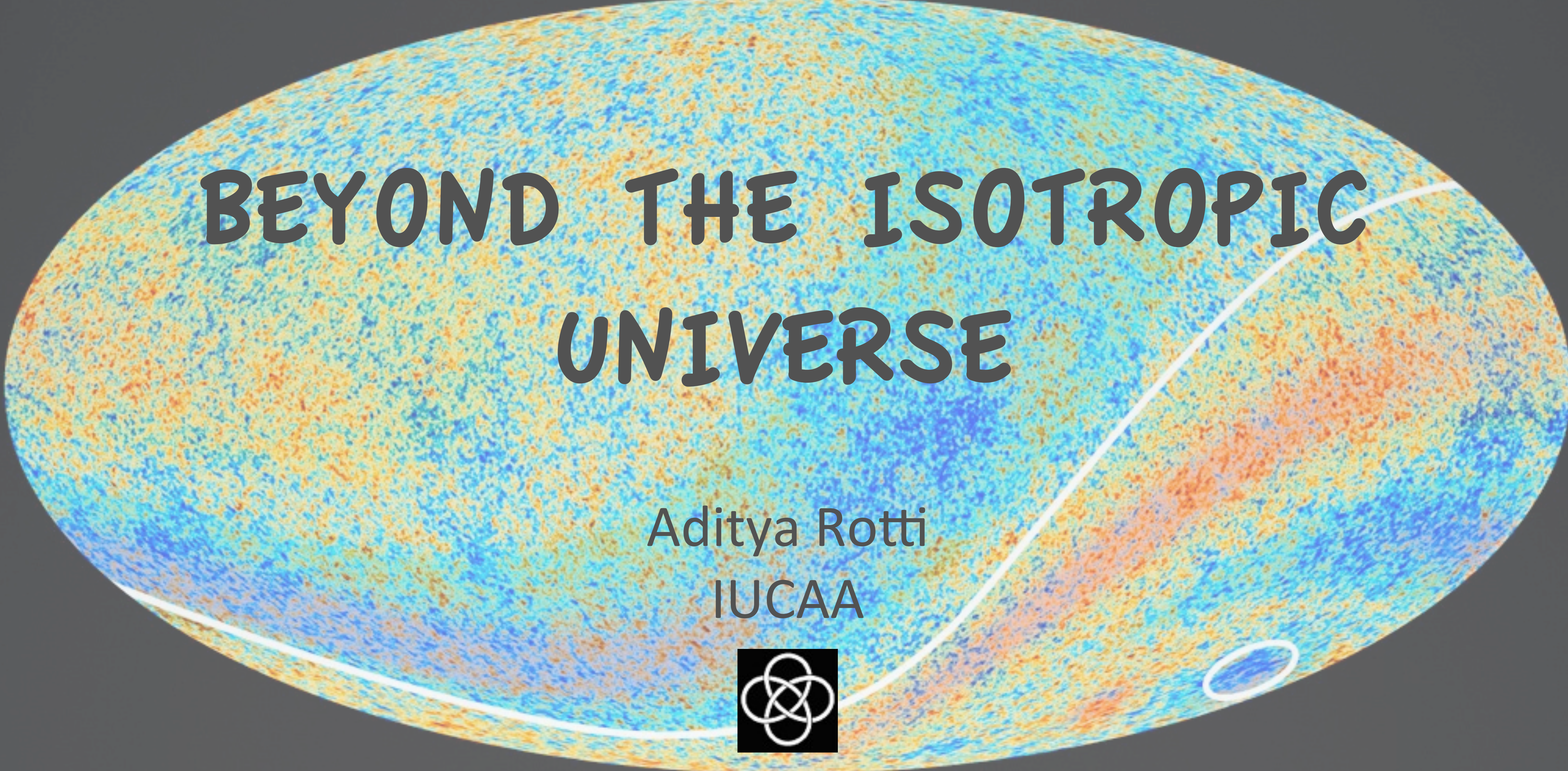
BEYOND THE ISOTROPIC UNIVERSE



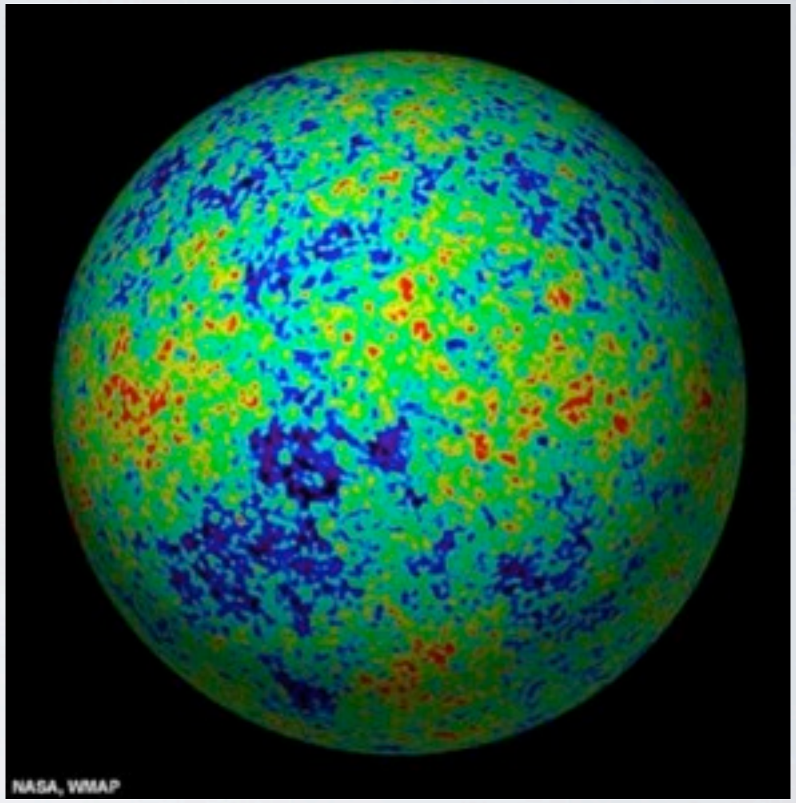
Aditya Rotti
IUCAA

Quantifying the CMB sky.

$T_0 = 2.73\ K$ $\langle T(\hat{n}) \rangle$

Mean

$\Delta T \sim 10^{-5}$



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

$\ell \sim 1/\theta$

Where θ represents the angular scale in radians.

$\langle \Delta T(\hat{n}_1) \Delta T(\hat{n}_2) \rangle$

Angular power Spectrum

$\langle \Delta T(\hat{n}_1) \Delta T(\hat{n}_2) T(\hat{n}_3) \rangle$

Bispectrum

MEASURABLES

$\langle \Delta T(\hat{n}_1) \Delta T(\hat{n}_2) T(\hat{n}_3) T(\hat{n}_4) \rangle \cdots$

Trispectrum

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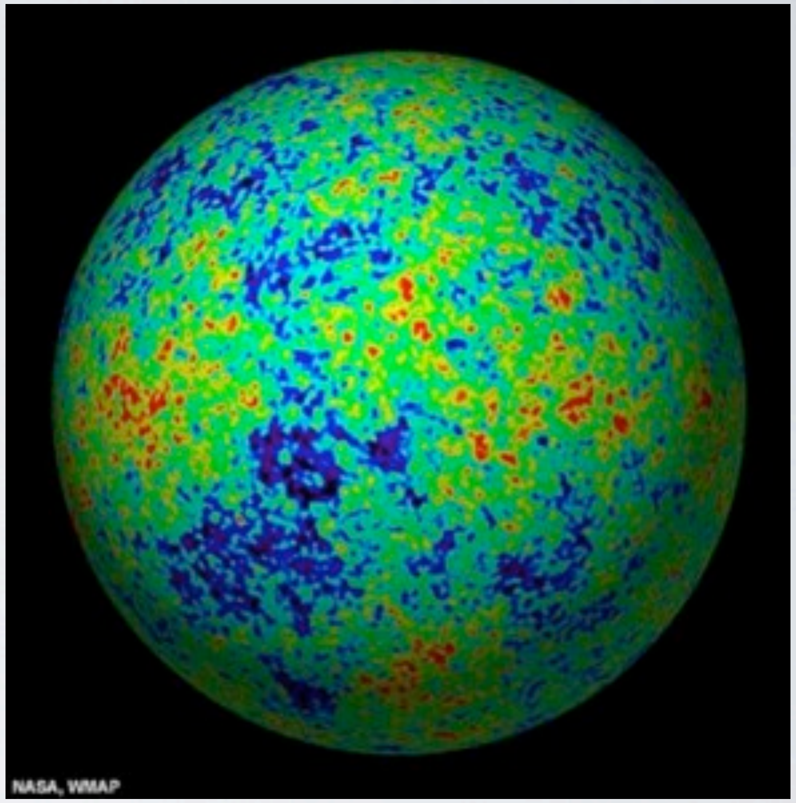
$$\Delta T \sim 10^{-5}$$



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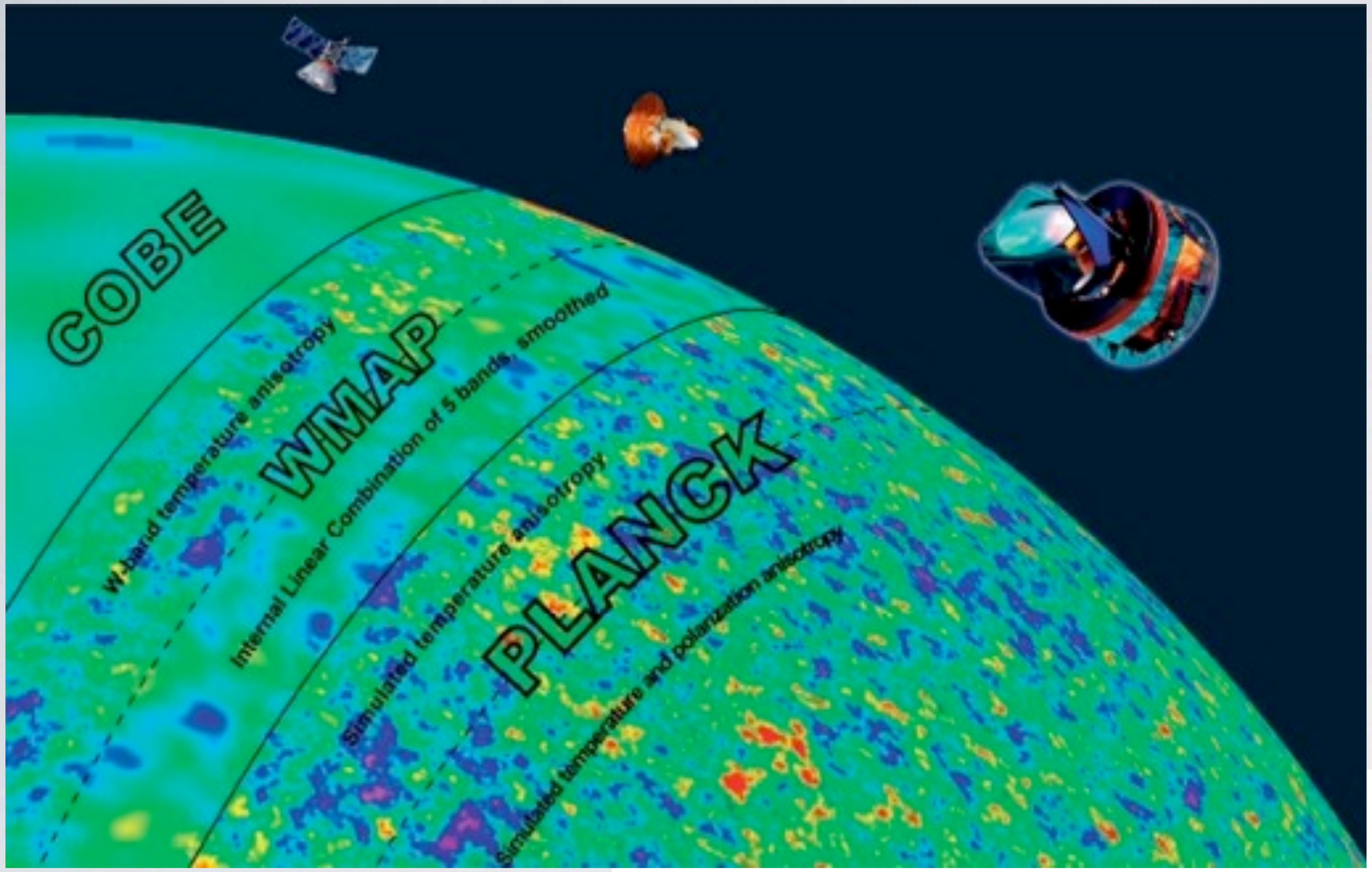
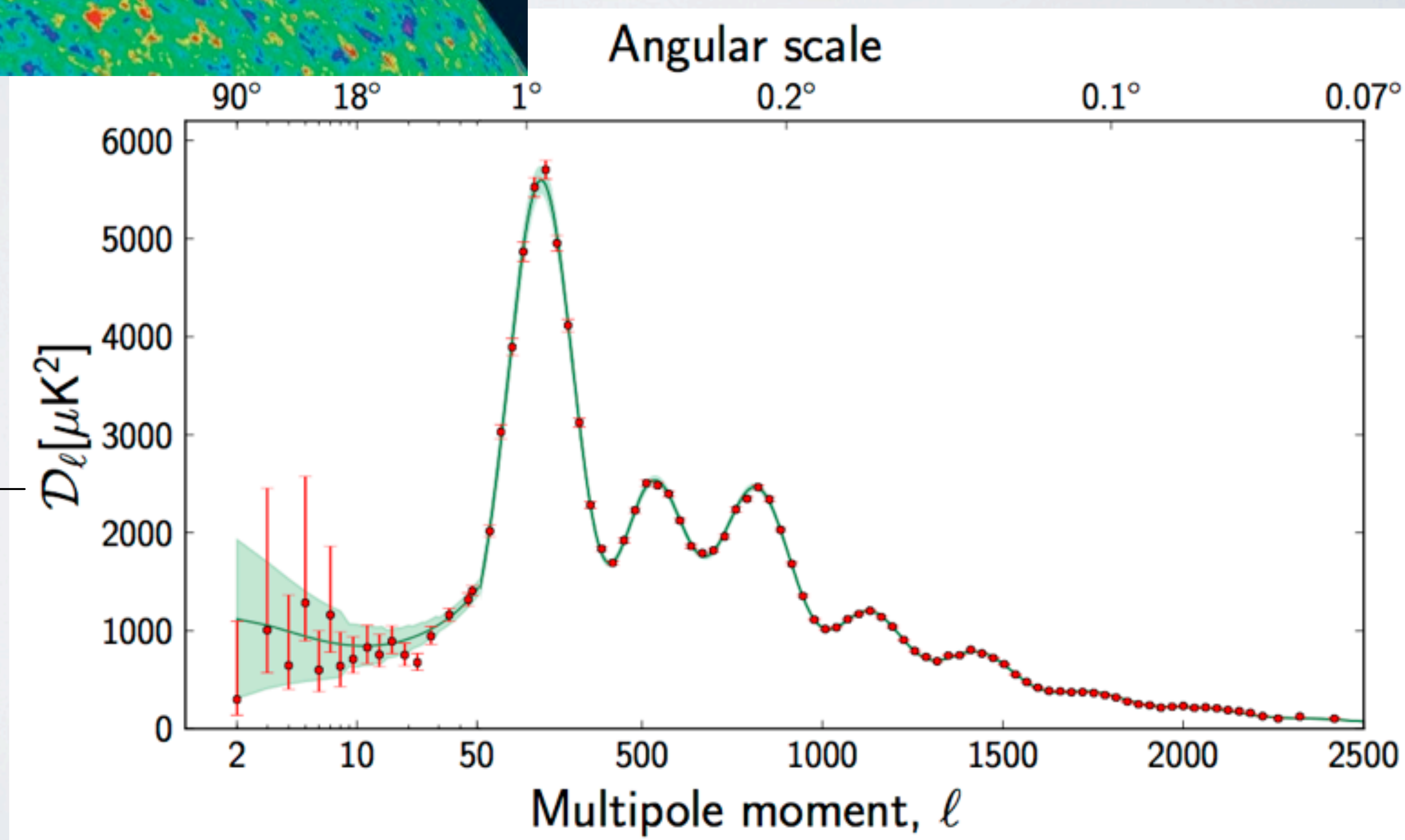
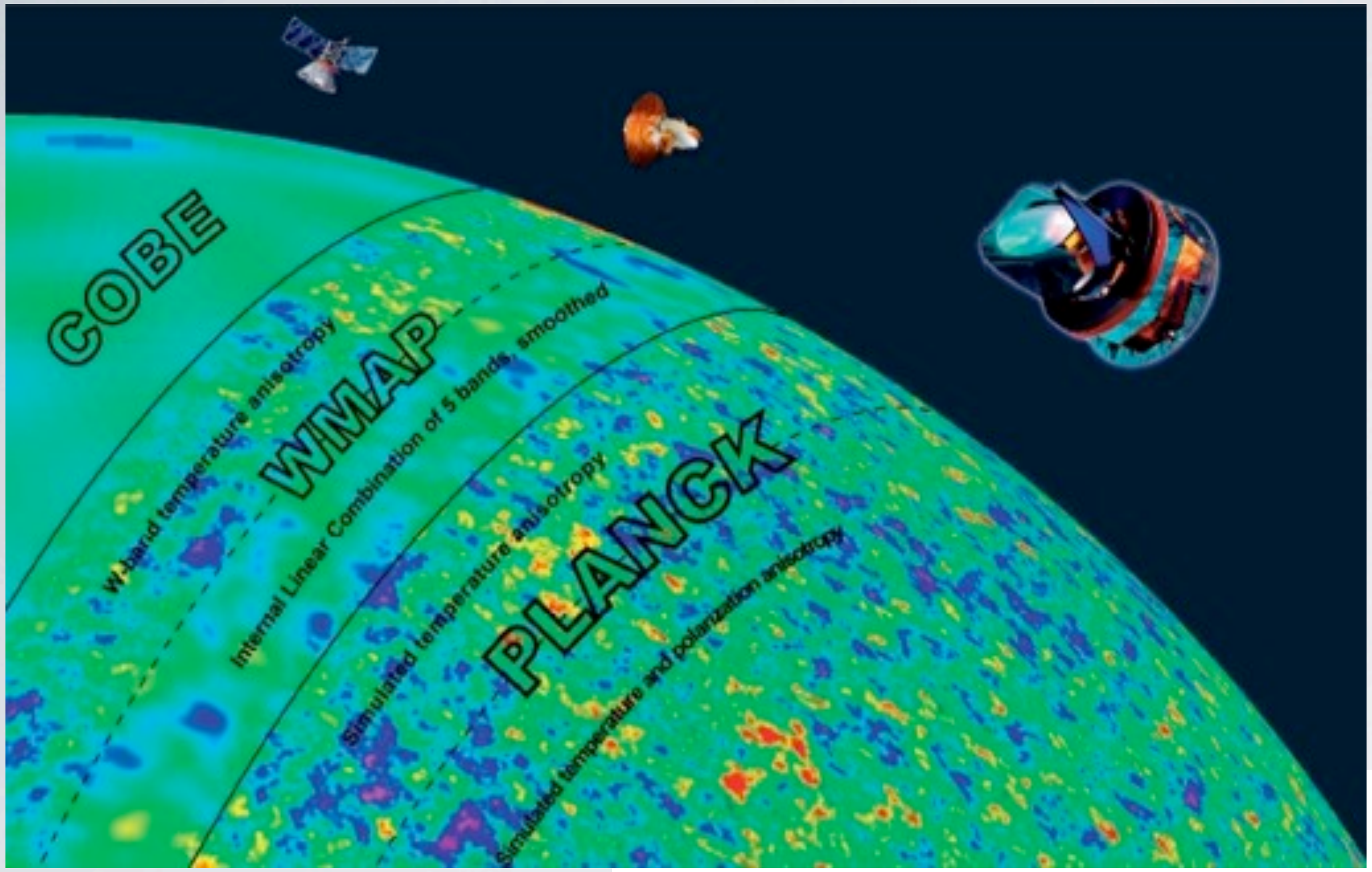


- Better angular resolution.
- Reduced noise
- Larger Sky Coverage

$\ell(\ell+1)\mathcal{C}_\ell/2\pi \leftarrow$





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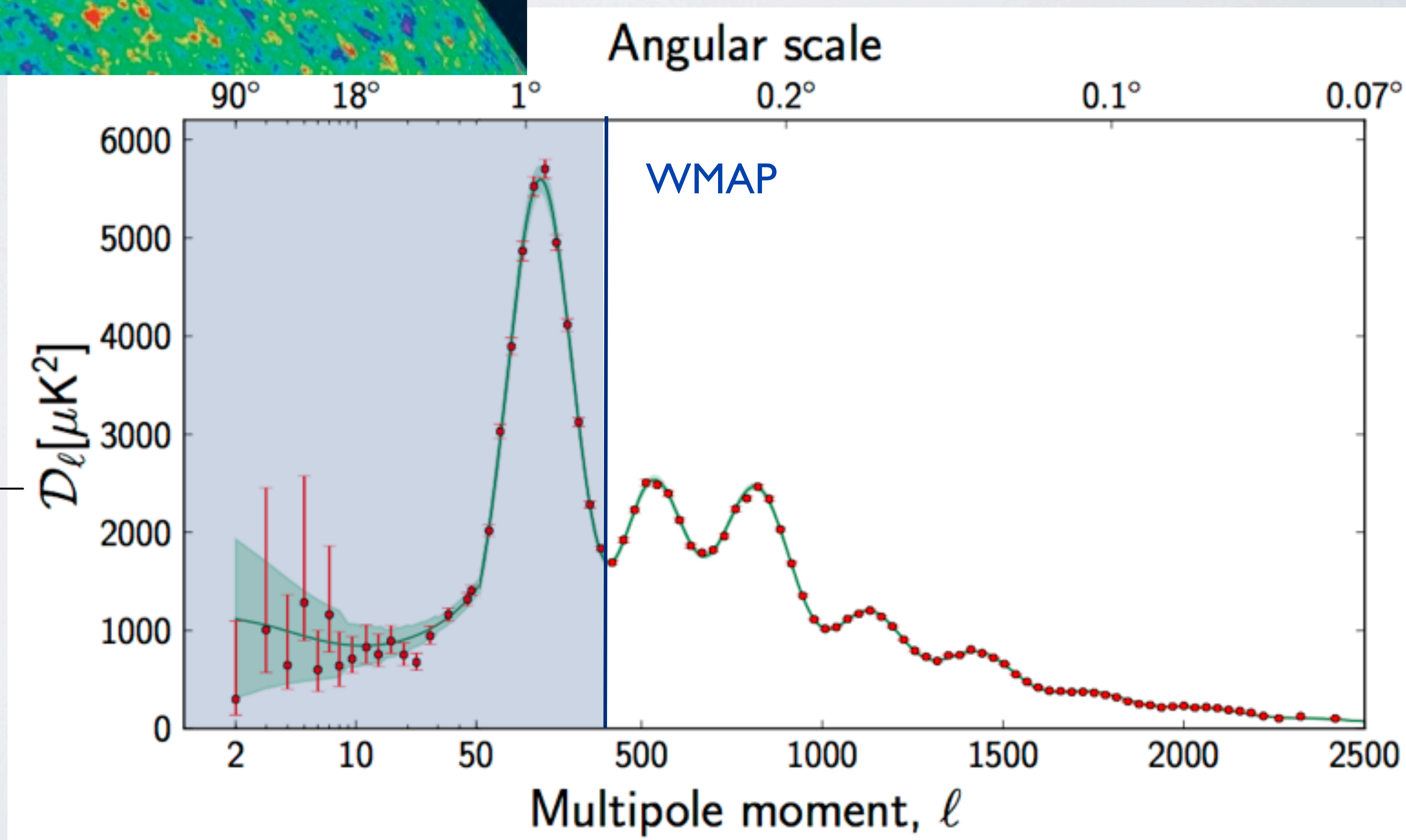

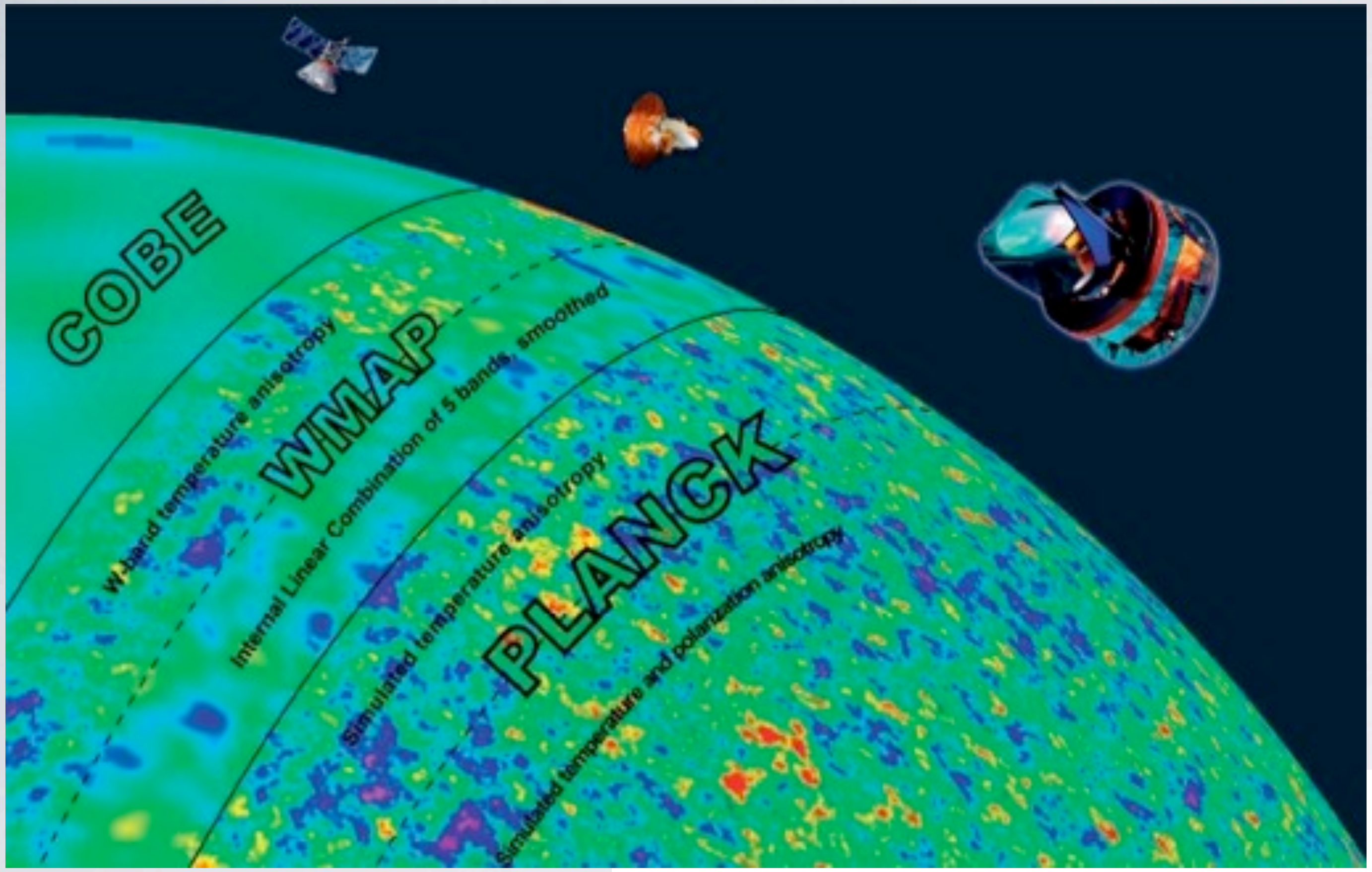

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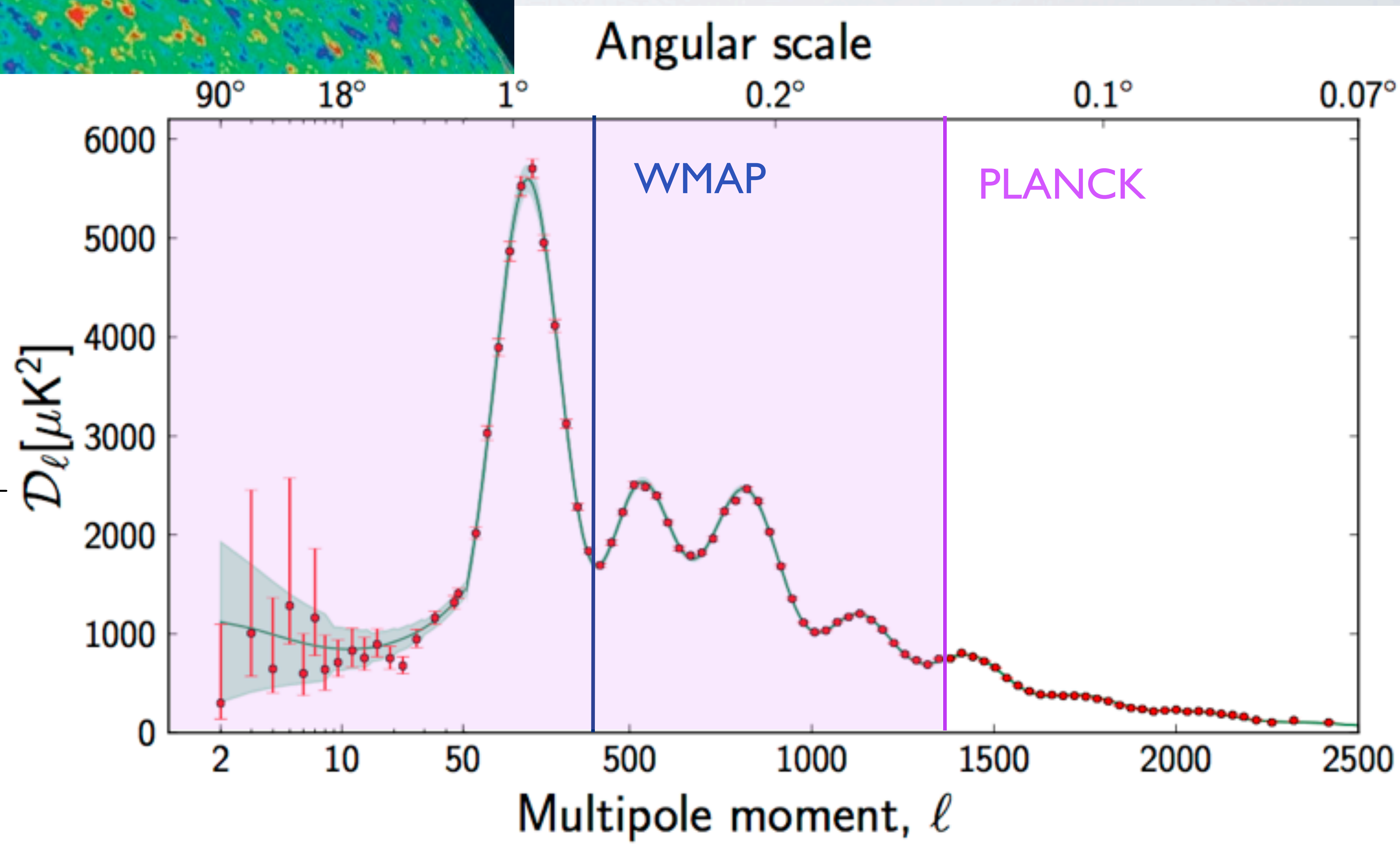
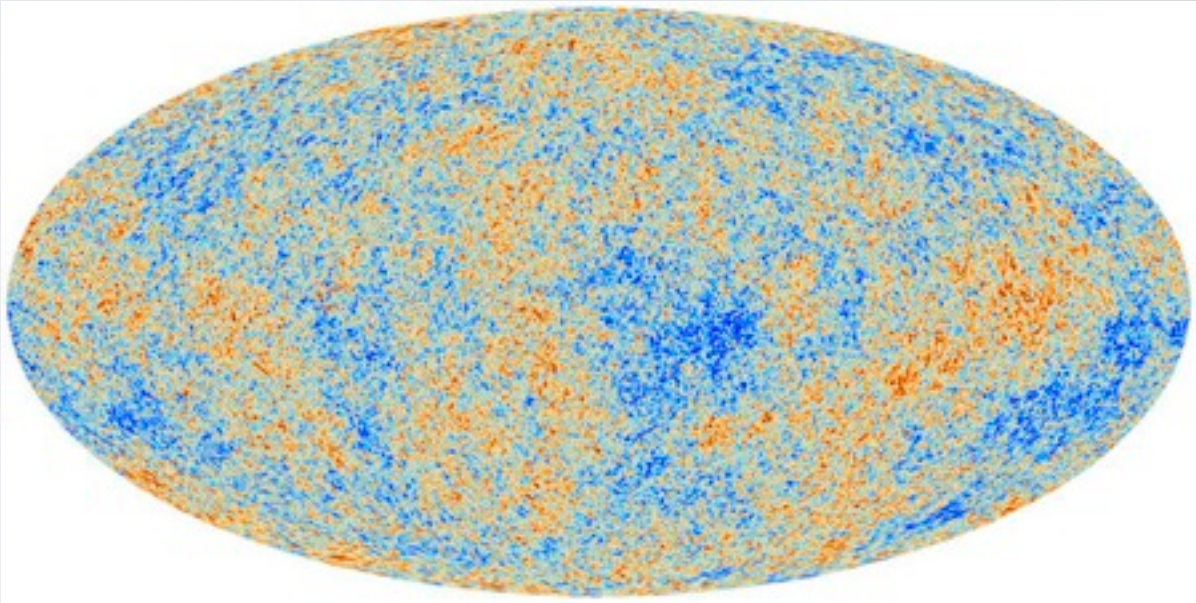


Understanding Isotropy Violation

The CMB sky is clearly anisotropic !!



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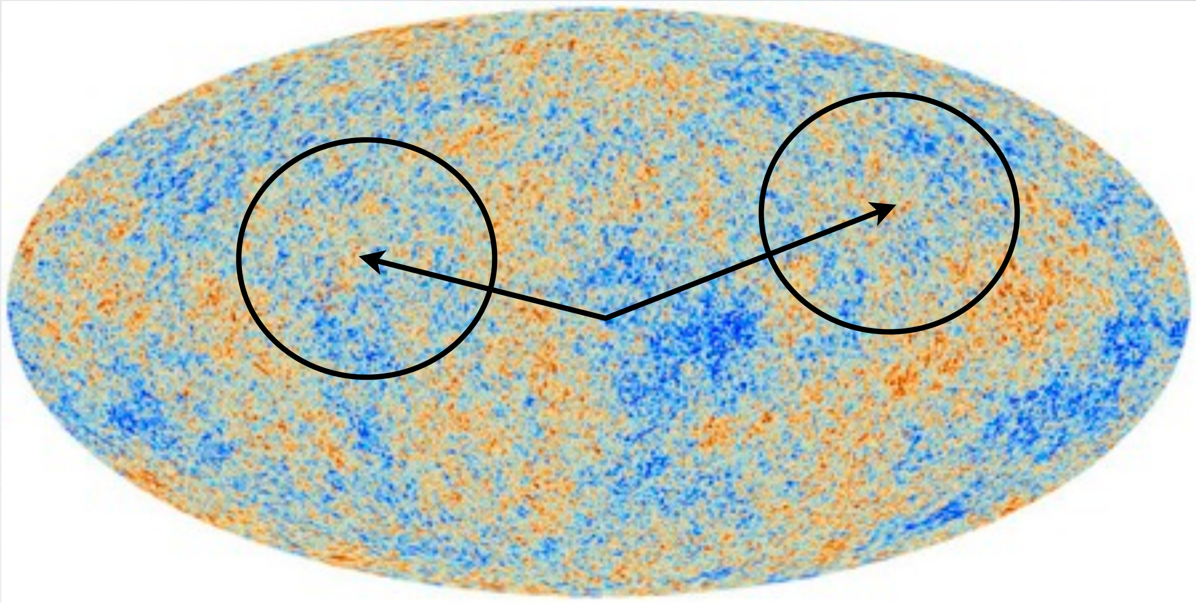

What then is meant by **testing for isotropy** ?

We test whether the **statistically properties** of this random field are **direction independent**.

Understanding Isotropy Violation

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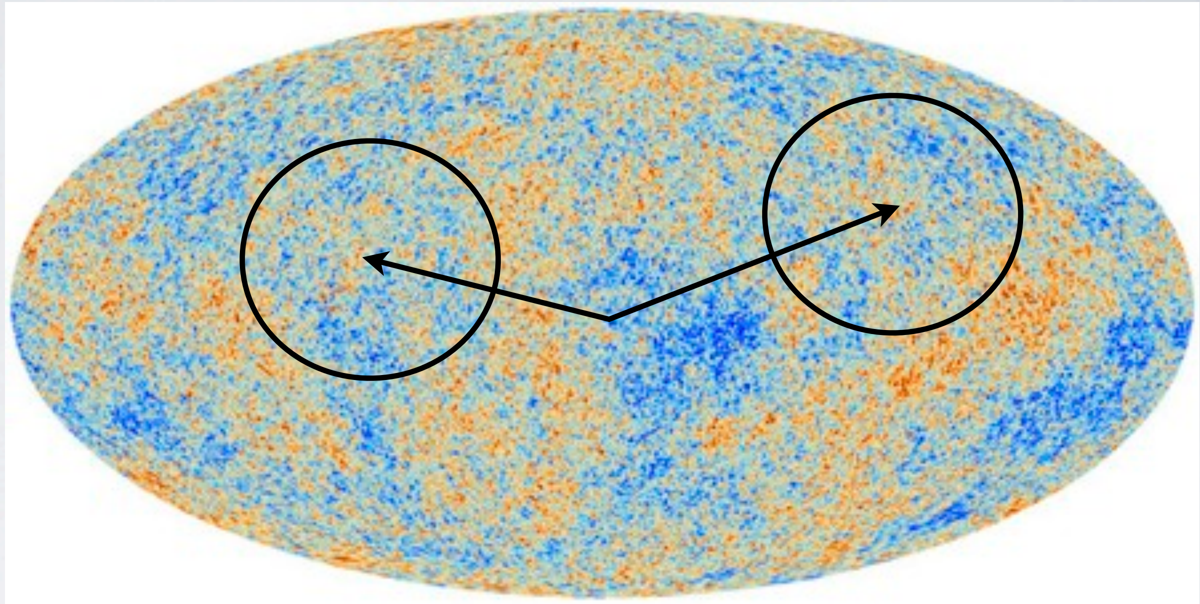


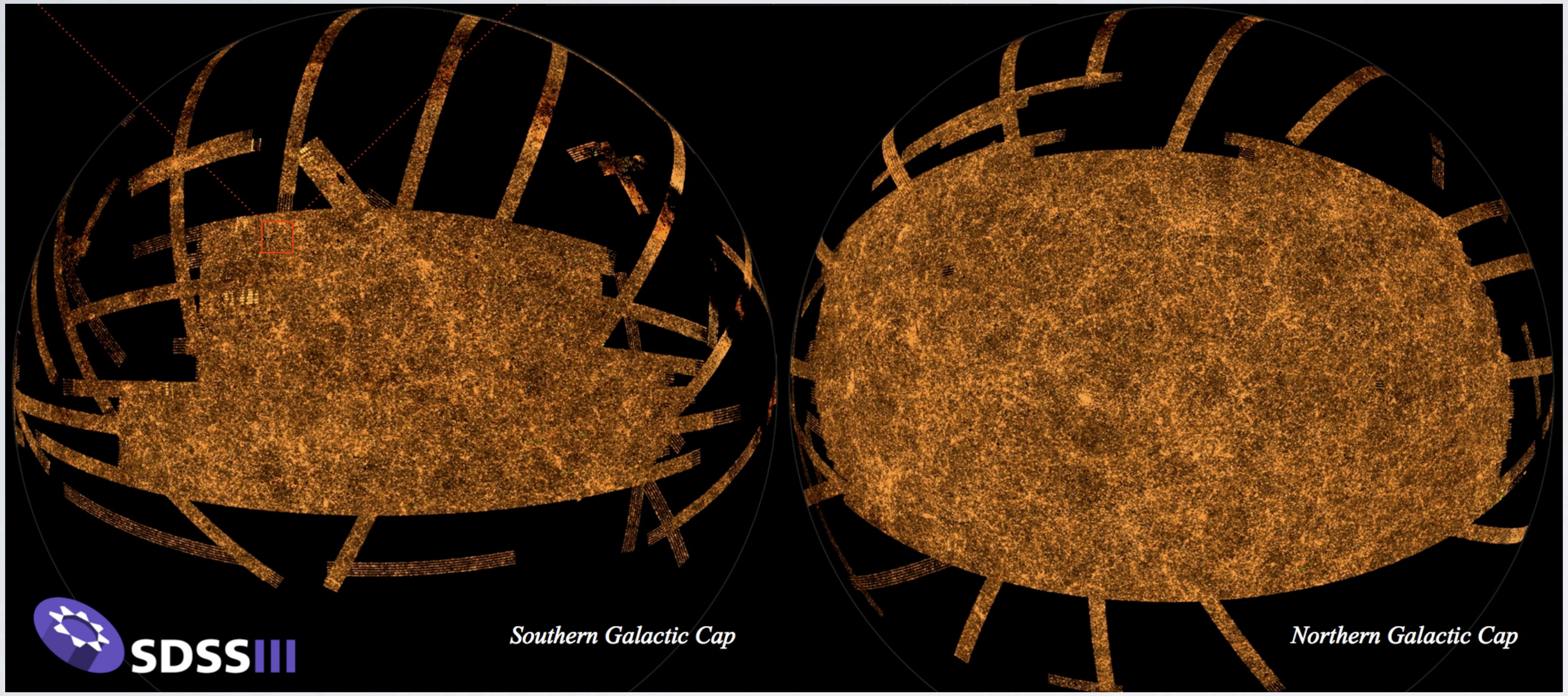
What then is meant by **testing for isotropy** ?

We test whether the **statistically properties** of this random field are **direction independent**.

Fortunately it is found that the the **fluctuations** in the CMB temperature field are extremely close to being **Gaussian**.

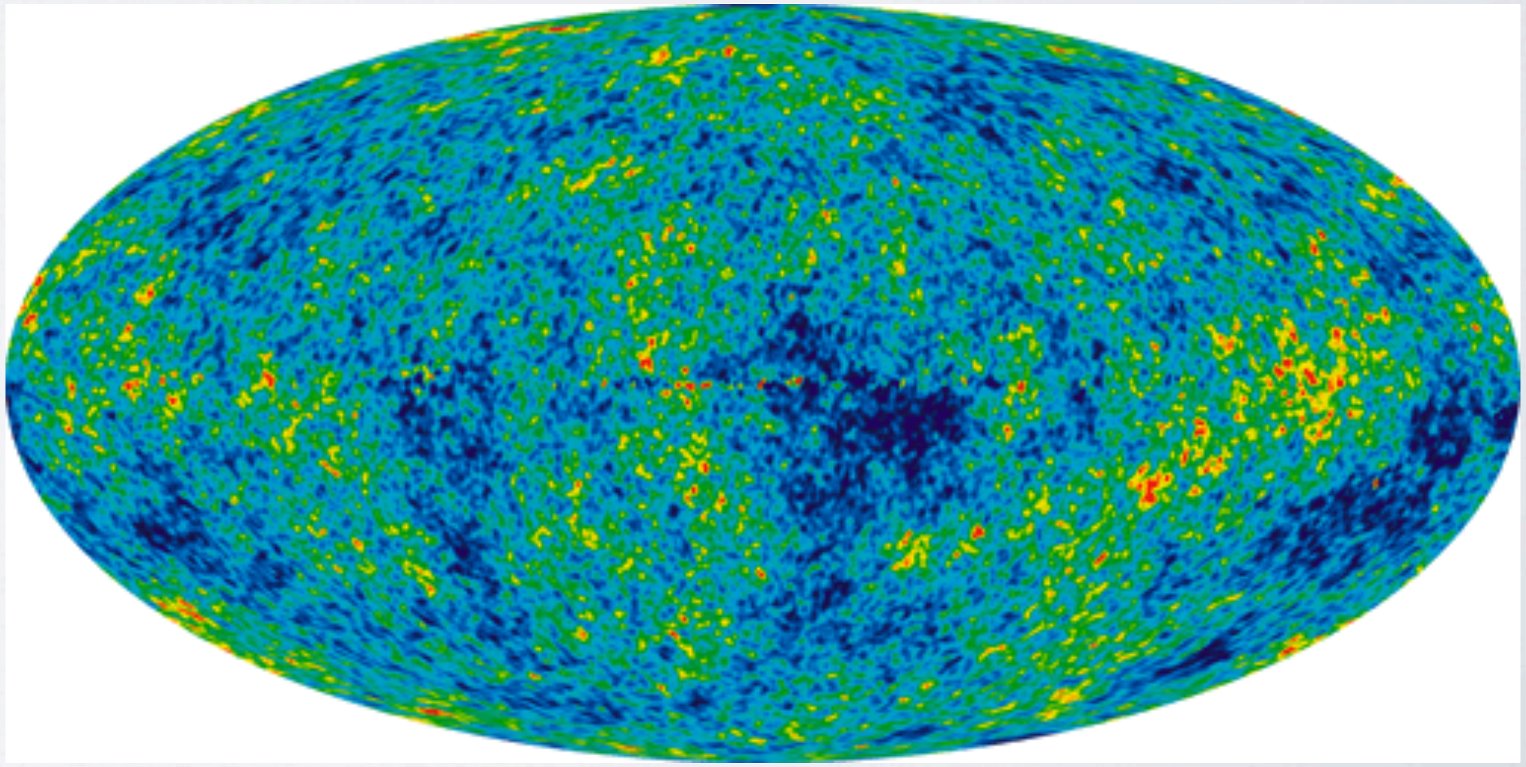
The **two point correlation function** then completely characterizes this random field.

Why use CMB to test isotropy ??



~ 30 % Sky coverage

> 90 % Sky coverage



ISOTROPIC CASE

$$\mathcal{C}(\hat{n}_1, \hat{n}_2) = \mathcal{C}(\hat{n}_1 . \hat{n}_2) = \mathcal{C}(\theta)$$

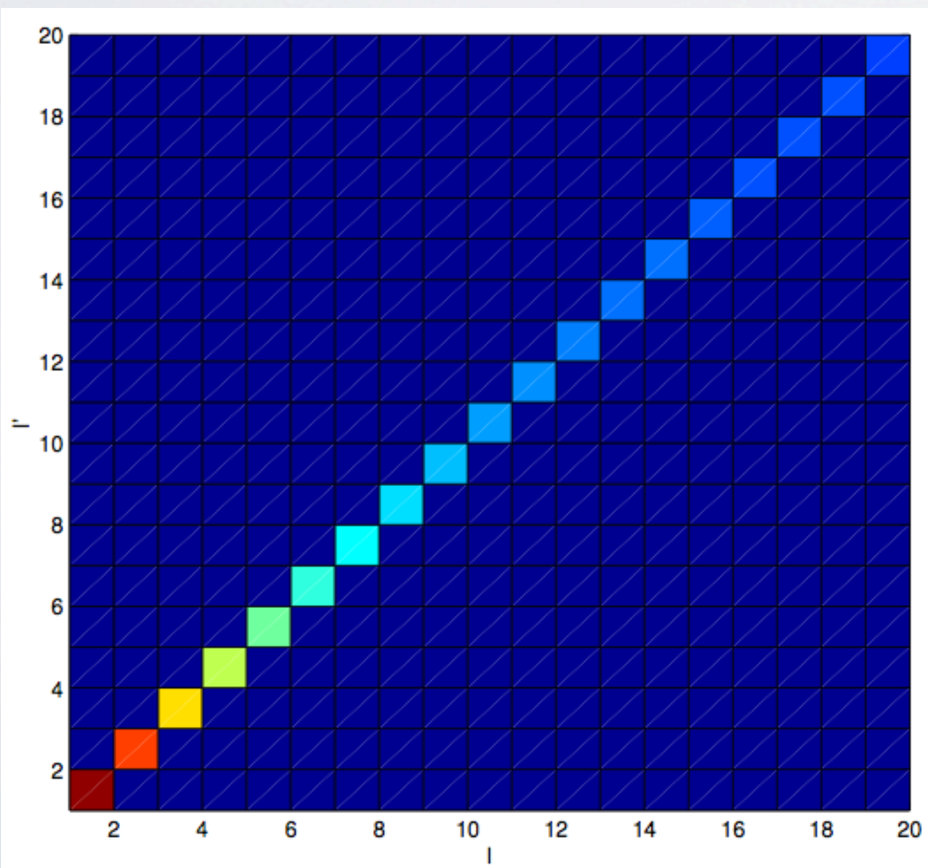
→ The correlation function is direction independent.

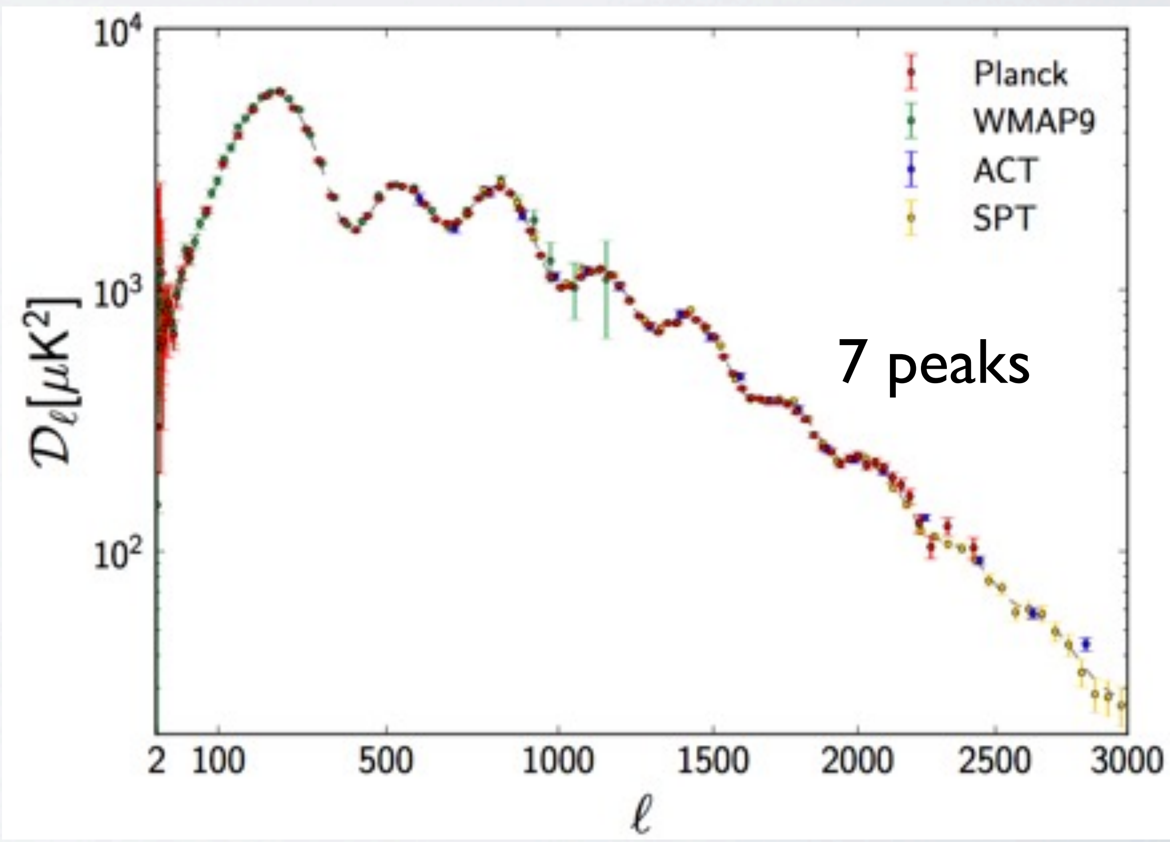
⇓

ASSUMPTION !!

$$\mathcal{C}(\theta) = \sum_{\ell} \frac{2\ell + 1}{4\pi} \mathcal{C}_\ell P_\ell(cos\theta)$$

→ CMB angular power spectrum fully characterizes the ISOTROPIC CMB sky.





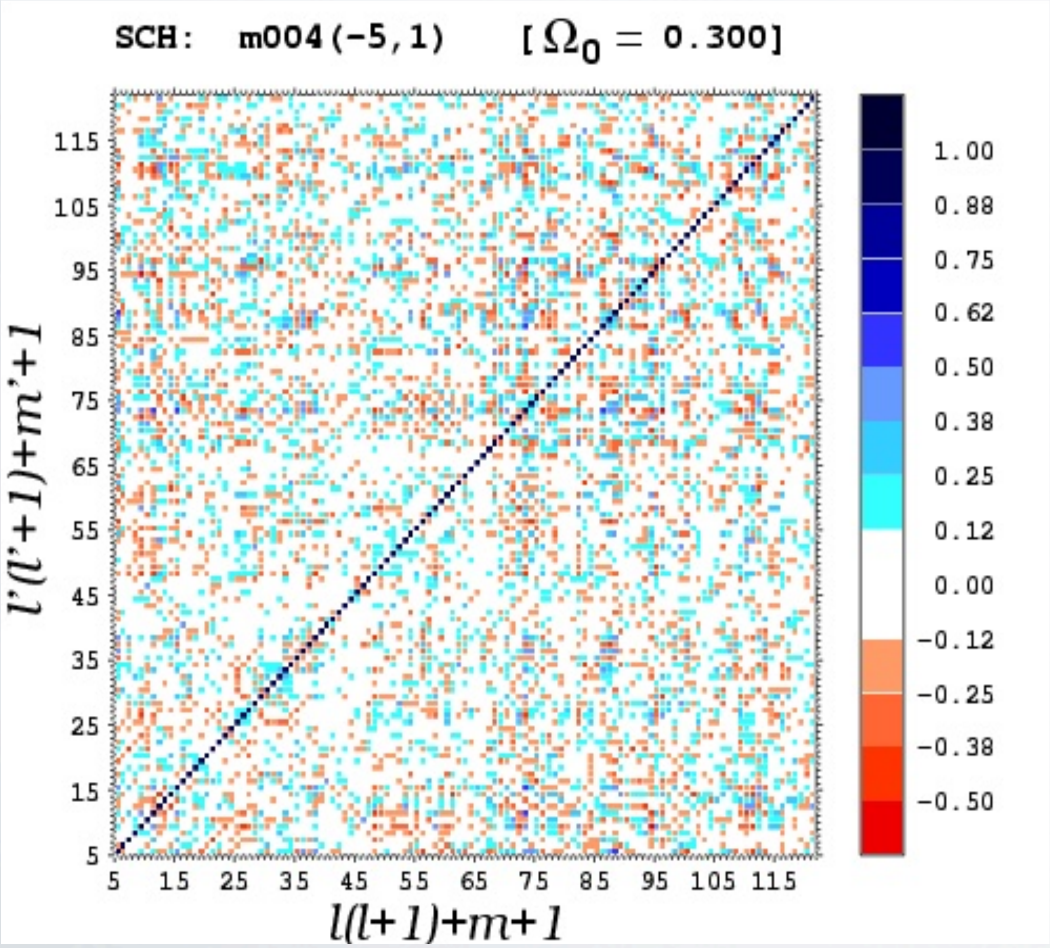
Bipolar Spherical Harmonic Basis

Hajian & Souradeep

$$\mathcal{C}(\hat{n}_1, \hat{n}_2) = \langle \Delta T(\hat{n}_1) \Delta T(\hat{n}_2) \rangle$$

Explicit directional dependence

$$\mathcal{C}(\hat{n}_1, \hat{n}_2) = \sum_{L,M,\ell_1,\ell_2} A^{LM}_{\ell_1 \ell_2} \{Y_{\ell_1}(\hat{n}_1) \otimes Y_{\ell_1}(\hat{n}_2)\}_{LM}$$



Bipolar map

$$\mathcal{R}_{LM} = \sum_{l_1 l_2} A^{LM}_{l_1 l_2}$$

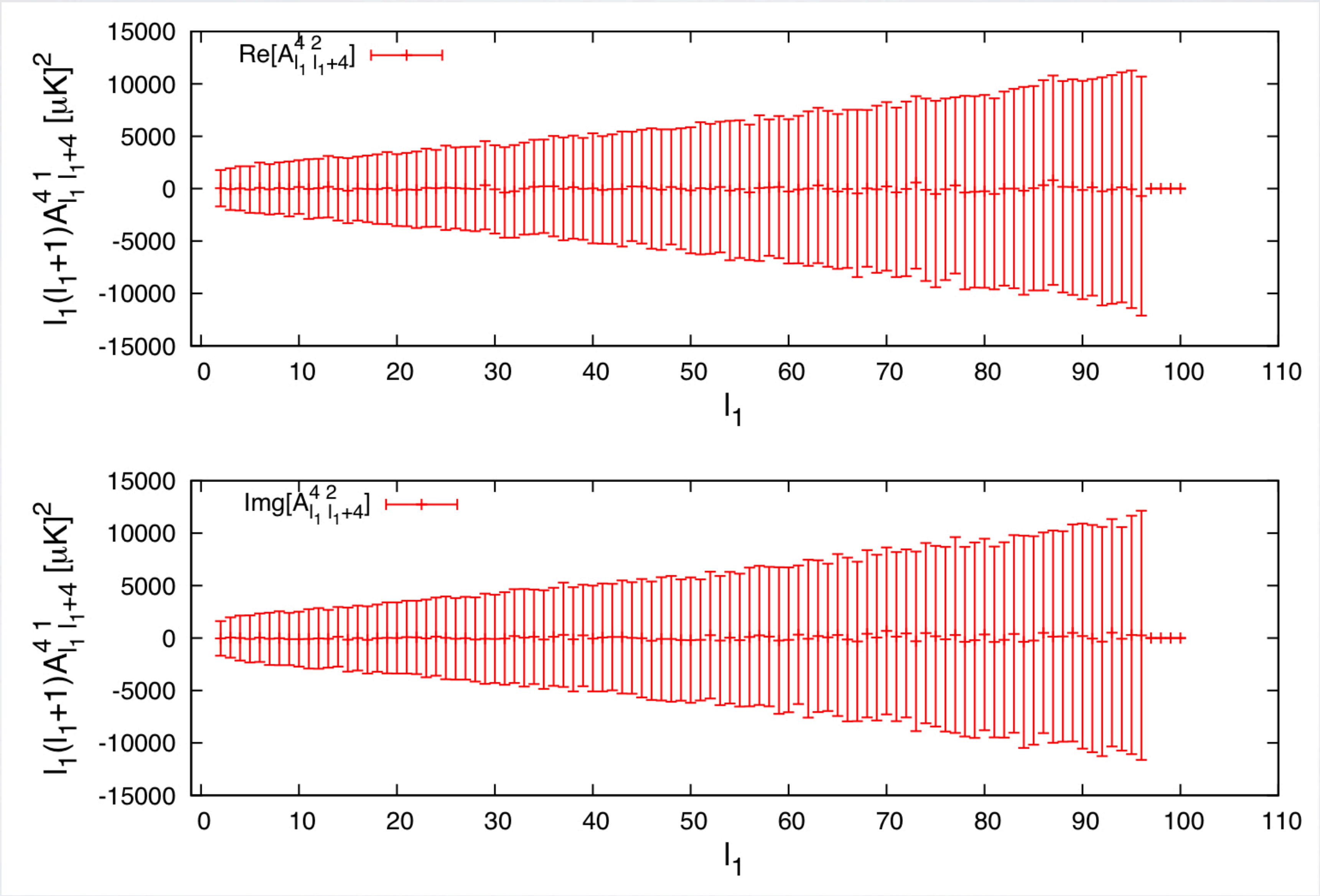
Bipolar power spectrum

$$\kappa_L = \sum_{l_1 l_2 M} |A^{LM}_{l_1 l_2}|^2$$

The null test for detecting isotropy violation

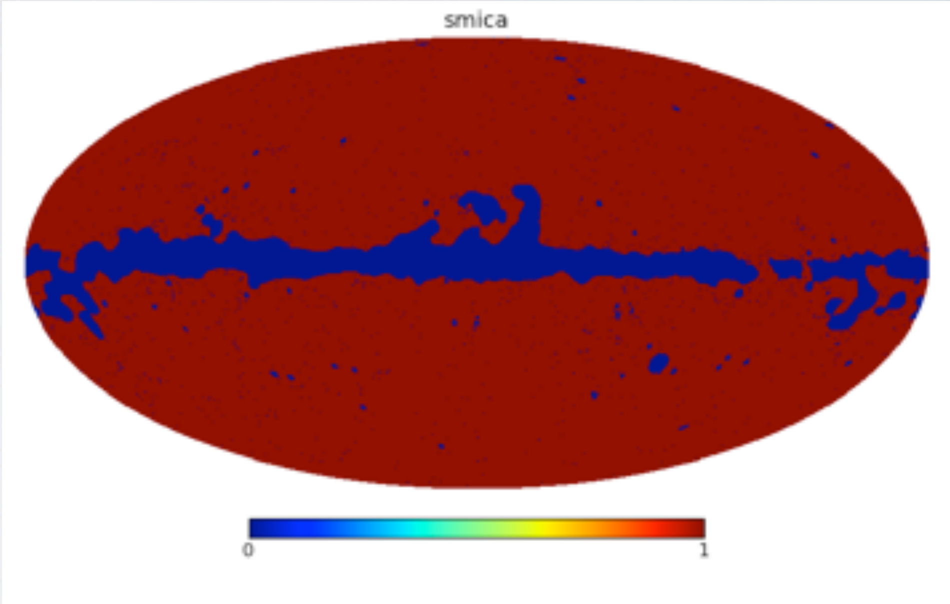
$$A^{LM}_{l_1 l_2} = \sum_{m_1 m_2} \langle a_{l_1 m_1} a_{l_2 m_2} \rangle \mathcal{C}^{LM}_{l_1 m_1 l_2 m_2}$$

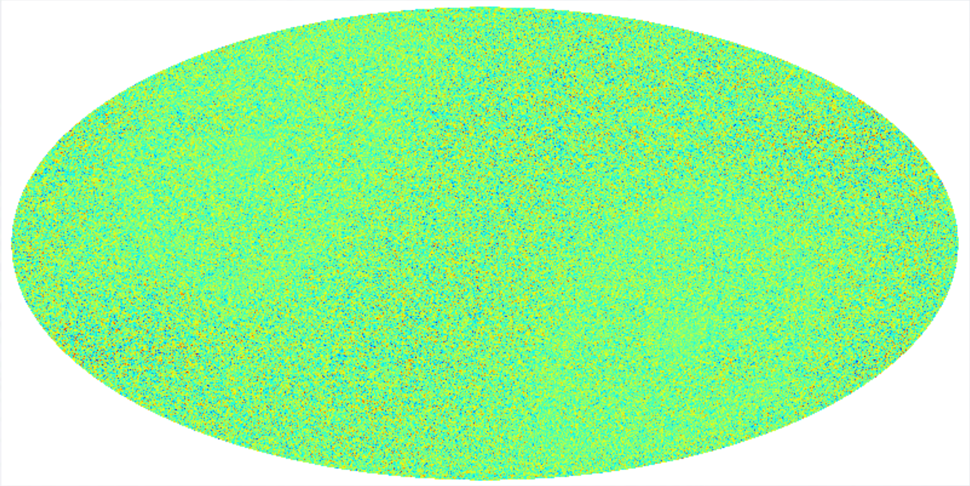
$$\langle A^{LM}_{l_1 l_2} \rangle \sim C_l \delta_{L0} \delta_{M0} \delta_{l_1 l_2}$$



Systematics

- Asymmetric beam
- Mask (to cover remnant foregrounds and point sources)
- Anisotropic noise

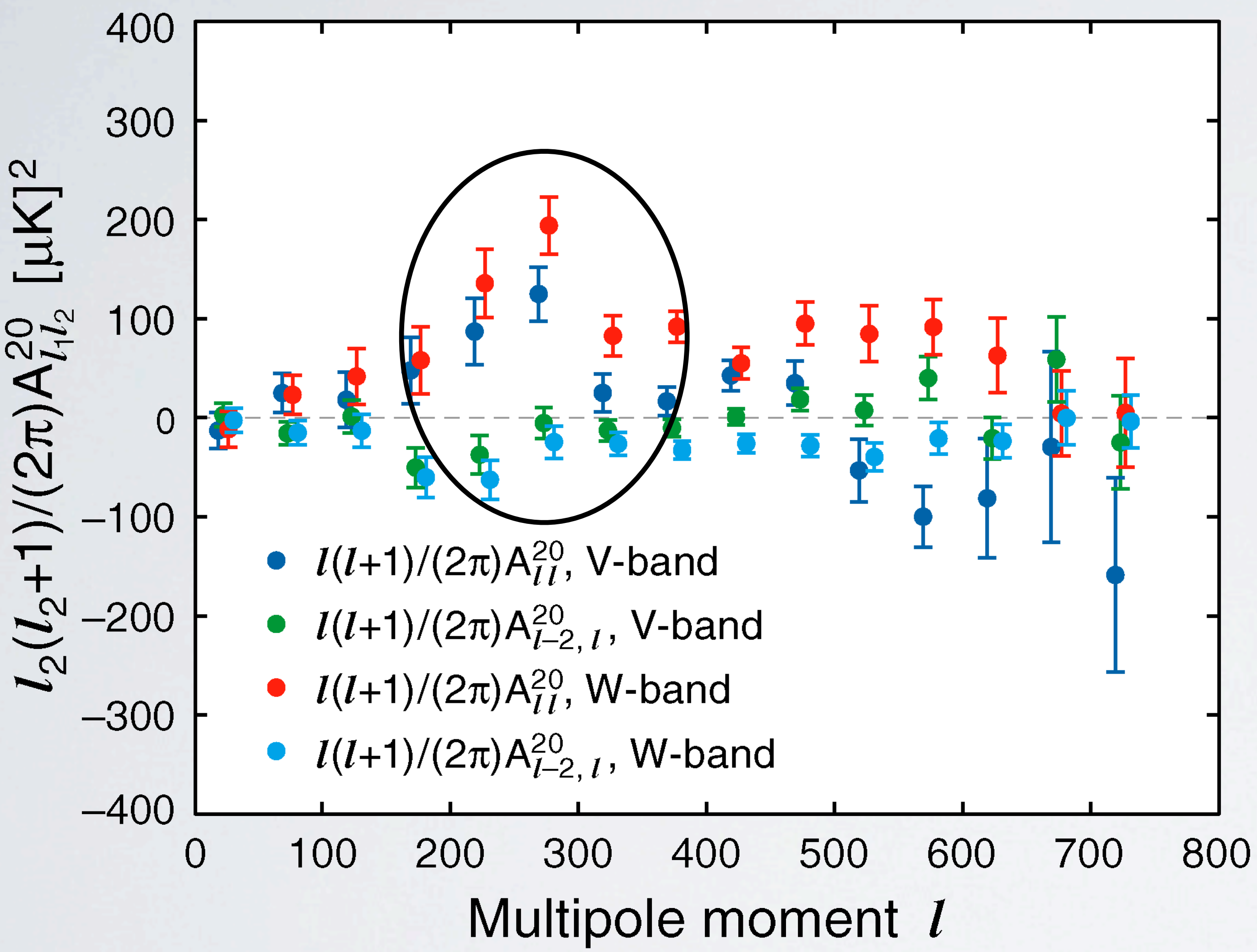




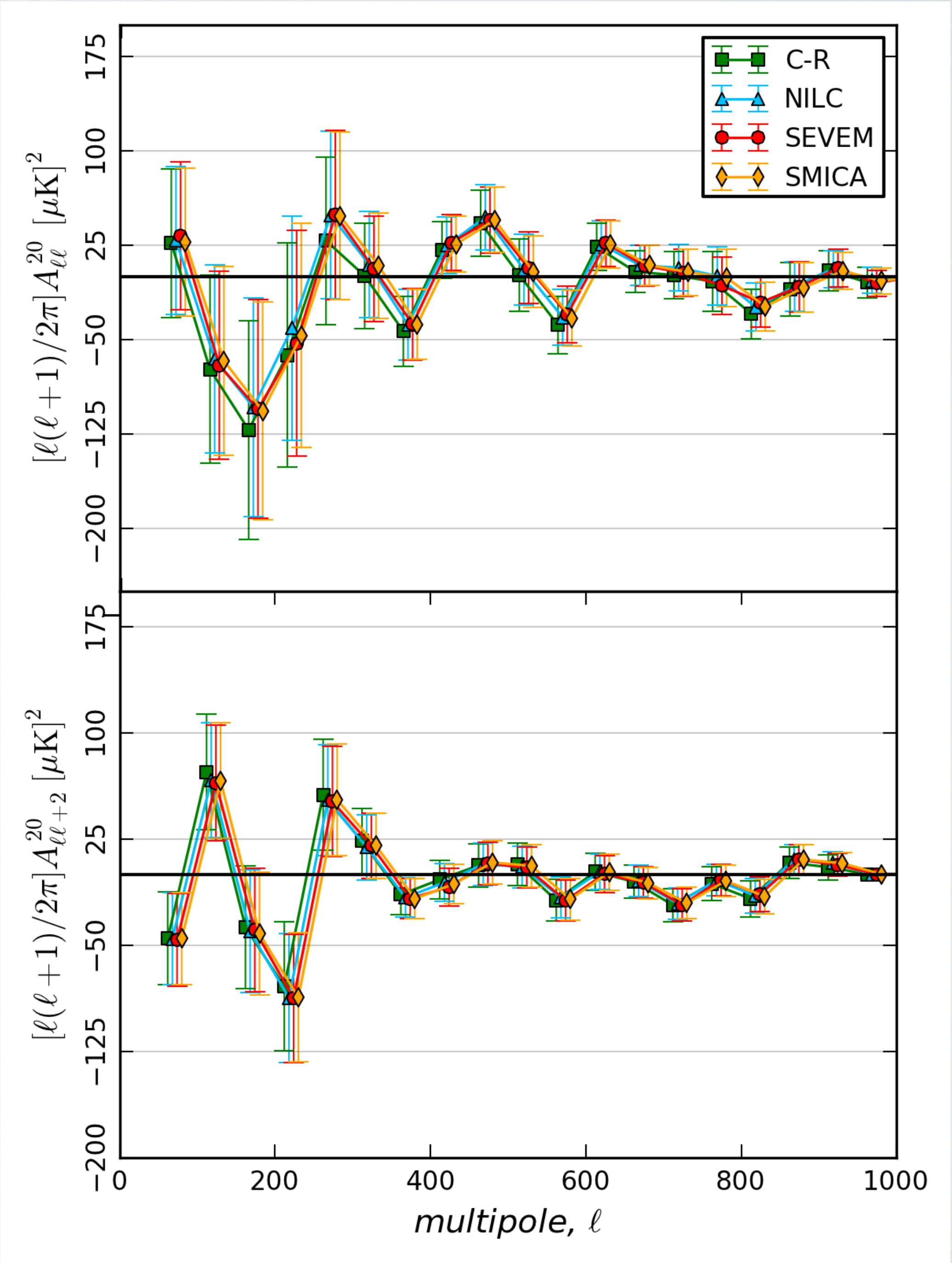
All known systematics are incorporated into simulations to account for the biases.

Searching for the WMAP quadrupolar anomaly in PLANCK

WMAP



PLANCK



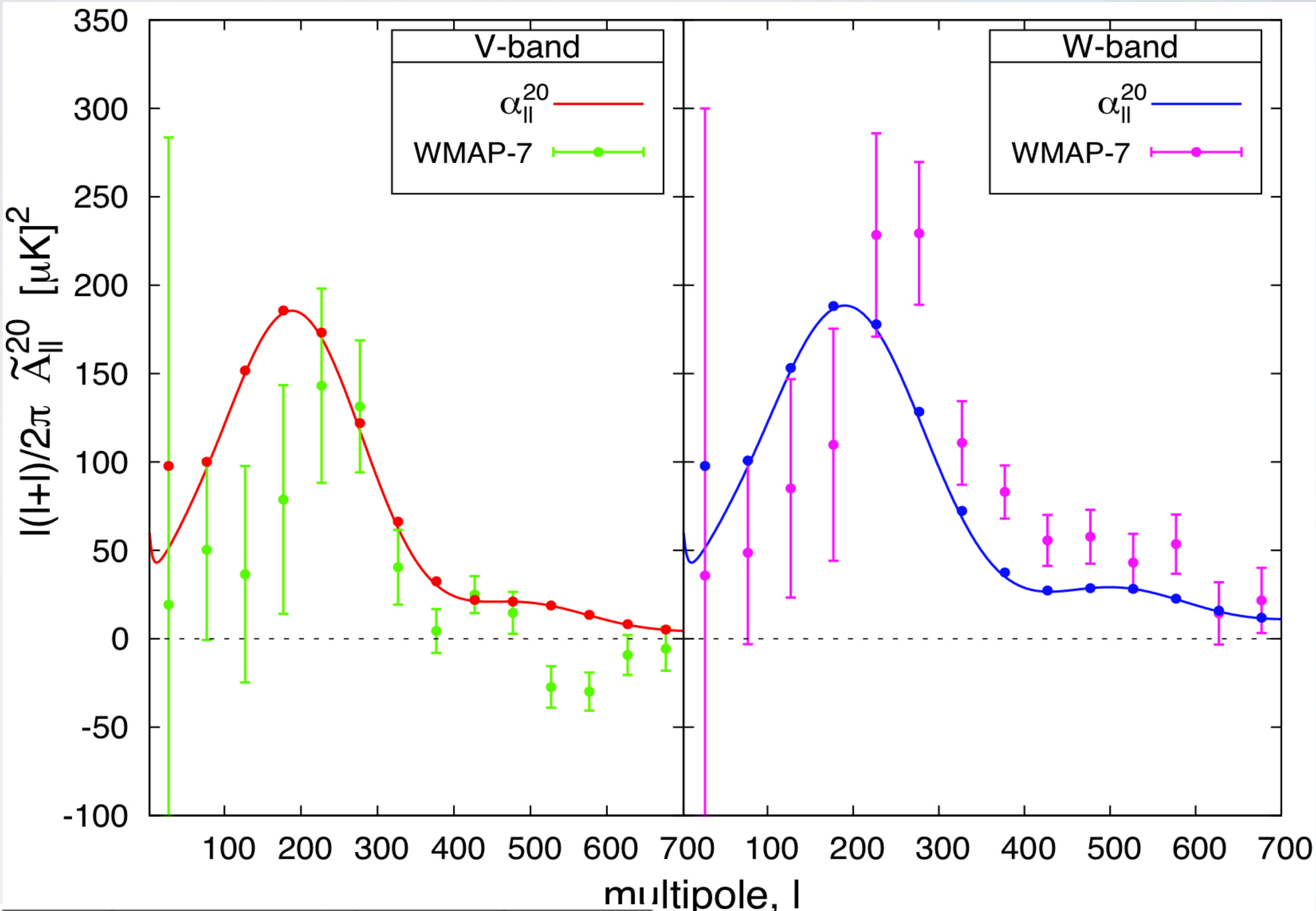
>6 sigma detection of isotropy violation was seen in WMAP

The BipoSH space needs to be further explored.

Work done by IUCAA Planck team

Isotropy violations from LSS !!
Will they show up in the CMB sky ?

LSS quadrupole moment larger by a factor of 100 could result in such an anomaly !!



	FWHM (in degrees)	χ^2 per d.o.f	ψ_{20}
V-band	0.326	1.62	3.09×10^{-2}
W-band	0.202	3.33	

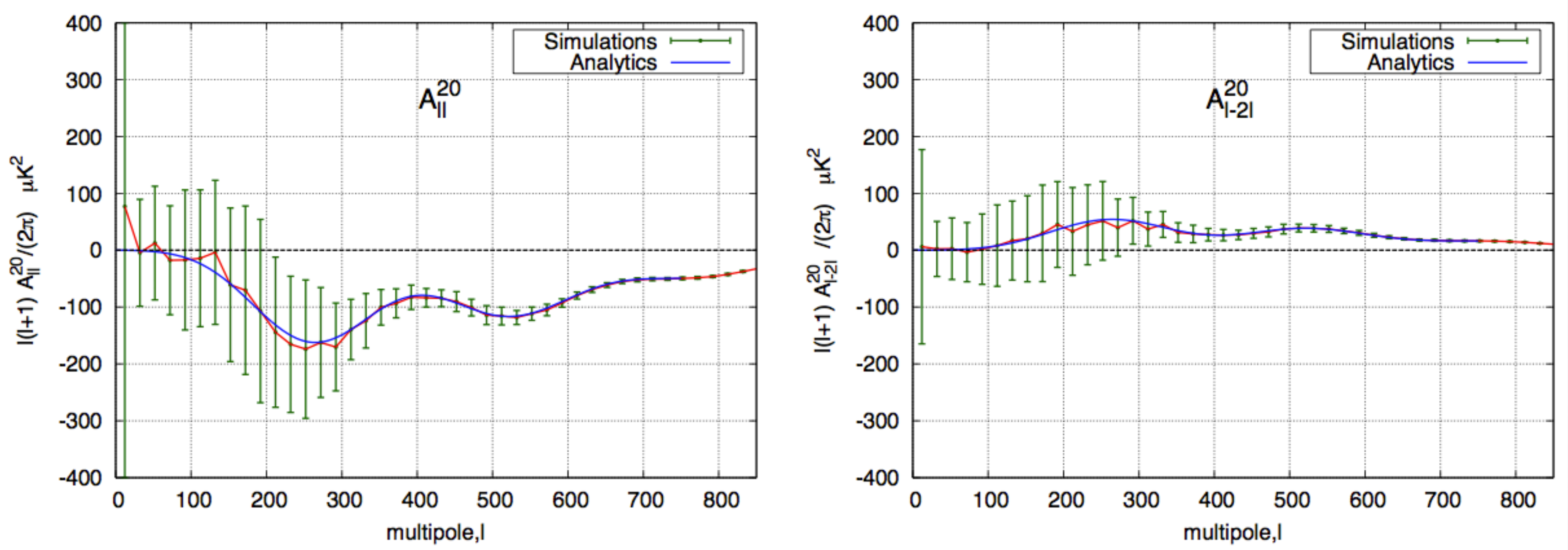
Aditya Rotti, Moumita Aich, Tarun Souradeep
arXiv : 1111.3357

The culprit >> Non-circular beams.

$$\tilde{A}^{20}_{ll} = \frac{(-1)^l\, 2\sqrt{5}\, C_l\, B^{00}_{ll} B^{20}_{ll}}{(\prod_l)^3 C^{20}_{l0l0}}$$

Nidhi Joshi et. al. arXiv:1210:7318

$$\tilde{A}^{20}_{l-2l} = \frac{\sqrt{5}(-1)^l}{\prod_{l-2l} C^{20}_{l-20l0}} \left[\frac{C_{l-2} B^{00}_{l-2l-2} B^{20}_{ll-2}}{\prod_{l-2}} + \frac{C_l B^{00}_{ll} B^{20}_{l-2l}}{\prod_l}\right]$$



The Beam BipoSH coefficients are given by

$$B^{LM}_{l_1 l_2} = \sum_{m_1 m_2} C^{LM}_{l_1 m_1 l_2 m_2} \sum_{m'} b_{l_2 m'}(\hat{z}) \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} D^{l_2}_{m_2 m'}(\phi, \theta, \rho(\theta,\phi)) Y^*_{l_1 m_1}(\theta,\phi) \sin\theta d\theta d\phi.$$

Non-circular beam

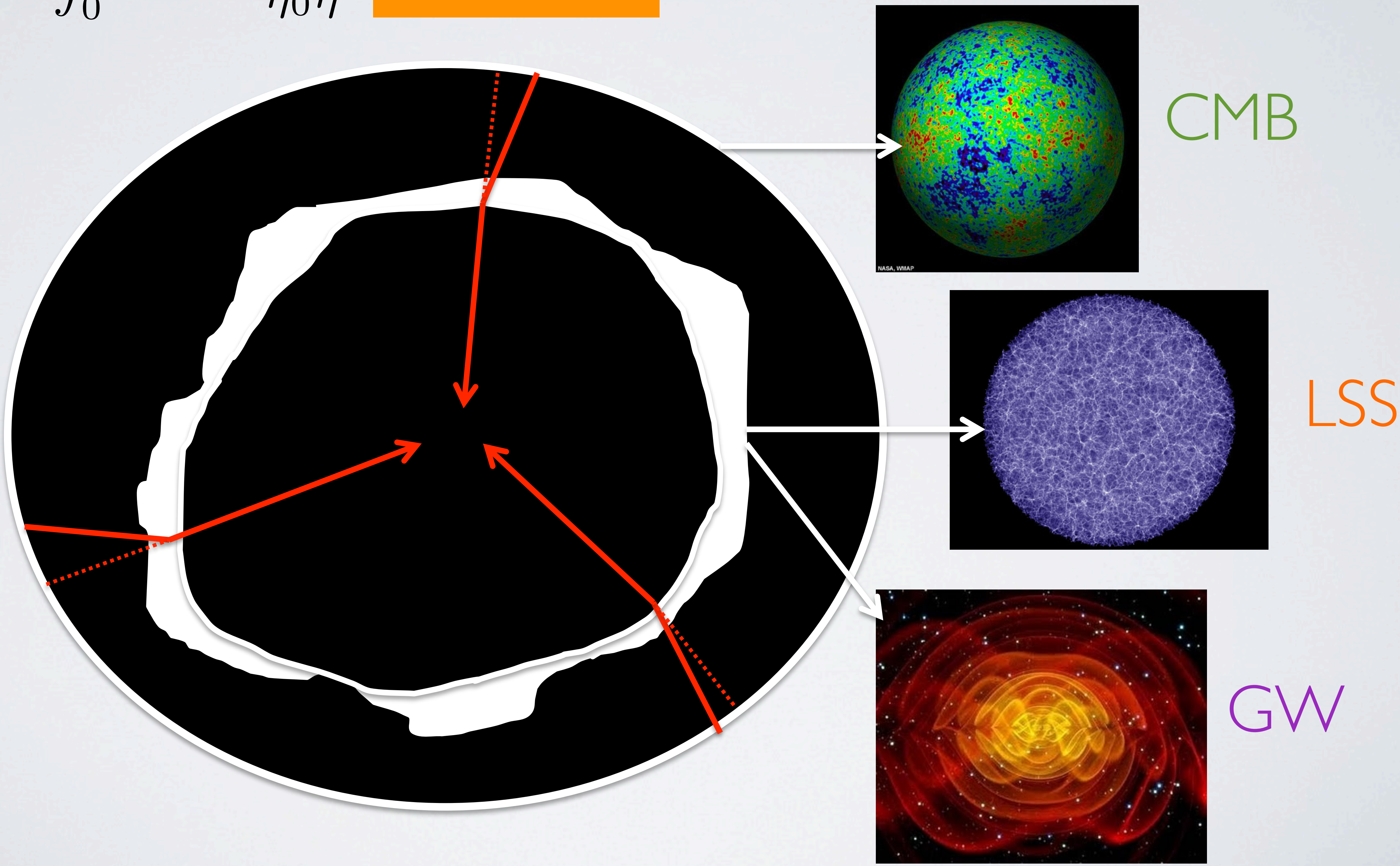
Scan

Weak lensing of the CMB

$$\psi(\hat{n}) = -2\int_0^{\eta_0} d\eta \frac{\eta_0 - \eta}{\eta_0 \eta} \Psi(\hat{n}, \eta_0 - \eta)$$

Projected lensing potential

Gravitational potential



Weak lensing of the CMB

$$\tilde{T}(\hat{n}) = T(\hat{n} + \vec{\Delta})$$

$$\vec{\Delta} = \nabla\psi + \nabla \times \Omega$$

LSS (ψ) GW (Ω)

Even BipoSH

$L + l_1 + l_2 \rightarrow Even$

Odd BipoSH

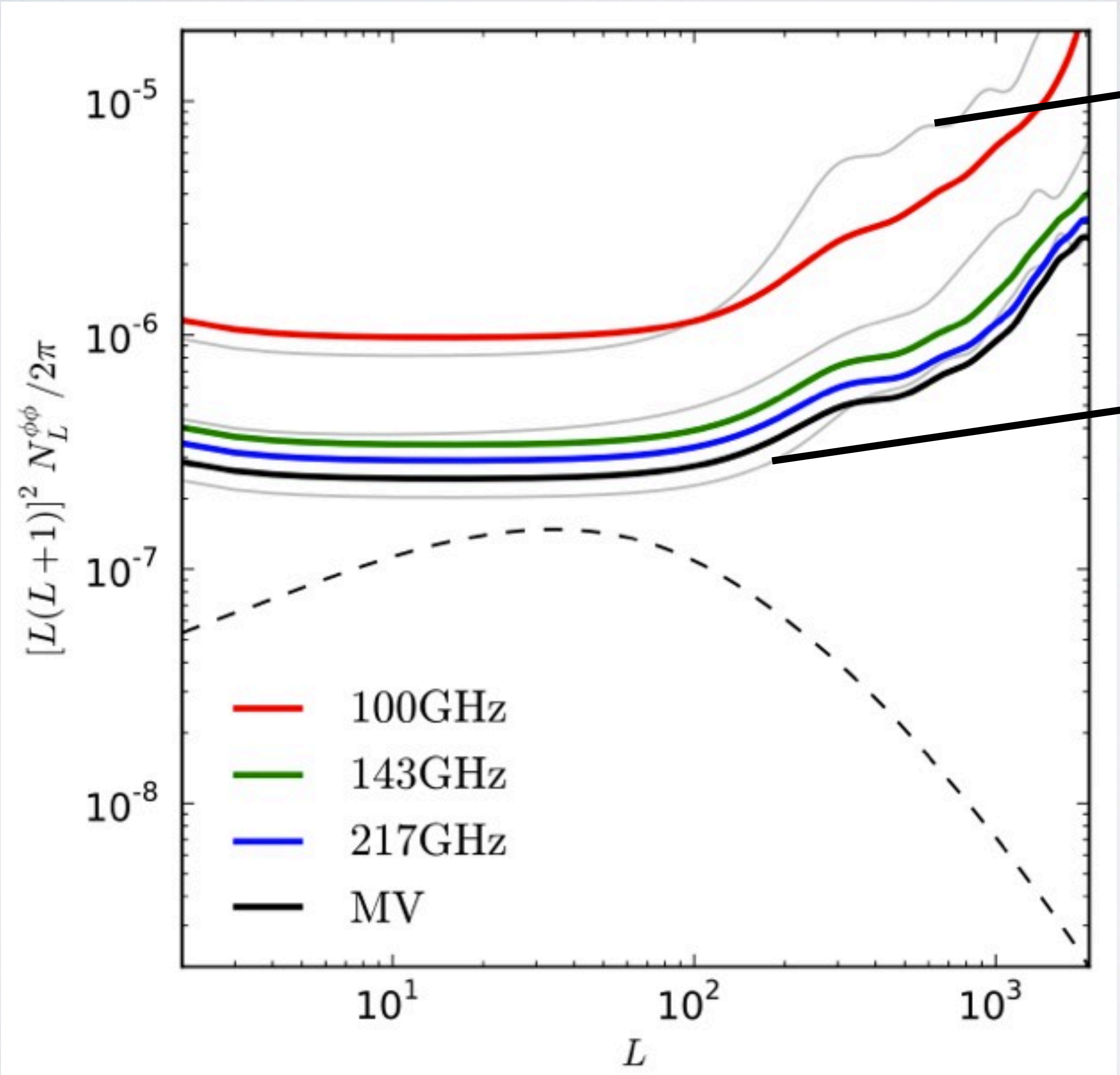
$L + l_1 + l_2 \rightarrow Odd$

Anisotropic two point correlation function.

$$\tilde{A}^{LM}_{l_1 l_2} = A^{LM}_{l_1 l_2} + \psi_{LM} \frac{C_{l_1} F(l_2, L, l_1) + C_{l_2} F(l_1, L, l_2)}{\sqrt{4\pi}} \frac{\Pi_{l_1}\Pi_{l_2}}{\Pi_L} \mathcal{C}^{L0}_{l_1 0 l_2 0}$$

Shape function

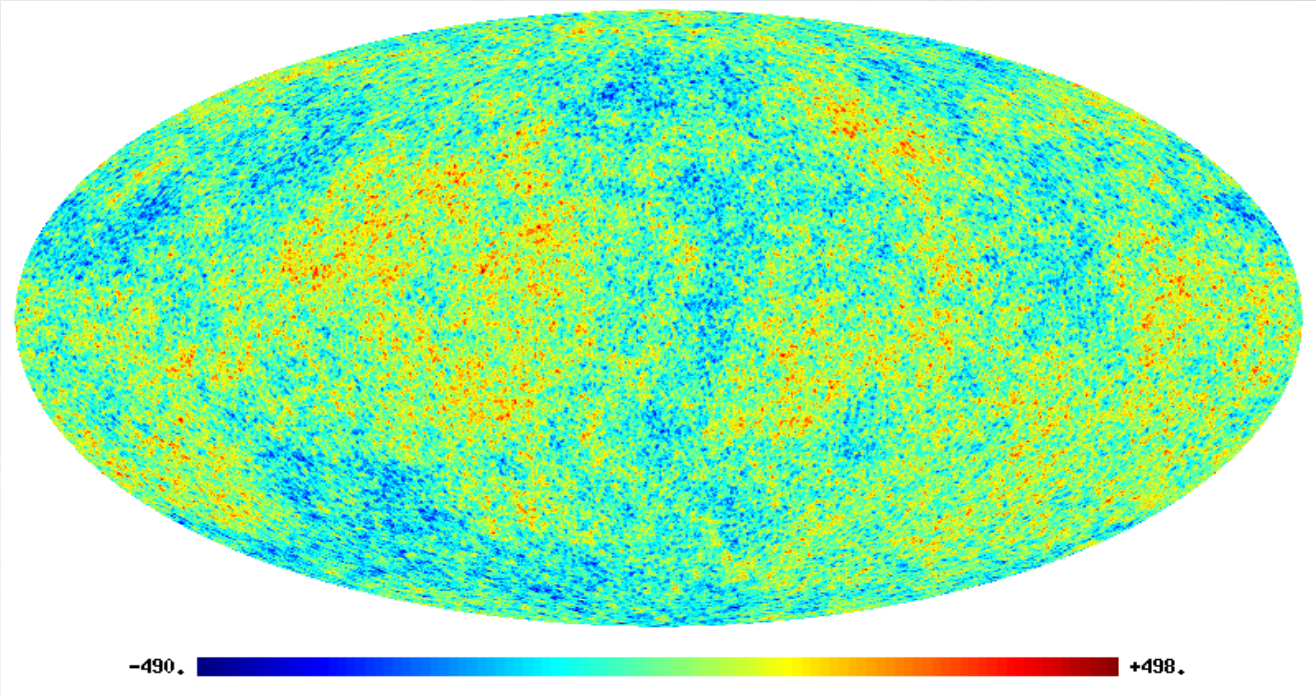
Why couldn't WMAP see the cosmic lens?



WMAP

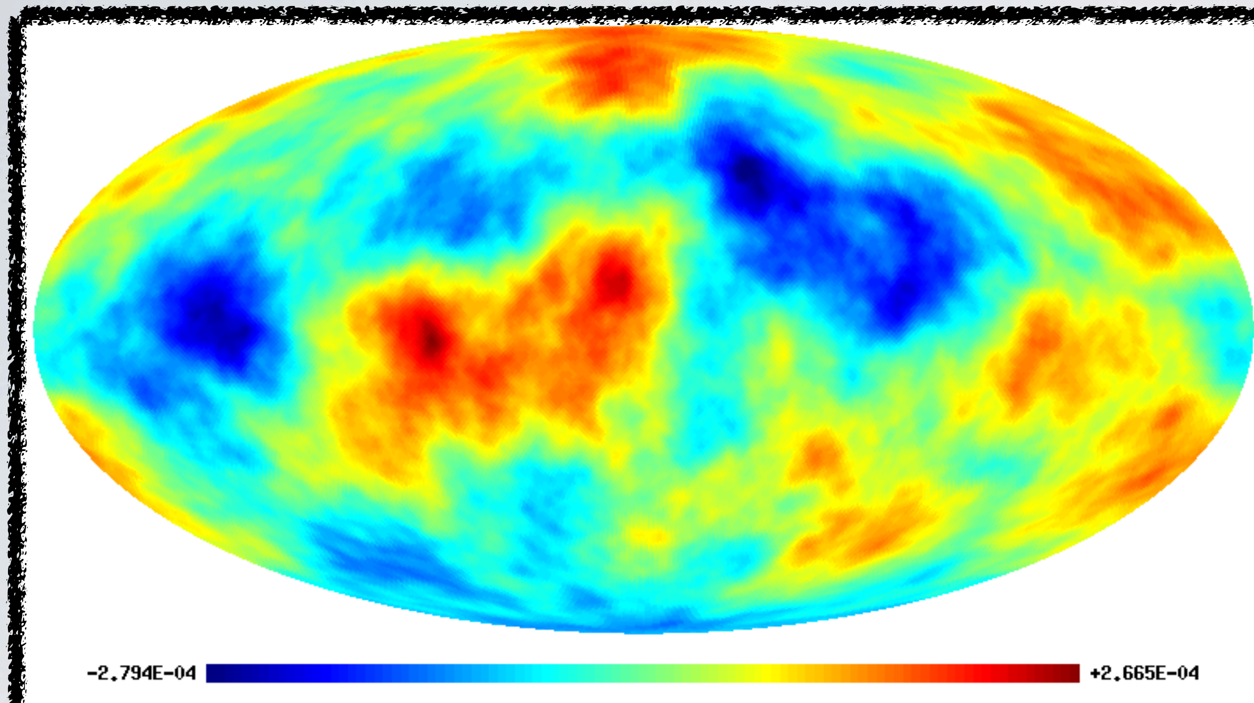
PLANCK
SNR <= 1

Measuring the cosmic lens.

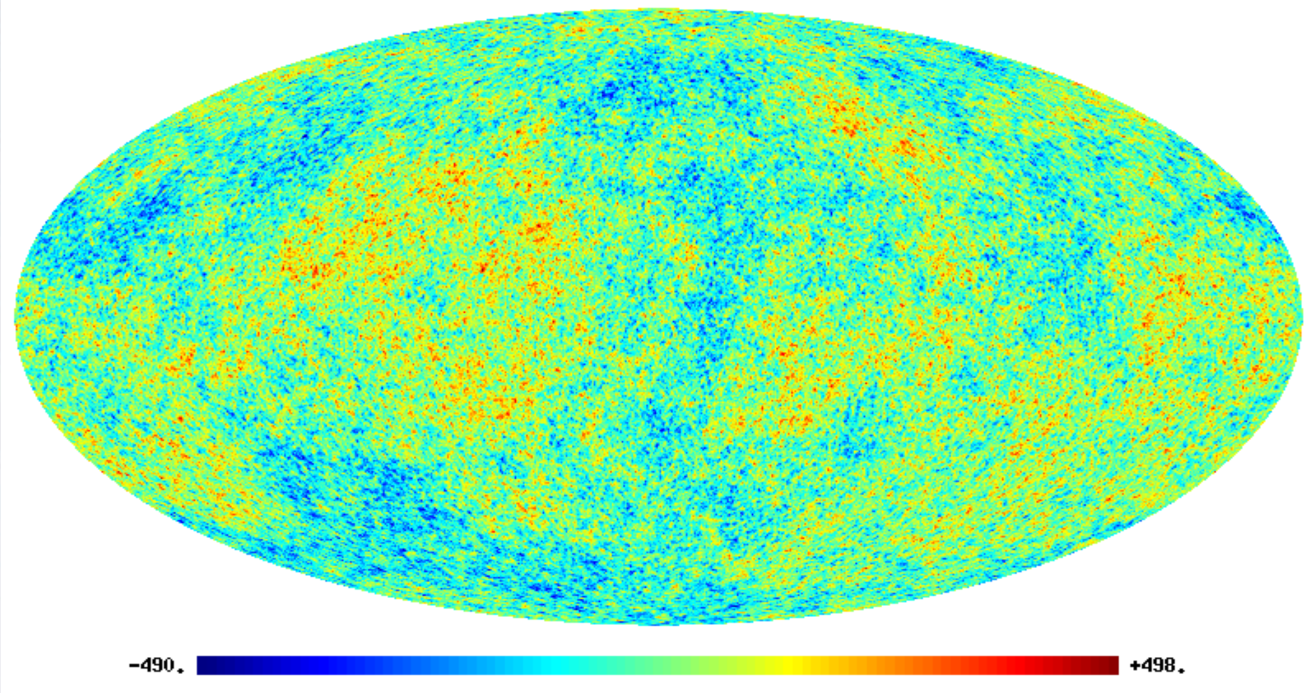


Simulated lensed CMB map.

Measuring the cosmic lens.



Reconstructed lensed CMB map.



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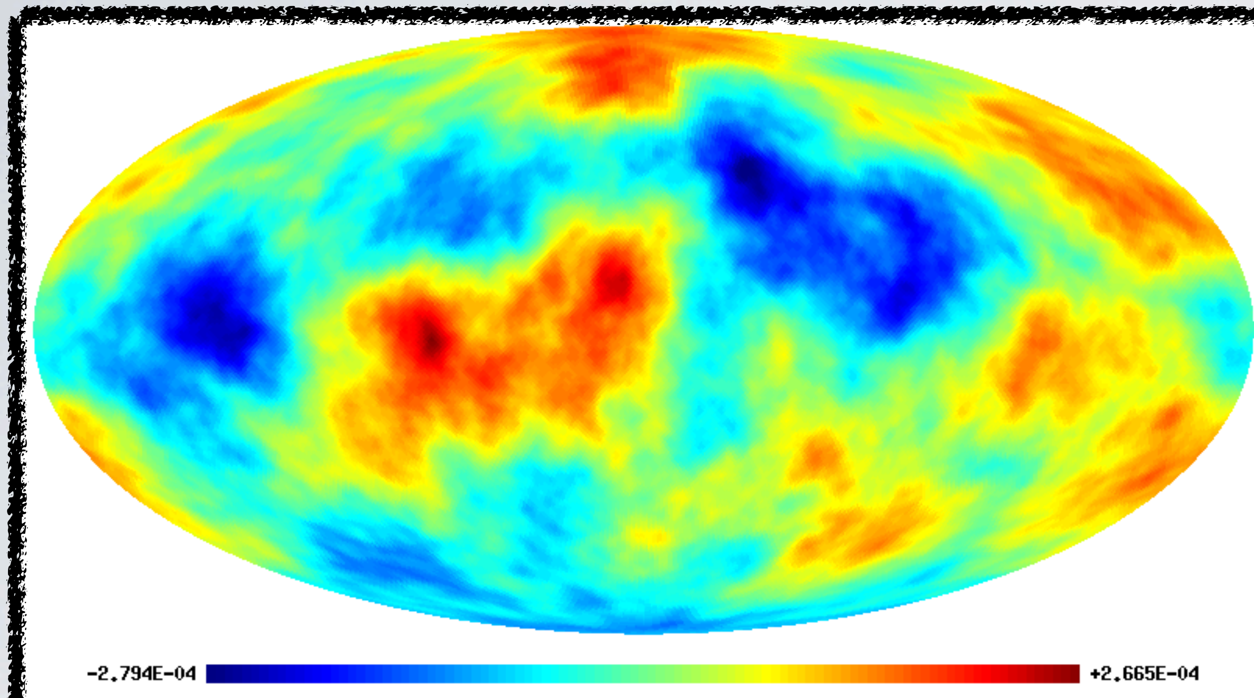

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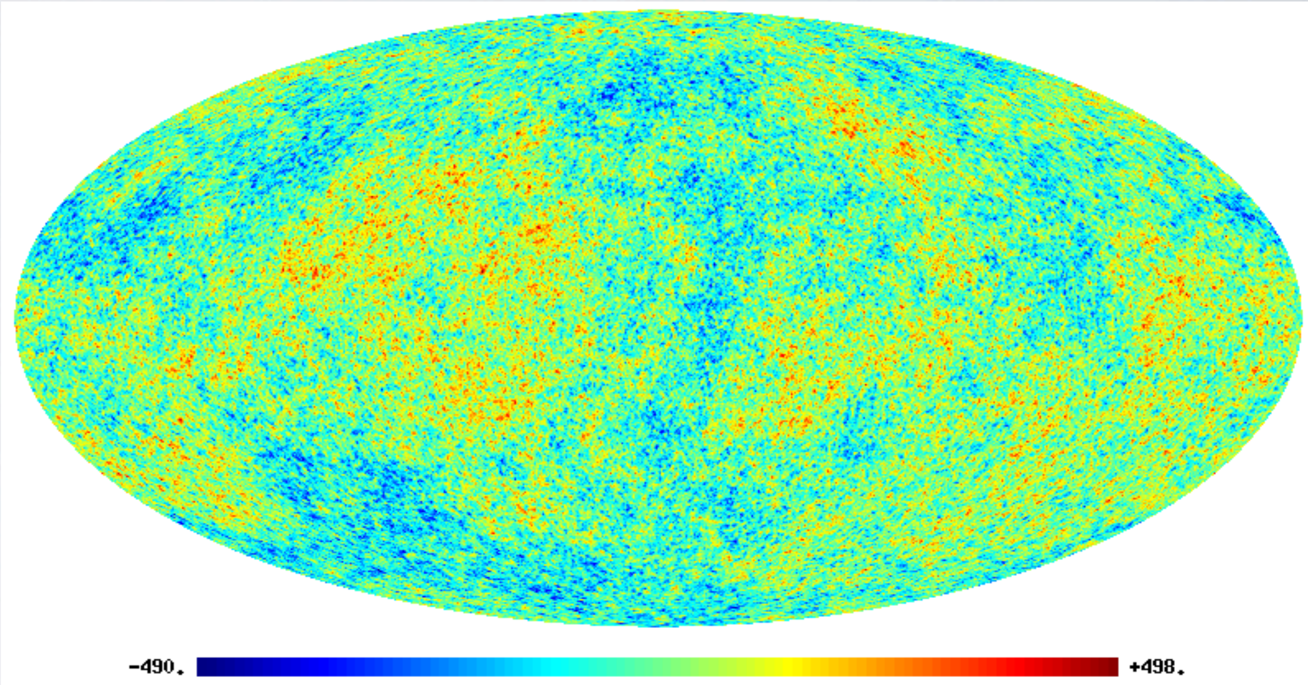

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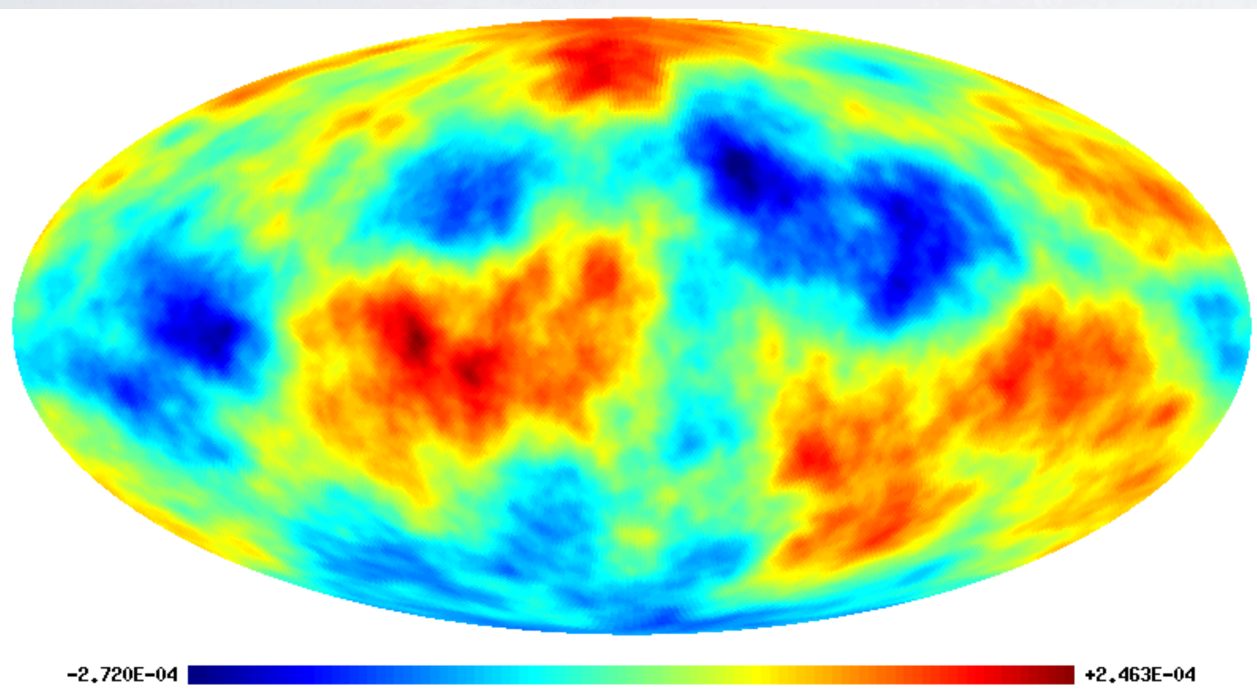
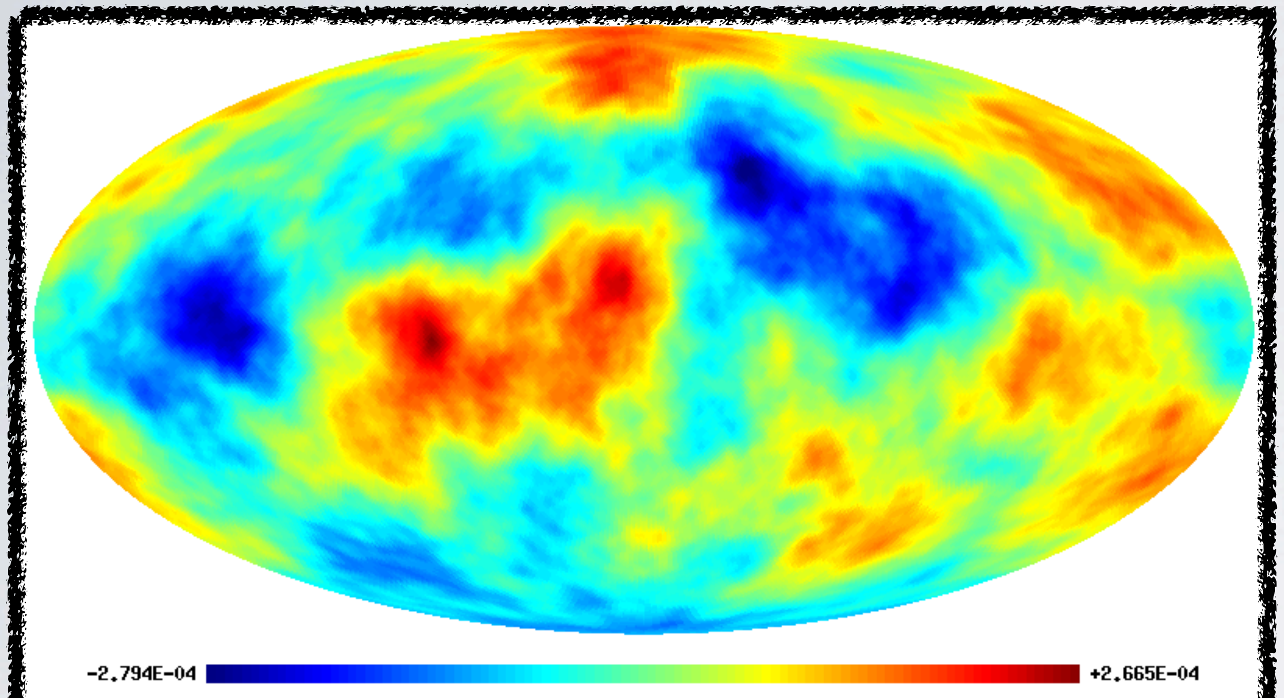


Input lensing potential map.

Measuring the cosmic lens.



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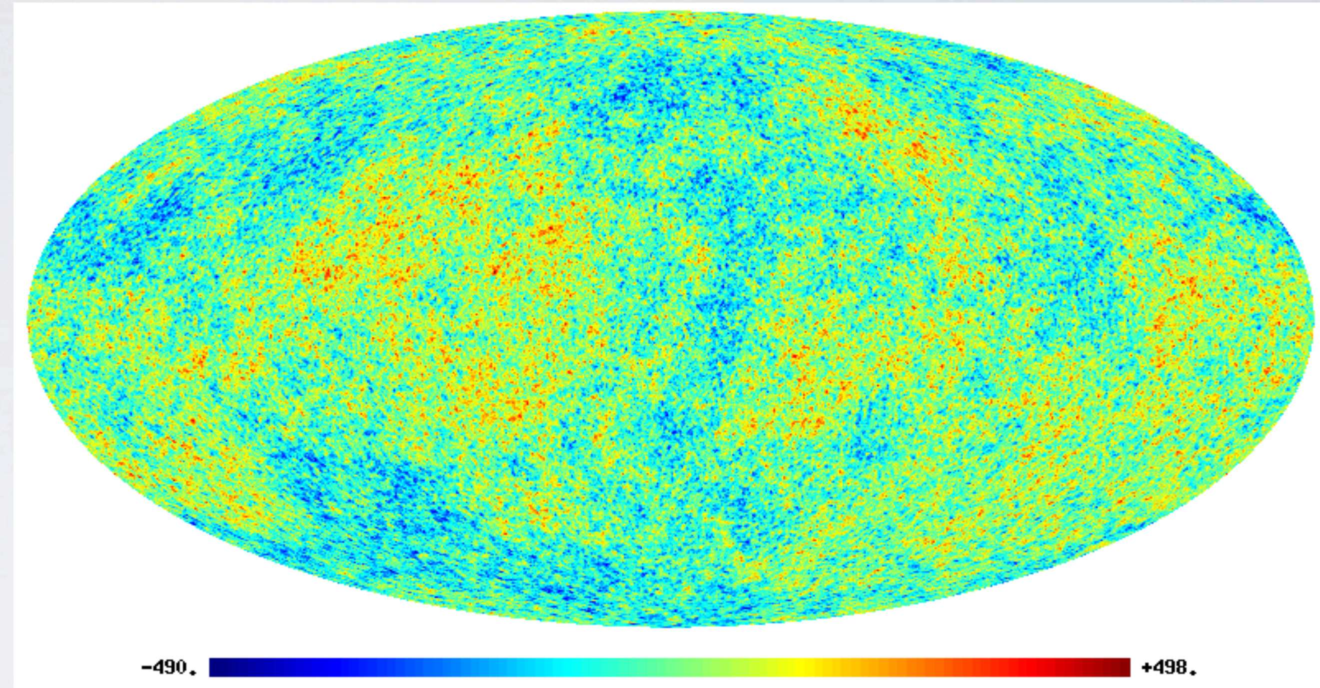

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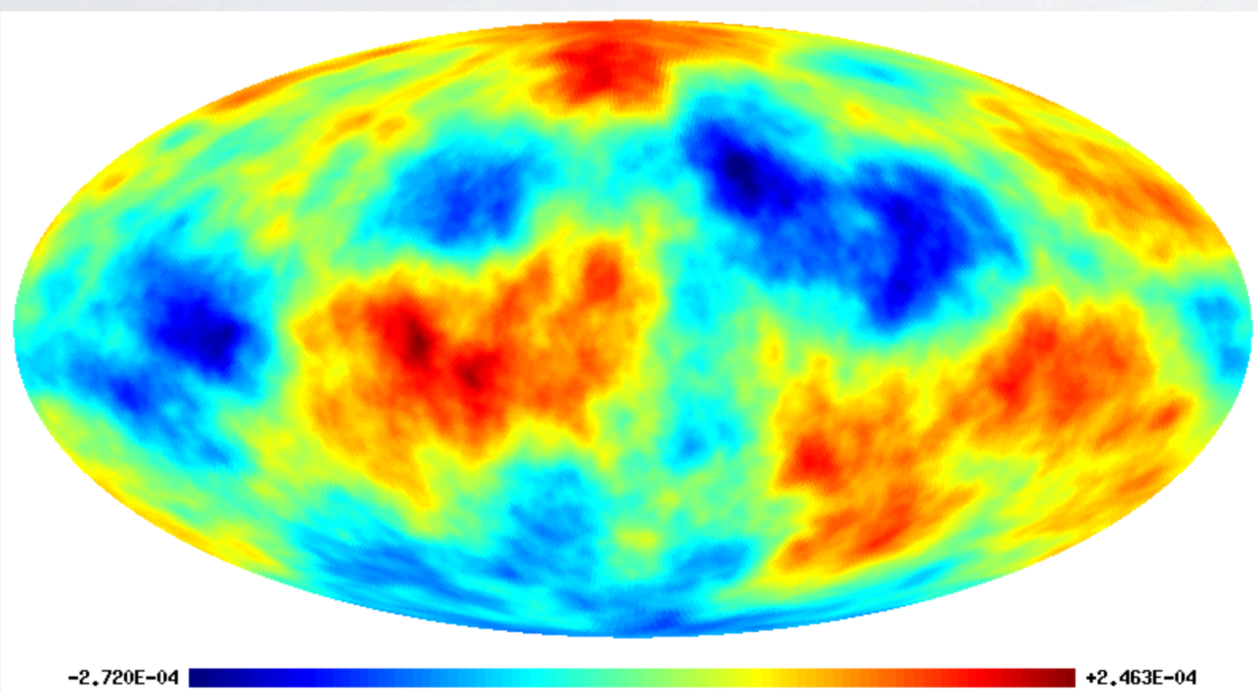

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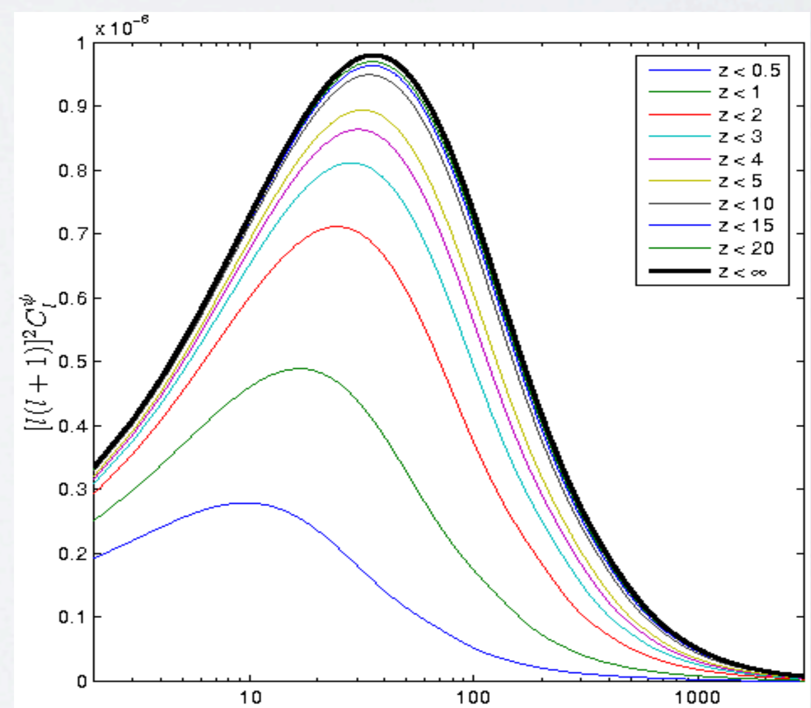
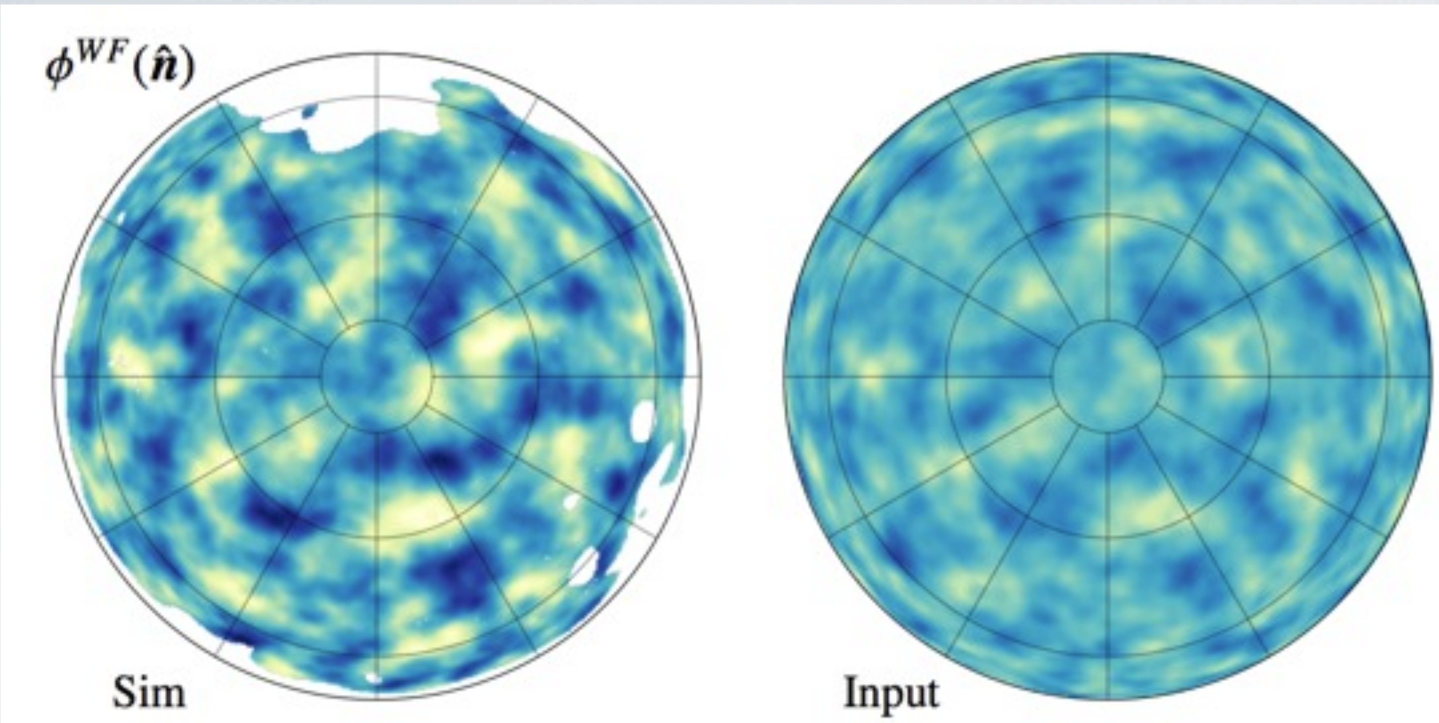


Lewis & Challinor

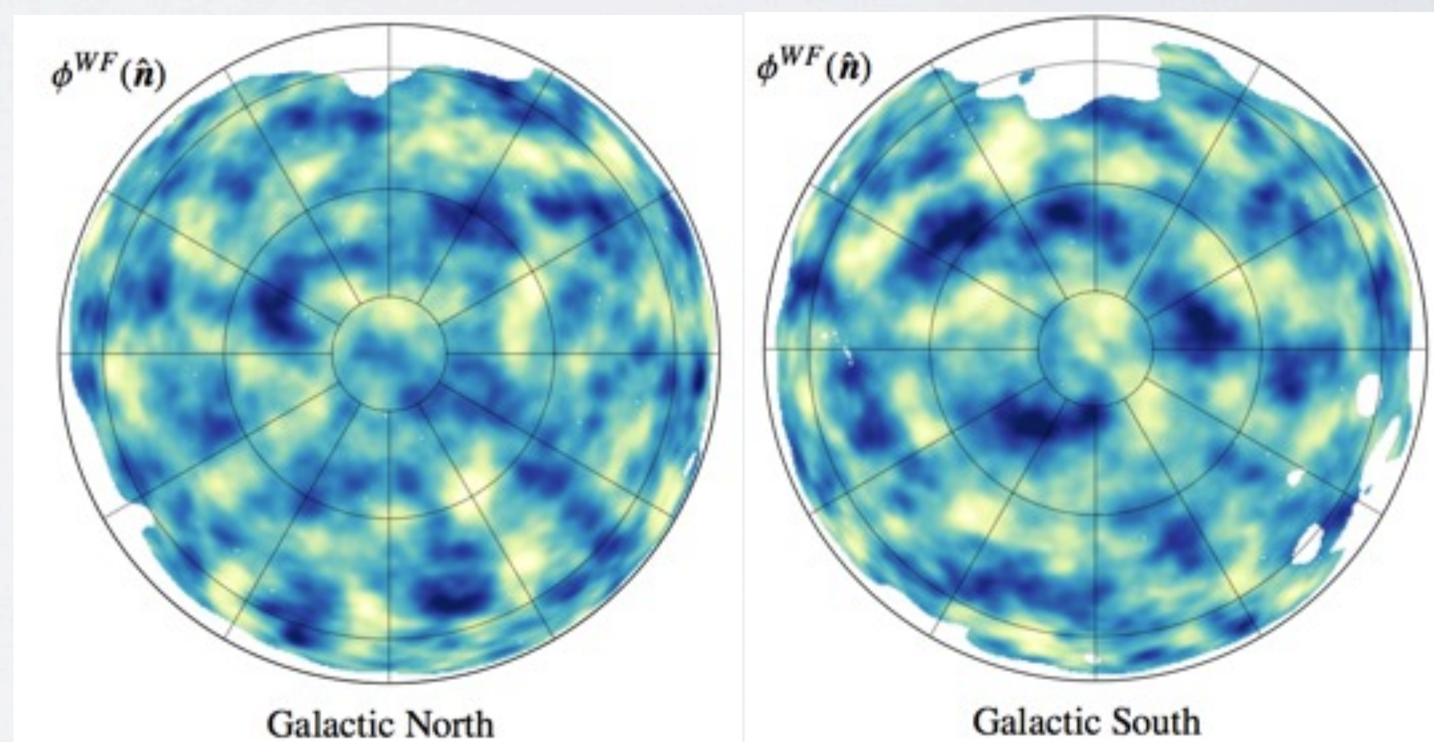
Contribution to the lens from gravitational potentials at various

The Cosmic lens

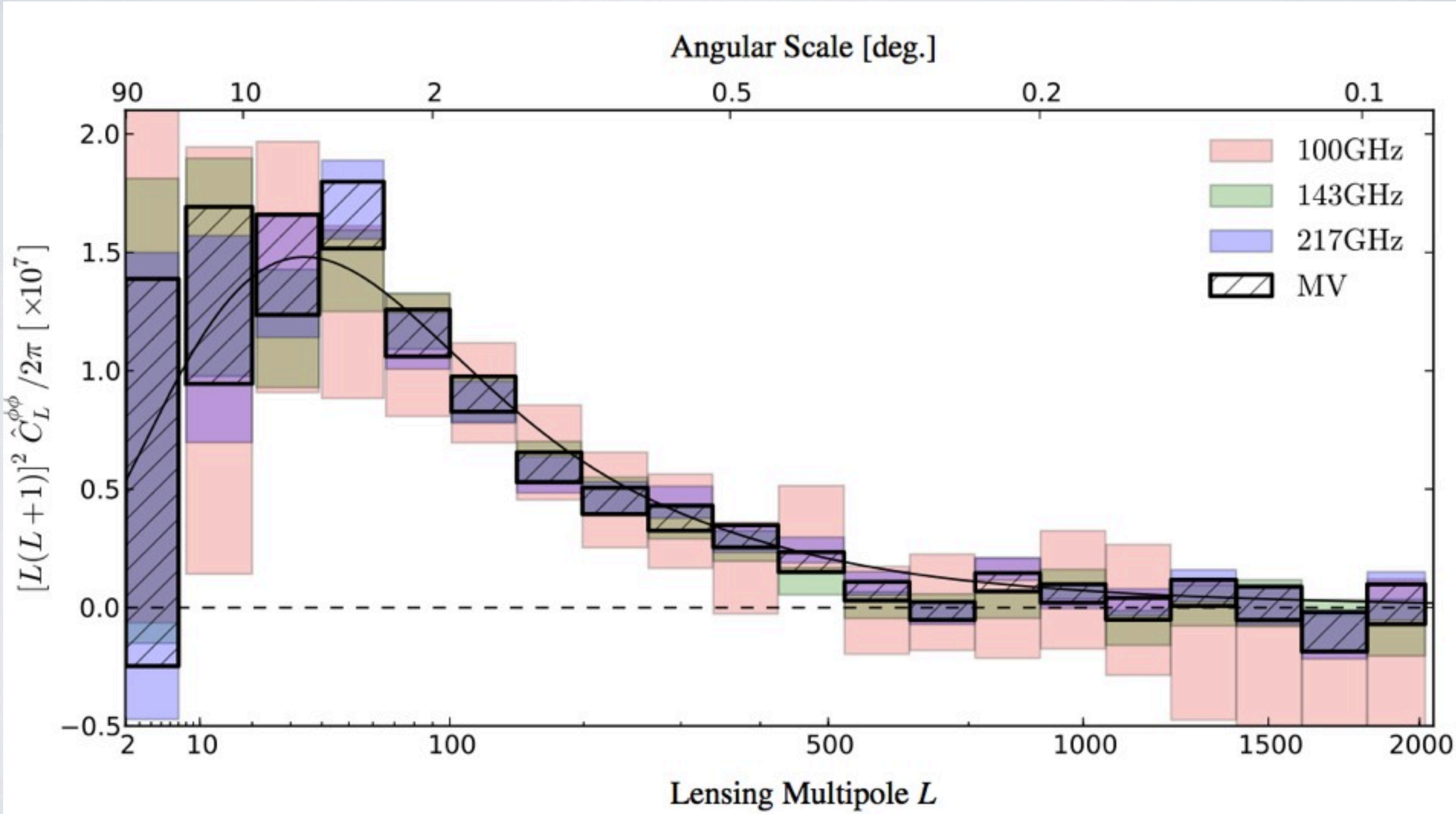


Simulated reconstruction with realistic simulations. Note the correlation between the input lens and the reconstructed lens

Reconstructed projected lensing potential from PLANCK CMB anisotropy maps



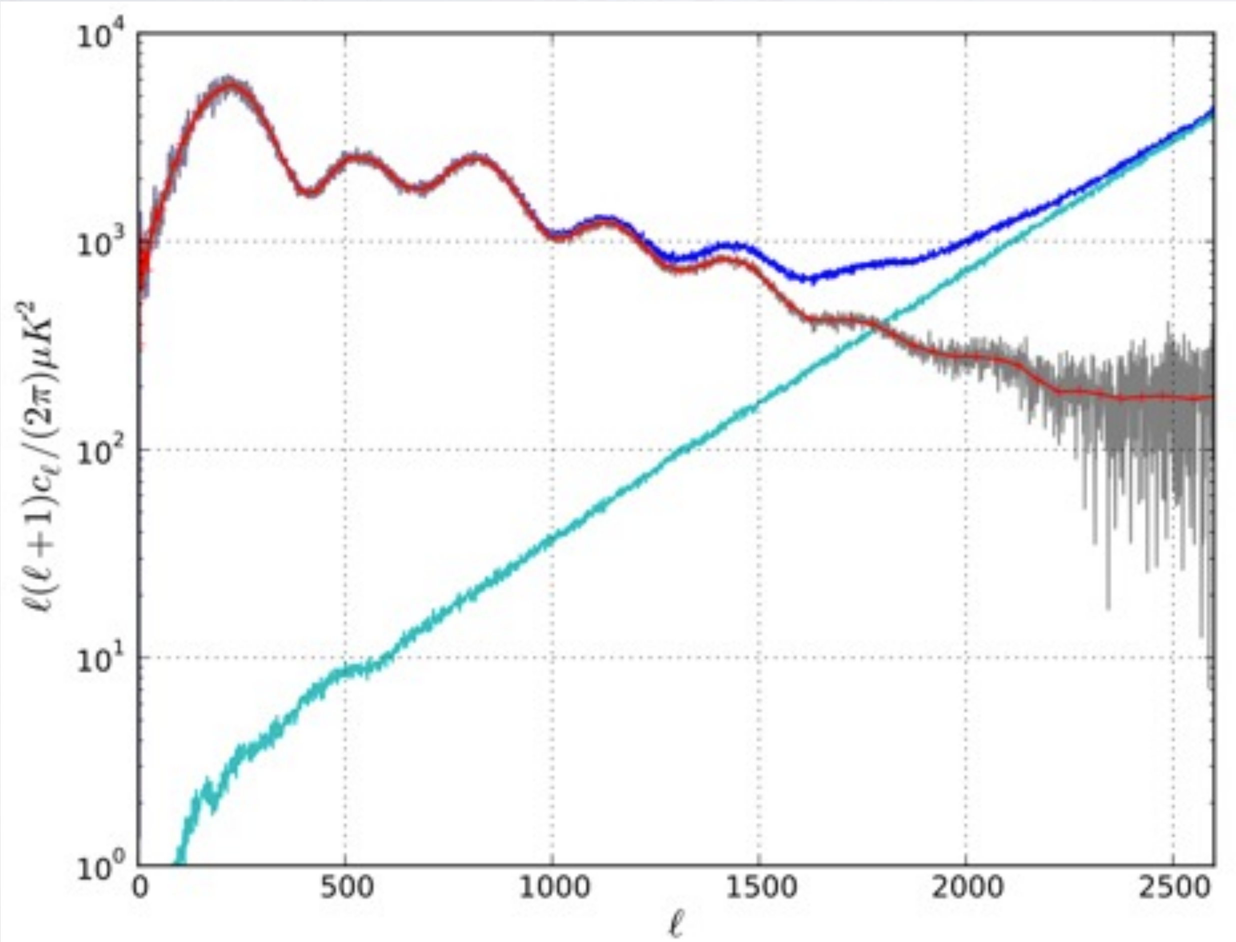
Lens power spectrum

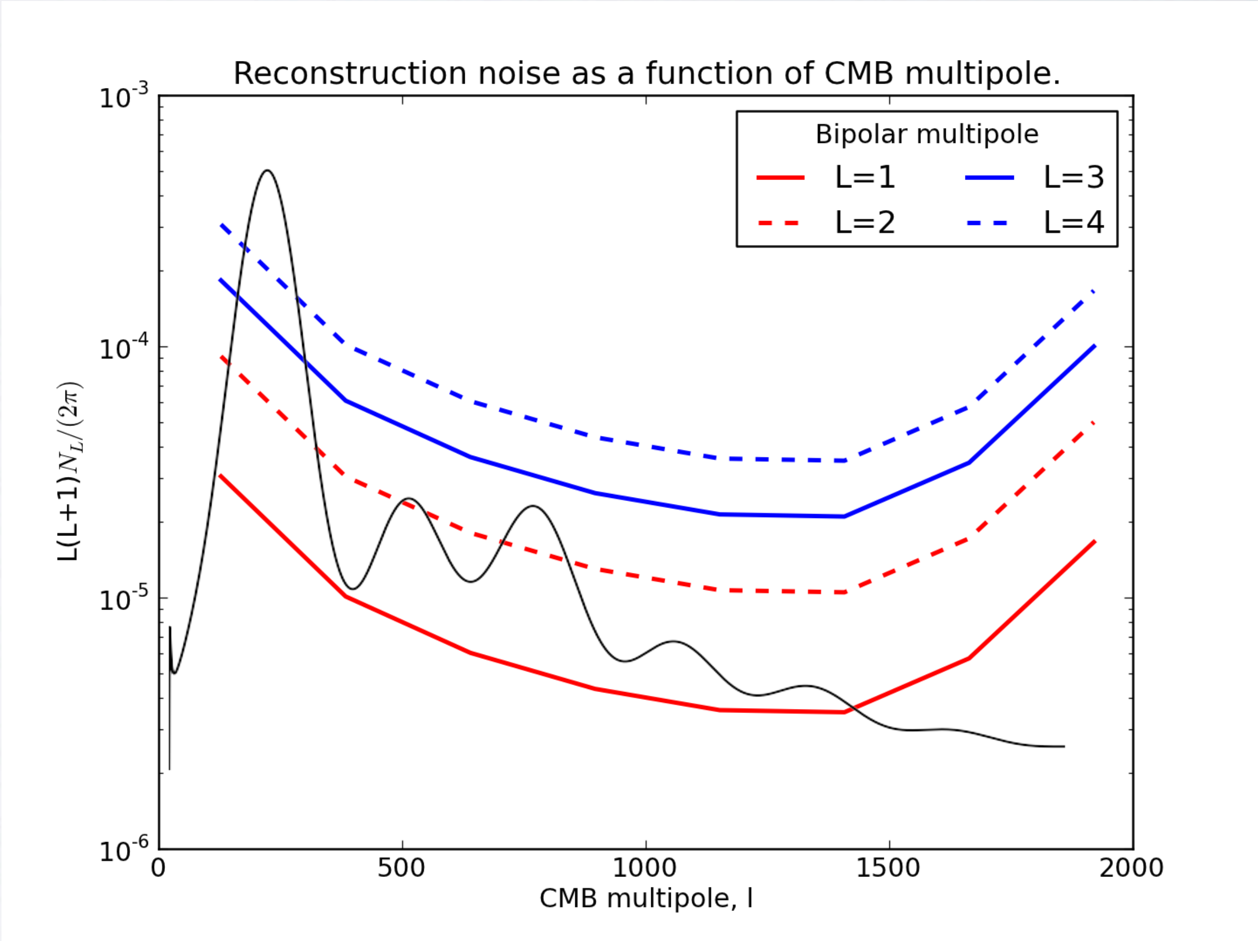


Modulation in the CMB sky.

$$\Delta T(\hat{n}) = [1 + M(\hat{n})]\, \Delta T^{SI}(\hat{n})$$

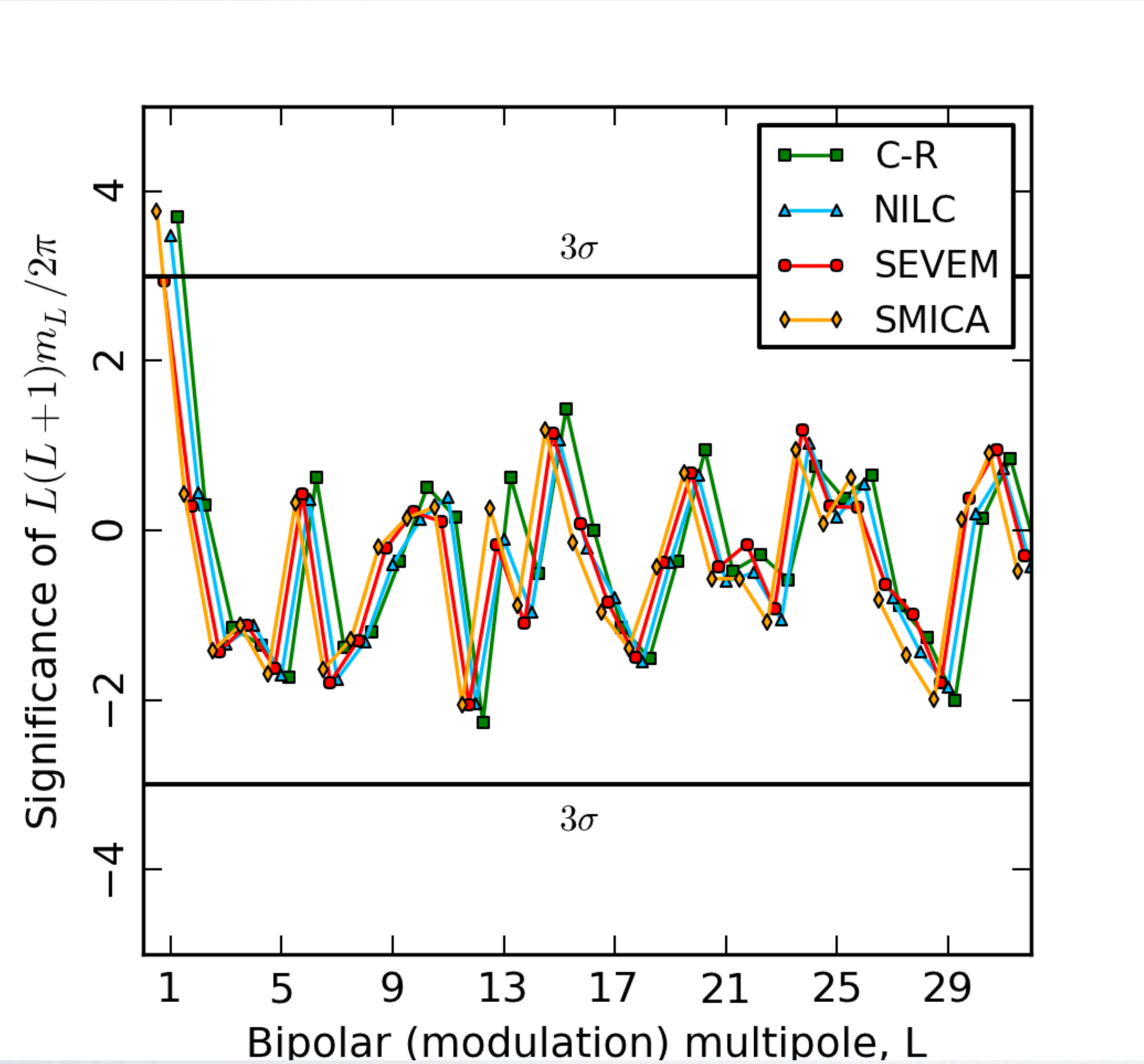
$$\tilde{A}^{LM}_{l_1 l_2} = A^{LM}_{l_1 l_2} + m_{LM} \frac{C_{l_1} + C_{l_2}}{\sqrt{4\pi}} \frac{\Pi_{l_1}\Pi_{l_2}}{\Pi_L} \mathcal{C}^{L0}_{l_1 0 l_2 0}$$



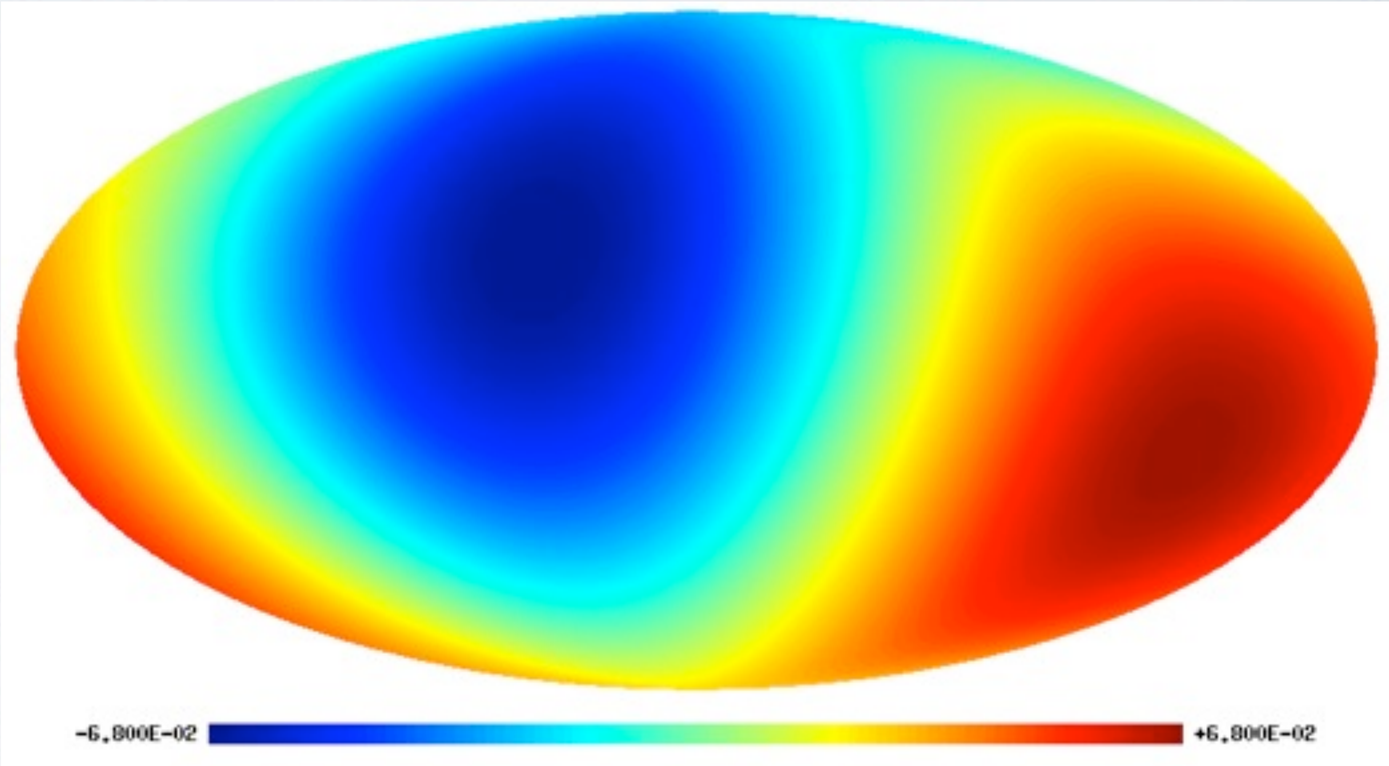


Modulation in the CMB sky

Significance of power in the modulation field.



Dipole of the reconstructed modulated map.

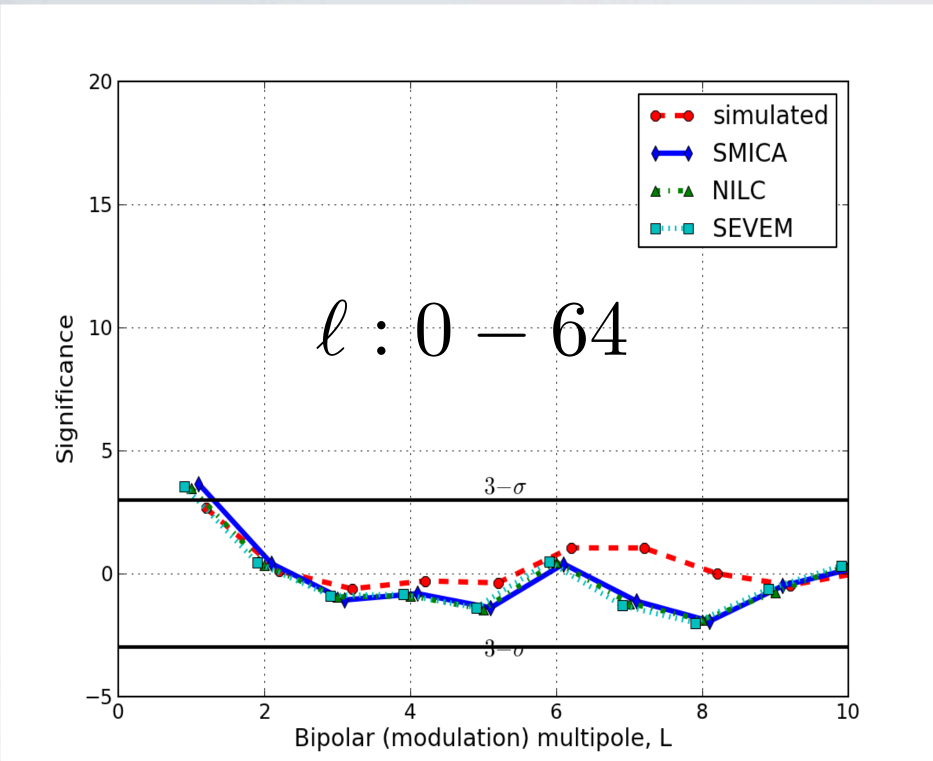


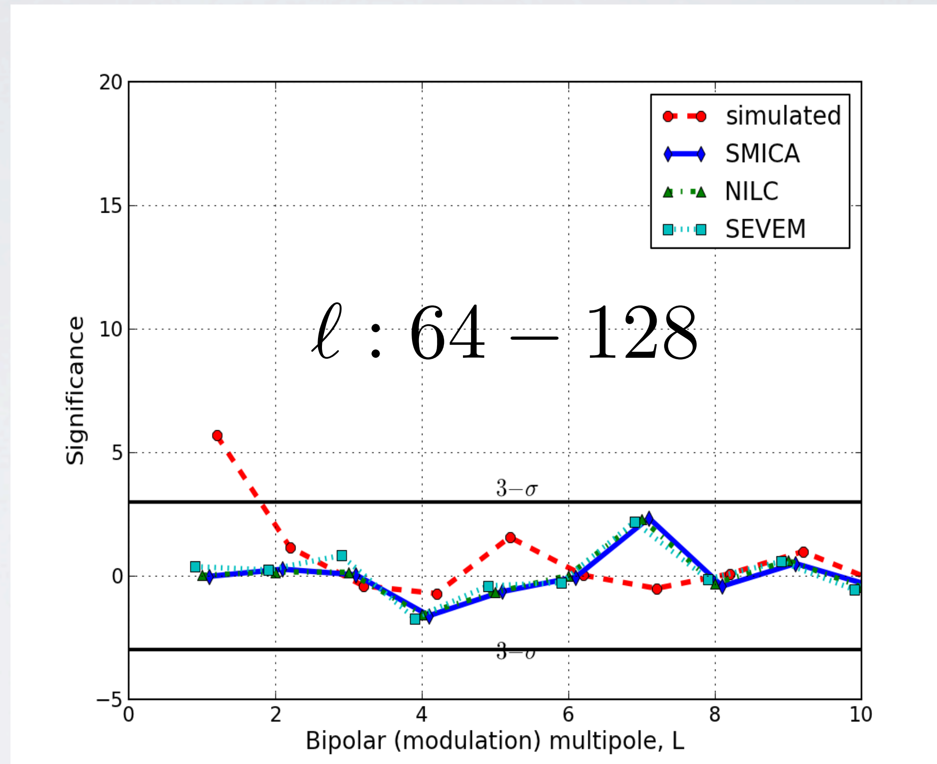
Galactic coordinates

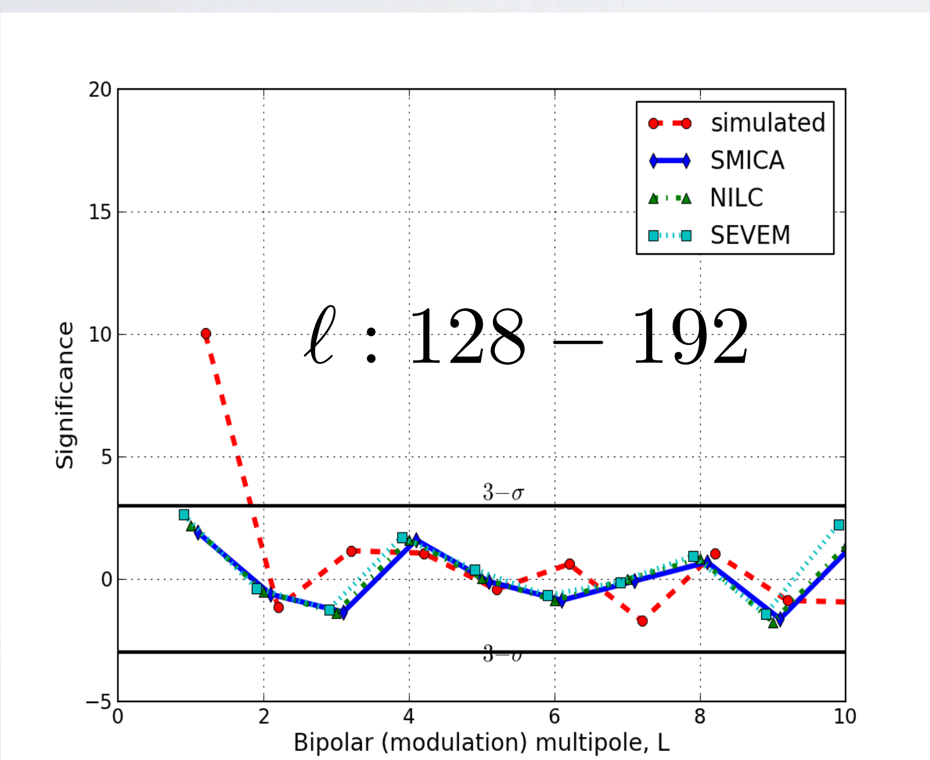
$\ell : 0 - 64$

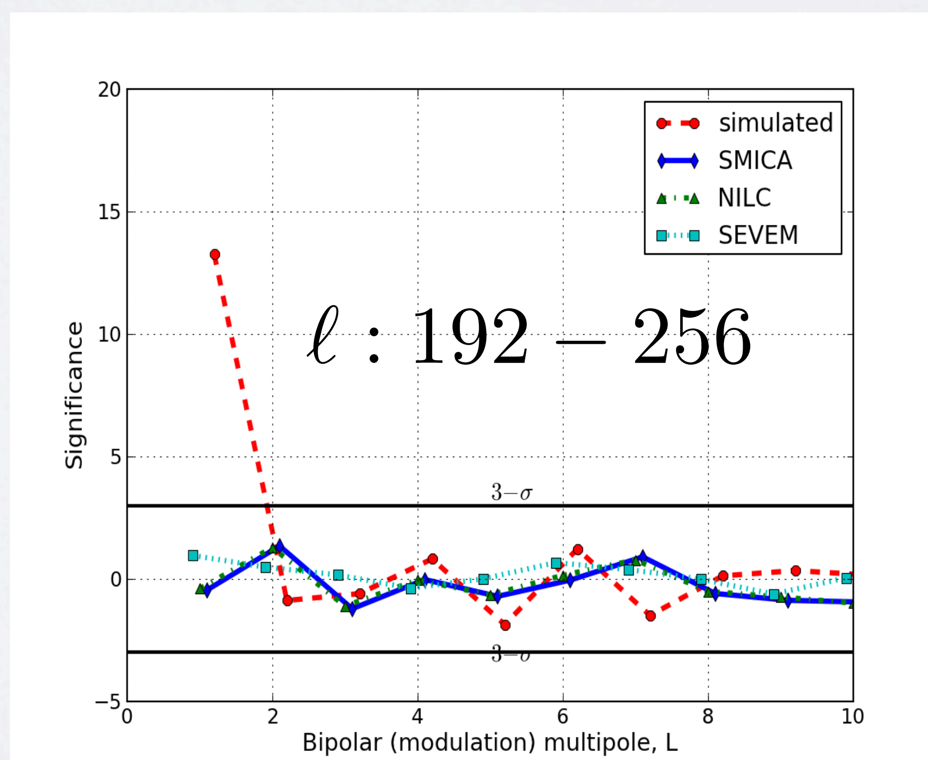
Work done by IUCAA Planck team

Scale dependent modulation



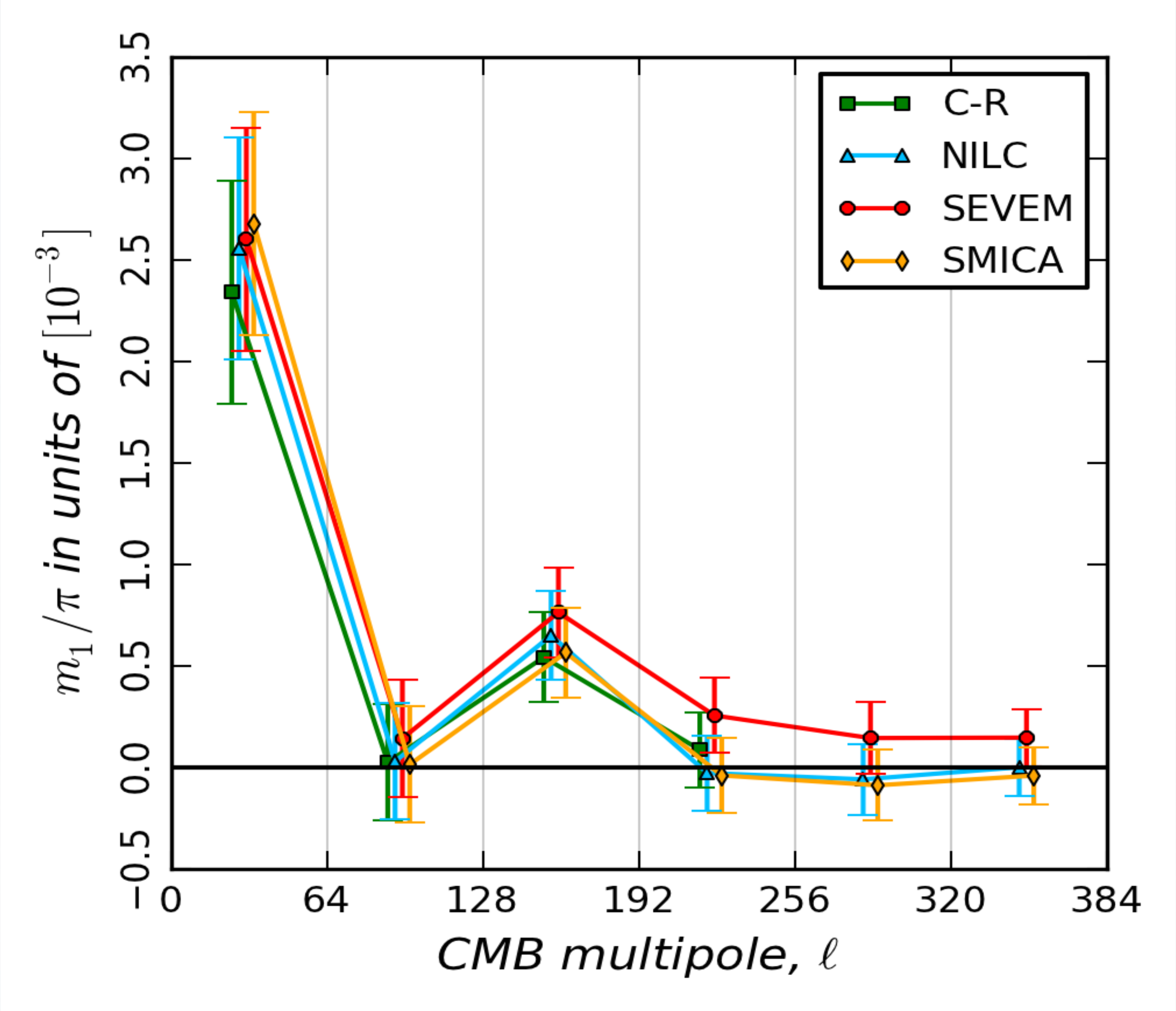






- The red curve shows the significance of the detection for a true modulated CMB sky.
- Rest of the curves correspond to those derived from various component separated PLANCK maps.
- The cosmic variance goes down on moving to large CMB multipoles. Consequently the reconstruction noise also reduces, resulting in an increase in the significance of the detection

Modulation in the CMB sky.



Work done by IUCAA Planck team

Summary

- Planck results are very **robust**. All cosmological results are reproduced by using different analysis techniques.

- PLANCK high precision measurements have made it possible for the first time to create an **image of the cosmic lens**. This makes possible to do cross correlation studies with other LSS probes.

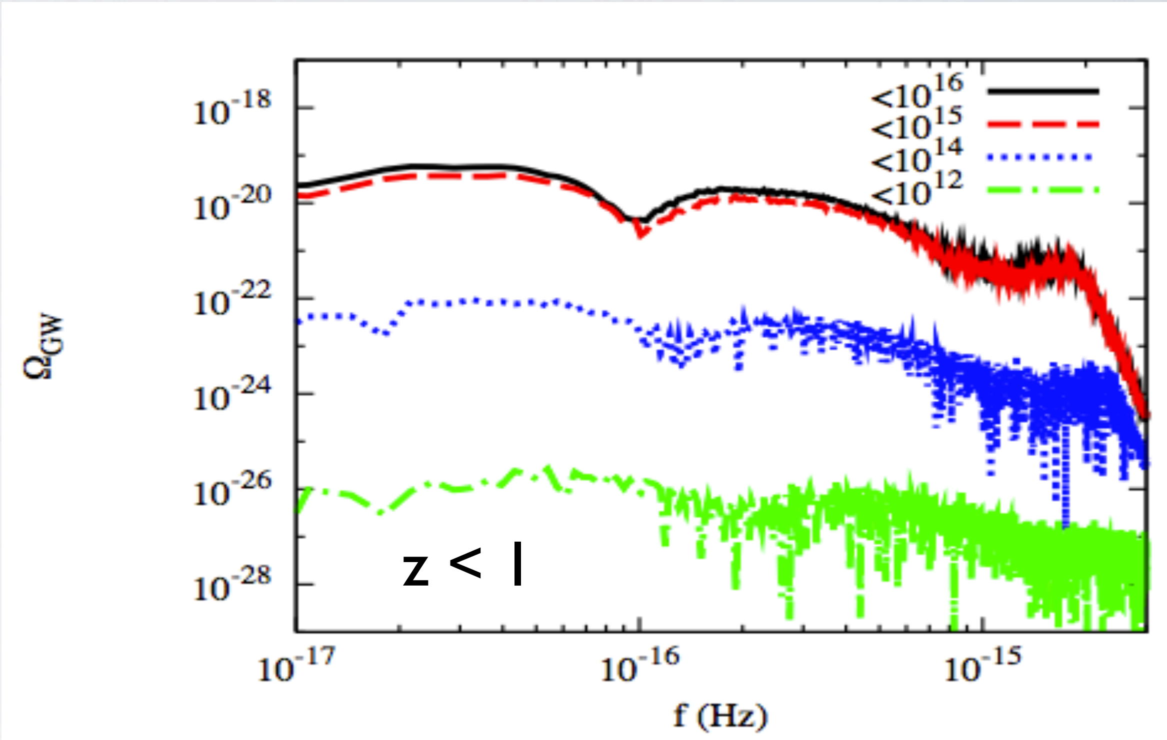
- **Persistent** signatures of **isotropy violation at large angular scales**.

Low frequency GW sources

- Inflation

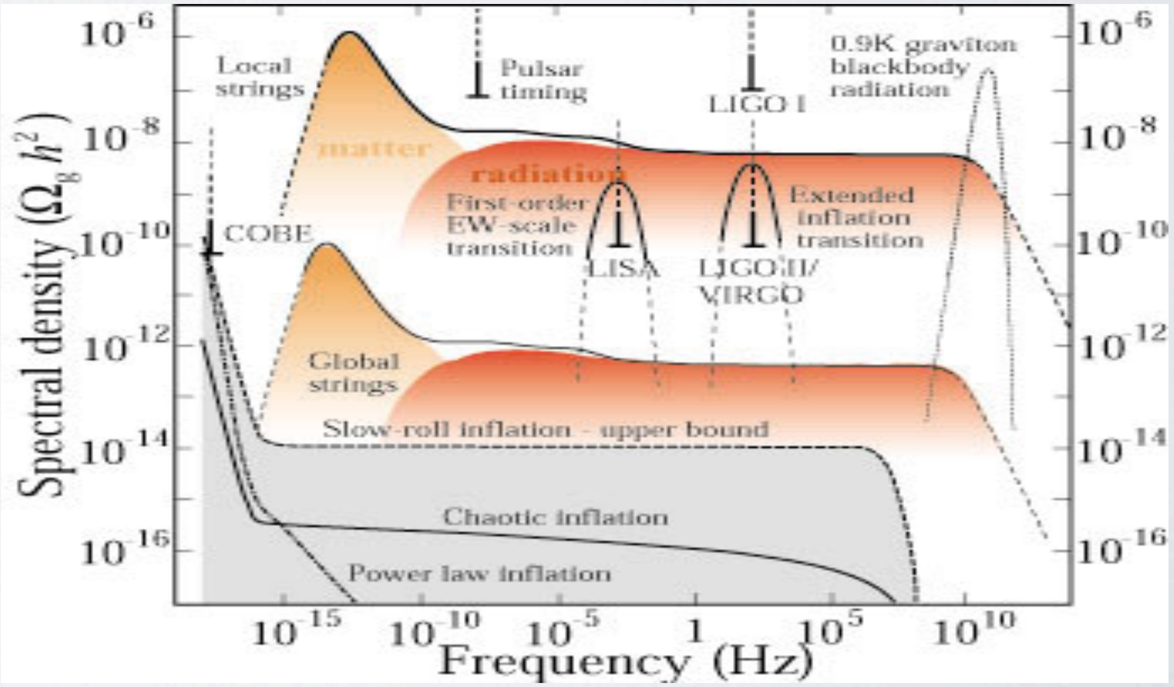
- Stochastic gravitational wave background originating from halo mergers.

Takahiro Inagaki, Keitaro Takahashi, Naoshi Sugiyama arXiv:1204.1439v1

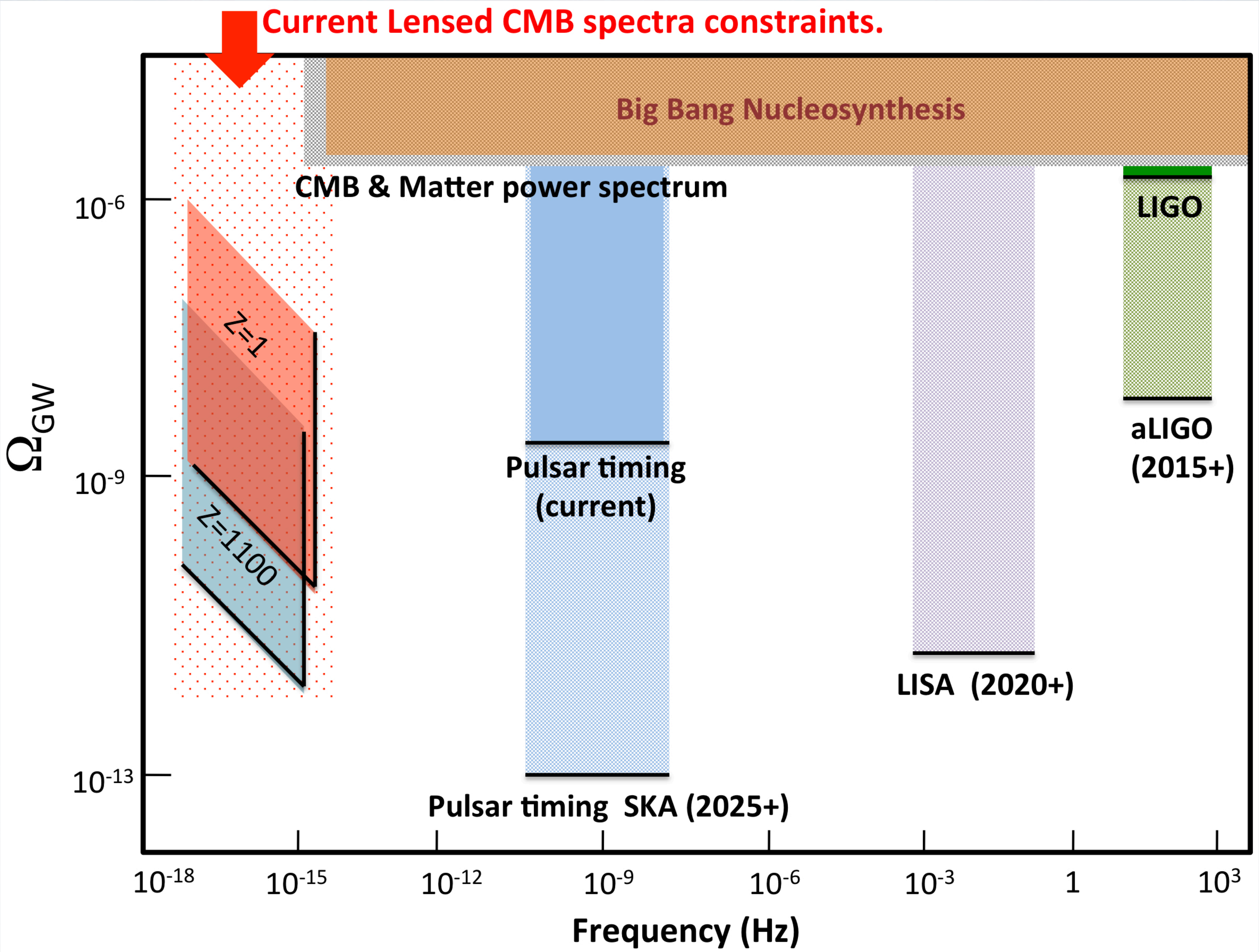


- Strings !!

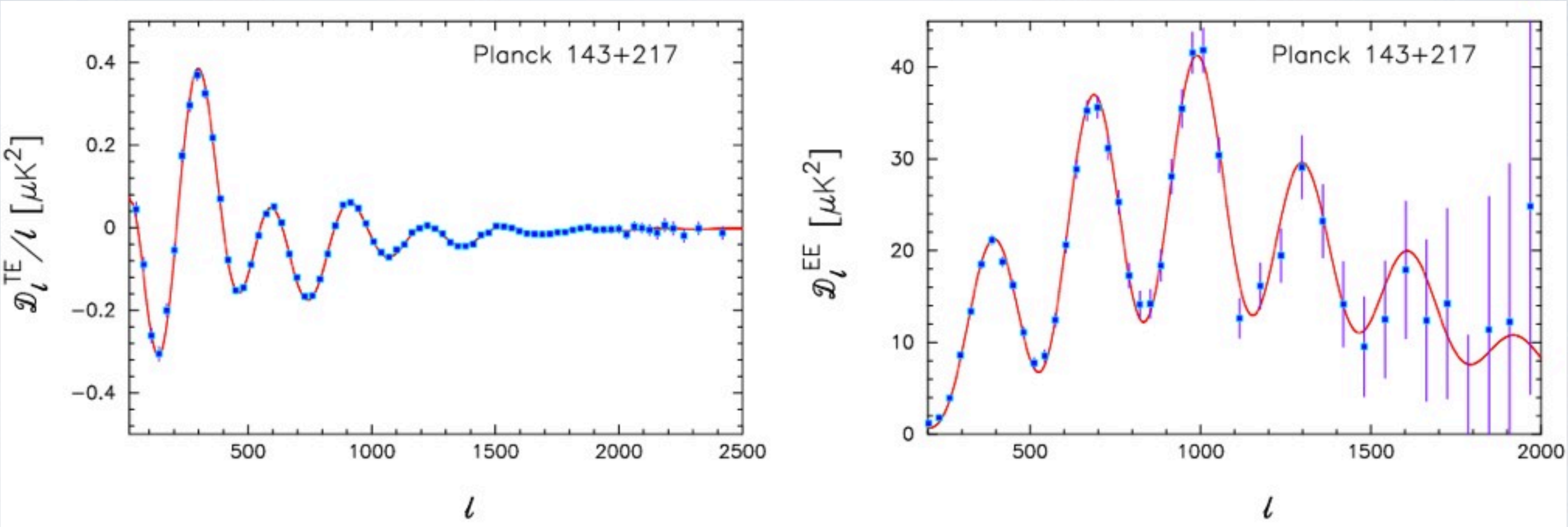
- Other unknown sources.



New window into Gravitational Waves



Prospects with PLANCK polarization measurements.

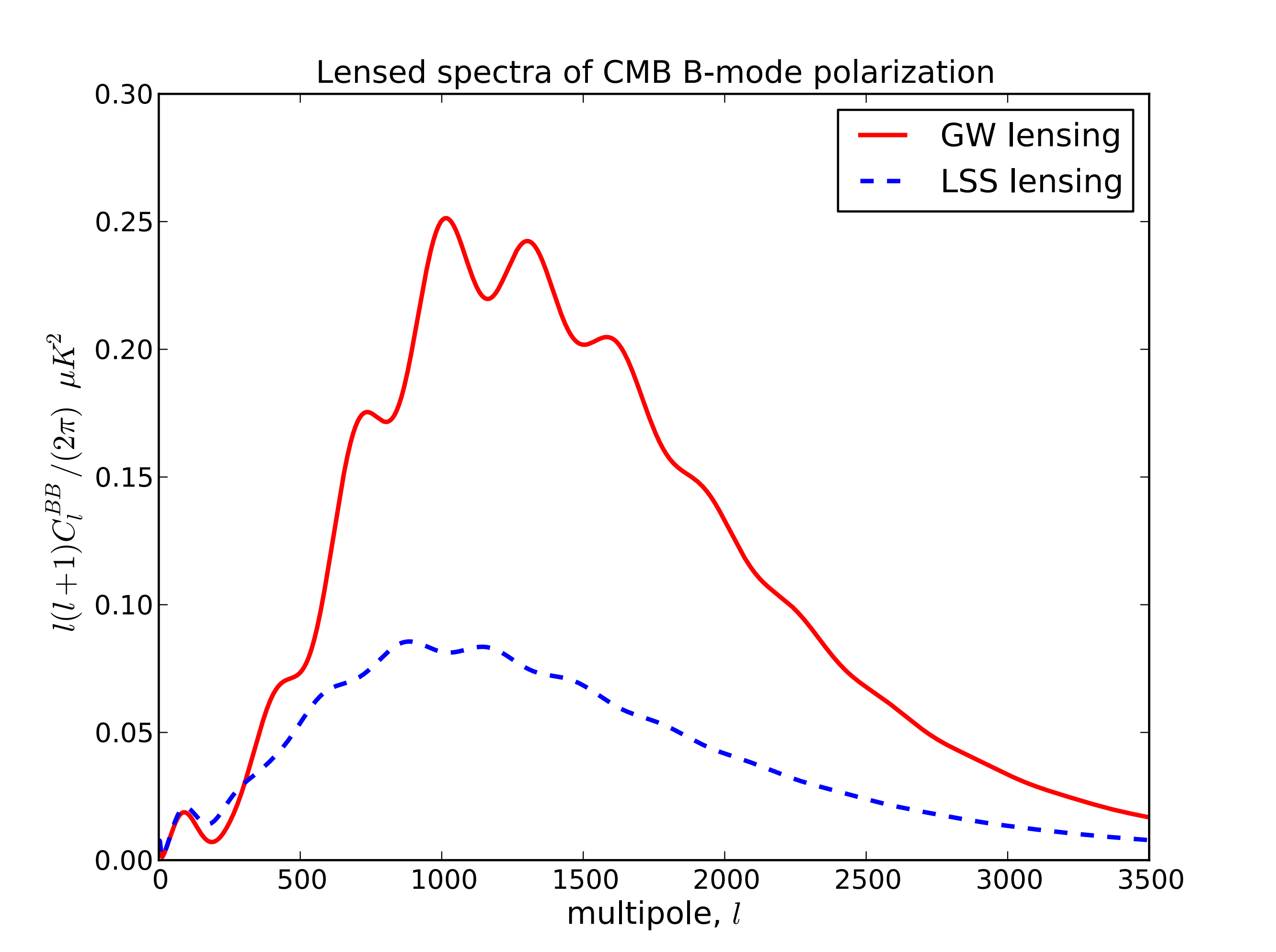


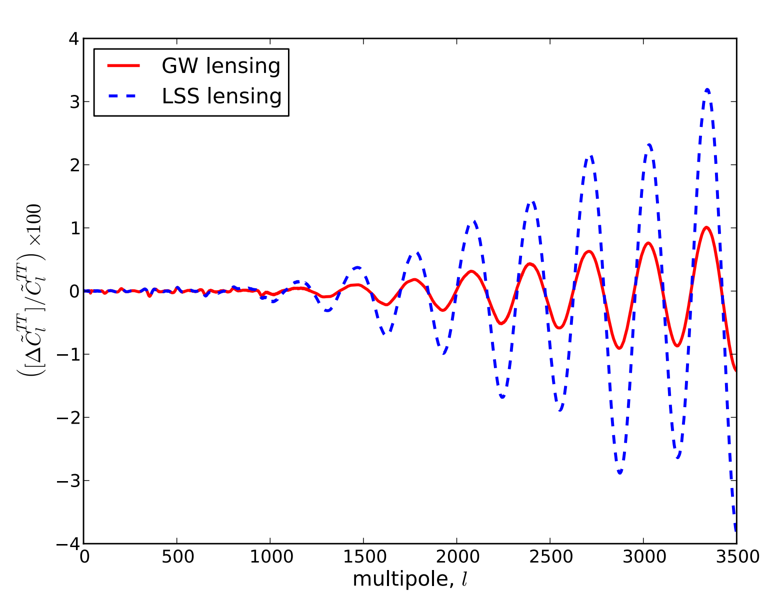
Weak lensing efficiency GW vs LSS

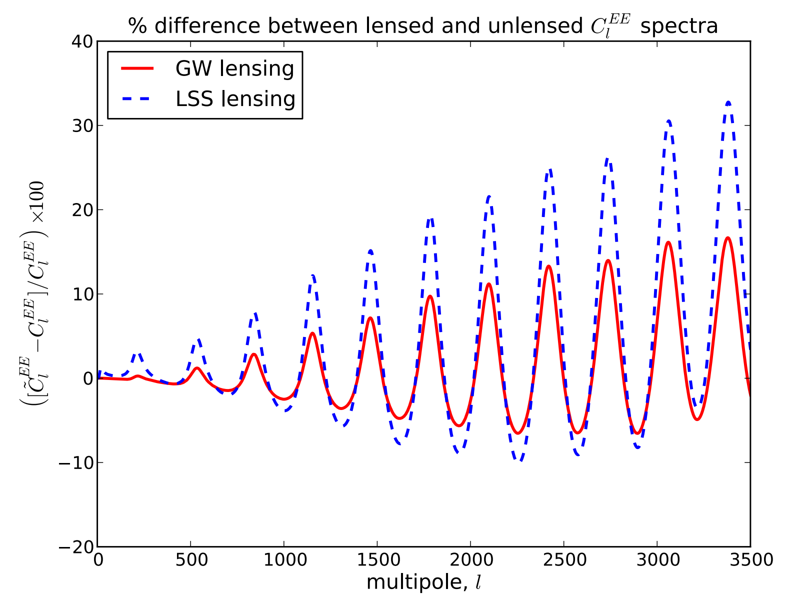
Lensing modifications to CMB spectra.

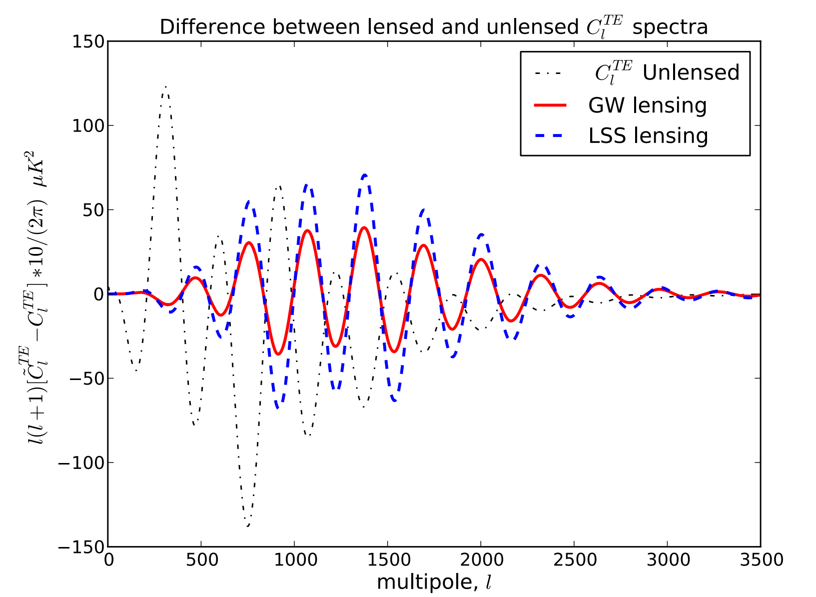
$$\begin{pmatrix} \tilde{C}_l^{TT} \\ \tilde{C}_l^{EE} \\ \tilde{C}_l^{BB} \\ \tilde{C}_l^{TE} \end{pmatrix} = \begin{pmatrix} A_{11} & 0 & 0 & 0 \\ 0 & A_{22} & A_{23} & 0 \\ 0 & A_{32} & A_{33} & 0 \\ 0 & 0 & 0 & A_{44} \end{pmatrix} \begin{pmatrix} C_l^{TT} \\ C_l^{EE} \\ C_l^{BB} \\ C_l^{TE} \end{pmatrix}$$

Lensing by gravitational waves generates more B-mode of CMB polarization.

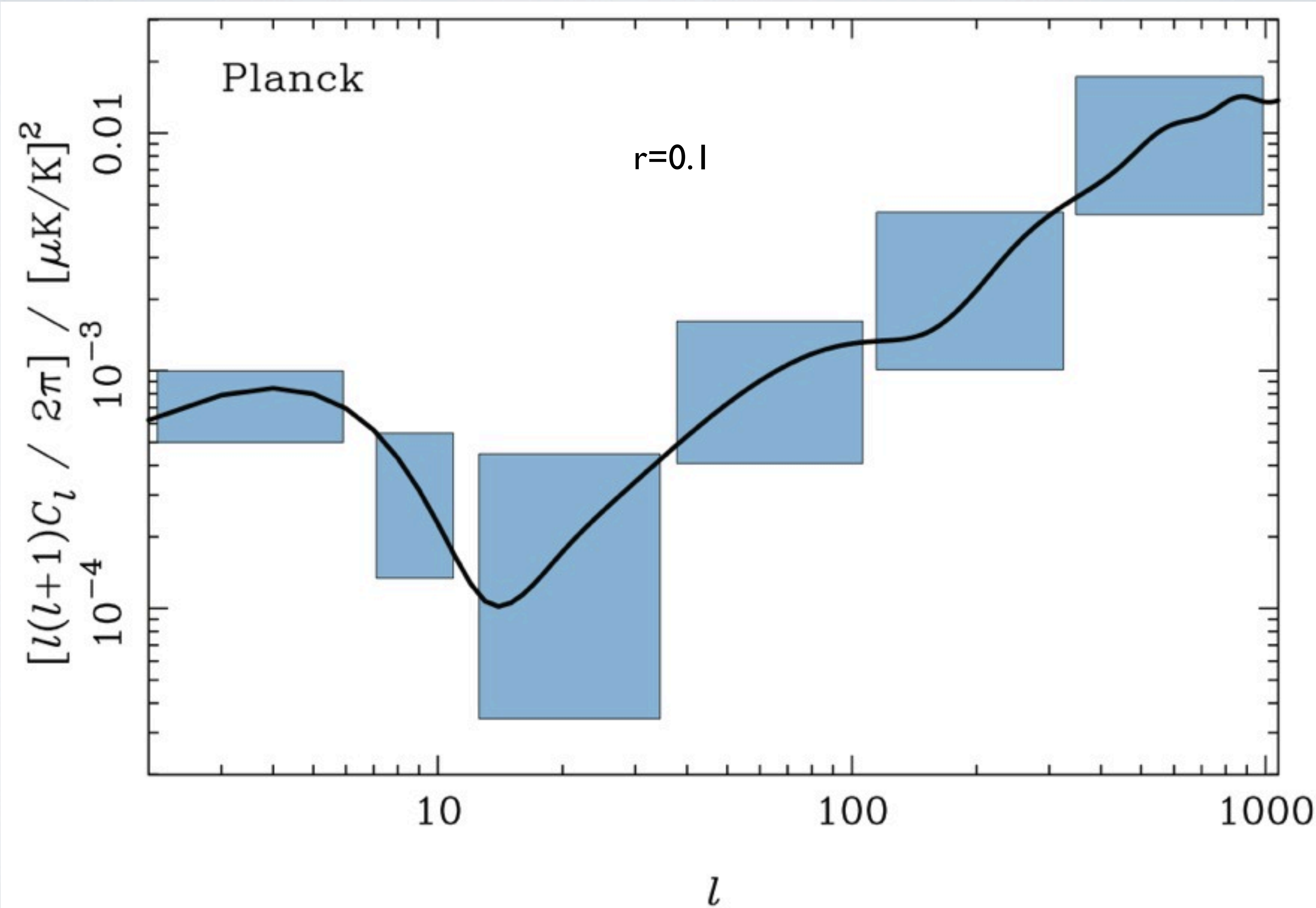




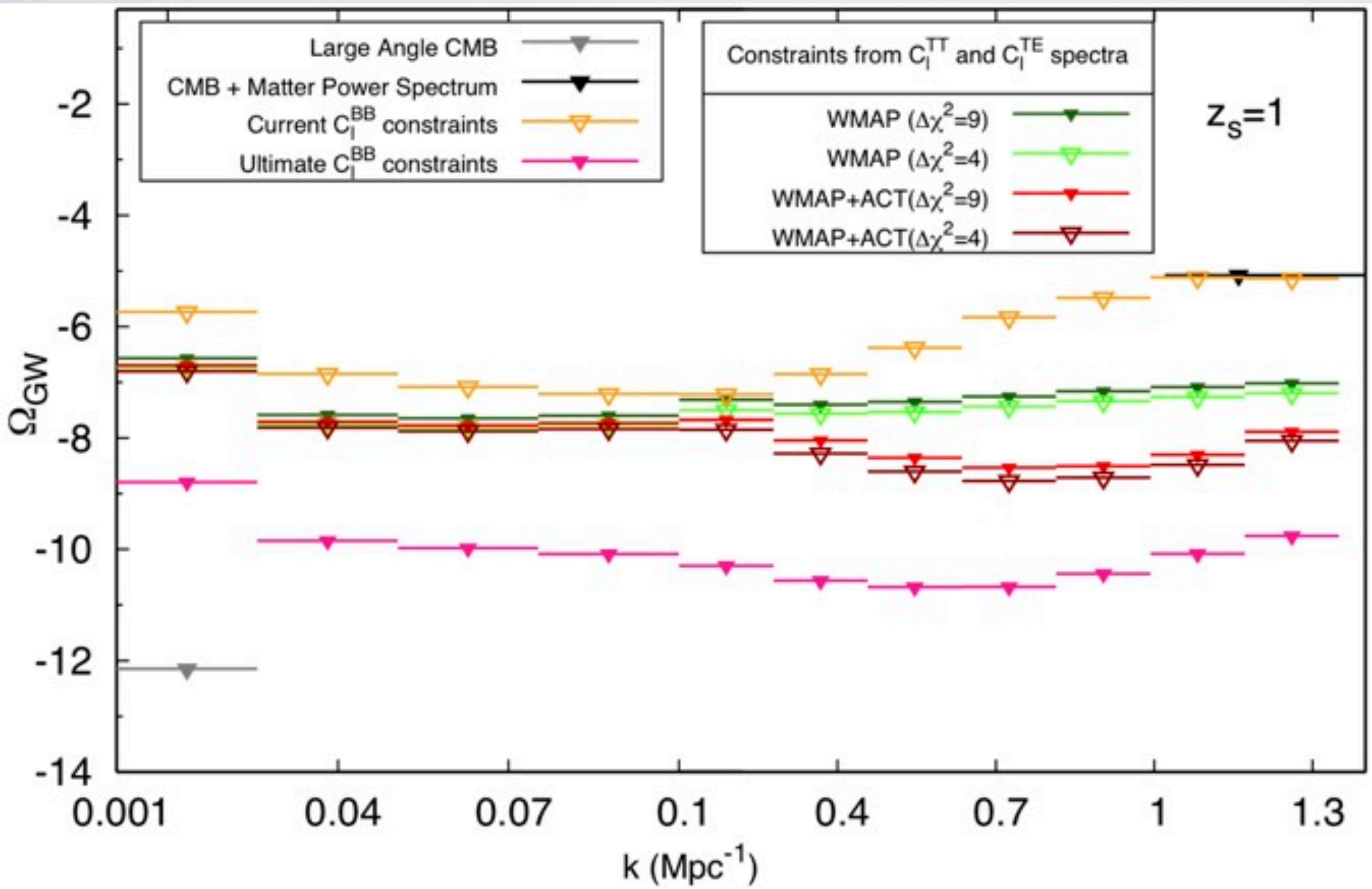




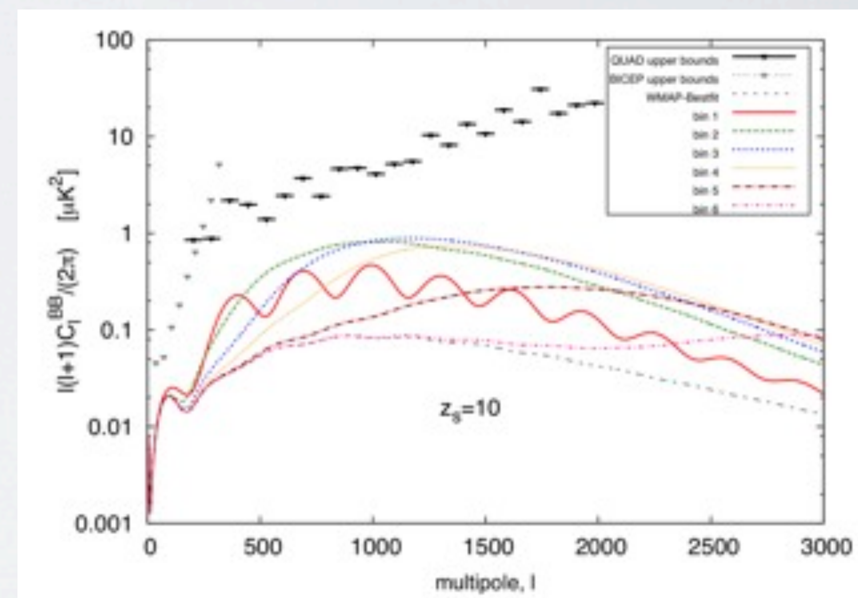
B-mode forecast for PLANCK



Constraints on GW energy densities



Current best constraints on B-mode of CMB polarization are from BICEP and QUAD.



A. Rotti & T. Souradeep. Phys. Rev. Lett. 109, 221301 (2012)