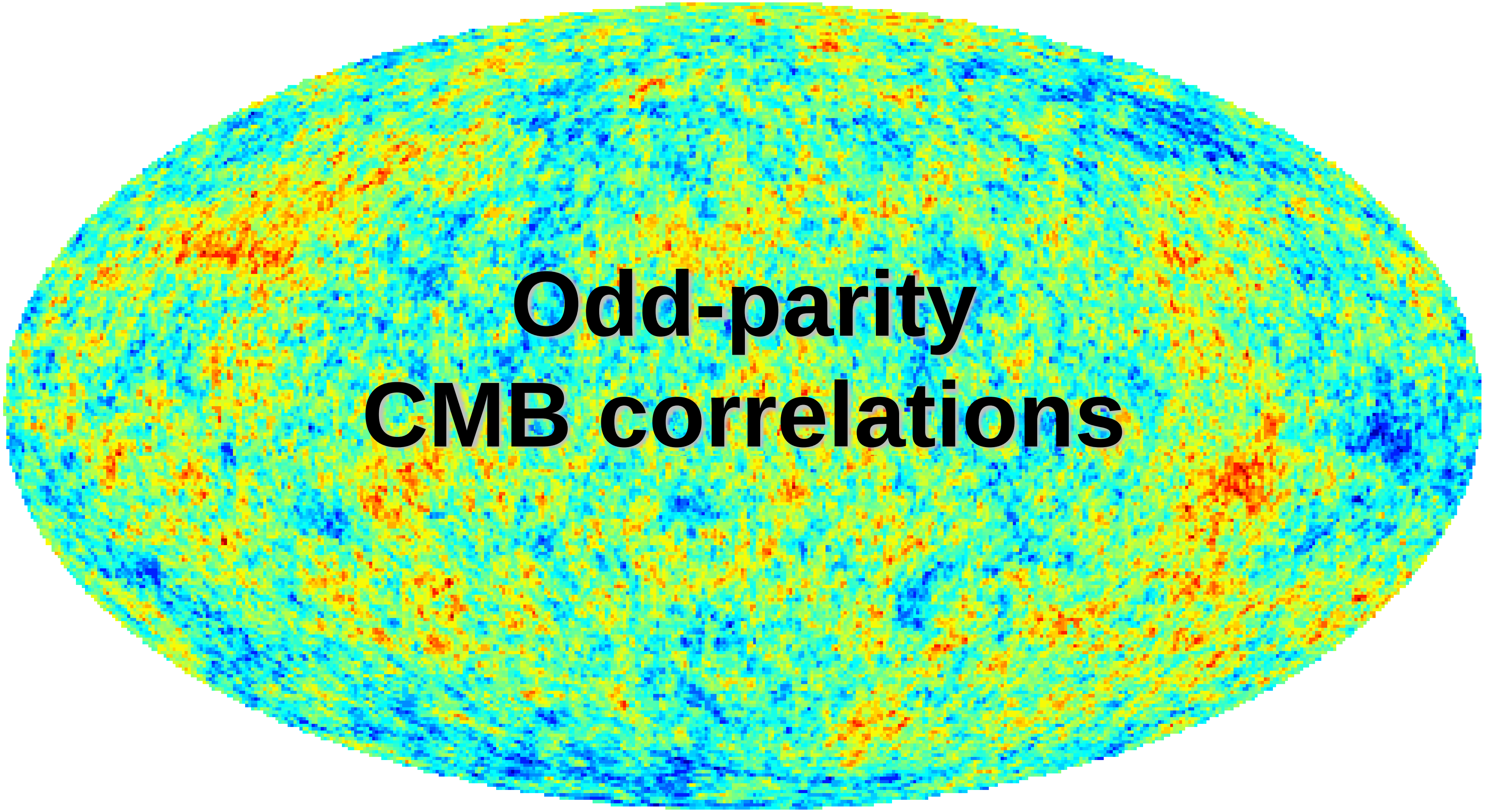


Odd-parity CMB correlations

PFNG-2010

HRI, Allahabad

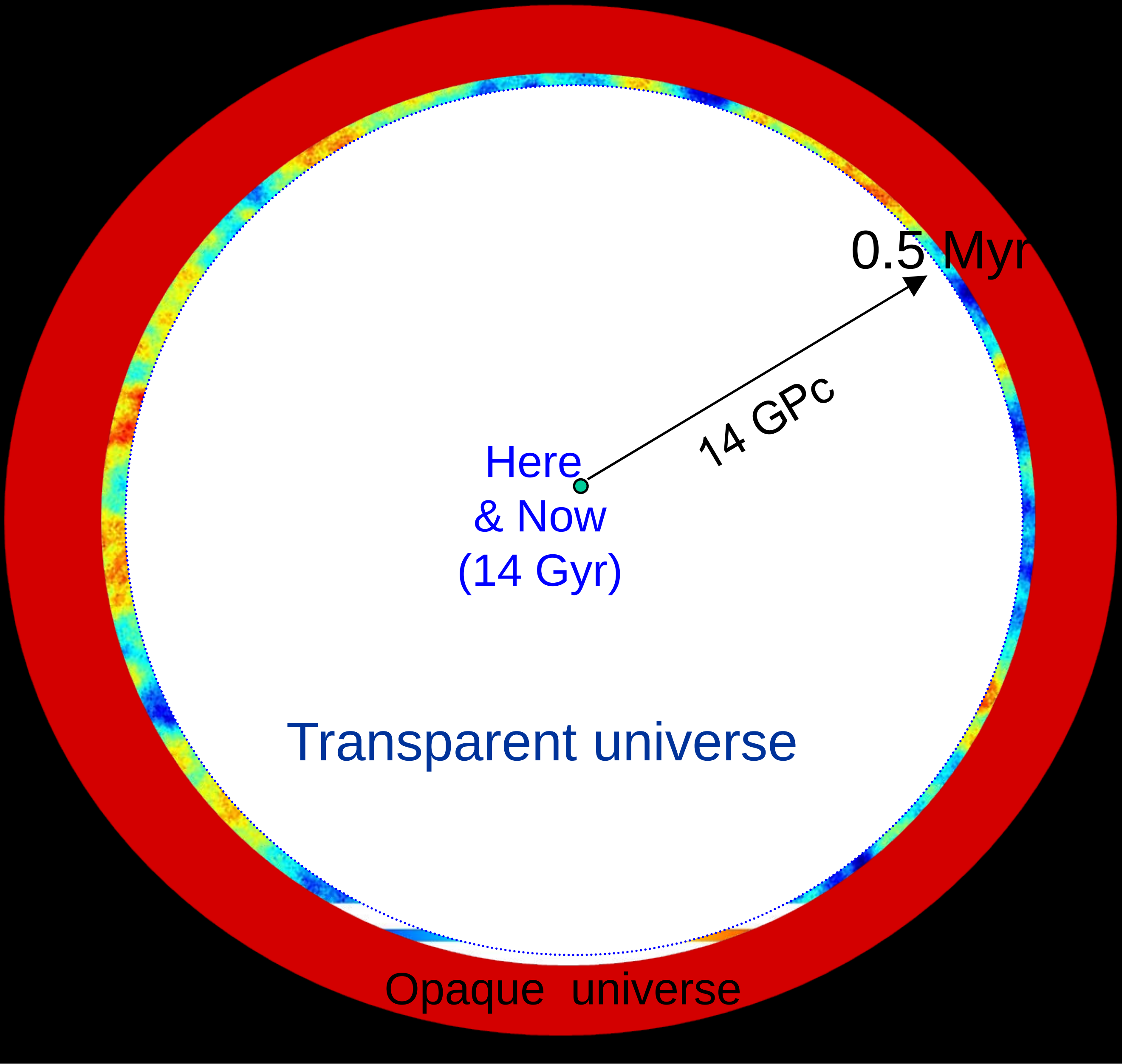
(Dec. 16, 2010)

Tarun Souradeep

I.U.C.A.A, Pune, India

Collab.: Marc Kamionkowski

Cosmic “Super–IMAX” theater



Good old Cosmology, … New trend !

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$

$\Omega_b h^2 = 0.022\ldots^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{\ldots}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}\ \mathrm{cm}^{-3}$

$\ldots 031^{+0.016}_{-0.018}$

$\Delta z_{dec} = 195^{+2}_{-2}$

Total energy density

Dark energy density

Baryonic matter densit…

'Standard' cosmological model:

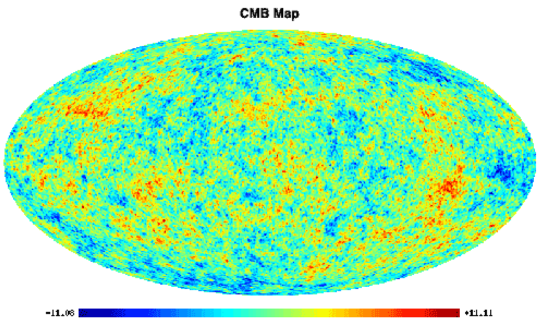
Flat, ΛCDM with nearly

Power Law primordial power spectrum

NASA/WMAP scien…

Statistics of CMB

CMB Anisotropy Sky map => Spherical Harmonic decomposition



$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

Gaussian CMB anisotropy completely specified by the ***angular power spectrum*** IF

Statistical isotropy

$$\langle a_{lm} a^{*}_{l'm'} \rangle = C_l \; \delta_{ll'} \delta_{mm'}$$

=> Correlation function C(n,n') is rotationally invariant

Beyond C_l :

Detecting patterns in CMB

Universe on Ultra-Large scales:

- Global topology
- Global anisotropy/rotation
- Breakdown of global syms, Magnetic field,…

Deflection fields

Observational artifacts:

- Foreground residuals
- Inhomogeneous noise, coverage
- Non-circular beams (eg., Hanson et al. 2010)

Statistics of CMB

$$C(\hat{n}_1, \hat{n}_2) \neq C(\hat{n}_1 \bullet \hat{n}_2)$$

Possibilities:

- Statistically Isotropic, Gaussian models
- Statistically Isotropic, ***non***-Gaussian models
- Statistically ***An***-isotropic, Gaussian models
- Statistically ***An***-isotropic, ***non***-Gaussian models

Ferreira & Magueijo 1997,
Bunn & Scott 2000,
Bond, Pogosyan & TS 1998, 2000

Iso-contours of correlation around a point

$$f(\hat{n}) \equiv C(\hat{n}, \hat{z})$$

Radical breakdown of SI

disjoint iso-contours

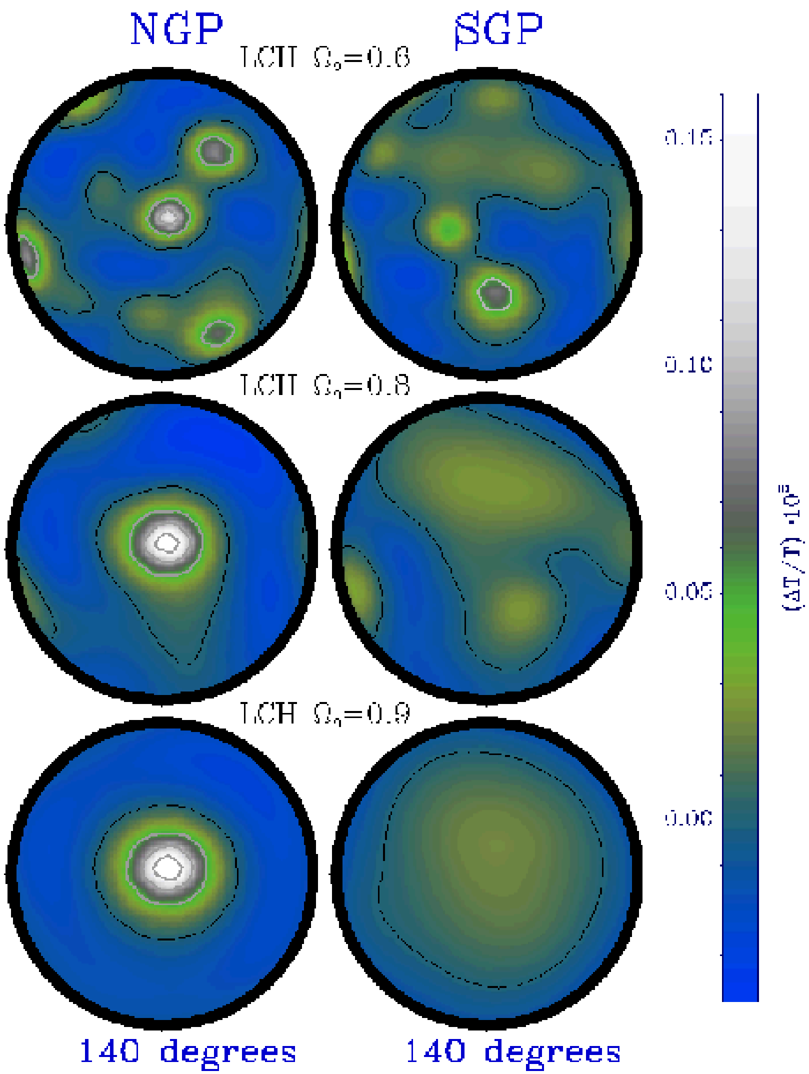
multiple imaging

Mild breakdown of SI

Distorted iso-contours

Statistically isotropic (SI)

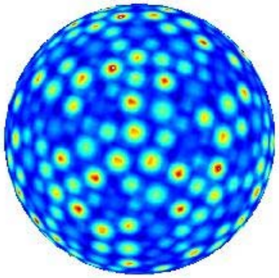
Circular iso-contours



E.g.. Compact hyperbolic Universe .

(Bond, Pogosyan & Souradeep 1998, 2002)

SI violation, or ... Correlation patterns



Beautiful Correlation patterns could underlie the CMB tapestry

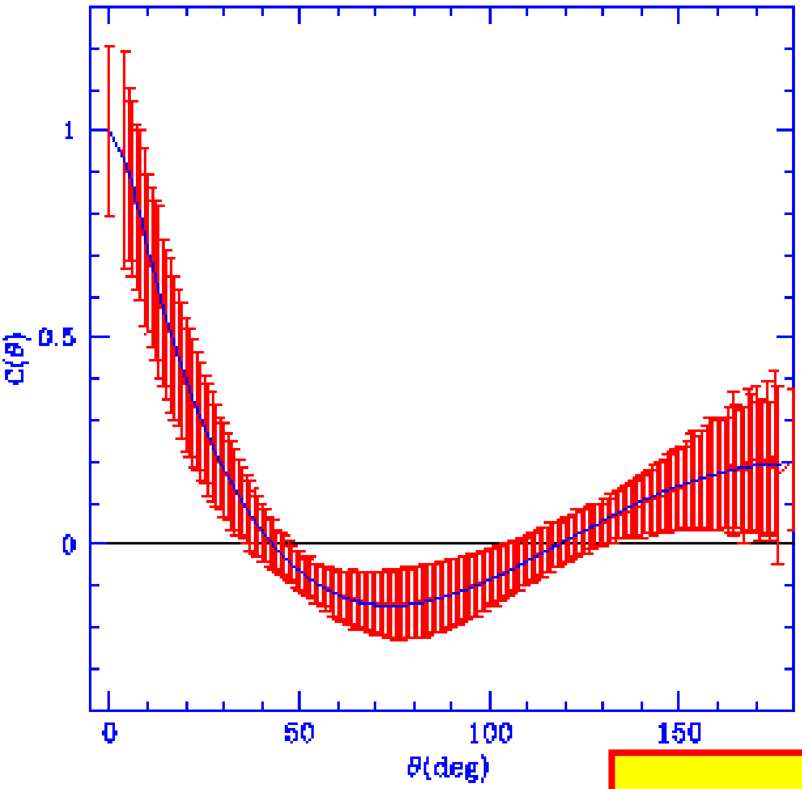
Figs. J. Levin

Can we measure correlation patterns?

the *COSMIC CATCH* is

there is only one CMB sky !

Measuring the SI correlation



Statistical isotropy

$C(\theta)$ can be well estimated by averaging over the temperature product between all pixel pairs separated by an angle θ.

$$\tilde{C}(\theta) = \sum_{\hat{n}_1} \sum_{\hat{n}_2} \Delta T(\hat{n}_1) \Delta T(\hat{n}_2) \delta(\hat{n}_1 \cdot \hat{n}_2 - \cos\theta)$$

$$C(\hat{n}_1 \bullet \hat{n}_2) = \frac{1}{8\pi^2} \int d\Re \;\; C(\Re \hat{n}_1, \Re \hat{n}_2)$$

Measuring the non-SI correlation

In the absence of statistical isotropy

Estimate of the correlation function from a sky map given by a single temperature product $\tilde{C}(\hat{n}_1, \hat{n}_2) = \Delta T(\hat{n}_1)\Delta T(\hat{n}_2)$

is poorly determined!!

(unless it is a KNOWN pattern)

- **Matched circles statistics** **(Cornish, Starkman, Spergel '98)**
- **Anticorrelated ISW circle centers** **(Bond, Pogosyan,TS '98,'02)**
- **Planar reflective symmetries** **(de OliveiraCosta, Smoot Starobinsky '96)**

Bipolar Power spectrum (BiPS) :

A Generic Measure of Statistical Anisotropy

$$\text{Recall}: C(\hat{n}_1 \bullet \hat{n}_2) = \frac{1}{8\pi^2}\int d\Re \; C(\Re\hat{n}_1, \Re\hat{n}_2)$$

Bipolar multipole index

$$\kappa^\ell = \int d\Omega_{n_1} \int d\Omega_{n_2} \left[\frac{1}{8\pi^2}\int d\Re \; \chi^\ell(\Re) \, C(\Re\hat{n}_1, \Re\hat{n}_2) \right]^2$$

A **weighted average** of the correlation function over all rotations

$$\chi^\ell(\Re) = \sum_{m=-\ell}^{\ell} D^\ell_{mm}(\Re)$$

Characteristic function

Wigner rotation matrix

Statistical Isotropy

$$\Rightarrow \kappa^{\ell} = \kappa^{0}\delta_{\ell 0}$$

Correlation is invariant under rotations

$$C(\Re\hat{n}_1, \Re\hat{n}_2) = C(\hat{n}_1, \hat{n}_2)$$

$$\kappa^{\ell} = (2\ell + 1)^2 \int d\Omega_{n_1} \int d\Omega_{n_2} C^2(\hat{n}_1, \hat{n}_2)[\frac{1}{8\pi^2} \int d\Re \chi^{\ell}(\Re)]^2$$

$$\int d\Re \chi^{\ell}(\Re) = \delta_{\ell 0}$$

Bipolar Power spectrum (BiPS) :
A Generic Measure of Statistical Anisotropy

- Correlation is a *two point function* on a sphere

$$C(\hat{n}_1,\hat{n}_2) = \sum_{l_1 l_2 LM} A^{LM}_{l_1 l_2} \{Y_{l_1}(\hat{n}_1)\otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

BiPoSH

Bipolar spherical harmonics.

$$C(n_1 \bullet n_2) = \sum \frac{2l+1}{4\pi} C_l P_l(n_1 \bullet n_2)$$

$$\{Y_{l_1}(\hat{n}_1)\otimes Y_{l_2}(\hat{n}_2)\}_{LM} = \sum_{m_1 m_2} C^{LM}_{l_1 l_2 m_1 m_2} Y_{l_1 m_1}(\hat{n}_1) Y_{l_2 m_2}(\hat{n}_2)$$

Clebsch-Gordan

- Inverse-transform

$$A^{LM}_{l_1 l_2} = \int d\Omega_{n_1} \int d\Omega_{n_2} C(\hat{n}_1,\hat{n}_2)\{Y_{l_1}(\hat{n}_1)\otimes Y_{l_2}(\hat{n}_2)\}^*_{LM}$$

$$= \sum_{m_1 m_2} \langle a_{l_1 m_1} a_{l_2 m_2} \rangle \; C^{LM}_{l_1 m_1 l_2 m_2}$$

Linear combination of off-diagonal elements

Recall: Coupling of angular momentum states

$\langle l_1 m_1 l_2 m_2 | \ell M \rangle \qquad |l_1 - \ell| \le l_2 \le l_1 + \ell, \quad m_1 + m_2 + M = 0$

BiPoSH coefficients :

$$A^{\ell M}_{l_1 l_2} = \sum_{m_1} \left\langle a_{l_1 m_1} a^{*}_{l_2\ M+m_1} \right\rangle \ C^{\ell M}_{l_1 m_1 l_2\ M+m_1}$$

- Complete,Independent linear combinations of off-diagonal correlations.
- Encompasses other specific measures of off-diagonal terms, such as
  - Durrer et al. '98 :
  - Prunet et al. '04 :

$$D_l \equiv \left\langle a_{lm} a_{l+2\ m} \right\rangle = \sum_{\ell M} A^{\ell M}_{ll'} C^{\ell M}_{l+2\ m\ l\ m}$$

$$D^{(i)}_l \equiv \left\langle a_{lm} a_{l+1\ m+i} \right\rangle = \sum_{\ell M} A^{\ell M}_{ll'} C^{\ell M}_{l+1\ m+i\ l\ m}$$

BiPS:

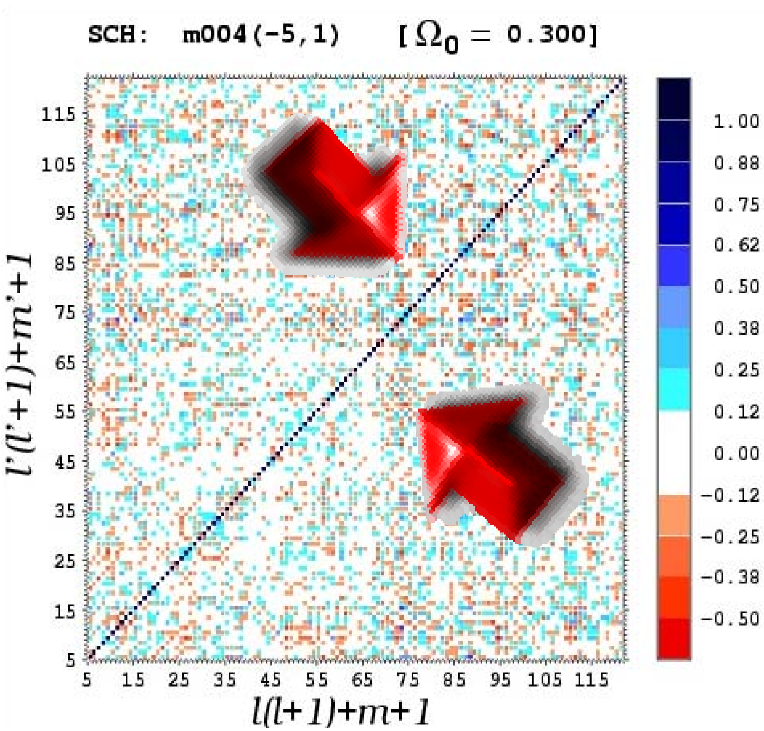
rotationally invariant

$$\kappa^{\ell} \equiv \sum_{M, l_1, l_2} |A^{\ell M}_{l_1 l_2}|^2 \ge 0$$

Understanding BiPoSH coefficients

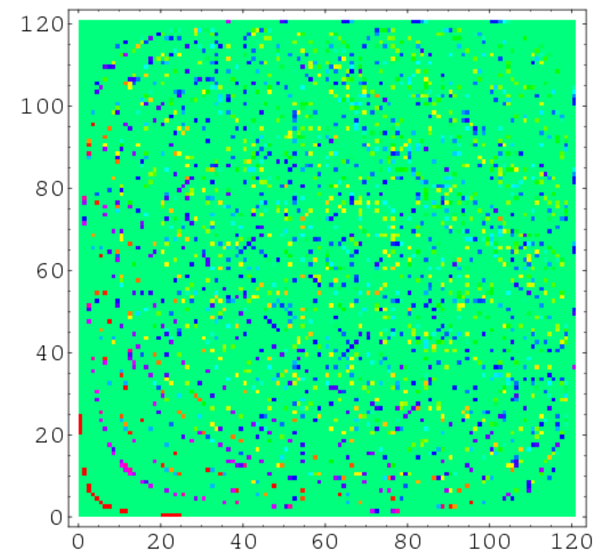
SI violation:

$$\langle a_{lm}\, a^{*}_{l'm'} \rangle \neq C_l\ \delta_{ll'}\delta_{mm'}$$

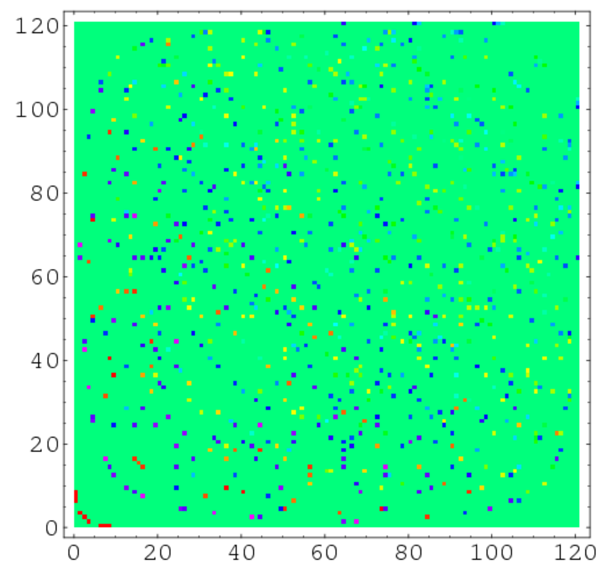


$$A^{LM}_{ll'} = \sum_{mm'} \langle a_{lm} a_{l'm'} \rangle\ C^{LM}_{lml'm'}$$

Measure cross correlation in a_{lm}



$A^{4M}_{ll'}$



$A^{2M}_{ll'}$

Spherical harmonics	Bipolar spherical harmonics
a_{lm}	$A^{\ell M}_{ll'}$
Spherical Harmonic coefficents	BiPoSH coefficents
C_l	κ^{ℓ}
Angular power spectrum	BiPS

Bipolar Power spectrum (BiPS) :

A Generic Measure of Statistical Anisotropy

Spherical harmonics	**Bipolar spherical harmonics**
a_{lm}	$A^{\ell M}_{ll'}$
Spherical Harmonic Transforms	BipoSH Transforms
C_l	κ^{ℓ}
Angular power spectrum	**BiPS**

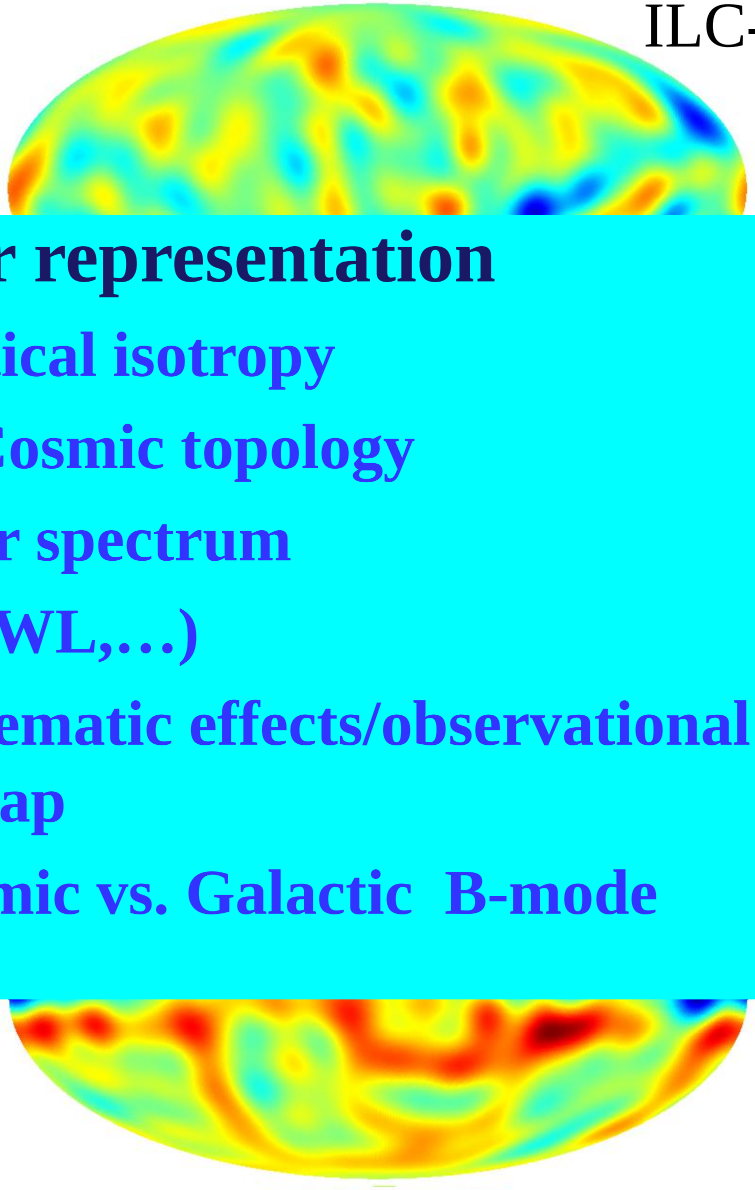
Statistical Isotropy
i.e., NO Patterns

$$\Rightarrow \kappa^{\ell} = \kappa^{0}\delta_{\ell 0}$$

BIPOLAR maps of WMAP

Hajian & Souradeep (PRD 2007)

ILC-3



Reduced BipoSH

$$A_{\ell M} = \sum_{ll'} \ldots$$

Bipolar m…

$$\theta(\hat{n}) = \sum_{\ell M} \ldots$$

Bipolar representation

- **Measure of statistical isotropy**
- **Spectroscopy of Cosmic topology**
- **Anisotropic power spectrum**
- **Deflection fields (WL,…)**
- **Diagnostic of systematic effects/observational artifacts in the map**
- **Differentiate Cosmic vs. Galactic B-mode polarization**

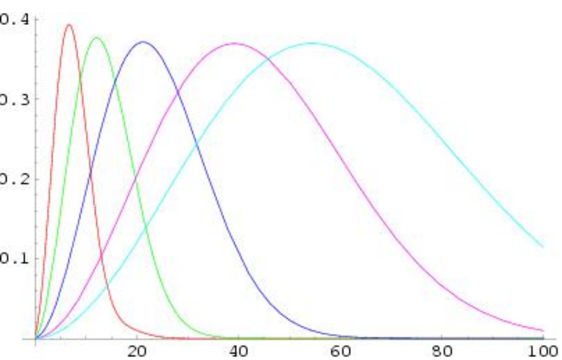
•SI part corresponds to the "monopole" of the map.

Testing Statistical Isotropy of WMAP-3yr

Hajian & Souradeep, (PRD 2007)

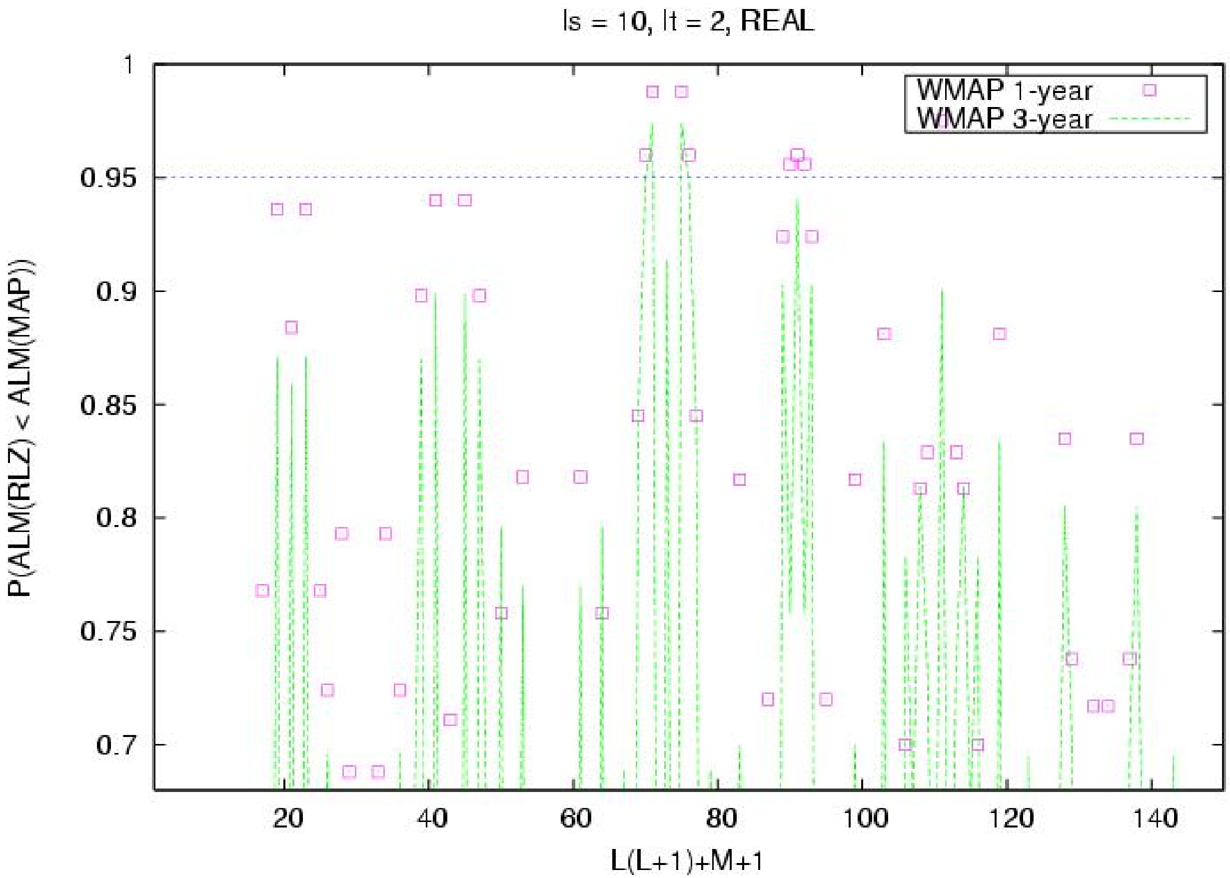
Retain orientation information: Reduced BipoSH

$$A_{\ell M} = \sum_{ll'} A_{ll'}^{\ell M}$$



Filters

Outliers (> 95%)



$$\ell(\ell+1)+M+1$$

Even & odd Bipolar coefficients

$$C(\hat{n}_1,\hat{n}_2) = \sum_{l_1 l_2 LM} A^{LM}_{l_1 l_2} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

$$\Rightarrow C(\hat{n}_1,\hat{n}_2) = \sum_{ll'LM} A^{(+)LM}_{ll'} \frac{[1+(-1)^{L+l+l'}]}{2} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

$$+ \sum_{ll'LM} A^{(-)LM}_{ll'} \frac{[1-(-1)^{L+l+l'+1}]}{2} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

If only even $L+l'+l$ contribute, it is becoming popular to use

$$A^{(+)LM}_{l_1 l_2} \rightarrow \frac{A^{(+)LM}_{l_1 l_2}}{C^{L0}_{l0l'0}} \sqrt{\frac{2L+1}{(2l_1+1)(2l_2+1)}}$$

- Anisotropic P(k)
- Linear order templates

BIPOLAR measurements by WMAP-7 team

(Bennet et al. 2010)

$$\frac{A^{(+)LM}_{l_1 l_2}}{C^{L0}_{l0l'0}}$$

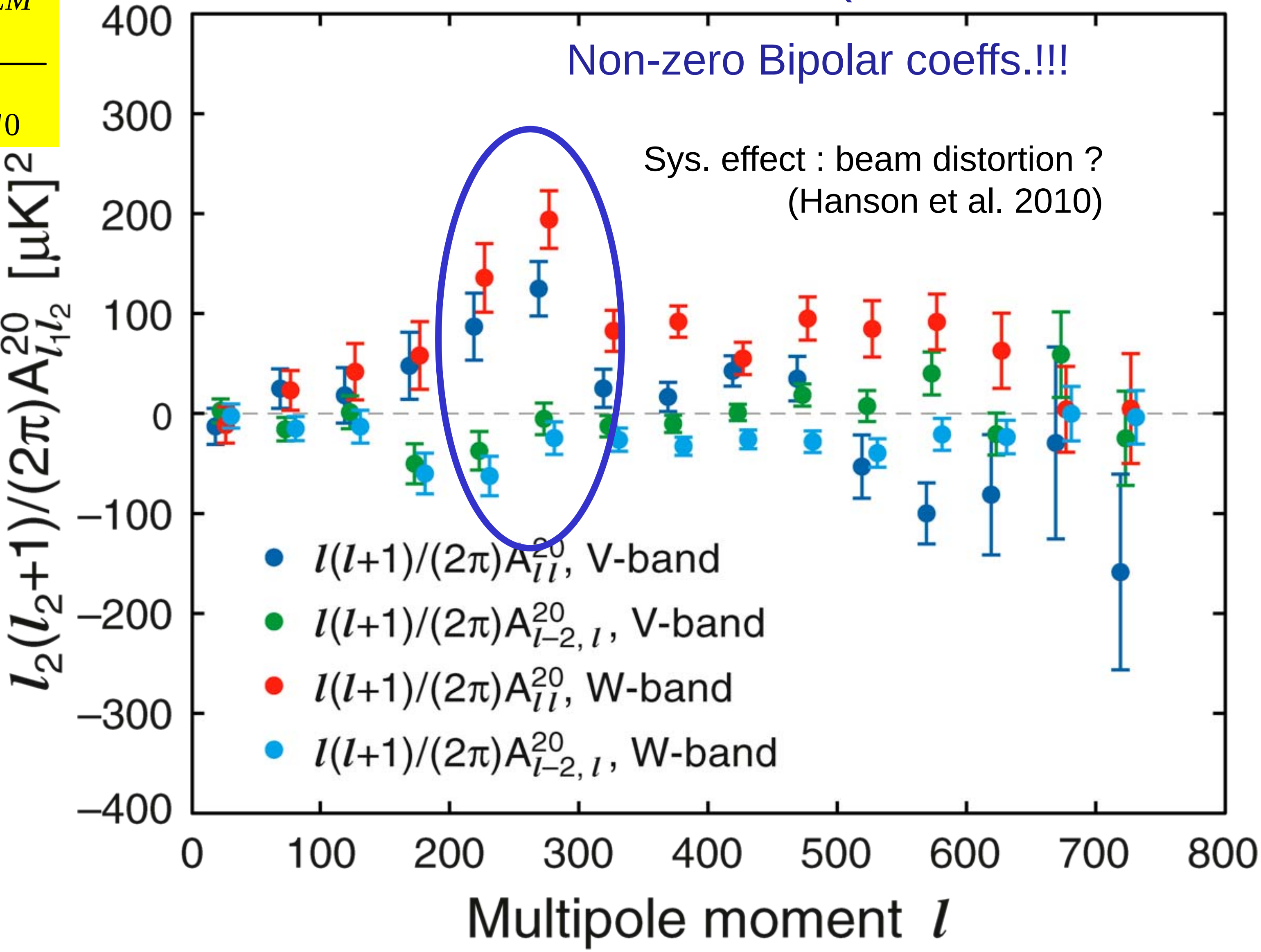


Image Credit: NASA / WMAP Science Team

Even & odd parity BipoSH

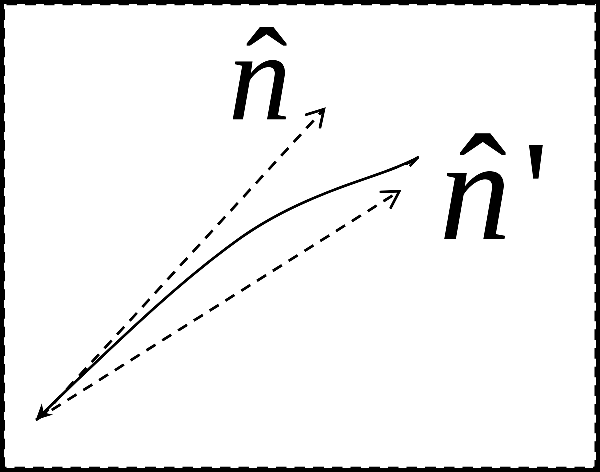
$$A^{(+)LM}_{l_2 l_1} = A^{(+)LM}_{l_1 l_2}$$ symmetric

$$A^{(-)LM}_{l_2 l_1} = -A^{(-)LM}_{l_1 l_2}$$ antisymm.

$$[A^{(+)LM}_{l_1 l_2}]^* = (-1)^M A^{(+)L,-M}_{l_1 l_2}$$ Even parity

$$[A^{(-)LM}_{l_1 l_2}]^* = (-1)^{M+1} A^{(-)L,-M}_{l_1 l_2}$$ Odd parity

SI violation : Deflection field



$$T(\hat{n}') = T(\hat{n} + \vec{\Theta}) = T(\hat{n}) + \vec{\Theta} \bullet \vec{\nabla} T(\hat{n})$$

$$\vec{\Theta} = \vec{\nabla}\phi(\hat{n}) + \vec{\nabla} \times \Omega(\hat{n})$$
$$= \nabla_i \phi(\hat{n}) + \varepsilon_{ij} \nabla_j \Omega(\hat{n})$$

Gradient Curl

WL:scalar WL: tensor/GW

SI violation : Deflection field

Kamionkowski & Souradeep

$$T(\hat{n}) \rightarrow a_{lm} = a^S_{lm} + \delta a_{lm}, \quad \phi(\hat{n}), \Omega(\hat{n}) \rightarrow \phi_{LM}, \Omega_{LM}$$

$$\delta a_{lm} = \frac{1}{2} \sum_{LM} \sum_{l'm'} a^S_{l'm'} \left[\phi_{LM} E^L_{ll'} - i\Omega_{LM} O^L_{ll'} \right] G^L_{ll'} C^{LM}_{lml'm'}$$

$$G^L_{ll'} = [\ldots]\, C^{L1}_{l0l'-1} \qquad (= [\ldots.] C^{L0}_{l0l'0} \text{ for } l + l' + L : even)$$

even: $E^L_{ll'} = \frac{1}{2}\left[1 + (-1)^{l+l'+L}\right]$ & odd: $O^L_{ll'} = \frac{1}{2}\left[1 - (-1)^{l+l'+L}\right]$

SI violation: $\langle a_{lm} a_{l'm'} \rangle \neq C_l \delta_{ll'} \delta_{mm'}$

Deflection field: Even & Odd parity BipoSH

Kamionkowski & Souradeep

$$A_{ll'}^{(+)LM} = \phi_{LM}\left[\frac{C_l G_{l'l}^{L}}{\sqrt{l'(l'+1)}} + \frac{C_{l'} G_{ll'}^{L}}{\sqrt{l(l+1)}}\right]$$

WL: scalar

$$A_{l_2 l_1}^{(-)LM} = i\Omega_{LM}\left[\frac{C_l G_{l'l}^{L}}{\sqrt{l'(l'+1)}} - \frac{C_{l'} G_{ll'}^{L}}{\sqrt{l(l+1)}}\right]$$

WL: tensor

BipoSH Measures of deflection field

Estimators

$$\tilde{\phi}_{LM} = \frac{\sum_{ll'} Q^{+}_{ll'} A^{(+)LM}_{ll'} / \sigma^{2\ LM}_{ll'}}{\sum_{ll'} (Q^{+}_{ll'})^2 / \sigma^{2\ LM}_{ll'}}$$

$$\tilde{\Omega}_{LM} = \frac{\sum_{ll'} Q^{-}_{ll'} A^{(-)LM}_{ll'} / \sigma^{2\ LM}_{ll'}}{\sum_{ll'} (Q^{-}_{ll'})^2 / \sigma^{2\ LM}_{ll'}}$$

Variance

$$\mathrm{var}\left(\tilde{\phi}_{LM}\right) = \left[\sum_{ll'} (Q^{+}_{ll'})^2 / \sigma^{2\ LM}_{ll'}\right]^{-1}$$

$$\mathrm{var}\left(\tilde{\Omega}_{LM}\right) = \left[\sum_{ll'} (Q^{-}_{ll'})^2 / \sigma^{2\ LM}_{ll'}\right]^{-1}$$

$$A^{(\pm)LM}_{l_1 l_2} \rightarrow \frac{A^{(\pm)LM}_{l_1 l_2}}{C^{L1}_{l0l'1}} [\cdots] = \frac{A^{(\pm)LM}_{l_1 l_2}}{G^{L}_{ll'}}$$

CMB BipoSHs & Bispectra

Kamionkowski & Souradeep, (arXiv:1010.4504)

For deflection field $$a_{lm} = a^{S}_{lm} + \delta a_{lm}$$

$$A^{LM}_{ll'} \sim \phi_{LM} \sum_{mm'} \left\langle a^{s}_{lm} a^{s}_{l'm'} \right\rangle C^{LM}_{lml'm'}$$

$$\phi_{LM} \rightarrow a_{LM} \qquad \Rightarrow A^{LM}_{ll'} \sim \sum_{mm'} \left\langle a_{LM} a_{lm} a_{l'm'} \right\rangle C^{LM}_{lmlm'}$$

BipoSH related to Bispectrum

$$B_{Lll'} \sim \sum_{Mmm'} \left\langle a_{LM} a_{lm} a_{l'm'} \right\rangle C^{LM}_{lml'm'} \quad (\ldots)$$

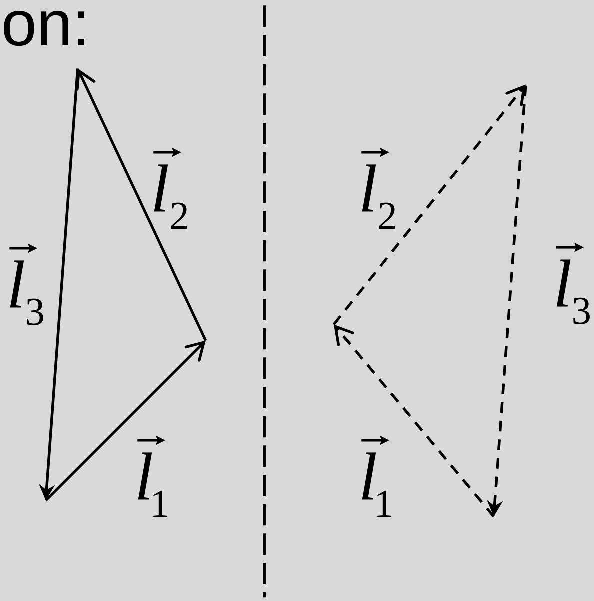
$$\sim \sum_{M} A^{(+)LM}_{ll'}$$

Consider only: $l + l' + L =$ even

Odd parity Bispectra ?

$$B^{(-)}_{Ll l'} \sim \sum_M A^{(-)LM}_{l l'}$$

Flat sky intuition:



$$l_1 < l_2 < l_3$$

$$B^{(-)} \sim \frac{\vec{l}_1 \times \vec{l}_2}{l_1 l_2}$$

has opposite sign in the two mirror configurations.

Odd parity Bispectra

For local NG model

Flat sky approx

$$B(\vec{l}_1,\vec{l}_2) = 2\left[f_{\rm nl} + f_{\rm nl}^{\rm odd}\frac{\vec{l}_1\times\vec{l}_2}{l_1 l_2}\right](C_{l_1}C_{l_2} + \text{perms.})$$

In general

$$\tilde{f}_{\rm nl} = \sigma_{f_{\rm nl}}^2 \sum_{l_1<l_2<l_3} 6\, G_{l_1 l_2}^{l_3}\frac{(C_{l_1}C_{l_2} + \text{perms.})}{C_{l_1}C_{l_2}+C_{l_3}C_{l_2}+C_{l_1}C_{l_3}} E_{l_1 l_2}^{l_3}$$

$$\tilde{f}_{\rm nl}^{\rm odd} = \sigma_{f_{\rm nl}}^2 \sum_{l_1<l_2<l_3} 6\, G_{l_1 l_2}^{l_3}\frac{(C_{l_1}C_{l_2} + \text{perms.})}{C_{l_1}C_{l_2}+C_{l_3}C_{l_2}+C_{l_1}C_{l_3}} O_{l_1 l_2}^{l_3}$$

$$\sigma_{f_{\rm nl}}^{-2} = \sum_{l_1<l_2<l_3}\frac{\left[6\, G_{l_1 l_2}^{l_3}(C_{l_1}C_{l_2} + \text{perms.})\right]^2}{C_{l_1}C_{l_2}+C_{l_3}C_{l_2}+C_{l_1}C_{l_3}}$$

Summary

Thank you !!! &

Thanks a lot, Sriram

- Current observations now allow a meaningful search for deviations from the `standard' flat, ΛCDM cosmology.
- Anomalies in WMAP suggest possible breakdown of statistical isotr

- **Bipolar harmonics provide a mathematically complete, well de representation of SI violation.**
  - Possible to include SI violation in CMB arising **both** from ***direction dependent Primordial Power Spectrum*** , as well as, ***SI violation in the CMB photon distribution function.***
  - ***BipoSH*** provide a well structured representation of the systematic breakdown of rotational symmetry [Talk by Nidhi Joshi on Friday].
  - Bipolar observables have been measured in the WMAP data.

- **BipoSH coefficients can be separated into even and odd parity parts.**
  - For a general deflection field, gradient & curl parts are represented by even & odd parity BipoSH, respectively. Eg., Weak lensing by scalar & tensor (or 2nd order scalar) perturbations.
  - Estimators for grad/curl deflections field harmonics in terms of even/odd BipoSH
- **BipoSH** for correlated deflection field relate to **Bispectra**
  - ***Pointed to, hitherto unexplored, odd-parity bispectrum***.
  - Minor modification to existing estimation methods for even-parity bispectra
  - Odd parity bispectrum may arise in exotic parity violations, but, also an interesting null test for usual bispectrum analysis.