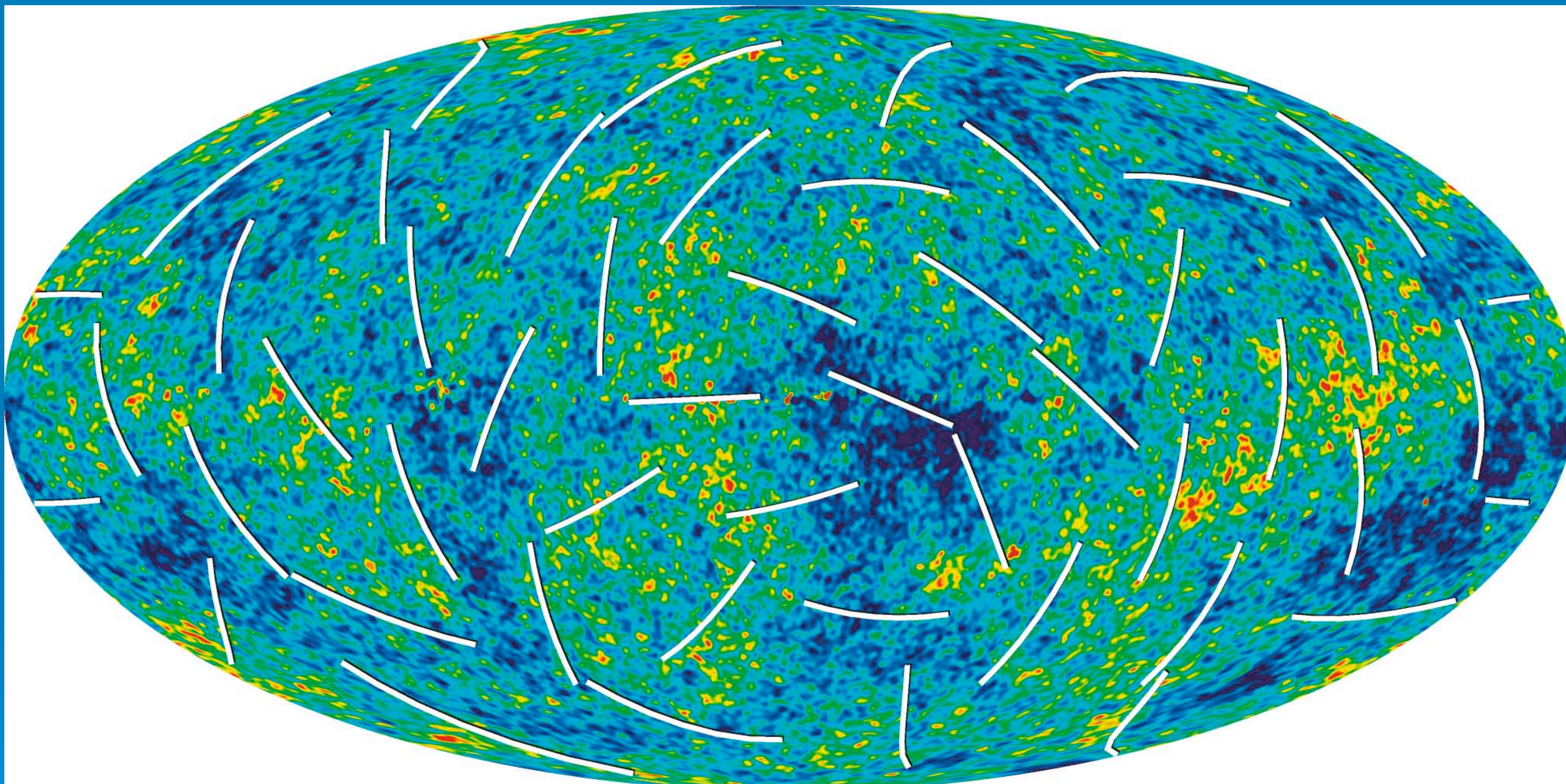
Cosmology After WMAP (5)



David Spergel

Geneve

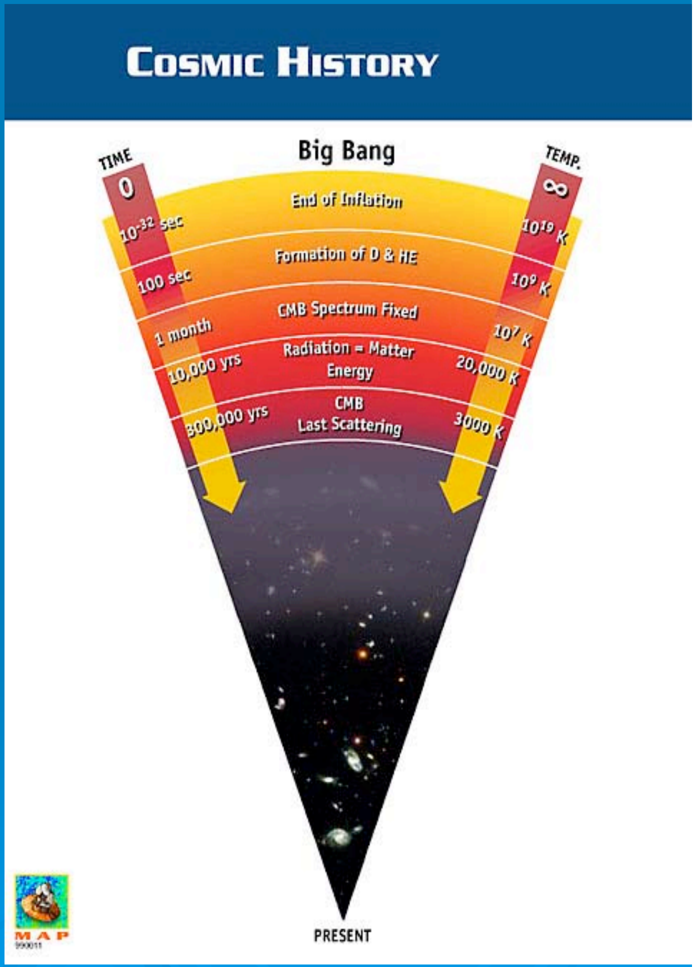
June 2008

Standard cosmological model Still Fits the Data

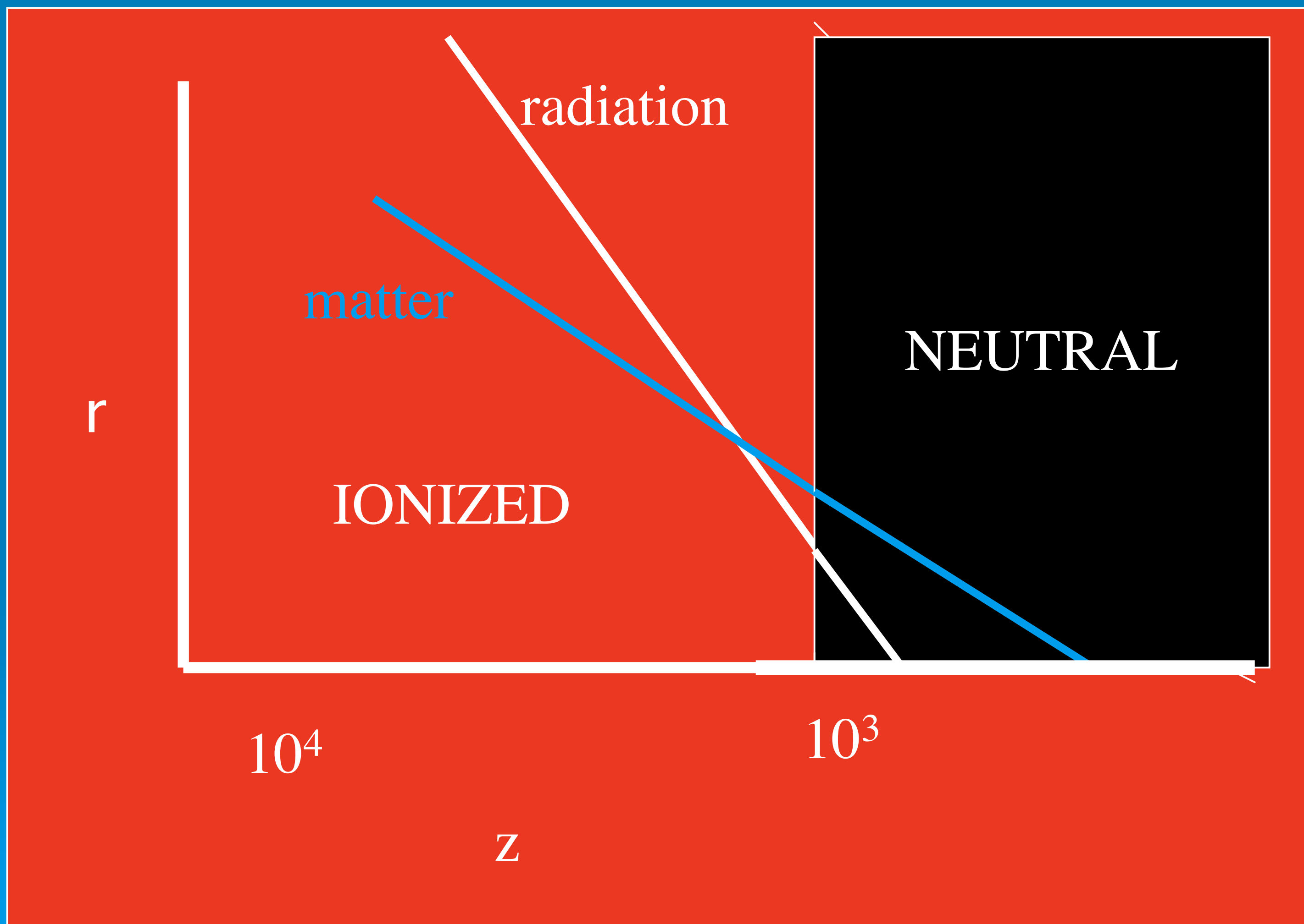
- General Relativity + Uniform Universe ⇒ Big Bang
  - Density of universe determines its fate + shape
- Universe is flat (total density = critical density)
  - Atoms 4%
  - Dark Matter 23%
  - Dark Energy (cosmological constant?) 72%
- Universe has tiny ripples
  - Adiabatic, scale invariant, Gaussian Fluctuations
  - Harrison-Zeldovich-Peebles
  - Inflationary models

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

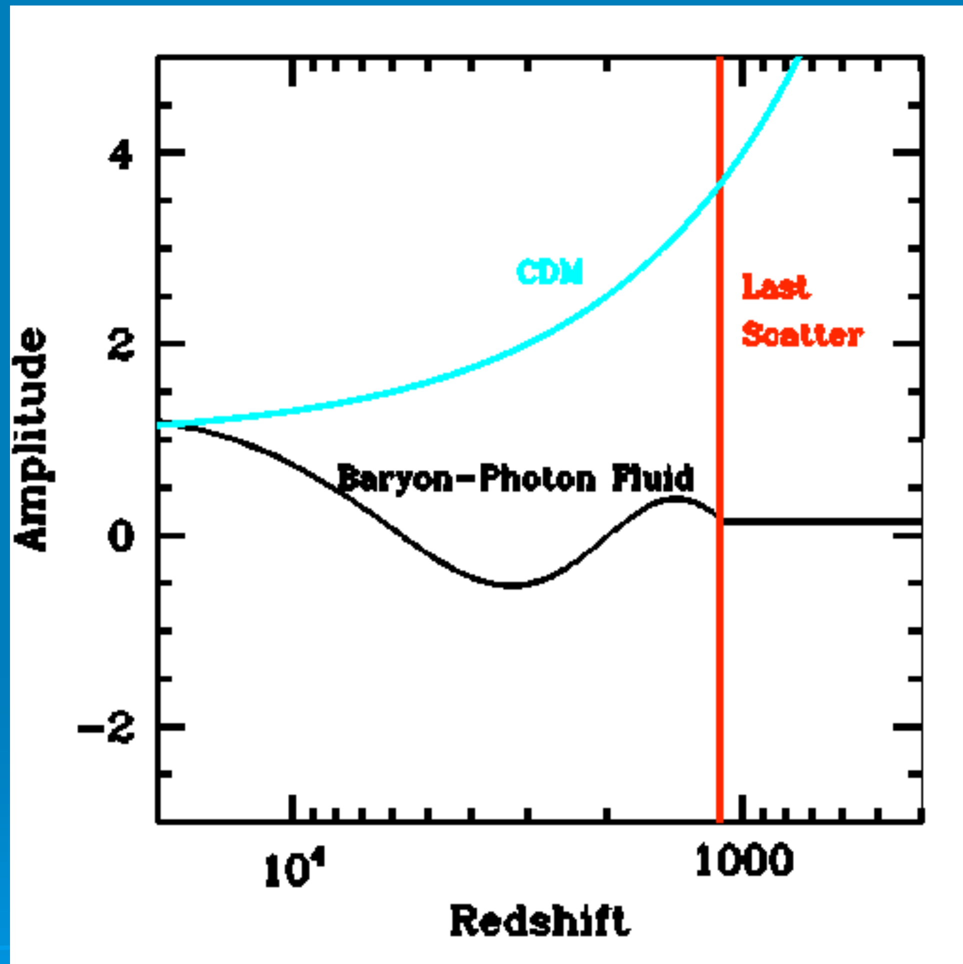


Thermal History of Universe



Growth of Fluctuations

- Linear theory
- Basic elements have been understood for 30 years (Peebles, Sunyaev & Zeldovich)
- Numerical codes agree at better than 0.1% (Seljak et al. 2003)



SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

Abstract. Perturbations of the matter density in a homogeneous and isotropic cosmological model which leads to the formation of galaxies should, at later stages of evolution, cause spatial fluctuations of relic radiation. Silk assumed that an adiabatic connection existed between the density perturbations at the moment of recombination of the initial plasma and fluctuations of the observed temperature of radiation $\delta T/T = \delta \varrho_m / 3\varrho_m$. It is shown in this article that such a simple connection is not applicable due to:

(1) The long time of recombination;

(2) The fact that when regions with $M < 10^{15} M_{\odot}$ become transparent for radiation, the optical depth to the observer is still large due to Thompson scattering;

(3) The spasmodic increase of $\delta \varrho_m / \varrho_m$ in recombination.

As a result the expected temperature fluctuations of relic radiation should be smaller than adiabatic fluctuations. In this article the value of $\delta T/T$ arising from scattering of radiation on moving electrons is calculated; the velocity field is generated by adiabatic or entropy density perturbations. Fluctuations of the relic radiation due to secondary heating of the intergalactic gas are also estimated. A detailed investigation of the spectrum of fluctuations may, in principle, lead to an understanding of the nature of initial density perturbations since a distinct periodic dependence of the spectral density of perturbations on wavelength (mass) is peculiar to adiabatic perturbations. Practical observations are quite difficult due to the smallness of the effects and the presence of fluctuations connected with discrete sources of radio emission.

Sunyaev & Zeldovich

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University

AND

J. T. YU‡
Goddard Institute for Space Studies, NASA, New York
Received 1970 January 5; revised 1970 April 1

ABSTRACT

The general qualitative behavior of linear, first-order density perturbations in a Friedmann-Lemaître cosmological model with radiation and matter has been known for some time in the various limiting situations. An exact quantitative calculation which traces the entire history of the density fluctuations is lacking because the usual approximations of a very short photon mean free path before plasma recombination, and a very long mean free path after, are inadequate. We present here results of the direct integration of the collision equation of the photon distribution function, which enable us to treat in detail the complicated regime of plasma recombination. Starting from an assumed initial power spectrum well before recombination, we obtain a final spectrum of density perturbations after recombination. The calculations are carried out for several general-relativity models and one scalar-tensor model. One can identify two characteristic masses in the final power spectrum: one is the mass within the Hubble radius *ct* at recombination, and the other results from the linear dissipation of the perturbations prior to recombination. Conceivably the first of these numbers is associated with the great rich clusters of galaxies, the second with the large galaxies. We compute also the expected residual irregularity in the radiation from the primeval fireball. If we assume that (1) the rich clusters formed from an initially adiabatic perturbation and (2) the fireball radiation has not been seriously perturbed after the epoch of recombination of the primeval plasma, then with an angular resolution of 1 minute of arc the rms fluctuation in antenna temperature should be at least $\delta T/T = 0.00015$.

I. INTRODUCTION

CMB Overview

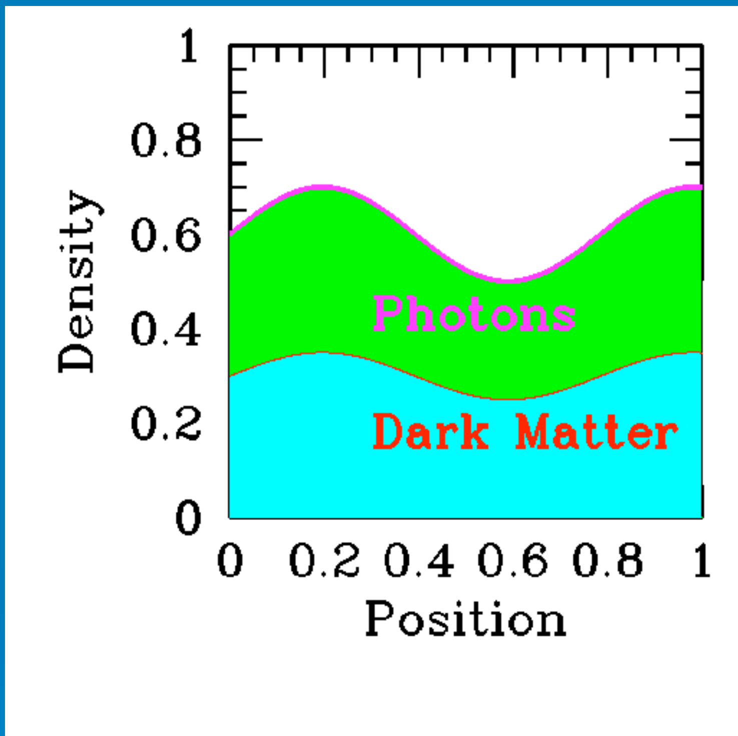
$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

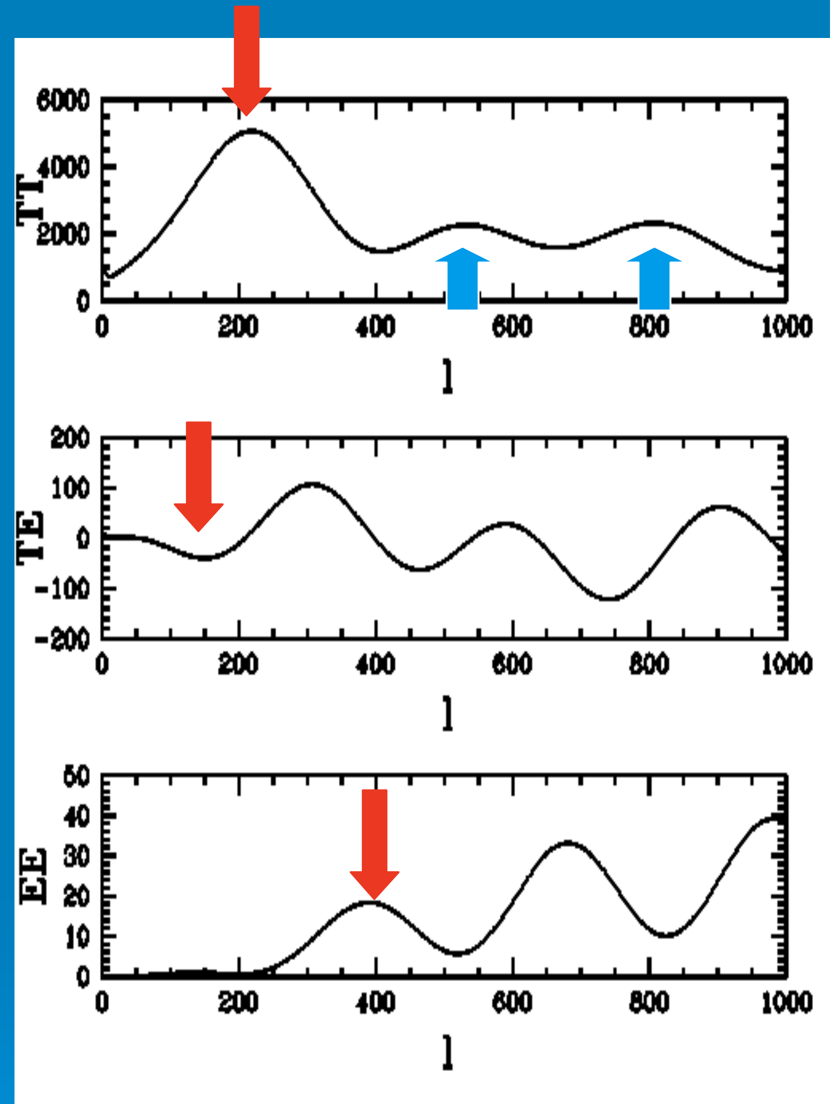
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

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

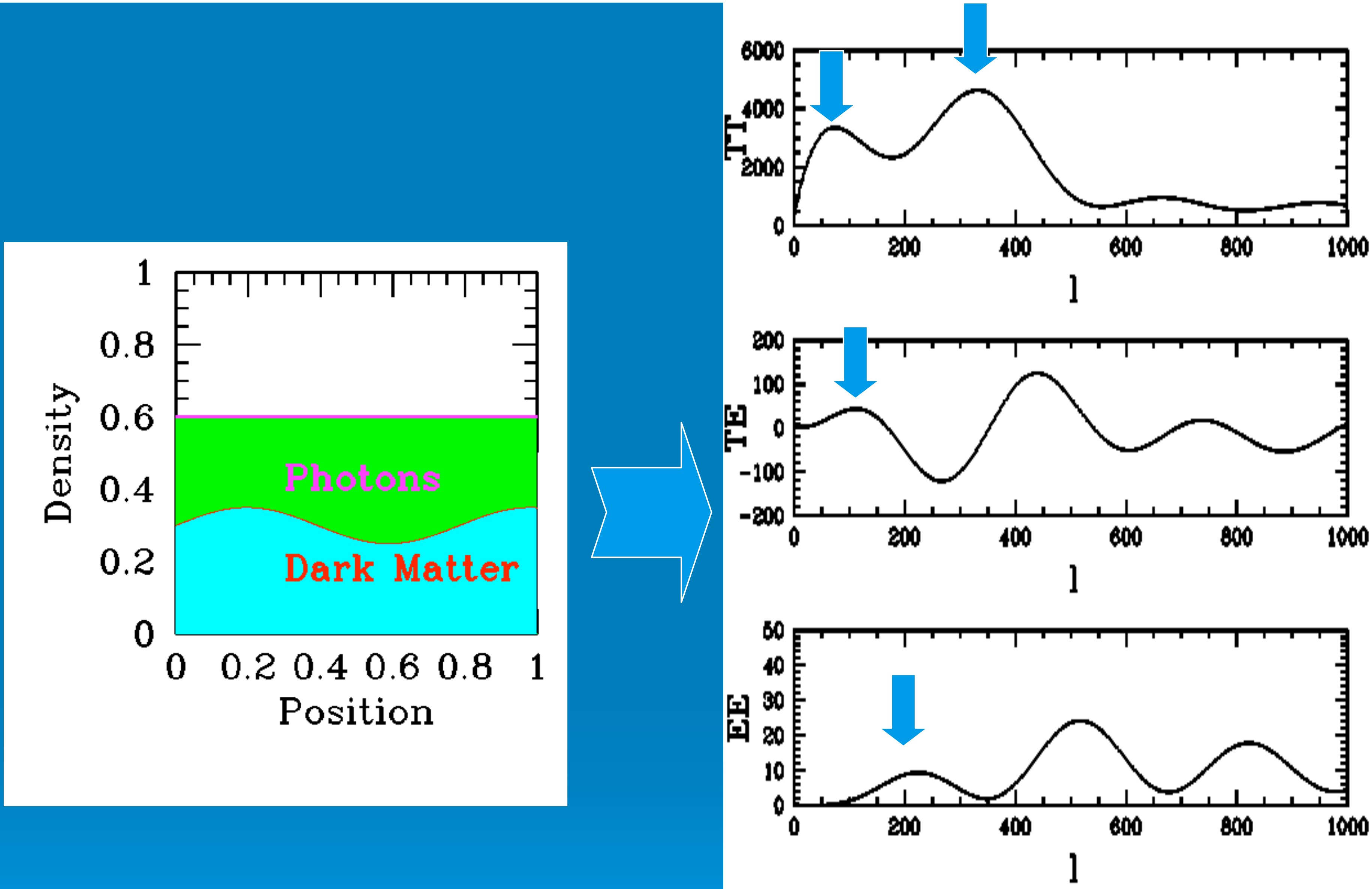
- We can detect both CMB temperature and polarization fluctuations
- Polarization Fluctuations can be decomposed into E and B modes

q ~180/ℓ





ADIABATIC DENSITY FLUCTUATIONS



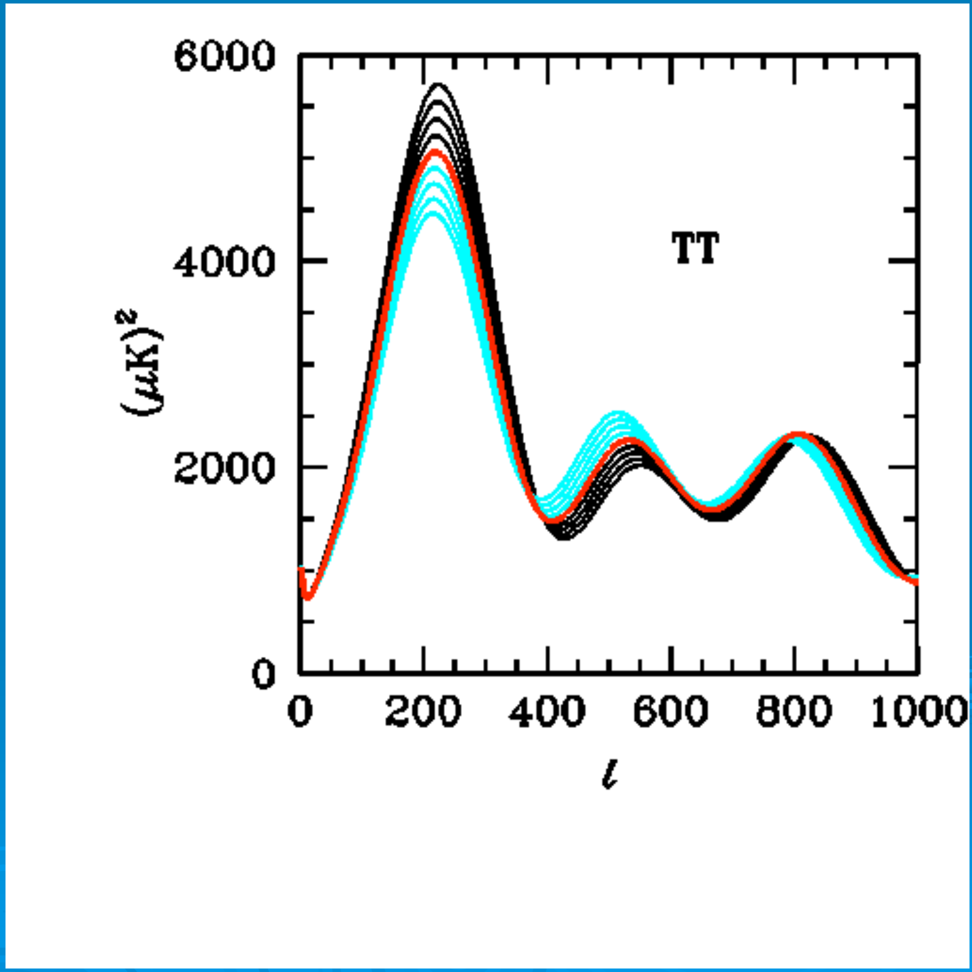
ISOCURVATURE ENTROPY FLUCTUATIONS

Determining Basic Parameters

Baryon Density

$W_b h^2 = 0.015, 0.017..0.031$

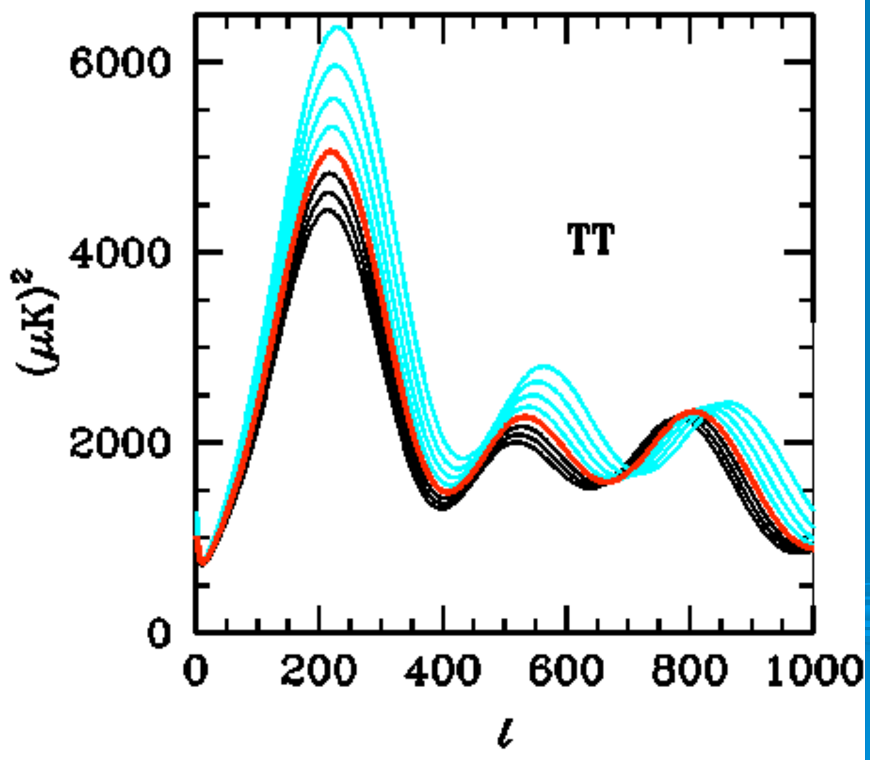
also measured through D/H



Determining Basic Parameters

Matter Density

$W_m h^2 = 0.16,..,0.33$

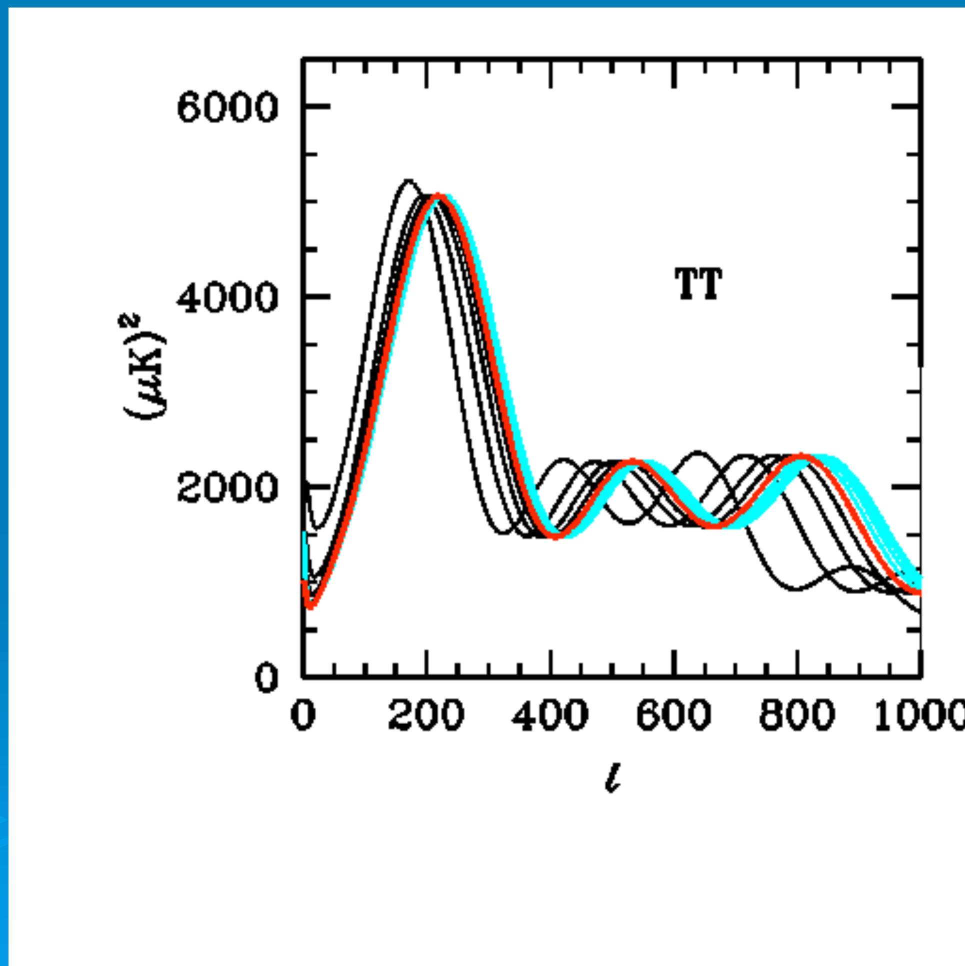


Determining Basic Parameters

Angular Diameter Distance

w = -1.8,..,-0.2

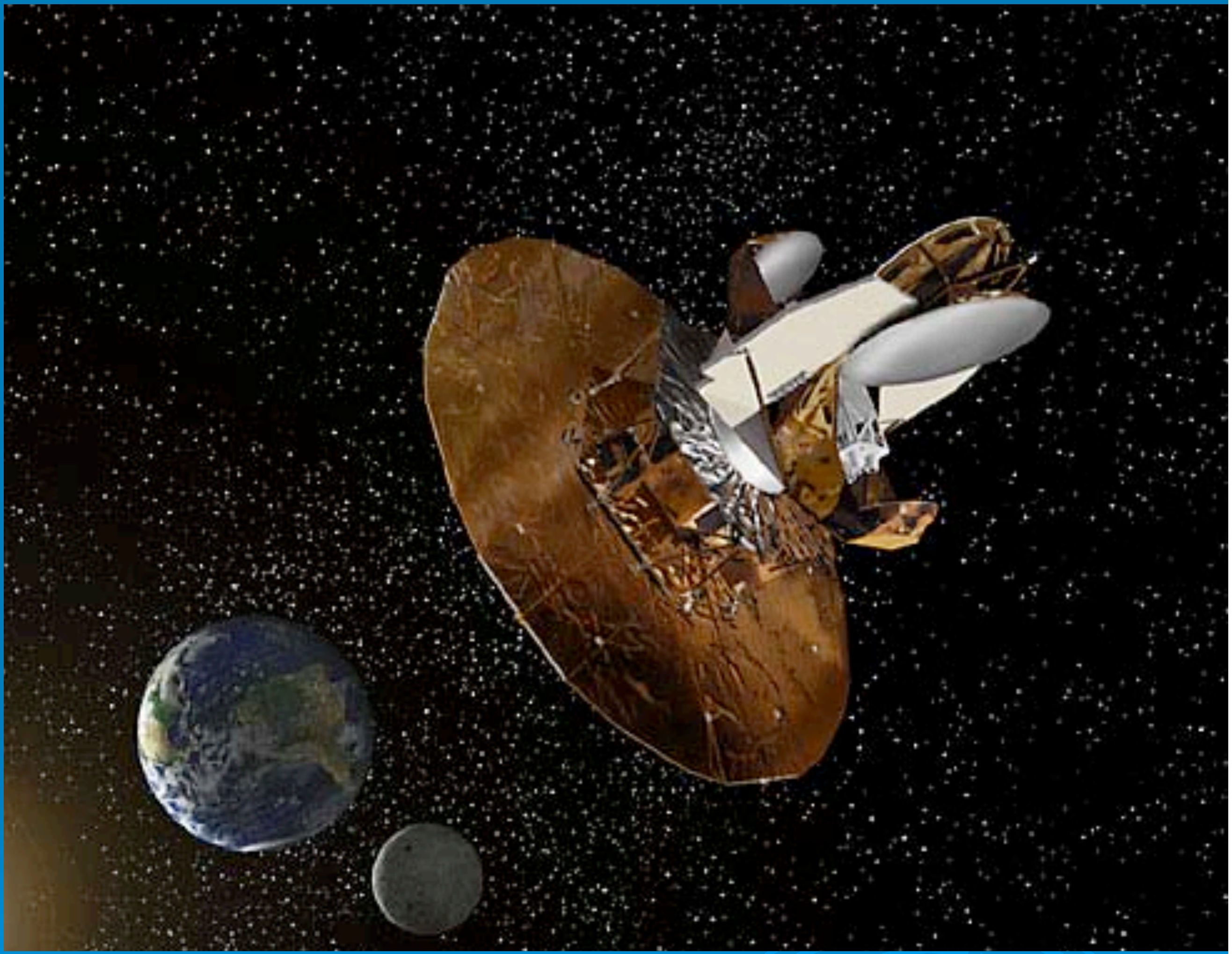
When combined with measurement of matter density constrains data to a line in Ω_m-w space



Wilkinson Microwave Anisotropy Probe

A partnership between NASA/GSFC and Princeton

Science Team:



NASA

Michael Greason
Bob Hill
Gary Hinshaw
Al Kogut
Michele Limon
Nils Odegard
Janet Weiland
Ed Wollack

UCLA

Ned Wright

Brown

Greg Tucker

Chicago

Stephan Meyer

UBC

Mark Halpern

Texas

Eiichiro Komatsu

Toronto

Michael Nolta

Princeton

Norm Jarosik
Lyman Page
David Spergel
Joanna Dunkley

Johns Hopkins

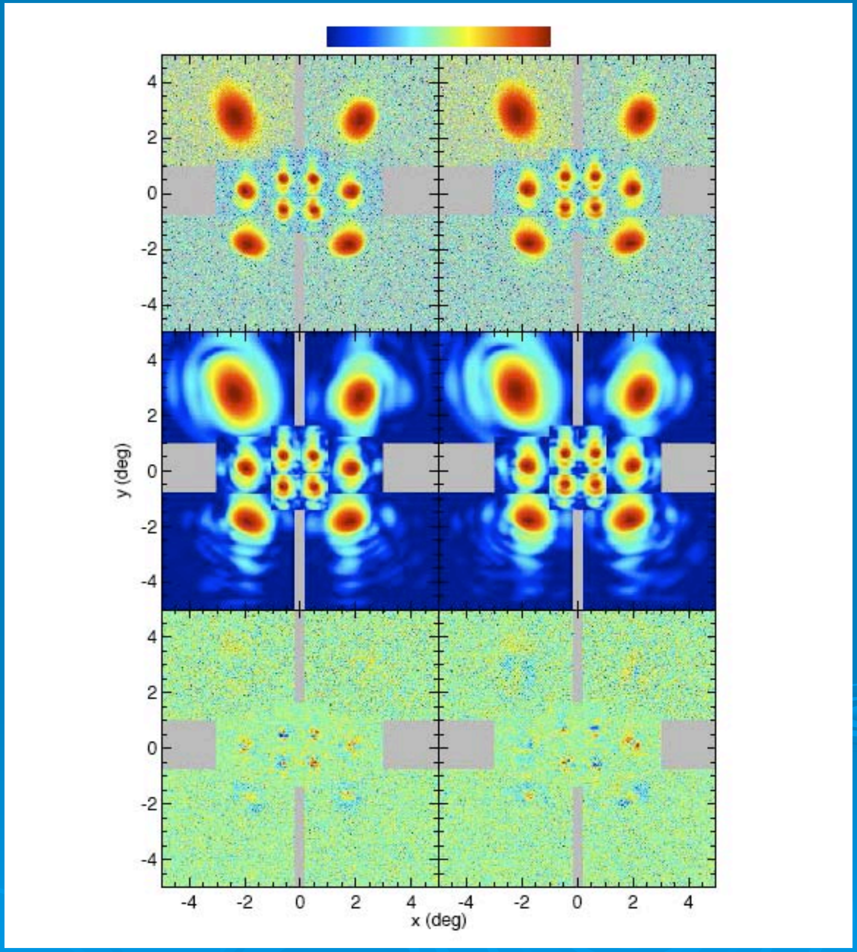
Chuck Bennett
Ben Gold
David Larson

What is New in the Analysis?

- More data (errors reduced by 3/5)
- Better beam model
- Improvements in gain model
  - Calibration uncertainty drops from 0.5% to 0.2%
- Improvements in likelihood function
- Improved Sky Mask
- Better estimators for non-linearity

Beam Modelling

- Full Vector EM modelling of distortions in primary and secondary mirror
- Calibration off of Jupiter, Moon, and ground-based testing



Beam Modelling

- Full Vector EM modelling of distortions in primary and secondary mirror
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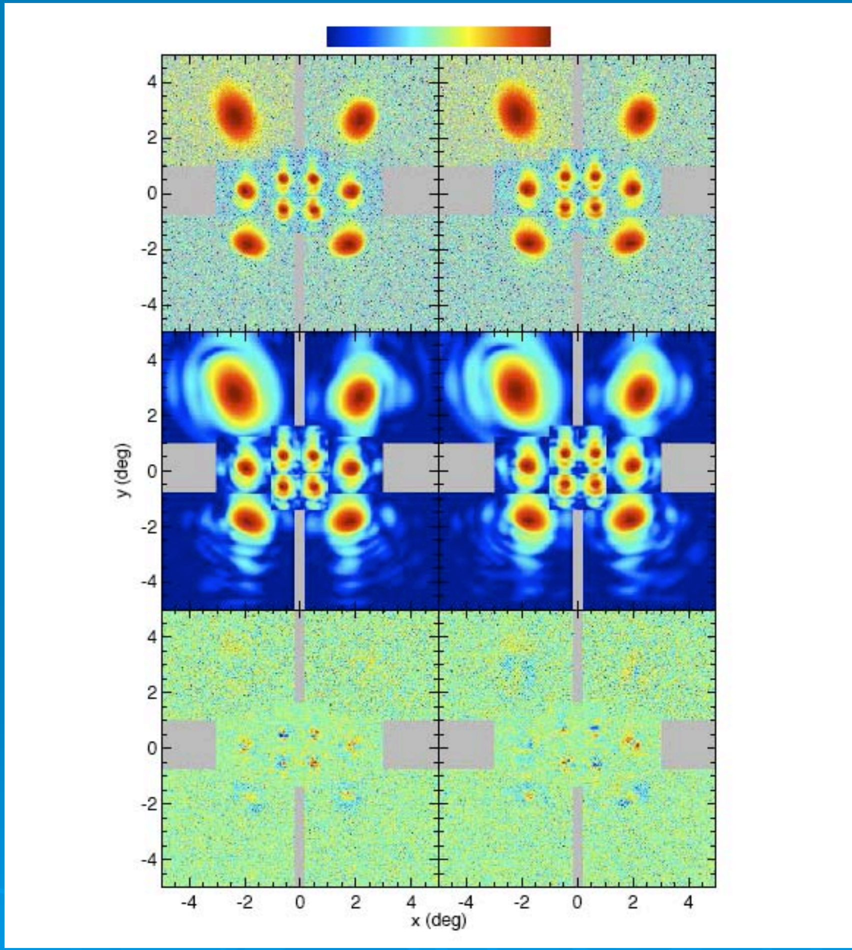
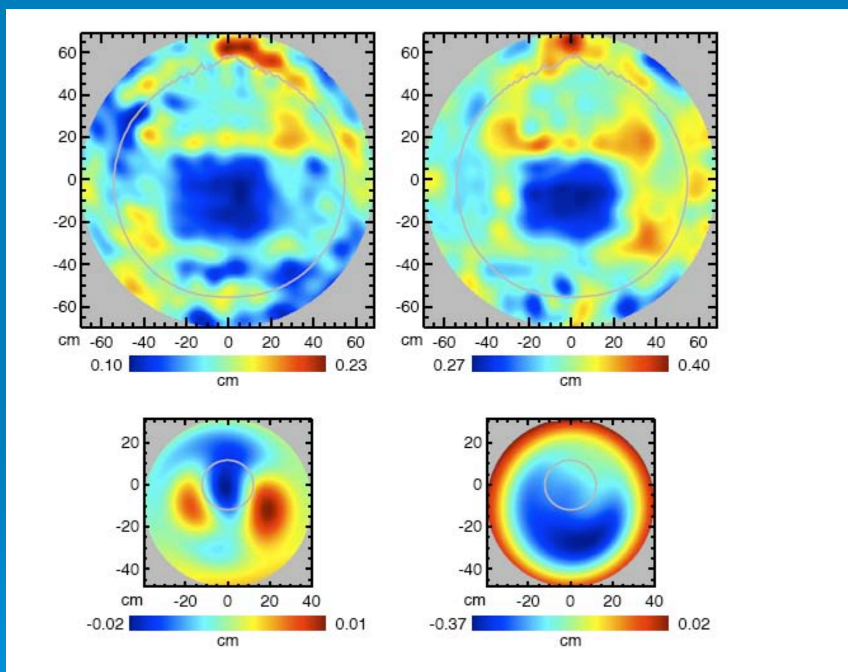
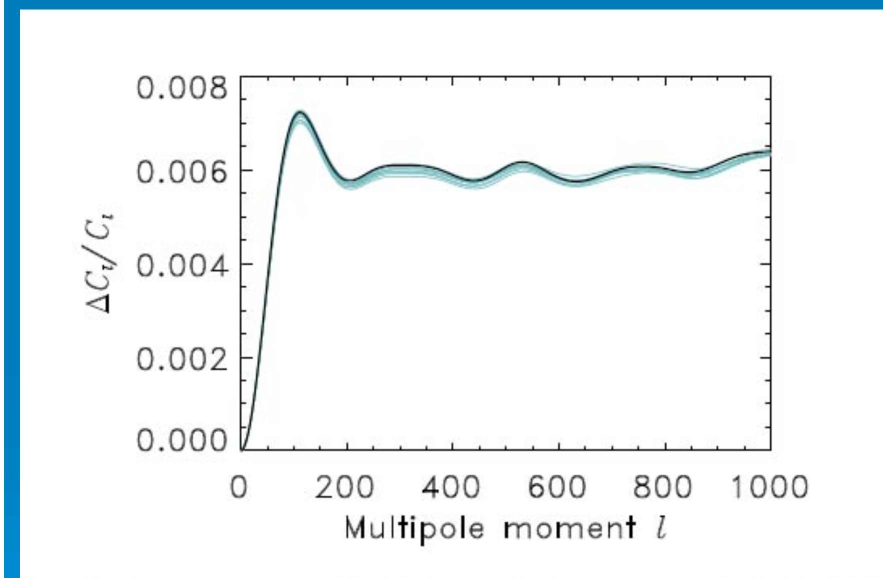


Beam Models

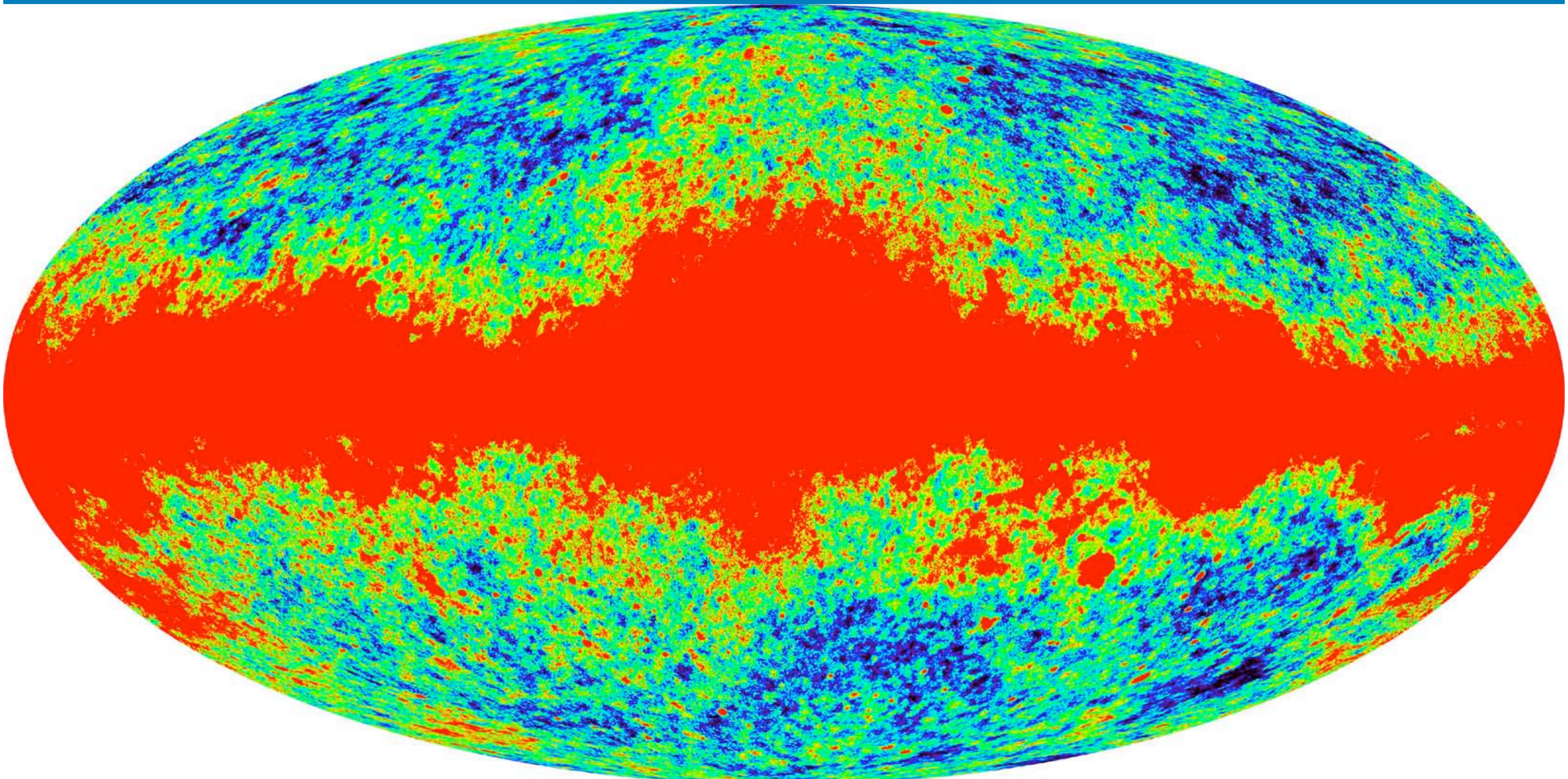


cm
0.10
0.23
0.27
0.40
-0.02
0.01
-0.37
0.02

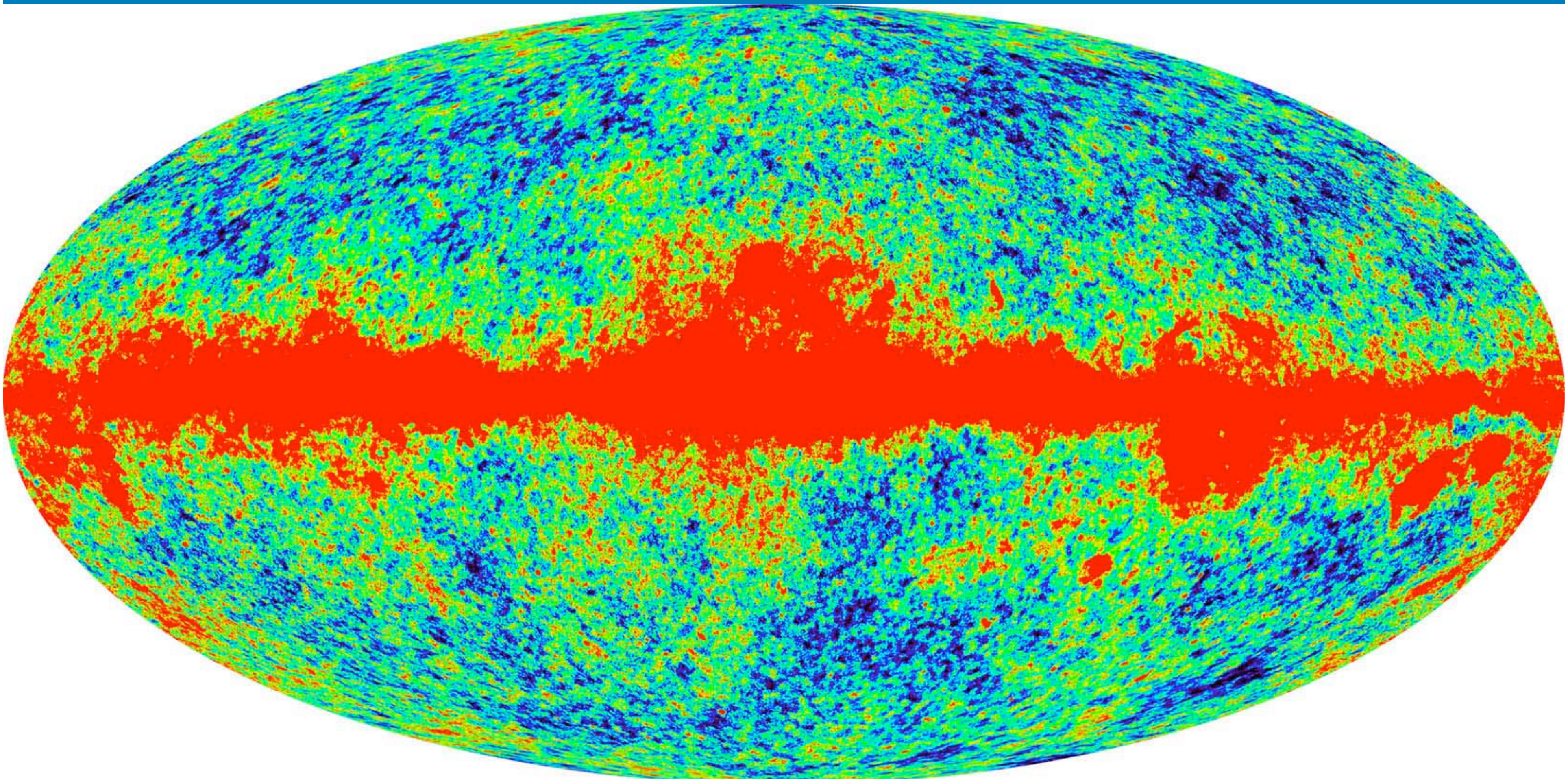


$\Delta C_l / C_l$
Multipole moment l

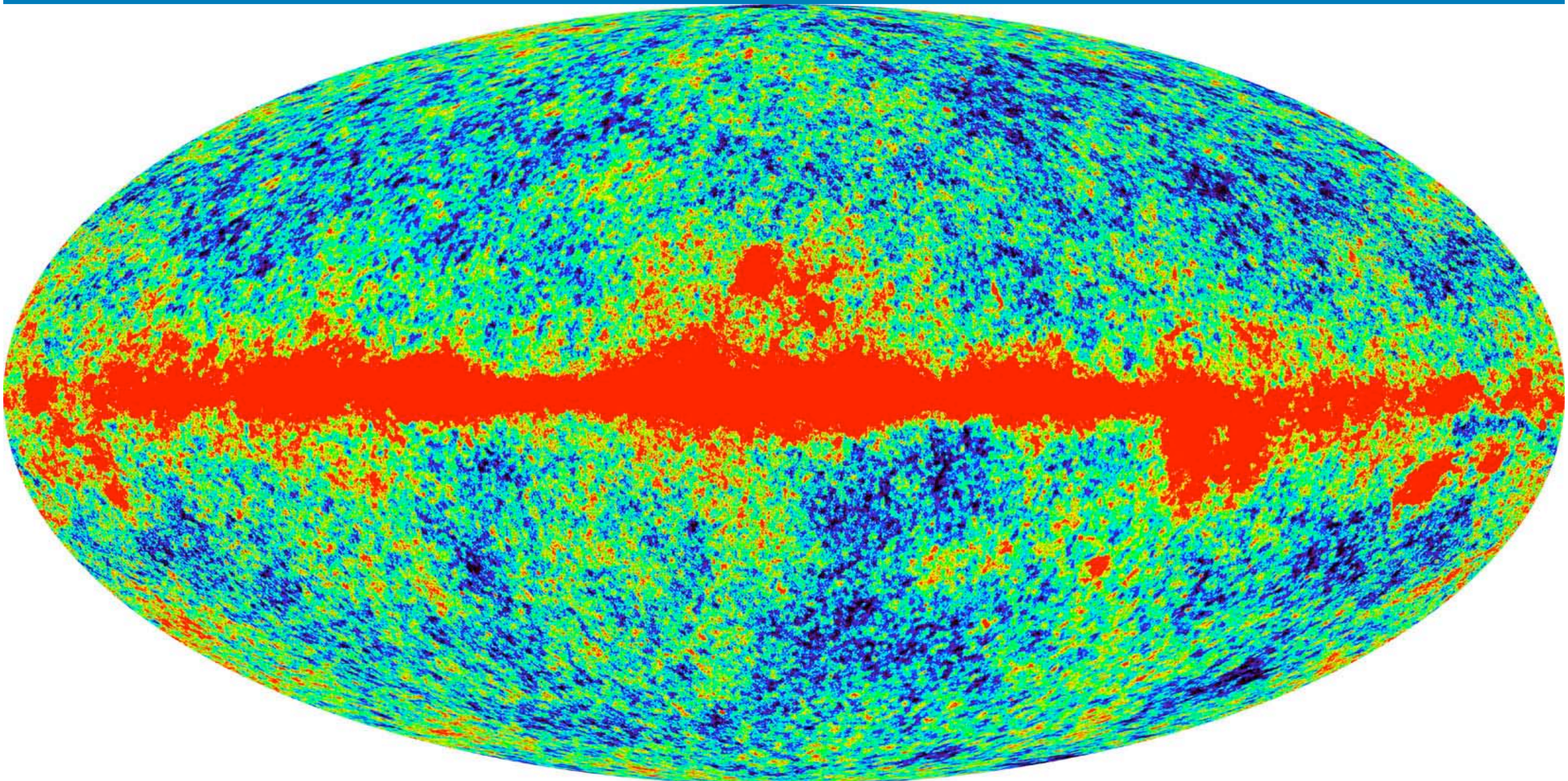
K - 22GHz



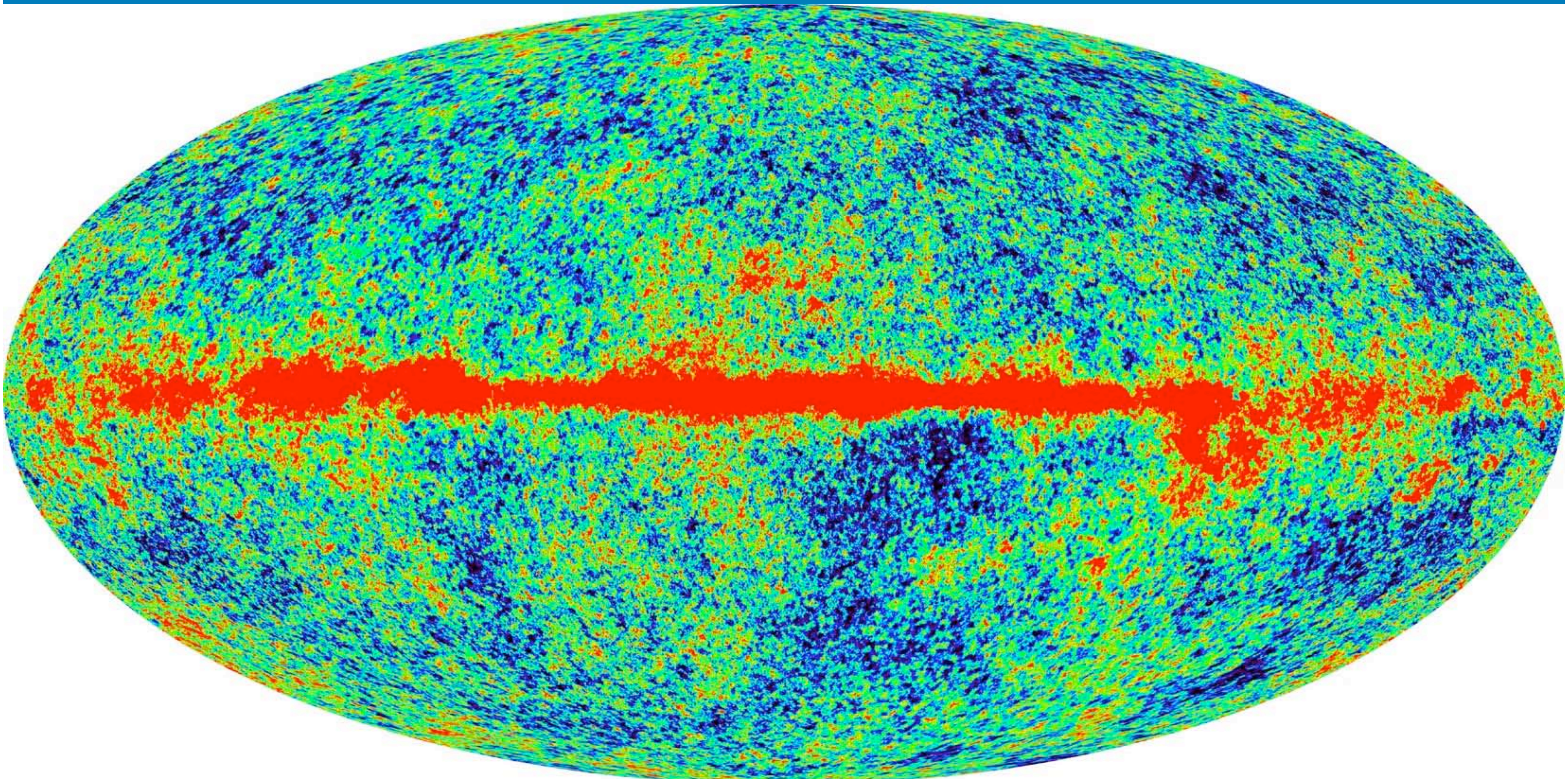
Ka - 33GHz



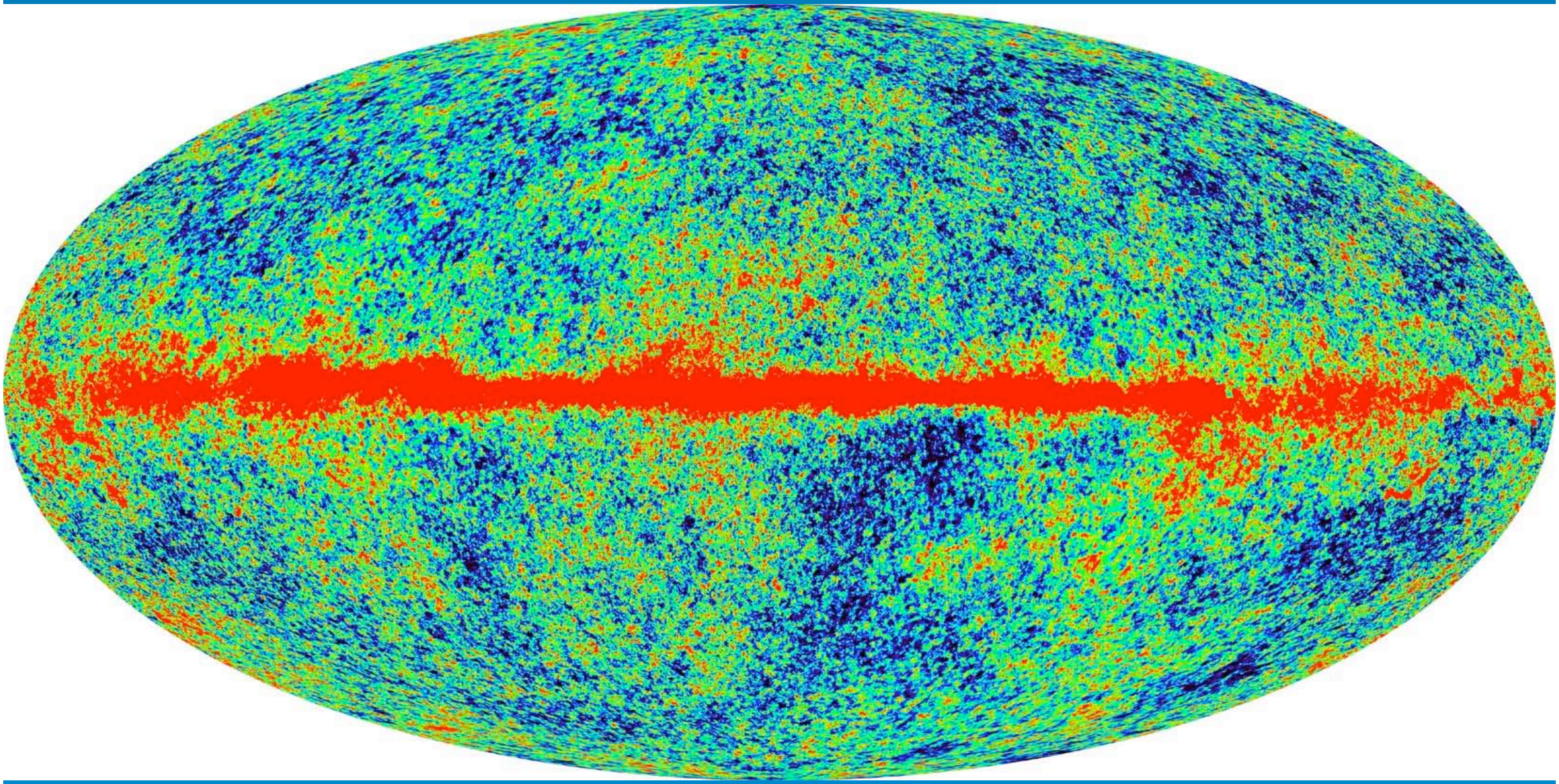
Q - 41GHz

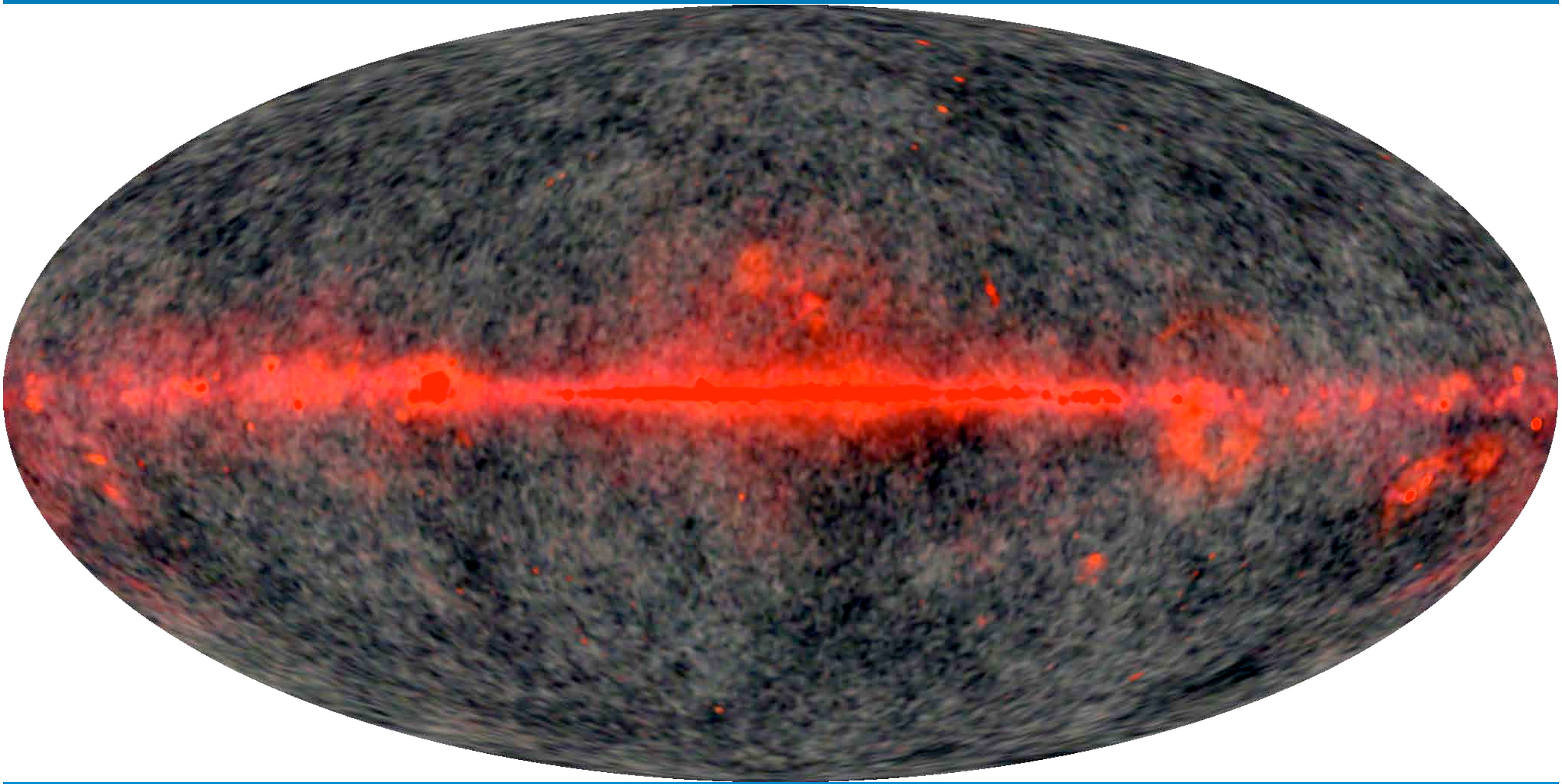


V - 61GHz

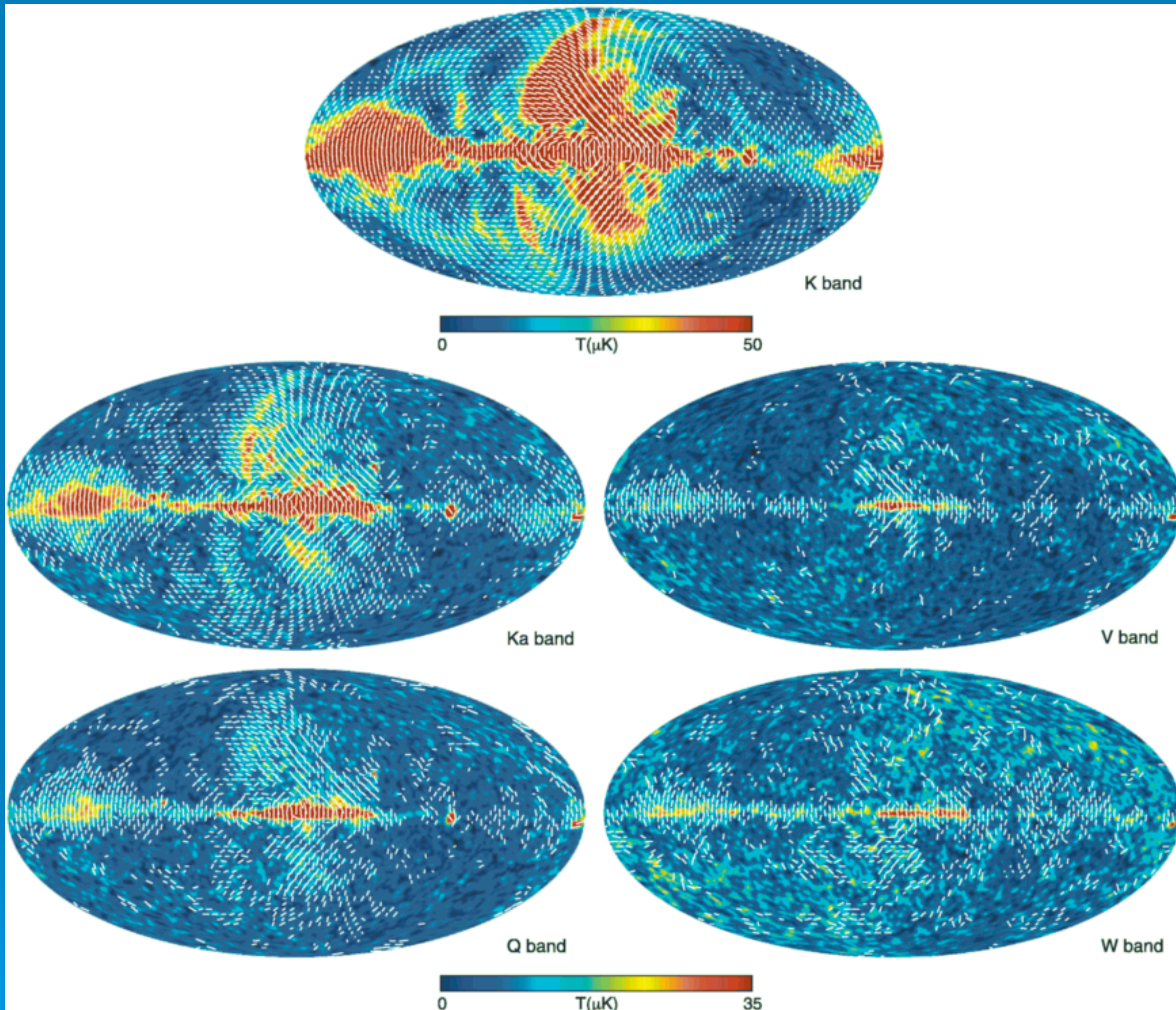


W - 94GHz



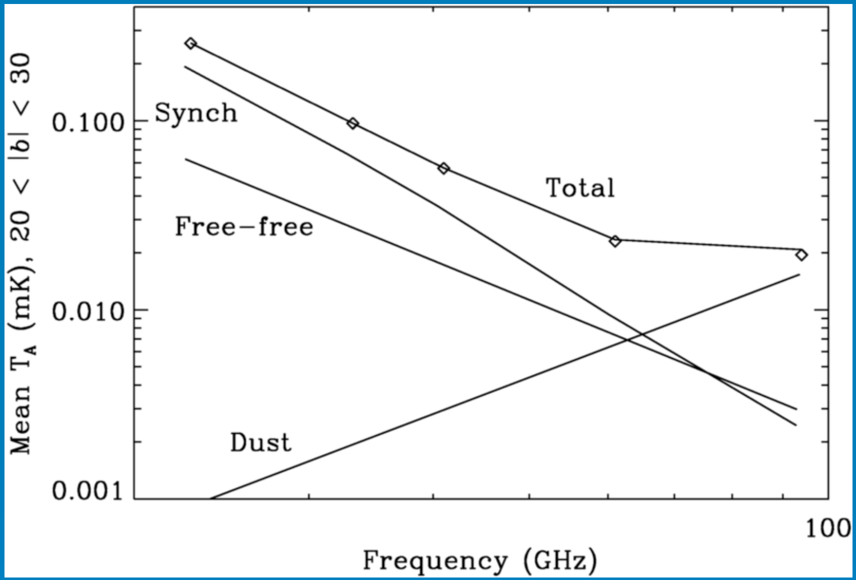


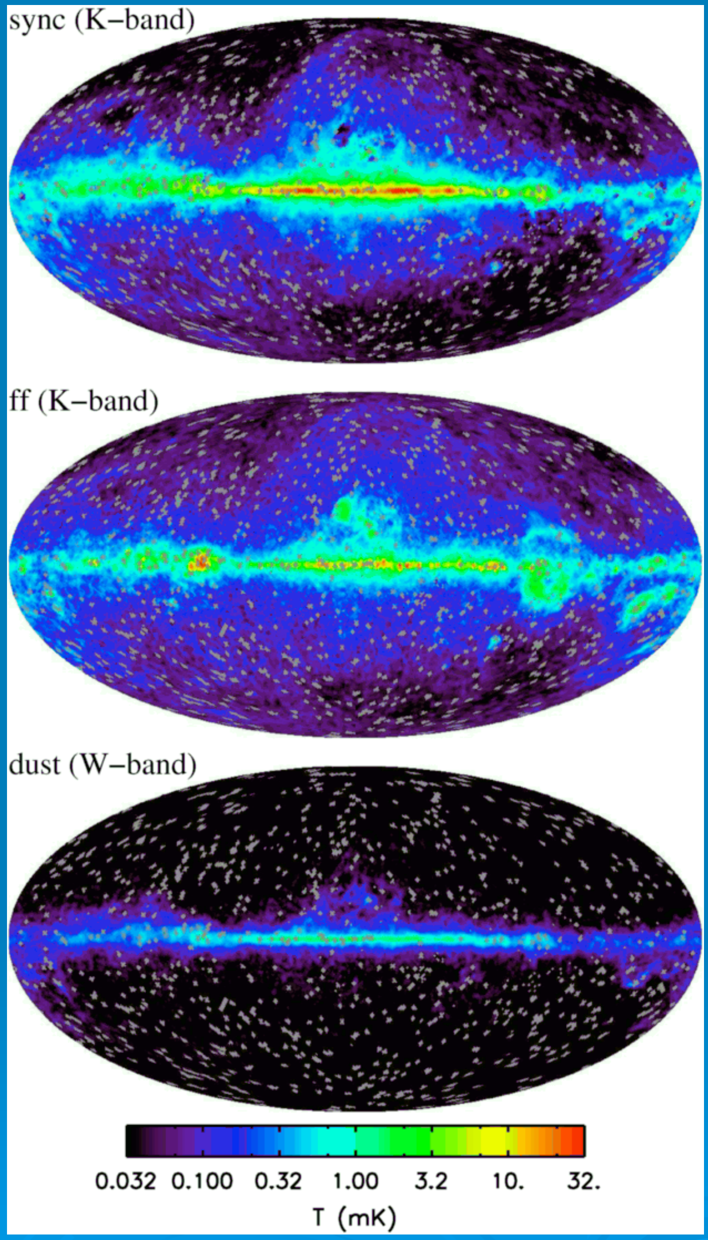
Q band
V band
W band

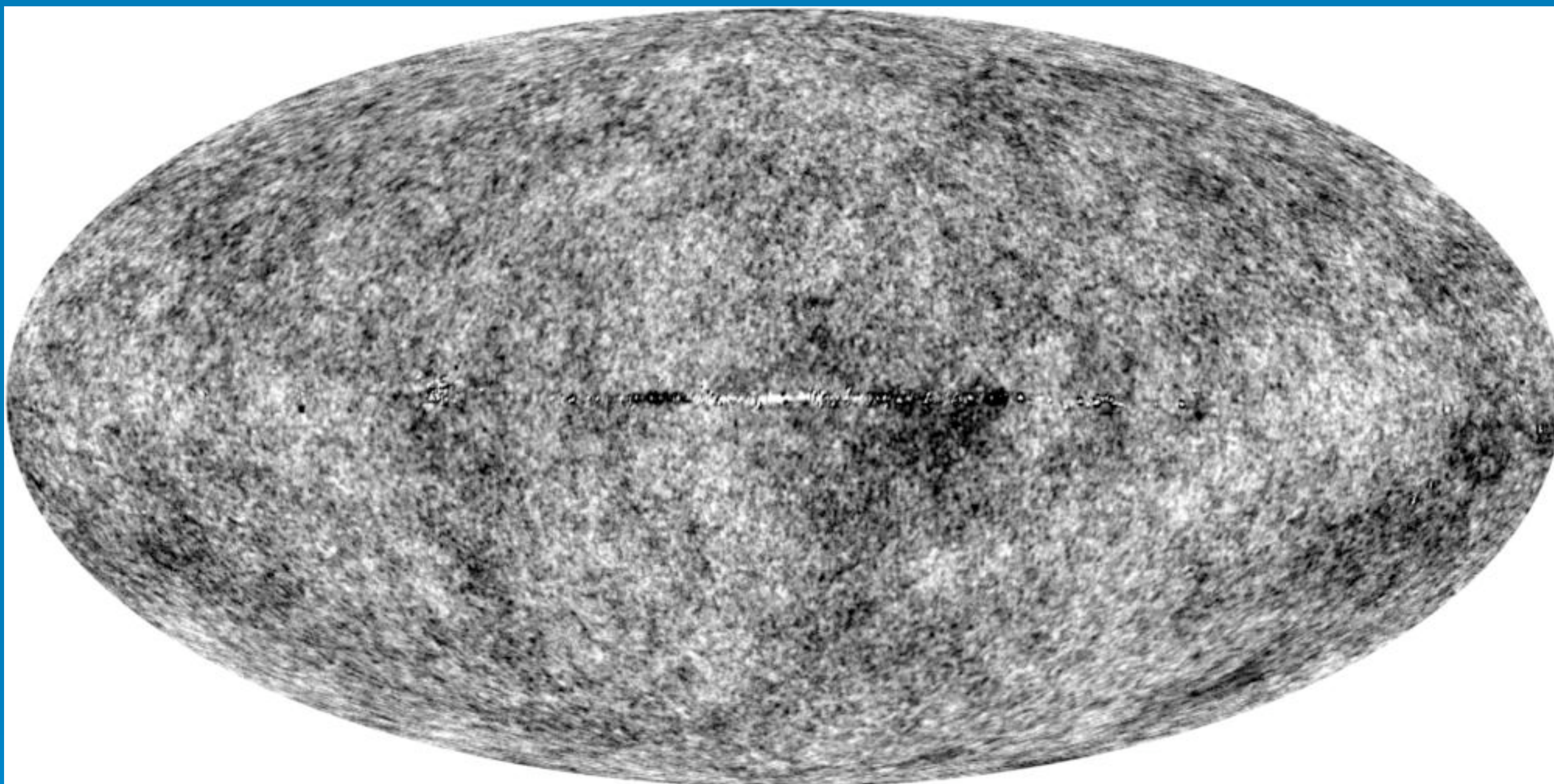

K band
0
T(μK)
50
Ka band
V band
Q band
W band
0
T(μK)
35

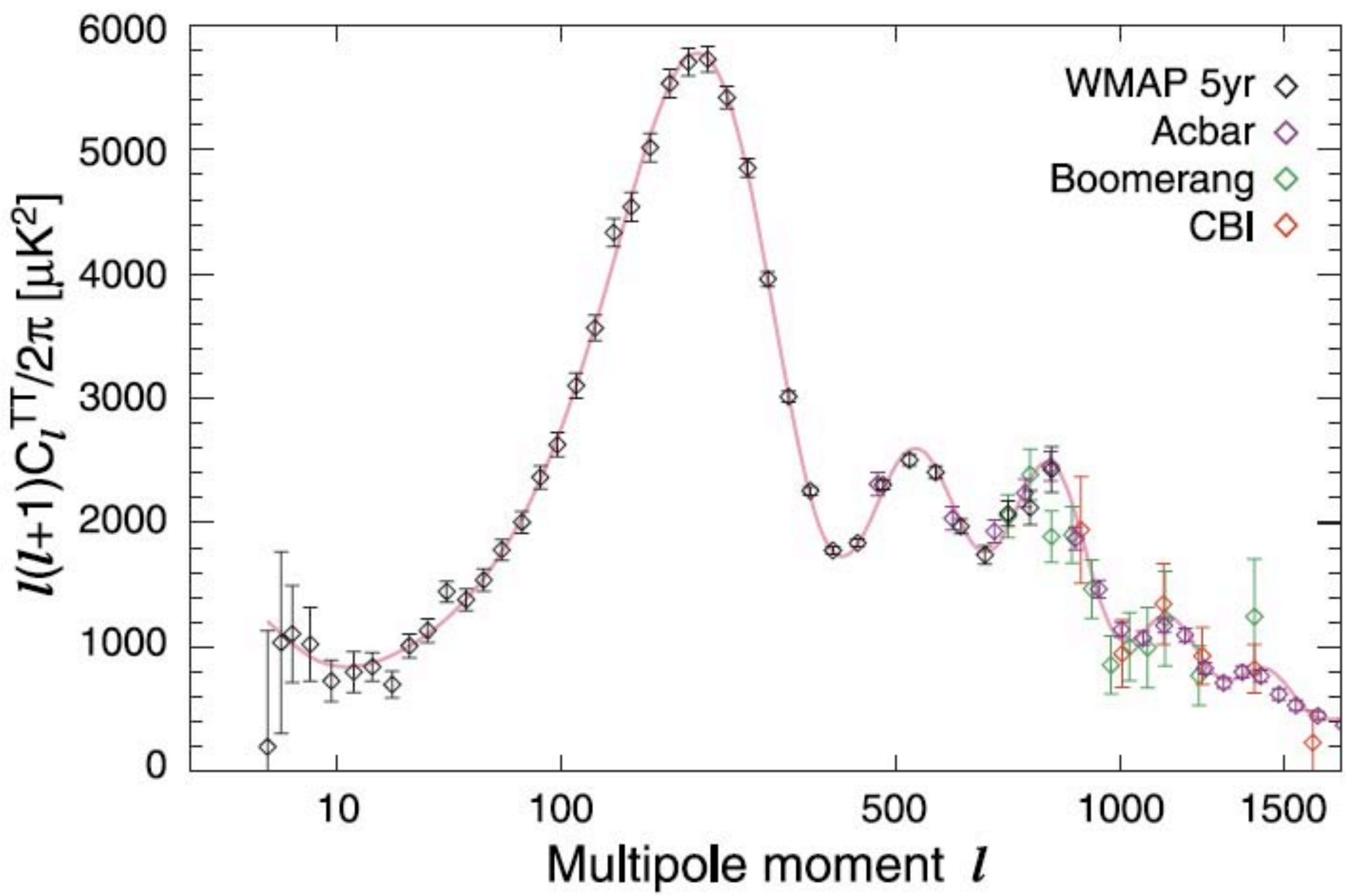
Foregrounds

- Galactic
  - Synchrotron (polarized)
  - Free-Free
  - Thermal Dust
  - Spinning Dust
- Radio Sources



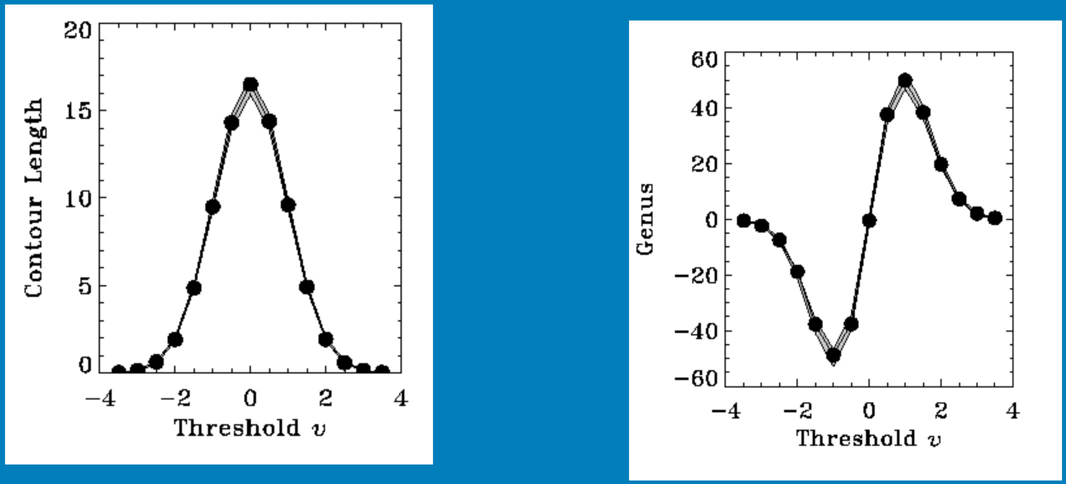

sync (K−band)
ff (K−band)
dust (W−band)
0.032 0.100 0.32 1.00 3.2 10. 32.
T (mK)

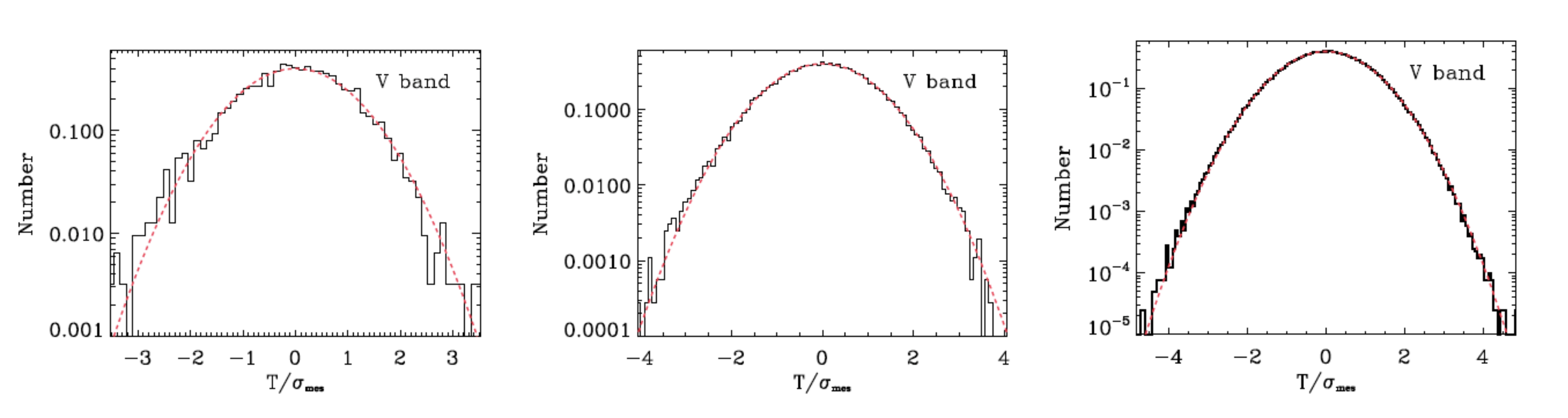




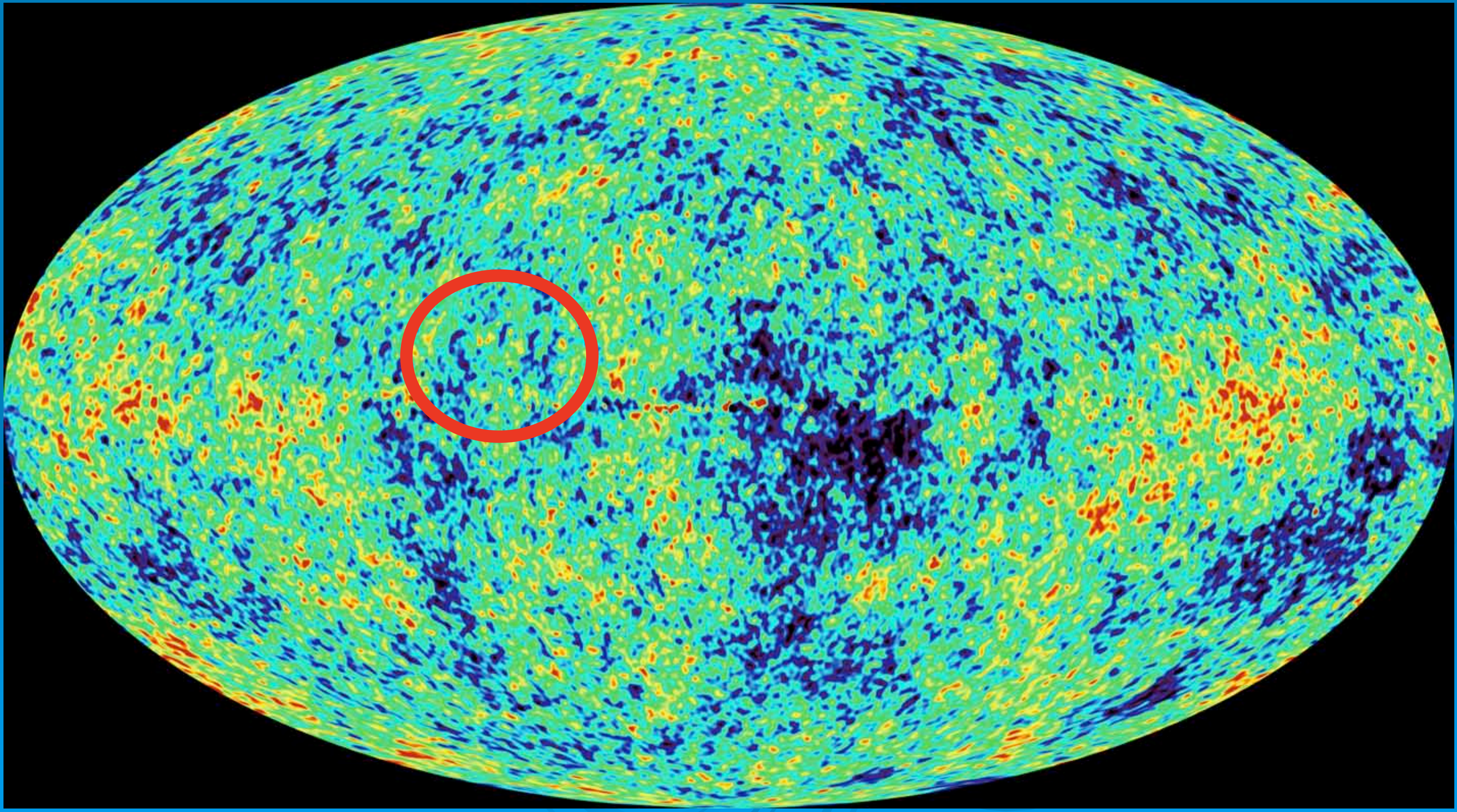
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l
$l(l+1)C_l^{TT}/2\pi\ [\mu K^2]$
WMAP 5yr
Acbar
Boomerang
CBI

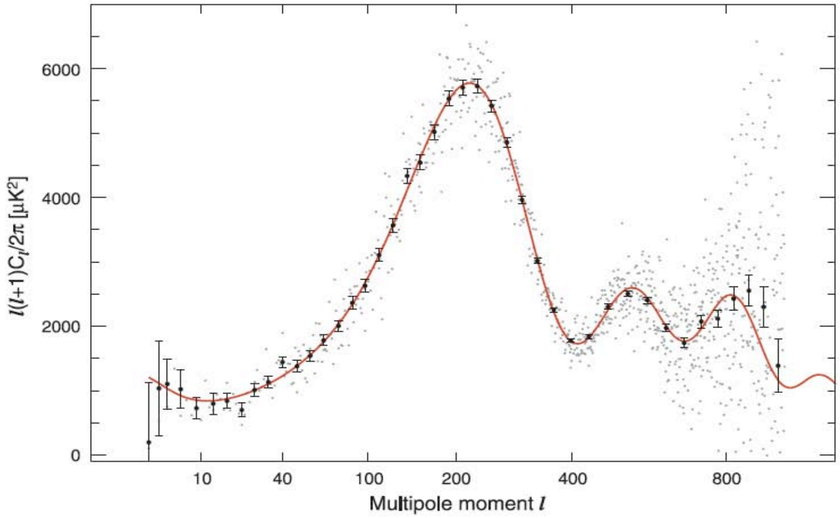
Fluctuations Appear to be Gaussian

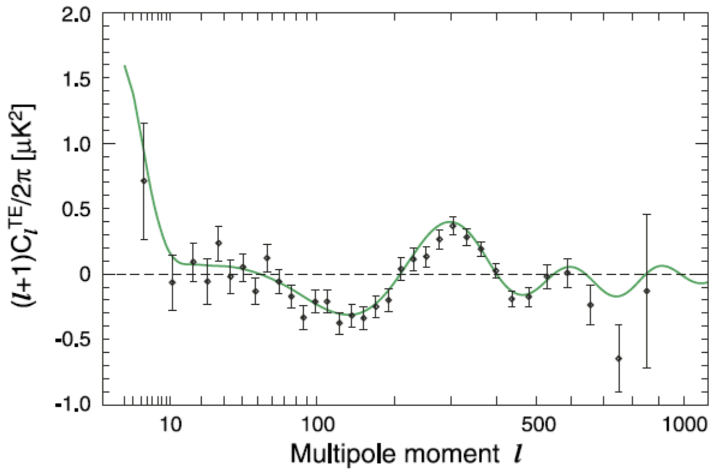




FOREGROUND CORRECTED MAP



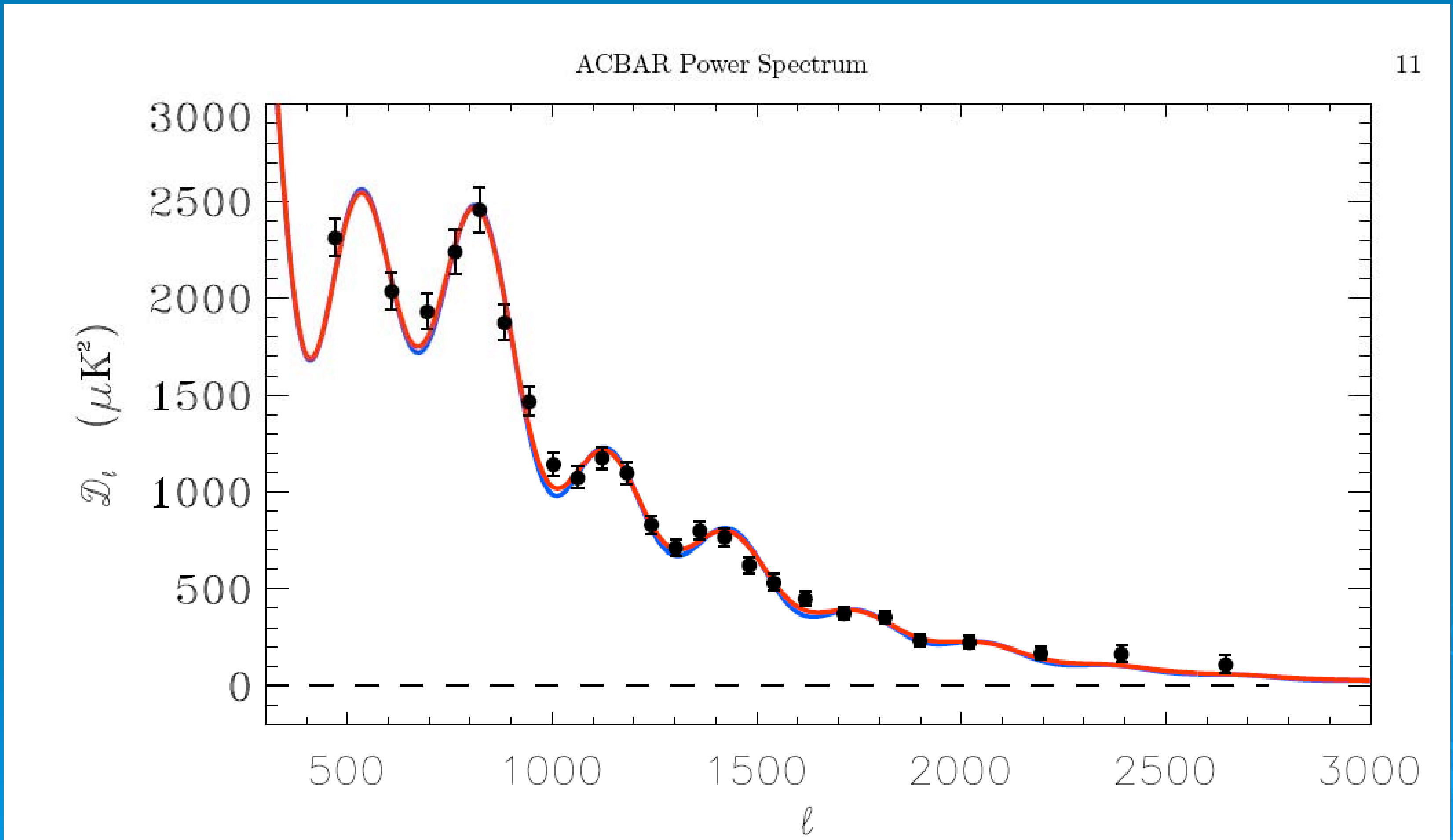




Reduced C^2 =1.06 for l = 33-1000

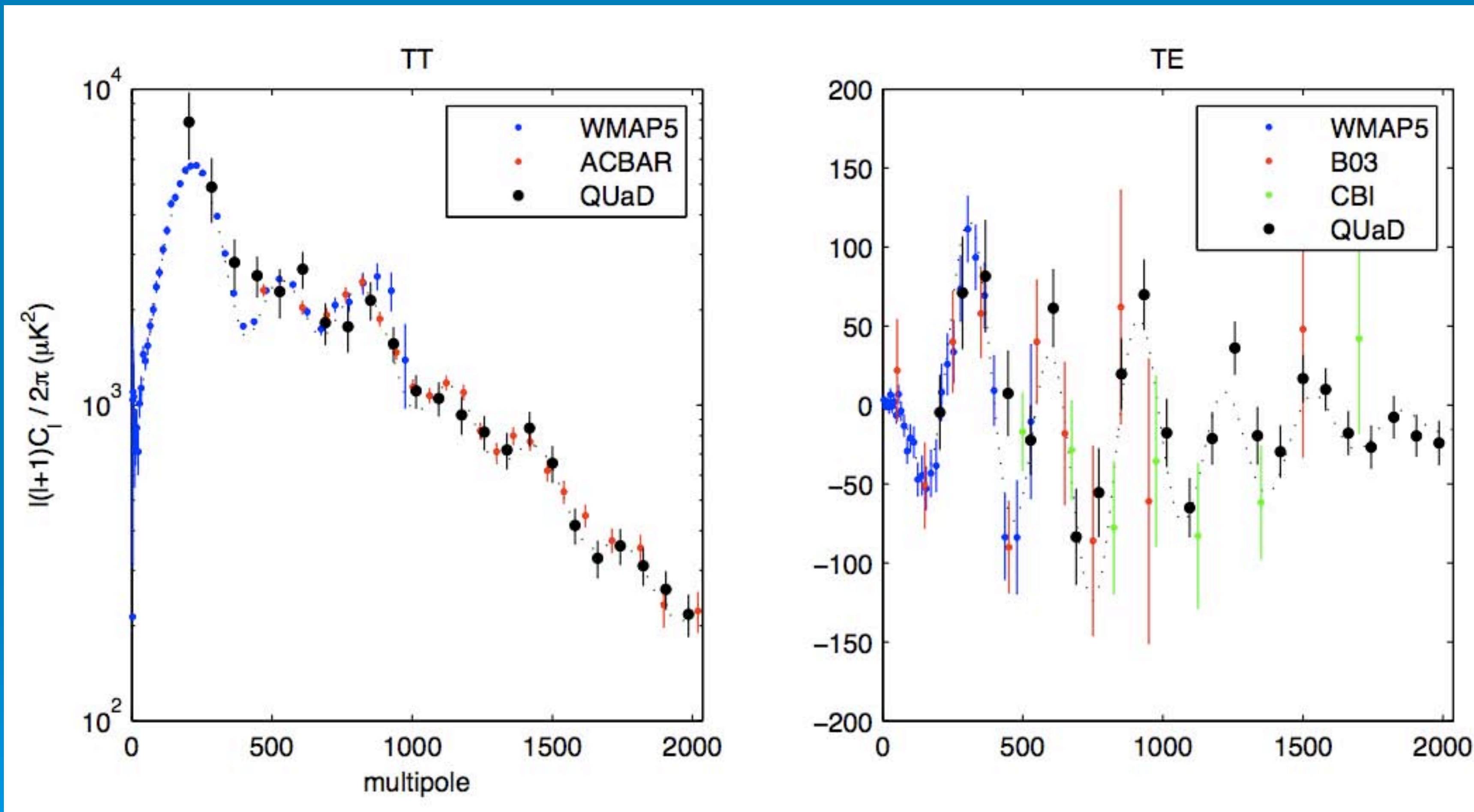
Atomic Density	$\Omega_b h^2$	$2.273 \pm 0.062 \times 10^{-2}$
Matter Density	$\Omega_m h^2$	0.1326 ± 0.0063
Amplitude	σ_8	0.796 ± 0.036
Spectral Index	n_s	$0.963^{+0.014}_{-0.015}$
Age	t_0	13.69 ± 0.13
Optical Depth	τ	0.087 ± 0.017

ACBAR



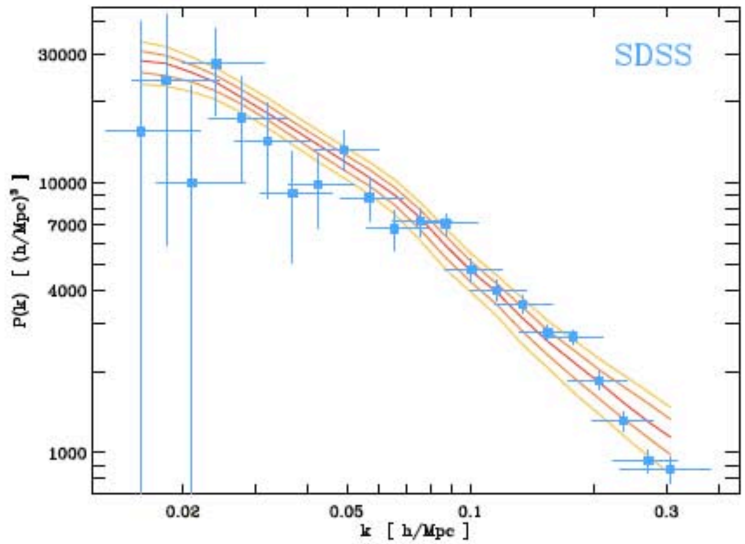
Reichardt et al. 2008 astro-ph/0801.1491

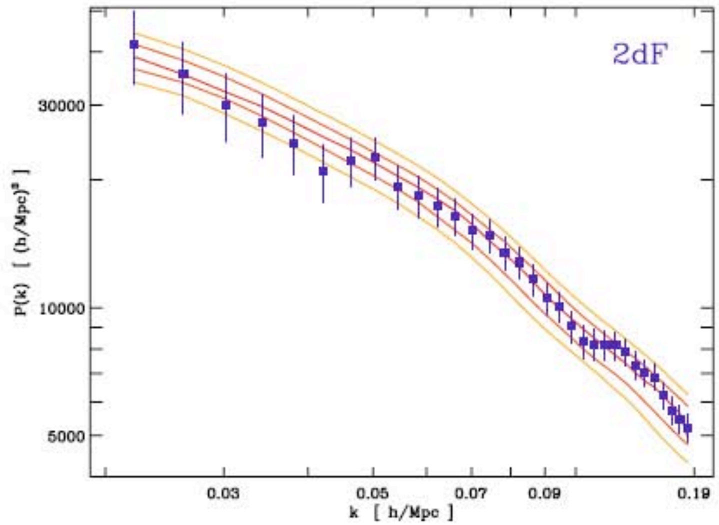
QUAD

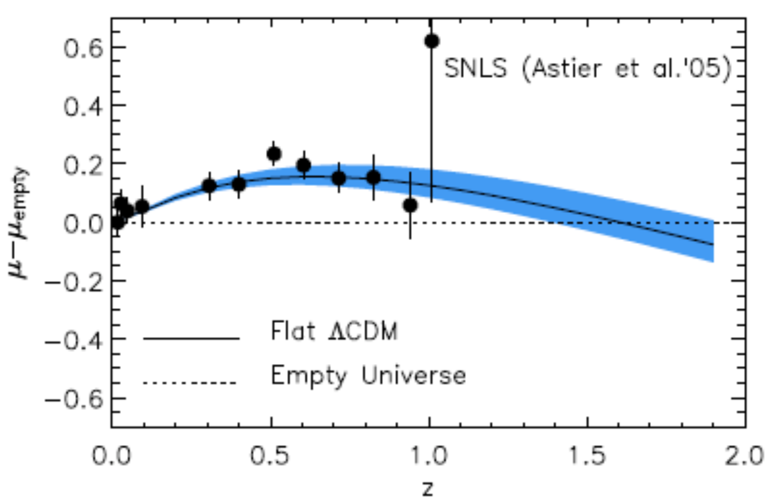


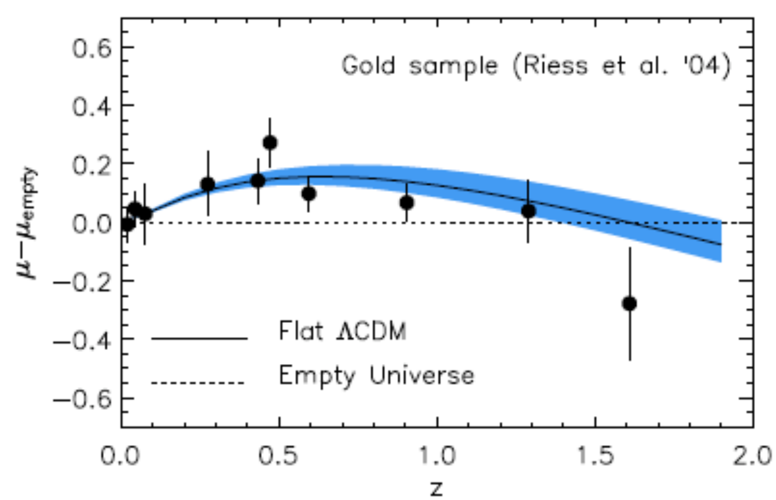
Pryke et al. 0805.1944

From Baby Pictures to Today's Universe


SDSS
P(k) [(h/Mpc)³]
30000
10000
7000
4000
1000
0.02
0.05
0.1
0.3
k [h/Mpc]

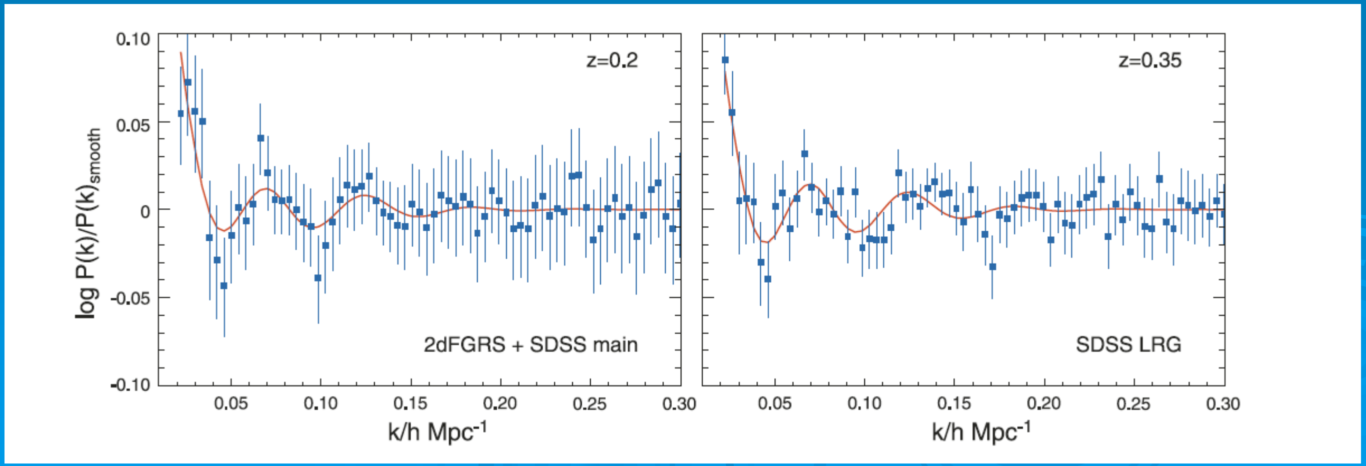

2dF
P(k) [(h/Mpc)³]
30000
10000
5000
0.03
0.05
0.07
0.09
0.19
k [h/Mpc]


SNLS (Astier et al.'05)
$\mu - \mu_{empty}$
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Flat ΛCDM
Empty Universe
0.0
0.5
1.0
1.5
2.0
z


Gold sample (Riess et al. '04)
$\mu - \mu_{empty}$
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Flat ΛCDM
Empty Universe
0.0
0.5
1.0
1.5
2.0
z

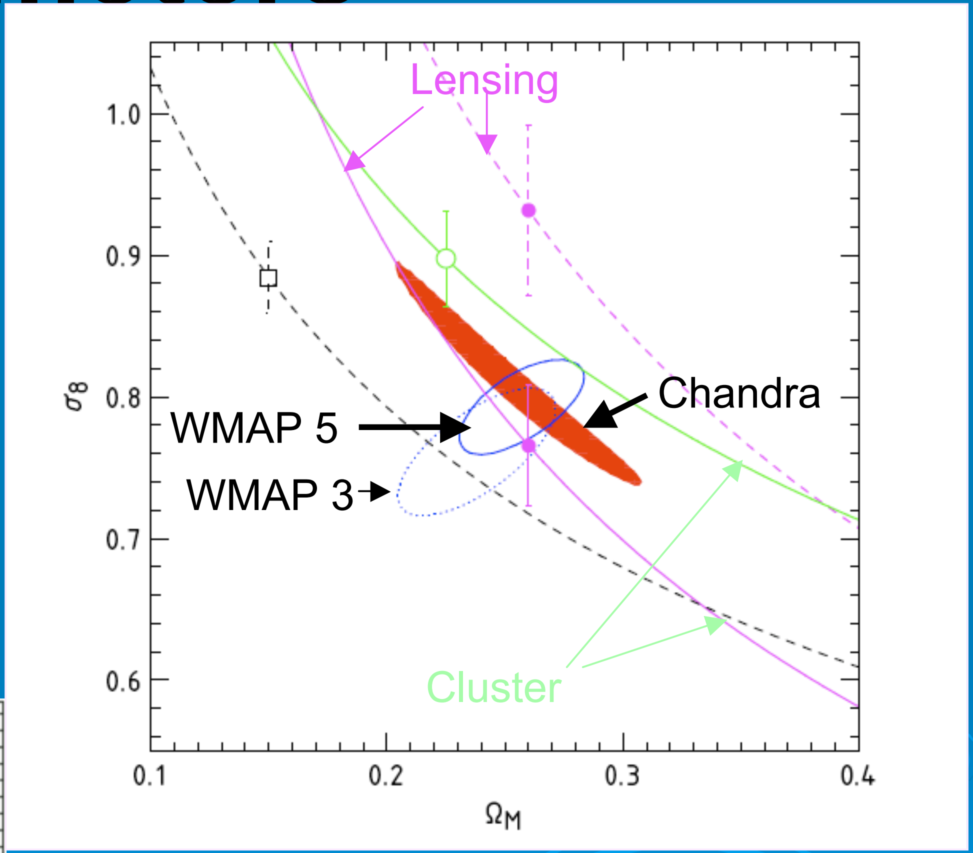
Consistency

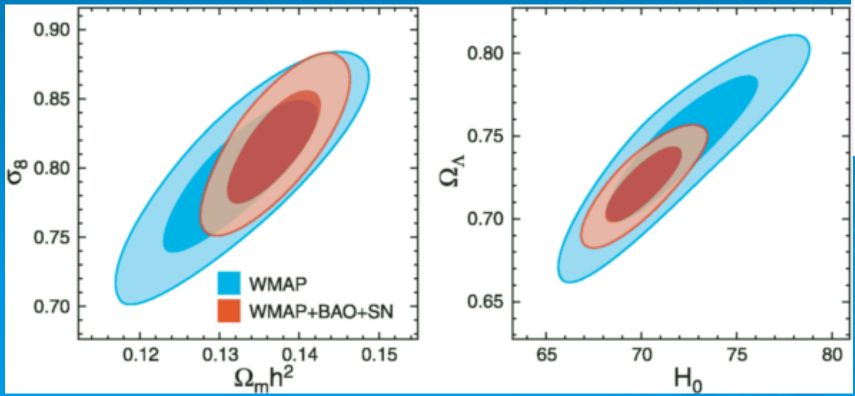
- Baryon Oscillations
- Supernova
- Weak & Strong Lensing
- Cluster Abundances
- Lyman a Forest
- Hubble Constant
- Stellar Ages
- Deuterium Abundance
- Large Scale Structure
- Velocity Field



Additional Data Sets and Parameters

- Since the other data sets are consistent with WMAP, combining data sets improves parameter constraints
- Supernova measure distance to z~0.5-1. BAO to z~0.2-0.35
- Cluster and lensing measurements constrain the amplitude of structure



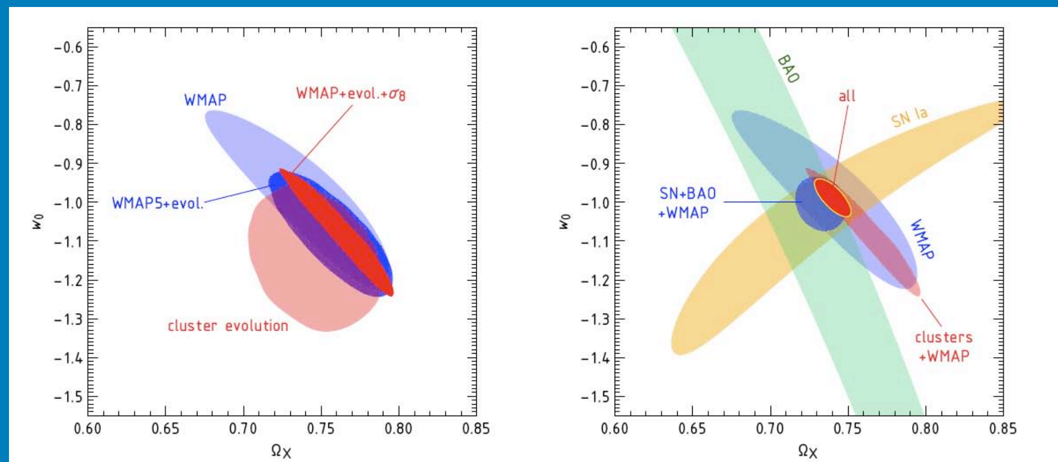


Viklinin et al 2008

Lensing results (Hoekstra et al. 2007, Fu et al. 2008)

Clusters (Rines et al. 2007; Reiprich and Bohringer 2007)

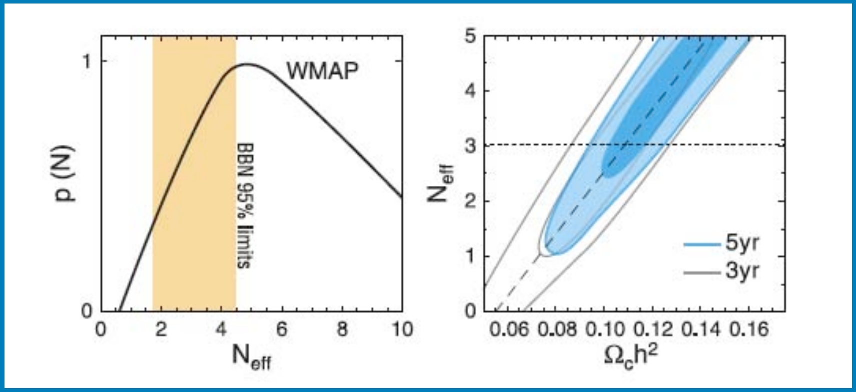
Dark Energy Parameters

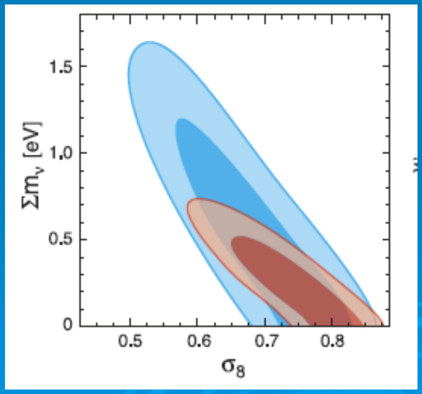


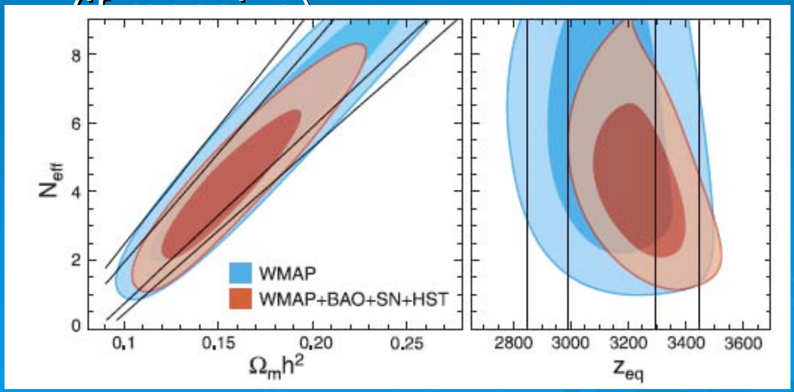
- Viklinin et al. used Chandra to determine “Yx” for a sample of 400 nearby (z ~0.05) and distant (z ~0.55) sample
- Clusters measure s_8 and W_m. When combined with WMAP measurements of primordial amplitude yield interesting constraints on w.

Neutrinos

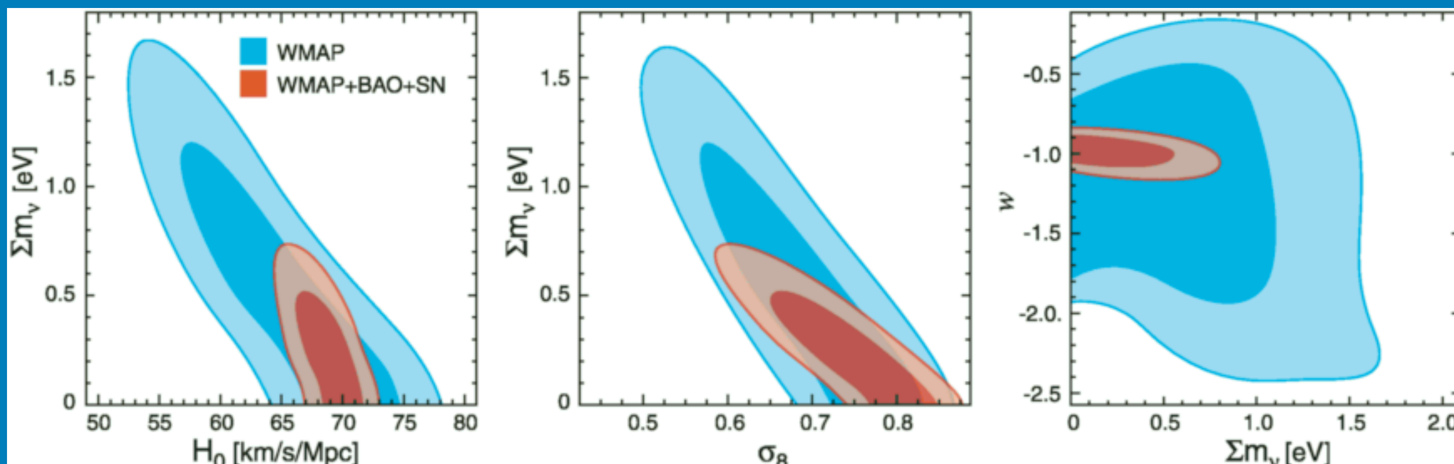
- Presence of neutrinos have several effects:
  - Change matter/radiation transition
  - Shift peak position (free-streaming)
  - Suppress growth of structure







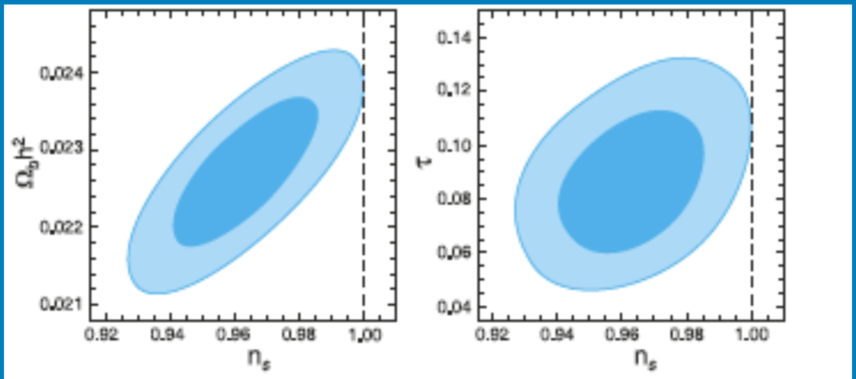
Neutrino Mass

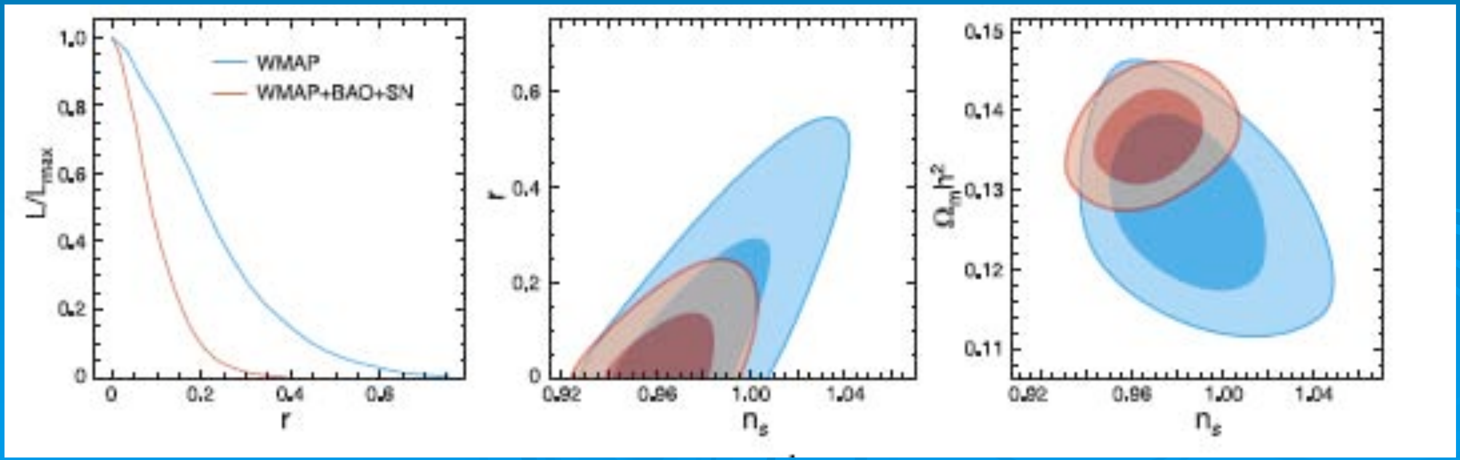


- Massive Neutrinos alter peak structure (limits ~1.6 eV with degeneracies.
- Massive Neutrinos suppress the growth of structure. Combined with lensing/galaxy surveys/Lyman a can give stronger constraints.

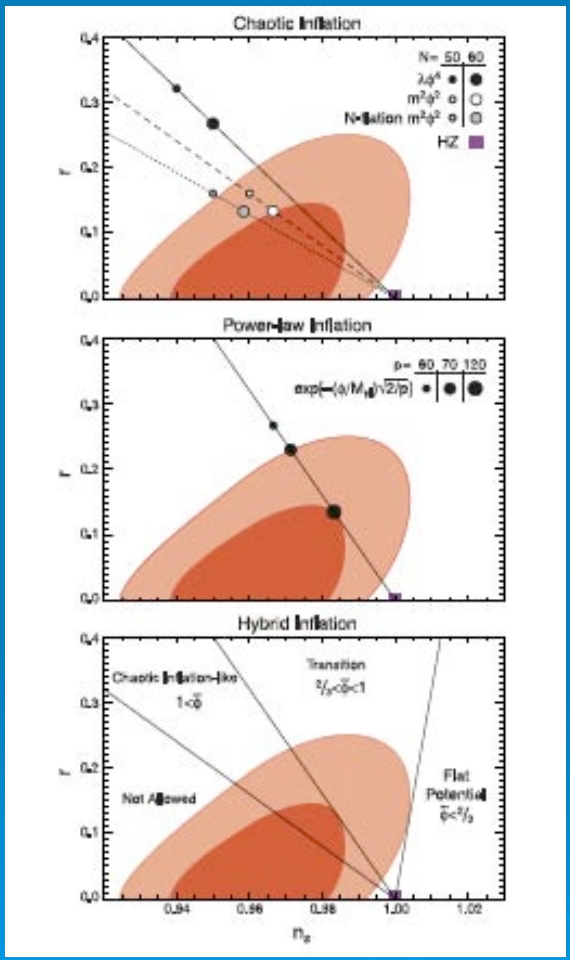
Inflation

- Spectral index < 1
- Constraint on tensor modes improves (particularly with SN+BAO in LCDM)

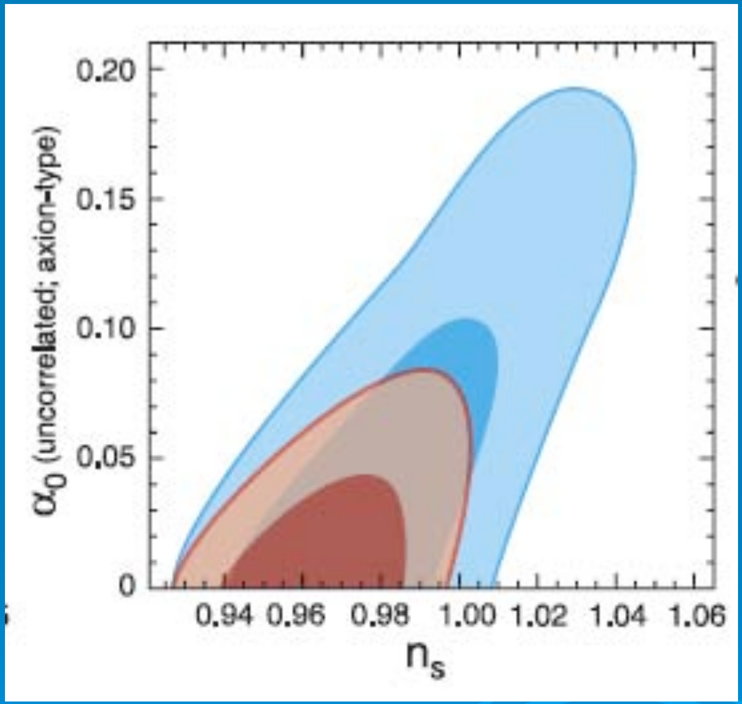




Inflationary Models



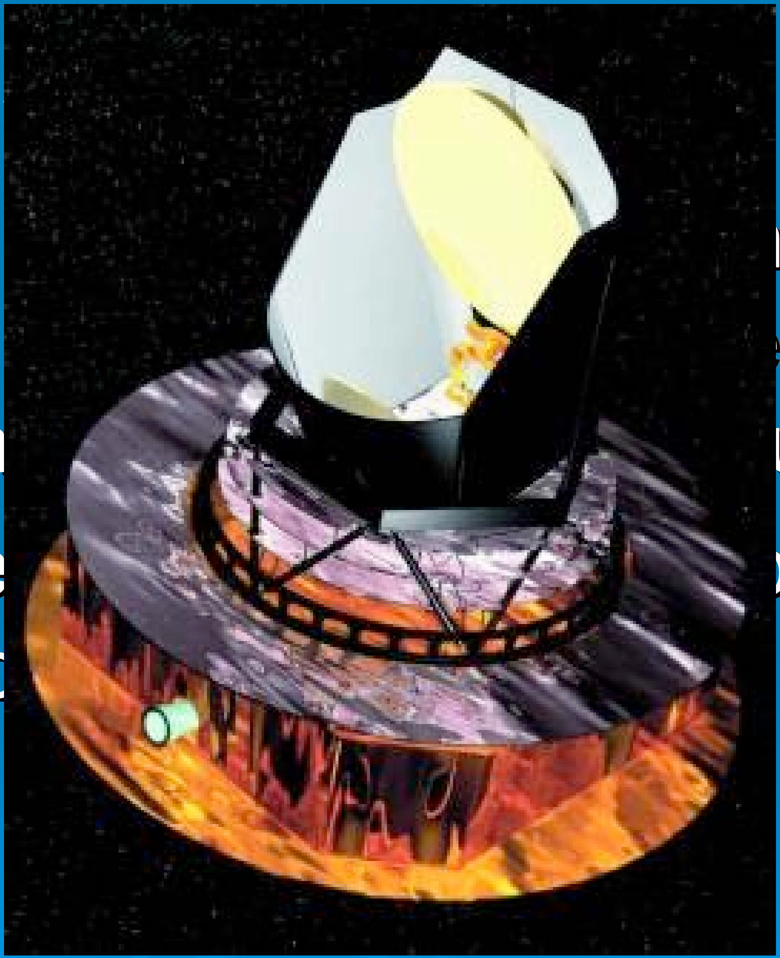
One field models



Multi field models

Conclusions

- Cosmolog
- Advances ... abling us to probe the ... early universe a... ure
- So far, the ... pears to fit the data, b



Coming Soon!