Our Simple but Strange Universe

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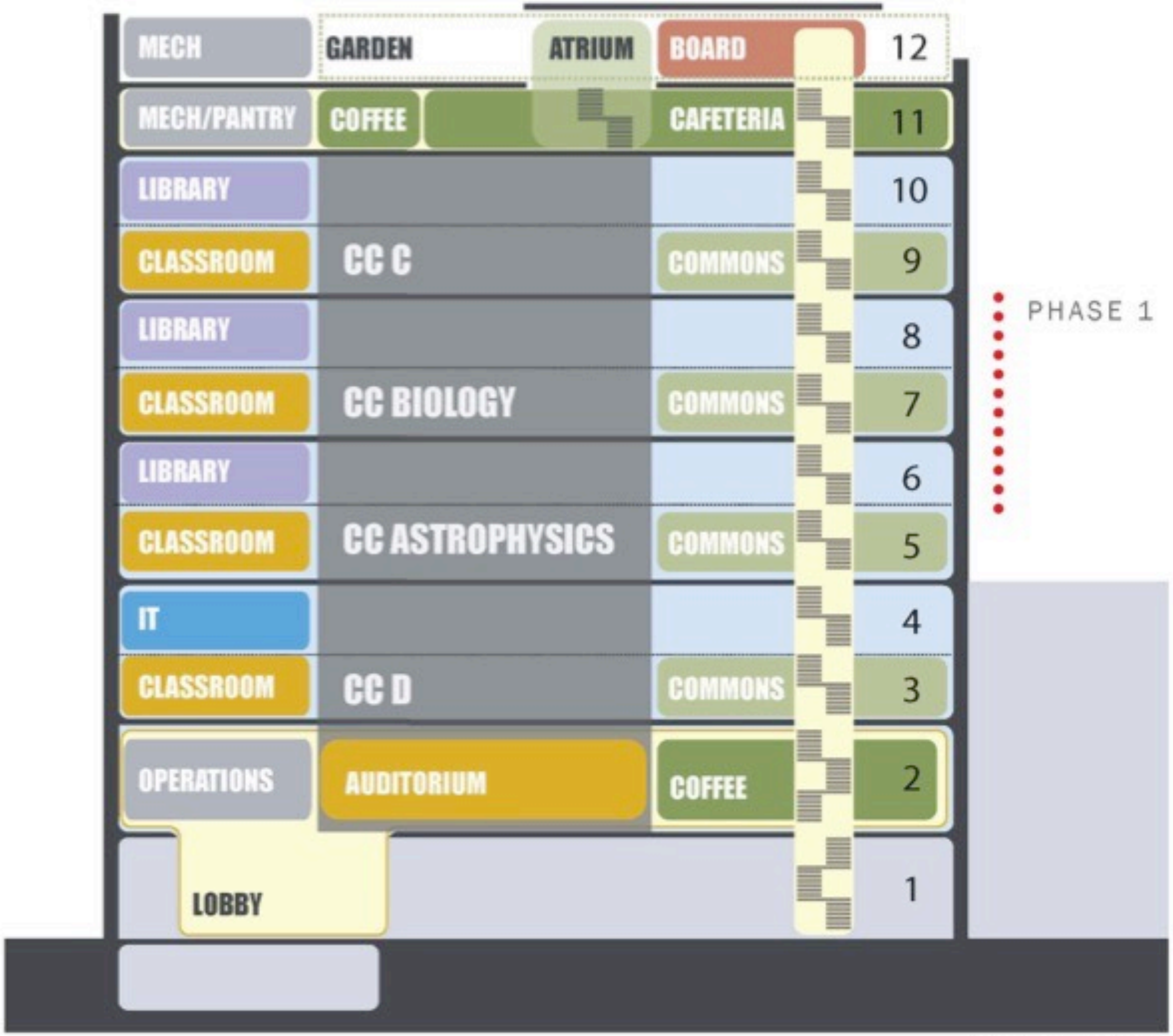
Tokyo October 2017

Flatiron Institute



Perkins Eastman

A Simple but Strange Universe

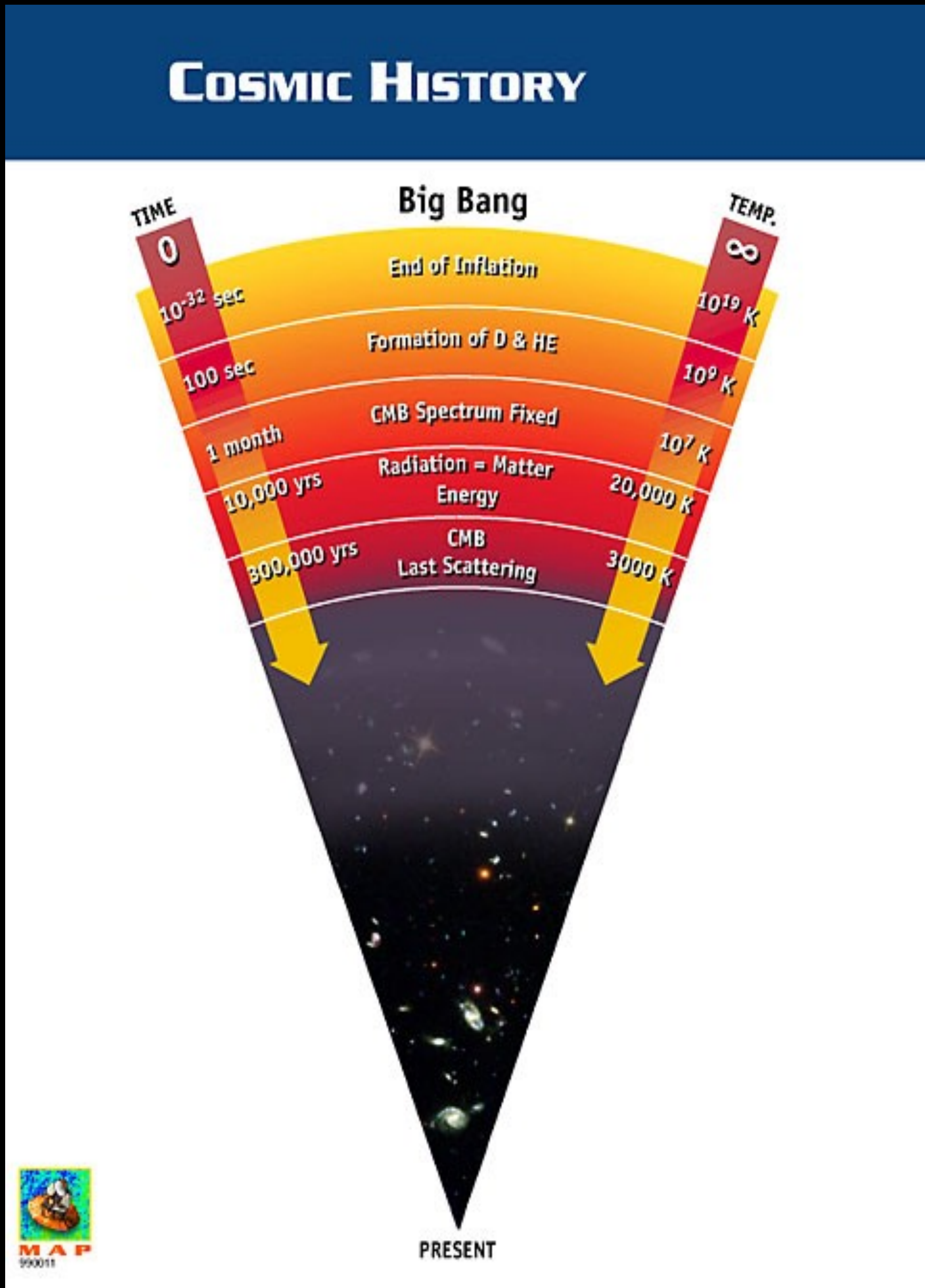
- A simple model with a handful of parameters (the age of the universe, the density of atoms, the density of matter, the amplitude of fluctuations and how the amplitude varies with scale) fits all of our cosmological data

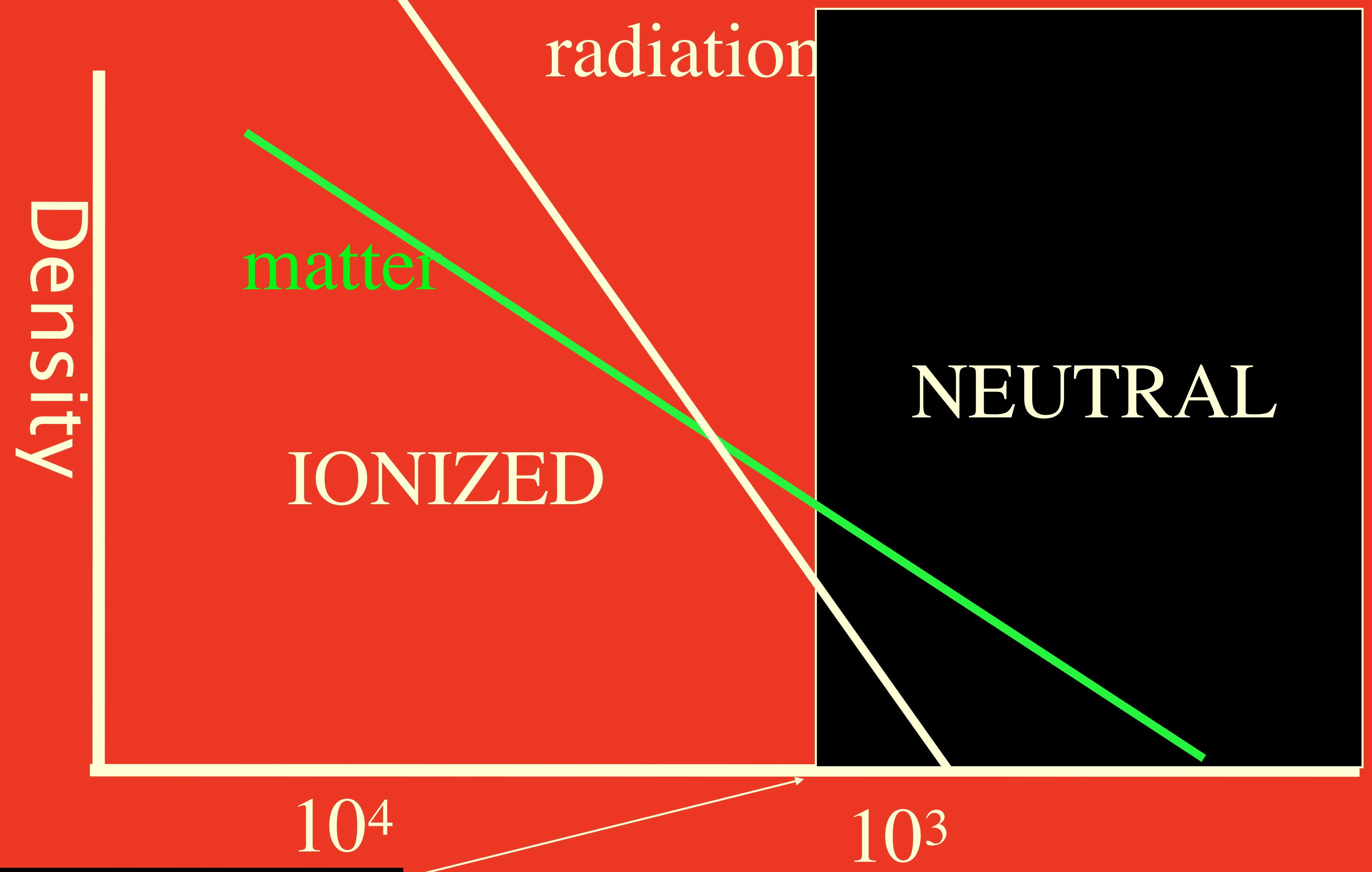
- The model implies that the atoms make up ~5% of the universe and the rest is in the form of dark matter and dark energy

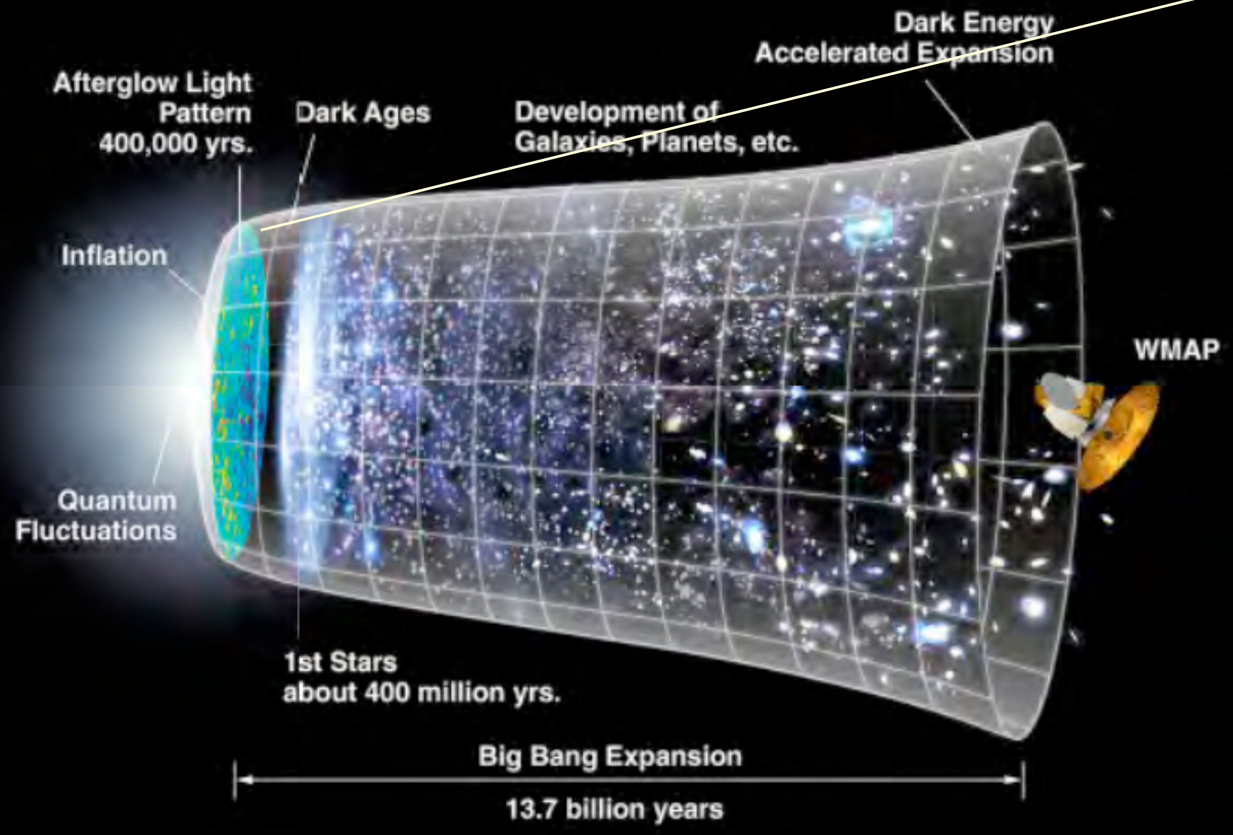
- The early universe underwent a period of accelerated expansion called inflation. During this very early epoch, tiny variations in the expansion rate led to the formation of all known structure.

Quick History of the Universe

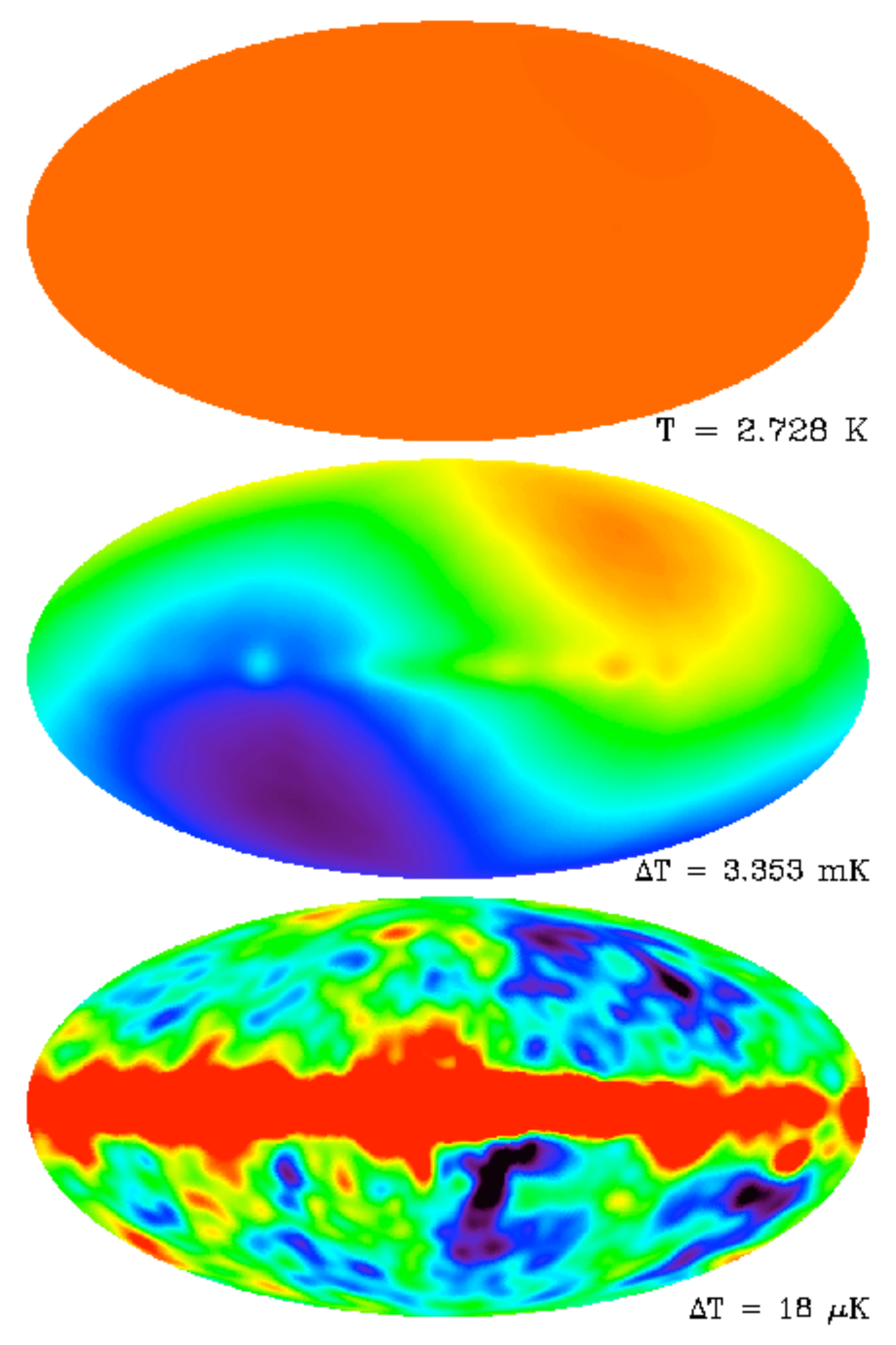
- Universe starts out hot, dense and filled with radiation
- As the universe expands, it cools.
  - During the first minutes, light elements form
  - After 500,000 years, atoms form
  - After 100,000,000 years, stars start to form
  - After 1 Billion years, galaxies and quasars




radiation
Density
matter
IONIZED
NEUTRAL
10^4
10^3
redshift


Dark Energy Accelerated Expansion
Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic Background Radiation



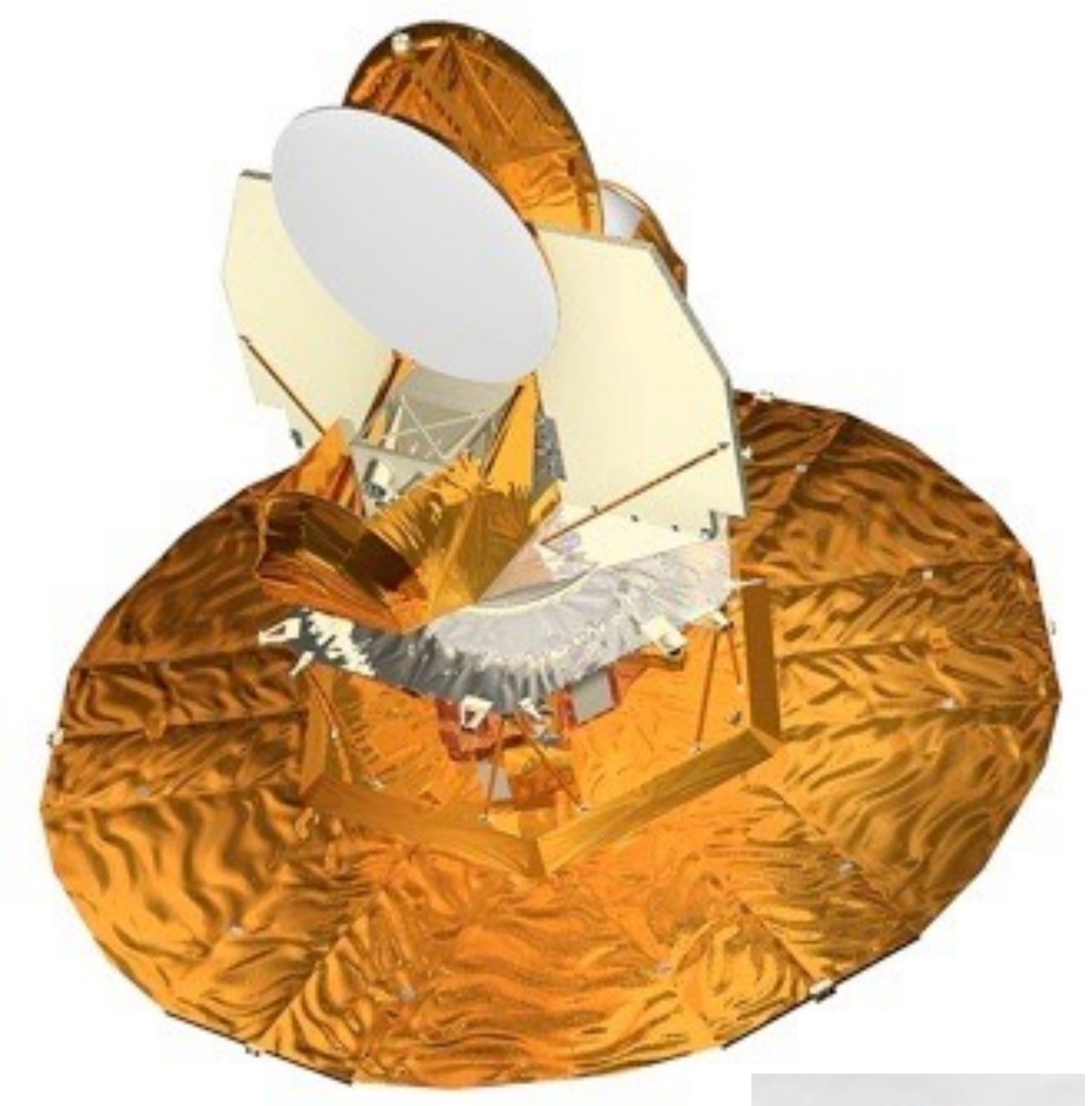
COBE map

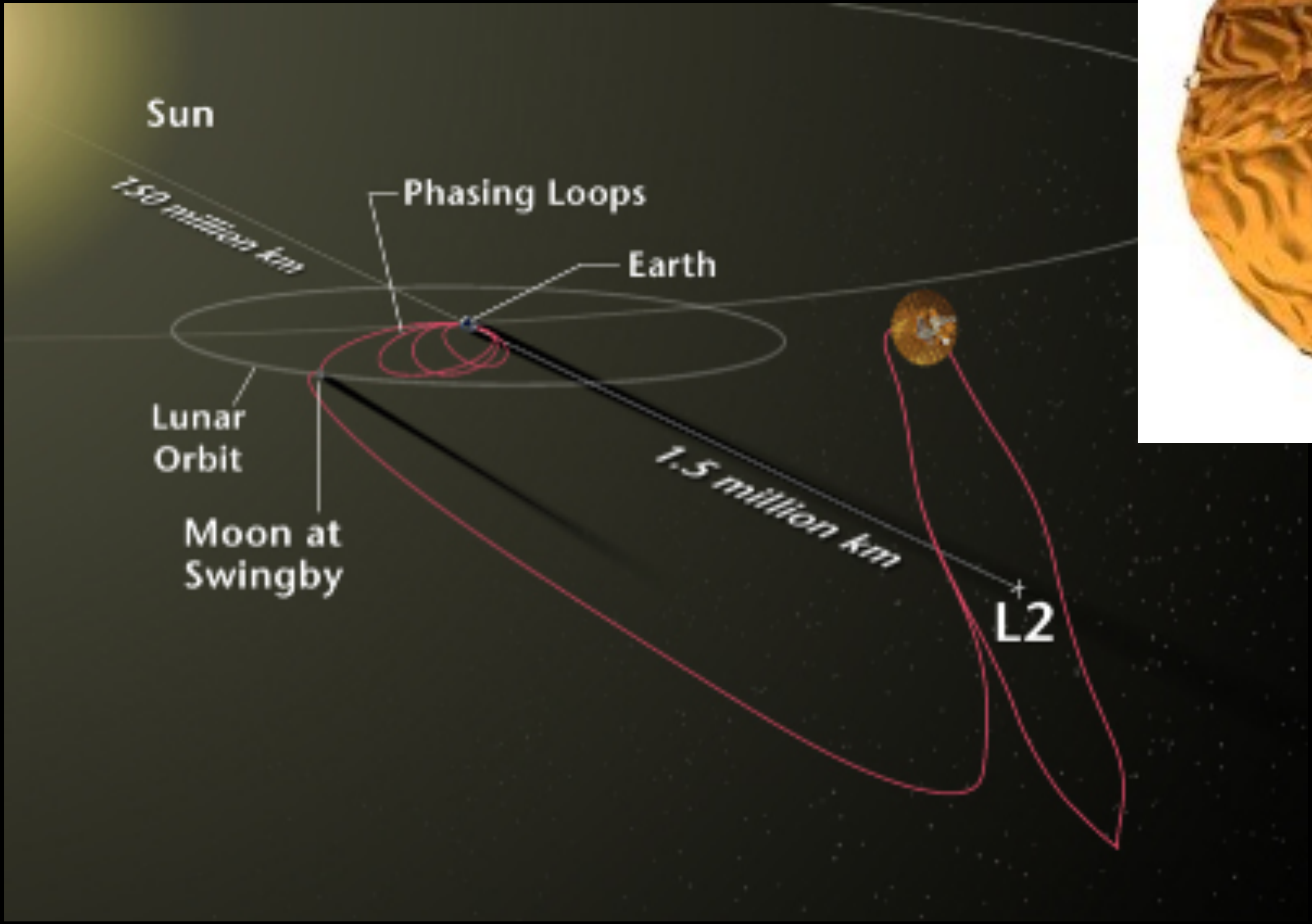
- Top: 0-4 degrees K

- Center: Dipole due to the Earth's motion (**1 part in 1000**)

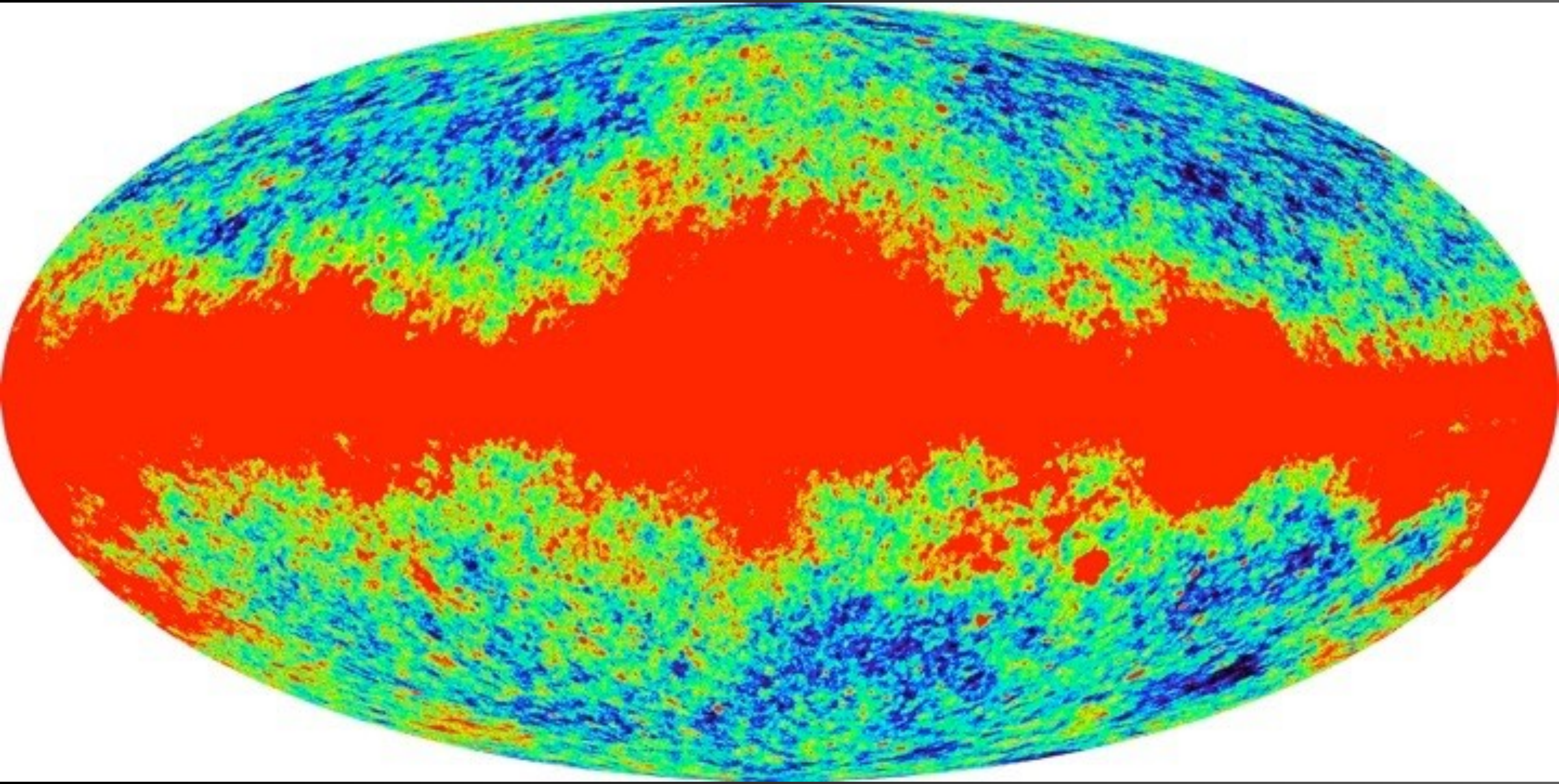
- Bottom: After removing the diple, the cosmic anisotropies are **1 part in 100,000**

Wilkinson Microwave Anisotropy Probe (WMAP)

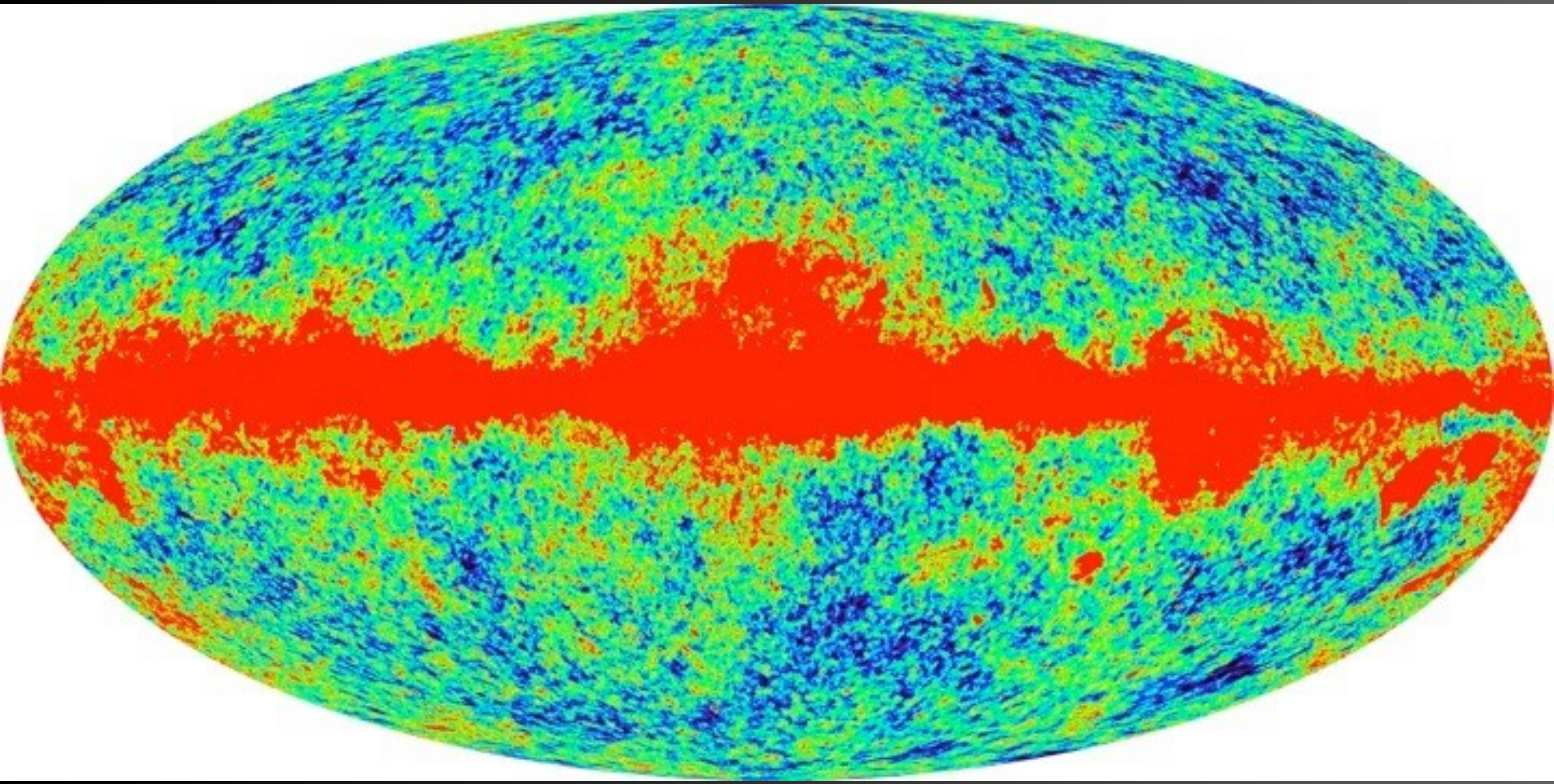




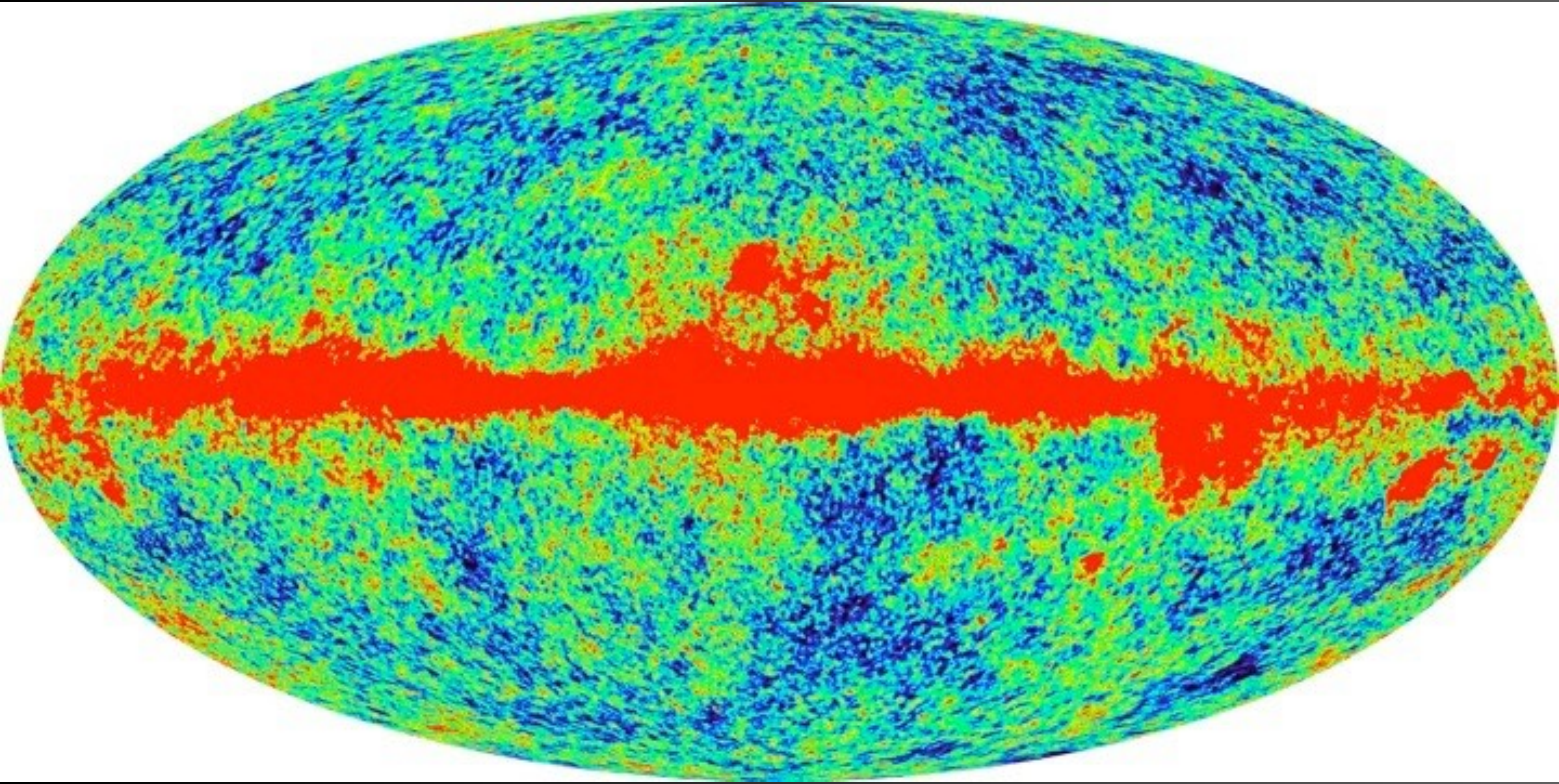
K - 22GHz



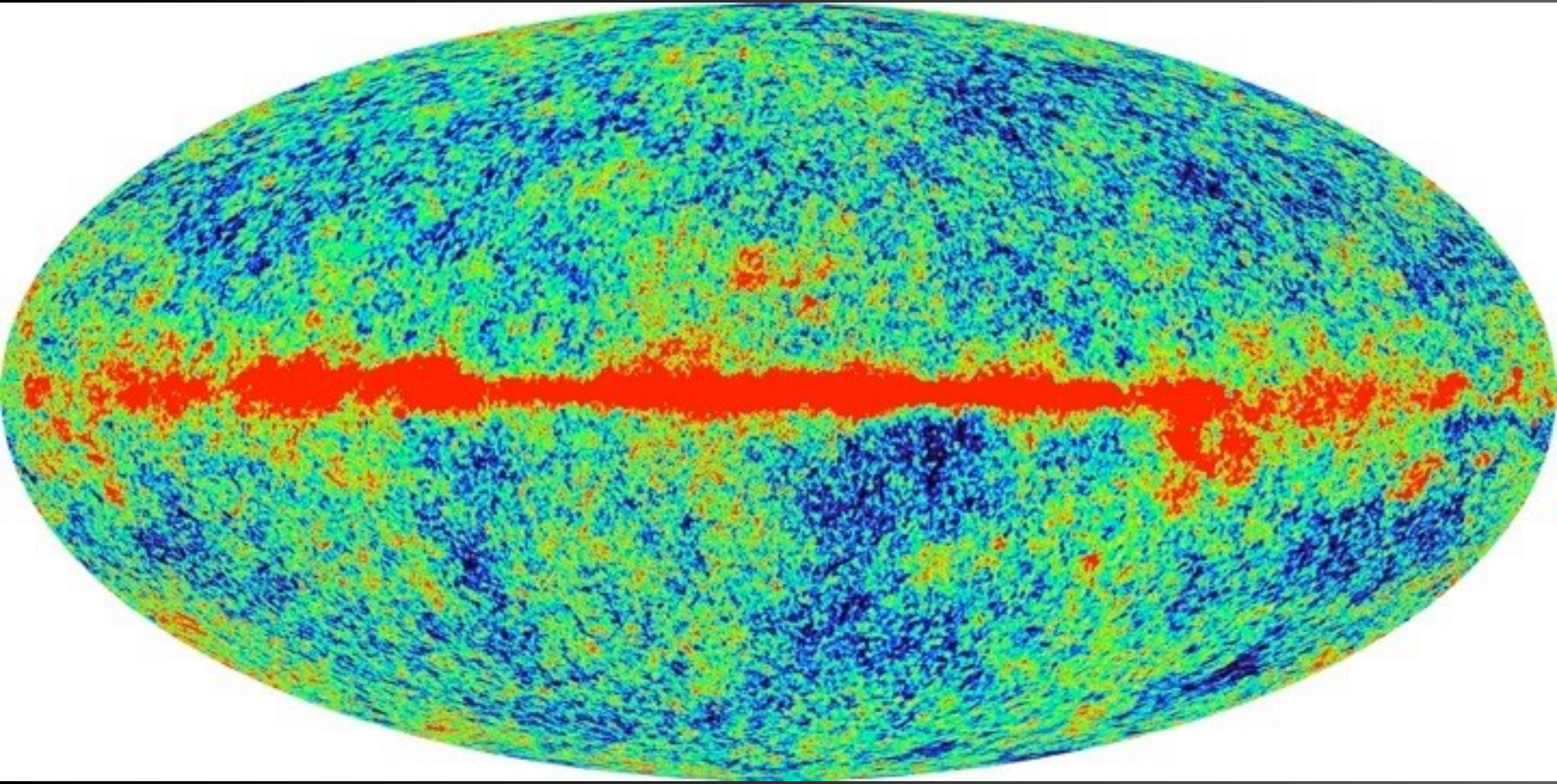
Ka - 33GHz



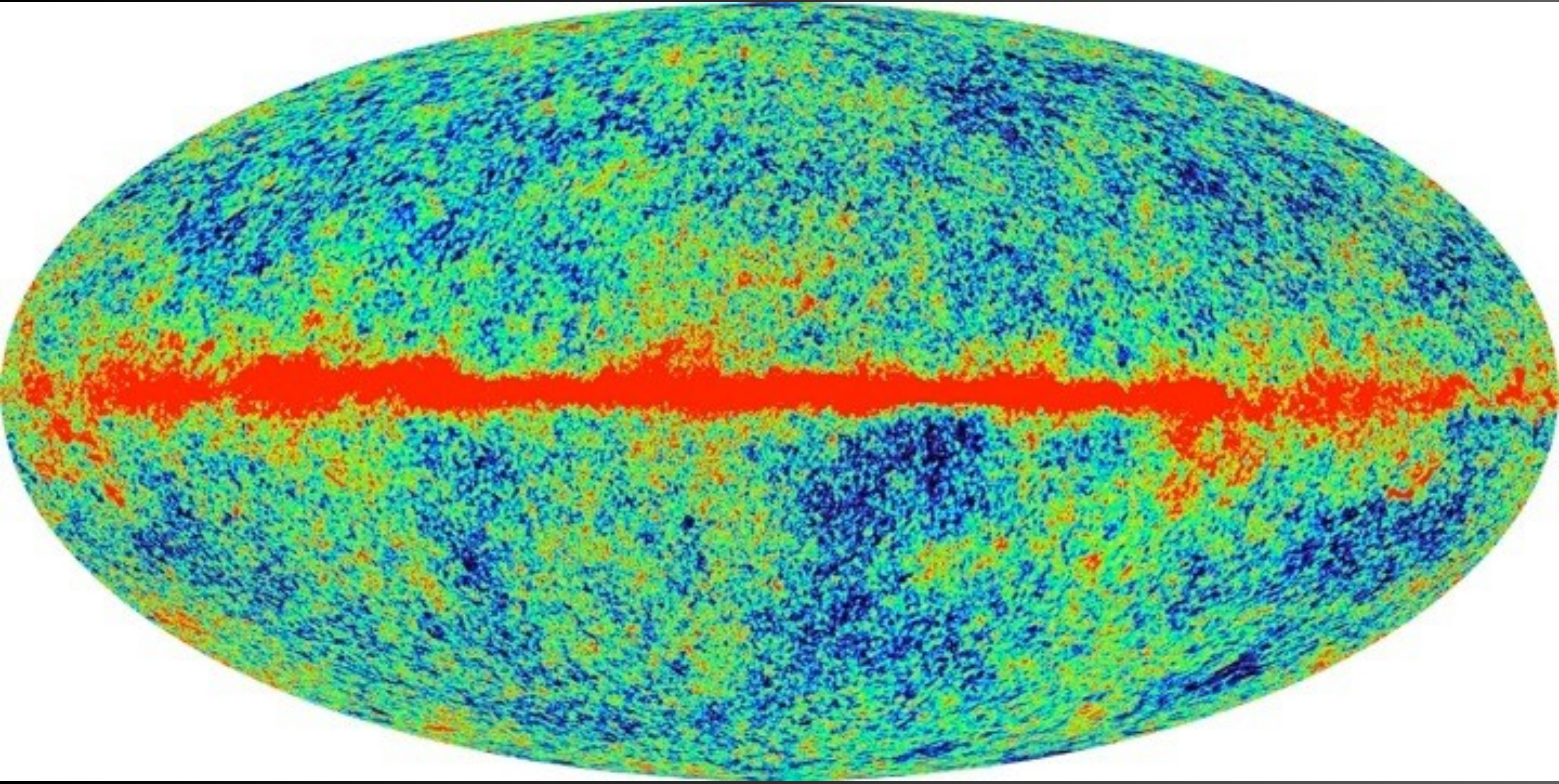
Q - 41GHz



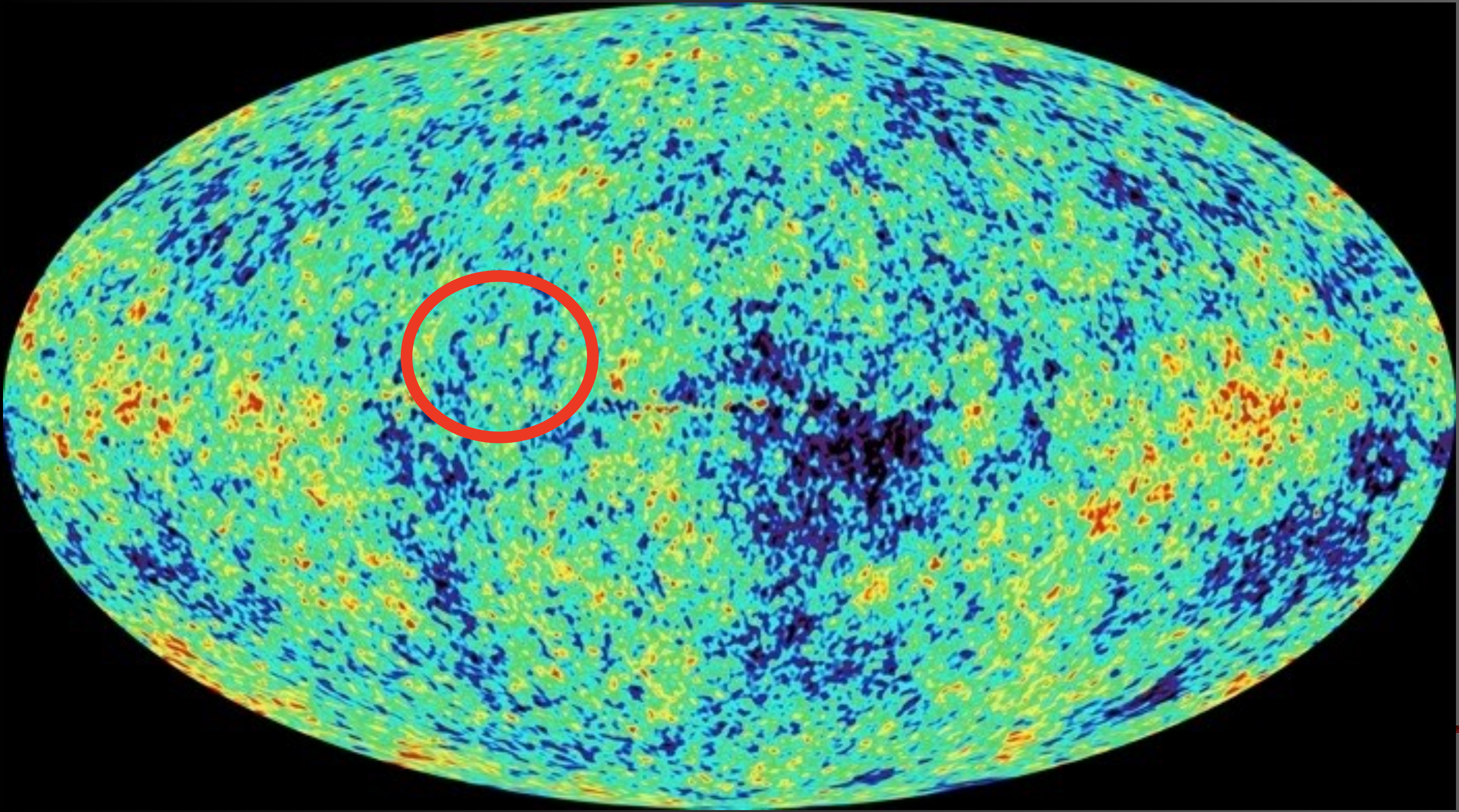
V - 61GHz



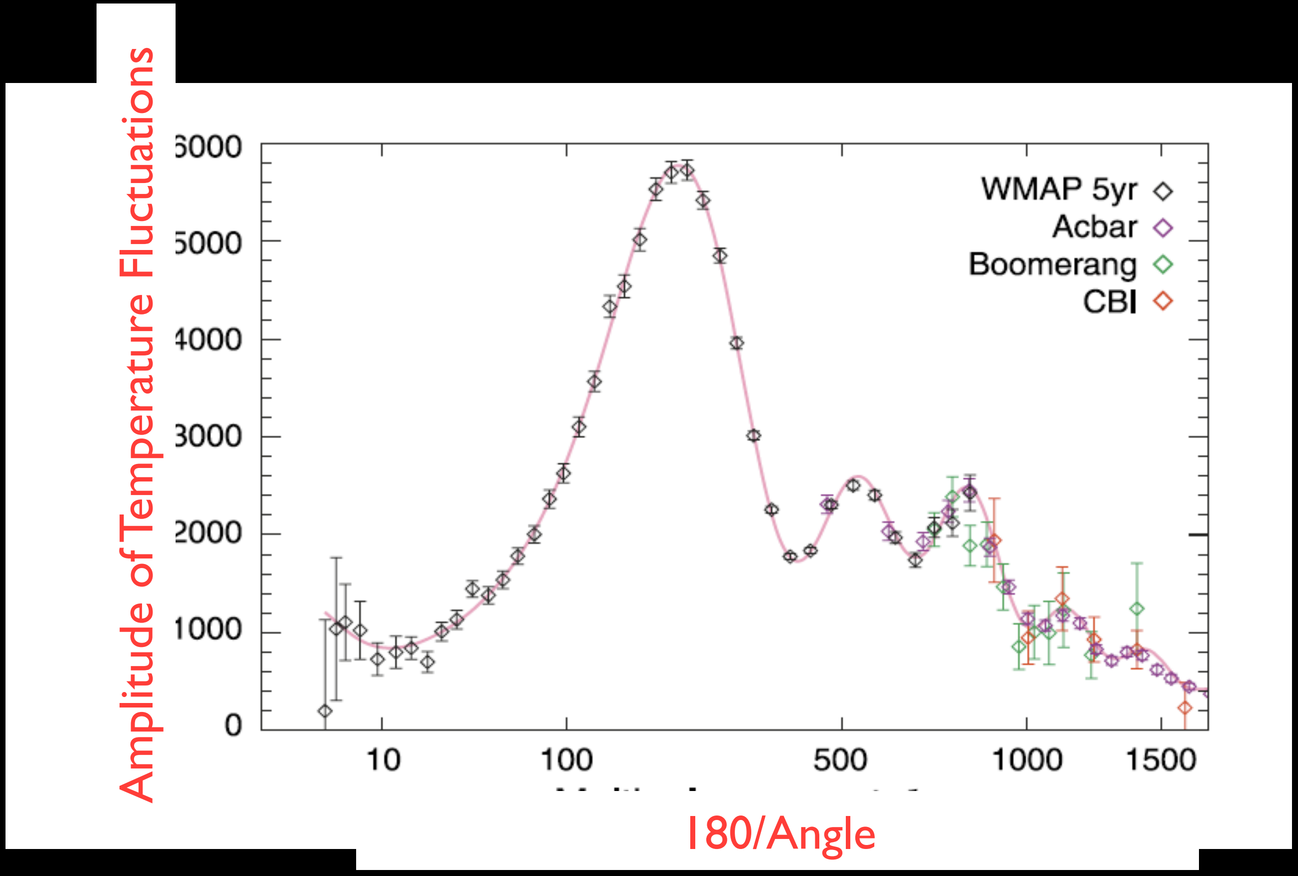
W - 94GHz



“Clean” Map of the Universe (Our baby picture)



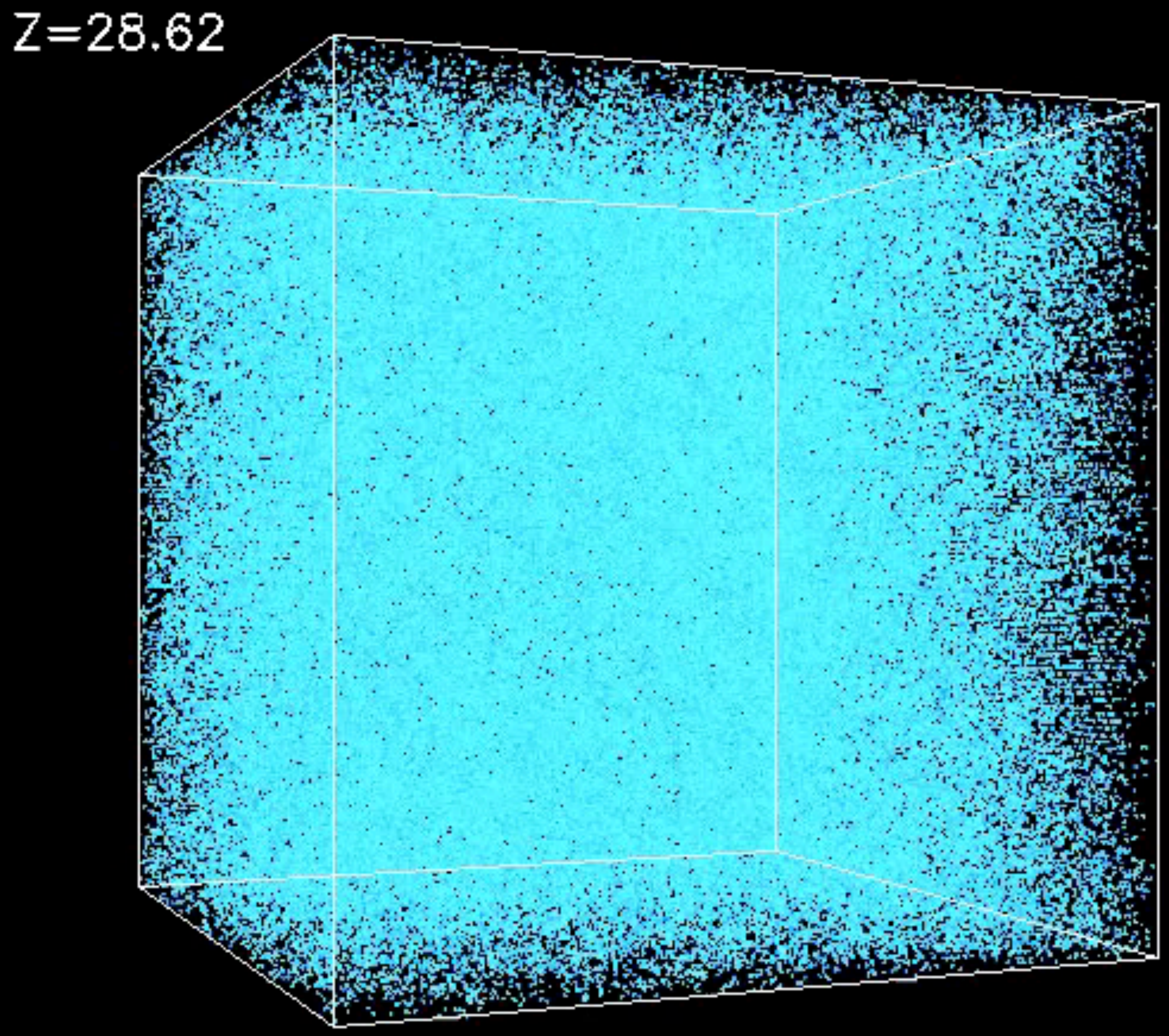
What Have We Learned?



- Simple model fits a wide range of data (only 5 numbers)
- Age of universe: 13.7 Gyr
- Composition:
  - Atoms: 4%
  - Matter: 23%
  - Dark Energy: 73%

- Scale Invariant Fluctuations seed growth of galaxies

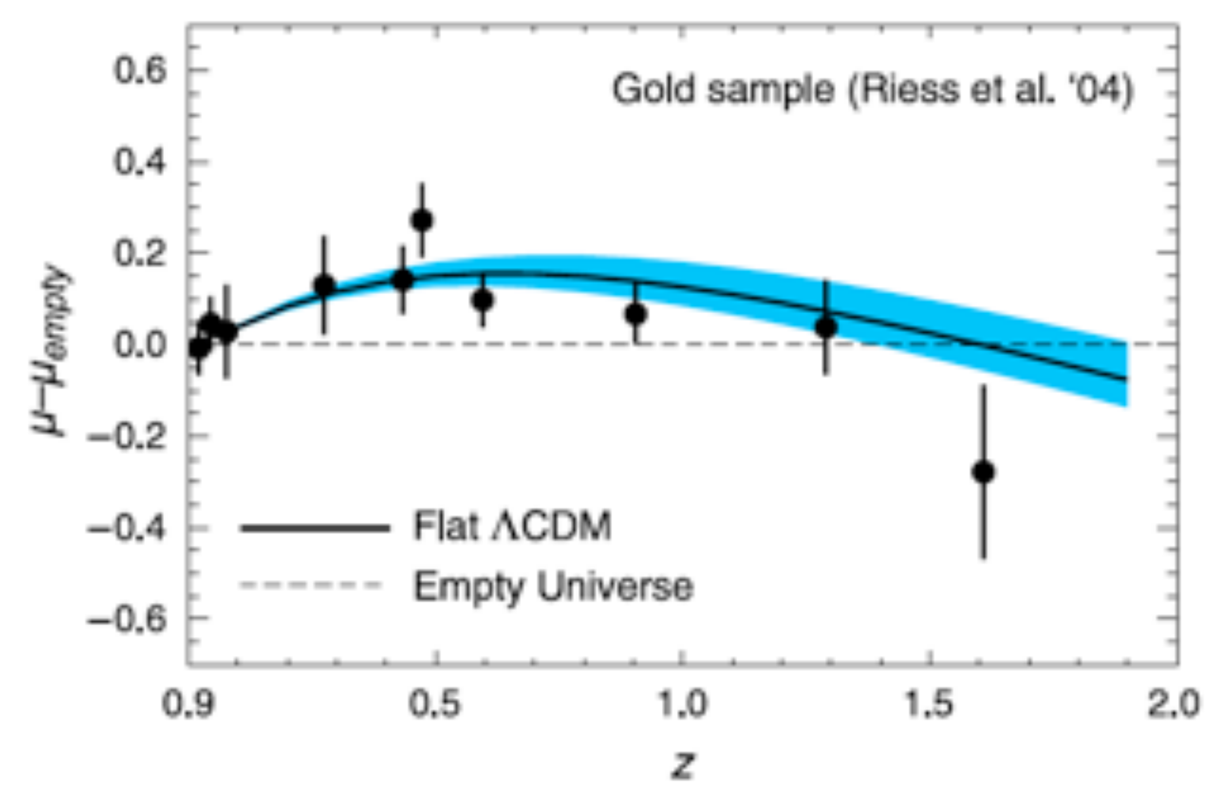
Growth of Structure



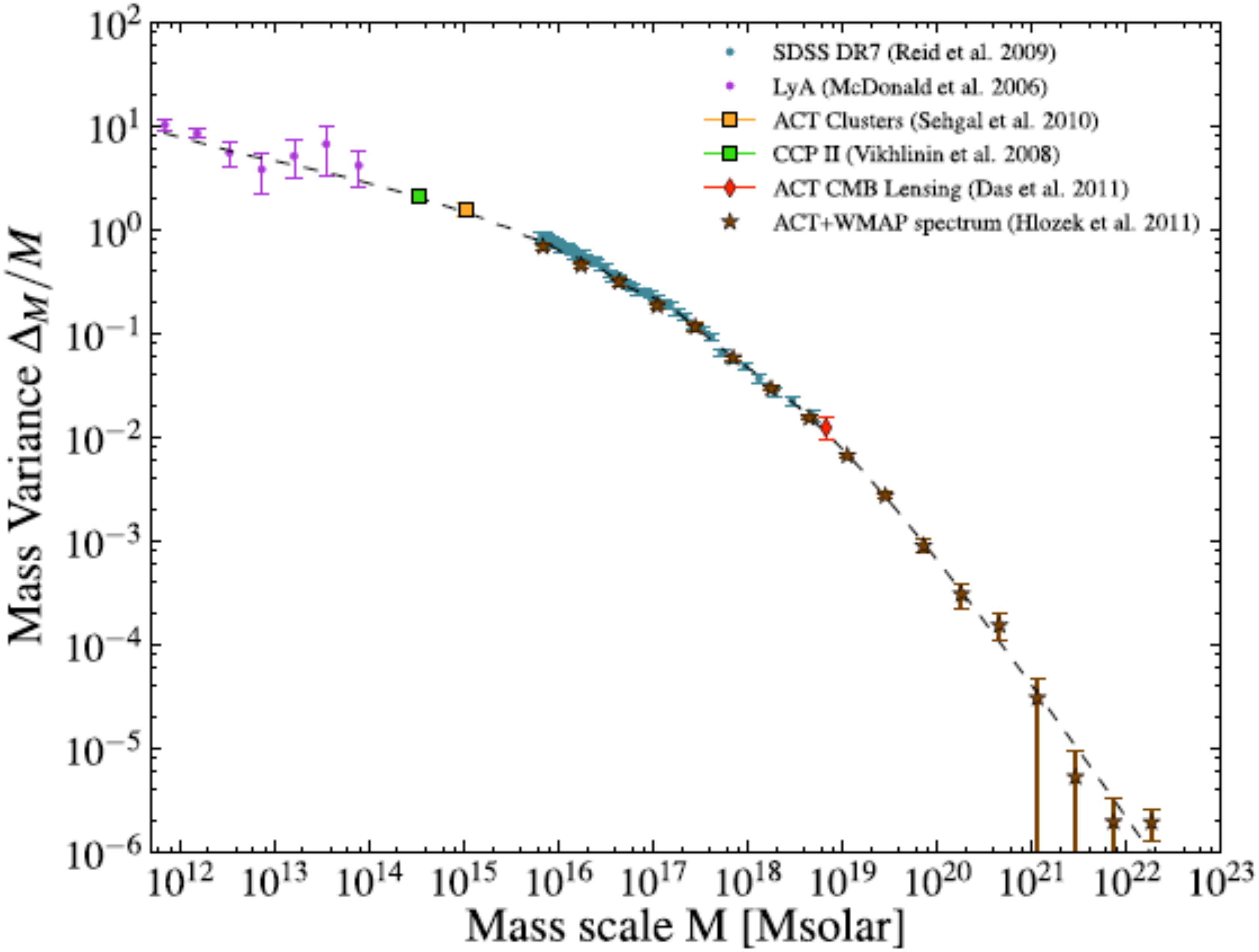
National Center for Supercomputer Applications by Andrey Kravtsov

The pieces seem to fit….

- Supernova distance
  - NOBEL PRIZE 2011!
- Hubble Constant
- Age of Universe
- Cluster Properties
- Cosmic Abundances
- Gravitational Lensing
- Absorption Line Statistics

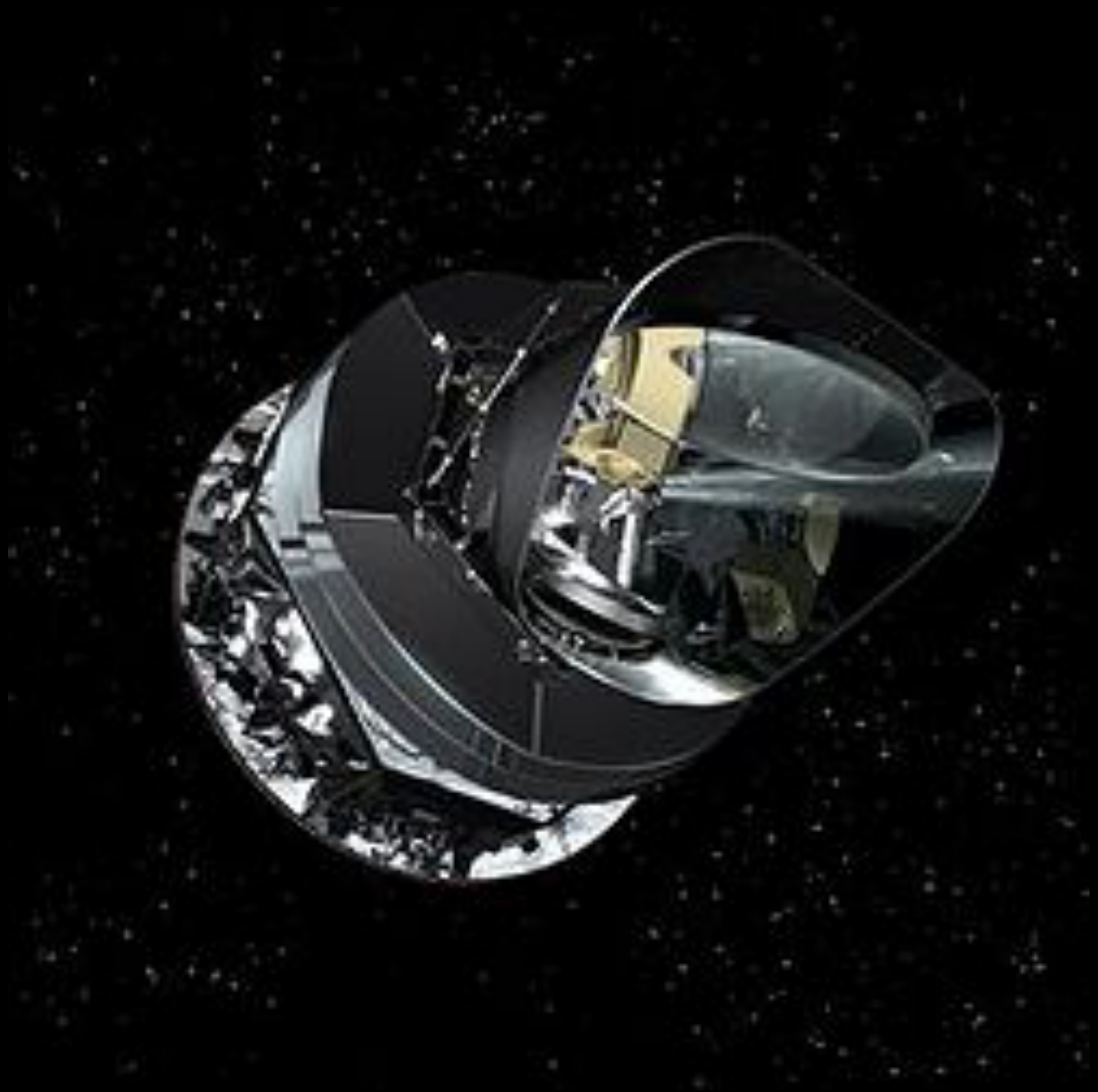


Model fits data over 10^{13}solar masses in scale and 10^{8} in time



Hlozek 2011

Planck Satellite



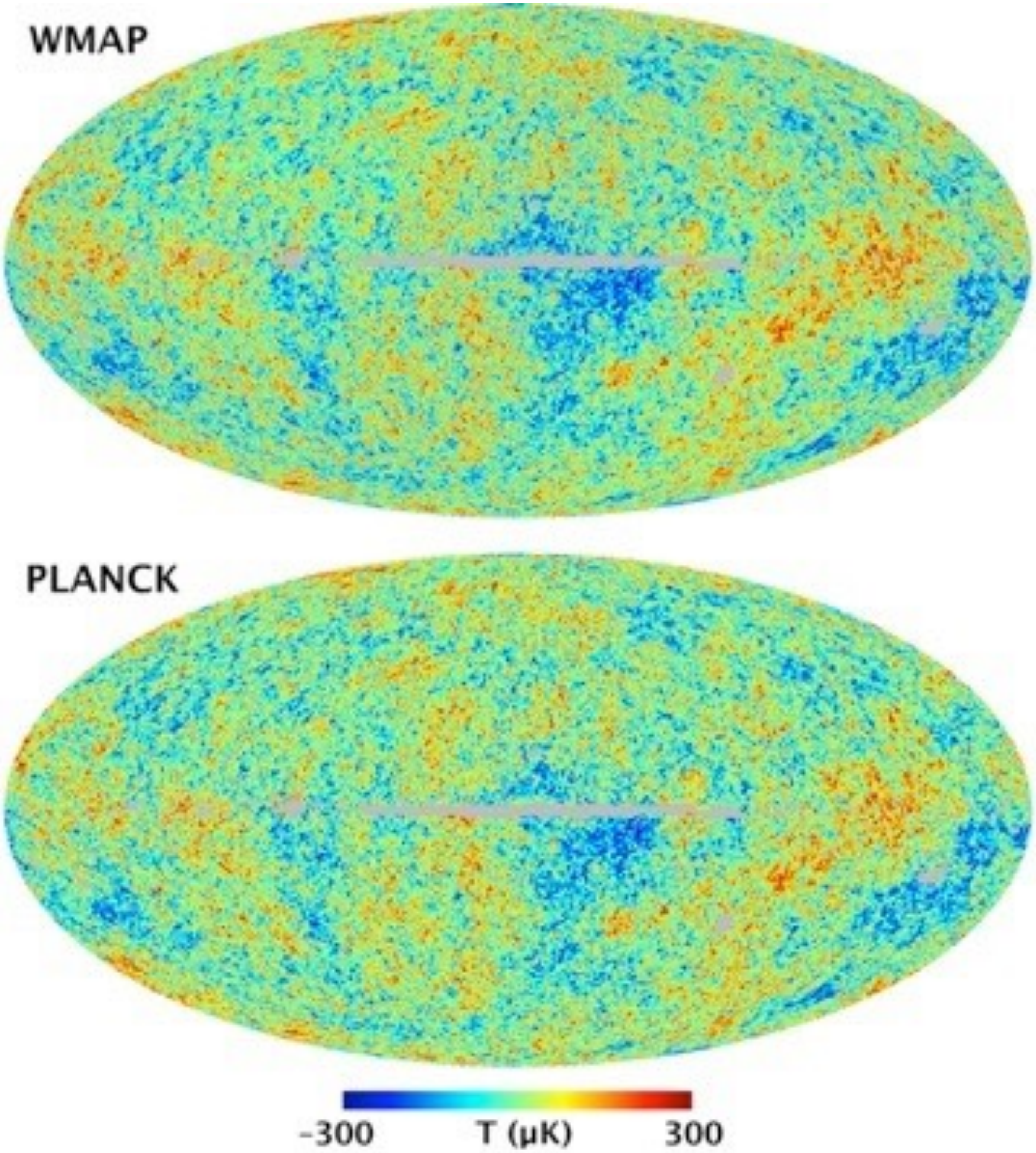
CMB Analysis

$$T(\hat{n}) = \sum a_{lm} Y_{lm}(\hat{n})$$

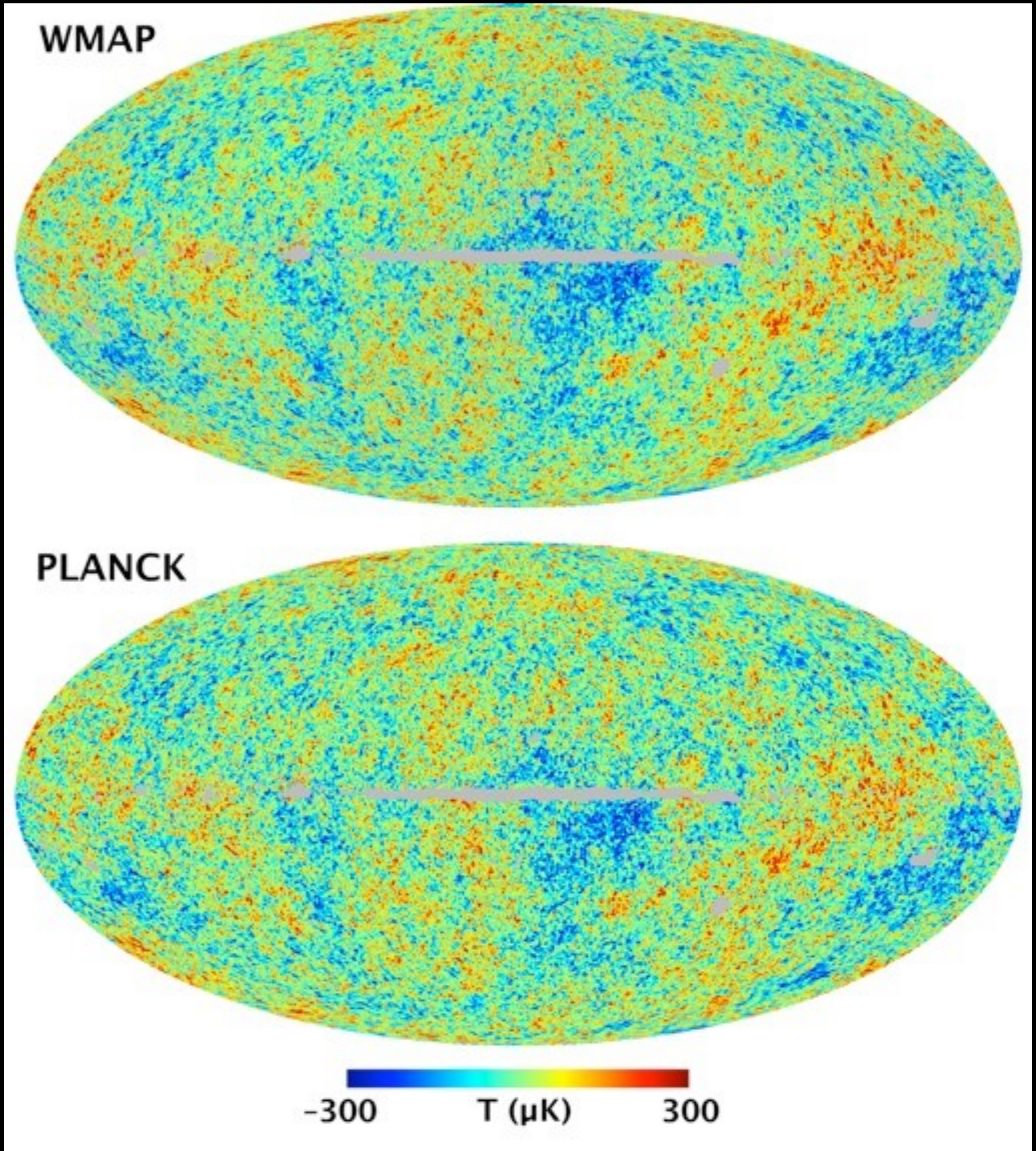
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{m=l} |a_{lm}|^2$$

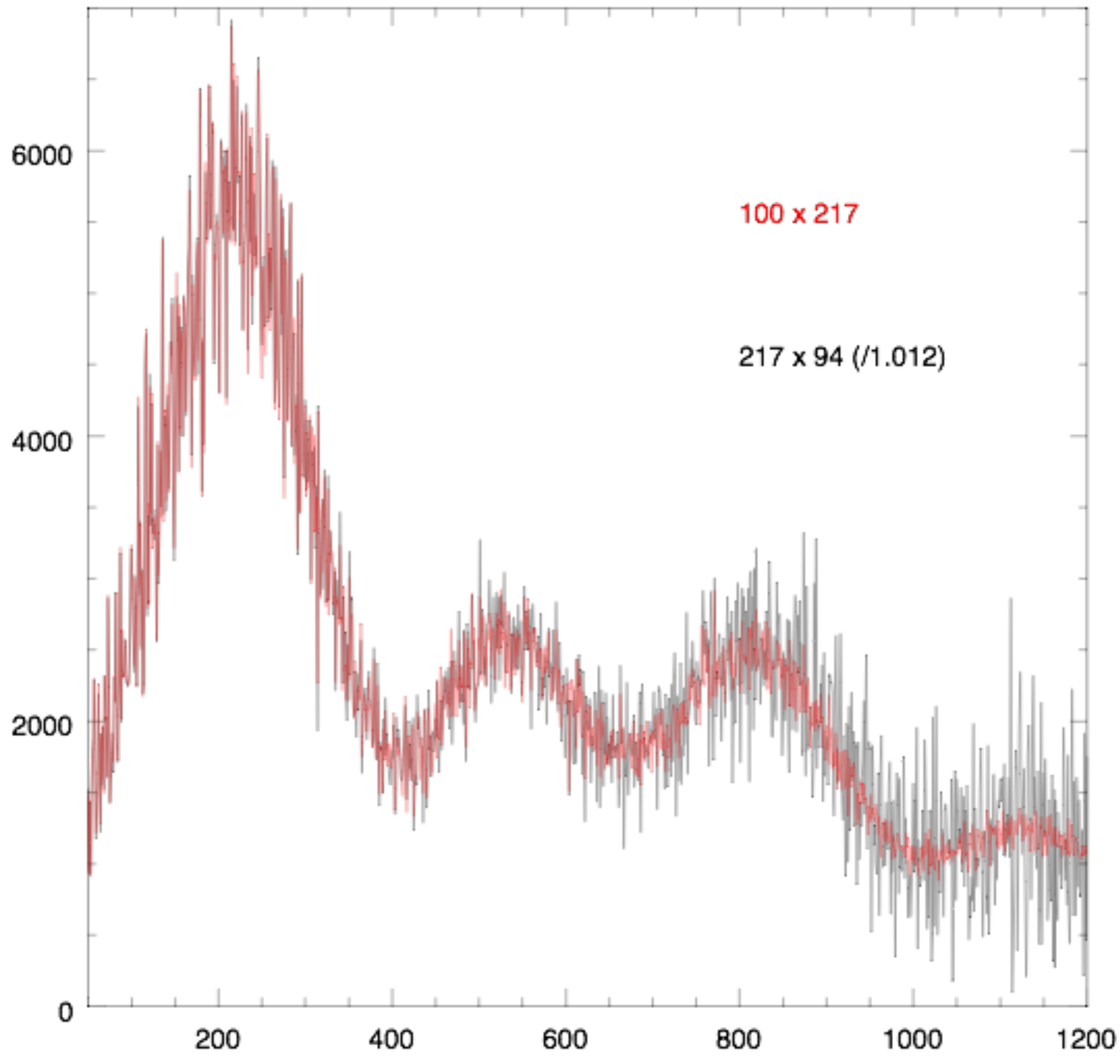
$$D_l = \frac{l(l+1)}{2\pi} c_l$$

$$l \sim \frac{180^o}{\theta}$$



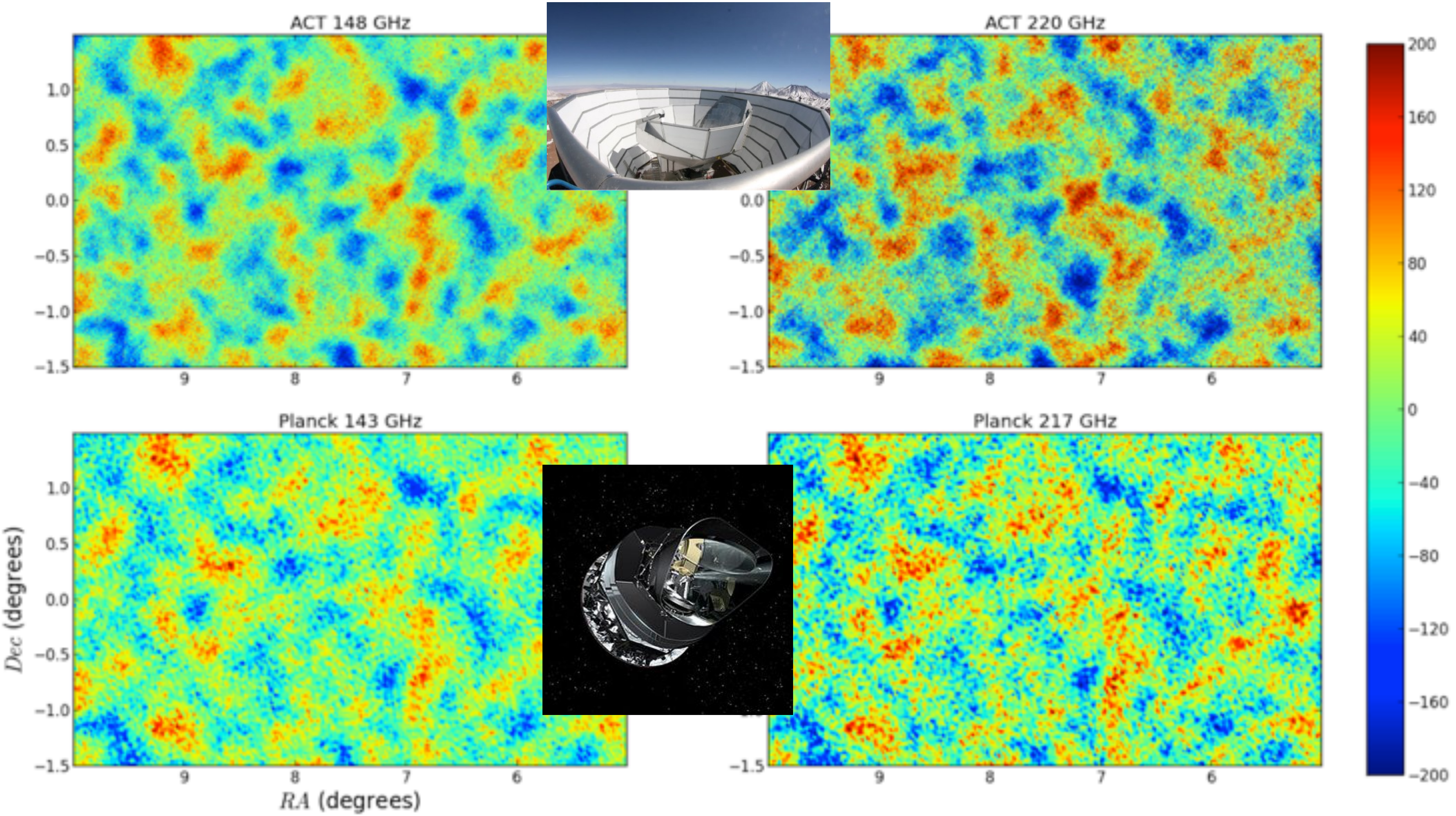
Planck and WMAP: the same sky



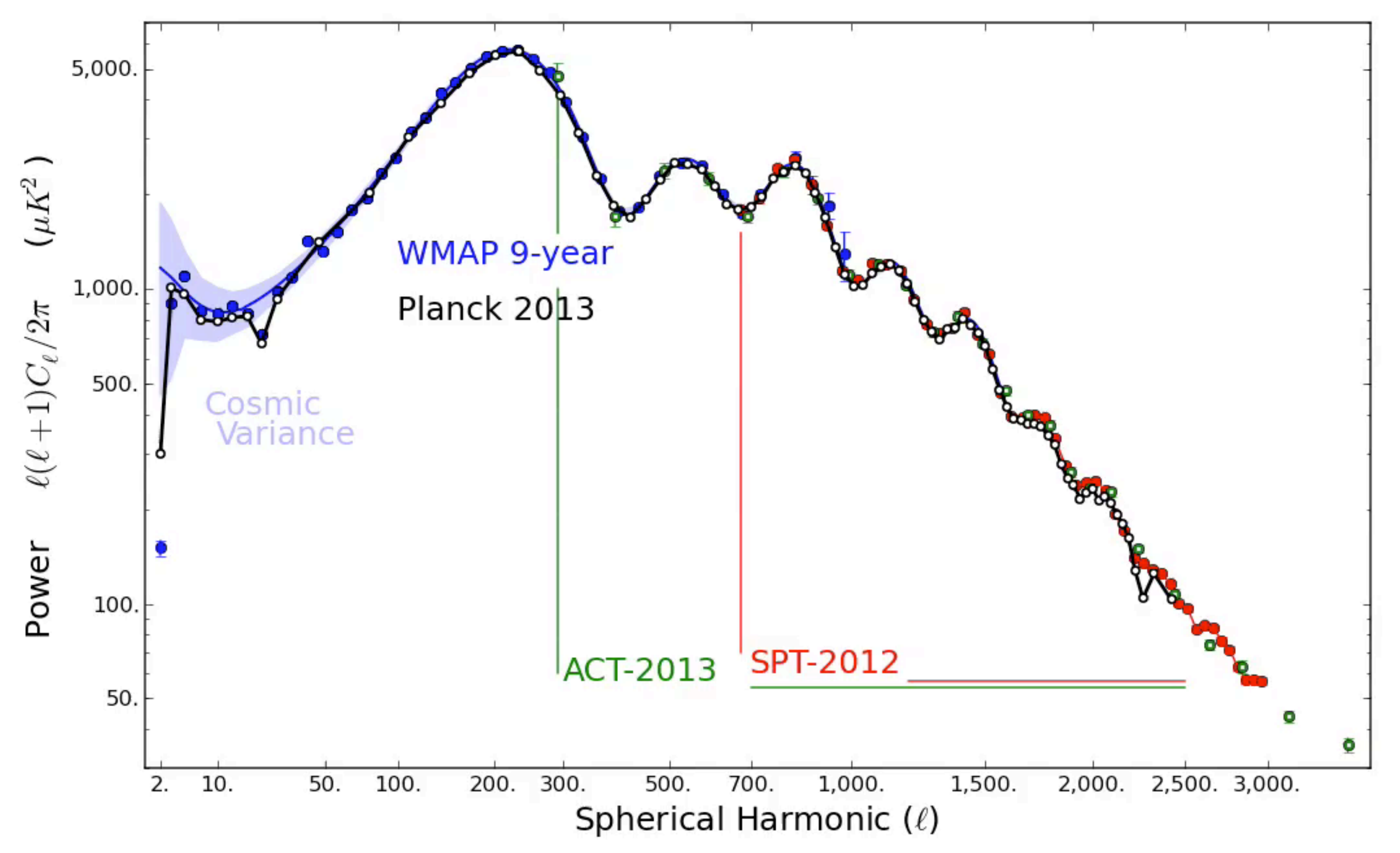


Temperature Variance $\mathcal{D}_\ell$

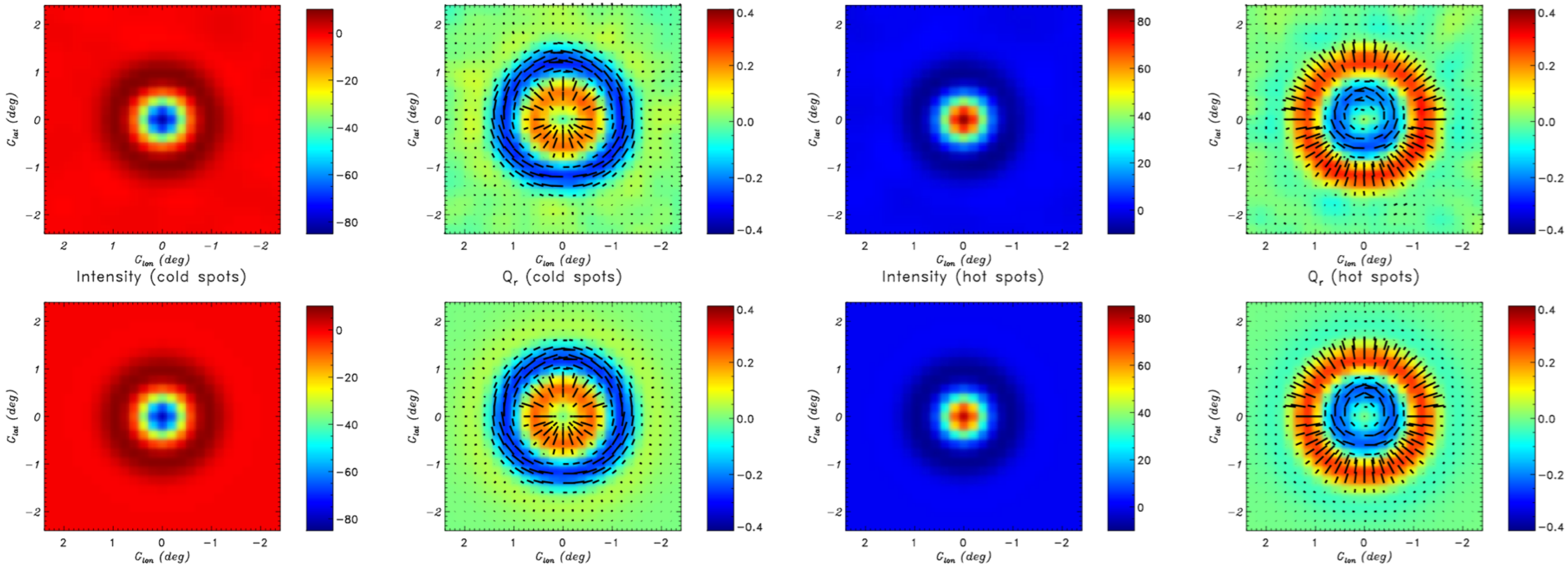
Multipole ℓ


ACT 148 GHz
ACT 220 GHz
Planck 143 GHz
Planck 217 GHz
1.0
0.5
0.0
−0.5
−1.0
−1.5
9
8
7
6
Dec (degrees)
RA (degrees)
200
160
120
80
40
0
−40
−80
−120
−160
−200

LCDM Model Fits CMB

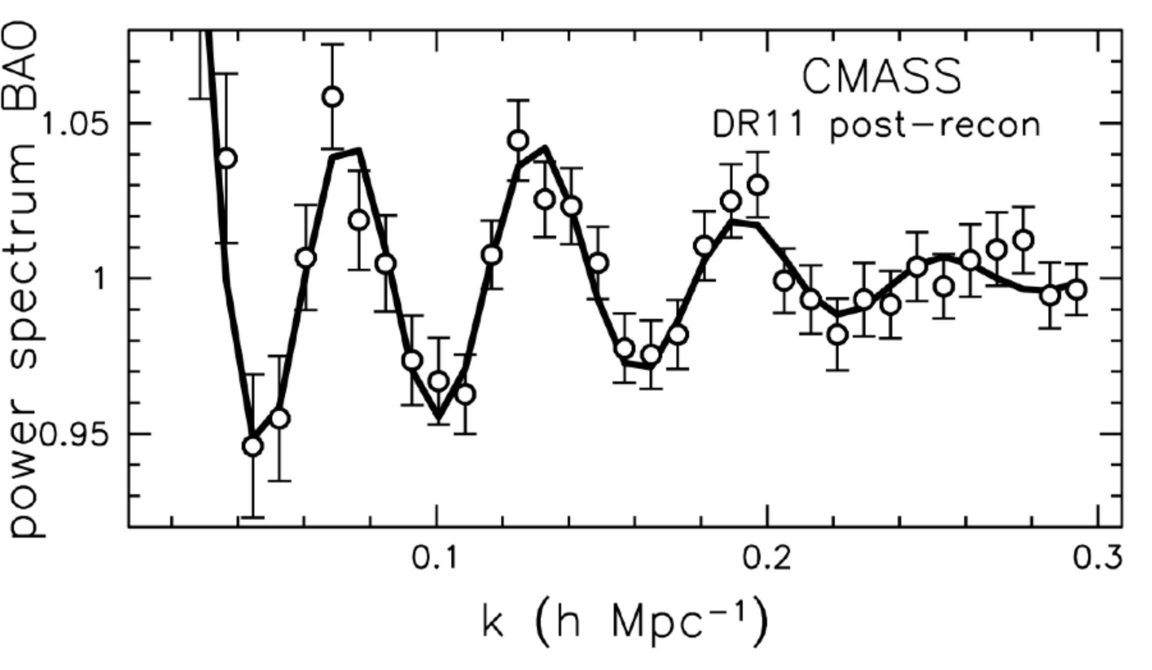


Acoustic Fluctuations

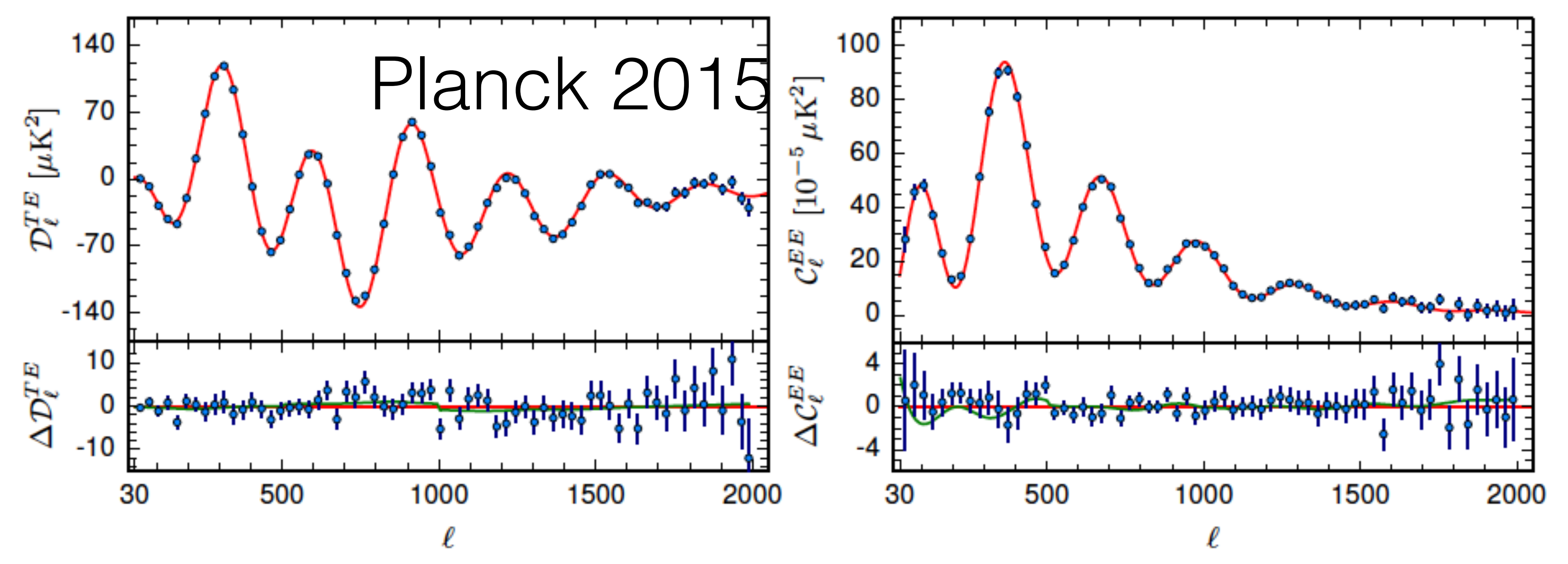


Planck Paper 1 (2013)

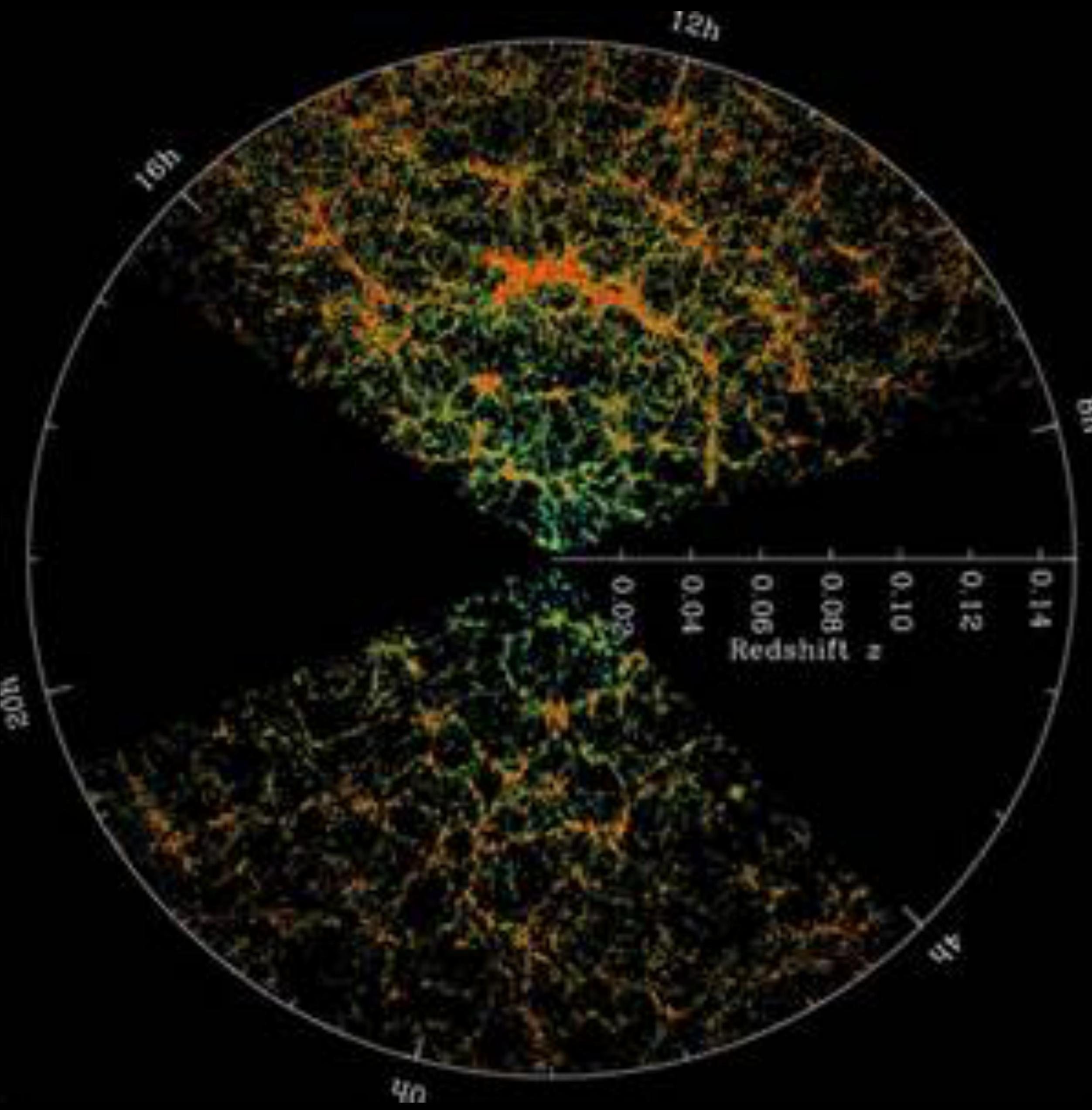
Multiple Precision Probes



"A detailed investigation of the spectrum of fluctuations may, n principle, lead to an understanding of the nature of initial density perturbations, since a distinct periodic dependance of the spectral density of perturbations on wavelength (mass) is peculiar to adiabatic perturbations." - SZ 1970 abstract

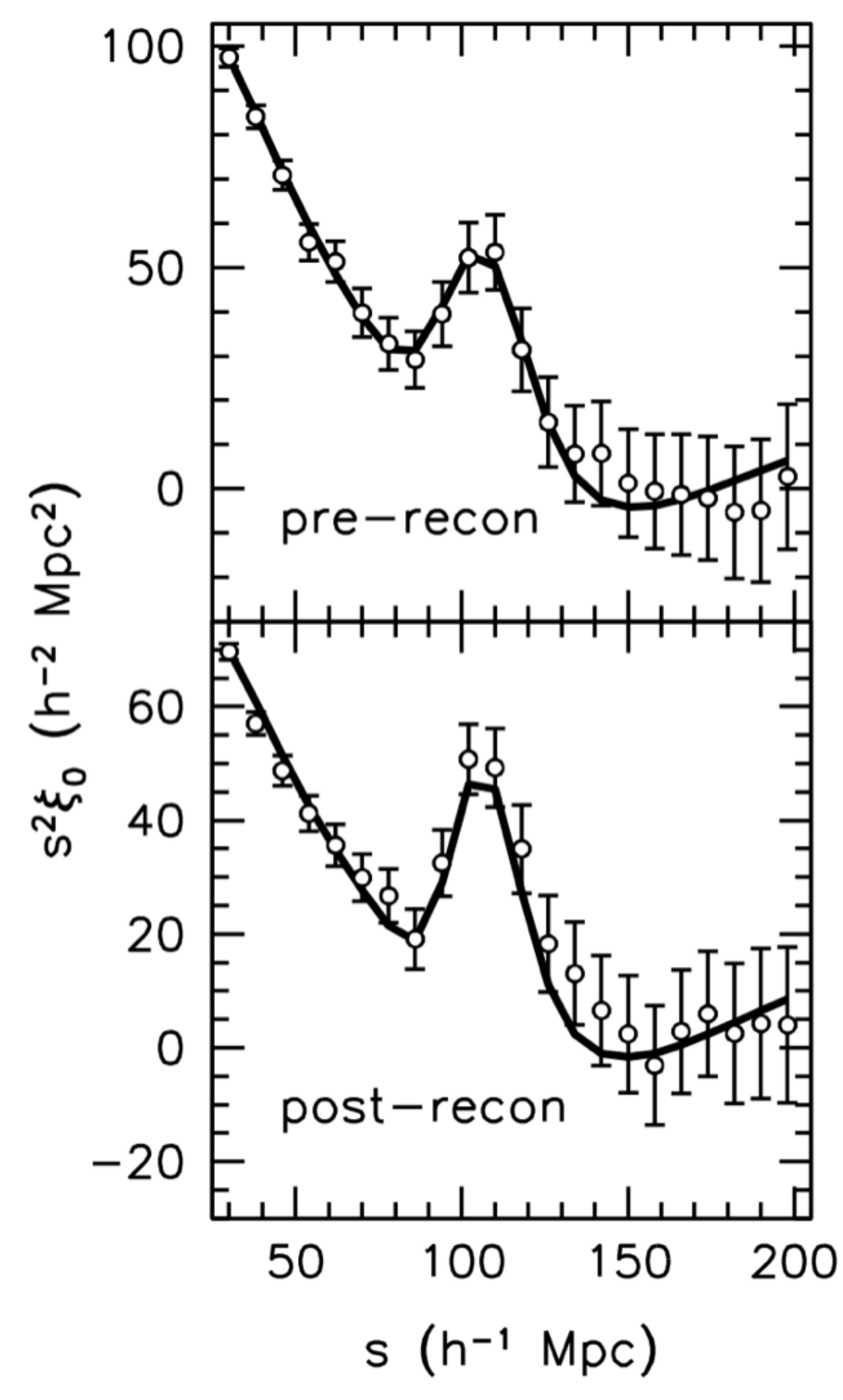

Planck 2015

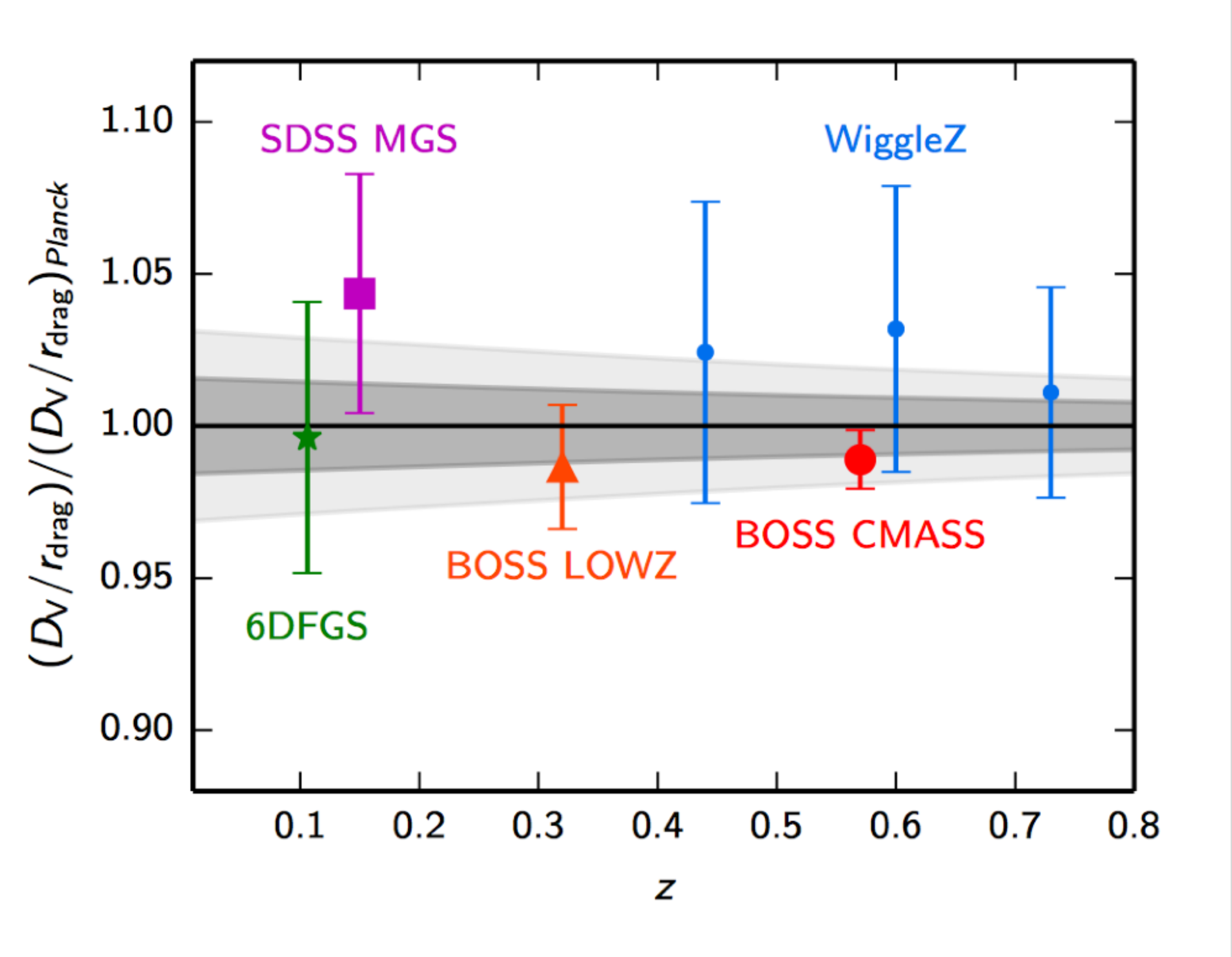
Sloan Digital Sky Survey



Sound Waves in the Sky

SDSS 3

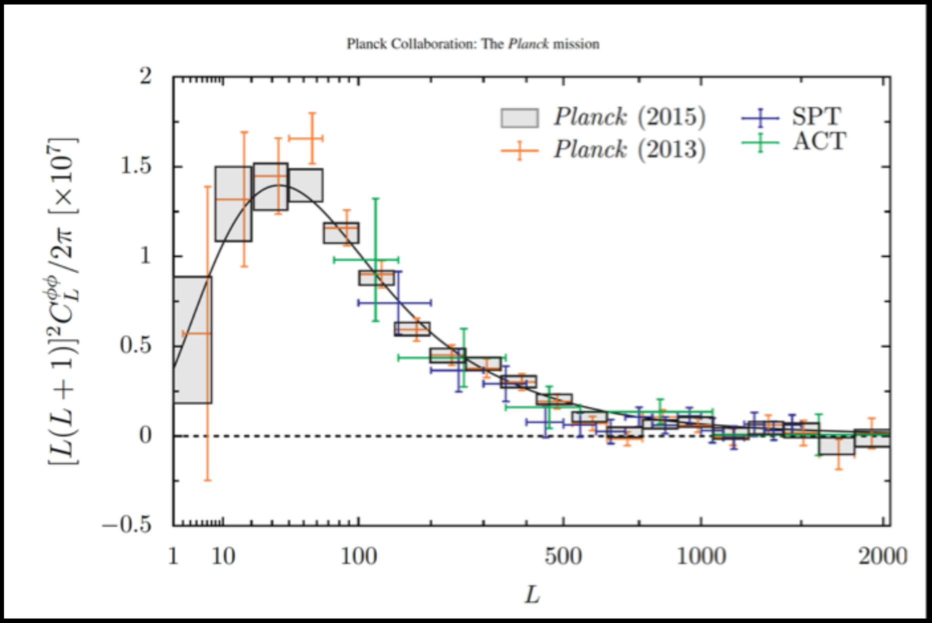




Planck 2015 XIII

Consistent Cosmology

- Supernova data
- Large-scale structure data (galaxies, quasars, Lyman alpha forest)
- Gravitational Lensing (CMB + Optical)
- Stellar, Nucleosynthesis and Cosmology Ages
- Big Bang Nucleosynthesis

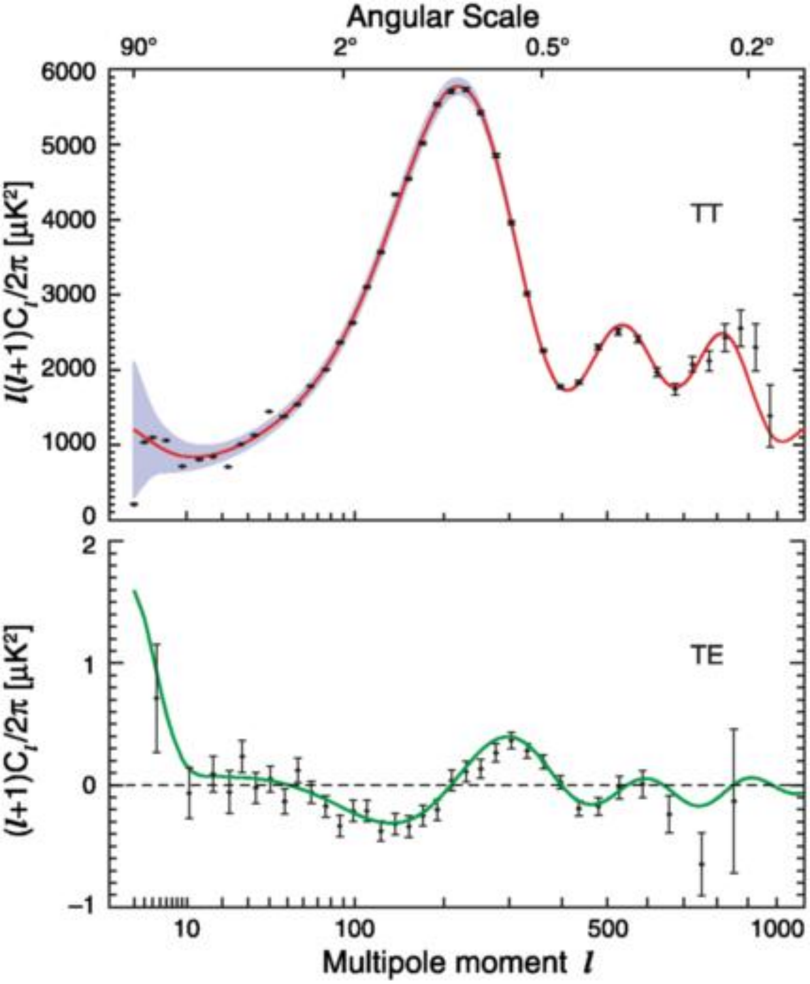


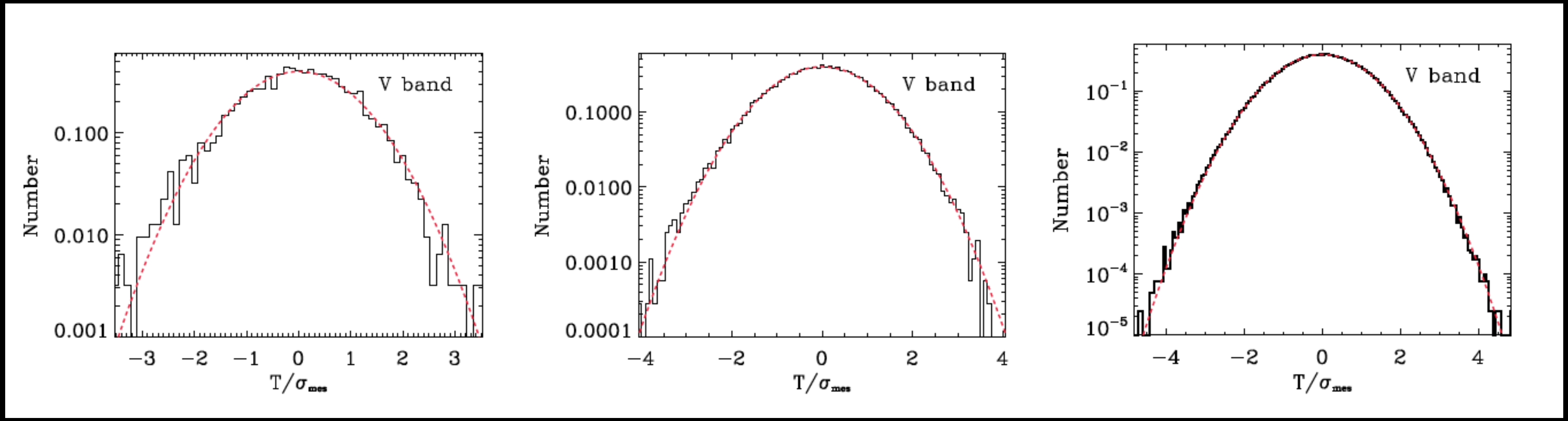
Need New Physics!

- Dark matter
- Dark energy
- Baryongenesis
- What generates the fluctuations that we see in the microwave sky and that form microwave background

Testing Inflation

- Fluctuations are gaussian, nearly-scale invariant, adiabatic and SUPER-HORIZON



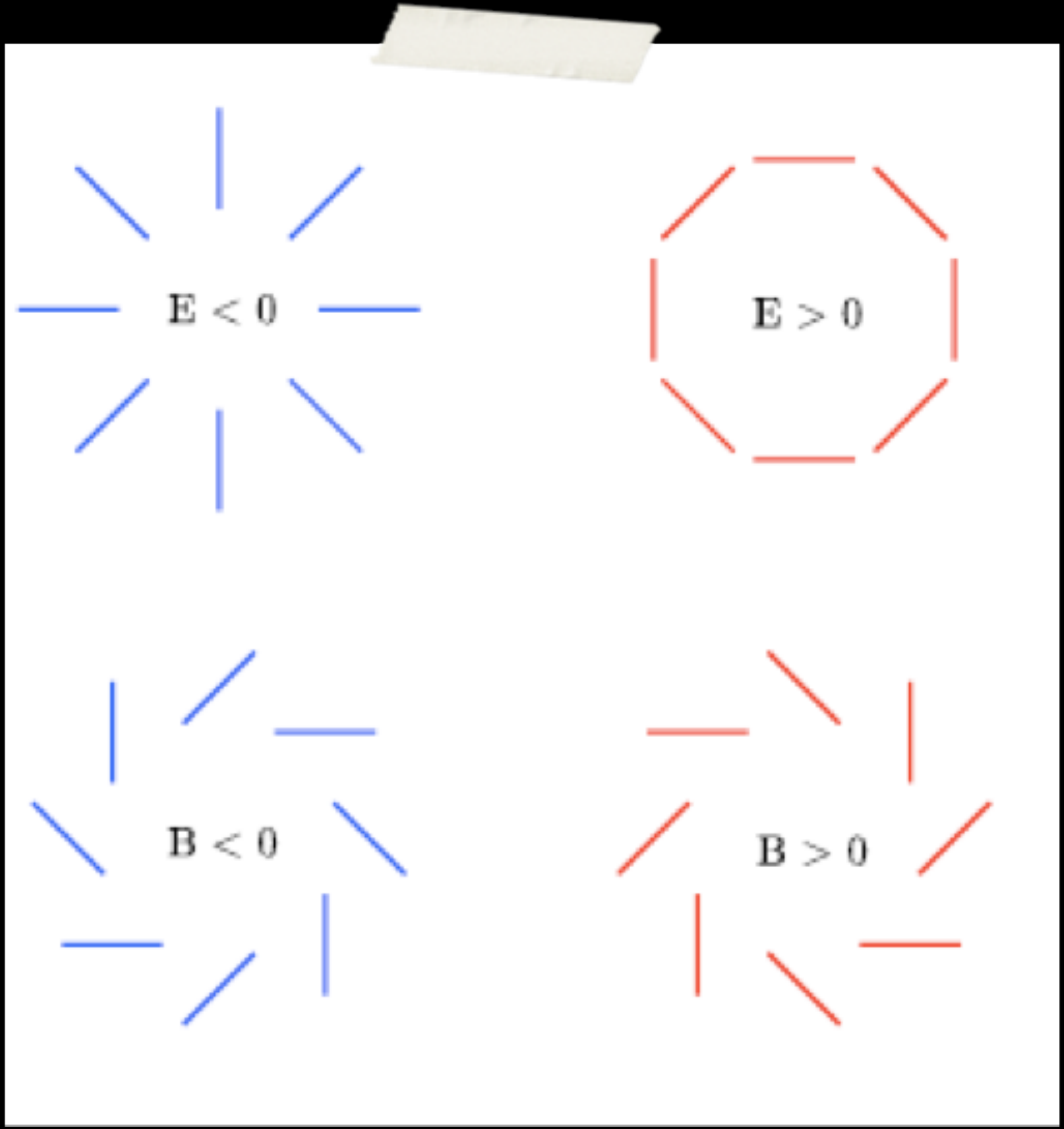


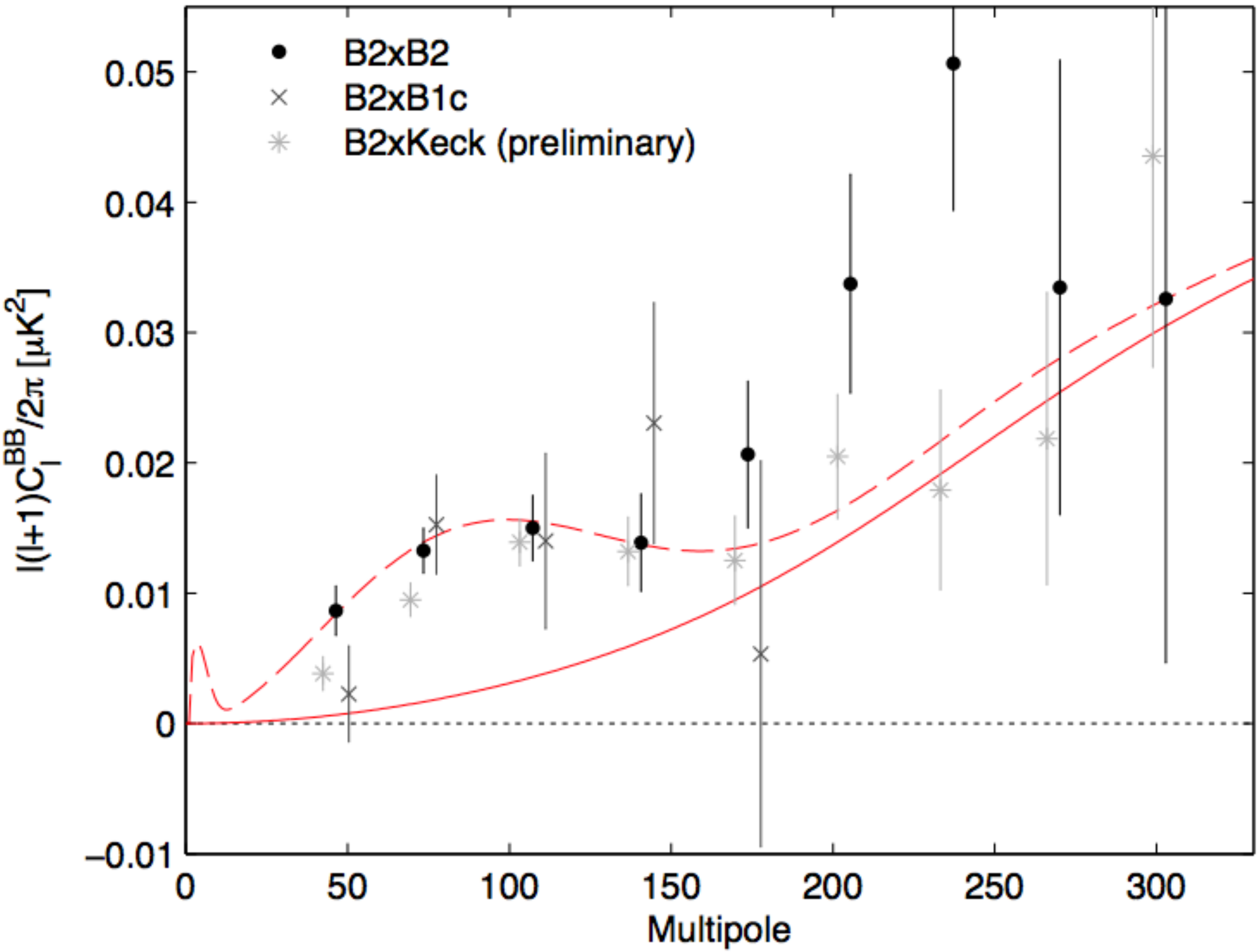
WMAP3

Inflationary Check List

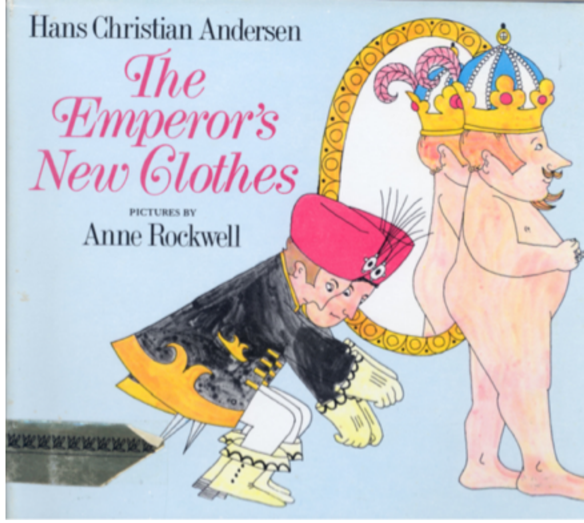
- Flat universe ✓
- Superhorizon fluctuations ✓
- Adiabatic fluctuations ✓
- Gaussian fluctuations ✓
- Gravitational Waves

E + B modes

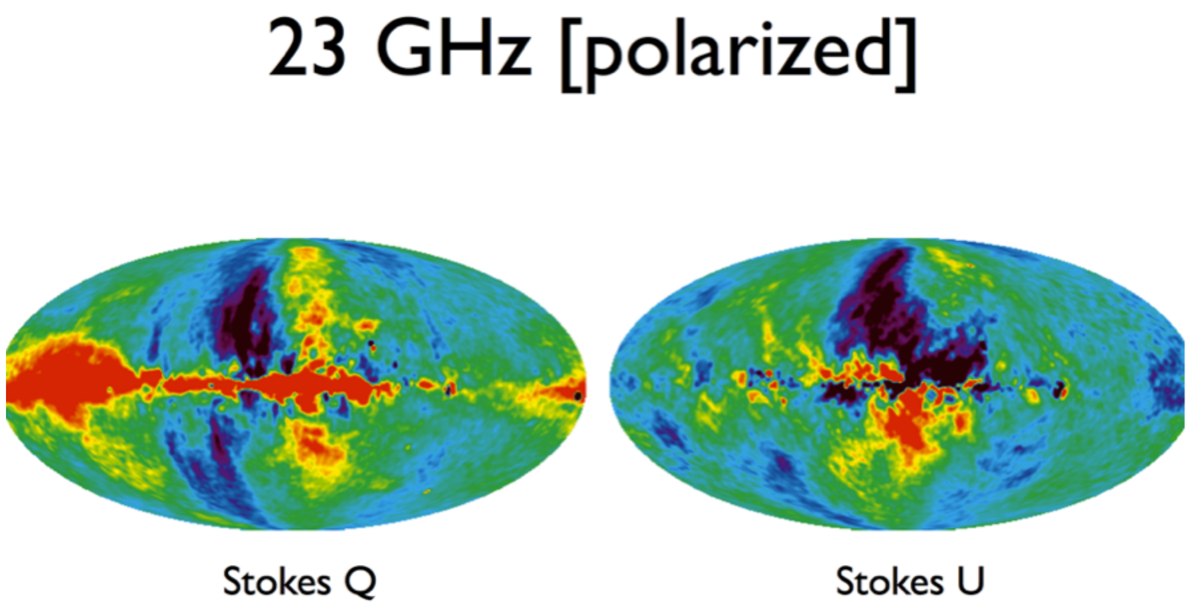



B2xB2
B2xB1c
B2xKeck (preliminary)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300
Multipole

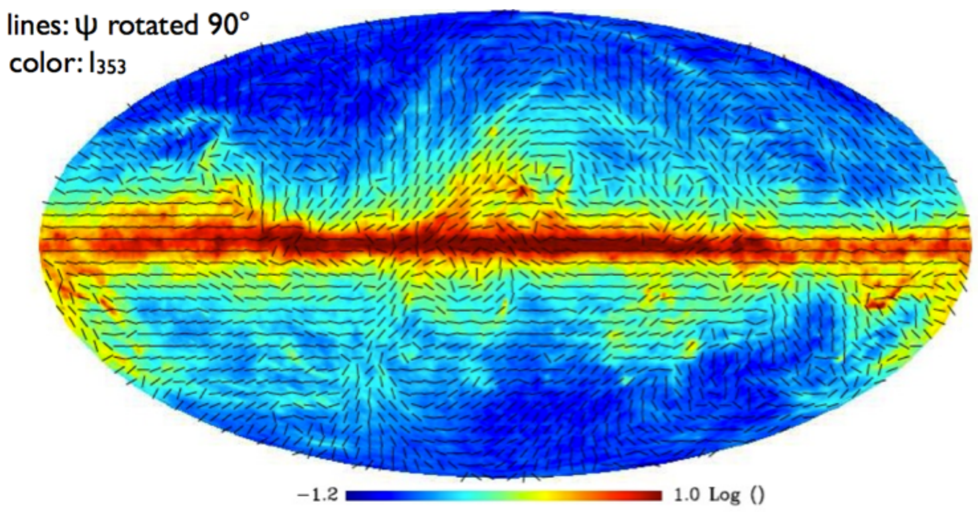
Is it correct?



- Is it on the sky? No systematics paper..
- Could it be galactic emission?

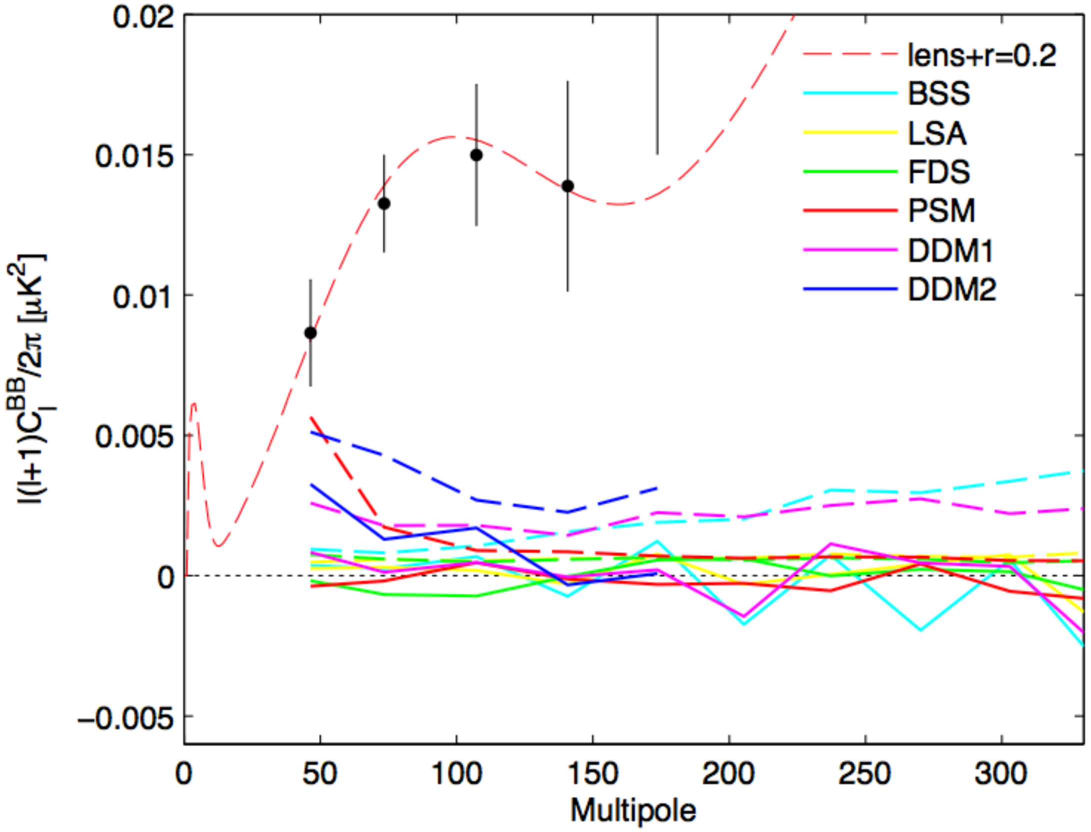


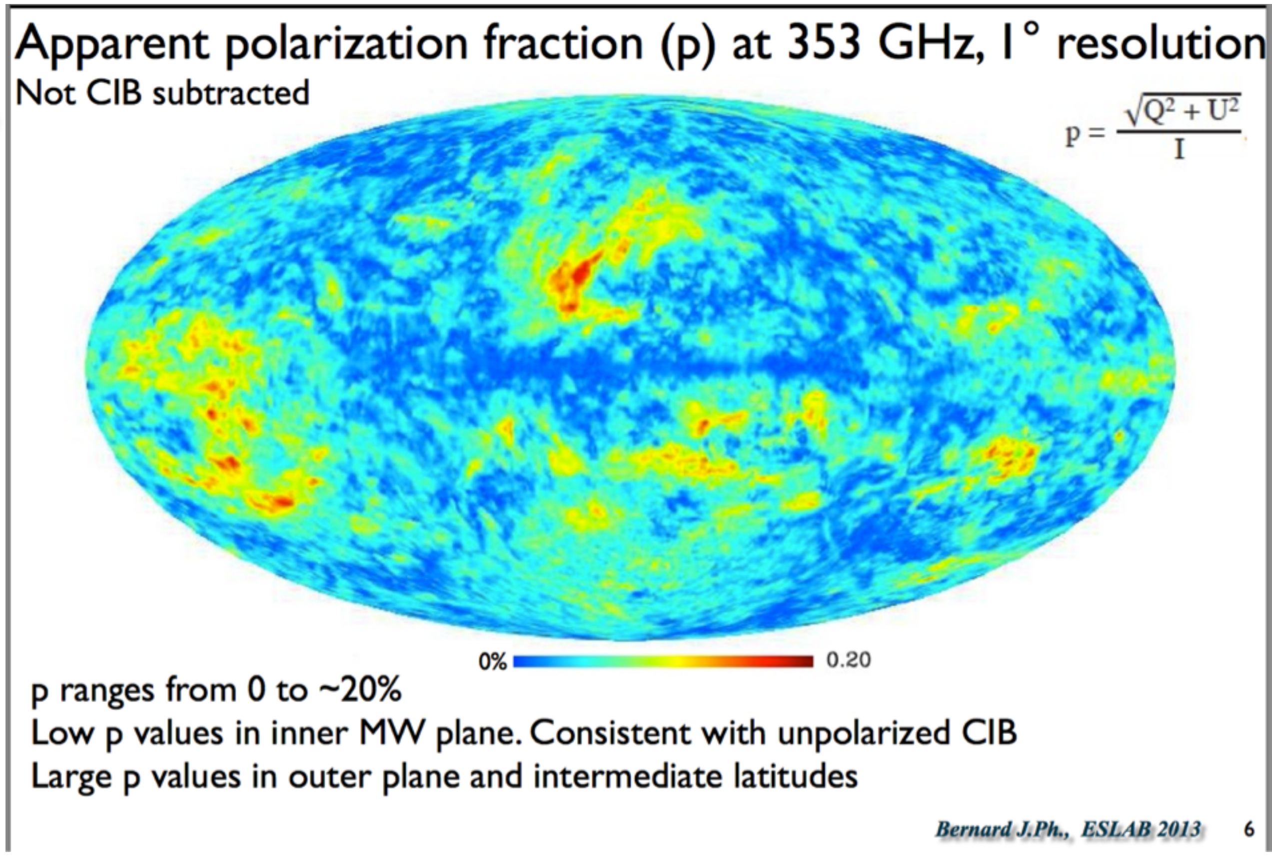
Synchrotron



Dust at 353 GHz (Planck)

Need to Rely on Planck 353 GHz Data to Estimate Dust Contribution





Apparent polarization fraction (p) at 353 GHz, 1° resolution

Not CIB subtracted

$p = \frac{\sqrt{Q^2 + U^2}}{I}$

p ranges from 0 to ~20%

Low p values in inner MW plane. Consistent with unpolarized CIB

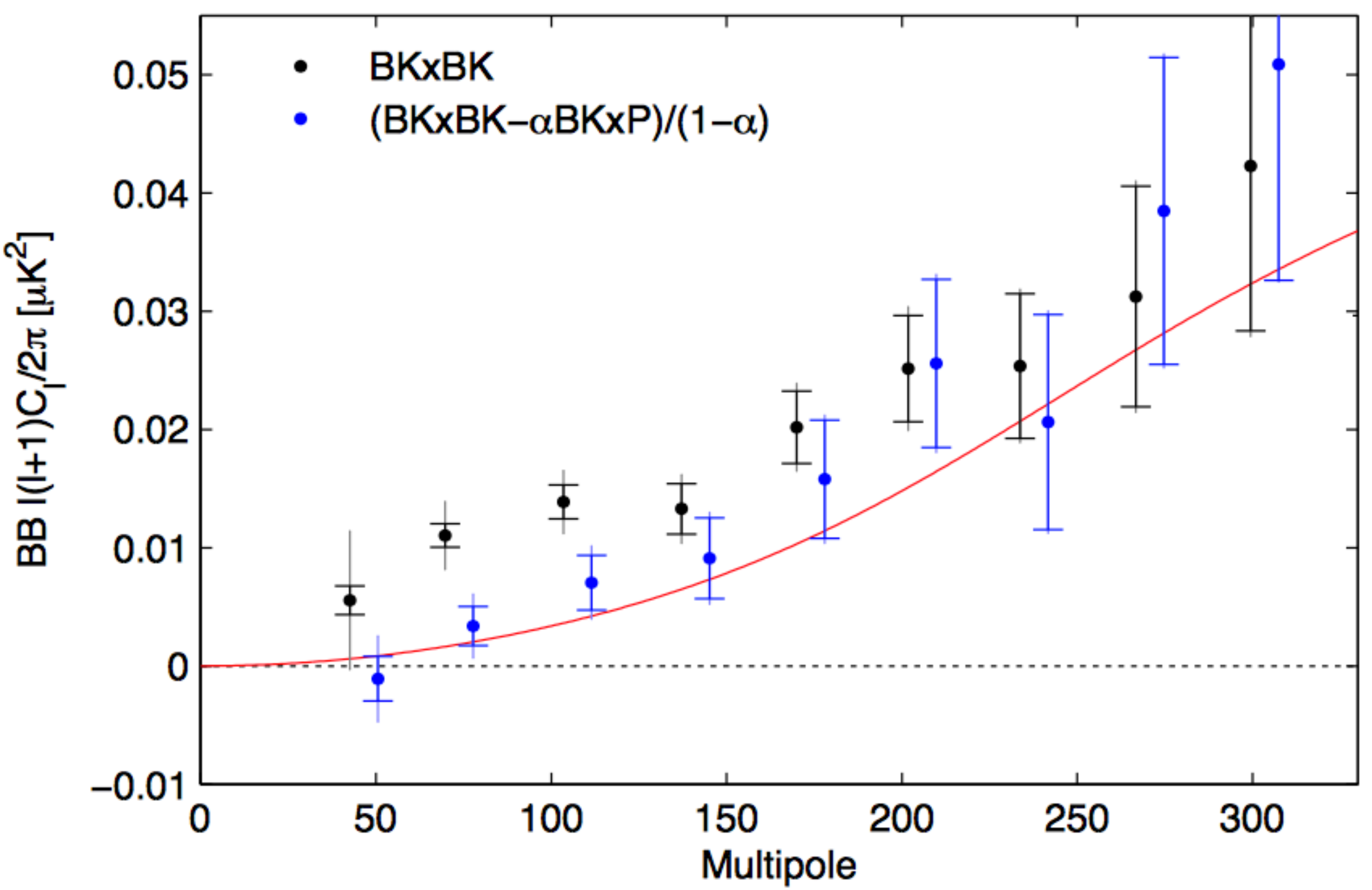
Large p values in outer plane and intermediate latitudes

Bernard J.Ph., ESLAB 2013 6

$$\vec{P} = p_{gal} I_{gal} \hat{p}$$

$$p_{gal} = \frac{P_{gal} + P_{CIB}}{I_{gal} + I_{CIB}}$$

Joint Bicep/Keck/Planck Analysis



Litebird

- Japanese led small satellite with US & European participation
- Multifrequency data should enable definitive measurement of optical depth and reionization history
- Should improve constraints on r (or detect gravitational waves) — 1-2 orders of magnitude improvement
- Currently in phase A

Tensions

- Hubble Constant
  - BAO + Nucleosynthesis or Planck -> 68
  - Local distance ladder -> 73
- Amplitude of Fluctuations
  - Lensing measurements: 0.77
  - Planck: 0.83

DES Y1 vs. Planck

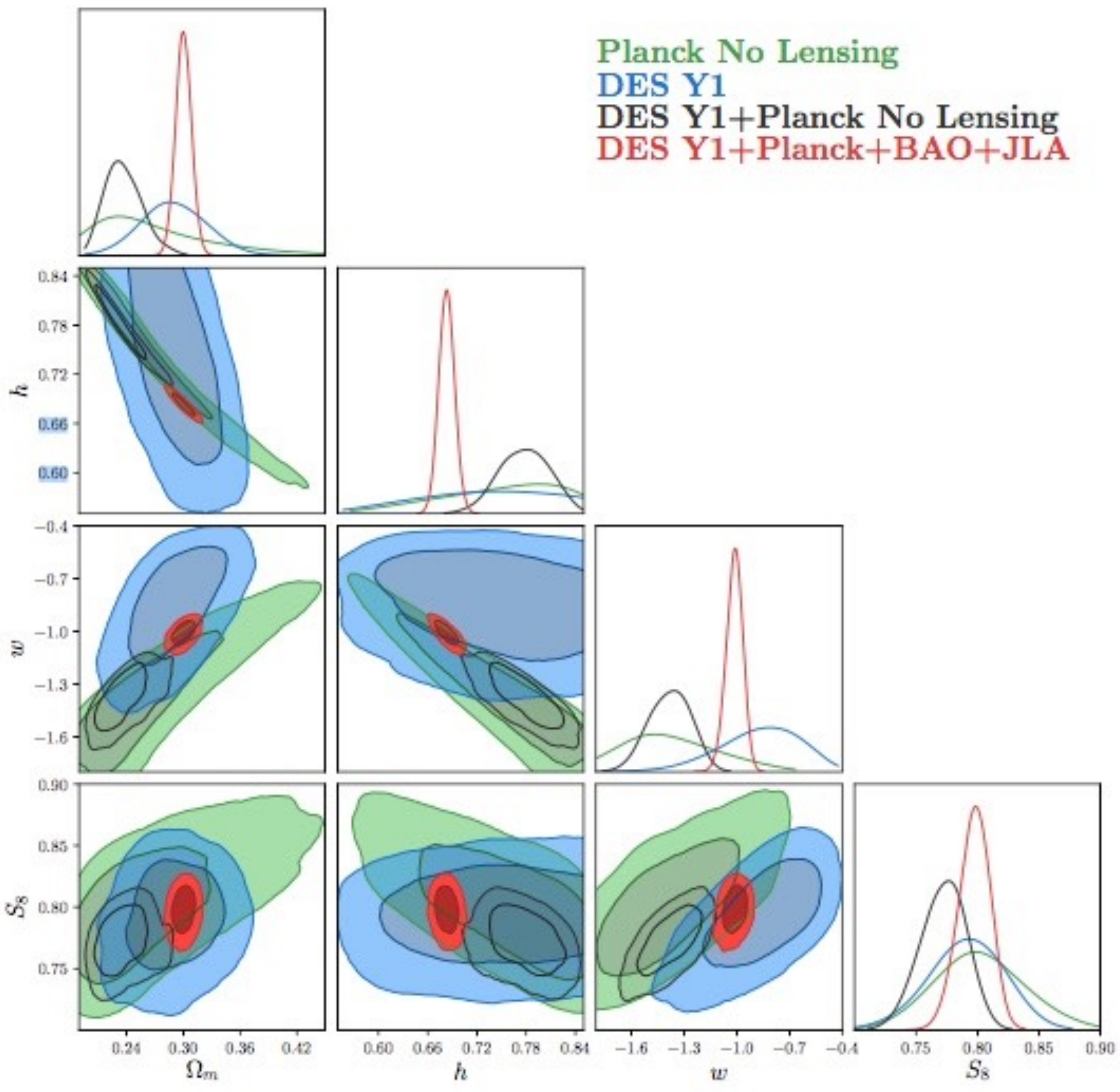
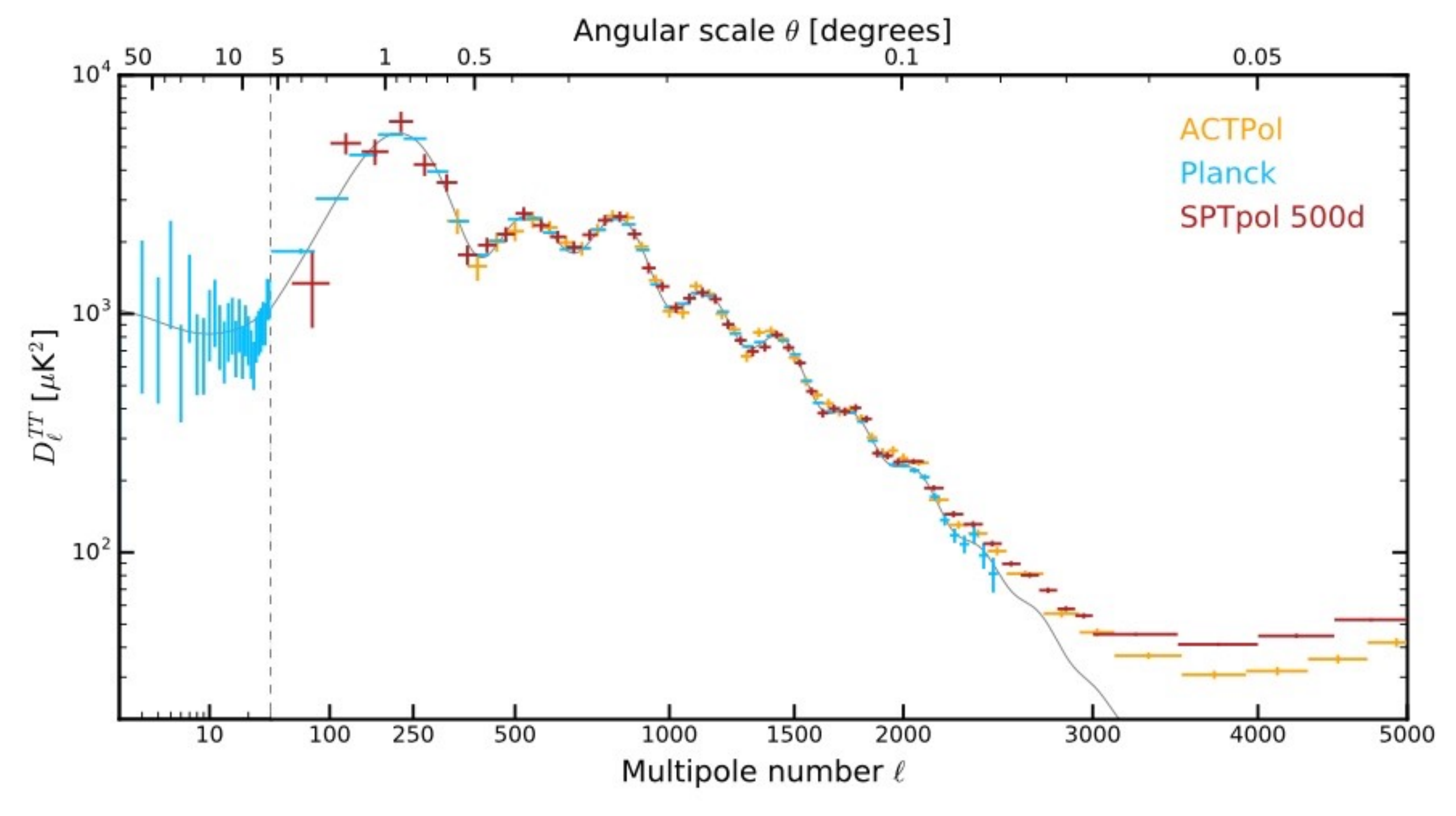


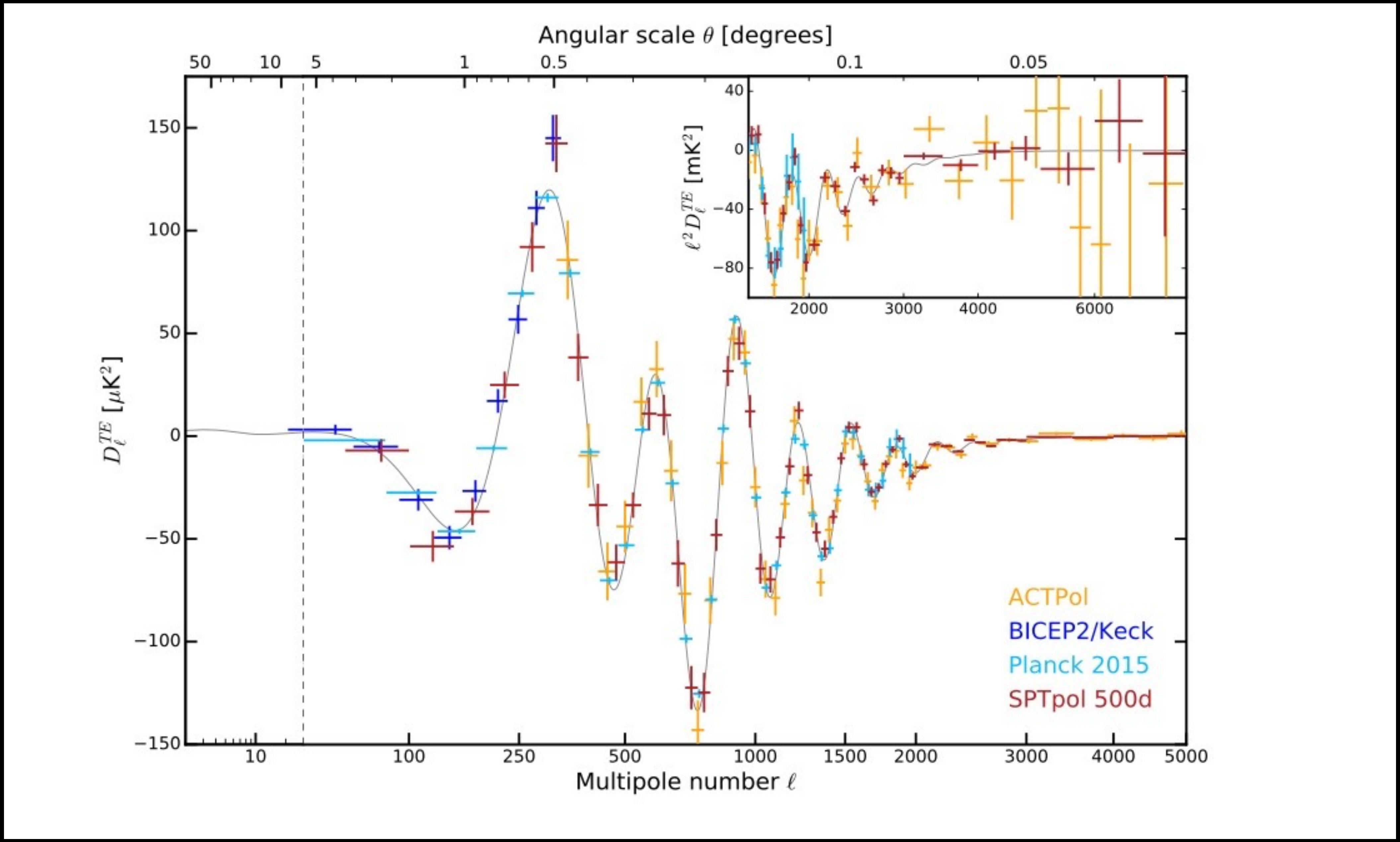
FIG. 14. wCDM constraints from the three combined probes in DES Y1 and Planck with no lensing in the Ω_m-w-S_8-h subspace. Note the strong degeneracy between h and w from Planck data. The lowest values of w are associated with very large values of h, which would be excluded if other data sets were included.

CMB Spectrum: TT



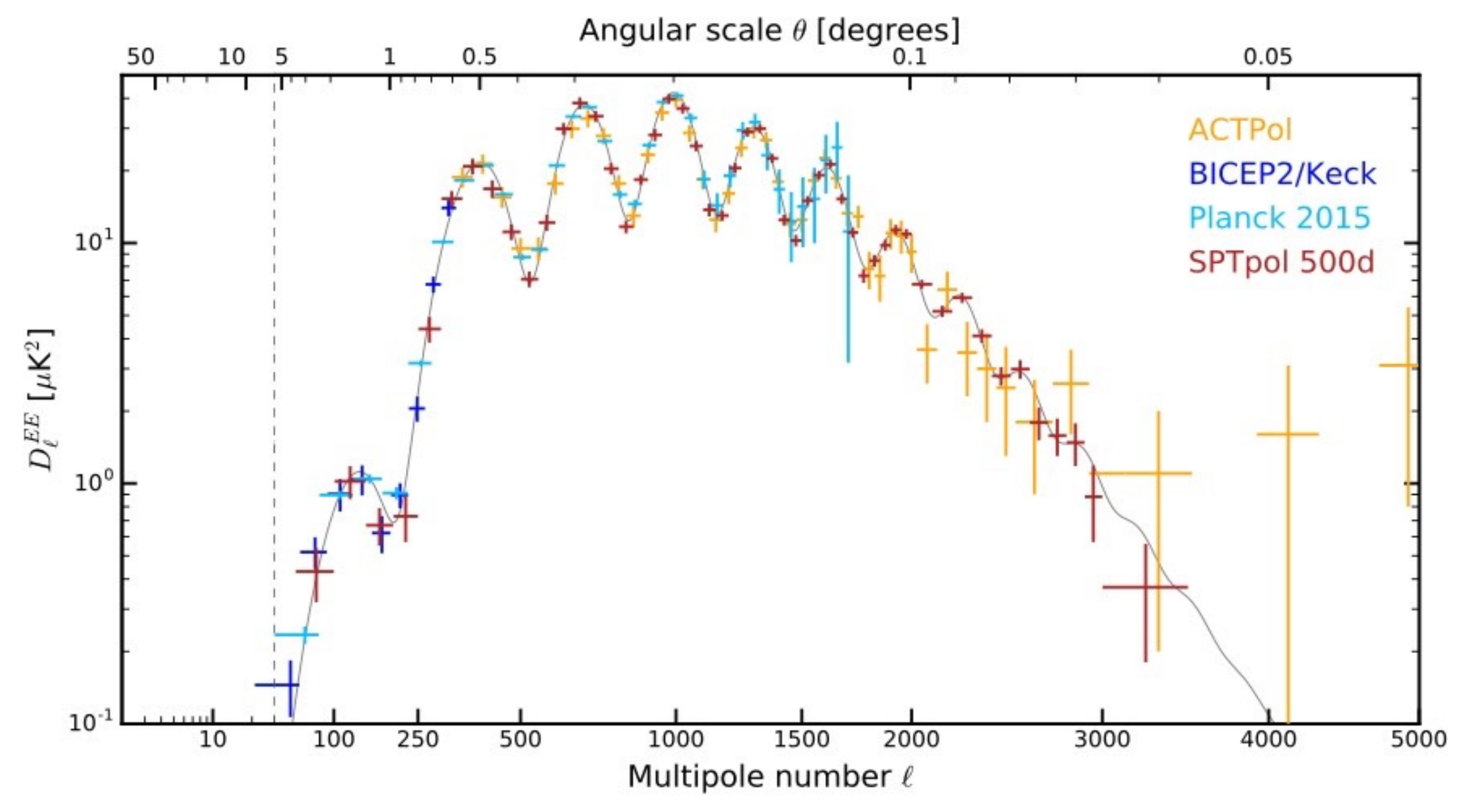
Henning et al. Astro-ph/1707.09353

CMB Spectrum: TE



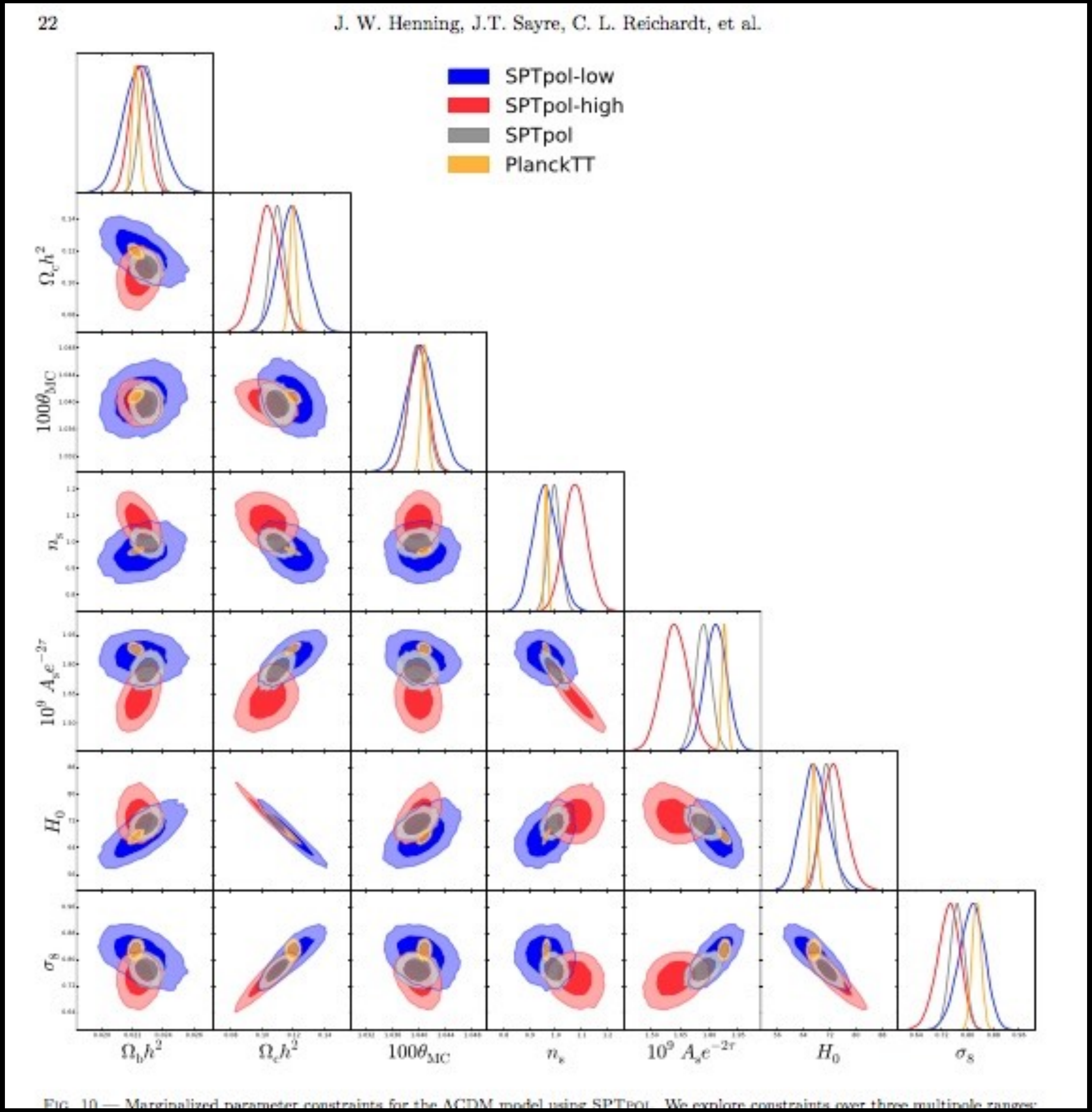
Henning et al. Astro-ph/1707.09353

CMB Spectrum: EE



Henning et al. Astro-ph/1707.09353

Tensions Continued



22 J. W. Henning, J.T. Sayre, C. L. Reichardt, et al.

FIG. 10 — Marginalized parameter constraints for the ΛCDM model using SPTPOL. We explore constraints over three multipole ranges:

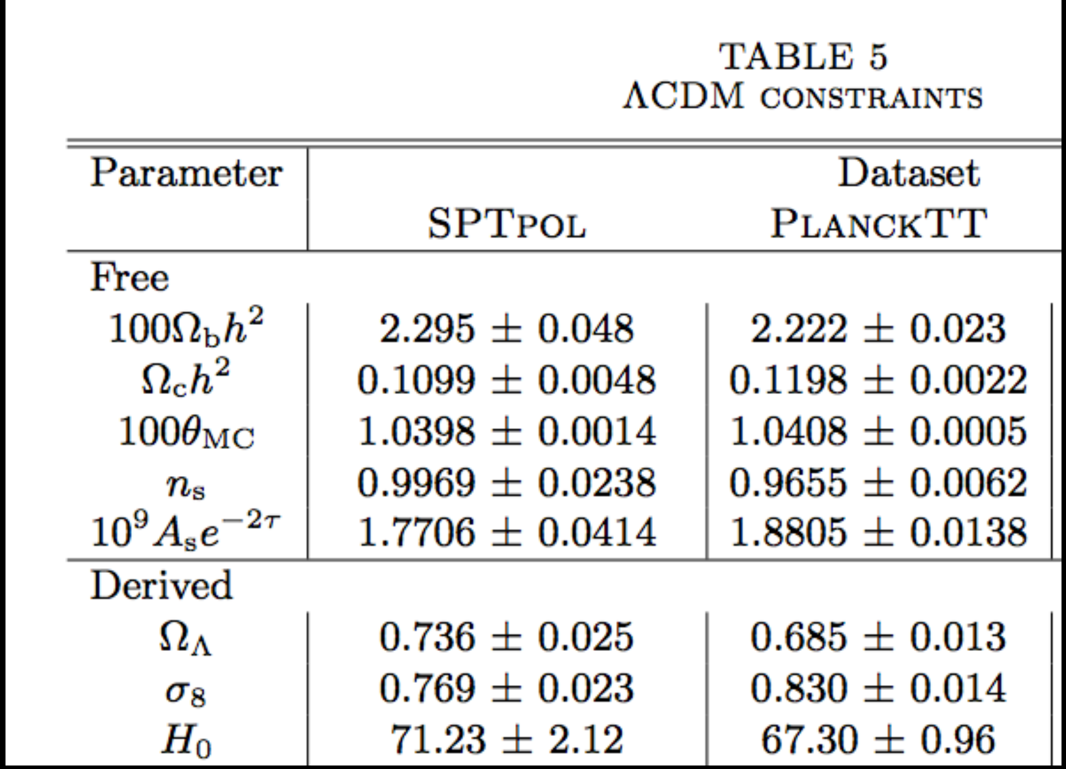
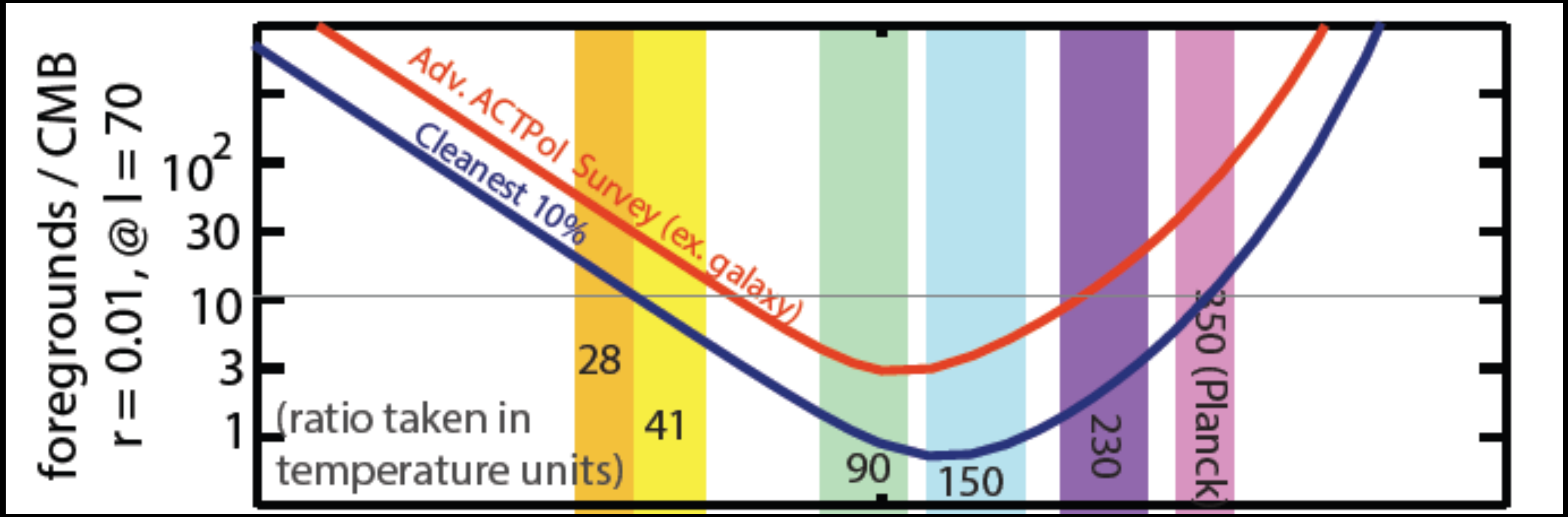


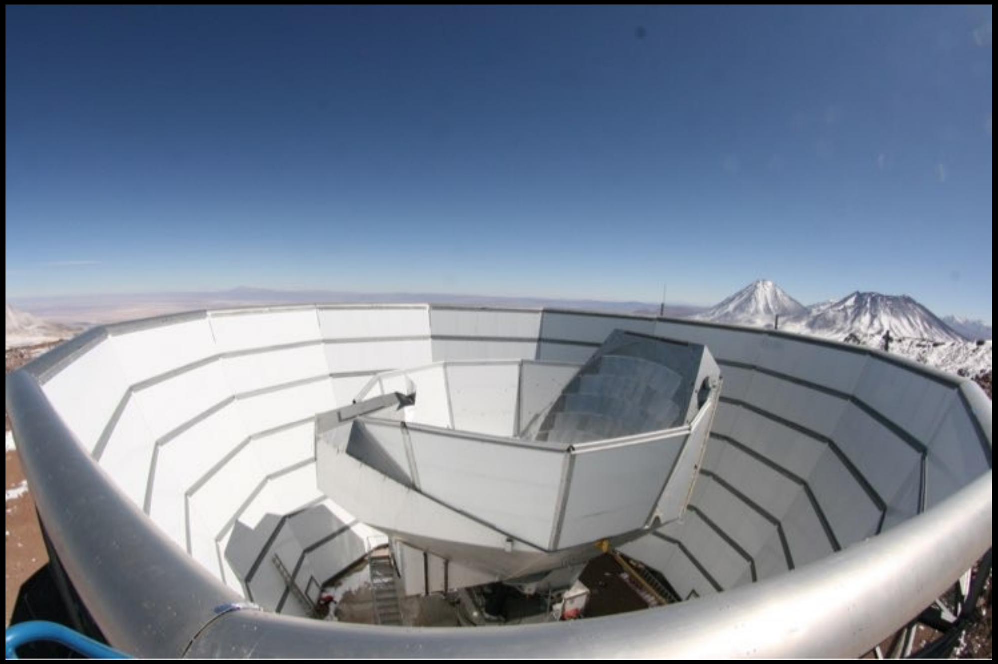
TABLE 5
ΛCDM CONSTRAINTS

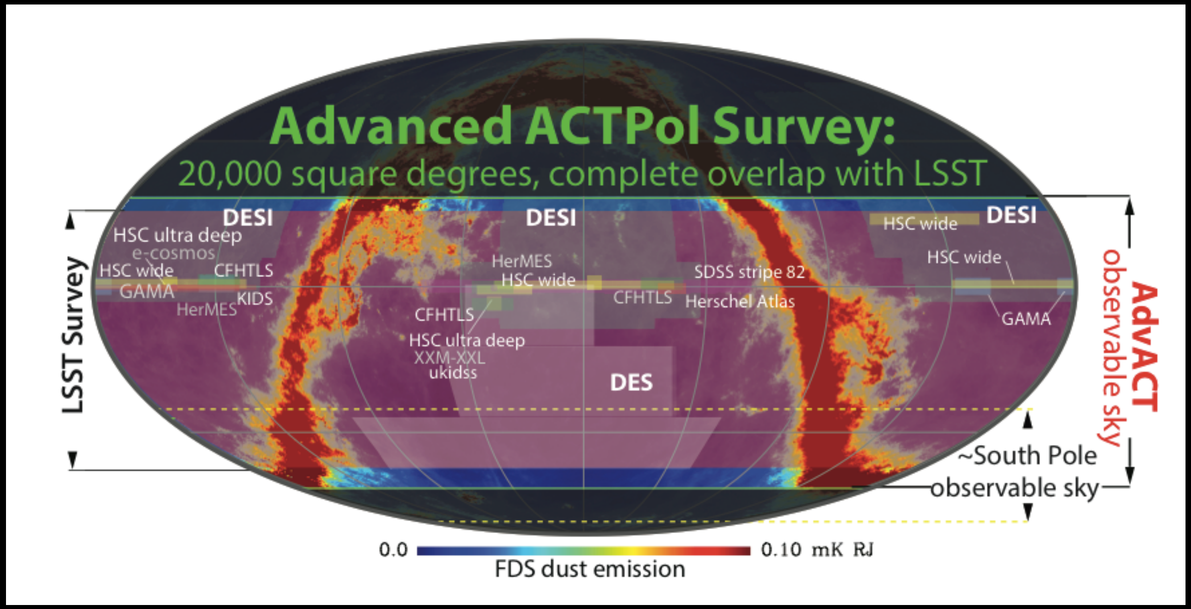
Parameter	Dataset	
	SPTPOL	PLANCKTT
Free		
$100\Omega_b h^2$	2.295 ± 0.048	2.222 ± 0.023
$\Omega_c h^2$	0.1099 ± 0.0048	0.1198 ± 0.0022
$100\theta_{MC}$	1.0398 ± 0.0014	1.0408 ± 0.0005
n_s	0.9969 ± 0.0238	0.9655 ± 0.0062
$10^9 A_s e^{-2\tau}$	1.7706 ± 0.0414	1.8805 ± 0.0138
Derived		
Ω_Λ	0.736 ± 0.025	0.685 ± 0.013
σ_8	0.769 ± 0.023	0.830 ± 0.014
H_0	71.23 ± 2.12	67.30 ± 0.96

Henning et al. 2017

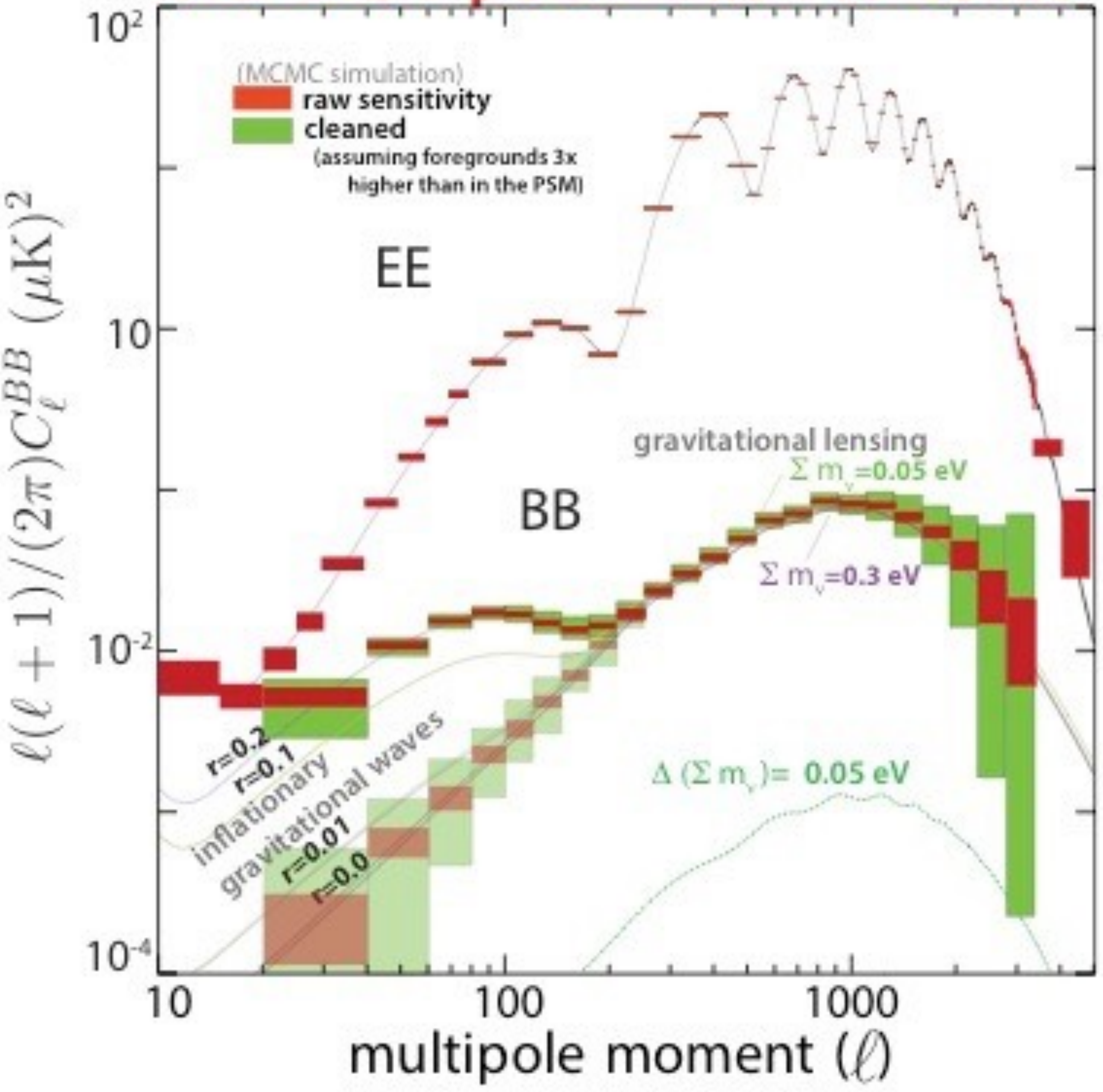
AdvACT: Deep Wide and Multi-frequency







AdvACT polarization forecast



The Simons Observatory

United States

- Arizona State University
- Carnegie Mellon University
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

- 8 Countries
- 35+ Institutions
- 160+ Researchers

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Simon Fraser University
- University of British Columbia

Chile

- Pontificia Universidad Catolica
- University of Chile

Europe

- APC - France
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

Japan

- KEK
- IPMU

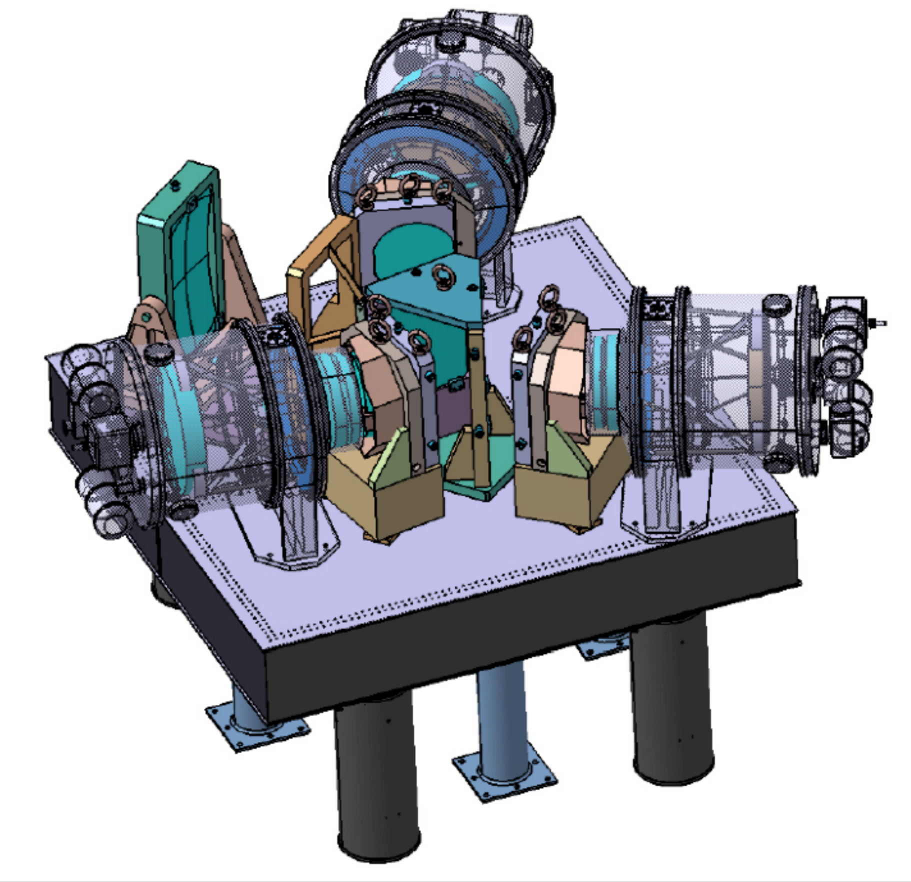
South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

SUMIRE: HSC+PFS



Premier Dark Energy Observatory

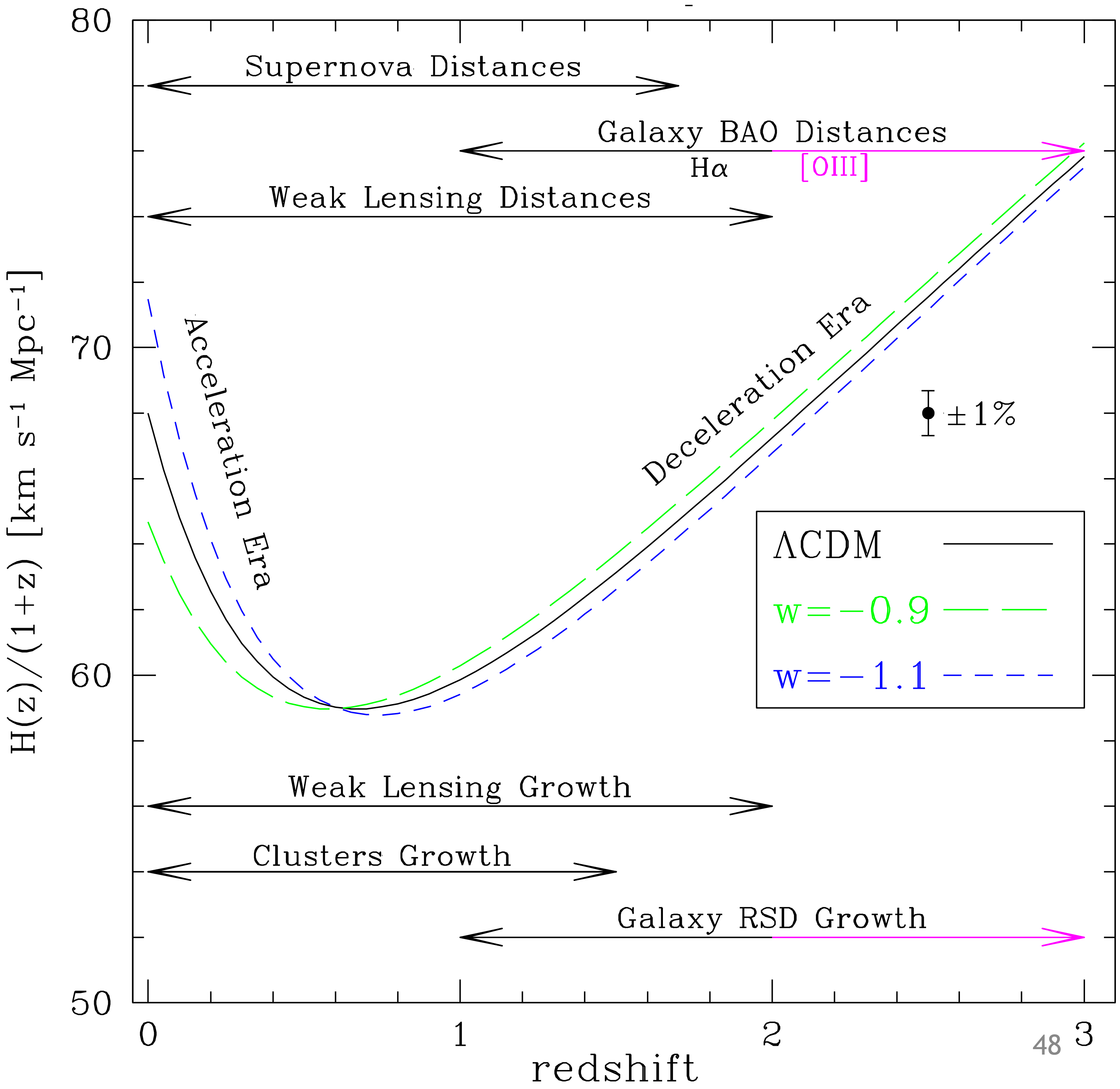
- WFIRST combines all techniques to determine the nature of Dark Energy.

- Only observatory doing such comprehensive observations

- High precision measurements will be optimally combined for the best measurement

Weinberg & SDT 2015

WFIRST Probes of Expansion and Growth



Conclusions

- The start of the millenium has been an exciting time for cosmology. We have discovered that our universe seems to be both simple and strange.
  - The last millenium ended with the discovery of dark energy and the new one began with precision CMB measurements
  - Intriguing tension could be pointing to new physics (or more likely systematics in the data)
  - Next steps: discover the nature of dark energy and dark matter, understand the origin of the universe!