Planck constrains on Isotropy and Geometry of the Universe

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On behalf of the Planck collaboration

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Before pondering the universe take a look at the #2 and #1 roundest man-made objects:

The Avogadro project's
1 kg of Si^{28} 93.6 mm ball

$\Delta r/r \sim 3.7 \times 10^{-7}$, $\Delta r \sim 35$ nm
(~2.8 m "hills" on the surface of the Earth)

Gravity Probe B gyroscope
38.1 mm fused-quartz ball

$\Delta r/r \sim 1.8 \times 10^{-7}$, $\Delta r \sim 3.4$ nm
(~1.4 m "hills" on the surface of the Earth)

Now on to *Planck* and the Universe

- This talk presents a few highlights from two of the Planck 2013 results papers:
  - "Planck 2013 results. XXIII. Isotropy and statistics of the CMB"
    - A suite of non-parametric tests for non-Gaussianity, and
    - Phenomenological assessment of the isotropy of the CMB fluctuations, including a reassessment of the so called "WMAP anomalies"
  - "Planck 2013 results. XXVI. Background geometry and topology of the Universe"
    - Tests of selected models of the universe that abandon global isotropy

Synopsis

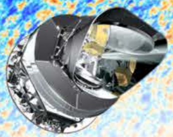
- Isotropy and Statistics project, leading to the paper, was undertaken to support the sufficiency, or otherwise, of the use of the two-point statistic (i.e. the power spectrum) for the extraction of the principal science results of the mission

- Regarding Statistics, a non-parametric data interrogation leads to the conclusion that Gaussian statistics are sufficient to describe the primordial CMB fluctuation, although a small number of exceptions remain

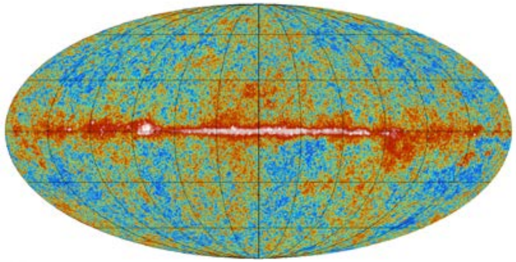
- The Isotropy part targeted WMAP anomalies for scrutiny in confrontation with the new, independent data set
  - since the original claims were met with noticeable skepticism
  - because *Planck* data offers significant advantages due to frequency coverage and foreground mitigation potential, and provides complete systematic redundancy

- Yet the anomalies proved resilient – not surprisingly given the very good overall Planck/WMAP consistency on large and intermediate angular scales

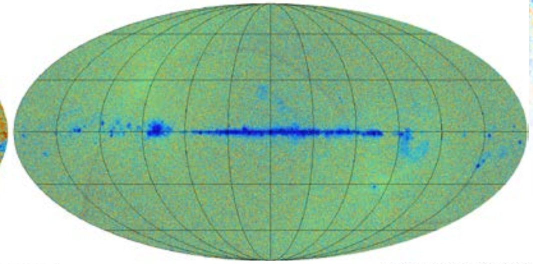
- **Are these anomalies of the observed CMB sky a figment of the imagination, or messengers from the universe on super-horizon scales indicating**
  - **Possible new physics of generation of primordial perturbations, or**
  - **Breakdown of global isotropy**



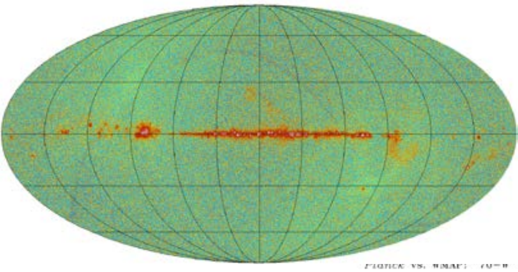
Microwave Sky between V band and 143 GHz



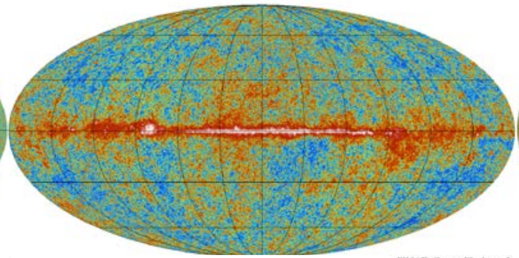
WMAP 9yrs V-band



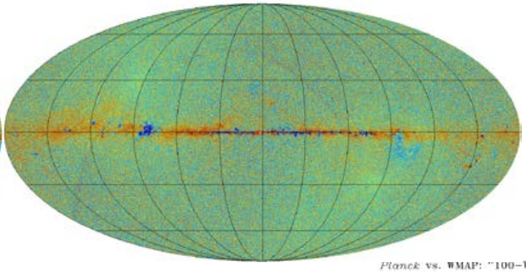
Planck vs. WMAP: "70−V"



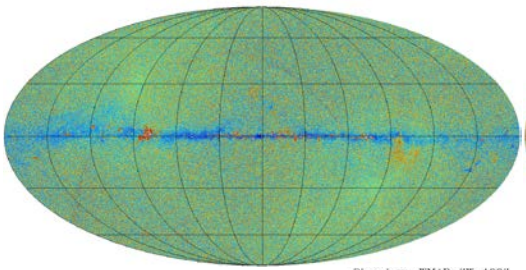
Planck vs. WMAP: "V−70"



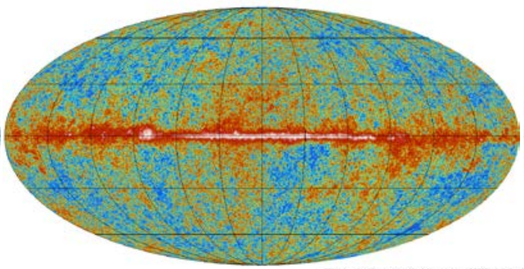
Planck Nominal Mission LFI 70 GHz



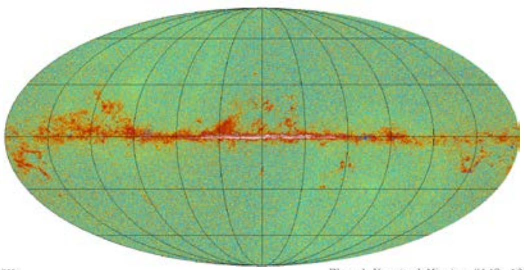
Planck vs. WMAP: "W−70"



Planck vs. WMAP: "70−W"

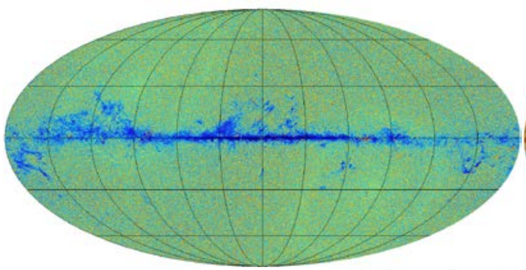


WMAP 9yrs W-band

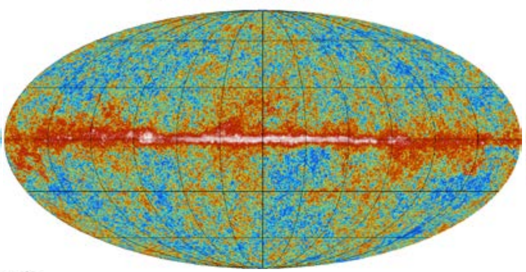


Planck vs. WMAP: "100−W"

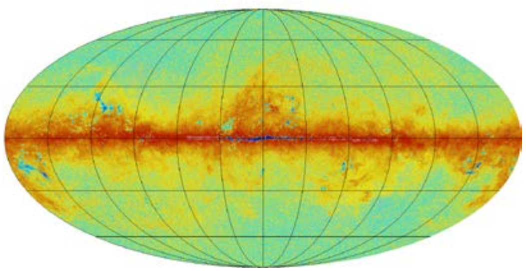
Impressive Inter-instrument CMB nulling!



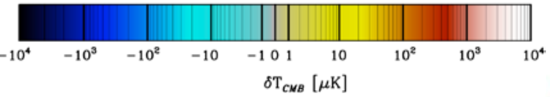
Planck vs. WMAP: "W−100"

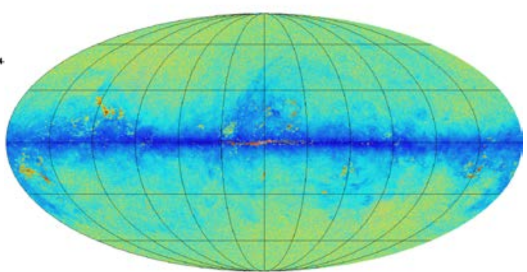


Planck Nominal Mission HFI 100 GHz

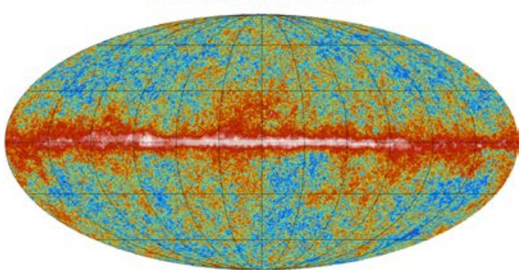


Planck Nominal Mission "143−100"





Planck Nominal Mission "100−143"

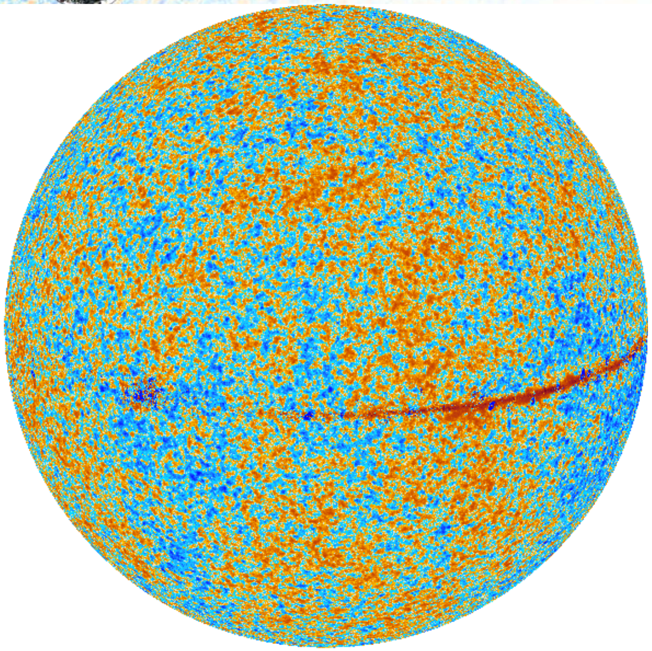


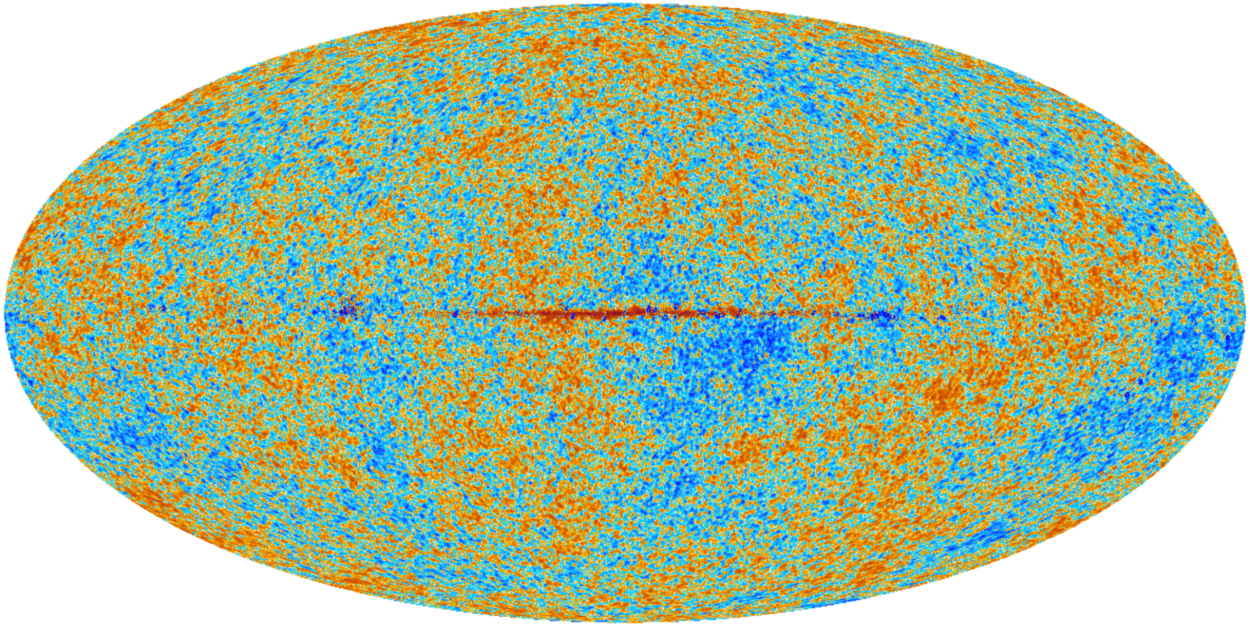
Planck Nominal Mission HFI 143 GHz

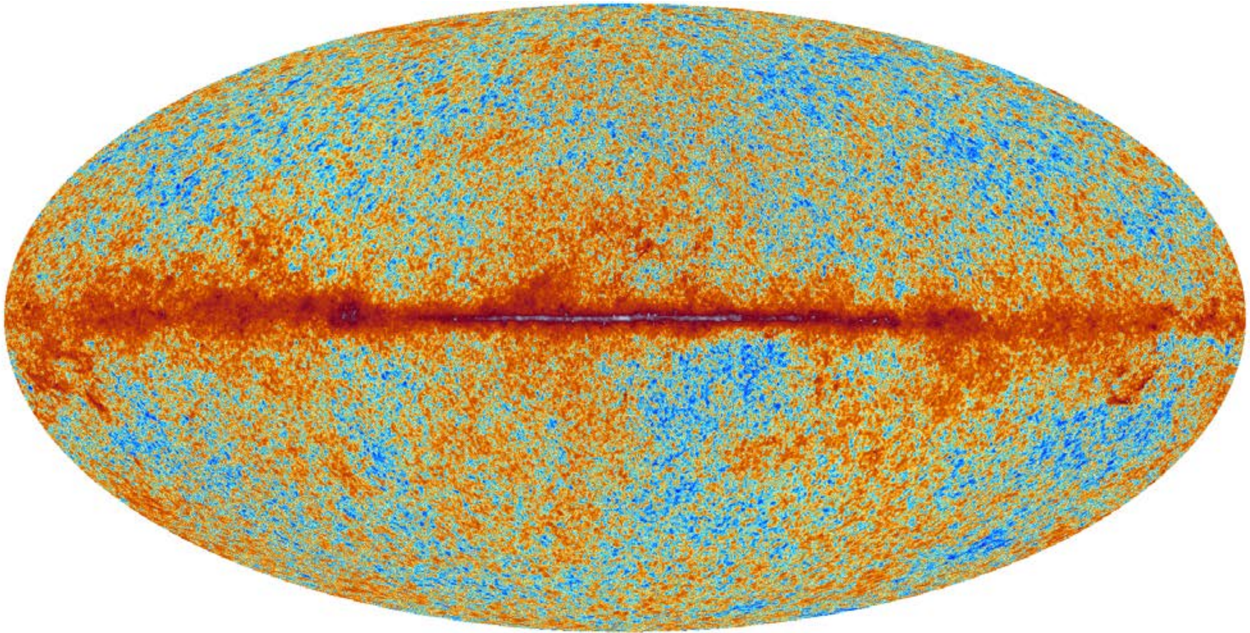
Planck at JPL

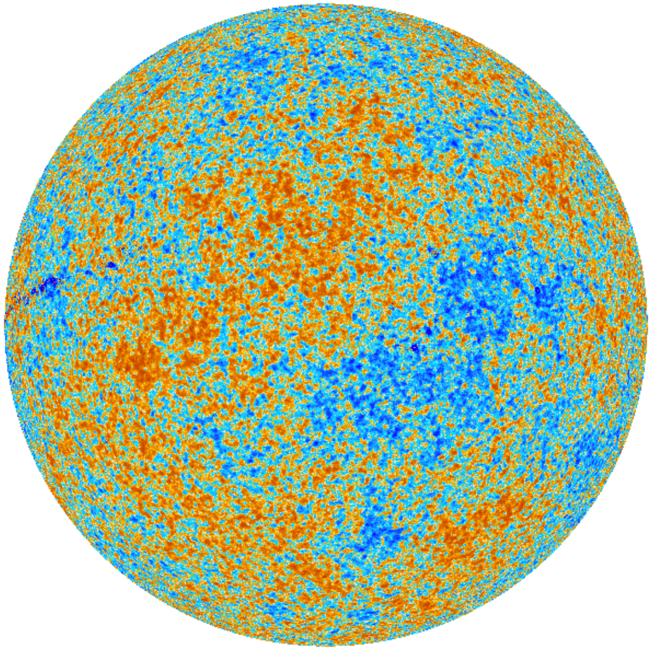
K. M. Gorski

100GHz, post component separation CMB, and “the” Hemispheres









A "mother" of WMAP anomalies – the quadrupole-octopole alignment

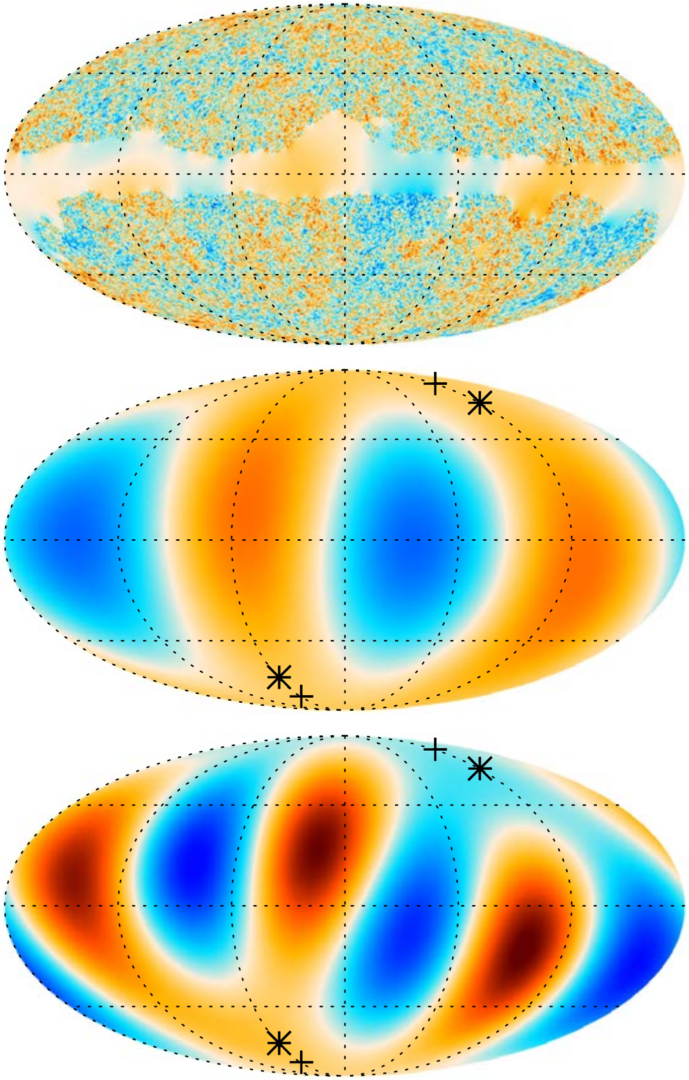


Fig. 20. Upper: The Wiener filtered SMICA CMB sky (temperature range ± 400 μK). Middle: the derived quadrupole (temperature range ± 35 μK). Lower: the derived octopole (temperature range ± 35 μK). Cross and star signs indicate axes of the quadrupole and octopole, respectively, around which the angular momentum dispersion is maximized.

Less remarkable in *Planck* than in WMAP

Candidate theoretical models with explicit deviations from global isotropy

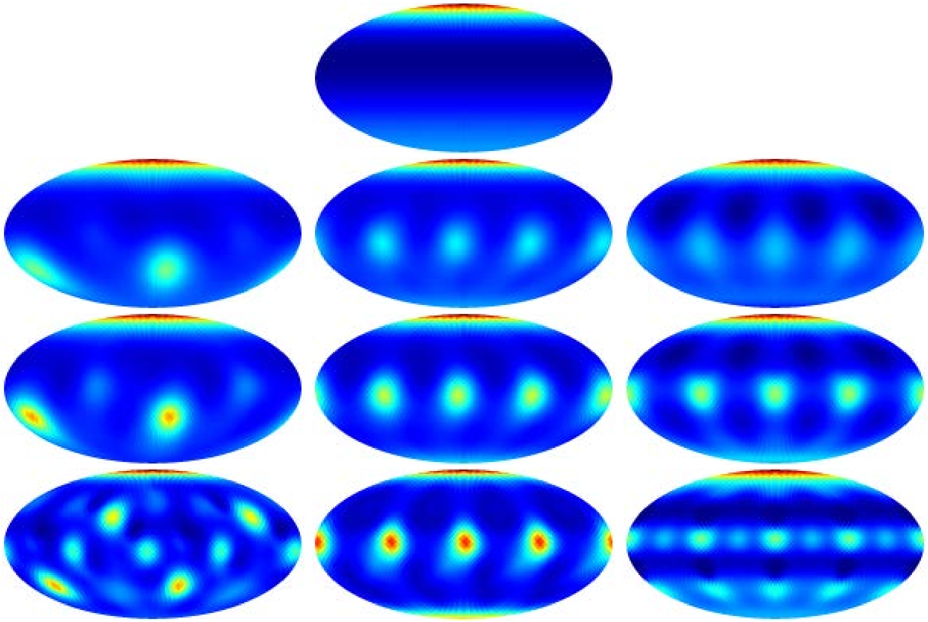
- COBE-DMR, WMAP, and now *Planck* are all indicating low amplitude of the power spectrum of CMB fluctuations at large angular scales
- This has originally inspired an ongoing investigation of alternatives to standard FRW homogeneous, and isotropic background spaces
- Compact topology and Bianchi models (example will be shown later) were fitted to *Planck* CMB maps generated in the process of component separation
- Results are:
  - No detection of compact topology, fundamental domain size limited to at least ~diameter of the last scattering sphere
  - Bianchi model analysis finds models that fit the data … but see comments later

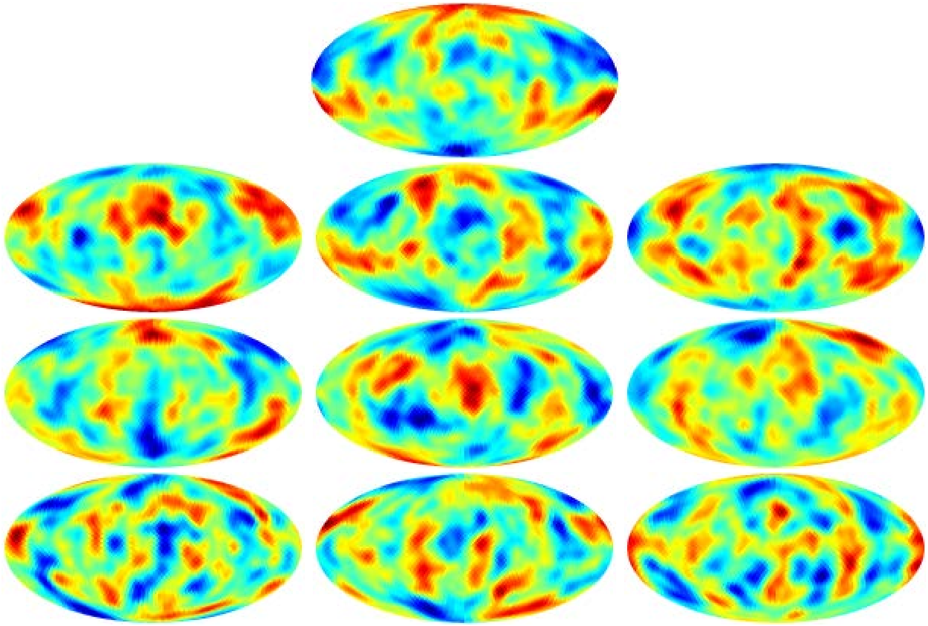
Compact topology models
of background geometry of the universe

Correlation structure for CMB anisotropy

(Fundamental domain size shrinks going down)

Random realizations therof

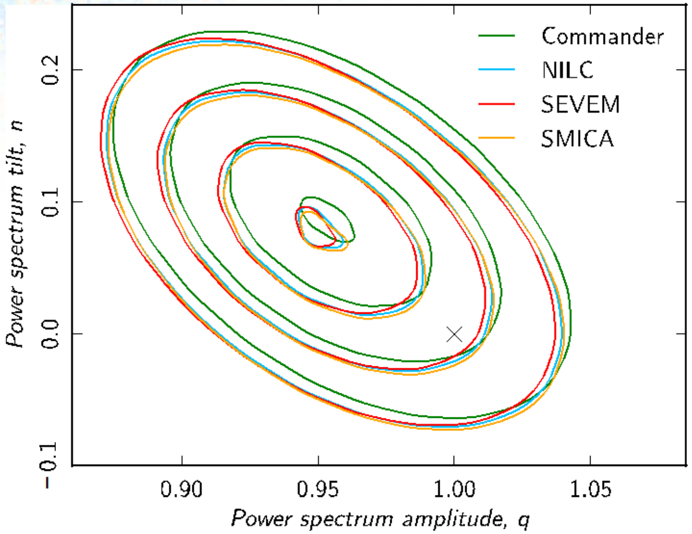




dodecahedral octahedral Equal-sided tori

Multiply connected spaces

Fitting for a dipolar modulation field at low-l



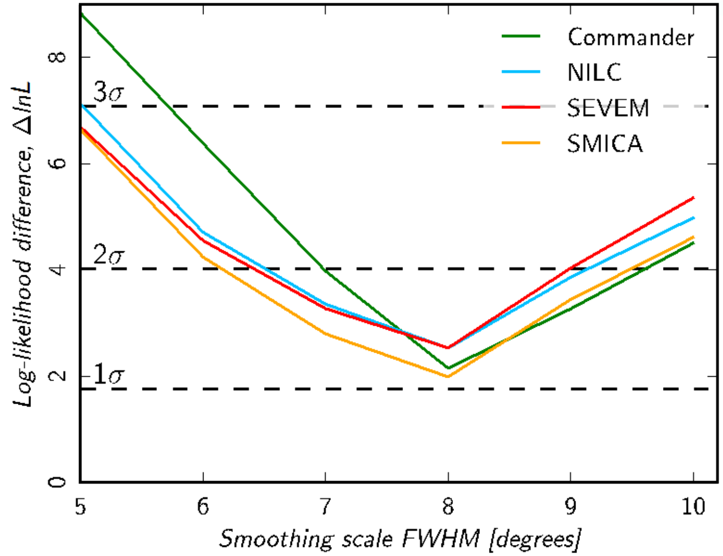
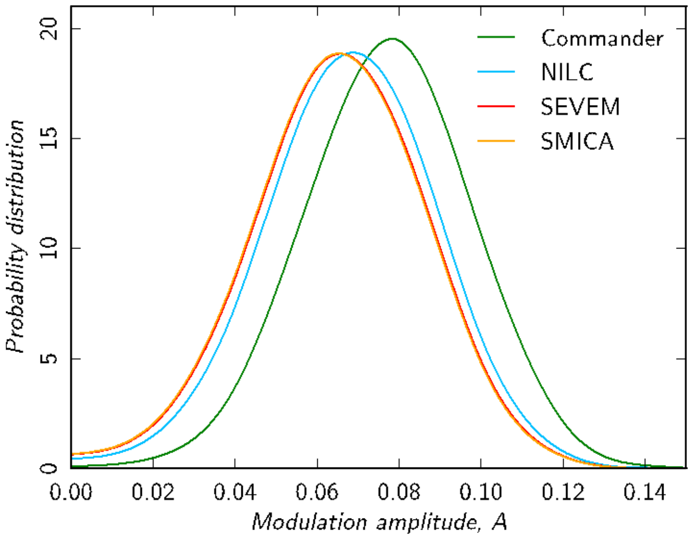
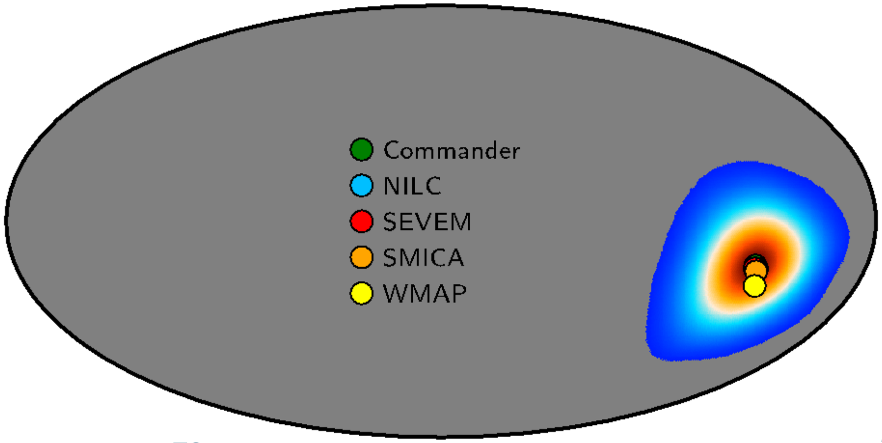


Fig. 31. Log-likelihood difference between the best-fit dipole modulation model and the fiducial isotropic model as a function of smoothing scale. Horizontal dashed lines indicate 1, 2 and 3σ thresholds.





Regionalized N-point correlation function evaluation

Example of a striking difference of 3-, and 4-point functions evaluated on the opposite ecliptic hemispheres

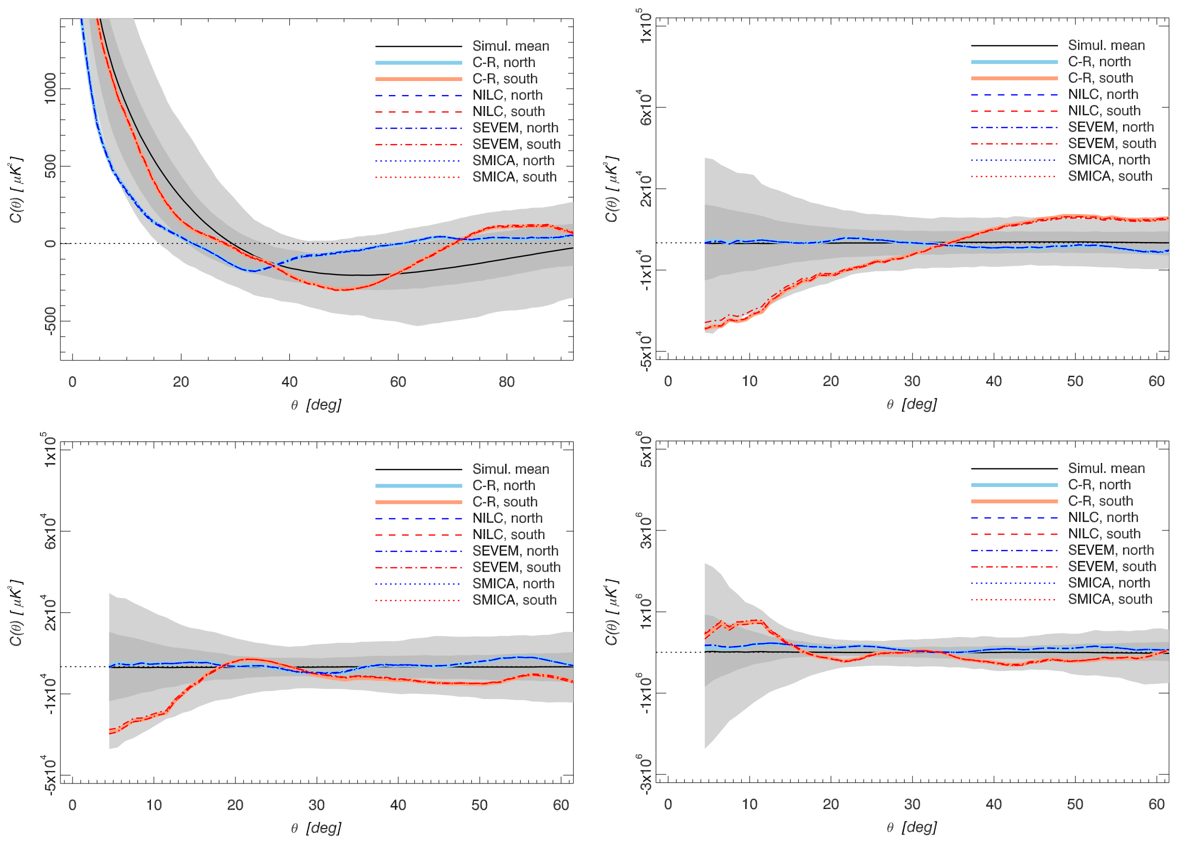


Fig. 23. The 2-point (upper left), pseudo-collapsed (upper right), equilateral 3-point (lower left) and rhombic 4-point (lower right) correlation functions ($N_{\rm side}$ = 64). Correlation functions are shown for the analysis performed on northern (blue) and southern (red) hemispheres determined in the Ecliptic coordinate frame. The shaded dark and light grey bands indicate the 68% and 95% confidence regions, respectively.

Bipolar Spherical Harmonics at work

Detection of dipolar modulation power

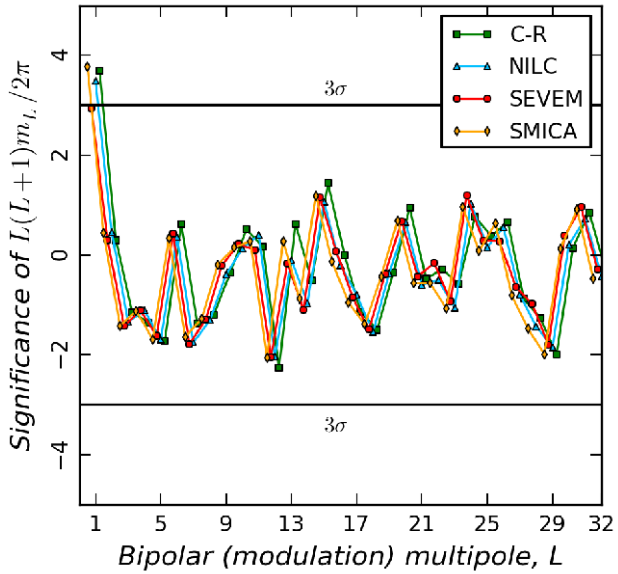


Fig. 32. The significance of the modulation power, $L(L+1)m_L/2\pi$, at bipolar multipoles L. The modulation spectra obtained from the four component separation maps (C-R, NILC, SEVEM and SMICA) are consistent with each other. Dipole ($L = 1$) modulation power is detected in all the spectra at a significance ranging from 3.7 to 2.9σ. The solid black lines denote the 3σ significance thresholds. There is no significant power detected at higher multipole of the modulation field $1 < L \leq 32$.

Spectral localization of the dipolar modulation power

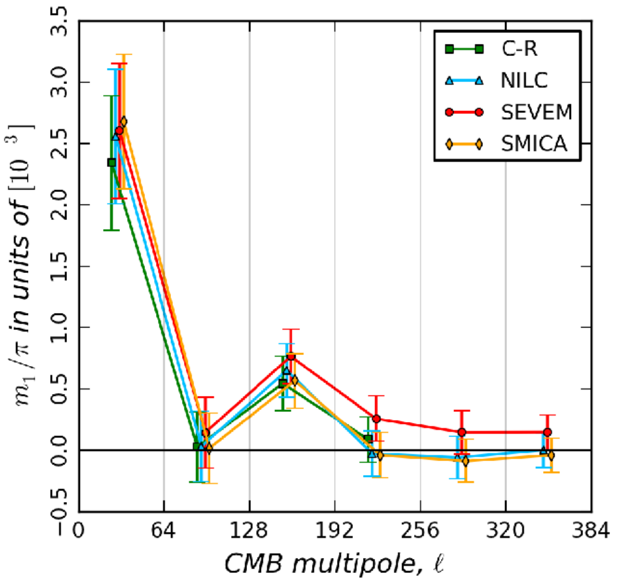
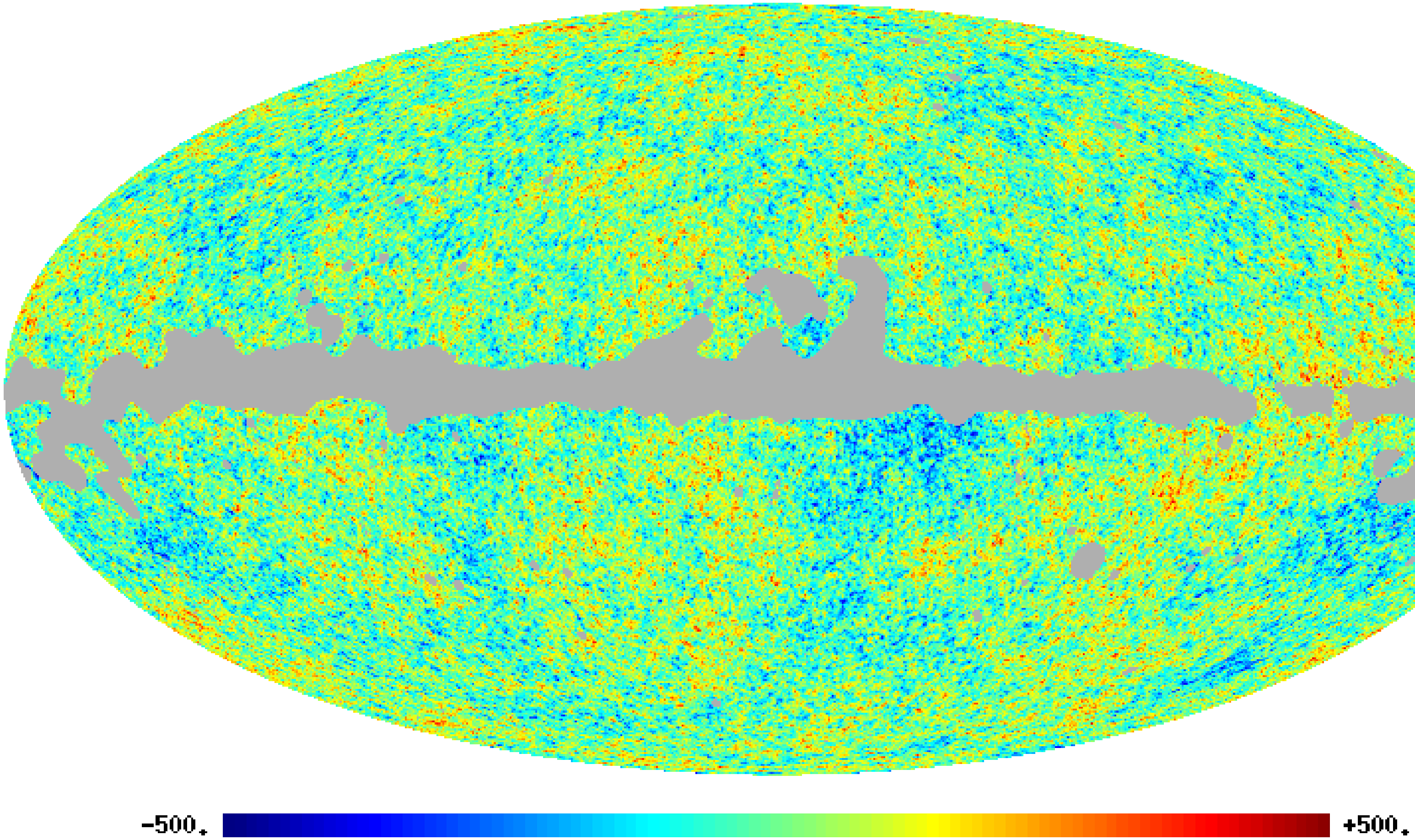


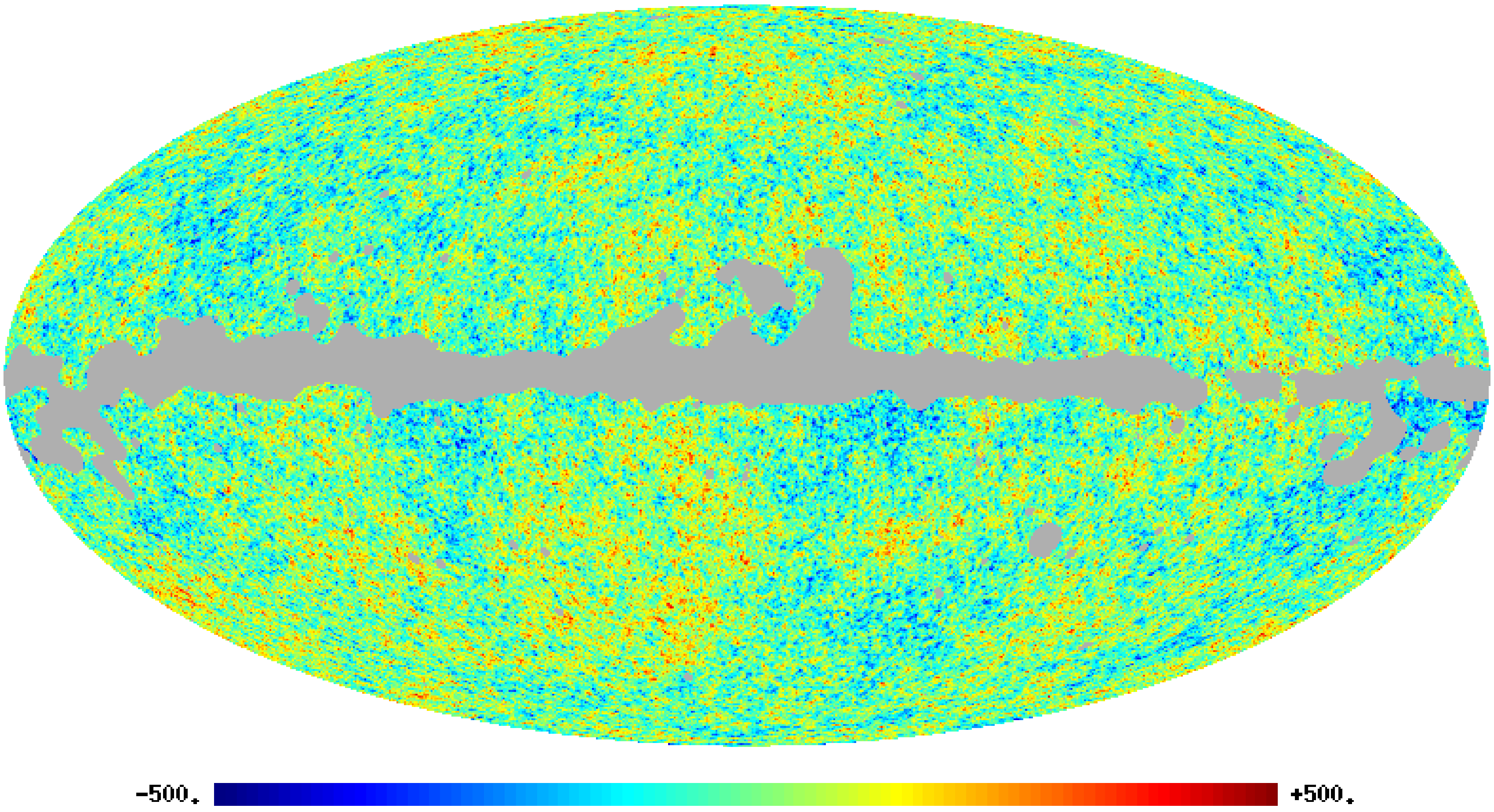
Fig. 33. The CMB multipole dependence of the BipoSH (modulation) power $L(L+1)m_L/2\pi$ can be dissected into bins in ℓ-space. This figure plots the measured dipole modulation ($L = 1$) power in CMB multipole bins. We establish that significant power in the dipole modulation is limited to $\ell \in (2, 64)$ and does not extend to the higher CMB multipoles, ℓ, considered. The vertical grid lines denote the CMB multipole ℓ-bins.

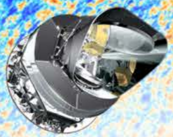
The Bianchi Conundrum …

The Observed CMB Sky



The Corrected, More Manifestly Isotropic CMB Sky

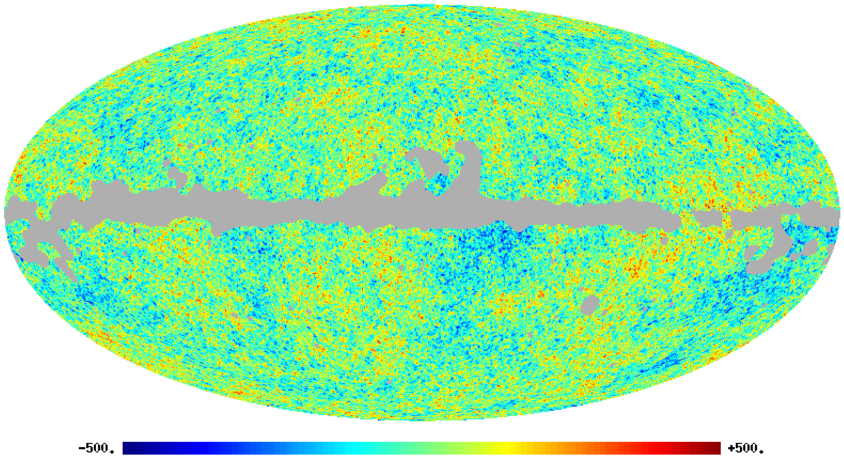




A Paradoxical "Solution" to the Idiosyncratic Appearance of our CMB Sky

The Bianchi model **must be open** to fit the data, and cannot be merged with the overall flat cosmology that describes the observed universe

Real CMB Sky



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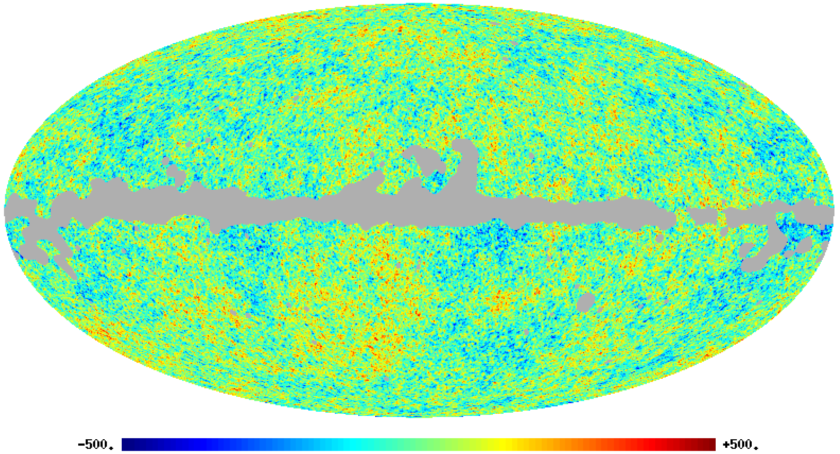
Corrected CMB Sky



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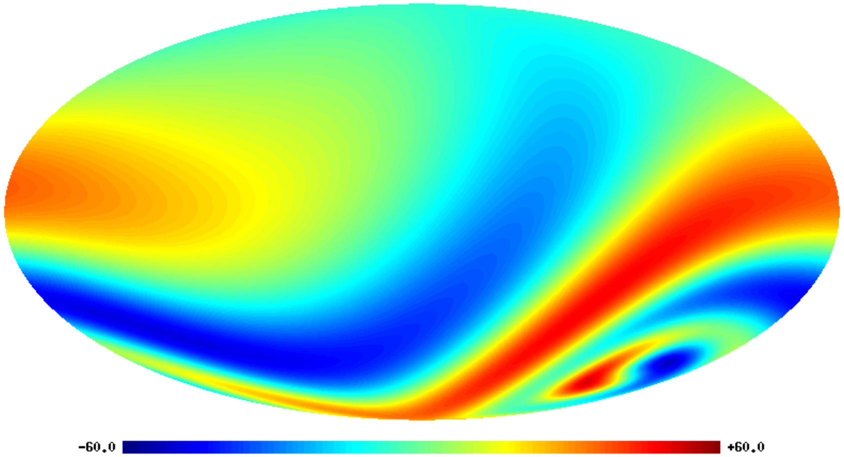
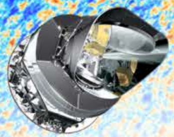


Correction that fits the sky:
a homogeneous, anisotropic Bianchi VII_h model

Prospects

- The situation is excellent, but not yet hopeless …
- Dai, Jeong, Kamionkowski, and Chluba already try to come to the rescue in arXiv:1303.6949v1:
  - "This power asymmetry is, as we explain below, extremely difficult to reconcile with inflation."
  - "While there are some who may wave away the asymmetry as a statistical fluctuation [7], evidence is accruing that it is statistically significant."
  - "There is moreover the tantalizing prospect that it may be an artifact of some superhorizon pre-inflationary physics."
- Theoretical possibilities discussed include:
  - Superhorizon perturbation to the curvaton field
  - Spatial modulation of n_s
  - Variable gravitational-wave amplitude
  - Modulation of the optical depth of reionisation
- Most important, further scrutiny will be possible as some of these proposed scenarios generate discernible effects in polarization via TE and EE correlations

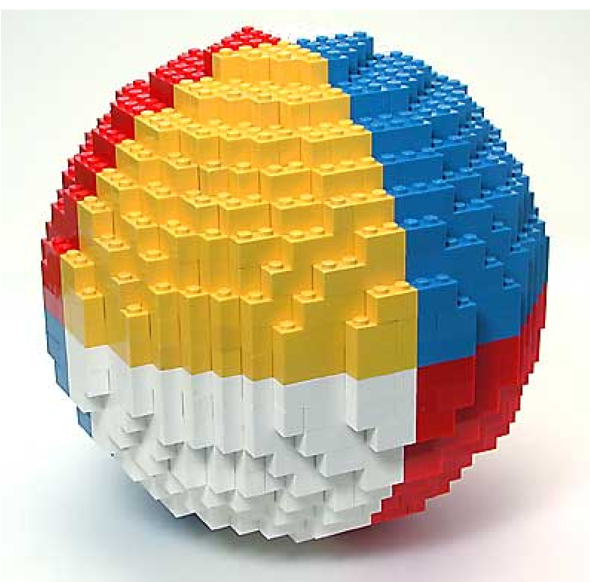


Studying Sphericity one can be

sophisticated, like Escher's (well, at least one can try),

or

simplified, as with LEGO,



BUT IT IS ALWAYS FUN