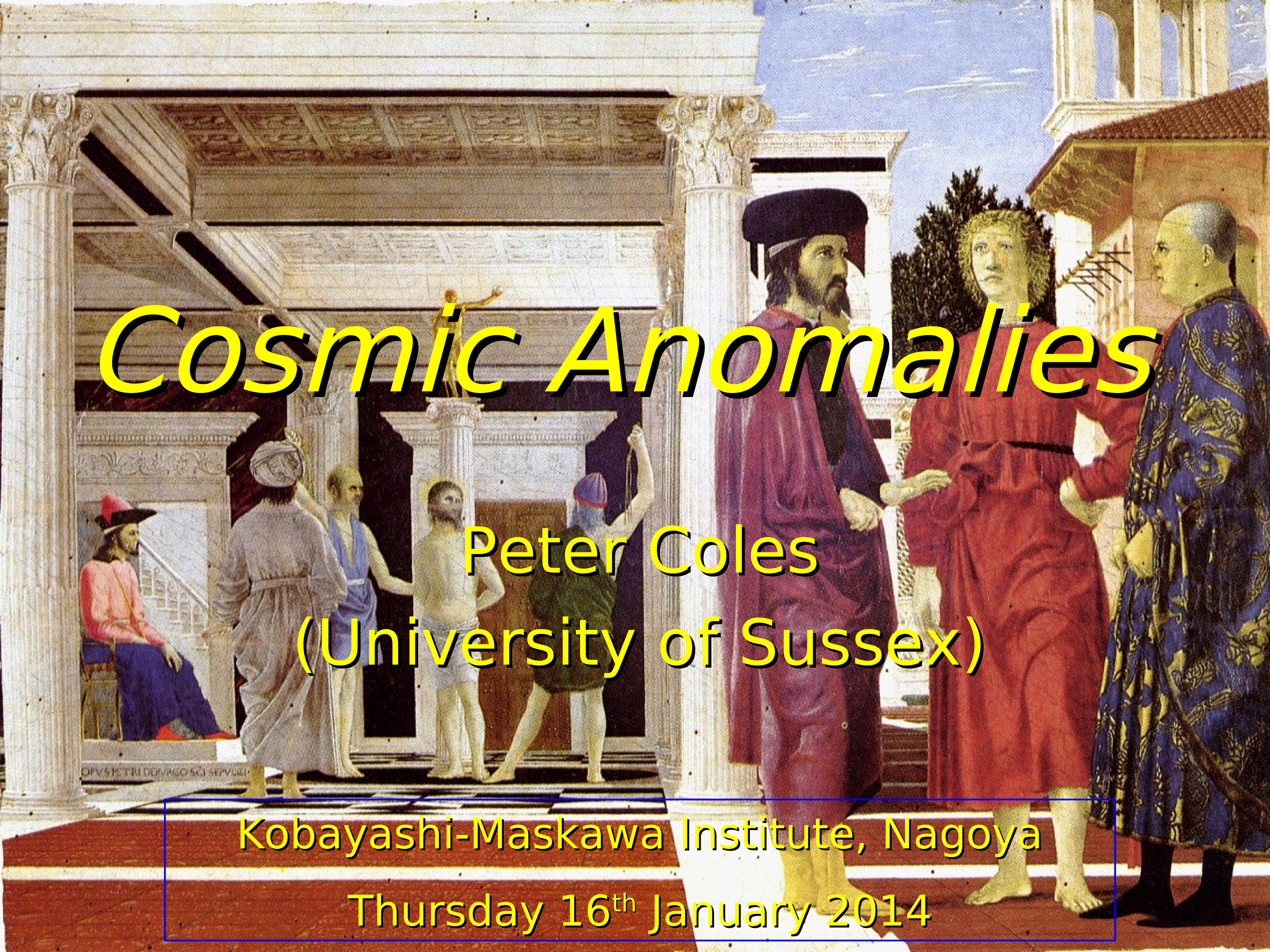
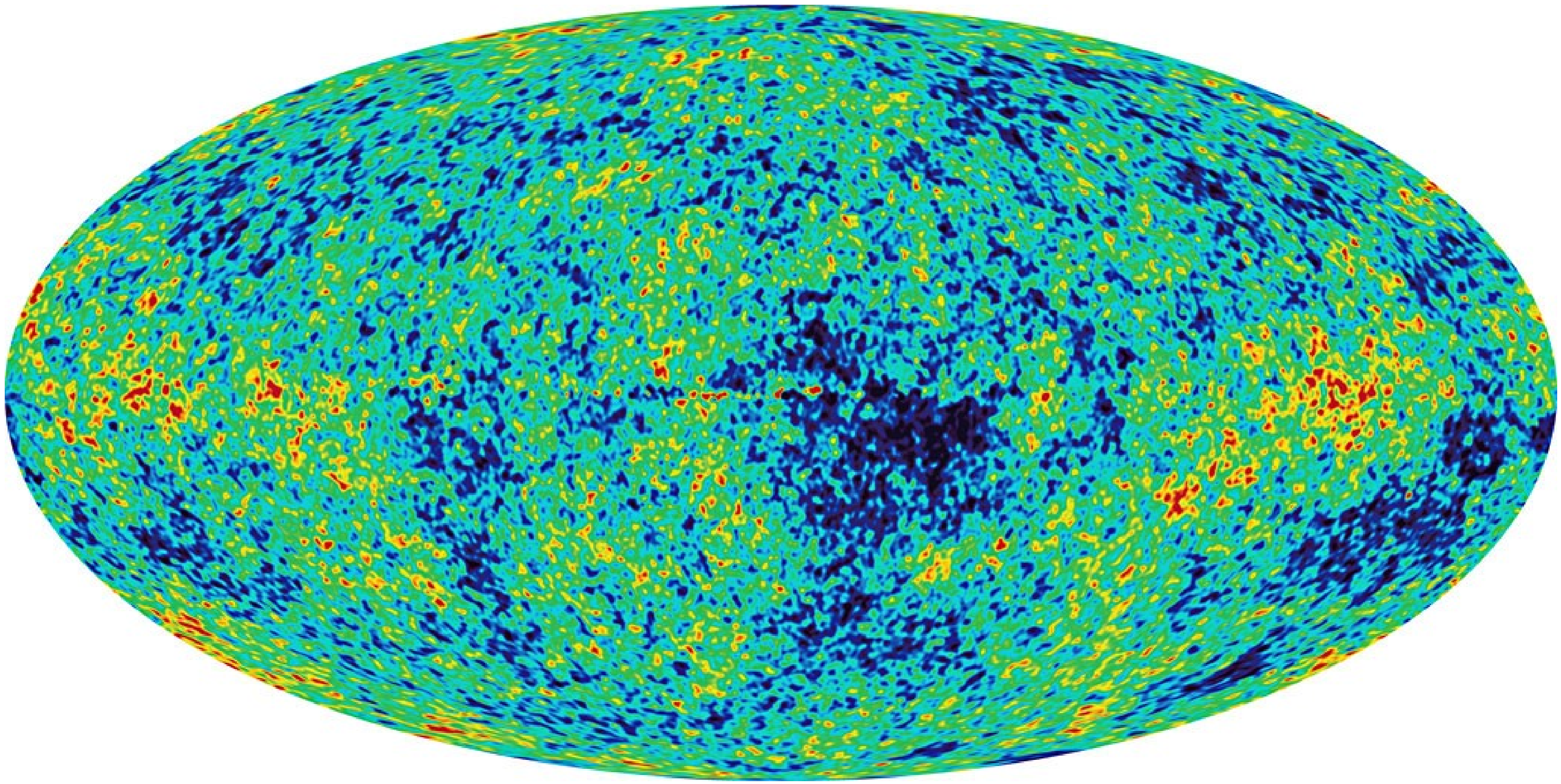


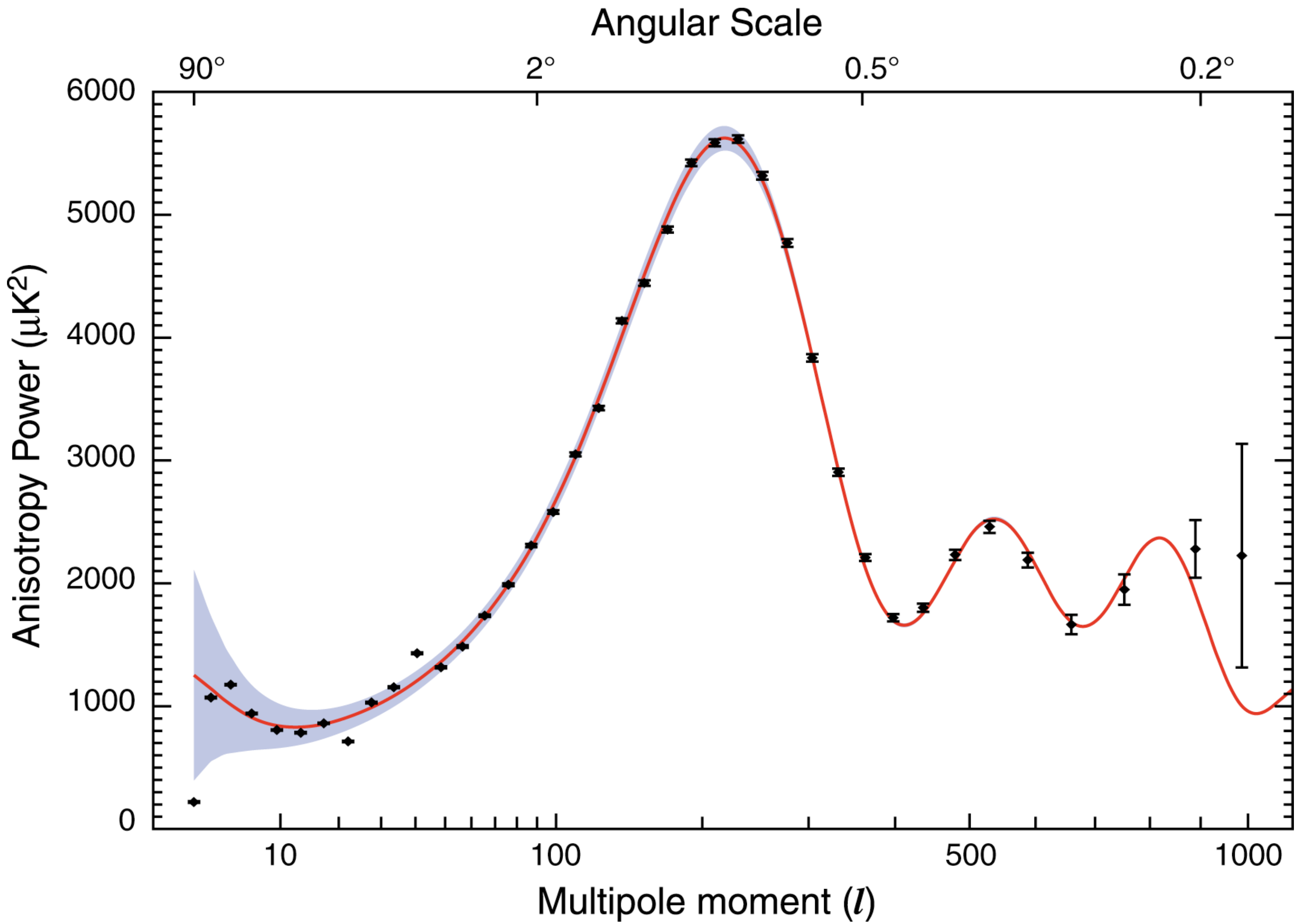
Cosmic Anomalies

Peter Coles
(University of Sussex)

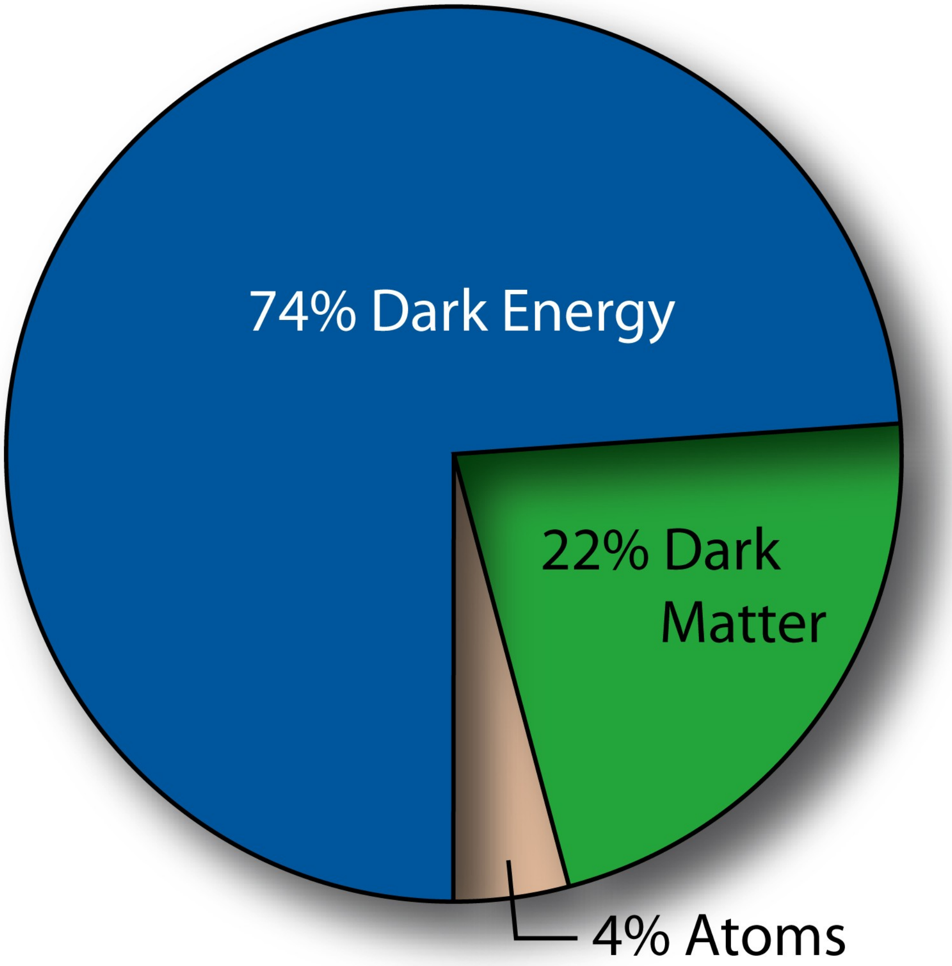
Kobayashi-Maskawa Institute, Nagoya

Thursday 16th January 2014

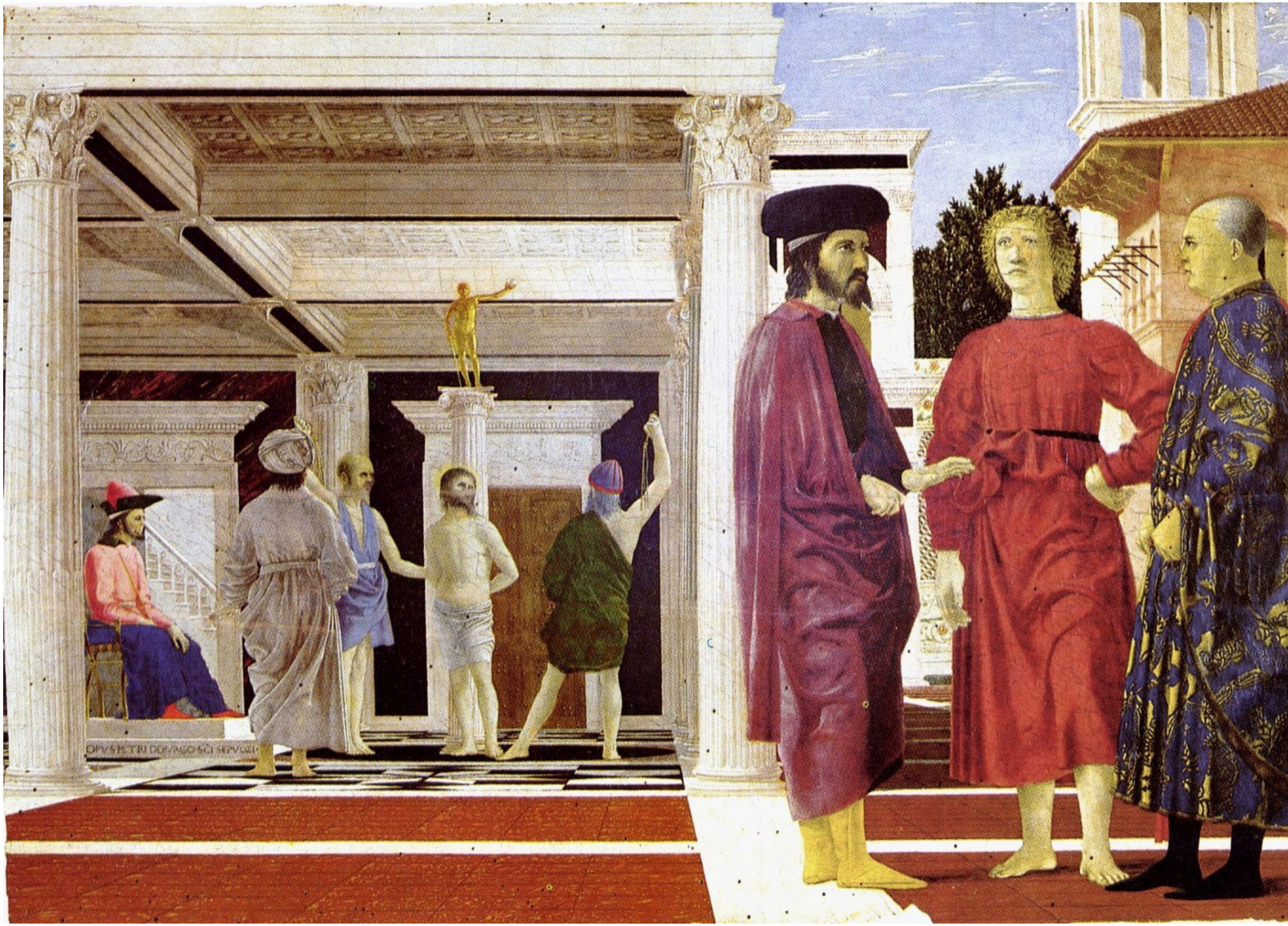


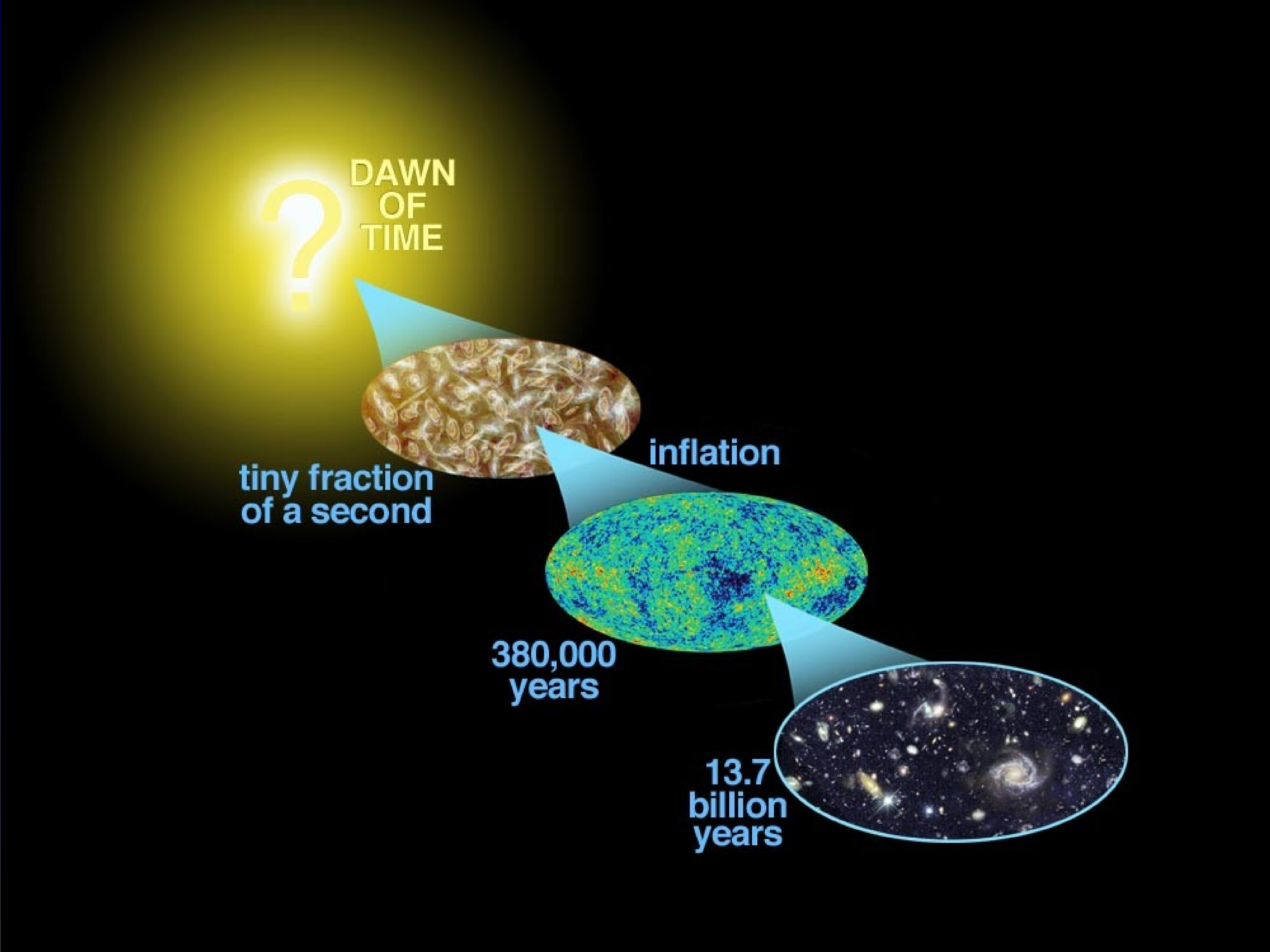


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK²)
10
100
500
1000
Multipole moment (l)


74% Dark Energy
22% Dark
Matter
4% Atoms

WMAP Cosmological Parameters Model: lcdm Data: wmap	
$10^2\Omega_b h^2$	$2.230^{+0.075}_{-0.073}$
$\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$	$(23.7 \pm 1.4) \times 10^{-10}$
h	0.735 ± 0.032
H_0	73.5 ± 3.2 km/s/Mpc
$n_s(0.002)$	0.951 ± 0.016
$\Omega_b h^2$	$0.02230^{+0.00075}_{-0.00073}$
Ω_Λ	0.763 ± 0.034
Ω_m	0.237 ± 0.034
$\Omega_m h^2$	$0.1265^{+0.0081}_{-0.0080}$
σ_8	0.742 ± 0.051
A_{SZ}	1.00 ± 0.64
t_0	$13.73^{+0.16}_{-0.15}$ Gyr
τ	$0.088^{+0.029}_{-0.030}$
θ_A	$0.5948^{+0.0021}_{-0.0022}$ $^\circ$
z_r	10.9 ± 2.5



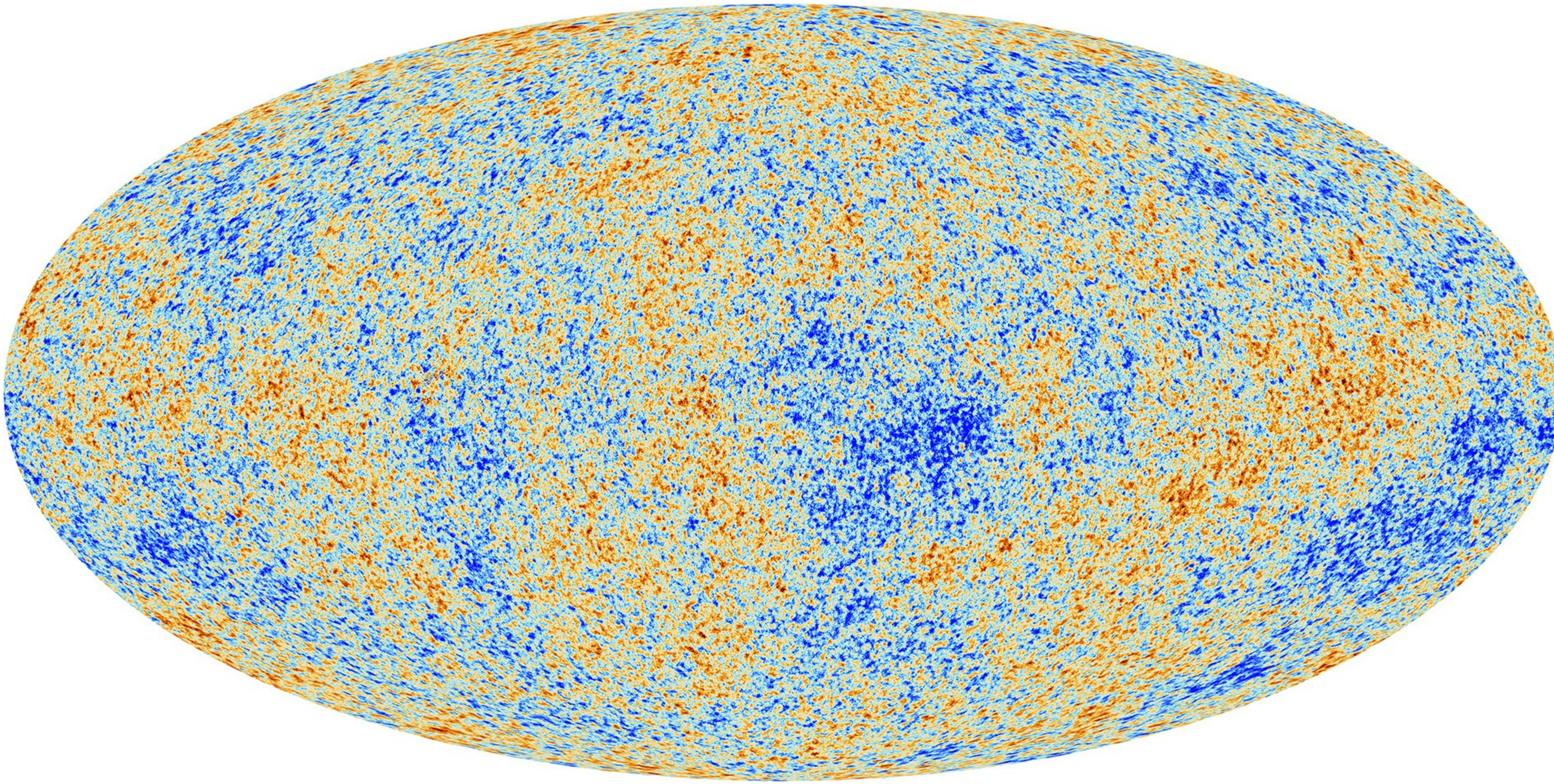

DAWN
OF
TIME
inflation
tiny fraction
of a second
380,000
years
13.7
billion
years

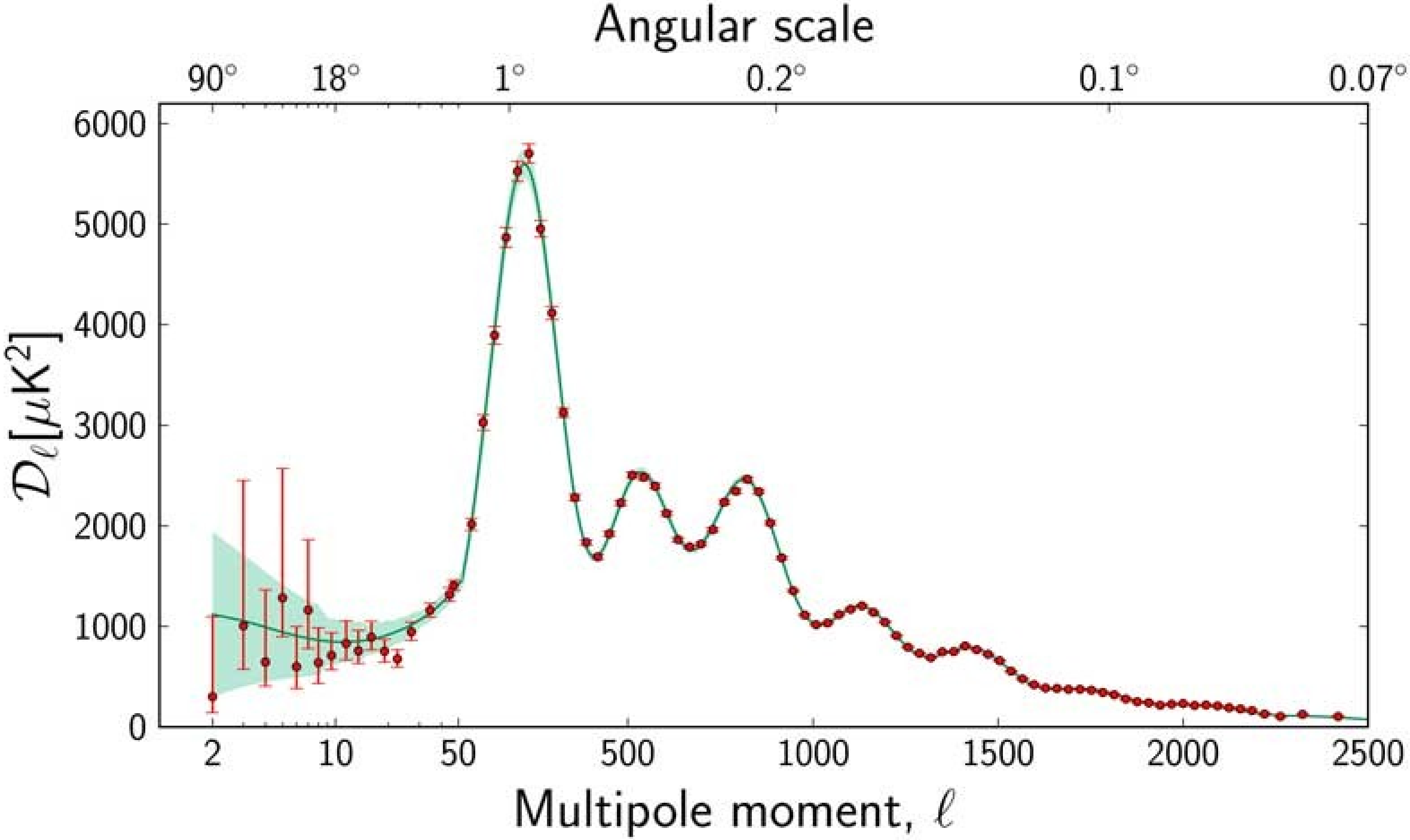
The Meaning of Inflation (OED)

1. The action of inflating or distending with air or gas
2. The condition of being inflated with air or gas, or being distended or swollen as if with air
3. The condition of being puffed up with vanity, pride or baseless notions
4. The quality of language or style when it is swollen with big or pompous words; turgidity, bombast

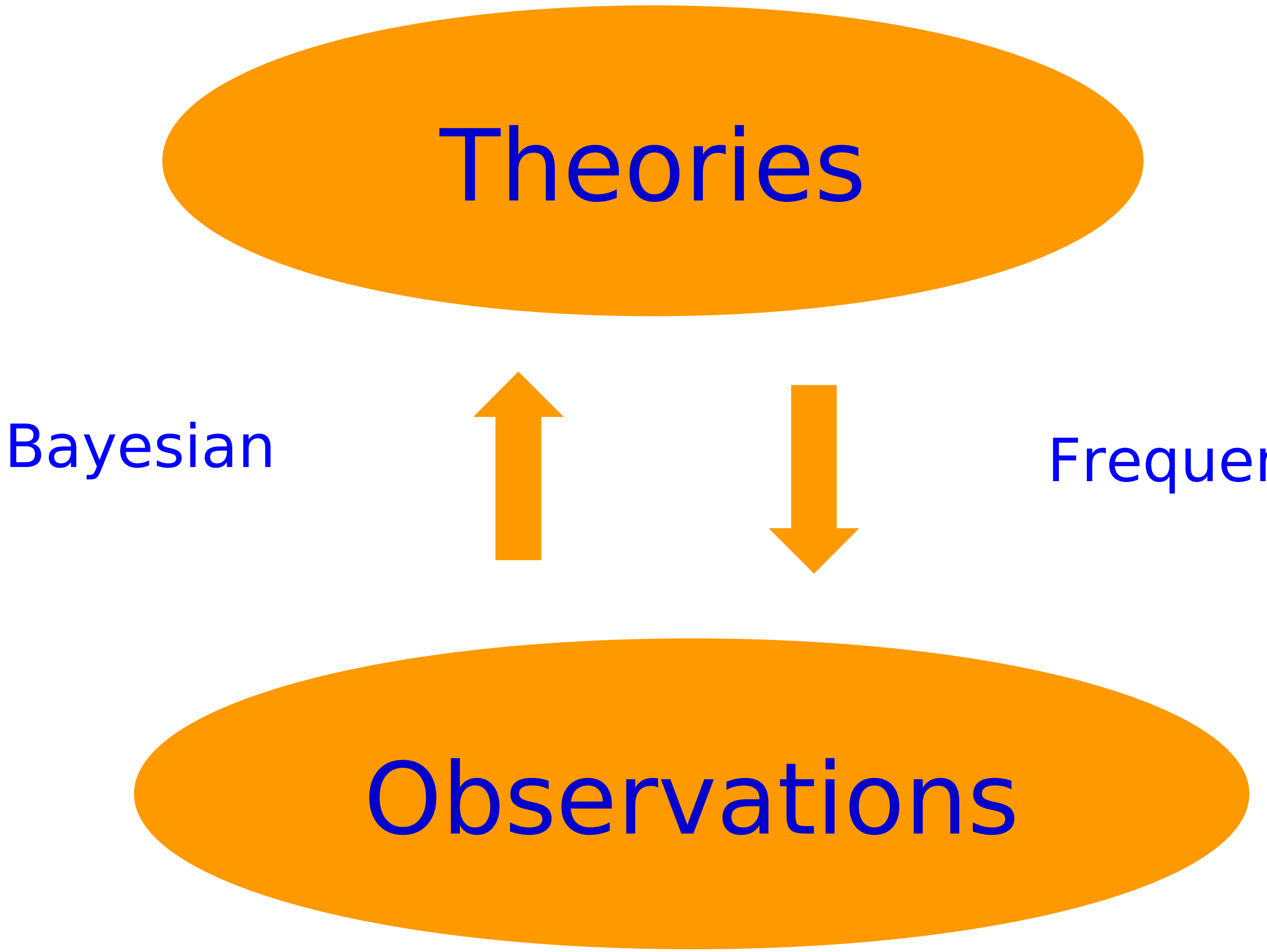
“CONCORDANCE”

Planck Time!





Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ


Theories
Bayesian
Frequentist
Observations

Cosmology is a massive exercise in data compression...

….but it is worth looking at the information that has been thrown away to check that it makes sense!

Precision Cosmology

"...as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns -- the ones we don't know we don't know."

Is there an Elephant in the Room?

How Weird is the Universe?

- The (zero-th order) starting point is FLRW.
- The concordance cosmology is a “first-order” perturbation to this
- In it (and other “first-order” models), the initial fluctuations were a statistically homogeneous and isotropic Gaussian Random Field (GRF)
- These are the “maximum entropy” initial conditions having “random phases” motivated by inflation.
- Anything else would be *weird….*

Precision Cosmology

"…as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns -- the ones we don't know we don't know."

There are many ways of being weird

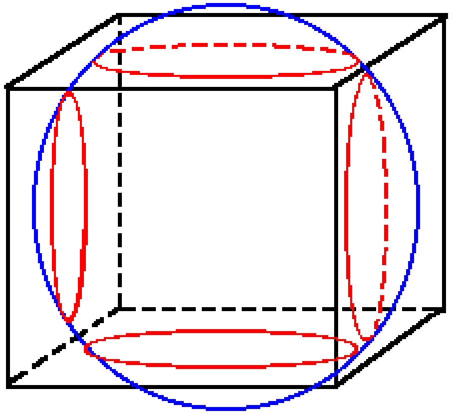
- Initial Perturbations:

$$\Phi = \Phi_L + f_{NL}\left[\Phi_{L^2} - \langle \Phi_{L^2} \rangle\right]$$

- Non-stationary fluctuations, e.g. statistical anisotropy from a vector field?
- Global inhomogeneity or anisotropy
- Non-trivial topology, etc…

Weird Topology

- GR is a *local* theory
- Simplest topology chosen in standard models, e.g sphere.
- Small universes suppress power on large scales…but introduce phase correlations (Dineen, Rocha & Coles, MNRAS, 358, 1285)

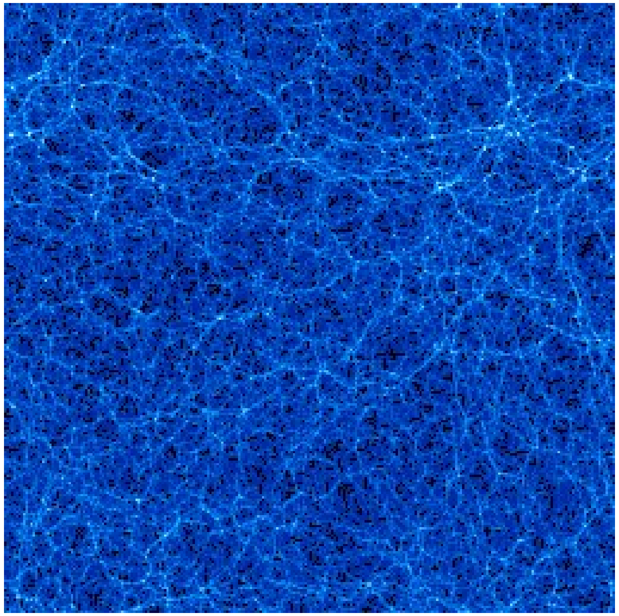


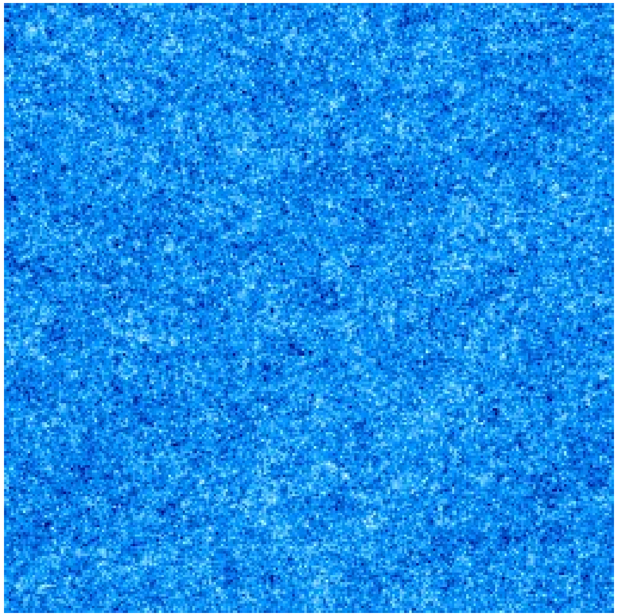
Intersection of the CMB sphere with the (imaginary) walls of the fundamental domain of a 3-torus. The intersections with the front and back walls are not shown.

Fourier Phases

- The usual thing $\delta(x) = \sum_k \delta(k) \exp(ik \cdot x)$
- where $\delta(k) = |\delta(k)| \exp[i\phi_k]$
- In a homogeneous and isotropic GRF then the phases ϕ are random...
- ..apart from $\delta^{*}(k) = \delta(-k)$
- ..as are differences, e.g. $\phi_{k_1} - \phi_{k_2}$
- The power spectrum

$$P(k) \propto \langle |\delta(k)|^2 \rangle$$





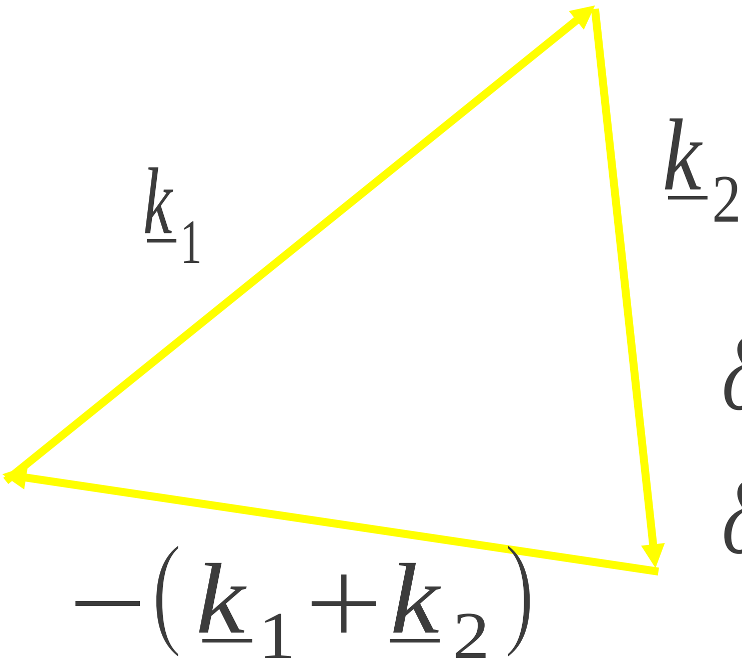
The Bispectrum

- The power spectrum is blind to phase information
- Phase information is encoded in an infinite hierarchy of polyspectra, e.g. the bispectrum:

$$\left\langle \delta\left(\underline{k}_1\right)\delta\left(\underline{k}_2\right)\delta^{*}\left(\underline{k}_1+\underline{k}_2\right)\right\rangle=\left\langle \delta\left(\underline{k}_1\right)\delta\left(\underline{k}_2\right)\delta\left(-\underline{k}_1-\underline{k}_2\right)\right\rangle$$

- Averaging is done over triangles in k-space
- This measures a specific form of phase coupling; quadratic phase coupling, so it is tailor-made for quadratic non-Gaussianity

Quadratic Phase Coupling

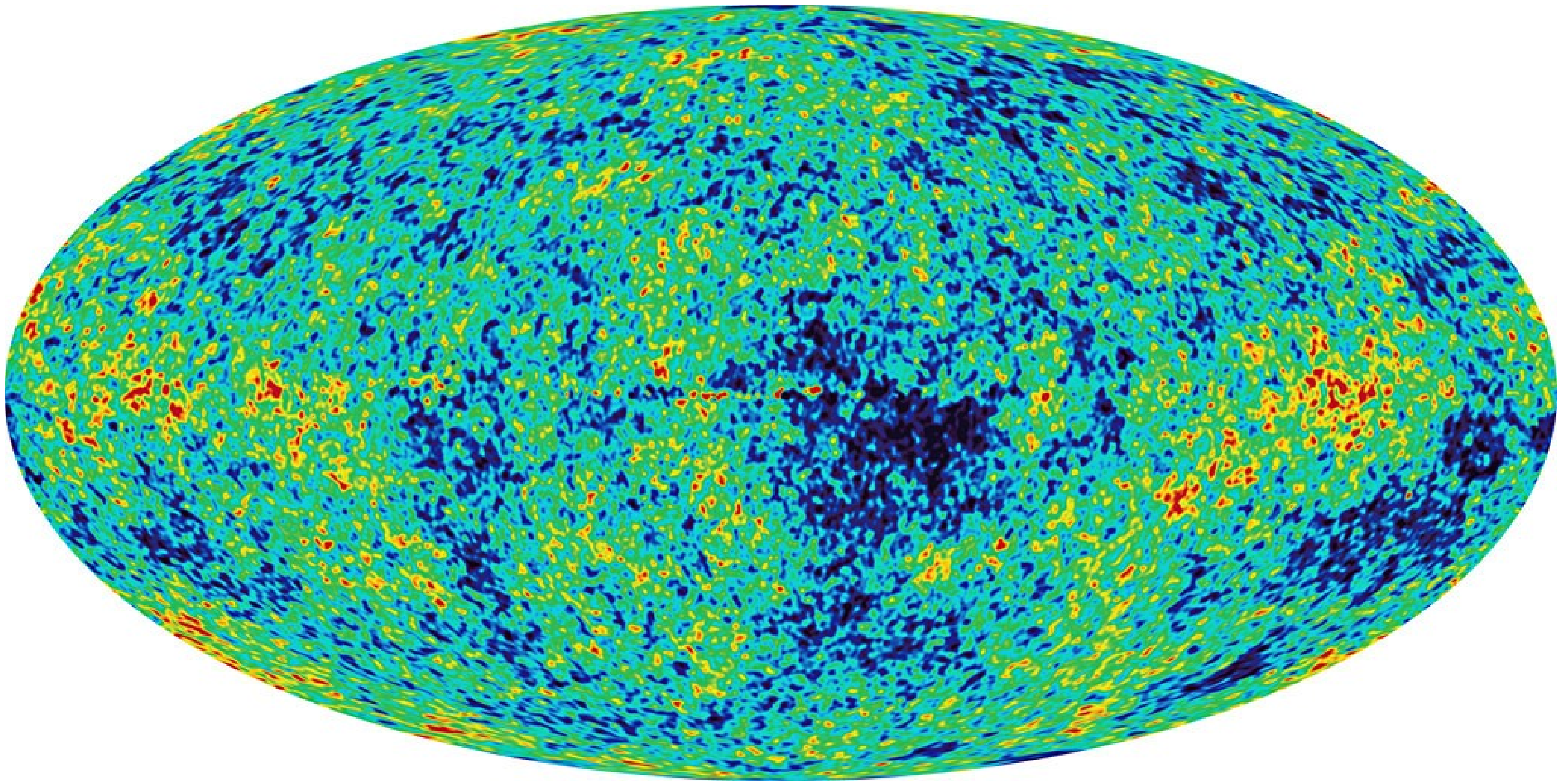


$$\delta_1 = \exp\left(i\,\underline{k}_1\cdot\underline{x} + \varphi_1\right) \Rightarrow \left(\underline{k}_1, \varphi_1\right)$$

$$\delta_2 = \exp\left(i\,\underline{k}_2\cdot\underline{x} + \varphi_2\right) \Rightarrow \left(\underline{k}_2, \varphi_2\right)$$

$$\left(\delta_1 + \delta_2\right)^2 \Rightarrow \left(2k_1, 2\varphi_1\right) + \left(2k_2, 2\varphi_2\right) + \left(k_1 + k_2, \varphi_1 + \varphi_2\right)$$

$$\arg\left(\delta_1\delta_2\delta_{-(1+2)}\right) = \varphi_1 + \varphi_2 - \varphi_{1+2}$$



Weirdness in Phases

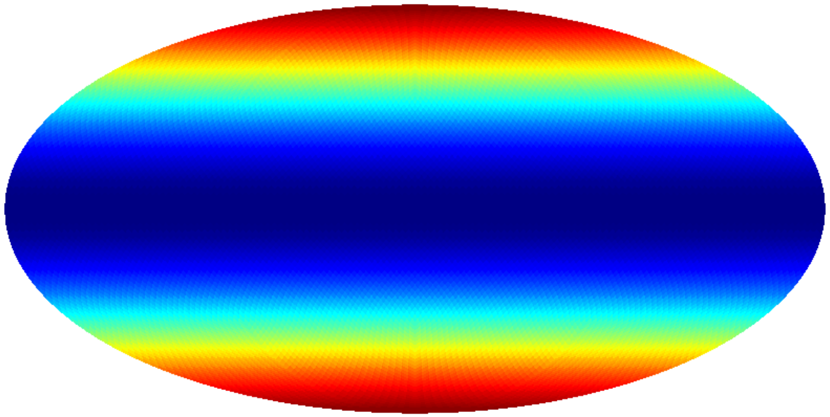
$$\frac{\Delta T(\theta,\varphi)}{T} = \sum\sum a_{l,m} Y_{lm}(\theta,\varphi)$$

$$a_{l,m} = |a_{l,m}| \exp\left[i\phi_{l,m}\right]$$

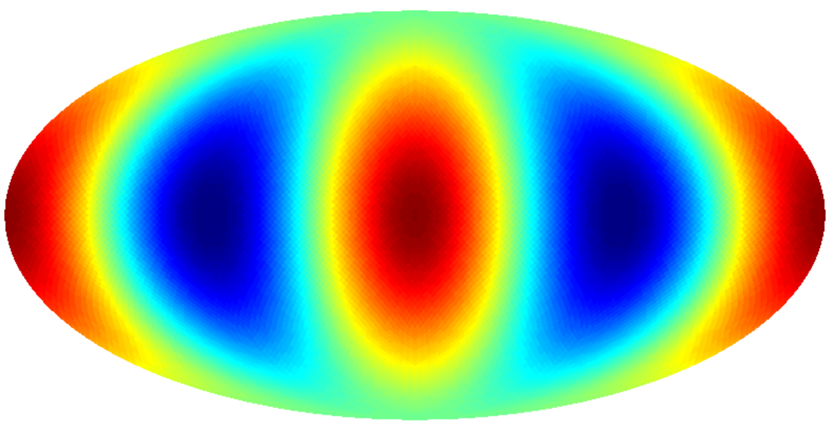
For a homogeneous and isotropic Gaussian random field (on the sphere) the **phases** are independent and uniformly distributed. Non-random phases therefore indicate weirdness..

Spherical Harmonic Phases

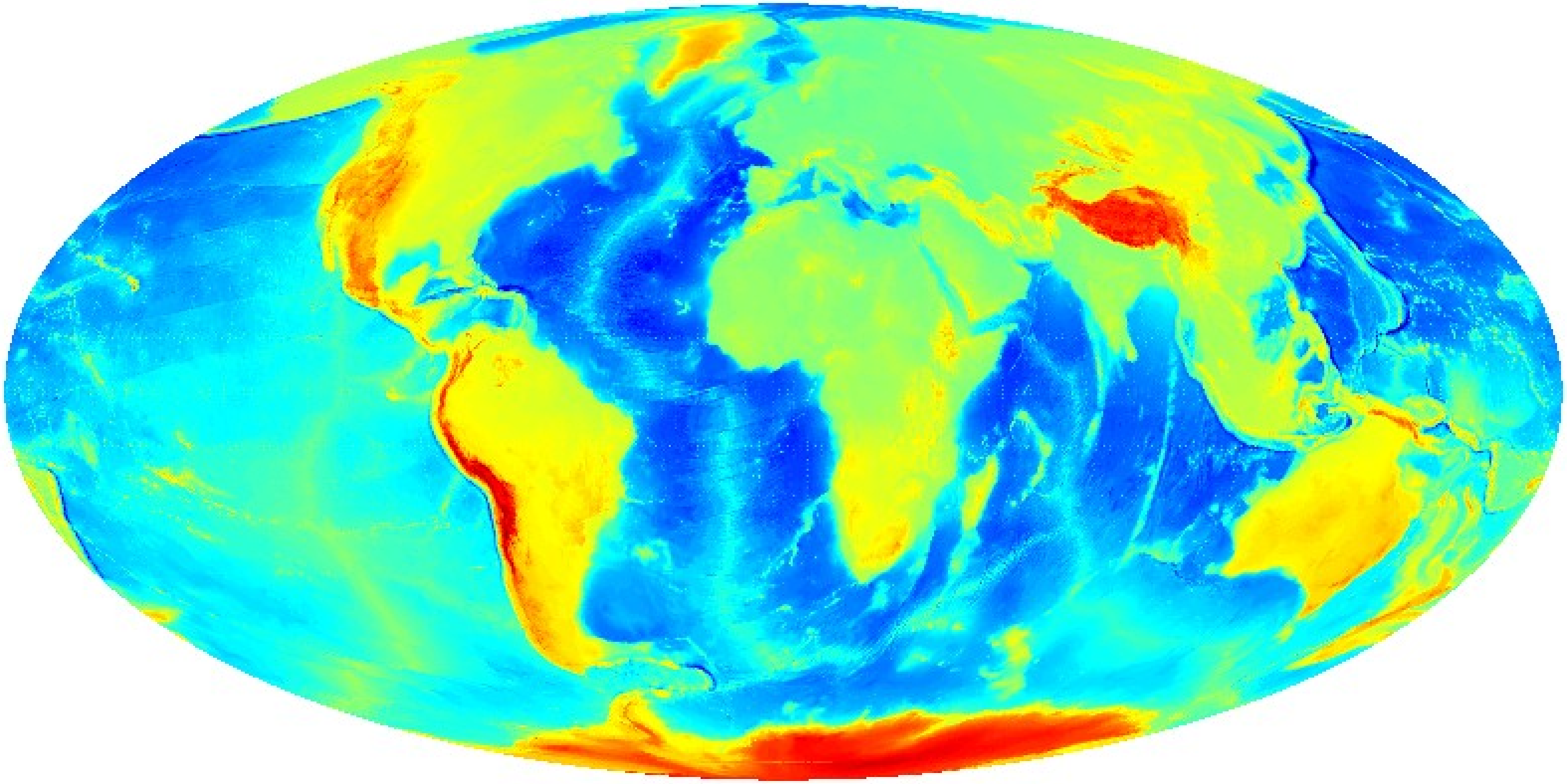
- The usual thing $$\frac{\Delta T(\theta,\varphi)}{T}=\sum\sum a_{l,m}Y_{lm}(\theta,\varphi)$$
- where $a_{l,m}=|a_{l,m}|\exp[i\phi_{l,m}]$
- If the fluctuations are a homogeneous and isotropic GRF then the phases $\phi_{l,m}$ are random…
- ..apart from $a^{*}_{lm}=a_{l,-m}$
- ..as are differences, e.g. $\phi_{l,m}-\phi_{l,m-1}$

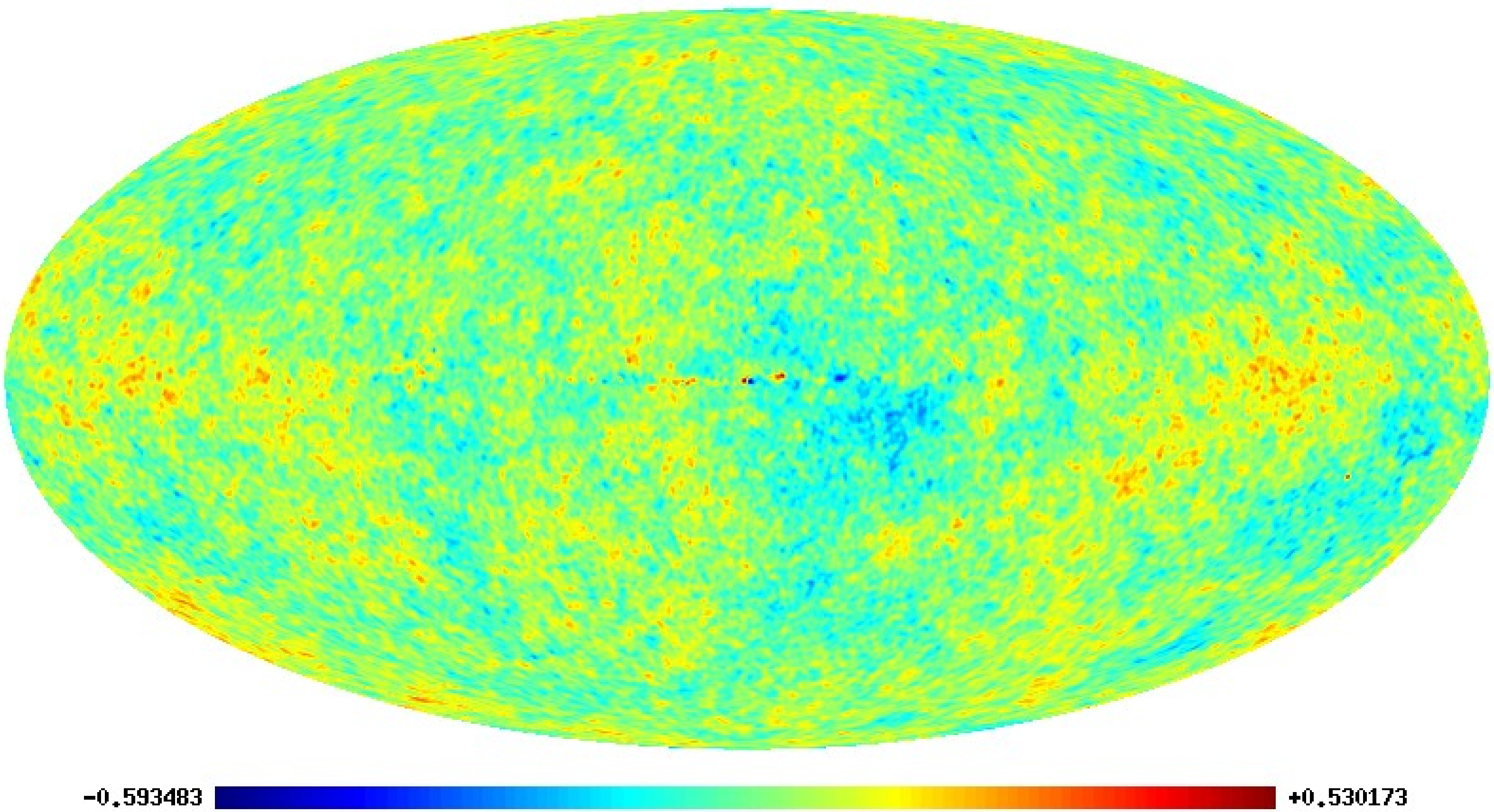


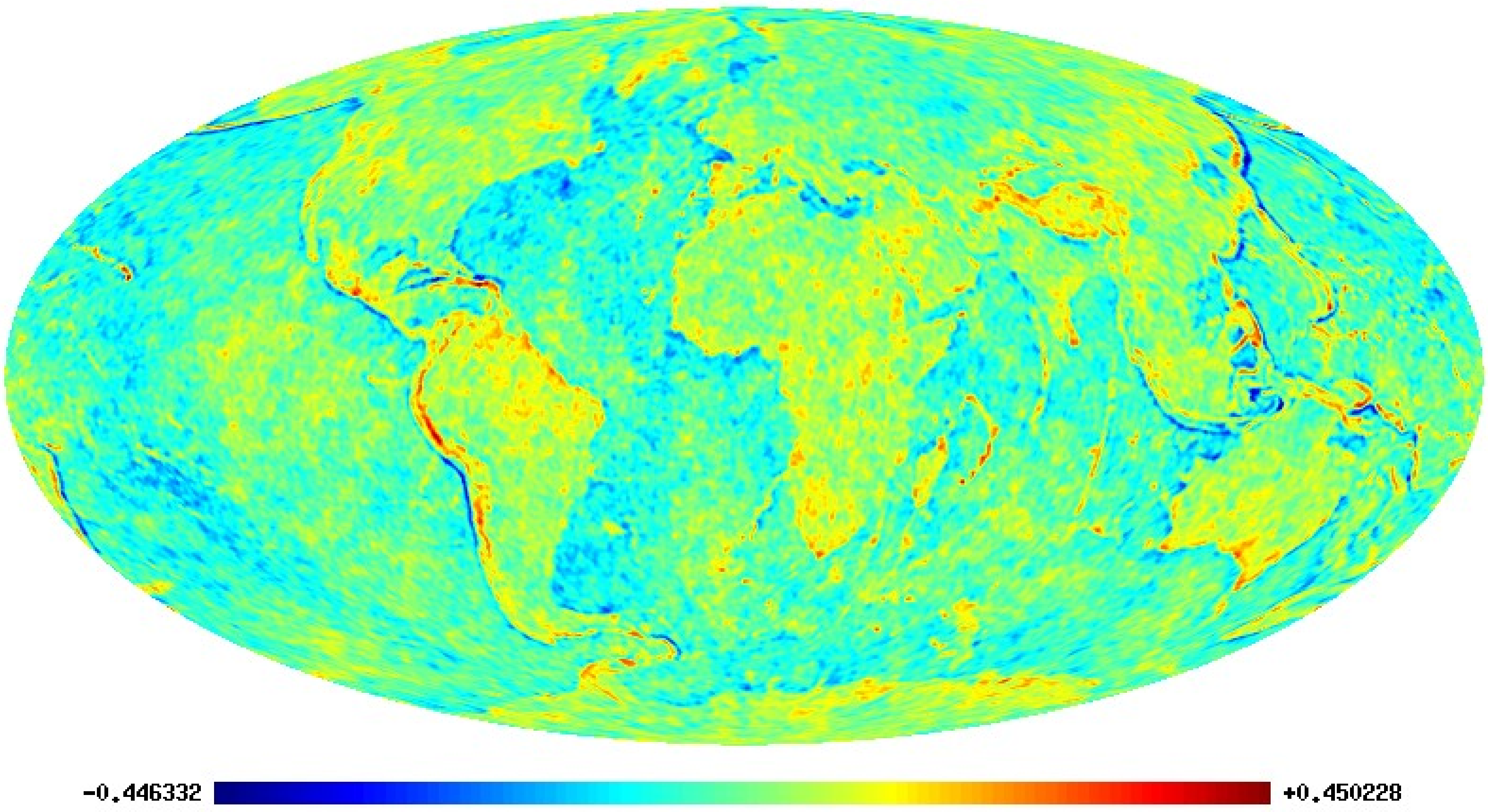
Zonal
(m=0)

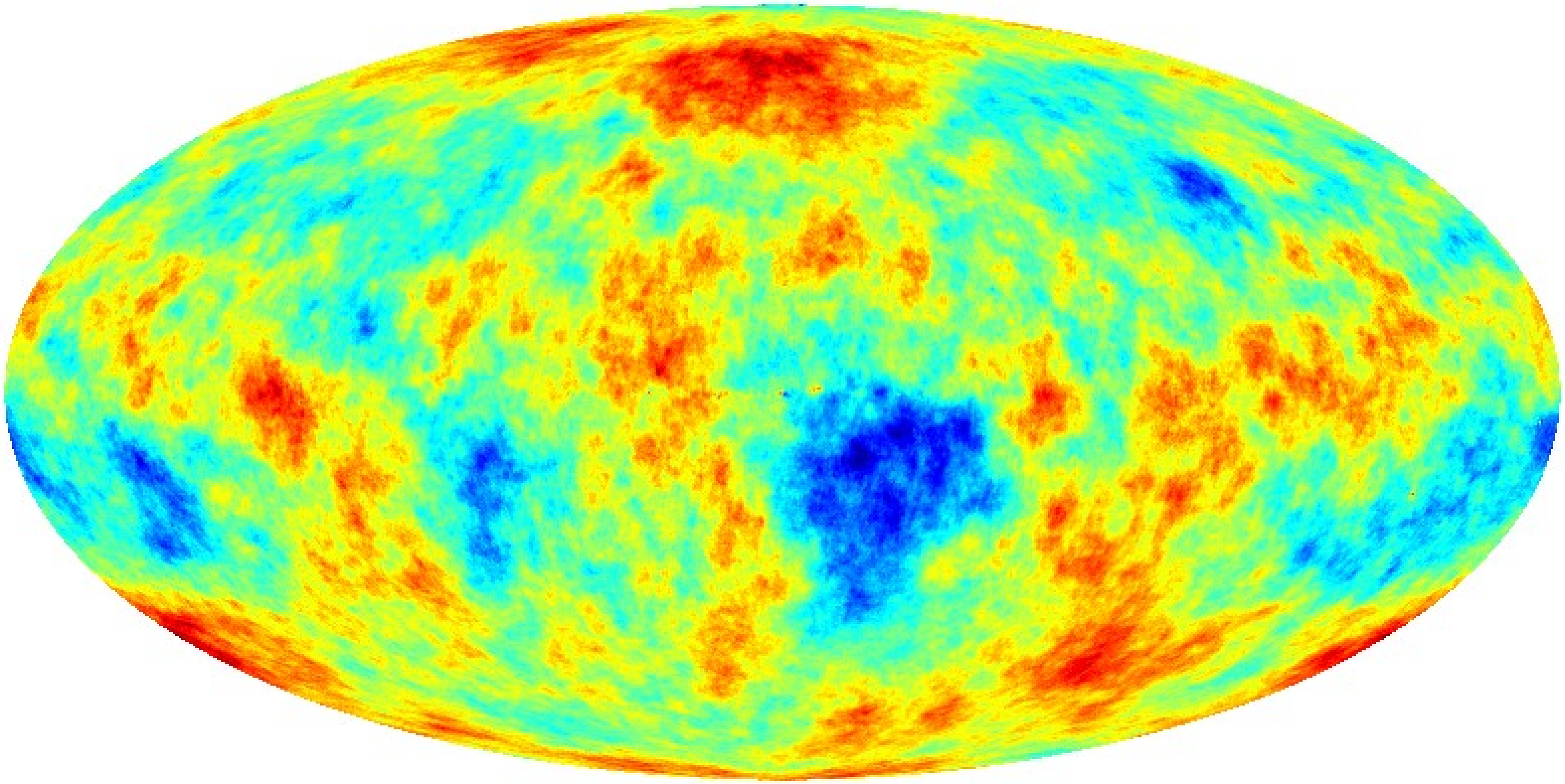


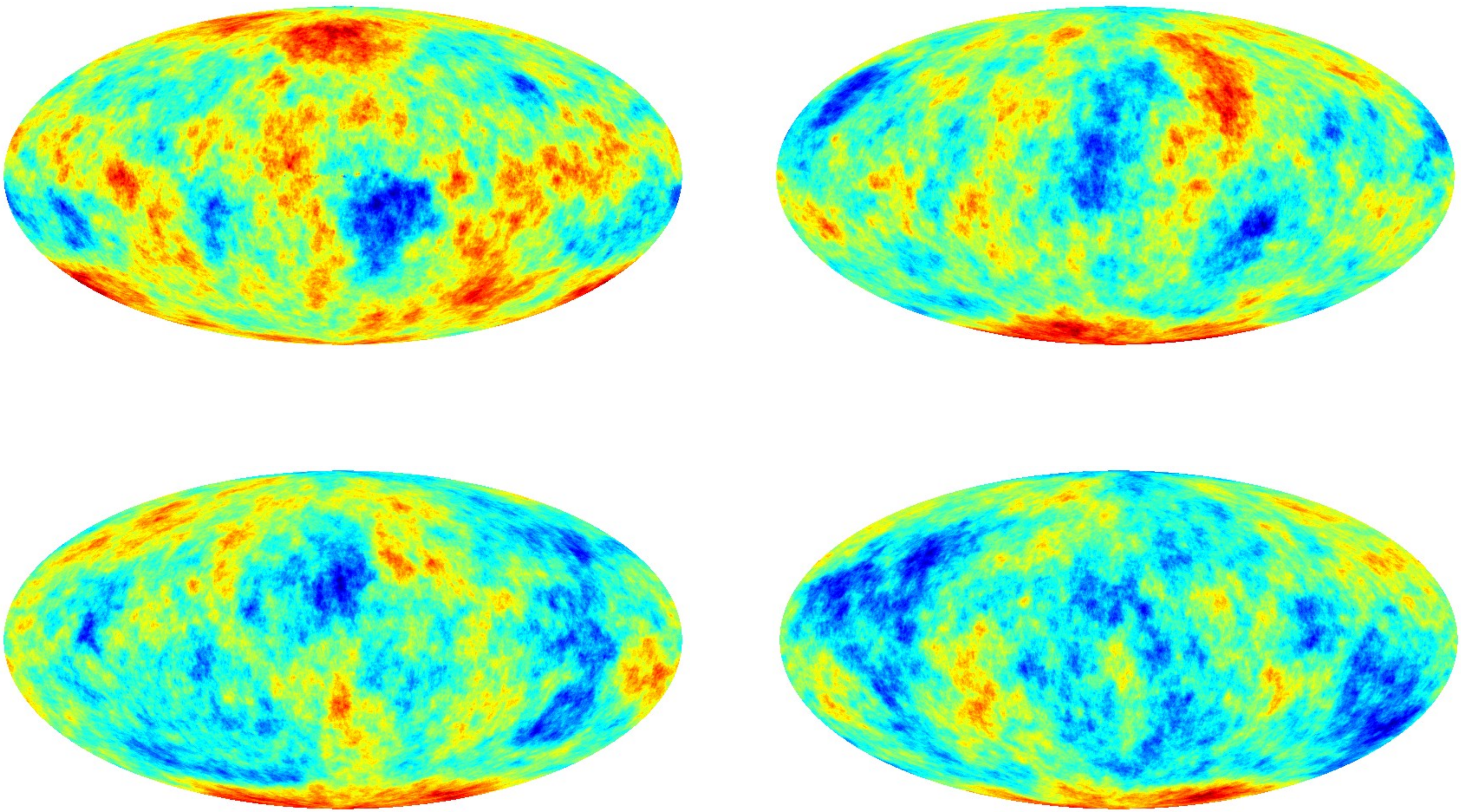
Sectoral
(m=l)

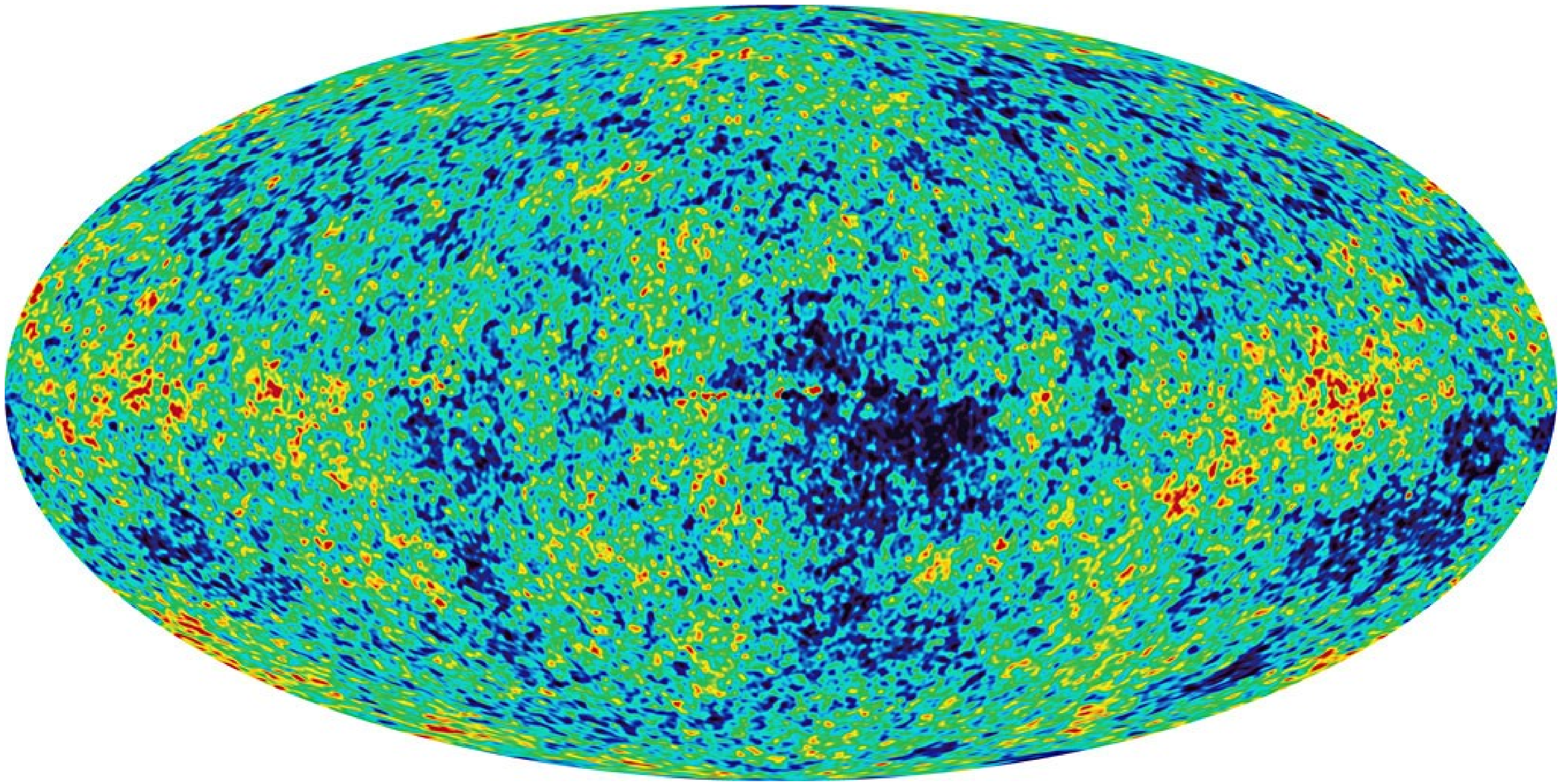


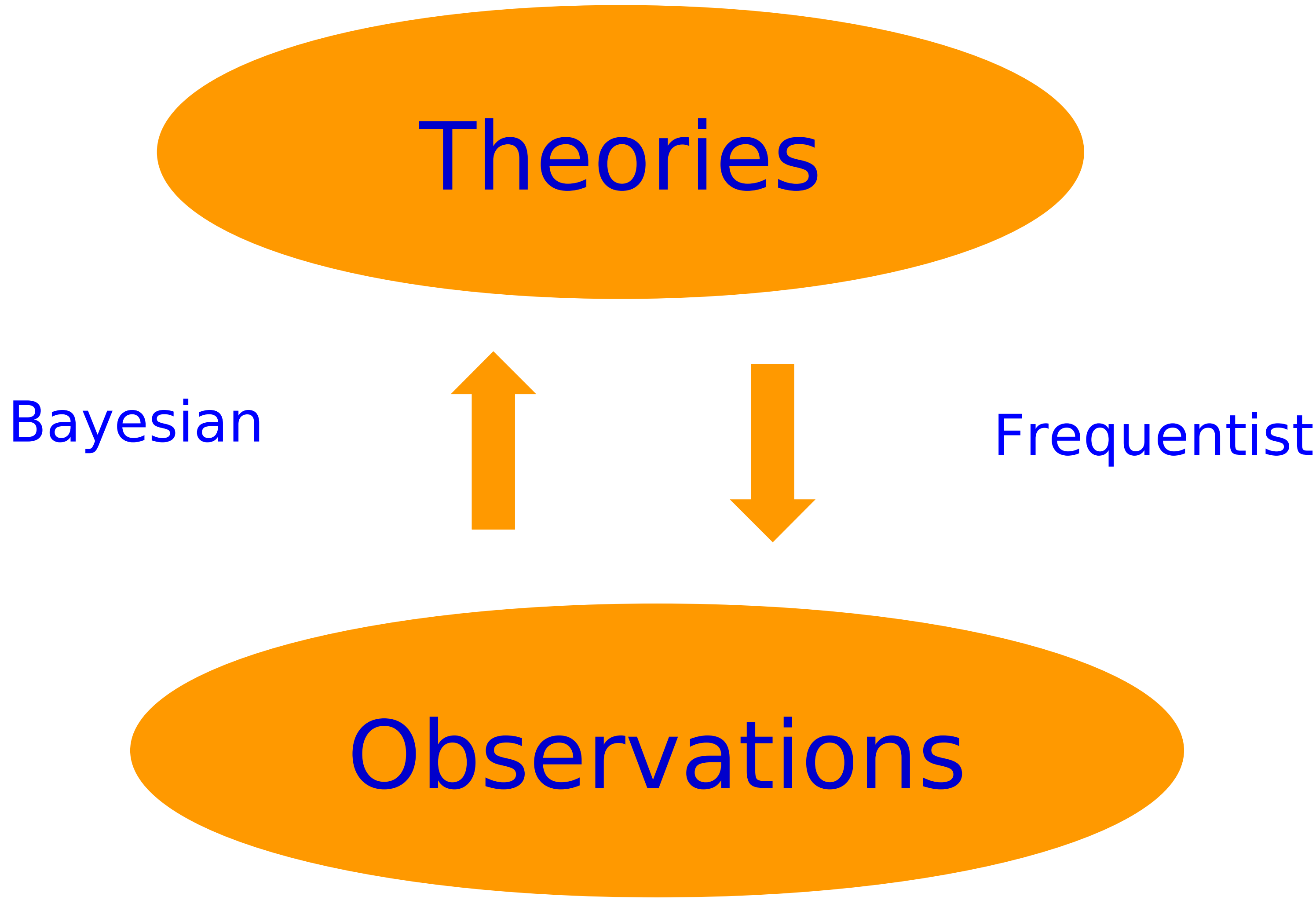

-0.593483
+0.530173

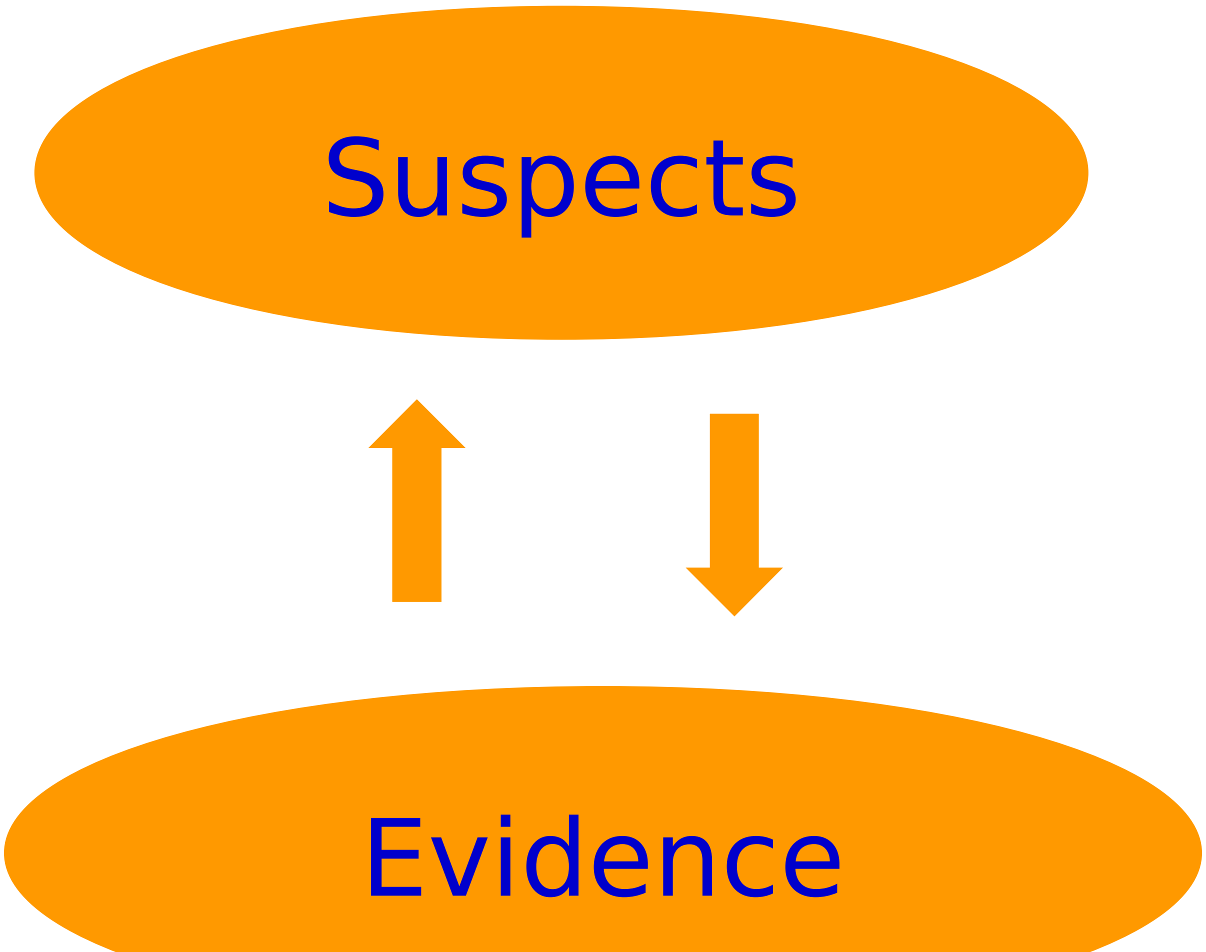

-0.446332
+0.450228








Theories
Bayesian
Frequentist
Observations

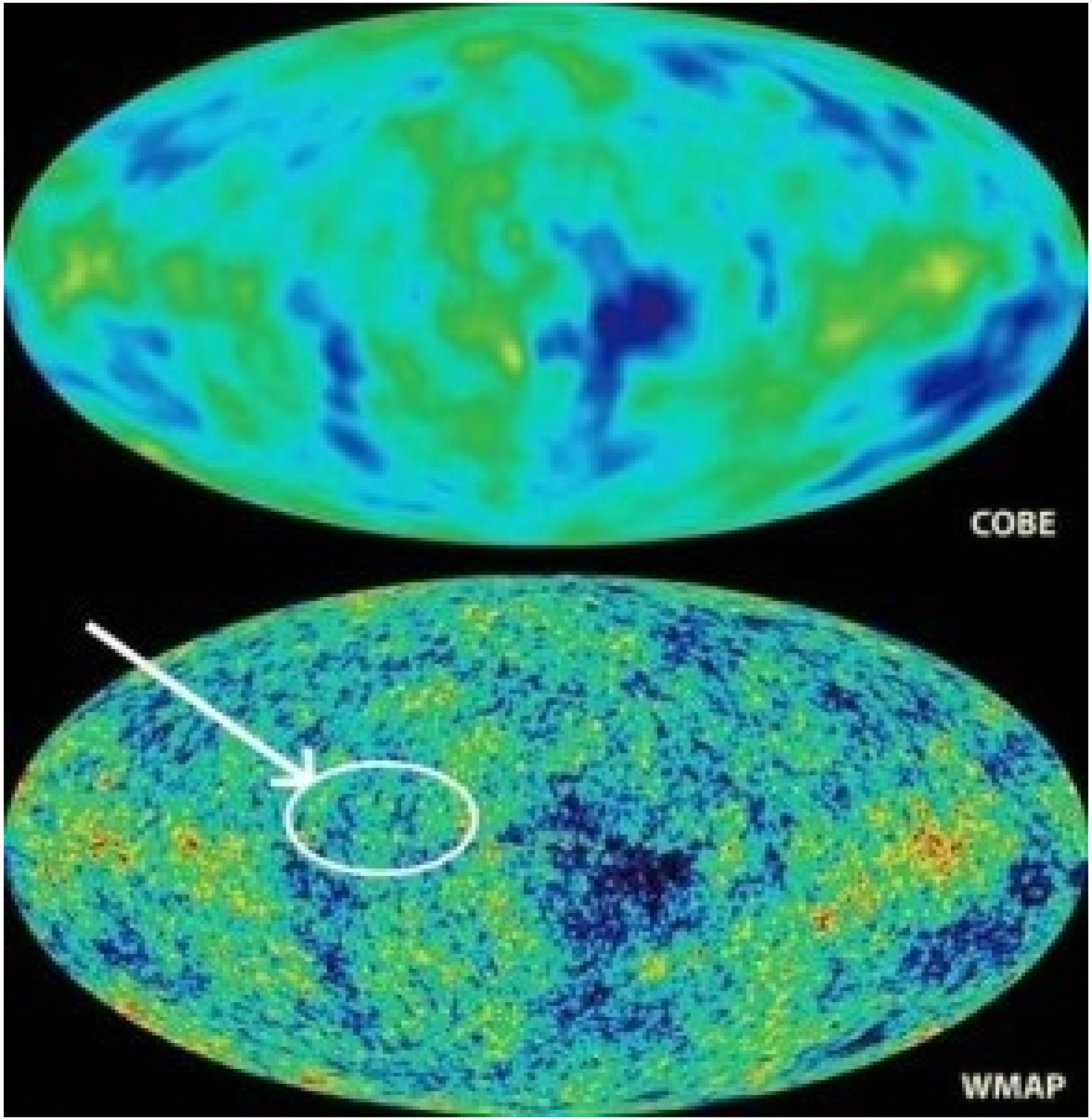

Suspects
Evidence

Beware the Prosecutor’s Fallacy!

$$P\left(A|M\right) \neq P\left(M|A\right)!$$

“If tortured sufficiently, data will confess to almost anything”

Fred Menger

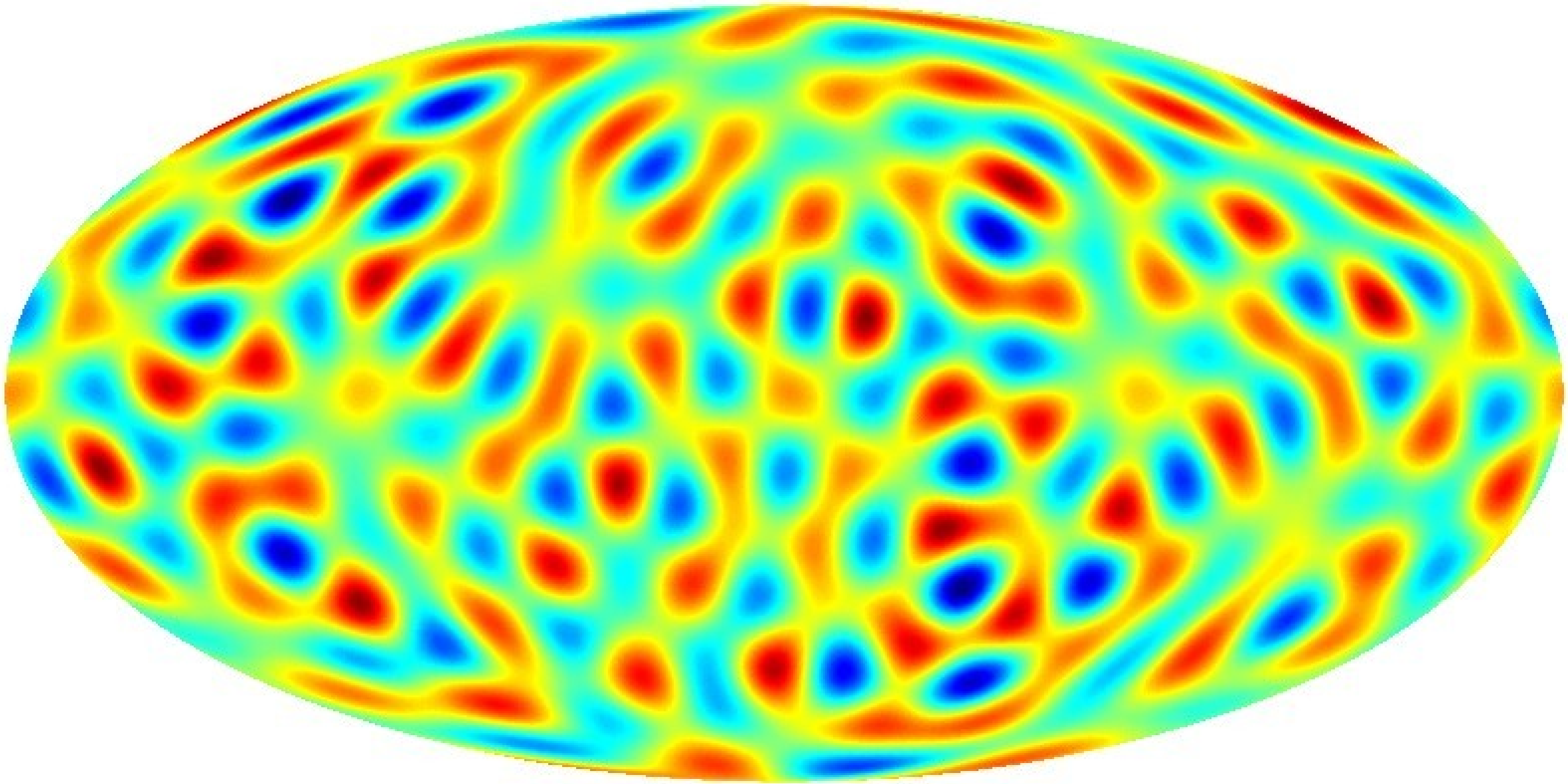

COBE
WMAP

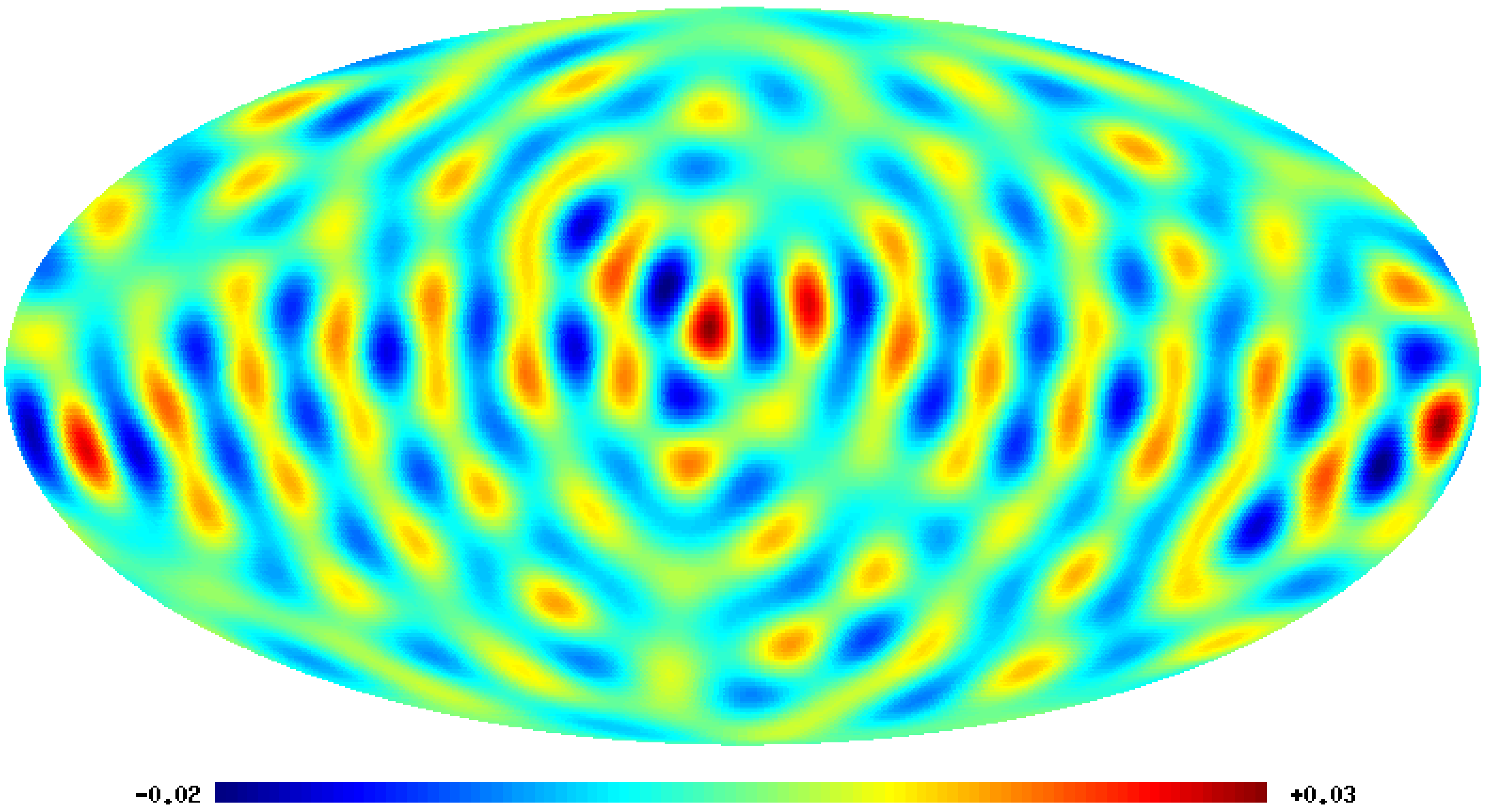
Types of CMB Anomalies

- Type I – obvious problems with data (e.g. foregrounds)
- Type II – anisotropies and alignments (North-South, Axis of Evil..)
- Type III – localized features, e.g. “The Cold Spot”
- Type IV – Something else (even/odd multipoles, magnetic fields, ?)

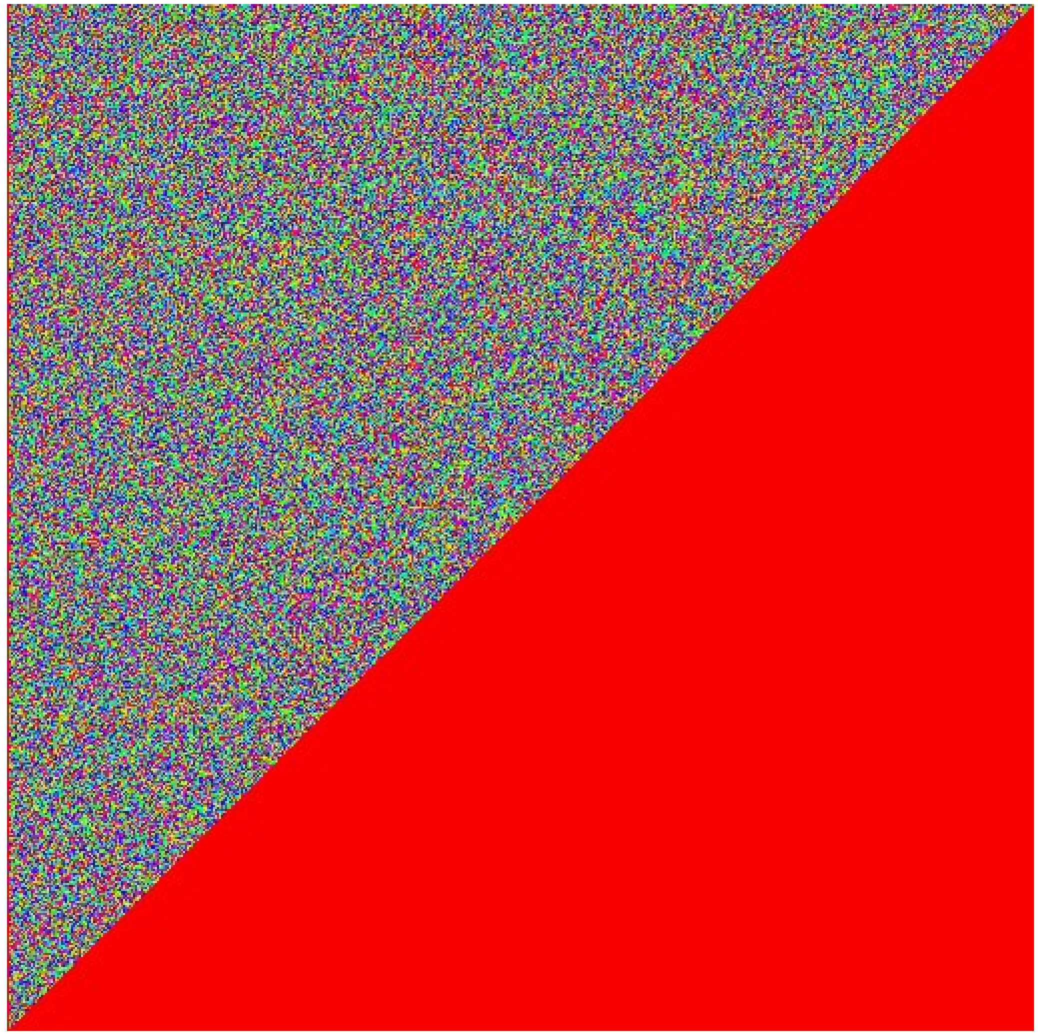
Anomalies-I

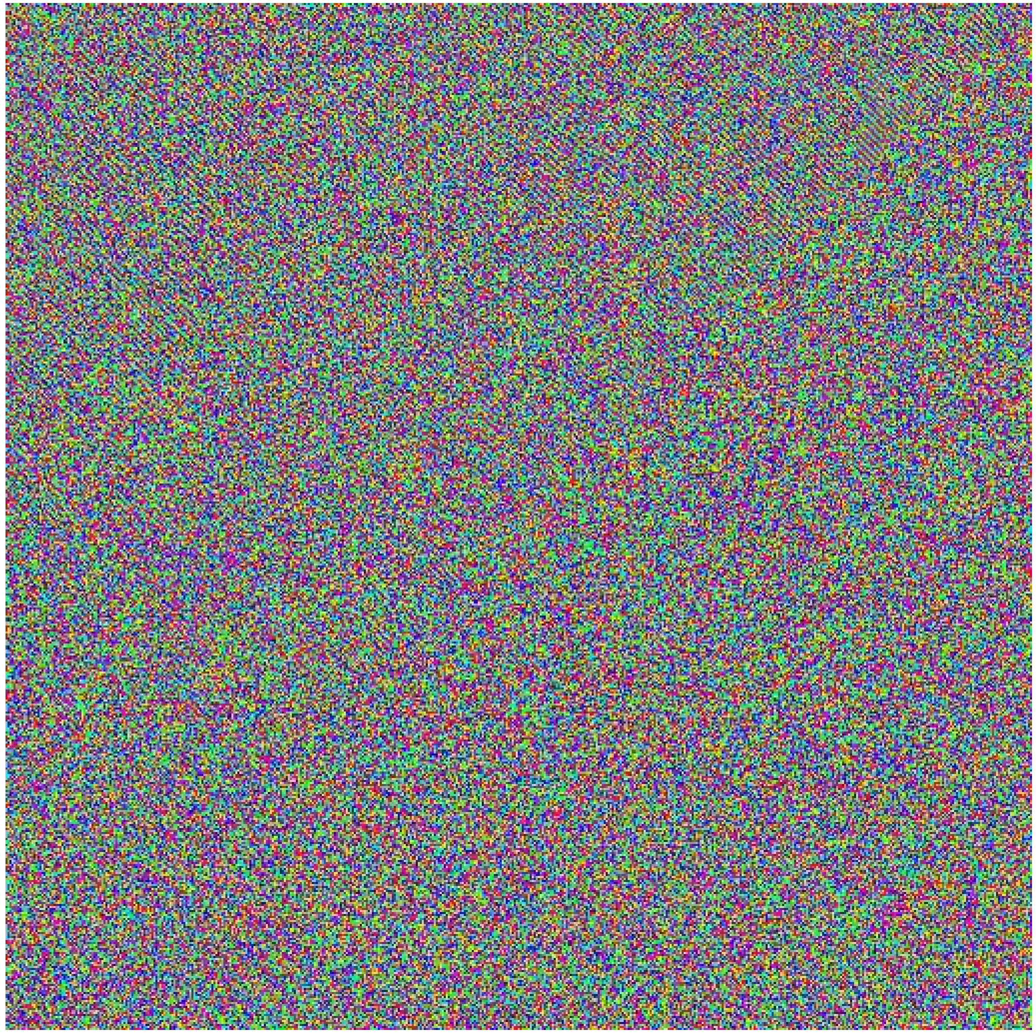
- The whole sky is not actually completely clean so there is residual foreground contamination
- Modes up to l=10 are claimed to be “clean” but probably aren’t
- Accurate statistical analysis therefore still requires a mask.

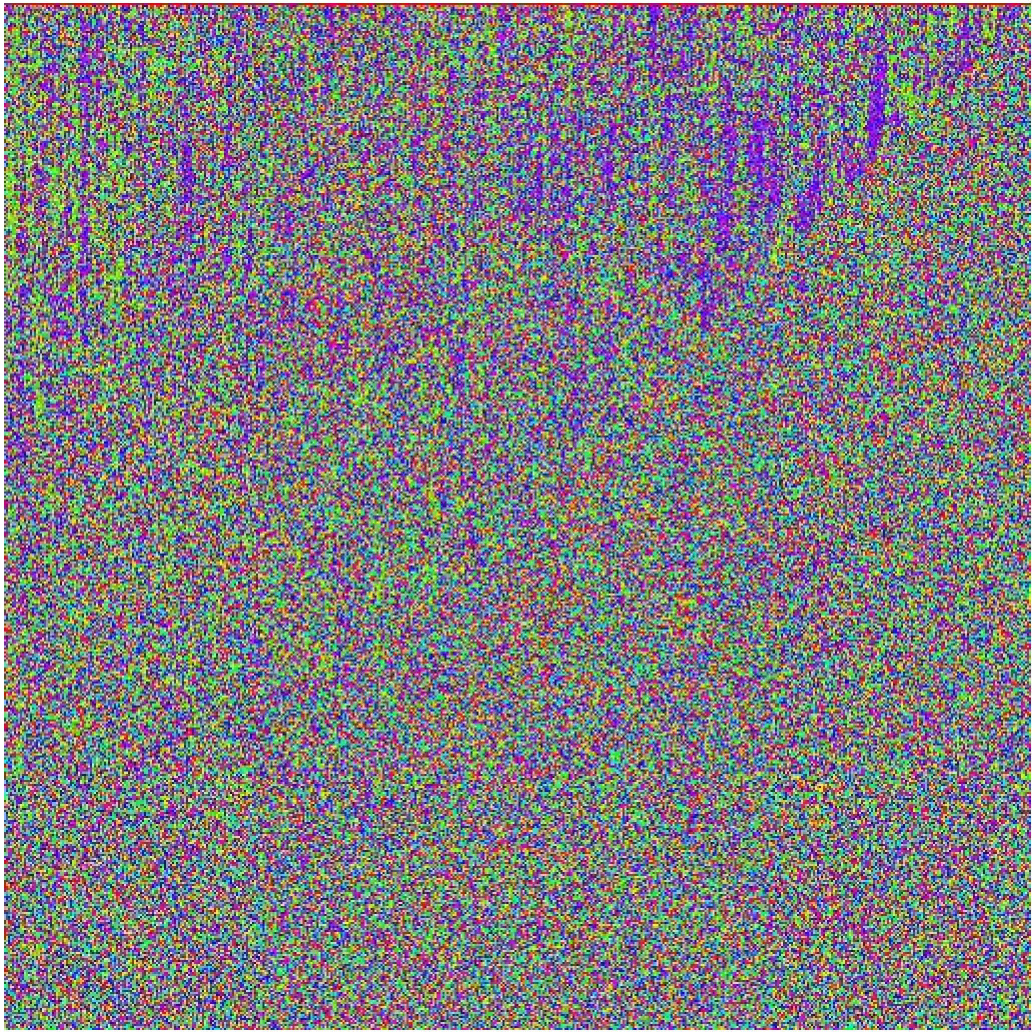




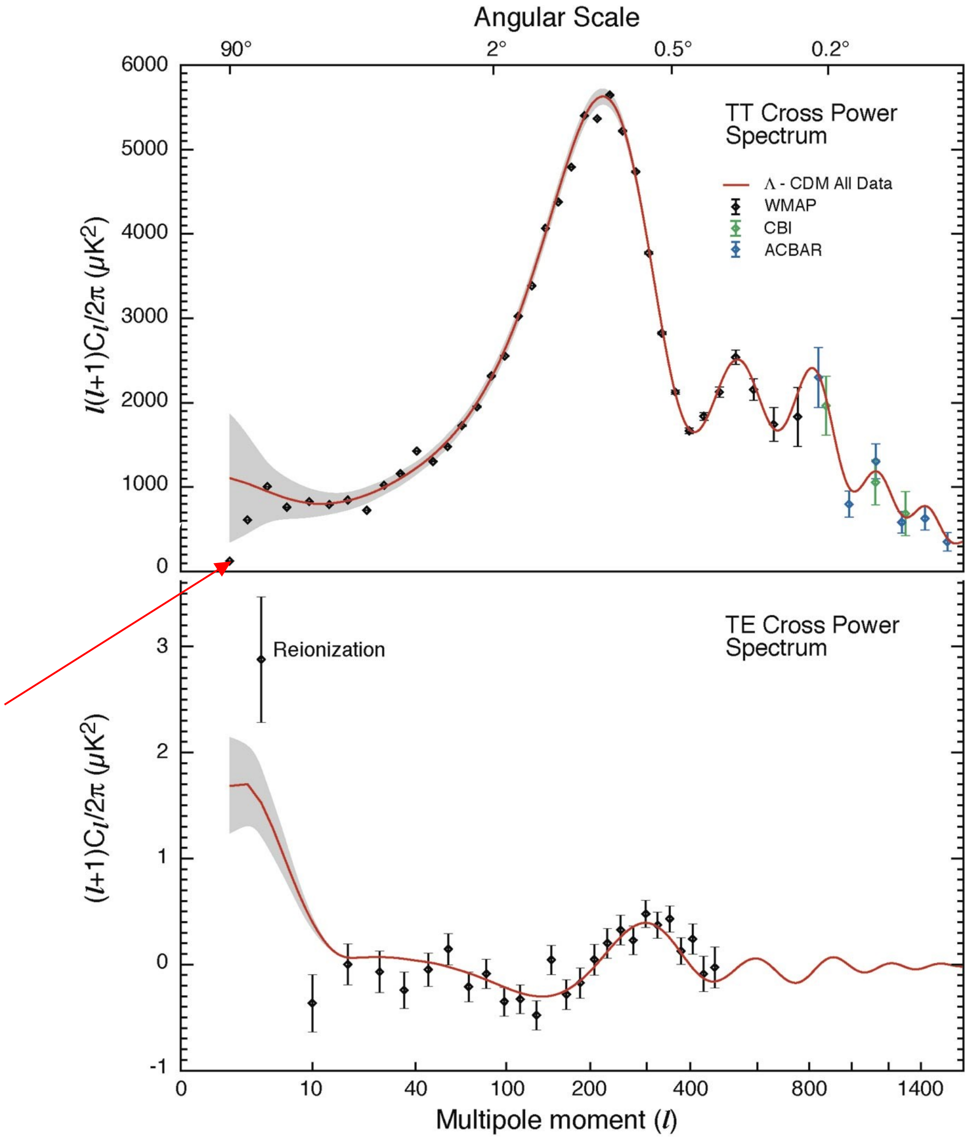
-0.02
+0.03

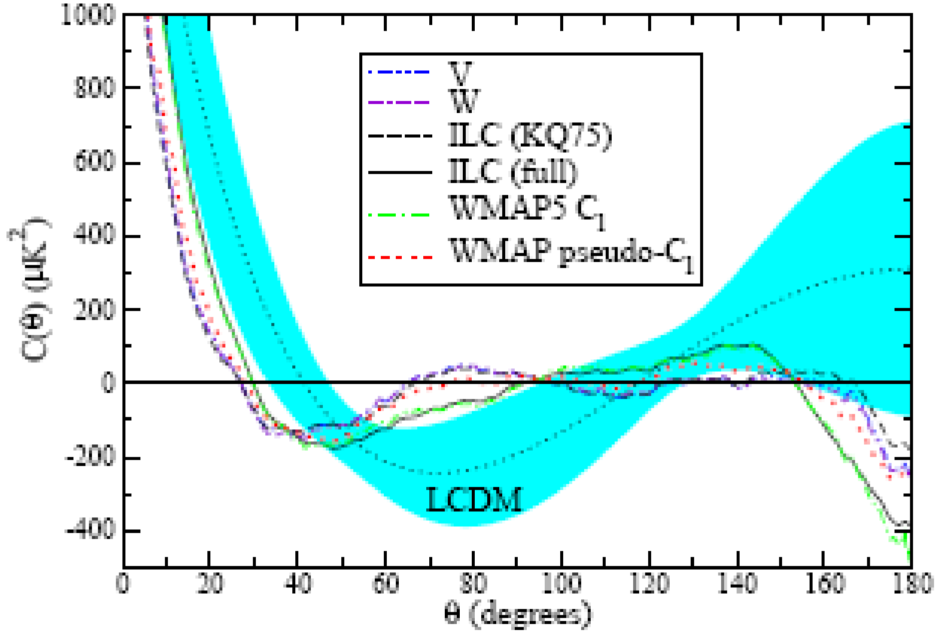




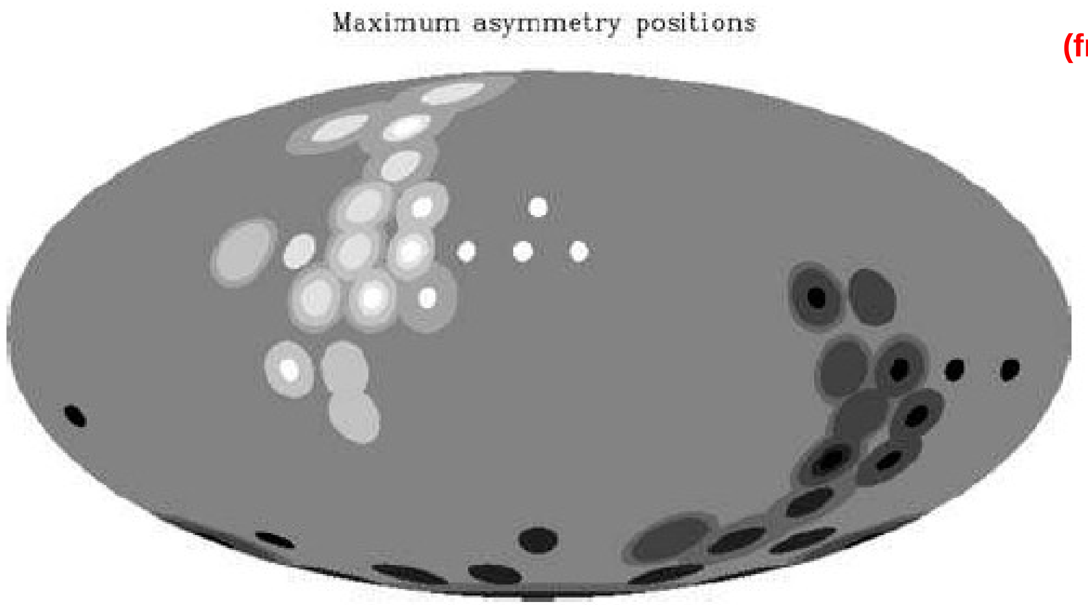


Low Quadrupole?



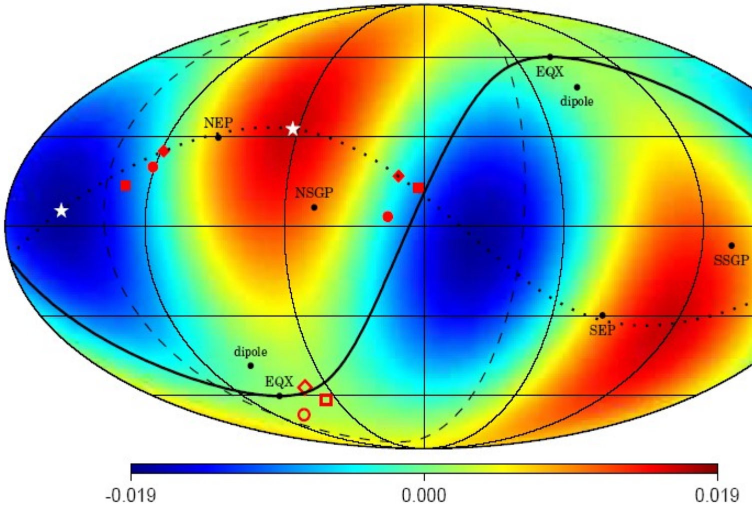


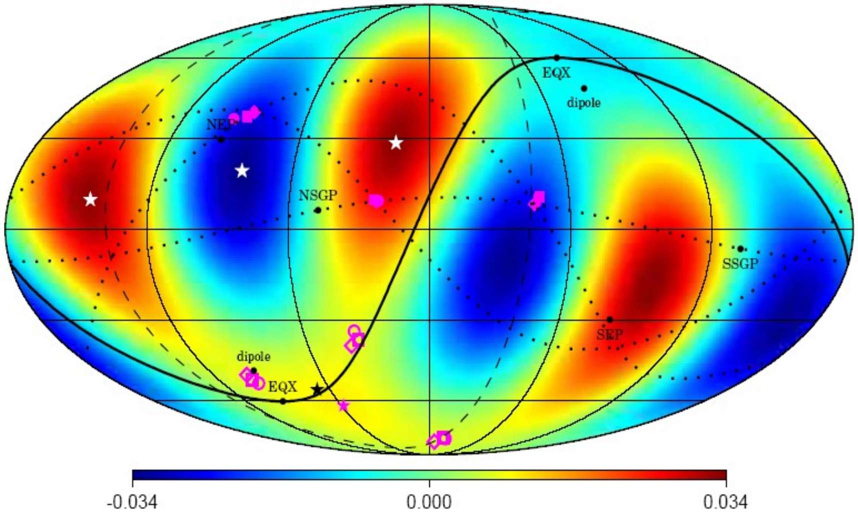
1000
800
600
400
200
0
-200
-400
0
20
40
60
80
100
120
140
160
180
C(θ) (μK²)
θ (degrees)
V
W
ILC (KQ75)
ILC (full)
WMAP5 C_l
WMAP pseudo-C_l
LCDM



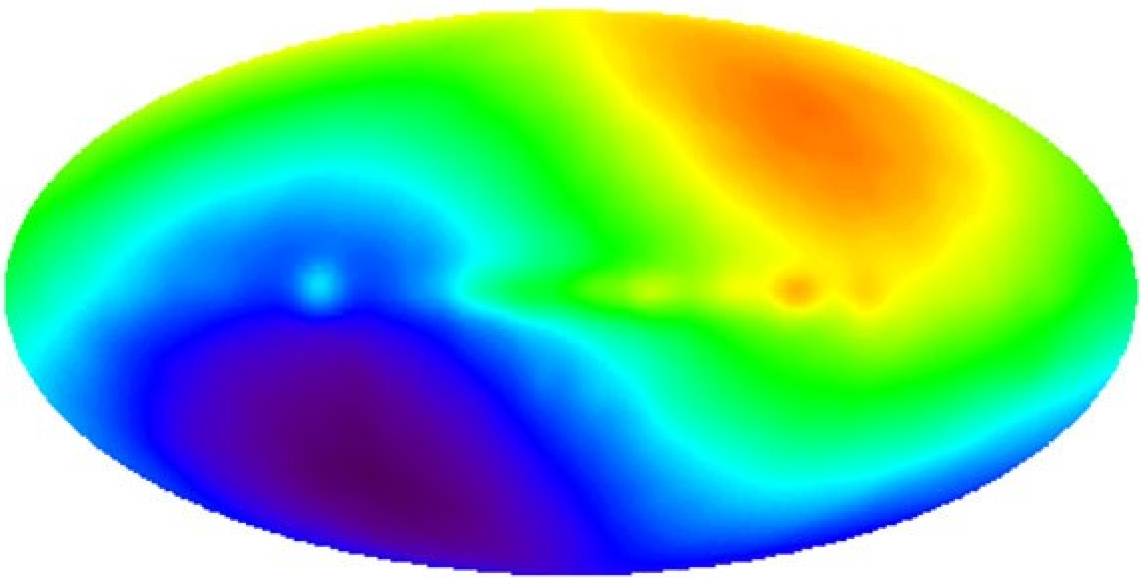
(from Hansen et al. 2004)

Figure 24. The discs show the positions of the hemispheres with the 10 highest (black discs) and 10 lowest (white discs) bin values. The power-spectrum bins considered were $\ell = 2$–40 (large discs), $\ell = 8$–40 (second-largest discs), $\ell = 5$–16 (second-smallest discs) and $\ell = 29$–40 (smallest discs).

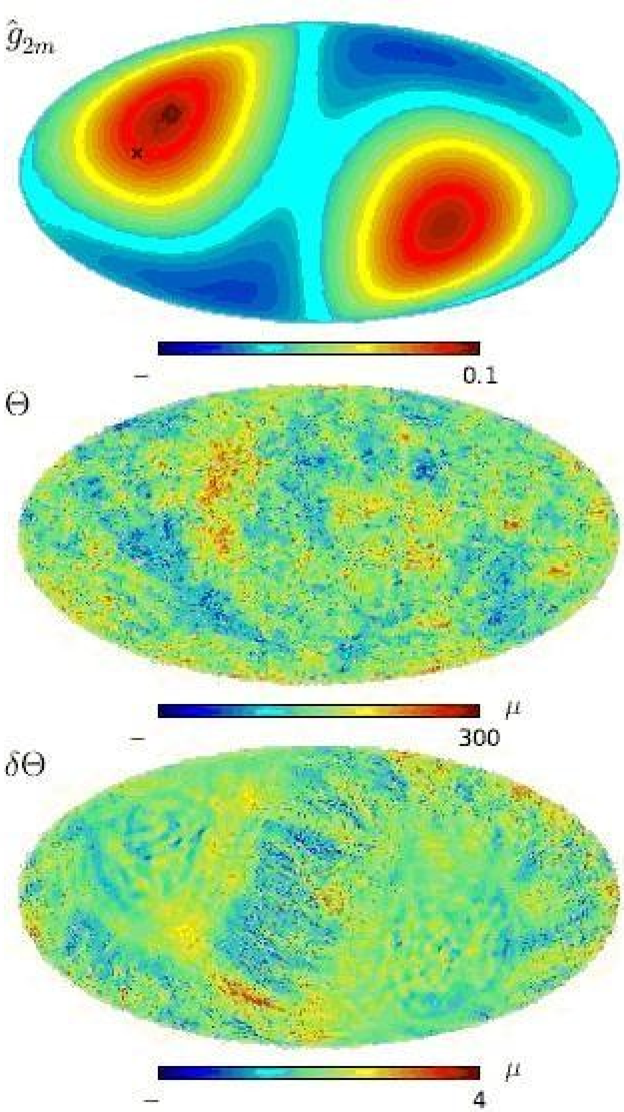


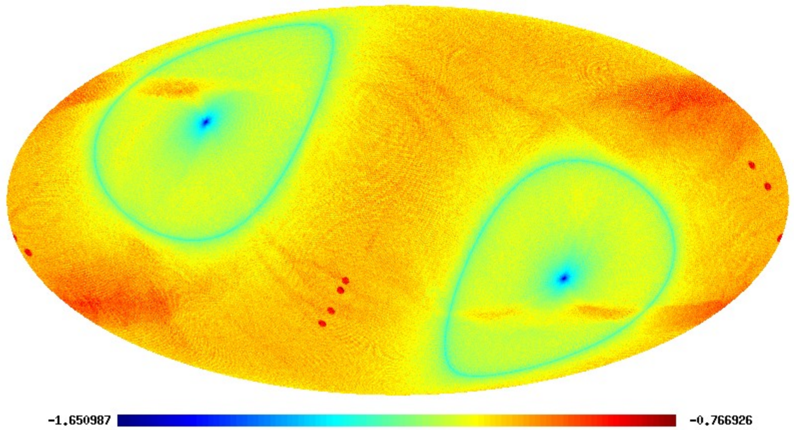


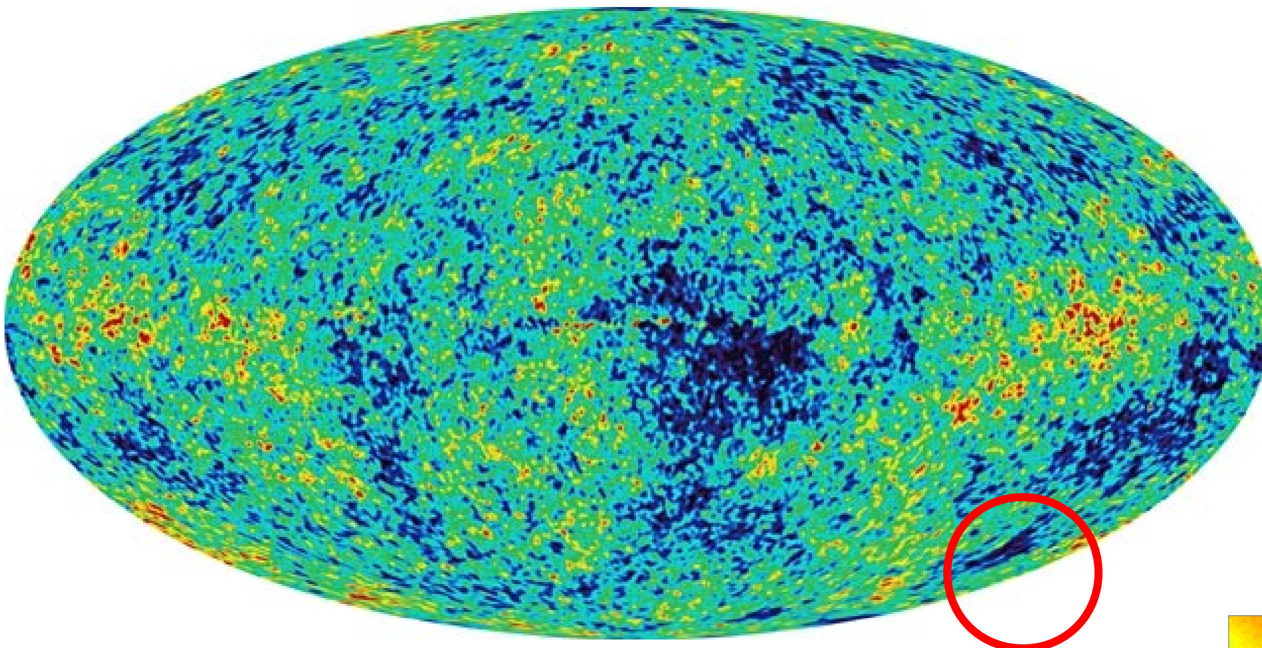
(from Copi et al. 2005)

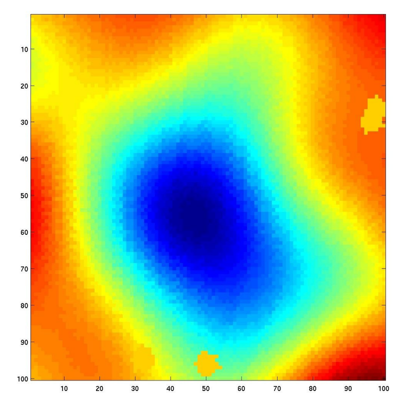


Hanson & Lewis, arXiv:0908.0963

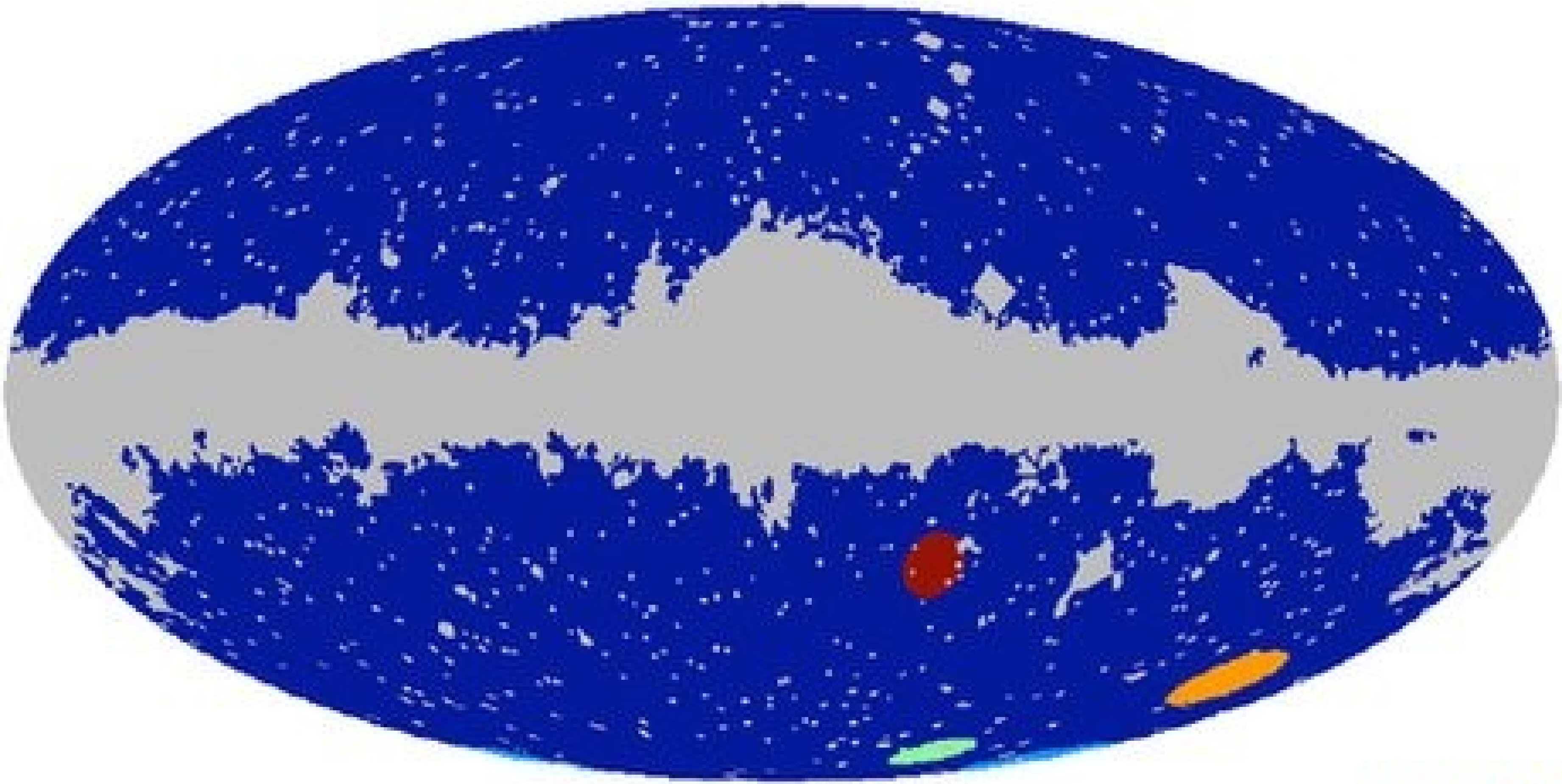








10 20 30 40 50 60 70 80 90 100
10 20 30 40 50 60 70 80 90 100



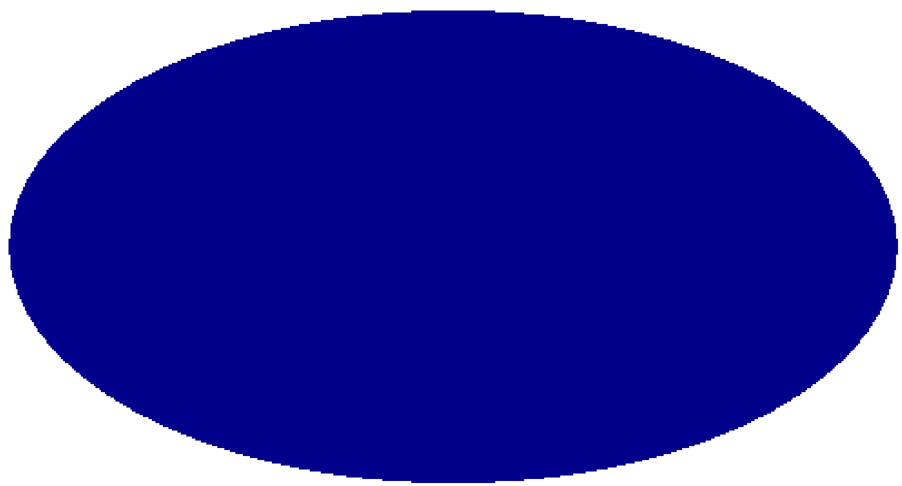
FEENEY ET AL

Global Asymmetry?

- It has been suggested that the answer may be departure from FRW cosmology, e.g. Bianchi (homogenous but anisotropic)
- This can trivially solve the quadrupole problem (e.g. Bianchi I is a pure quadrupole)
- Such models produce a specific polarization pattern which is set by the temperature pattern.
- These (almost) inevitably have a large B-mode…

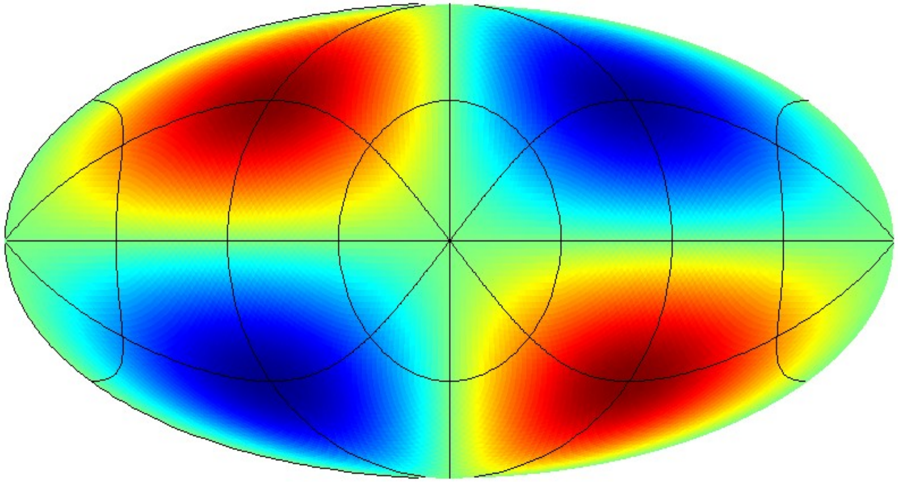
(Pontzen & Challinor 2007; Pontzen 2009; Sung & Coles 2009; Sung & Coles 2010)

Friedman-Robertson-Walker



Bianchi I

Temperature

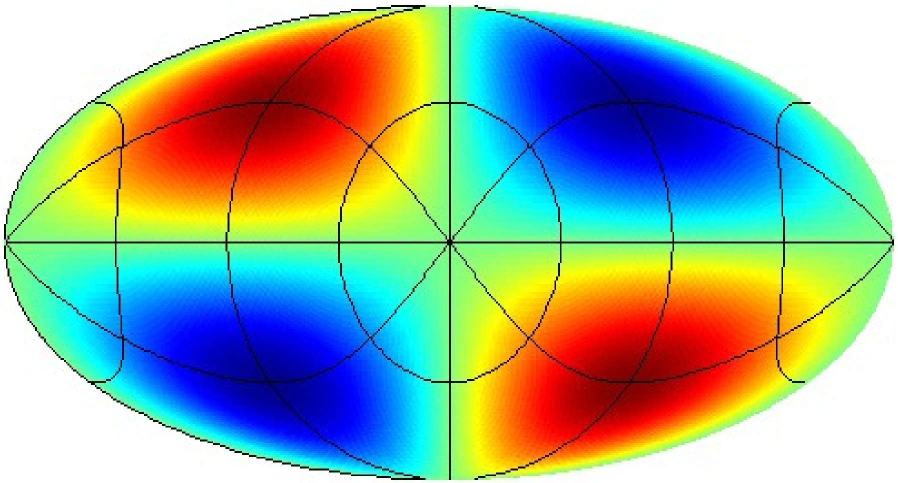


Bianchi vectors $a = 0, n_i = 0$

Scalar curvature $R = 0$

Bianchi V

Temperature



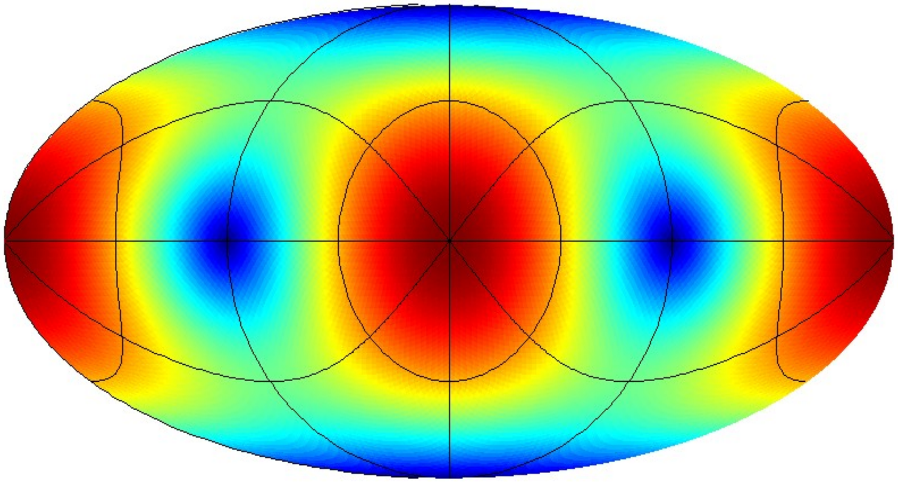
Bianchi vectors $a \neq 0, n_i = 0$

Scalar curvature $R = -6a^2$

Bianchi V

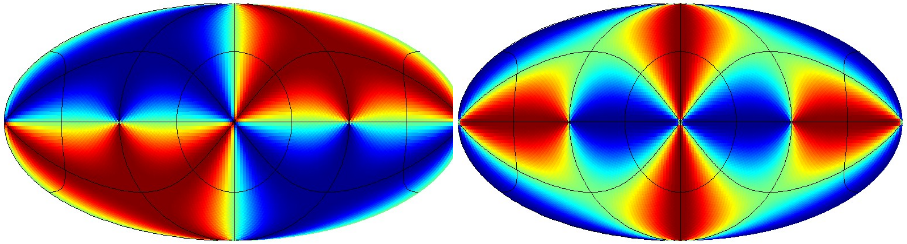
Polarization

Amplitude



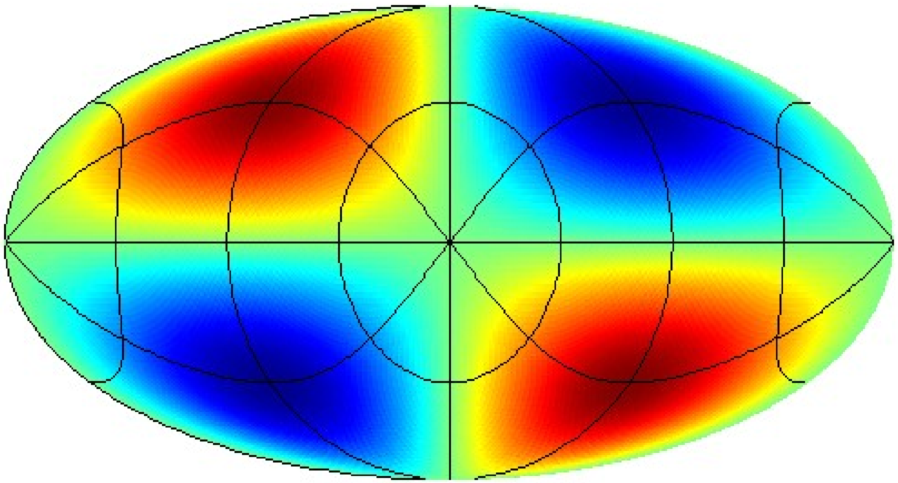
Stokes parameter:

Q and U



Bianchi VII_0

Temperature



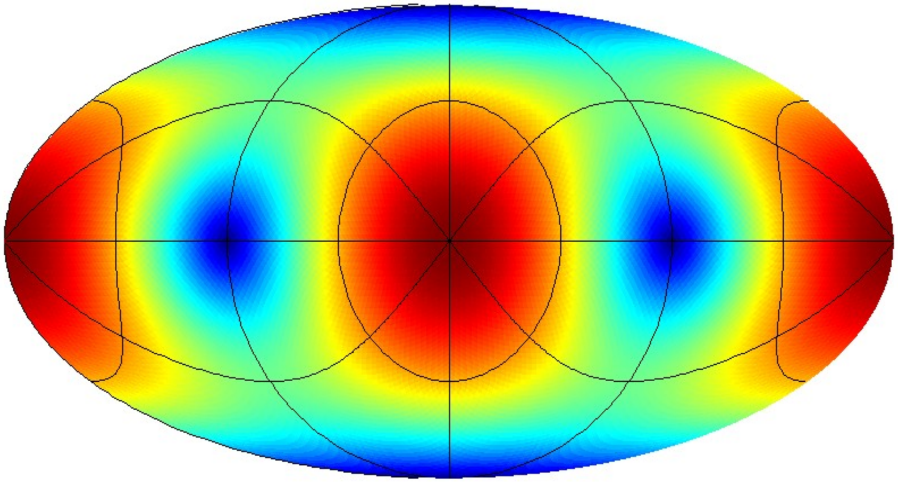
Bianchi vectors $a = 0, n_1 = 0, n_2 = n_3 \square 0$

Scalar curvature $R = 0$

Bianchi VII_0

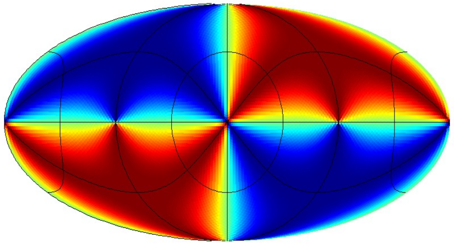
Polarization

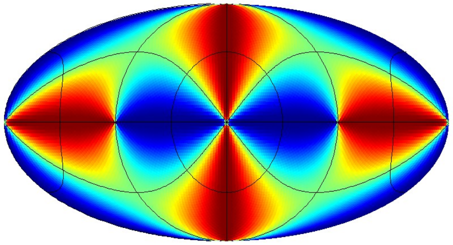
Amplitude



Stokes parameter:

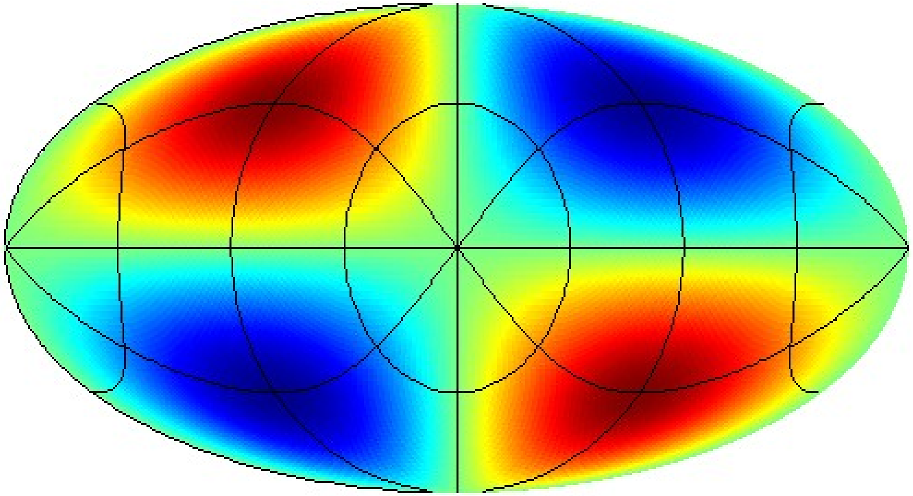
Q and U





Bianchi VII_h

Temperature



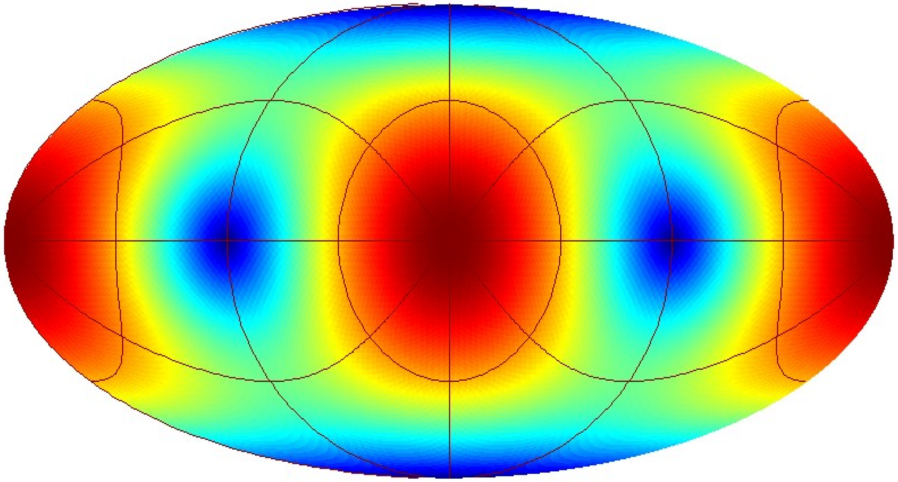
Bianchi vectors $a \neq 0, n_1 = 0, n_2 = n_3 \neq 0$

Scalar curvature $R = -6a^2$

Bianchi VII_h

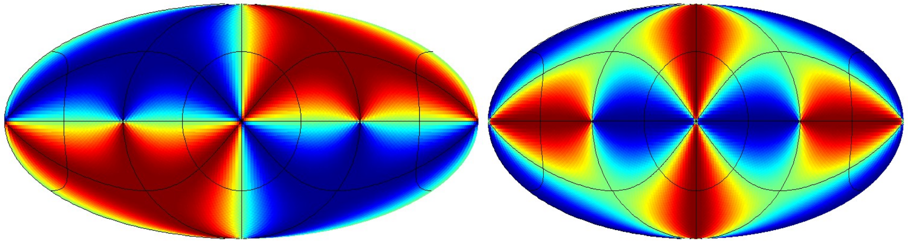
Polarization

Amplitude



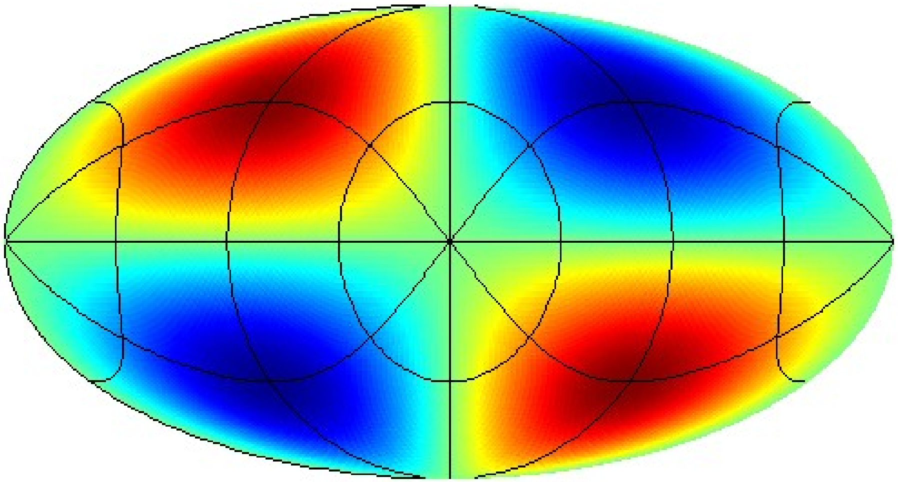
Stokes parameter:

Q and U



Bianchi IX

Temperature



Bianchi vectors

Scalar curvature

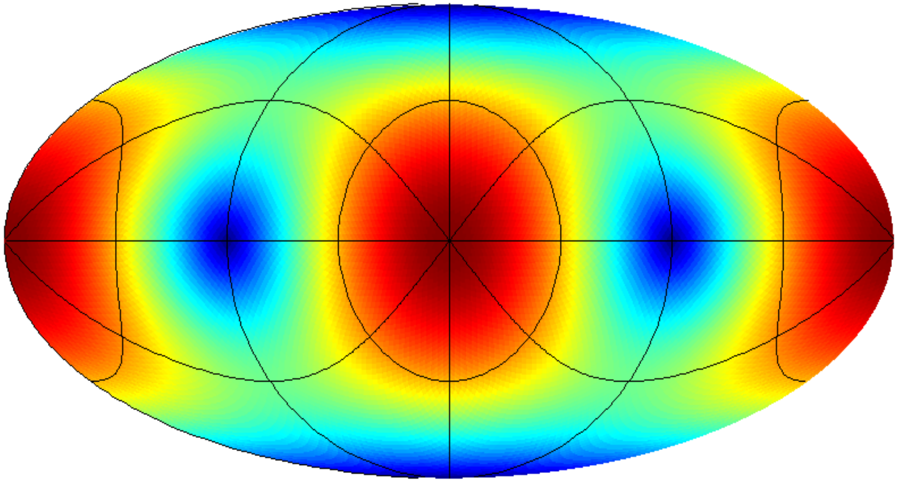
$$a = 0, n_1 = n_2 = n_3 \square 0$$

$$R = \frac{1}{2}(n_1^2 + n_2^2 + n_3^2)$$

Bianchi IX

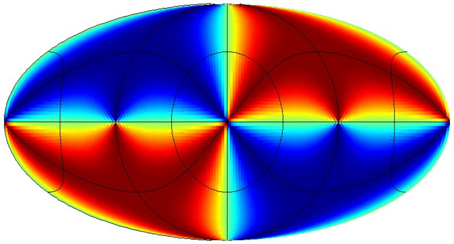
Polarization

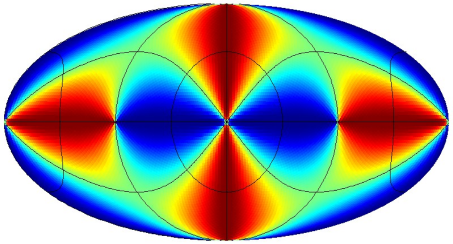
Amplitude

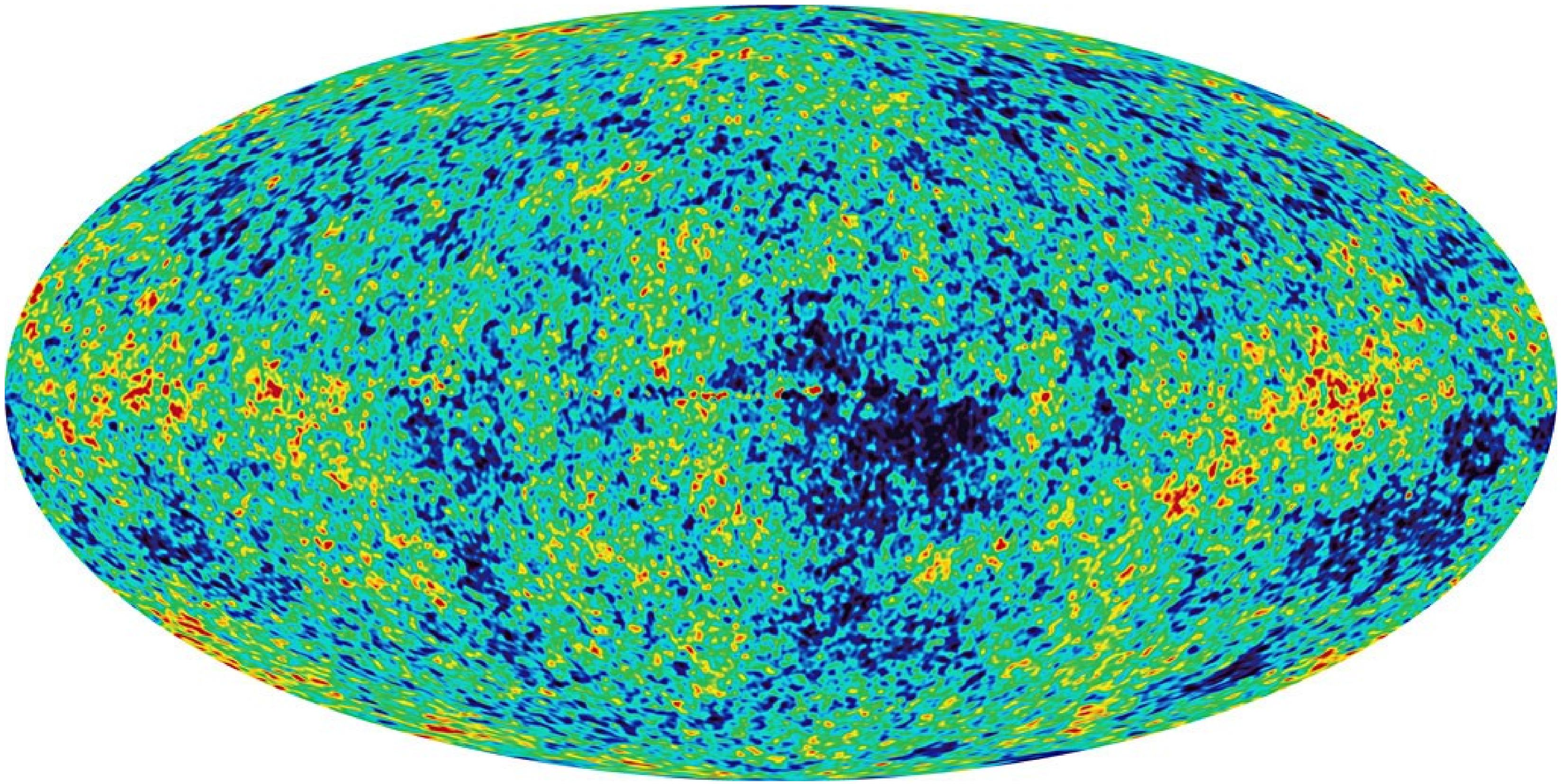


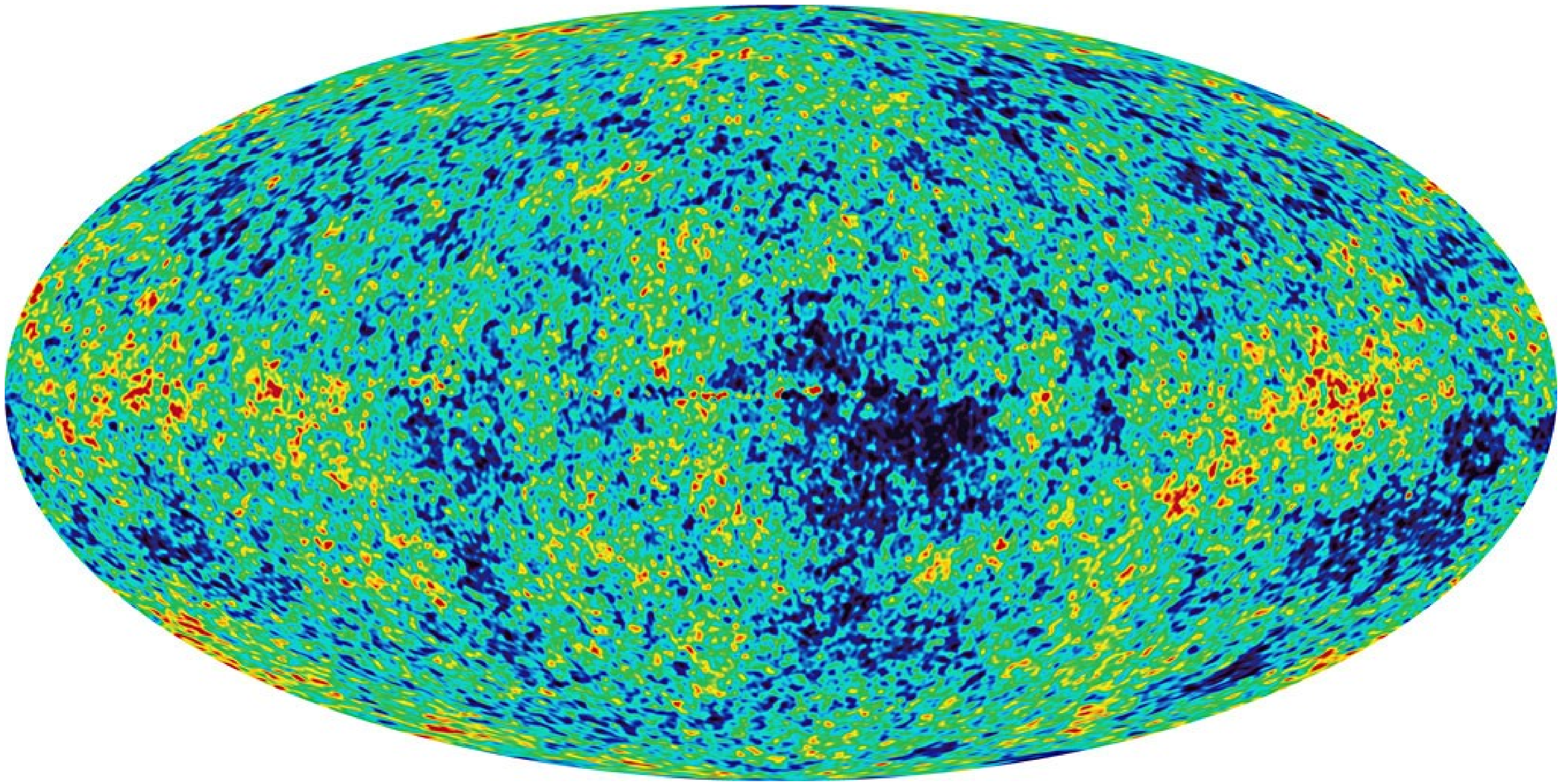
Stokes parameter:

Q and U









Wise Words from WMAP (7) arXiv:1001.4758

In this paper we examine potential anomalies and present analyses and assessments of their significance. **In most cases we find that claimed anomalies depend on posterior selection** of some aspect or subset of the data. Compared with sky simulations based on the best fit model, one can select for low probability features of the WMAP data. Low probability features are expected, but it is not usually straightforward to determine whether any particular low probability feature is the result of the *a posteriori* selection or of non-standard cosmology.....**We conclude that there is no compelling evidence for deviations from the LCDM model, which is generally an acceptable statistical fit to WMAP and other cosmological data**.

Summary

- The concordance cosmology has had many successes, but that doesn't make it the Gospel truth.
- There is intriguing evidence suggesting that the Universe might be more interesting than we thought..
- Focussing exclusively on measuring parameters of the standard model may result in us missing the Elephant in the Room.

A. There’s no problem at all with ΛCDM…

B. There are interesting indications…

C. There’s definitely evidence of new physics