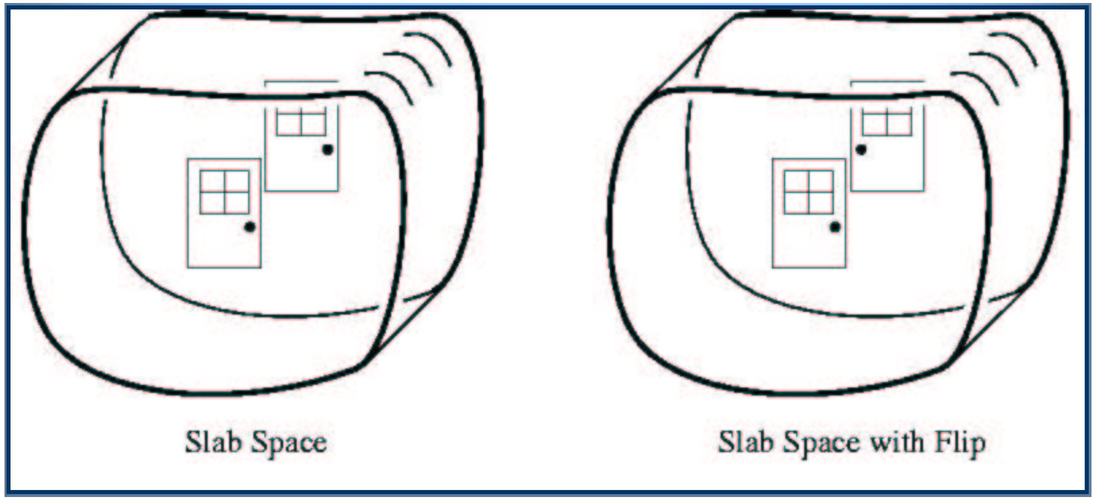
XX Meeting of Physics

CMB anomalies: a review

Low CMB angle correlations with slab topology

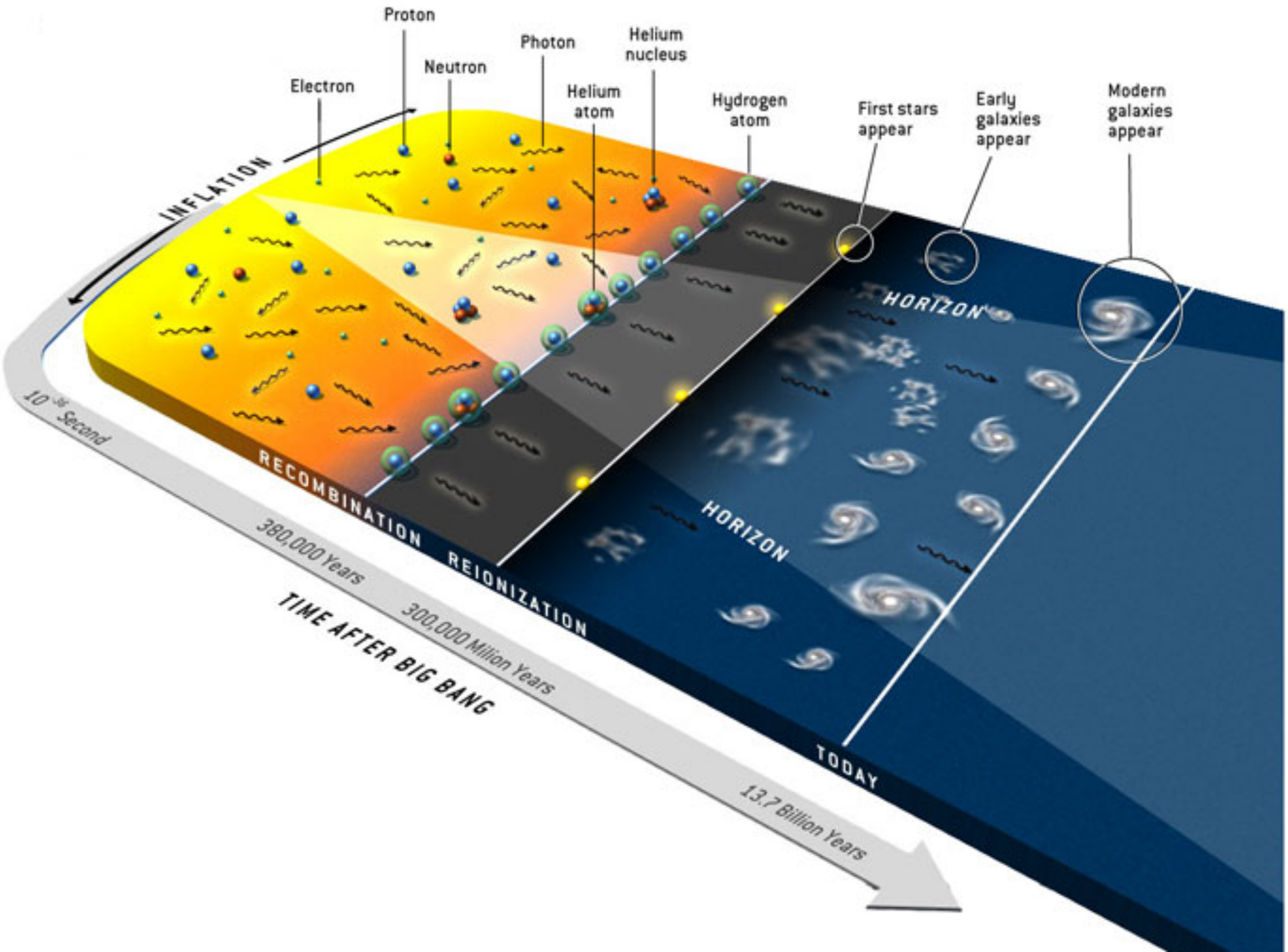
Armando Bernui

Observatório Nacional

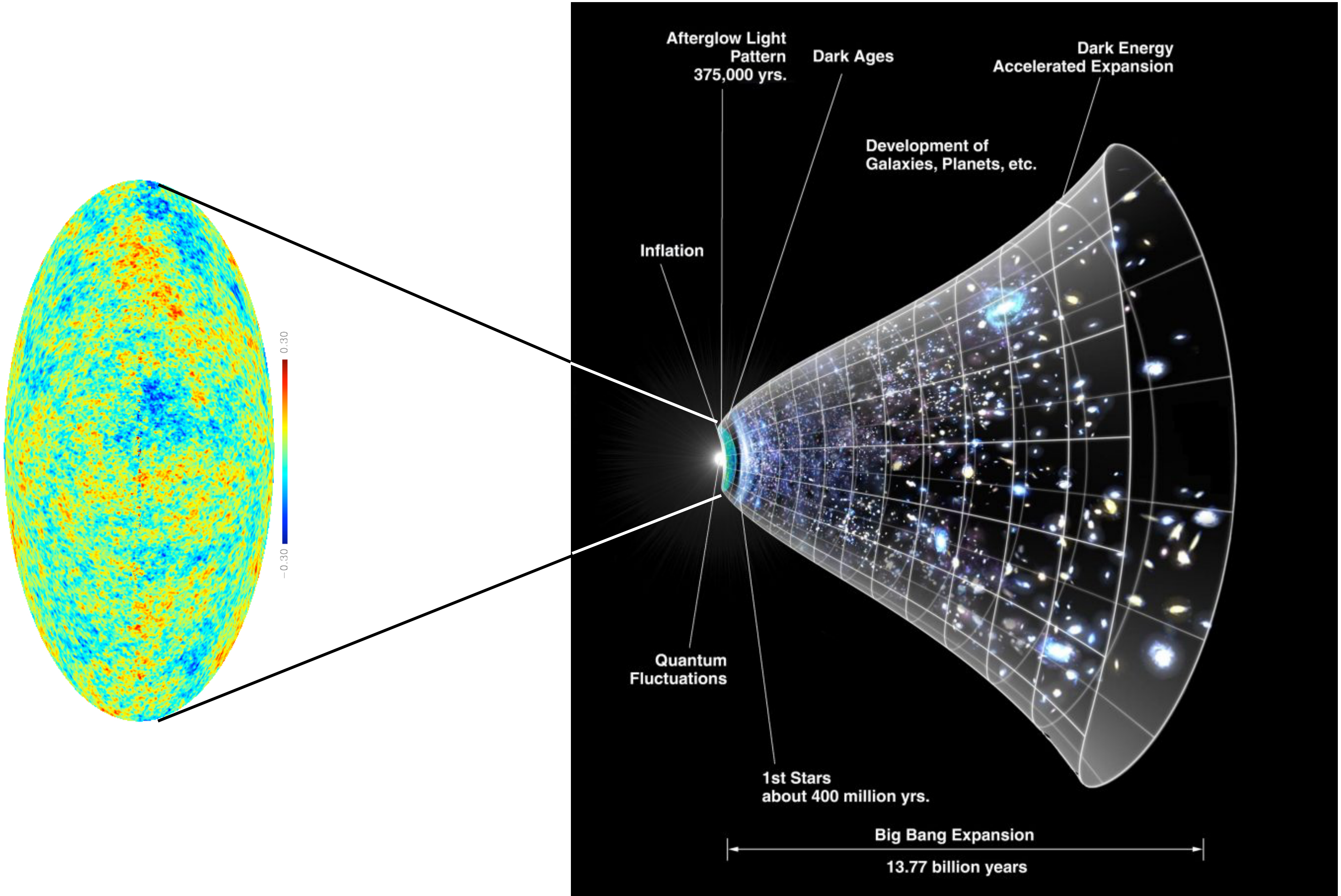


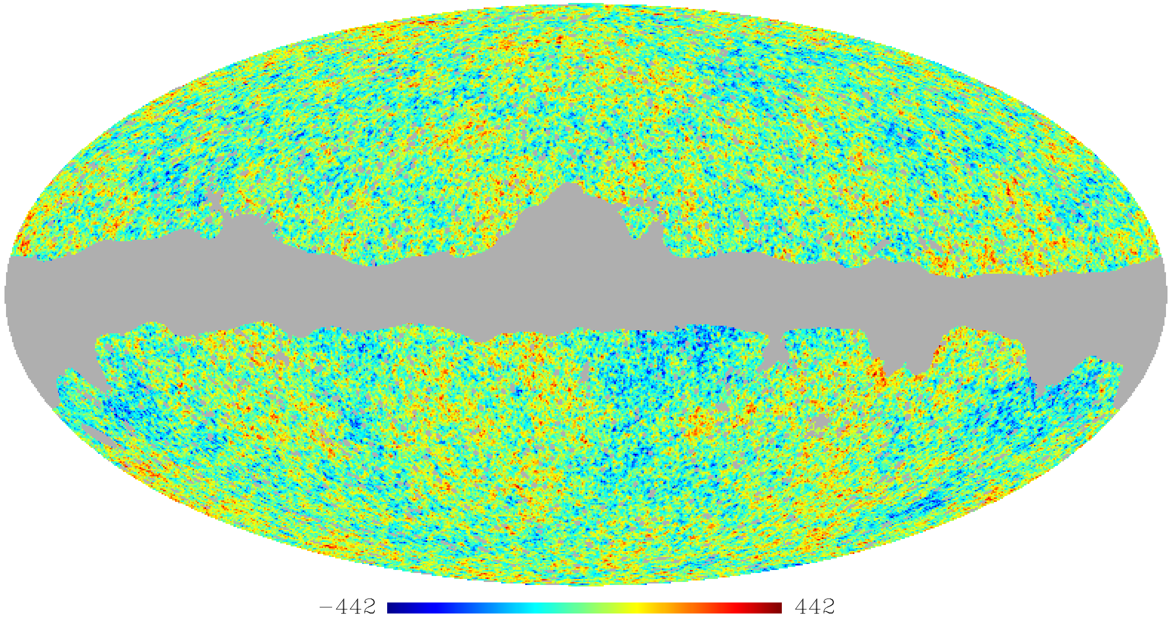
in collaboration w/ Camila Novaes,
Thiago Pereira, Glenn Starkman

Thermal history of the Universe

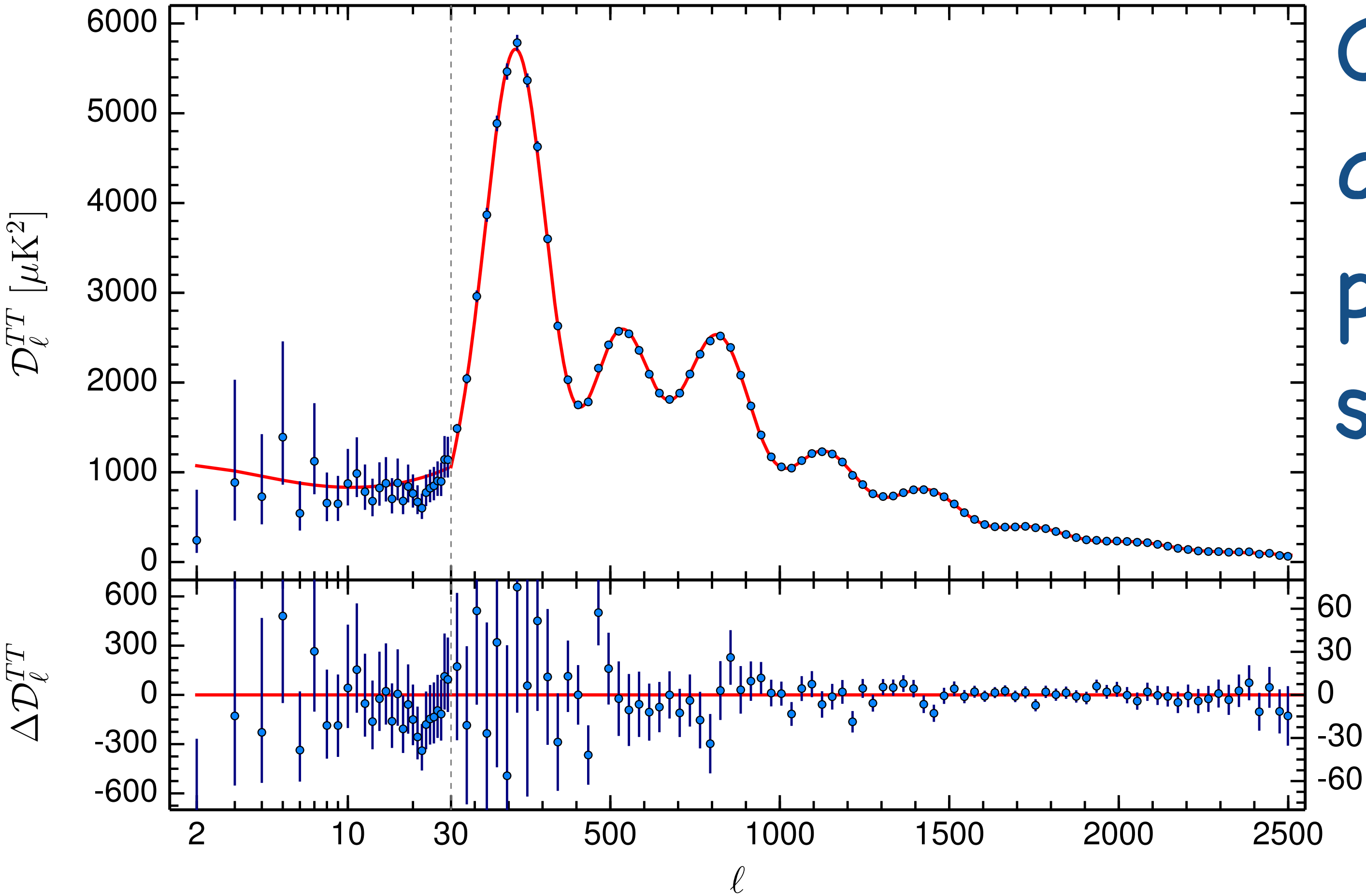


Thermal history of the Universe





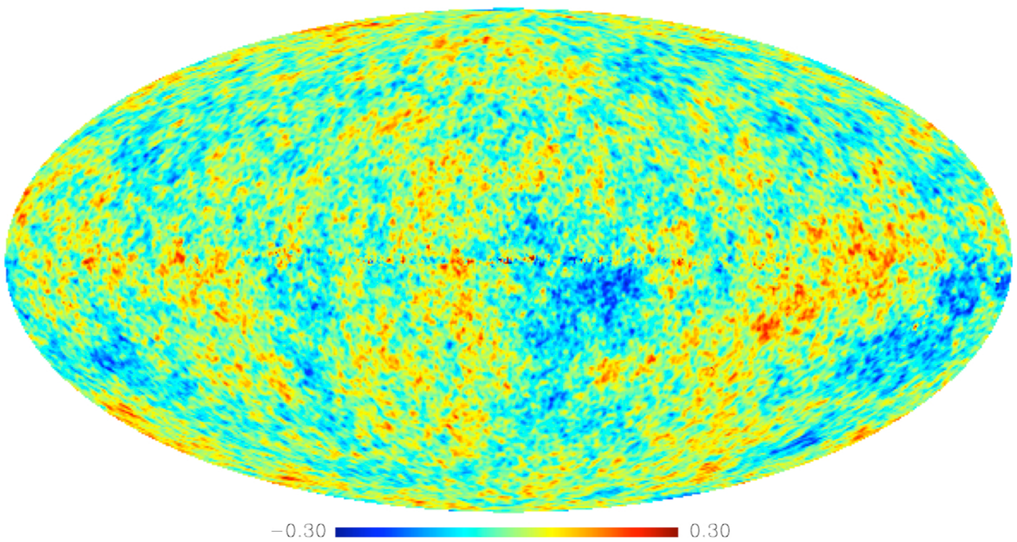
CMB field



CMB angular power spectrum

Is the CMB angular distribution isotropic?

- Null hypothesis: "the observed universe is isotropic". Current observational data show no strong evidence against it, does this imply that the universe must be isotropic?



CMB temperature fluctuations

Is the CMB angular distribution isotropic?

- Null hypothesis: "the observed universe is isotropic". Current observational data show no strong evidence against it, does this imply that the universe must be isotropic?

- Data can't disprove exact isotropy, or the opposite, it just indicate {compatibility, accordance, remarkable consistency with,…} statistical isotropy or statistical anisotropy

- Why? Because we just see one (SI or SA) realization!

Large angular scale CMB anomalies:

Reports of breakdown of statistical isotropy of CMB at large angular scales

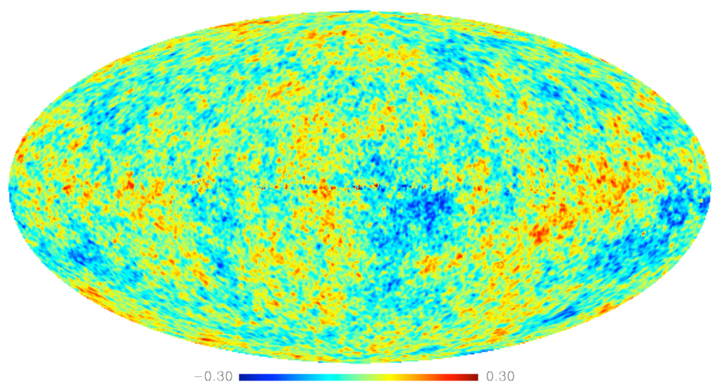
Large angular scale CMB anomalies:

Reports of breakdown of statistical isotropy of CMB at large angular scales

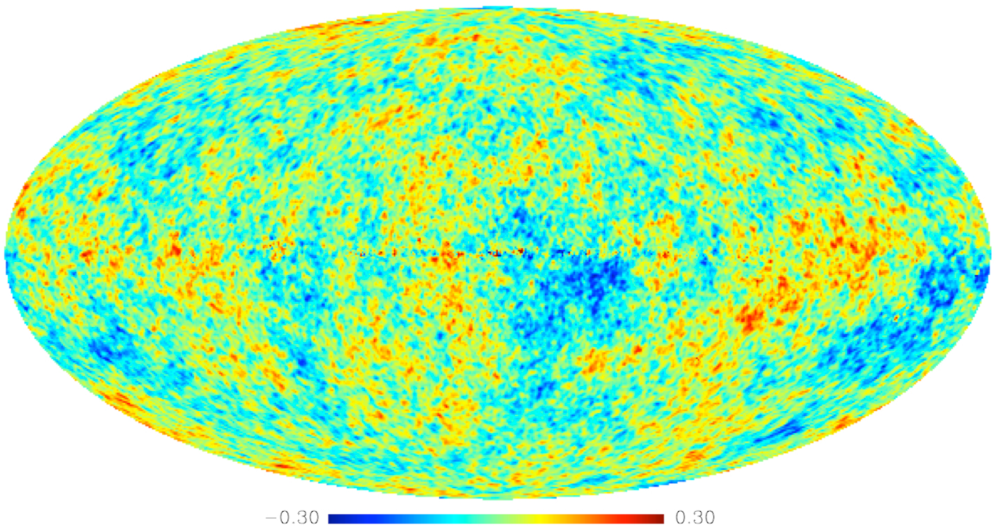
"extraordinary claims require extraordinary evidence" C. Sagan

$$\text{Anomalies} \quad \Leftrightarrow \quad > 3\,\sigma$$

Is the CMB field anomalous?



CMB anomalies



the state of the art…

Large angular scale CMB anomalies: a review

- Lack of large angular correlations, i.e., $\theta > 60^\circ$
- Power spectrum deficit at large scales, i.e., $\ell < 30$
- Quadrupole-Octopole alignment
- Hemispherical asymmetry
- Low variance
- Parity asymmetry, i.e., $\ell_{2n} < \ell_{2n+1},\, n \geq 1$
- etc. (low quadrupole, cold-spot,…)

p-values of some CMB anomalies

feature	p-value	data	reference
in angular space			
low variance ($N_{\mathrm{side}} = 16$)	$\leq 0.5\%$	Planck 15	Tab. 12 [7]
2-pt correlation $\chi^2(\theta > 60°)$	$\leq 3.2\%$	Planck 15	Tab. 14 [7]
2-pt correlation $S_{1/2}$	$\leq 0.5\%$	Planck 15	Tab. 13 [7]
2-pt correlation $S_{1/2}$	$\leq 0.3\%$	Planck 13 &	
		WMAP 9yr	Tab. 2 [31]
2-pt correlation $S_{1/2}$ (larger masks)	$\leq 0.1\%$	Planck13	Tab. 2 [31]
	$\leq 0.1\%$	WMAP 9yr	[31, 32]
hemispherical variance asymmetry	$\leq 0.1\%$	Planck 15	Tab. 20 [7]
cold spot	$\leq 1.0\%$	Planck 15	Tab. 19 [7]
in harmonic space			
quadrupole-octopole alignment	$\leq 0.5\%$	Planck 13	Tab. 7 [33]
$\ell = 1, 2, 3$ alignment	$\leq 0.2\%$	Planck 13	Tab. 7 [33]

Schwarz et al., 2015

Arguments: in-favor vs. against CMB anomalies

- Various large-scale anomalies
- Many non-cosmol. hypotheses tested and discarded (systematics, galactic foregrounds, local effects, masks,...)
- Three data sets: COBE, WMAP, Planck

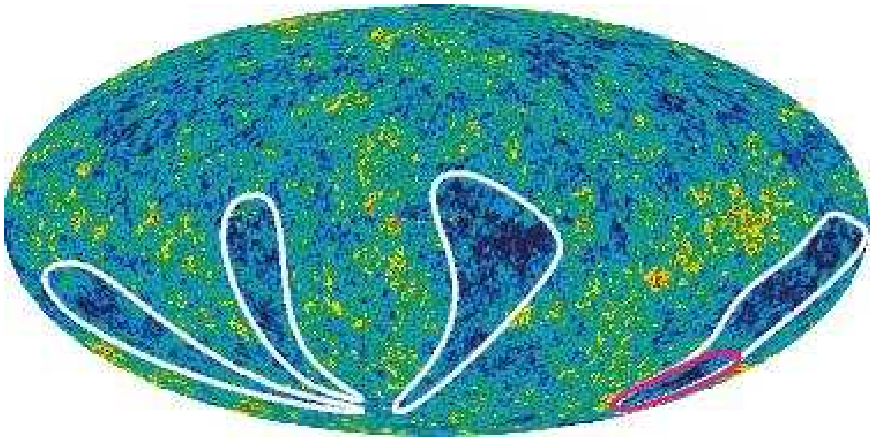
- Look-elsewhere Effect (LEE)
  LEE -> can lead to spurious false detections
- Anomalies have been found using a posteriori estimators
- p-values are not so small

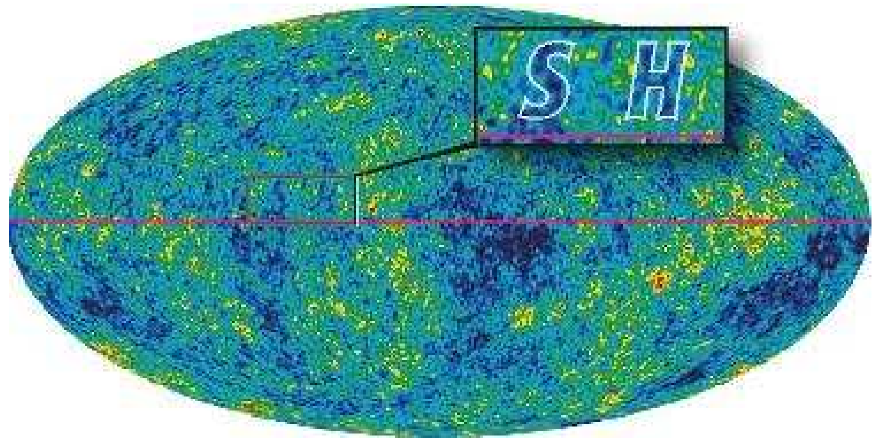
"extraordinary claims require extraordinary evidence"

very low p-value is extraordinary evidence?

Example of LEE

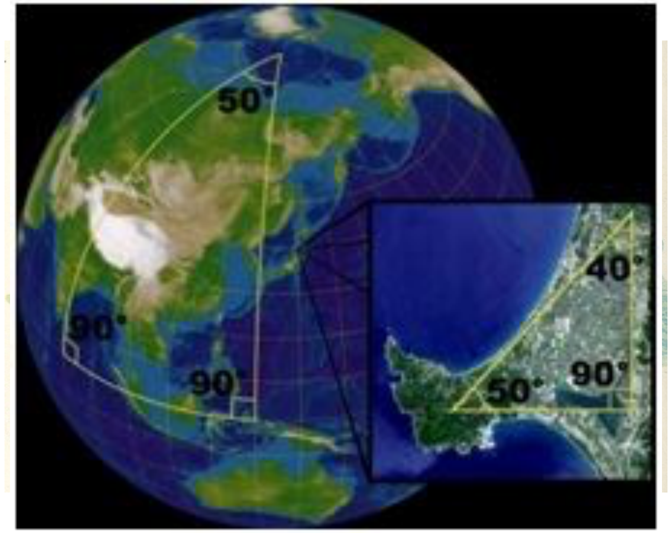
Pattern recognition: LEE





C. Bennett et al. 2010,
arXiv:1001.4758

The form of the Universe



the geometry of the Universe?

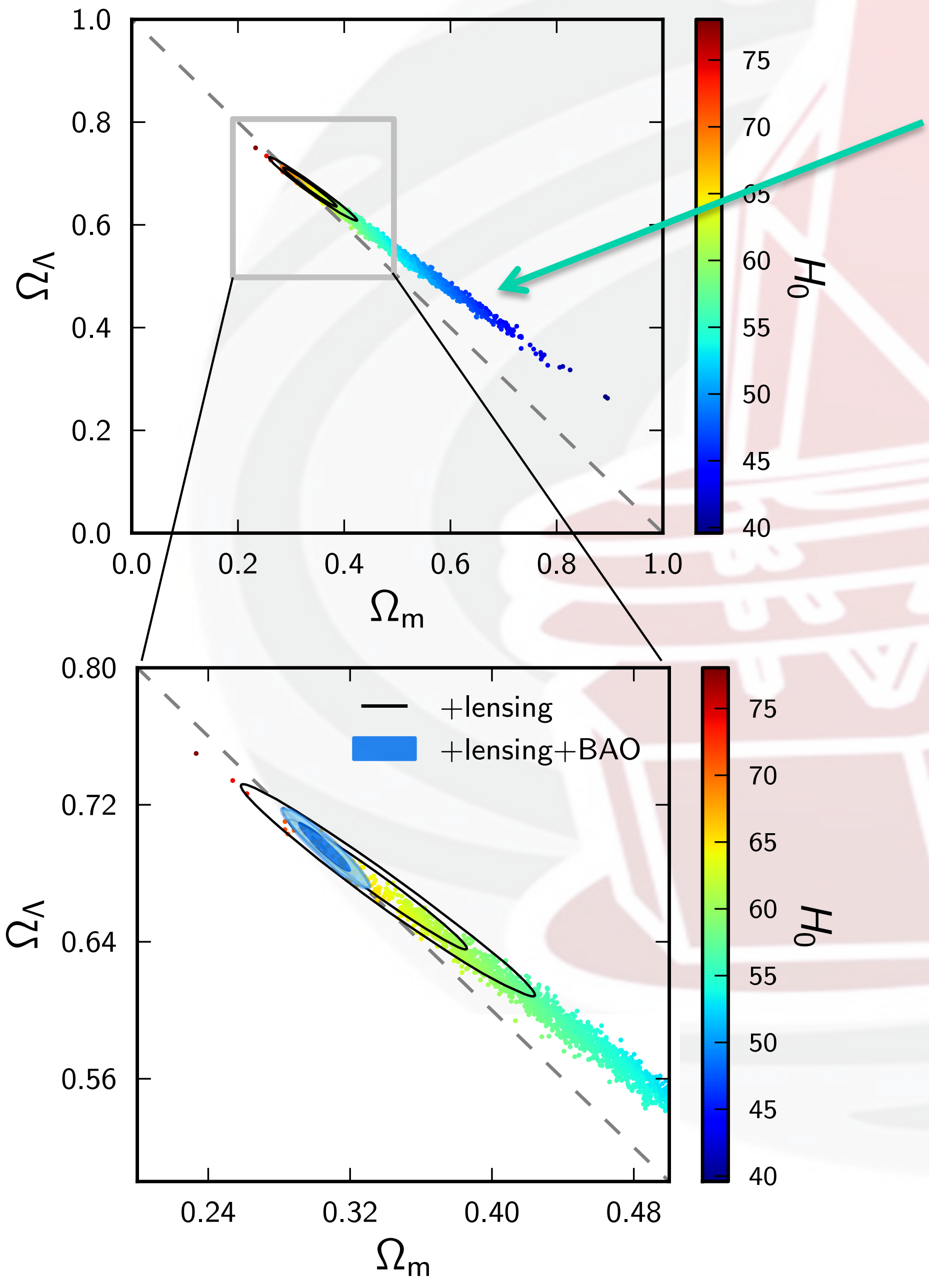
<u>local properties</u>: angles, distances, areas, parallelism,...

the topology of the Universe?

<u>global properties</u>:
without boundary,
connectedness, isometries,...

Is space really flat?

P. Natoli, 2013



The 0.06% precision measurement of the sound horizon scale at last scattering gives us a known ruler!

A single measurement only gives one constraint → *geometric degeneracy*

The models in the tail have a higher lensing signal, and so CMB lensing breaks partially the geometric degeneracy, allowing us to rule out Λ=0 and constrain Ω_k at the percent-level with CMB data alone.

(first done by ACT/SPT in 2011/12)

important question

Why the universe should be flat and stat. isotropic?

Perhaps, it <u>appears</u> flattened and "<u>looks like</u>" isotropic

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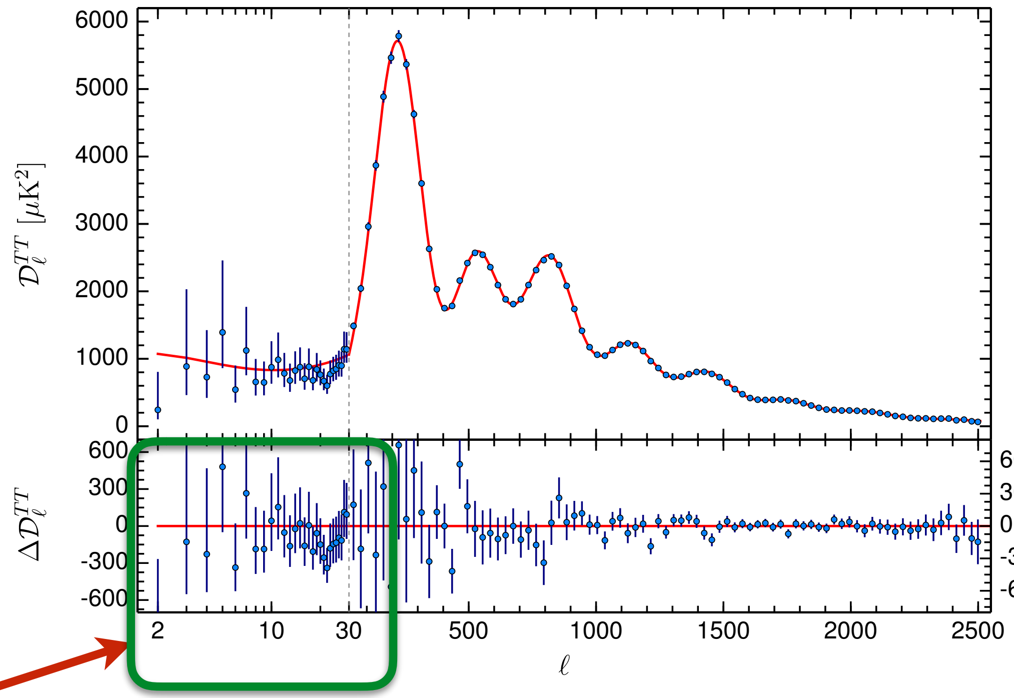
- etc. (low quadrupole, cold-spot,…)



- Power spectrum deficit at large scales $\ell < 30$

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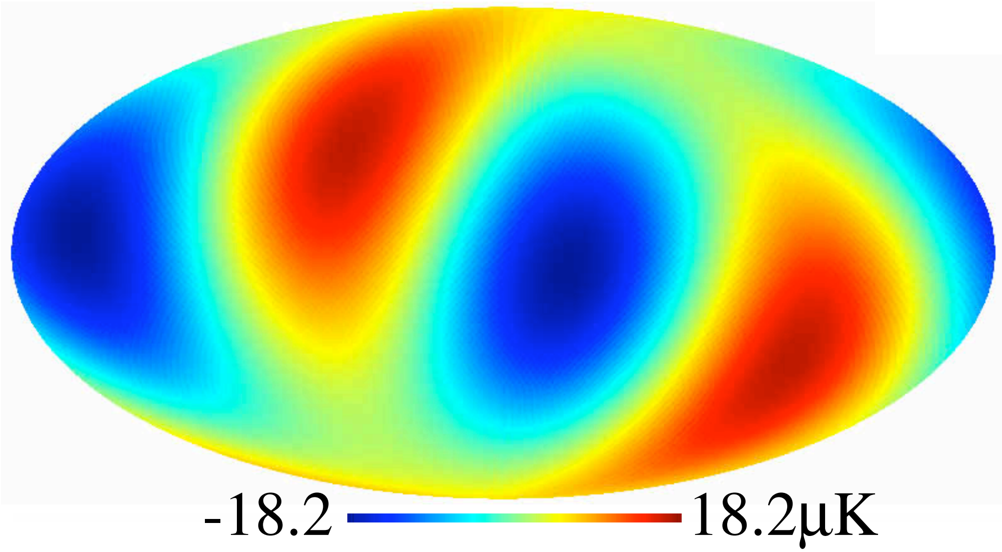
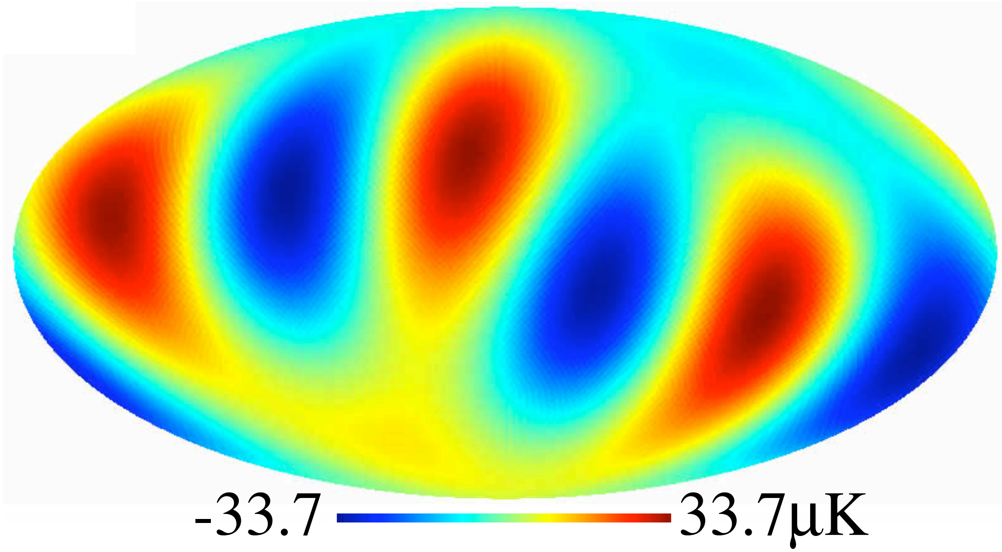
Quadrupole-Octopole alignment



quadrupole



octopole

... planar and aligned

Why is this a CMB anomaly? $\Rightarrow$ $p < 0.5\%$

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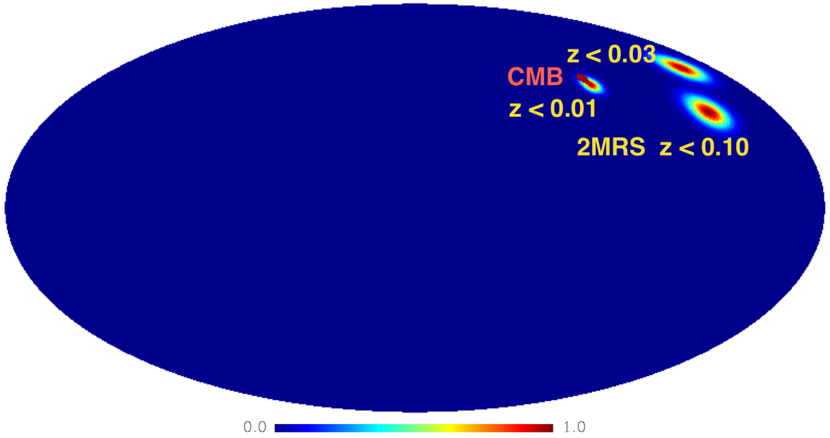
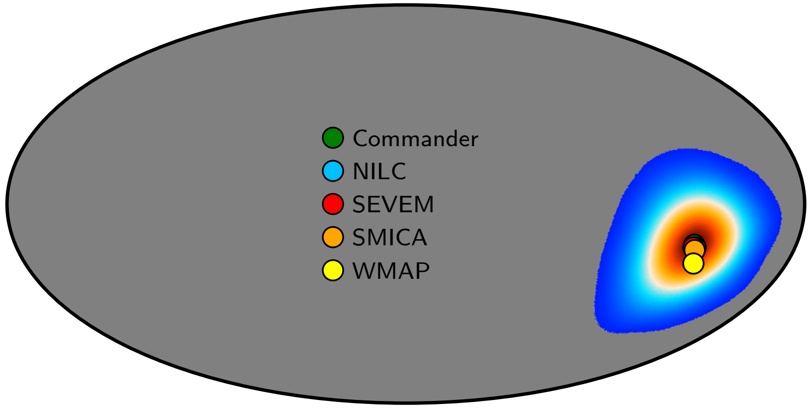
- Quadrupole-Octopole alignment
- Hemispherical asymmetry $\Leftrightarrow$ `dipole`
- Low variance
- Parity asymmetry, i.e., $\ell_{2n} < \ell_{2n+1}, \; n \geq 1$
- etc. (low quadrupole, cold-spot,…)

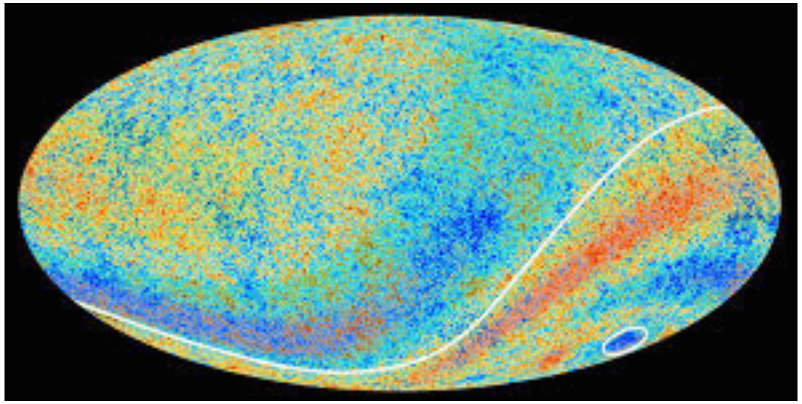
Dipole searches: hemis. asymmetry



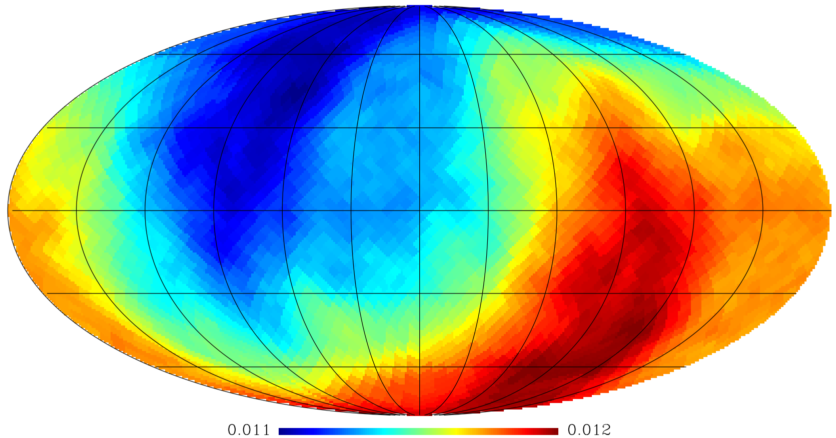
2MRS (V+g)



CMB



Geometric



hemis. asym.

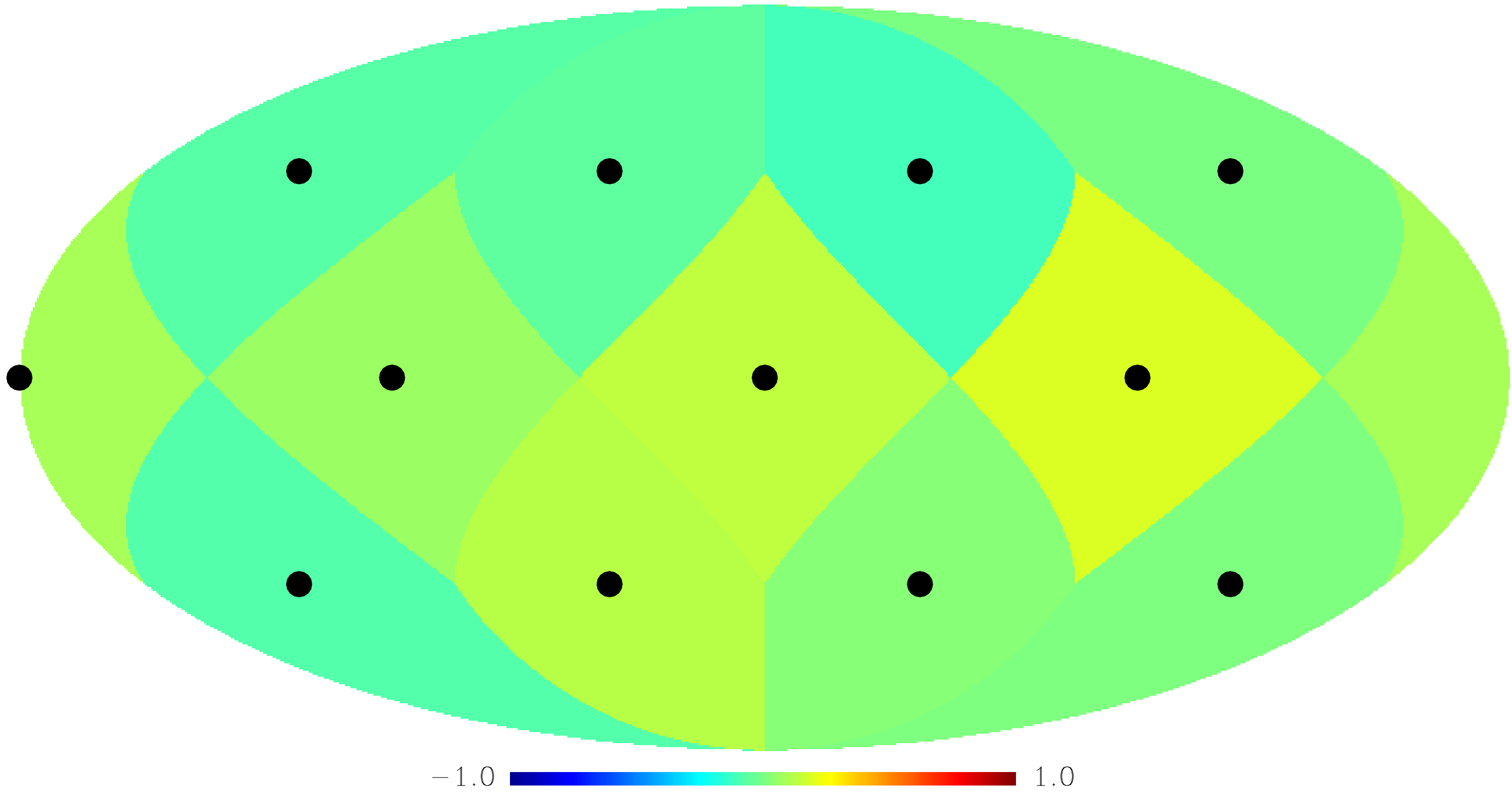
many origins: local (grav., geom., mag. field, etc.) or global

Looking for

Hemispherical asymmetry

in the angular correlations

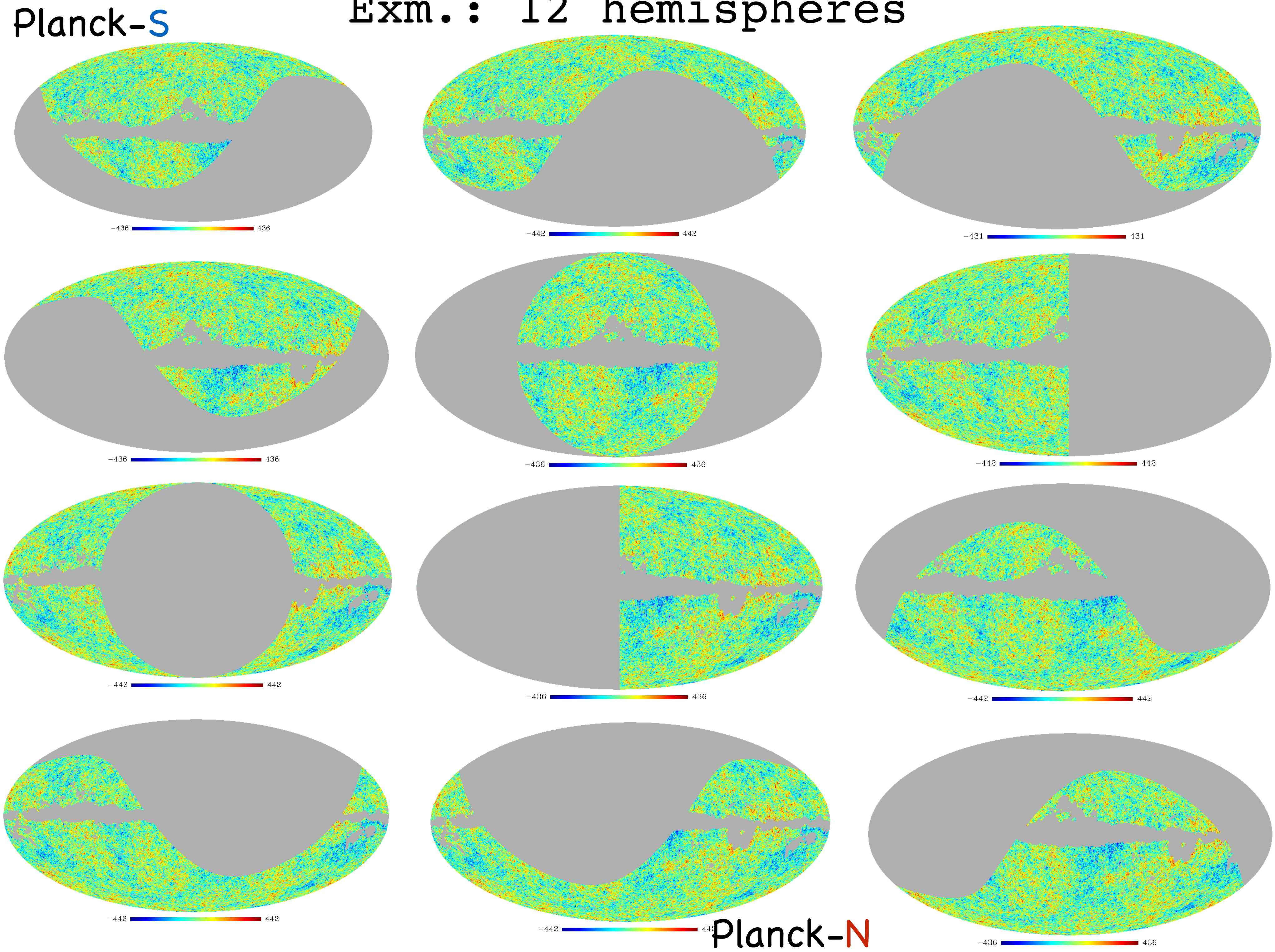
Points uniformly distributed in the celestial sphere
that shall be centers of caps (i.e., hemispheres)

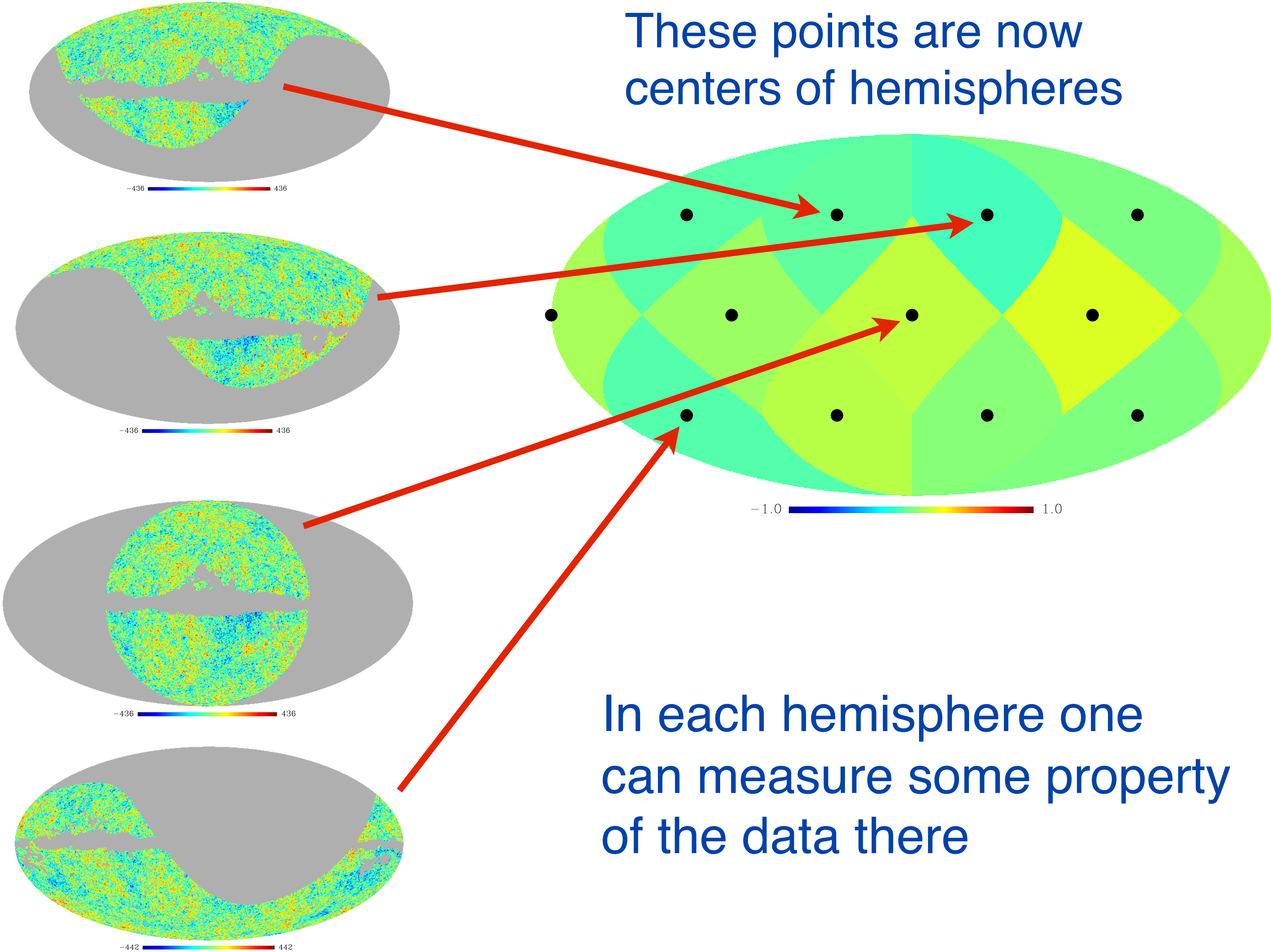


because we want to perform a directional analysis

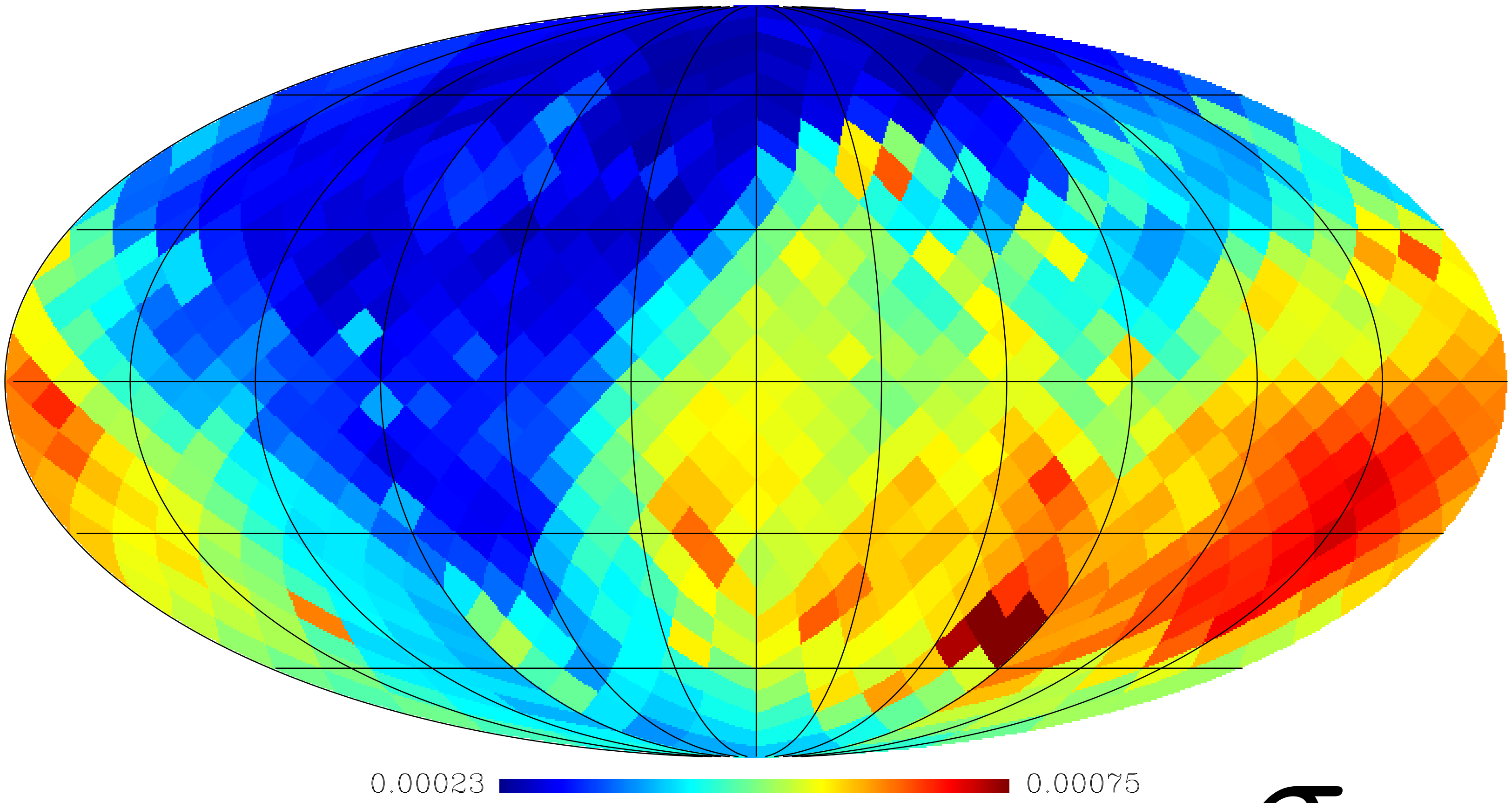
e.g., 12 hemisphs.

Exm.: 12 hemispheres



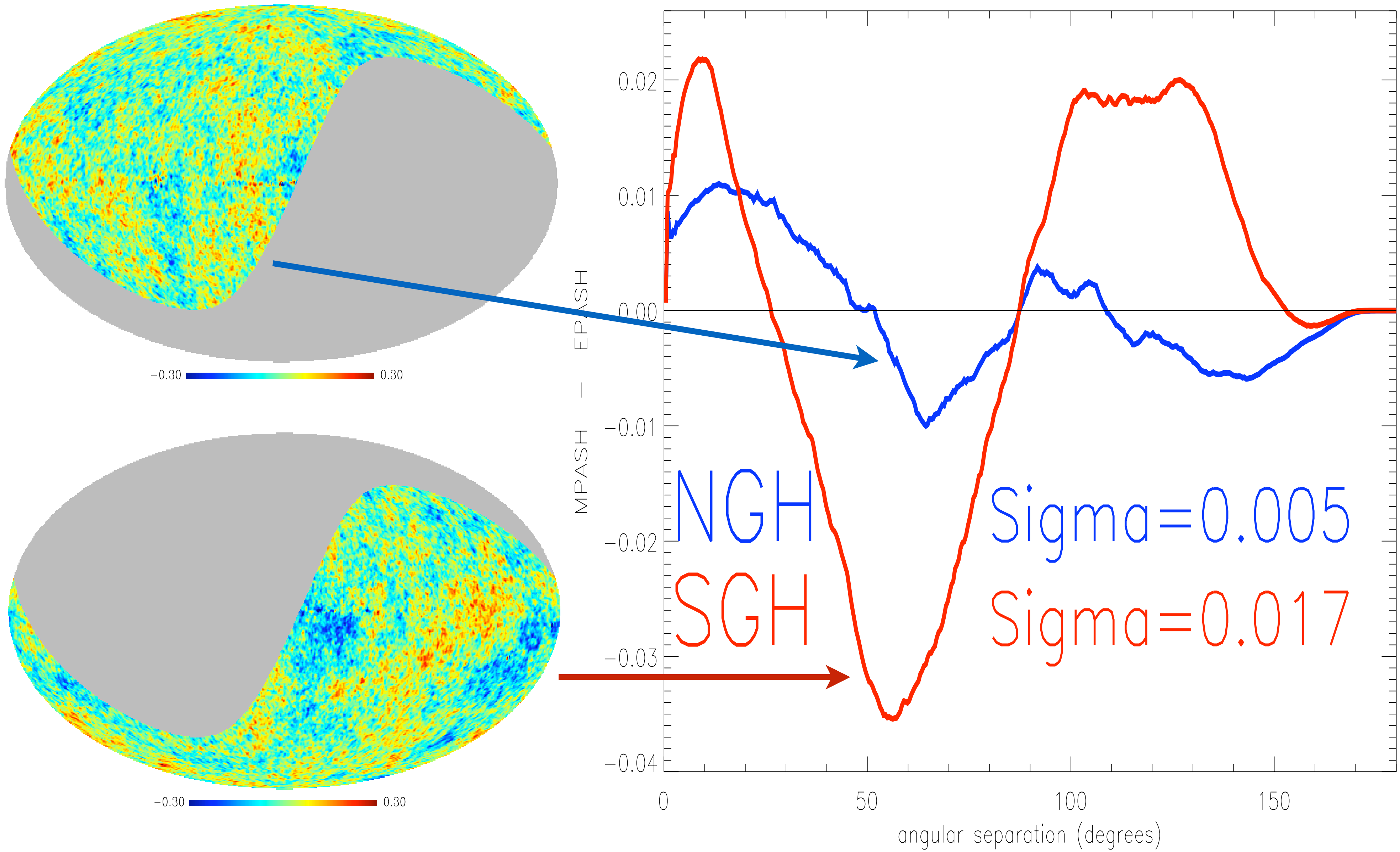

These points are now centers of hemispheres
−436
436
−436
436
−436
436
−442
442
−1.0
1.0
In each hemisphere one can measure some property of the data there

Hemispherical asymmetry



σ-map

Hemispherical asymmetry



WMAP3, 2006

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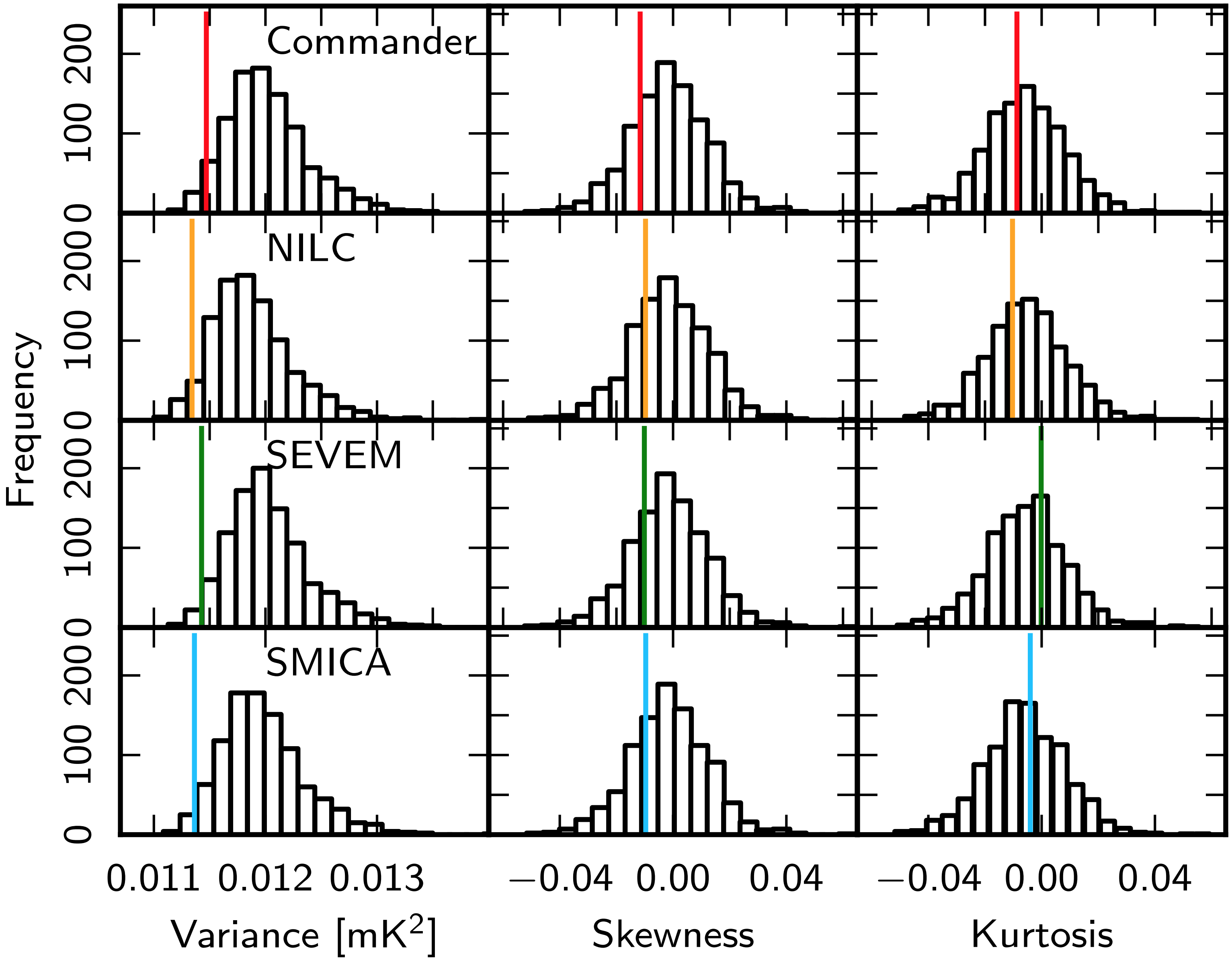
Low CMB Variance (full-sky)



2013,
2015

CMB variance hemis. asymmetry

2013

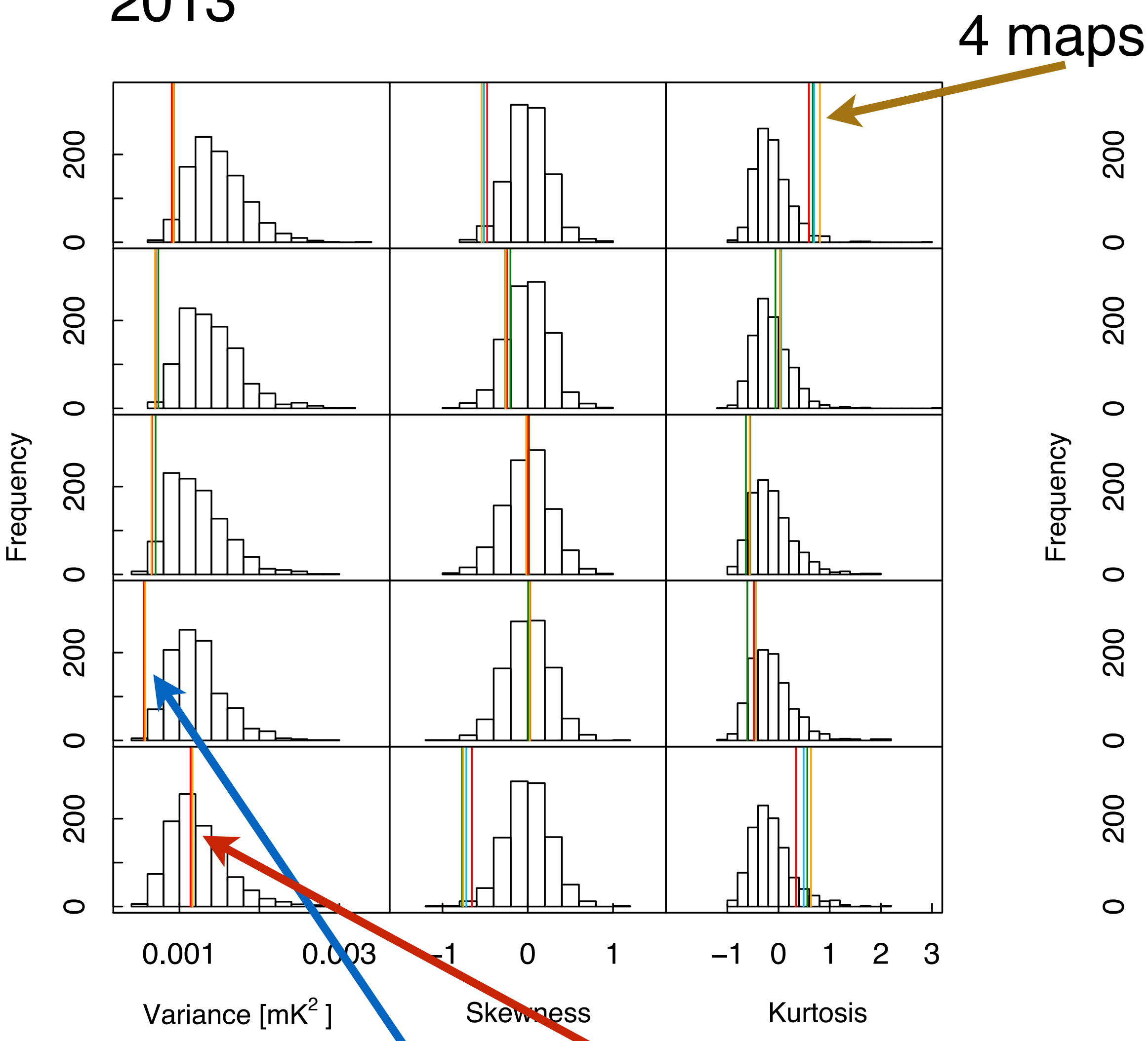


Fig. 18. Variance, skewness and kurtosis at $N_{\rm side} = 16$, for the U73 mask, CL58, CL37, ecliptic North, and ecliptic South (from top to bottom). The different lines represent the four component separation methods `C-R` (green), `NILC` (blue), `SEVEM` (red), and `SMICA` (orange).

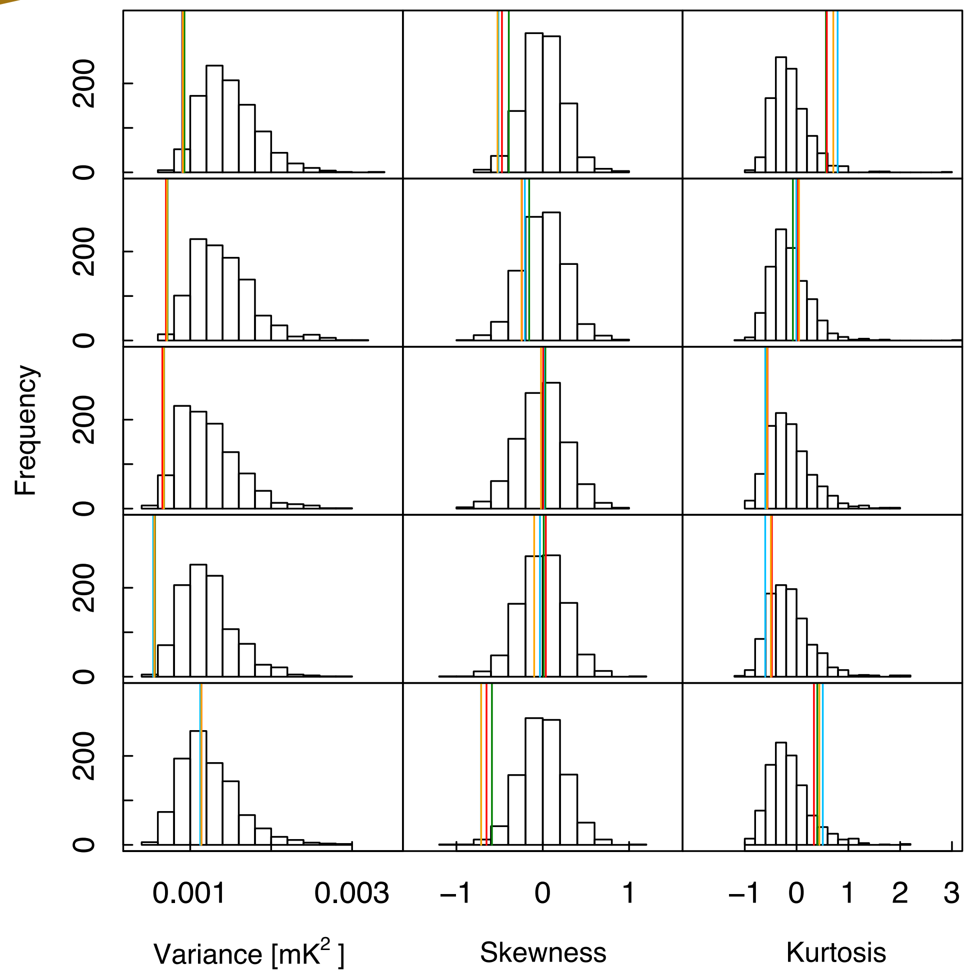
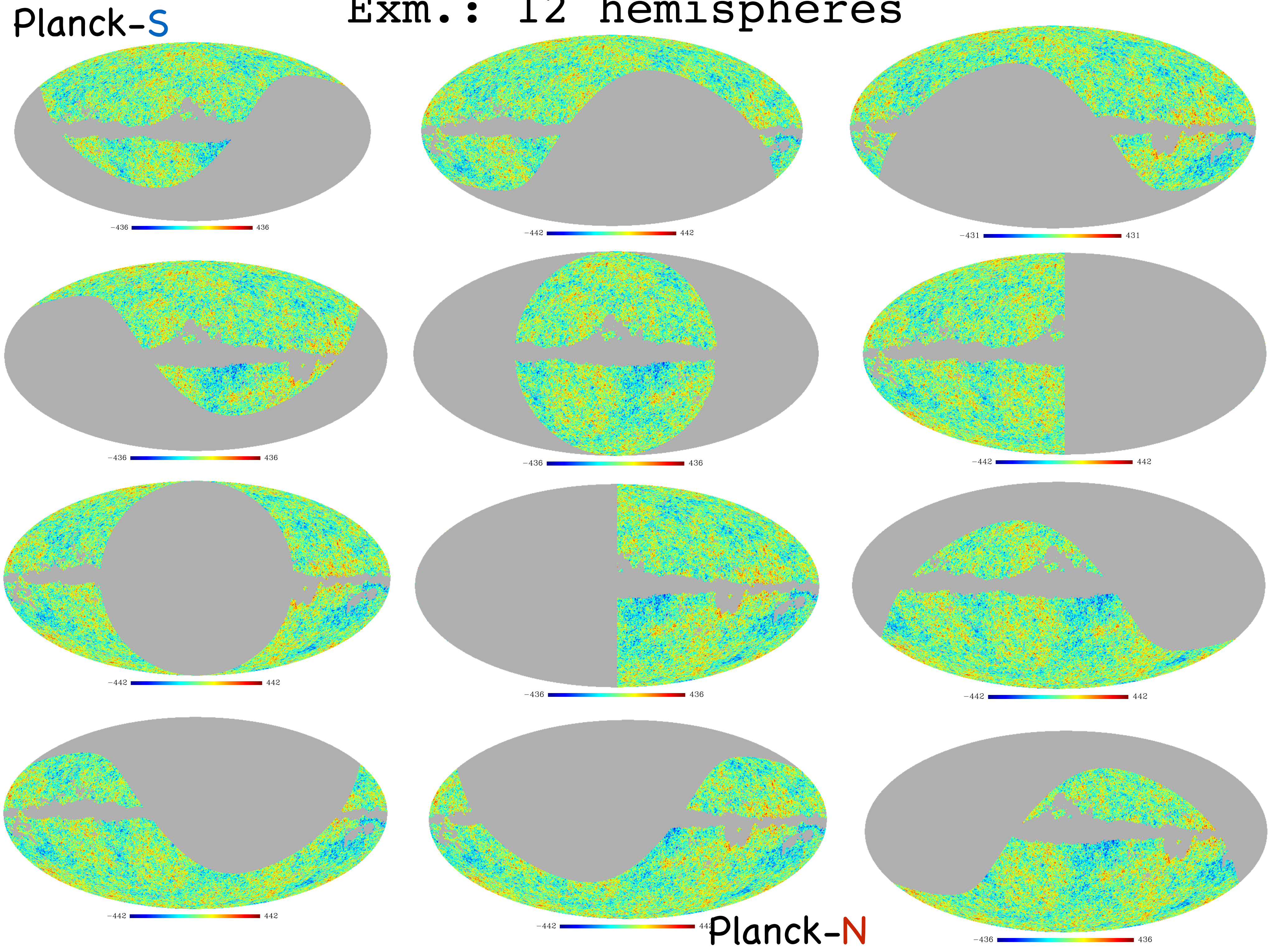
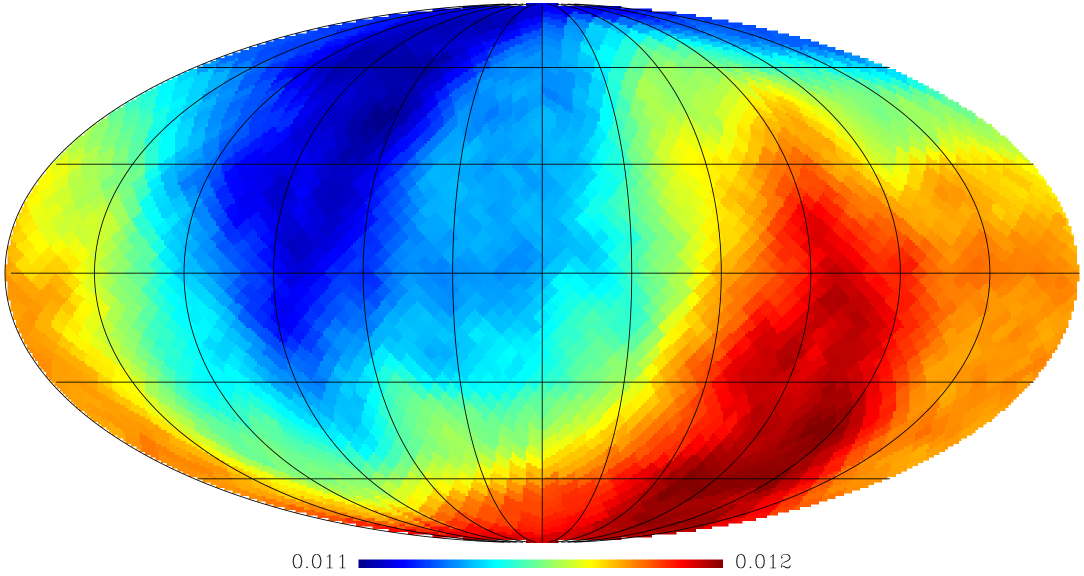


Fig. 19. Variance, skewness and kurtosis at $N_{\rm side} = 16$, for the U73 mask, CL58, CL37, ecliptic North, and ecliptic South (from top to bottom). The different lines represent the four considered frequencies, namely 70 GHz (green), 100 GHz (blue), 143 GHz (red), and 217 GHz (orange).

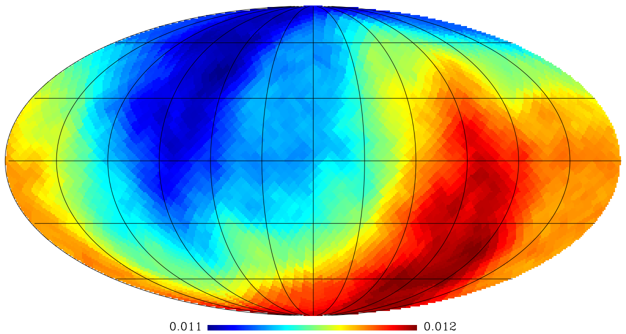
Exm.: 12 hemispheres

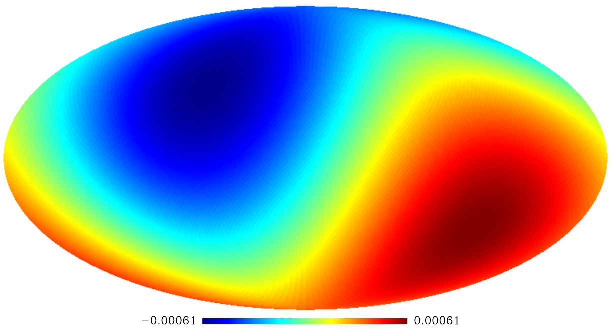


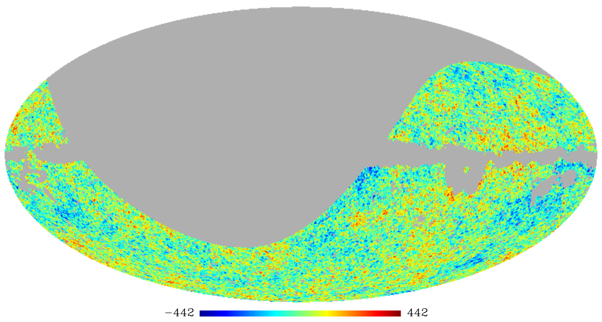
Variance hemispherical asymmetry



- Interestingly, the variance-map shows a North-South asymmetry distribution







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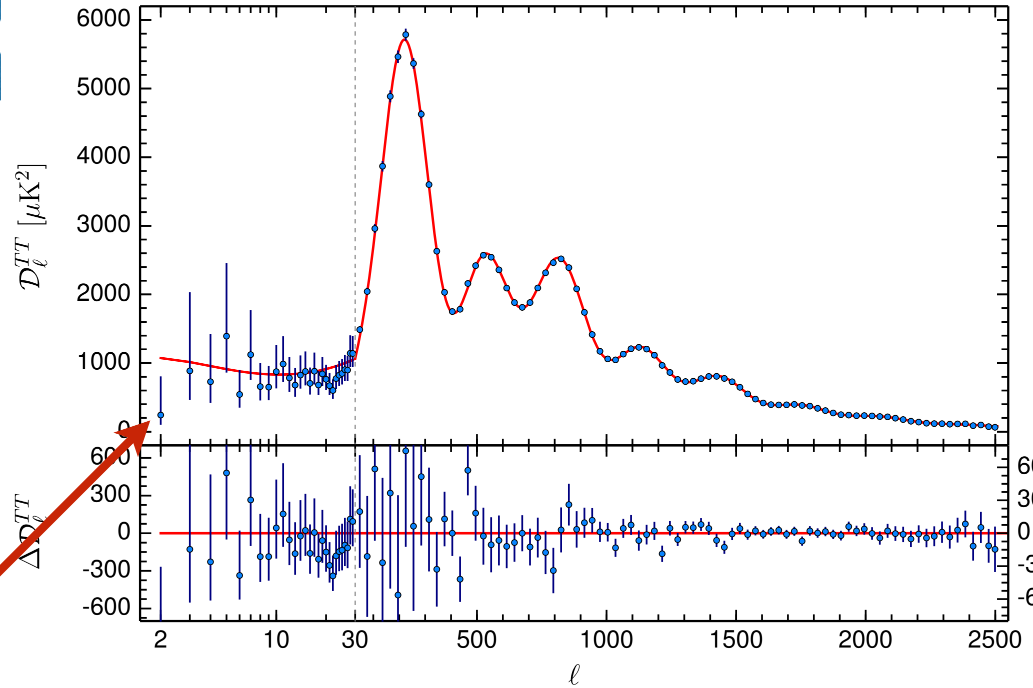
- Low quadrupole: $C_2 << 1150$ muK (LCDM)

$C_2 \in [1150/8, 1150/5]$

Large angular scale CM



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Low Quadrupole C_2 … hint: finite space!

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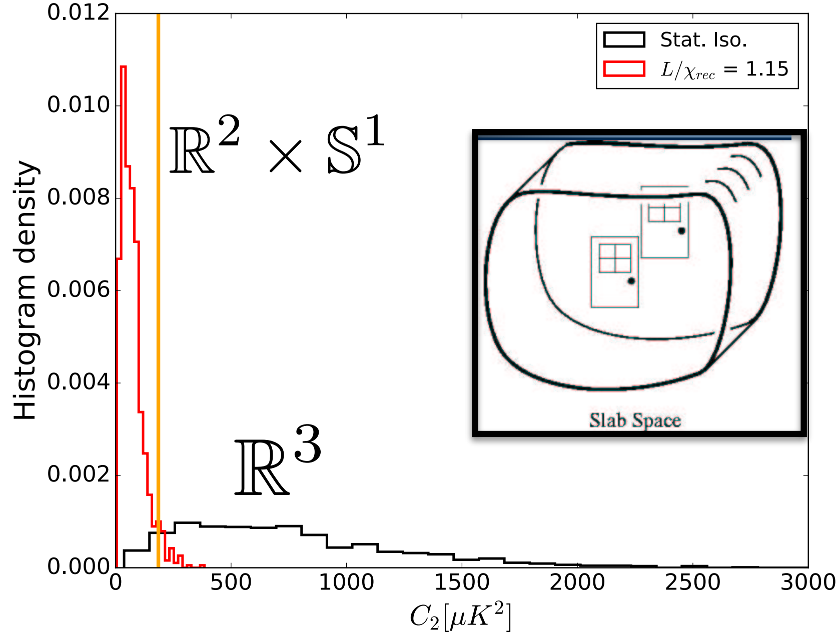

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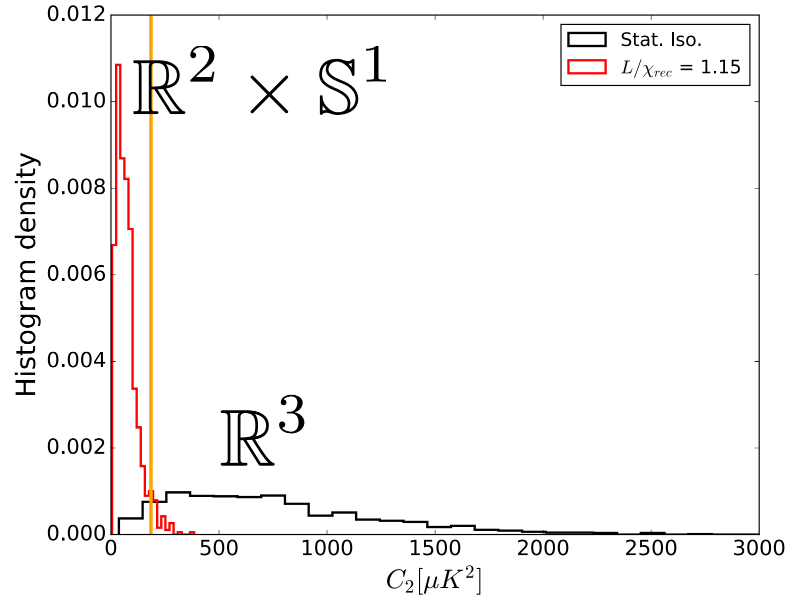


- Low quadrupole: C_2 << 1150 muK (LCDM)

many features … no unique explanation (lit.)!

Perhaps: cosmic topology?

CMB anomalies vs. cosmic topology

In the last ∼18 years of CMB-anomalies literature:

- dozens of models (hypotheses, explanations,..)
- hundreds of papers (data analyses &/ models)
- thousands of citations

What we have learned:

(1) the model with chance to be the correct one, should explain all the large-scale anomalies, not just one or two

(2) such model should have one global preferred axis

Brief review: cosmic topology

simple vs. multiple-connectedness

$$\mathbb{R} \times \mathbb{S}^1$$

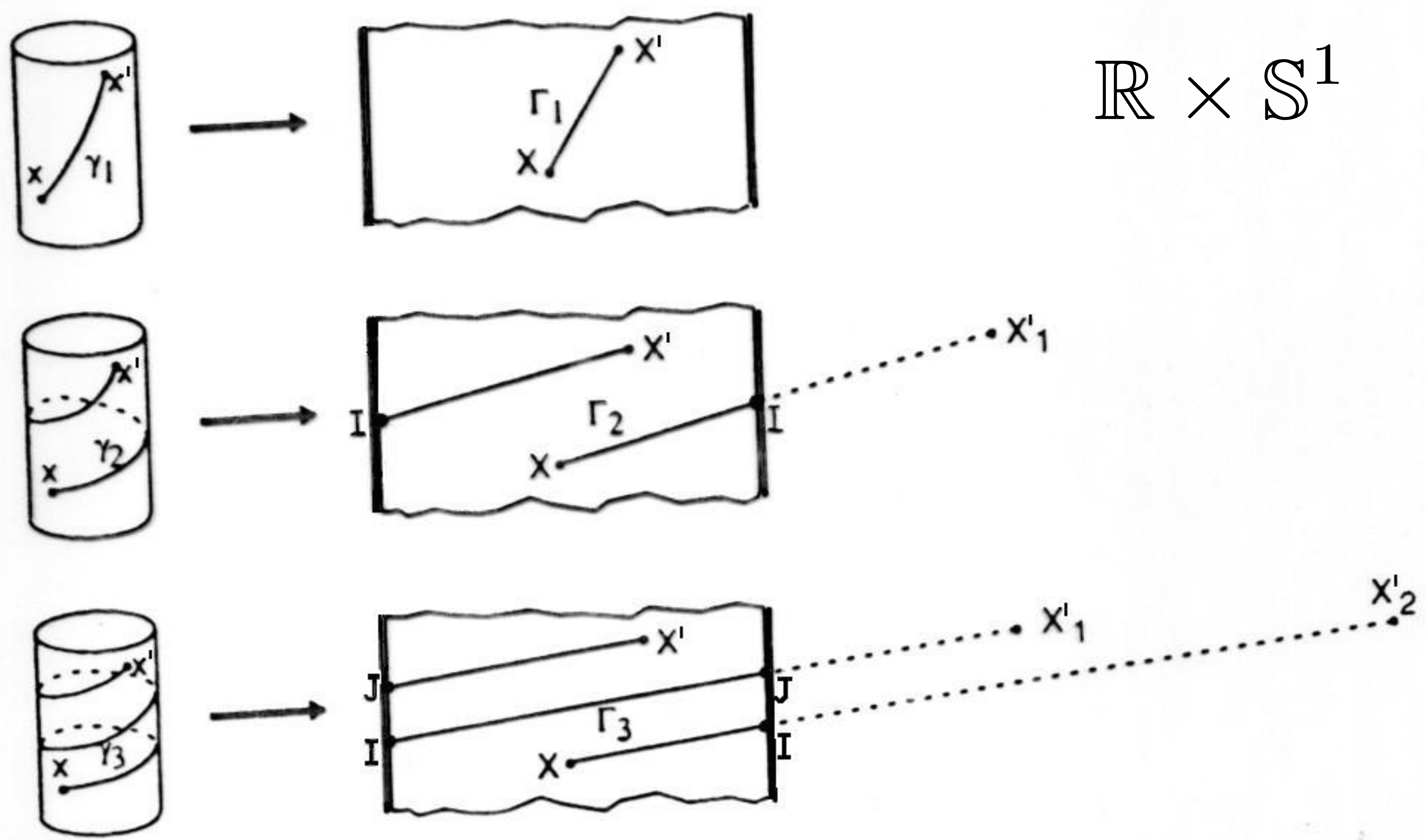
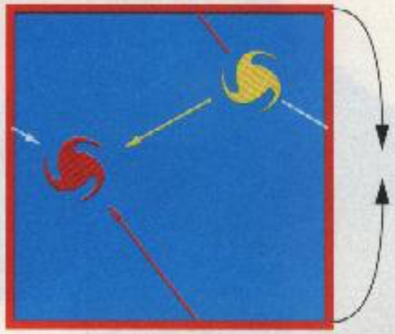


Fig. 3. Las geodésicas del cilindro

simple vs. multiple-connectedness $\mathbb{T}^2$

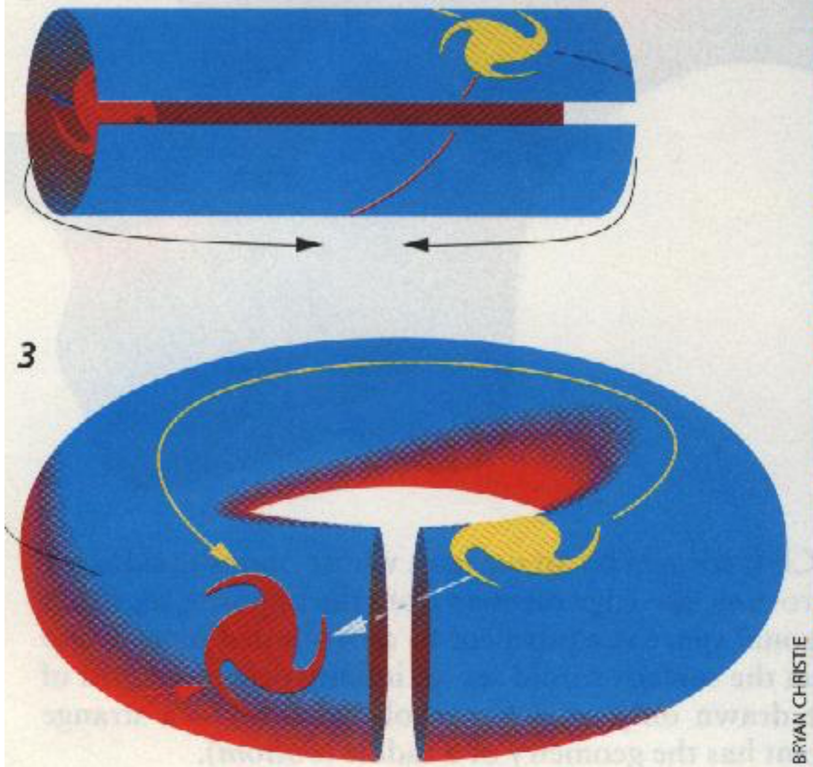
1

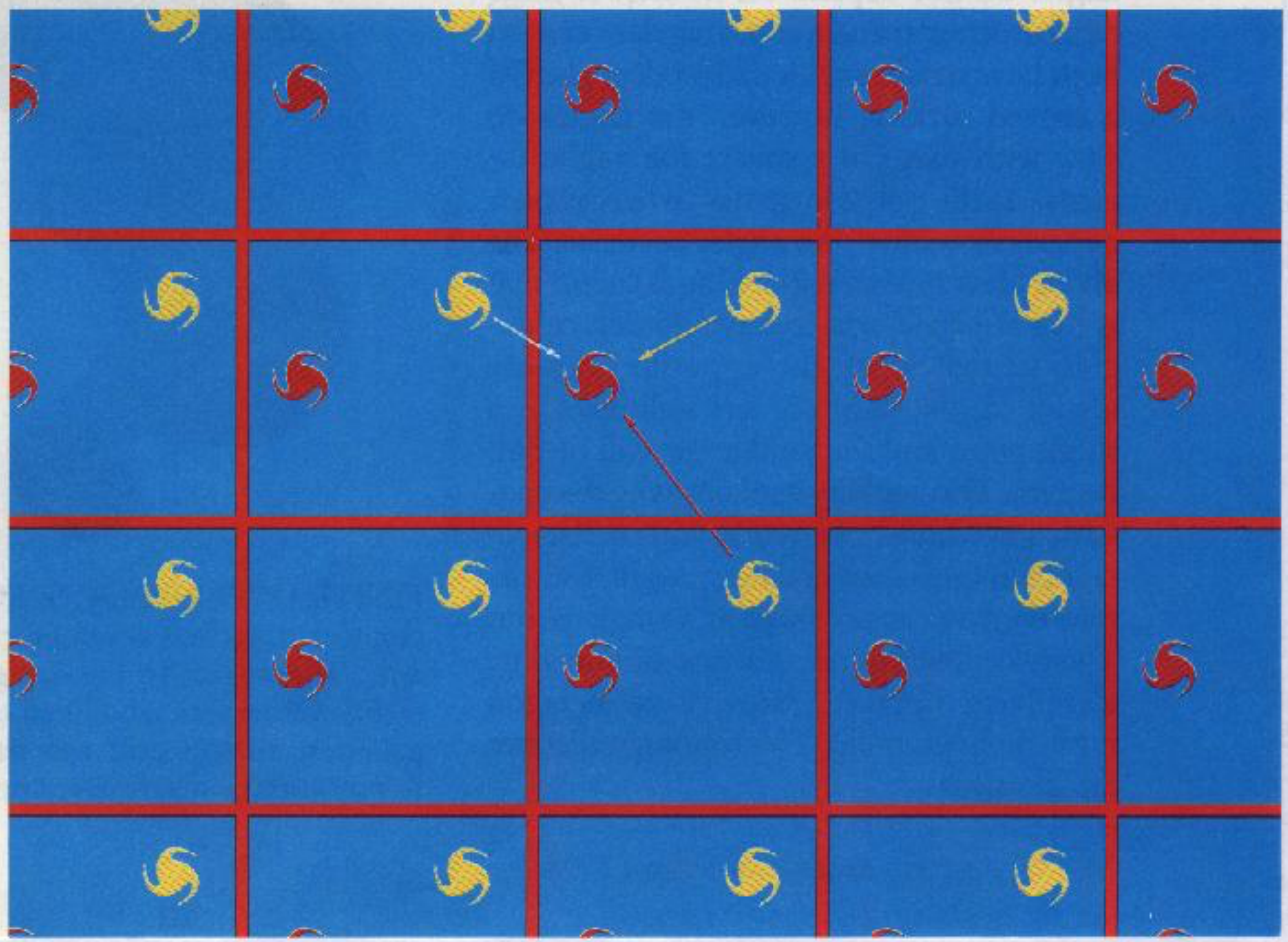


DOUGHNUT SPACE, more properly known as the Euclidean 2-torus, is a flat square whose opposite sides are connected (*1*). Anything crossing one edge reenters from the opposite edge. Although this surface cannot exist within our three-dimensional space, a distorted version can be built by taping together top and bottom (*2*) and scrunching the resulting cylinder into a ring (*3*). For observers in the pictured red galaxy, space seems infinite because their line of sight never ends (*below*). Light from the yellow galaxy can reach them along several different paths, so they see more than one image of it. A Euclidean 3-torus is built from a cube rather than a square.

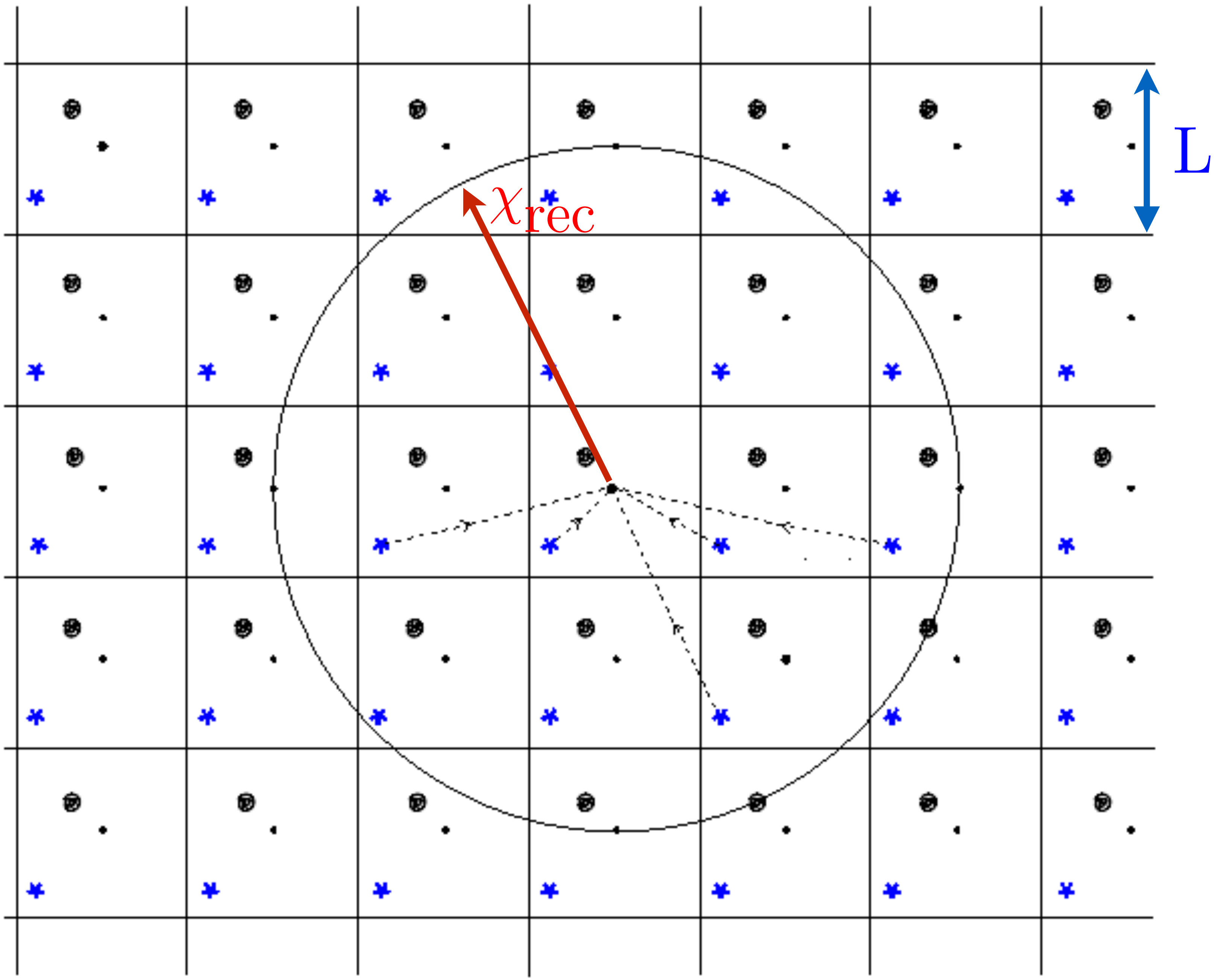
2

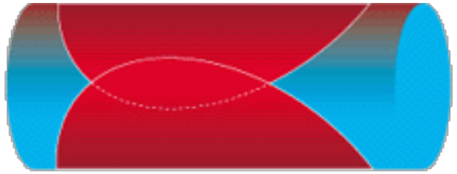
3

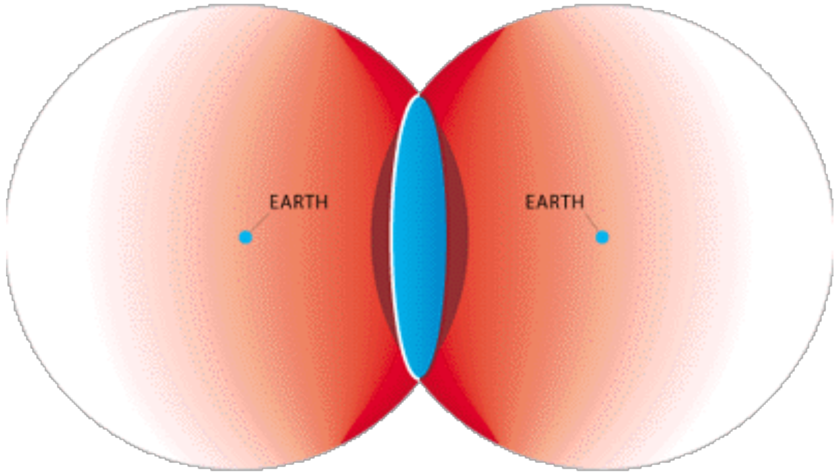


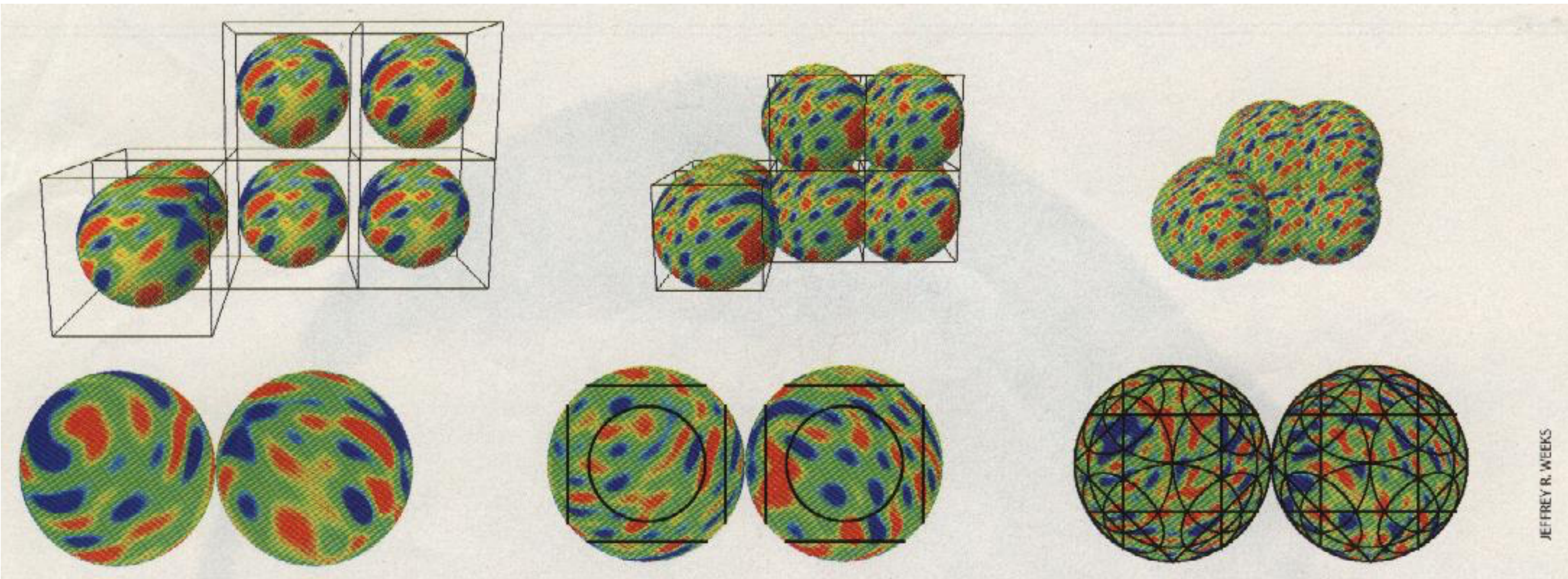


The observed universe






EARTH
EARTH


JEFFREY R. WEEKS

1D compact 2D space: the cilinder $\mathbb{R} \times \mathbb{S}^1$

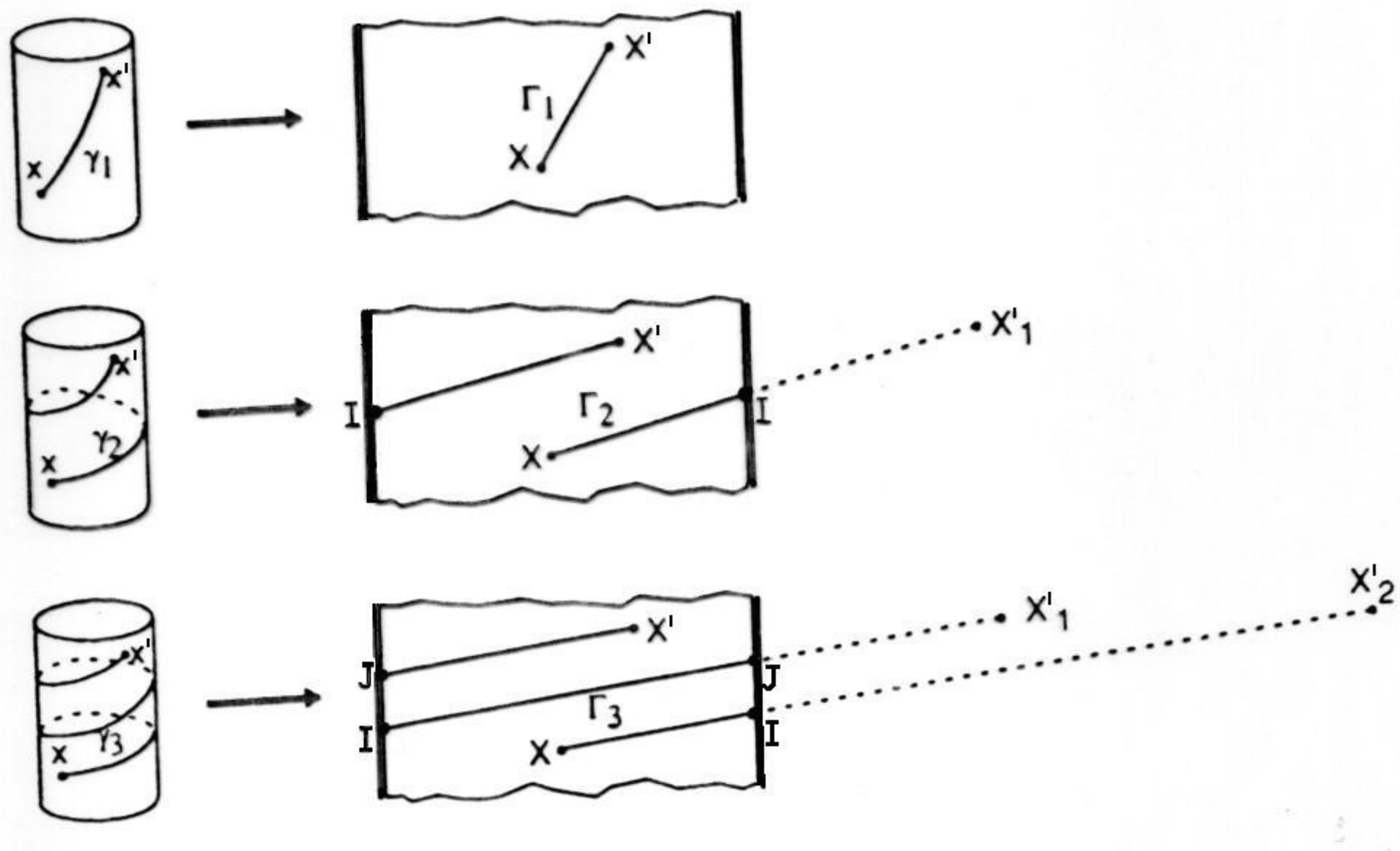
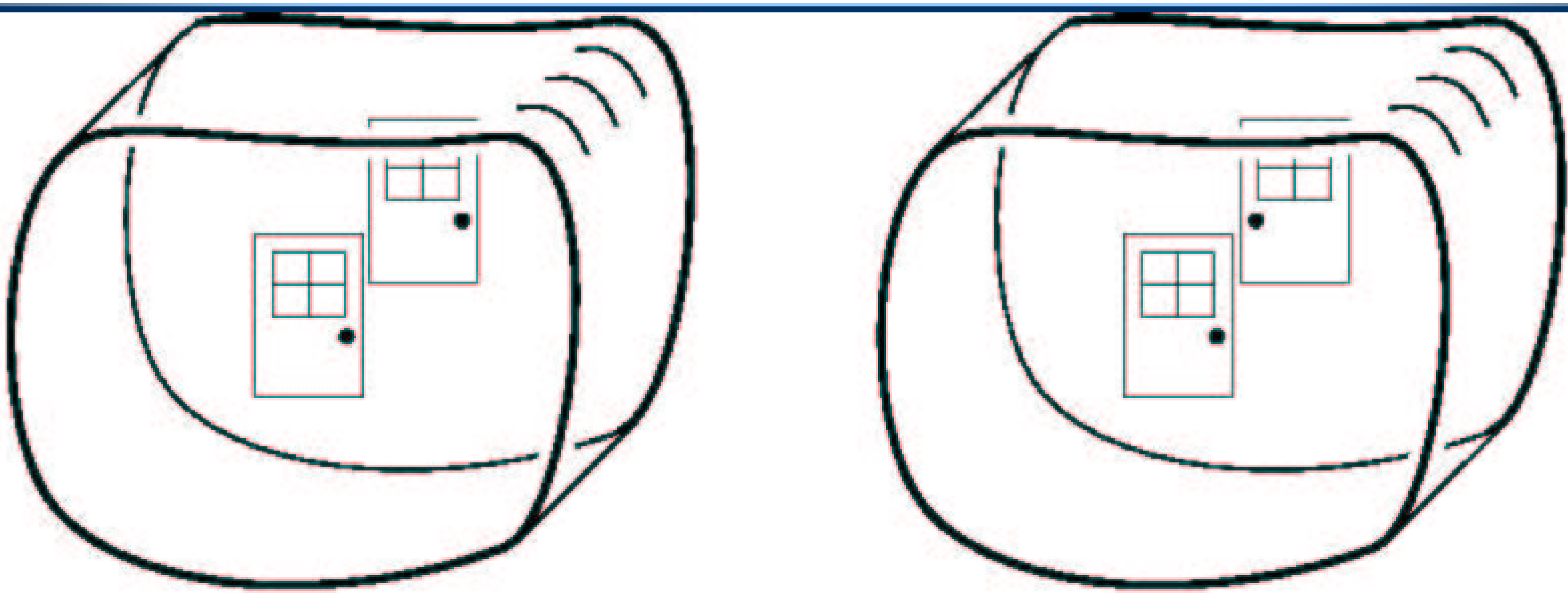


Fig. 3. Las geodésicas del cilindro

1D compact 3D space: $\mathbb{R}^2 \times \mathbb{S}^1$



Slab Space

Slab Space with Flip

Inmediate consequences CT hypot.:

- small values of $\{C_\ell\}$ (APS), for low ℓ

- introduce axes of symmetry: 1, 2, 3,...

remember:

Statistical isotropy $\Longrightarrow$ no symmetry axes

1 symmetry axis $\Longrightarrow$ Statistical Anisotropy

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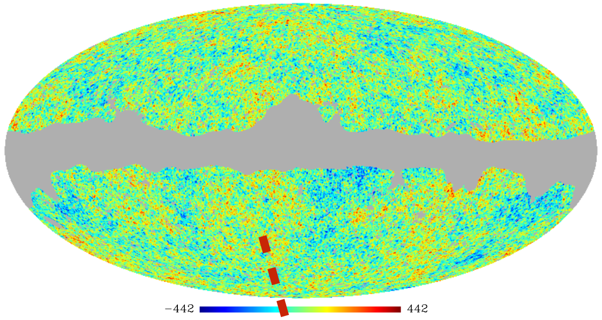
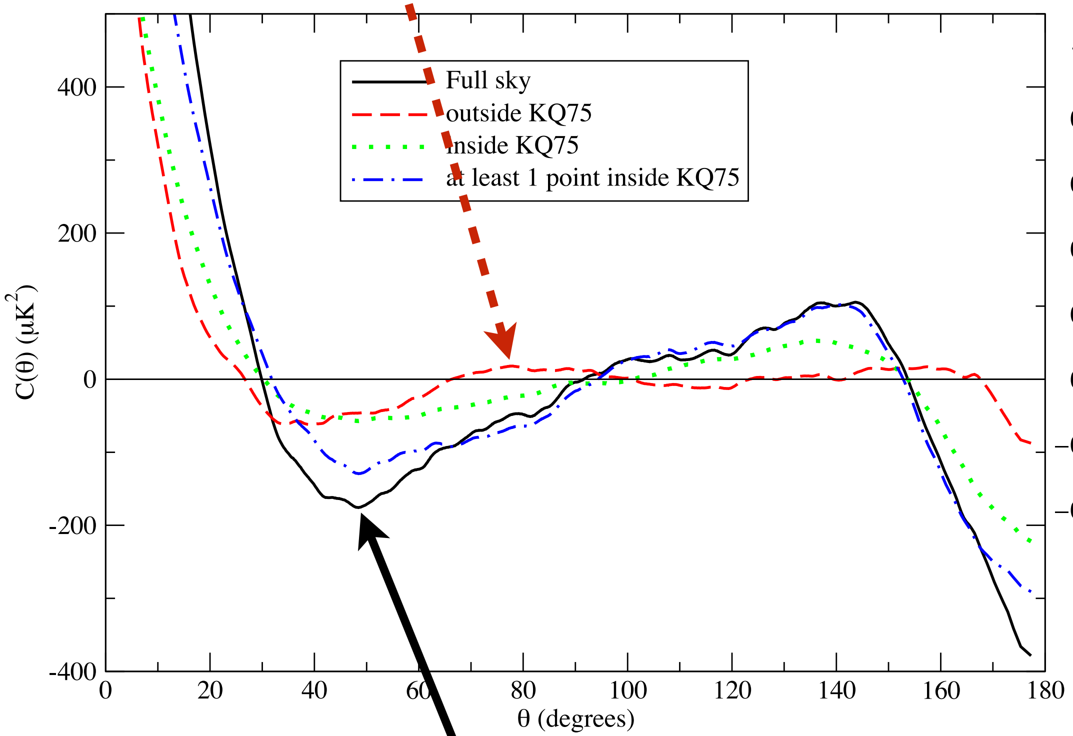
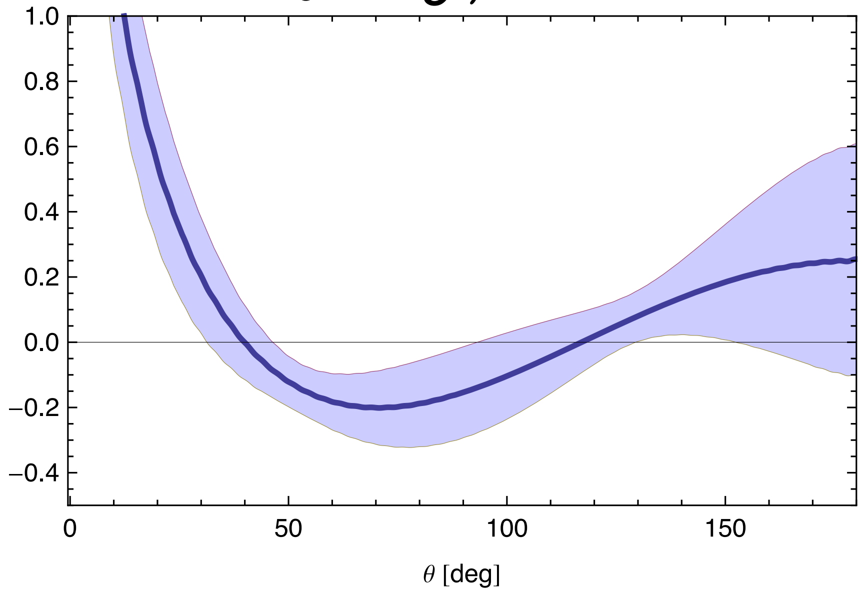
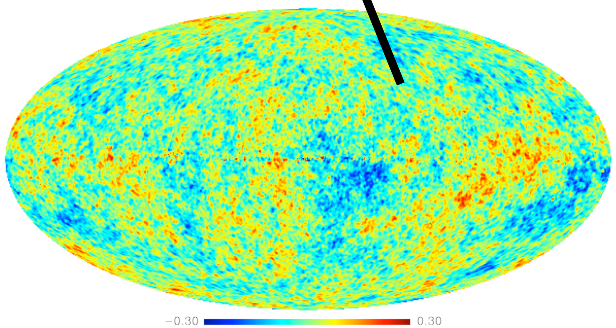


2PACF



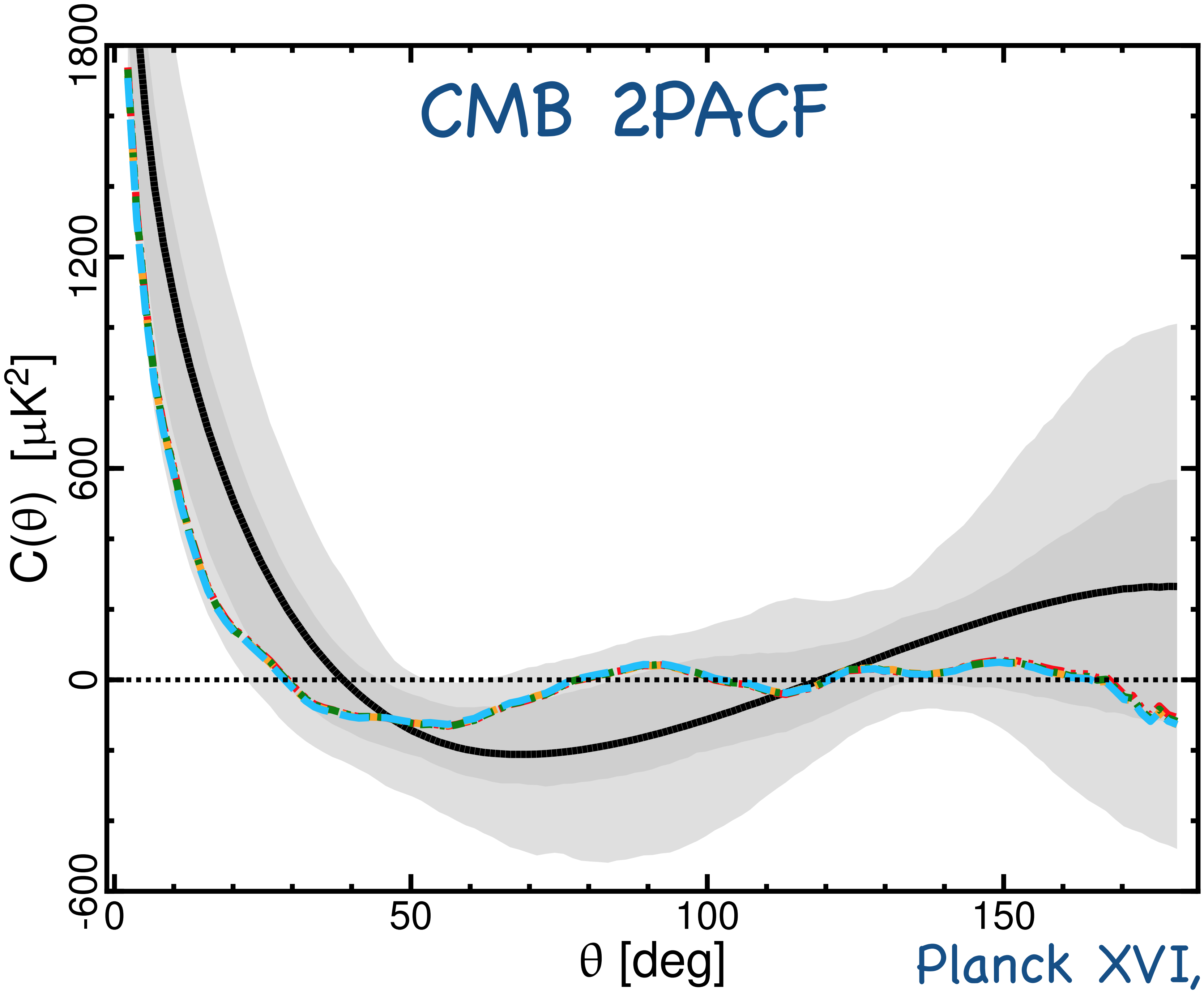
full-sky, stat. iso.





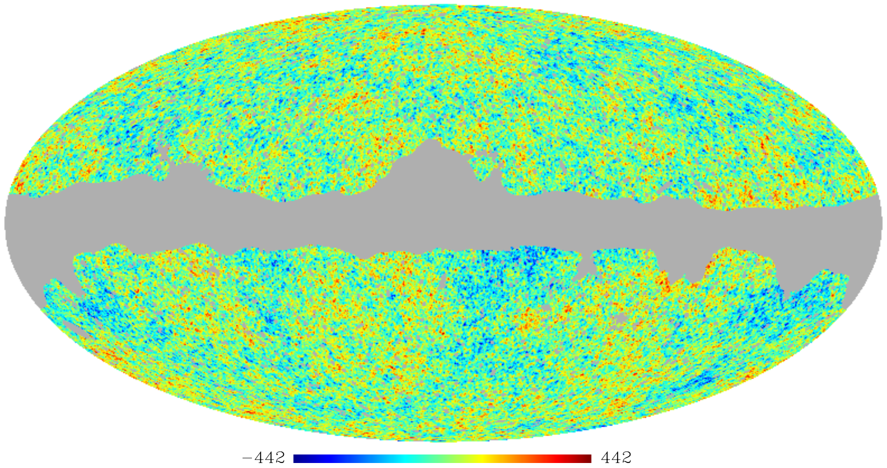
WMAP, 2007

Lack of angular correlations at large scales



Planck XVI, 2015

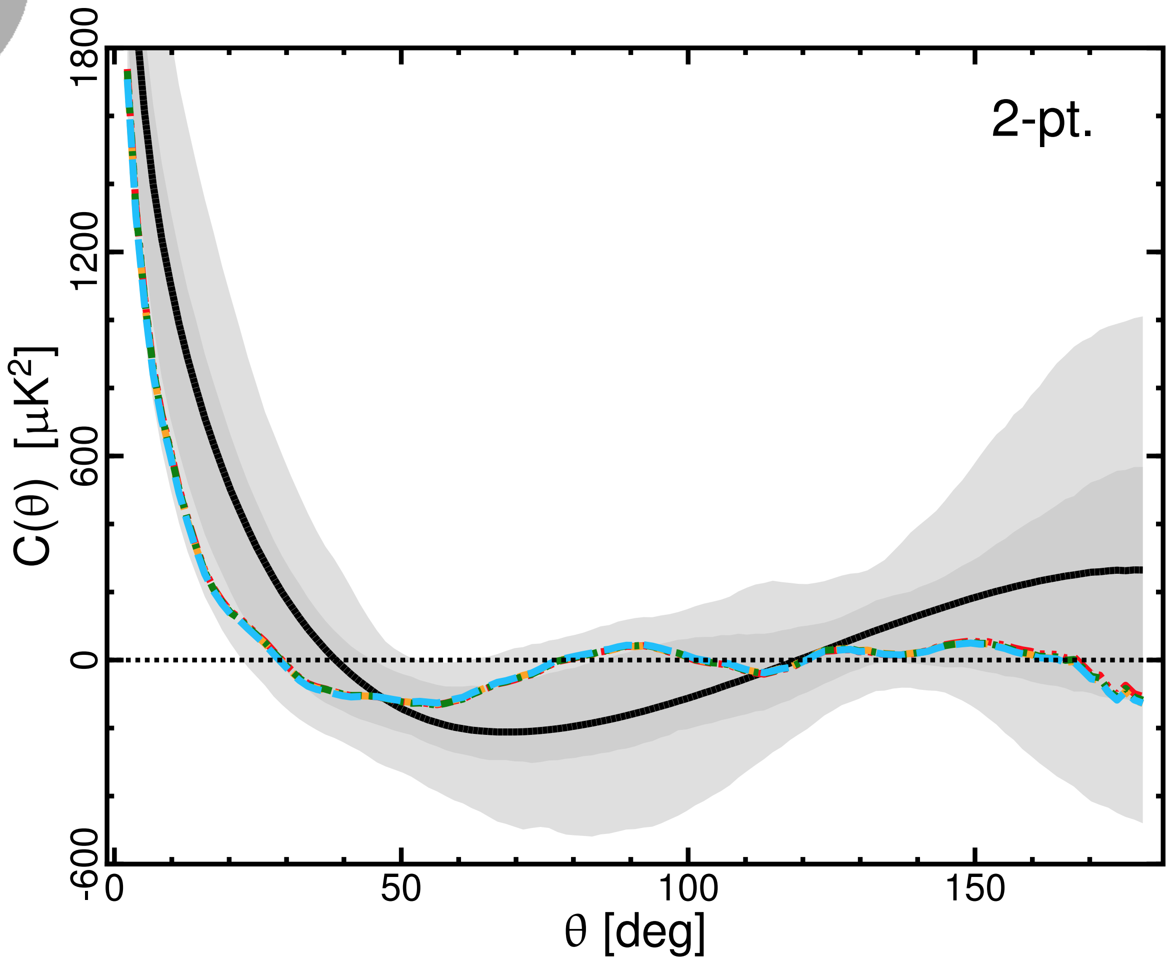
Lack of correlation at large scales



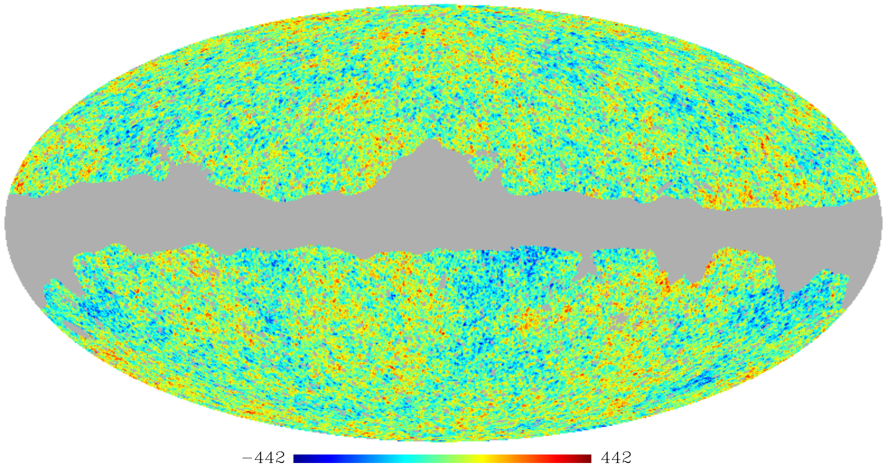
$$\hat{n} \cdot \hat{n}' = \cos(\theta)$$

2PACF

$$\mathbf{C}(\theta) \equiv \langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$$

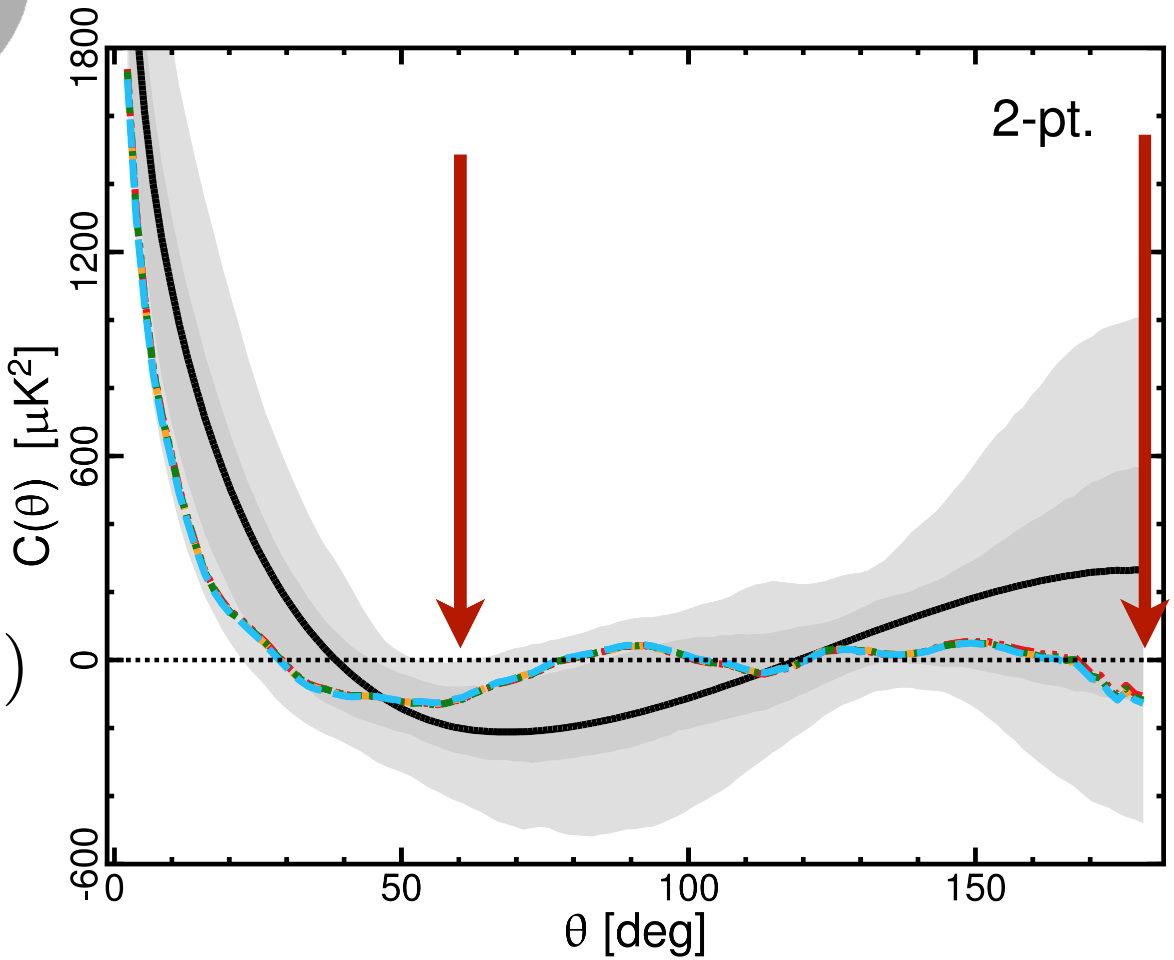


Why is this a CMB anomaly?



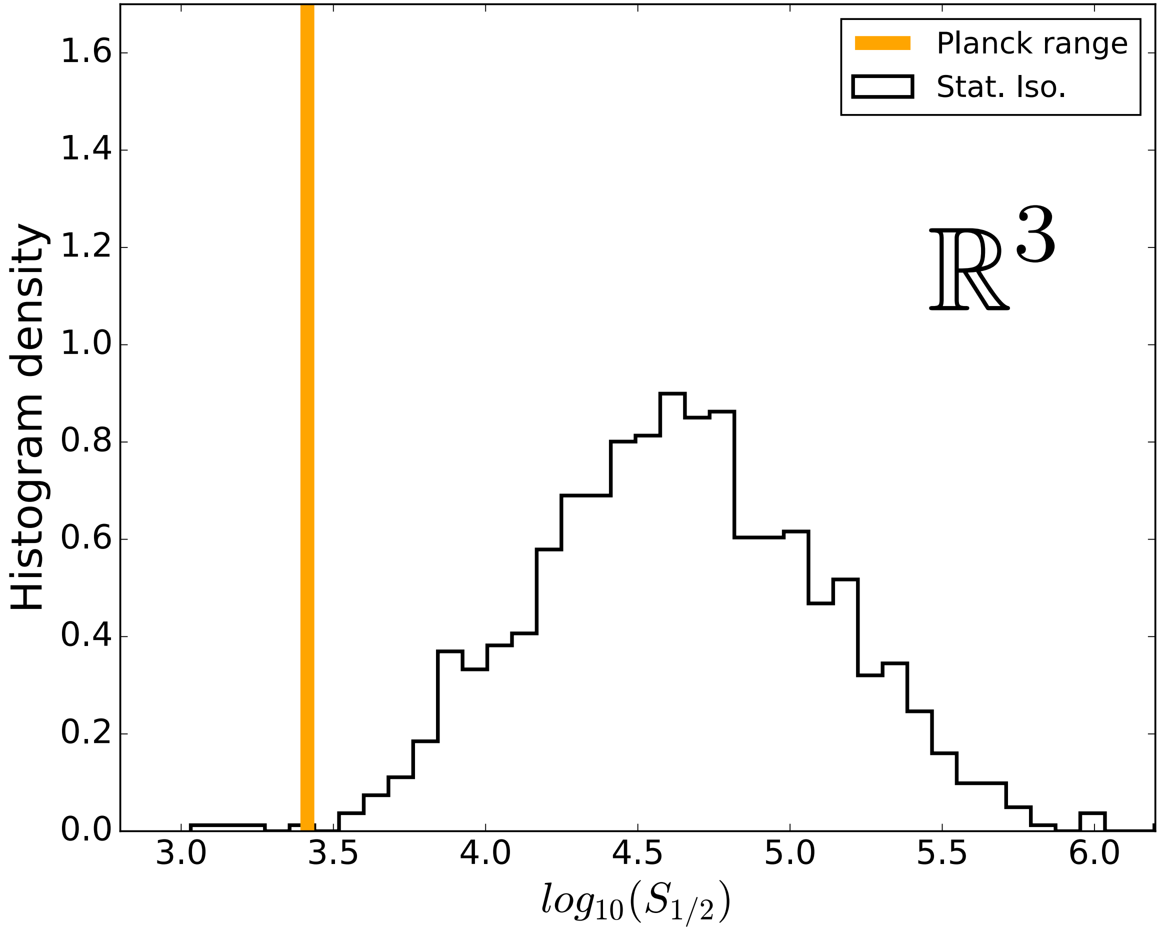
2PACF

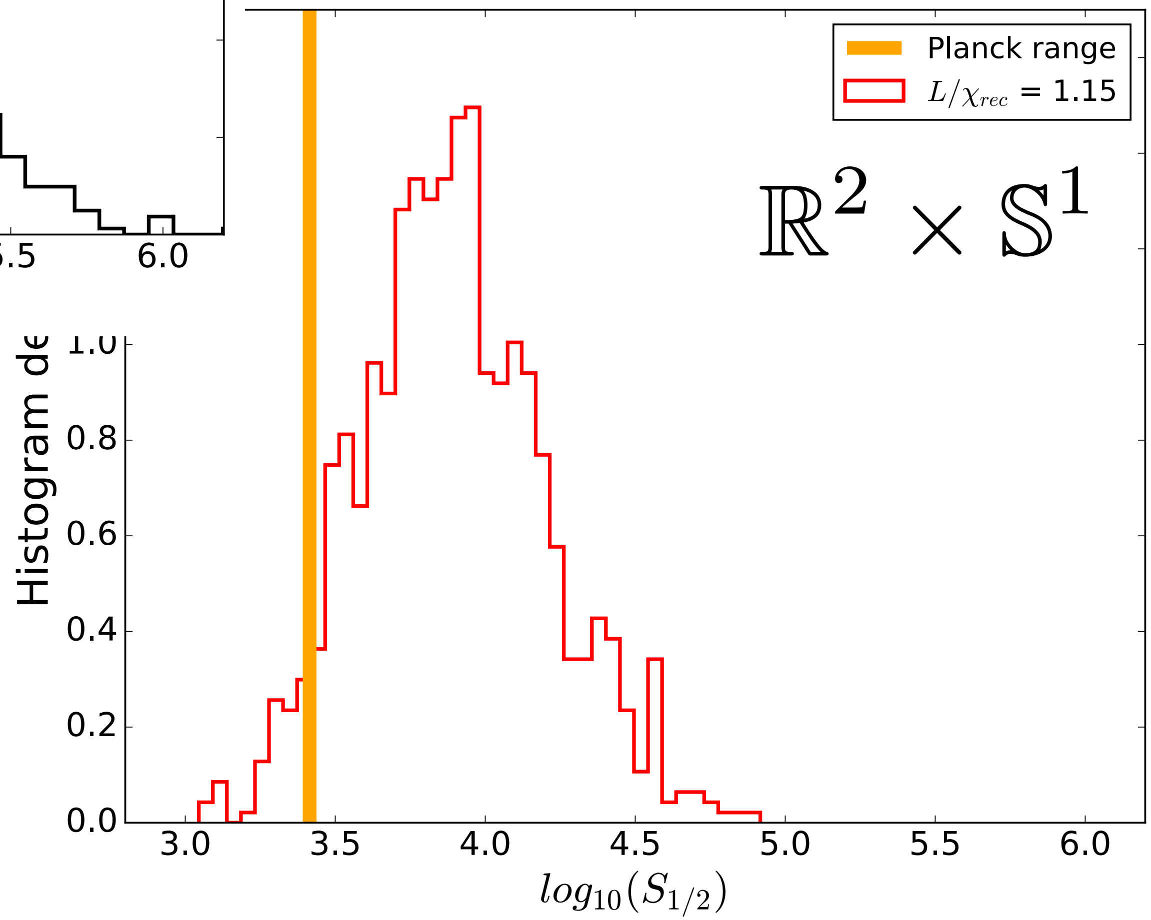
$$\mathbf{C}(\theta) \equiv \langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$$



$$S_{1/2} \equiv \int_{-1}^{1/2} \mathbf{C}(\theta)^2 \, d(\cos\theta)$$

p-value: 0.3% - 1%

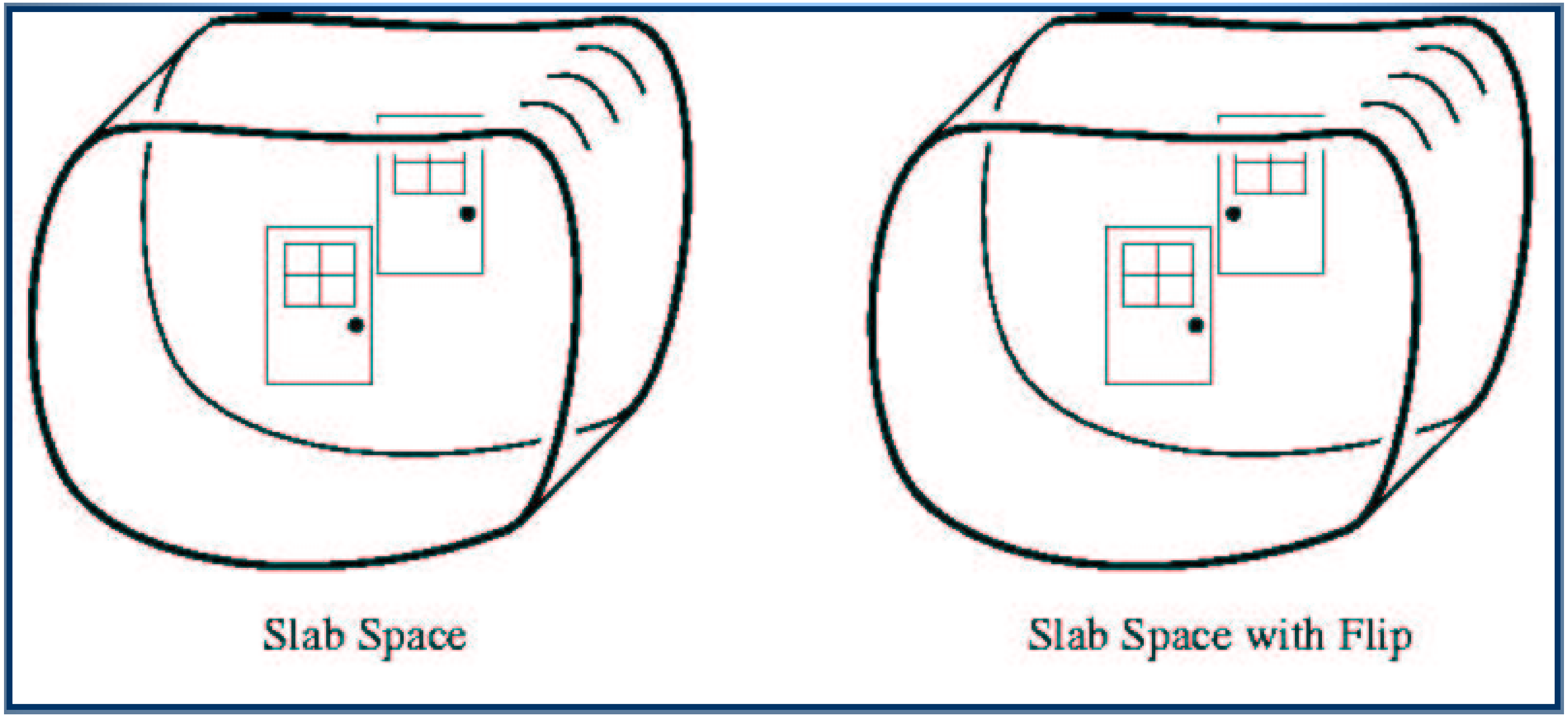




The increasing of p-value suggest stat. anisotropy?

hypothesis

slab topology: $\mathbb{R}^2 \times \mathbb{S}^1$ (1 sym. axis)



the slab-space (3d):

the current Planck limit: $L/\chi_{rec} > 1.12$

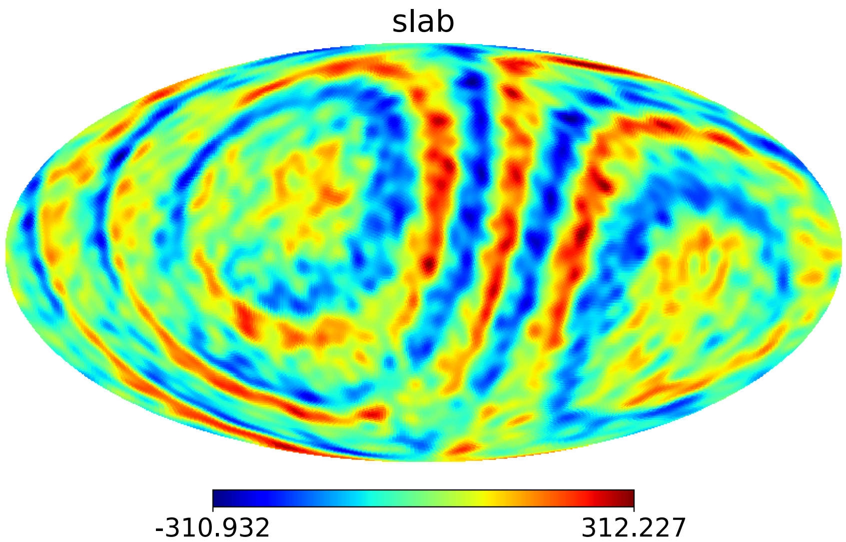
(χ_rec = conformal radius of the CMB's last scattering surface

$$\mathcal{M}_3 = \mathbb{R}^2 \times \mathbb{S}^1$$

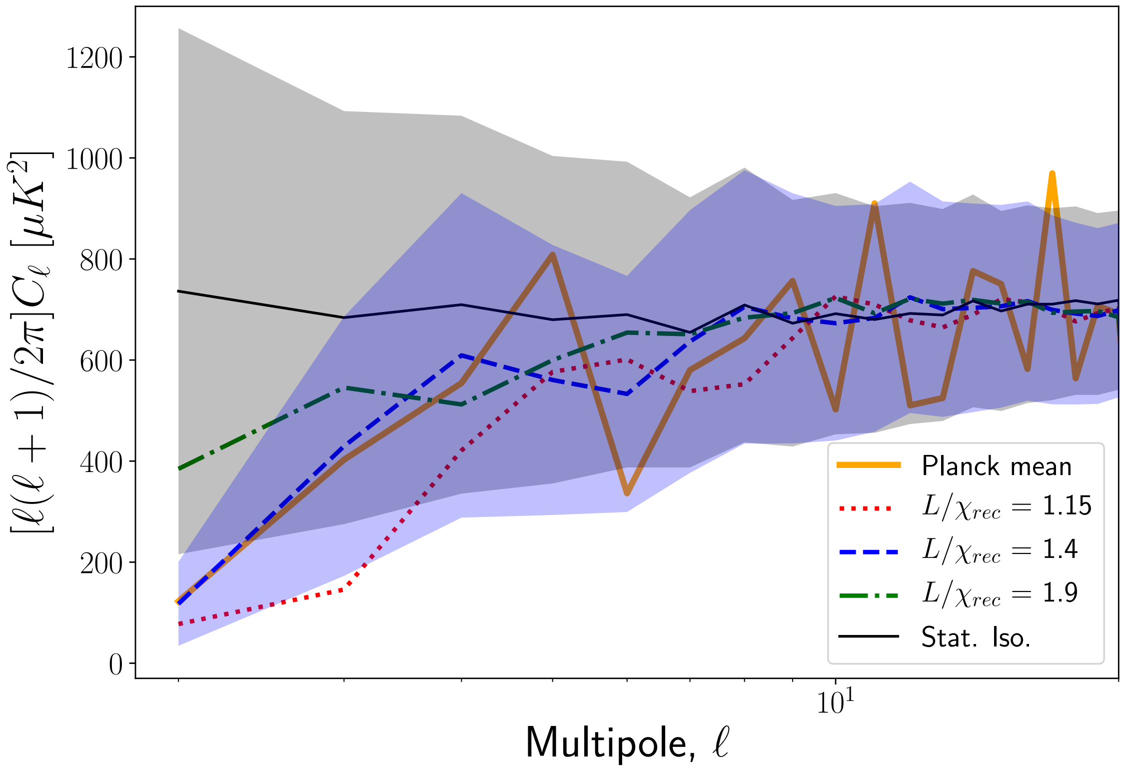
$$L/\chi_{rec} = 1.15, 1.4, 1.9$$

slab topology

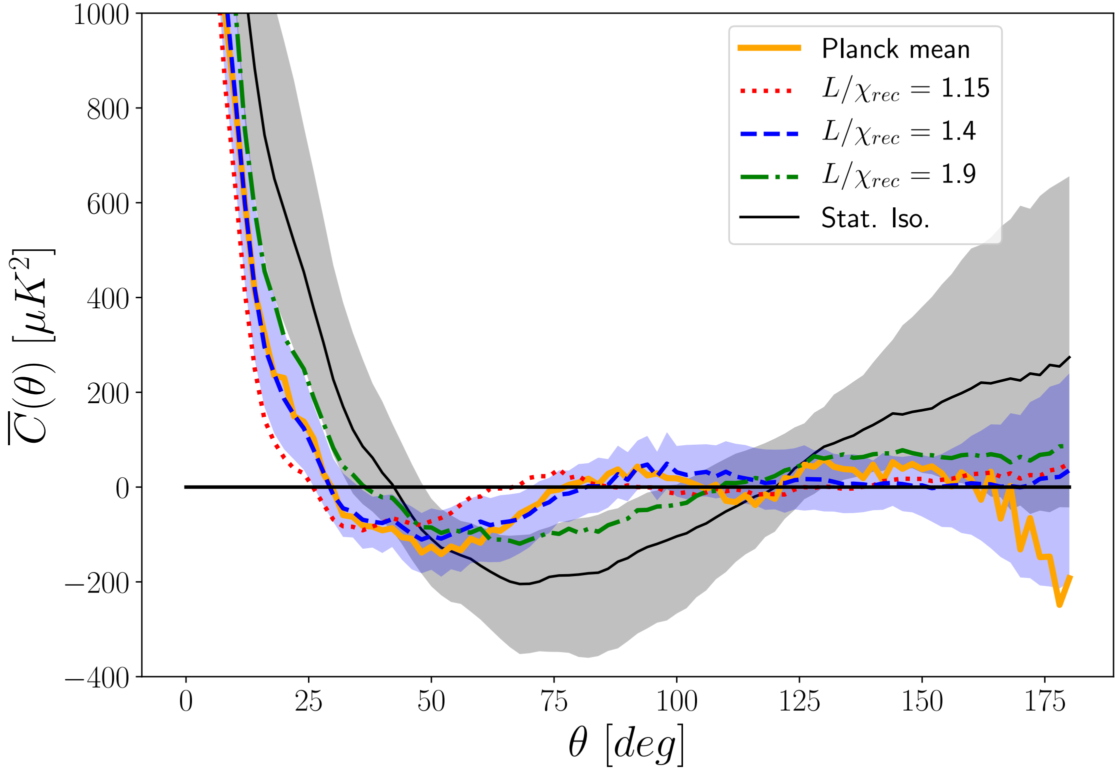
$$L/\chi_{rec} = 0.5$$



Power spectrum deficit at large scales ✅



$$\mathrm{L}/\chi_{rec} = 1.4$$

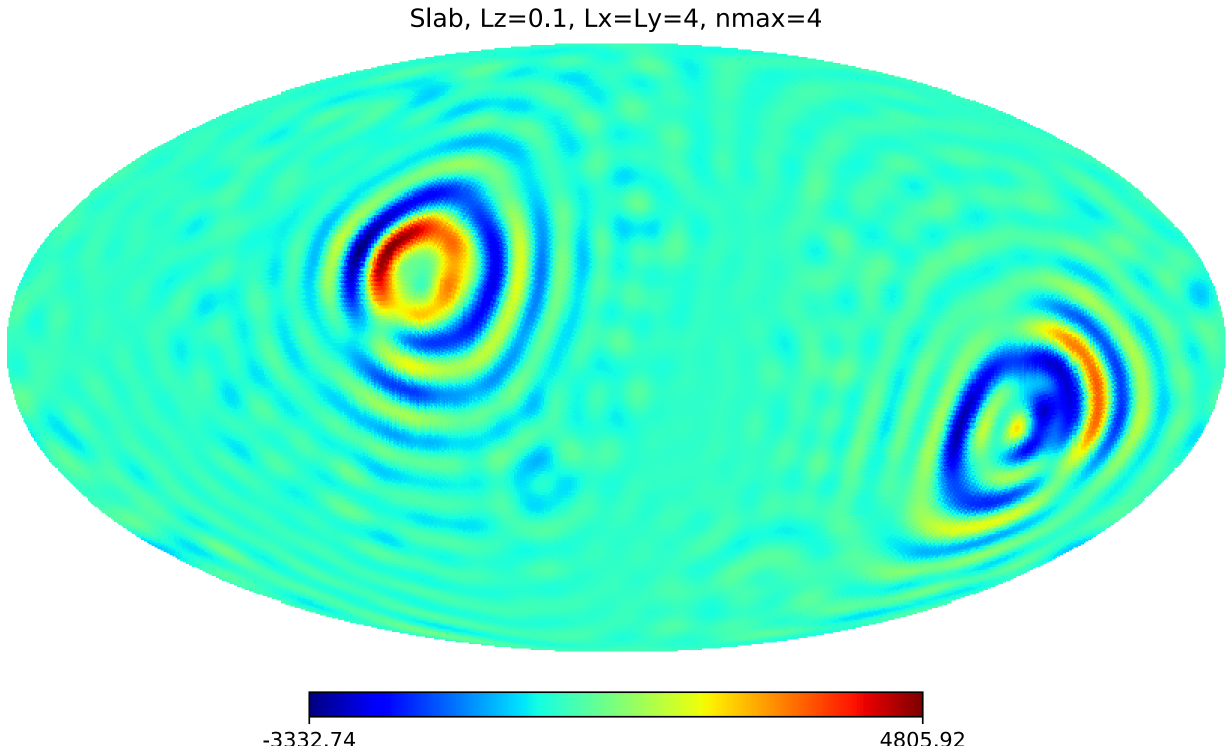


Lack of correlation at large scales ✅

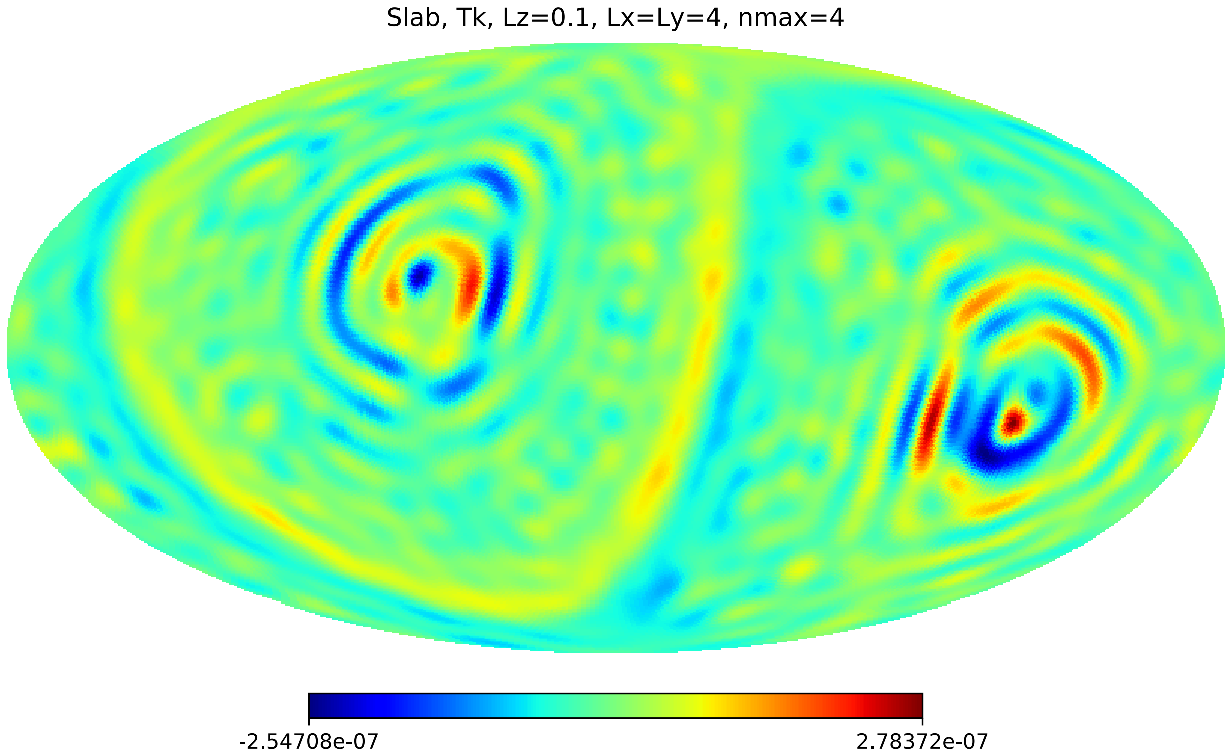
But, there is a problem!

All these calculations assume only SW, but... T.F.

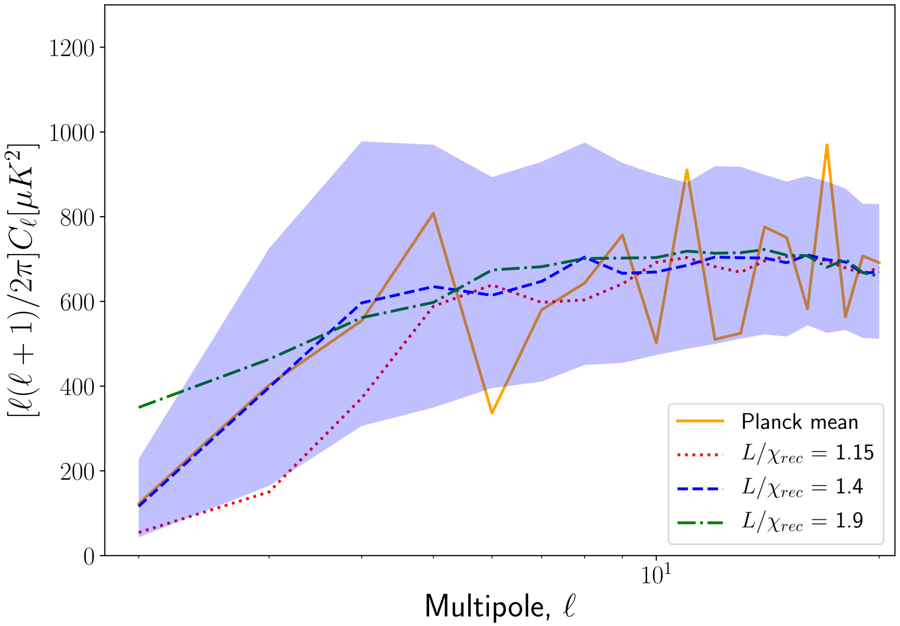
only SW


Slab, Lz=0.1, Lx=Ly=4, nmax=4
-3332.74
4805.92

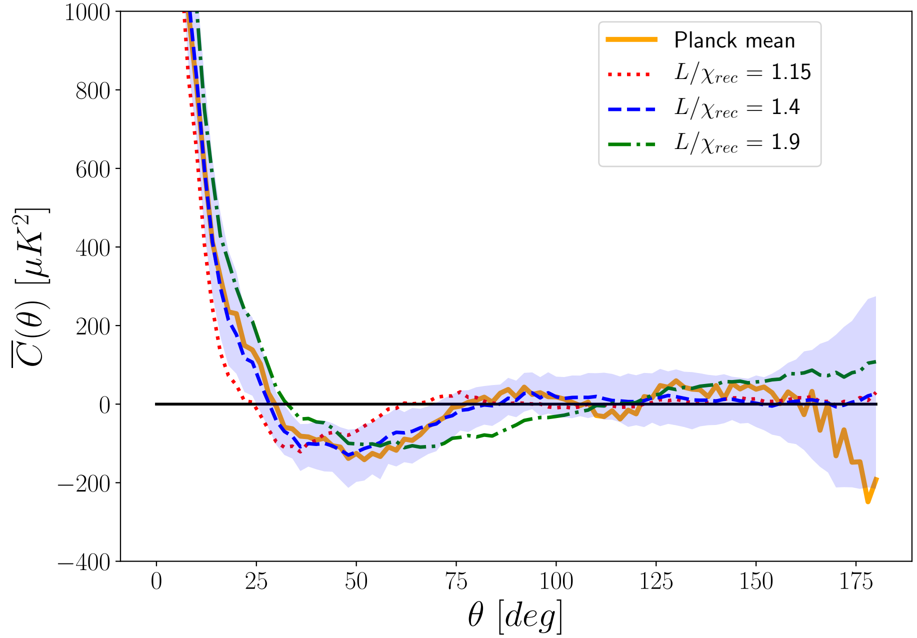
SW+T.F.


Slab, Tk, Lz=0.1, Lx=Ly=4, nmax=4
-2.54708e-07
2.78372e-07

only SW

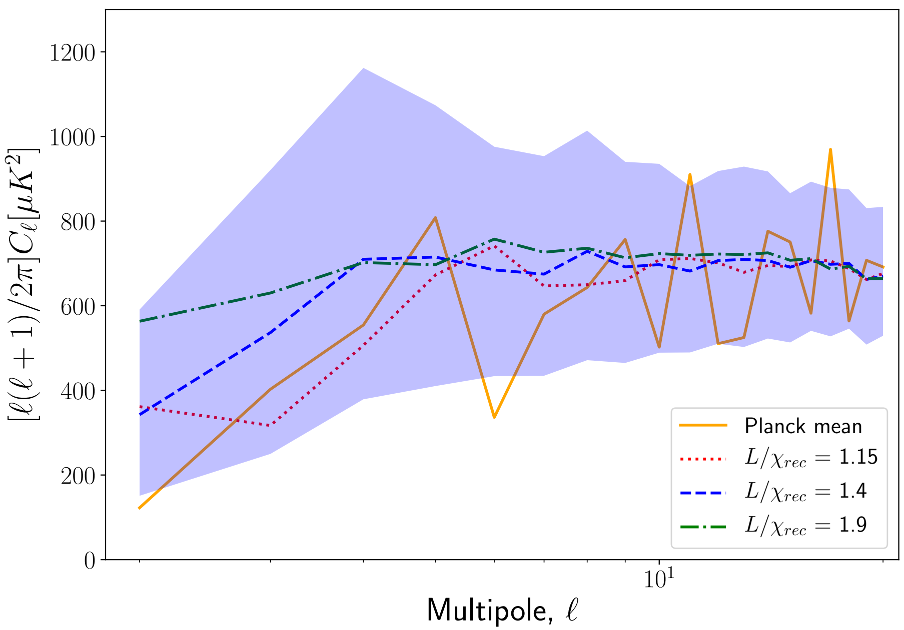


$[\ell(\ell+1)/2\pi]C_\ell[\mu K^2]$
Multipole, ℓ
Planck mean
$L/\chi_{rec} = 1.15$
$L/\chi_{rec} = 1.4$
$L/\chi_{rec} = 1.9$

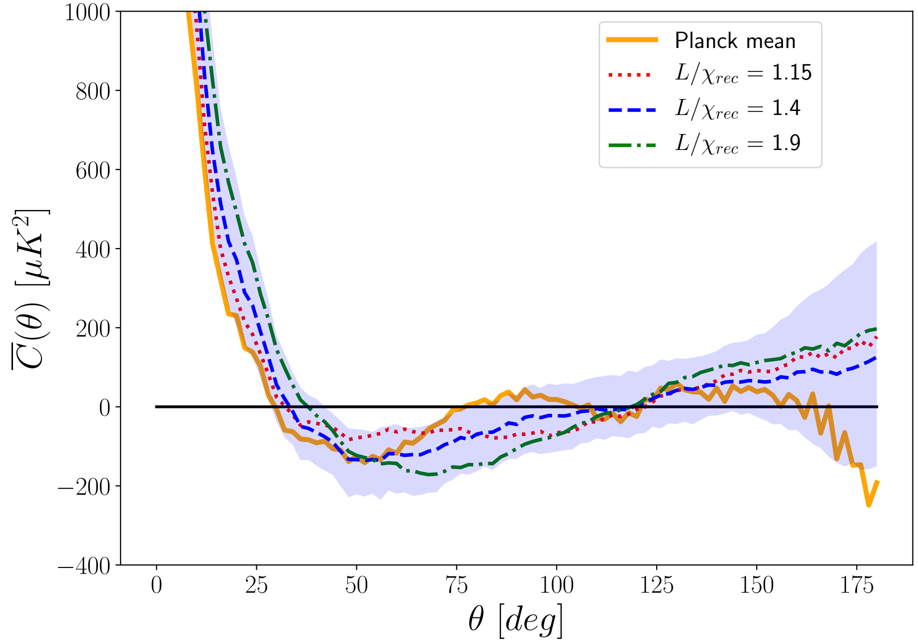


$\overline{C}(\theta)\ [\mu K^2]$
$\theta\ [deg]$
Planck mean
$L/\chi_{rec} = 1.15$
$L/\chi_{rec} = 1.4$
$L/\chi_{rec} = 1.9$

SW+T.F.



$[\ell(\ell+1)/2\pi]C_\ell[\mu K^2]$
Multipole, ℓ
Planck mean
$L/\chi_{rec} = 1.15$
$L/\chi_{rec} = 1.4$
$L/\chi_{rec} = 1.9$



$\overline{C}(\theta)\ [\mu K^2]$
$\theta\ [deg]$
Planck mean
$L/\chi_{rec} = 1.15$
$L/\chi_{rec} = 1.4$
$L/\chi_{rec} = 1.9$

Conclusions

- CMB anomalies 'suggest' -but not prove- that we could live in a statistically anisotropic universe with one axis of symmetry

- We have to perform complete analyses for SW+T.F. in the slab-with-half-turn topology $\mathbb{R}^2 \times \mathbb{S}^1$