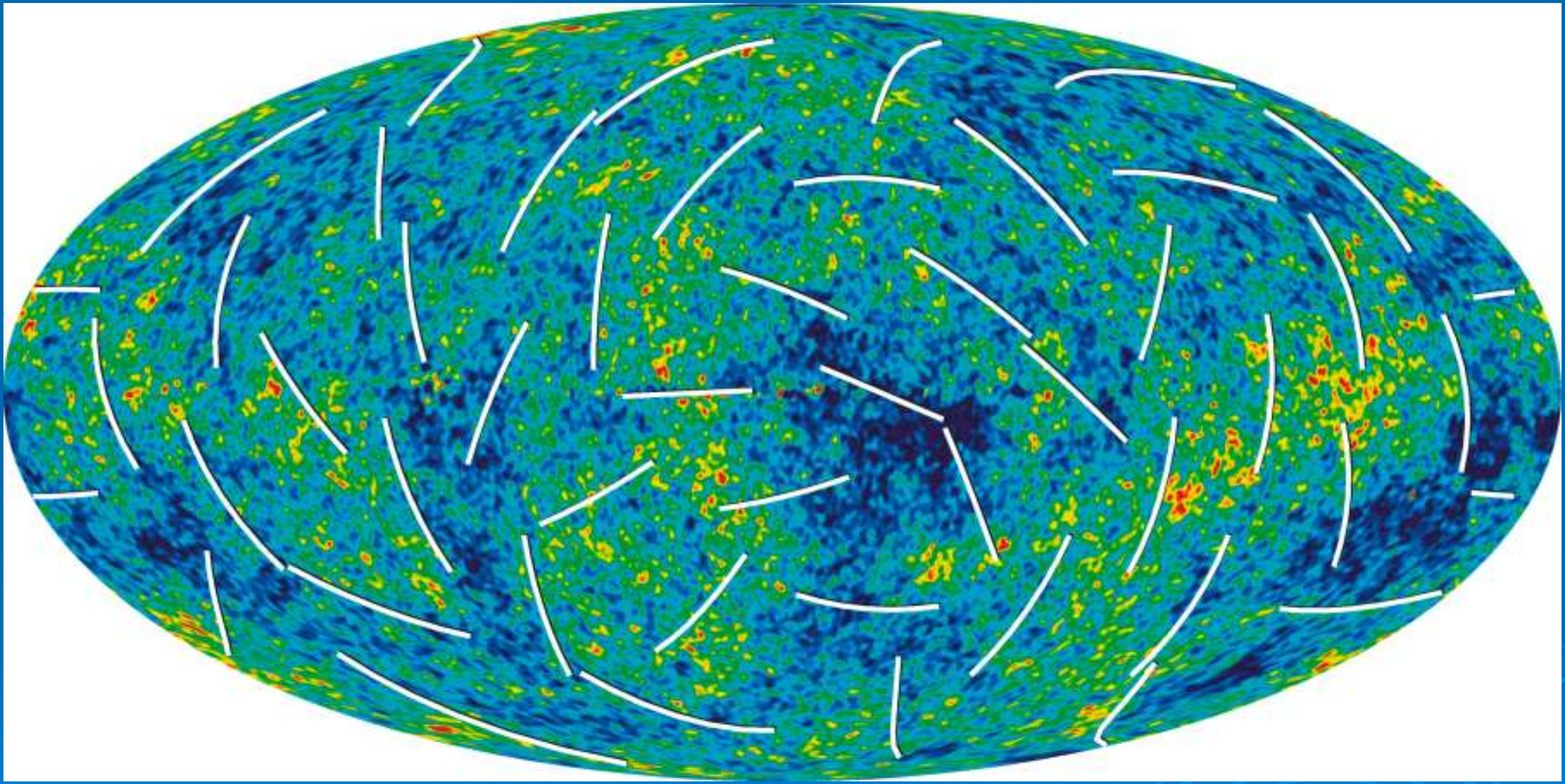
Cosmology After WMAP (5)



David Spergel

Stockholm

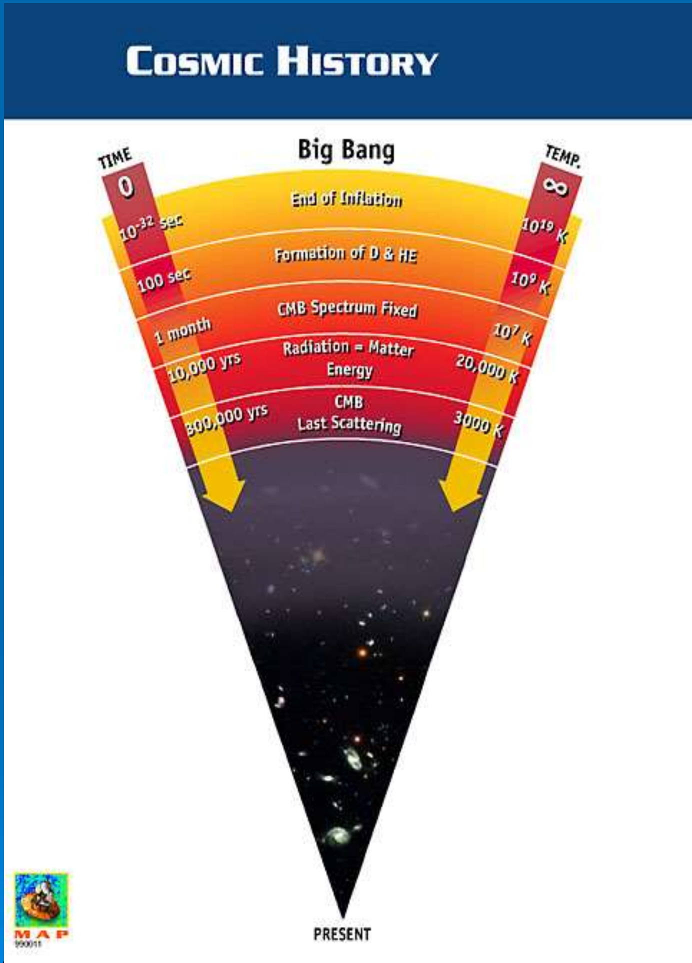
June 2008

Standard cosmological model Still Fits the Data

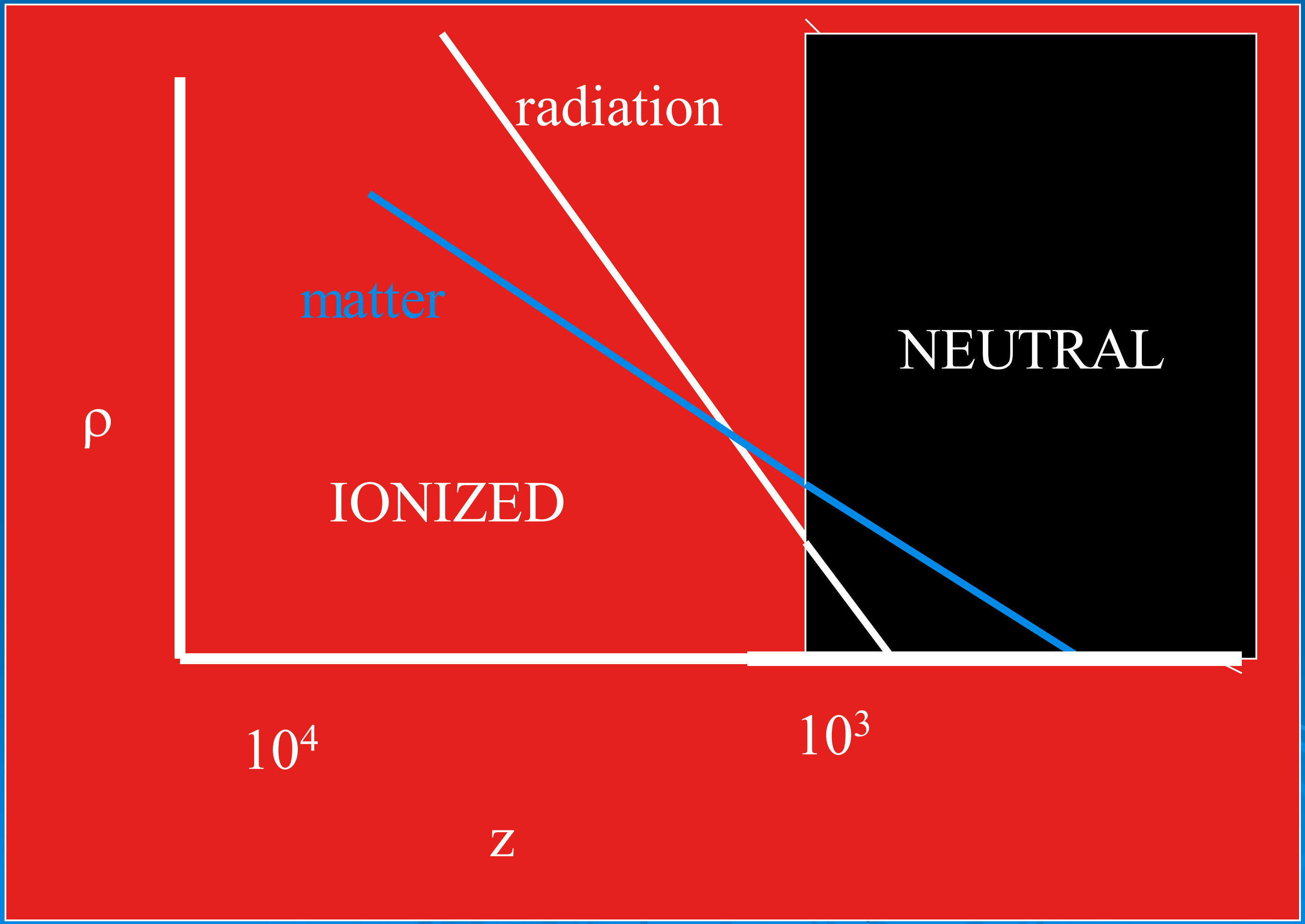
- General Relativity + Uniform Universe ⇨ Big Bang
  - Density of universe determines its fate + shape
- Universe is flat (total density = critical density)
  - Atoms 4%
  - Dark Matter 23%
  - Dark Energy (cosmological constant?) 72%
- Universe has tiny ripples
  - Adiabatic, scale invariant, Gaussian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

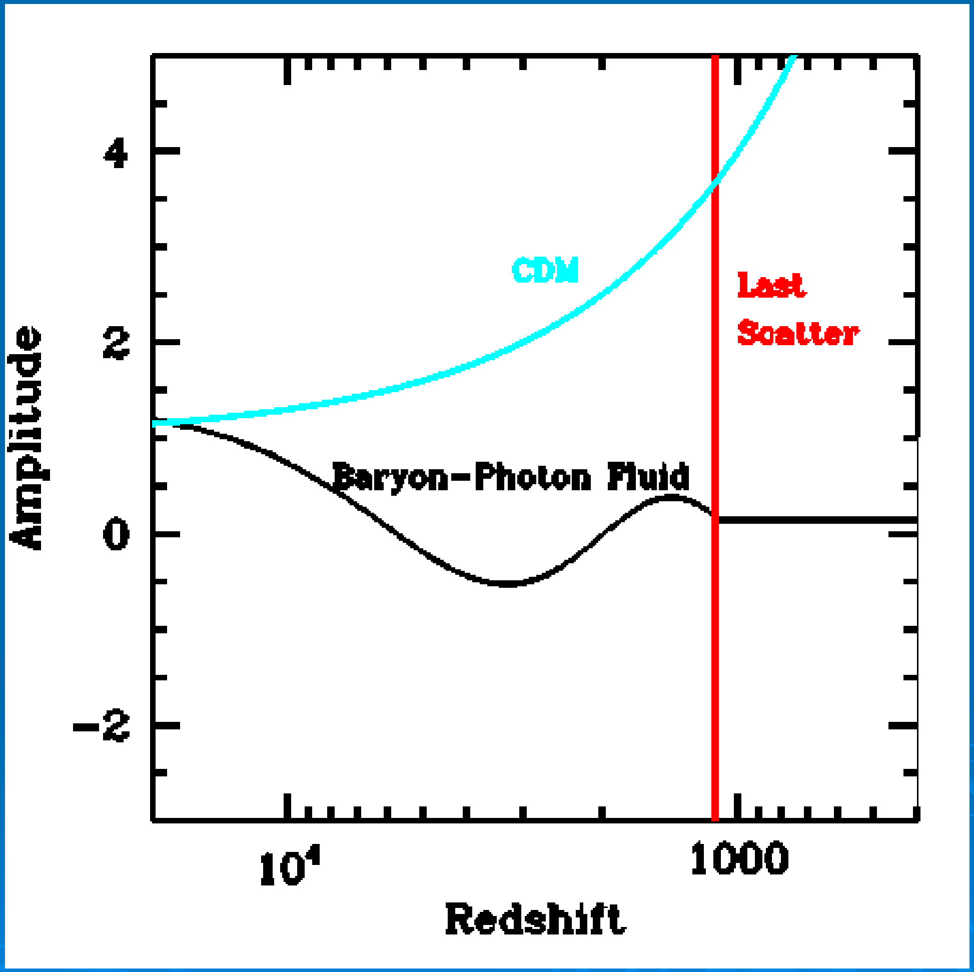


Thermal History of Universe



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

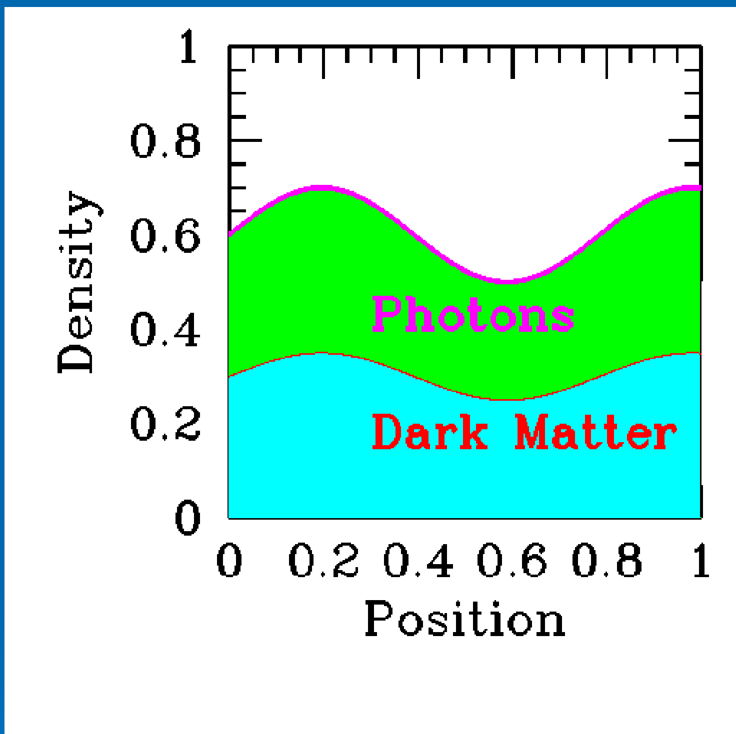
$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

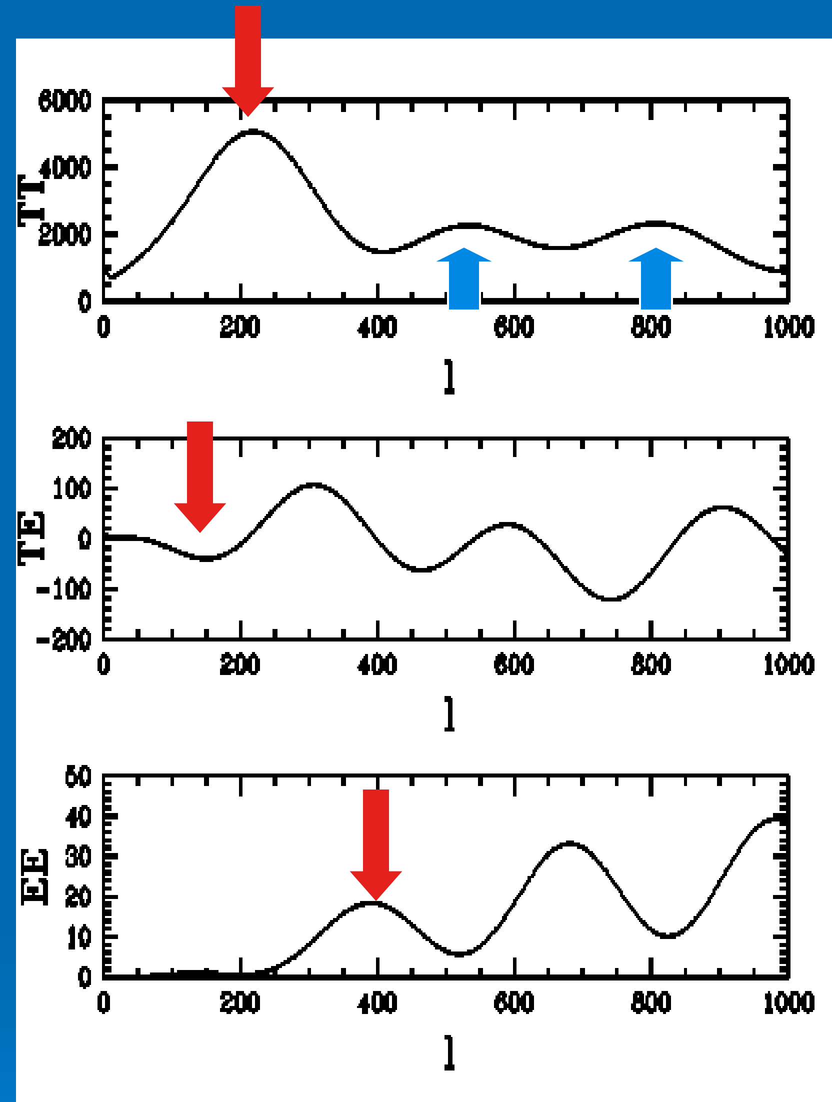
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

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

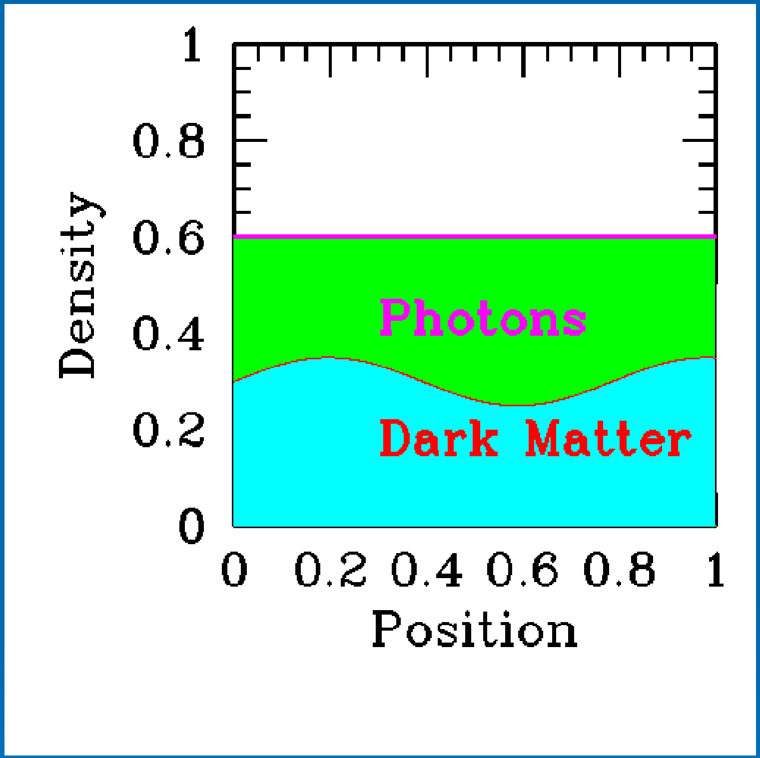
- We can detect both CMB temperature and polarization fluctuations
- Polarization Fluctuations can be decomposed into E and B modes

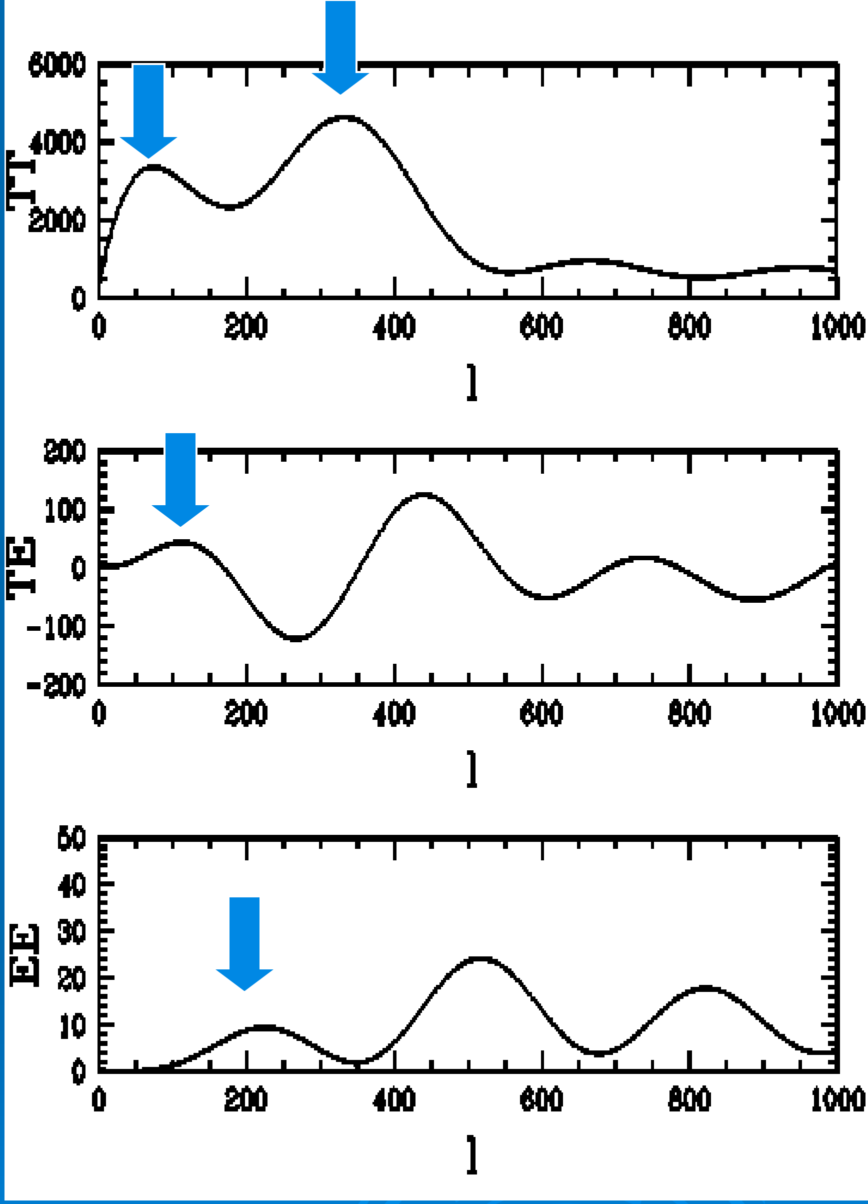
$\theta \sim 180/\ell$





ADIABATIC DENSITY FLUCTUATIONS





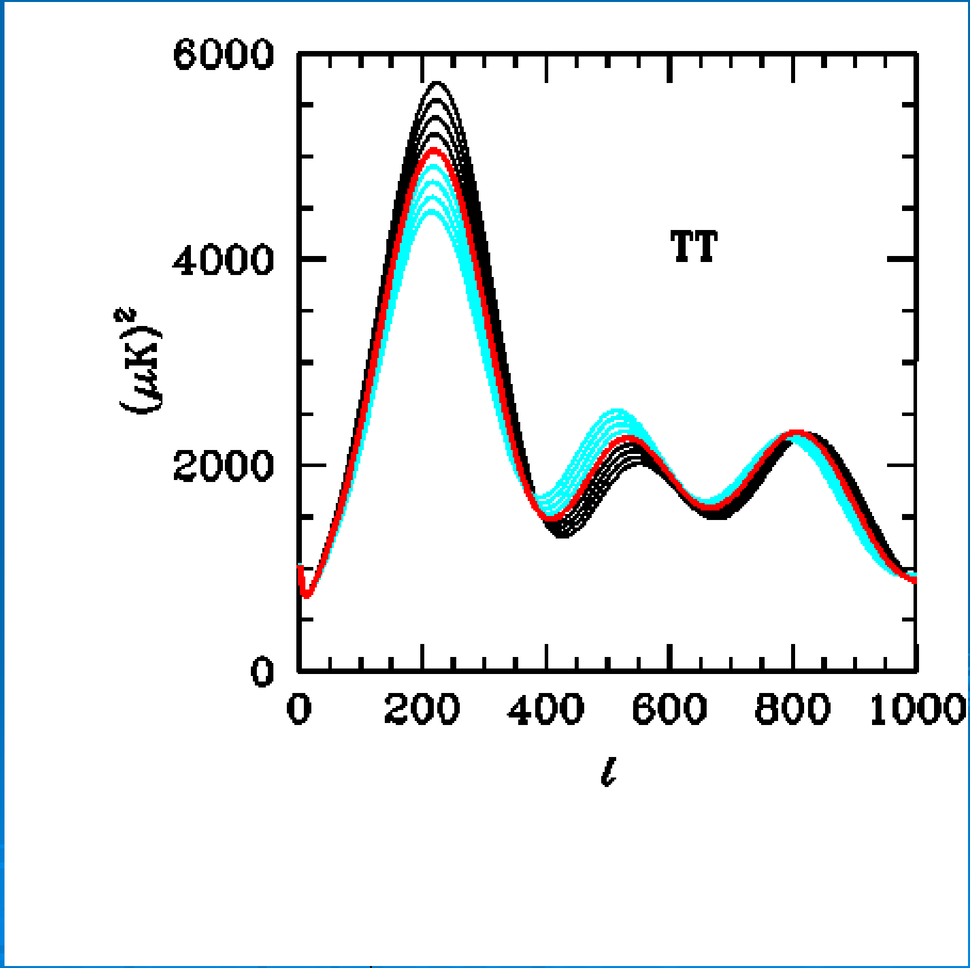
ISOCURVATURE ENTROPY FLUCTUATIONS

Determining Basic Parameters

Baryon Density

$\Omega_b h^2 = 0.015, 0.017..0.031$

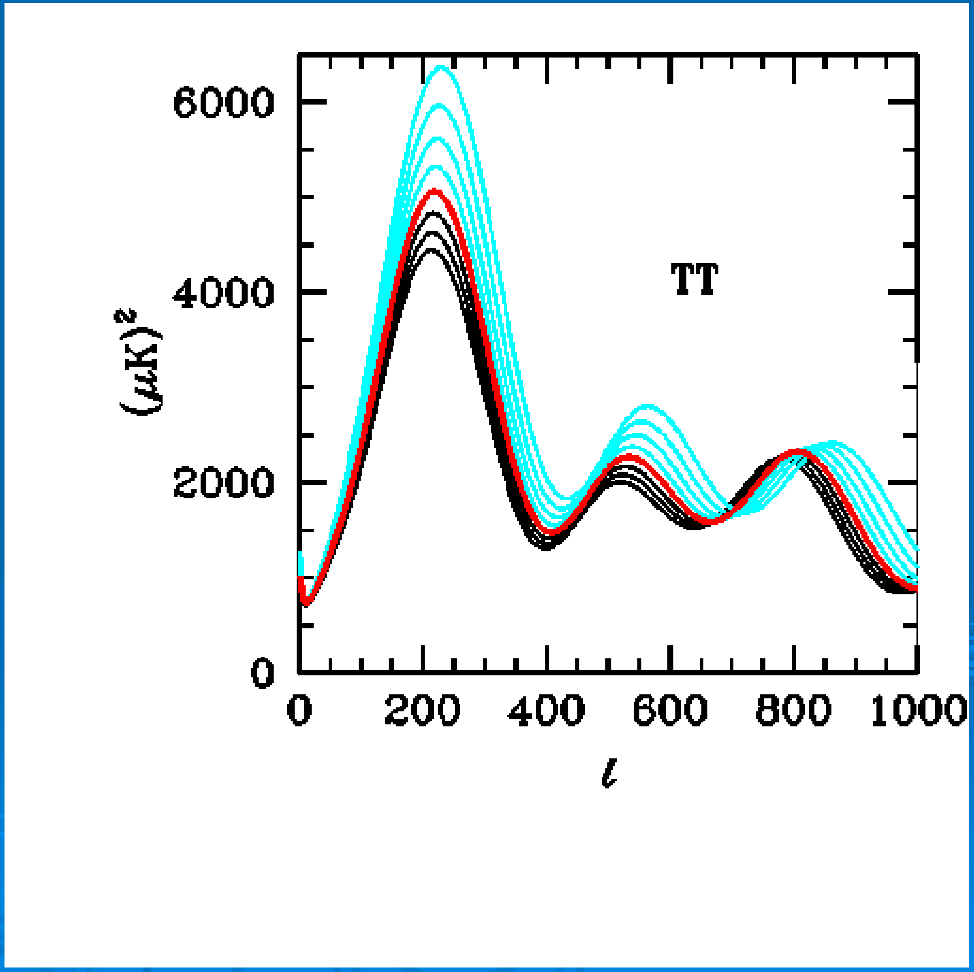
also measured through D/H



Determining Basic Parameters

Matter Density

$\Omega_m h^2 = 0.16,..,0.33$

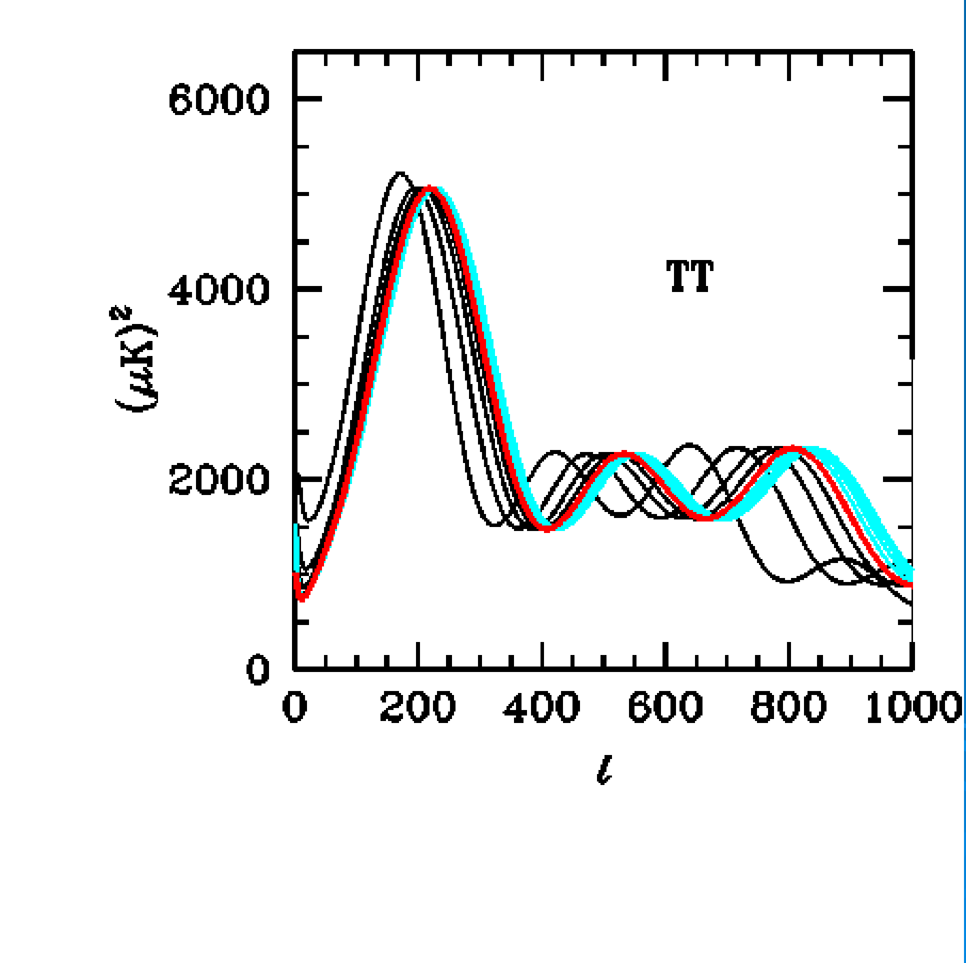


Determining Basic Parameters

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

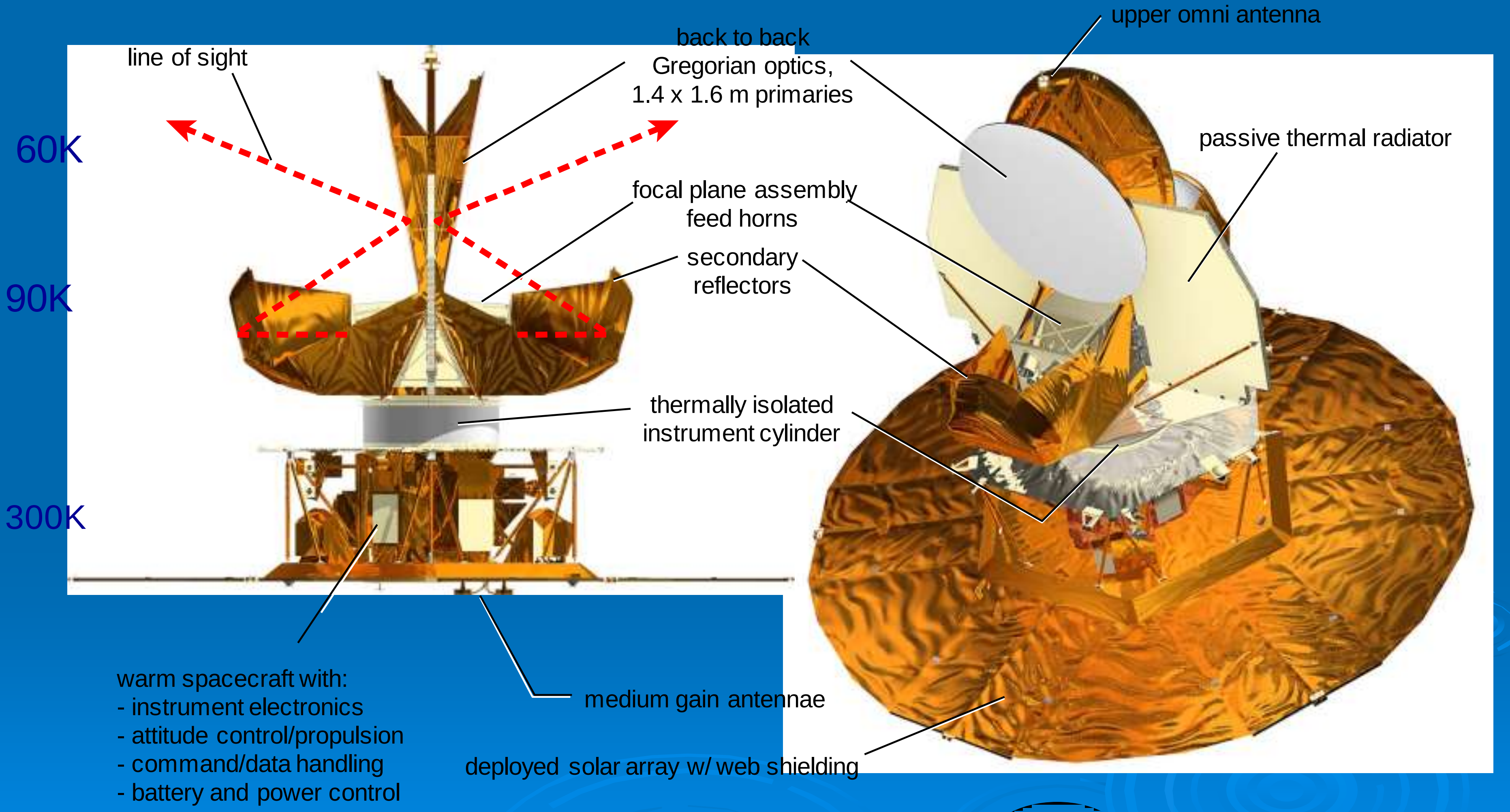
Norm Jarosik
Lyman Page
David Spergel
Joanna Dunkley

Johns Hopkins

Chuck Bennett
Ben Gold
David Larson

June 30, 2001

WMAP Spacecraft



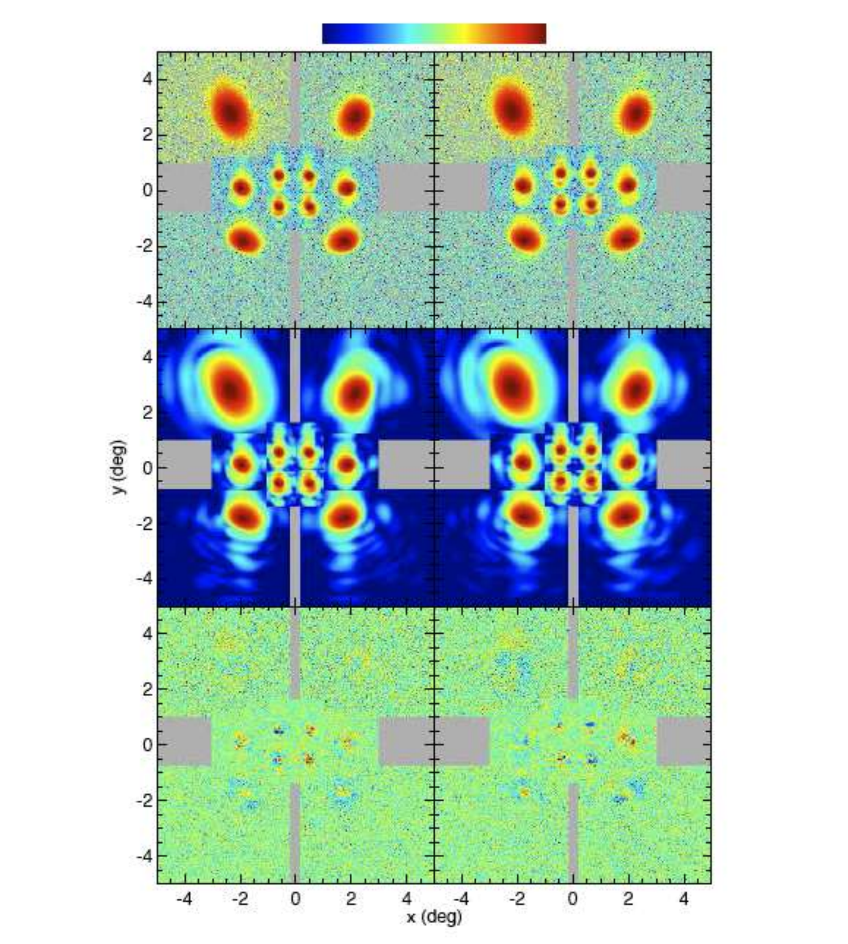
MAP990422

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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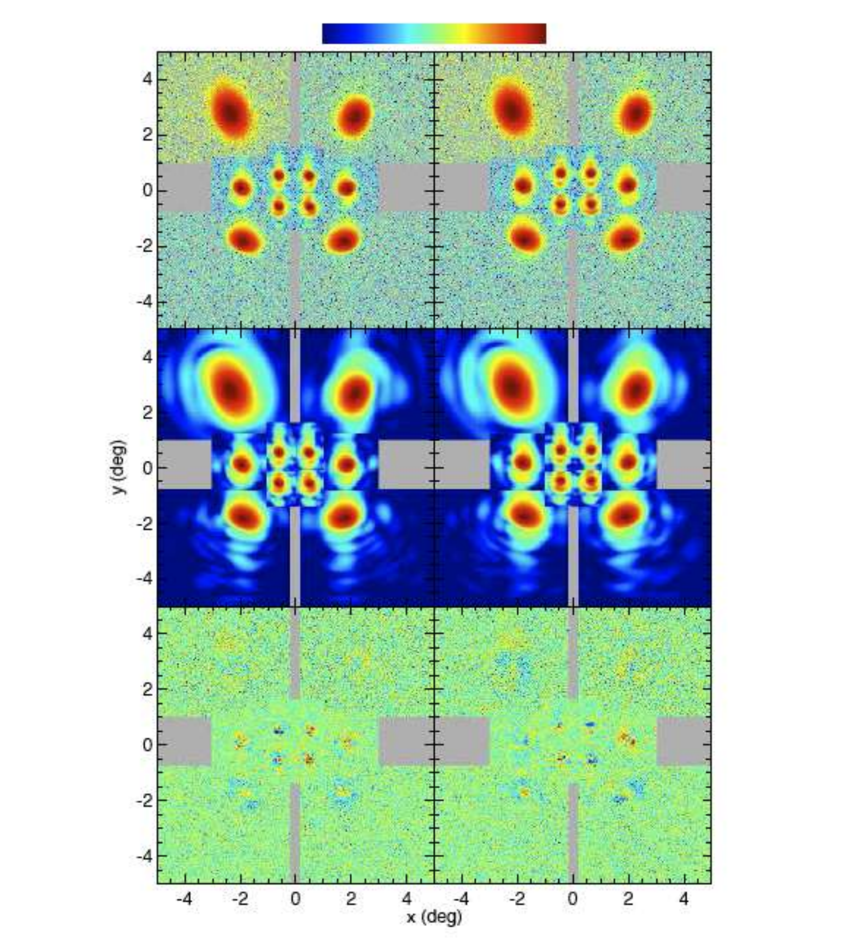
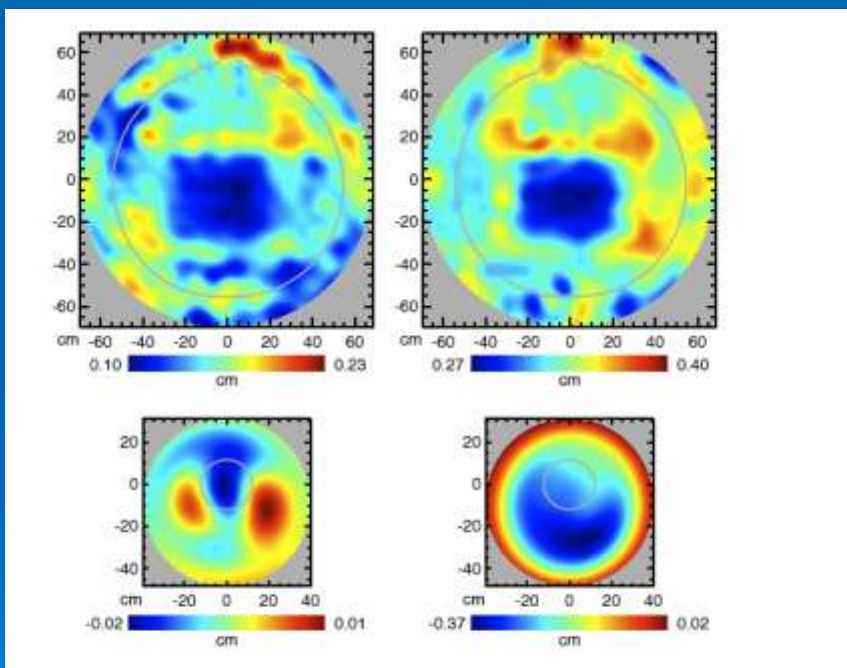
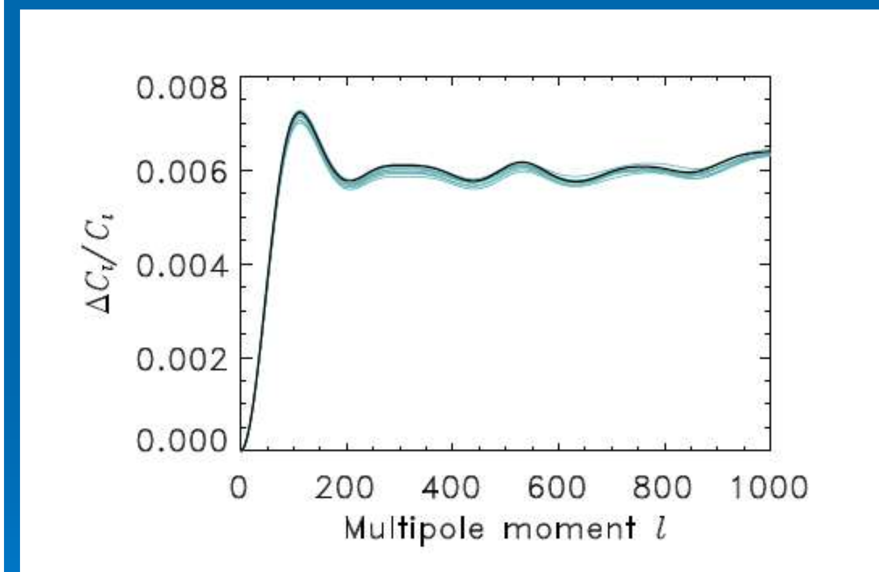
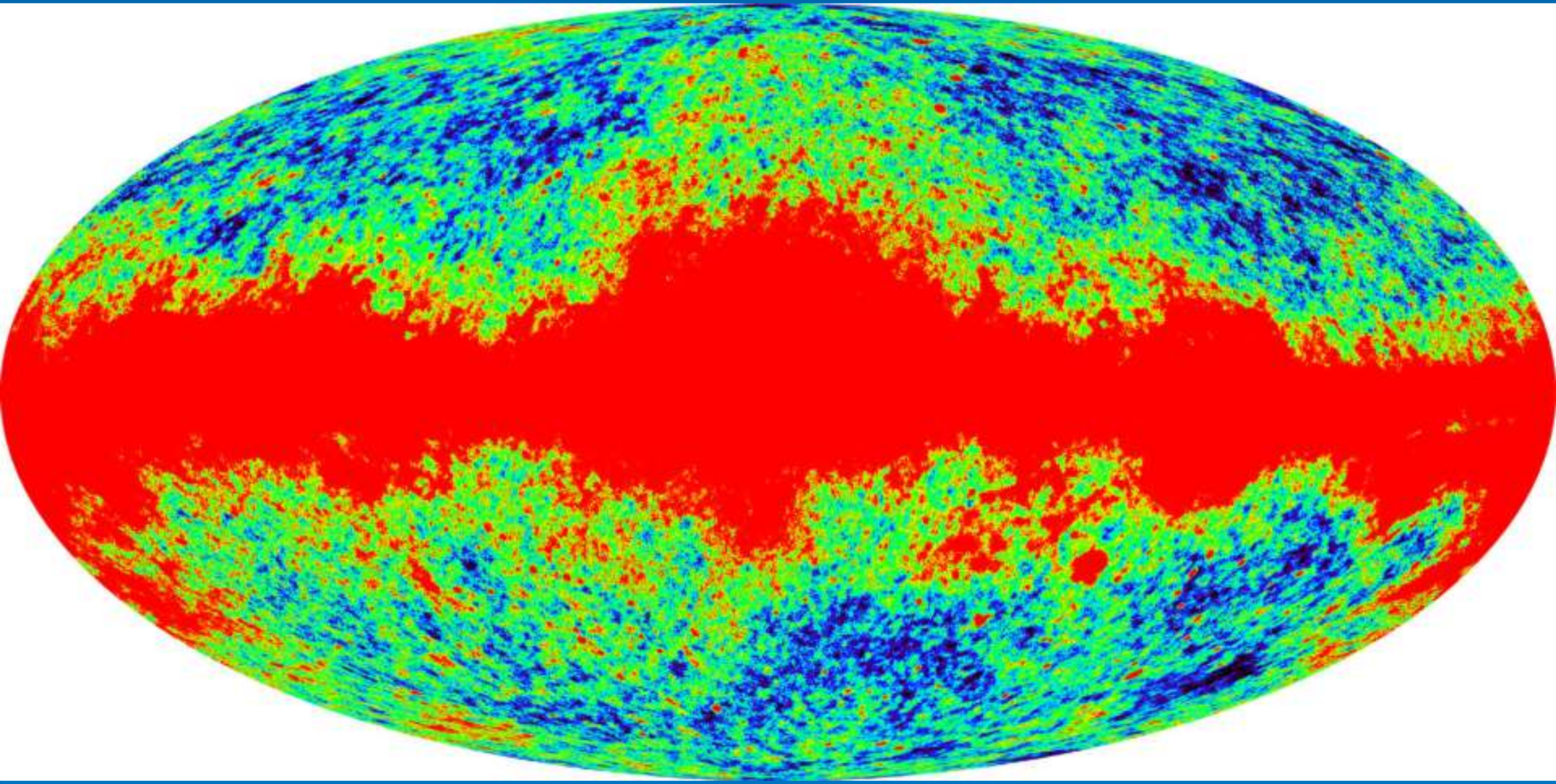


Beam Models

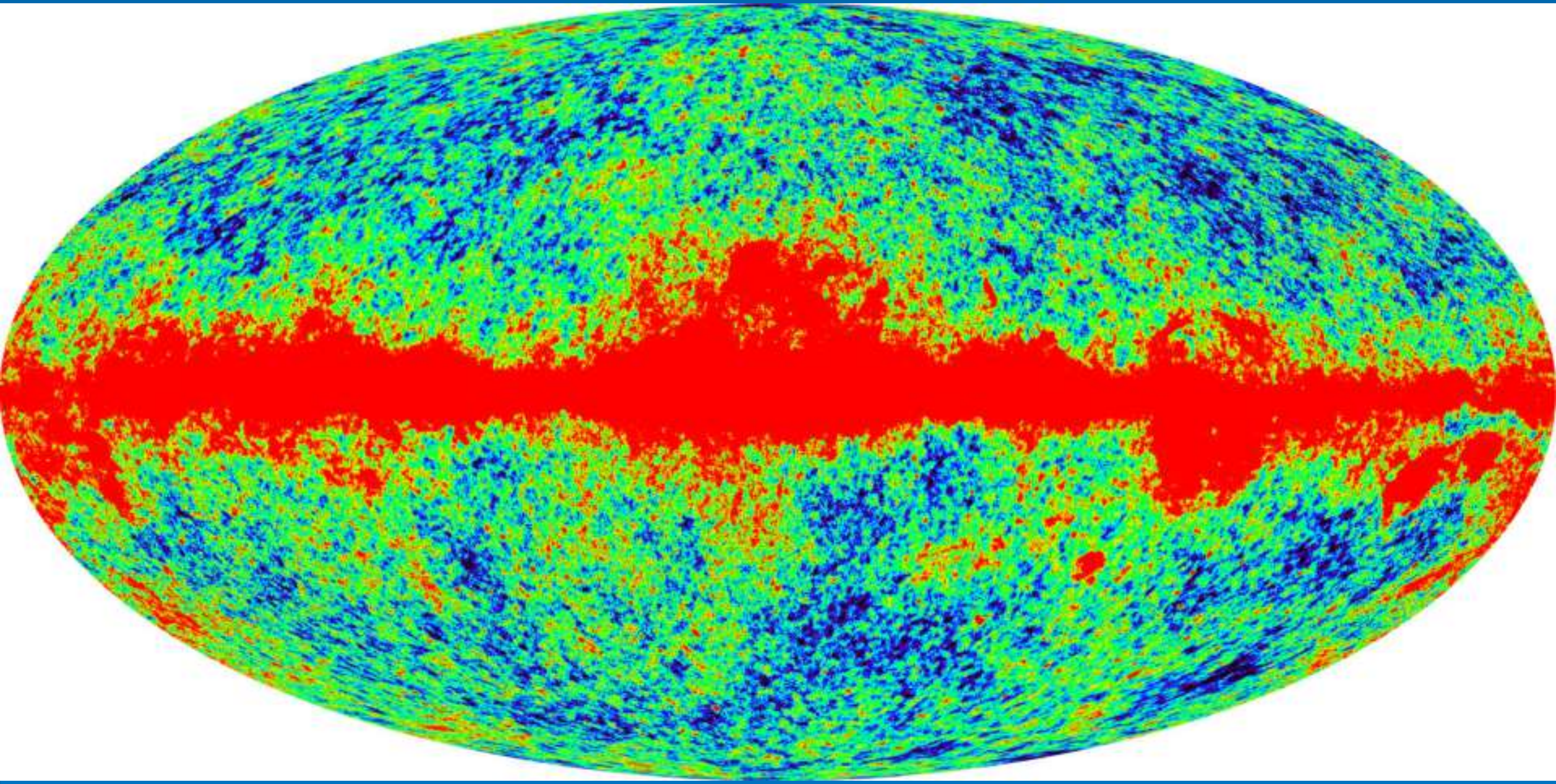

60
40
20
0
-20
-40
-60
cm -60 -40 -20 0 20 40 60
0.10
0.23
cm
0.27
0.40
cm
20
0
-20
-40
cm -20 0 20 40
-0.02
0.01
cm
-0.37
0.02
cm


0.008
0.006
0.004
0.002
0.000
$\Delta C_l / C_l$
0 200 400 600 800 1000
Multipole moment l

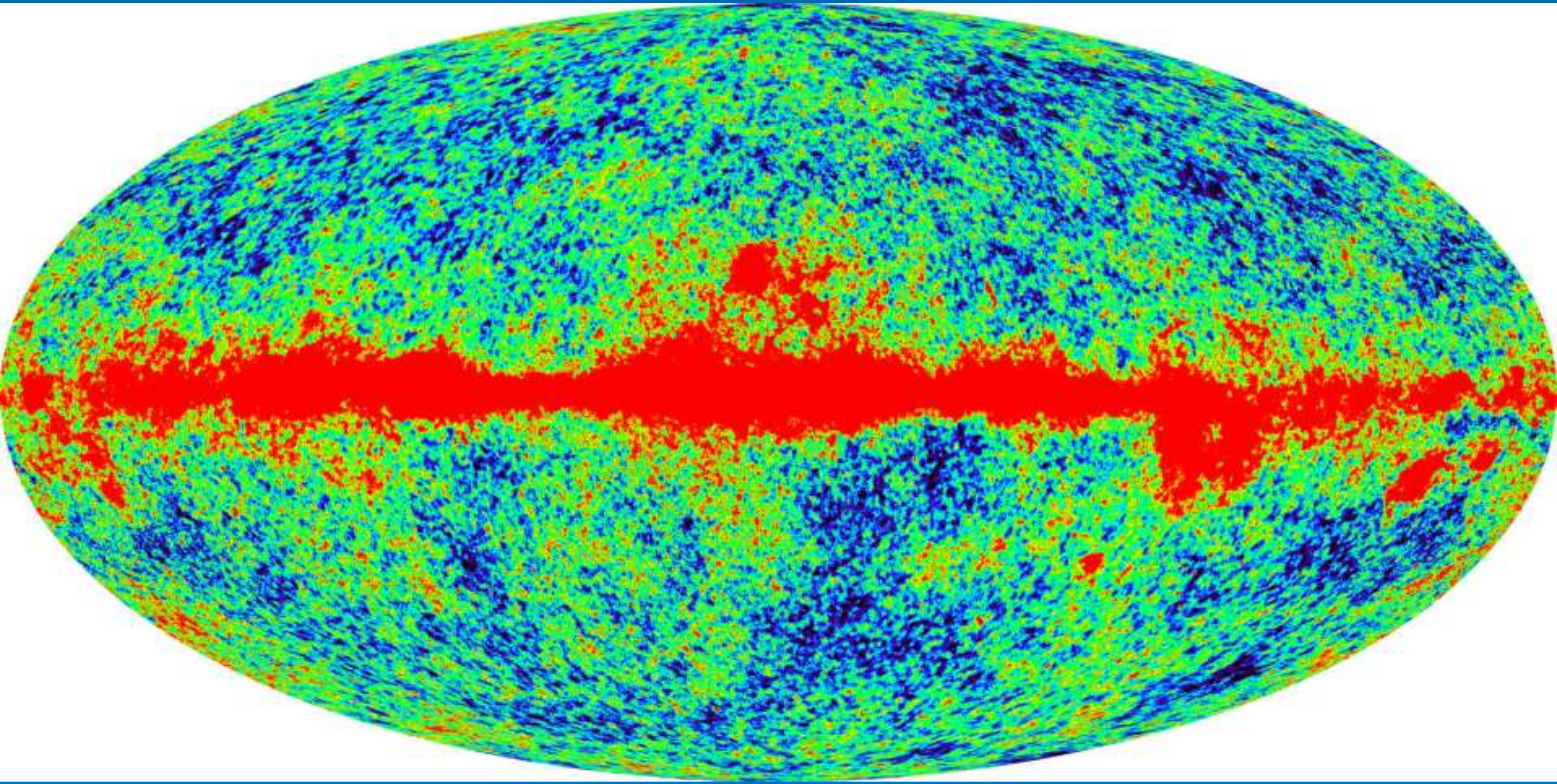
K - 22GHz



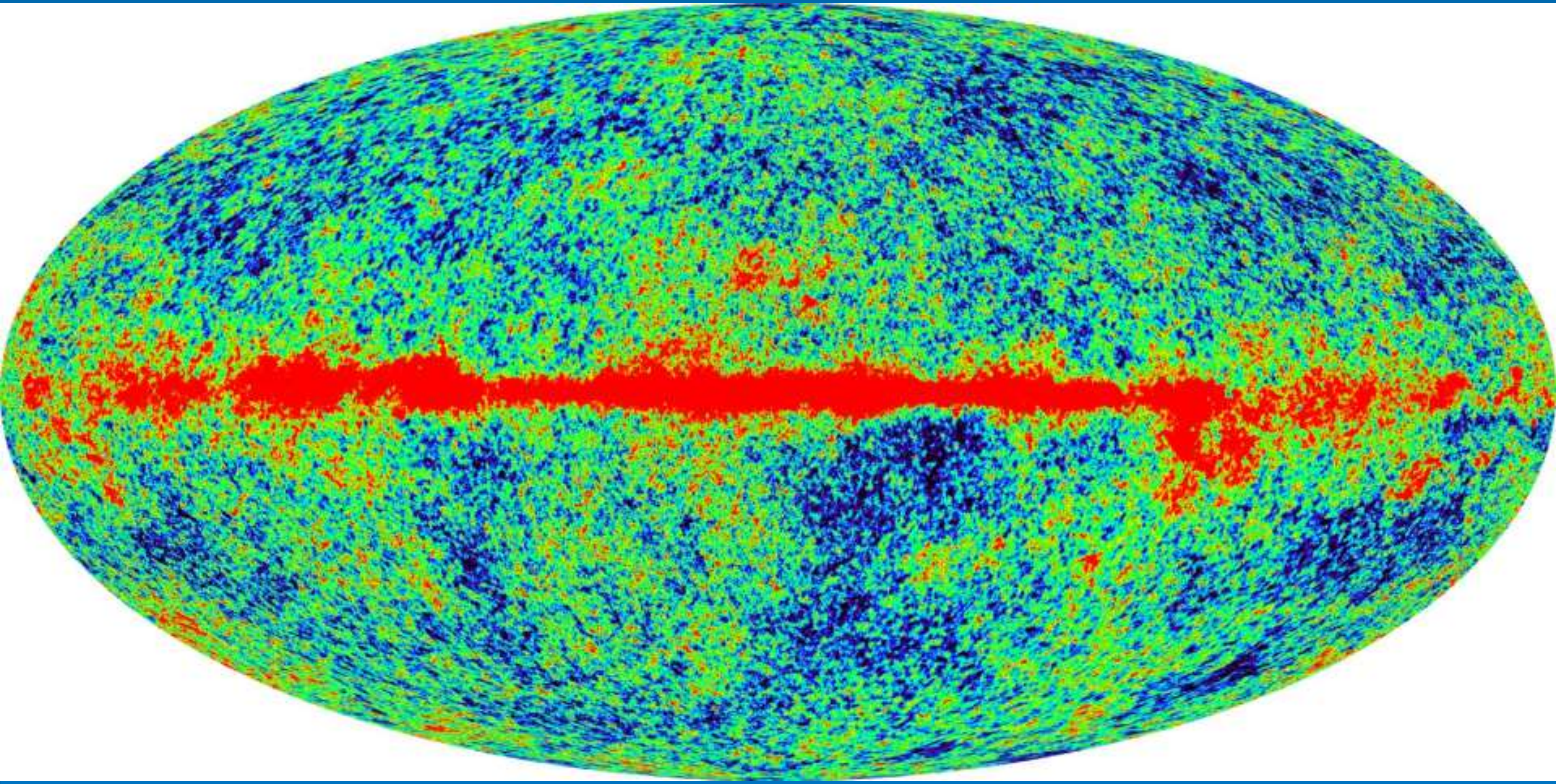
Ka - 33GHz



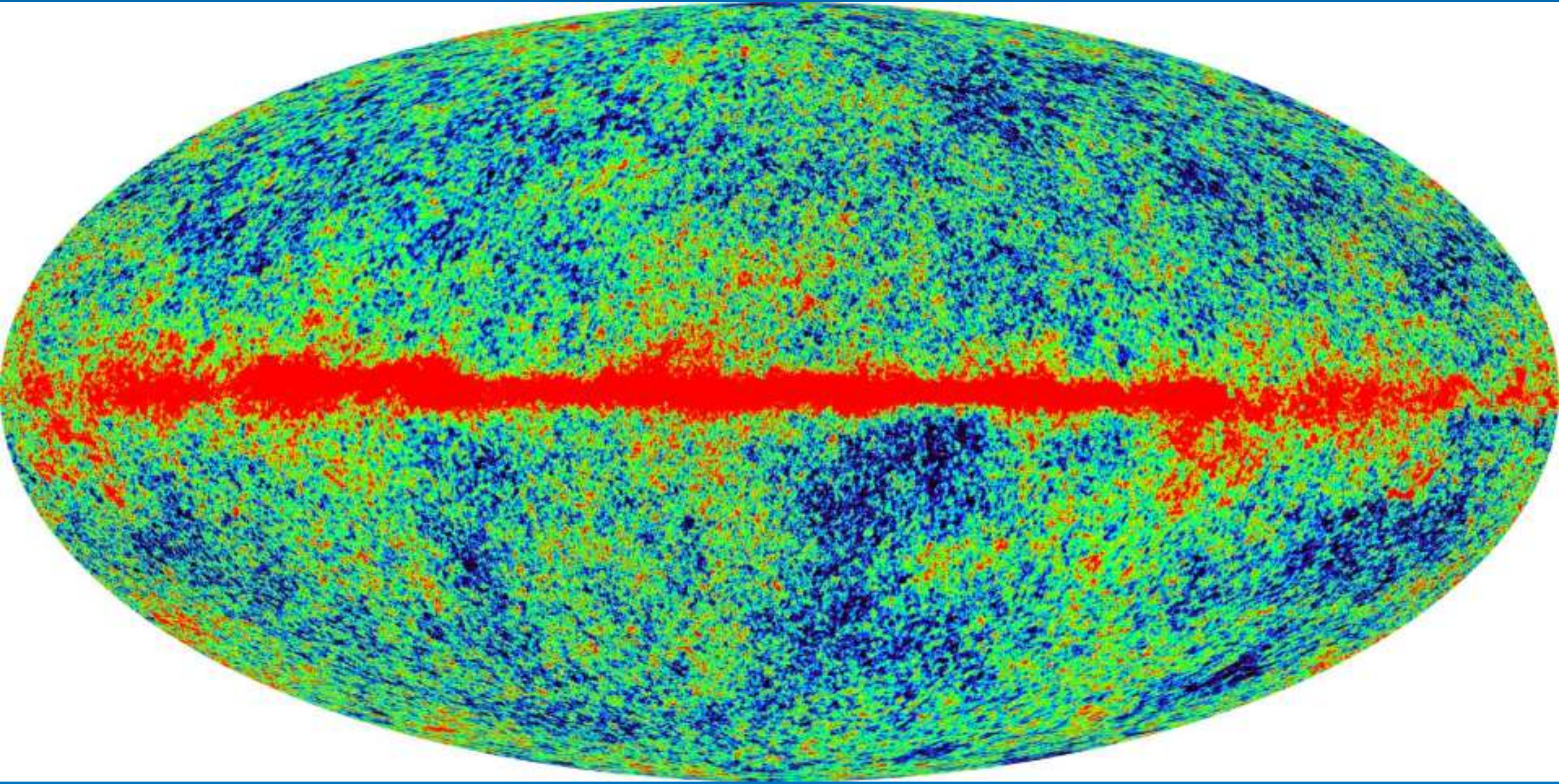
Q - 41GHz

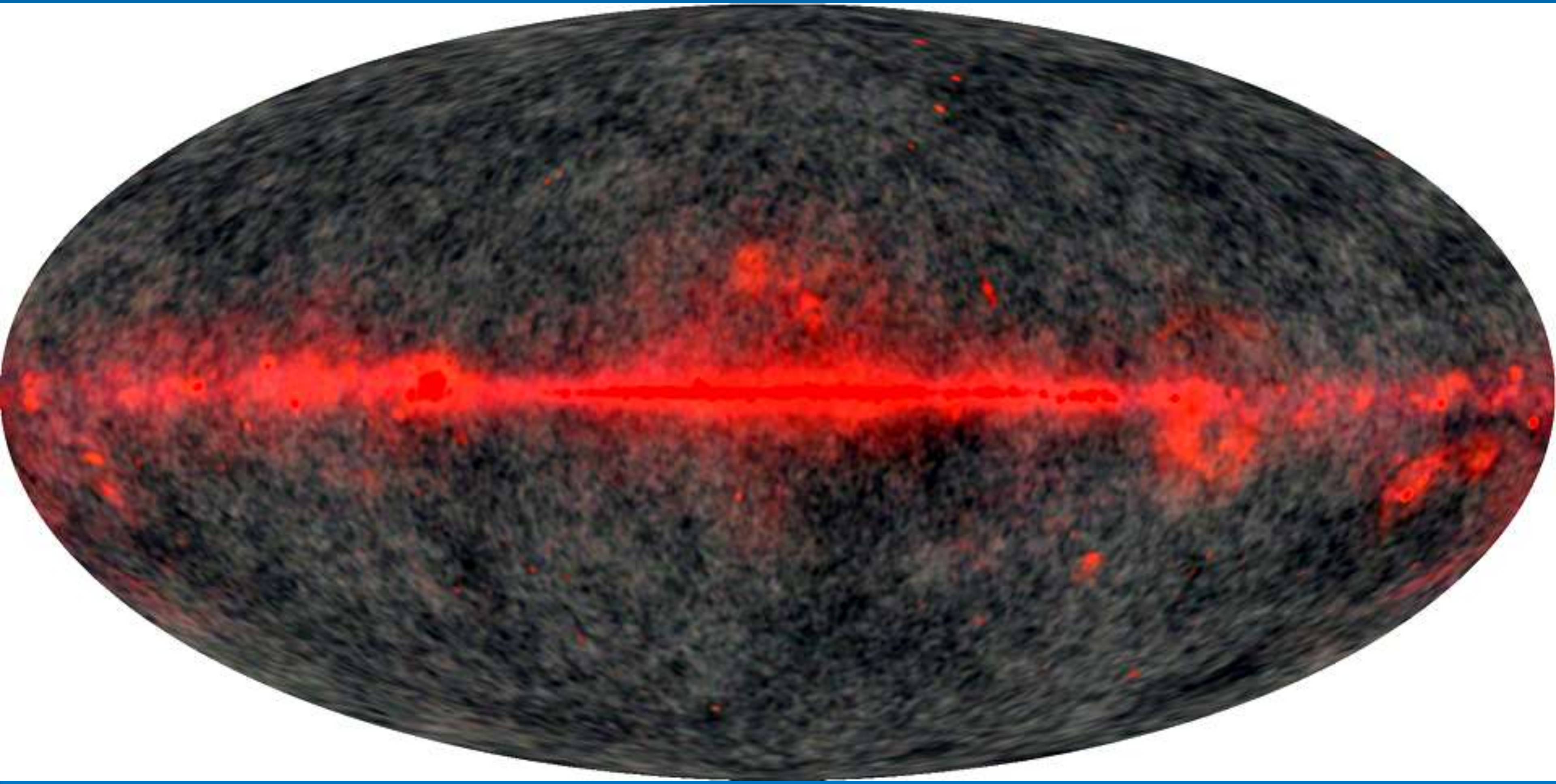


V - 61GHz

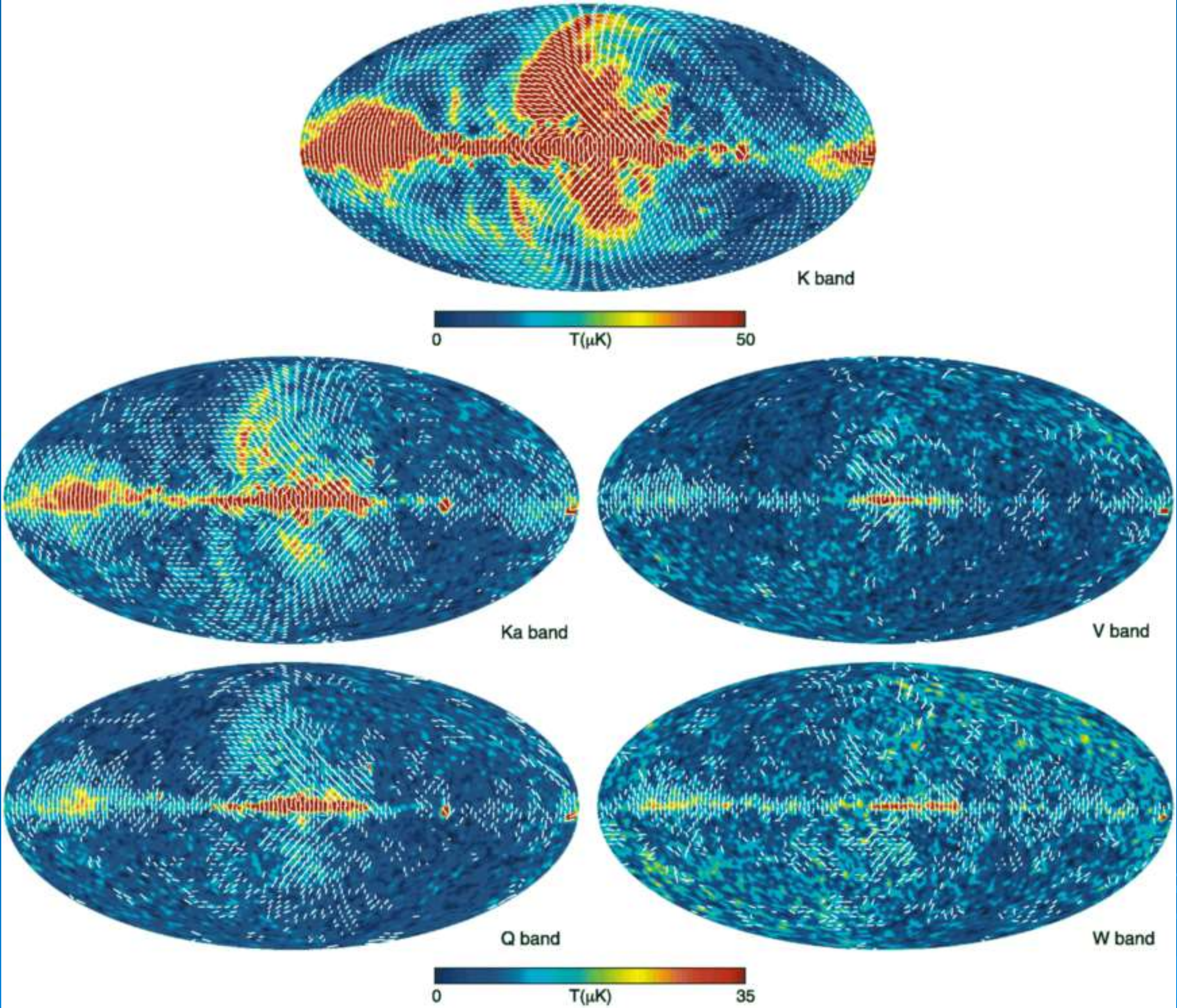


W - 94GHz



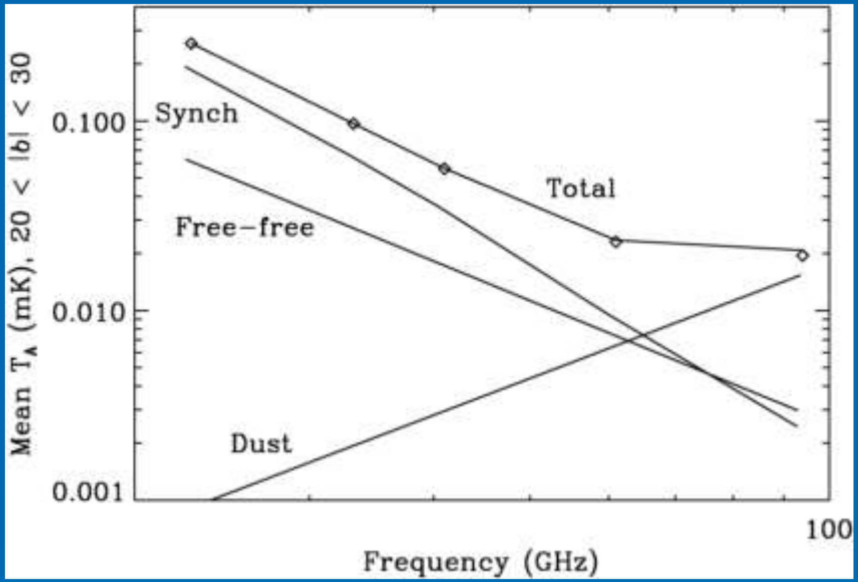


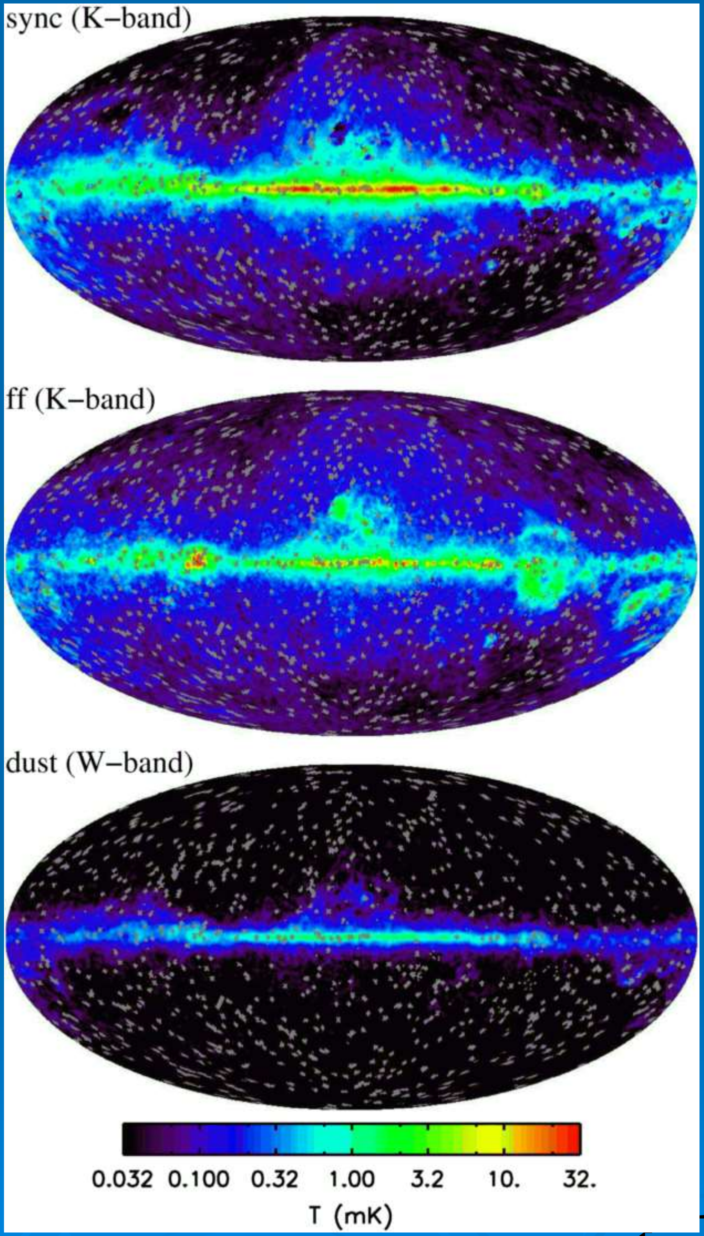
Q band
V band
W band

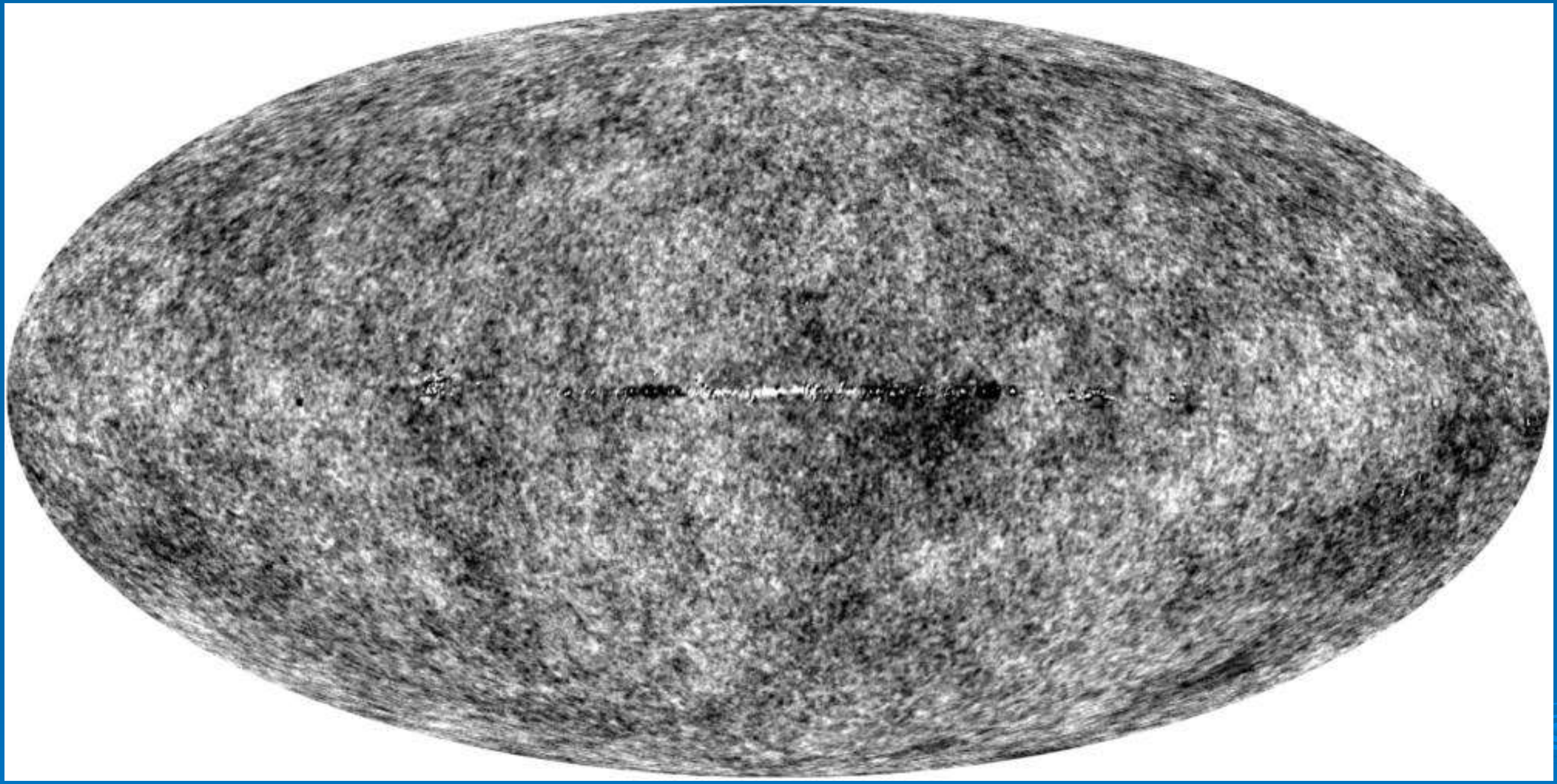

K band
0
T(μK)
50
Ka band
V band
Q band
W band
0
T(μK)
35

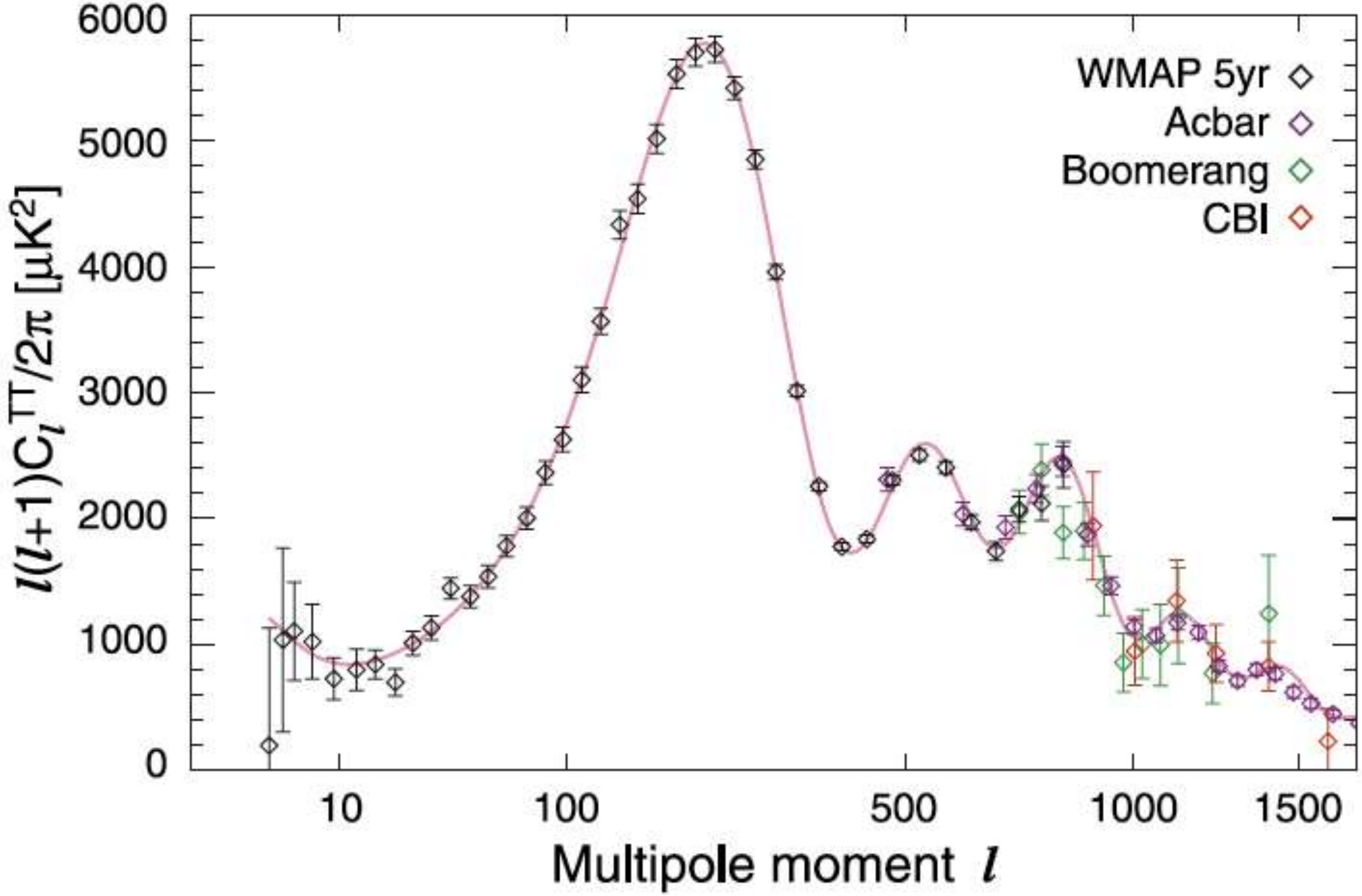
Foregrounds

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



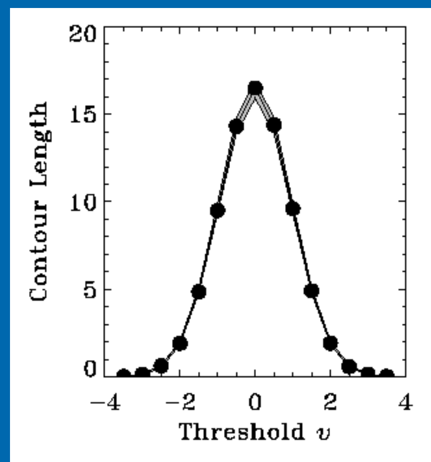

sync (K–band)
ff (K–band)
dust (W–band)
0.032 0.100 0.32 1.00 3.2 10. 32.
T (mK)

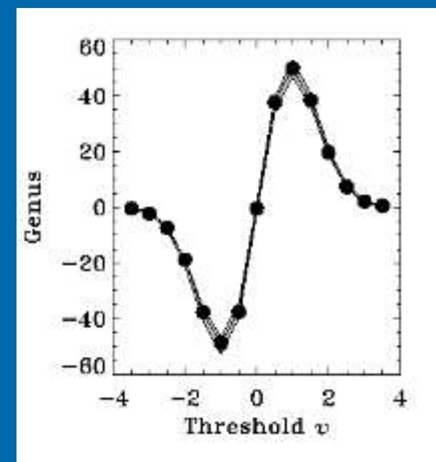


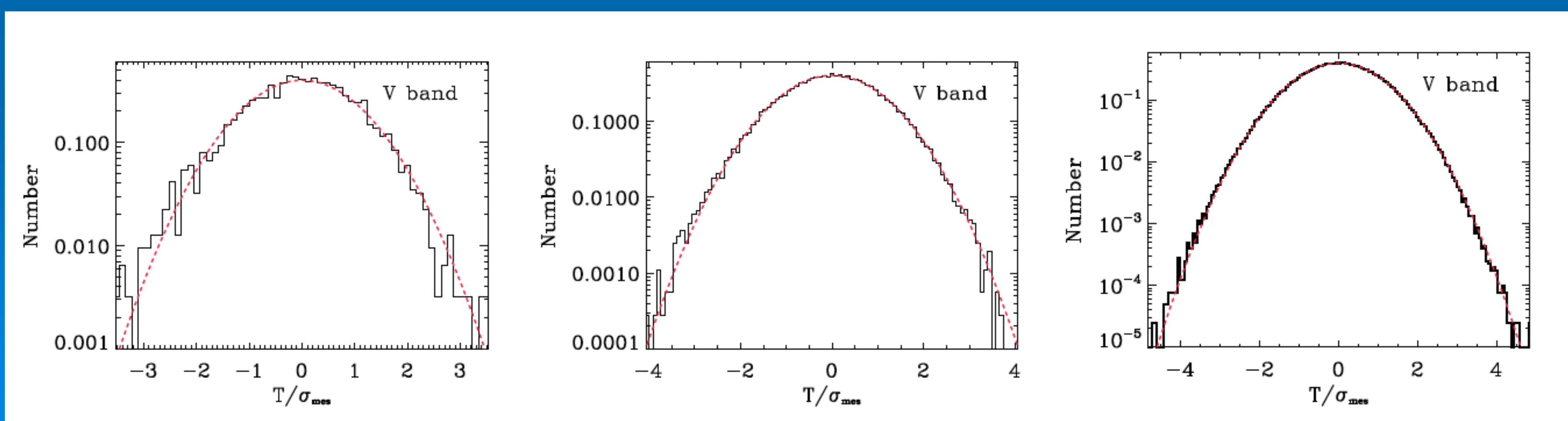


6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l
l(l+1)C_l^TT/2π [μK²]
WMAP 5yr
Acbar
Boomerang
CBI

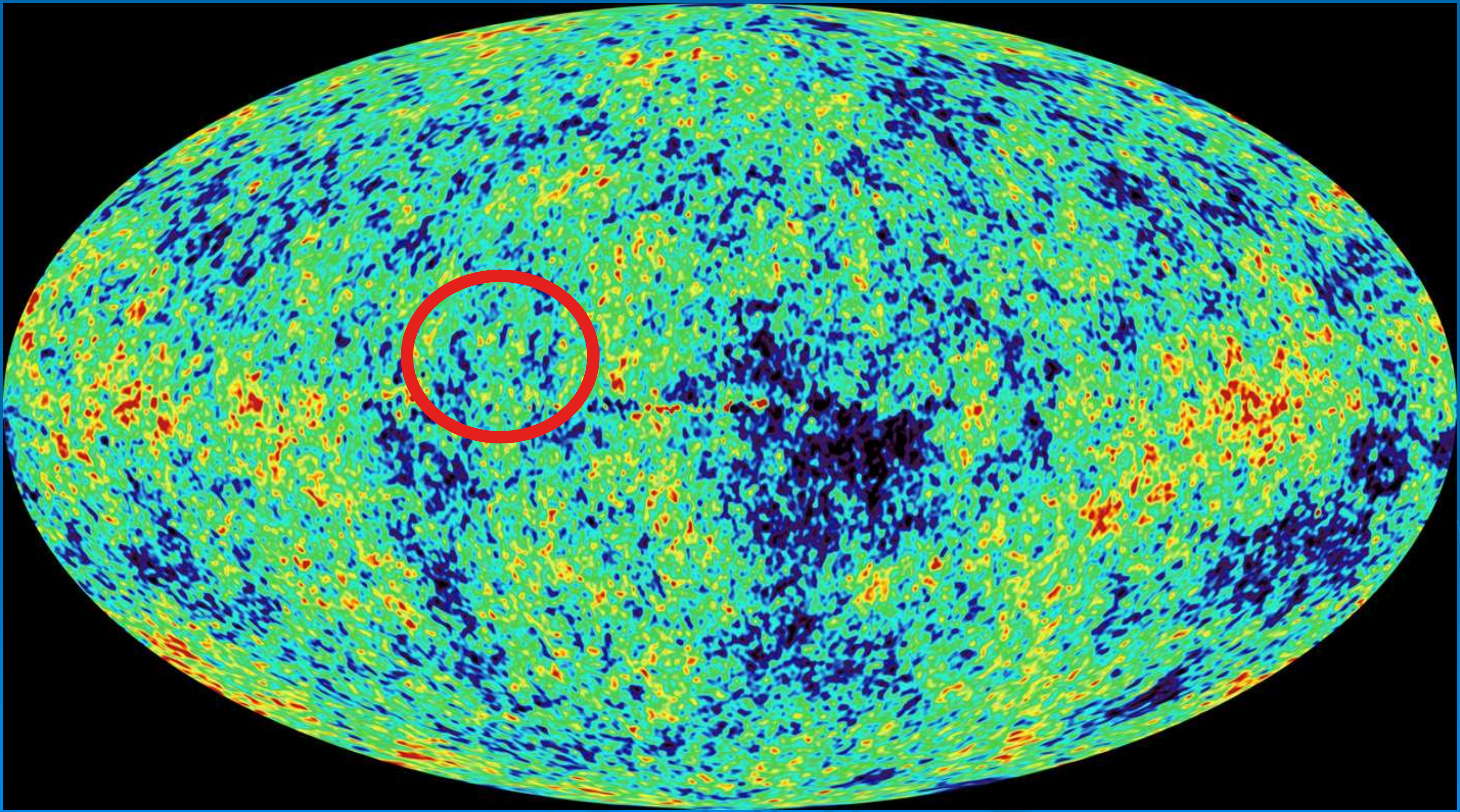
Fluctuations Appear to be Gaussian

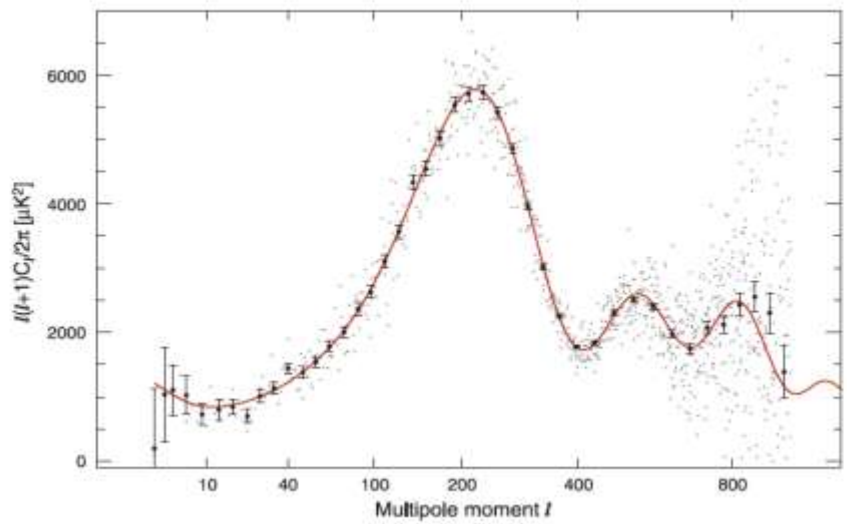


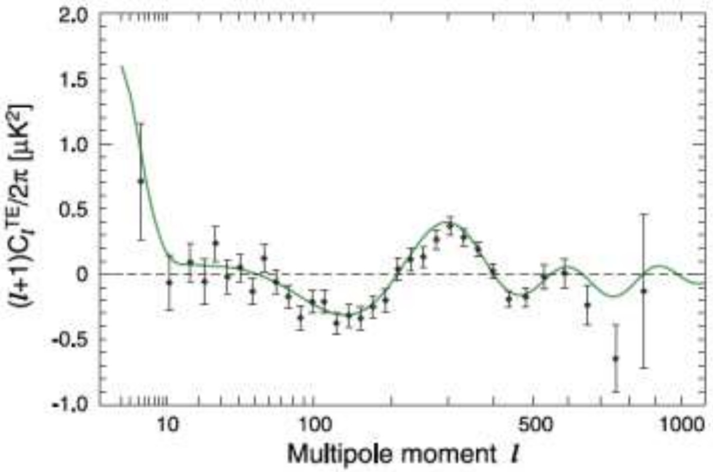




FOREGROUND CORRECTED MAP







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

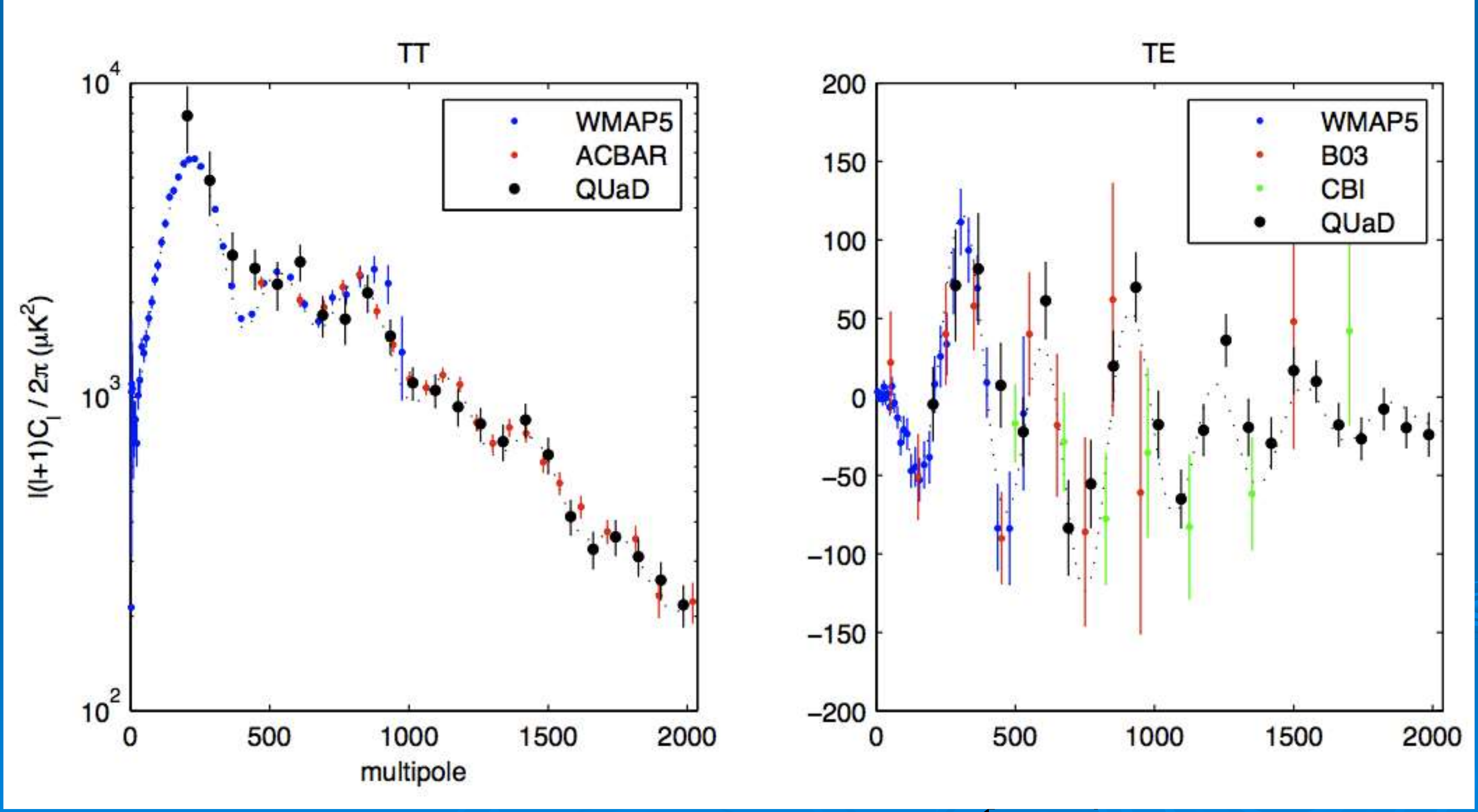
Atomic Density	$\Omega_b h^2$	$2.273 \pm 0.062 \times 10^{-2}$
Matter Density	$\Omega_m h^2$	0.1326 ± 0.0063
Amplitude	σ_8	0.796 ± 0.036
Spectral Index	n_s	$0.963^{+0.014}_{-0.015}$
Age	t_0	13.69 ± 0.13
Optical Depth	τ	0.087 ± 0.017

ACBAR

QuickTime™ and a
decompressor
are needed to see this picture.

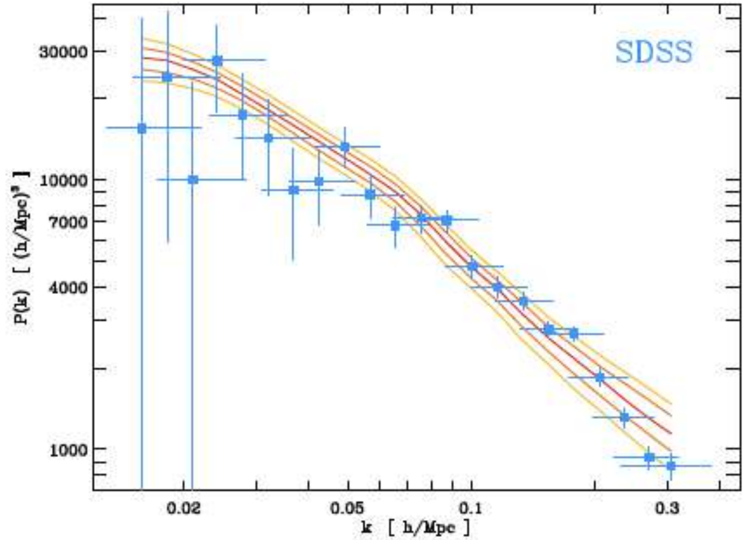
Reichardt et al. 2008 astro-ph/0801.1491

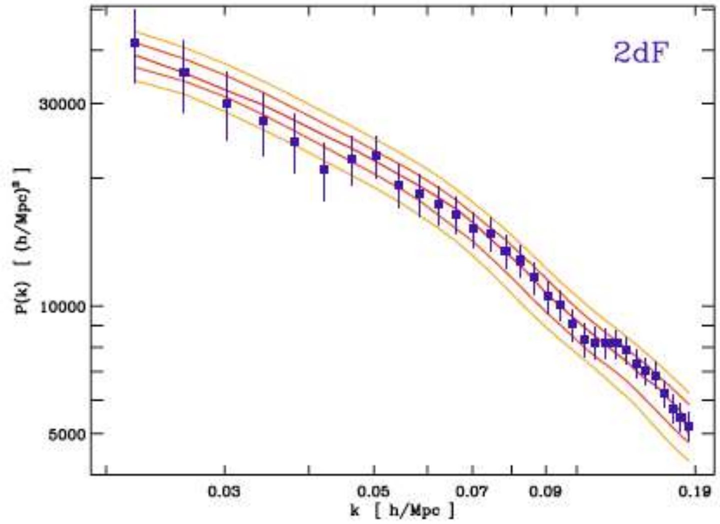
QUAD

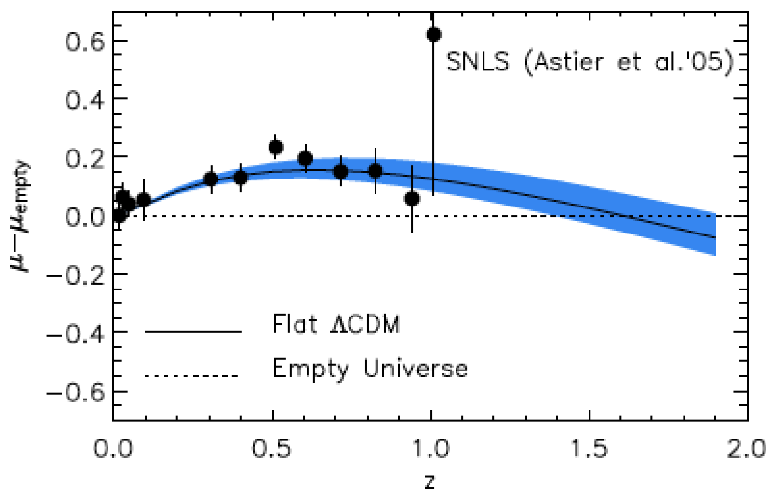


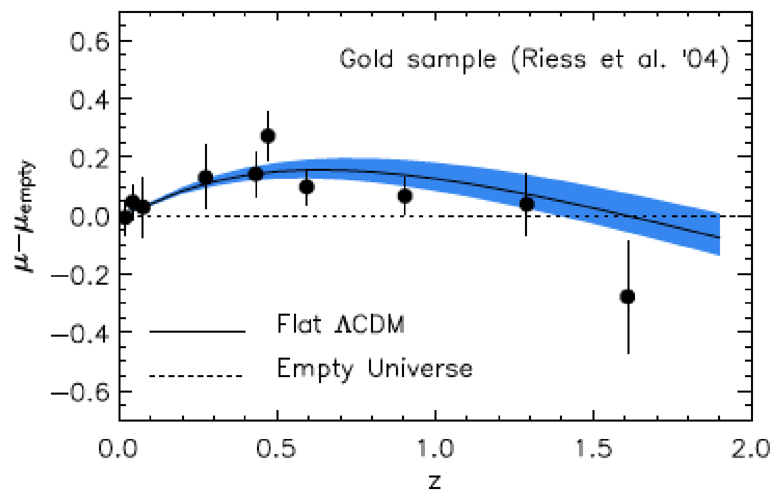
Pryke et al. 0805.1944

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]

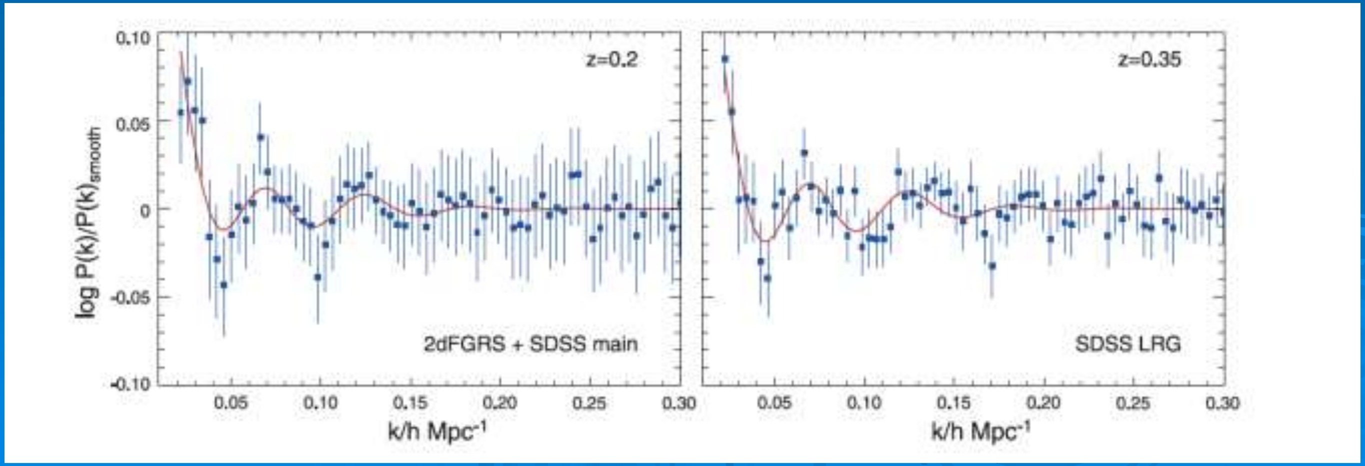

2dF
P(k) [(h/Mpc)³]
30000
10000
5000
0.03
0.05
0.07
0.09
0.19
k [h/Mpc]


SNLS (Astier et al.'05)
μ−μempty
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

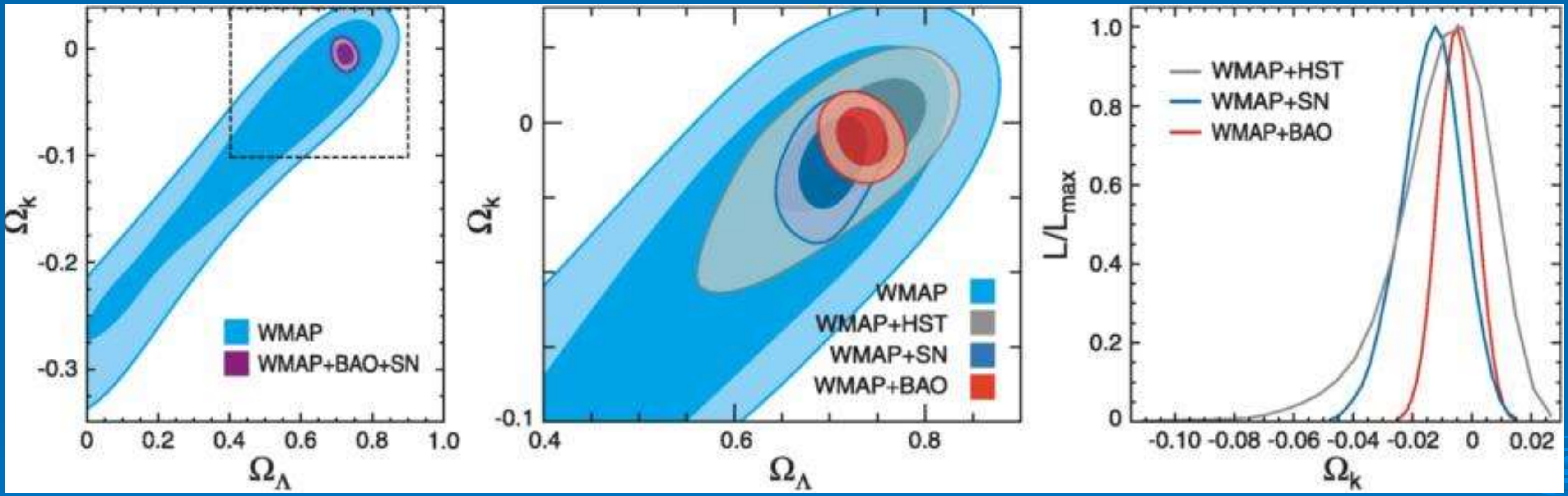

Gold sample (Riess et al. '04)
μ−μempty
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Flat ΛCDM
Empty Universe
0.0
0.5
1.0
1.5
2.0
z

Consistency

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

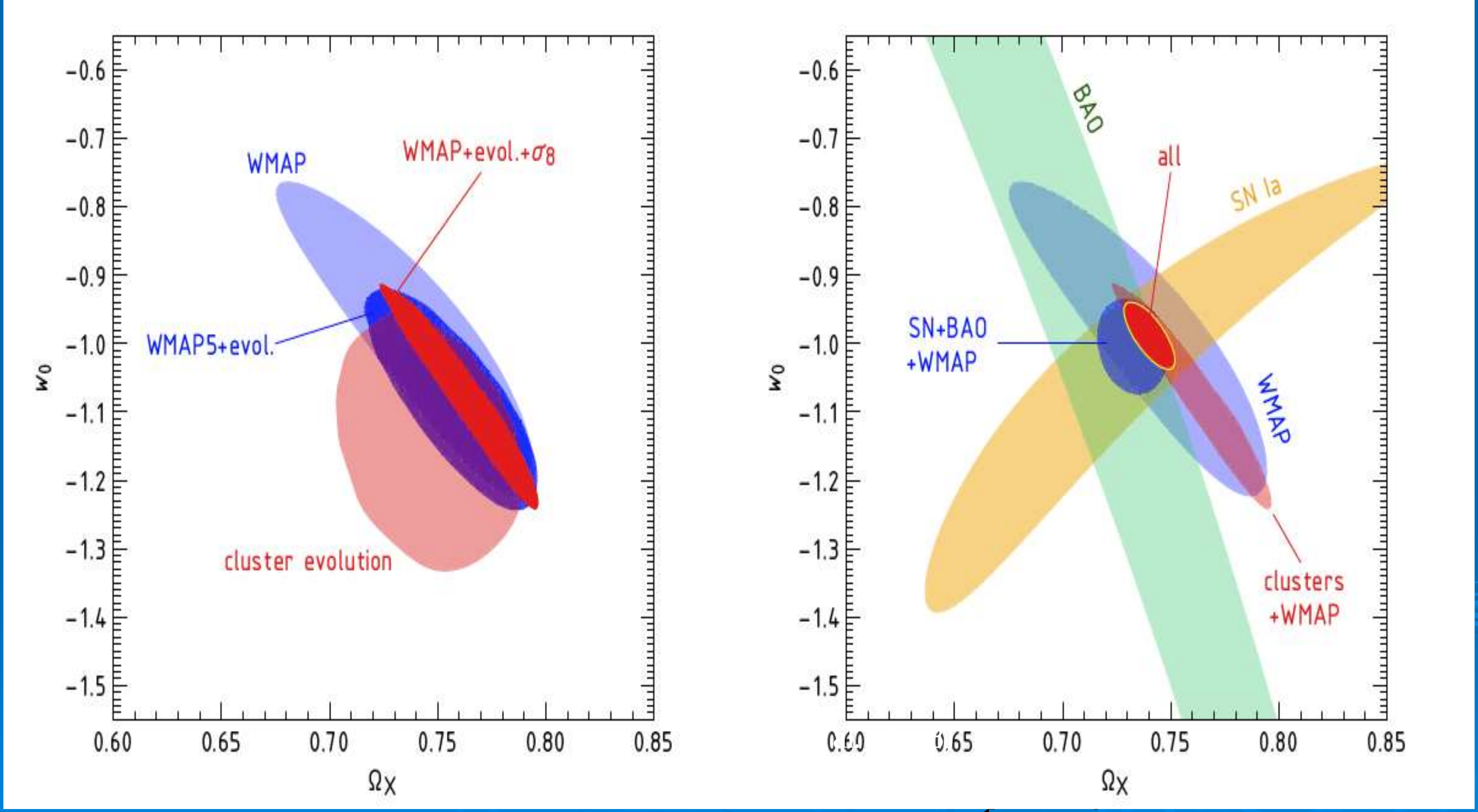


Geometry



0
-0.1
-0.2
-0.3
Ω_k
0 0.2 0.4 0.6 0.8 1.0
Ω_Λ
WMAP
WMAP+BAO+SN
0
-0.1
Ω_k
0.4 0.6 0.8
Ω_Λ
WMAP
WMAP+HST
WMAP+SN
WMAP+BAO
1.0
0.8
0.6
0.4
0.2
0
L/L_{max}
WMAP+HST
WMAP+SN
WMAP+BAO
-0.10 -0.08 -0.06 -0.04 -0.02 0 0.02
Ω_k

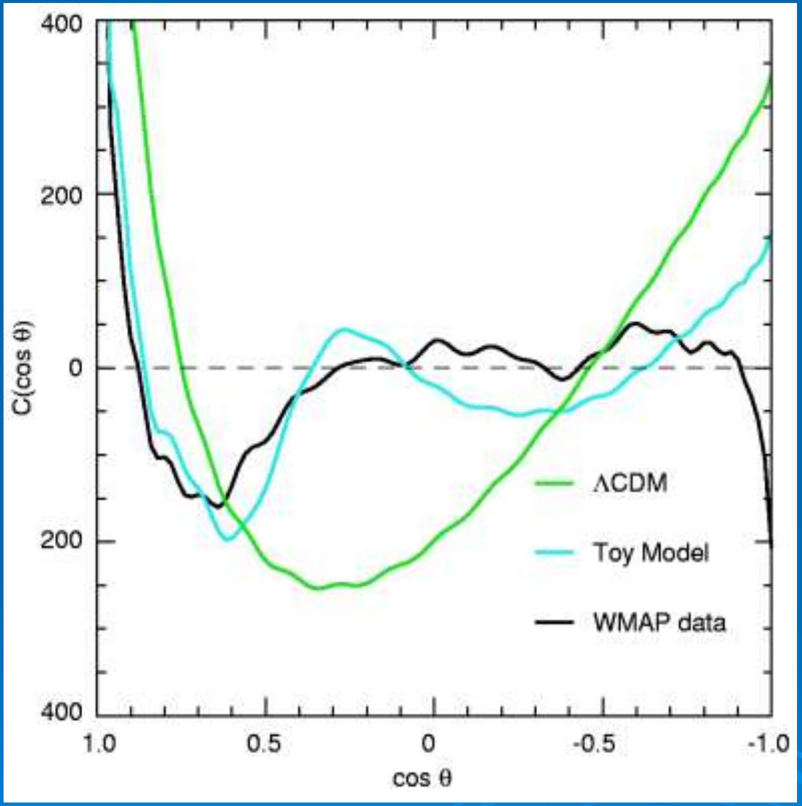
Dark Energy



Vikhlinin et al. (2008)

Too Little Large Scale Power?

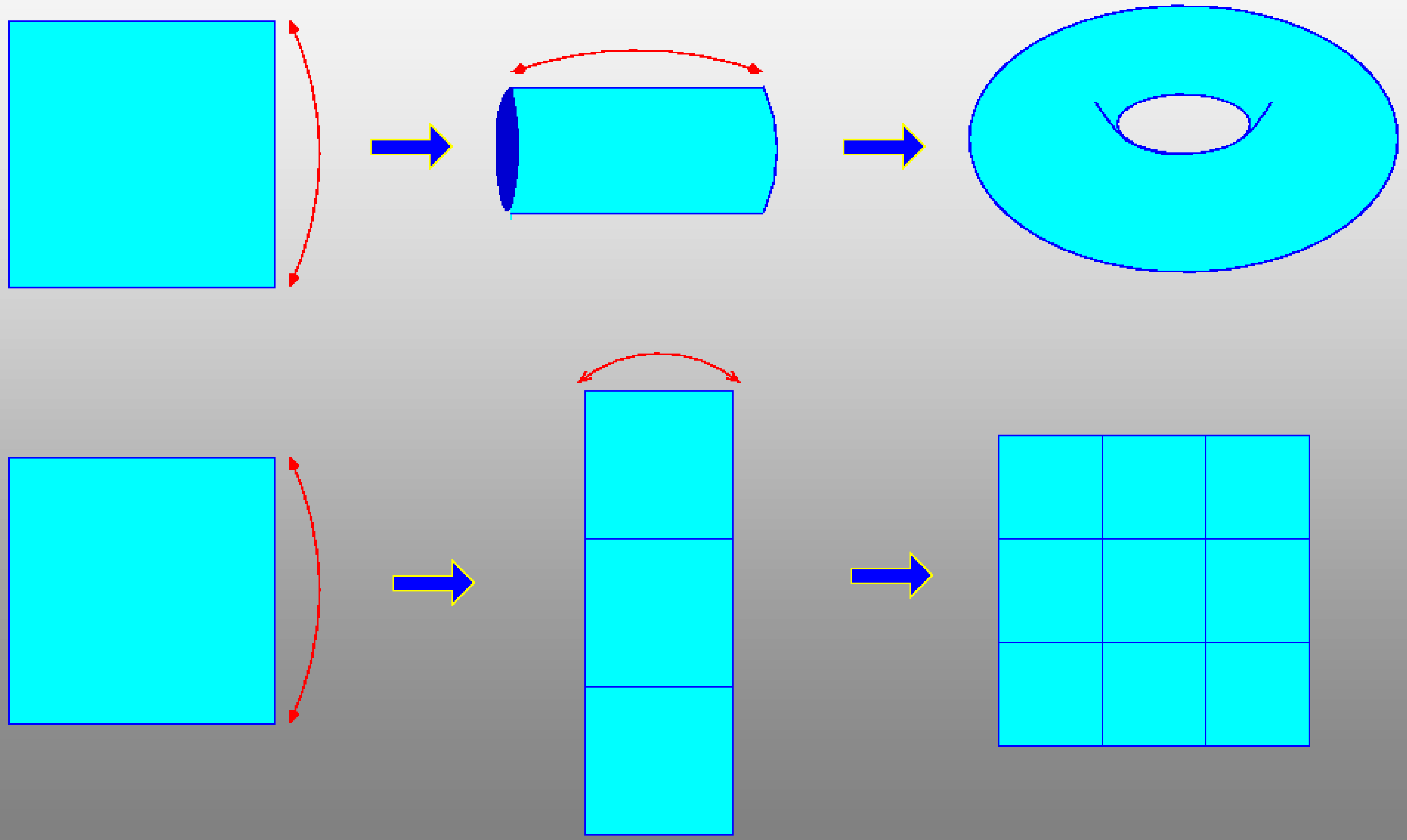
- Lack of large scale power
  - Seen in COBE but clearer now
  - Is the universe finite?
  - Are we seeing a characteristic scale?
  - Is it just chance?



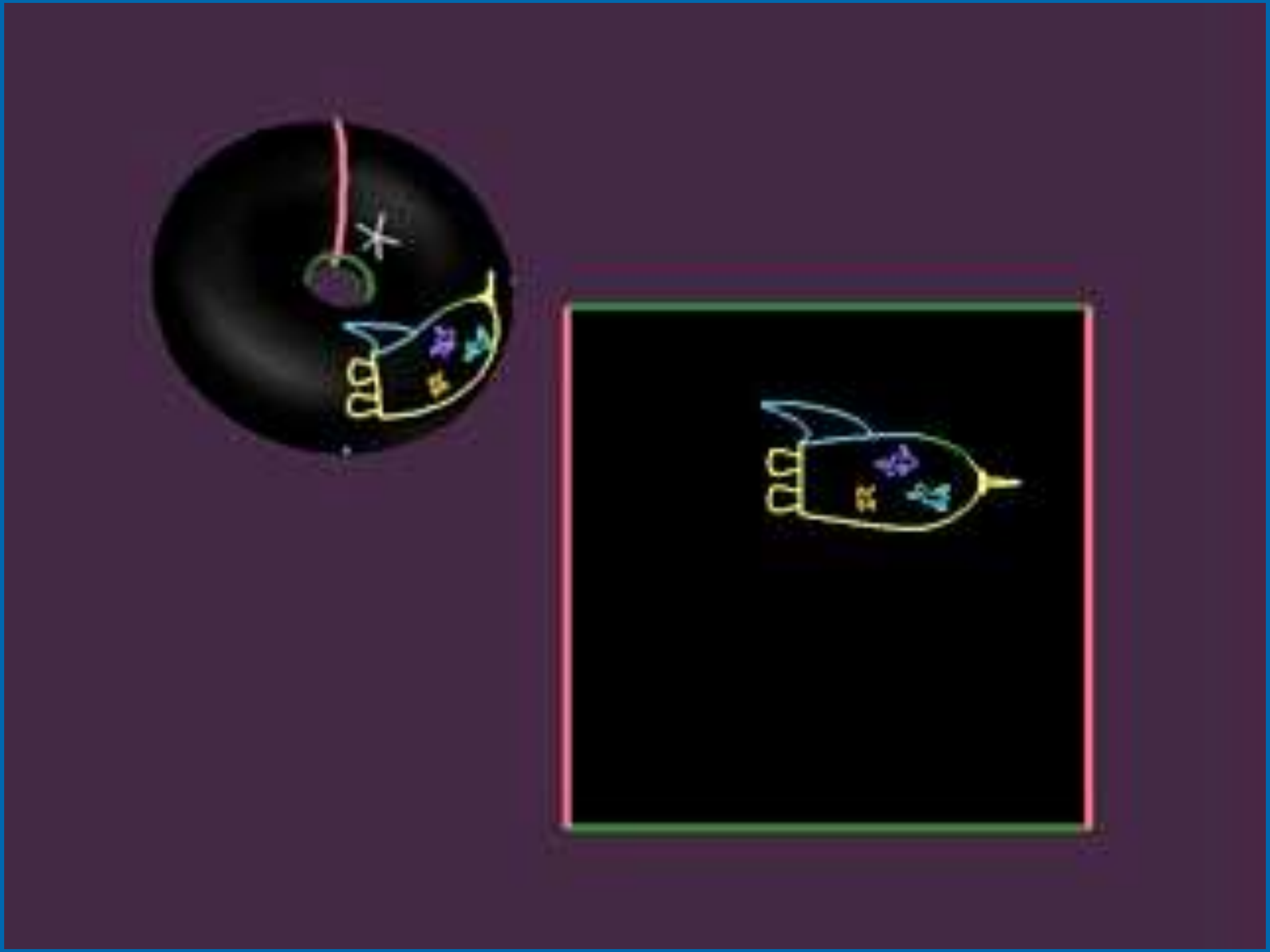
Is the Universe Finite or Infinite?

Work with Neil Cornsih, Glenn Starkman, Eiichrio Komatsu and Joey Key Shapiro

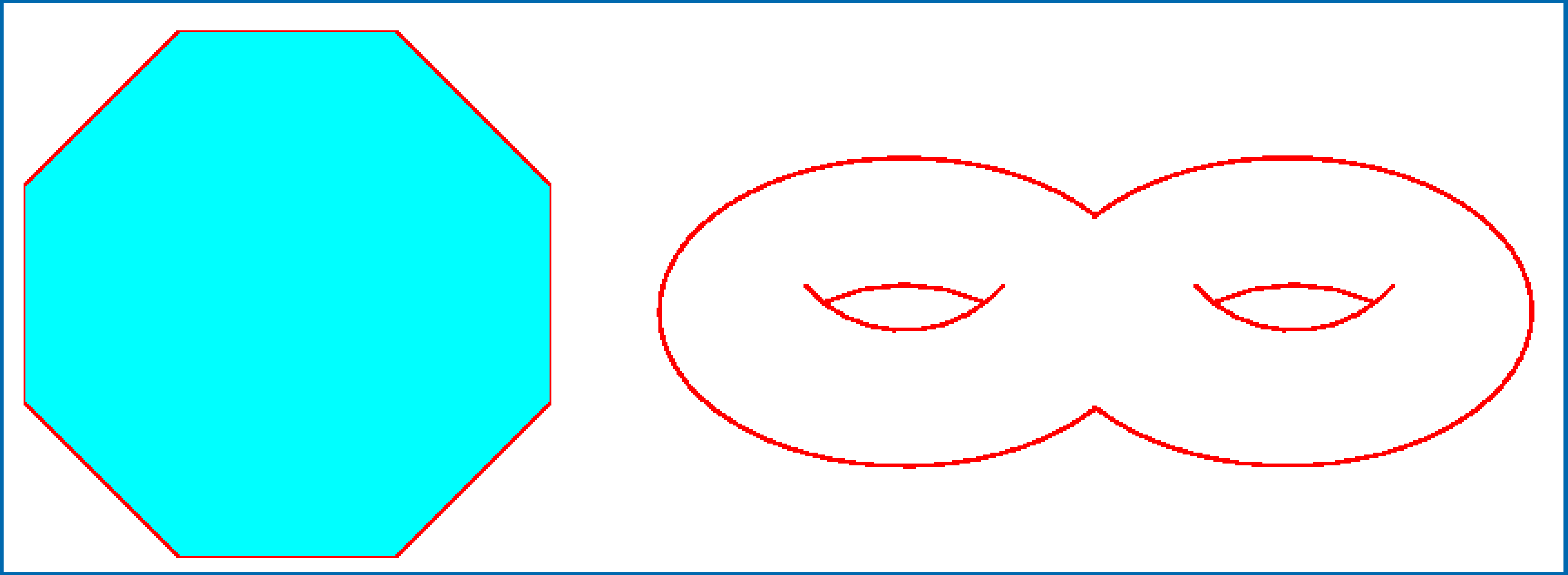
Topology



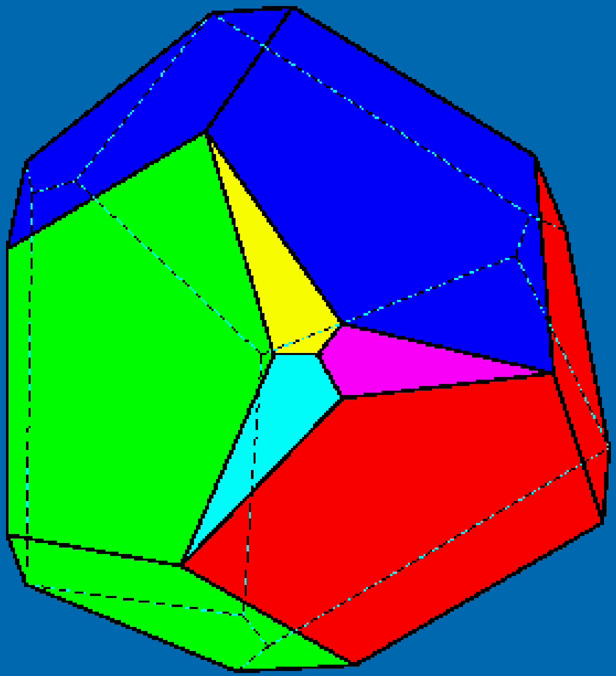
Two Torus

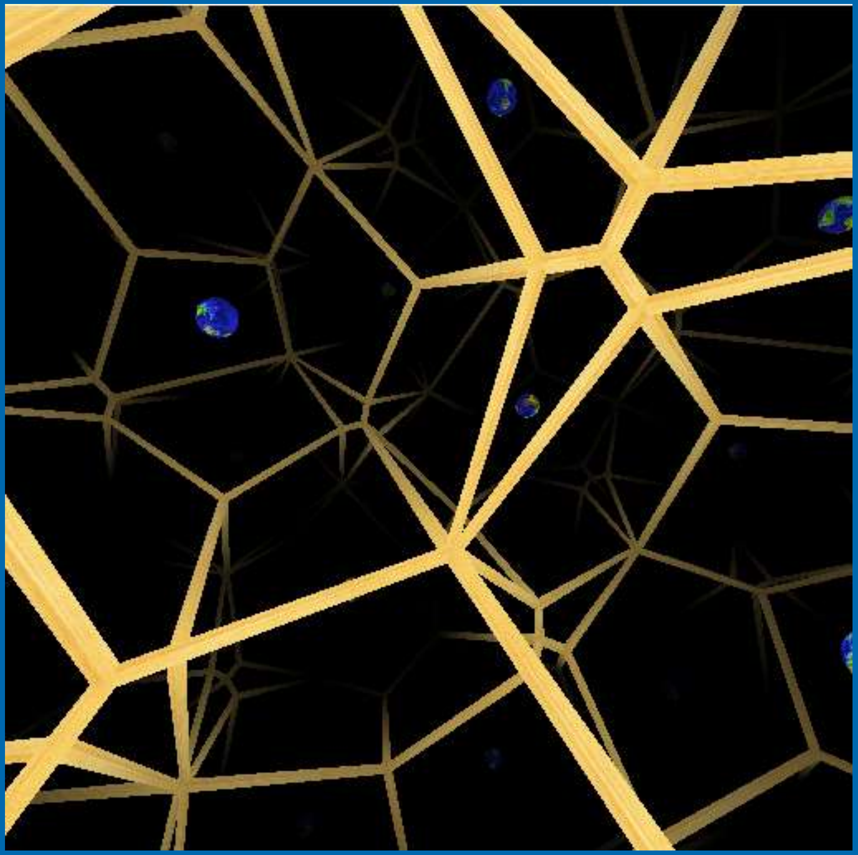


Other Tilings



Infinite number of tiling patterns

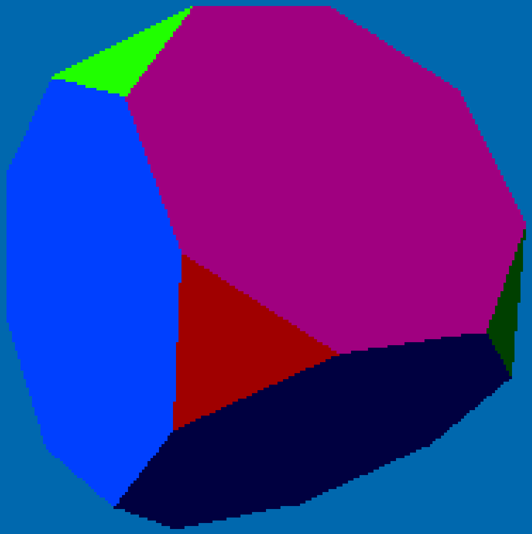


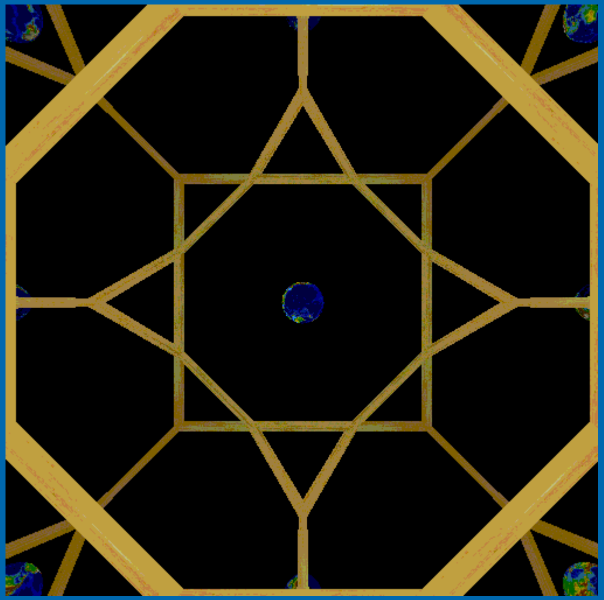


This one only works in hyperbolic space

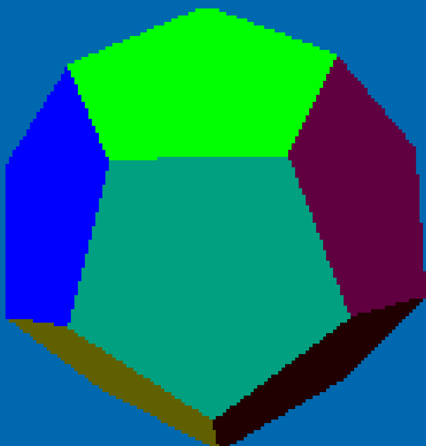
Spherical Topologies

This example only works in spherical space

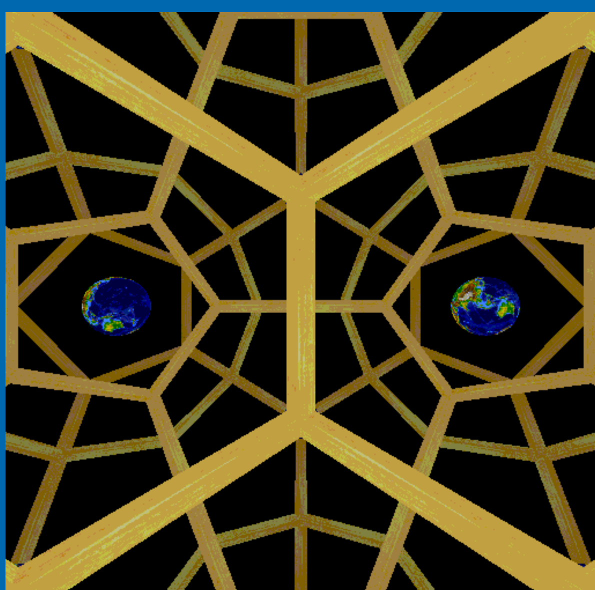


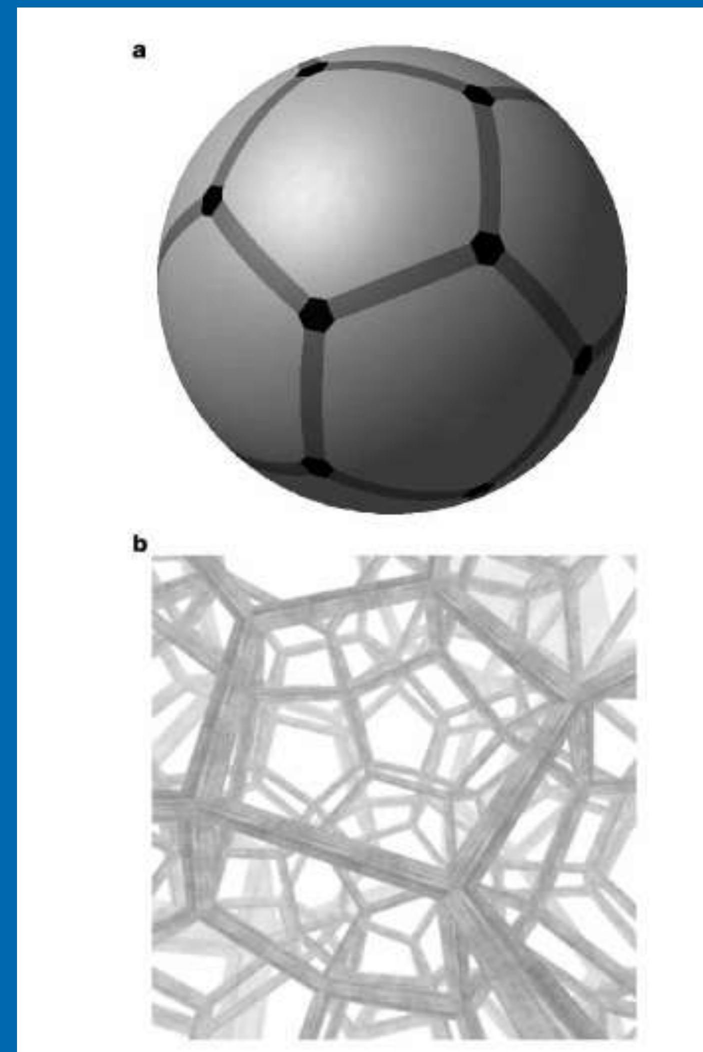


Dodecahedral Space

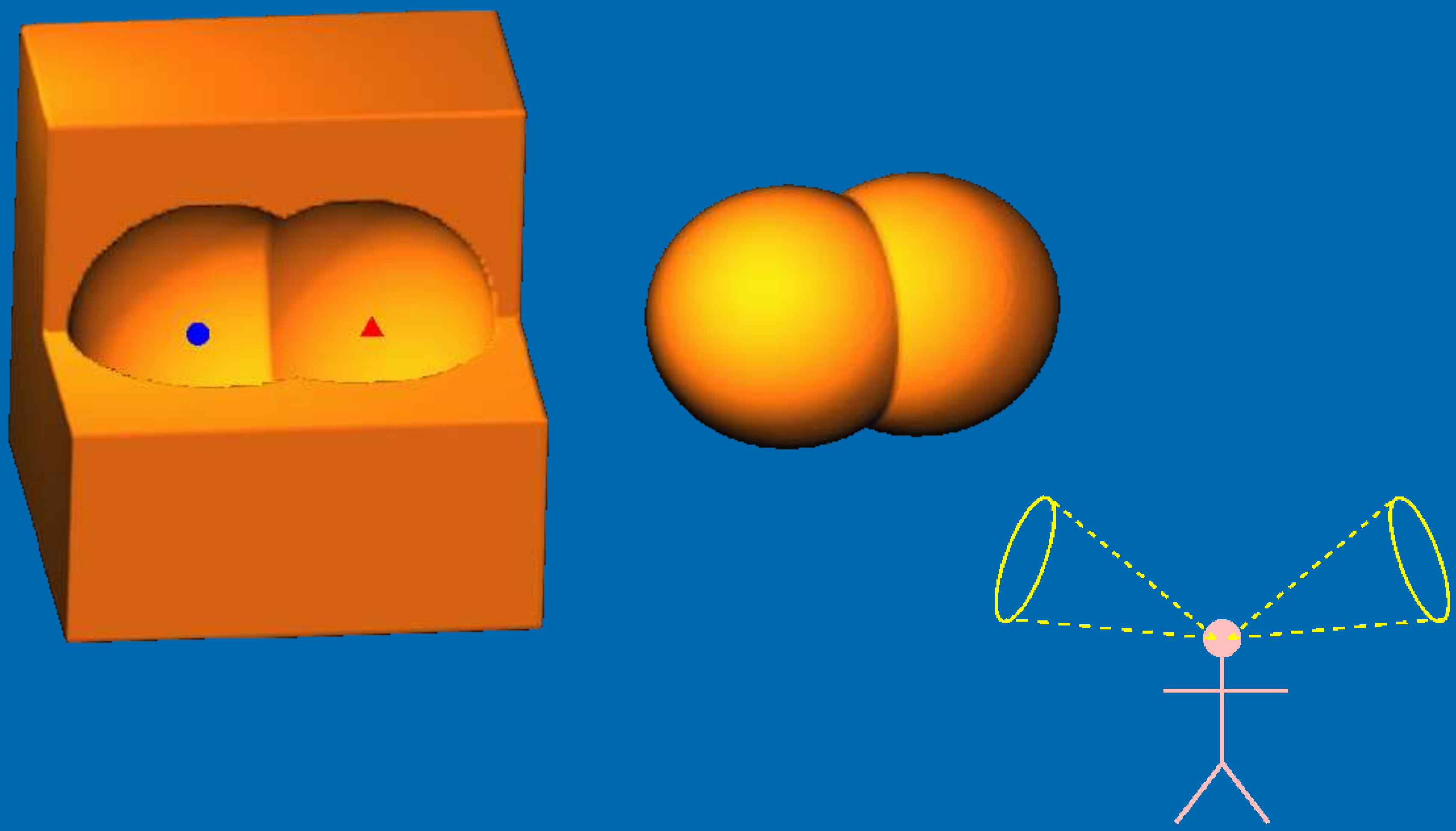


Tiling of the three-sphere by 120 regular dodecahedrons

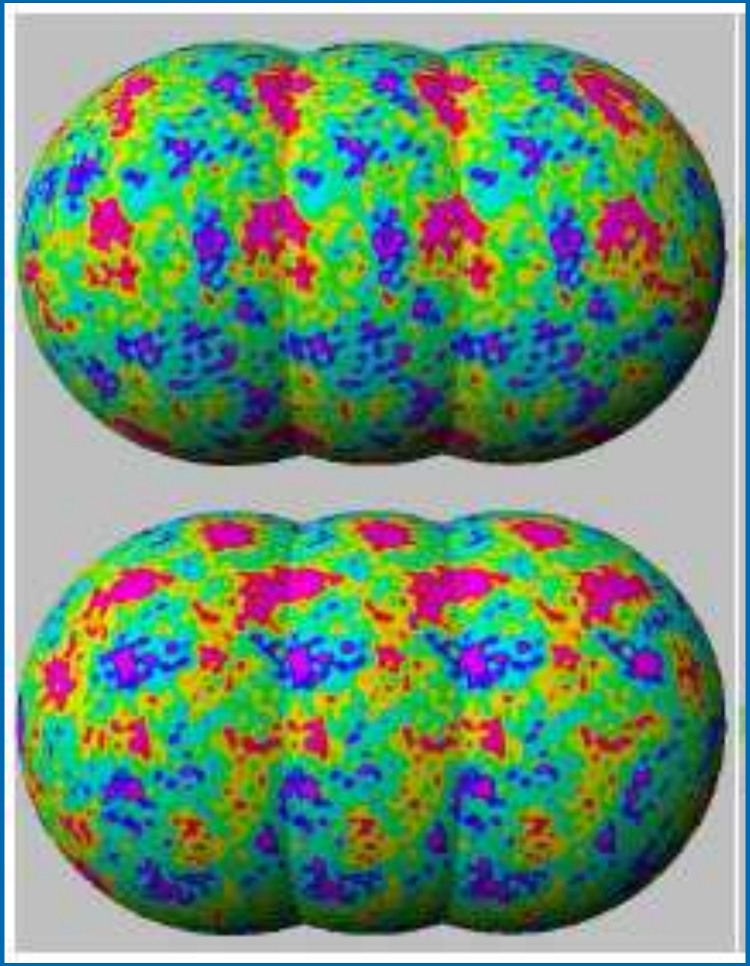


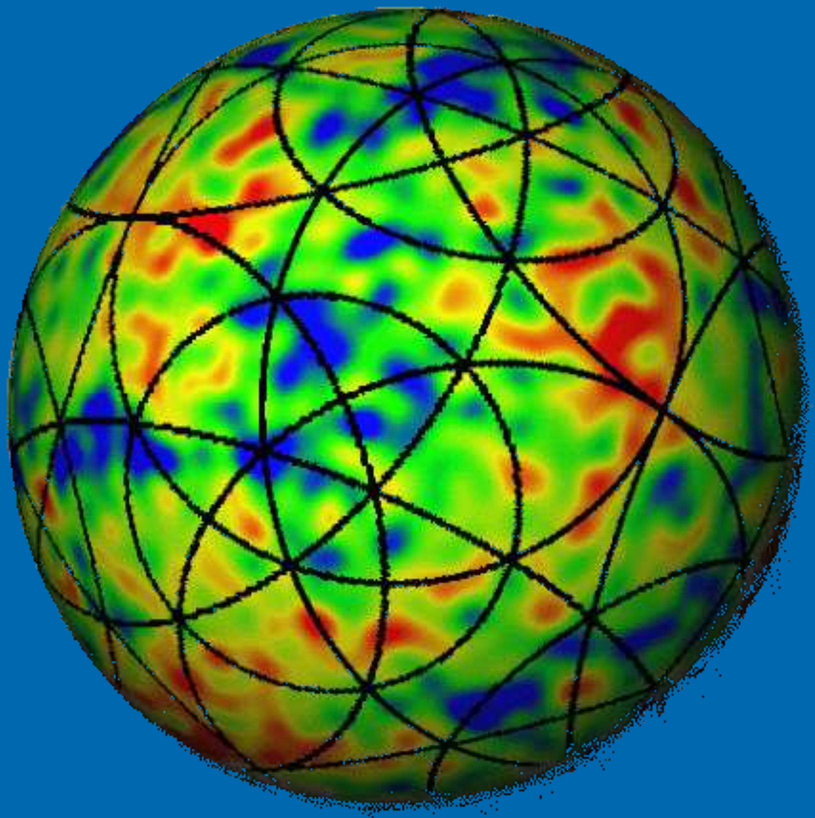


The microwave background in a multi-connected universe



Matched circles in a three torus universe





Statistics for matched circles

Spatial comparisons:

Use a RES r Healpix grid ($3 \times 2^{2r+2}$ pixels)

Draw a circle radius α around center,

linearly interpolate values at 2^{r+1} points around circle

$$S_{12} = 2\langle T_1(\phi)\, T_2(\phi) \rangle_\phi / (\langle T_1(\phi)^2 \rangle_\phi + \langle T_2(\phi)^2 \rangle_\phi)$$

Perfect match $S_{12} = 1$ Random circles $\langle S_{12} \rangle = 0$

Fourier space comparisons:

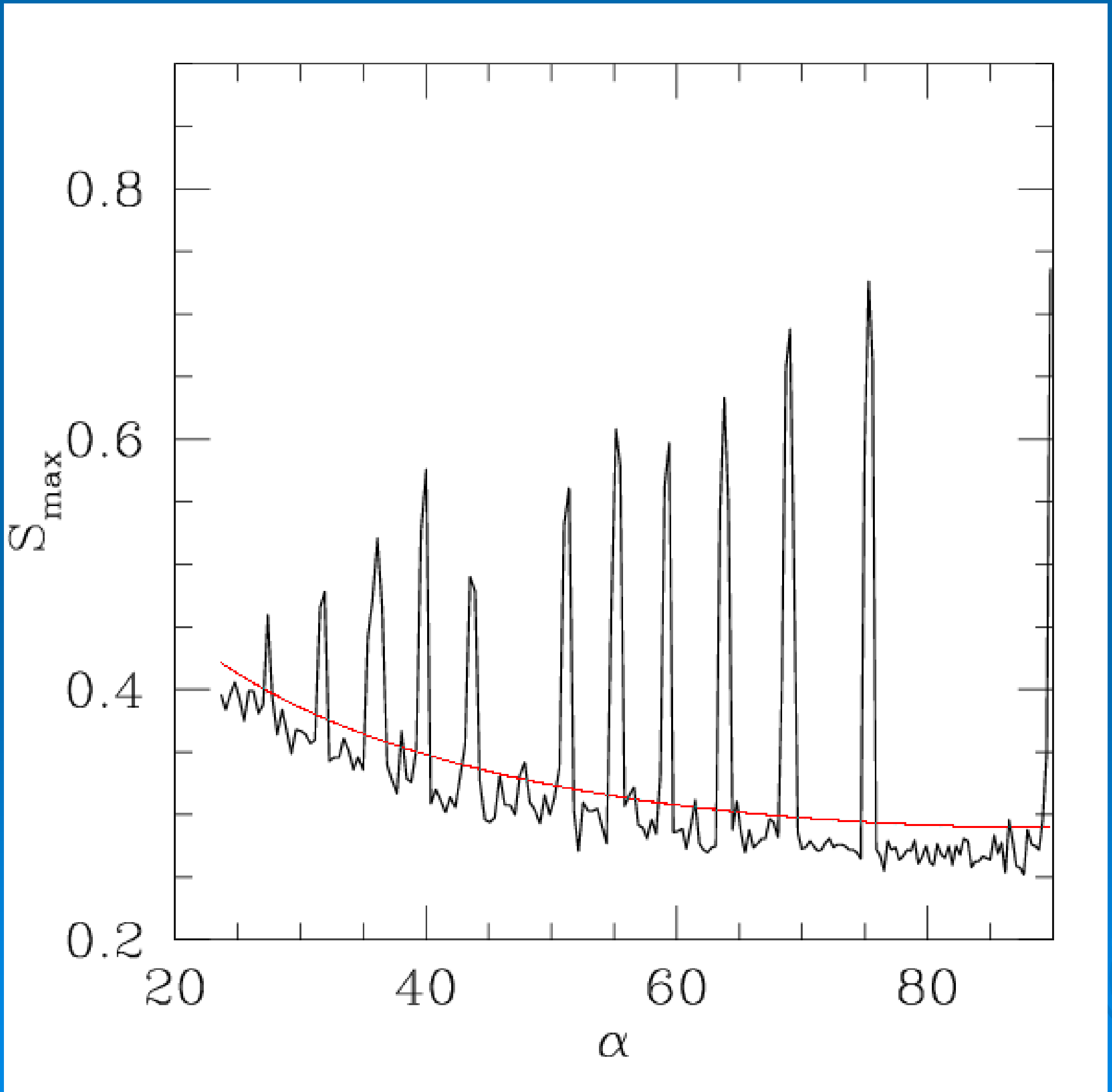
$T_i(\phi) = \sum_m T_{im}\, e^{im\phi}$

$S_{ij}(\beta) = 2\sum_m m T_{im} T_{jm}\, e^{-im\beta} / \sum_m m(|T_{im}|^2 + |T_{jm}|^2)$ β is relative phase

We write as: $S_{ij}(\beta) = \sum_m s_m\, e^{-im\beta}$ and calculate $S_{ij}(\beta)$ as an FFT of s_m

for a n / logn speed-up (to $n^4 \log(n)$)

Matched Circles in Simulations



In a blind test >99% of circles found in a "deliberately difficult" universe

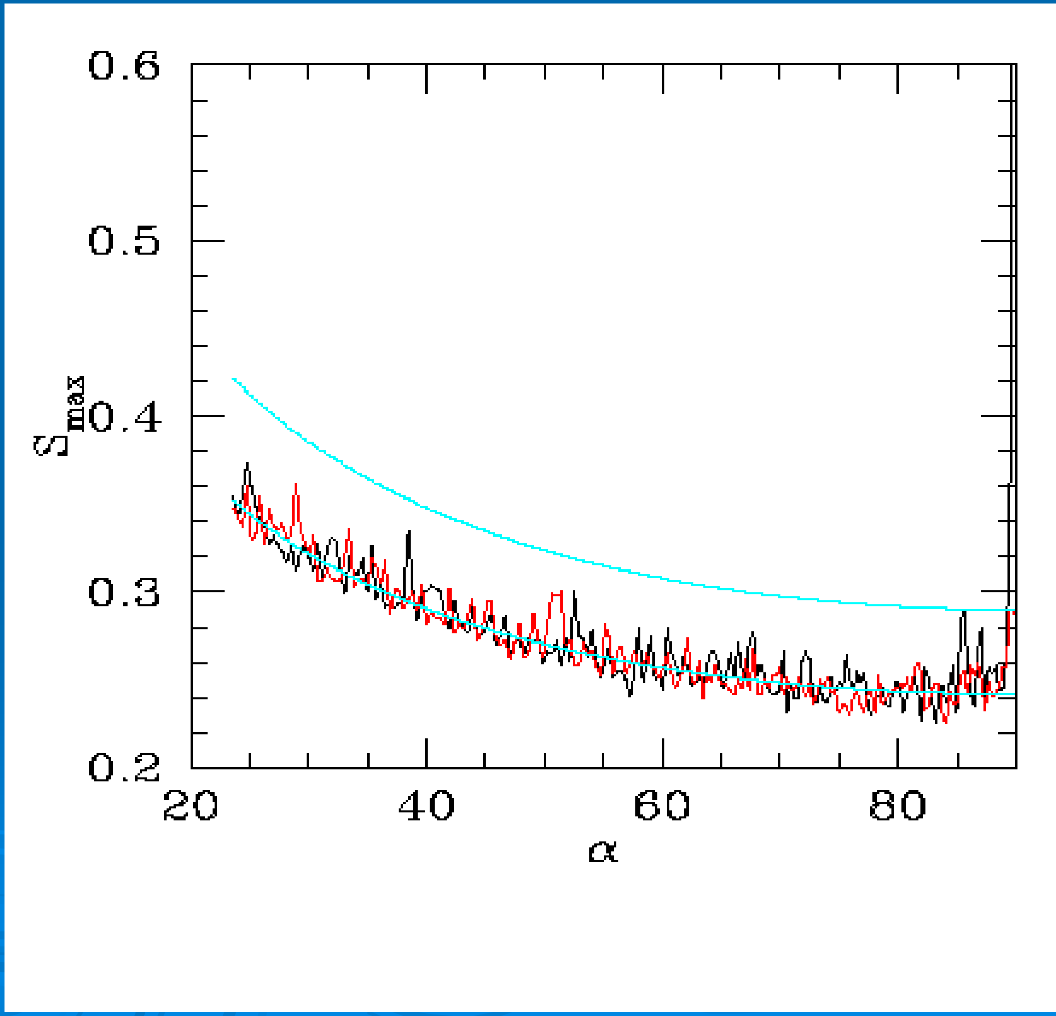
Blind test (simulated sky supplied by A. Riazuelo):

Manifold (S_3/Z_2) with 98304 visible circle pairs at each radius, α
Parameters chosen to maximize ISW, Doppler de-coherence --"worst case".

α	missed 1st cut	made 1st cut	missed 2nd cut	made 2nd cut	false-negative rate
24	334	97970	1642	96328	2%
30	154	98150	118	98032	0.4%
36	55	98249	11	98238	0.07%
42	19	98285	3	98282	0.02%
48	13	98291	2	98289	0.02%
54	8	98296	0	98296	<0.01%
60	1	98303	0	98303	<0.01%
65	2	98302	0	98302	<0.01%
71	5	98299	0	98299	<0.01%
76	1	98303	0	98303	<0.01%
80	2	98302	0	98302	<0.01%
85	0	98304	0	98304	0%
90	0	98304	0	98304	0%

What we see in the WMAP data:

UNIVERSE IS BIG!



Conclusions

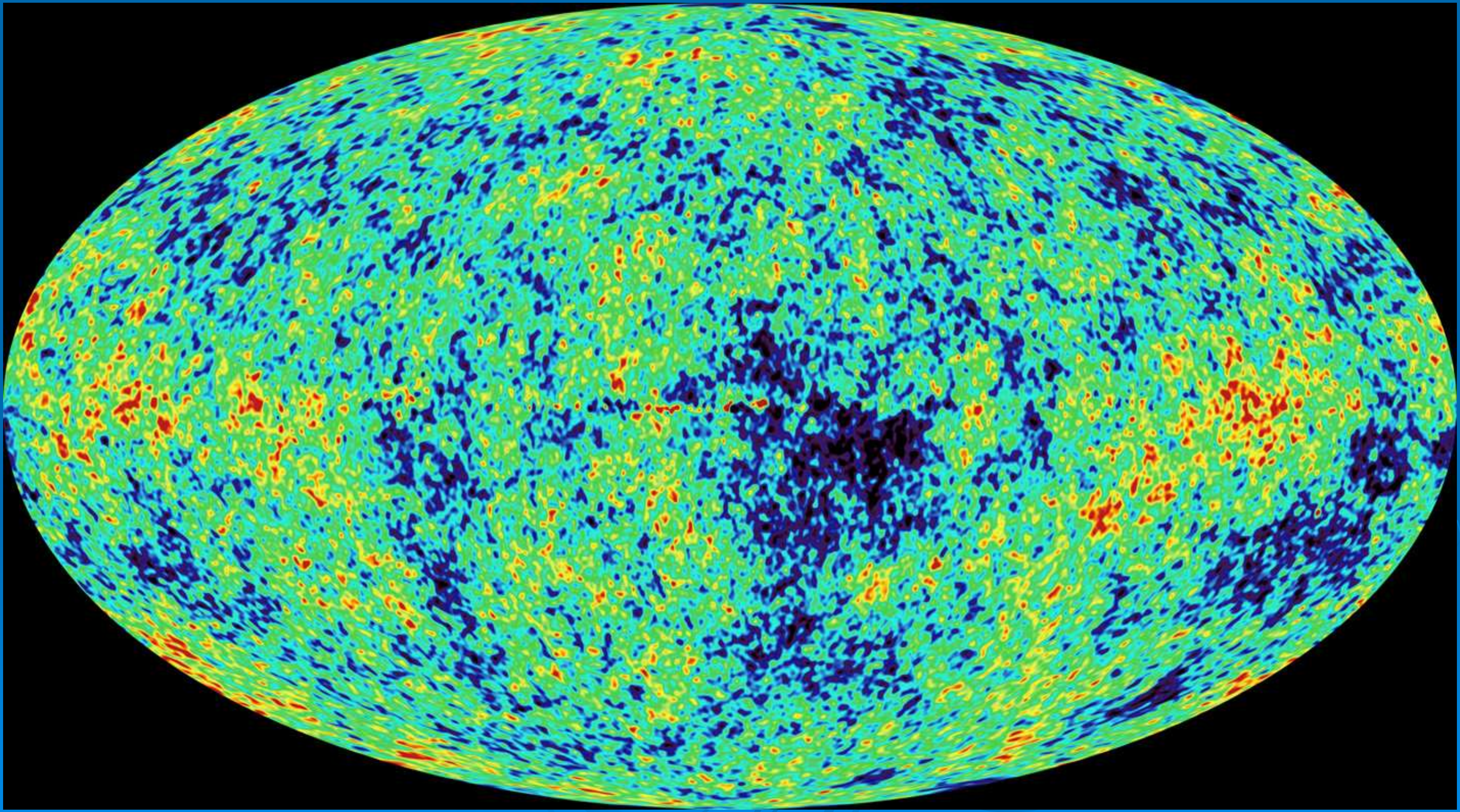
- Cosmology is in a golden age!
- Advances in technology are enabling us to probe the physics of the very early universe and the birth of structure

QuickTime™ and a
decompressor
are needed to see this picture.

- So far, the standard model appears to fit the data, but stay tuned!

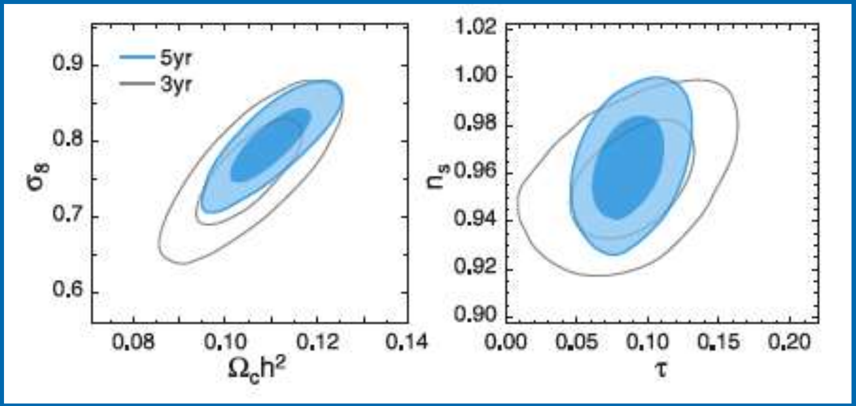
Coming Soon!

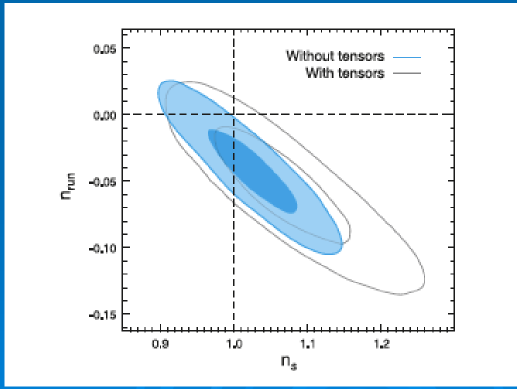
THANK YOU !

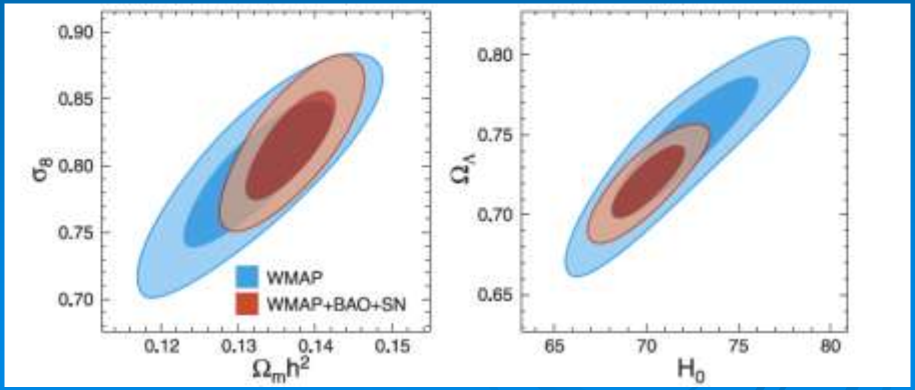


Parameters

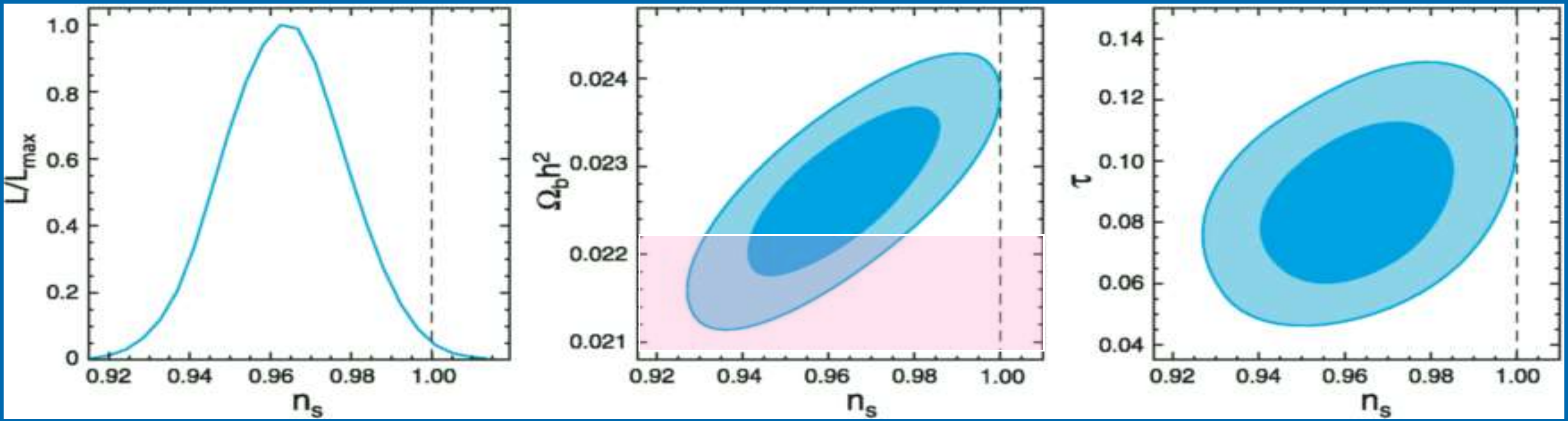
- Improved (and higher) values for matter density and amplitude of fluctuations
- No significant change in other parameters
- Optical depth is robust against treatments of foregrounds
- Adding SN + BAO data improves matter density constraint and sharpens parameter measurements







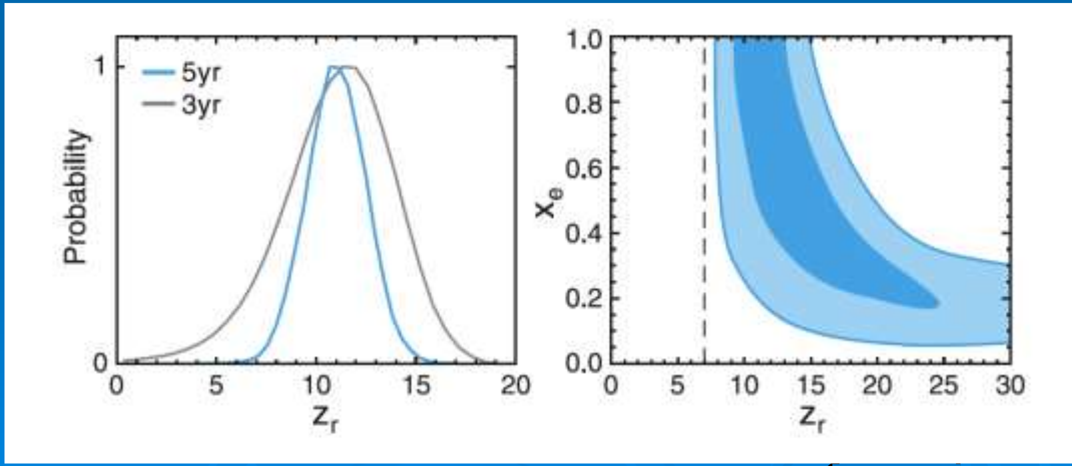
Baryon Density



- Pettini et al. (astro-ph/0805.0594) report $\Omega_b h^2 = 0.0213 +/- 0.010$
- WMAP + D/H measurements imply
  $n_s = 0.959 +/- 0.013$

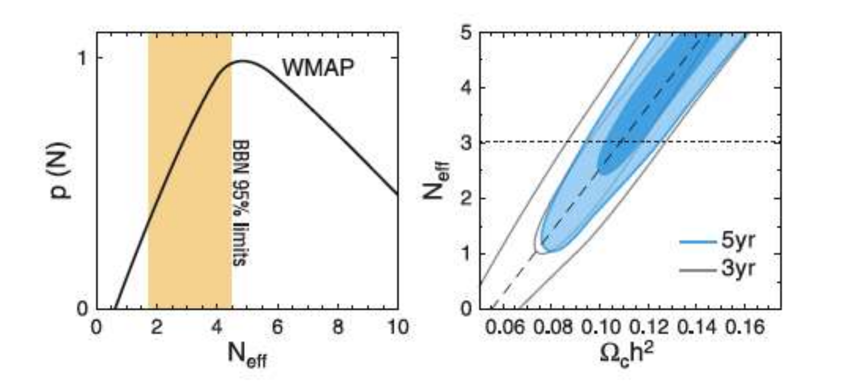
Reionization

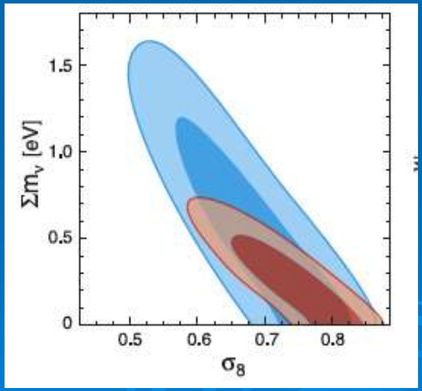
- Measurement of optical depth improves from 3 to 5 σ
- Reionization is an extended process
- Detailed study of sensitivity to foreground removal

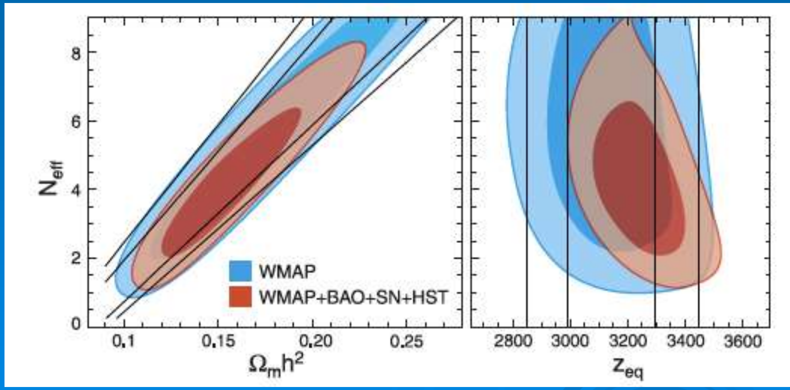


Neutrinos

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

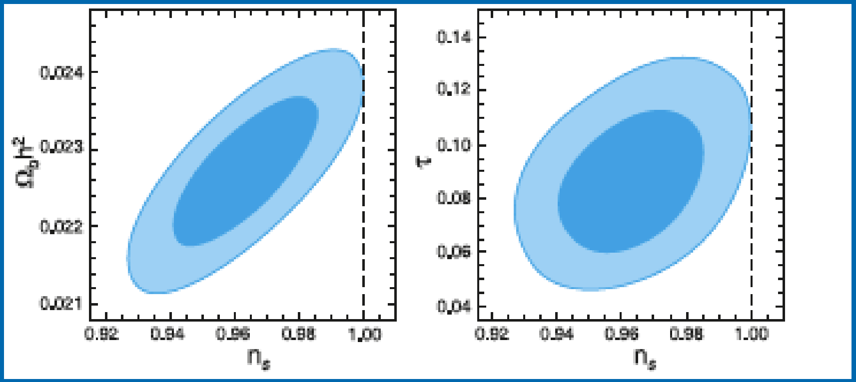


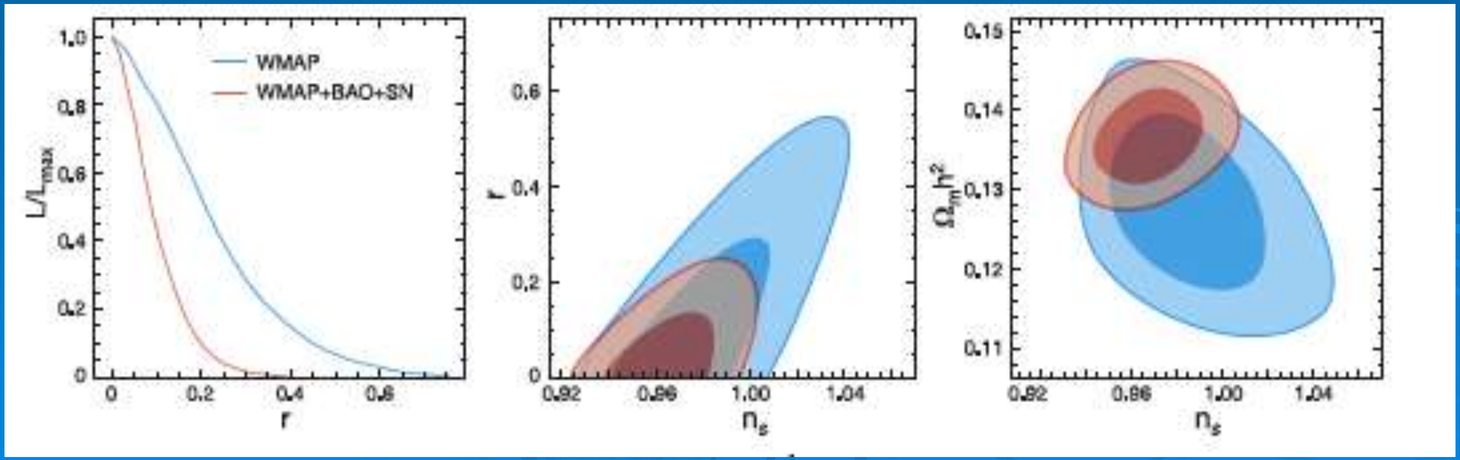




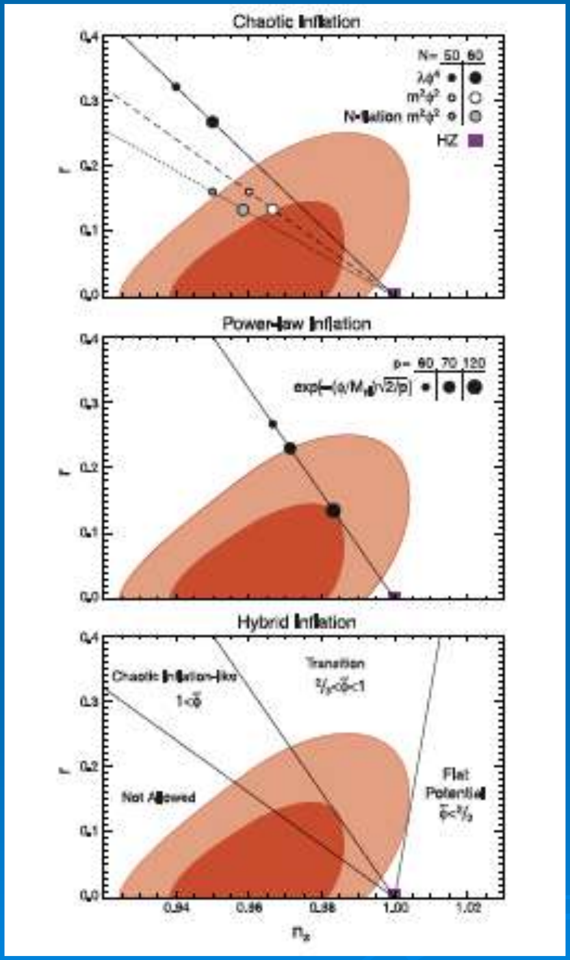
Inflation

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

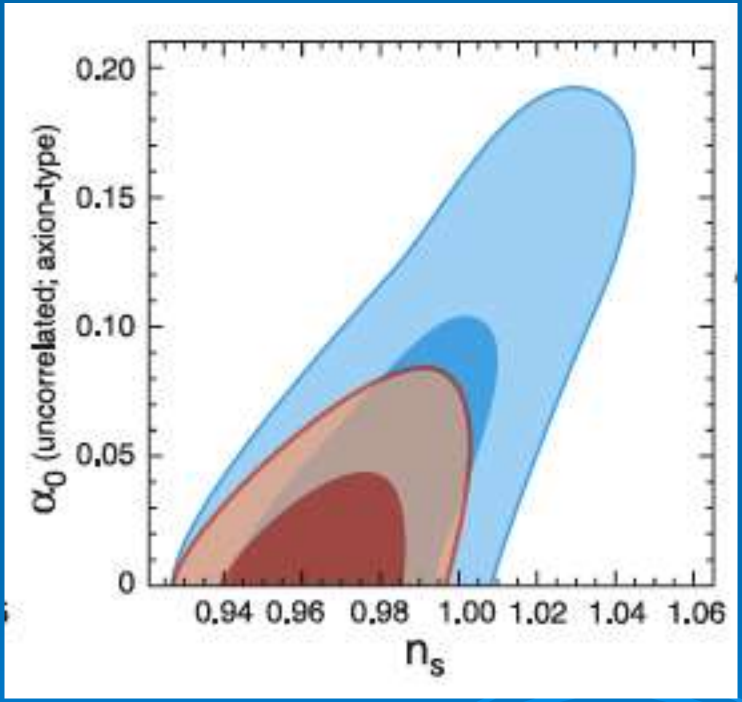




Inflationary Models



One field models

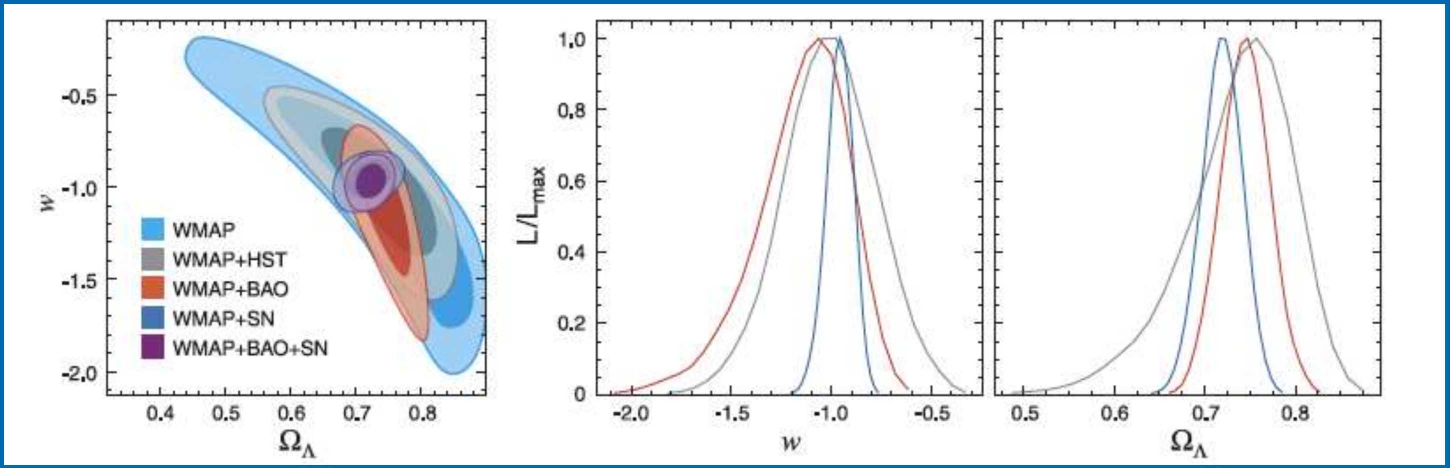


Multi field models

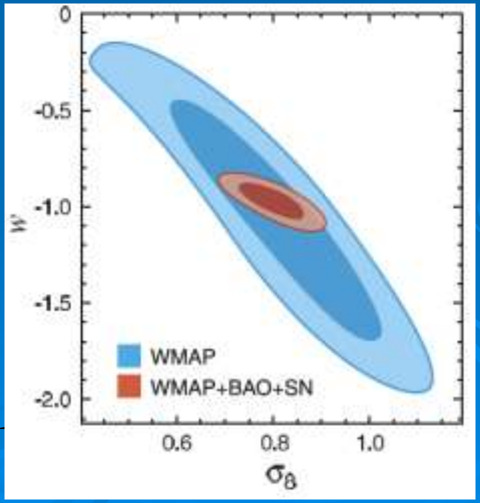
Cosmology Now Has A Standard Model

- Basic parameters are accurately determined
  - Improved constraints on parameters
  - CMB best fit consistent with other measurements
- Mysteries remain: dark matter, dark energy, physics of inflation
  - WMAP observations provides constraints on models beyond the standard model
  - Hints of non-Gaussianity but marginally at 2 σ; more data needed
- More to come! Planck, ACT, ….

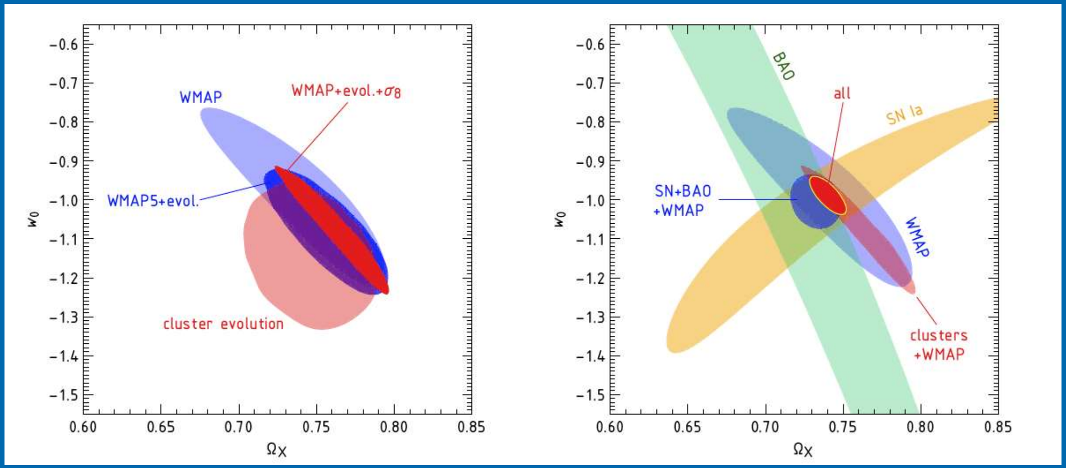
Dark Energy



- WMAP data constrains angular distance to z = 1090
- Amplitude of fluctuations at z = 1090



Amplitude Constraints



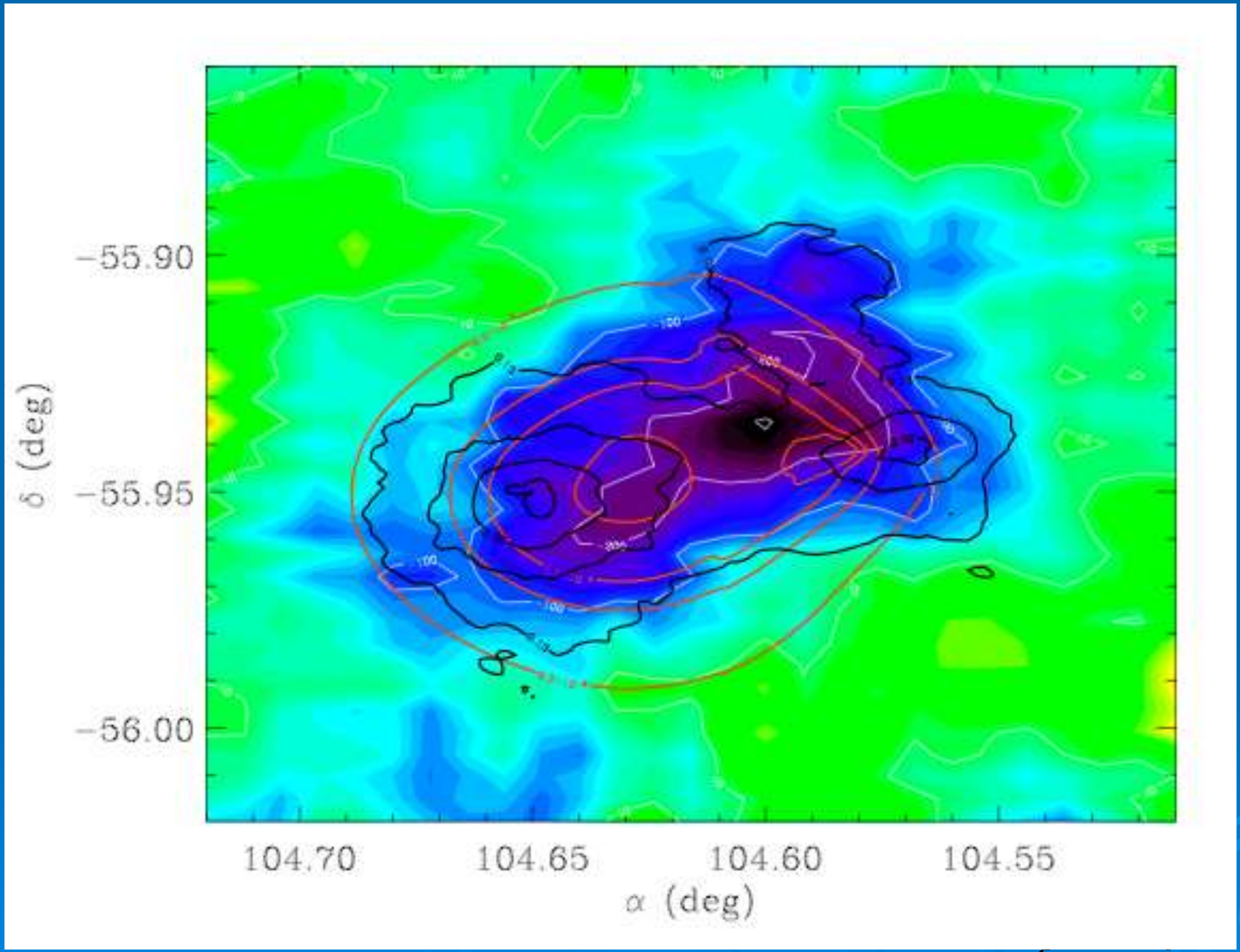
- Viklinin et al. used Chandra to determine “Yx” for a sample of 400 nearby (z ~0.05) and distant (z ~0.55) sample
- Clusters measure σ_8 and Ω_m. When combined with WMAP measurements of primordial amplitude yield interesting constraints on w.

ACT in Chile

March 2007

Photos: M. Limon

First Results from ACT



Lensing: Black Contours

X-ray: Red Contours

SZ: Color

green: positive

blue: negative

"Bullet" Cluster (6 minutes of integration)

ACT 2007 Expected Power Spectrum

QuickTime™ and a
decompressor
are needed to see this picture.

ACT should have 20 times more data in the 2008 season!

NSF funding
began Jan 2004

ACT Institutions

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Penn

Princeton

U Mass

RUTGERS

Católica

CUNY

Columbia

U of T
Toronto

UBC

Haverford

UNIVERSITY OF KWAZULU-NATAL

NIST
National Institute of Standards and Technology

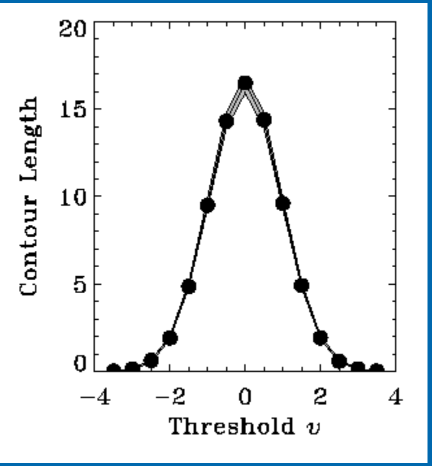
Pittsburgh

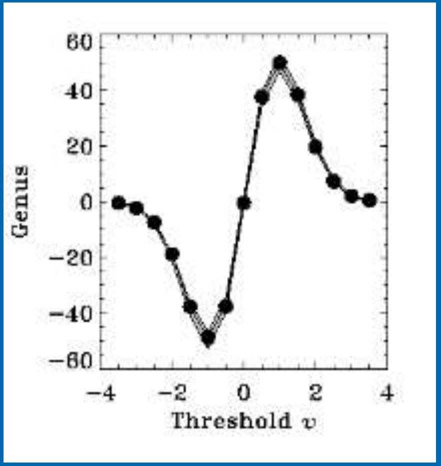
NASA Goddard Space Flight Center

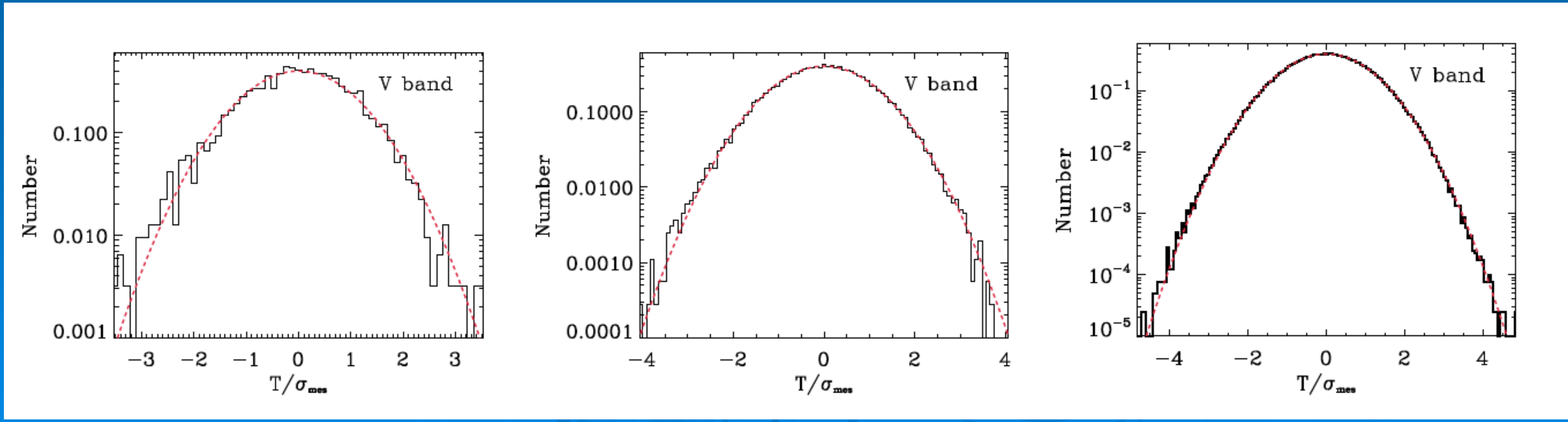
Hunting for Non-Gaussianities

- Axis of Evil (Land and Maguiejo)
- Cold Spot (Cruz et al.)
- Too few cold and hot spots (Larson and Wandelt)
- Vorticity and Shear
- Features in the power spectrum
- Bianchi VIIh models
- Alignment of quadrupole and octopole

Fluctuations Appear to be Gaussian







Cold Spot Tests

- Is it a low density region?
  - Minnesota group (Rudnick et al.)
- Is it a texture?

- Key observational tests
  - TE correlation - test if fluctuation is adiabatic fluctuation at SLS
  - Small scale CMB measurements
    - Low density region will produce significant lensing

Primordial Skewness

Spergel and Goldberg 1999

Komatsu and Spergel 2001

$$\Phi(\mathbf{x}) = \Phi_L(\mathbf{x}) + f_{NL}\left(\Phi_L^2(\mathbf{x}) - \langle\Phi_L^2(\mathbf{x})\rangle\right)$$

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

Non-linear Bispectrum Terms

Spergel and Goldberg 1999

QuickTime™ and a
decompressor
are needed to see this picture.

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decompressor
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decompressor
are needed to see this picture.

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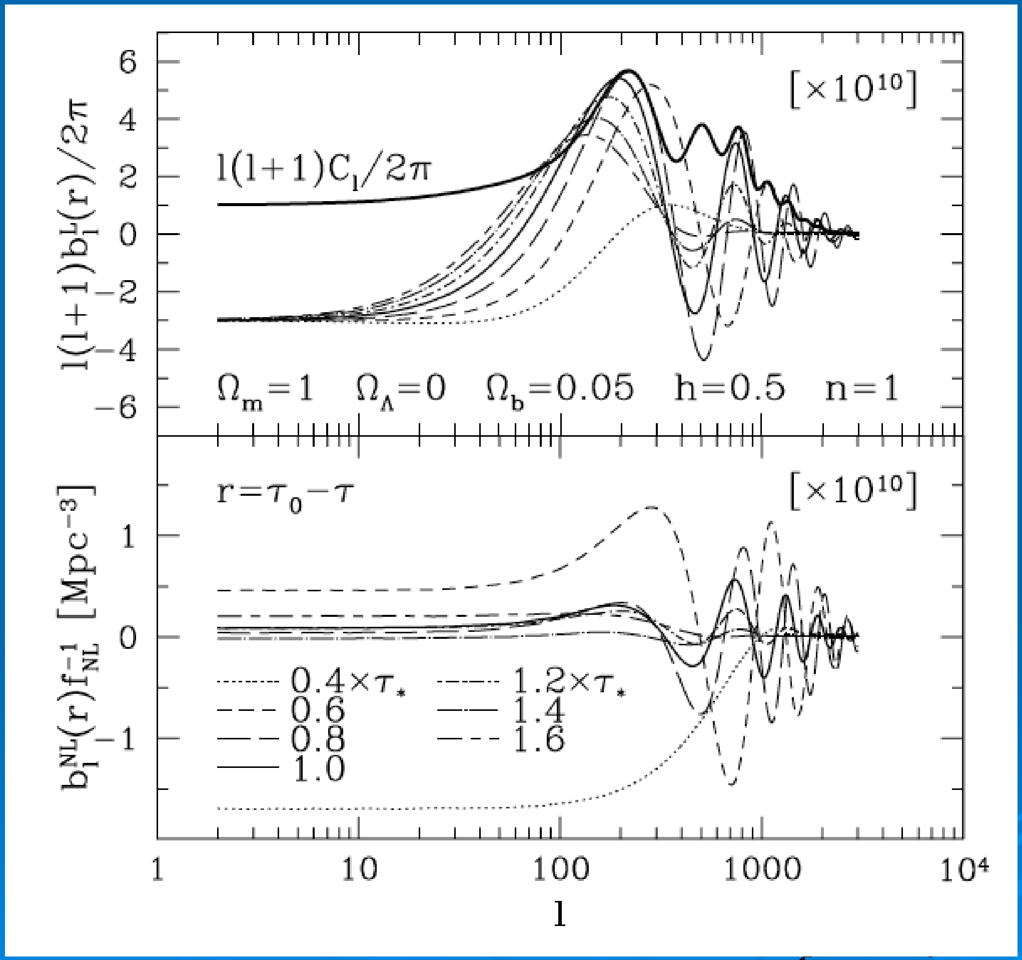
decompressor
are needed to see this picture.

Bispectrum changes sign…



Bispectrum

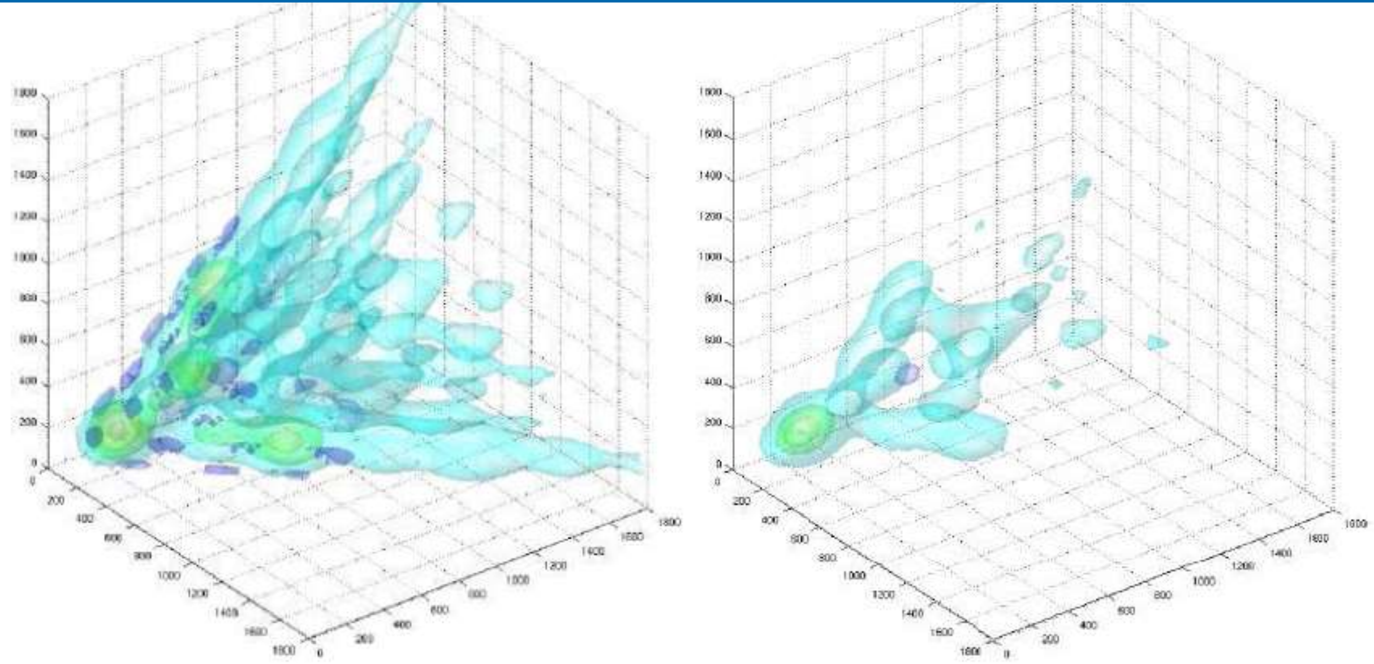


Figure 13: Plots of the bispectrum for the local case (on the left) and for the equilateral case (on the right) for $l < 1800$. Note how in the equilateral case all perturbations off the central axis are suppressed

Fergusson and Shellard 2007

f_{NL} in WMAP Data?

- Statistical significance overestimated (choose highest amplitude cut and frequency combination)
  - Most of the signal is coming from triangles that don't have most of the S/N!
  - S/N goes up as errors goes up! Adding very noisy data increases the signal--something is odd

ℓ_{max}	f_{NL}			
	$f_{sky} = 94.2\%$ Kp12	$f_{sky} = 84.7\%$ Kp2	$f_{sky} = 76.8\%$ Kp0	$f_{sky} = 64.3\%$
350	-3145.22	-26.68	34.62	19.24
450	-1425.06	-15.63	67.94	64.69
550	-1509.92	-13.09	79.99	83.53
650	-1559.91	-22.43	79.18	81.29
750	-1575.11	-22.81	86.81	86.52

TABLE II: Measured non-linear coupling parameter f_{NL} using the coadded V+W WMAP 3-year maps, as a function of mask (i.e. f_{sky}) and maximum multipole used in the analysis ℓ_{max}.

~2/3 of data

Minimum variance

The same strange jumps are seen in both VW and QVW

~2/3 of data

ℓ_{max}	f_{NL}			
	$f_{sky} = 94.2\%$ Kp12	$f_{sky} = 84.7\%$ Kp2	$f_{sky} = 76.8\%$ Kp0	$f_{sky} = 64.3\%$
350	-2383.67	-75.16	24.91	8.32
450	-2791.83	-79.79	55.36	65.31
550	-3135.82	-93.49	65.57	79.93
650	-3307.15	-93.7	62.91	77.02
750	-3368.26	-108.23	64.75	78.35

TABLE I: Measured non-linear coupling parameter f_{NL} using the coadded Q+V+W WMAP 3-year maps, as a function of mask (i.e. f_{sky}) and maximum multipole used in the analysis ℓ_{max}.

The multiples between $l = 350$ and 450 are 1/3 of the data and produce a big jump in fNL. This implies f_NL =200 in this region (a > 4 σ detection).

Minimum variance

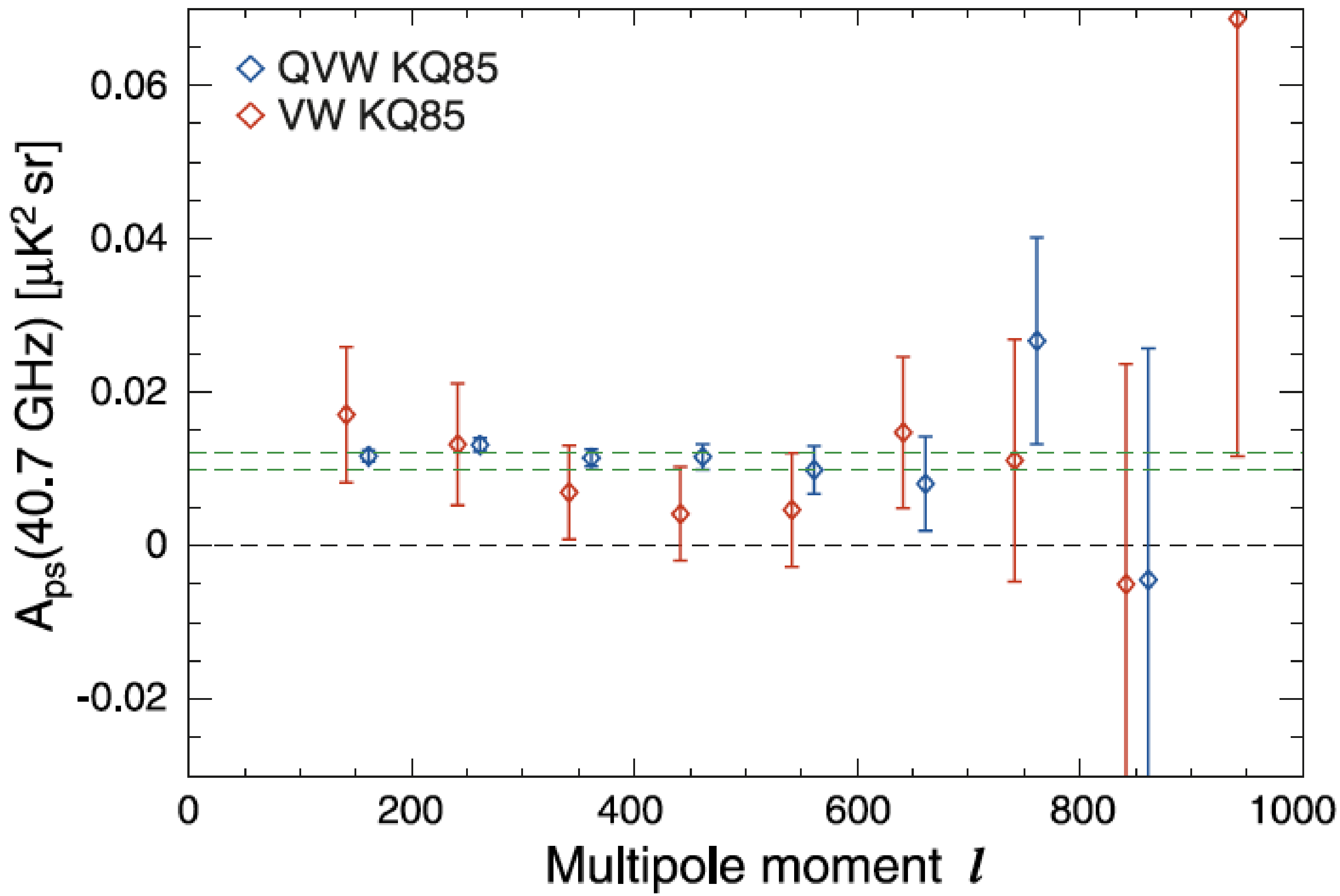
10% more data (Kp2 - Kp0) change fNL by 172! This implies that f_NL in the Kp2-Kp0 region is huge (5 σ detection)

5 year Results

- We do see a positive fNL but its amplitude is only ~2 s
- Amplitude is lower than values claimed by Yadav and Wandelt; however, we see a consistent set of values as a function of sky cut
- Still see contamination effects in Q band
- Need more data to make a convincing case

Band	Mask	l_{max}	f_{NL}^{local}	Δf_{NL}^{local}	b_{src}
V+W	*KQ85*	400	50 ± 29	1 ± 2	0.26 ± 1.5
V+W	*KQ85*	500	61 ± 26	2.5 ± 1.5	0.05 ± 0.50
V+W	*KQ85*	600	68 ± 31	3 ± 2	0.53 ± 0.28
V+W	*KQ85*	700	67 ± 31	3.5 ± 2	0.34 ± 0.20
V+W	*Kp0*	500	61 ± 26	2.5 ± 1.5	
V+W	*KQ75p1*[a]	500	53 ± 28	4 ± 2	
V+W	*KQ75*	400	47 ± 32	3 ± 2	-0.50 ± 1.7
V+W	*KQ75*	500	55 ± 30	4 ± 2	0.15 ± 0.51
V+W	*KQ75*	600	61 ± 36	4 ± 2	0.53 ± 0.30
V+W	*KQ75*	700	58 ± 36	5 ± 2	0.38 ± 0.21

Q	Raw	*KQ75p1*[a]	-42 ± 45
V	Raw	*KQ75p1*	38 ± 34
W	Raw	*KQ75p1*	43 ± 33
Q	Raw	*KQ75*	-42 ± 48
V	Raw	*KQ75*	41 ± 35
W	Raw	*KQ75*	46 ± 35
Q	Clean	*KQ75p1*	9 ± 45
V	Clean	*KQ75p1*	47 ± 34
W	Clean	*KQ75p1*	60 ± 33
Q	Clean	*KQ75*	10 ± 48
V	Clean	*KQ75*	50 ± 35
W	Clean	*KQ75*	62 ± 35



QVW KQ85
VW KQ85
0.06
0.04
0.02
0
-0.02
A_{ps}(40.7 GHz) [μK² sr]
0
200
400
600
800
1000
Multipole moment l