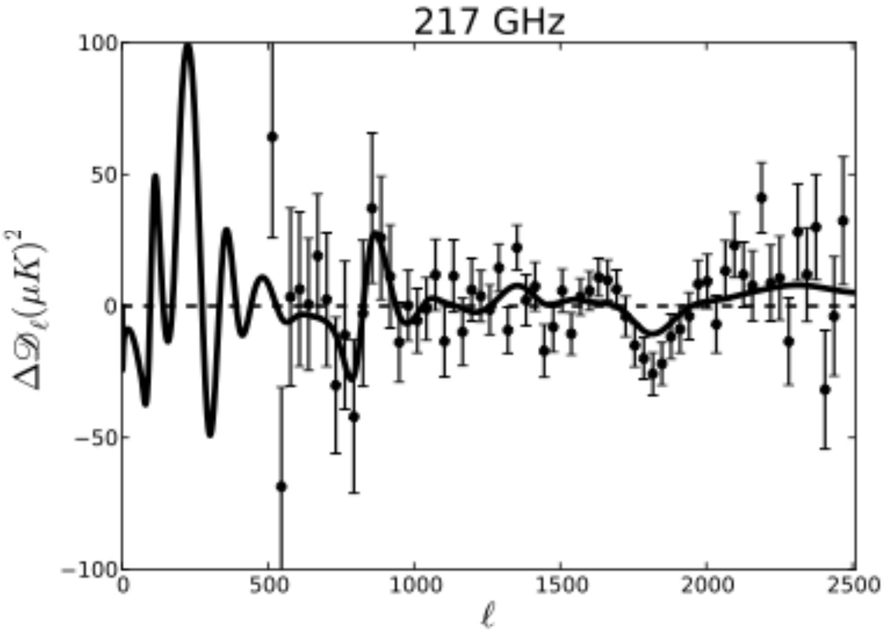


Model	$-2\Delta \ln \mathcal{L}_{\max}$	$\ln B_{0X}$	Parameter	Best fit value
Wiggles	-9.0	1.5	α_w	0.0294
			ω	28.90
			φ	$0.075\,\pi$
Step-inflation	-11.7	0.3	$\mathcal{A}_f$	0.102
			$\ln(\eta_f/\mathrm{Mpc})$	8.214
			$\ln x_d$	4.47
Cutoff	-2.9	0.3	$\ln\left(k_c/\mathrm{Mpc}^{-1}\right)$	-8.493
	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

PLANCK 2014

THE MICROWAVE SKY IN TEMPERATURE AND POLARIZATION

1-5 December 2014, Palazzo Costabili, Ferrara, Italy

NEW RESULTS FROM PLANCK AND OTHER EXPERIMENTS ON COSMOLOGY, FUNDAMENTAL PHYSICS, GALACTIC AND EXTRAGALACTIC ASTROPHYSICS, DATA ANALYSIS AND NEXT OBSERVATIONAL CHALLENGES

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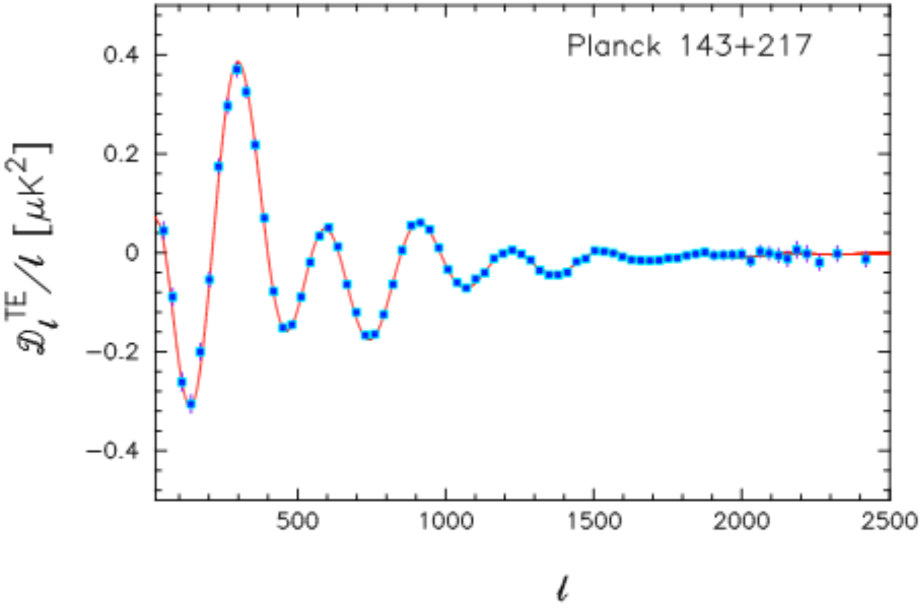
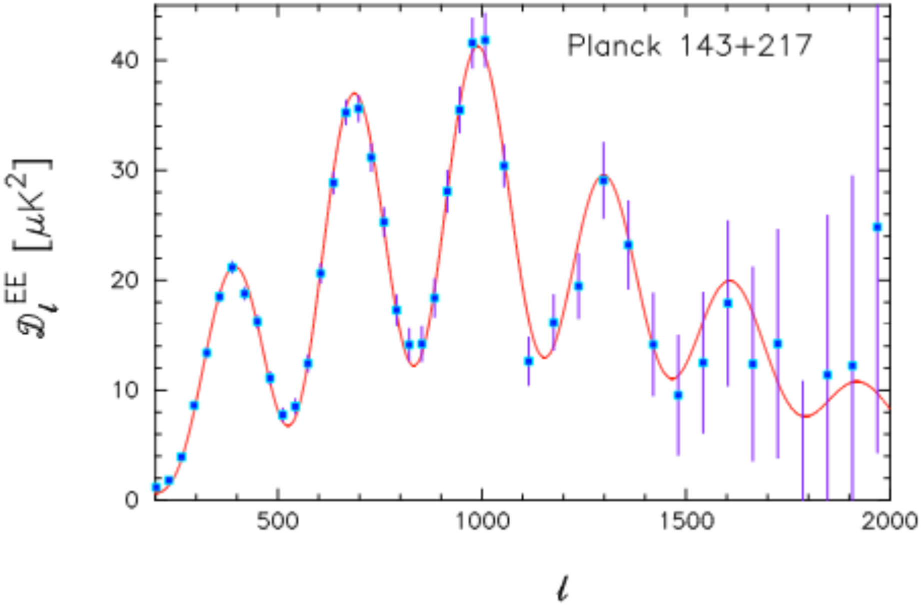
“Teaser” plot…



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

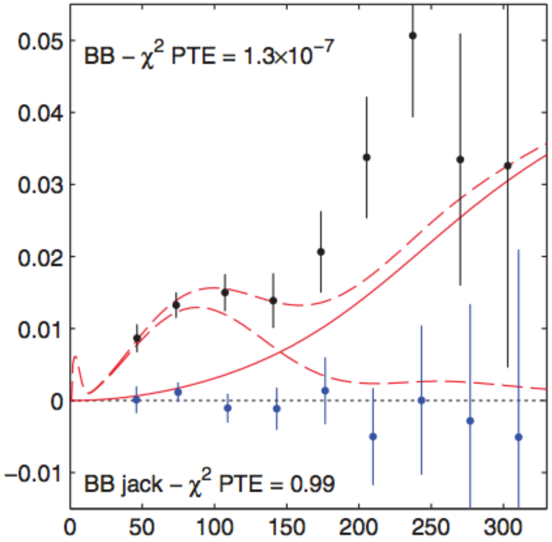


Planck 143+217
$\mathcal{D}_\ell^{EE}$ [μK^2]
40
30
20
10
0
500
1000
1500
2000
ℓ

- 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

BICEP2 & Planck 353

- **BICEP2 2014 I: Detection of B-mode Polarization at Degree Angular Scales by BICEP2** *The BICEP2 Collaboration, Phys. Rev. Lett.* ***112****, 241101, 2014*



  - Primordial <-> polarized dust?

- Planck 353 can help with understanding dust emission, both generically across the sky and in the Bicep2 field

Conclusions

- Six-parameter LCDM fits the high-/ data as well as any other plausible model
- Stay tuned for our next release!