Cosmic Parity Violation
Anomaly vs. Anomaly

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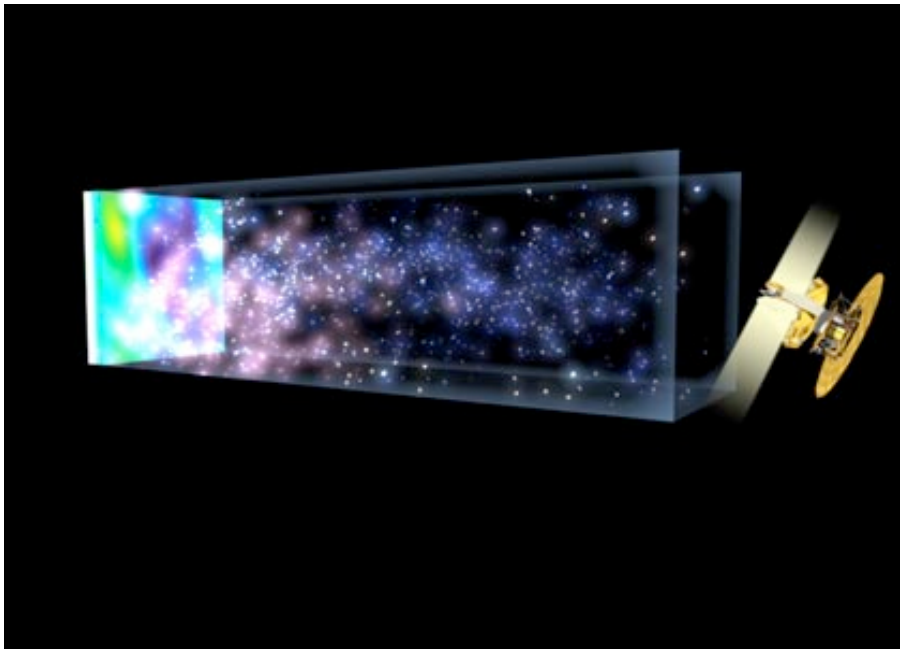
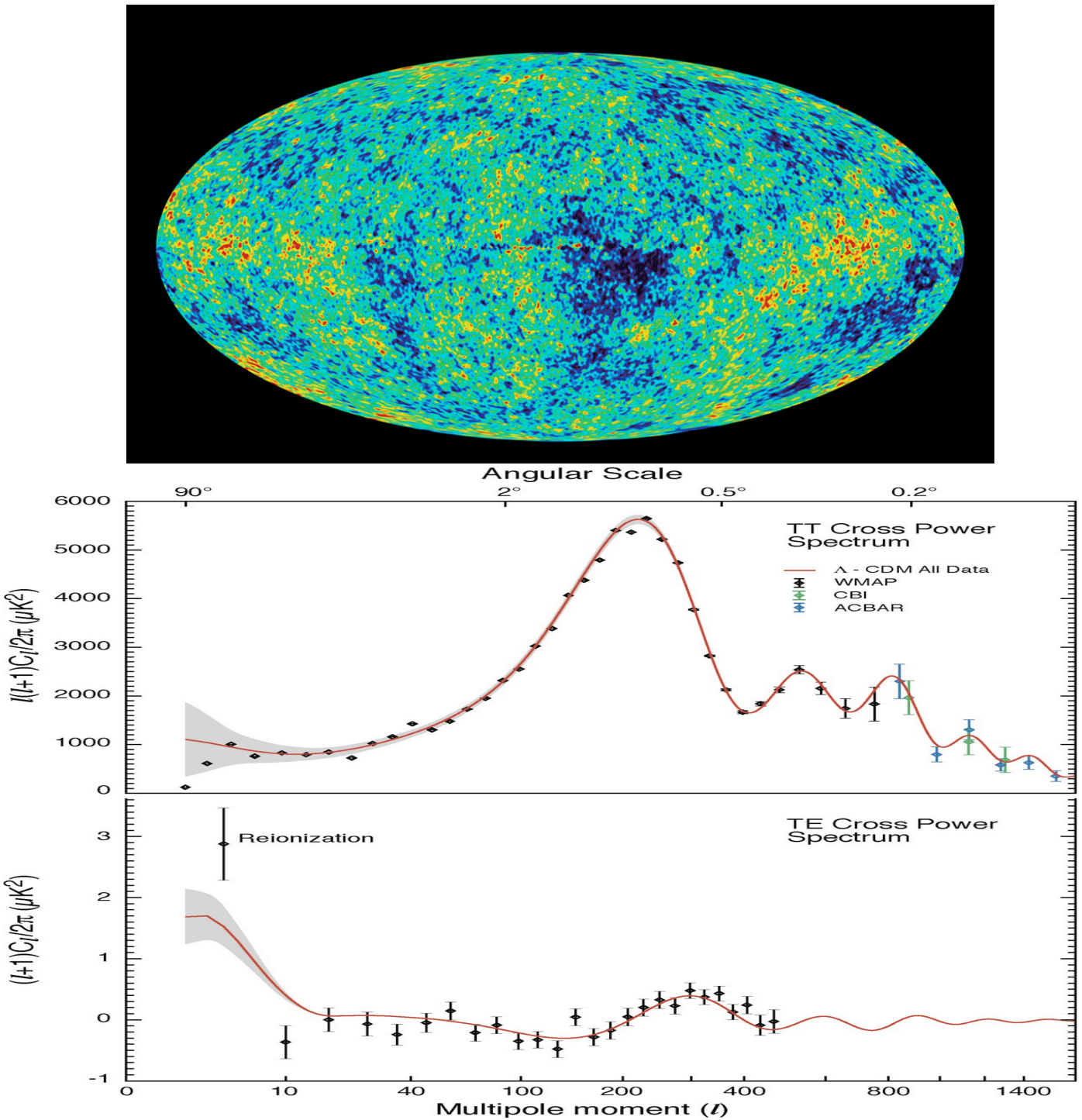
Berkeley Theoretical Astro.

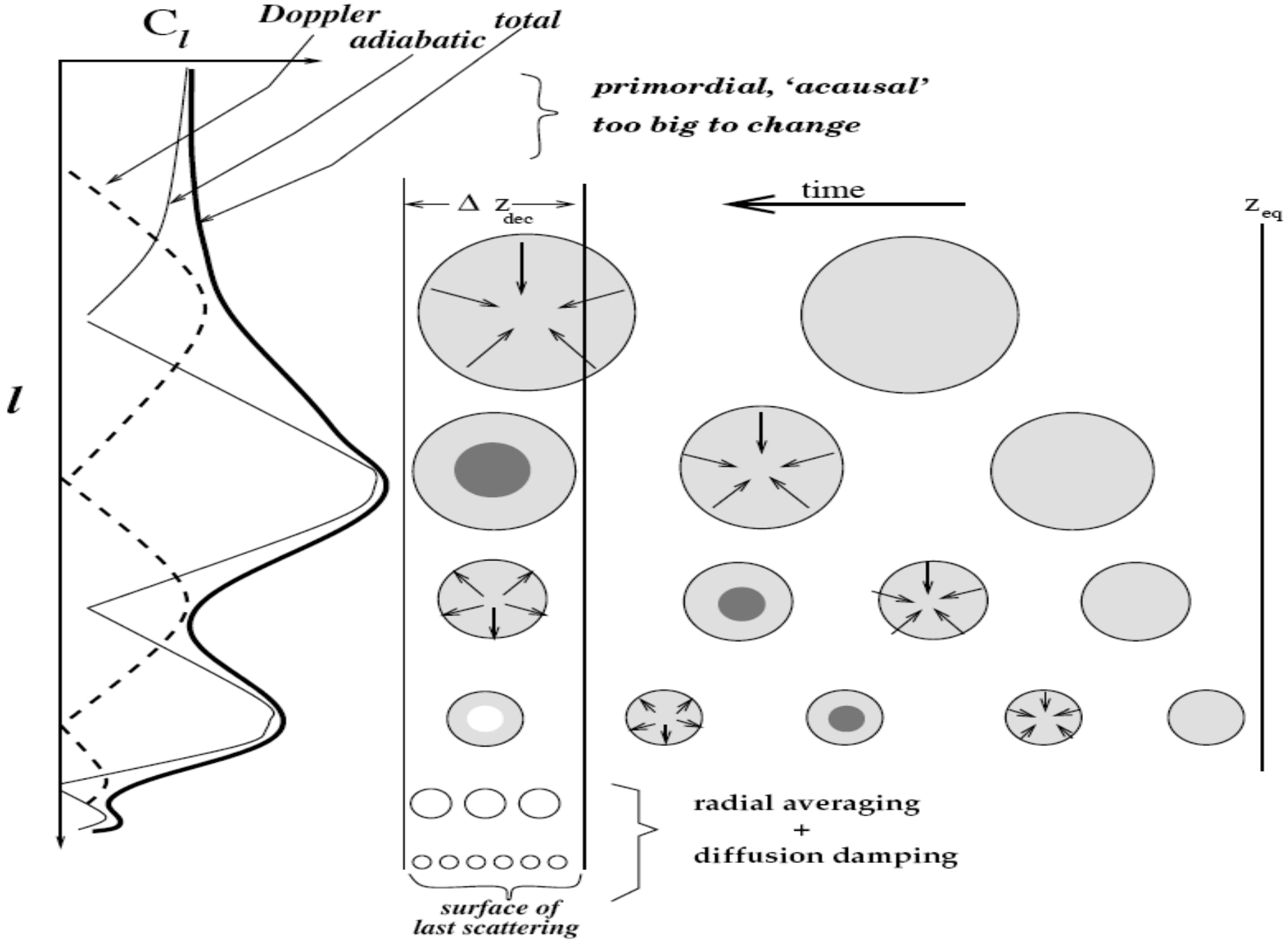
Outline

- CMB Quickie
- WMAP Anomaly
- Parity Violation in General Relativity
- Gravitational Baryogenesis
- Results
- Discussion & Outlook

CMB Quickie




Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK²)
6000
5000
4000
3000
2000
1000
0
TE Cross Power Spectrum
Reionization
(l+1)C_l/2π (μK²)
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)


C_l
Doppler
adiabatic
total
primordial, 'acausal'
too big to change
l
Δz_{dec}
time
z_{eq}
radial averaging
+
diffusion damping
surface of
last scattering

The Axis of Evil

The Quadrapole and Octopole are aligned along the same Axis.

There is loss of power in the Quadrapole

Apparent breaking of Statistical Isotropy:

Statistical Isotropy: Rotational Invariance of statistical Expectation values of temperature fluctuations; ie. Angular Powerspectrum

TODAY WE WILL DISCUSS SOMETHING ELSE

MOTIVATION: Common Assumptions

- 'The Cosmological Principle':
  The universe is Homogeneous and Isotropic, on large scales.

  ➔ **Statistical Isotropy**

- **Gaussianity -** as predicted by simple inflationary models

These issues are often mixed

THE CMB

Gaussianity

a_{lm} **from GAUSSIAN RANDOM FIELD**

$\langle a_{lm} \rangle = 0$

$\langle a_{lm} a_{lm} \rangle = C_l$

Isotropy

STATISTICALLY ISOTROPIC CMB

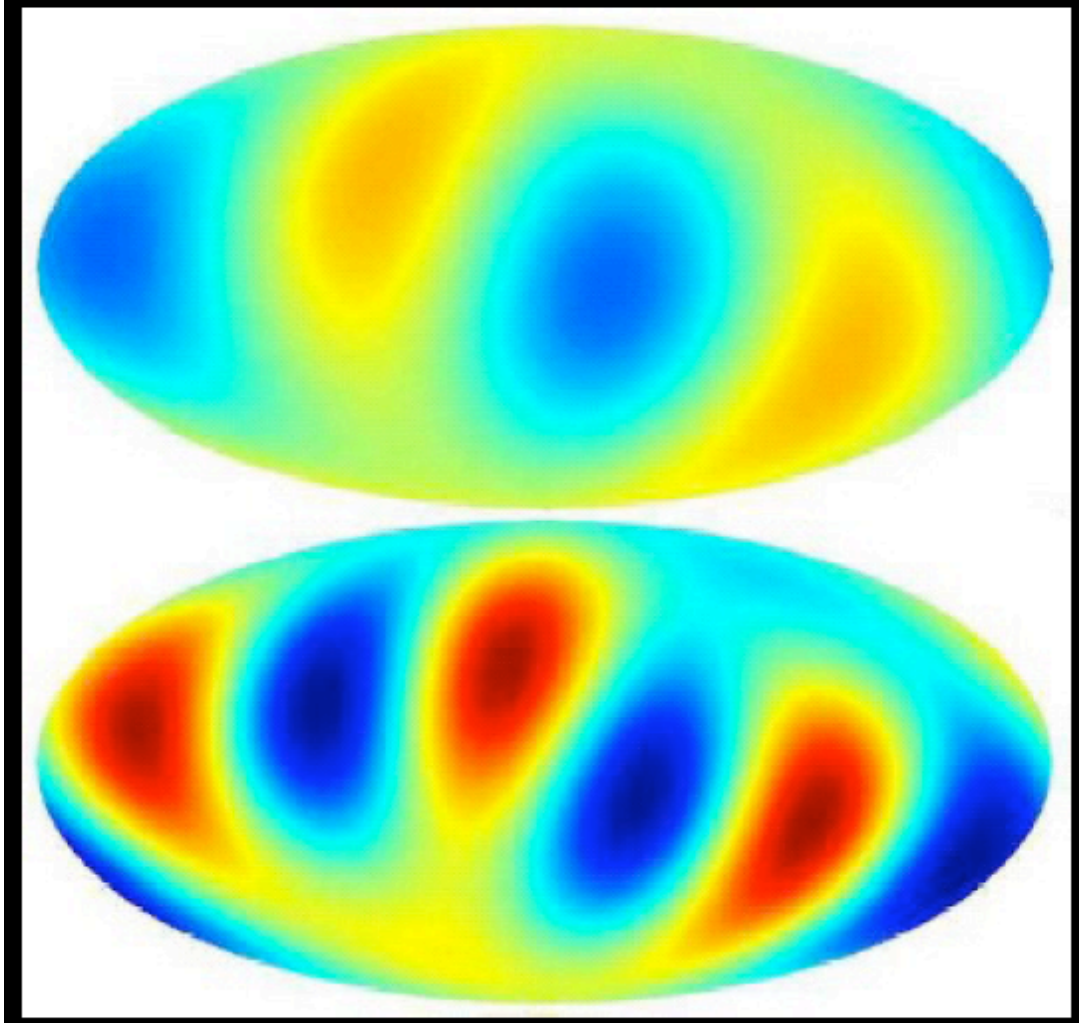
l independence

m equality

$$T(\mathbf{n}) = \sum_{lm} a_{lm} Y_{lm}(\mathbf{n}) = \sum_{l} T_l(\mathbf{n})$$

Degrees of freedom $(2l+1) = 3 + (2l-2)$

MULTIPOLE FRAMES



"Intriguingly, both the quadrupole and the octopole are seen to have power suppressed along a particular spatial axis, which lines up between the two, roughly towards

(l, b) ~ (-110, 60)

in Virgo."

Tegmark & al.PRD(68)123523

MULTIPOLE FRAMES II

When does a multipole look most like a pure m-mode?

$$r_l = \max_{mn} \frac{2|a_{lm}|^2}{\sum_{m'}|a_{lm'}|^2}$$

RATIO - how much
'm preference'

SHAPE -
which m

DIRECTION

Land & Magueijo PRL(95)071301

In Search of Mirror Parity

Let us ask of the data: Can I find an axis which gives a pure Y_{lm} ?

Given this let us decompose the CMB map into Even and odd parity parts.

$$\hat{C}_\ell^{\pm}(\mathbf{n}_\ell) = \frac{1}{2\ell+1}\sum_m p_{\ell m}^{\pm}|a_{\ell m}|^2$$

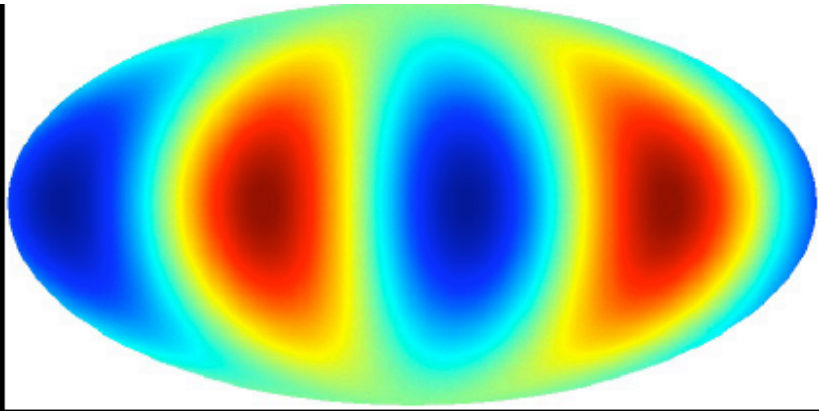
where $p_{\ell m}^{\pm}$ is 1 or 0 depending on the parity of $\ell + m$

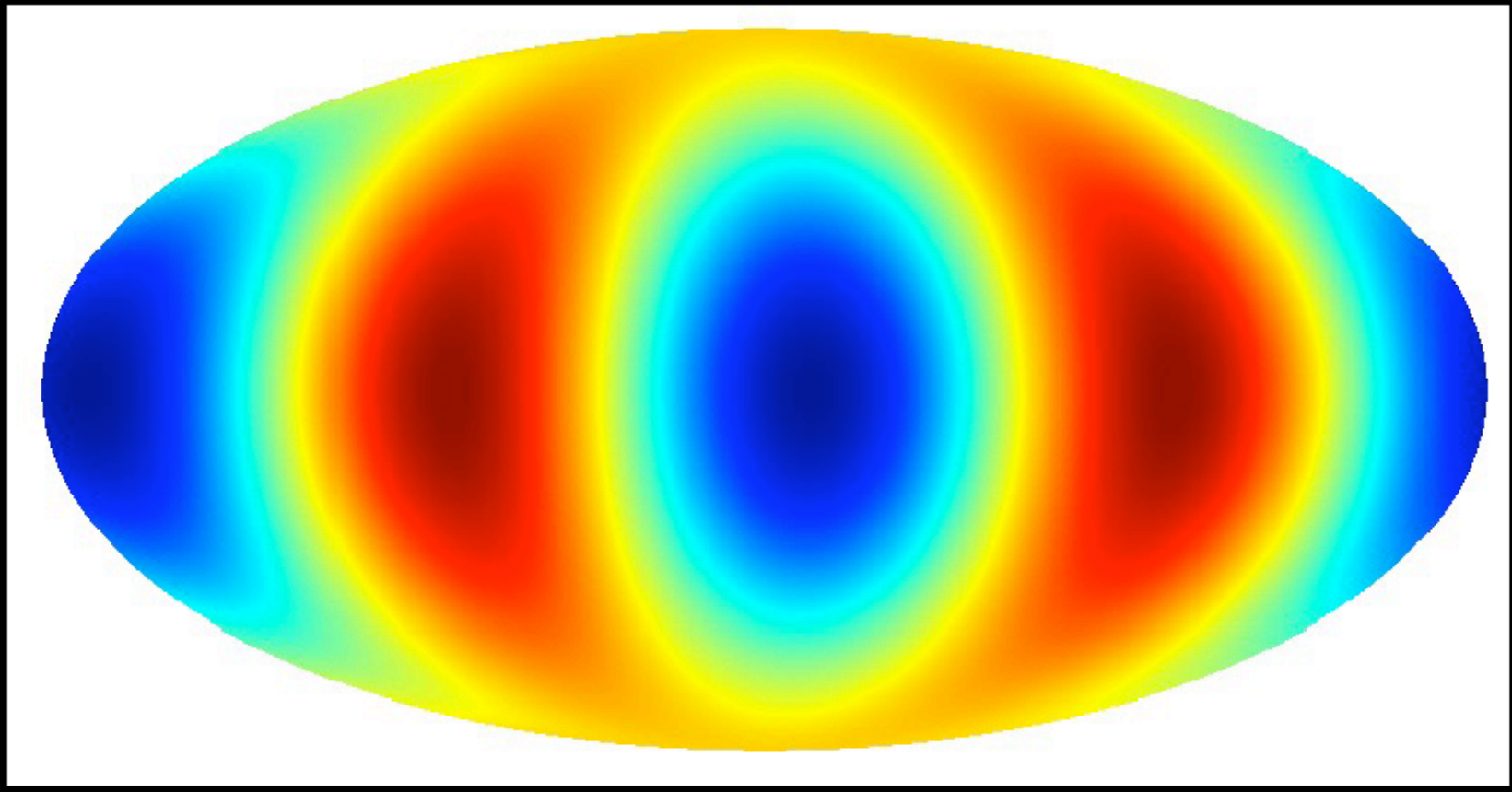
We can use this statistic to select the direction $\mathbf{n}_\ell$ in which to evaluate $\hat{C}_\ell^\pm$ and assess mirror handedness. The asymmetry between odd and even modes may then be measured by the ratio:

$$r_\ell^+ = \frac{\hat{C}_\ell^+(\mathbf{n}_\ell) - \hat{C}_\ell^-(\mathbf{n}_\ell)}{\hat{C}_\ell} \tag{6}$$

l = 2 (Quadrupole)

SHAPE m = 2
RATIO 0.957

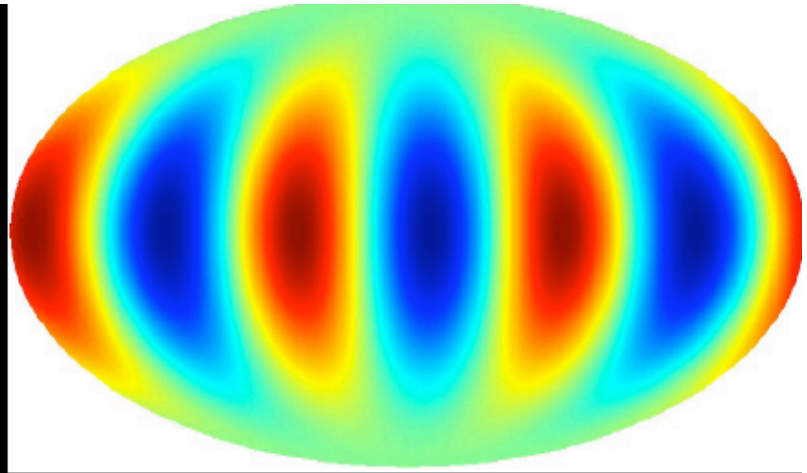


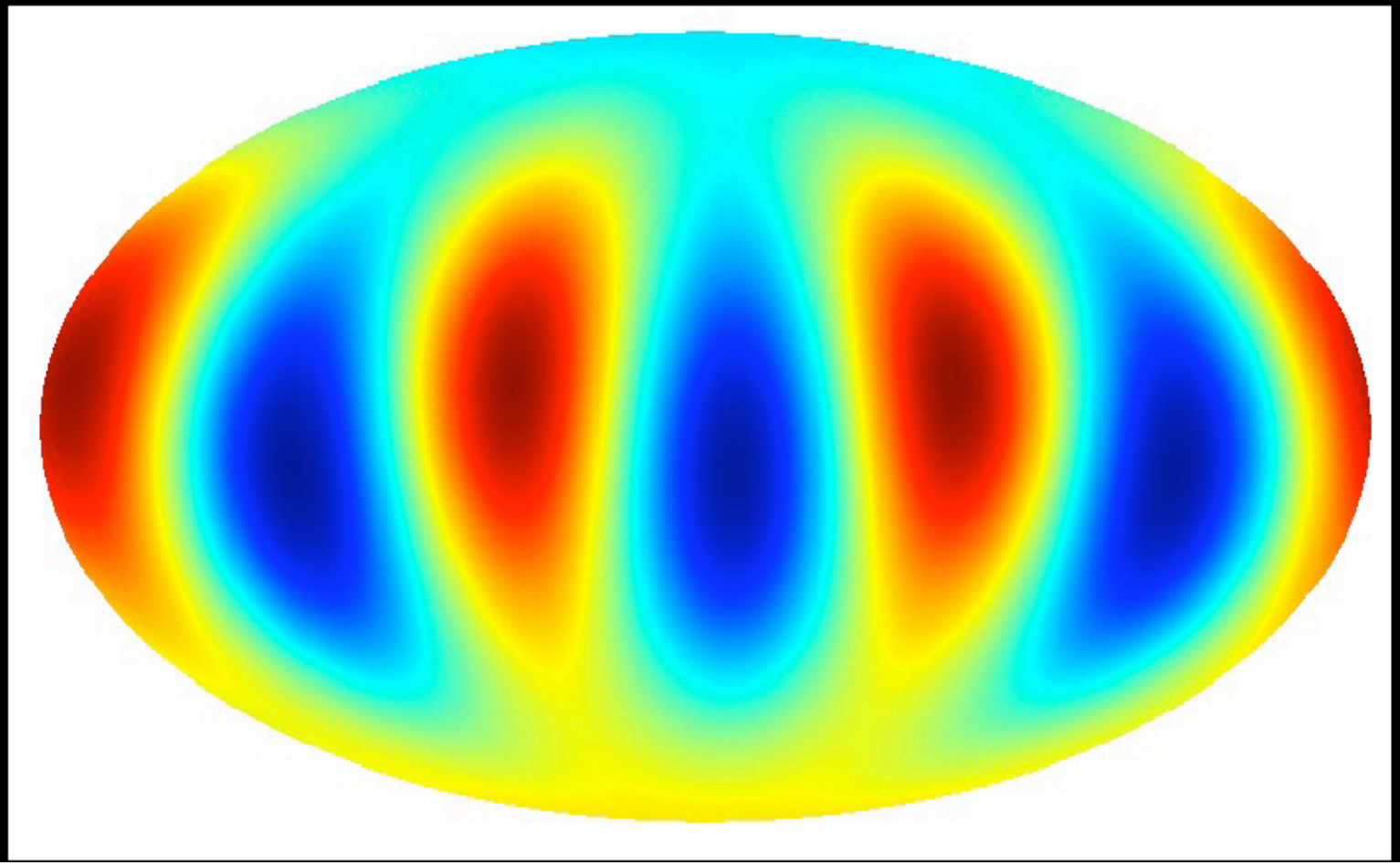


l = 3 (Octopole)

SHAPE m = 3

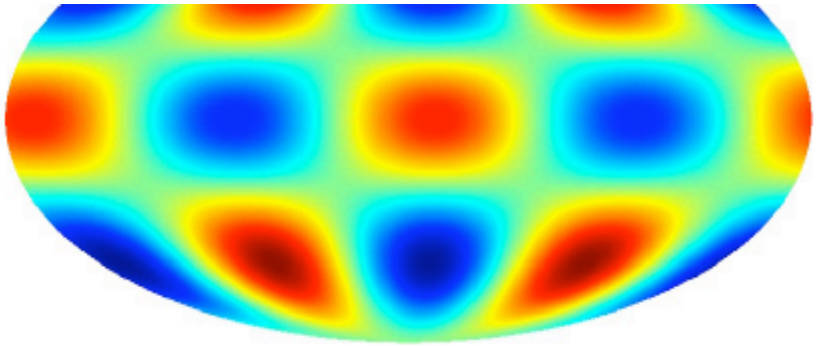
RATIO 0.942

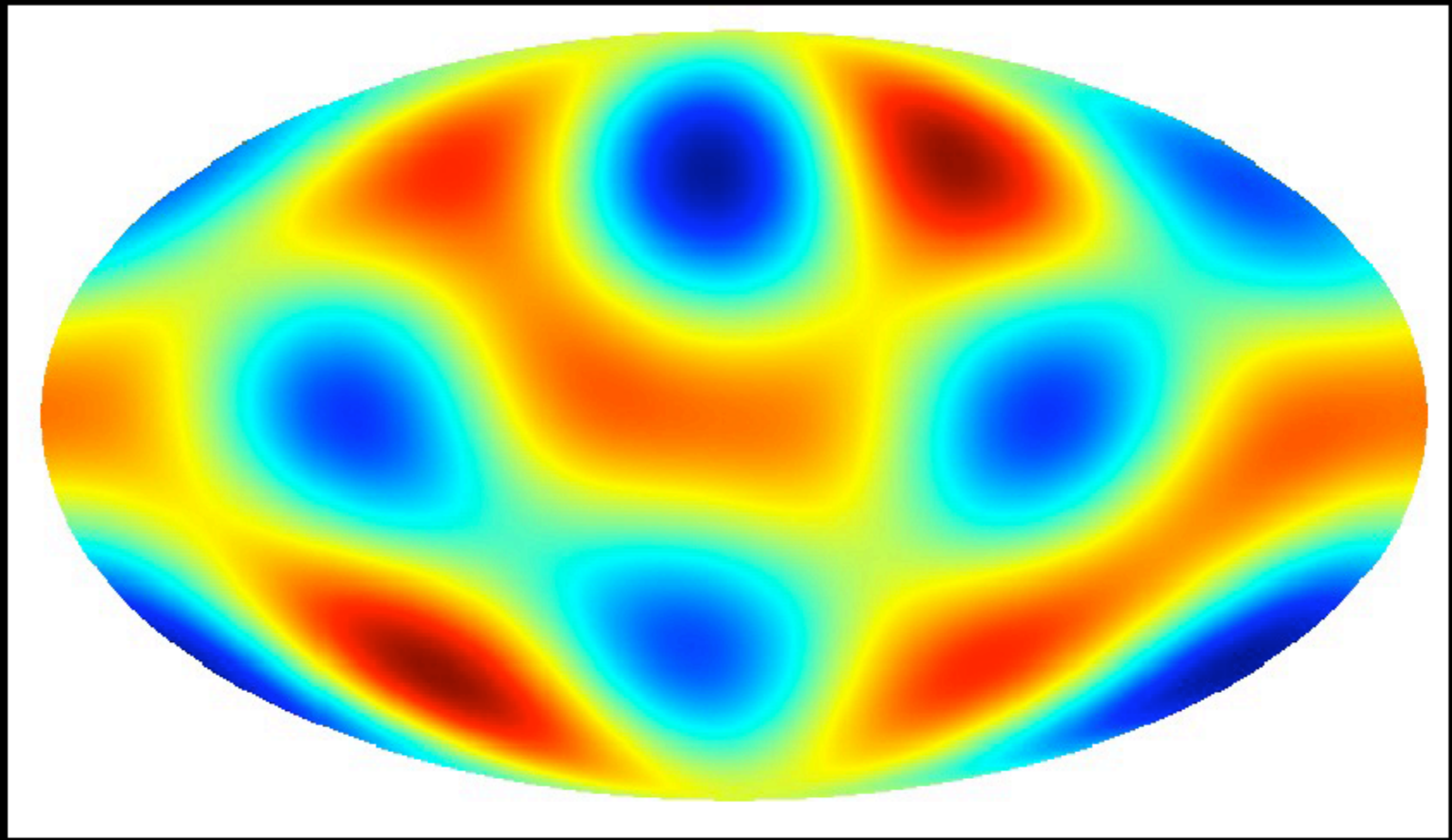




$l = 4$

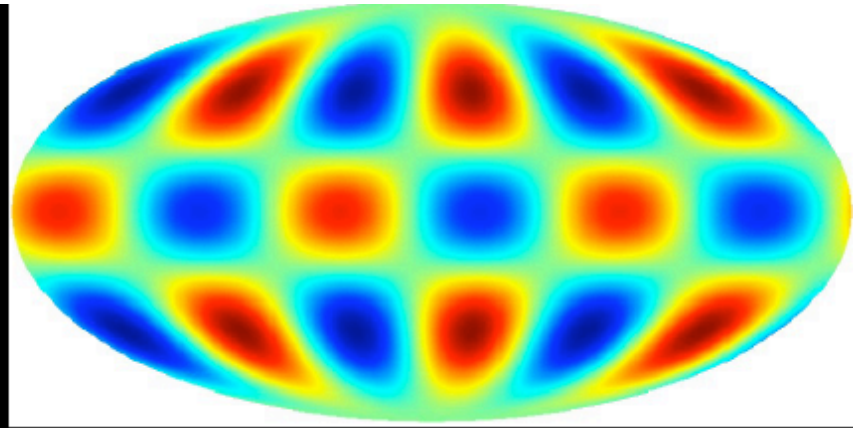
SHAPE $m = 2$
RATIO 0.875

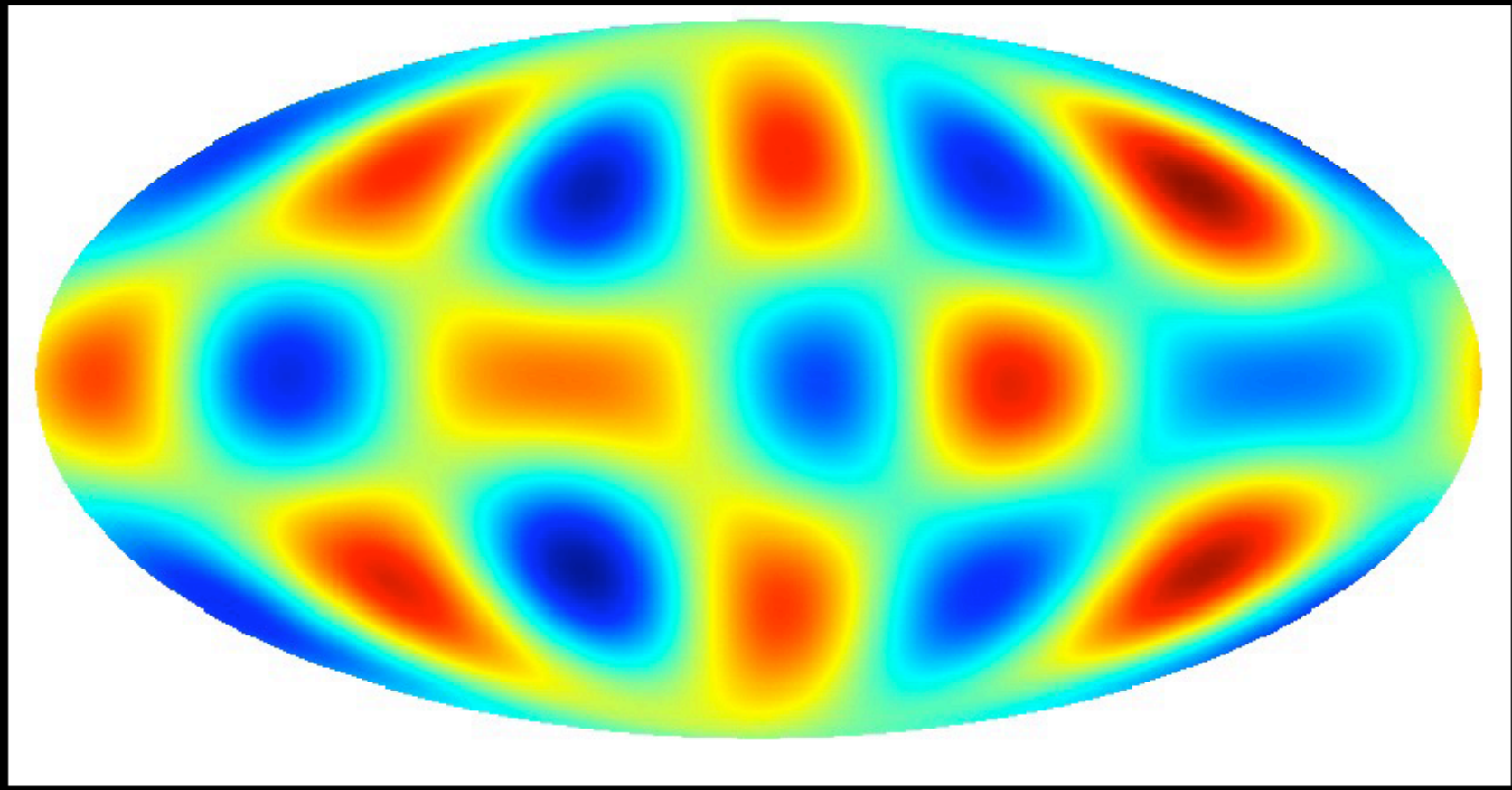




$l = 5$

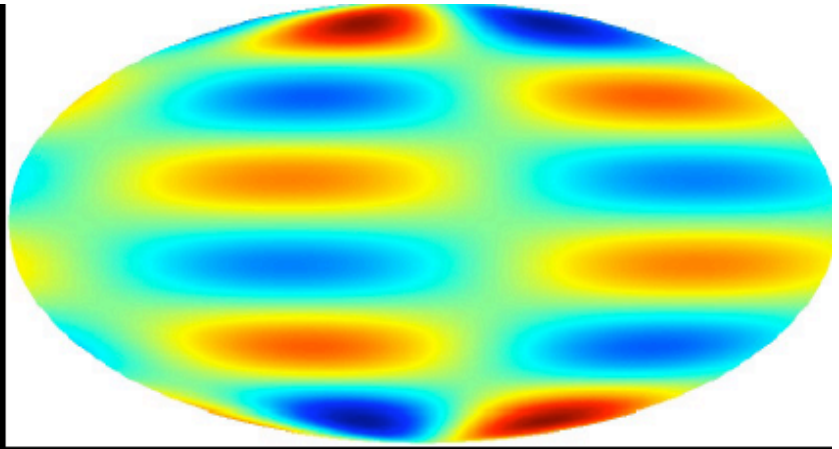
SHAPE $m = 3$
RATIO 0.895

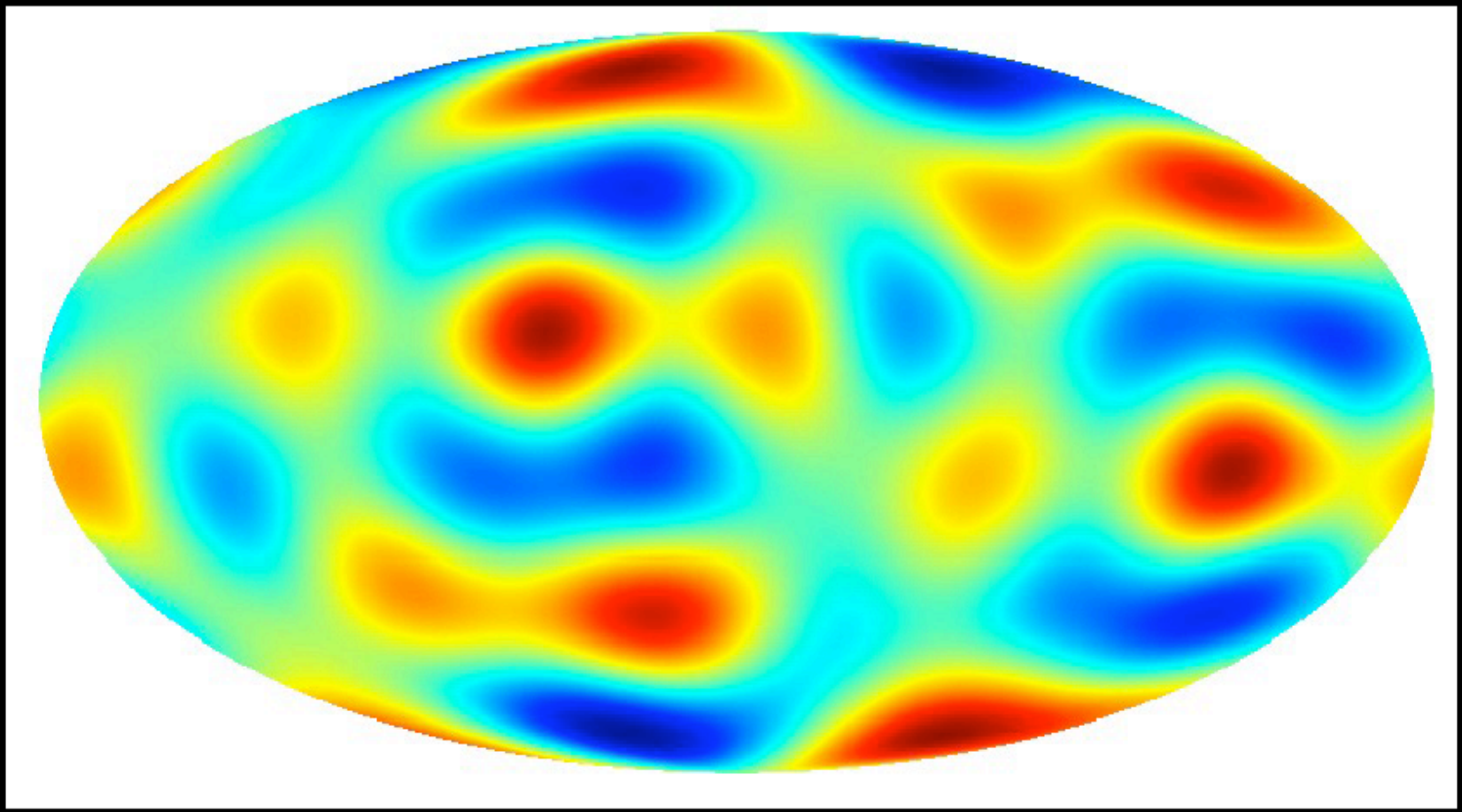




$l = 6$

SHAPE $m = 1$
RATIO 0.802





What does this mean?

Power for odd parity modes (about the same axis)
Is suppressed.

Even parity along this plane is preserved.

Copi et al.

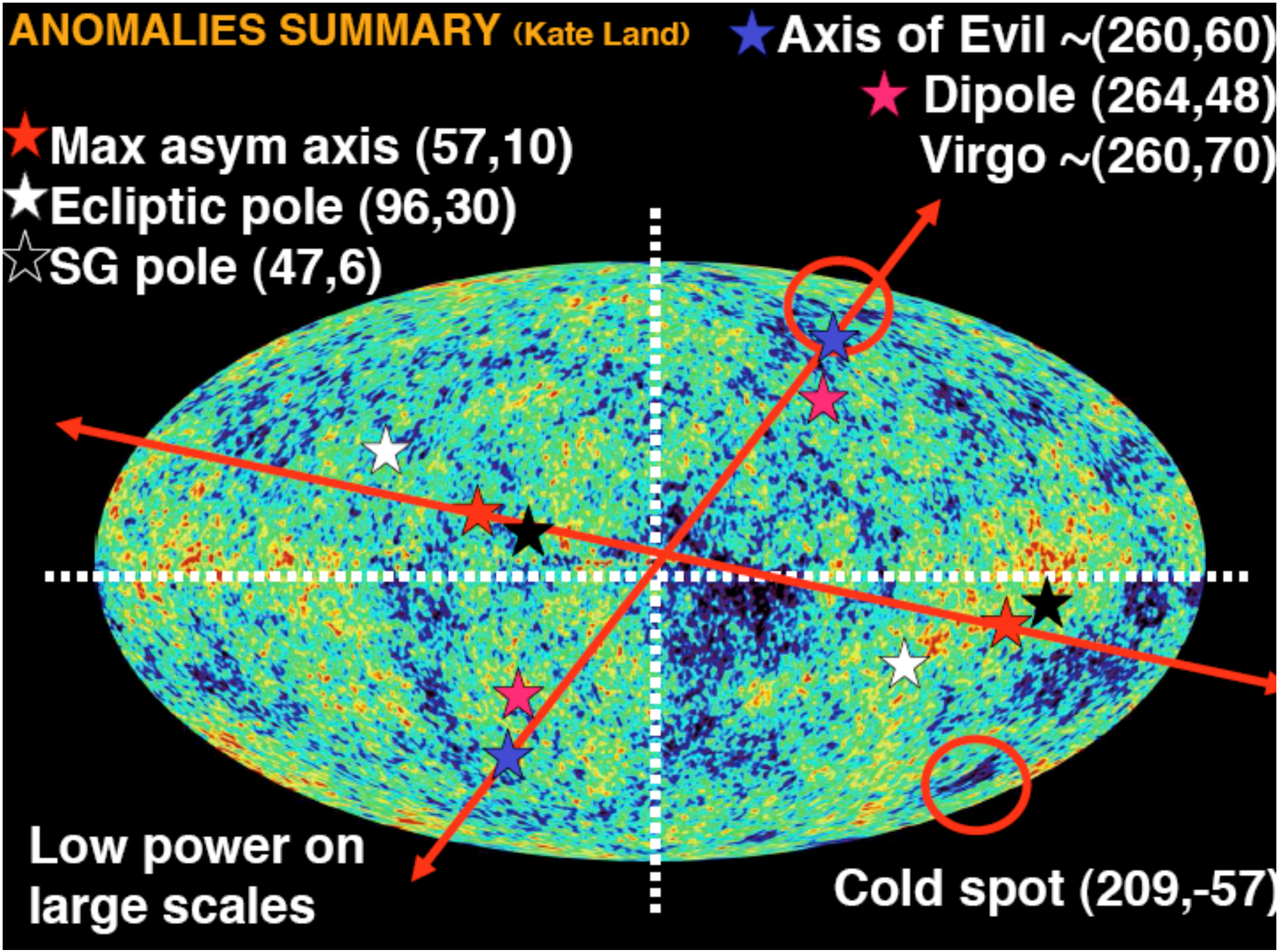
What are the consequences and possible explanations of these correlations? There are several options — they are statistical flukes, they are cosmological in origin, they are due to improper subtraction of known foregrounds, they are due to a previously unexpected foreground, or they are due to WMAP systematics. As remarked above it is difficult for us to accept the occurrence of a 10^{-8} unlikely event as a scientific explanation.

An Interesting Astrophysical account by Vale '05

Let us take the cosmological path

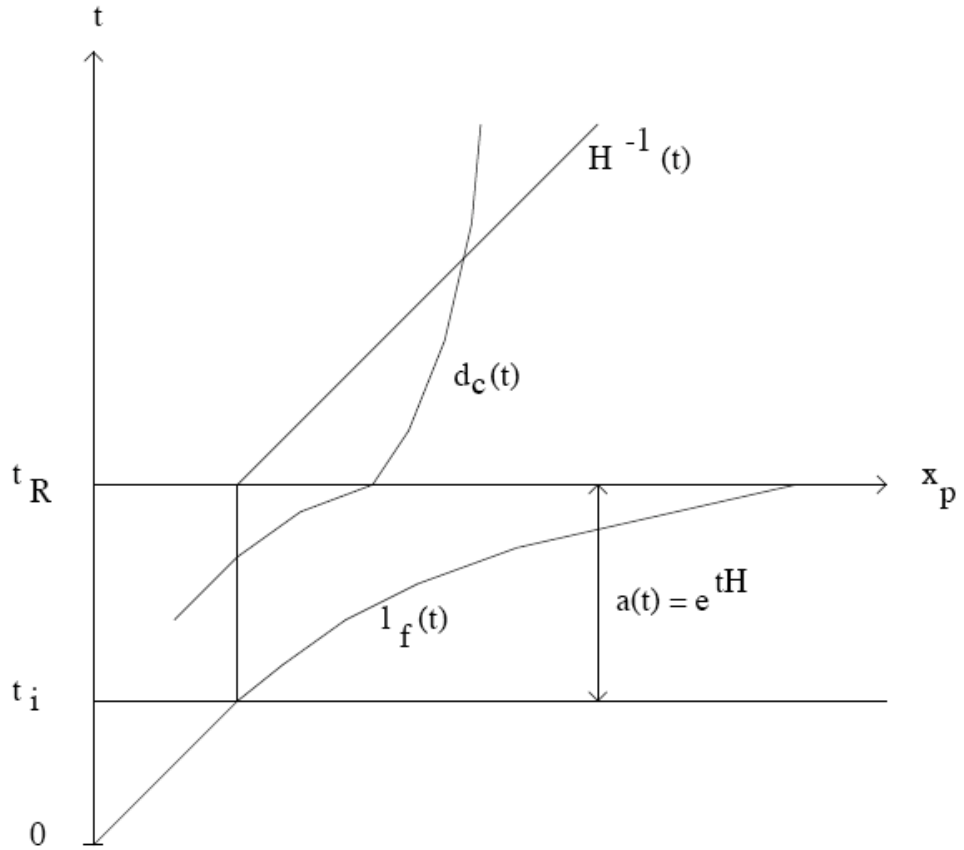
Is inflation in trouble
If this effect is cosmological
In origin, due to the violation of
Statistical isotropy?

No! Non trivial topology can
Break statistical isotropy and still
Be consistent with inflation.


ANOMALIES SUMMARY (Kate Land)
Axis of Evil ~(260,60)
Dipole (264,48)
Virgo ~(260,70)
Max asym axis (57,10)
Ecliptic pole (96,30)
SG pole (47,6)
Low power on large scales
Cold spot (209,-57)

Inflation and Structure Formation

Inflation provides us with a causal and predictive
Mechanism for generating the primordial perturbations
Required for galaxies, clusters and super-clusters (LSS)



Topology and Inflation

- Some have argued that this axis effect is due to topology of our universe
- What sort of topology can account for this observation that is consistent with inflation?
- Can we still have homogeneity and isotropy

With this feature of m-preference?

Yes, we can incorporate the non-trivial topology
By a small change in the Einstein Equation

Chern-Simons term encodes parity violation

This term is very relevant in QCD (neutron electric dipole moment)

What about Gravity?

General Relativity with Parity Violation

$$S = \int d^4x\sqrt{-g}(R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi) + \frac{\phi}{M_{Pl}}\epsilon^{\alpha\beta\gamma\delta}R_{\alpha\beta\rho\sigma}R_{\gamma\delta}{}^{\rho\sigma})$$

Parity Violation

Does Parity violation have observational Consequences?

We will now show that we can get power Suppression of large scale modes of odd parity

This Term is like $E.B\cos\theta$
Electromagnetism

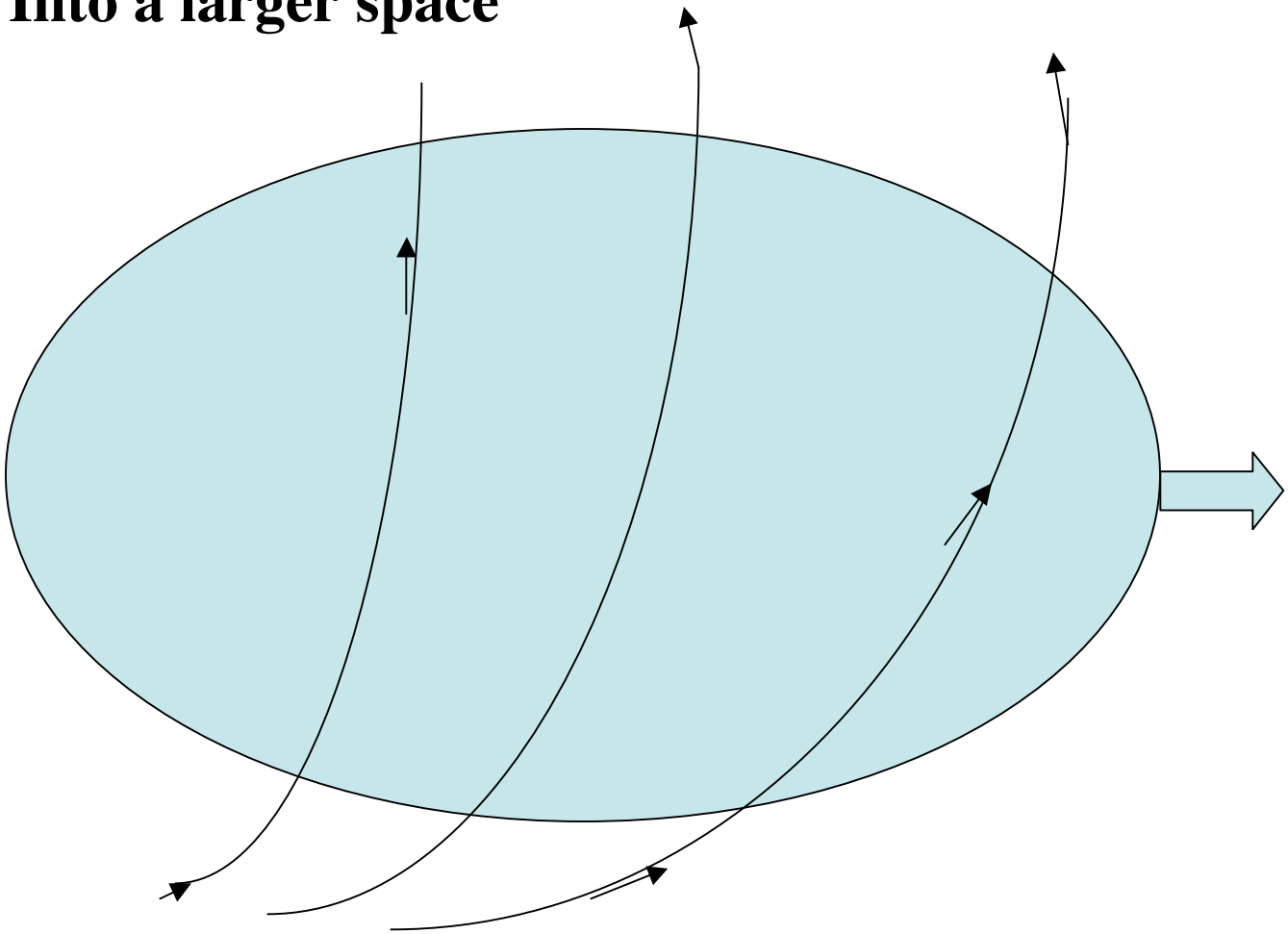
Analogously, space-time violates parity intrinsically

$$\int_{R^4} R\tilde{R}$$

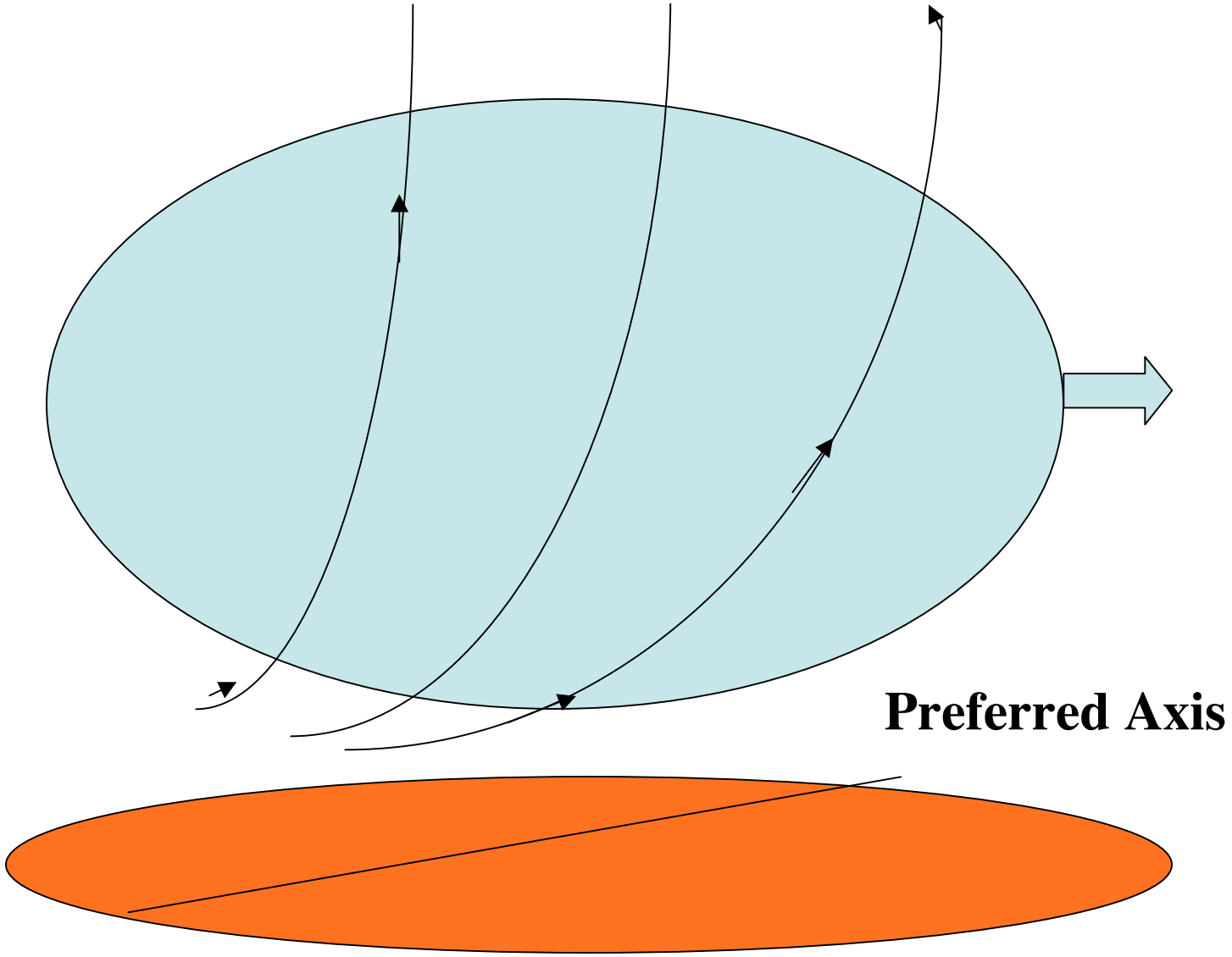
Tells us that space time is parity violating

An easy way to view this topology is:

The same way we can see curvature by embedding Into a larger space



Our Universe Has an Intristic Angular Momentum (Dipole Moment)



The Projection of Universe's spin chooses an Axis

The Choice of Axis is connected
To the parity violation

But can we see this in the power
Spectrum?

First we need to discuss Baryogenesis
And Parity Violation in Gravity

During Inflation we can generate
The baryon asymmetry!

Baryon Number is generated
In the Standard model by
The Parity Violating term in GR

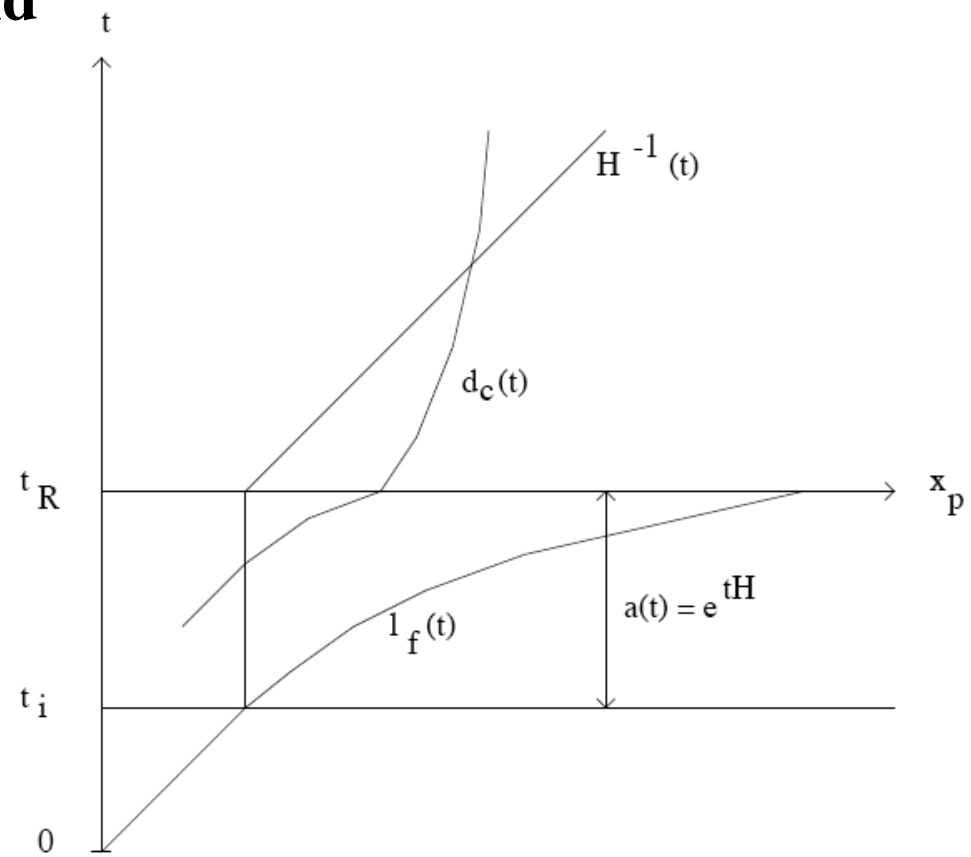
$$\partial_\mu J^\mu_\ell = \frac{3}{16\pi^2} R\tilde{R}$$

S.A, Peskin, Sheikh-Jabbari PRL 06

How?

Cosmic Inflation.

Idea: During inflation gravity waves can generate Lepton number if they are sourced by the phase of the Inflaton field



Some Equations

Perturbed FRW metric:

$$ds^2 = -(1+2\varphi)dt^2 + w_i dt dx^i + a^2(t)\left[\left((1+2\psi)\delta_{ij} + h_{ij}\right)dx^i dx^j\right]$$

$$R\tilde{R} = \frac{4i}{a^3}\left[\left(\partial_z^2 h_R\ \partial_z\partial_t h_L + a^2\partial_t^2 h_R\ \partial_t\partial_z h_L + \frac{1}{2}\partial_t a^2 \partial_t h_R\ \partial_t\partial_z h_L\right) - (L \leftrightarrow R)\right]$$

During inflation the gravity waves obey:

$$\Box h_L = -2i\frac{\Theta}{a}\dot{h}'_L\ , \qquad \Box h_R = +2i\frac{\Theta}{a}\dot{h}'_R\ ,$$

where

$$\Theta = 8(\frac{H}{M_{\rm Pl}})^2\dot{\phi})/HM_{\rm Pl}\ ,$$

MAIN POINT: This General Modification To GR can potentially explain both matter-antimatter Asymmetry and Alignment anomaly

Now back to the evaluation of the Powerspectrum

This term has consequences on angular power spectrum C_l in CMB

The parity violating term modifies Energy momentum Tensor for the inflaton field.

$$\delta I_{CS} = \delta \int d^4x \phi^* RR = \int d^4x \sqrt{-g} C_{\mu\nu} \delta g^{\mu\nu}$$

where ${}^*R_{\mu\nu} = \epsilon_{\alpha\beta\mu\nu} R^{\alpha\beta}$ and

$$C^{\mu\nu} = \frac{1}{-2\sqrt{-g}} [v_\sigma (\epsilon^{\sigma\mu\alpha\beta} D_\alpha R^\nu_\beta + \epsilon^{\sigma\nu\alpha\beta} D_\alpha R^\alpha_\beta) + v_{\sigma\tau} ({}^*R_{\tau\mu\sigma\nu} + {}^* R^{\tau\nu\sigma\mu})]$$

Leading to the modified Einstein Equations:

Inflaton field picks up a velocity dependent potential
Effective action for inflaton:

$$\mathcal{L}_\phi = -\partial_\mu \phi \partial^\mu \phi + \mathrm{V}(\phi) + \frac{1}{\mathrm{HM_{pl}}} \dot{\phi} * \mathrm{RR}$$

Modified Powerspectrum

$$P(k,t_f)_H = \frac{1+\omega(t(k)_f)}{1+\omega(t(k)_i)} P(k,t_i)^0_H$$

Plugging in w in terms of inflaton field

$$\omega(t(k)_i) + 1 = \frac{\dot{\phi}(1+f(t(k)))}{\rho}$$

We finally get the modified powerspectrum:

$$P(k)_H = \frac{P(k)^0}{1+\frac{f(t(k))}{H}}$$

The final result

$$P(k)_H = \frac{P_H^0}{(1 + 10^{-22} \times e^{3N(k)})}.$$

Notice that only the odd parity modes Will be suppressed.

Also, the large l's (high efoldings N(k) will Be suppressed the most.

This reproduces the axis anomaly

What is going on Physically?

During the inflationary epoch space-time parity Violation is reflected in gravity waves.

These gravity waves produce matter asymmetry, Precisely because of parity violation.

As a result most of the power in the odd parity modes Are are depleted so as to produce matter.

This shows up in the WMAP power spectrum.

Therefore it is not anomaly, but in this context, A PREDICTION!

The Future:

We still need to understand the systematics Underlying The axis of evil.

A more robust powerspectrum analysis including The transfer function is necessary.

What does this mean for the contemporary universe?

Can we see Parity Violation via. Weak Lensing?