The Last Word on Large Scale CMB Anomalies

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NBIA–APCTP Workshop
August, 2014

The Niels Bohr International Academy

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Outline

- Introduction: Large scales – potential and problems
- Review of some large scale CMB anomalies:
  - The "Axis of Evil"
  - Low power on large scales
  - Lack of large-angular correlations
  - Hemispherical power asymmetry
  - Point parity
  - Mirror parity [ABD & Kovetz, 2014, arXiv:1403.2104]
- The Integrated Sachs–Wolfe Effect
  - Estimation
  - New insight on large scale anomalies?
- Future prospects

The Standard Model

Assumption:

$$\boxed{\text{On large enough scales the universe is homogeneous and isotropic}}$$

- Quantum fluctuations of the inflaton field seed Gaussian fluctuations in the metric perturbation field $\mathbf{\Phi}$

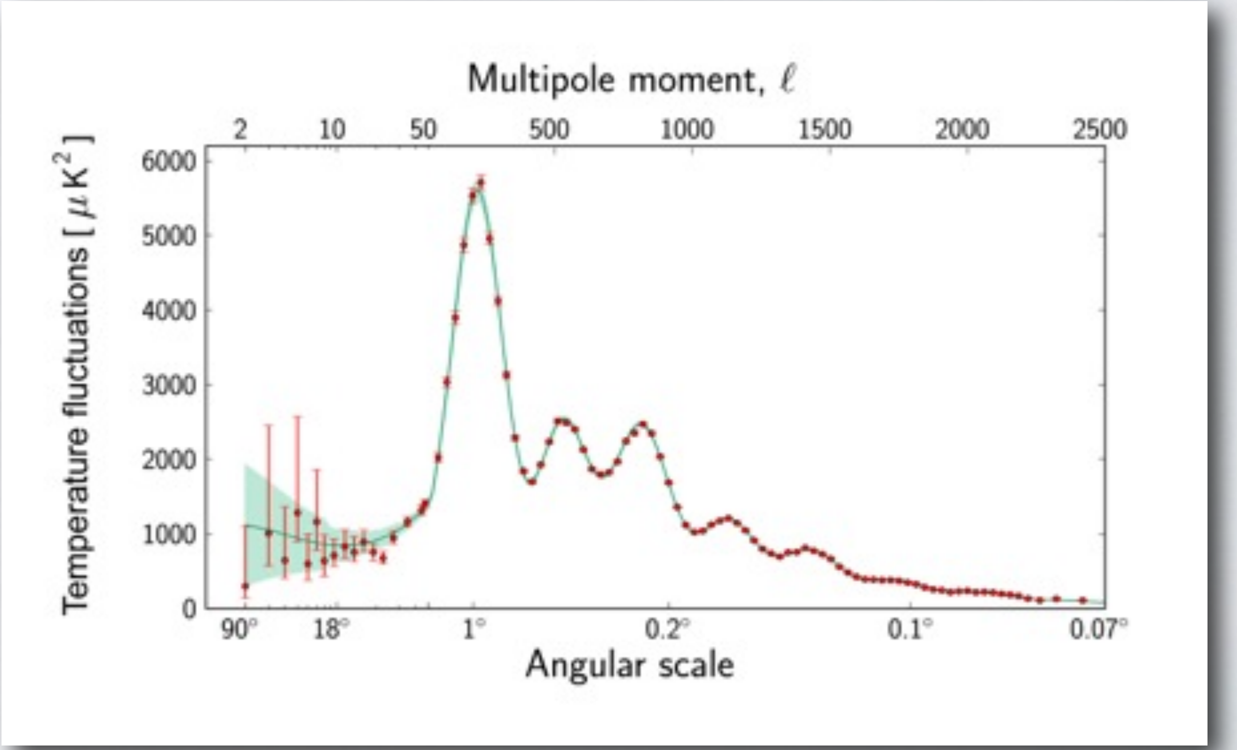
$$\langle \Phi_{\mathbf{k}} \rangle = 0 \qquad\qquad \langle \Phi_{\mathbf{k}} \Phi^*_{\mathbf{k}'} \rangle = (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}') P_\Phi(k)$$

- Projected onto the sphere, we get the CMB temperature anisotropy

$$T(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

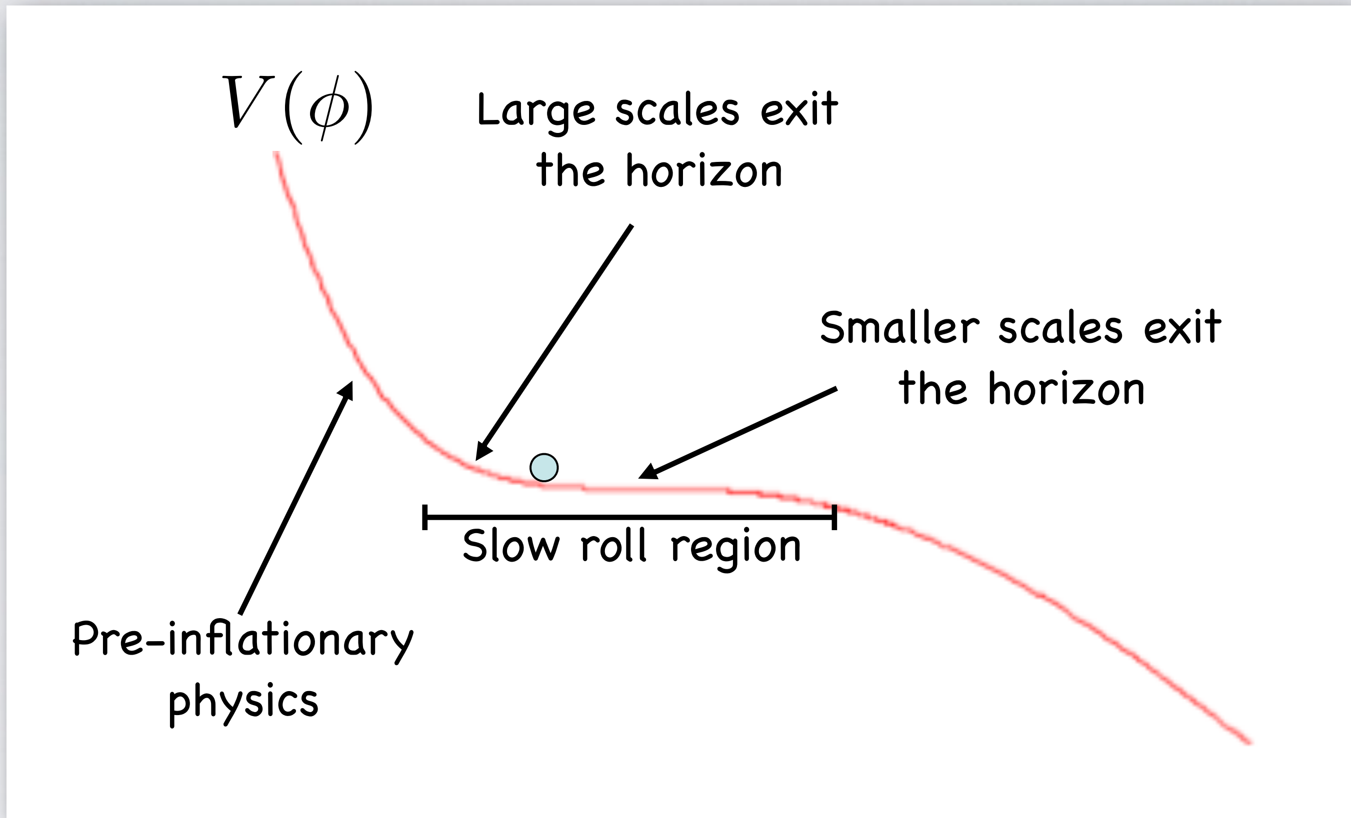
- The coefficients are uncorrelated Gaussian random variables

$$\langle a_{\ell m} \rangle = 0 \qquad \langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$$



[Planck Collaboration XV, 2013, arXiv:1303.5075]

Why are Large Scales Interesting?



- Short inflation is theoretically preferred.
- If some pre-inflationary signal exists, it will affect the largest scales.

- Largest cosmic variance – Anomalies are limited to ~3σ.
- Use large scale anomalies as clues.
- A-posteriori choices affect the statistical interpretation of the results!

Deformations on Large Scales

$$\cancel{\langle \Phi_{\mathbf{k}} \rangle = 0}$$

$$\cancel{\langle \Phi_{\mathbf{k}} \Phi^*_{\mathbf{k}'} \rangle = (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}') P_\Phi(k)}$$

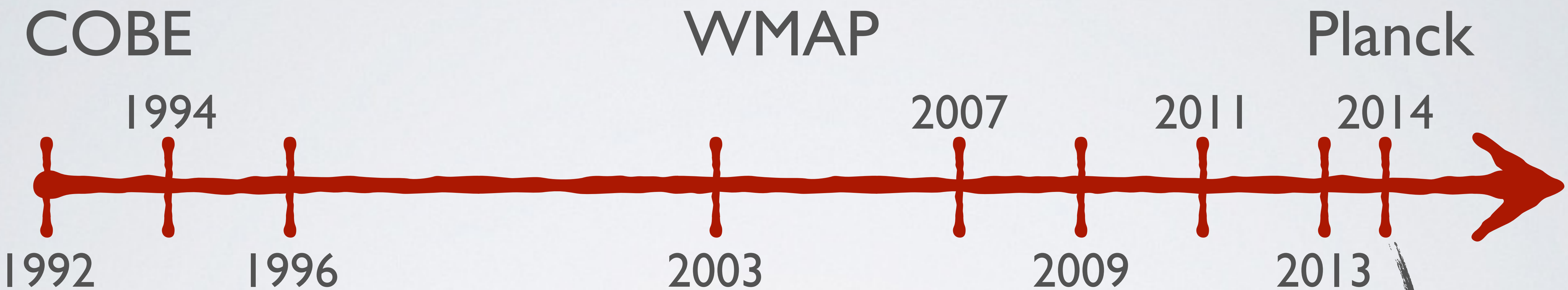
- Pre-inflationary relics
- Example – the PIP model:
  [Fialkov *et al.*, JCAP 2010]
  - A relic pre-inflationary particle (PIP) creates a one-point contribution on large scales, $\Phi \propto \log r$.
  - Does not affect the two-point function.
  - Search the CMB for a set of giant concentric rings.
    [Kovetz, ABD & Itzhaki, ApJ 2010]

- A non-trivial topology:
  - Change the global structure of the Universe by identifying points in space.
  - Compact dimensions limit the power on large scales.
  - Example – A compact 3-torus with dimensions $L_x \times L_y \times L_z$:

$$\mathbf{k} = 2\pi \left(\frac{n_x}{L_x}, \frac{n_y}{L_y}, \frac{n_z}{L_z} \right) \qquad n_i \in \mathbb{Z}$$

  - Example – "Stringy" topologies: orbifold point, orbifold line.
    [ABD, Rathaus & Itzhaki, JCAP 2012; Rathaus, ABD & Itzhaki, JCAP 2013]

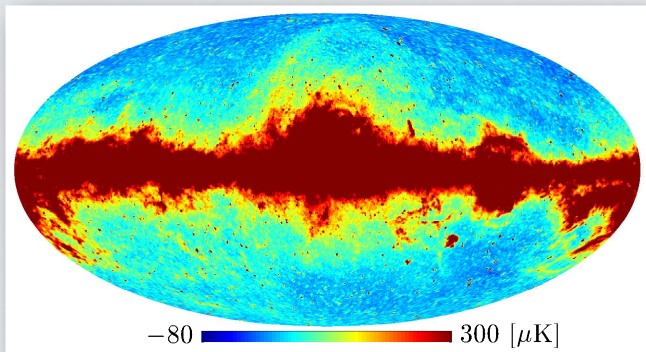
Large Scale CMB Data



- Better removal of Galactic foregrounds
- Polarization

Is this it??

Contributions to Large Scale Signal



Observed Microwave Sky

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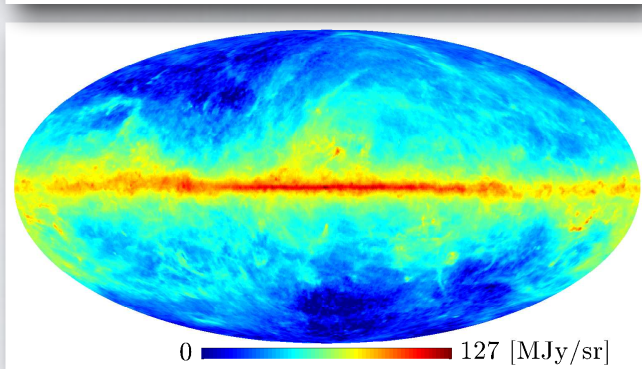

Galactic Foregrounds

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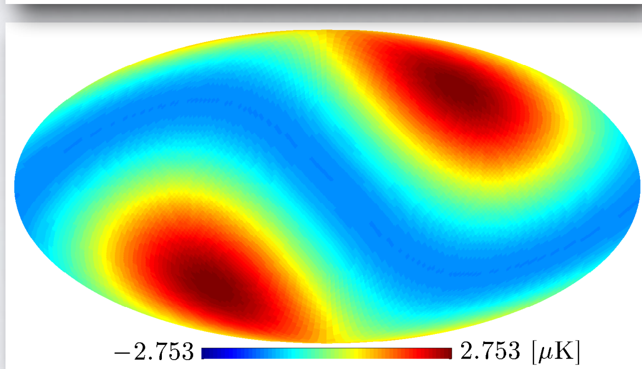
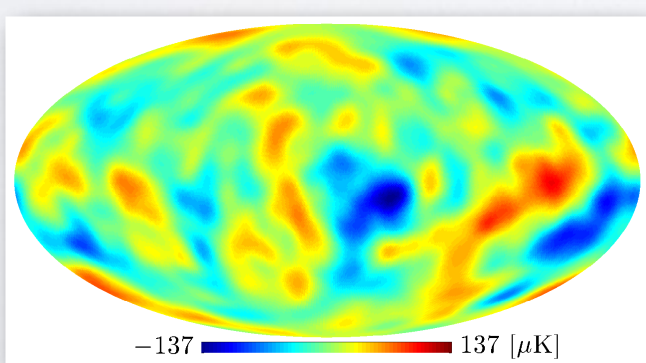


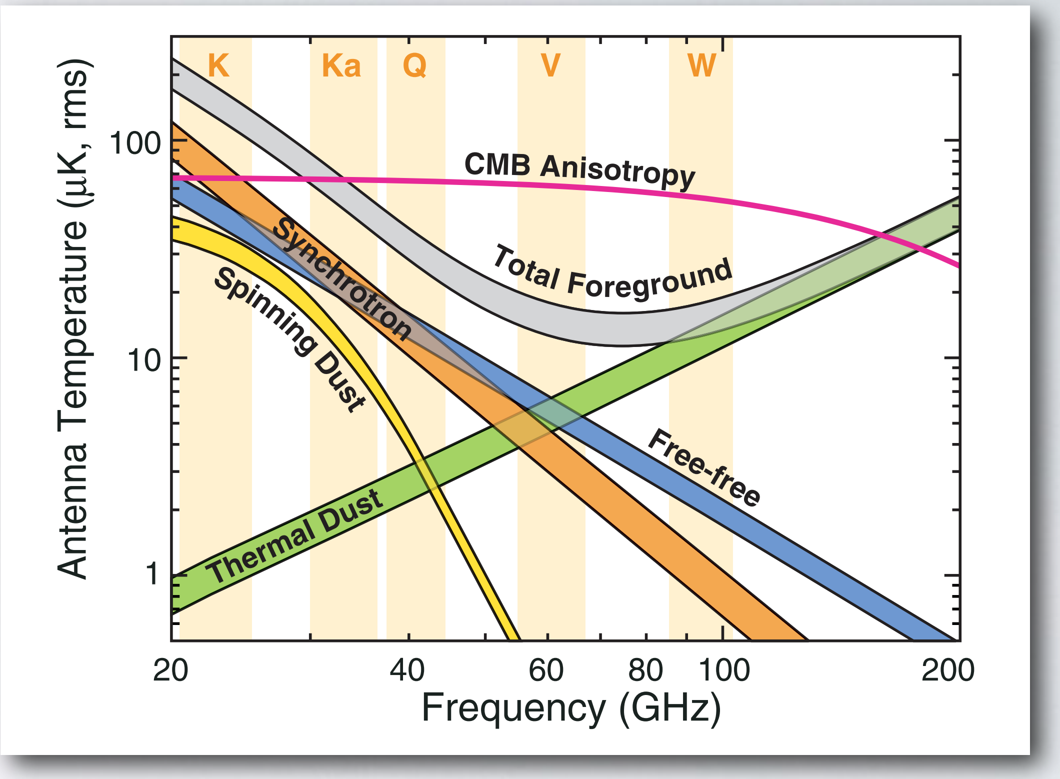
Doppler Quadrupole



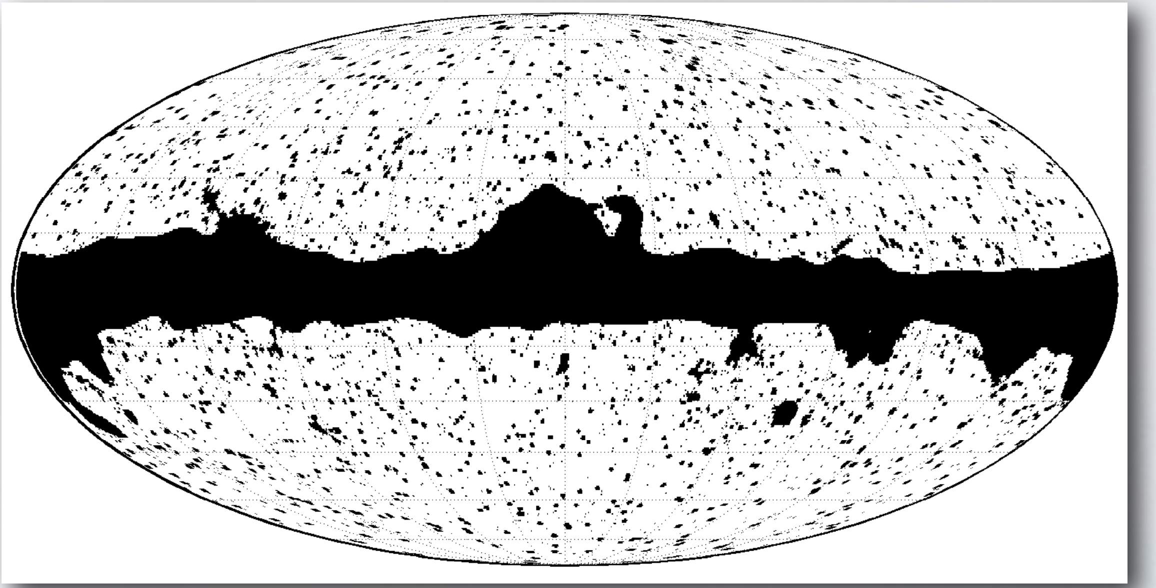
CMB

Galactic Foregrounds

- Component separation methods provide high-quality CMB maps.
- Maps are still contaminated in the Galactic plane area.
- In pixel-space, masking is straightforward. However, masking breaks isotropy!
- In harmonic-space, masking is problematic, since the spherical harmonics are not orthogonal on the masked sky.



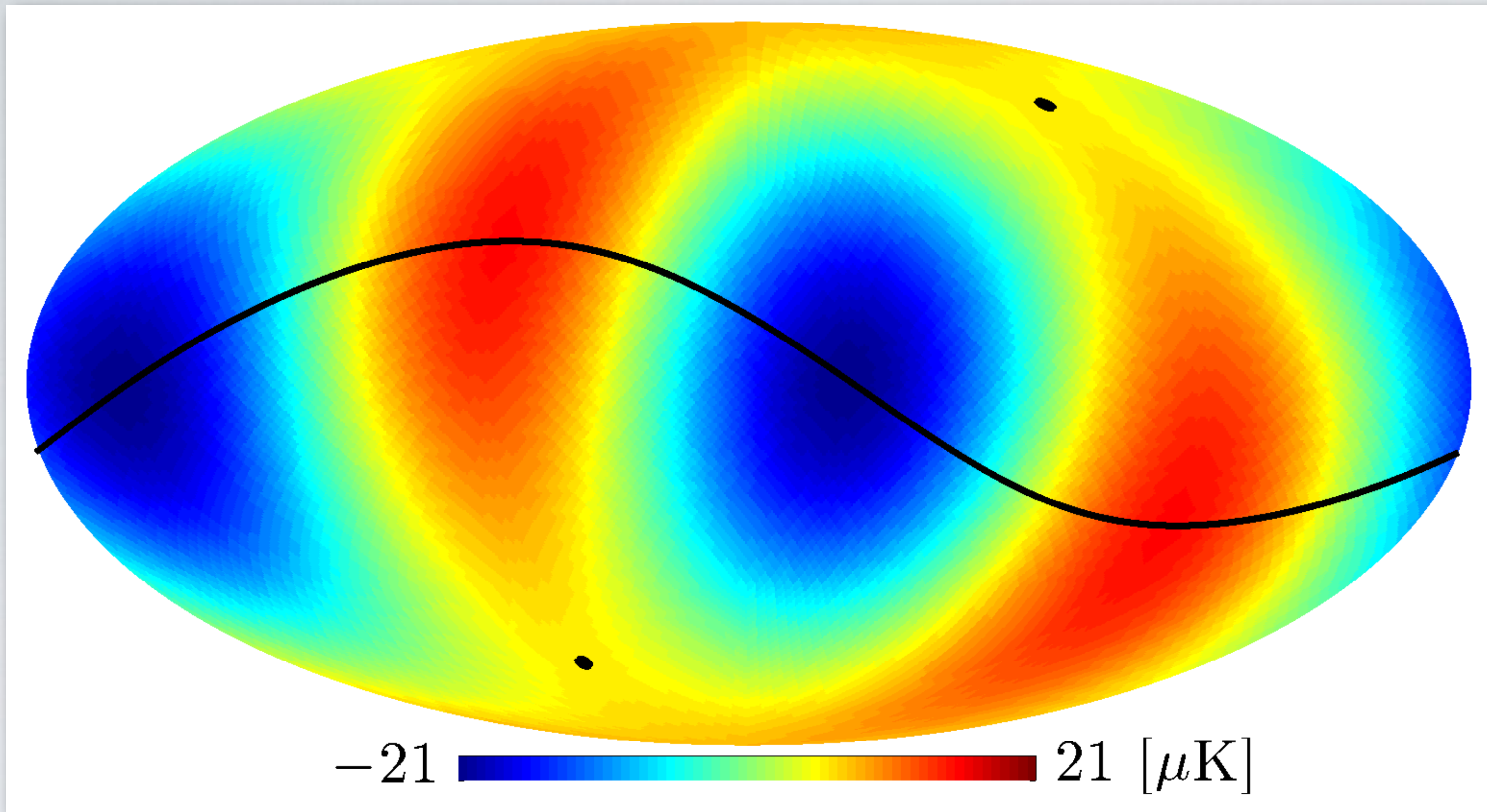
[Bennett *et al.*, ApJS 2013]

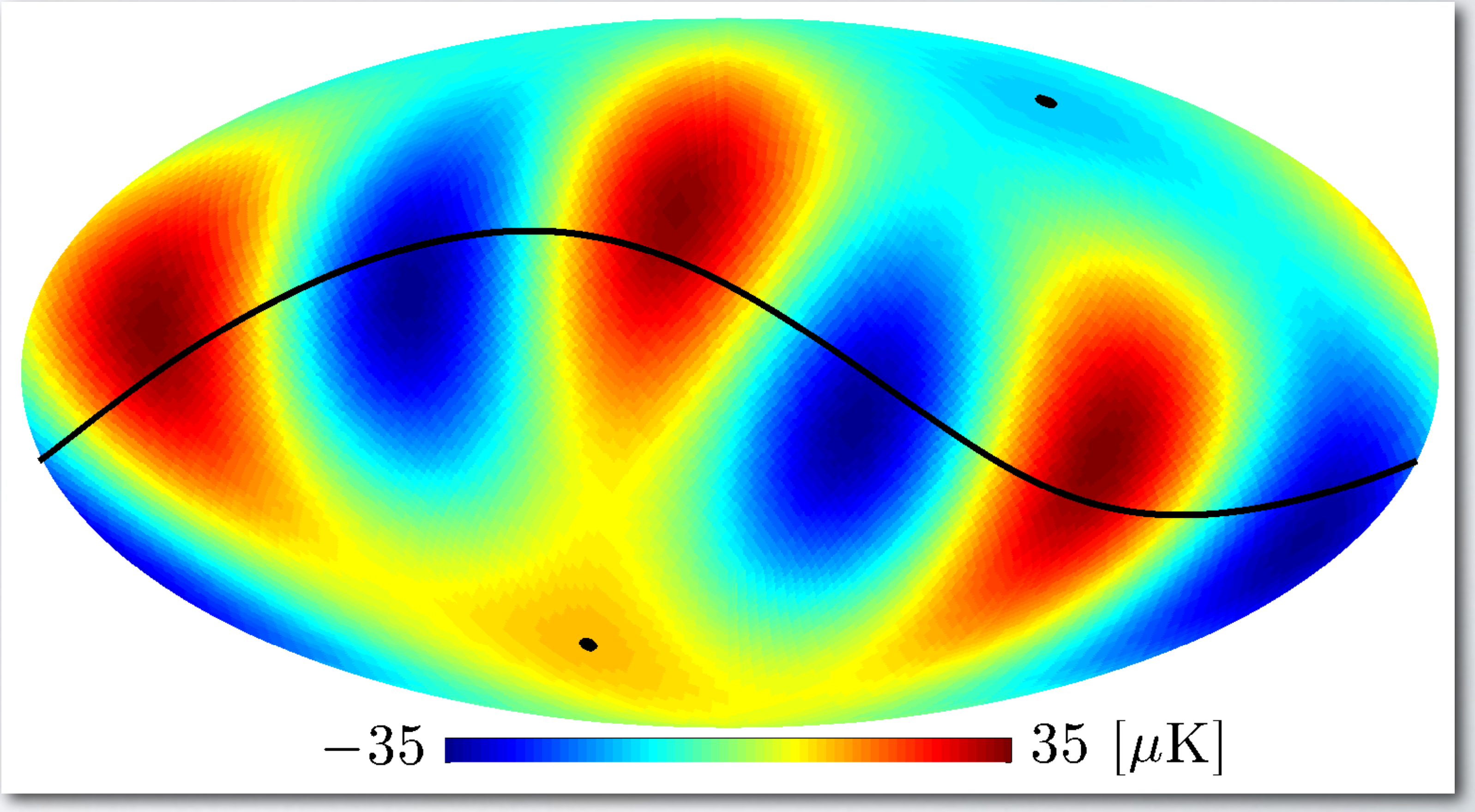


Large Scale CMB Anomalies

The “Axis of Evil”
Low Power on Large Scales
Lack of Large-Angular Correlations
Hemispherical Power Asymmetry
Point Parity
Mirror Parity

The “Axis of Evil”





The "Axis of Evil"

[de Oliveira-Costa *et al.*, PRD 2004
Copi *et al.*, PRD 2004
Copi *et al.*, MNRAS 2006
Abramo *et al.*, PRD 2006
Copi *et al.*, Advances in Astronomy 2010
Planck Collaboration XXIII, 2013, arXiv:1303.5083
Rassat and Starck, A&A, 2013
Rassat *et al.*, A&A, 2013
Copi *et al.*, 2013, arXiv:1311.4562
Rassat *et al.*, 2014, arXiv:1405.1844]

- Quadrupole and octupole are both "planar" – dominated by $|m| = \ell$ modes.
- Their two planes are closely aligned.
- Statistic – "Maximum Angular Momentum Dispersion":
  - Find $\hat{\mathbf{n}}_\ell = \arg\max_{\hat{\mathbf{n}}} \sum_{m=-\ell}^{\ell} m^2 \left|a_{\ell m}(\hat{\mathbf{n}})\right|^2$ and test $\hat{\mathbf{n}}_2 \cdot \hat{\mathbf{n}}_3$.
  - Significance: As high as 3.8σ on WMAP, 2.7–3.2σ on Planck data.
    [Copi *et al.*, 2013, arXiv:1311.4562]
- If allowing dominance by <u>*any*</u> m, all $\ell = 2$–5 are found to be correlated. [Land & Magueijo, PRL 2005; PRD 2005; MNRAS 2007]

The “Axis of Evil” – Multipole Vectors

- Irreducible representation of the rotation group independent of coordinate system. [Maxwell, 1873]
- Instead of $2\ell+1$ coefficients, each multipole ℓ is decomposed to ℓ axes and an amplitude:

$$T_\ell(\hat{\mathbf{n}}) = \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}}) = A_\ell \prod_{i=1}^{\ell} \left(\hat{\mathbf{v}}_i^{(\ell)} \cdot \nabla \right) \frac{1}{r} \bigg|_{r=1}$$

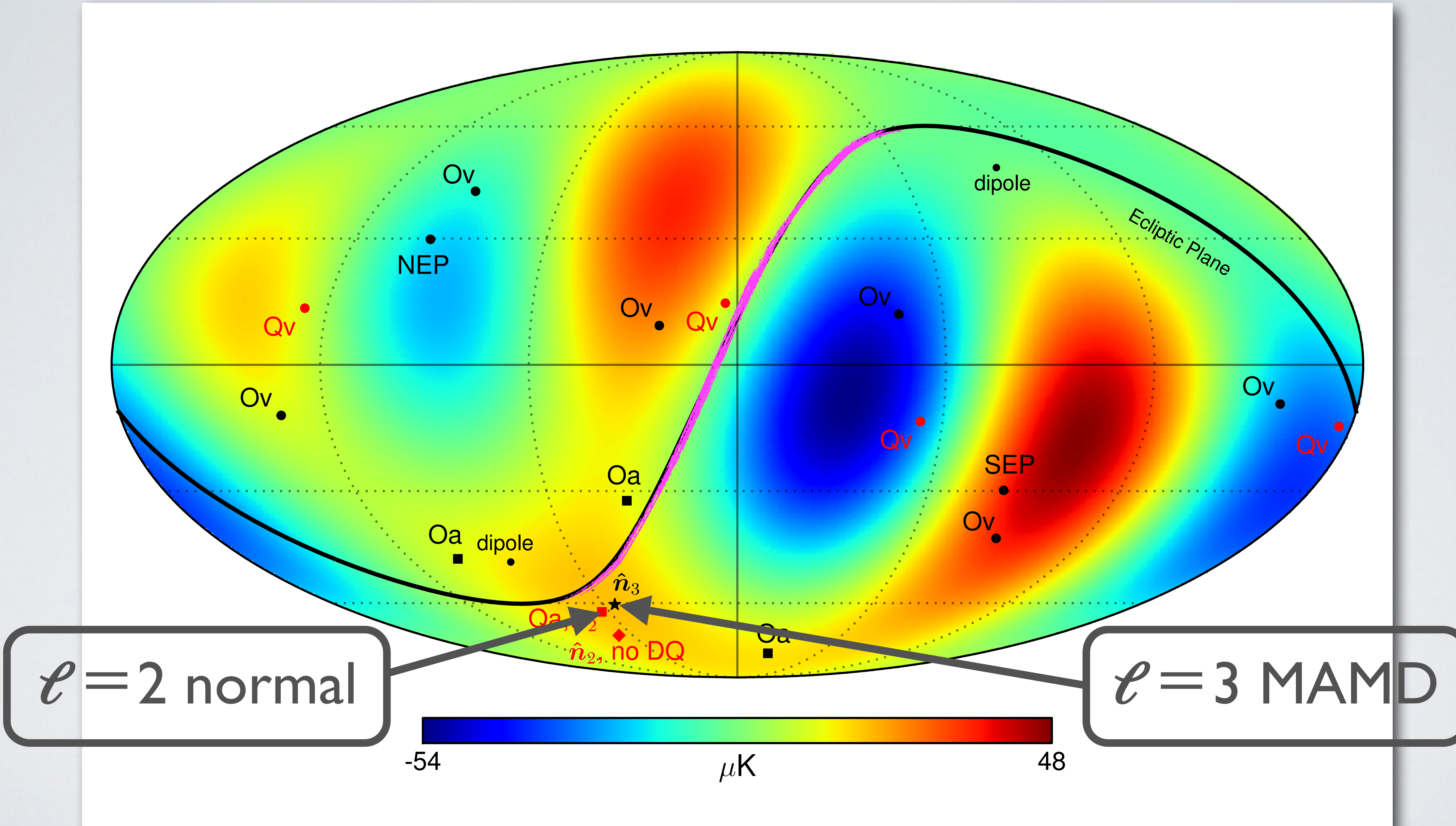
- Each pair defines a plane $\mathbf{w}_{i,j}^{(\ell)} = \hat{\mathbf{v}}_i^{(\ell)} \times \hat{\mathbf{v}}_j^{(\ell)}$.
- In this way each multipole defines $\ell(\ell-1)/2$ planes.
  - The normal to the quadrupole plane is the MAMD axis.
  - Octupole planarity → 3 octupole planes are aligned.
  - Quadrupole plane is aligned with the 3 octupole planes.
- Statistic:

$$D_i = \left| \mathbf{w}_{1,2}^{(2)} \cdot \mathbf{w}_{j,k}^{(3)} \right| \qquad S = \frac{1}{3} \sum_{i=1}^{3} D_i$$

  - Significance of 2.9σ on WMAP and 2.1–2.6σ on Planck data.

  [Copi *et al.*, 2013, arXiv:1311.4562]

The “Axis of Evil”



[Copi *et al.*, 2013, arXiv:1311.4562]

Low Power on Large Scales

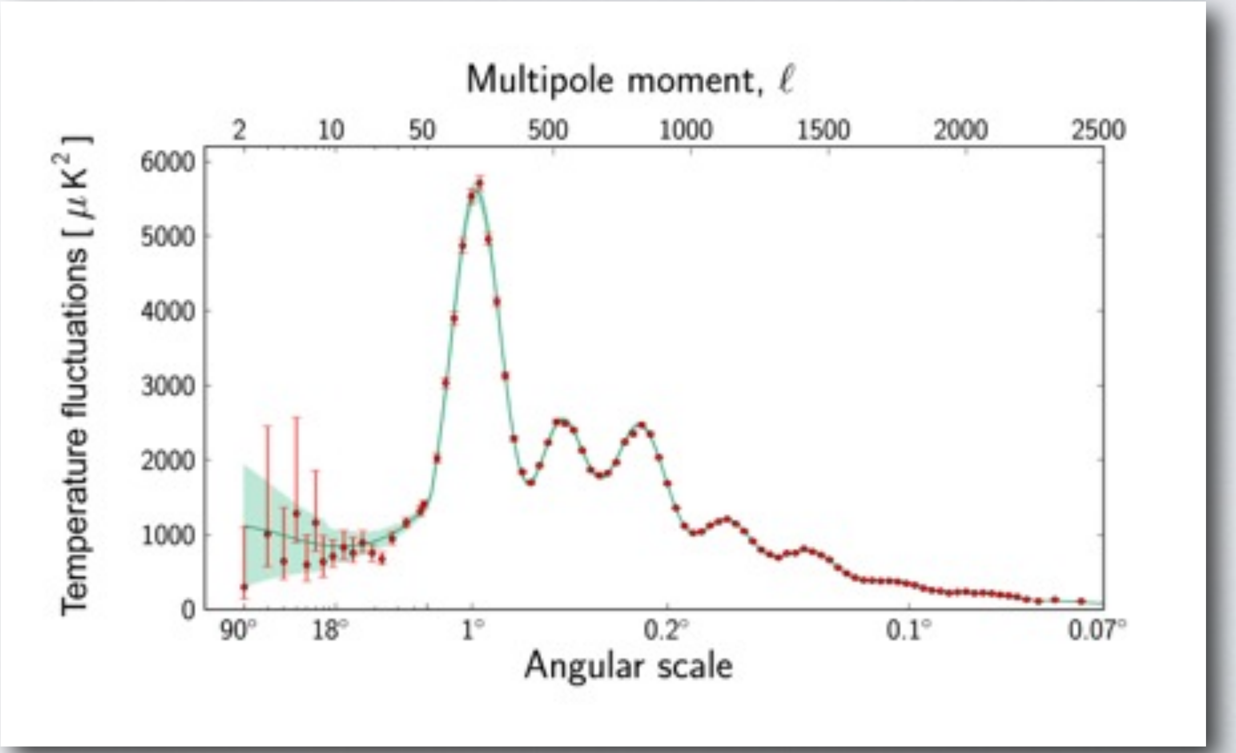
- Cosmological model is determined almost exclusively by small scales.

- It appears that the quadrupole amplitude is too low.

- WMAP: Quadrupole still within cosmic variance (<2σ).
  [Bennett *et al.*, ApJS 2013]

- Planck: Using the statistic $s_1 = \max_{r \in [0,1]} \frac{1}{\sqrt{\ell_{\max}}} \sum_{\ell=2}^{\lfloor \ell_{\max} r \rfloor} \frac{\hat{C}_\ell - C_\ell}{\Delta \hat{C}_\ell}$ report 2.5σ.
  [Planck Collaboration XV, 2013, arXiv:1303.5075]

- Only ℓ=2: C_2 is χ^2-distributed in ΛCDM.
  - On WMAP and Planck data: 1.7–2.3σ, depending on masking.
    [Rassat *et al.*, A&A 2013; Rassat *et al.*, 2014, arXiv:1405.1844]



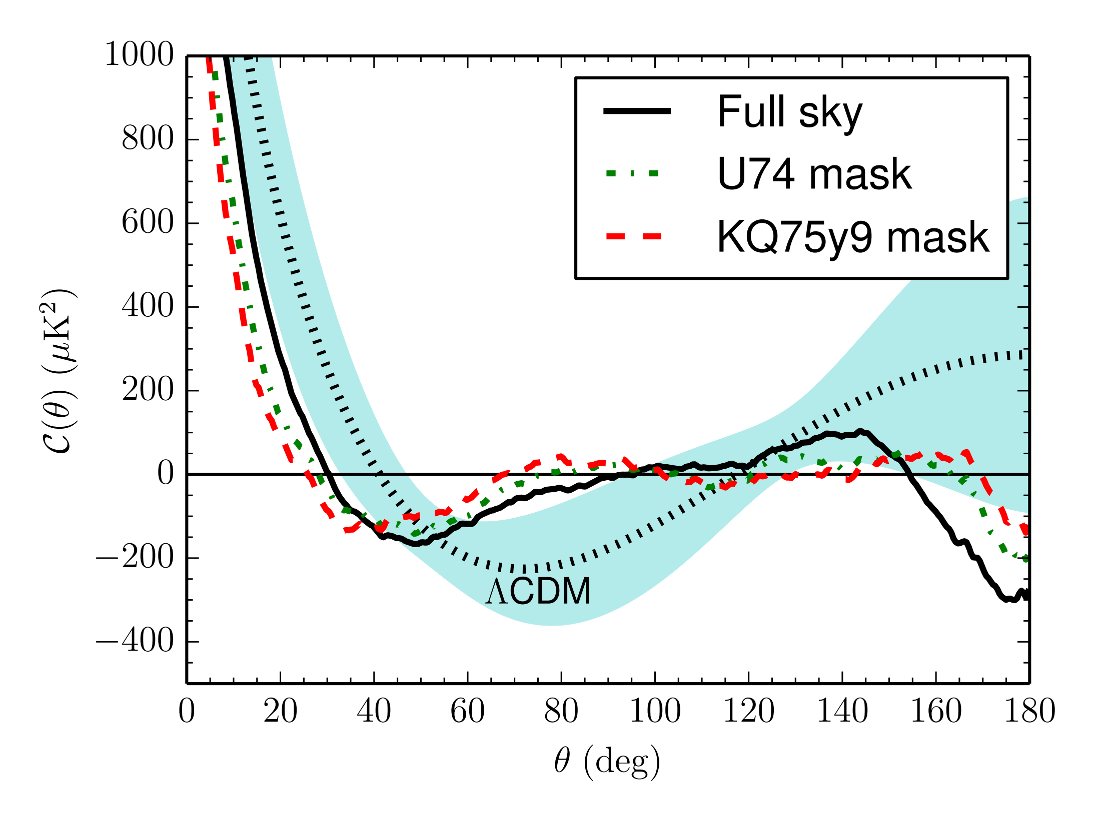
[Planck Collaboration XV, 2013, arXiv:1303.5075]

Lack of Large-Angular Correlations

- Angular correlation function $C(\theta) = \langle T(\hat{\mathbf{n}}_1) T(\hat{\mathbf{n}}_2) \rangle_{\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2 = \cos\theta}$ is near zero for large scales.

- Related to low-power anomaly: $C(\theta) = \sum_\ell \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta)$

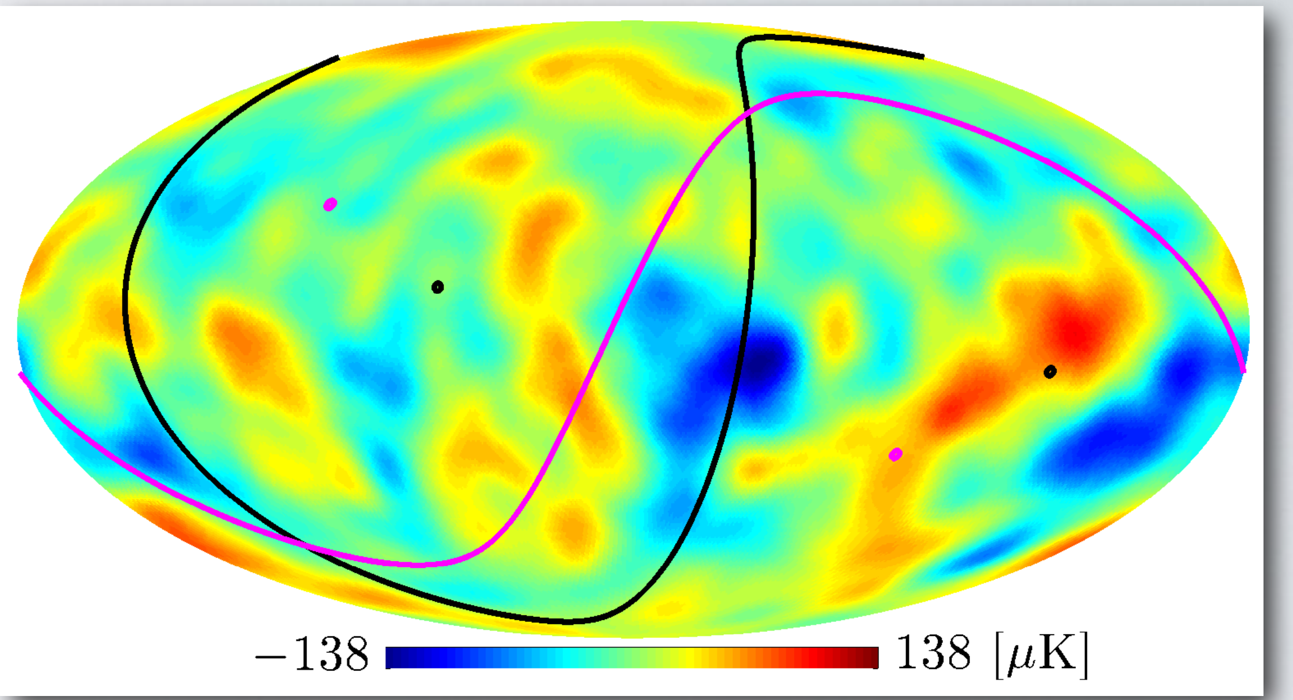
- Statistic: $S_{1/2} = \int_{-1}^{1/2} C(\theta)^2 \, \mathrm{d}\cos\theta$
  [Spergel *et al.*, ApJS 2003]
  - Significance of up to 3.3σ on masked WMAP and Planck maps.
    [Copi *et al.*, 2013, arXiv:1310.3831]
  - Limit of 1/2 chosen a-posteriori.
  - Compares $C(\theta)$ to zero, not to ΛCDM expectation.



[Copi *et al.*, 2013, arXiv:1310.3831]

- A more robust statistic: $\chi^2 = \sum_{i,j=1}^{N_\mathrm{bin}} (C(\theta_i) - \langle C(\theta_i) \rangle) M_{ij}^{-1} (C(\theta_j) - \langle C(\theta_j) \rangle)$
  [Planck Collaboration XXIII, 2013, arXiv:1303.5083]
  - No significant deviation from ΛCDM expectation.

Hemispherical Power Asymmetry



- When the large-scale power spectrum is estimated locally, it is not isotropic.

- Maximal isotropy at $(l, \mathrm{b}) = (57°, 10°)$, near the ecliptic pole.

  - About 2.7σ on WMAP data. [Eriksen *et al.*, ApJ 2004; Hansen *et al.*, MNRAS 2004]

- Can also be seen in two-, three- and four-point angular correlation functions.
  [Planck Collaboration XXIII, 2013, arXiv:1303.5083]

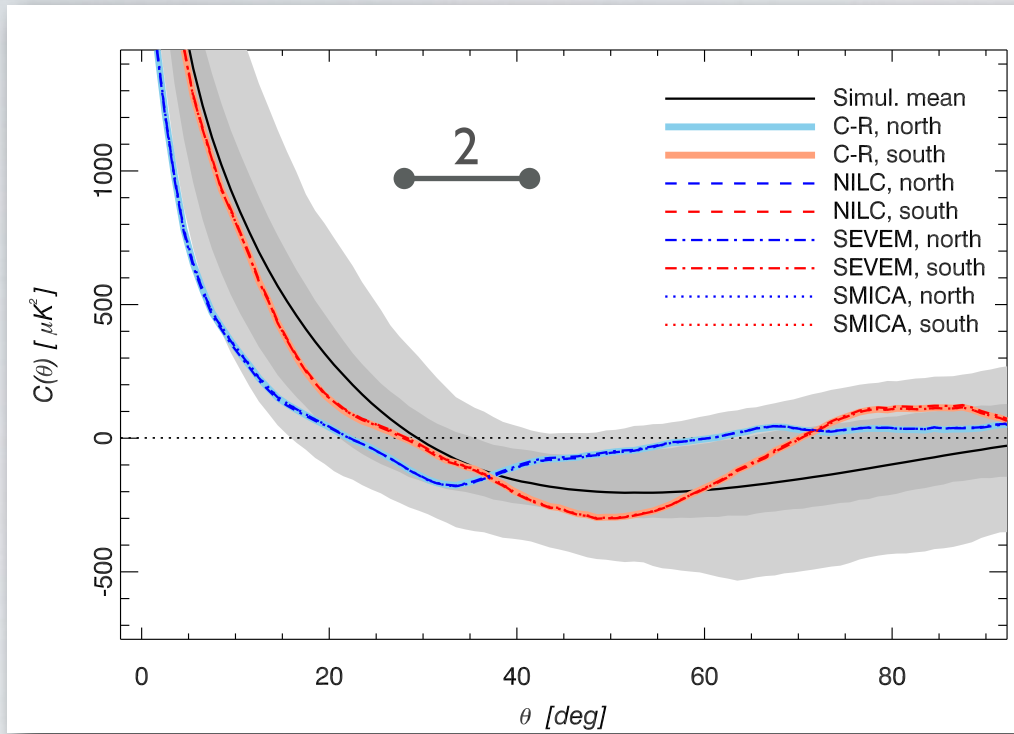
  - Using a χ^2 statistic, significance > 3.1σ.

- A phenomenological model – dipole modulation:
  [Gordon, ApJ 2007; Eriksen *et al.*, ApJL 2007; Akrami *et al.*, ApJL 2014]

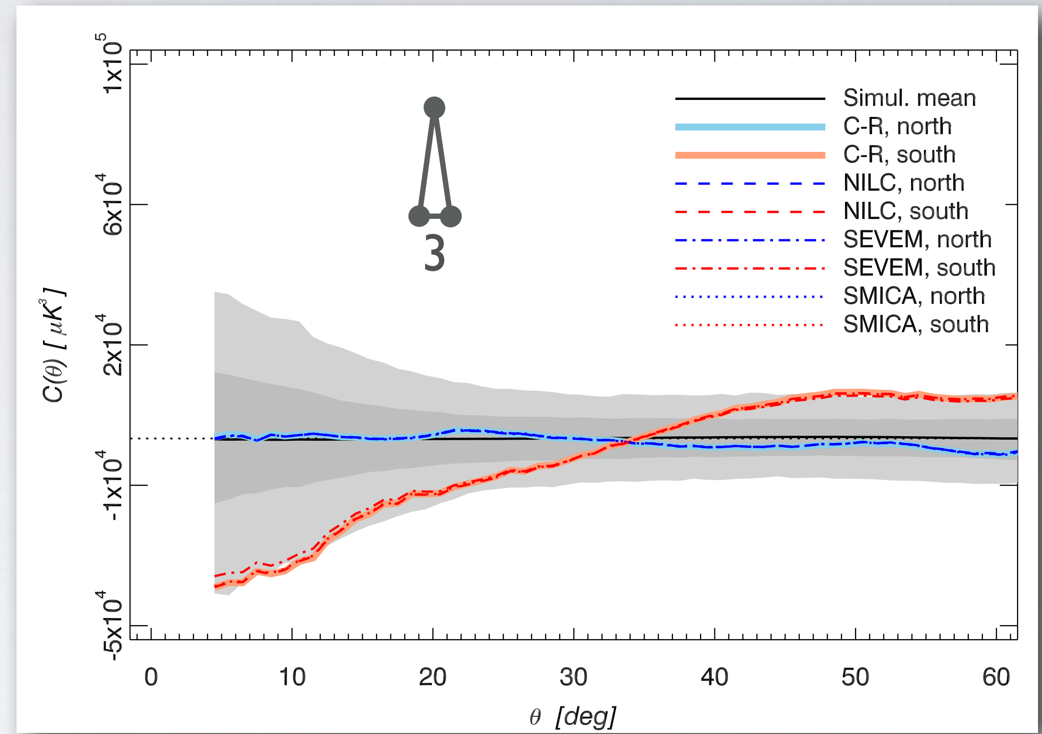
$$T(\hat{\mathbf{n}}) = T^{\mathrm{iso}}(\hat{\mathbf{n}})(1 + \mathbf{d} \cdot \hat{\mathbf{n}})$$

  - Provides a better fit on large scales than the isotropic model.

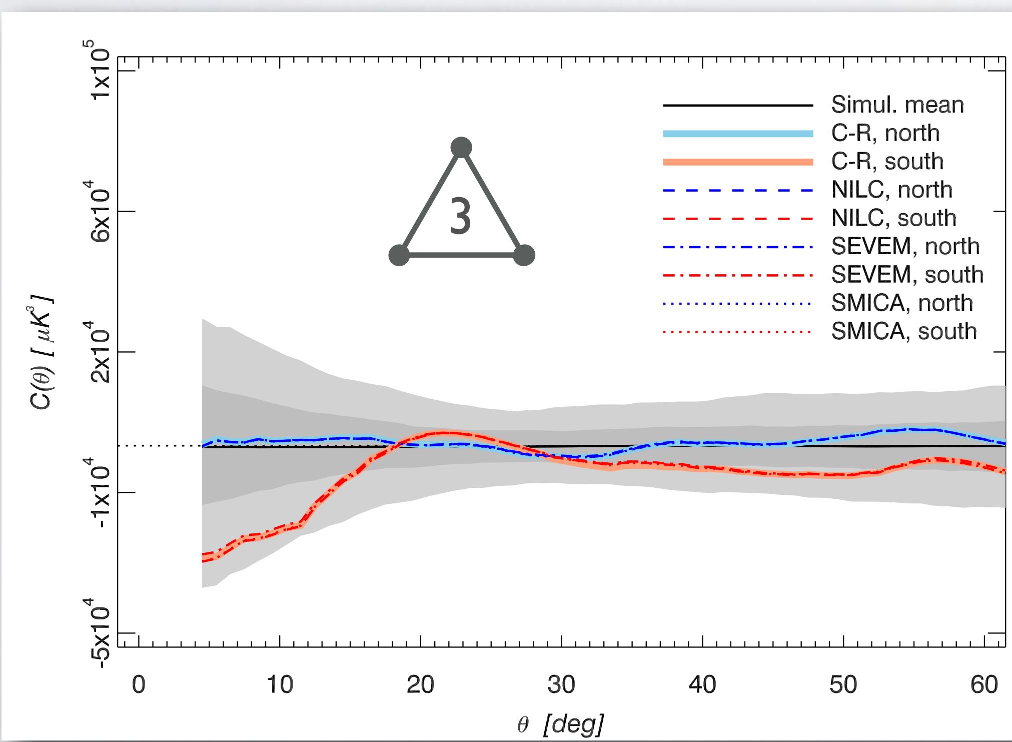
Hemispherical Power Asymmetry

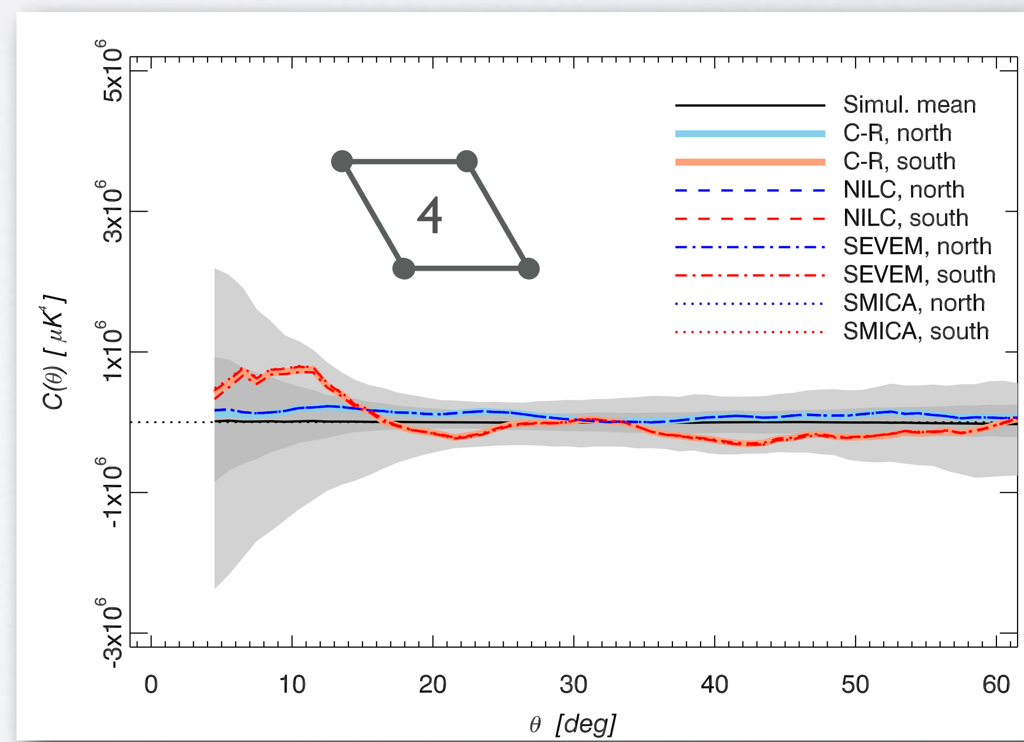


1.5σ



>3.1σ

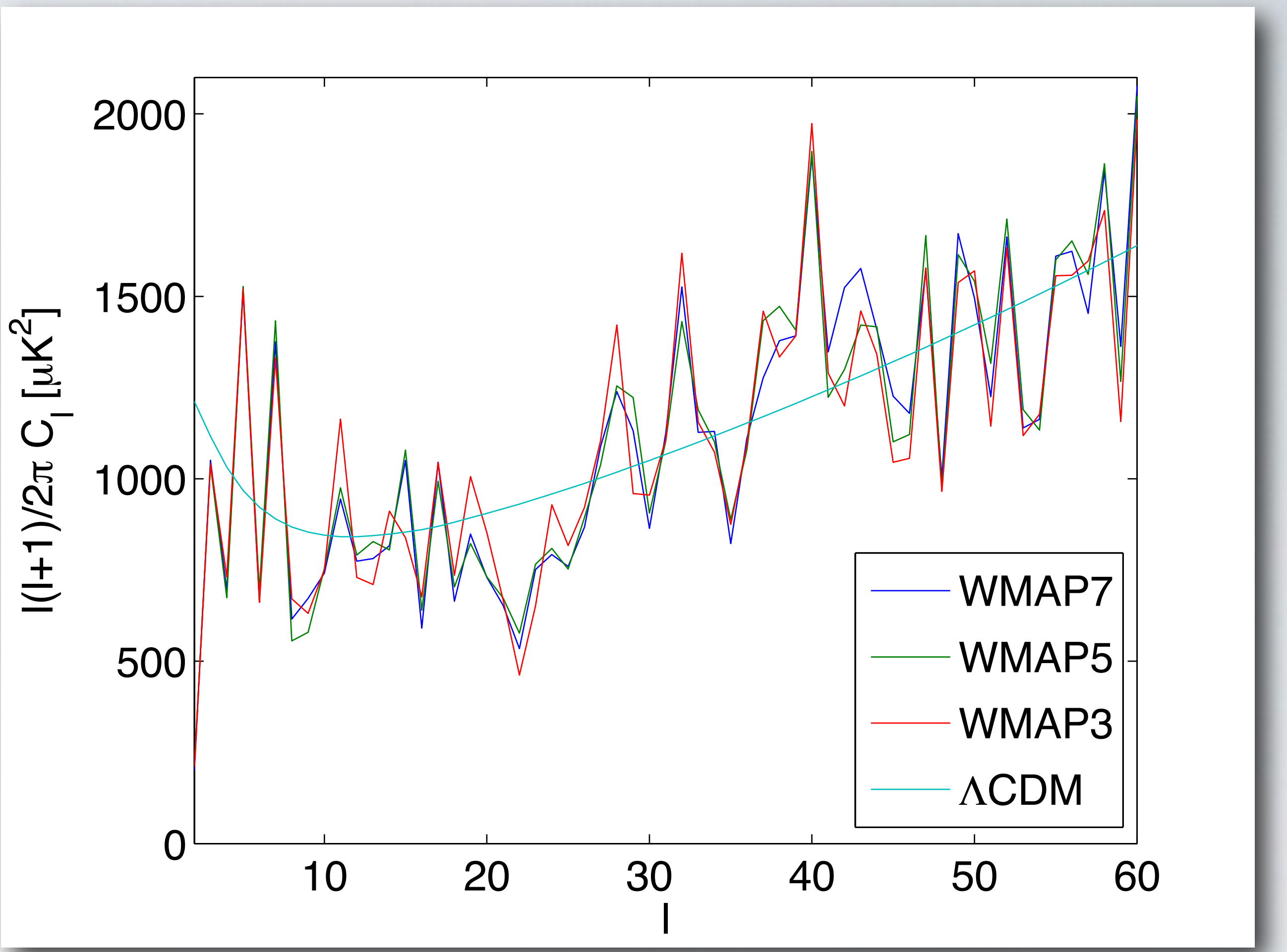




[Planck Collaboration XXIII, 2013, arXiv:1303.5083]

Point Parity

- Power spectrum shows preference for odd multipoles on large scales. [Land & Magueijo, PRD 2005; Kim & Naselsky, ApJL 2010; Kim & Naselsky, PRD 2010]



[Kim & Naselsky, PRD 2010]

- Equivalent to tendency for odd point-parity: under $\hat{\mathbf{n}} \to -\hat{\mathbf{n}}$, the harmonic coefficients transform as $a_{\ell m} \to (-1)^{\ell} a_{\ell m}$.

- Statistic:

$$P^{\pm}(\ell_{\max}) = \sum_{\ell=2}^{\ell_{\max}} \frac{1}{2}\left[1 \pm (-1)^{\ell}\right] \frac{\ell(\ell+1)}{2\pi} C_{\ell} \qquad g(\ell_{\max}) = \frac{P^{+}(\ell_{\max})}{P^{-}(\ell_{\max})}$$

- Maximal significance is for $\ell_{\max} = 22$. Both WMAP and Planck data show a ~ 2.8σ deviation. [Kim & Naselsky, PRD 2010; Planck Collaboration XXIII, 2013, arXiv:1303.5083]

- Is the low quadrupole part of a broader odd-parity preference?

Mirror Parity

[ABD & Kovetz, 2014, arXiv:1403.2104]

- Parity with respect to reflections through a plane, $\hat{\mathbf{r}} \to \hat{\mathbf{r}}_{\hat{\mathbf{n}}} = \hat{\mathbf{r}} - 2\,(\hat{\mathbf{r}}\cdot\hat{\mathbf{n}})\,\hat{\mathbf{n}}$.
- Pixel-space estimator:
  [de Oliveira-Costa *et al.*, ApJ 1996; PRD 2004; Finelli *et al.*, JCAP 2012; Planck Collaboration XXIII, 2013, arXiv:1303.5083]
  - Average difference between hemispheres: $S_{\rm p}^{\pm}(\hat{\mathbf{n}}) = \overline{\left[\frac{T(\hat{\mathbf{r}}) \pm T(\hat{\mathbf{r}}_{\hat{\mathbf{n}}})}{2}\right]^2}$
  - Seems easy to apply a Galactic mask.

✦ Planck data

✦ Large mask

➡ Odd parity ≲ 2.8σ

- Harmonic-space estimator:
  [ABD, Kovetz & Itzhaki, ApJ 2012; Rassat & Starck, A&A, 2013]
  - Under reflection through z-axis, $Y_{\ell m}(\hat{\mathbf{r}}) \to (-1)^{\ell+m} Y_{\ell m}(\hat{\mathbf{r}})$.
  - For each direction, compare for each ℓ the distribution of power between even and odd ℓ+m multipoles.
  - Normalized
  - Easy to test scale dependence.
  - Masking the Galactic plane is not straightforward.

✦ WMAP data

✦ Very small mask

➡ Odd parity ≲ 3.5σ

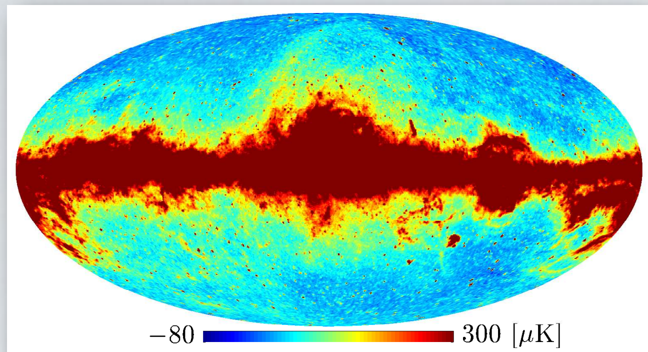
$$S_{\rm h}(\hat{\mathbf{n}}) = \sum_{\ell=2}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} (-1)^{\ell+m} \frac{|a_{\ell m}(\hat{\mathbf{n}})|^2}{\hat{C}_\ell} - (\ell_{\max} - 1)$$

$$\hat{C}_\ell = \frac{1}{2\ell+1} \sum_m |a_{\ell m}|^2$$

Anomaly Report Card

The "Axis of Evil"	3.2σ
Low Power on Large Scales	2.5σ
Lack of Large-Angular Correlations	3.3σ
Hemispherical Power Asymmetry	3.1σ
Point Parity	2.8σ
Mirror Parity	2σ

Contributions to Large Scale Signal



Observed Microwave Sky

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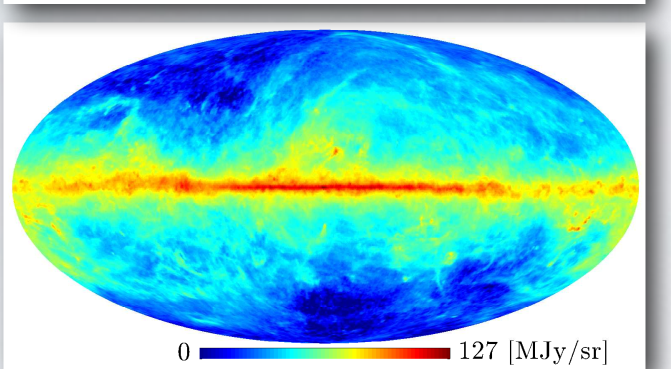

Galactic Foregrounds

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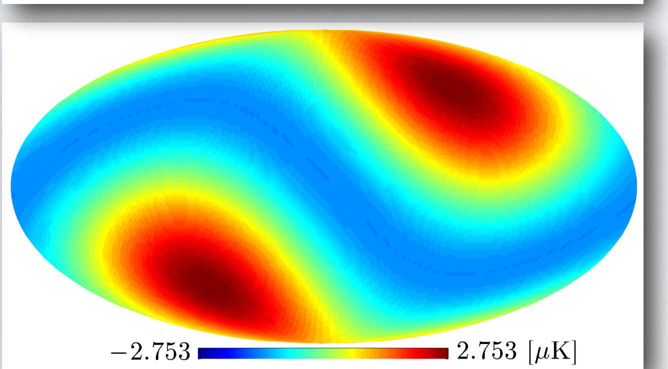
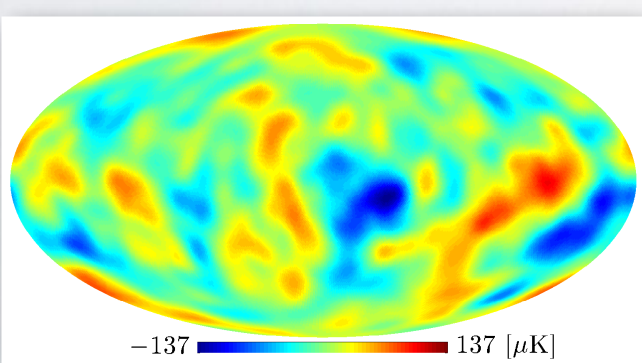


Doppler Quadrupole



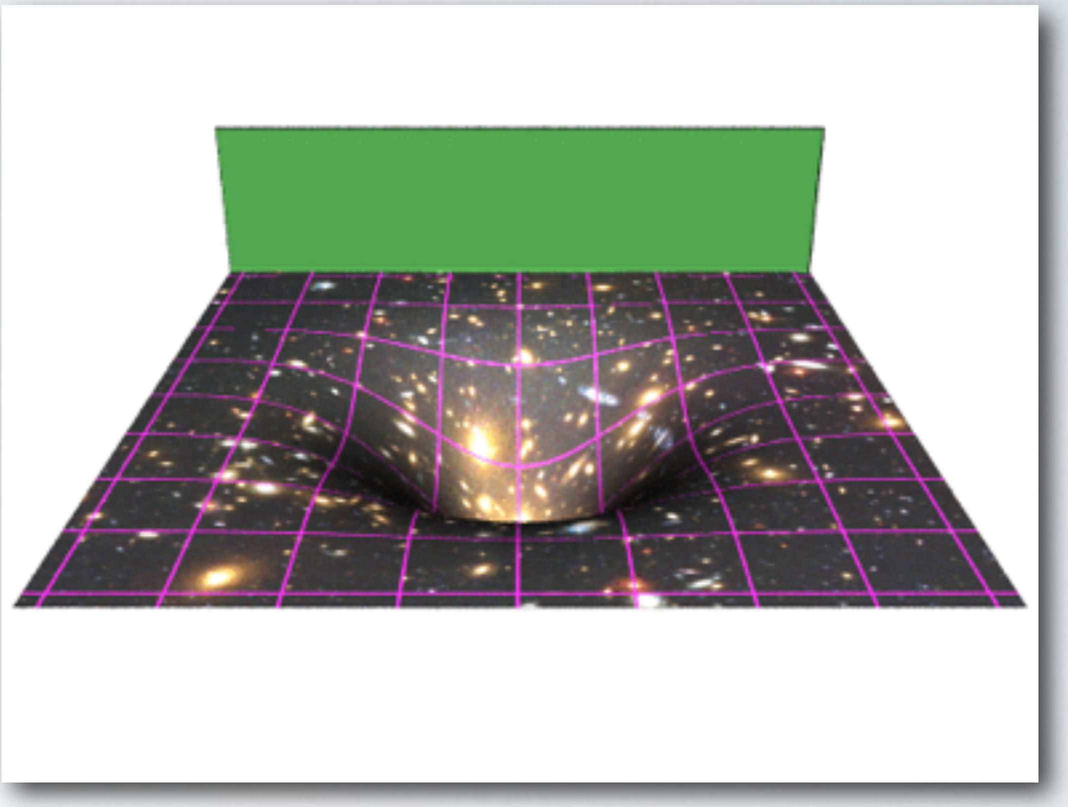
CMB = Primordial + ISW

The Integrated Sachs–Wolfe Effect

[Sachs & Wolfe, ApJ 1967]

$$\delta^{\mathrm{ISW}} = -2 \int_{\eta_{\mathrm{LS}}}^{\eta_0} \frac{\partial \Phi}{\partial \eta} \, \mathrm{d}\eta$$

- On large scales, this is the main secondary source of anisotropy.



- The energy of the photons is changed when crossing a potential well which evolves in time.

- When the Universe is:

    - Matter dominated → linear growth = expansion rate, $\mathbf{\Phi}$ = const. → no ISW.

    - Dark-energy dominated → linear growth < expansion rate, $\mathbf{\Phi} \neq$ const. → late-time ISW effect.

Estimation of the ISW Contribution

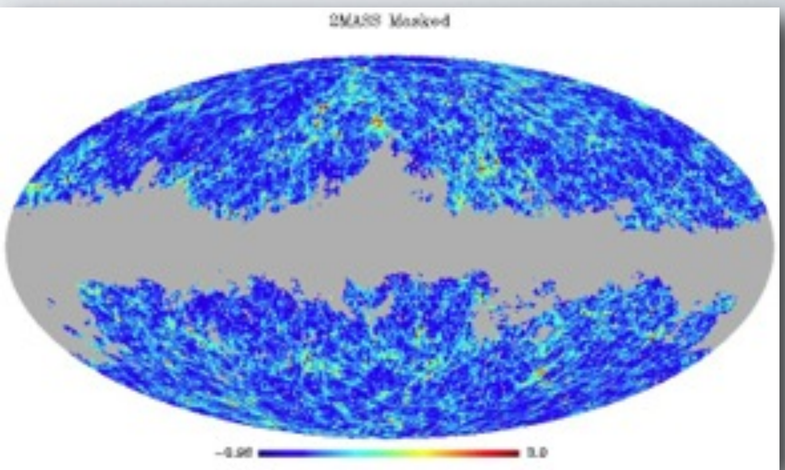
- Use galaxy surveys to estimate the local density perturbations.

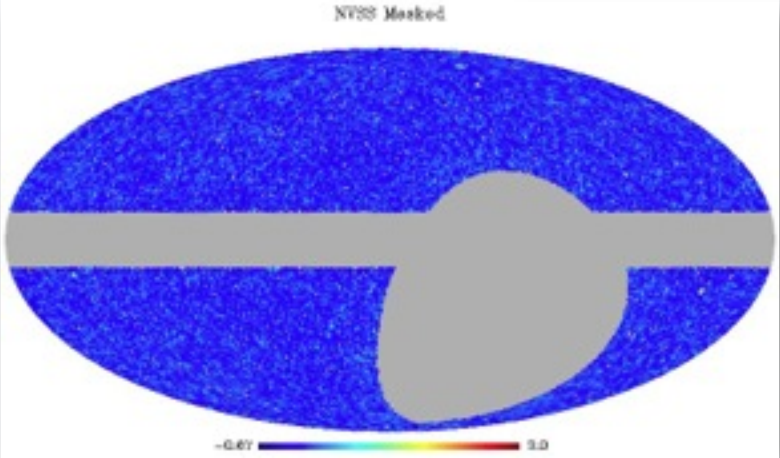
- Gravitational potential is given by the Poisson equation
  $\nabla^2\Phi(\mathbf{x},t) = 4\pi G\bar{\rho}(t)a^2\delta(\mathbf{x},t)$

- Use cross-correlation between CMB and LSS maps.

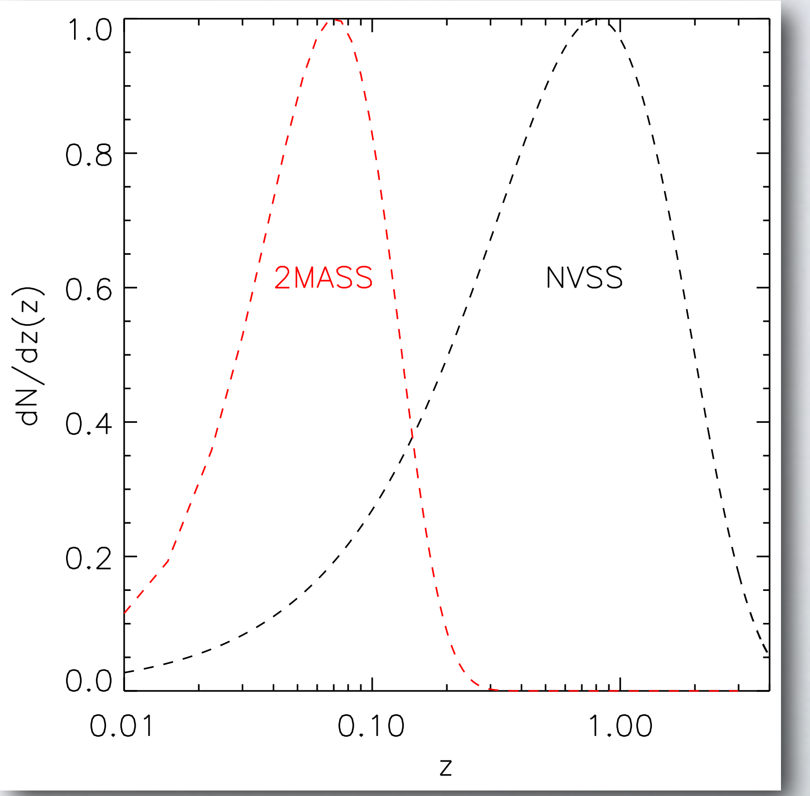
- Alternatively, build ISW map directly from LSS map.
  [Francis & Peacock, MNRAS 2010]

2MASS (IR)





NVSS (radio)



[Rassat *et al.*, A&A 2013]

ISW Estimation Methods

- Directly from LSS:
  [Francis & Peacock, MNRAS 2010]
  - Split 2MASS data to 3 redshift shells.
  - Need to estimate the galaxy bias $g_{\ell m} = b_{\rm g}\delta^{\rm m}_{\ell m}$ in each redshift shell.
  - Need to assume cosmological parameters.
- Using only cross-correlation:
  [Rassat et al., A&A 2013; Rassat & Starck, A&A 2013; Rassat *et al.*, 2014, arXiv:1405.1844]

$$\delta^{\rm ISW}_{\ell m} = \frac{C_\ell^{\rm g,ISW}}{C_\ell^{\rm gg}} g_{\ell m}$$

  - ISW map is independent of galaxy bias.
  - Spectra can be calculated assuming cosmological parameters.
  - Spectra can also be estimated from the data. This assumes the form of the ISW signal, not its presence.

ISW Estimation Methods (cont.)

- Using also CMB data: $\delta^{\rm obs} = \delta^{\rm p} + \delta^{\rm ISW}$
  [Barreiro *et al.*, 2008, 2013; Planck Collaboration XIX, 2013, arXiv:1303.5079]

$$\delta^{\rm ISW}_{\ell m} = \frac{C^{\rm g,ISW}_\ell}{C^{\rm gg}_\ell} g_{\ell m} + \frac{\widetilde{C}^{\rm ISW,ISW}_\ell}{\widetilde{C}^{\rm ISW,ISW}_\ell + C^{\rm pp}_\ell} \left[\delta^{\rm obs}_{\ell m} - \frac{C^{\rm g,ISW}_\ell}{C^{\rm gg}_\ell} g_{\ell m} \right]$$

$$\widetilde{C}^{\rm ISW,ISW}_\ell = C^{\rm ISW,ISW}_\ell - \frac{\left(C^{\rm g,ISW}_\ell \right)^2}{C^{\rm gg}_\ell}$$

- Maximum likelihood solution, assuming a Gaussian prior.
- Can be extended to include more correlated datasets, such as the gravitational lensing potential map.
  [Manzotti & Dodelson, 2014, arXiv:1407.5623]

Existing Works

Work	Method	Data	Tested Anomalies
Francis & Peacock, 2010	Direct integration	2MASS (3 slices)	✔ WMAP
Barreiro *et al.*, 2013	Cross + CMB	WMAP + NVSS	✘
Planck Collaboration XIX	Cross + CMB	(i) Planck + NVSS (ii) Planck + Lensing	✘
Rassat *et al.*, 2013; 2014	Only Cross	NVSS + 2MASS	✔ WMAP, Planck
Manzotti & Dodelson, 2014	Cross (2 tracers) + CMB	Planck + NVSS + Lensing	✘

Currently only $\ell \geq 10$

Anomalies After ISW Subtraction

		Francis & Peacock, 2010	Rassat *et al.*, 2014
The “Axis of Evil”	3.2σ	✘	✘
Low Power on Large Scales	2.5σ	✘	✔
Lack of Large-Angular Correlations	3.3σ		
Hemispherical Power Asymmetry	3.1σ		
Point Parity	2.8σ		
Mirror Parity	2σ		✘

Summary & Future Prospects

- Large scale anomalies can provide clues to the very early Universe.
  - "Fight against cosmic variance."
  - Significance is debated and sometimes strongly depends on dataset, estimator choice and masking technique.
  - A-posteriori choices can hinder analyses.
- Planck CMB maps are soon becoming extremely clean of Galactic foregrounds.
  - Could eliminate the need for masking!
- ISW is the main secondary source of anisotropy on large scales.
  - Will the CMB anomalies be alleviated once the ISW signal is removed?
  - Results may depend on assumptions used in ISW estimation.
  - Recovery of the primordial signal should be done even if one doesn't consider the anomalies significant!
- Polarization maps from Planck will allow improvement of the lensing reconstruction on large scales.
- Future LSS surveys are expected to improve ISW reconstruction accuracy.
  - Only 40% correlation signal up to z = 0.3. However, 90% signal up to z = 1.3.
  - Need extensive sky coverage to get large scale signal.
  - DES, LSST, Euclid