Cosmological Results from Planck

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A quick timeline

- Us, O(10) 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 (CMB)
- Light elements formed by 3 minutes after BB

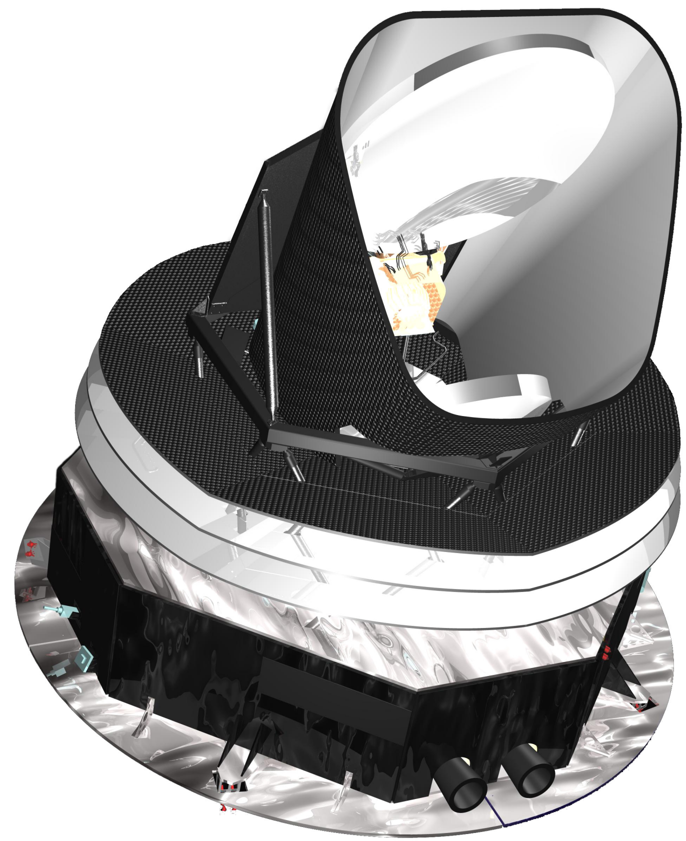
The Cosmic Microwave Background (CMB)

- A snapshot of the early universe from the time of “last scattering”, 380,000 years after the big bang
- A bit like looking at clearing fog
  - Earlier, the fog is too thick to see anything
  - Later, the fog is gone
- The universe is very simple this young, so any lumps seen then must have been there at the Big Bang

Simplified description of the Universe often suffices…

- We have distributions of:
  - Matter (Normal and “dark”)
  - Radiation (set by T_{CMB})
  - Dark Energy
- “Optical depth 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



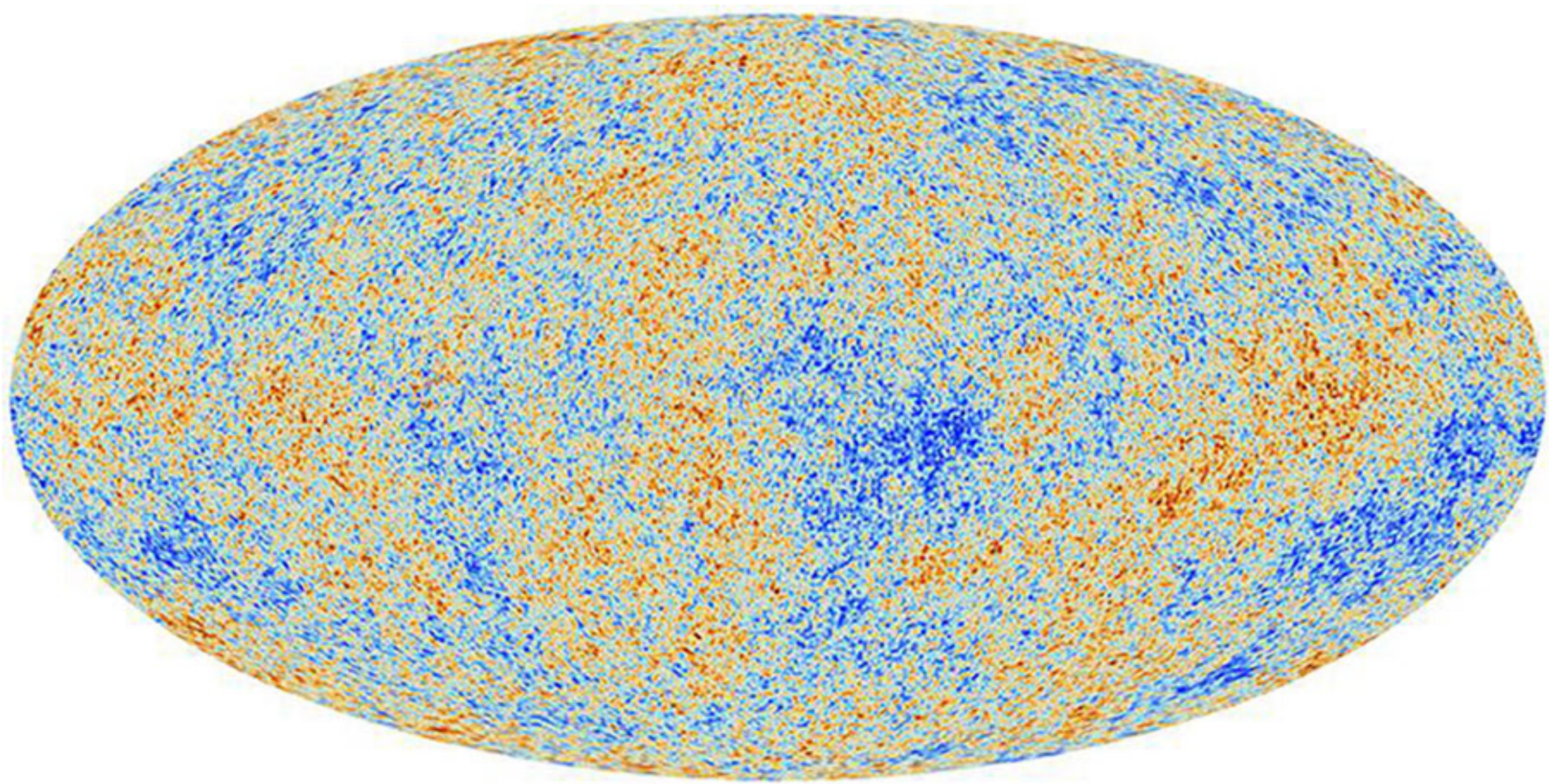
http://www.esa.int/Our_Activities/Space_Science/Planck (ESA)

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.

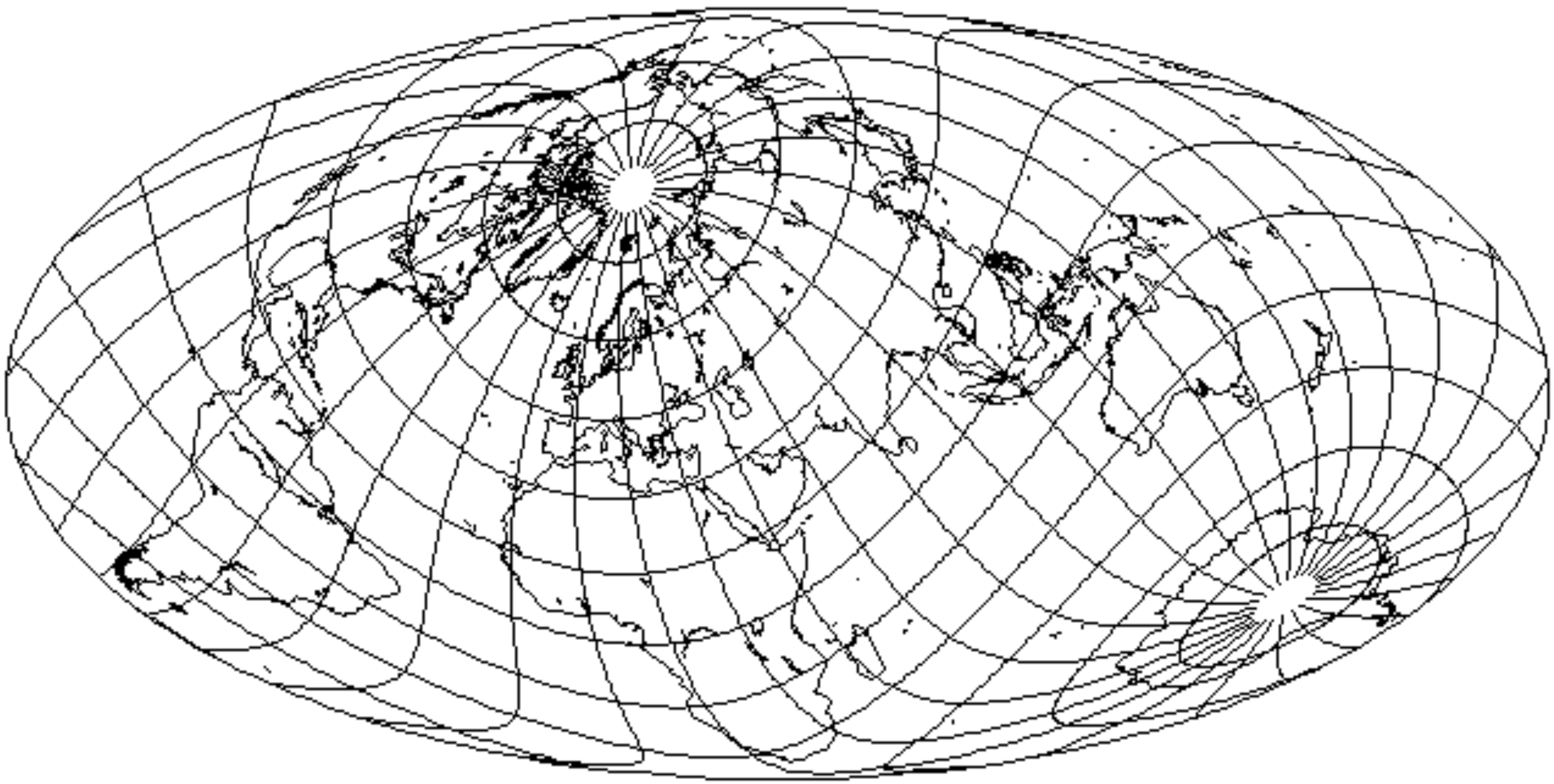
Planck CMB map



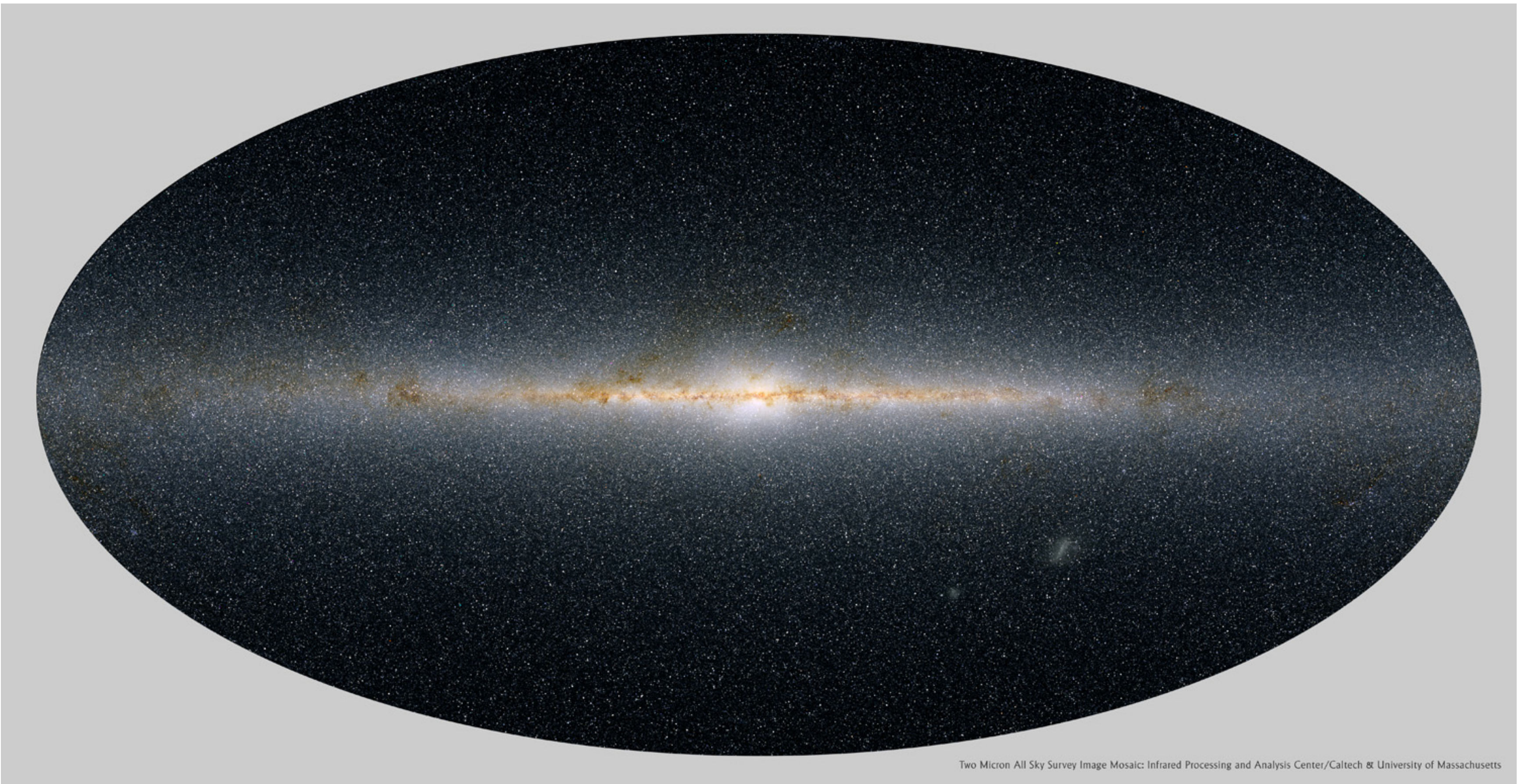
(ESA)

Cf. a projection of the Earth…

(Wikipedia)

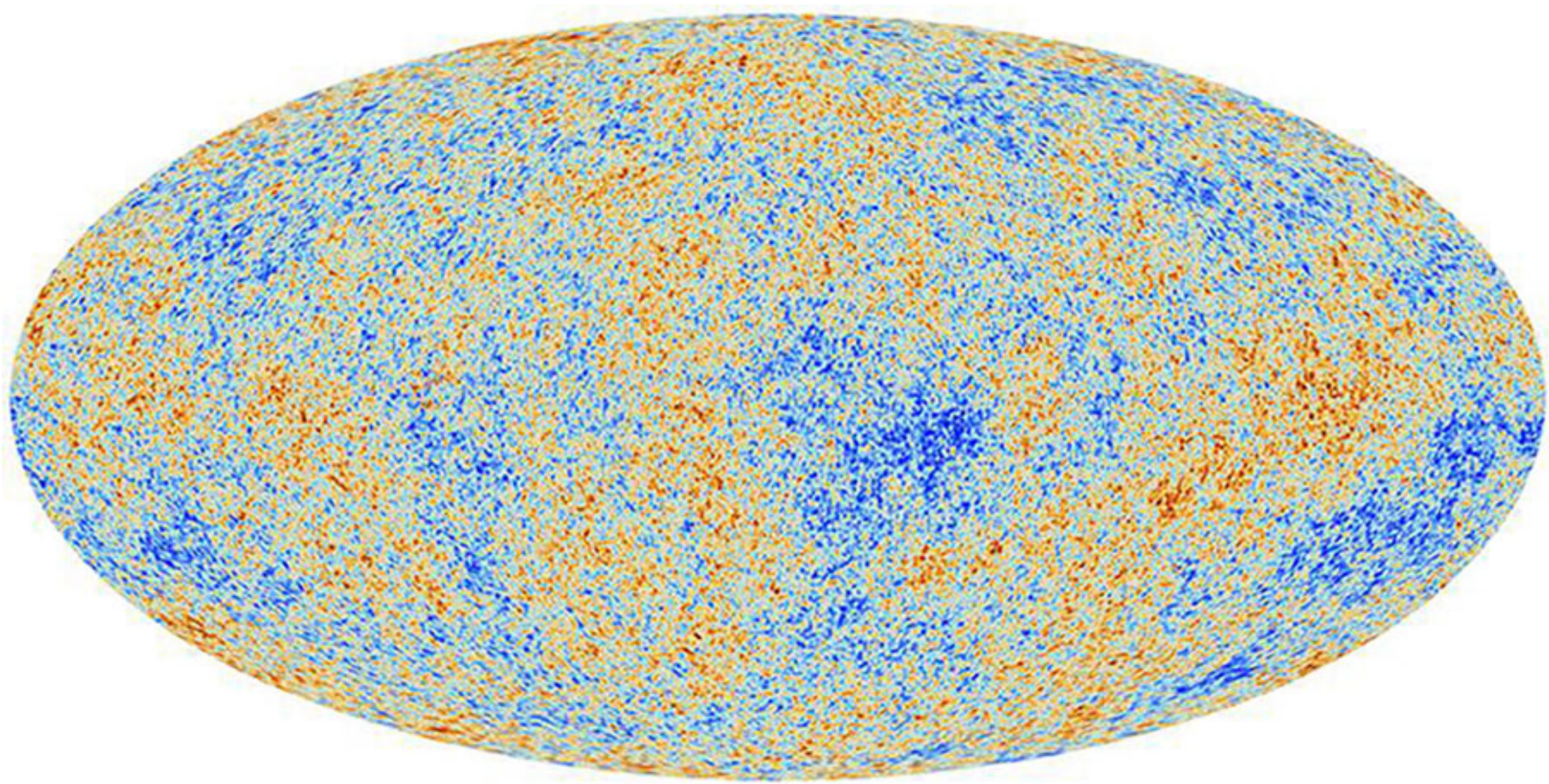


The night sky…



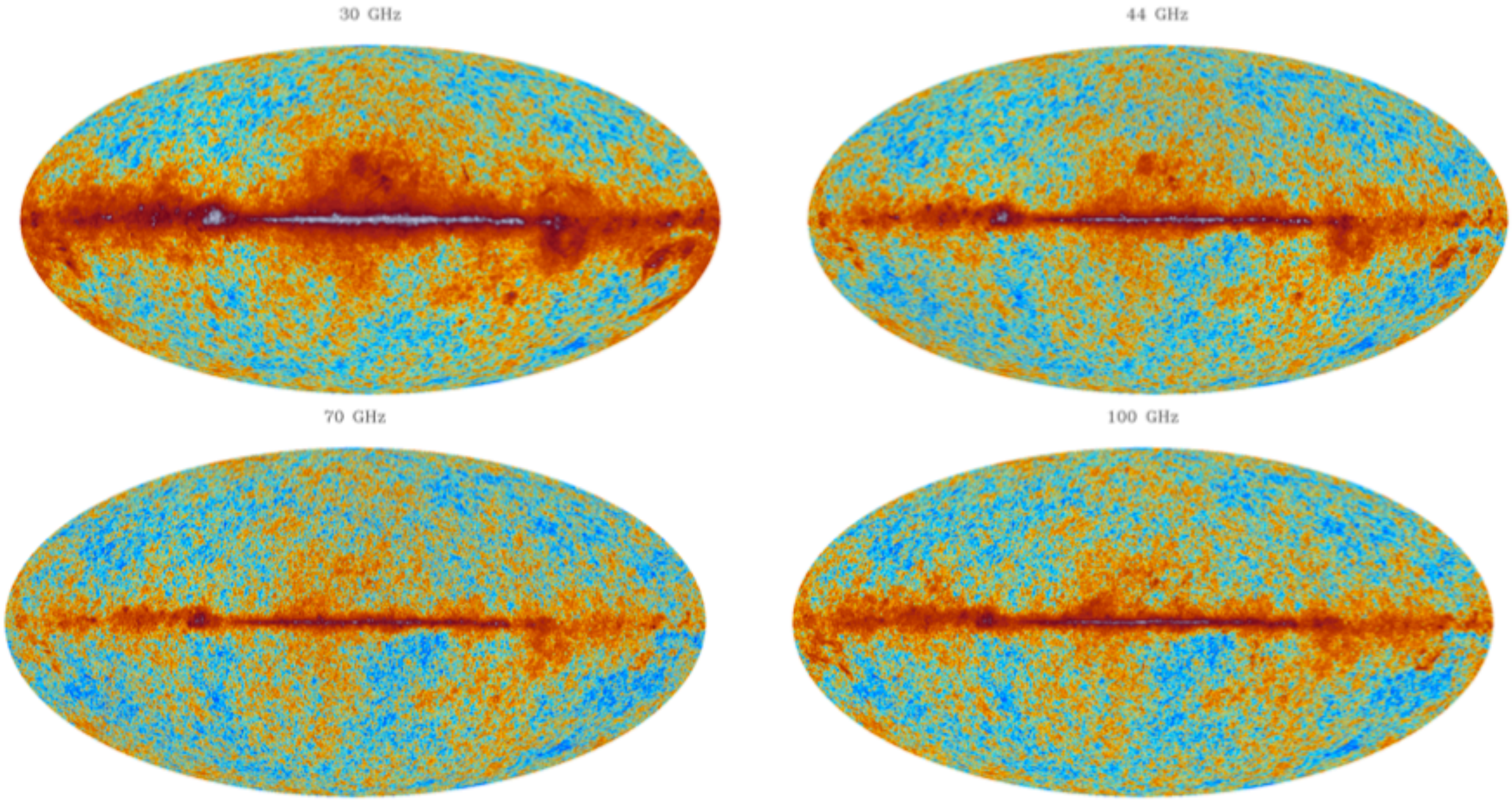
Atlas Image [or Atlas Image mosaic] courtesy of 2MASS/UMass/IPAC-Caltech/NASA/NSF

Planck CMB map



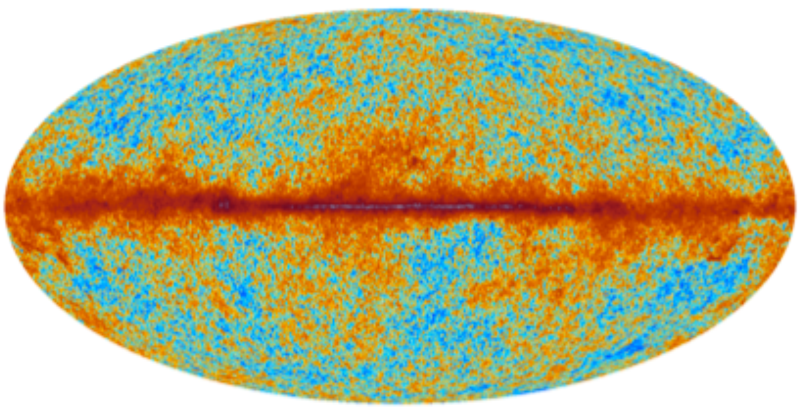
(ESA)

Actually, what we really see is…

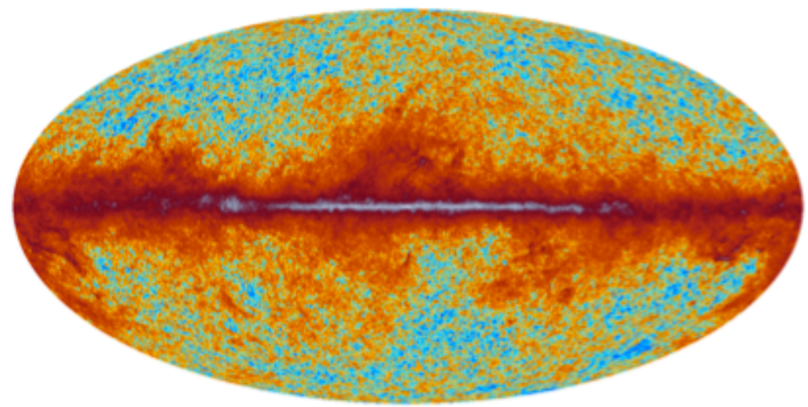


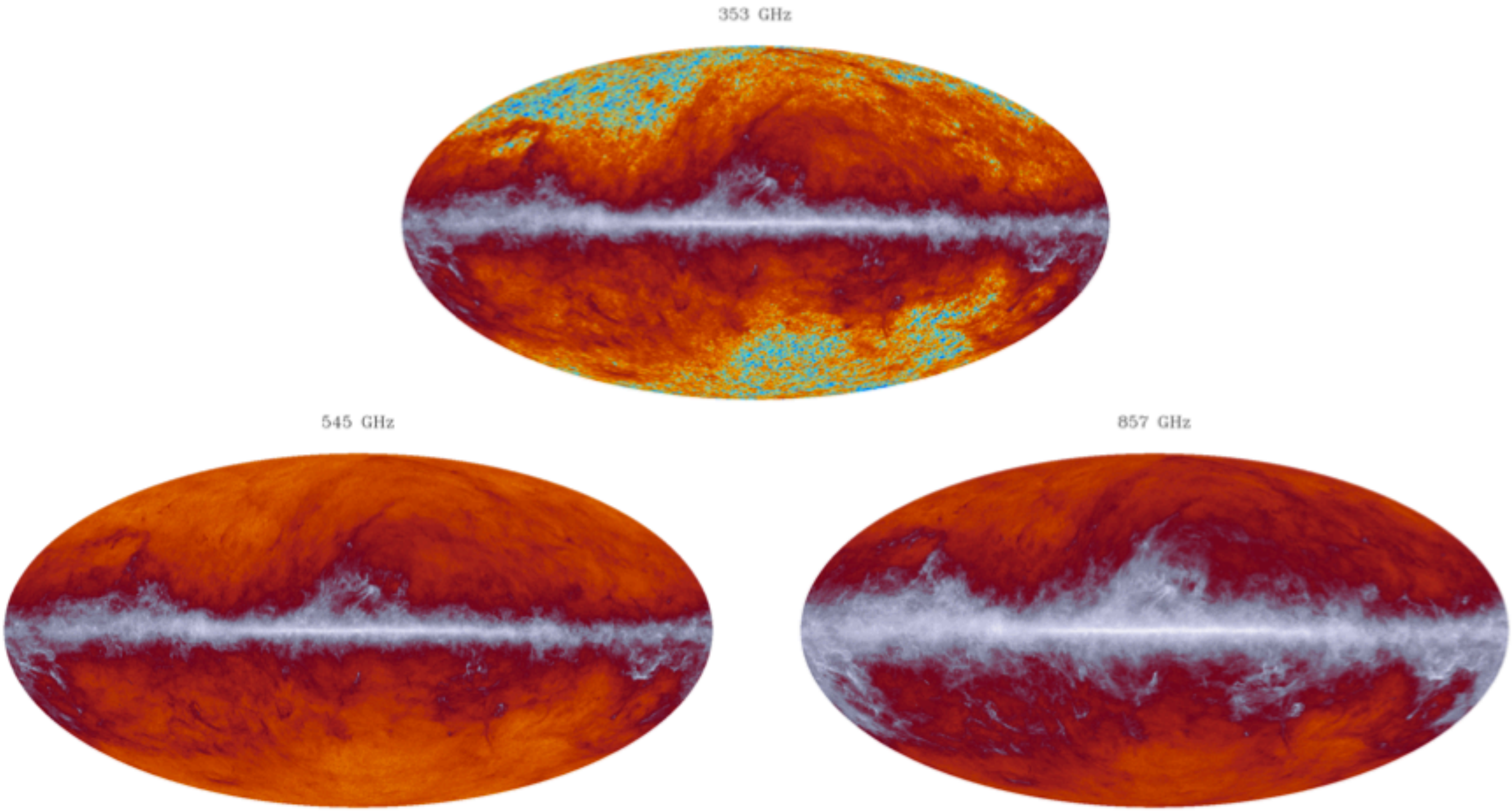
Planck 2013 results. I. Overview of products and scientific results

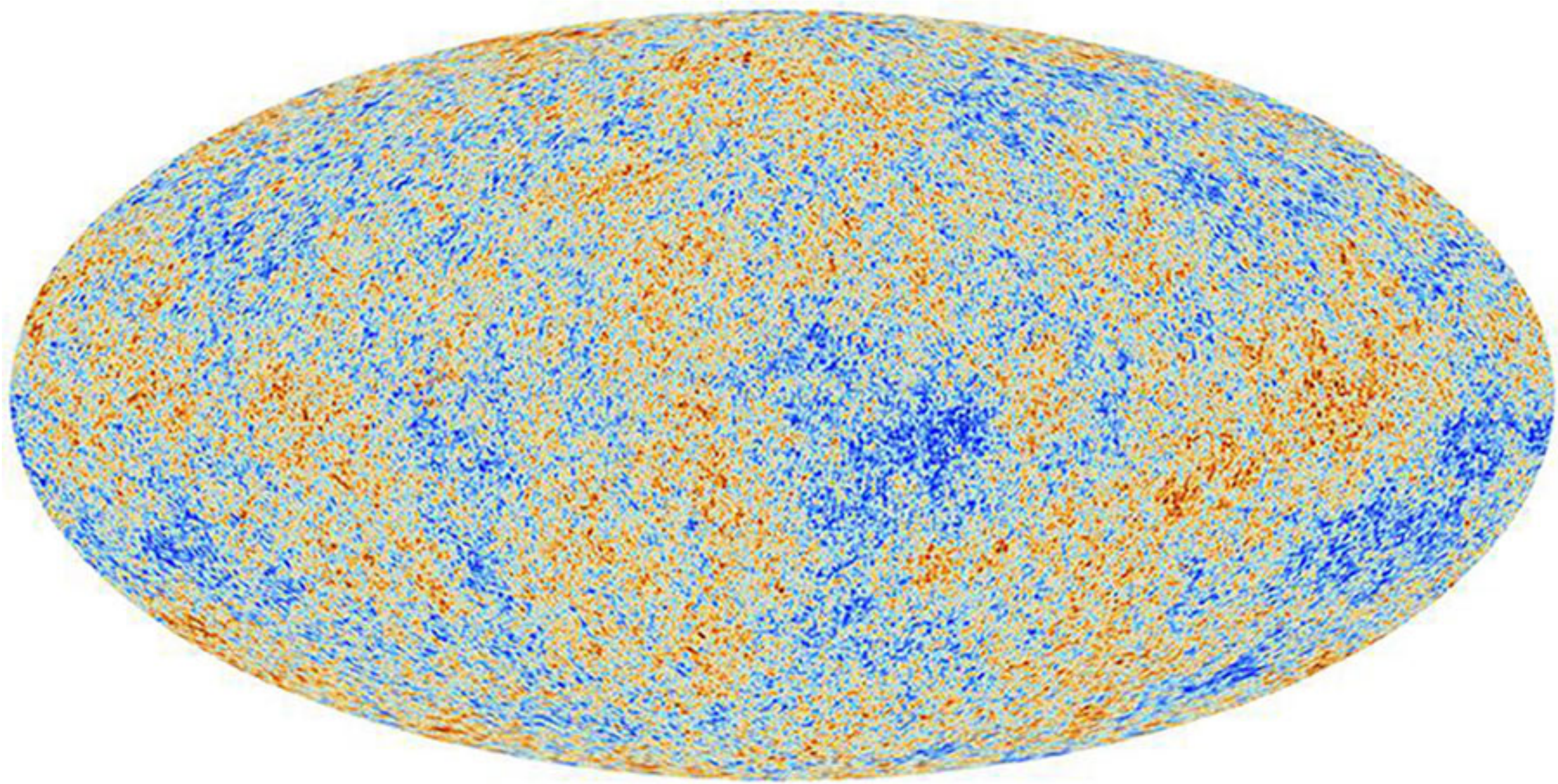
143 GHz



217 GHz

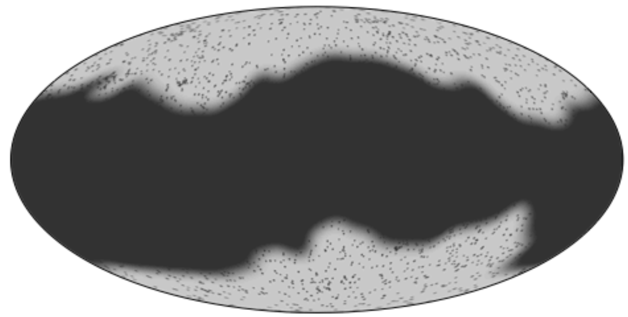


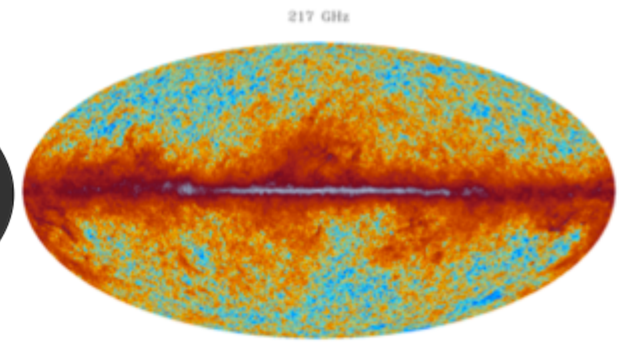

353 GHz
545 GHz
857 GHz

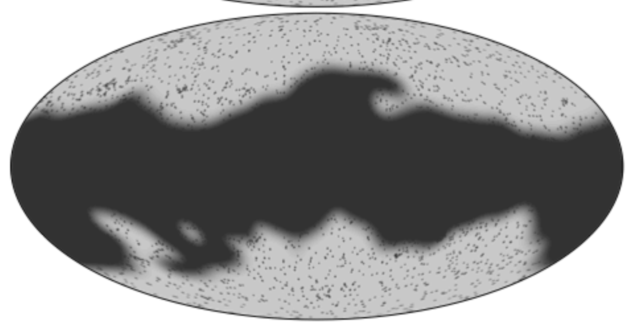


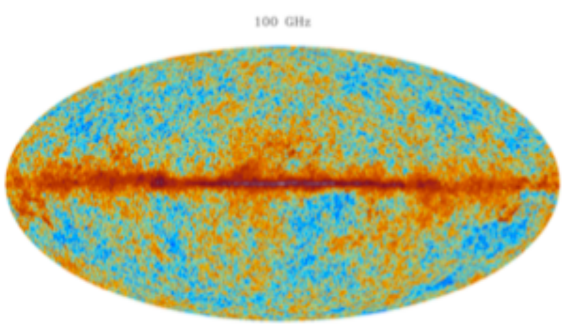
Planck 2013 results. XII.Component Separation

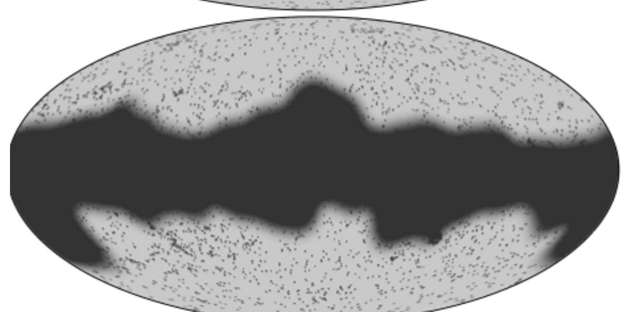
In fact we use the just cleanest channels and apply big masks…

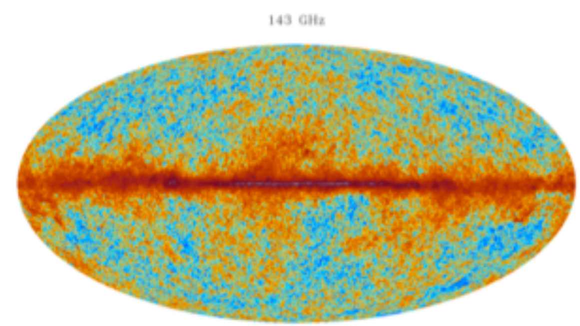




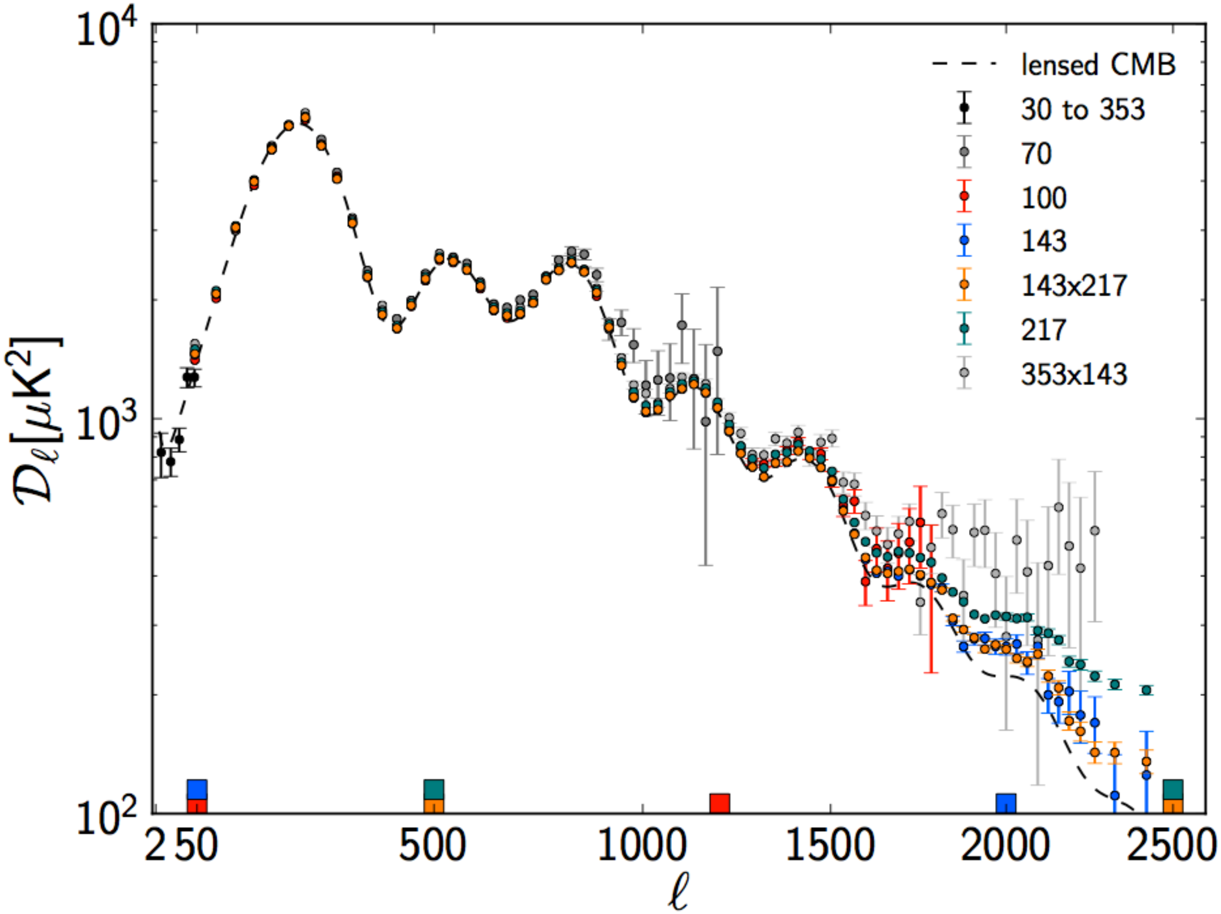








Mainly work in *harmonic space*, with power spectra…



Planck 2013 results. XV. CMB power spectra and likelihood

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 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)

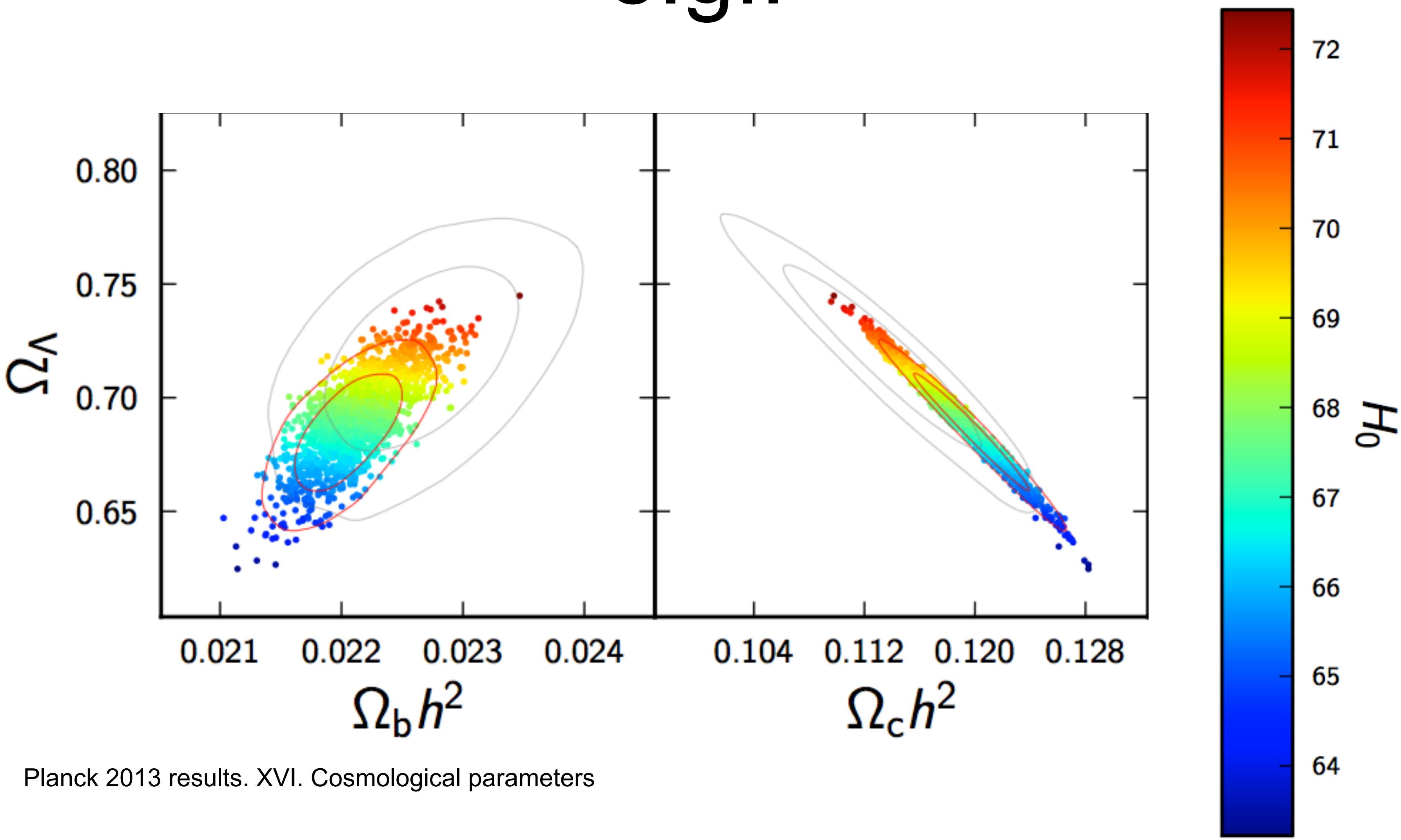
- Different theories lead to different predictions about what the CMB map should statistically look like
- Gives us a way to figure out what the universe is like

Compare theories to data using Bayes' Theorem:

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

(Wikipedia)

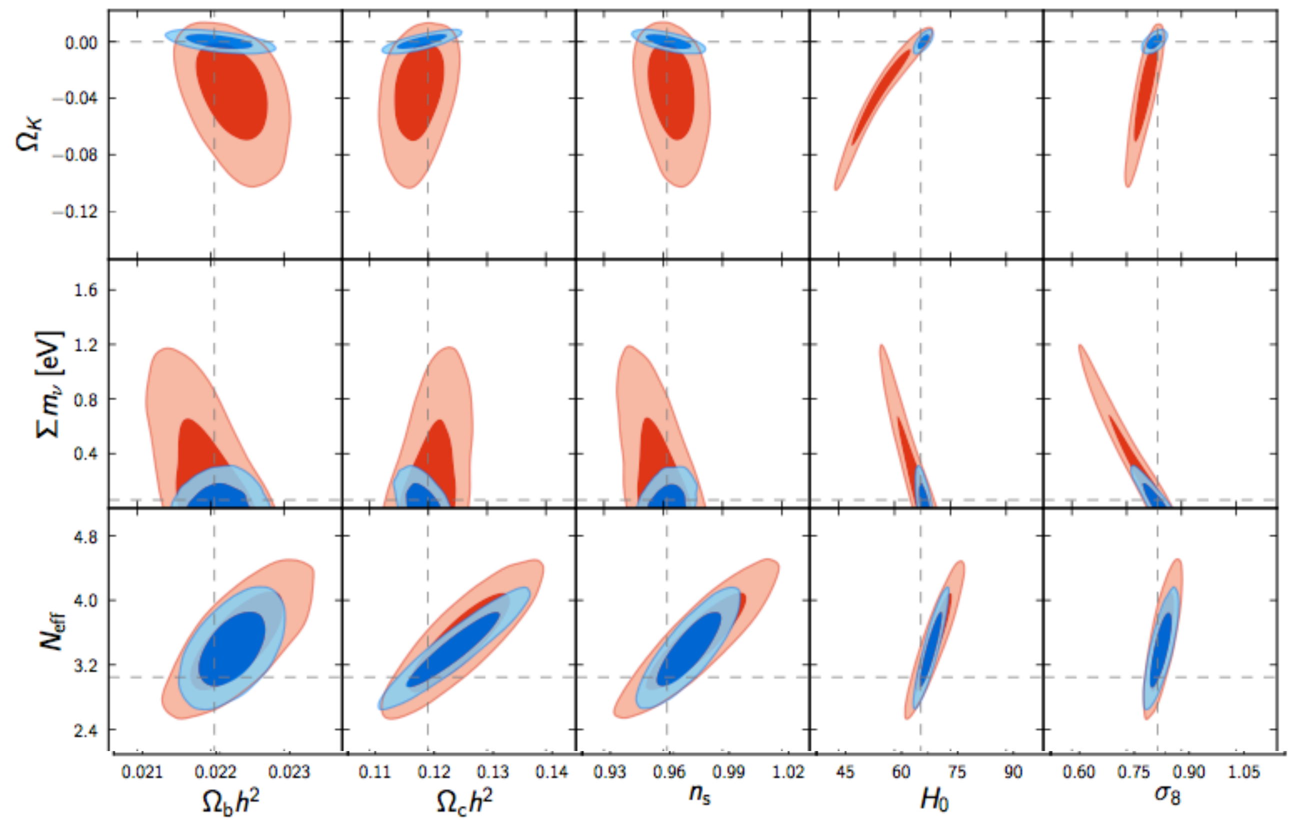
Gives us parameter constraints, e.g.:



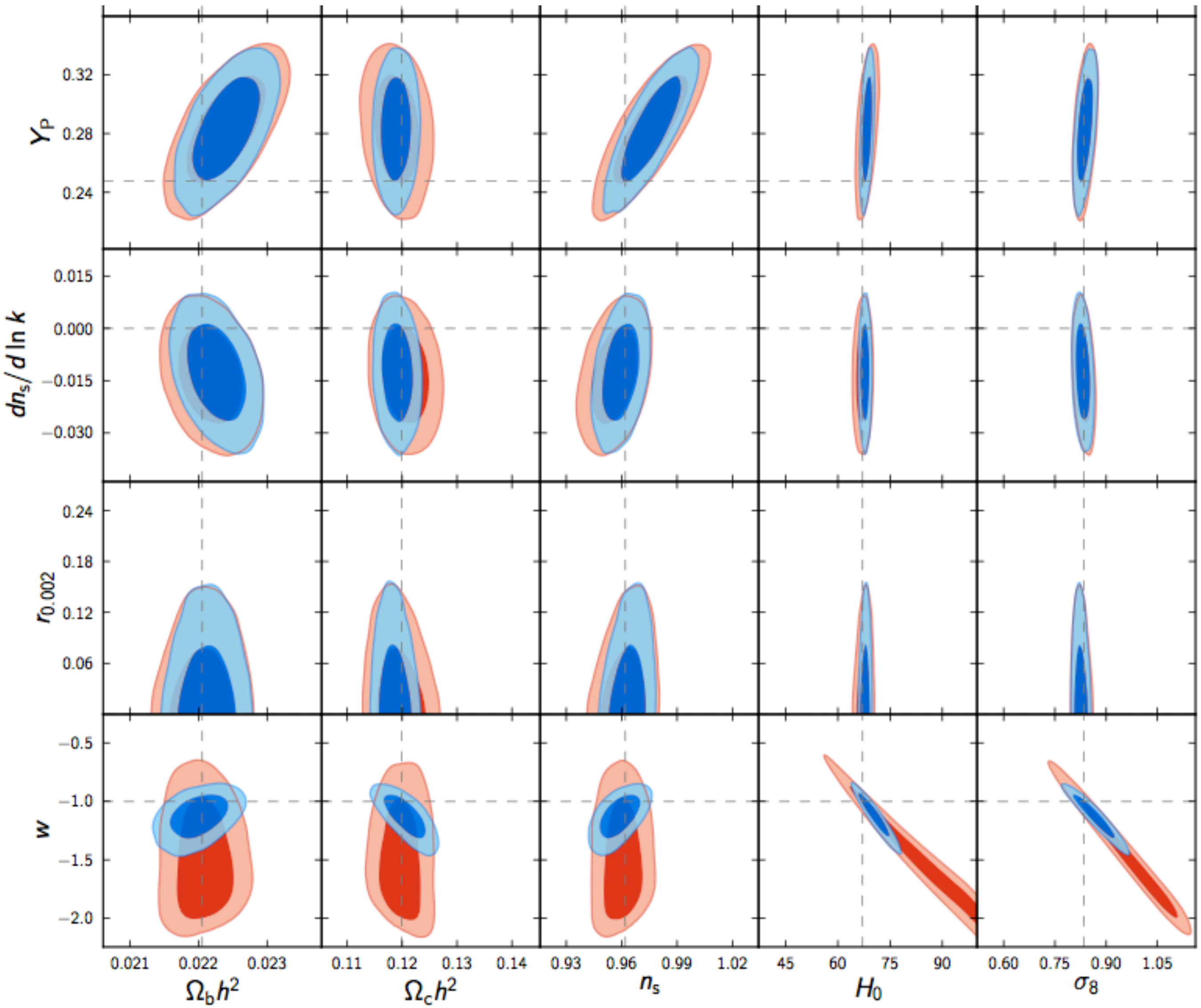
Planck 2013 results. XVI. Cosmological parameters

But what of plausible extensions? Nothing!

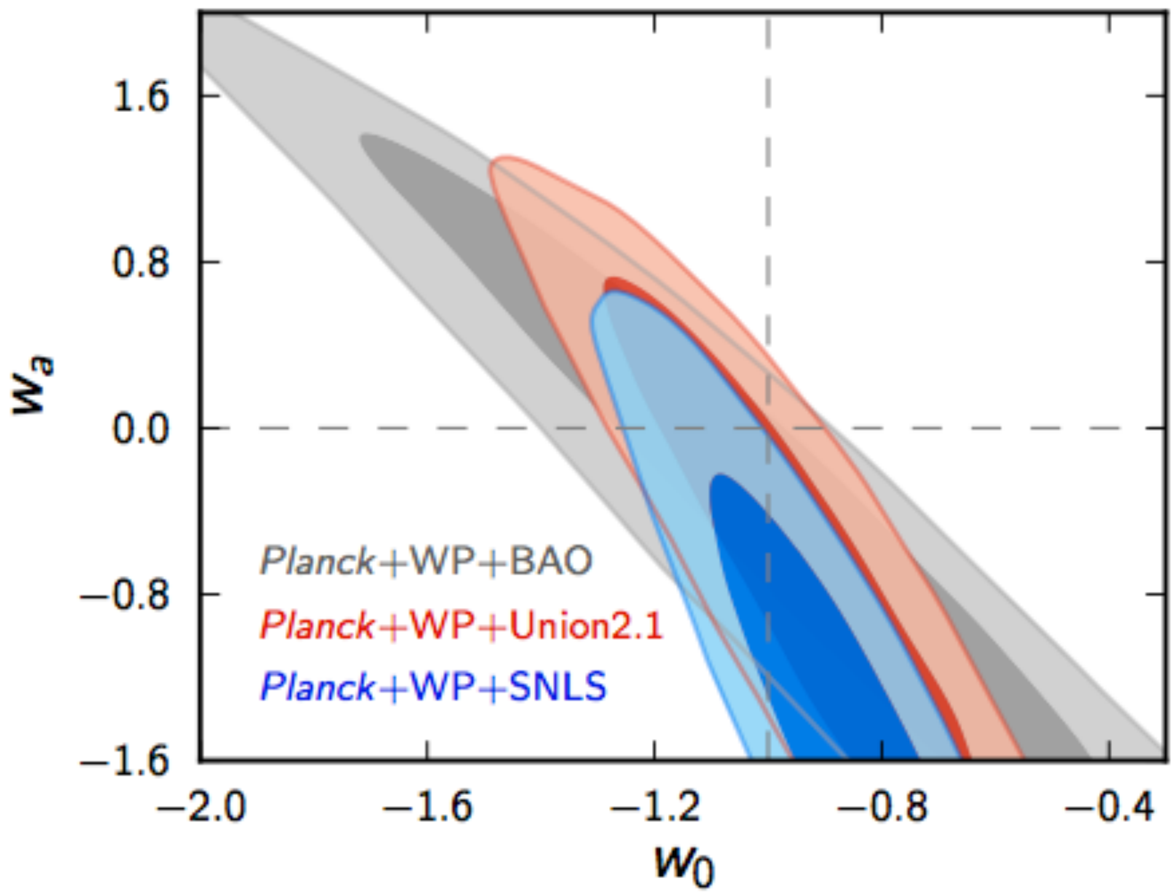
- Curvature, neutrino masses, varying number of neutrinos…



- Helium fraction, running, tensors, dark energy…



Some tensions with other datasets, e.g. …



Still Questions…

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

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

Why is there an horizon problem?

- Could the contents of the Universe might have interacted and mixed and regularized themselves
- But there is no more time to be had in a radiation-dominated universe…

- …one needs more time

Therefore, inflation…

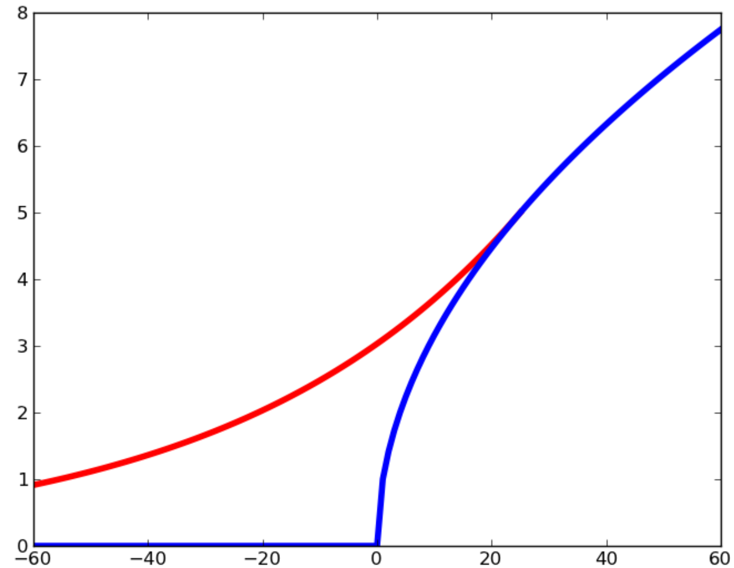
- A new form of material is needed, the *inflaton* scalar field

- If the universe is inflaton-dominated, it can expand exponentially, exceedingly rapidly at high energy

- The inflaton can decay into matter and radiation, starting off the normal “big bang”

Addressing the Horizon Problem

- exponential expansion in reverse corresponds to *slower* progress towards a singularity
- i.e. we have more time!



- In inflation, both the inflaton and spacetime are changing, so…

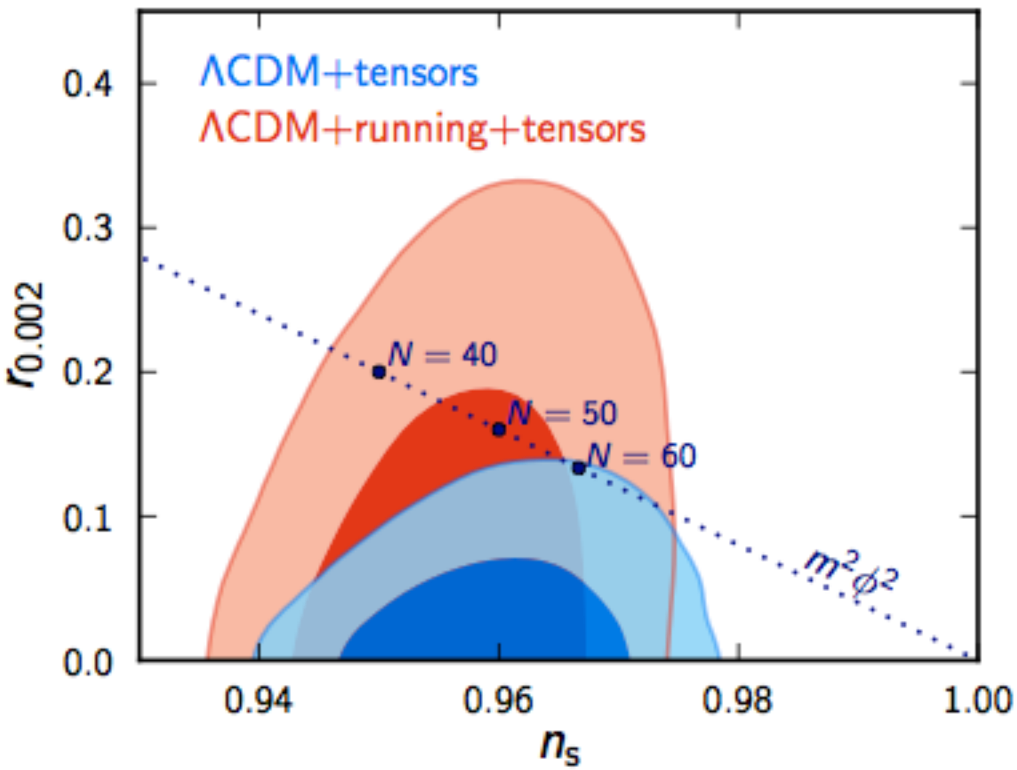
- Could tiny quantum uncertainty of the inflaton end up, after stretching and growing during inflation, being the "primordial fluctuations" in the big bang model?
  - Yes!
- So all the structure in the Universe might be intrinsically quantum!

Quantum Fluctuations during Inflation

- This is curved-spacetime QFT
- Assume GR with a scalar field
  - Background spacetime is FRW
  - Scalar field slowly rolls
- Consider small fluctuations in the scalar field and metric
  - “scalars” and “tensors”
- Work out their late-time two-point functions
  - Assuming an initial condition

Details of the inflaton potential affect the perturbations…

- Puts pressure on large-field models

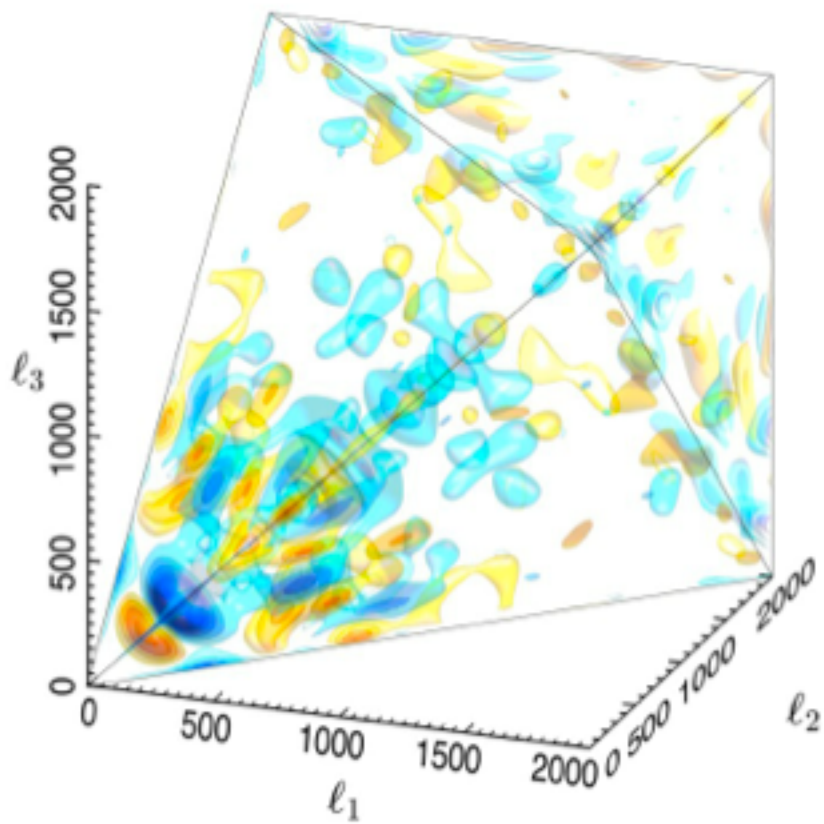


More complicated scenarios are possible

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

Higher order statistics

- The three-point function



Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity

No “normal” detection…

	ISW-lensing subtracted		
	KSW	Binned	Modal
Local	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	**−25 ± 39**	−17 ± 41	−14 ± 42

…but a "feature model" fits quite well!

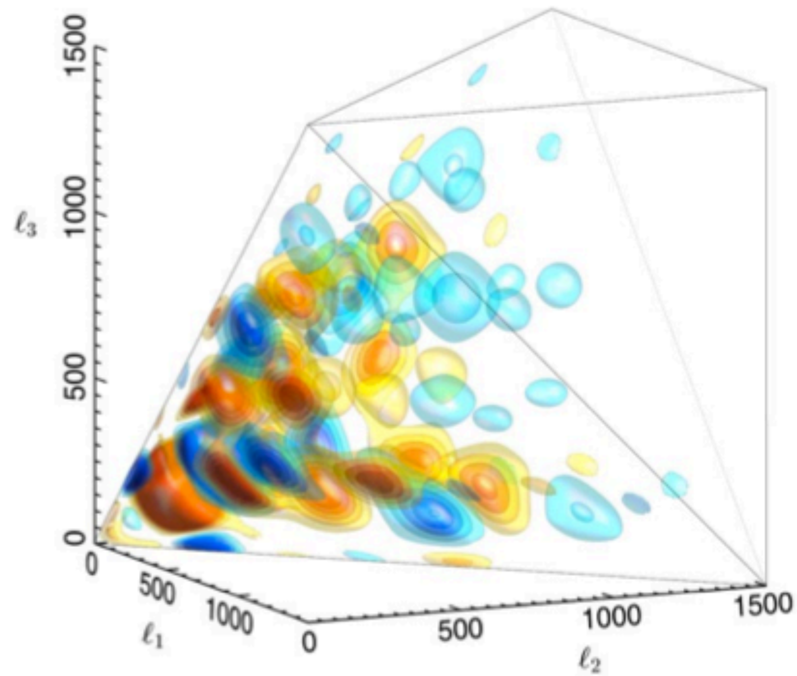


Fig. 12. CMB bispectrum shown for the best-fit feature model with an envelope with parameters $k = 0.01875$, phase $\phi = 0$ and $\Delta k = 0.045$ (see Table 13). Compare with the Planck bispectrum reconstruction, Fig. 7.

But how does inflation start?

- Out of a previous radiation phase?
- Or from “chaos”?
- Or if inflation can happen, is there a deep reason the universe should naturally start in an inflating state?

And did inflation end?

- We live in a region where inflation has ended
- But did it have to end everywhere at the same time?
  - If not, then there could be other BB regions, i.e. “universes” out there!

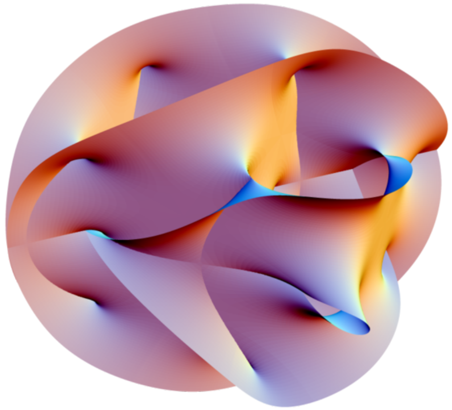
Eternal Inflation

- Perhaps “most” of space is inflating!
- Perhaps “inflation” carries on forever!
- Then there could be an infinite number of “mini-universes” around, a “multiverse” of universes!
- What might these other universes be like?

Enter string theory

- In QFT,
  - *Particles* are excitations of fields; fields are collections of *particles*
- But why not?:
  - *Strings* are excitations of fields; fields are collections of *strings*
- I.e. the string becomes the basic building block

- Many ways to wrap up six dimensions
  - Also can have fluxes
  - And their sources, branes



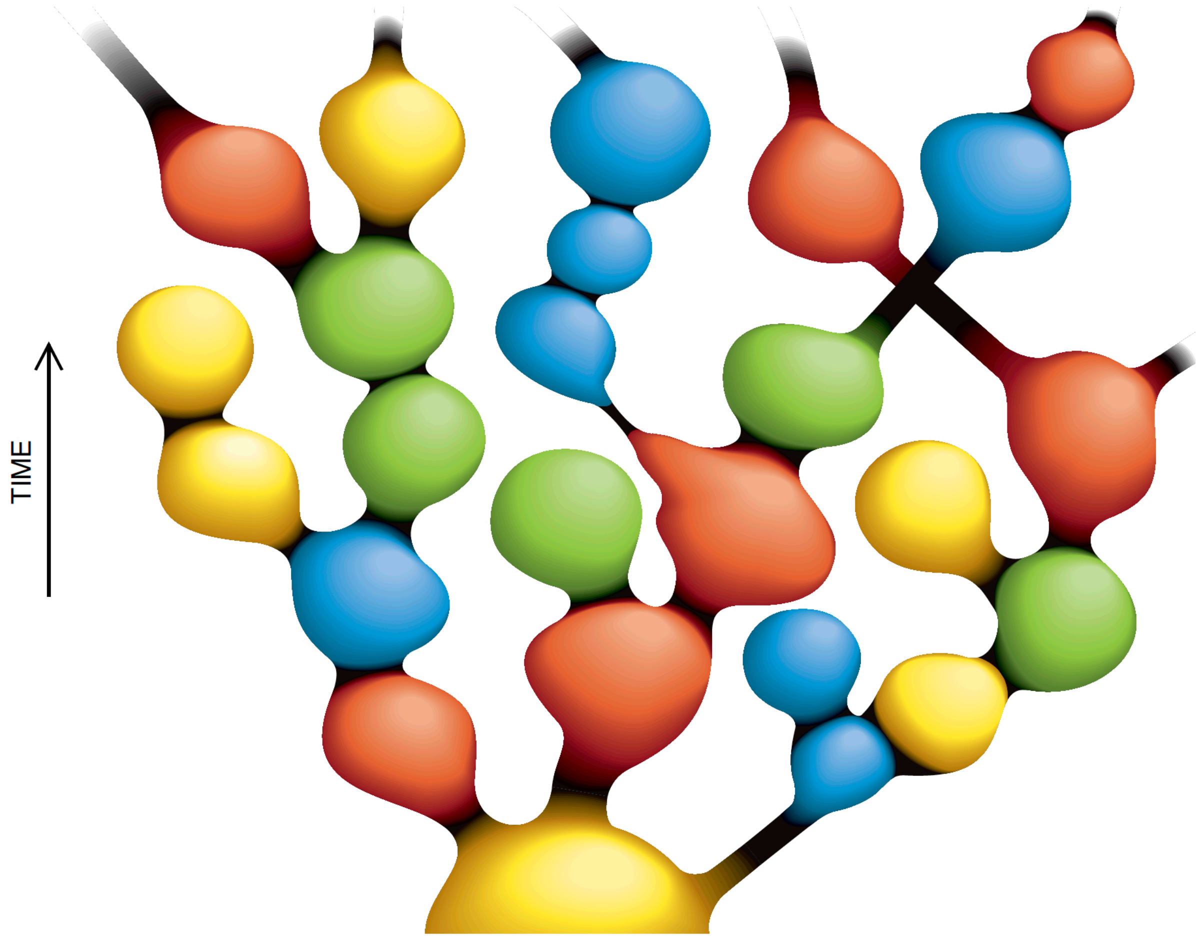
(Wikipedia)

- There seem to be a *lot* (10^{500} ?) of possibilities…
  - *The String Theory Landscape*

A String Multiverse

- So we can imagine
  - Eternal Inflation, perhaps in higher dimensions, giving an infinite number of universes
  - Each normal lower-dimensional “universe” being one of an immense number of possibilities from the string landscape
  - An infinity of (almost) infinities!

Might even consider Inflation restarting within mini-universes!...



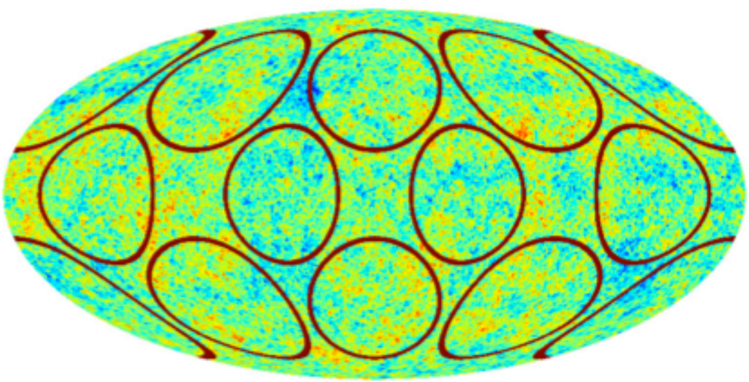
(A. Linde)

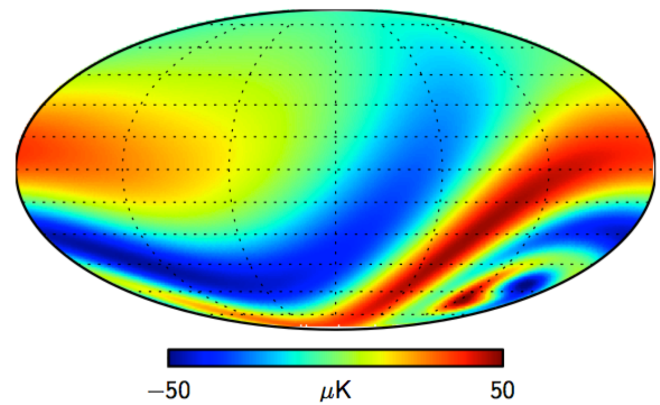
Can we Assess this Theoretically?

- Need to look for a suitable *measure* over the possibilities
- Selection effects need to be taken into account
  - We have to live in regions of any multiverse that are suitable to support life
- The Anthropic Principle
  - Are we “typical”?

And Can The CMB Help Us?…

- E.g. Bubble universe “collisions” in the CMB
- Topological identifications





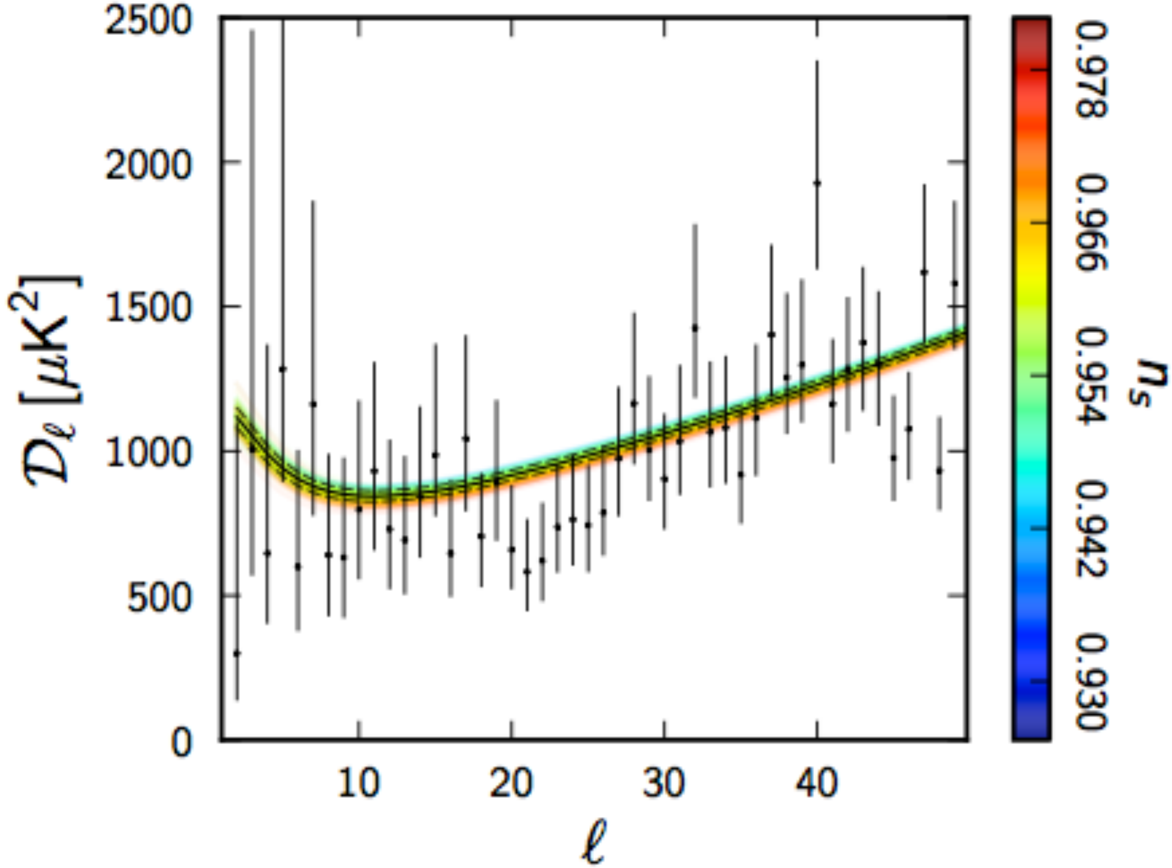
- Homogeneous, anisotropic universes
  – Nothing convincing found yet

Planck 2013 results. XXVI. Background geometry and topology of the Universe

There are *some* “curiosities”…

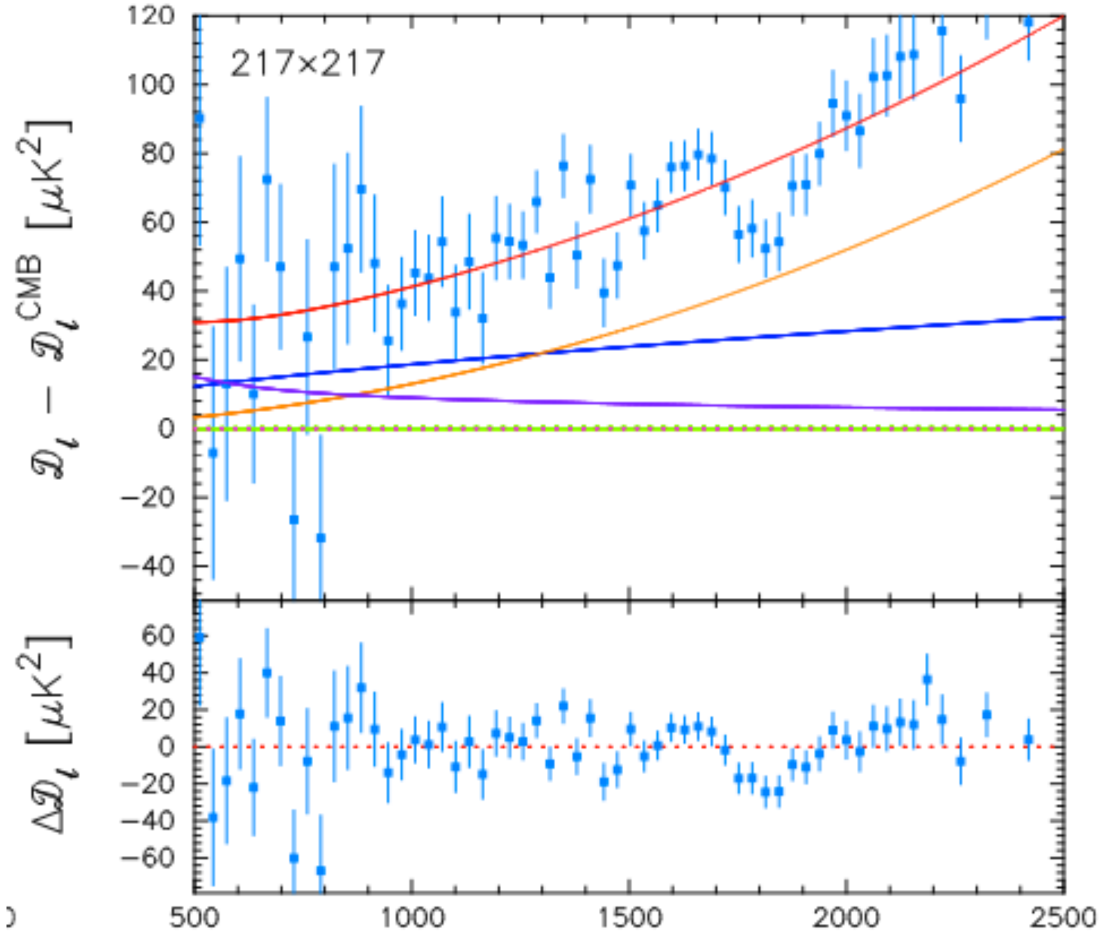
- Features in the power spectra
  - low-l dip
  - High-l dip
- Power asymmetries

Low-l dip…

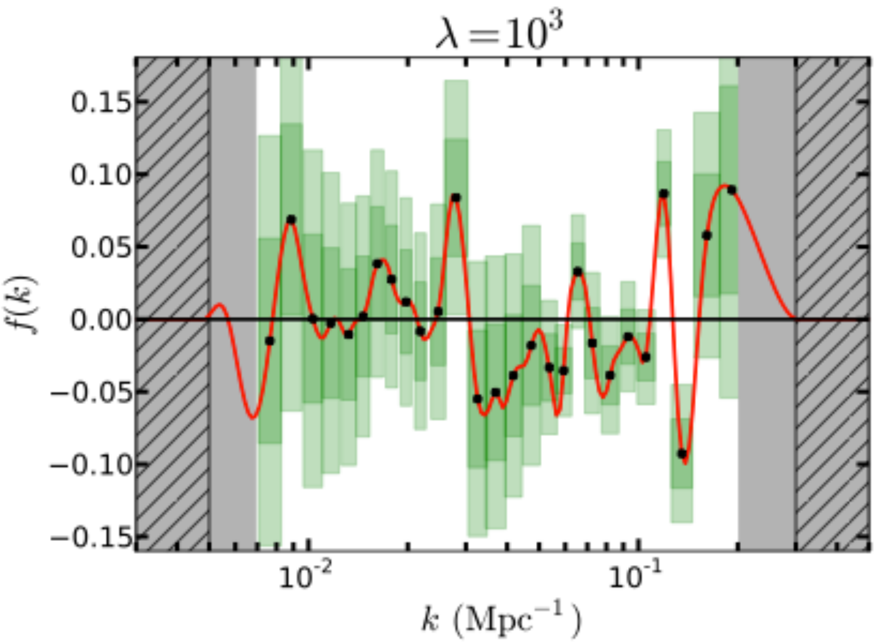


2500
2000
1500
1000
500
0
10
20
30
40
ℓ
$\mathcal{D}_\ell\,[\mu K^2]$
0.978
0.966
0.954
0.942
0.930
n_s

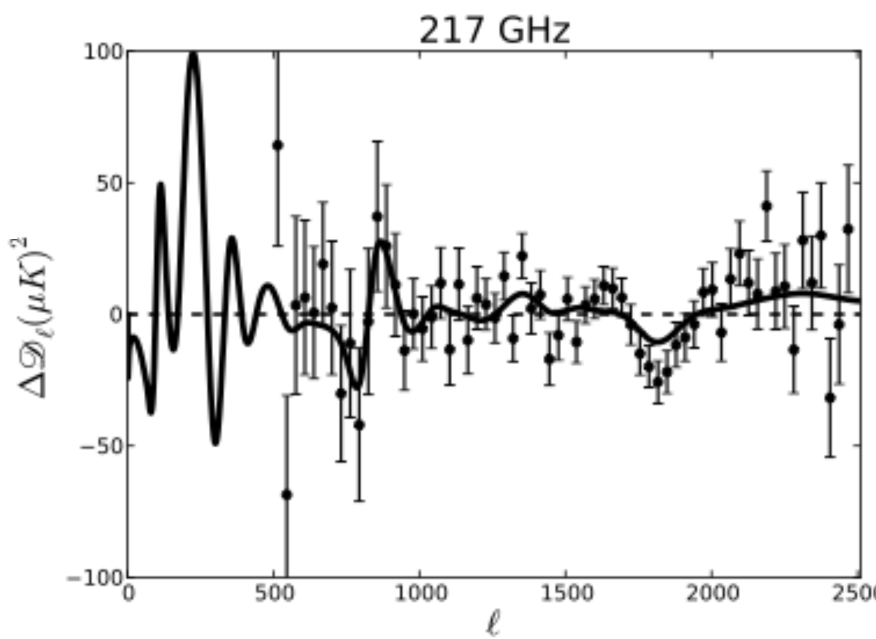
High-l dip…


217×217
$\mathcal{D}_\ell - \mathcal{D}_\ell^{\mathrm{CMB}}$ [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

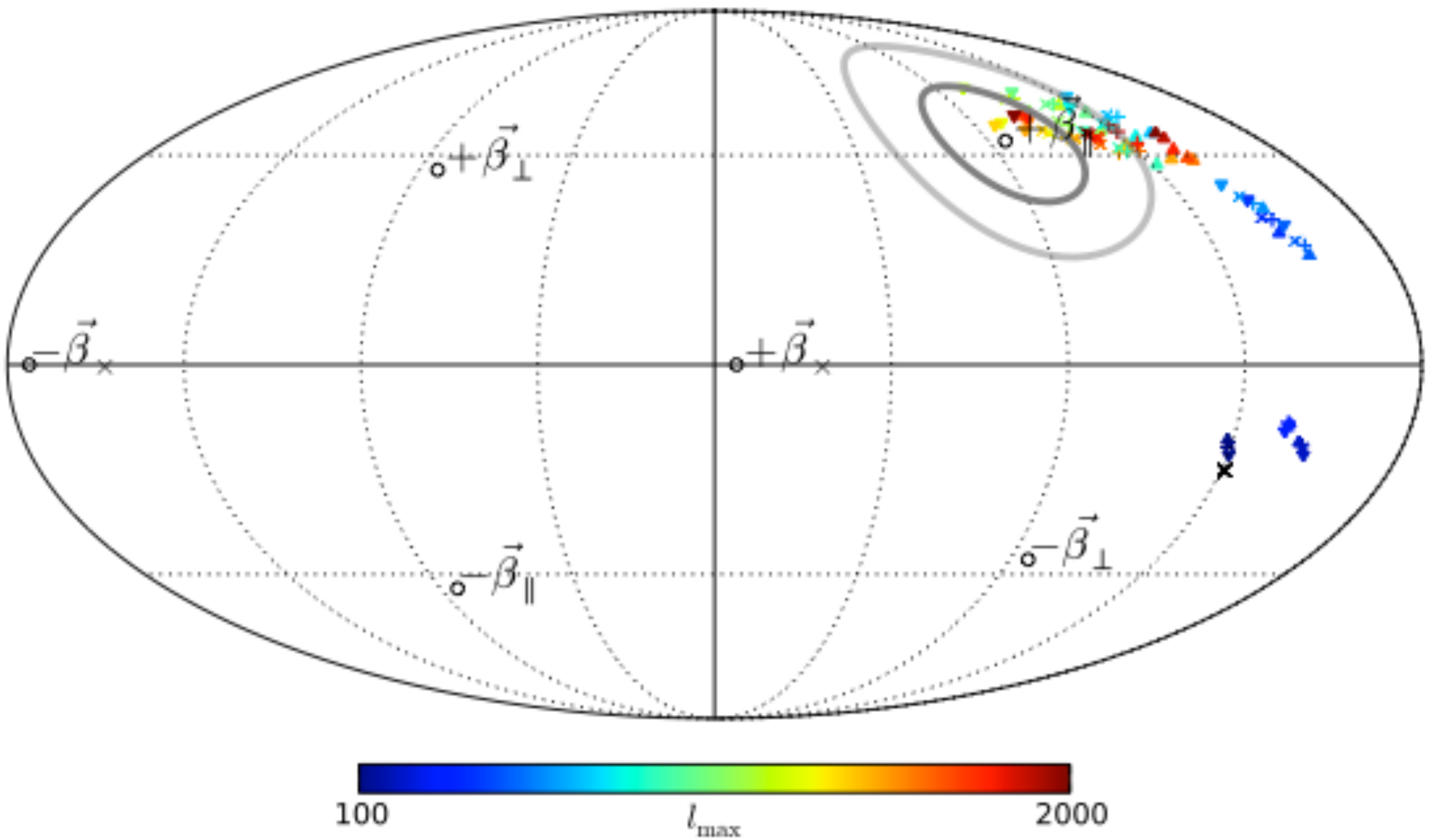
Power-spectrum reconstruction…



Planck 2013 results. XXII. Constraints on inflation



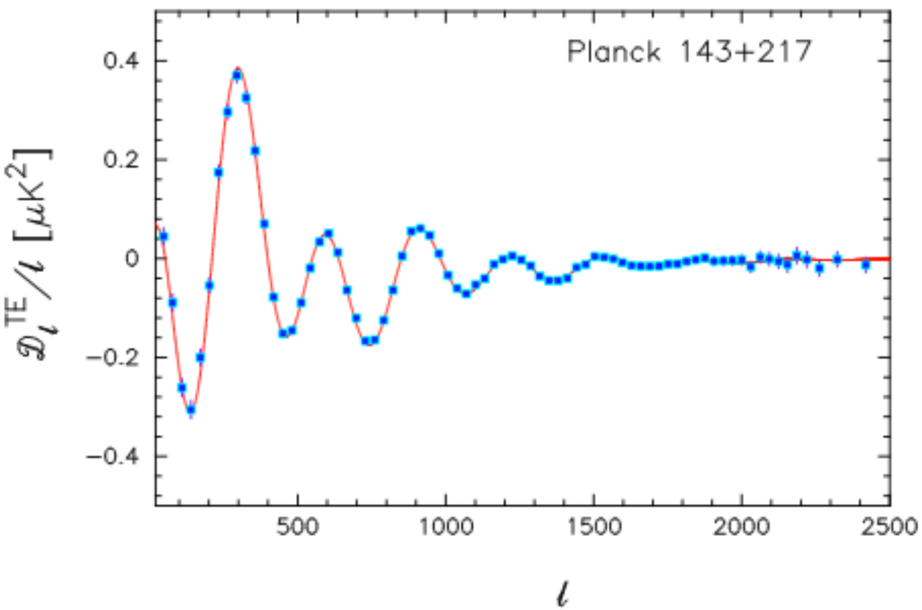
Hemispherical Power Asymmetries & dipole modulation



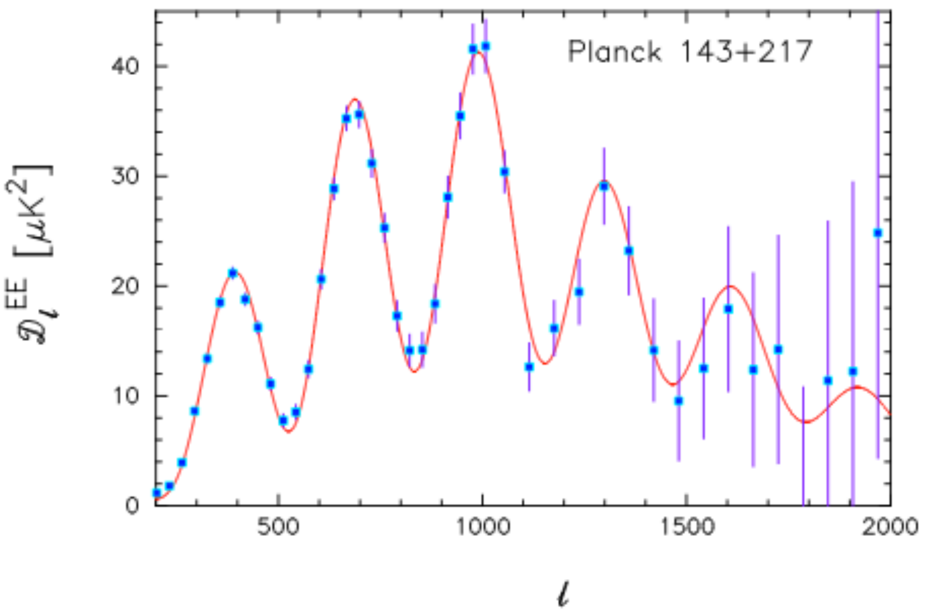
What’s coming…

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



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