Searches for Violations of **Statistical Isotropy**:

Power Asymmetry in WMAP and Planck Sky Maps

as Measured by a Local Variance Estimator

NBIA-APCTP Workshop, Niels Bohr Institute / Copenhagen / August 18, 2014

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Astrophys.J. 784 (2014) L42 [arXiv:1402.0870]

Sadra Jazayeri, Hassan Firouzjahi (IPM, Tehran), Adam R. Solomon, Yi Wang (Cambridge)

arXiv:1408.3057

- ✓ **Planck 2013 results. XXIII. Isotropy and statistics of the CMB, arXiv:1303.5083**
- ✓ **Directional dependence of ΛCDM cosmological parameters, Astrophys.J. 773 (2013) L3 [arXiv:1303.5371]**
- ✓ **Increasing evidence for hemispherical power asymmetry in the five-year WMAP data, Astrophys.J. 699 (2009) 985-989 [arXiv:0903.1229]**

Standard cosmology

Timeline of the Universe

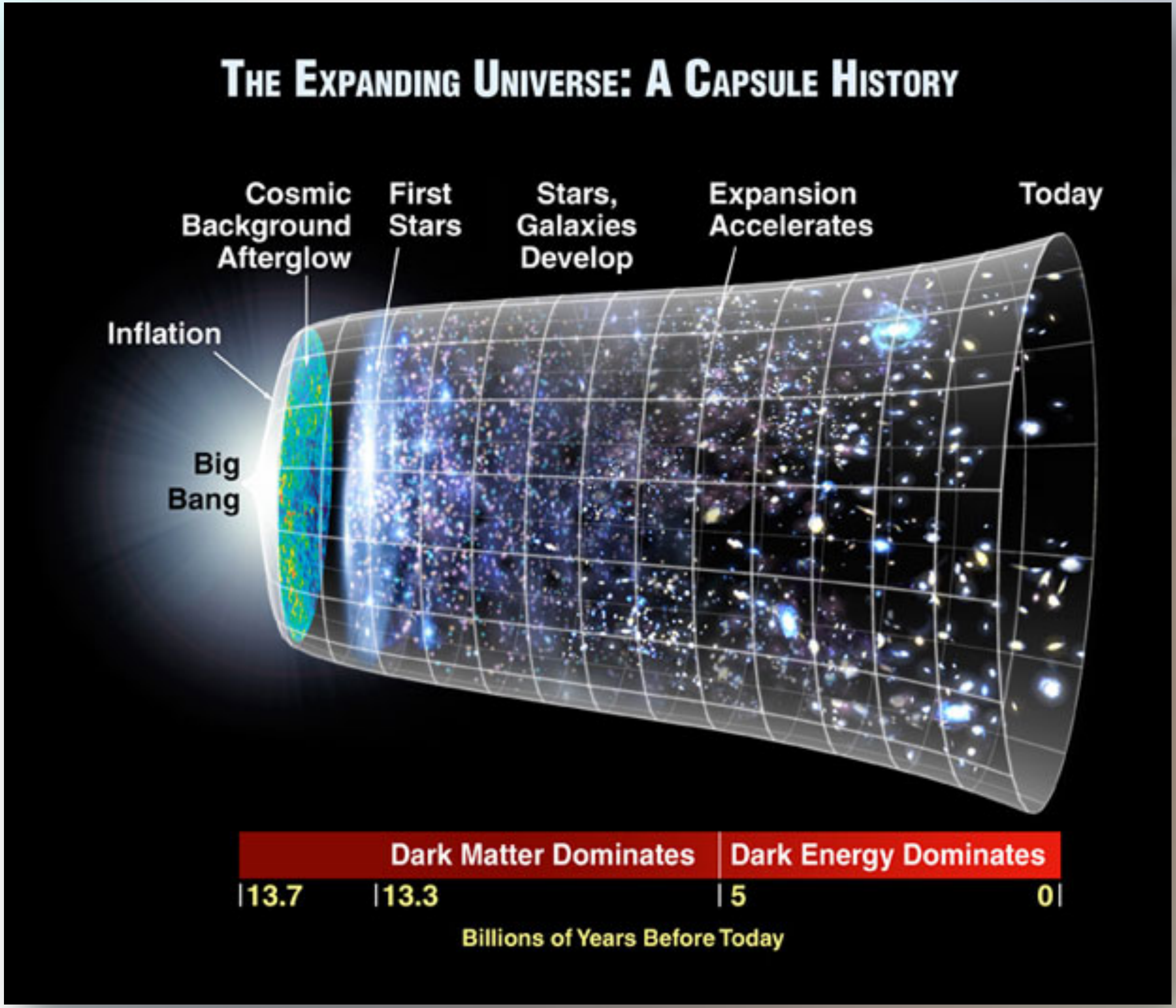


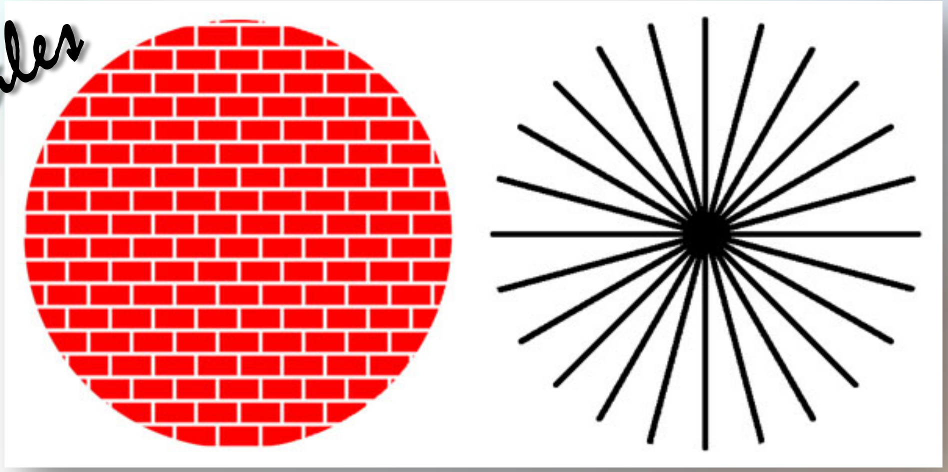
Photo: NASA

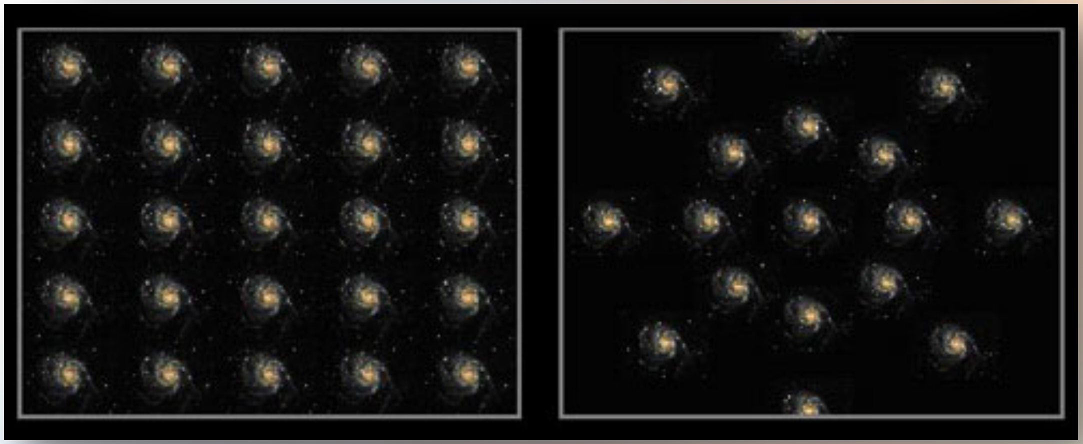
Cosmological principles

Two pillars of the Standard Model

Homogeneity **Isotropy**

Large Scales

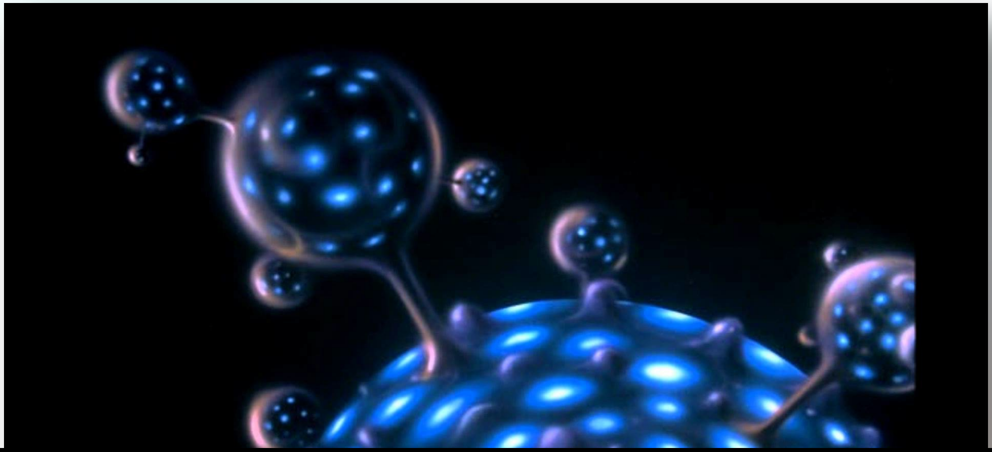


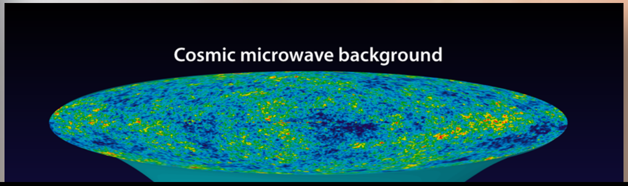


Why do we care?

Inflation homogenizes and isotropizes the Universe

Chaotic Inflation

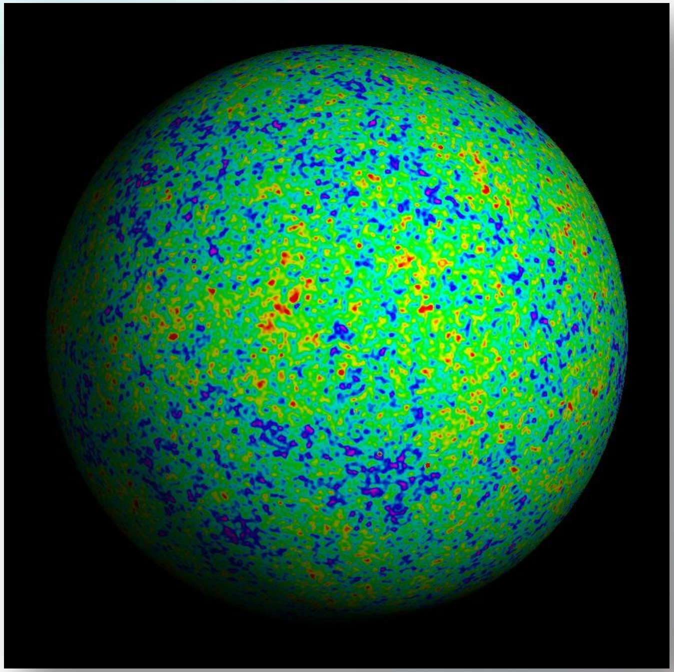




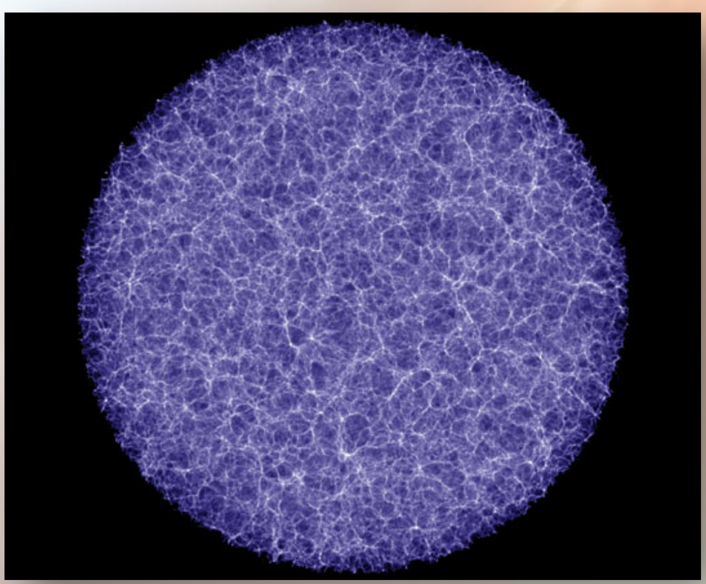
To be tested ...

Observational tests

Cosmic Microwave Background

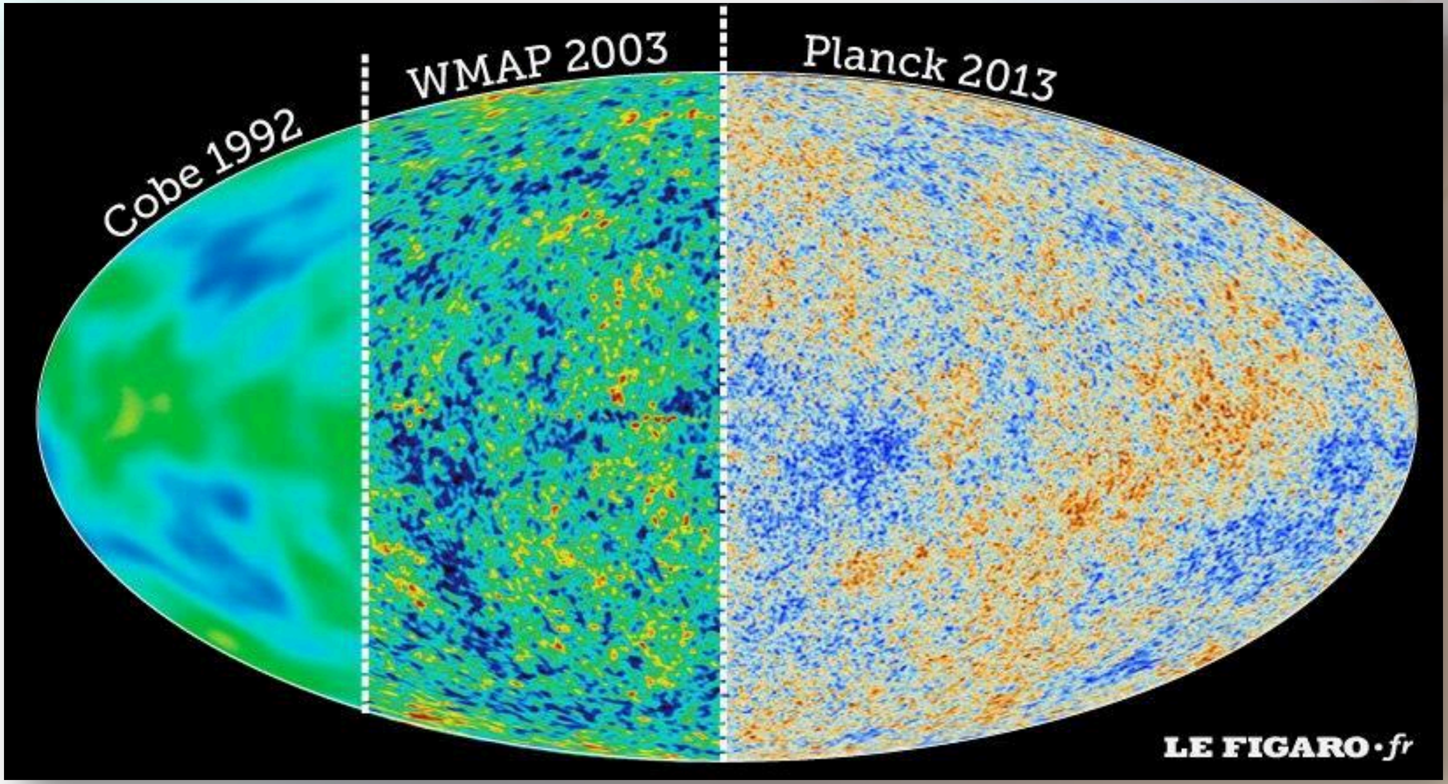


Large Scale Structure



Cosmic microwave background - measurements

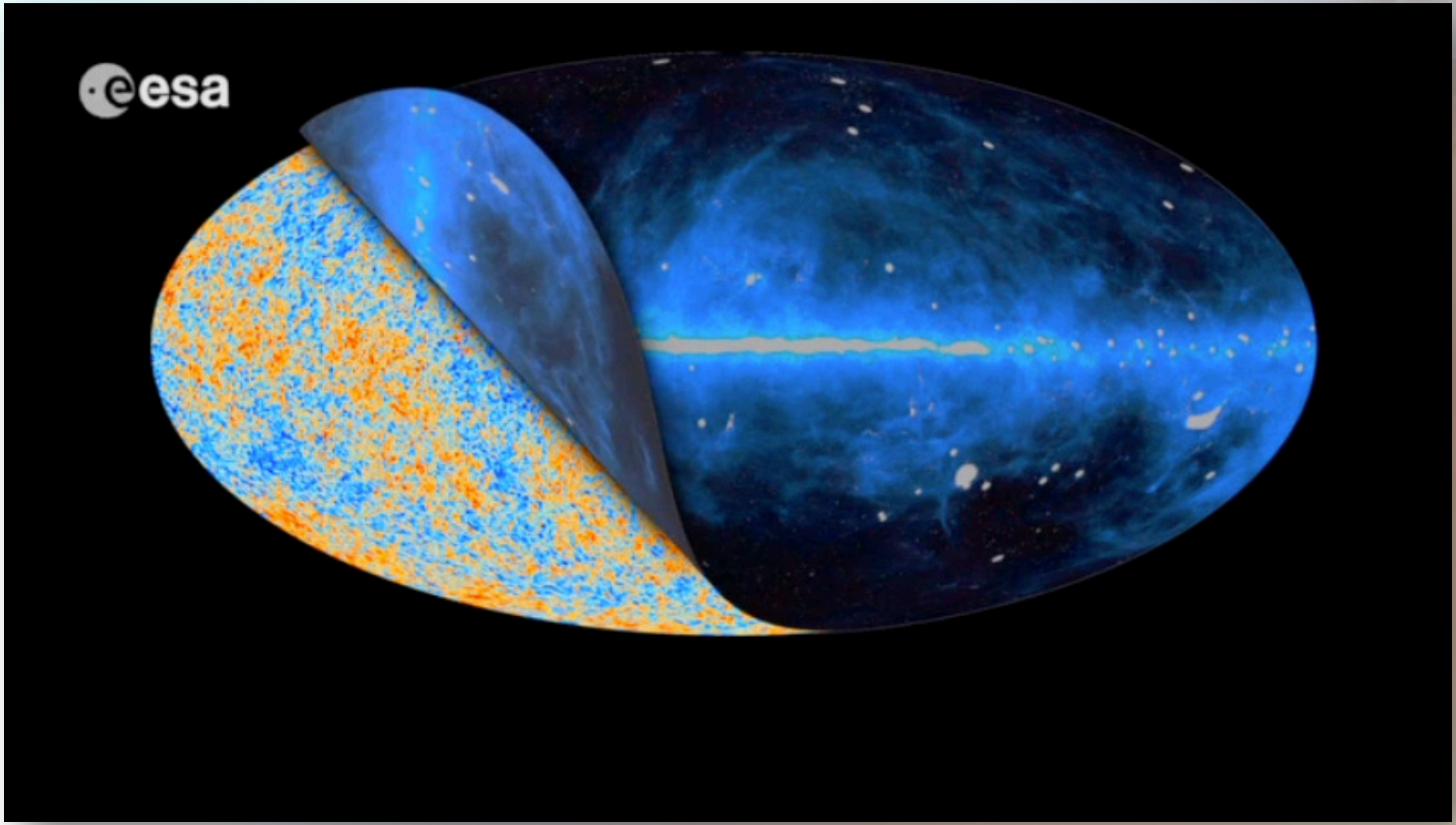
Full Sky (Temperature)



From data to CMB

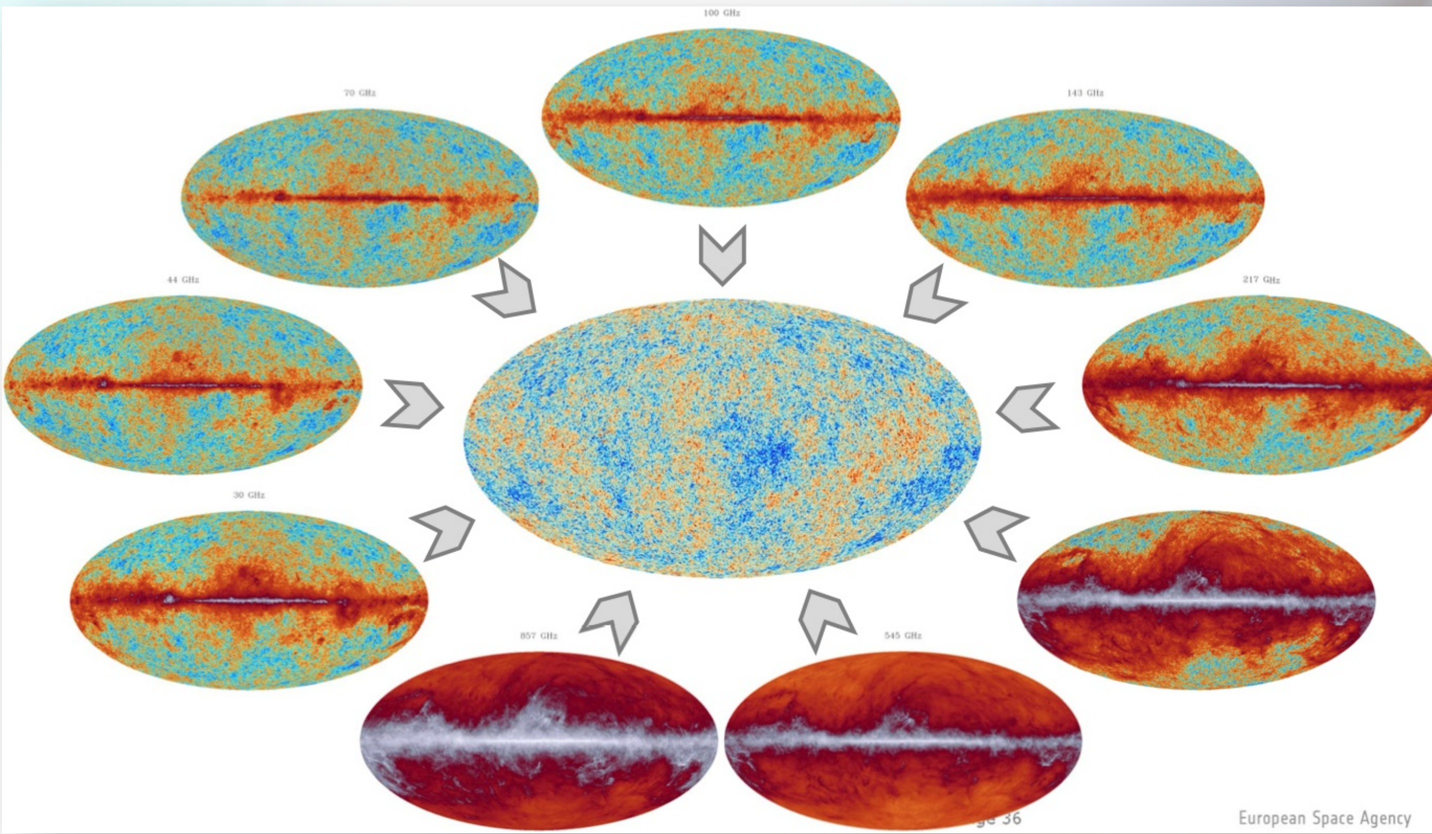
Noise and foregrounds must be removed.

Component Separation



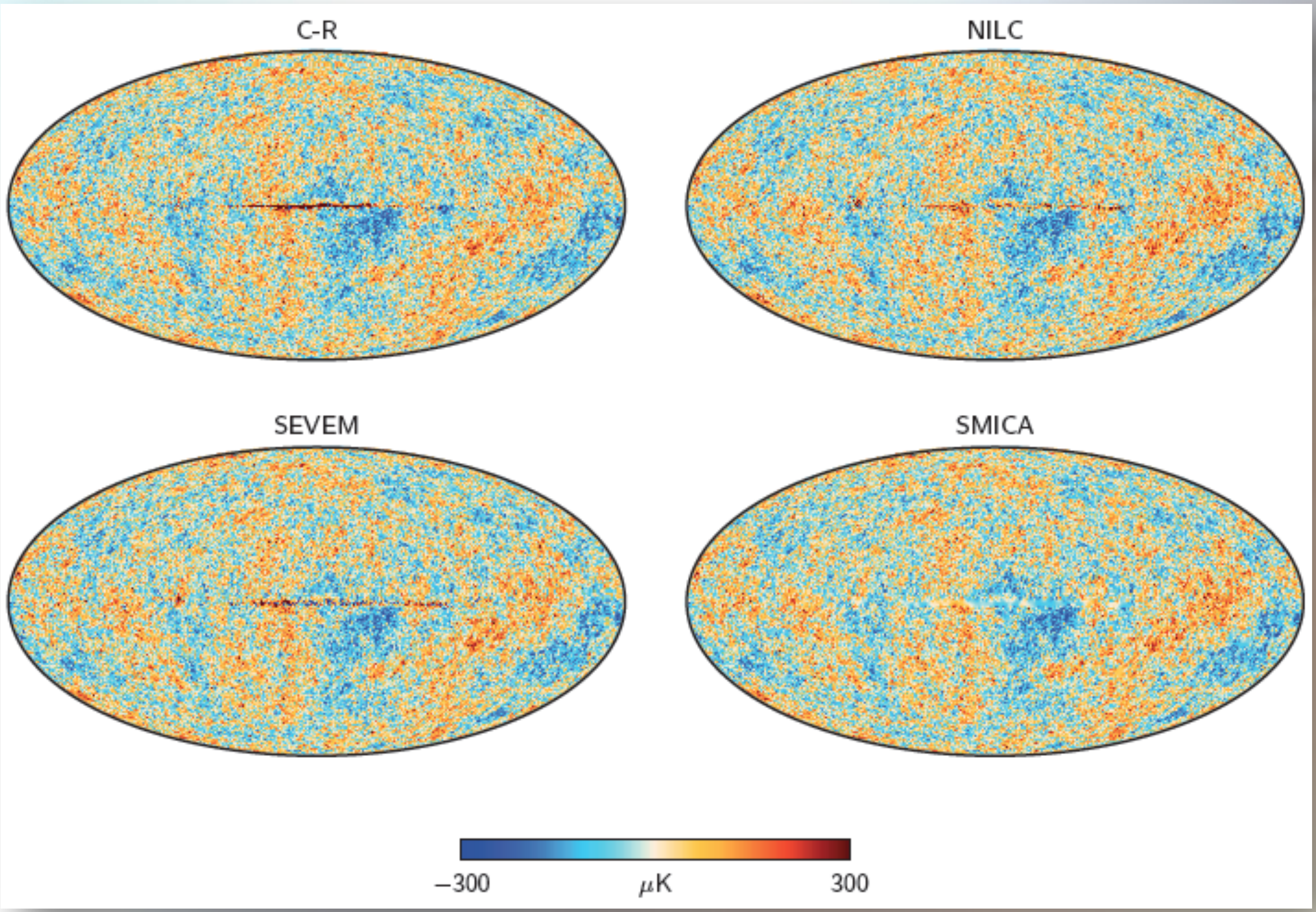
CMB foreground removal

Planck Frequency Channels

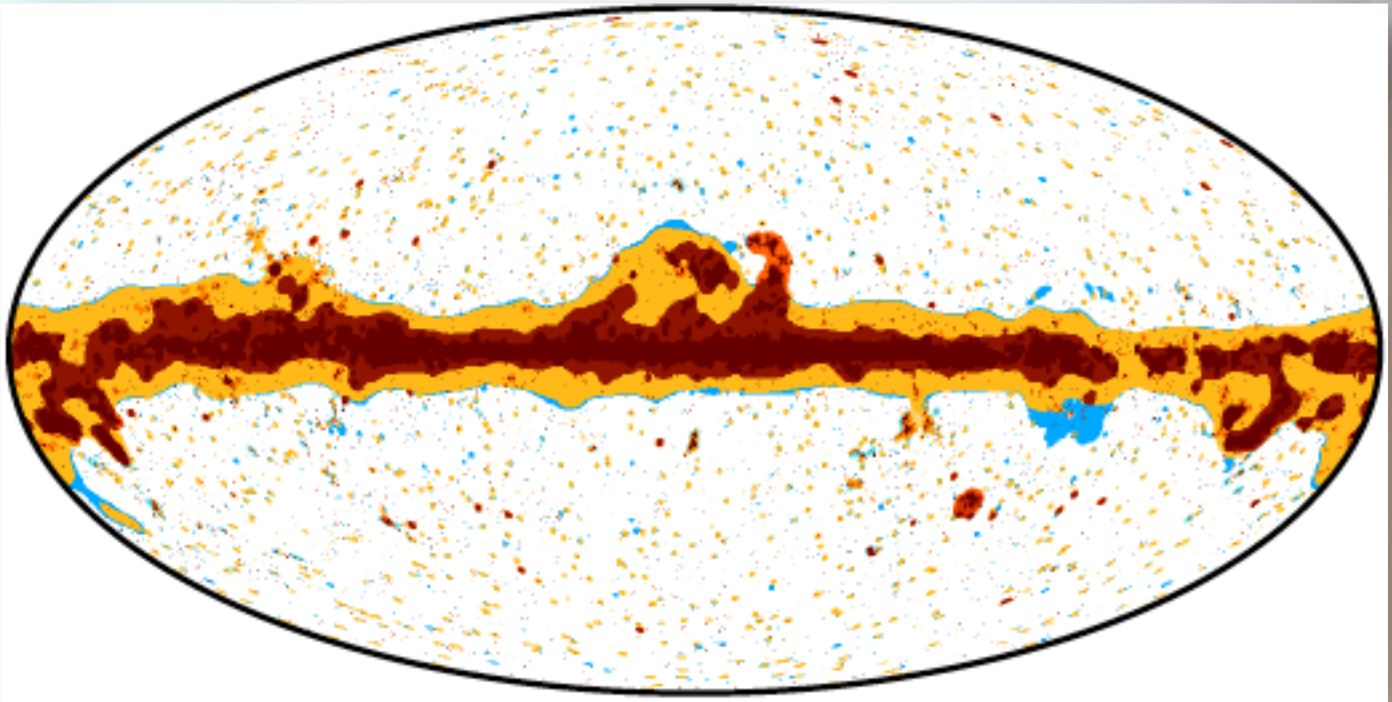


Cleaned maps

4 Planck Maps



Masks

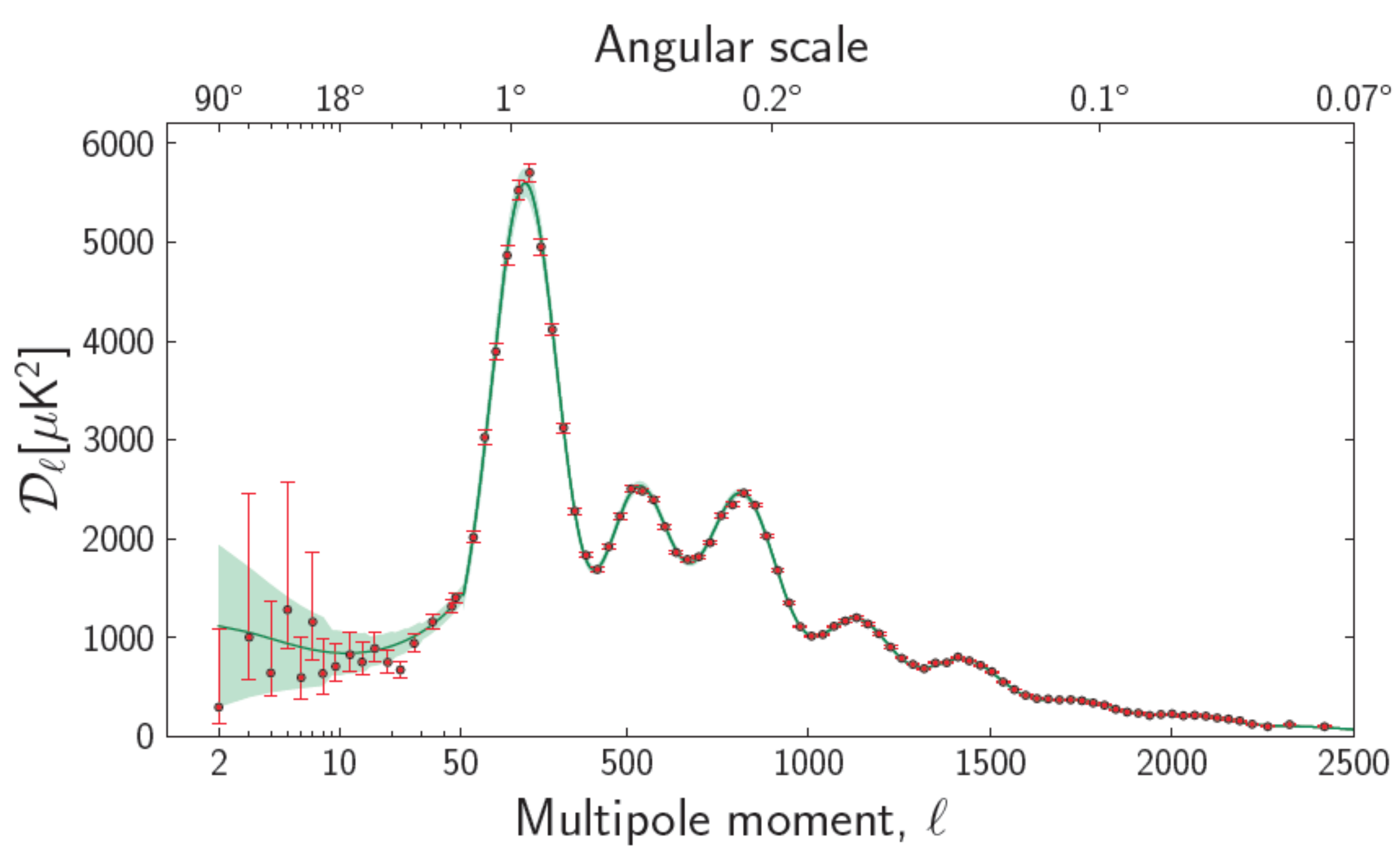


Planck Collaboration 2013

Temperature angular power spectrum

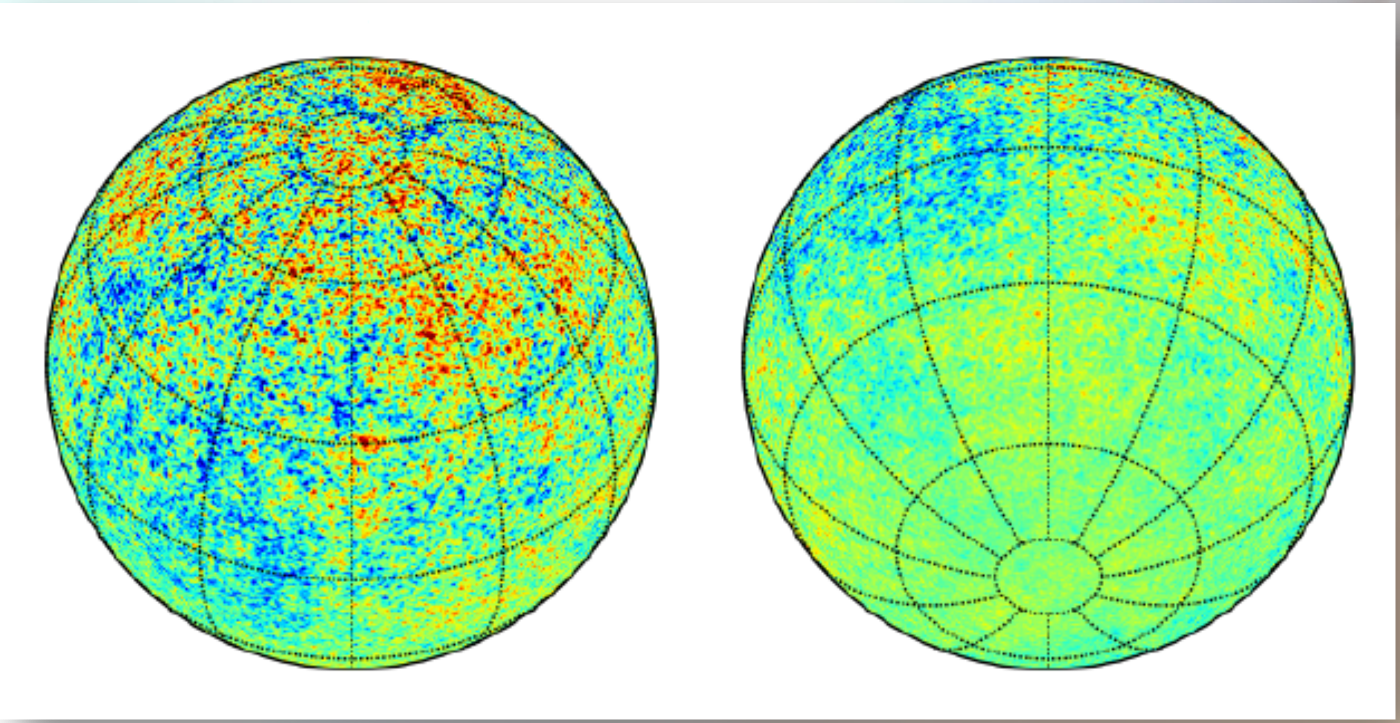
Includes all interesting information if isotropy and Gaussianity assumed.

Two-point Correlations



Planck Collaboration 2013

Is the CMB statistically isotropic?



Planck Collaboration 2013

Evidence for anisotropy: first claims

The Astrophysical Journal, 605:14–20, 2004 April 10

ASYMMETRIES IN THE COSMIC MICROWAVE BACKGROUND ANISOTROPY FIELD

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Mon. Not. R. Astron. Soc. **354**, 641–665 (2004)
doi:10.1111/j.1365-2966.2004.08229.x

Testing the cosmological principle of isotropy: local power-spectrum estimates of the *WMAP* data

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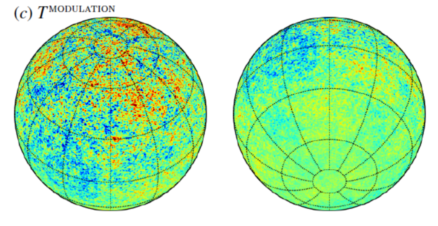
Dipole modulation (WMAP)

Phenomenological Model

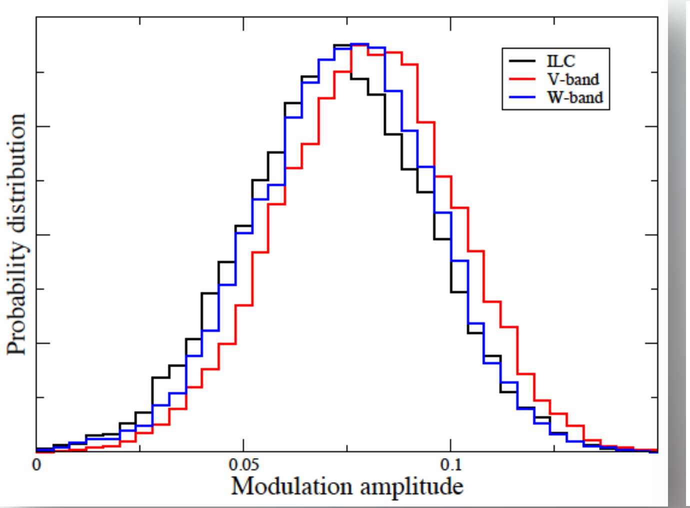
Gordon et al. 2005

$$\frac{\Delta T}{T}|_{\rm mod}(\hat{n}) = (1 + A\,\hat{n}\cdot\hat{p})\frac{\Delta T}{T}|_{\rm iso}(\hat{n})$$

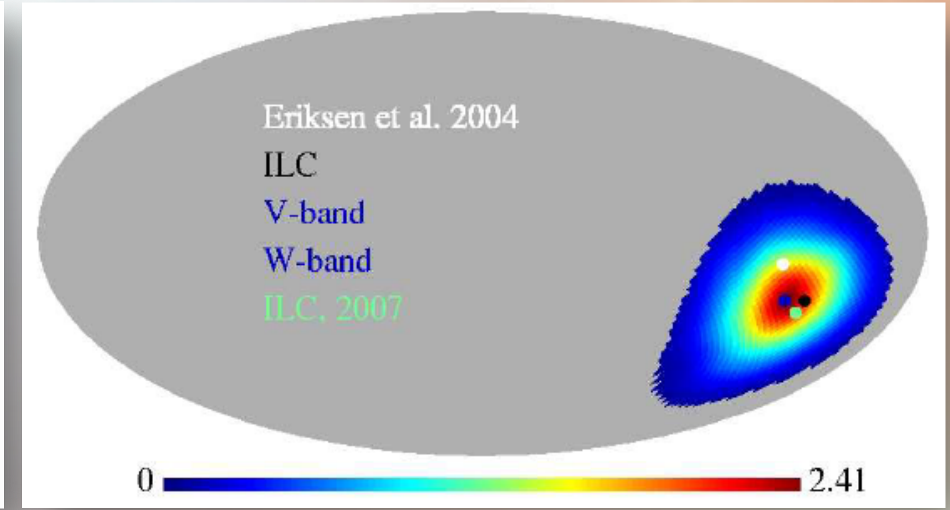


Likelihood Analysis

Amplitude



Direction



Hoftuft et al. 2009

Dipole modulation (Planck)

$$\mathbf{d}(\hat{n}) = [1 + f(\hat{n})]\mathbf{s}(\hat{n}) + \mathbf{n}(\hat{n}) \quad \Leftrightarrow \quad \mathcal{L}(A,p,q,n) \propto \frac{e^{-\frac{1}{2}d^T\left(\mathrm{M^TSM+N}+\alpha\sum_i f_i f_i^T\right)^{-1}d}}{\sqrt{|\mathrm{M^TSM+N}+\alpha\sum_i f_i f_i^T|}}$$

Gibbs Sampling (Commander)

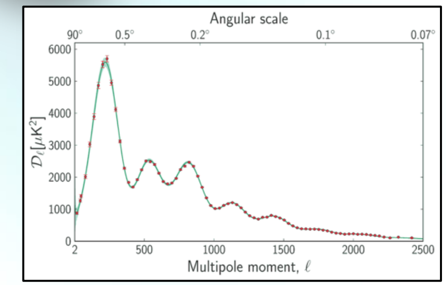
Data set	FWHM [°]	A	(l,b) [°]	$\Delta \ln \mathcal{L}$	Significance
Commander	5.0	$0.078^{+0.020}_{-0.021}$	$(227,-15) \pm 19$	8.8	$3.5\,\sigma$
NILC	5.0	$0.069^{+0.020}_{-0.021}$	$(226,-16) \pm 22$	7.1	$3.0\,\sigma$
SEVEM	5.0	$0.066^{+0.021}_{-0.021}$	$(227,-16) \pm 24$	6.7	$2.9\,\sigma$
SMICA	5.0	$0.065^{+0.021}_{-0.021}$	$(226,-17) \pm 24$	6.6	$2.9\,\sigma$
WMAP-5 ILC.	4.5	$0.072^{+0.021}_{-0.021}$	$(224,-22) \pm 24$	7.3	$3.3\,\sigma$

Planck Collaboration 2013

Model independence?

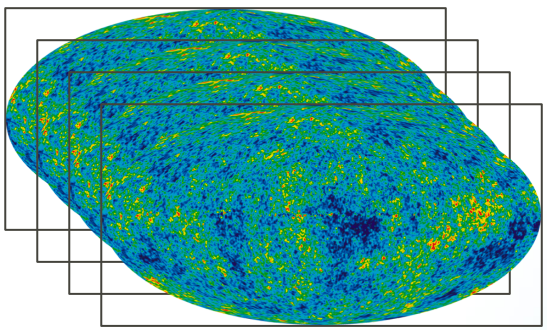
Local-variance estimator (frequentist approach)

Akrami et al. 2014

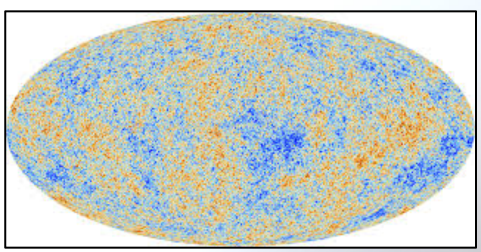


+

- ★ Noise
- ★ Foregrounds
- ★ Beam
- ★ …

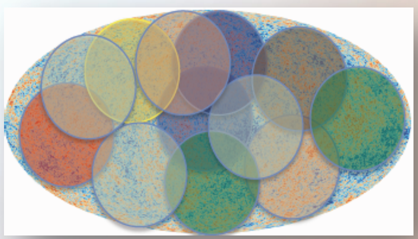


1000 simulations

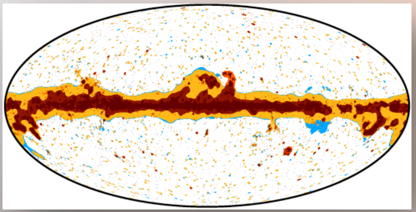


Data

3072 disks (HEALPix N_{side} = 16)



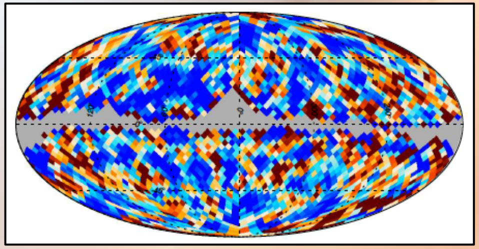
Mask



Compute temperature variance
Include only unmasked pixels

Low-resolution and almost full-sky map of the local variance

Subtract variance mean



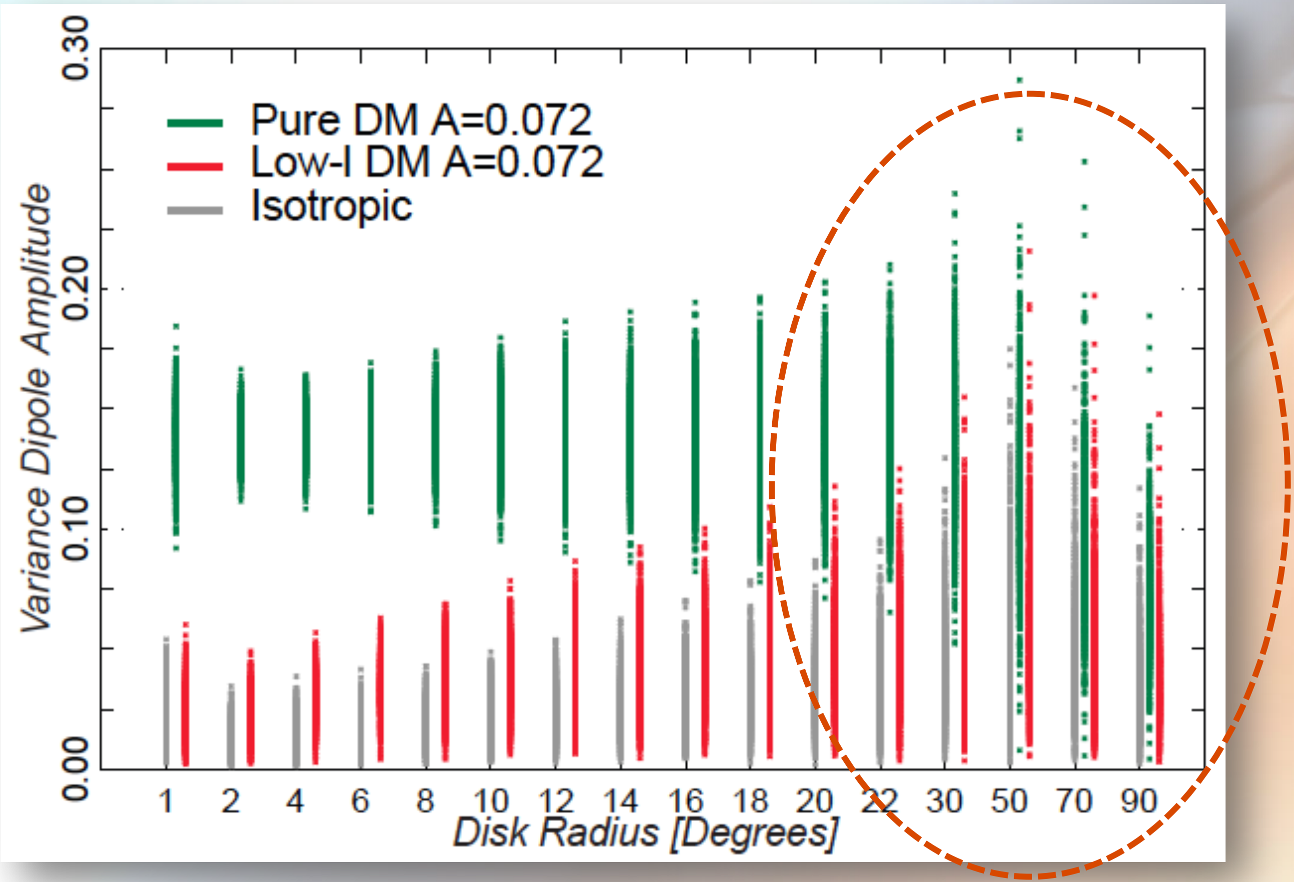
Mask and inverse variance weighting

Fit a dipole

(compute amplitudes and directions)

Choosing the disk sizes

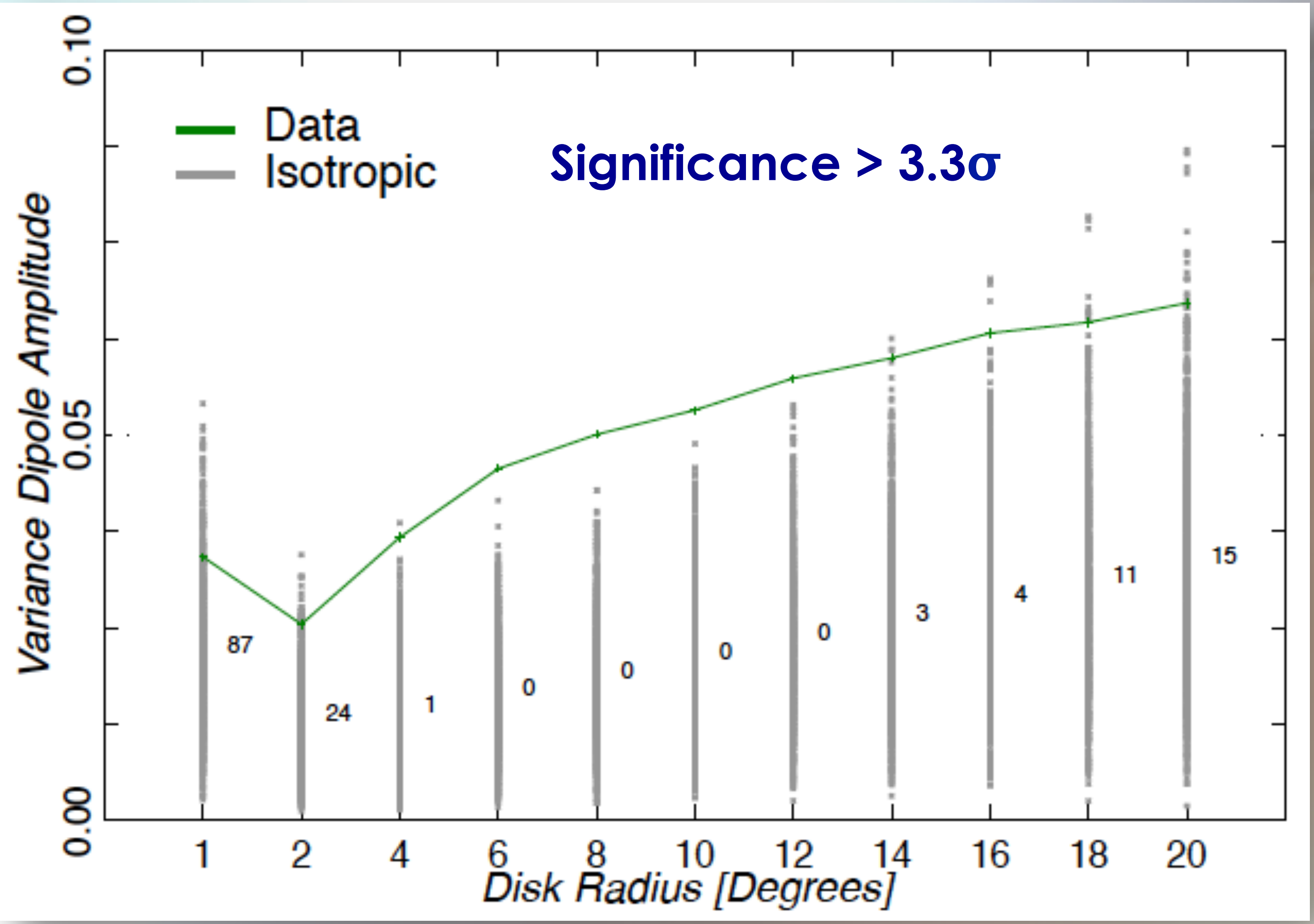
Analysis of anisotropic simulations



- The larger the radius, the more weight is put on the larger angular scales, and hence cosmic variance begins to dominate.
- Takes care of "look-elsewhere effects".

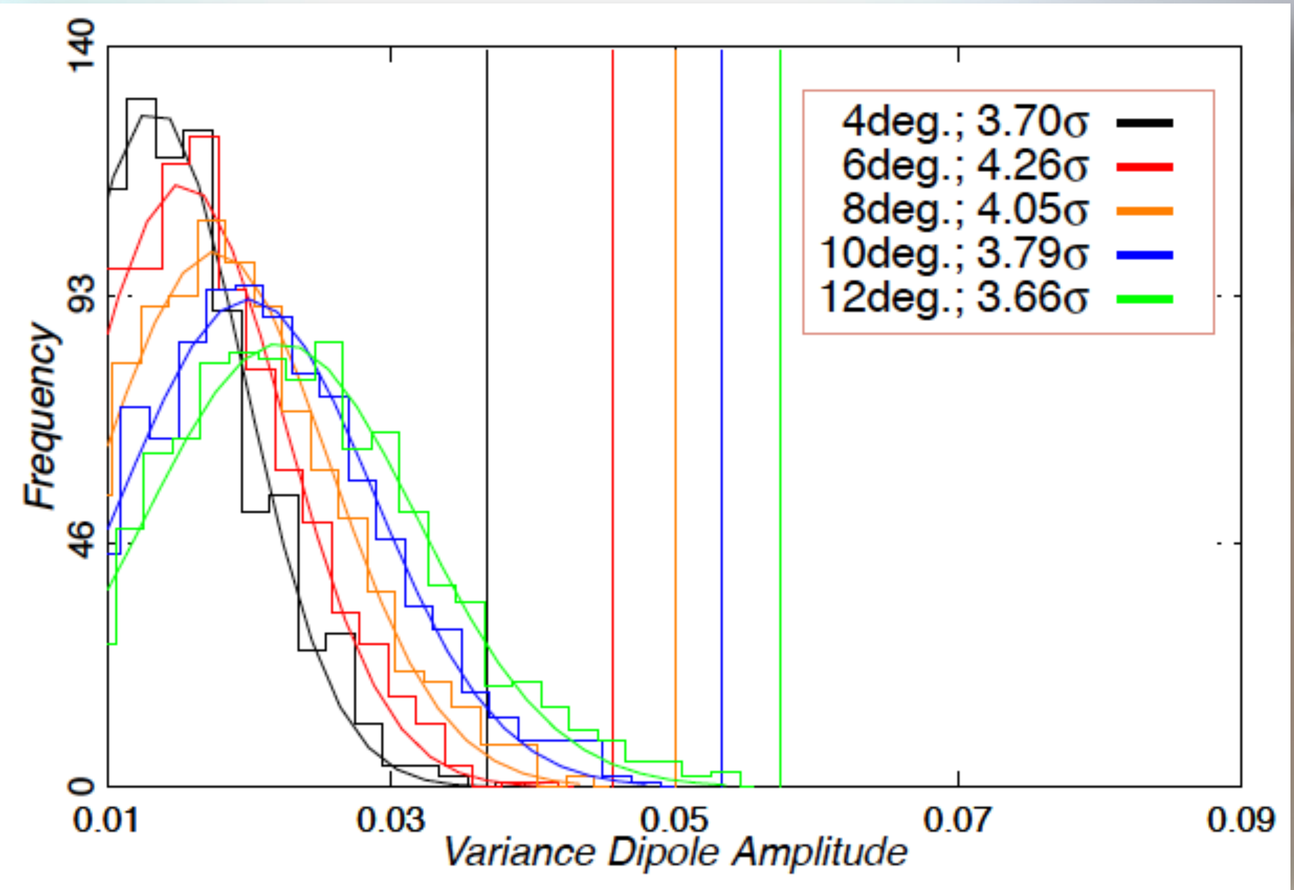
Local-variance estimator

Results: Planck (SMICA) Temperature, 2013 - Amplitude



Local-variance estimator - amplitude

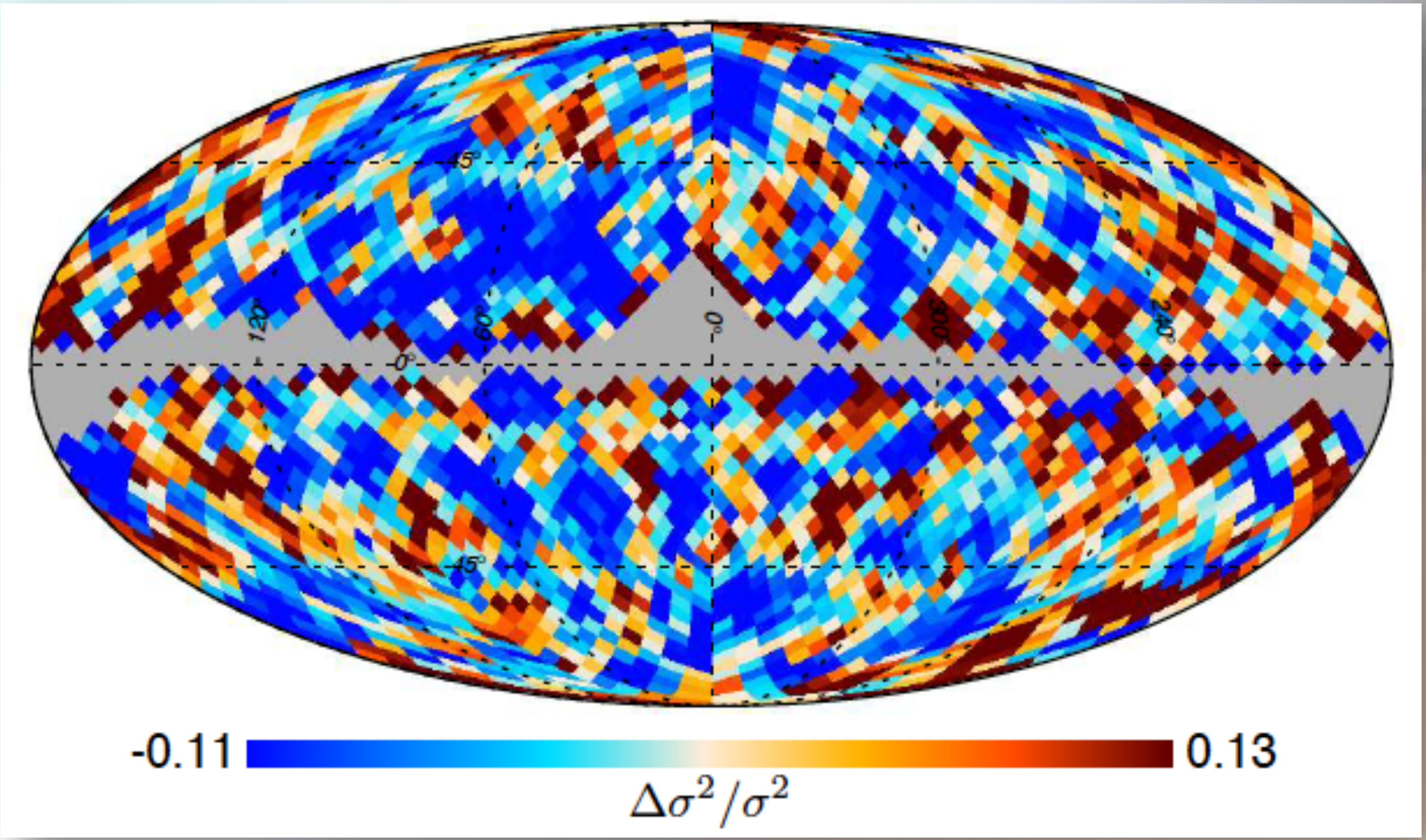
Results: Planck (SMICA) Temperature, 2013 - Histograms



Caution: tails are important!

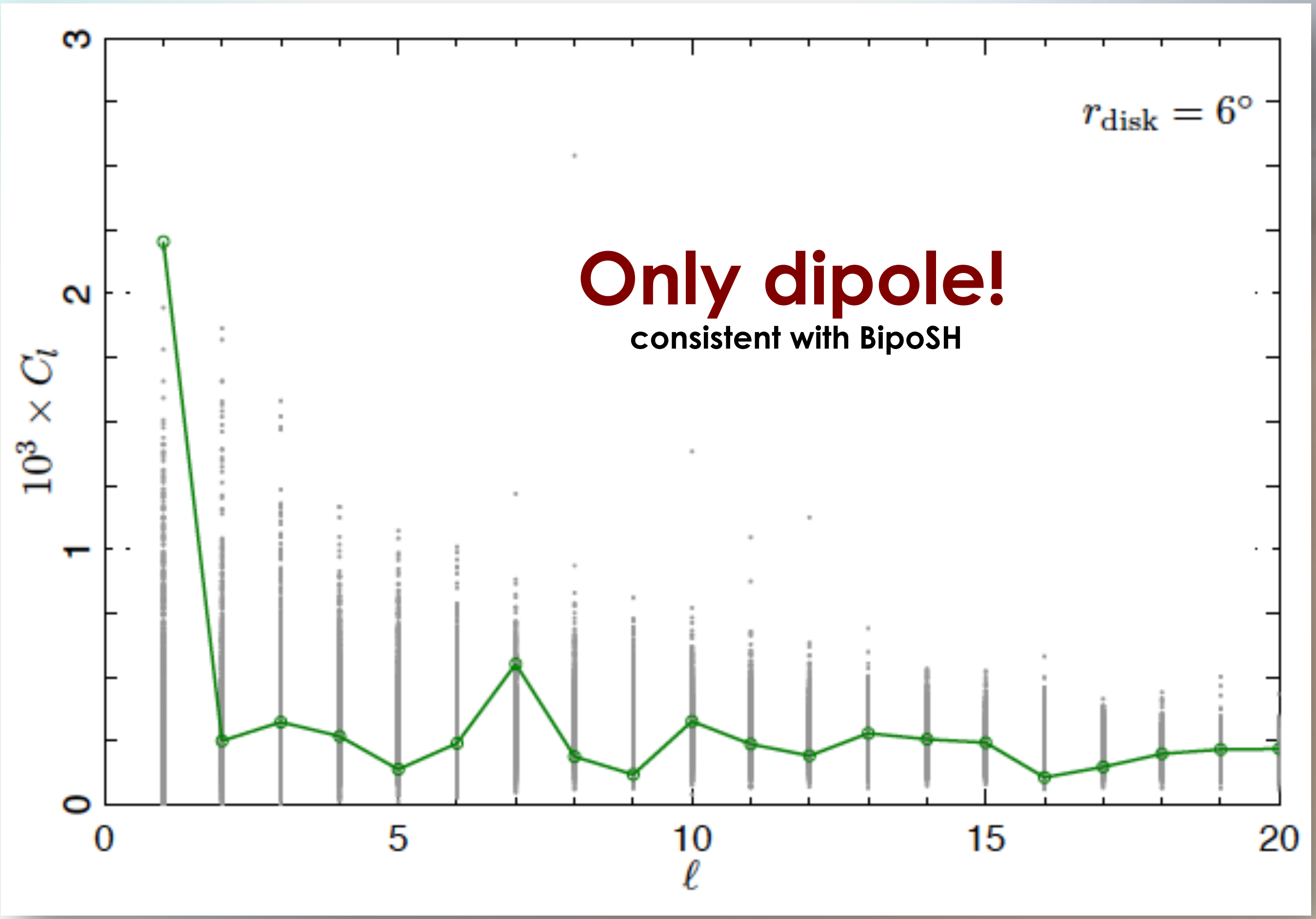
Local-variance estimator

Higher-multipole modulations?



Mean-field subtracted, local-variance map computed with 6° disks for Planck (SMICA) data.

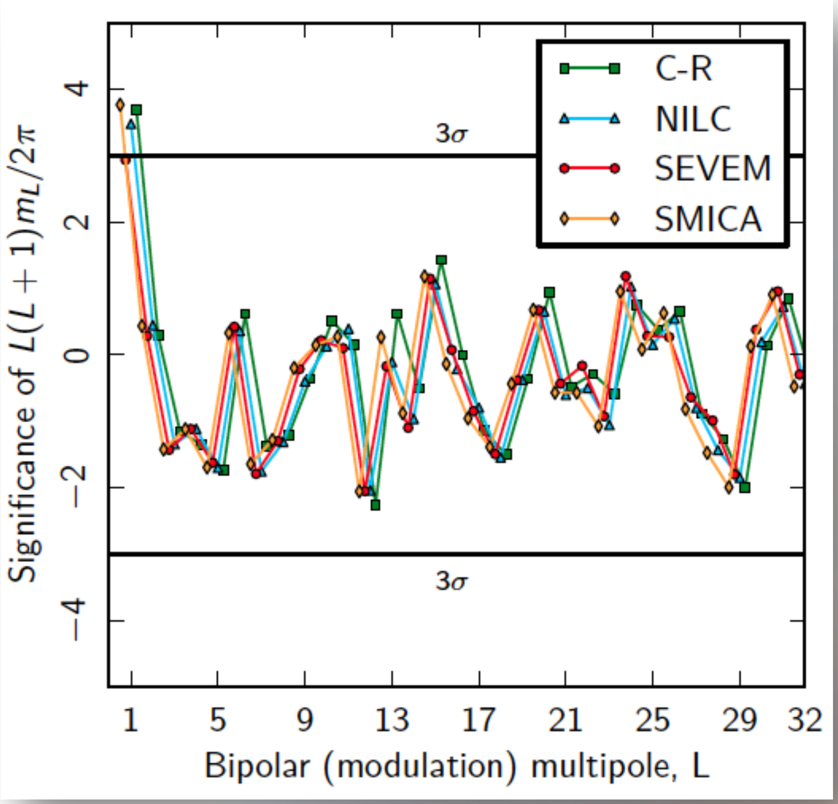
Local-variance estimator – power spectrum



Bipolar Spherical Harmonics (BipoSH)

Hajian and Souradeep 2003&2006

$$A^{LM}_{\ell_1\ell_2} = \sum_{m_1 m_2} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} \rangle C^{LM}_{\ell_1 m_1 \ell_2 m_2}$$



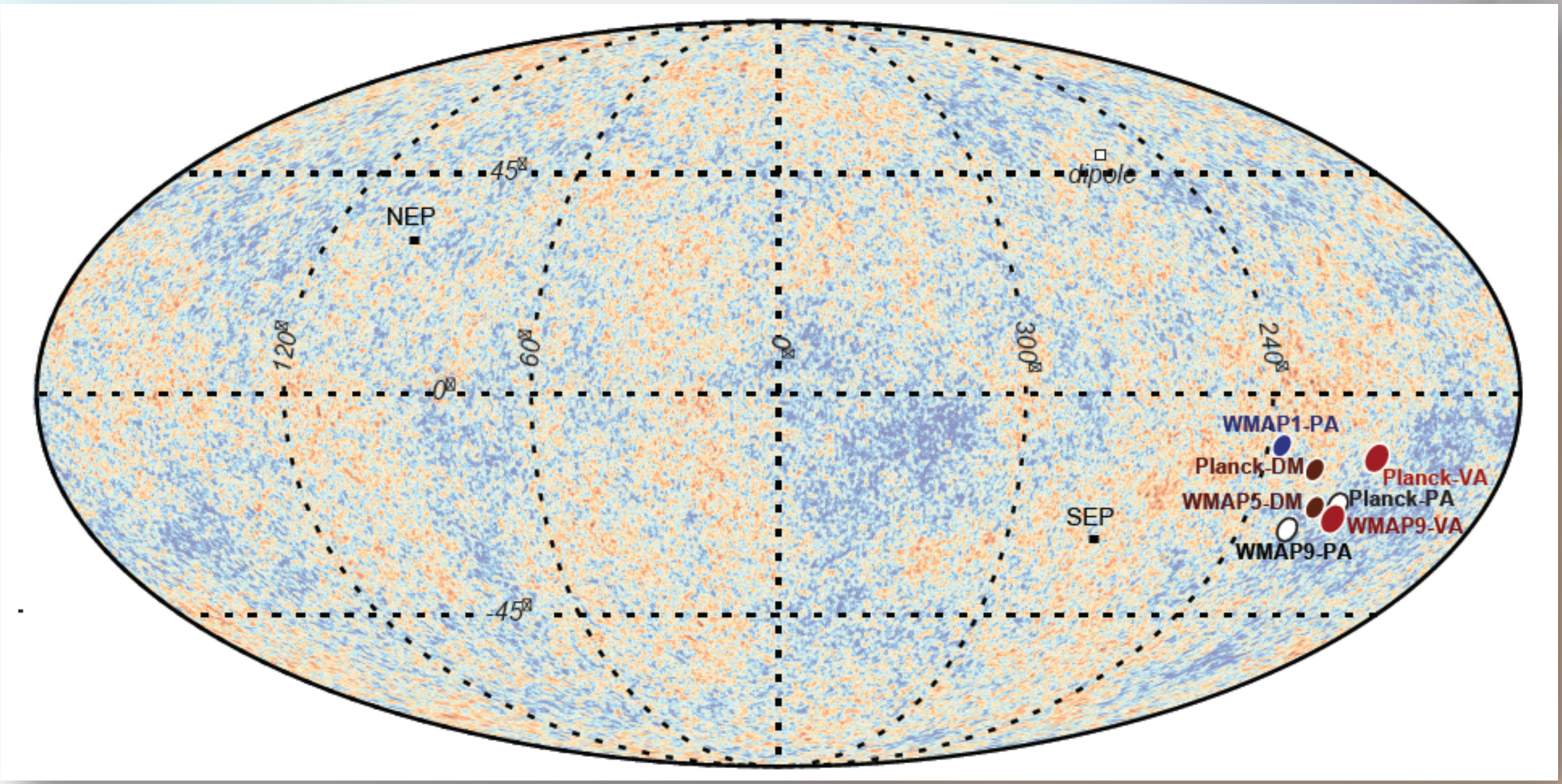
Map	A	(l, b) [°]
C-R	$0.072^{+0.010}_{-0.010}$	(218.9, −21.4)
NILC	$0.070^{+0.010}_{-0.010}$	(220.3, −20.2)
SEVEM	$0.065^{+0.011}_{-0.011}$	(221.7, −21.4)
SMICA	$0.073^{+0.010}_{-0.010}$	(217.5, −20.2)

Planck Collaboration 2013

Local-variance estimator - directions

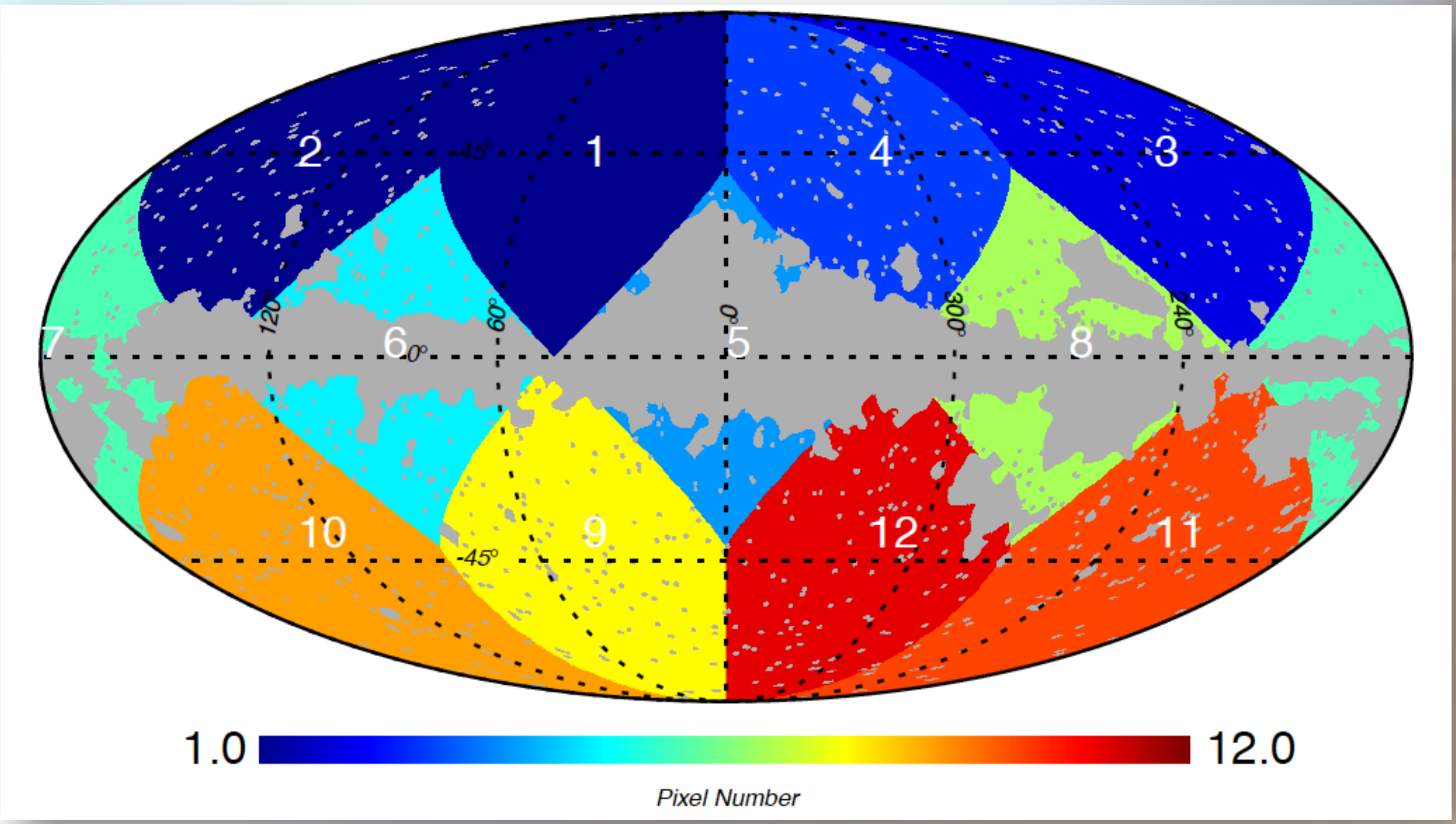
Map	(l,b) [°]	Significance or p-value	Reference
Planck-VA[a]	(212, -13)	0/1000	present work
WMAP9-VA	(219, -24)	5/1000	present work
Planck-DM	(227, -15)	3.5σ	Planck Collaboration (2013d)
WMAP5-DM	(224, -22)	3.3σ	Hoftuft et al. (2009)
Planck-PA	(218, -21)	0/500	Planck Collaboration (2013d)
WMAP9-PA	(227, -27)	7/10000	Axelsson et al. (2013)

Local-variance estimator - directions



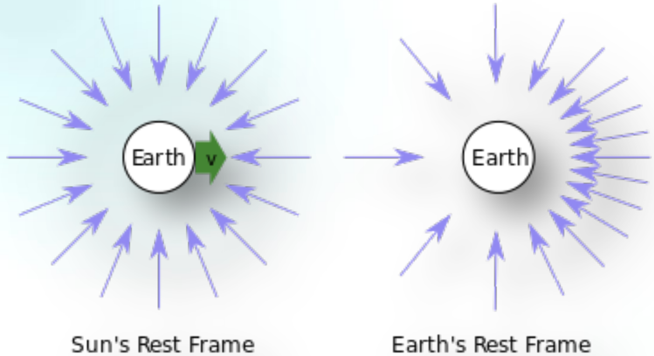
Local power-spectrum estimates

Axelsson et al. 2013



12 sky patches - regions are delineated by the intersection of the 12 HEALPix base pixels with the WMAP9 KQ85 mask.

CMB doppler boosting

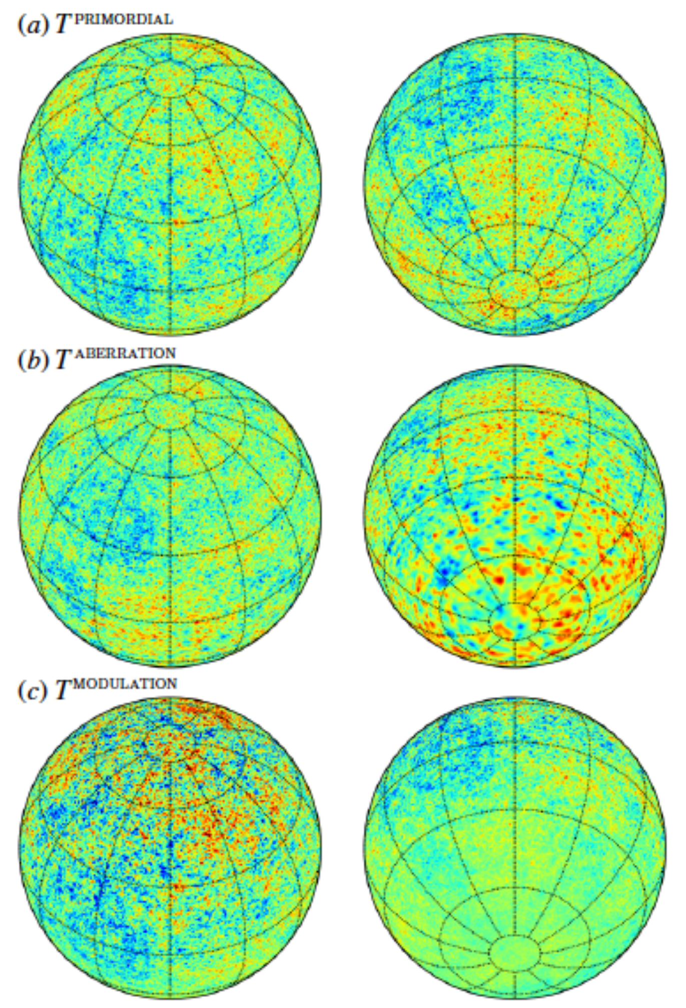


Special relativity predicts frequency-dependent intrinsic dipole modulation and aberration (due to the motion of the solar system barycenter with respect to the CMB):

- **Aberration**: Spots are smaller in the direction of Earth's motion, of order β = v/c = 0.00123. Correlates l -> l+1
- **Dipole modulation**: Features are enhanced in the direction of Earth's motion, frequency-dependent.

Planck measure the Earth's velocity independently of the CMB dipole:

v = 384± 78 (stat) ± 115 (sys) km/s



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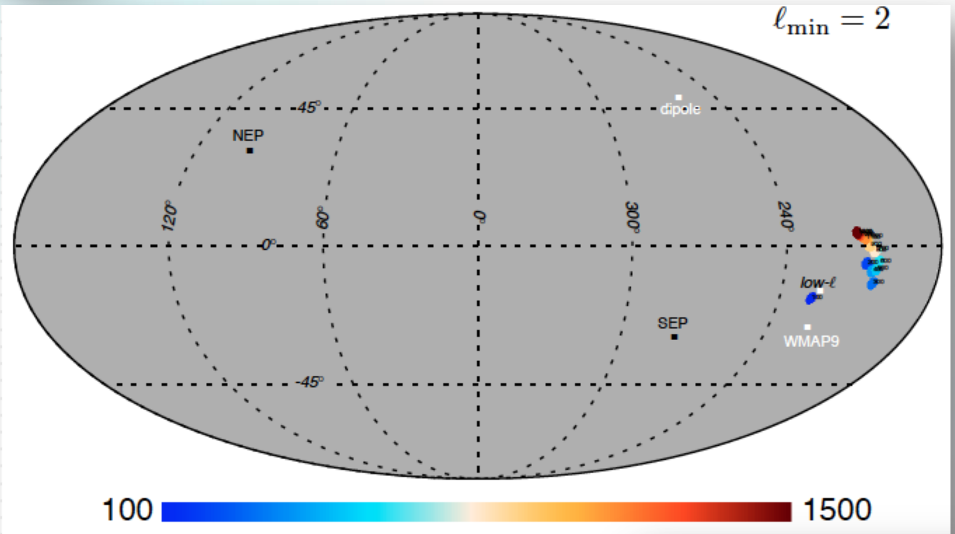
CMB doppler boosting



Power asymmetry dominant at low multipoles

Large-scale asymmetry seems to exist.

What Next?

Interesting questions

① Is the asymmetry significant?

② Is it cosmological?

③ Even if cosmological, do we need new physics to explain it?

④ If yes, what is the new physics? (theoretical explanation)

⑤ Have we reached the cosmic variance limit?

⑥ How does the asymmetry change with scales?

⑦ How to increase the significance if real?

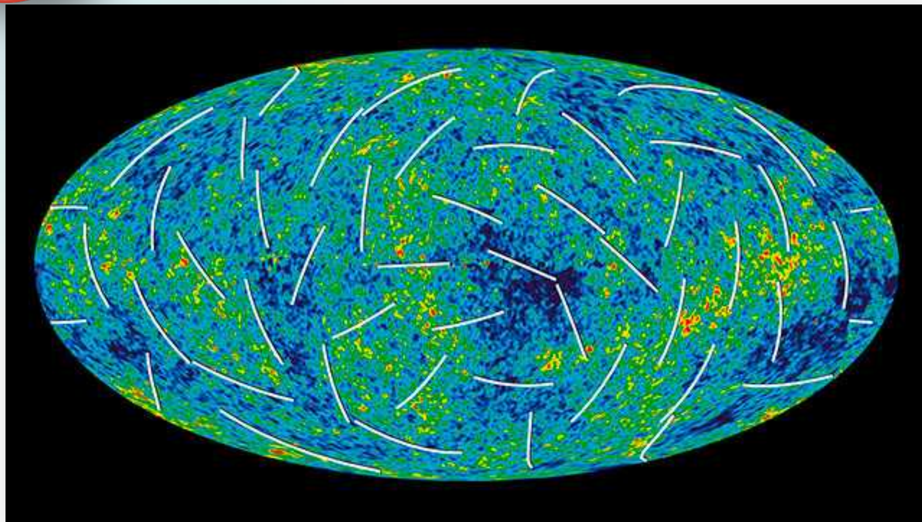
Other statistical techniques

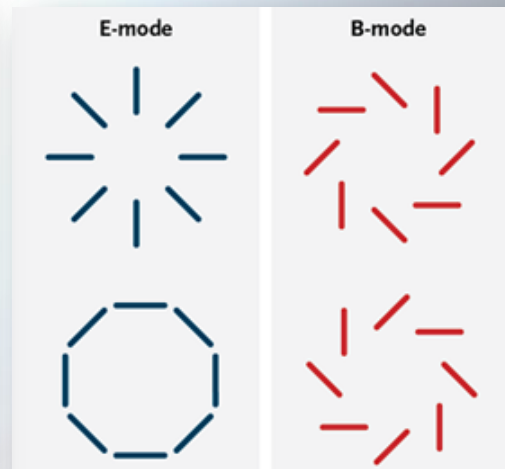
Confirmation

↓

Weakens a-posteriori criticisms

CMB polarization

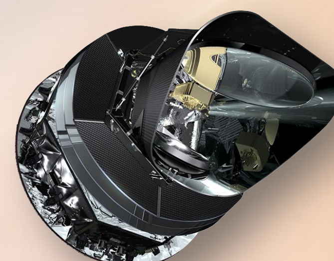




✓ Different systematics

✓ Different physics

Planck 2014

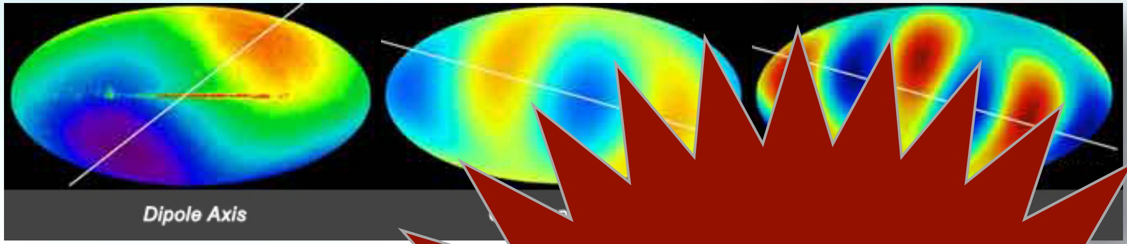


If the same asymmetry direction

1. Increases significance
2. Weakens “a-posteriori” criticisms

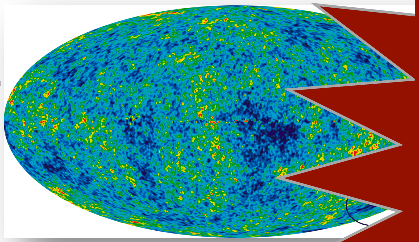
Other anomalies

Quadrupole - octopole alignment



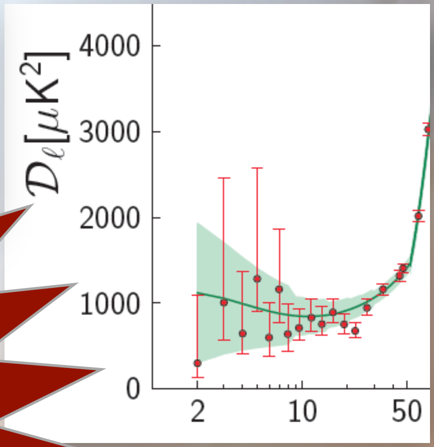
Tegmark et al. 2003, de Oliviera-C…

Cold spot



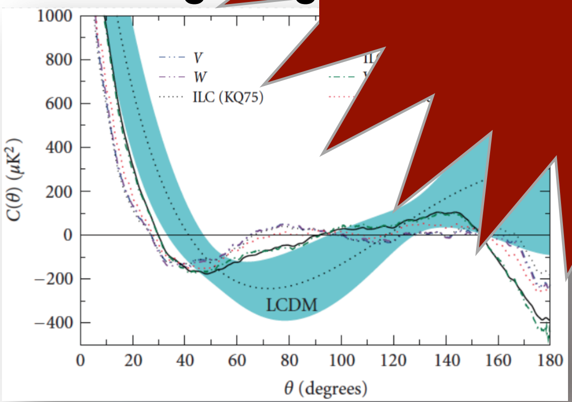
Vielva et al. 2004, Cruz …

Low quadrupole power



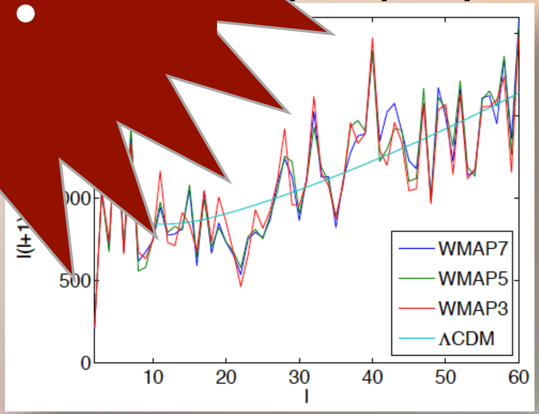
…et al. 2003; Tegmark et al. 2003

Lack of large-…



Spergel et al. 2003, Copi et al. 2007

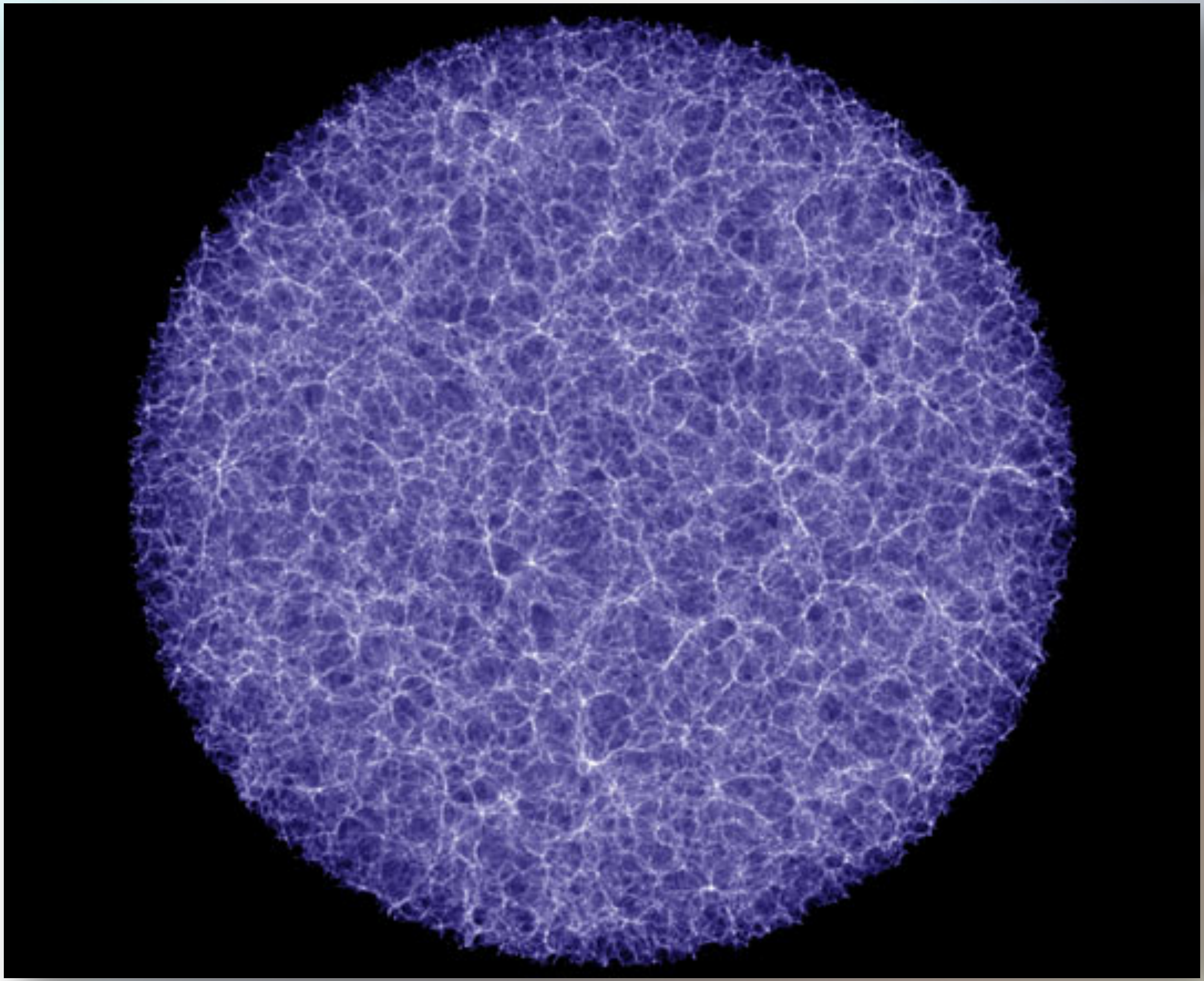
…ltipole parity



Land et al. 2005, Kim et al. 2012

Single explanation for all?

Other data sets (LSS)



Other data sets (LSS)

Dipolar modulation in number counts of WISE-2MASS sources

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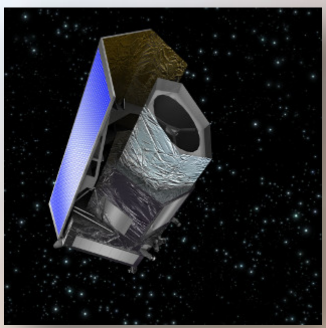
[3] *Institute for Astronomy, University of Hawaii 2680 Woodlawn Drive, Honolulu, HI, 96822*

1 July 2014

ABSTRACT
We test the statistical isotropy of the universe by analyzing the distribution of WISE extragalactic sources that were also observed by 2MASS. We pay particular attention to color cuts and foreground marginalization in order to cull a uniform sample of extragalactic objects and avoid stars. We detect a dipole gradient in the number-counts with an amplitude of $\sim$0.05, somewhat larger than expectations based on local structures corresponding to the depth and (independently measured) bias of our WISE-2MASS sources. The direction of the dipole, $(l, b) \simeq (310^\circ, -15^\circ)$, is in reasonably good agreement with that found previously in the (shallower) 2MASS Extended Source Catalog alone. Interestingly, the dipole direction is not far from the direction of the dipolar modulation in the CMB found by Planck, and also fairly closely matches large-scale-structure bulk-flow directions found by various groups using galaxies and type Ia supernovae. It is difficult, however, to draw specific conclusions from the near-agreement of these directions.

Other data sets (LSS)

1. We know that the amplitude dies off for l > 600.
2. It cannot be pure (all-scale) dipolar modulation.
3. The largest scales on LSS are much smaller than the smallest scales on the CMB.
4. Need better probes:



Euclid

5. Need better models:

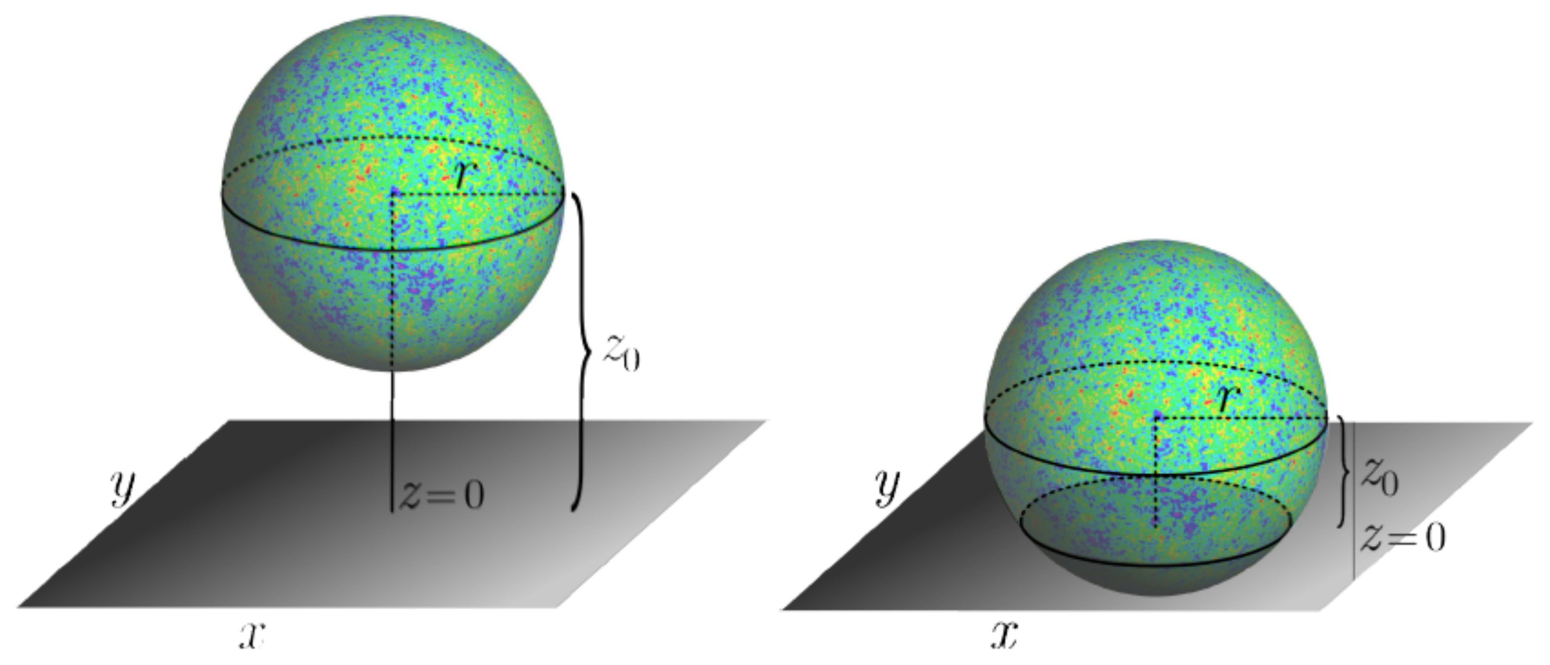
$$\frac{\Delta T}{T}(\hat{n}) = (1 + A(l)\hat{n}.\hat{p})s(\hat{n})$$

Scale-dependent dipolar modulation

An example

Jazayeri, Akrami et al. 2013

Inflationary power asymmetry from primordial domain walls



Anisotropies in curvature perturbations

Scale dependent: $1/\ell$

$$\langle \mathcal{R}_{\mathbf{k}} \mathcal{R}_{\mathbf{q}} \rangle = \frac{2\pi^2}{k^3} \mathcal{P}_0 \left[(2\pi)^3 \delta^3(\mathbf{k}+\mathbf{q}) - (2\pi)^3 \frac{\beta}{2q^3} \frac{k^2 q_z + q^2 k_z}{k_z + q_z} \delta^2(\mathbf{q}_{||} + \mathbf{k}_{||}) \right]$$

Structure of asymmetry:

Two-point correlation and variance in real space

$$\delta\langle\mathcal{R}^2(\mathrm{x})\rangle = -\frac{\beta}{4}\mathcal{P}_0 \int dk_z dq_z dq_{||} q_{||} \frac{q_{||}^2 + k_z q_z}{(q_{||}^2 + k_z^2)^{\frac{3}{2}}(q_{||}^2 + q_z^2)^{\frac{3}{2}}} e^{i(k_z+q_z)z}$$

$$\delta\langle\mathcal{R}^2(\mathrm{x})\rangle \simeq \beta\mathcal{P}_0 \ln\left|1 + \frac{r}{z_0}\cos\theta\right| + \widehat{C}$$

$$\delta\langle\mathcal{R}^2(\mathrm{x})\rangle = \mathcal{P}_0 \sum_\ell a_\ell P_\ell(\cos\theta)$$

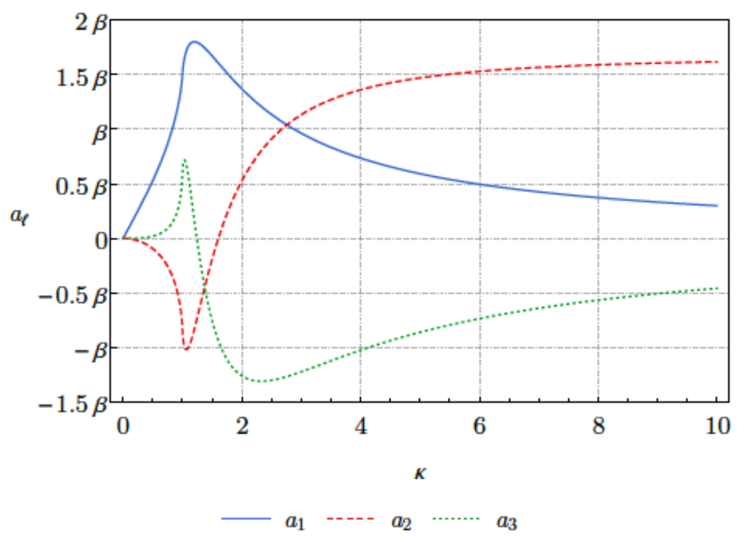
$$a_\ell = \frac{(2\ell+1)\beta}{2}\int_{-1}^{+1} d(\cos\theta) P_\ell(\cos\theta) \ln\left|1 + \kappa\cos\theta\right|$$

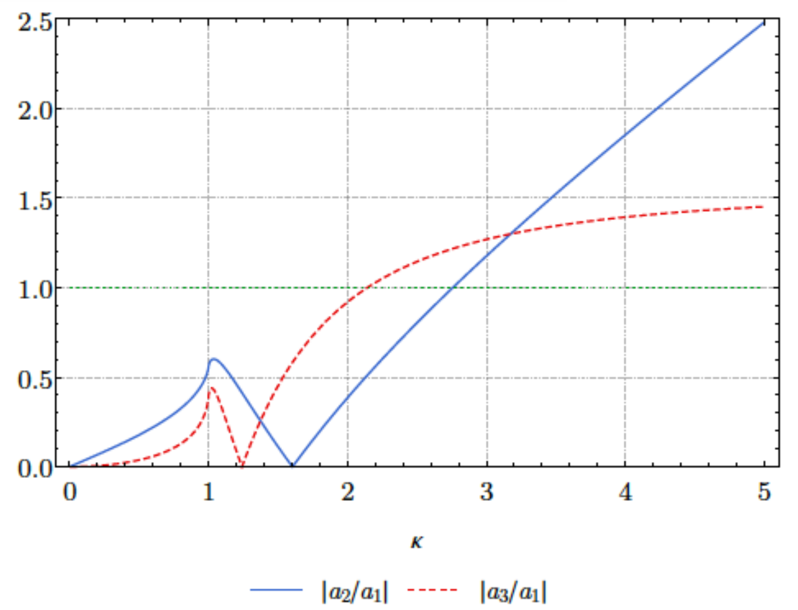
Inflationary power asymmetry from primordial domain walls

$$a_1 = -\frac{3\beta}{4\kappa^2}\left[(\kappa^2-1)\ln\left|\frac{1-\kappa}{1+\kappa}\right| - 2\kappa\right],$$

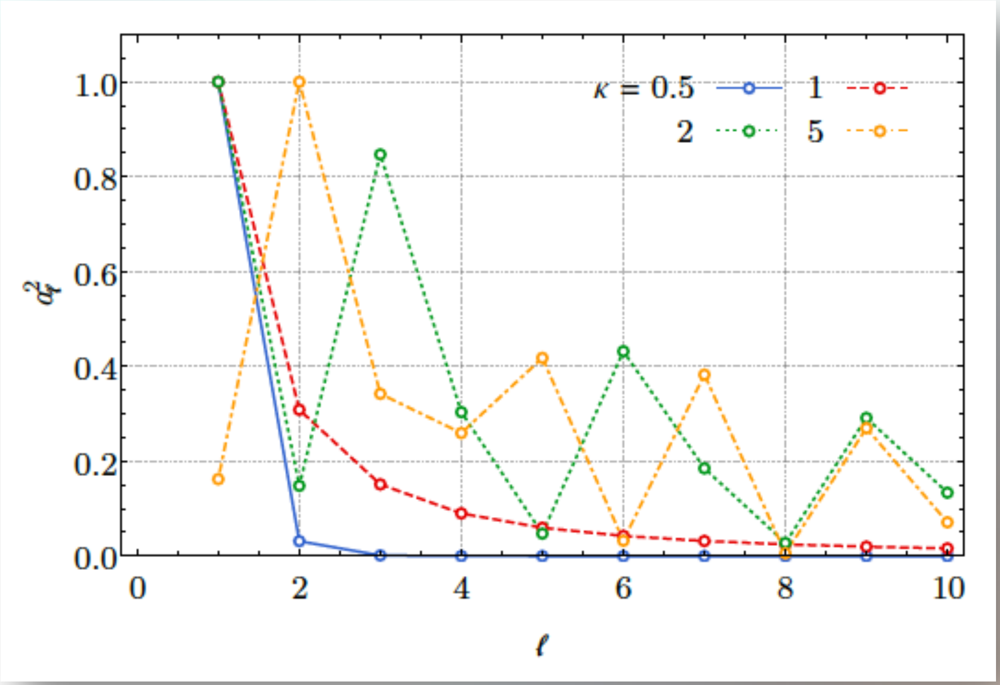
$$a_2 = \frac{5\beta}{12\kappa^3}\left[3(\kappa^2-1)\ln\left|\frac{1-\kappa}{1+\kappa}\right| + 4\kappa^3 - 6\kappa\right],$$

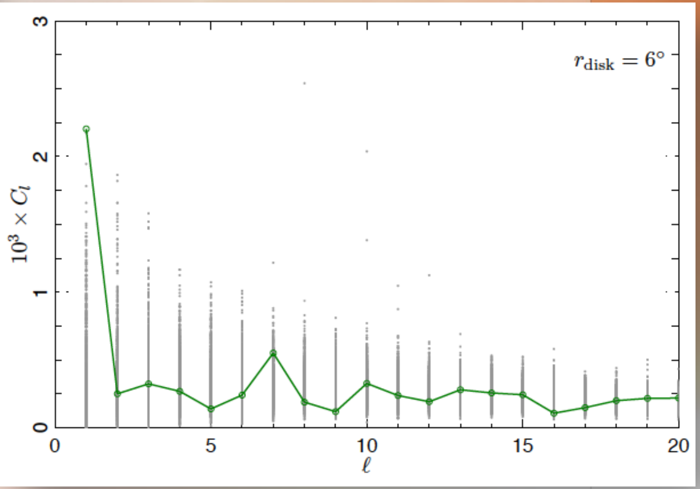
$$a_3 = \frac{7\beta}{48\kappa^4}\left[(15-18\kappa^2+3\kappa^4)\ln\left|\frac{1-\kappa}{1+\kappa}\right| + 30\kappa - 26\kappa^3\right].$$



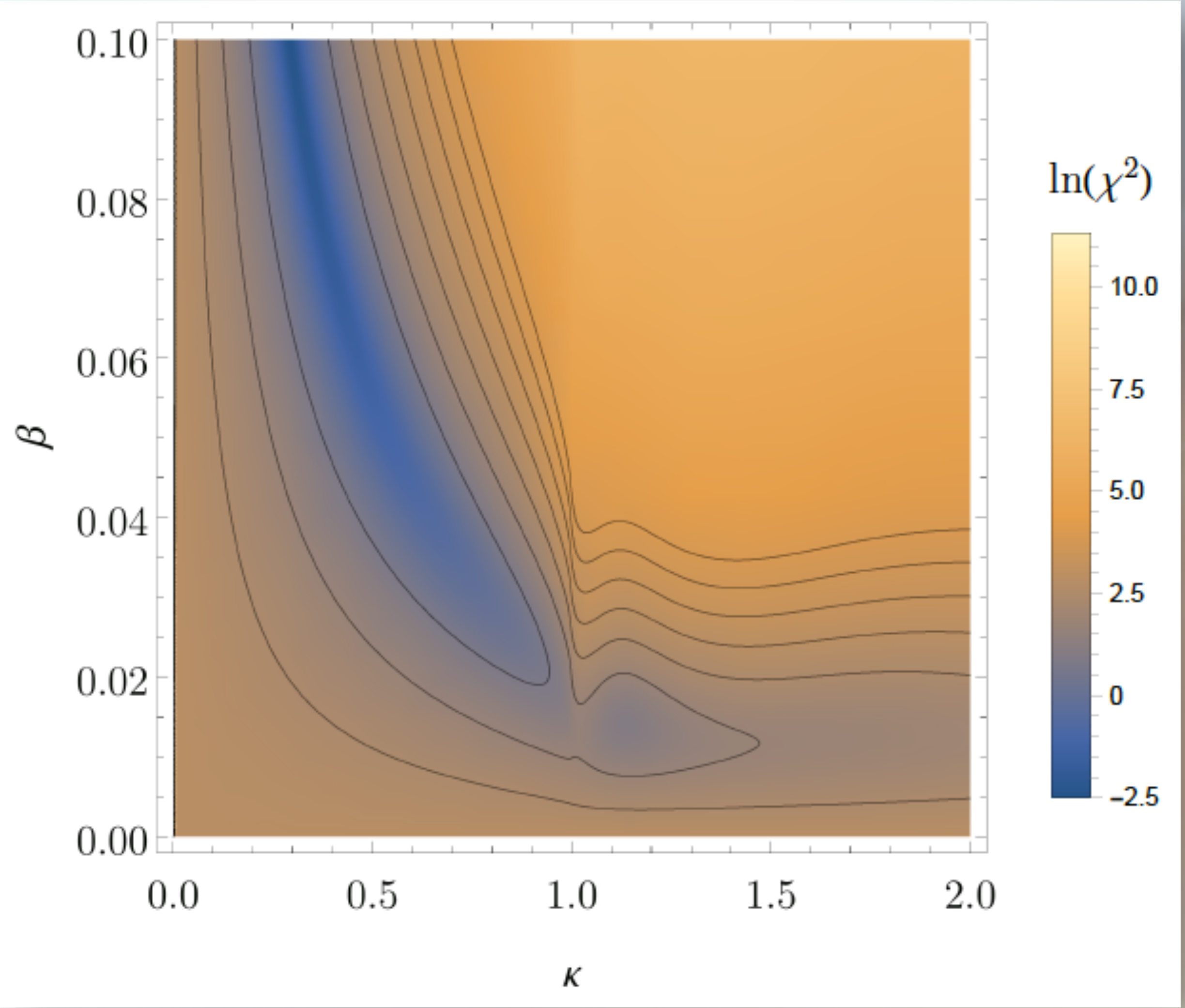


Comparison to measured quantities





Inflationary power asymmetry from primordial domain walls



UiO : 200 +3

Proper likelihood analysis:
Need full covariance matrix in harmonic space.

CMB angular power spectra

$$\langle a_{\ell_1,m_1} a_{\ell_2,m_2}\rangle = 4\pi\mathcal{P}_0\delta_{\ell_1,\ell_2}\int\frac{dk}{k}\,\Delta^2_{\ell_1}(k) - (4\pi)^2\mathcal{P}_0 2\pi^2\beta\,\mathcal{T}(\ell_1,\ell_2,m_1,m_2)$$

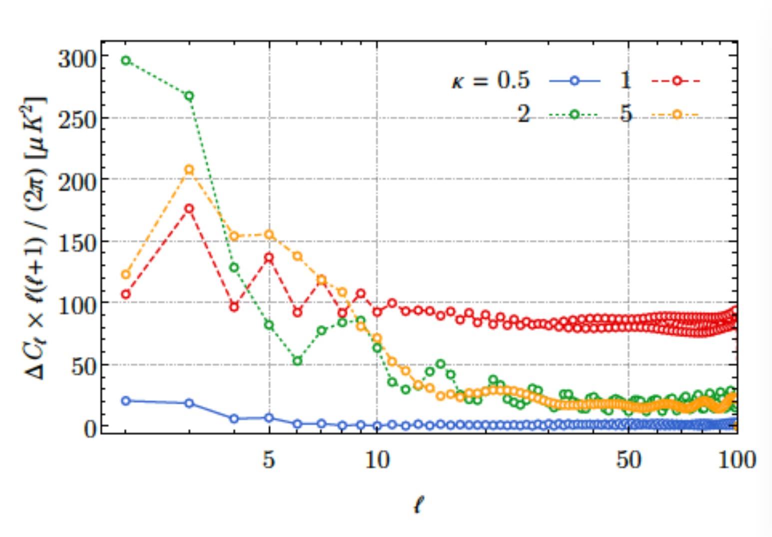
$$m_1 = m_2 = m$$

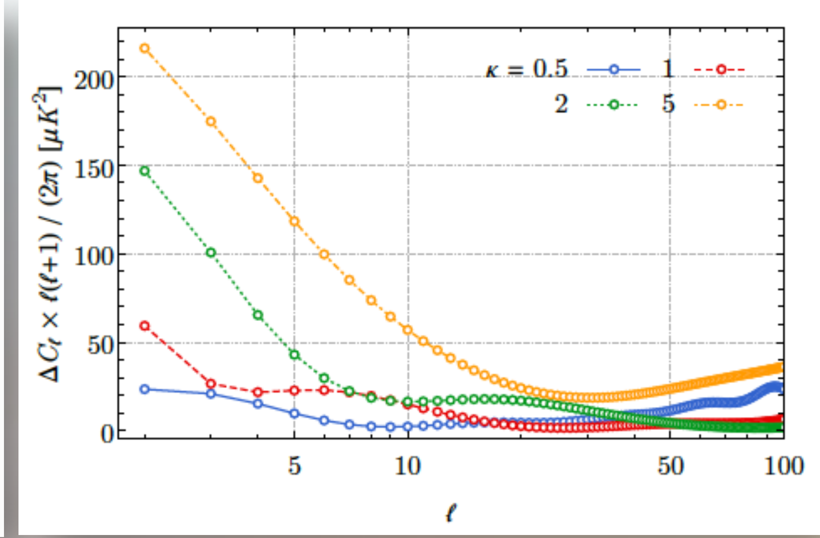
$$\mathcal{T}(\ell_1,\ell_2,m_1,m_2) = \mathcal{T}(\ell_1,\ell_2,m,m) = \frac{\sqrt{(2\ell_1+1)(2\ell_2+1)}}{8\pi^3}\sqrt{\frac{(\ell_1-m)!}{(\ell_1+m)!}}\sqrt{\frac{(\ell_2-m)!}{(\ell_2+m)!}}\times$$
$$\left[\int_0^\infty p^3dp\int_0^\infty dq_1\;\cos(q_1z_0)P^m_{\ell_1}(\cos\theta_1)\frac{\Delta_{\ell_1}(\sqrt{p^2+q_1^2})}{(p^2+q_1^2)^{3/2}}\int_0^\infty dq_2\;\cos(q_2z_0)P^m_{\ell_2}(\cos\theta_2)\frac{\Delta_{\ell_2}(\sqrt{p^2+q_2^2})}{(p^2+q_2^2)^{3/2}}\right.$$
$$\left.+\int_0^\infty pdp\int_0^\infty q_1dq_1\;\sin(q_1z_0)P^m_{\ell_1}(\cos\theta_1)\frac{\Delta_{\ell_1}(\sqrt{p^2+q_1^2})}{(p^2+q_1^2)^{3/2}}\int_0^\infty q_2dq_2\;\sin(q_2z_0)P^m_{\ell_2}(\cos\theta_2)\frac{\Delta_{\ell_2}(\sqrt{p^2+q_2^2})}{(p^2+q_2^2)^{3/2}}\right]$$

$$\Delta C_\ell \equiv -(4\pi)^2 \mathcal{P}_0 2\pi^2 \beta\, \mathcal{T}(\ell,\ell,m,m)$$

m=0

M=l

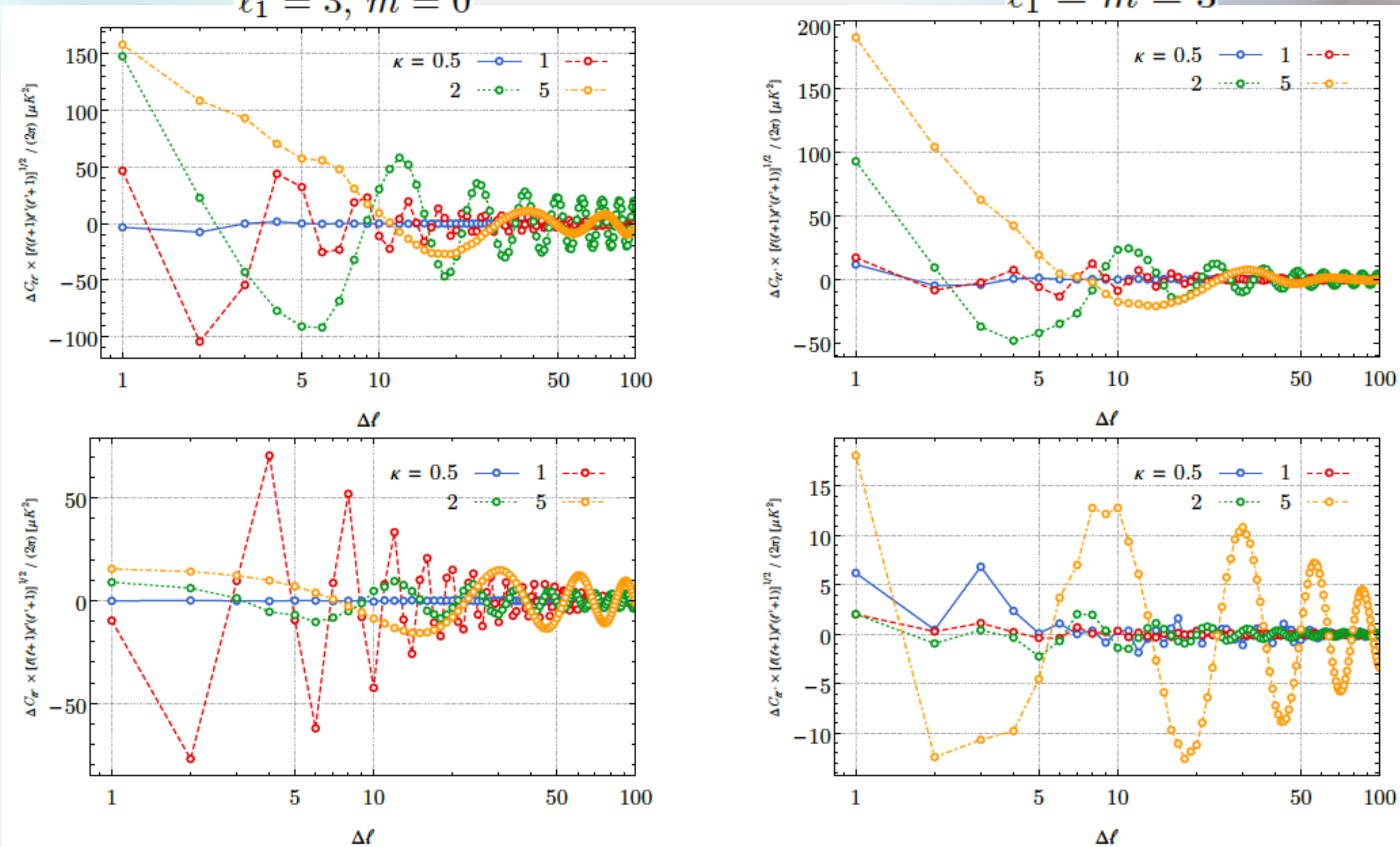




Inflationary power asymmetry from primordial domain walls

$$\Delta C_{\ell_1 \ell_2} \equiv -(4\pi)^2 \mathcal{P}_0 2\pi^2 \beta \, \mathcal{T}(\ell_1, \ell_2, m, m)$$

$\ell_1 = 3,\ m = 0$ | $\ell_1 = m = 3$



$\ell_1 = 50,\ m = 0$ | $\ell_1 = m = 50$

Summary

① Large-scale power asymmetry has been found on both WMAP and Planck temperature sky maps.

② The amplitude of the asymmetry is ~7% over $l<100$.

③ The amplitude decreases significantly at higher mutipoles and is consistent with zero for $l>600$.

④ Different statistical methods confirmed it (same direction).

⑤ Both model-independent and model-dependent (likelihood analysis) have been performed; results are in good agreement.

⑥ Statistical significance is 3σ-4σ.

⑦ Needs to be tested with other statistics and other data sets (polarization, LSS, …).

⑧ Models needed (theoretical or phenomenological).

⑨ An inflationary model exists which seems to be consistent with data: detailed statistical analysis needed to confirm it or rule it out.

Thank You

for your attention