Large-scale anomalies in WMAP data

Deviations from isotropy

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Outline

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1. Multipole alignments
   - Techniques
   - Results
2. Steerable wavelet anisotropy test
   - Method
   - Results
3. North-south power asymmetry
4. Cold spot
5. New physics?
   - Models
   - Corrections
   - Problems

Multipole alignments

- Decompose CMB into spherical harmonics

$$f(\omega) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\omega) = \sum_{\ell=0}^{\infty} f_\ell(\omega)$$

- Associate preferred directions with each multipole representation $f_\ell(\omega)$:
  - Maximum angular momentum dispersion (de Oliveira-Costa et al. 2003)
  - Multipole vectors (Copi et al. 2004)
  - Multipole invariants and frames (Land & Magueijo 2005)

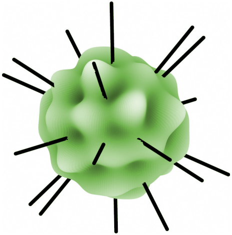
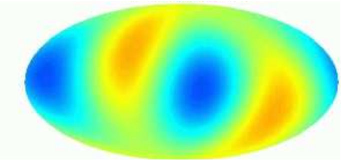


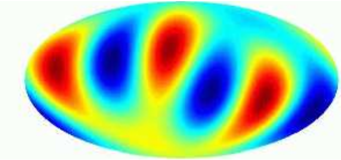
Figure: Illustration of random spherical function and corresponding multipole directions (Dennis 2005)

Multipole alignments

- Peculiar planarity and alignment of quadrapole and octopole (de Oliveira-Costa et al. 2003; Copi et al. 2004; etc.) (and also between some other low ℓ's)



(a) Quadrapole ($\ell = 2$)



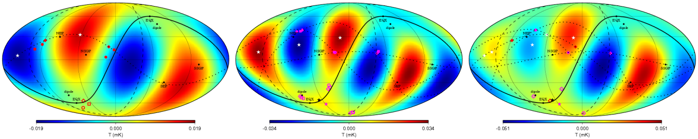
(b) Octopole ($\ell = 3$)

Figure: $f_\ell(\omega)$ multipole maps

- Some works claim that planar shape is not statistically significant (e.g. Slosar & Seljak 2005; Land & Magueijo 2005) but consensus is that alignment is peculiar (using range of tests)
- Infamously dubbed the Axis of Evil (AoE)

Multipole alignments

- Various works claim close alignment with ecliptic and/or dipole (e.g. Copi et al. 2006)



(a) Quadrapole (b) Octopole (c) Quadrapole + Octopole

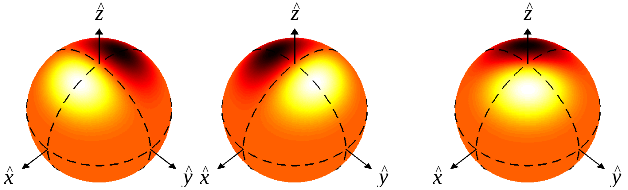
Figure: Quadrapole and octopole alignments with ecliptic and dipole

Outline

Steerable wavelets on the sphere

- Steerable wavelets may be expressed as a linear combination of a finite number of basis wavelets

$$[\mathcal{R}_{(\alpha=0,\beta=0,\gamma)}\Psi](\omega) = \sum_{m=1}^{M} k_m(\gamma)\, \Psi_m(\omega)$$



(a) Basis wavelets (b) Interpolated wavelet

Figure: First derivative of Gaussian on the sphere (Wiaux et al. 2005a)

- Thus wavelet coefficients for any orientation may be derived from coefficients computed for a small number of basis orientations

Steerable wavelet anisotropy test: Method

- Test methodology (Wiaux et al. 2005b, Vielva et al. 2006)
  - Use steerable wavelets to pick out preferred orientation
  - Increment votes for all points on great circle
  - Construct map giving probability a given pixel is *seen* by local CMB features

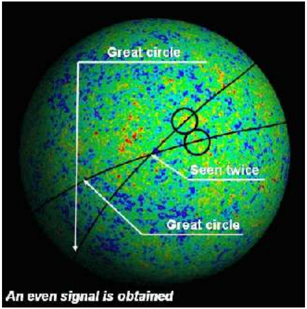
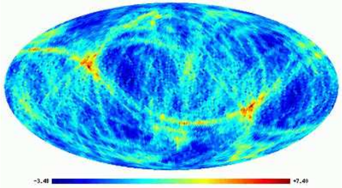


Figure: Illustration of steerable wavelet anisotropy test

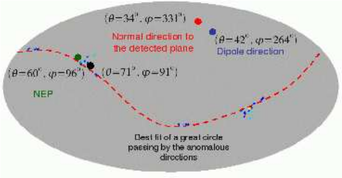
- Analysis run on WMAP data using second derivative of Gaussian

Steerable wavelets anisotropy test: Results

- Anisotropy map shows deviations from anisotropy relative to Monte Carlo simulations
- Pick out great circle, with pole very close to dipole



(a) Wavelet anisotropy map



(b) Anomalous directions

Figure: Steerable wavelet anisotropy results

Outline

North-south power asymmetry

- ML estimate of local angular power spectrum on small patches (Eriksen et al. 2004)
- Amplitude of disks in the northern Galactic hemisphere generally lower than in simulated maps; amplitude of disks in the southern Galactic hemisphere generally higher than in simulated maps

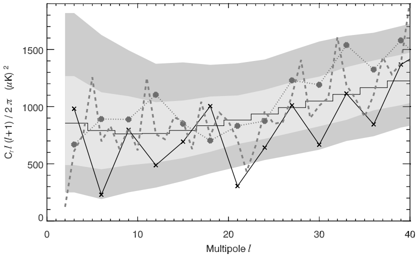


Figure: Power spectrum comparison

North-south power asymmetry

- Colour of disks indicates power ratio relative to overall power
- Axis of maximum asymmetry found to be close to ecliptic

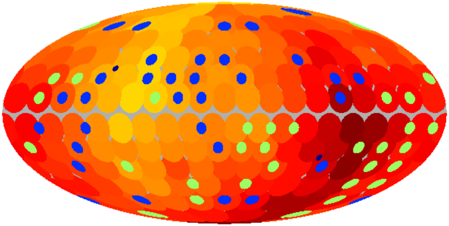


Figure: Local power spectrum analysis

Outline

Cold spot

- Deviations from Gaussianity detected in kurtosis of spherical Mexican hat wavelet (SMHW) (Vielva et al. 2004)

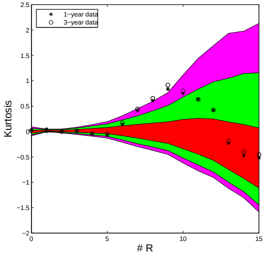
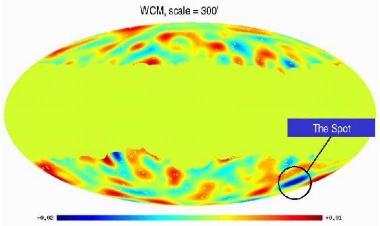


Figure: SMHW kurtosis

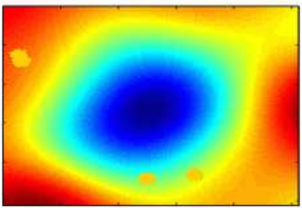
- Large non-Gaussian cold spot detected
- Various test statistics indicate extremely large and cold spot unlikely at >99% level (Cruz et al. 2004, 2006a, 2006b)

Cold spot

- Morphology – approximately circular
- Excluding the spot the data are consistent with Gaussianity (using the SMHW kurtosis test)
- Not systematics, not foregrounds
- Origin?
  - Topological defect (texture)
  - Rees-Sciama effect
  - Others?



(a) SMHW coefficients



(b) $22^\circ \times 22^\circ$ patch

Figure: Cold spot

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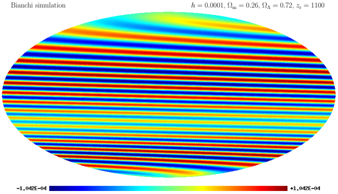
New physics?

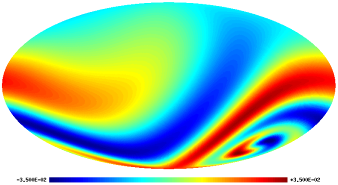
- Non-trivial topologies (de Oliveira-Costa et al. 2003; Cresswell et al. 2005)
- Spontaneous isotropy breaking (Gordon et al. 2005)
- Relic anisotropy due to initial conditions (Gümrükcüglu et al. 2006)
- Bianchi models exhibiting universal shear and rotation (Barrow et al. 1985)
- Other exotic models?

Bianchi models

- Relaxing assumption of isotropy about each point in universe yields more complicated solutions to Einstein's field equations
- A universal shear and rotation induce characteristic signature in the CMB
- CMB temperature fluctuations derived by Barrow et al. (1985), albeit in the absence of dark energy since it was not considered plausible at the time
- Interest in Bianchi models rekindled recently (will motivate soon)
- Recently, CMB temperature fluctuations derived when incorporating dark energy independently by Jaffe et al. (2006) and Lasenby (to appear)
- Statistically significant template detected in WMAP data (Jaffe et al. 2005)



(a) Varying Bianchi h parameter



(b) Best fit template

Bianchi corrections to WMAP

- Use best-fit Bianchi template to 'correct' the WMAP data

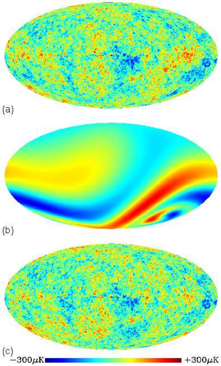


Figure: Bianchi correction (Jaffe et al. 2005)

- Remarkably, many of the anomalies discussed previously disappear after the WMAP data is corrected by the best-fit Bianchi component (Jaffe et al. 2005):

Bianchi corrections to WMAP

- Multipole alignments disappear or are significantly mitigated

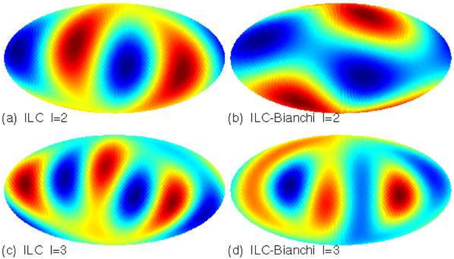


Figure: Quadrapole and octopole

Bianchi corrections to WMAP

- Significance of any power asymmetry drops from 99.3% to 86.4%

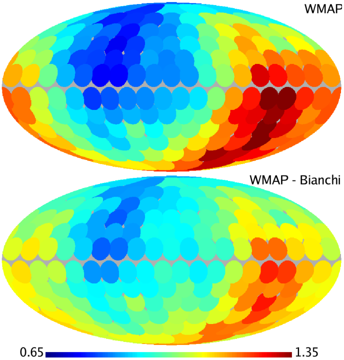


Figure: Power asymmetry

Bianchi corrections to WMAP

- SMHW kurtosis is essentially compatible with Gaussianity

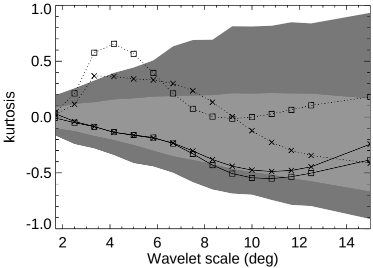


Figure: SMHW kurtosis

Bianchi corrections to WMAP

- Bianchi template is inconsistent with concordance cosmology
- Bianchi degeneracy tested using MCMC sampling (Bridges et al. 2006)
- Bianchi parameters detached from cosmological ones
- No longer physically motivated
- For more see Michael Bridges' talk at the Cavendish, Tue 17th Oct

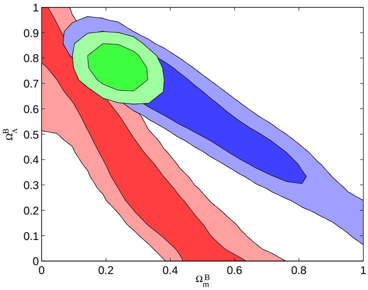


Figure: Bianchi template degeneracy (Bridges et al. 2006)

Summary

- Cosmological principle of fundamental importance
- Many anomalies reported in WMAP data violating this principle
- A number of attempts have been made to explain these anomalies (e.g. by foregrounds, systematics, exotic models) but no satisfactory solution is evident
- Motivation to pursue more exotic models that may be able to describe the observed anomalies