Data Analysis for Space Exploration of the Cosmic Microwave Background in satellite missions COBE, WMAP, and Planck

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CMB data analysis lectures

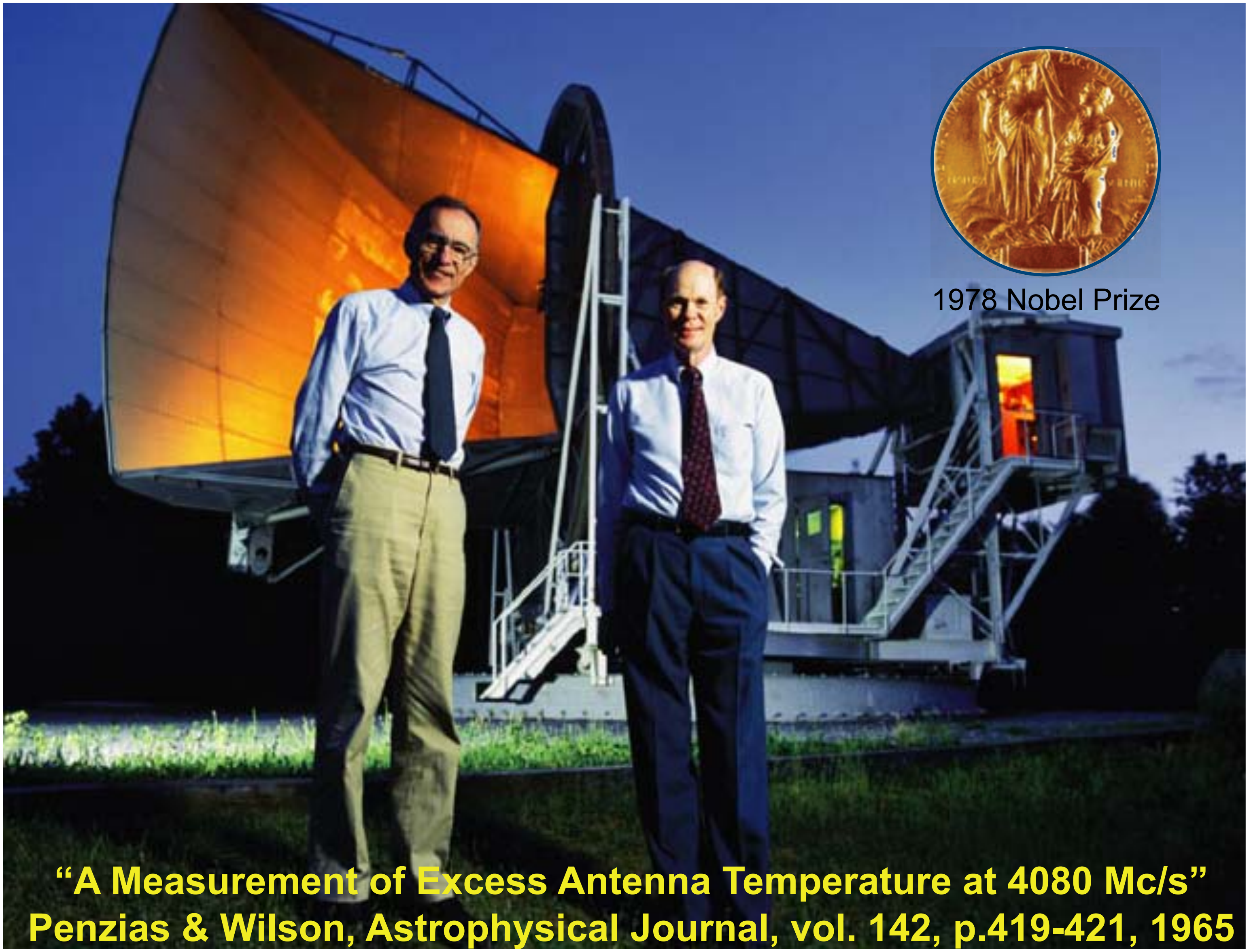
Saturday: General Introduction

Sunday: Modeling Effective Beams, Component Separation

Monday: Likelihood, Power Spectrum Estimation, Point Source Extraction, Summary

CMB

1965: Discovery of the CMB



1978 Nobel Prize

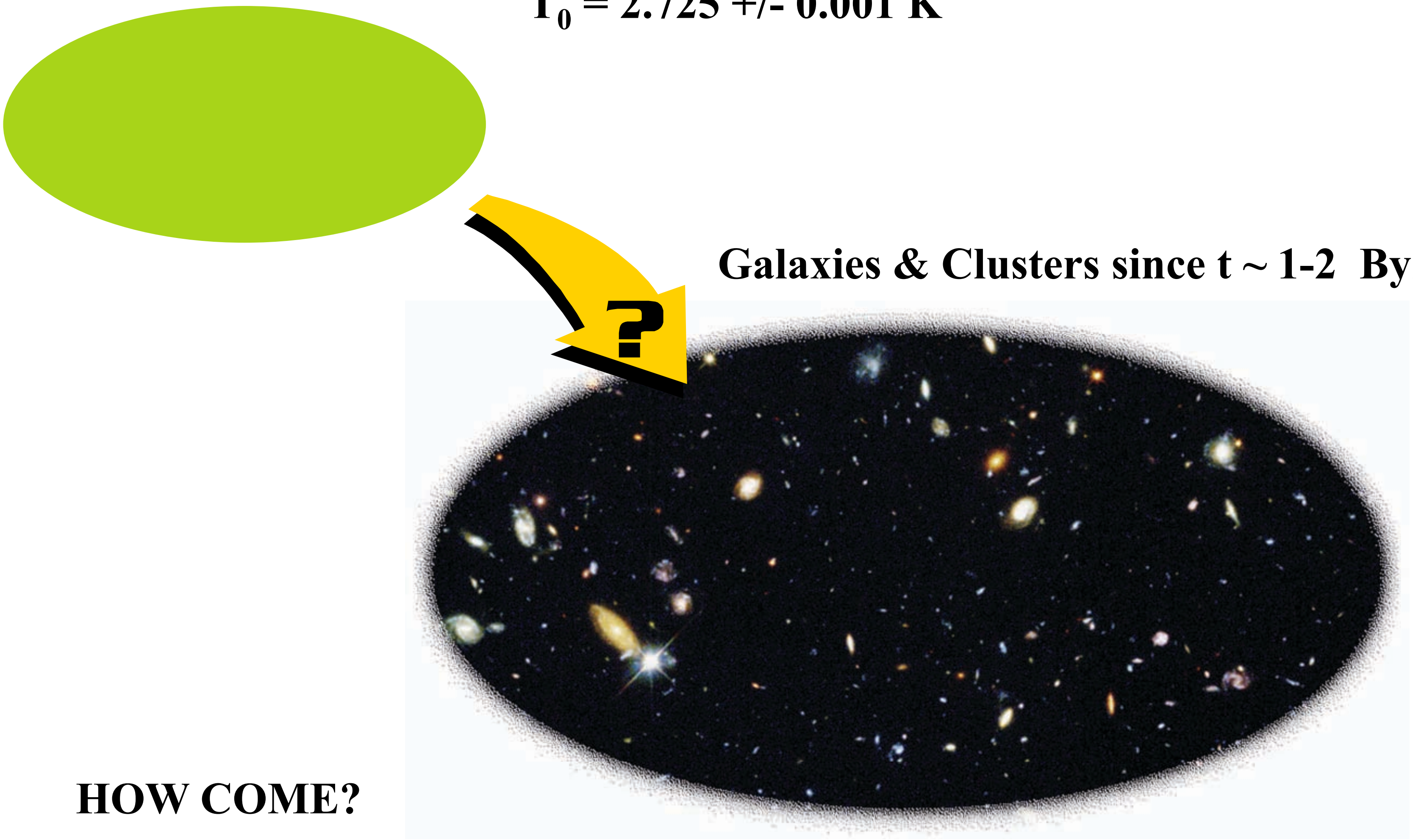
“A Measurement of Excess Antenna Temperature at 4080 Mc/s”
Penzias & Wilson, Astrophysical Journal, vol. 142, p.419-421, 1965

Emerging Structure in the Universe

Smooth Gas at t ~ 400,000 yrs

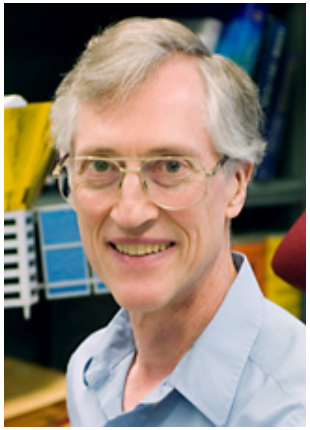
$T_0 = 2.725 \pm 0.001$ K

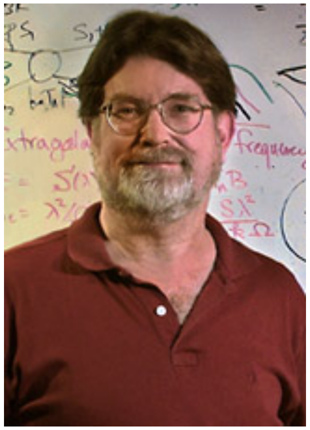
Galaxies & Clusters since t ~ 1-2 Byrs



HOW COME?

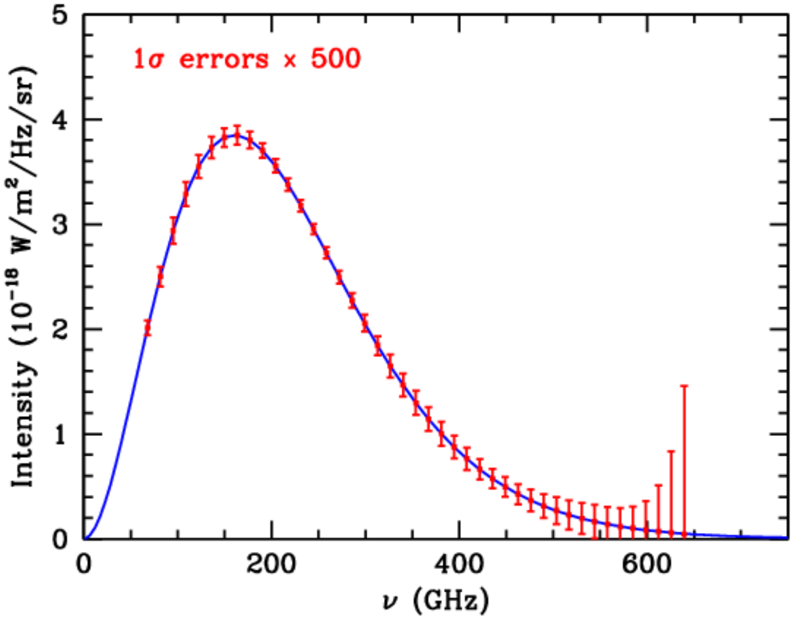
… and then there was COBE …

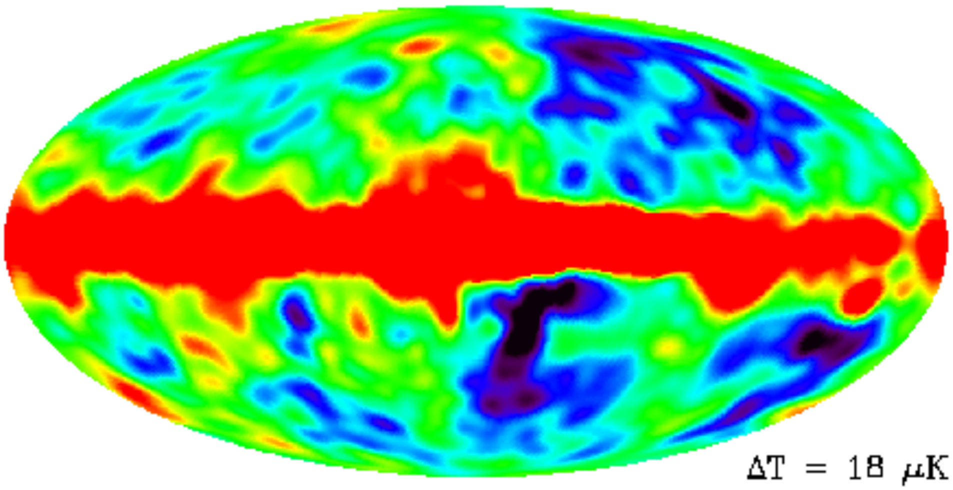




Nobel prize in Physics, 2006, awarded to John Mather and George Smoot

“for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation”



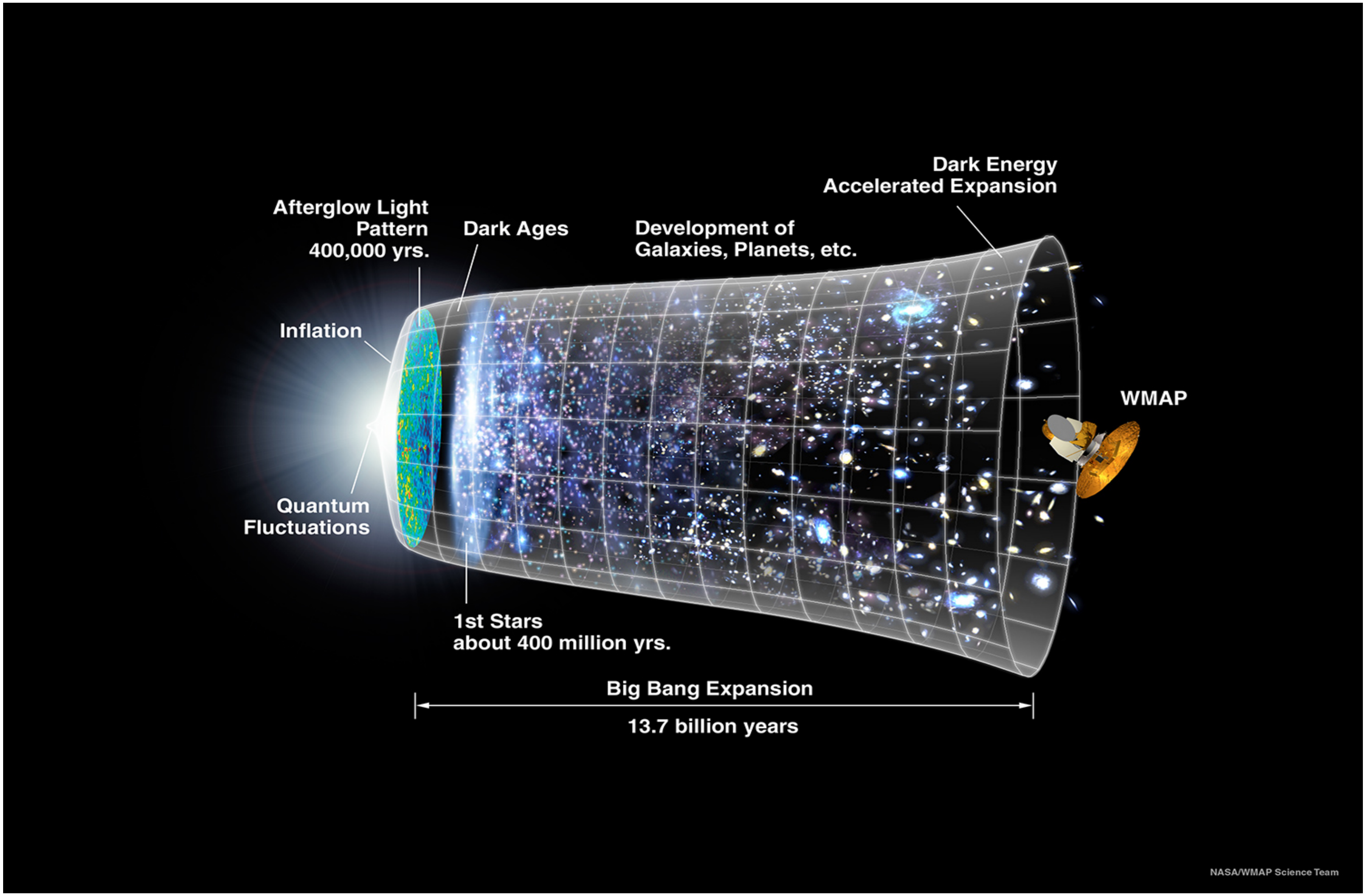


CMB drives a revolution in our understanding of the Universe

- Existence of CMB
  - One of the pillars of the hot big-bang model (expansion, origin of light elements, &CMB)
  - A snap-shot of the universe at the earliest epoch accessible to direct astronomical observation
- Measurement of the black-body spectrum
  - $T = 2.725 \pm 0.001$ K, deviations $< 10^{-4}$
  - Sets the temperature scale of the Universe
    - ➢ Only cosmological parameter known to better than 1%!
  - Rules out significant energy injection below $z \sim 10^{7}$.
- Measurement of the anisotropy
  - Shrunk substantially the range of viable cosmological models.
  - Gravitational instability in a dark matter dominated Universe formed large-scale structure seen by e.g. 2dF or SDSS.
  - The fluctuations are of the form predicted by inflation. (?)
  - The large-scale structure of space-time is “simple”. (?)
- Precise normalization of large-scale structure in the universe

> 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 ever done for us?
>
> Reg, spokesman for the People’s Front of Judea

CMB Timeline for the Universe



The angular power spectrum of the CMB anisotropy

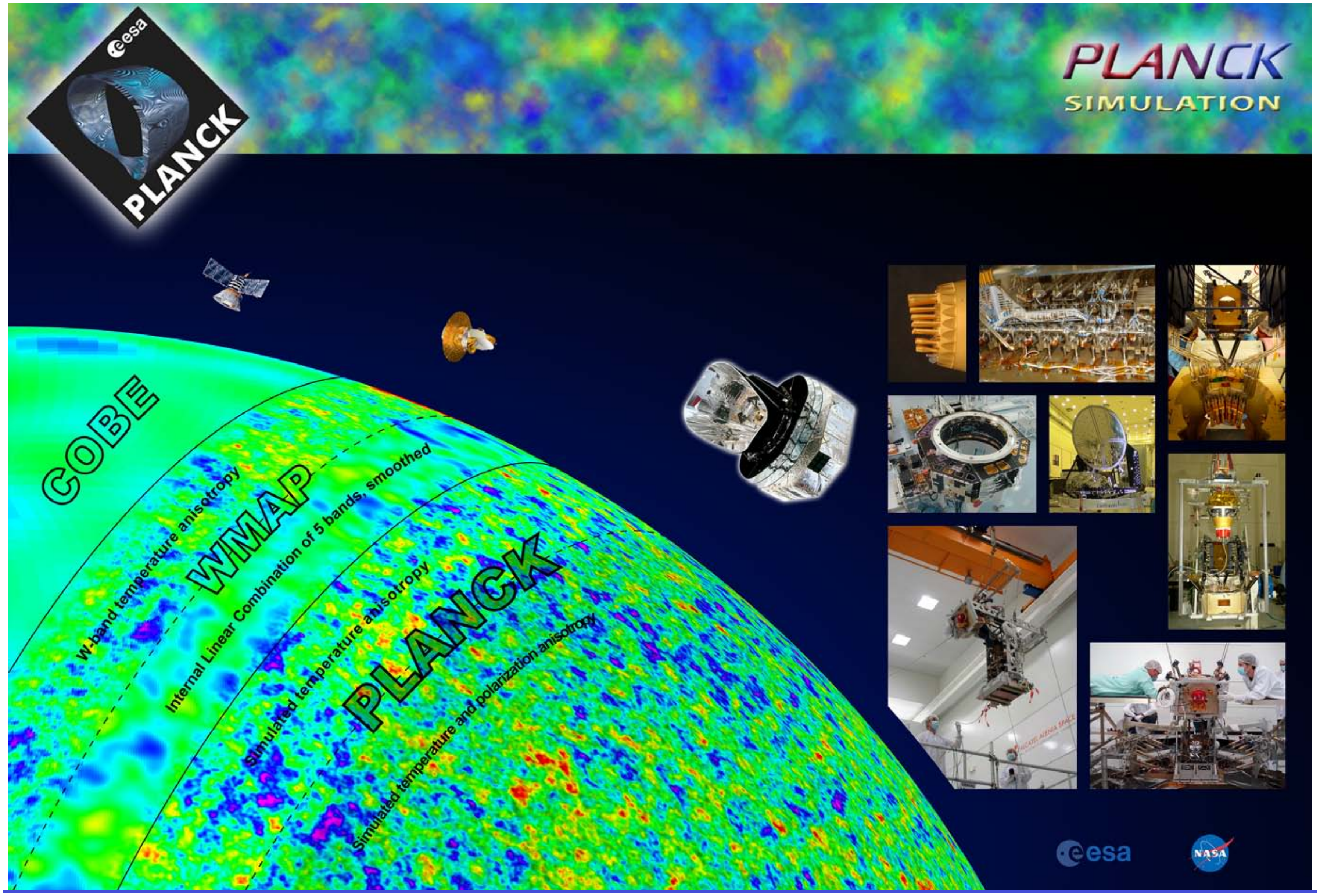
- **Current measurements are quite consistent with the primary fluctuations in the CMB being a Gaussian random field.**
- **The primary fluctuations in the CMB are thus well described by their angular power spectrum.**

$$\frac{\Delta T}{T} \equiv \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

Curved sky analogue of FT

$$\langle a_{\ell m} a_{\ell' m'} \rangle = \underset{\uparrow}{C_\ell}\, \underbrace{\delta_{\ell\ell'} \delta_{mm'}}$$

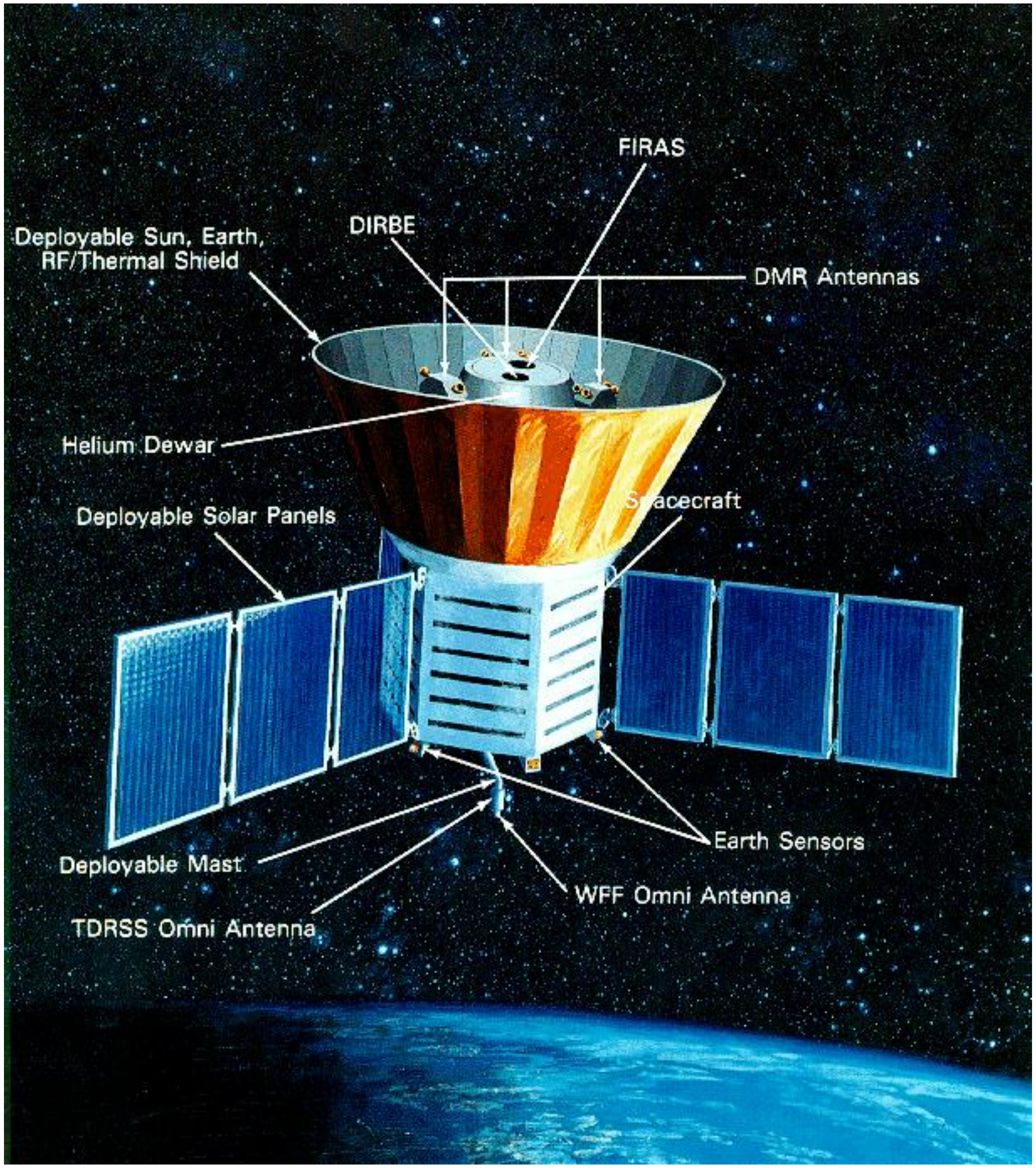
Statistical isotropy   Rotational invariance


PLANCK
SIMULATION
esa
PLANCK
COBE
W-band temperature anisotropy
WMAP
Internal Linear Combination of 5 bands, smoothed
Simulated temperature anisotropy
PLANCK
Simulated temperature and polarization anisotropy
esa
NASA

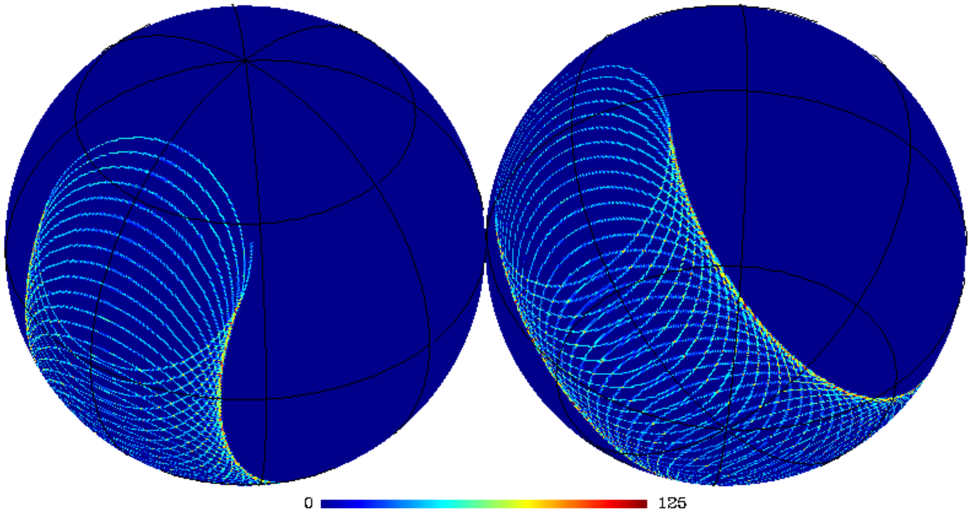
COBE

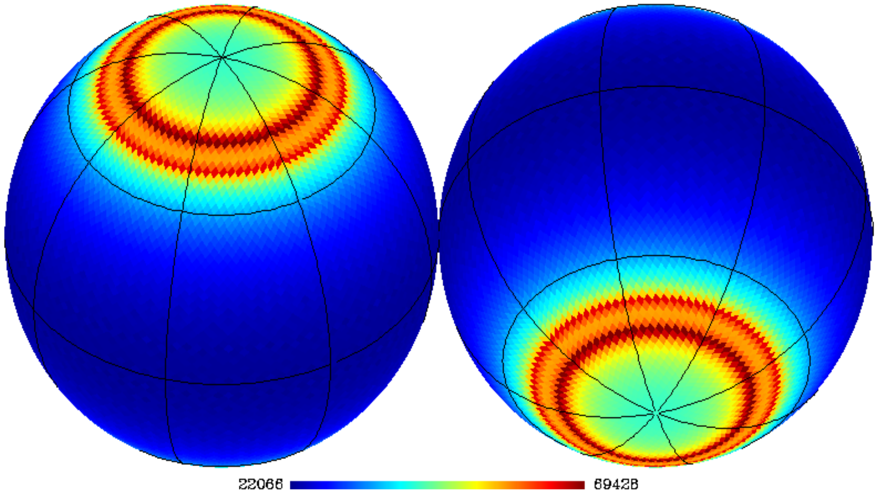
COsmic Background Explorer

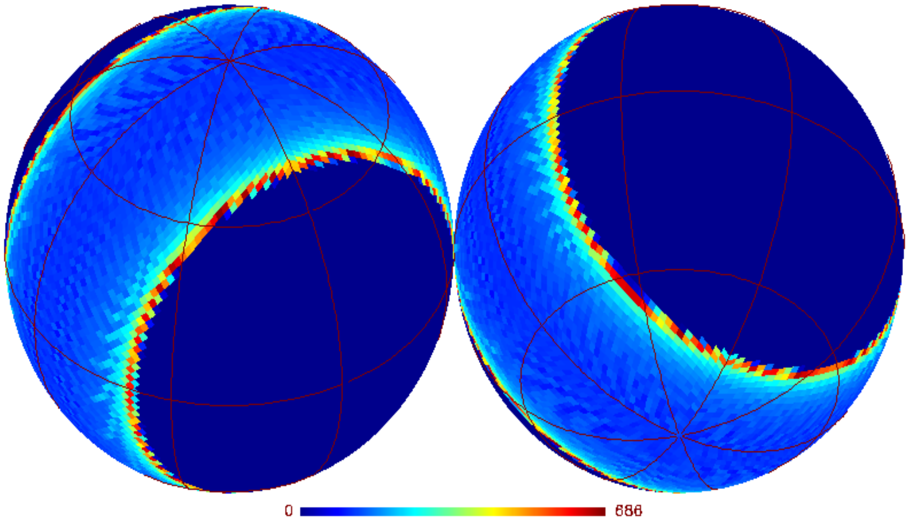
- COBE Satellite, 1989-1995
- FIRAS & DIRBE - < 1 year
- DMR - ~4 years
- COBE's motion -> scanning the sky with DMR
  - 'Bore' angle - 30 deg
  - Precession angle - 86 deg
  - Spin period - 73 sec
  - Precession period - 104 min

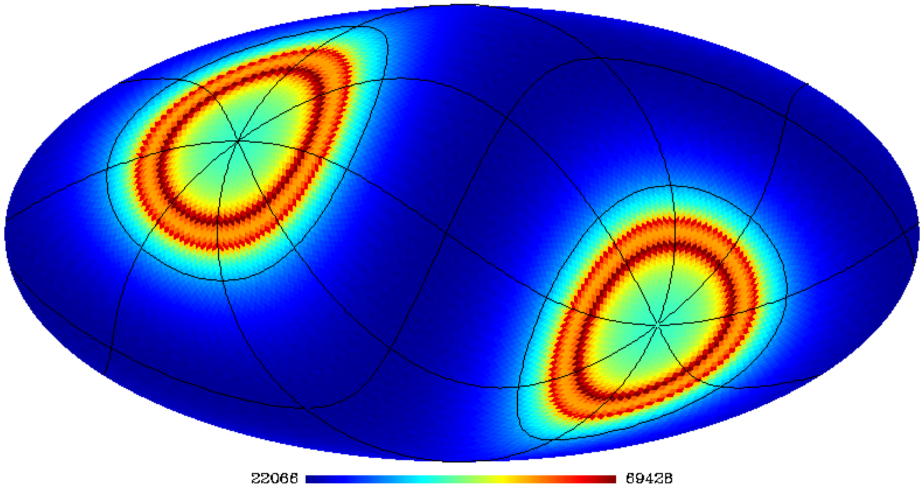


Scanning the sky with COBE

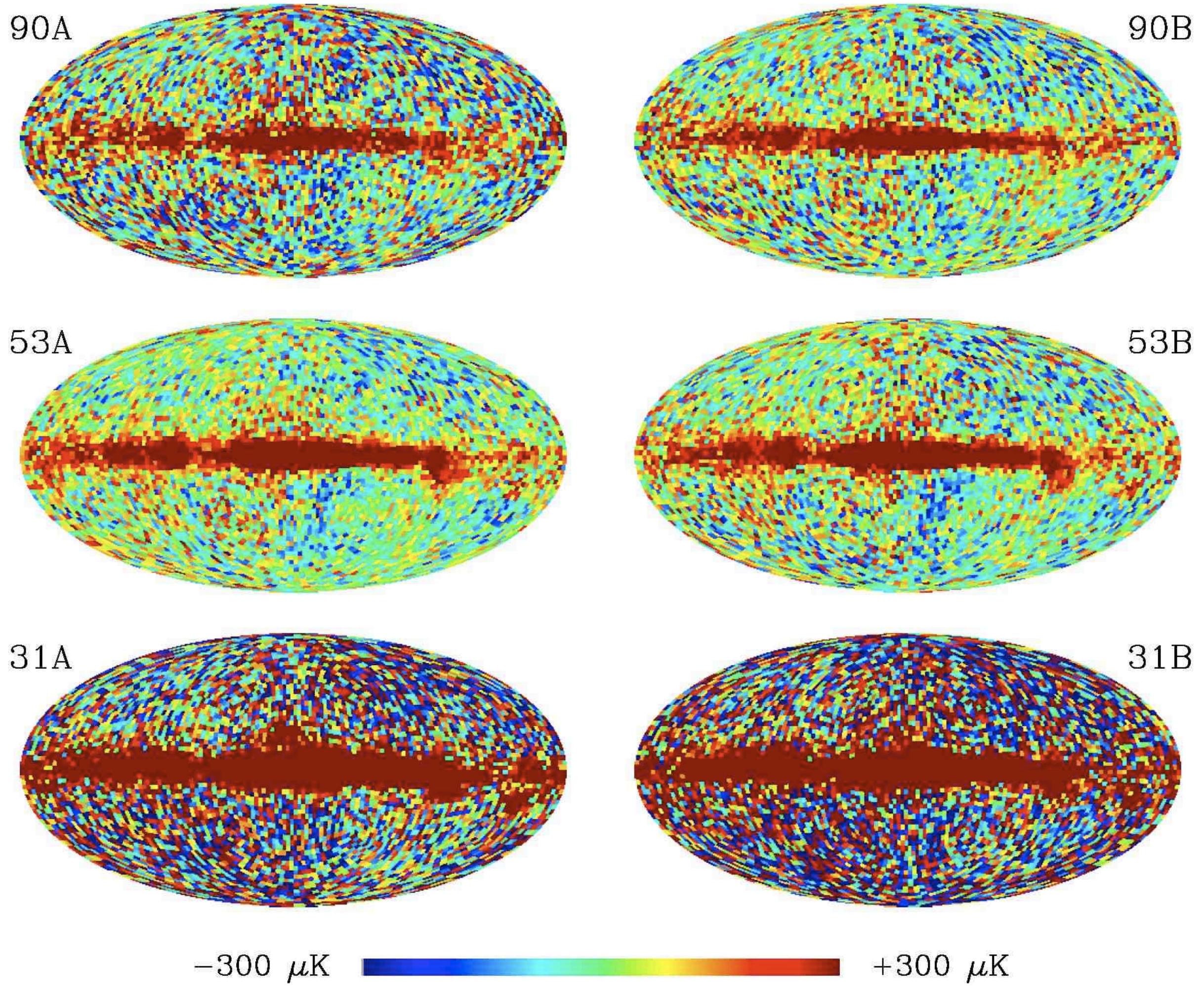

COBE-DMR 1 hr


DMR 1yr

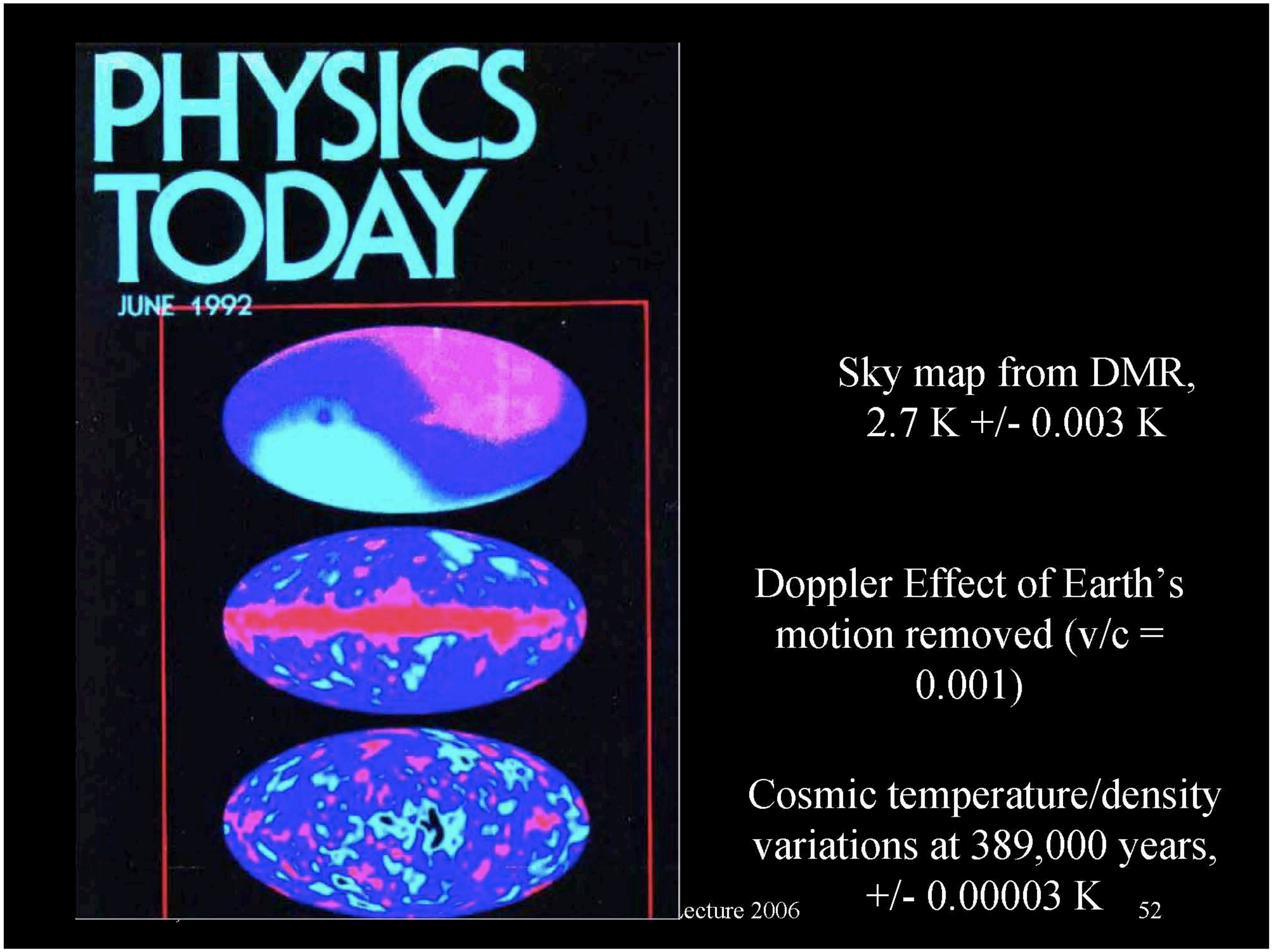

DMR 1day


DMR 1yr

DMR Data



COBE-DMR Delivers …



Sky map from DMR,
2.7 K +/- 0.003 K

Doppler Effect of Earth's motion removed (v/c = 0.001)

Cosmic temperature/density variations at 389,000 years, +/- 0.00003 K

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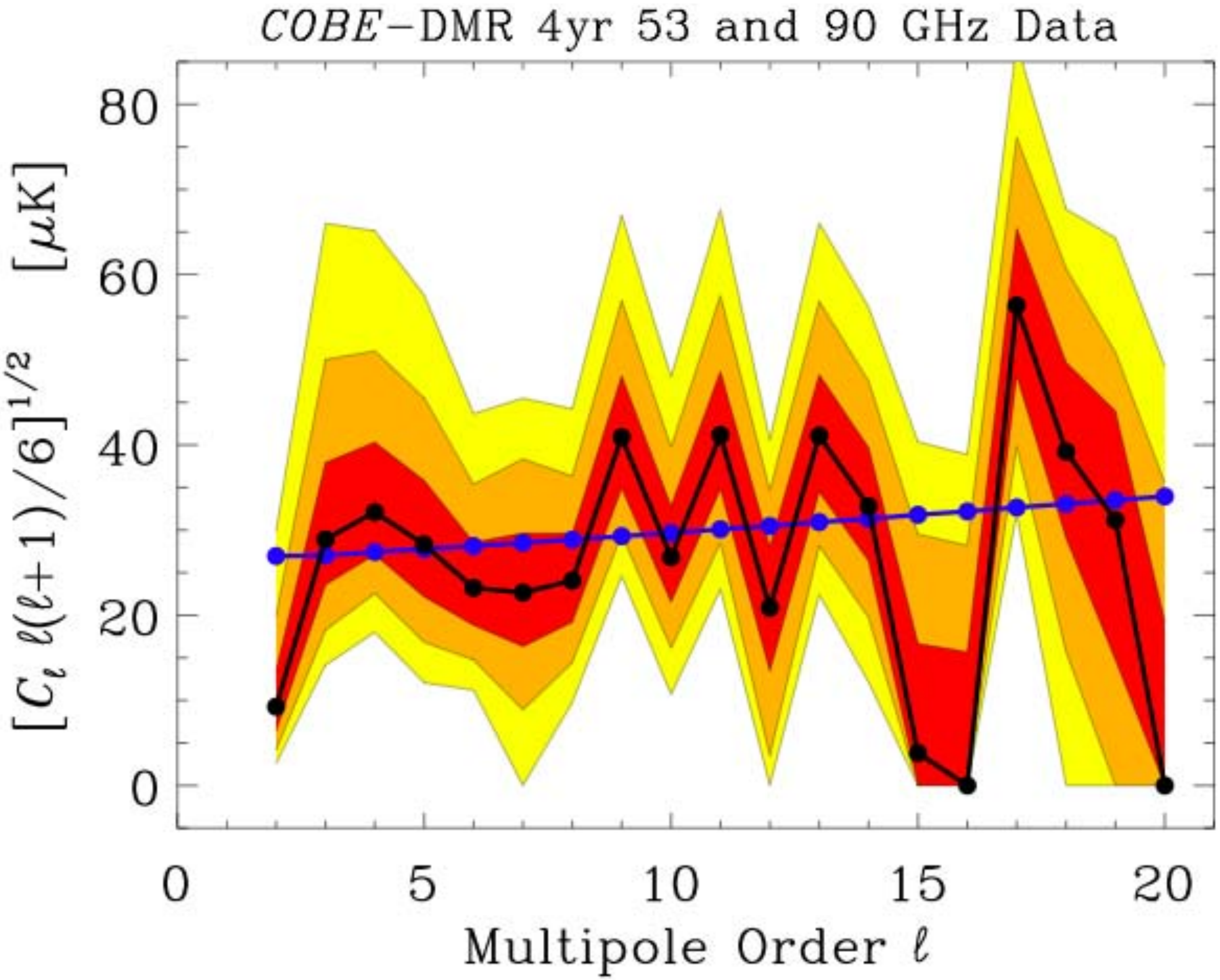
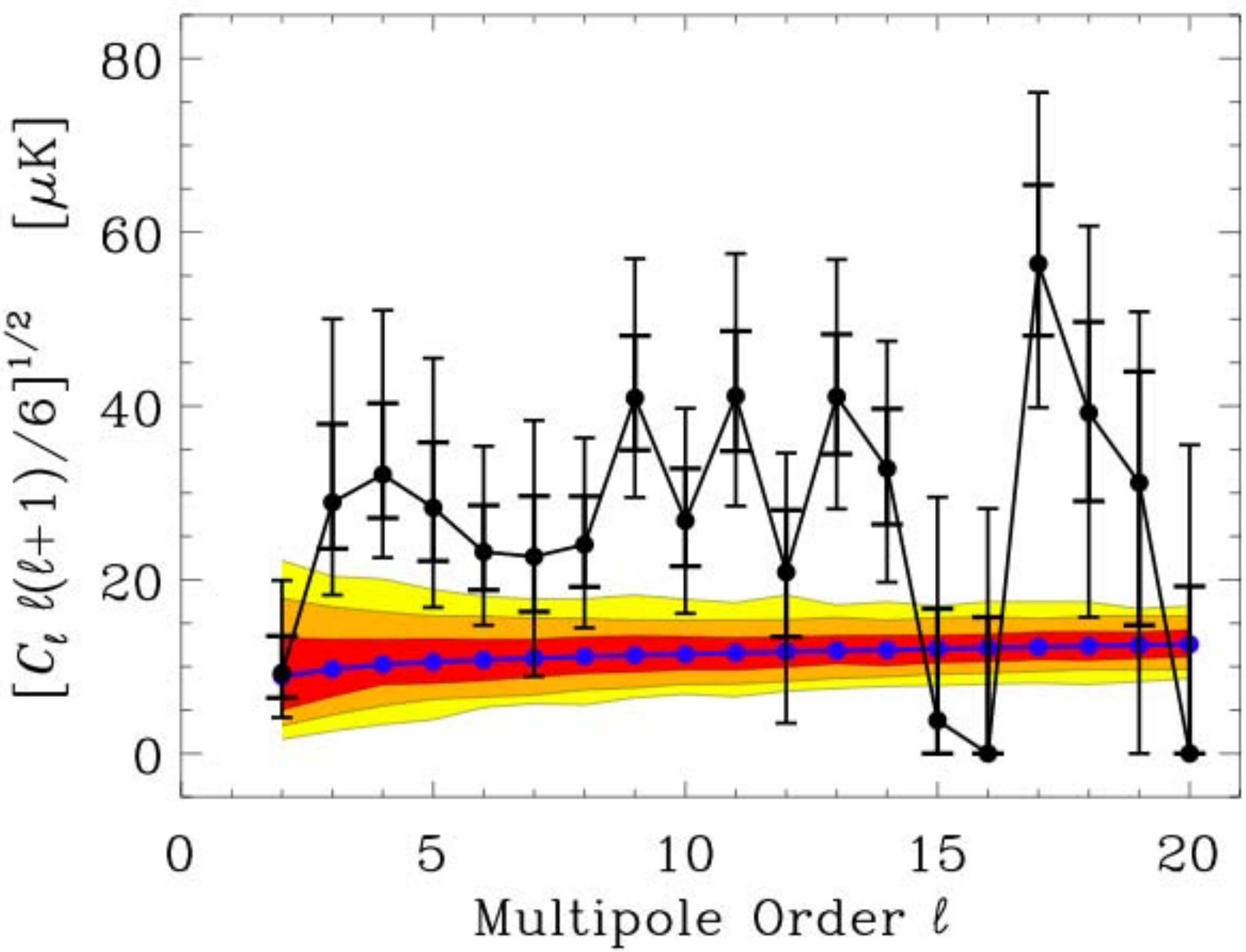
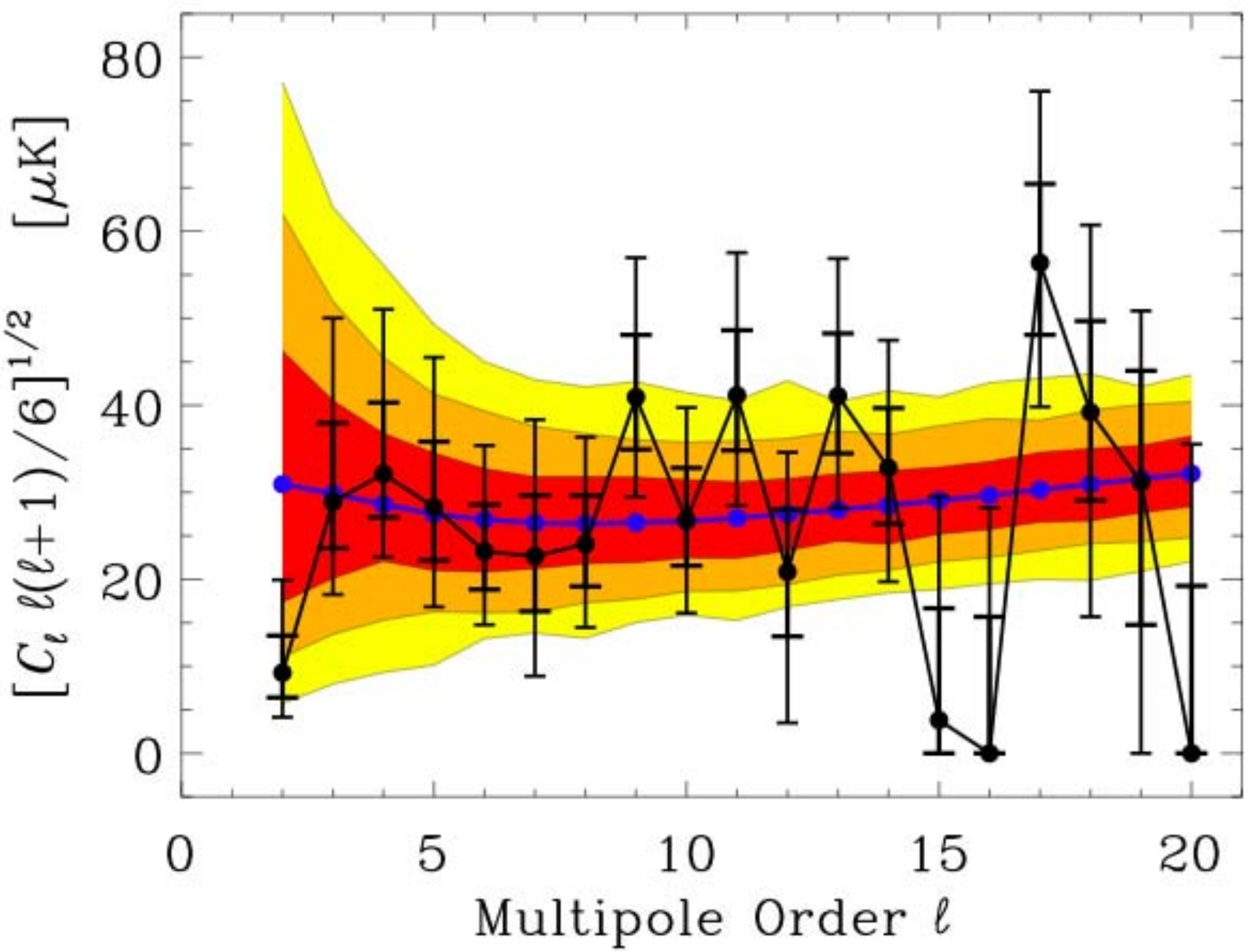
CMB Anisotropy Spectrum from COBE-DMR



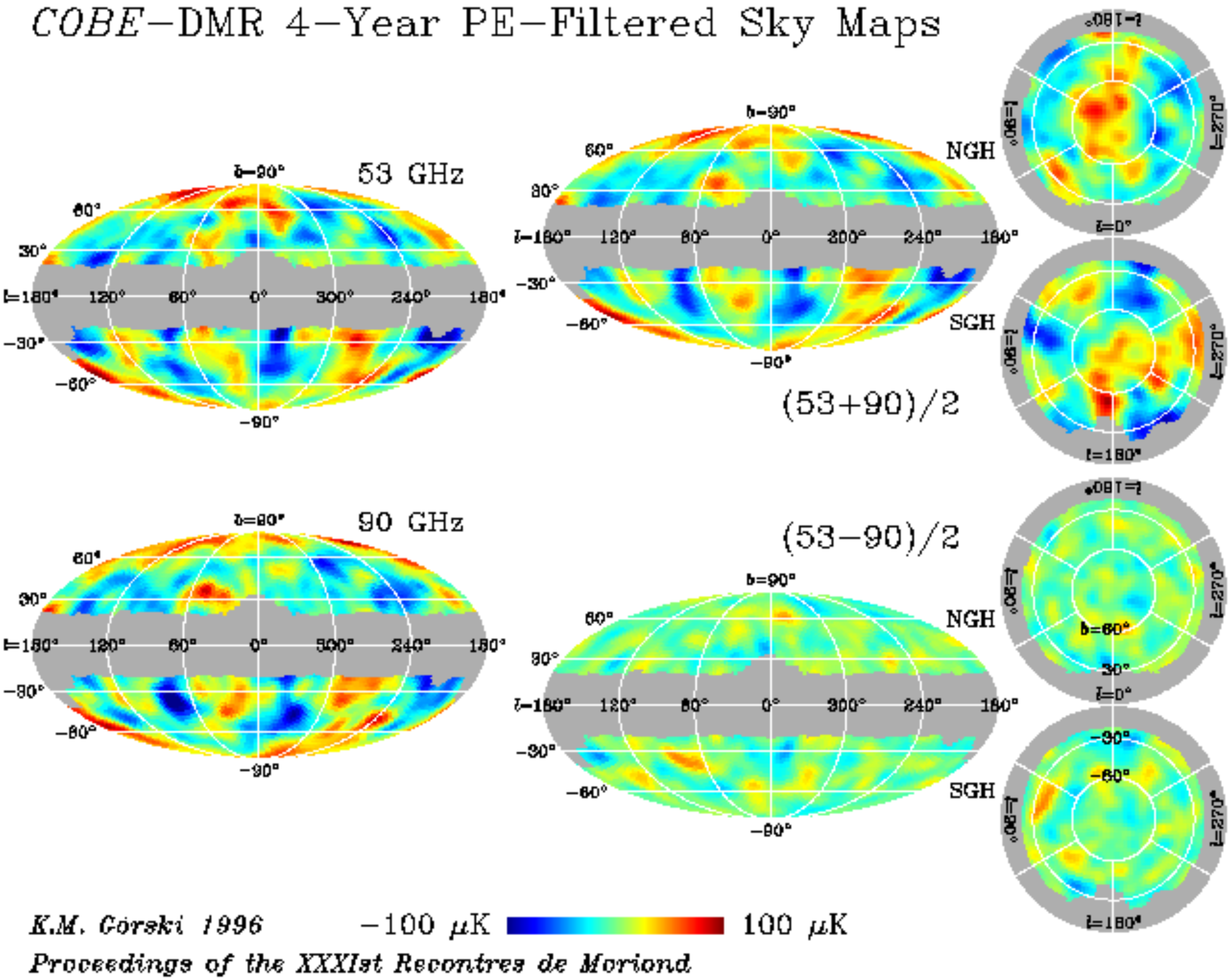
… comparison to biased-CDM theory



… and to Lambda-CDM



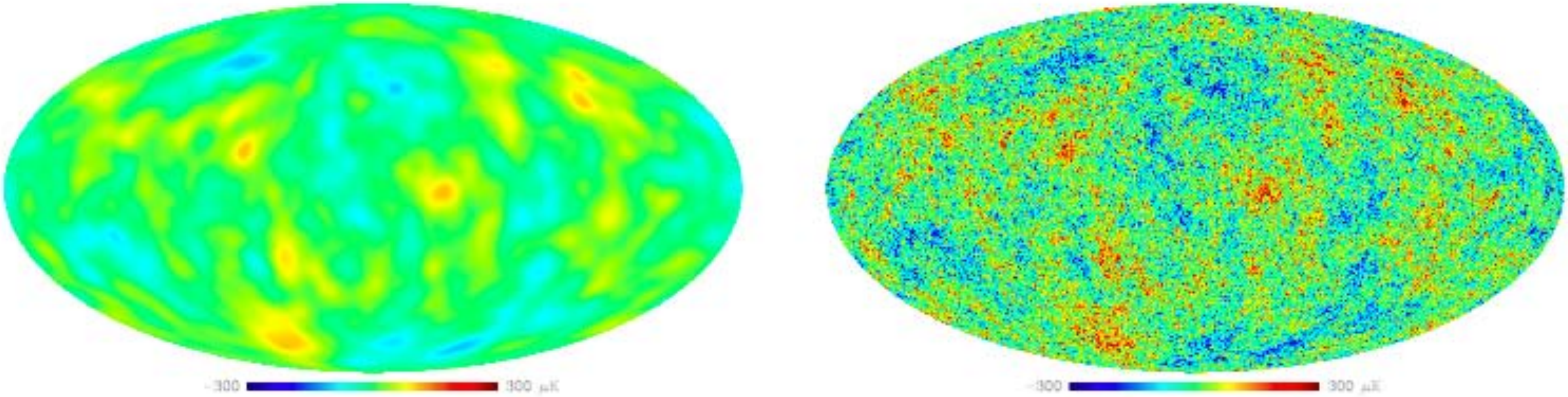
Last scattering surface according to COBE-DMR



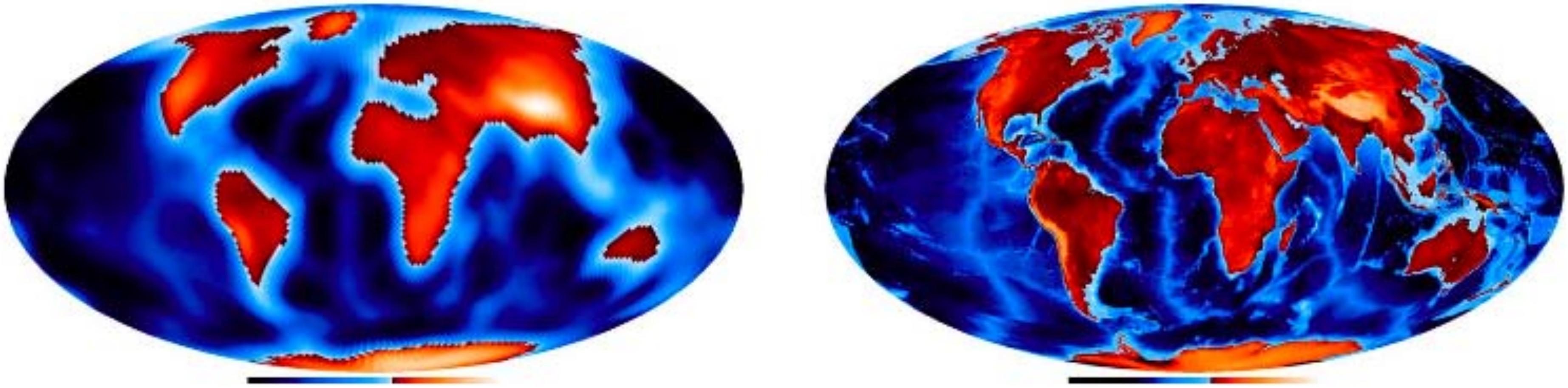
COBE–DMR 4–Year PE–Filtered Sky Maps

K.M. Górski 1996
Proceedings of the XXXIst Recontres de Moriond

CMB from Space - Great Discovery Era Unfolds …



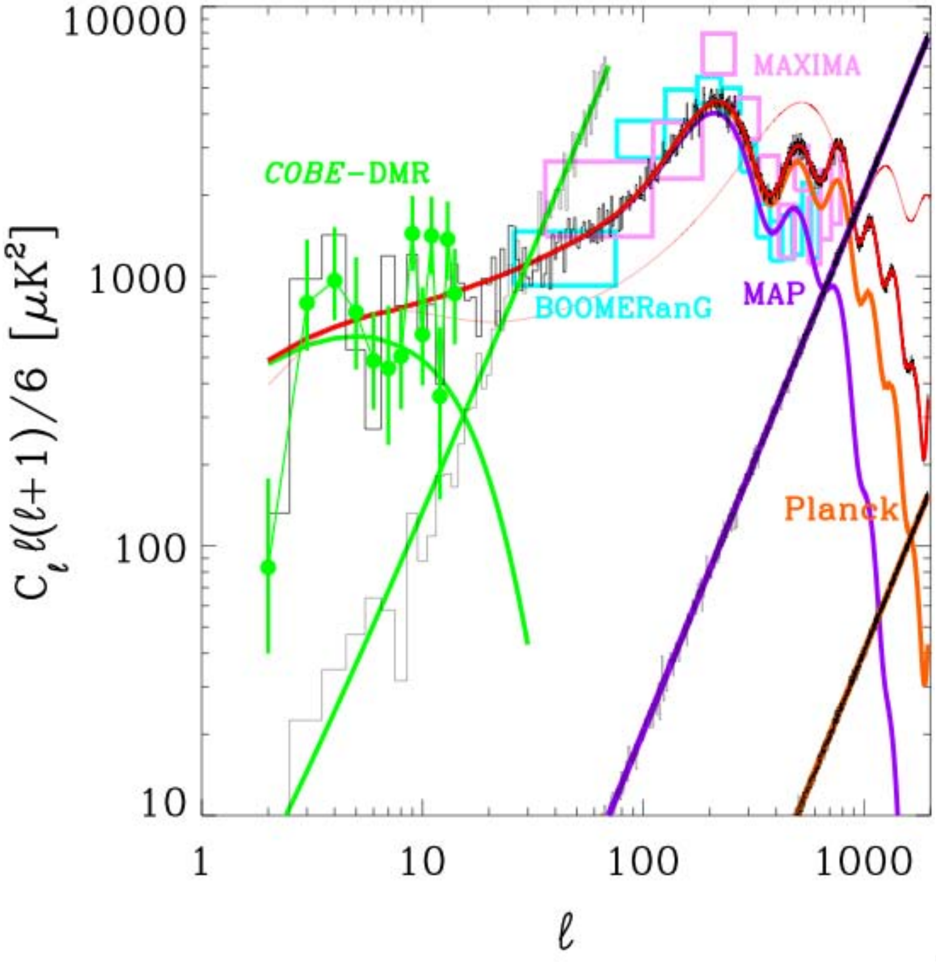
After COBE - We wanted more …

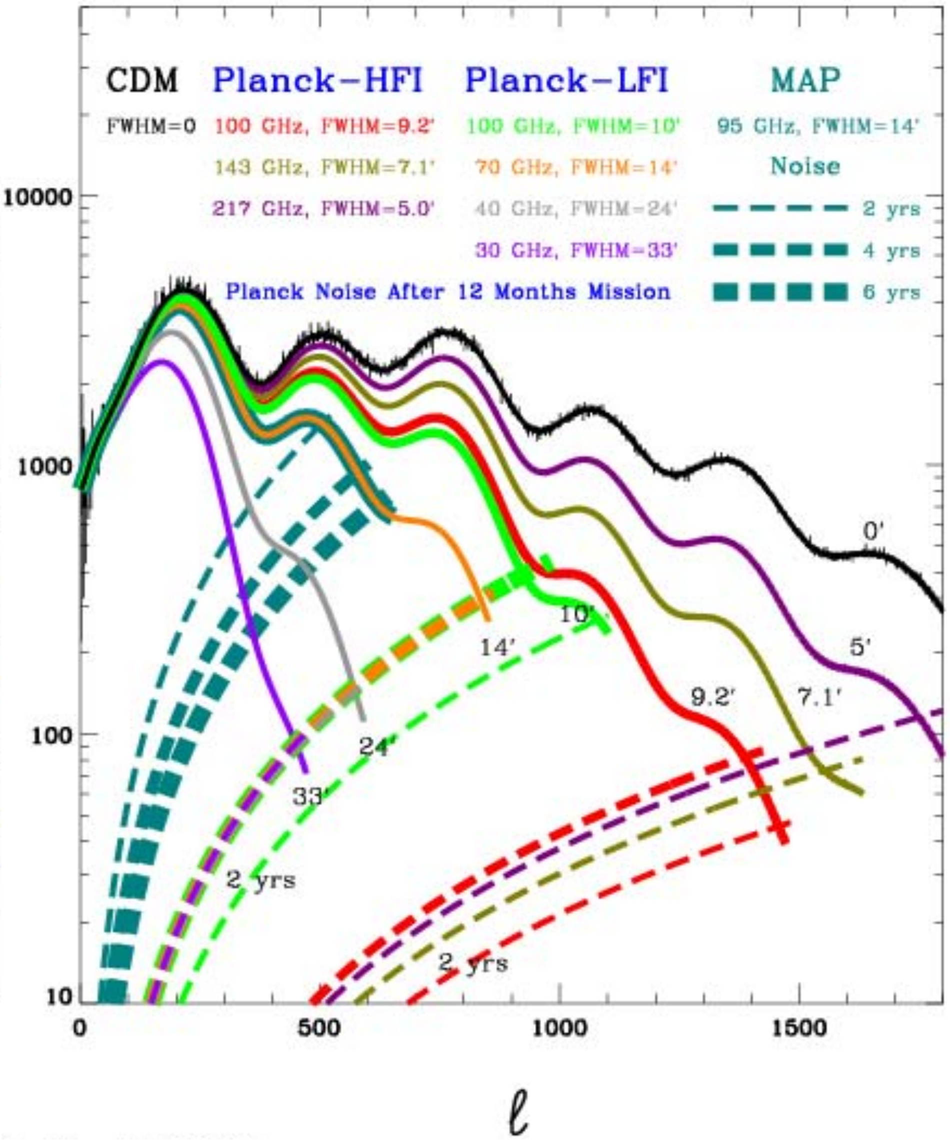


COBE made us want more …

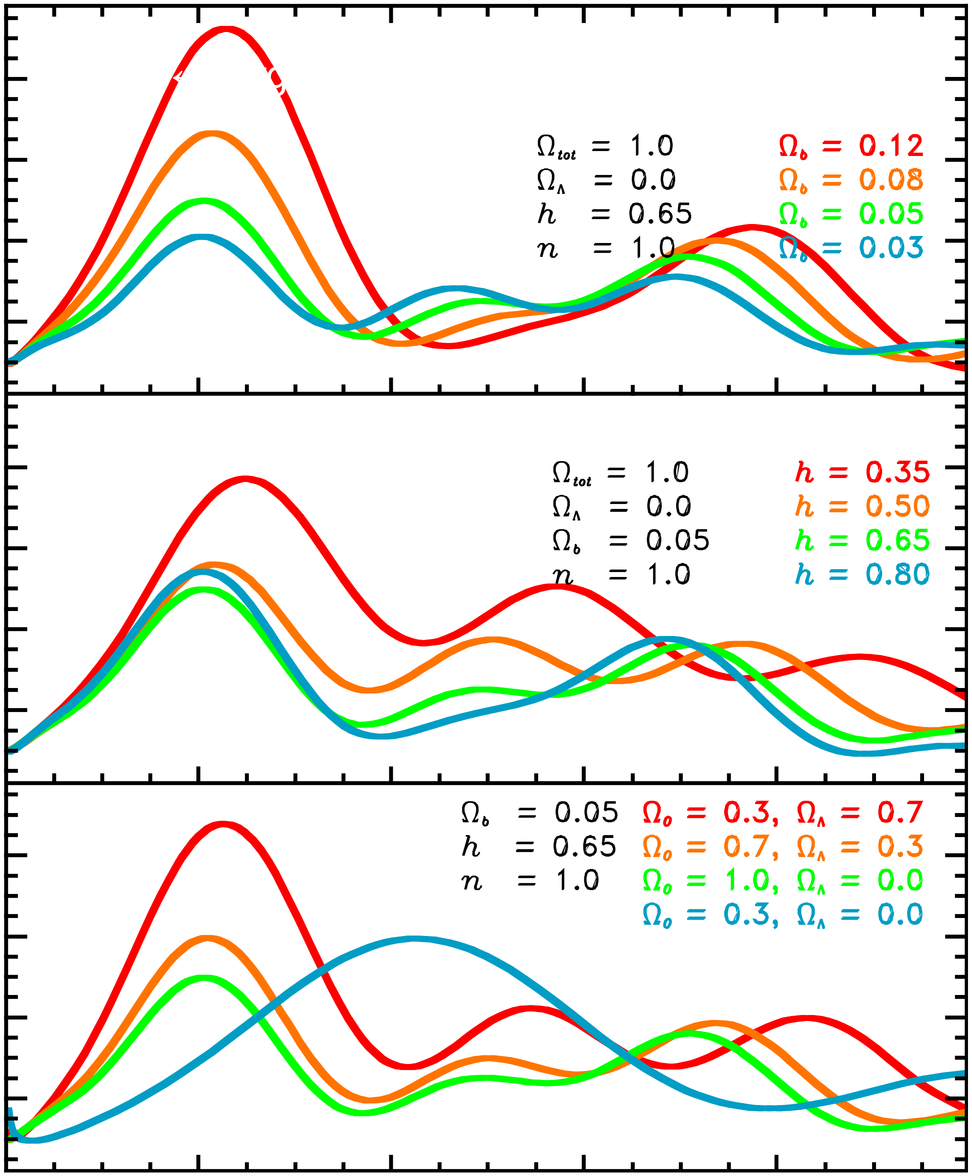
Looking Forward to Planck

- **What was required to make progress?**
  - Much more angular resolution
  - Much less noise





CMB Power Spectra: Where Theory and Data Meet



CMB temperature fluctuations on small angular scales (< 2 deg) depend strongly on cosmological parameters - hence, the anisotropy measurements can be used to determine the values of parameters that describe the observable universe.

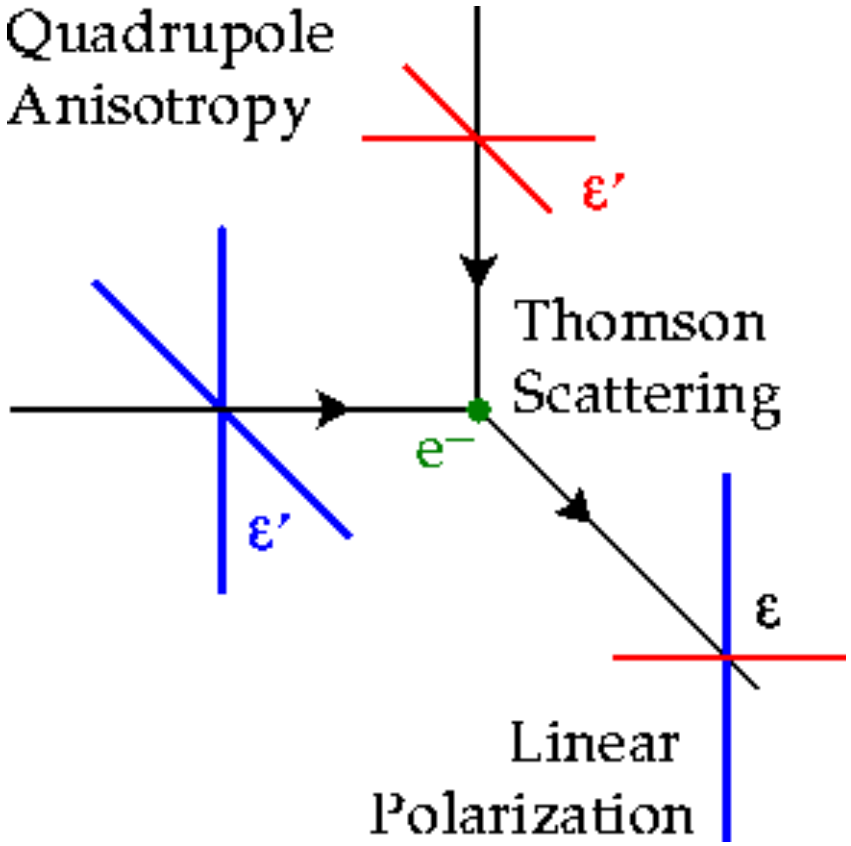
Polarization

In the presence of anisotropy we expect scattering to generate (linear) polarization.

Polarization provides a prediction, a cross-check and further information about conditions at last-scattering and reionization.

Rees (1968)

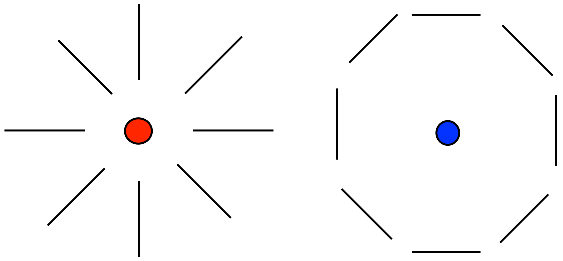
Kaiser (1983)



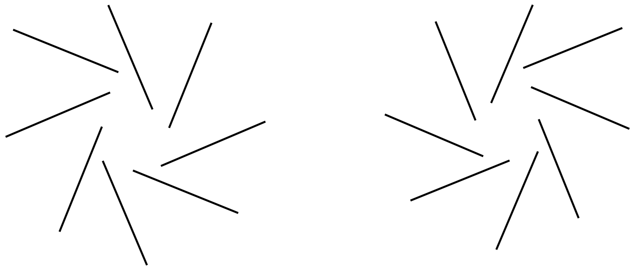
Hu & White (1997)

E- and B-modes

Polarization is made up of two “modes”, referred to as E- and B- modes because of their global parity properties.



E-modes



B-modes

Note that E-modes have no handedness, whereas B-modes do

and thus cannot be generated by scalar (density) perturbations.

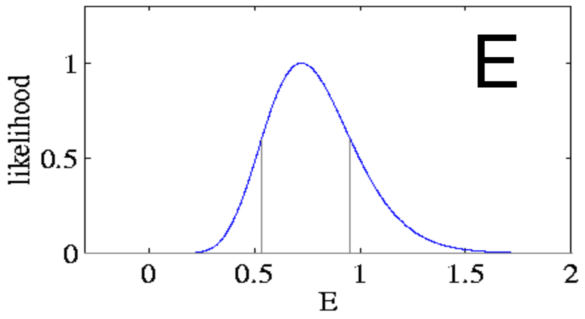
Hence, B-mode discovery would establish the new source for

perturbations - tensor perturbations, i.e. primordial gravity waves.

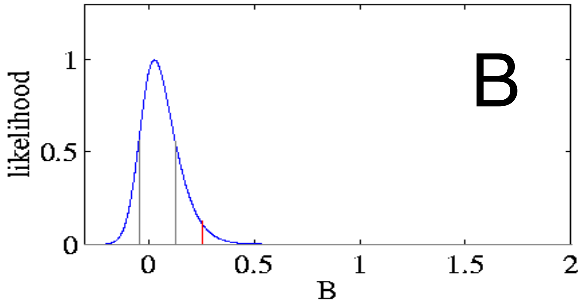
There are those who would call that “a smoking gun of inflation” …

Polarization: first detection by DASI

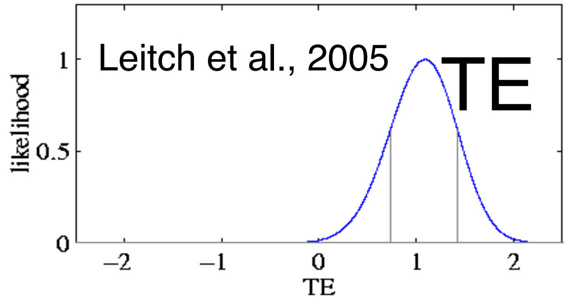
Single shaped l-bin



6.3σ detection consistent with theory.

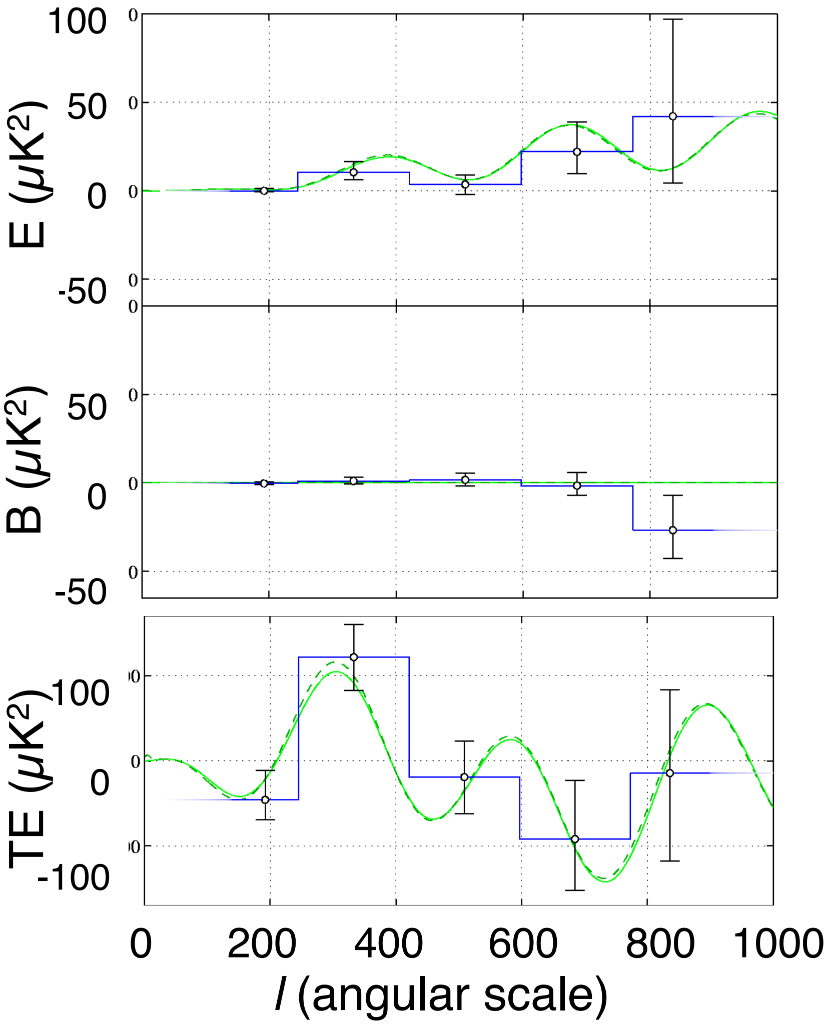


Consistent with zero (theory)



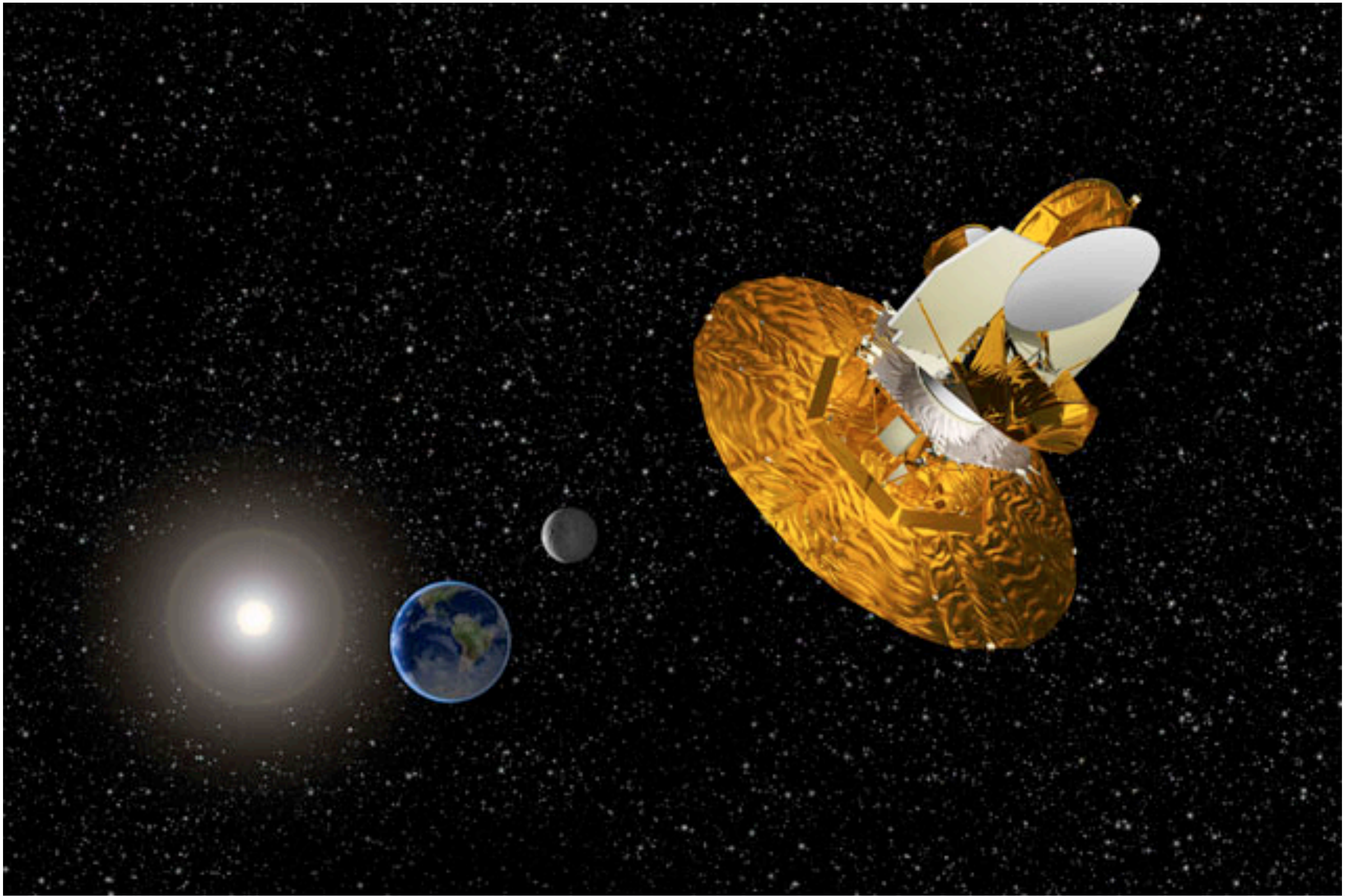
2.9σ detection consistent with theory

Five l-bins

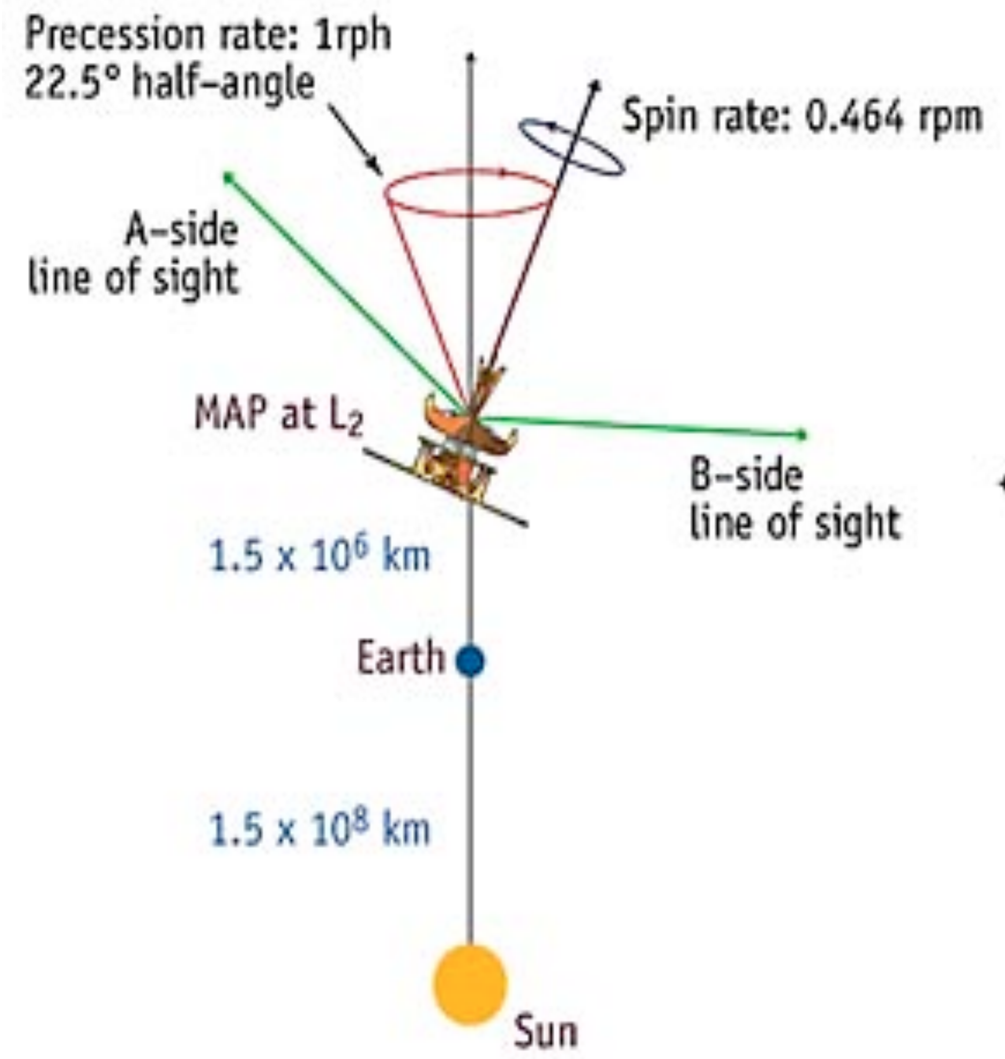


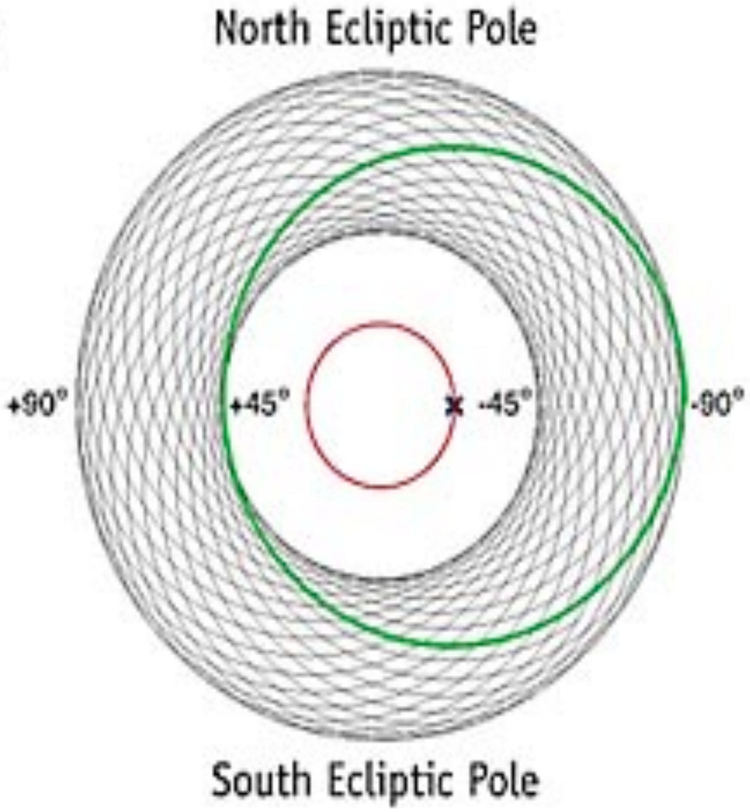
WMAP

WMAP in orbit at L-2

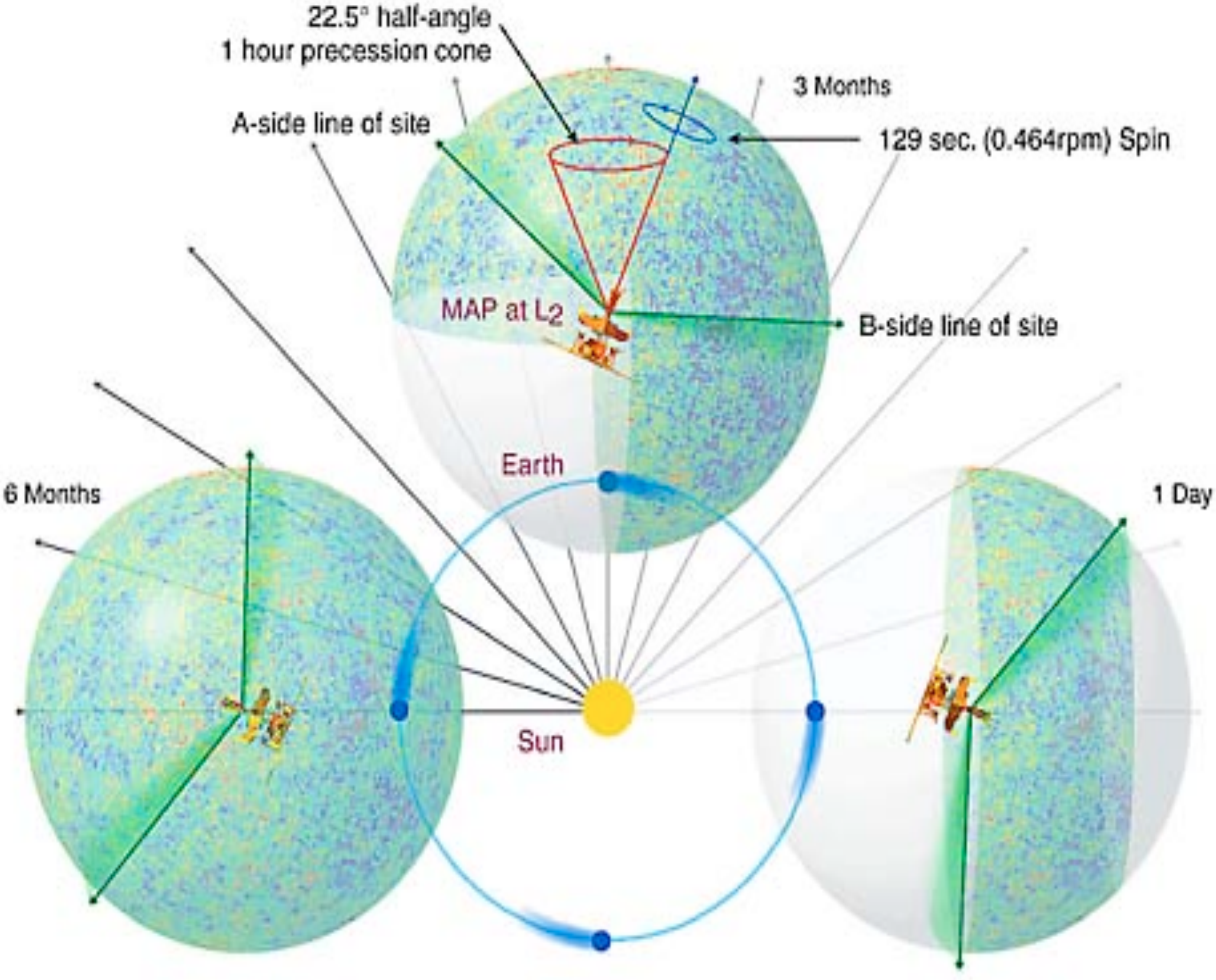


WMAP scanning specifications



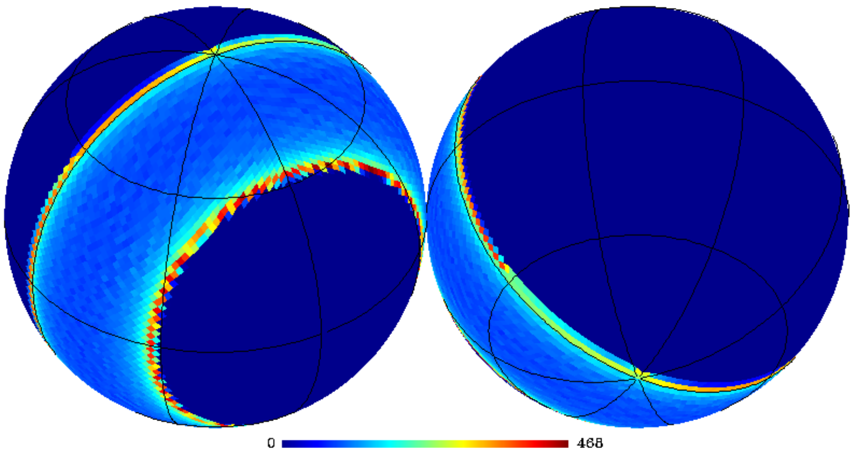


WMAP scanning II.

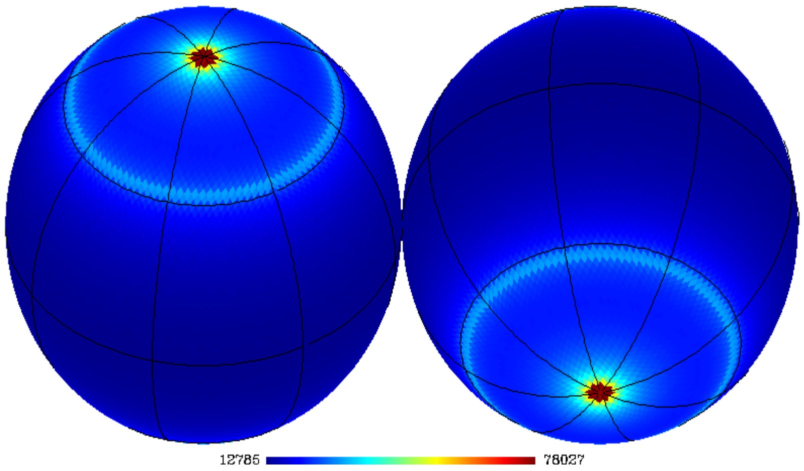


WMAP Scanning III.

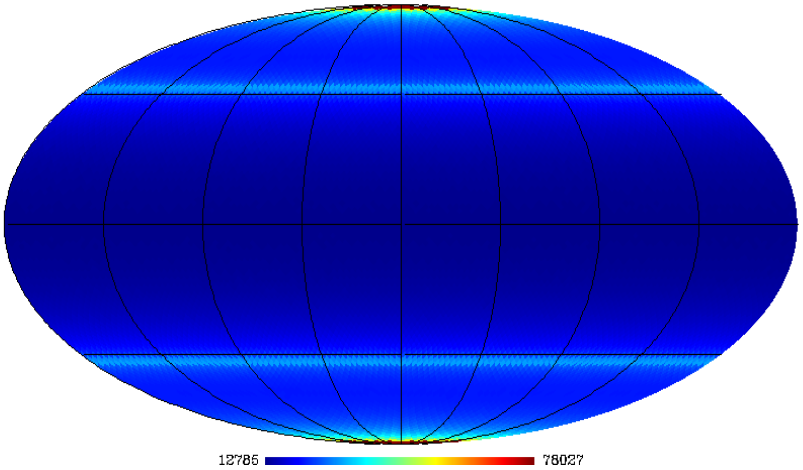
WMAP 1day



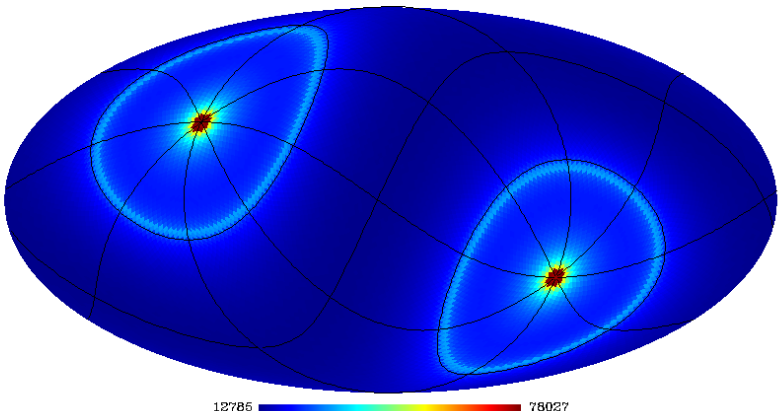
WMAP 1yr



WMAP 1yr



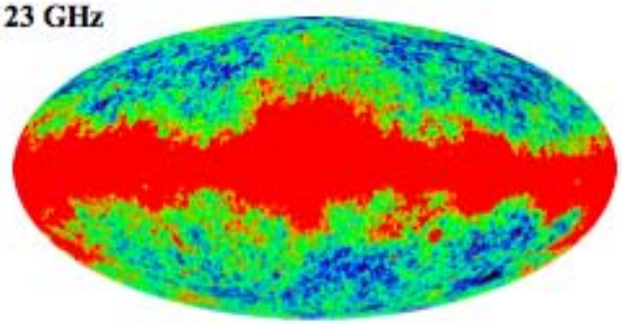
WMAP 1yr



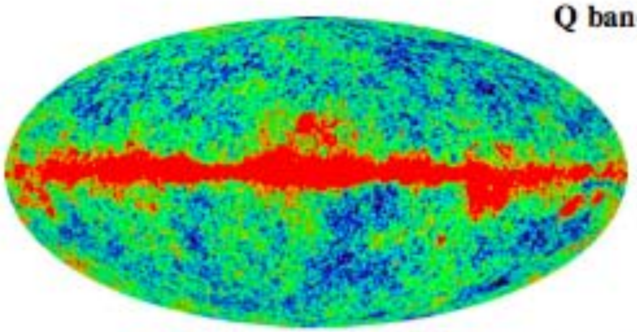
WMAP Sky Maps

Courtesy of the WMAP Science Team

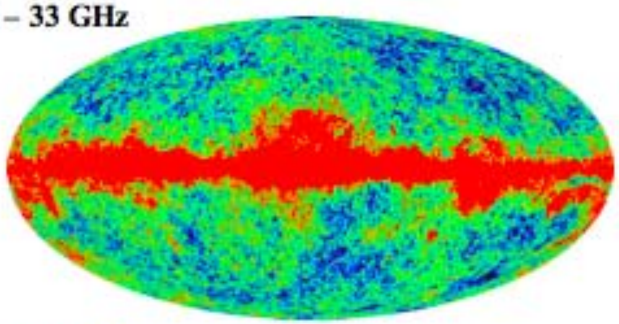
K band – 23 GHz



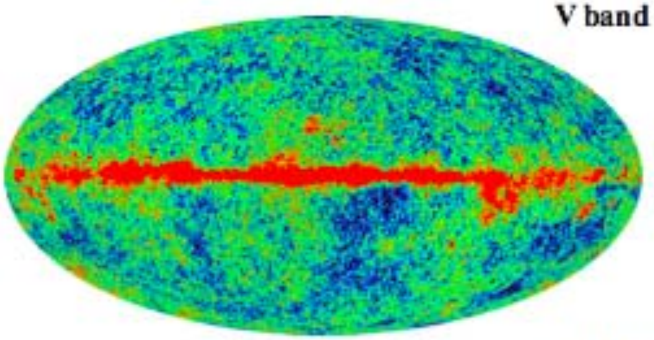
Q band – 41 GHz



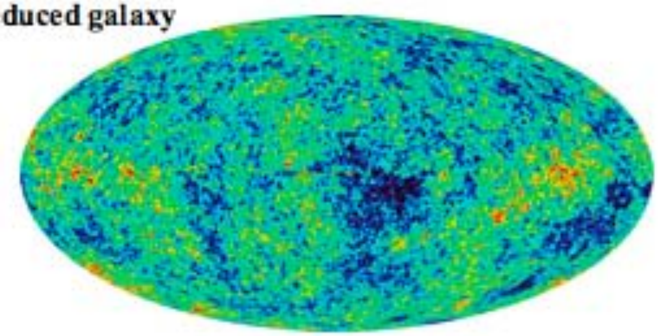
Ka band – 33 GHz



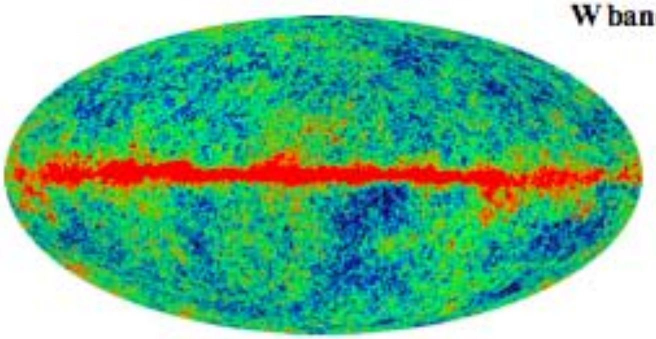
V band – 61GHz



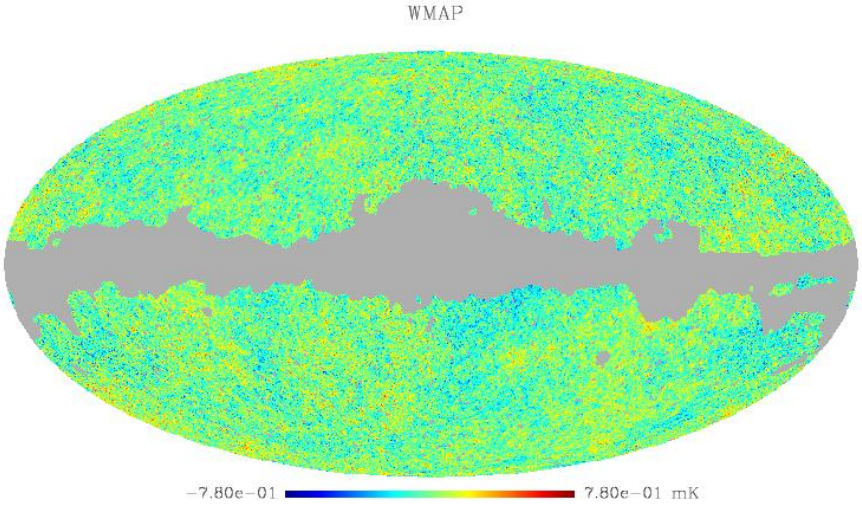
ILC reduced galaxy

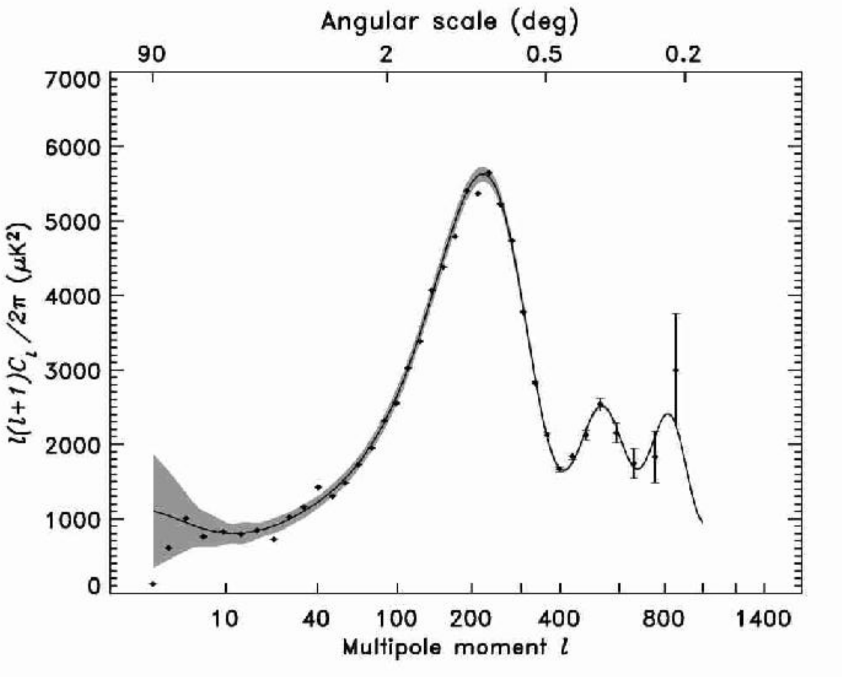


W band – 94 GHz



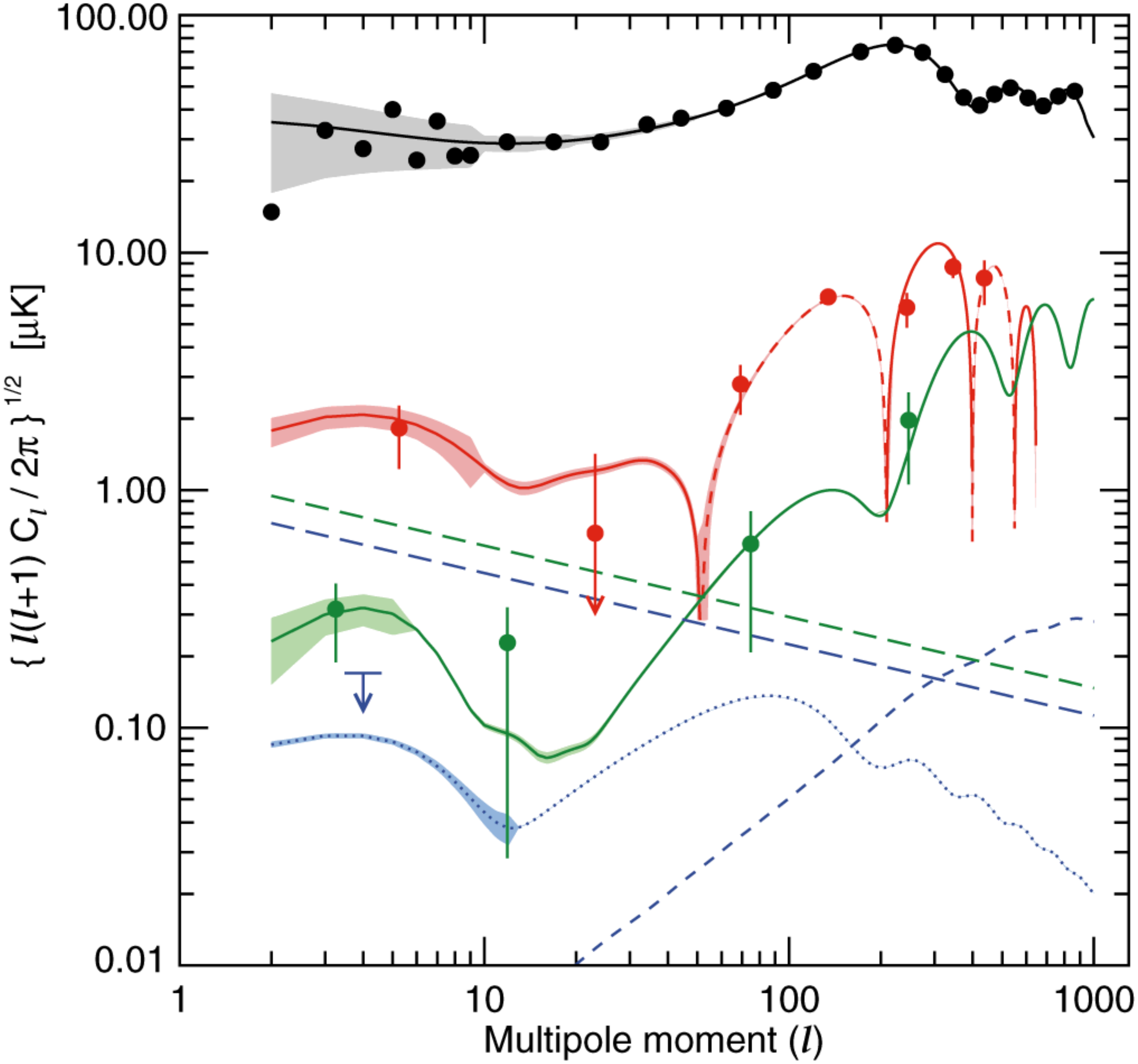
Post-COBE Dream that Came True





- It appears that the cosmological model has already been defined fairly tightly
- Is it, therefore, possible that what is left to be done is “just”
  - – Refinement, refinement, refinement ???
    - ➢ For example, with Planck, and with polarization measurements, etc.

Current WMAP <TT>, <TE>, & <EE> Spectra



Unbinned WMAP Spectrum from Spergel et al. 2003

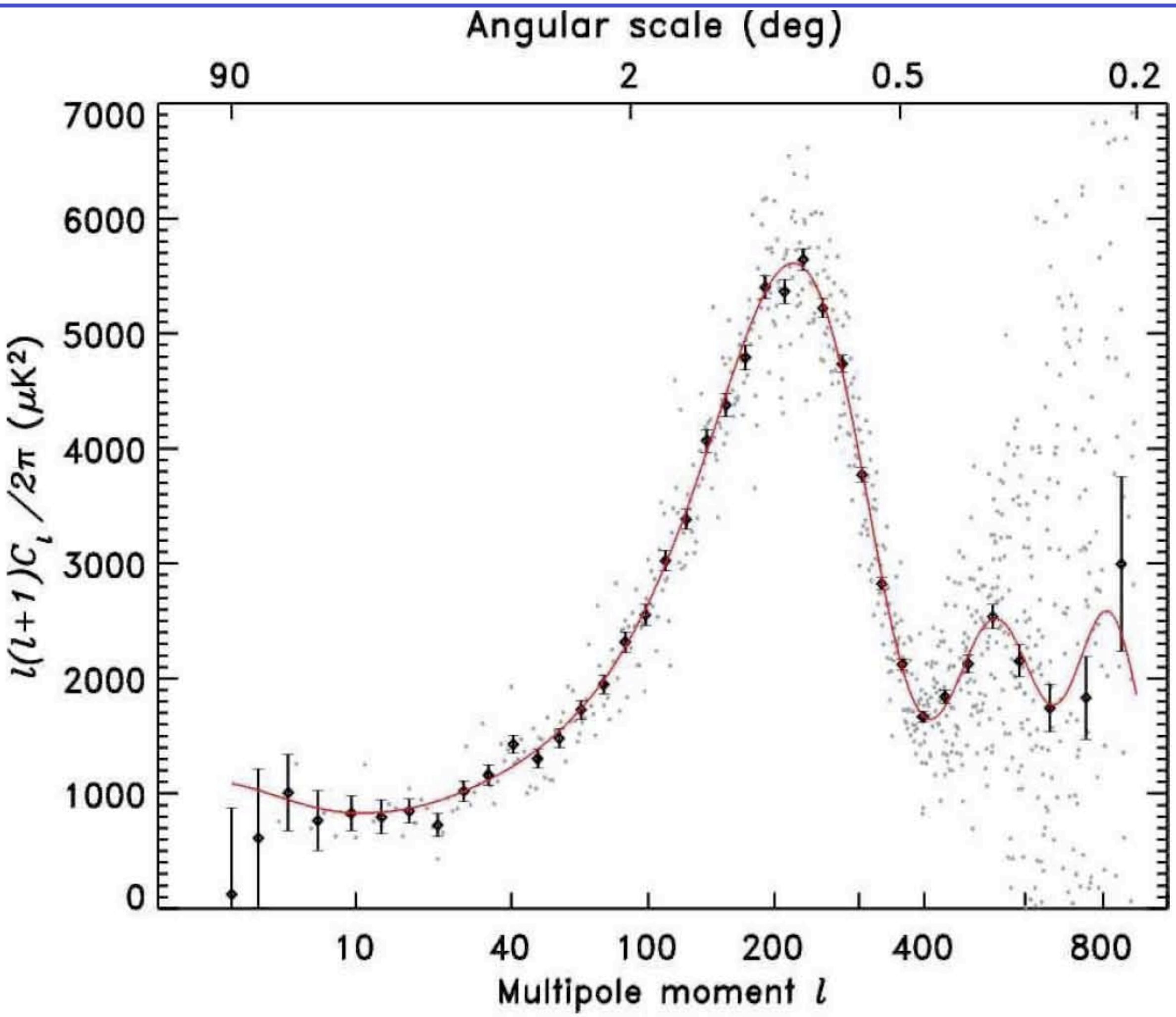
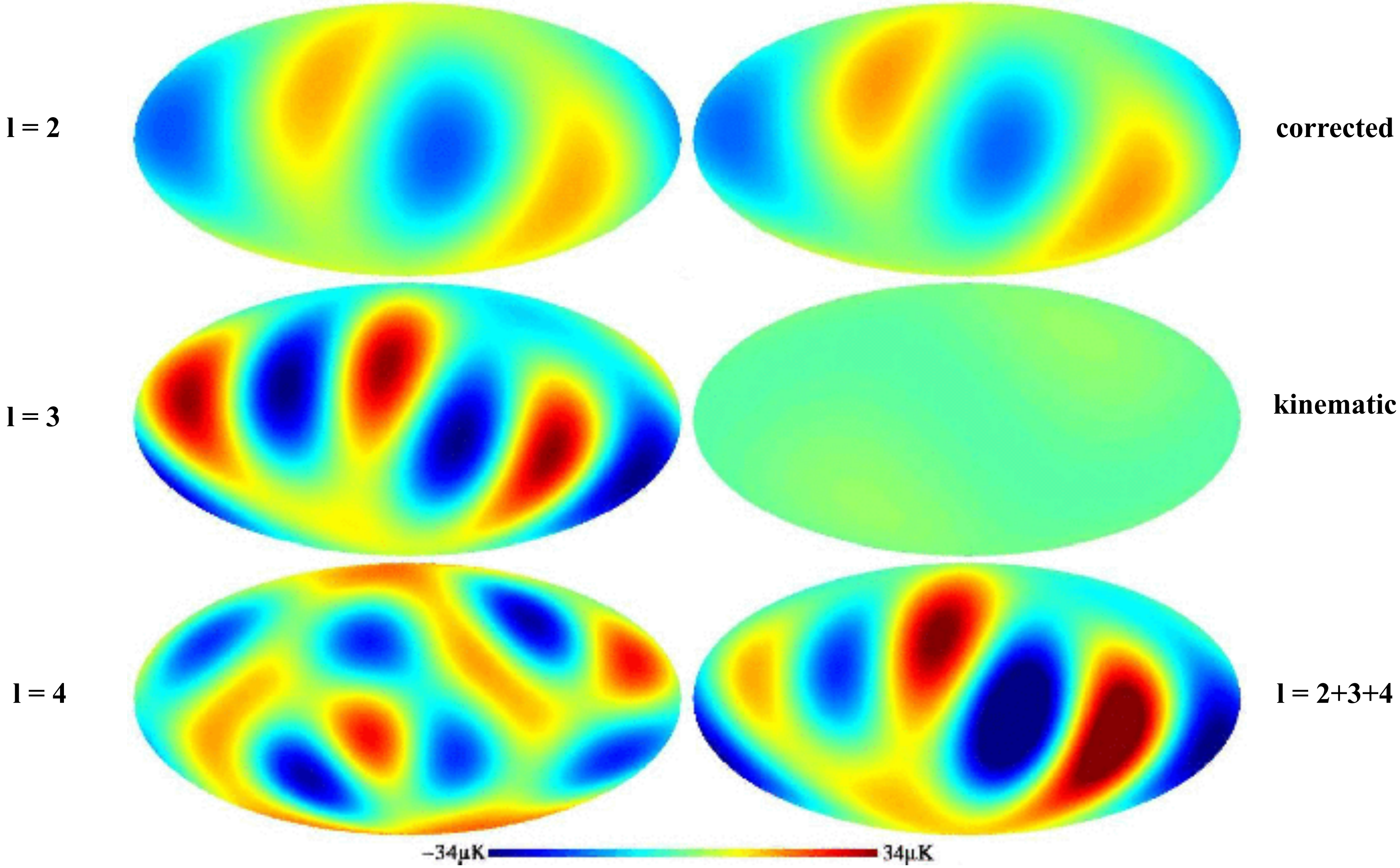


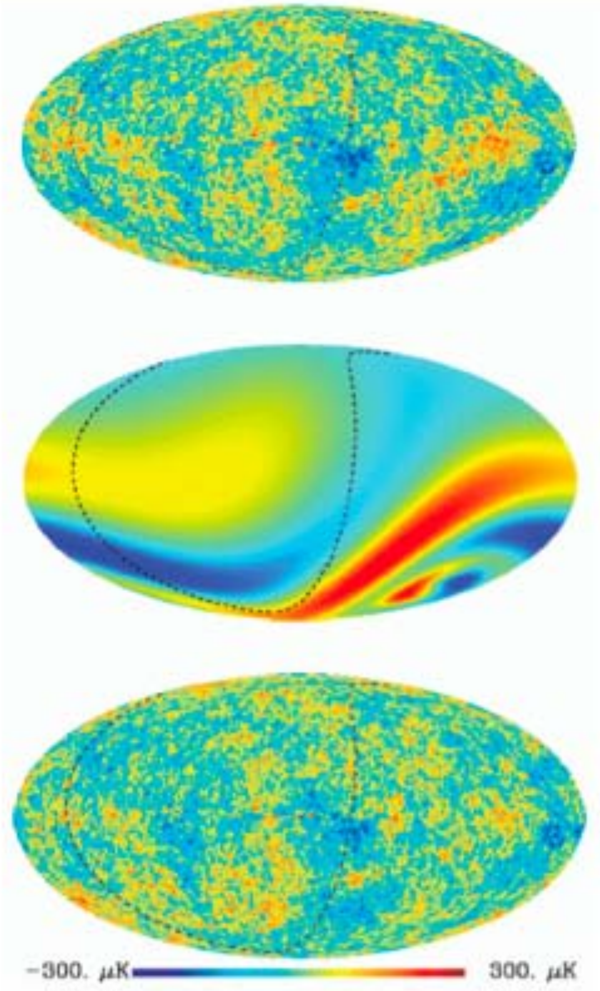
Fig. 1.— This figure compares the best fit power law ΛCDM model to the *WMAP* angular power spectrum. The gray dots are the unbinned data.

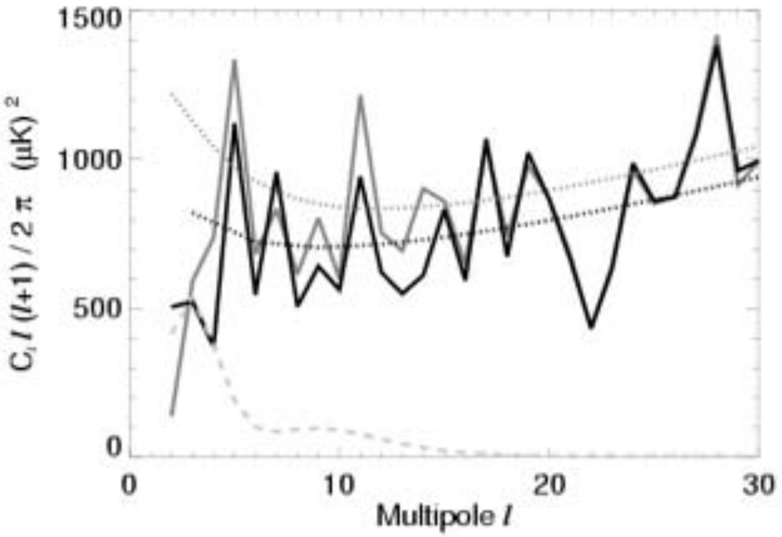
WMAP Anomalies - Mode alignment



Tegmark et al. *PRD,* 68, 123523 (2003)

Violation of Global Isotropy?





Shear $(\sigma/H)_0 = 4.3 \times 10^{-10}$

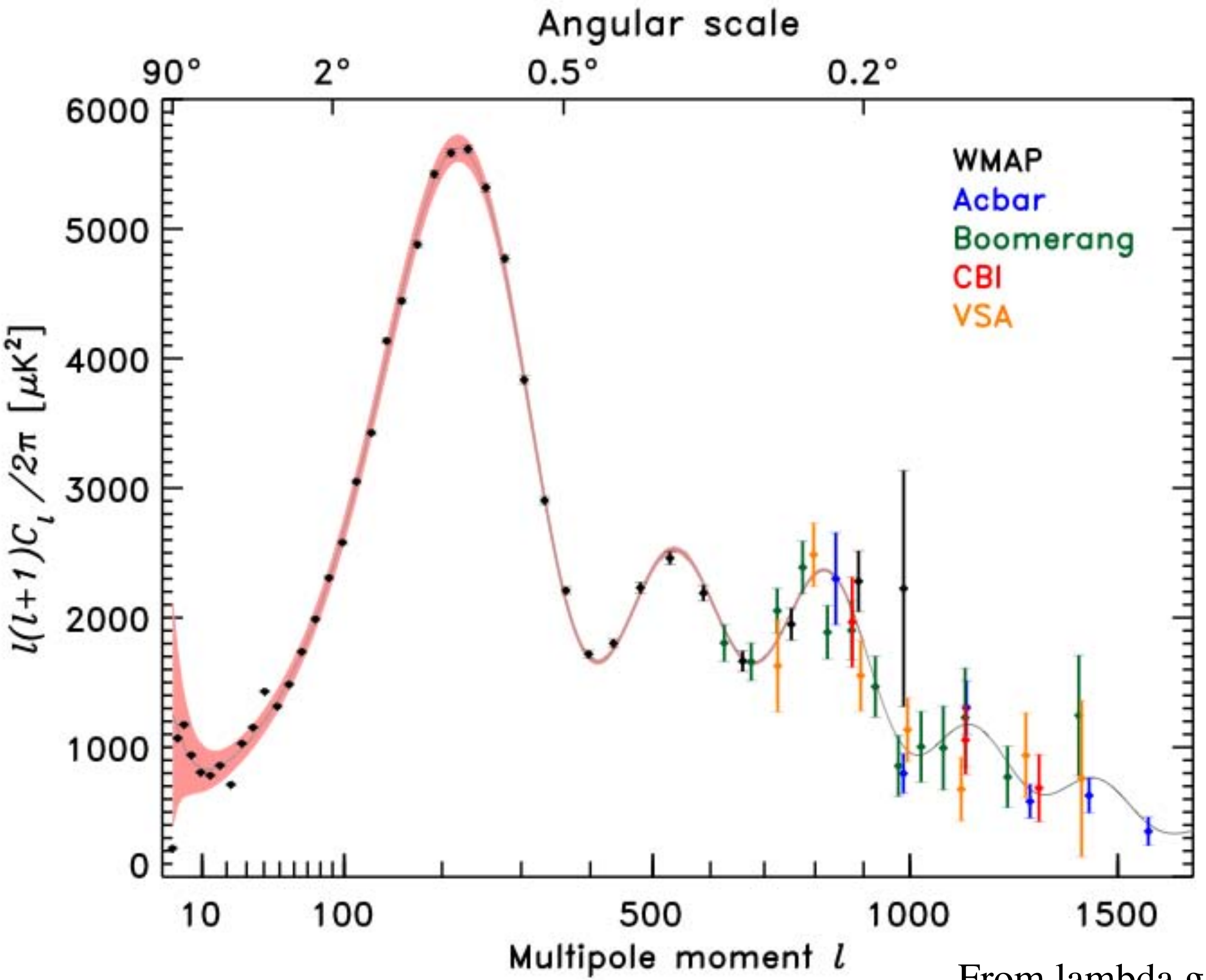
Vorticity $(\omega/H)_0 = 9.5 \times 10^{-10}$

Spiral axis {l,b} = {222,-62}

BUT $\Omega_0 = 0.5$!

Jaffe, Banday, Eriksen, Gorski, Hansen, 2005. ApJL, 629, 1

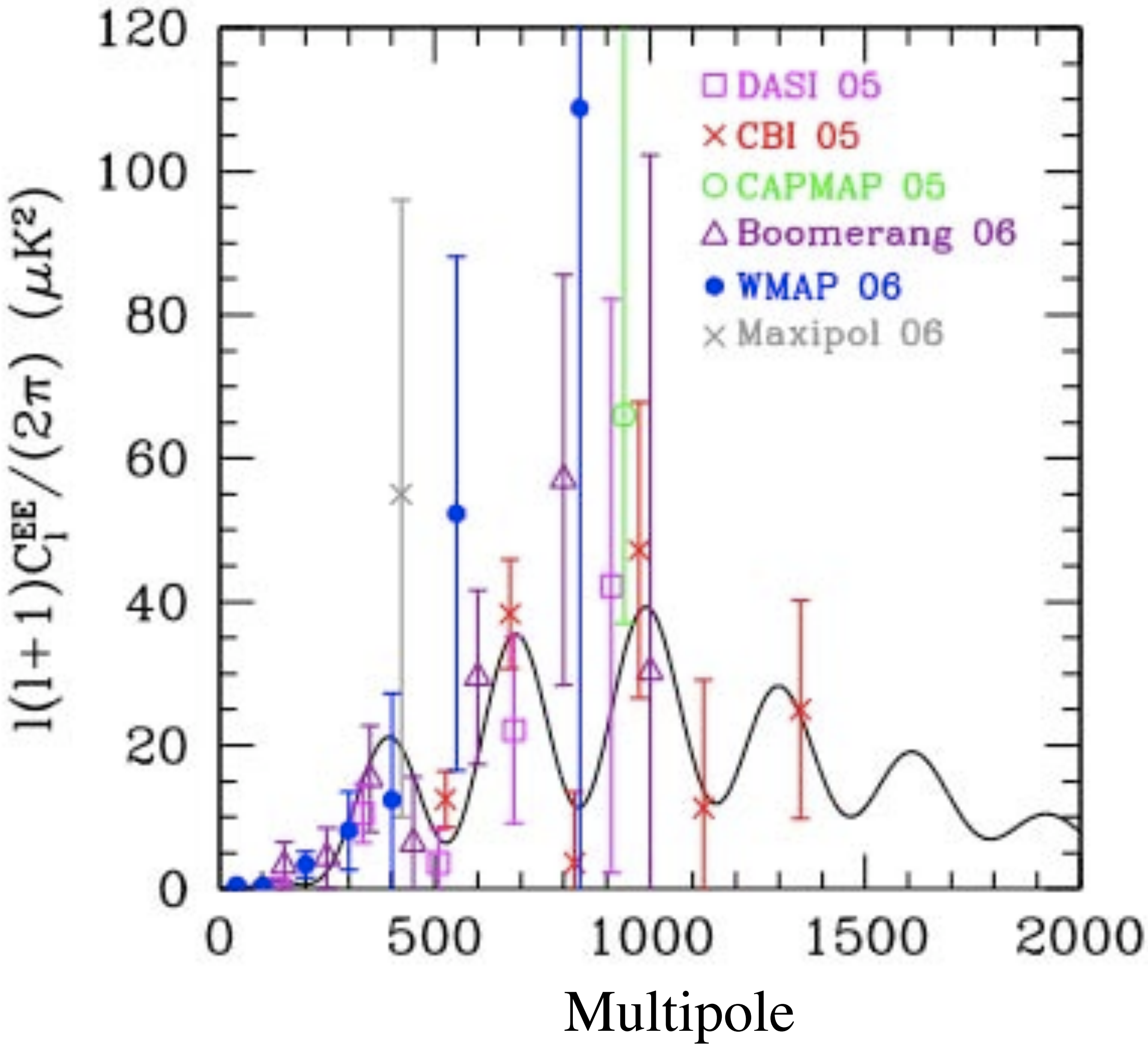
Current state-of-the-art



From lambda.gsfc.nasa.gov

The world compilation of CMB polarization measurements

Courtesy Lewis Hyatt

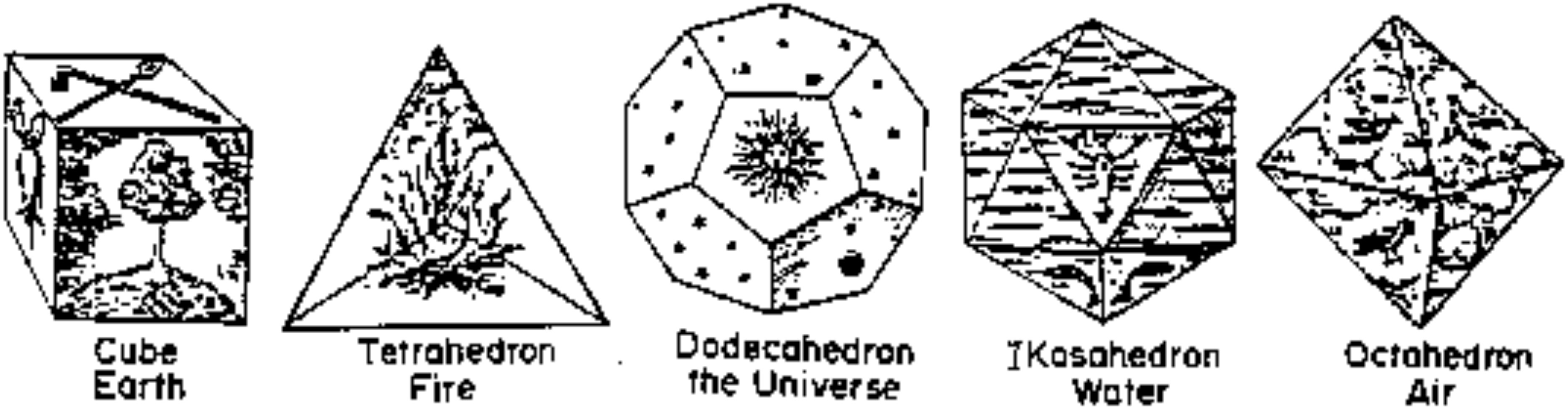


Intermission

HEALPix

5 Platonic Solids

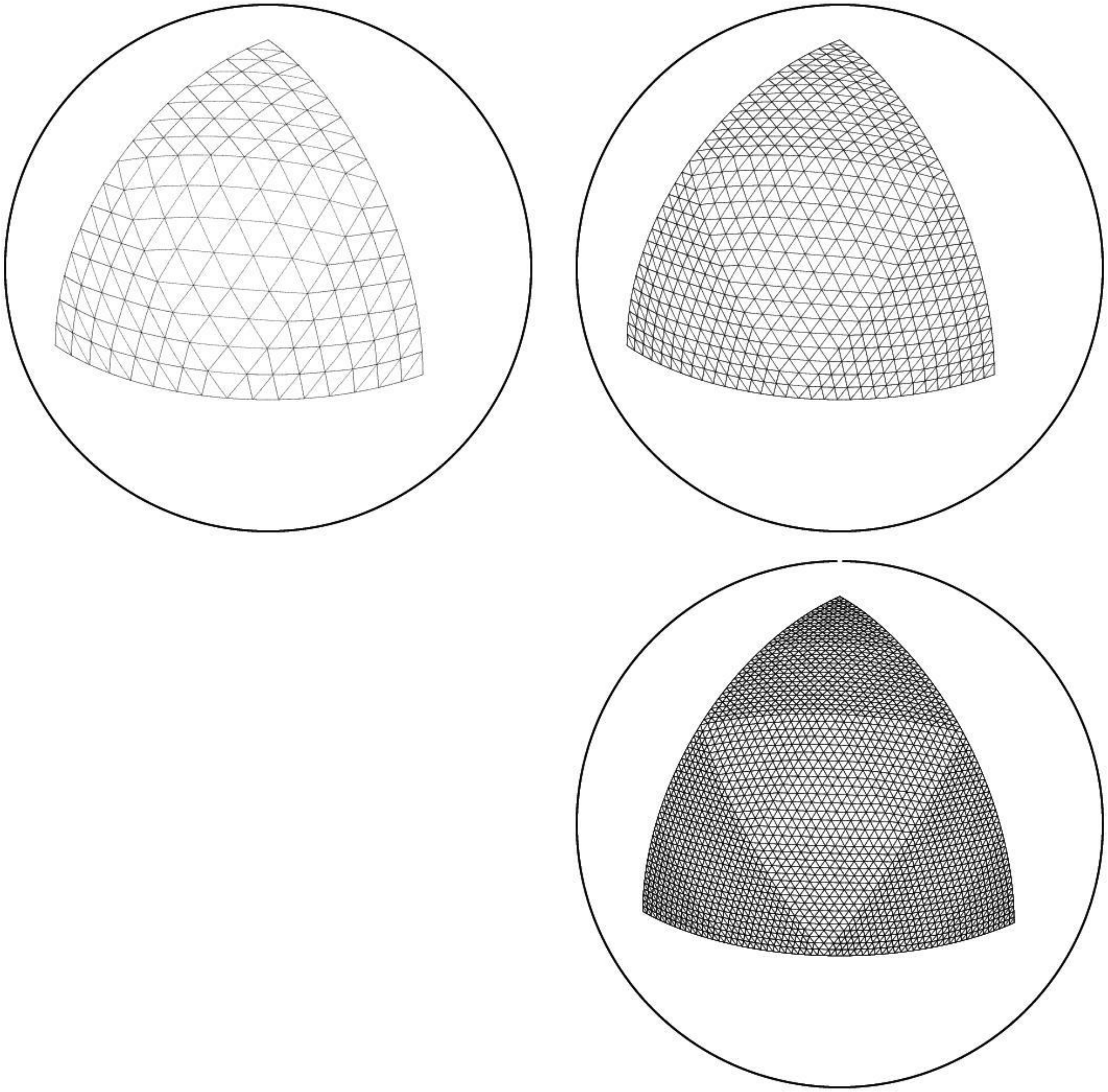
- **Drawing from Kepler's Mysterium Cosmographicum**



Icosahedral Dome, Epcot Center, Disneyworld, Florida

HTM
Hierarchical Triangular Mesh

Used extensively in SDSS

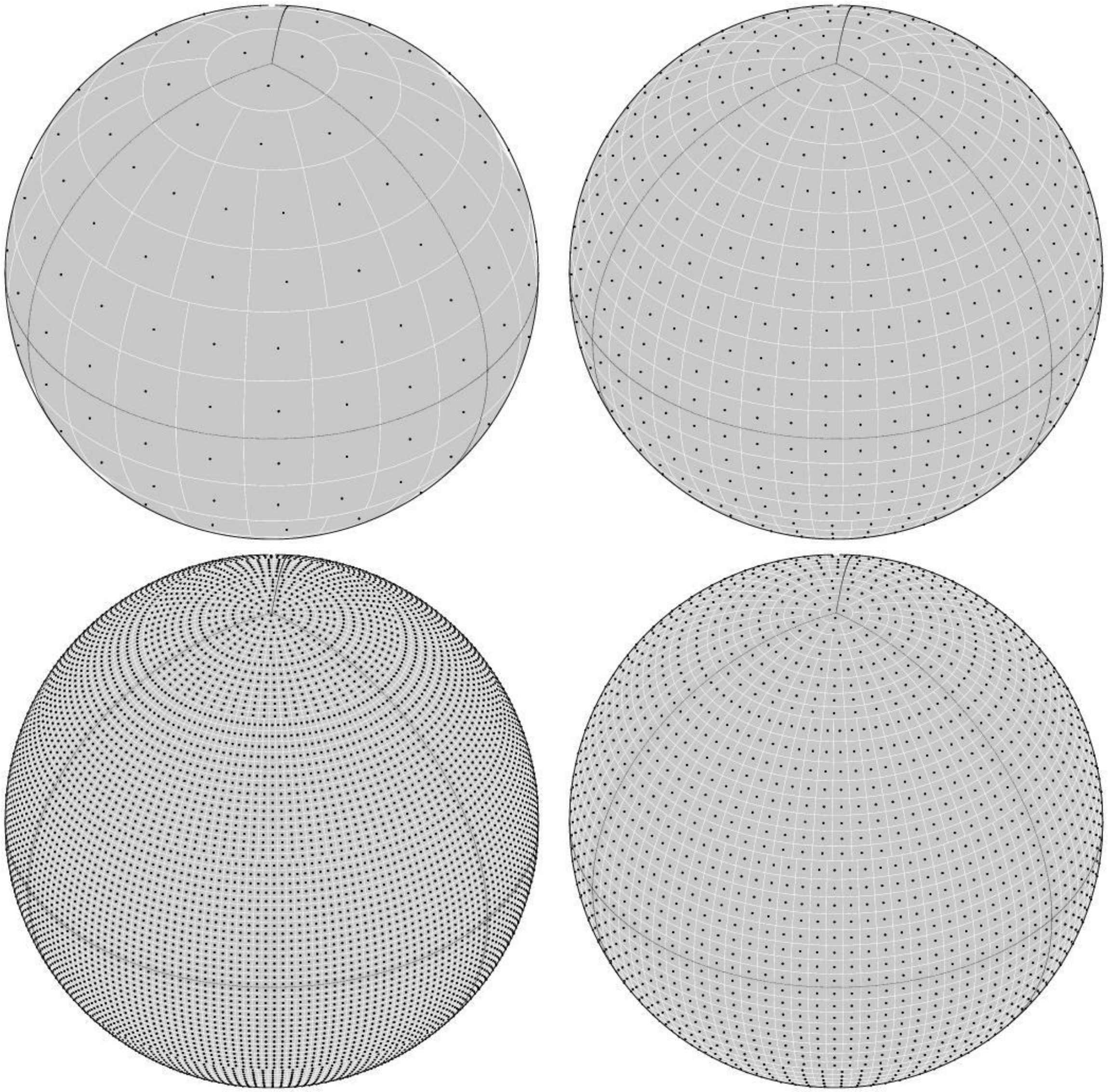


Discoball

- Used extensively in discos

IGLOO

Crittenden
and
Turok



Panteon, Rome

- Built in 124 AD!
- 43m dome
- The largest in the world until the XXth century!!!

The Next Four …

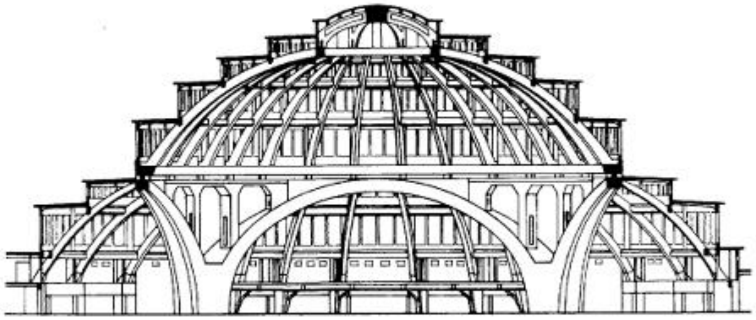
San Pietro
Rome
42m
1593 AD

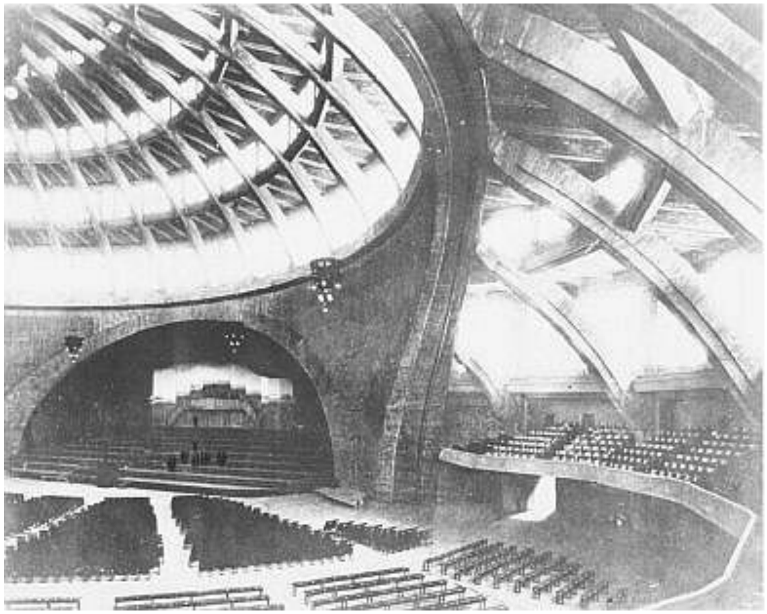
Santa Maria
del Fiore
Florence
42m
1420 AD

Hagia Sophia
Istanbul
32m
537 AD

St. Paul’s
London
33m
1710 AD

Jahrhunderthalle by Max Weber, 1913, Breslau





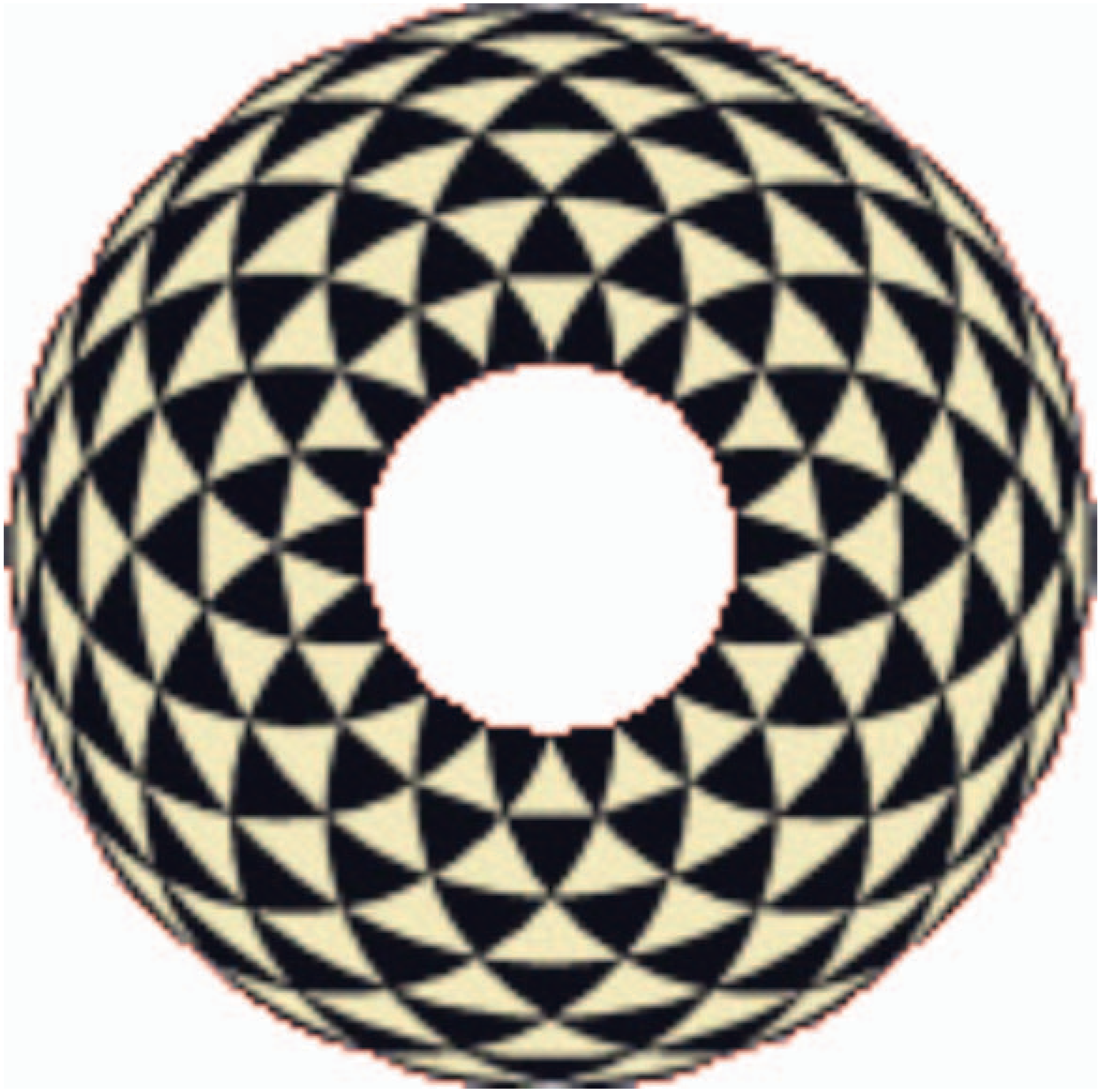
Krzysztof M. Górski

Azores School on Observational Cosmology, Angra do Heroismo, Sept. 2011

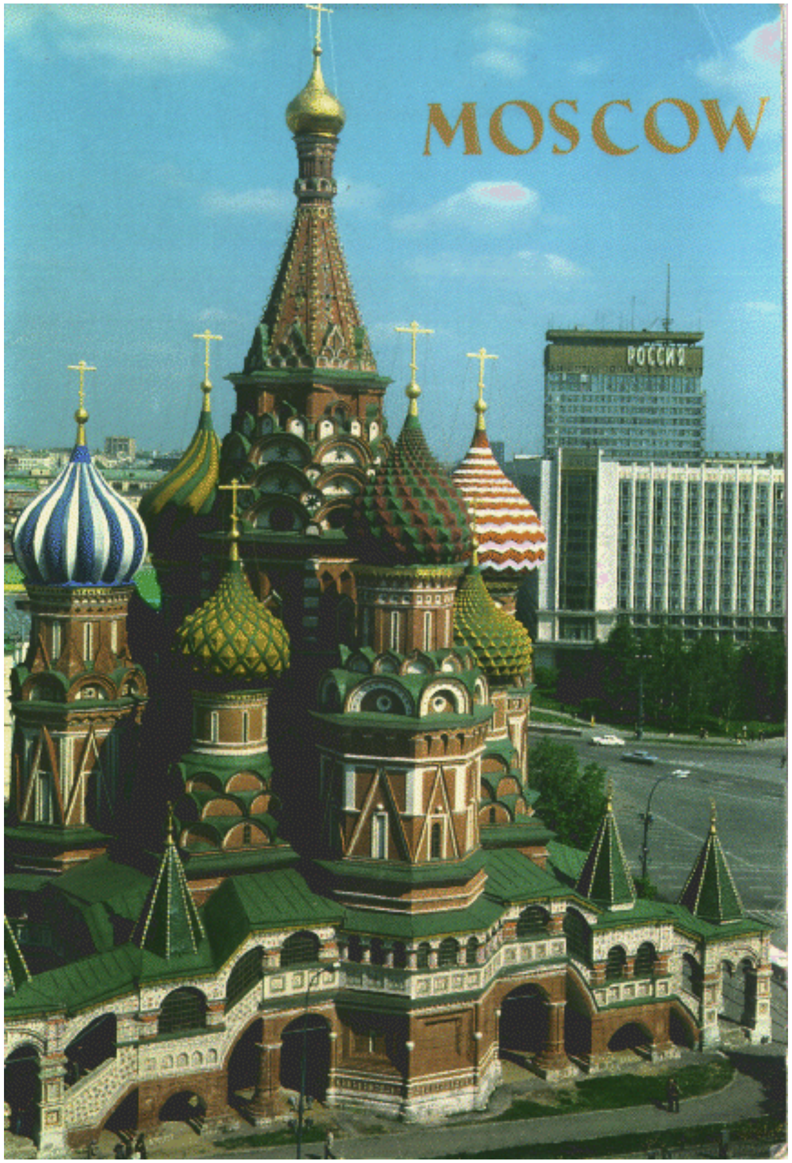
Temple of Venus and Roma

- **On Forum Romanum, across the road from Coloseum**

Roman Floor Mosaic



St. Basil, Moscow



HEALPix

- Hierarchical
- Equal Area
- Iso-Latitude
- Pixelization

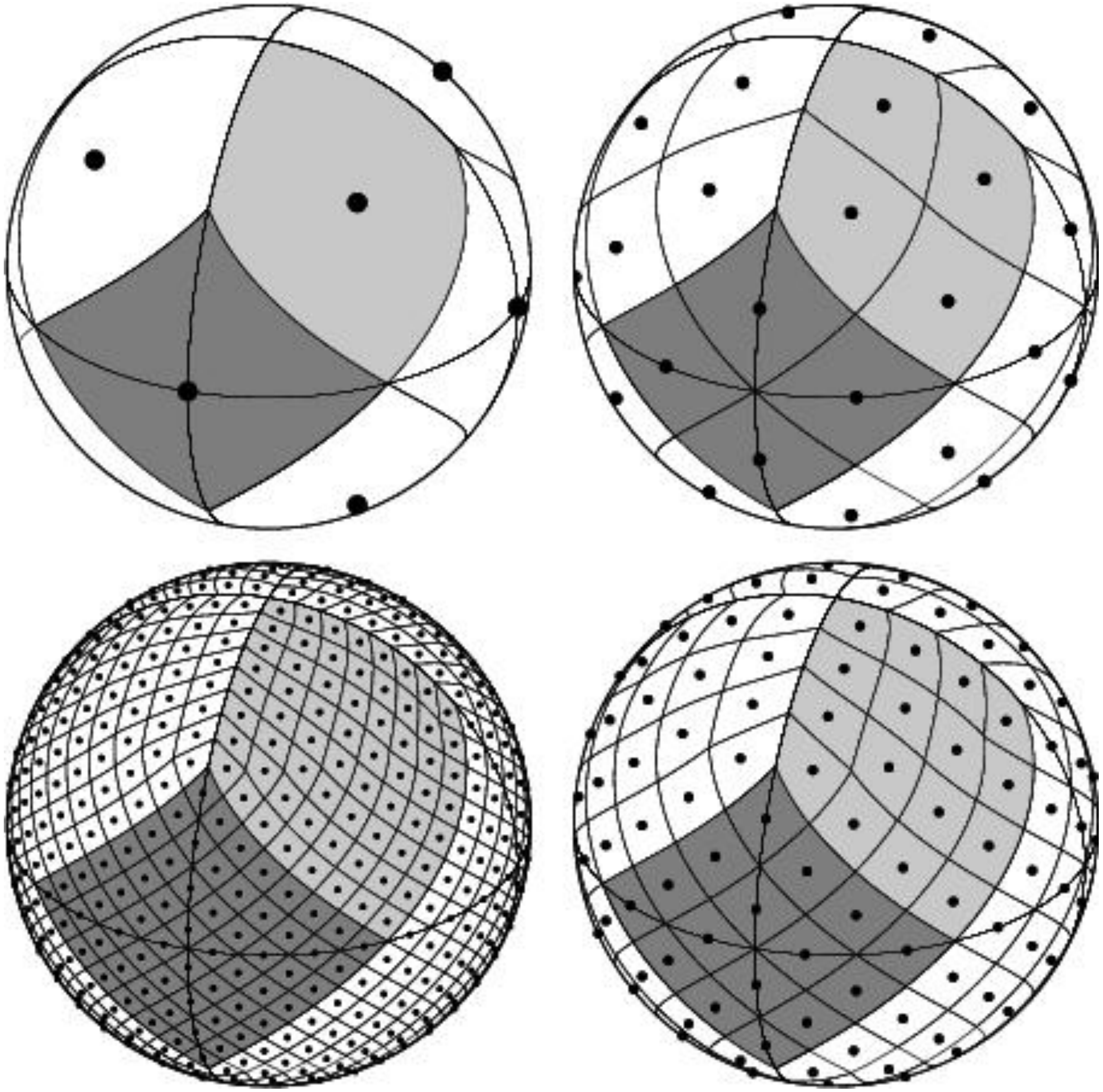
http://healpix.jpl.nasa.gov

Freely available, GNU-licensed software library (F90, C++, C, IDL) for discretization, synthesis, analysis, etc. of functions on the sphere;

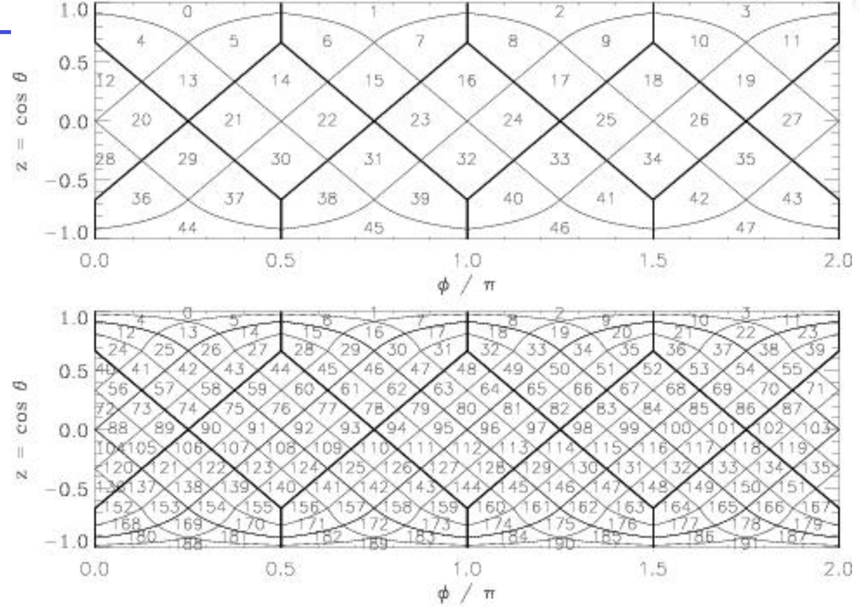
Developed and supported since 1997;

Used by WMAP and Planck; also Boomerang, Archeops, and other suborbital experiments;

Gorski, Hivon, Banday, Reinecke, Wandelt, Hansen, …

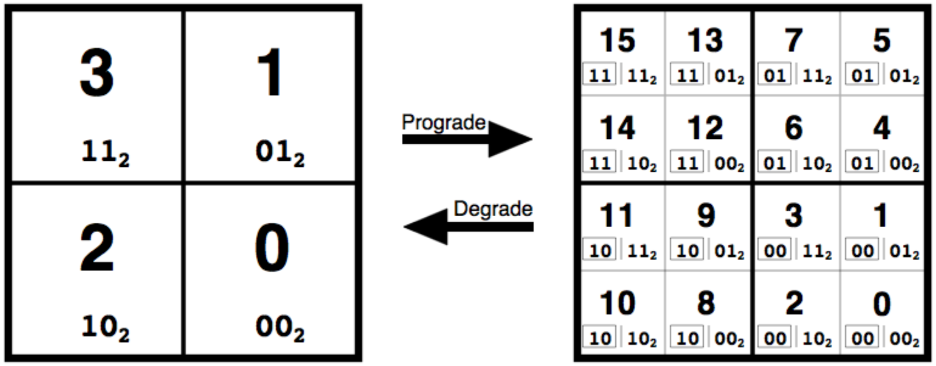


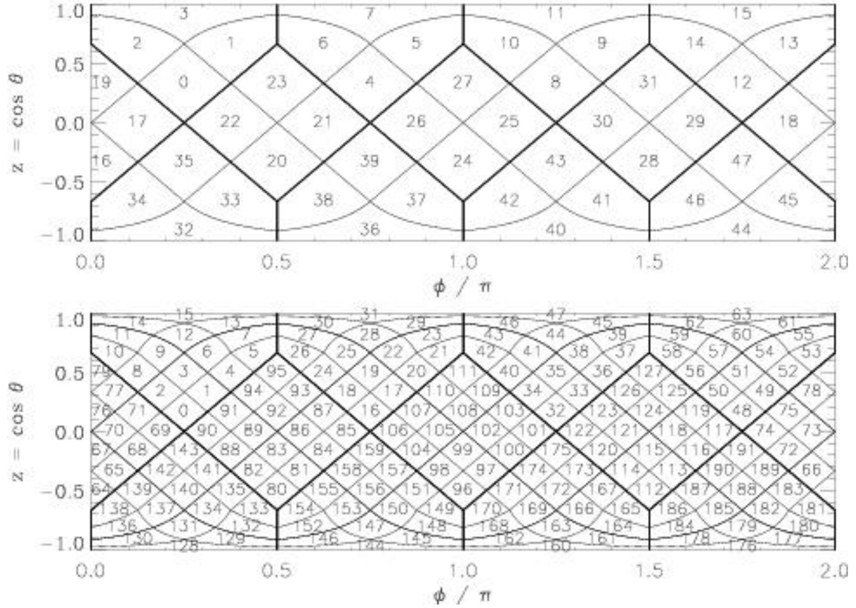
HEALPix - the Sky Map Indexing



Ring Scheme

Nested Scheme





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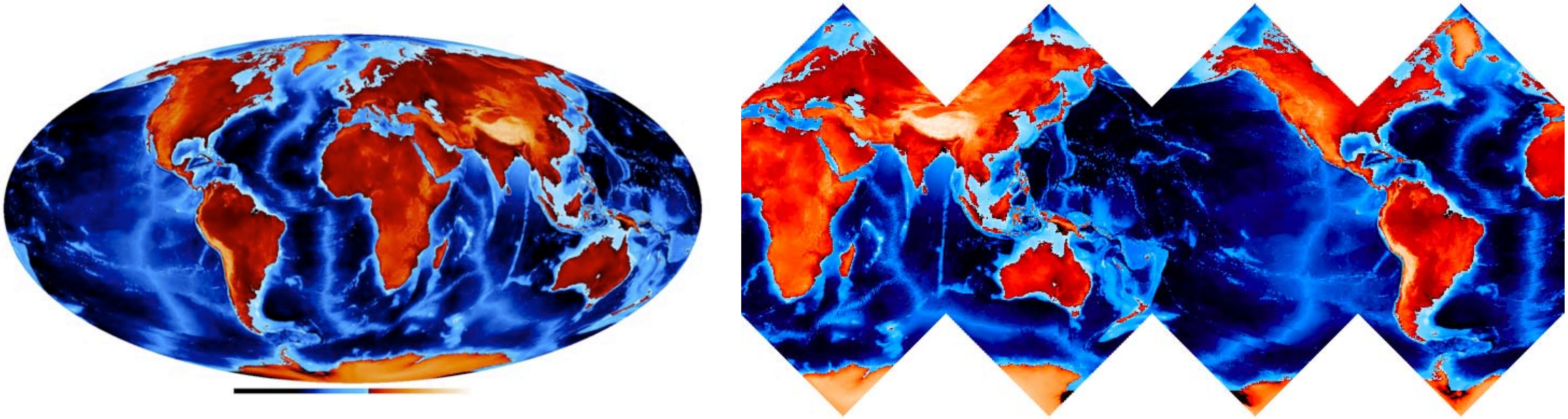
HEALPix Cartography

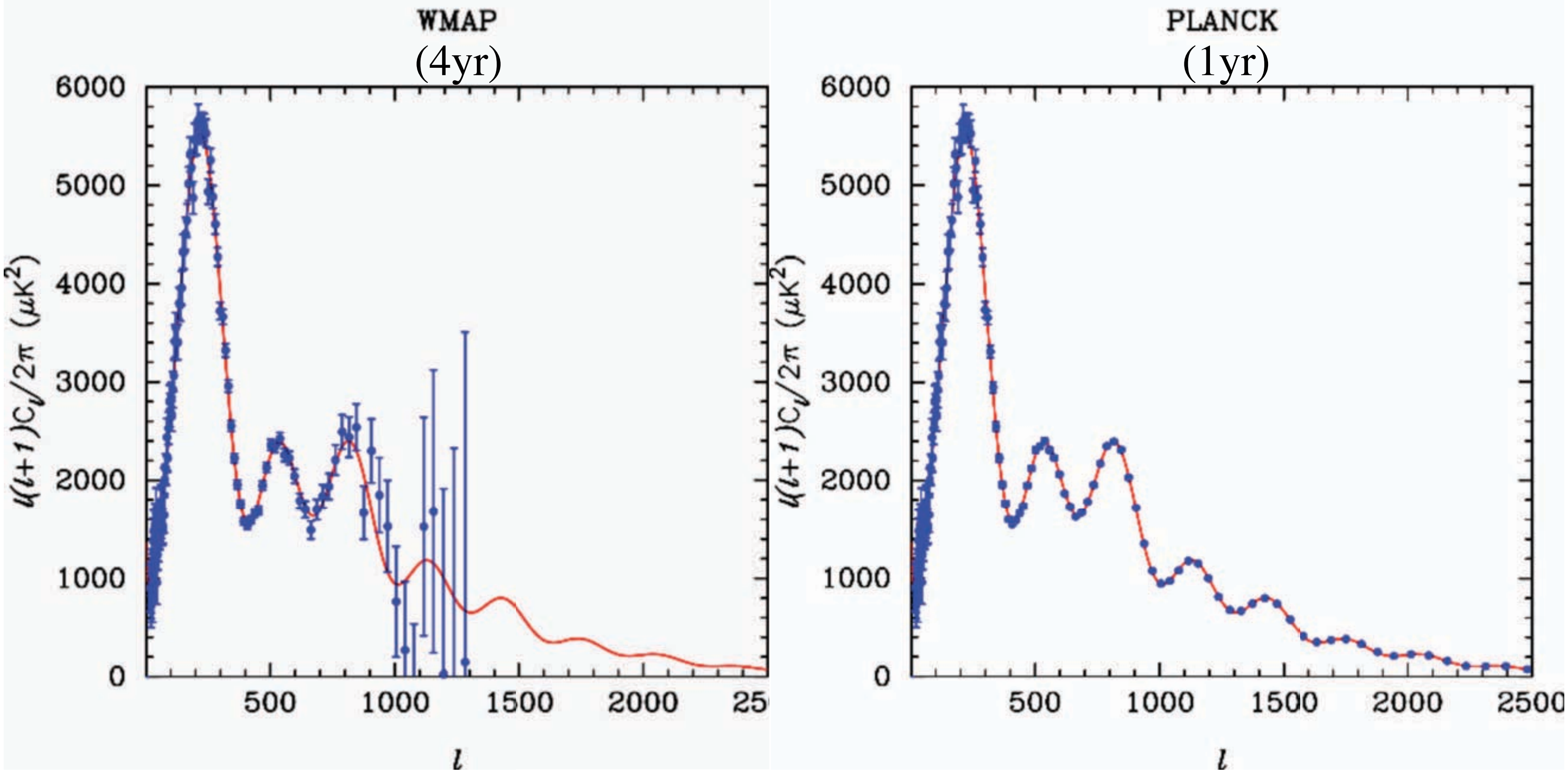


- Old subject in cartography - Flattening the Earth
- **Górski, K.M., Hivon, E., Banday, A.J., Wandelt, B.D., Hansen, F.K., Reinecke, M., Bartelmann, M.,** 2005, Ap.J., 622, pp. 759-771, “HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere”
  - Description of “HEALPix projection” from the sphere to the plane
- **Calabretta, M.R., and Roukema, B.F.,** 2007, MNRAS, 381, pp. 865-872, “Mapping on the HEALPix grid”
  - HEALPix - a hybrid of the cylindrical equal area (equatorial region), and interrupted Collignon (polar regions) cartographic projections

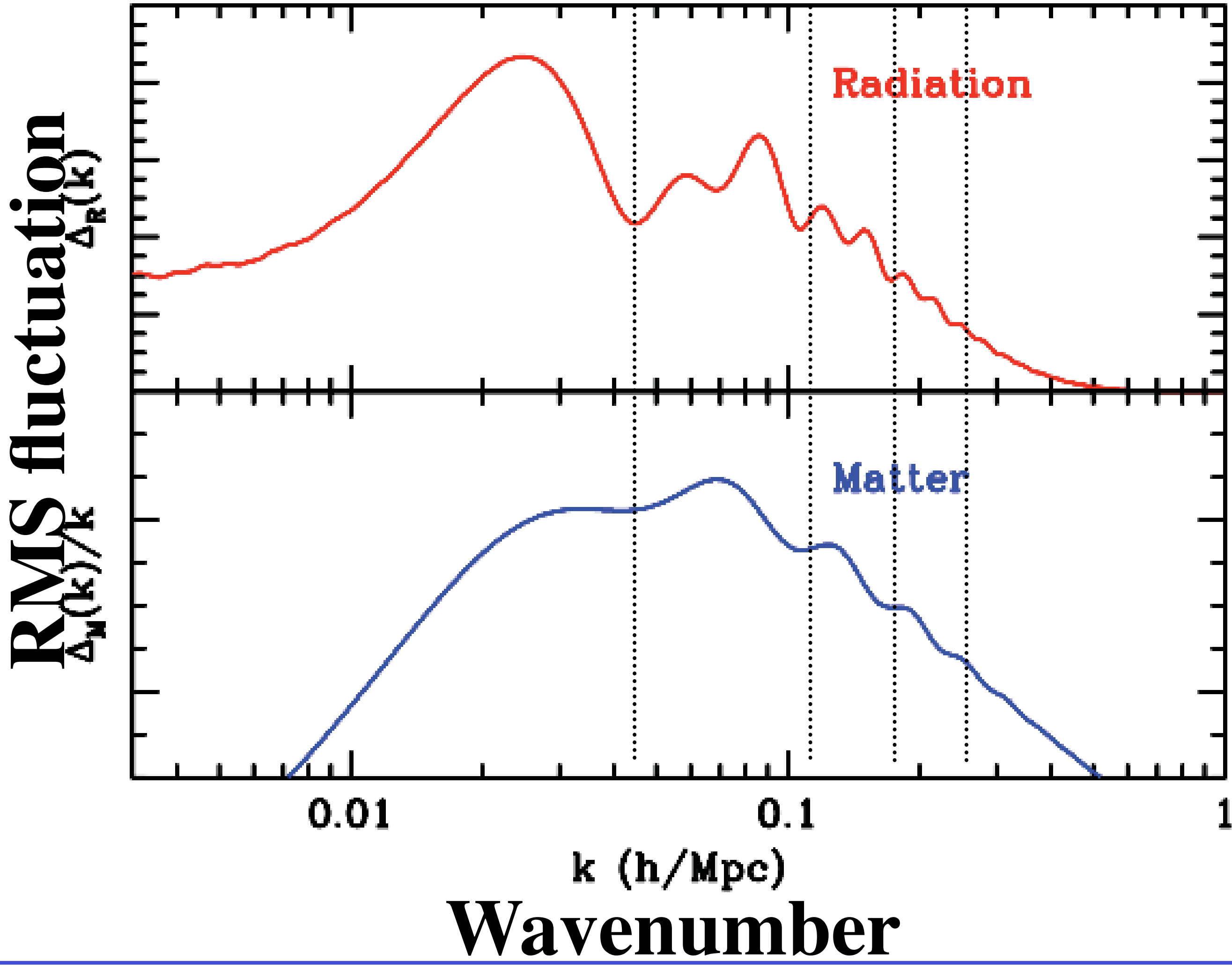
Planck

What (we expect) Planck will add: Primary CMB

In addition to wider frequency coverage and better sensitivity than WMAP, Planck has the resolution needed to see into the damping tail. It will be the first experiment to make a cosmic variance limited measurement of the scales around the 3rd and 4th peaks.

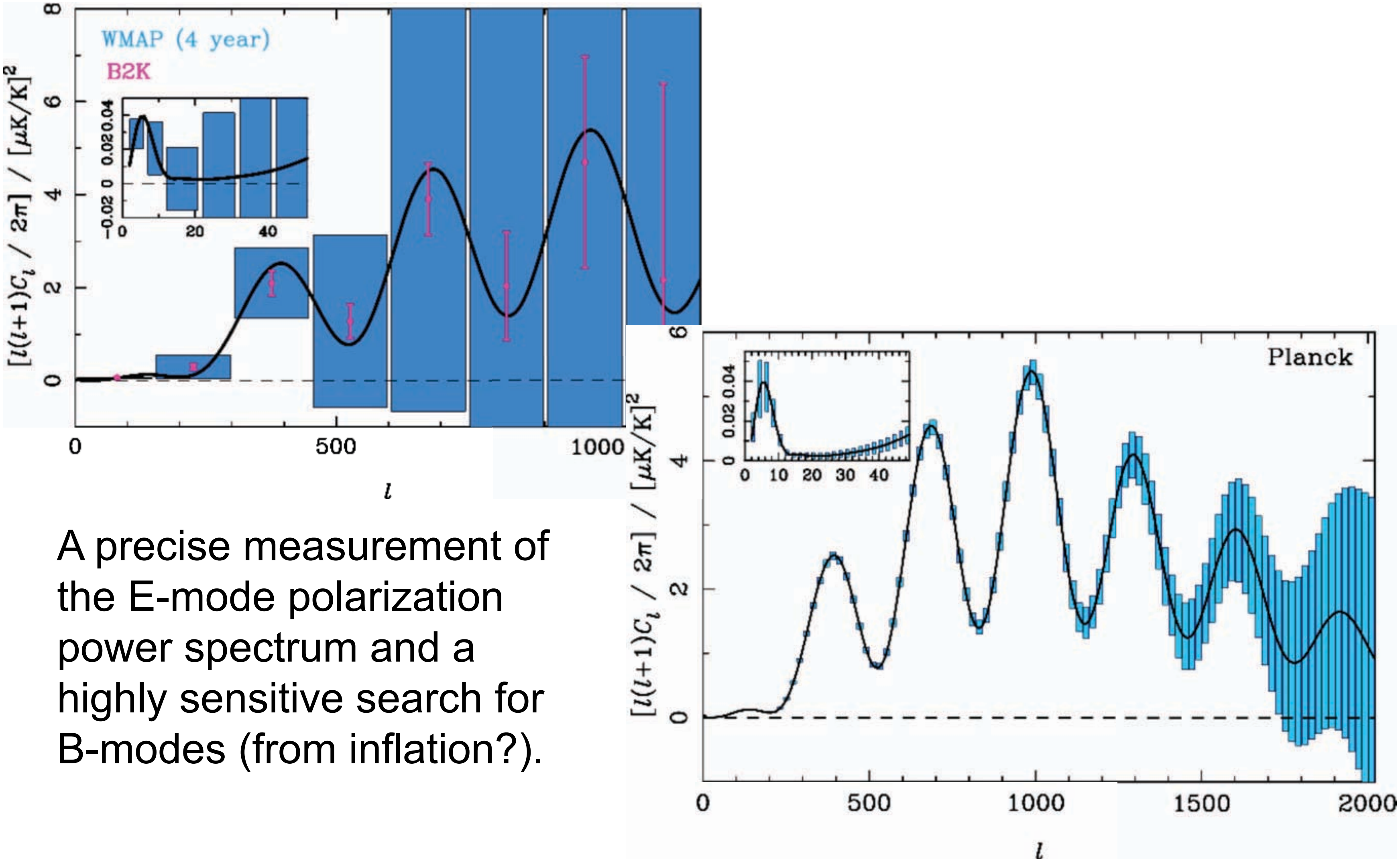


A calibrated standard ruler



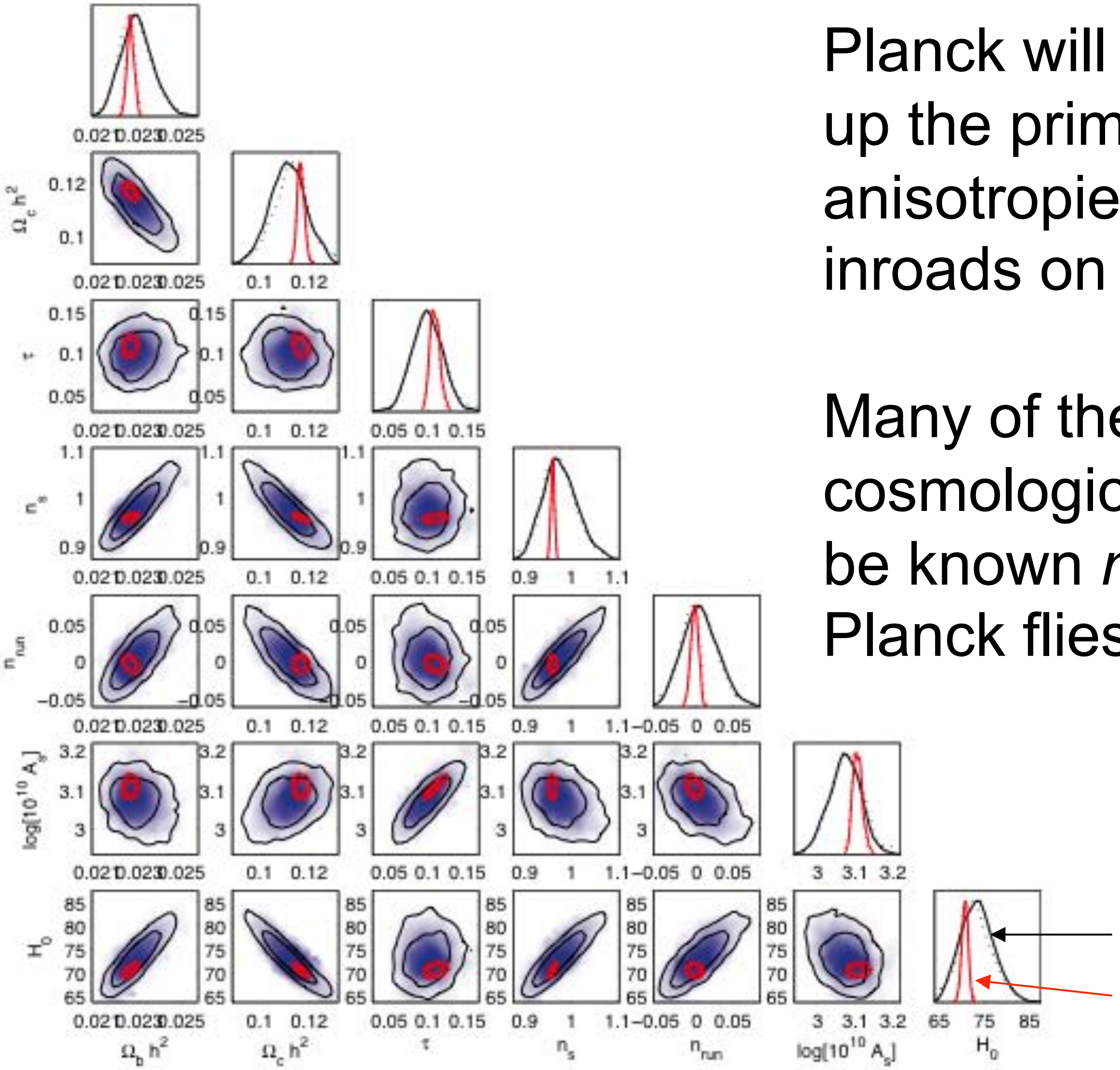
Both the large-scale “peak” in the matter power spectrum and the fine-scale “wiggles” are well calibrated by the CMB.

What (we hope) Planck will add



A precise measurement of the E-mode polarization power spectrum and a highly sensitive search for B-modes (from inflation?).

A dramatic advance



Planck blue book

Projected WMAP likelihood
Projected Planck likelihood
on Hubble constant

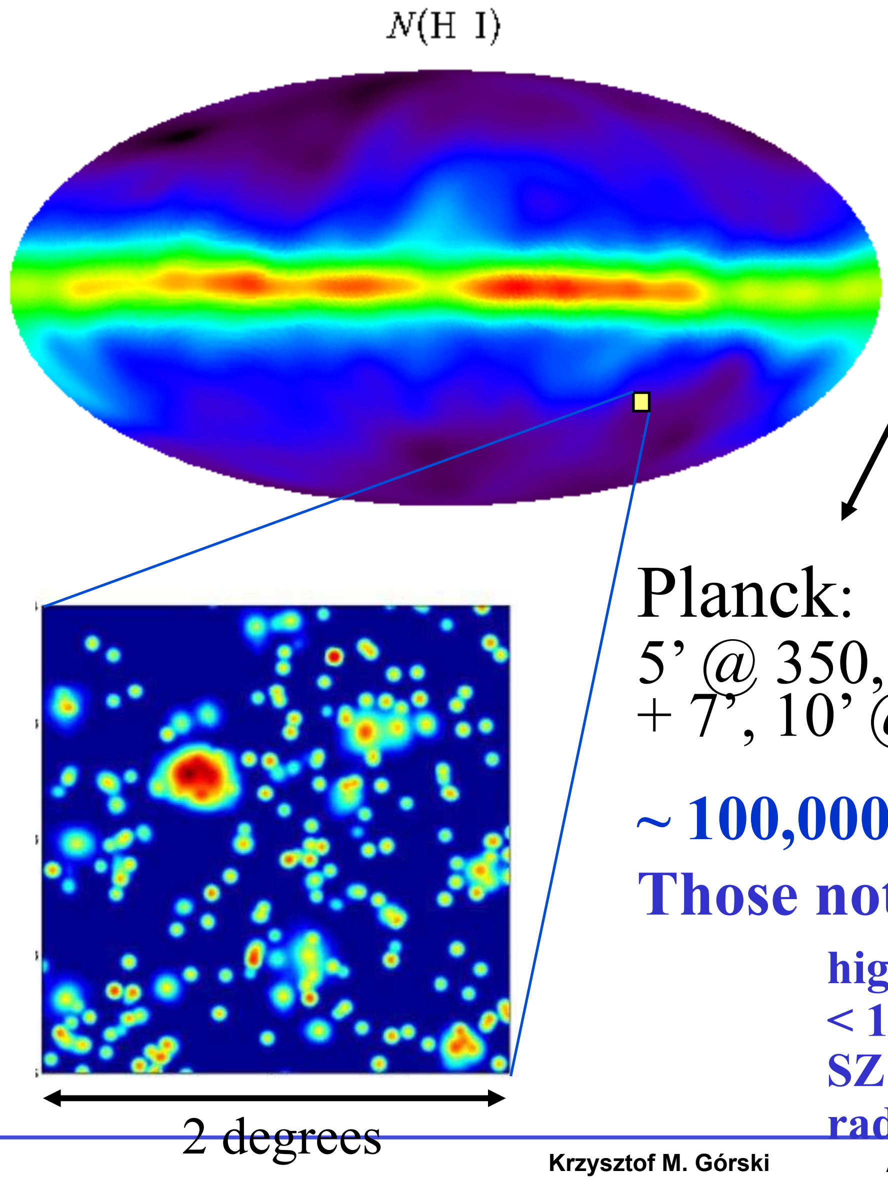
Planck will essentially clean up the primary temperature anisotropies and make great inroads on polarization.

Many of the most important cosmological parameters will be known *much* better after Planck flies.

Non-CMB Science

- Planck will measure the entire sky at 9 frequencies from 30 to 857 GHz
- At frequencies above 100 GHz, Planck will be the only all-sky survey since FIRAS
- Planck sensitivity to compact sources is >10^4 times better than FIRAS!
- Planck will see tens of thousands of discrete sources, both extragalactic and in the Milky Way, and provide extensive data for both galactic and extragalactic astrophysics.

All-sky survey @ 300 μm -> 3mm



COBE FIRAS:
7 degree resolution
No discrete sources

$[\theta_F / \theta_P]^2 > 7000$

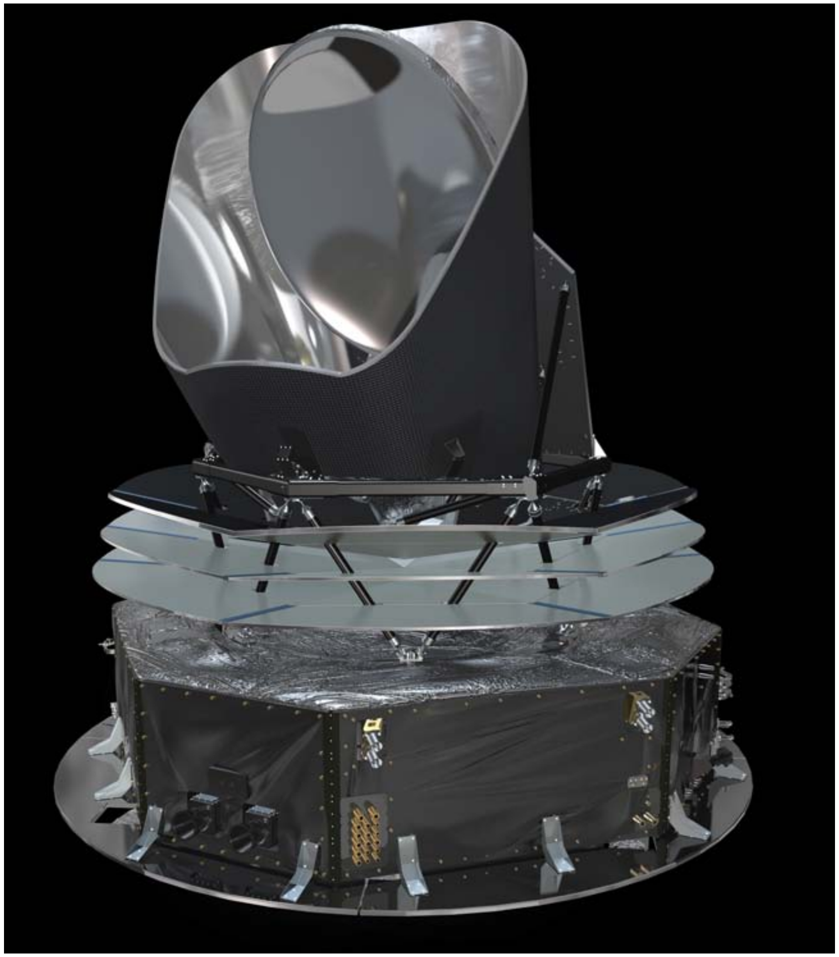
Planck:
5’ @ 350, 550, 850 and 1400 μm
+ 7’, 10’ @ 2 and 3 mm.

~ 100,000 sources

Those not seen in IRAS will include:

- **high Z ULIRGs**
- **< 15K dust**
- **SZ clusters**
- **radio bright galaxies**

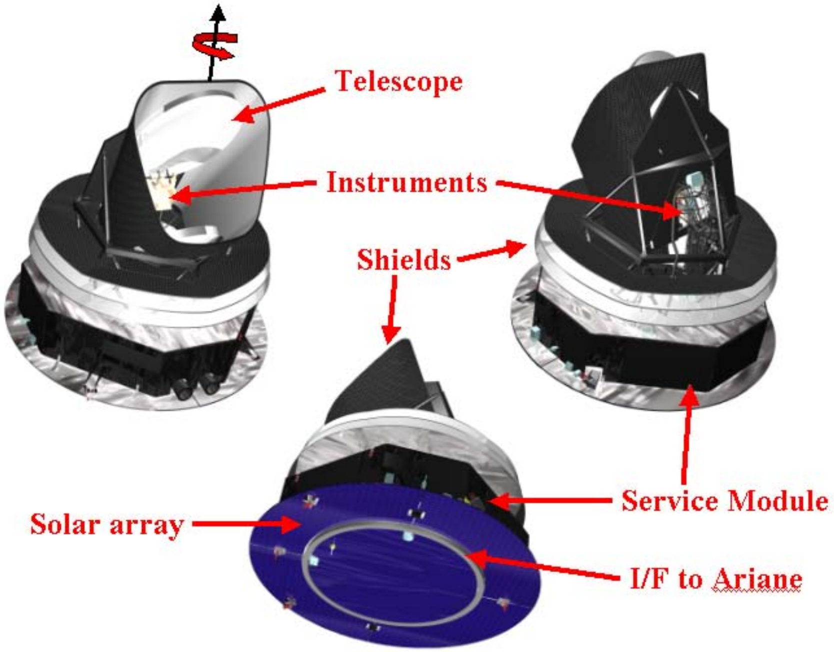
Planck - wizja i rzeczywistość



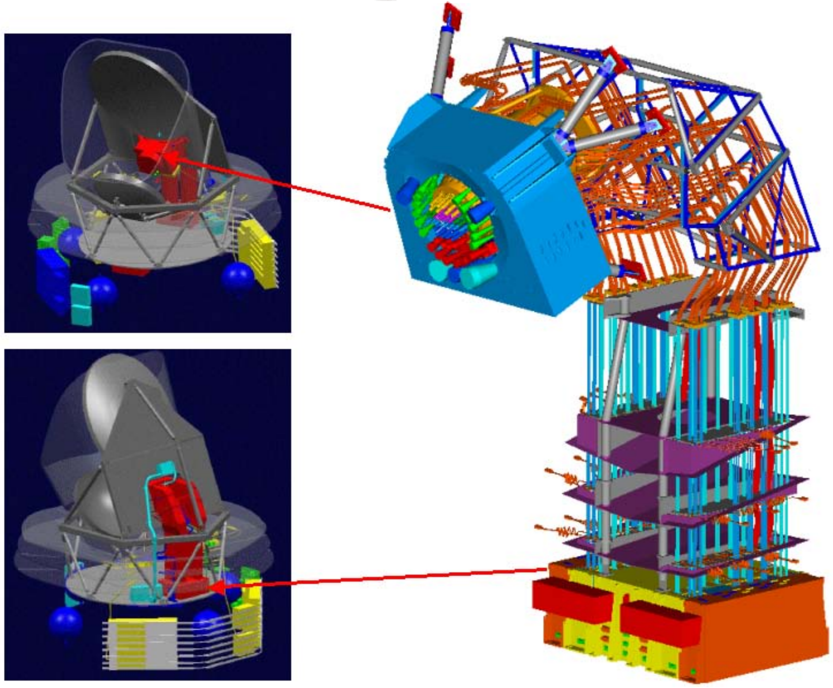
- Planck w Kourou i artystyczna wizja Plancka na orbicie

Kourou, French Guyana, May 14, ‘09, 10.12am
LAUNCH!

Planck in cartoons



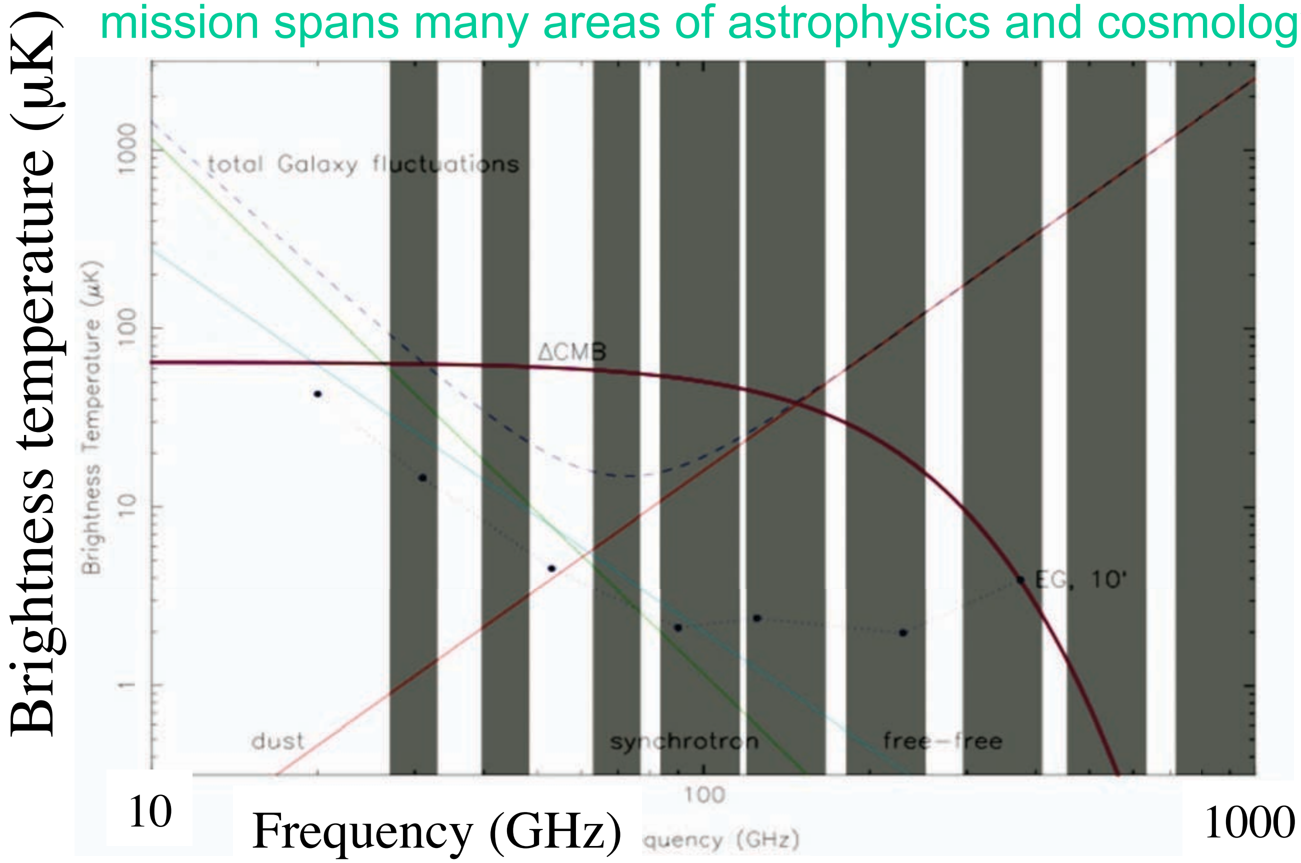
Planck has two instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI) in a shared focal plane containing 74 channels and covering an area 8 degrees-wide on the sky.



Enter Planck …

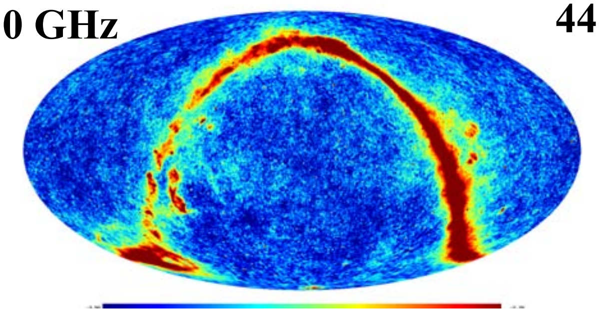
Planck is part of ESA's "Cosmic Visions" program and is currently scheduled for launch in July 2008 along with the Herschel satellite.

Planck will be the first sub-mm mission to map the entire sky with mJy sensitivity with resolution better than 10 arcminutes. The science enabled by such a mission spans many areas of astrophysics and cosmology.

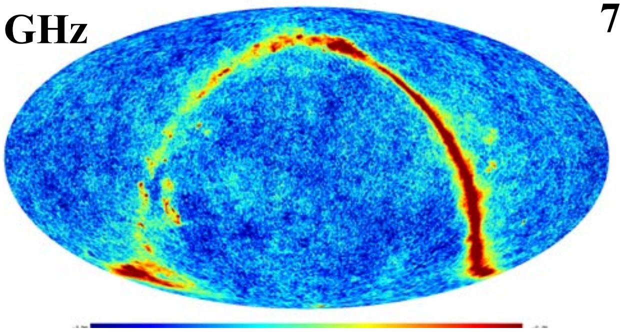


Simulated 9-frequency Planck Data Set for Temperature

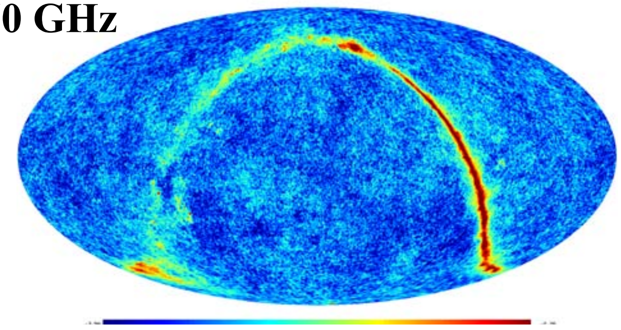
30 GHz



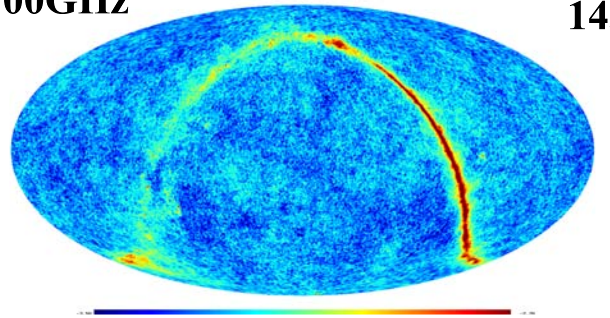
44 GHz



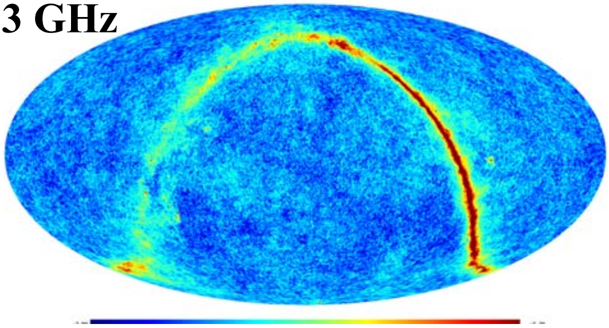
70 GHz



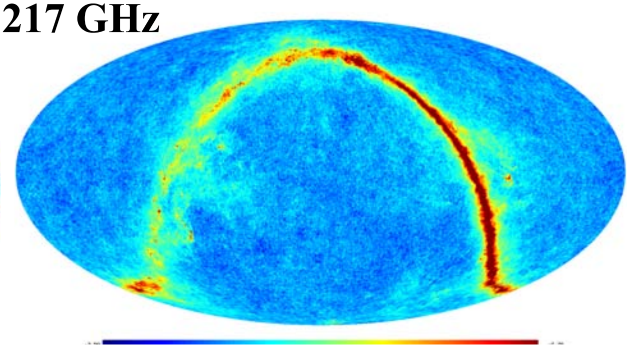
100GHz



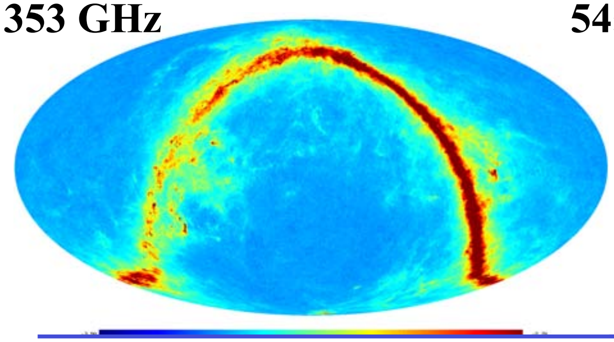
143 GHz



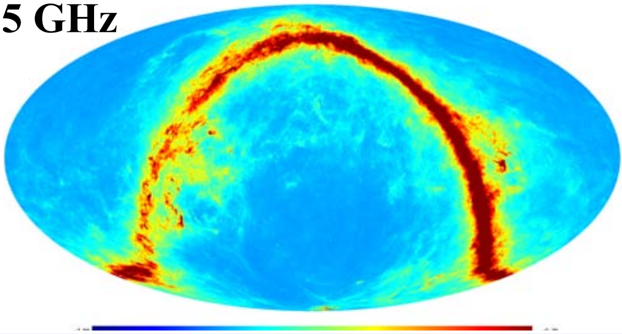
217 GHz



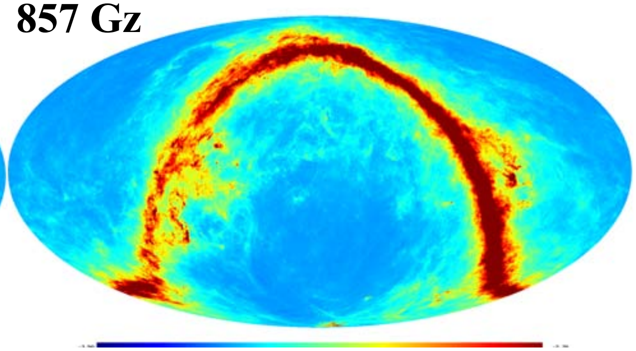
353 GHz



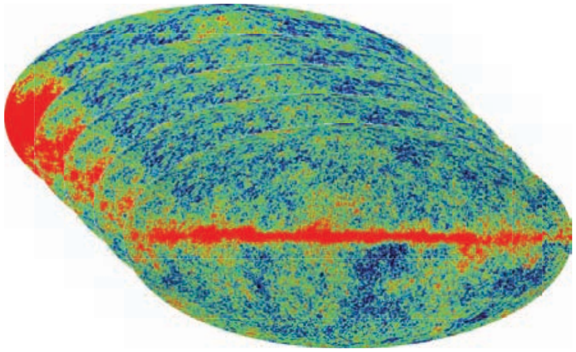
545 GHz



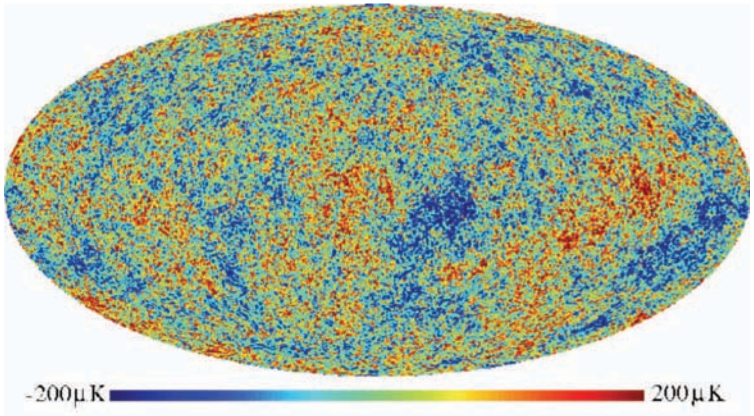
857 Gz



Science Extraction from the Multi-frequency CMB Sky Maps (in a Nutshell)



Template fitting



Frequency maps

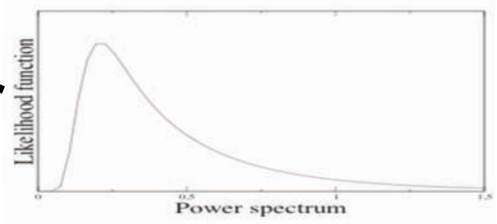
Cleaned CMB map

... or directly from sky maps to the likelihood by brute force or Gibbs

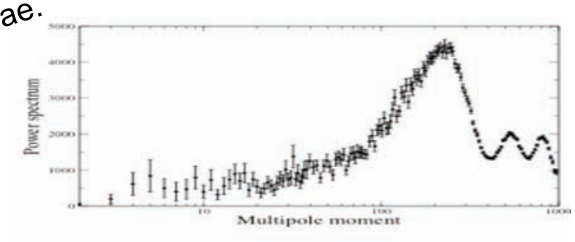
Pseudo-C_l estimators

n_s Ω_b σ_8 Ω_0 h τ

MCMC



Fitting formulae.

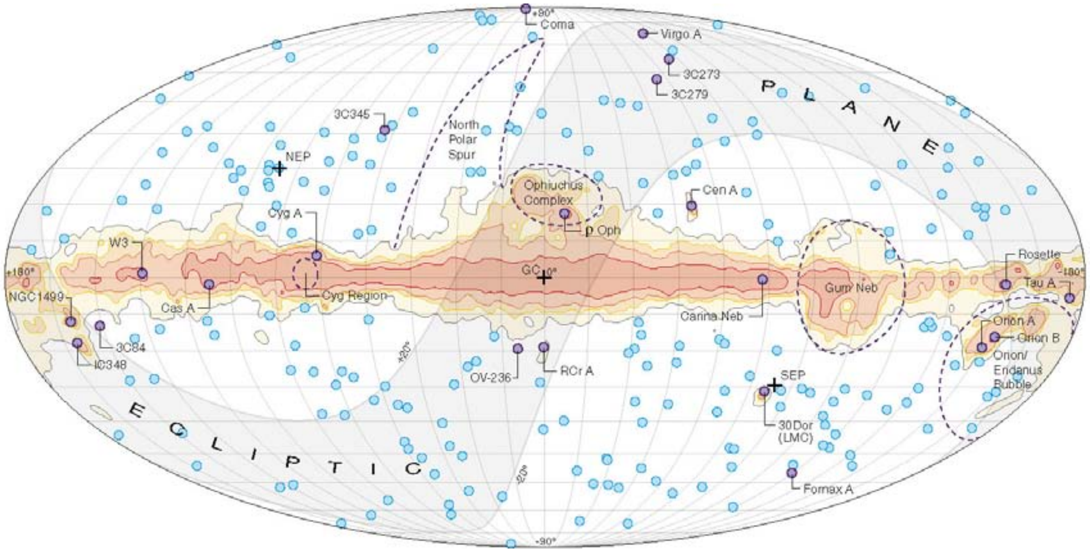


Cosmological parameters

Likelihood

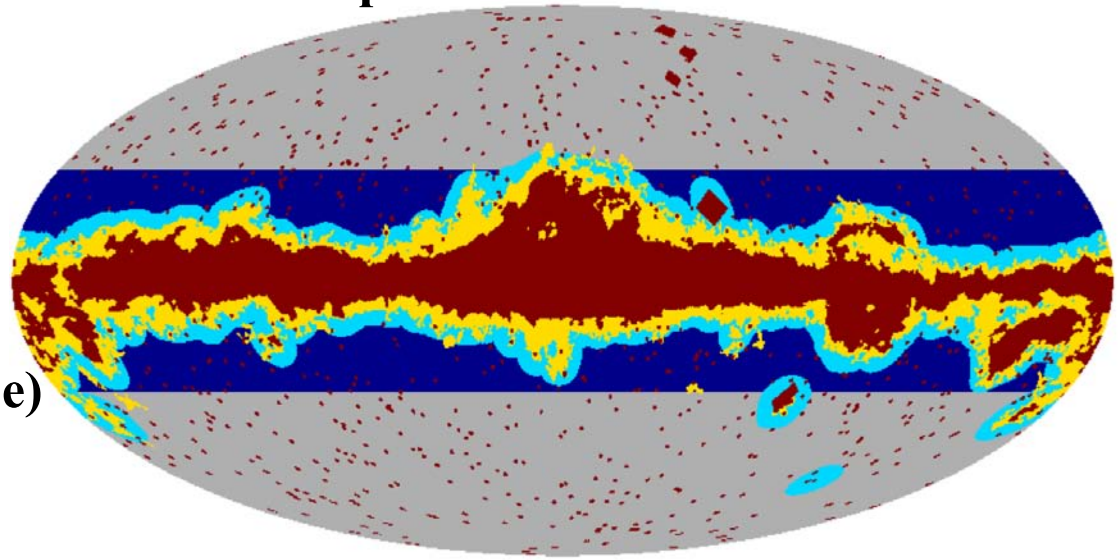
Power spectrum

Objects in the Microwave Sky



Courtesy of the WMAP Science Team

Representative masks



KQ85 (red)
KQ75 (yellow)
KQ75 ext (light blue)
|b|<30 degrees (dark blue)

Point sources (red)

Foreground Separation

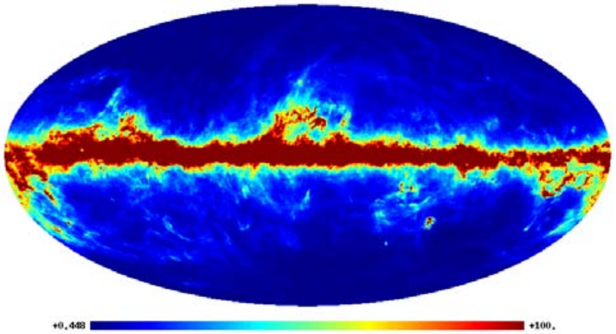
From Eriksen, Jewell, Dickinson, Banday, Górski, & Lawrence; ➡ApJ 2007

$$d(\mathbf{p},\nu) = s + \underbrace{\left(\sum_j a_j(\nu)\, t_j(\mathbf{p})\right) +}\underbrace{\left(\sum_k b_k \left(\frac{\nu}{\nu_{0,k}}\right)^{\beta_k} f_k(\mathbf{p})\right) +}\left(c(\mathbf{p})\underbrace{\left(\frac{\nu}{\nu_{ref}}\right)^{\alpha(\mathbf{p})}}\right) + n(\mathbf{p},\nu)$$

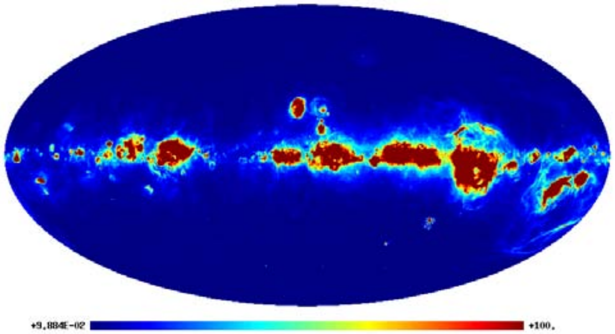
Monopole, Dipole, Dust:
Fit for amplitude at each frequency

Free-Free:
Fit for amplitude

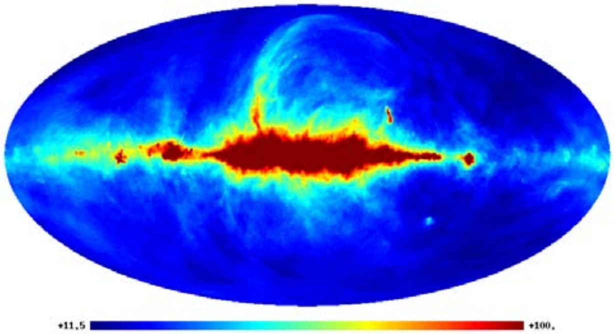
Synchrotron:
Fit pixel independent amplitudes, and spatially varying spectral index



FDS

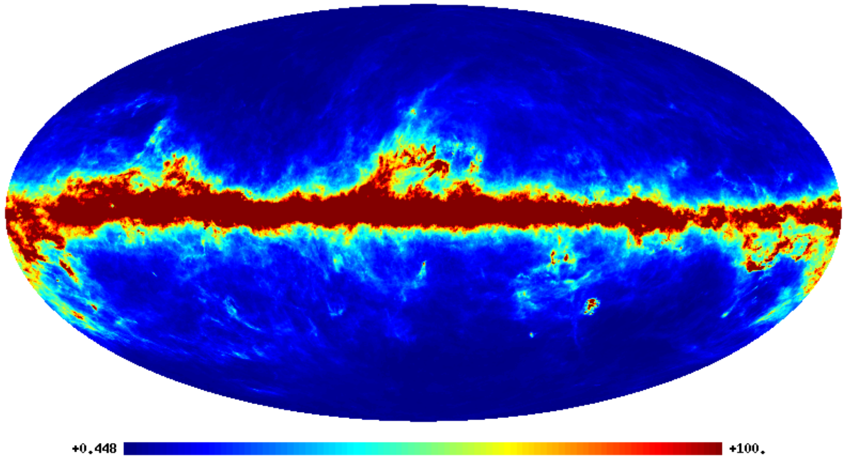


H-alpha



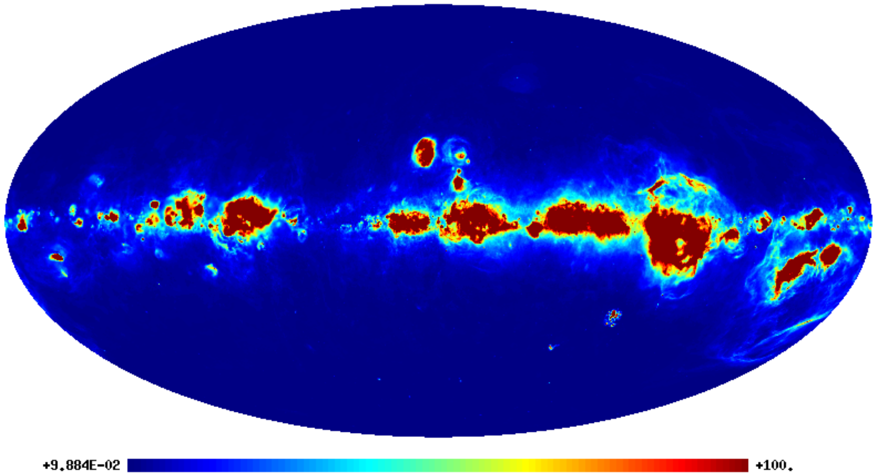
Haslam

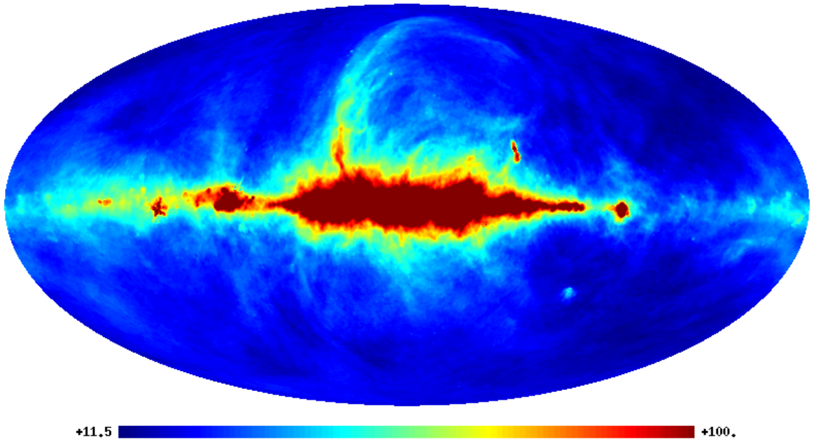
Foregrounds - Microwave Emission from the Galaxy



Dust emission according to the Finkbeiner Davis & Schlegel map derived from IRAS and DIRBE observations

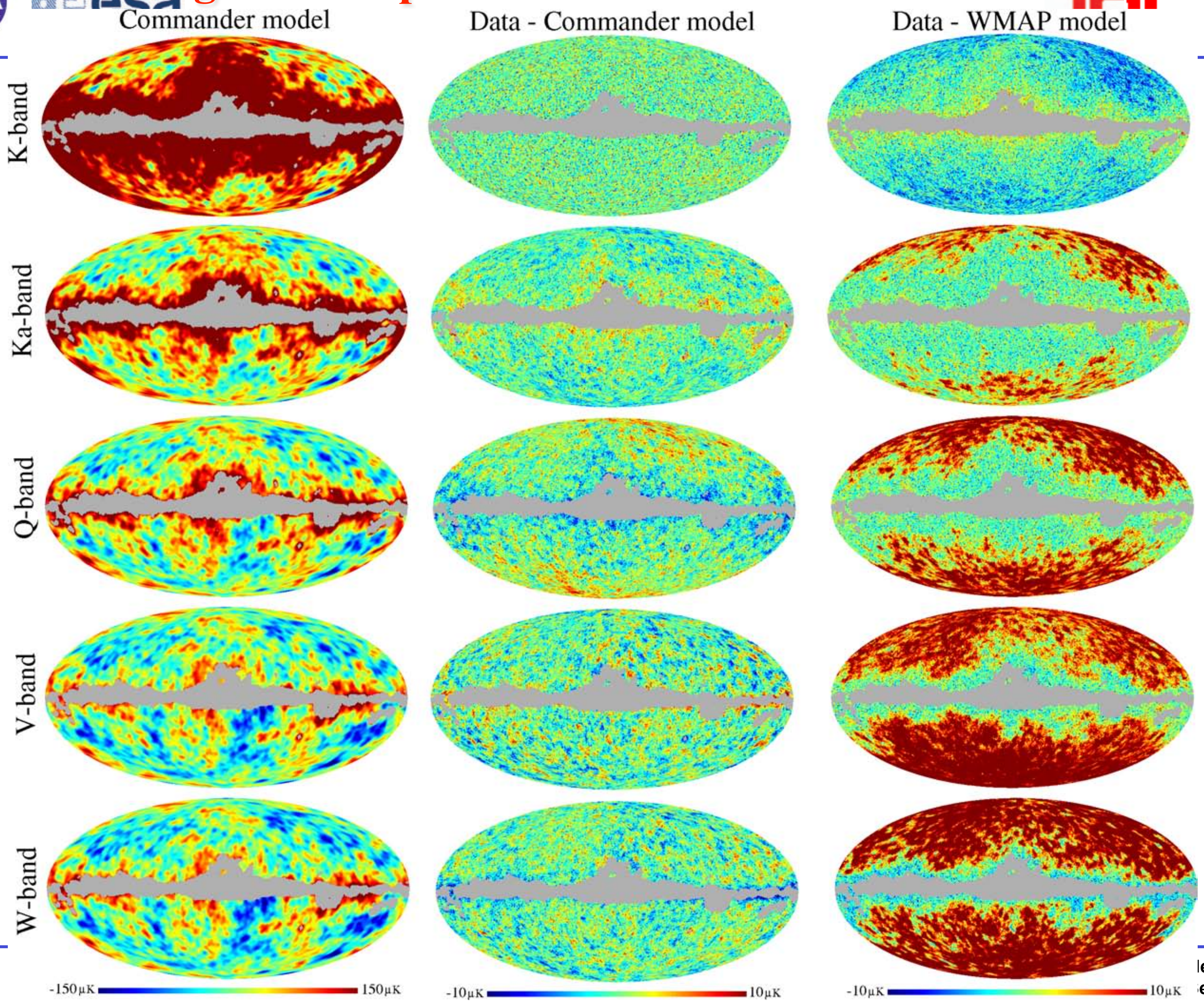
Free-free Emission traced by H-alpha





Synchrotron Emission traced by Haslam radio survey

Foreground Separation - Commander vs. WMAP3


Commander model

Data - Commander model

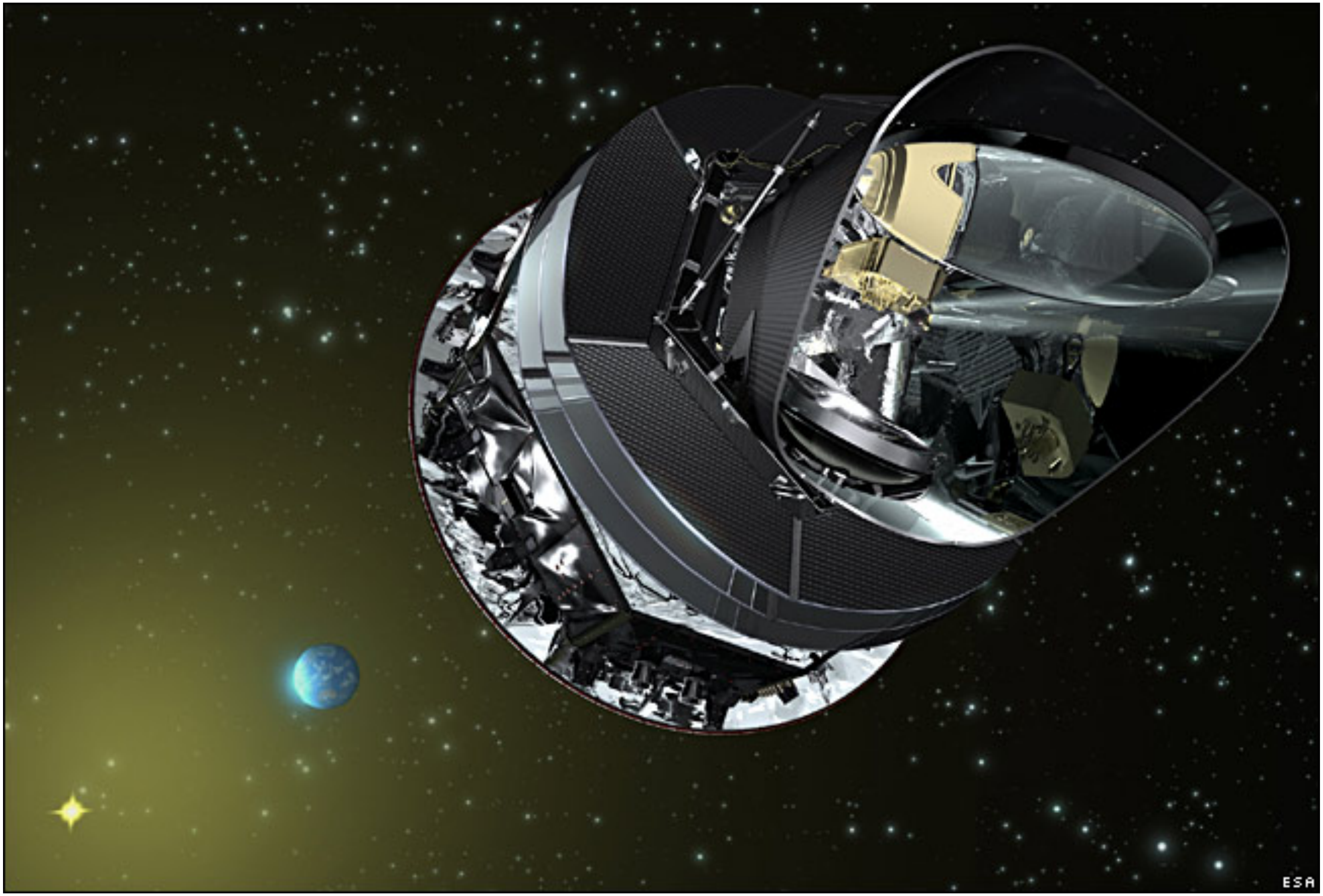
Data - WMAP model

NAIL IN THE COFFIN

Data Volume

- Planck data volume drives (almost) everything
  - LFI :
    - 22 detectors with 32.5, 45 & 76.8 Hz sampling
    - 4 x 10^{10} samples per year
    - 0.2 TB time-ordered data + 1.0 TB full detector pointing data
  - HFI :
    - 52 detectors with 200 Hz sampling
    - 3 x 10^{11} samples per year
    - 1.3 TB time-ordered data + 0.2 TB full boresight pointing data
  - LevelS (simulation example) :
    - 4 LFI detectors with 32.5 Hz sampling
    - 4 x 10^9 samples per year
    - 2 scans x 2 beams x 2 samplings x 7 components + 2 noises
    - 1.0 TB time-ordered data + 0.2 TB full detector pointing data

Enter Planck …

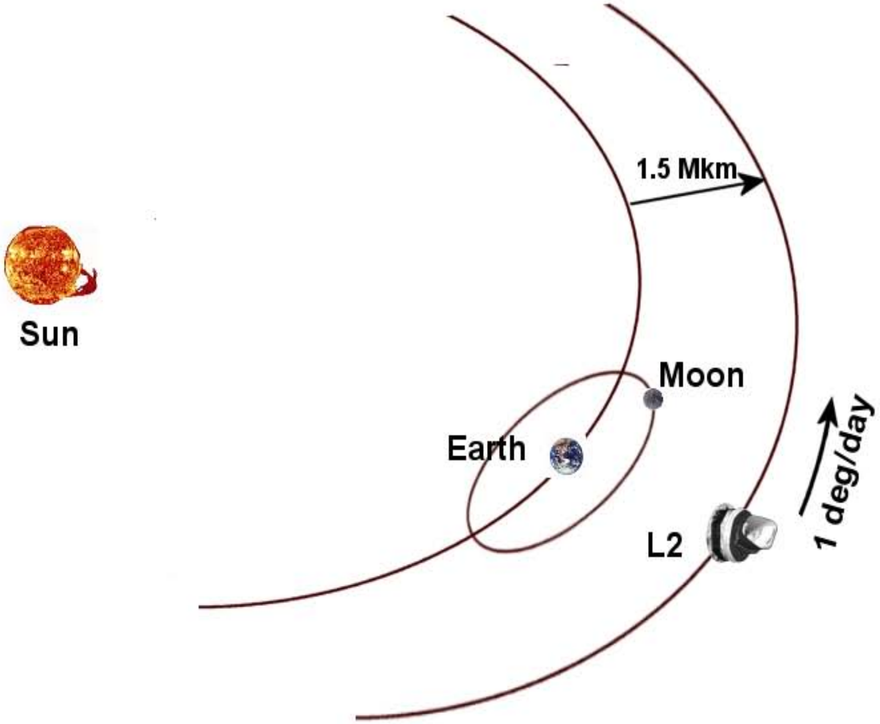


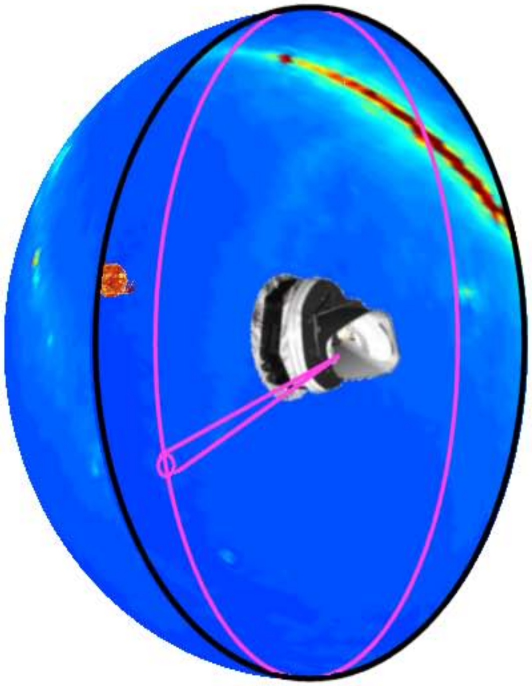
The orbit and scanning

Planck will make its measurements from the Earth-Sun L_2 point.

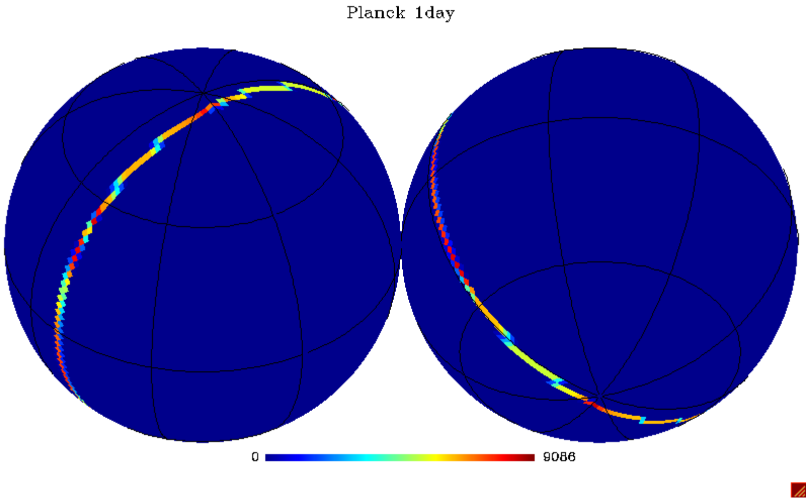
It will make a map of the full sky every 6 months.

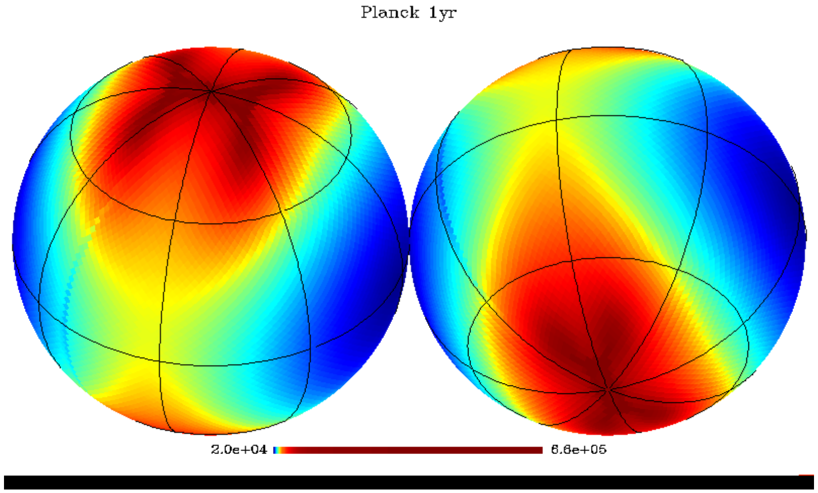
Currently, it is planned to run for 14 months, but should be extented to ~twice that for HFI, perhaps more for LFI.

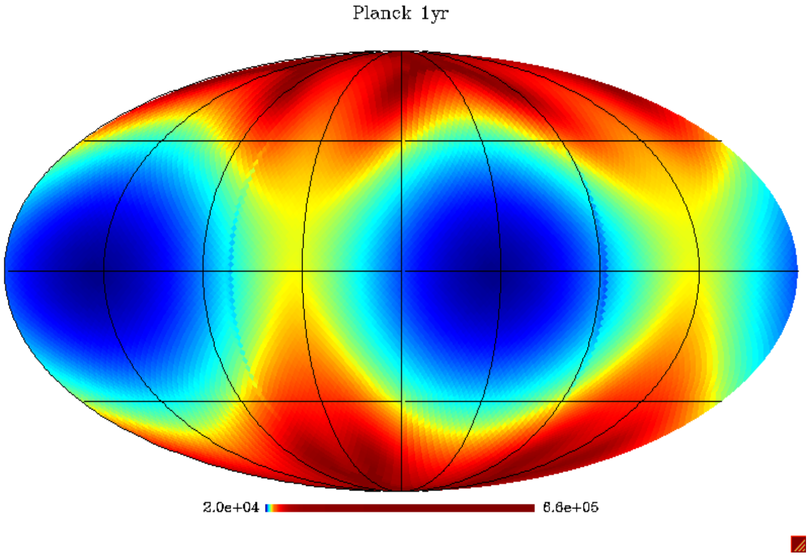


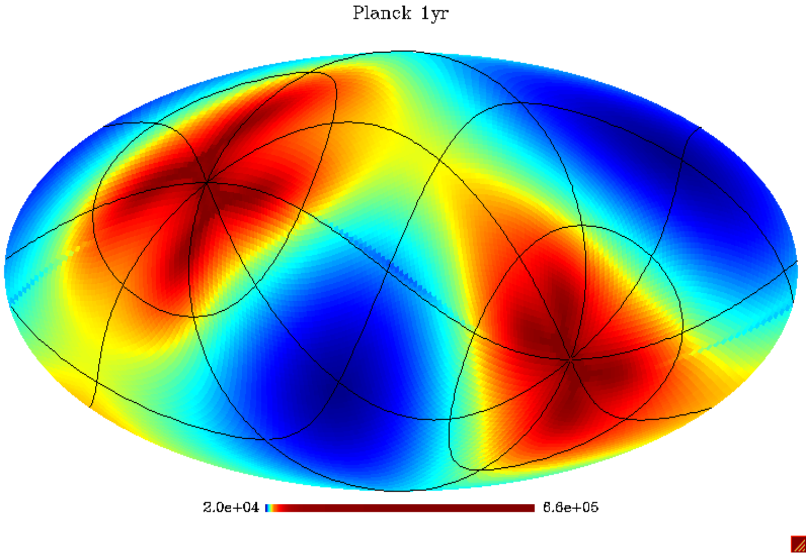


Planck Scanning Strategy –
Slow (6-months) Precession Case



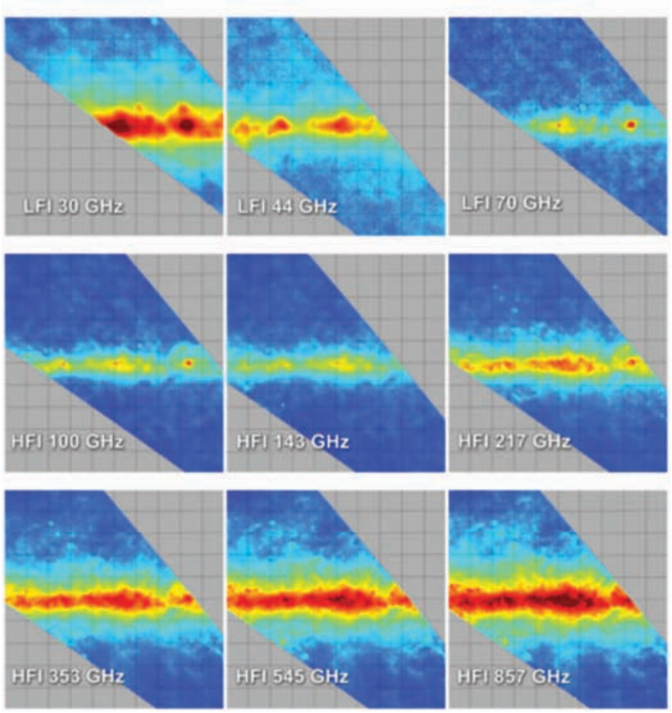




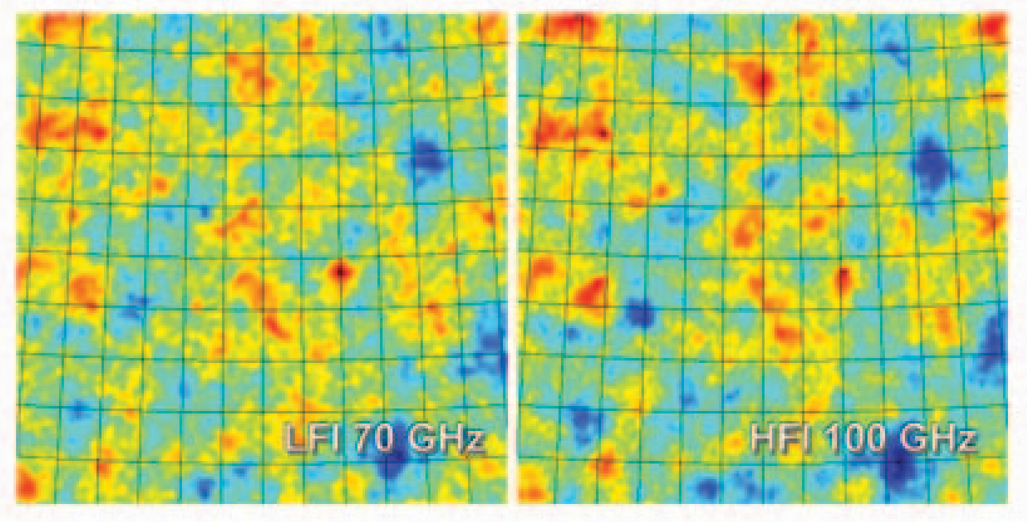


First PR snapshots form Planck

The Planck First Light Survey

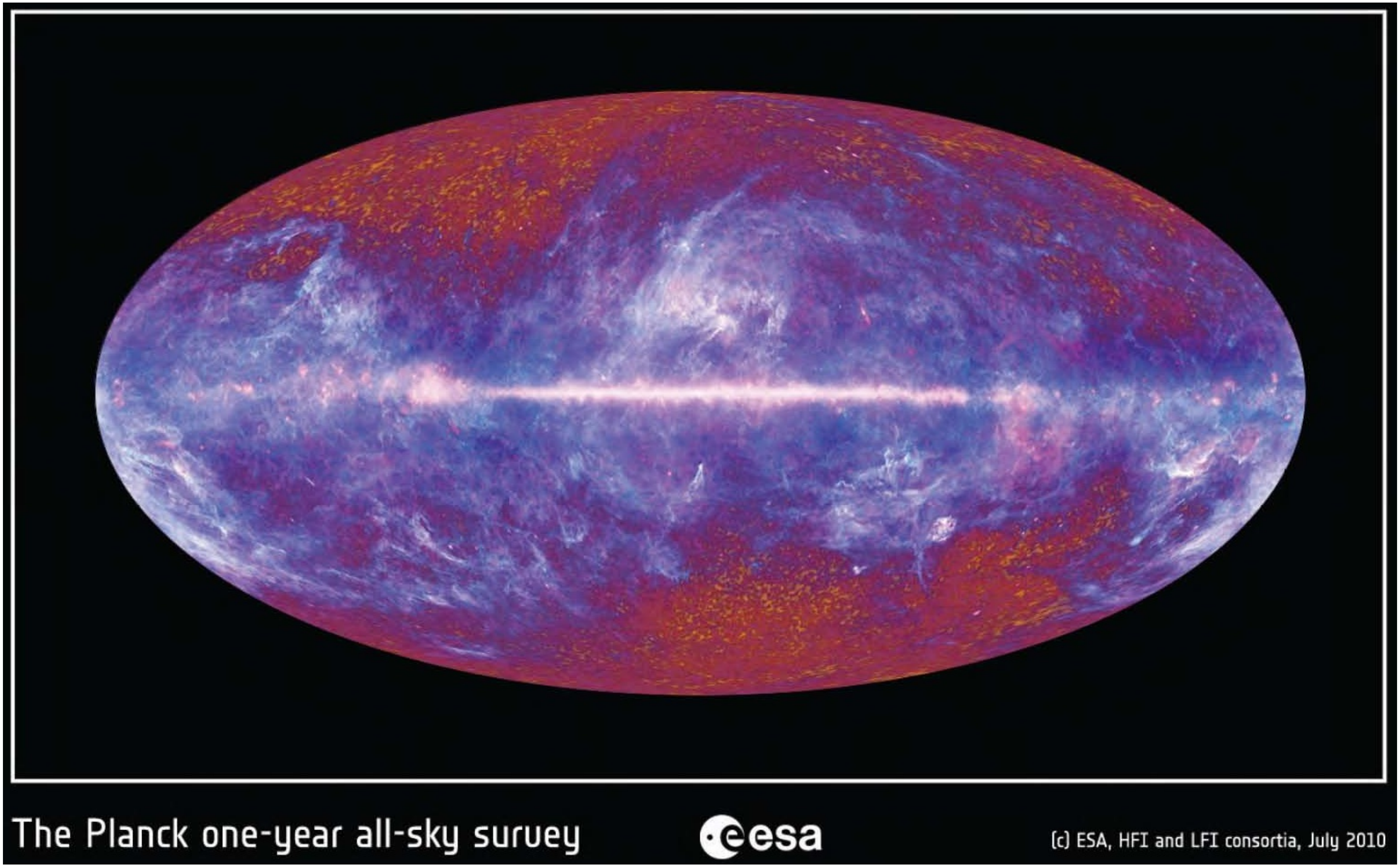


Mosaic of maps at 9 different frequencies, showing part of the Milky Way



Maps of the high-galactic-latitude sky at 70 and 100 GHz

Planck's Universe



The Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, July 2010

Plack Data Processing and Analysis Scope

- 50 x the data volume of WMAP
- 3 x the angular resolution ⇒ 10 x as many pixels in maps
- 10 x lower noise ⇒ deal with 10 x lower systematics
- 2 x as many frequencies

- Data analysis is a much bigger and harder job than for WMAP!
  - Approximately 10 x

TOD Generation and Map Making for the Planck HFI 100, 143, and 217 GHz TQU Data

- **Motivation (in a nutshell):**
  - Find out if residuals of the $1/f^2$ detector noise remaining in the sky maps made from the TODs with correlated noise compromise Planck's ability to measure the low-*l* reionization features in the *TQU* power spectra
- **Input Data:**
  - Generated by Level S Simulation Pipeline
  - Involved: G. Rocha, G. Prezeau, I. O'Dwyer, K. Huffenberger, C. Cantalupo
  - TOD Volume: about ~1.5 TB at all channels
- **Map Making:**
  - G. Rocha run DPC compliant version of Springtide to generate 3 TQU maps
  - M. Ashdown helped with running Springtide to generate the internally coadded single TQU map
- **Power Spectrum Evaluation**
  - Simple galactic cut developed by C. Cantalupo (based on tresholded, smoothed SFD Galaxy dust emission map; ~60% of the sky retained
  - KMG: HEALPix (MPI) anafast runs on full and cut-sky maps – Sun/ Linux 64bit, 4CPU, 32GB RAM machine at JPL; single anafast run on N_{side}=2048, l_{max}=3000 TQU map (~600 MB size) takes ~4 mins CPU

4 C. Rosset et al.: Beam mismatch in

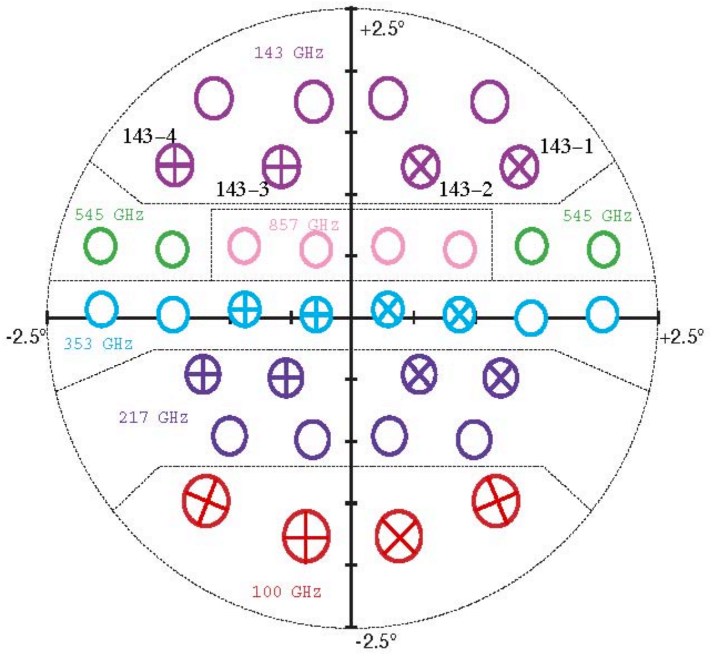
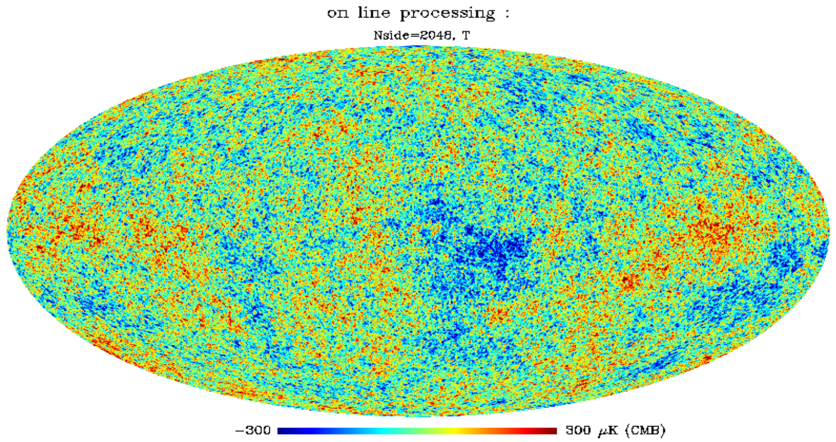
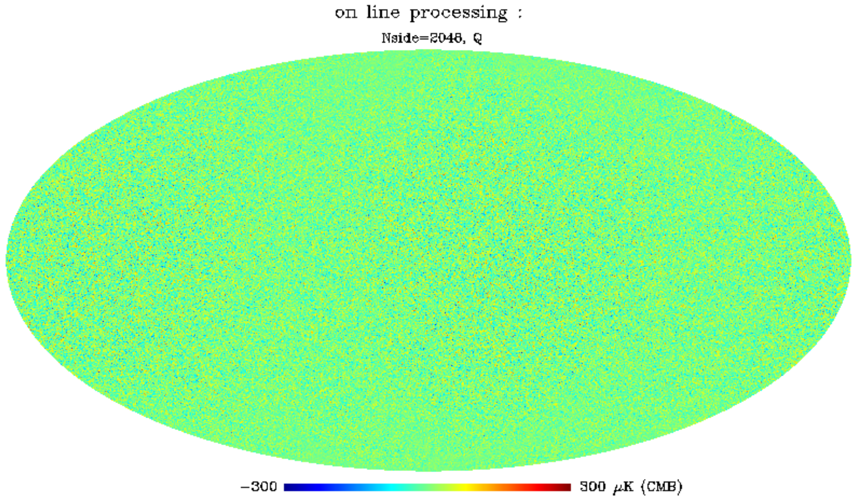


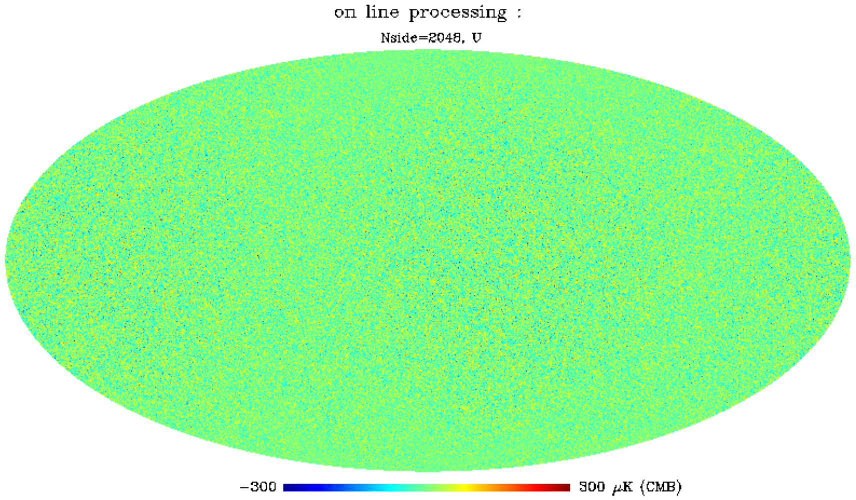
Fig. 2. Planck focal plane with polarization sensitive bolometers as seen from the sky. Complementary pairs of PSB detectors are arranged in two horns following each other while scanning the sky so that four detectors are in an optimized configuration for polarization measurement.

Input CMB Sky

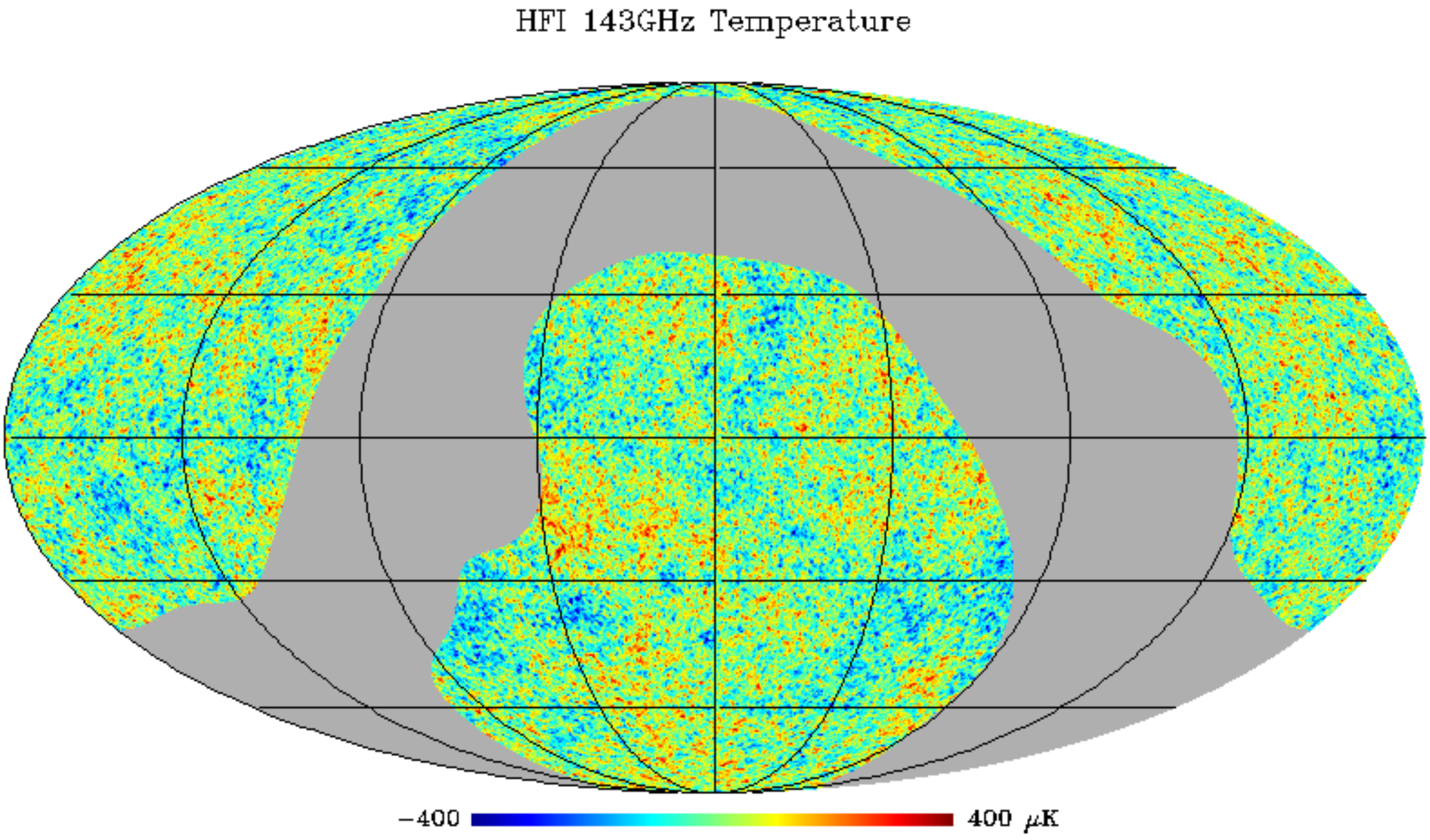


The input CMB signals for these simulations were generated by matching spherical harmonics up to l = 3000 to the WMAP data.





Galaxy Cut



Simulation Parameters and Computational Resources

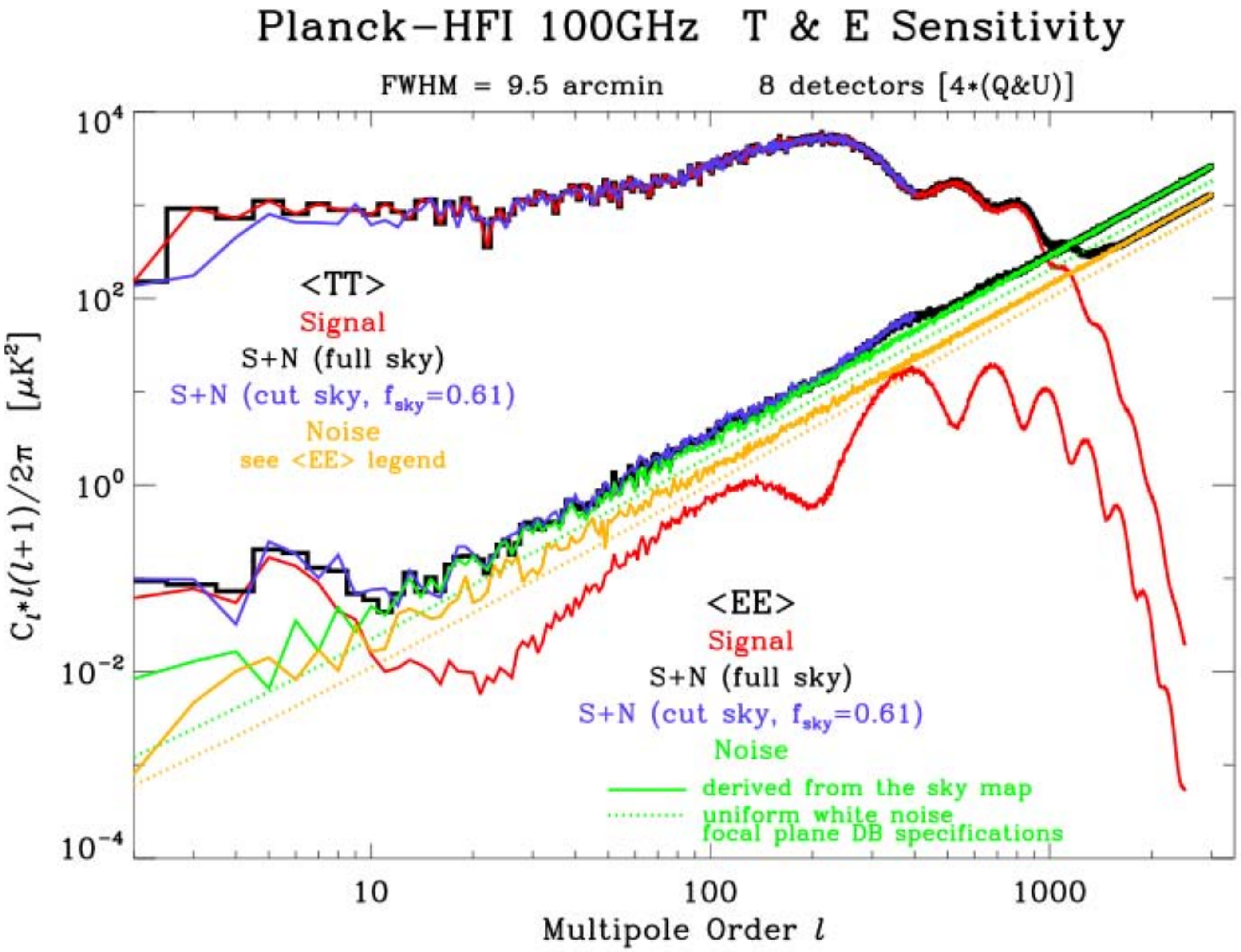
Parameters:

Detectors	8 @ 100 GHz (8 polarized) 12 @ 143 GHz (8 polarized, 4 unpolarized) 12 @ 217 GHz (8 polarized, 4 unpolarized)
Observations (ONLY CMB TQU signals are measured)	366 days @ 200 Hz = 6,324,480,000 samples per detector (× 32) Total number of samples ~2.024 × 10^{11}
Noise Properties	White + $1/f^2$, knee=30 mHz, 6-day piecewise stationary
Scanning Strategy/Pointing	Cycloidal - slow (6 month) precession; Satellite pointing with jitter
Resolution of the Sky Maps	HEALPix N_{side}= 2048 — 50,331,648 x 1.7' pixels per Stokes parameter

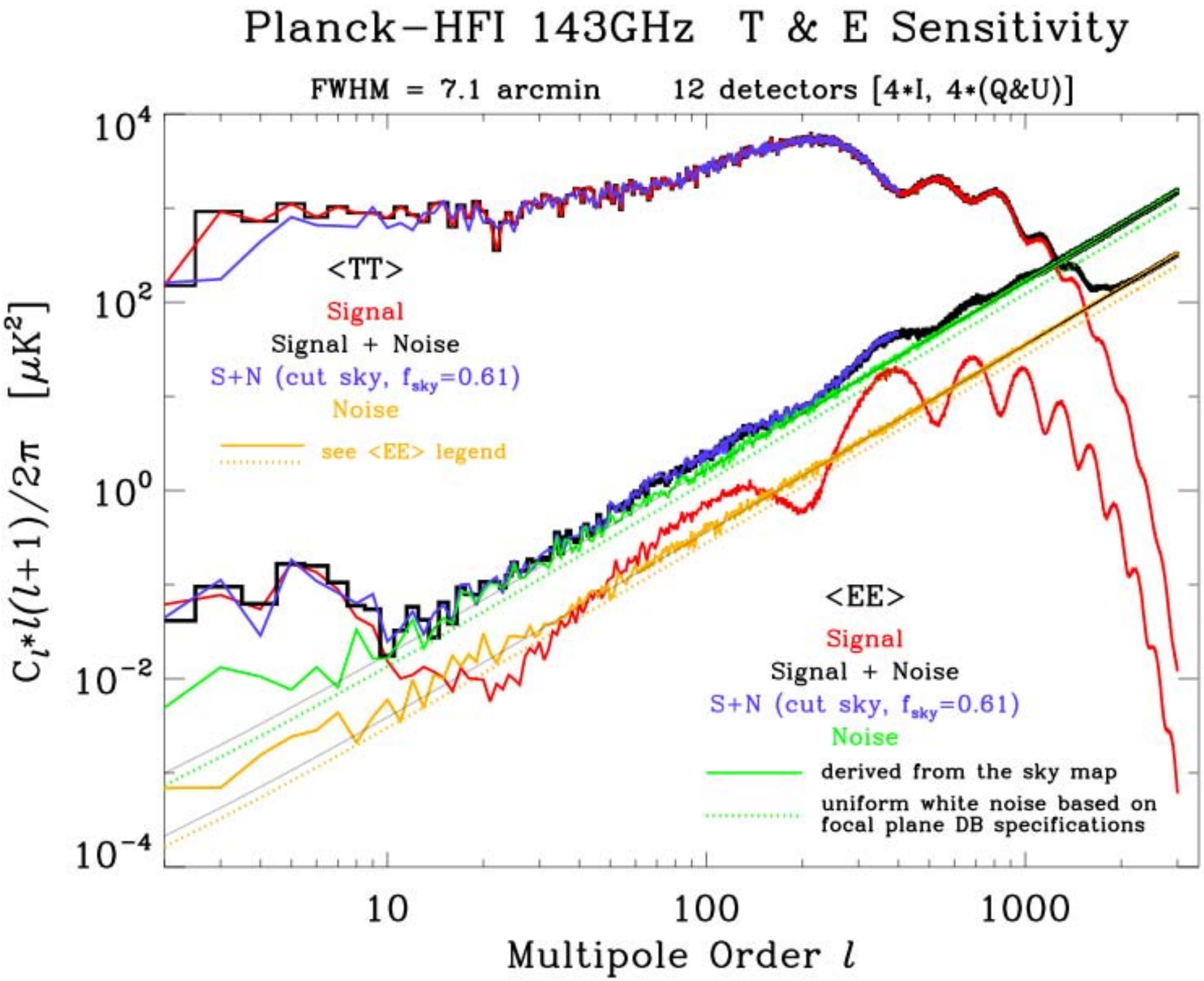
Computing:

Machines	Seaborg and Bassi at NERSC
Processors	6000 x 375 MHz; 976 x 1.9GHz
Run-time	<3 hr wallclock given CPUs deployed
Memory	Dominated by map size
Disk	~ 1.5 Tbytes (aggregate TODs)

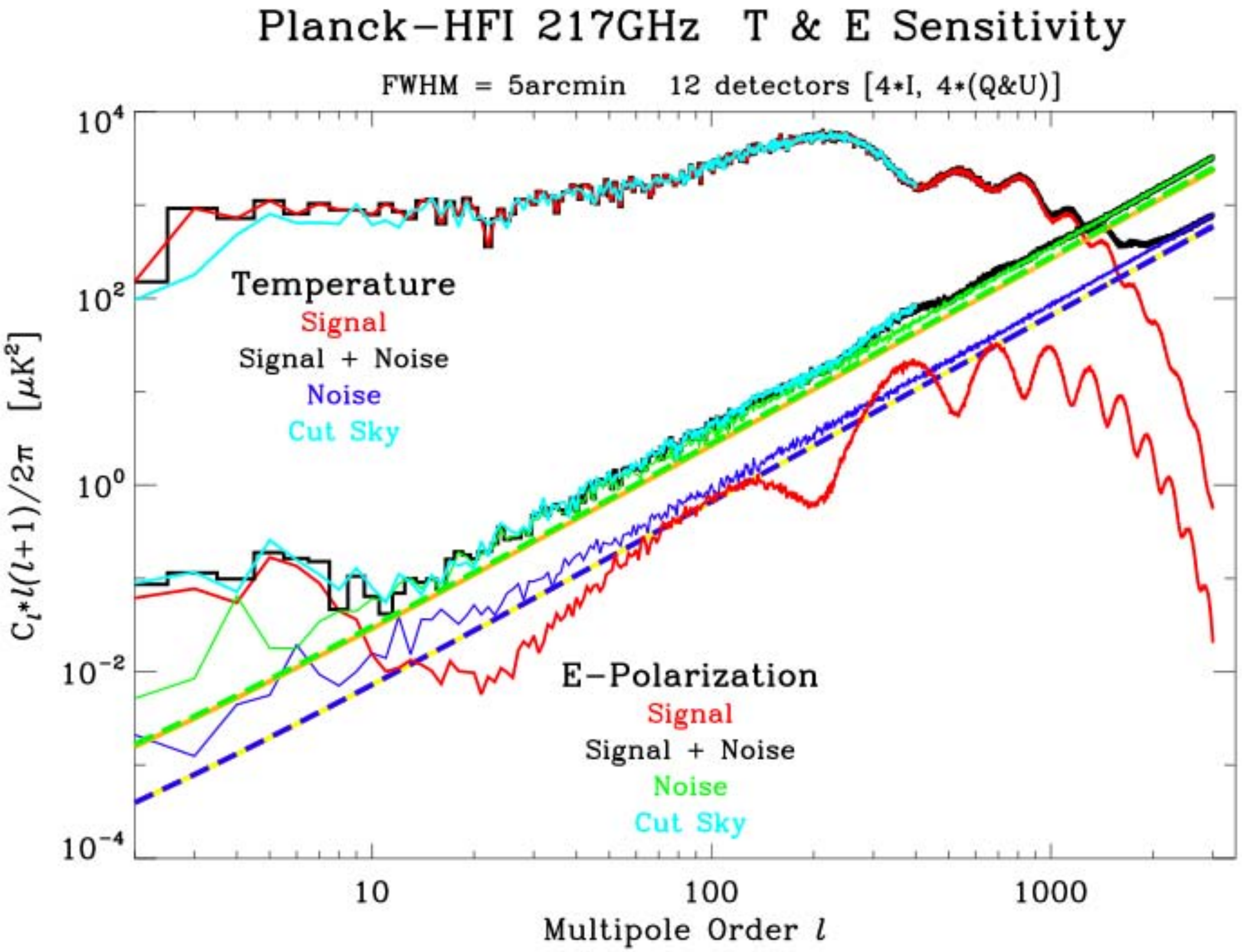
HFI 100 GHz Channel



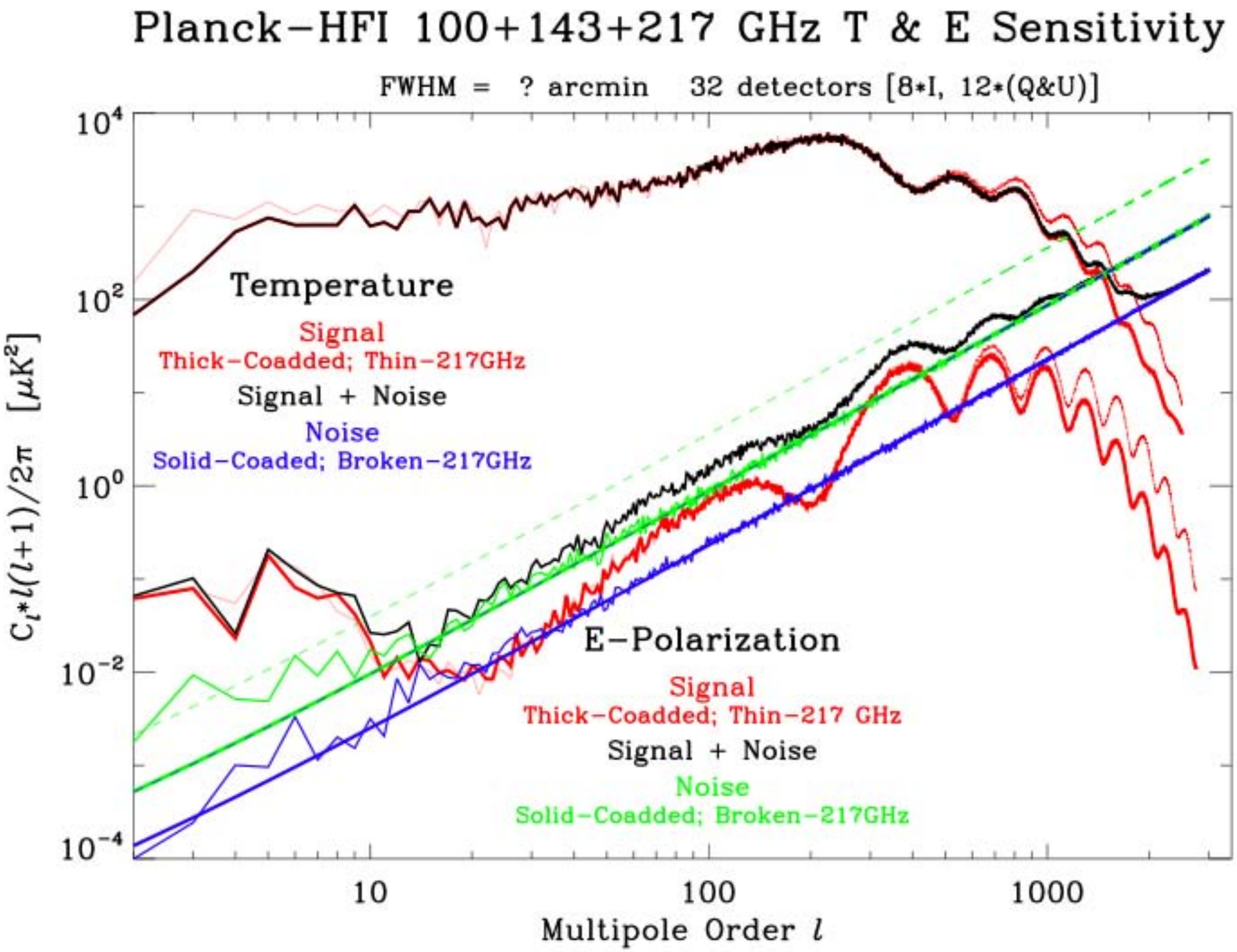
HFI 143 GHz Channel



HFI 217 GHz Channel



Coadded 100/143/217 GHz Channels



The CMB "prior"

- After Planck, we will have very precise knowledge of the universe at z~1000.
- We will have tightly constrained the physical densities of matter and baryons, the amplitude of the fluctuations in the linear phase over 3 decades in length scale and the shape of the primordial power spectrum.
- Our knowledge of physical conditions and large-scale structure at z~10^3 will be better than our knowledge of such quantities at z~0!
- If dark energy is a recent phenomenon, then we can translate this knowledge reliably to intermediate redshifts which are currently at the observational frontier.
- This CMB "prior" is assumed by all Beyond Einstein concepts, etc. (e.g., all JDEM concepts, Cosmic Inflation Probe, CMBPol)

After launch, before lunch …
with Planck PIs - Reno Mandolesi and Jean Loup Puget

Joint Core Teams of Planck

END