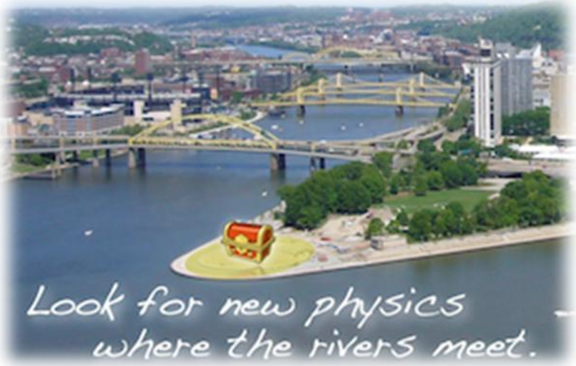
Phenomenology 2013
Symposium

University of Pittsburgh



Digging for inflation fossils in the cosmic microwave background

Liang Dai

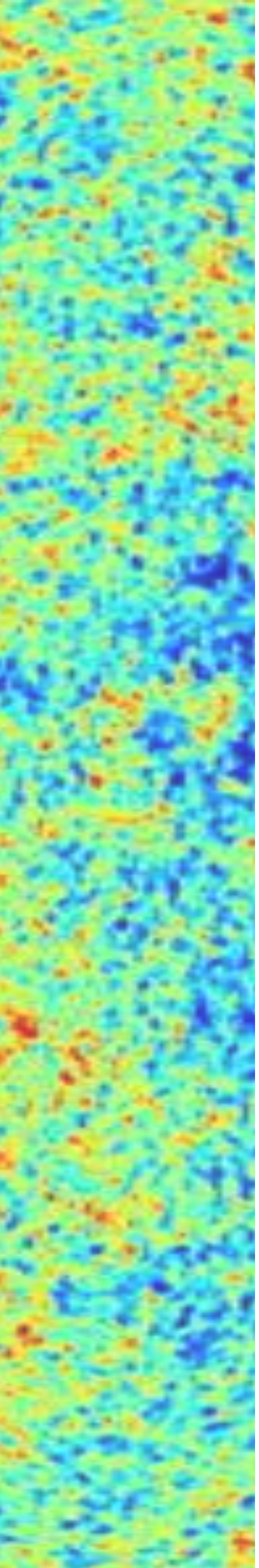
arXiv:1302.1868

with Donghui Jeong and Marc Kamionkowski

Johns Hopkins University

Outline

- Motivation: inflation and inflation fossils
- Fossil signatures in CMB
- Numerical results: prospects for detection
- Summary



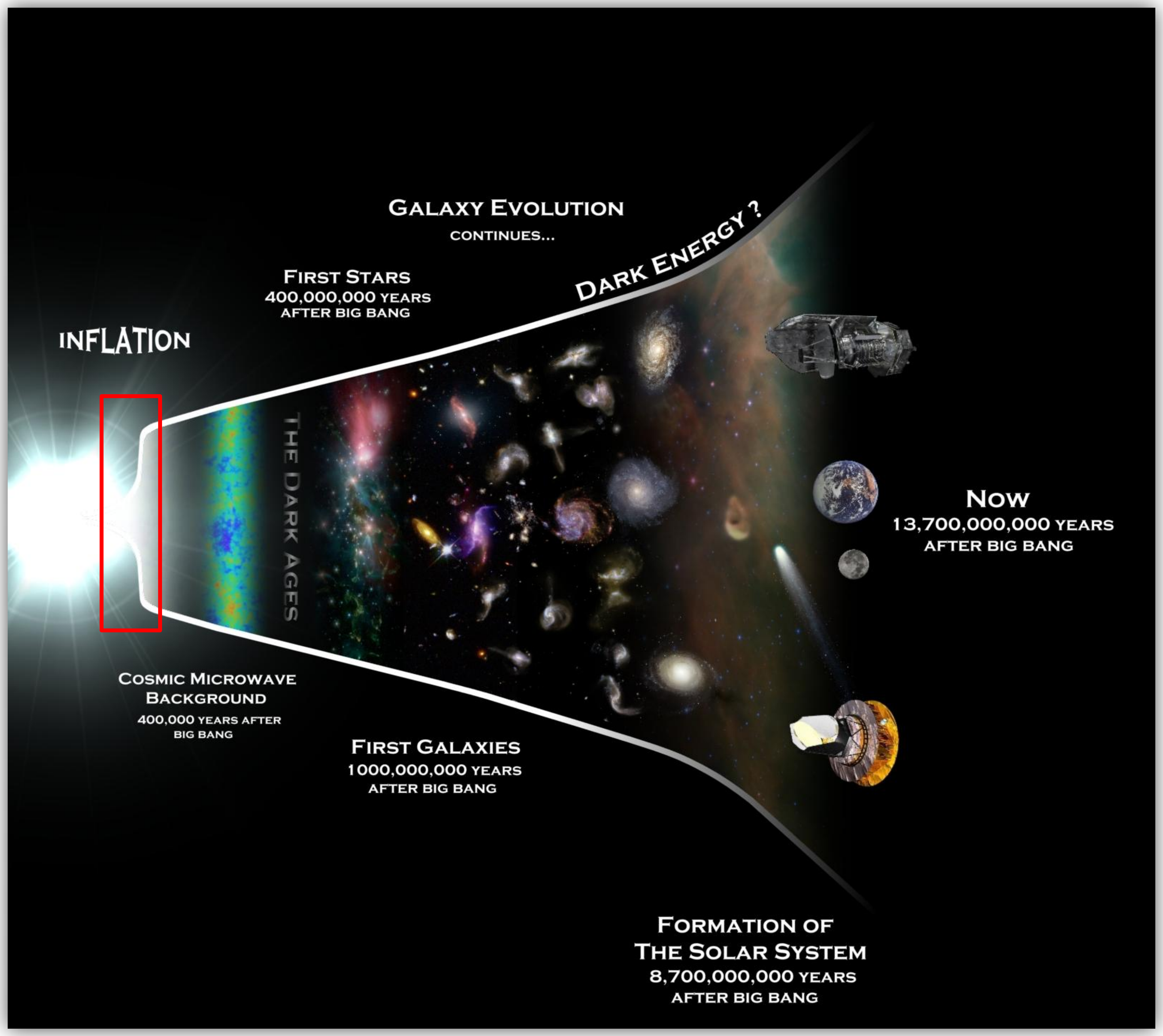
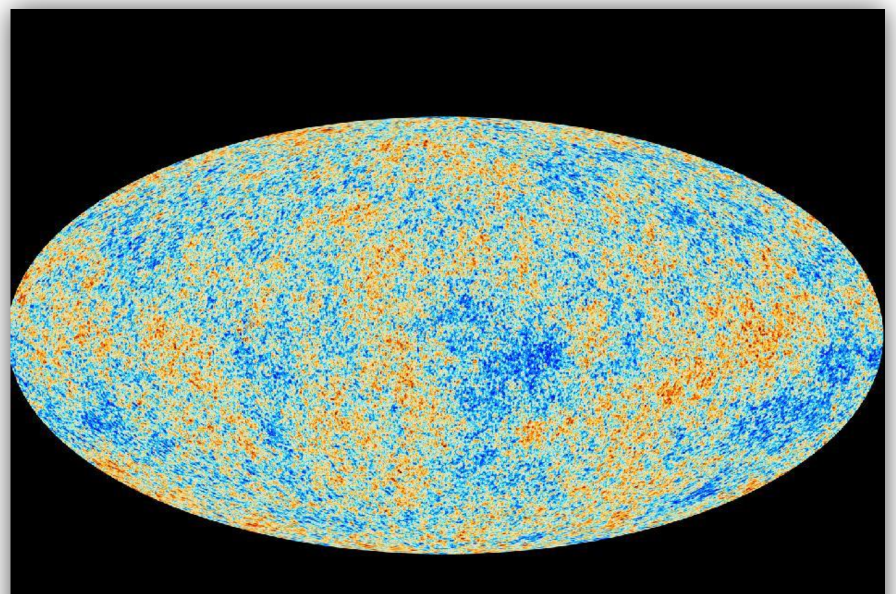
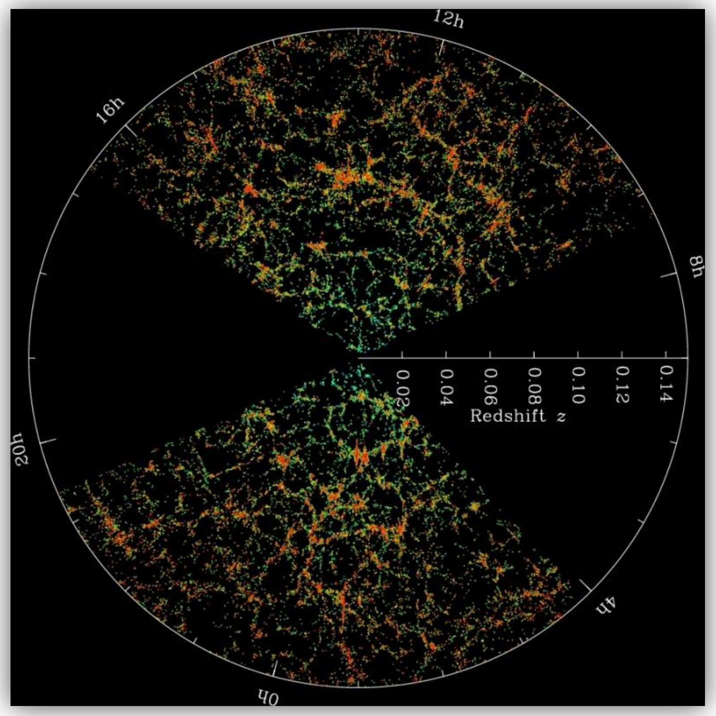


Image credit: Rhys Taylor, Cardiff University.

Inflation produces the right initial conditions


ESA and the Planck Collaboration



From M. Blanton, SDSS

adiabatic

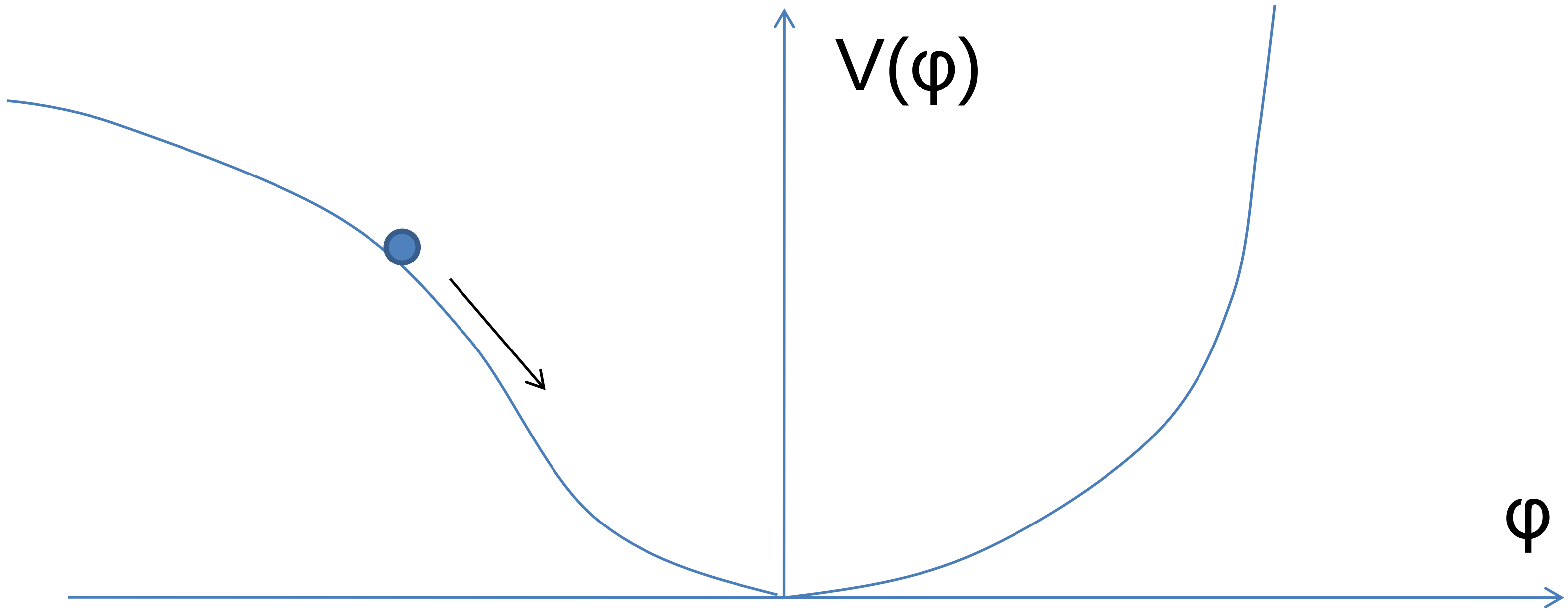
gaussian

scale-invariant

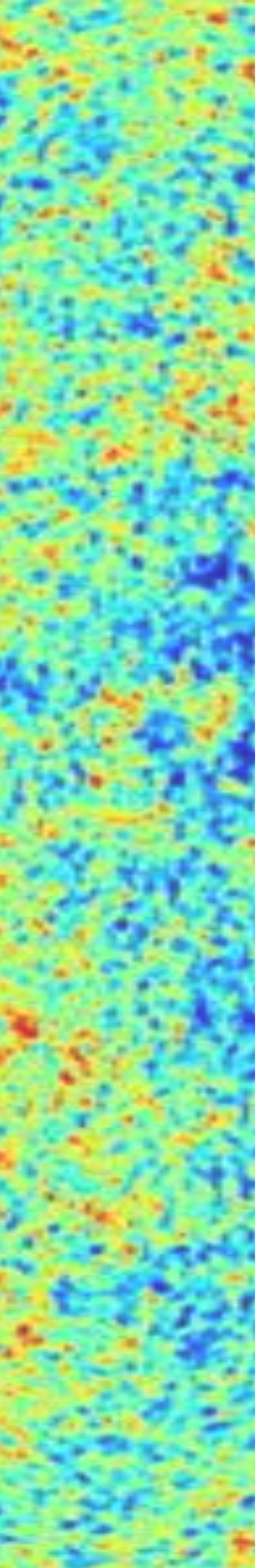
Subhorizon, microscopic,
quantum fluctuations

superhorizon, macroscopic,
classical perturbations

The simplest model works !



Single-field slow-roll can fit the observational data really well !



But what's the physical origin of inflation?

Encyclopaedia Inflationaris

Jerome Martin, Christophe Ringeval, Vincent Vennin

(Submitted on 15 Mar 2013)

The current flow of high accuracy astrophysical data, among which are the Cosmic Microwave Background (CMB) measurements by the Planck satellite, offers an unprecedented opportunity to constrain the inflationary theory. This is however a challenging project given the size of the inflationary landscape which contains hundreds of different scenarios. A reasonable approach is to consider the simplest models first, namely the slow-roll single field models with minimal kinetic terms, unless the data drive us to more complicated ones. This still leaves us with a very populated landscape, the exploration of which requires new and efficient strategies. It has been customary to tackle

How can we test/distinguish between those scenarios?

Scrutinize the initial conditions !

- **perfectly Gaussian or non-Gaussian?**
- **adiabatic or entropic?**
- **statistically isotropic or anisotropic?**
- **scale-dependent features?**

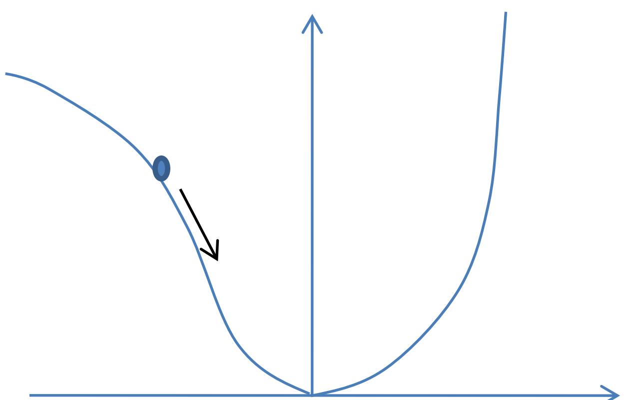
Higher order correlation functions contain rich information, e.g. 3-pts and 4-pts functions.

New fields might contribute to a non-trivial initial condition !

inflation fossils:

- have interacted with the inflaton
- “invisible” after inflation

Possible examples



Tensor fossil:
gravitational waves

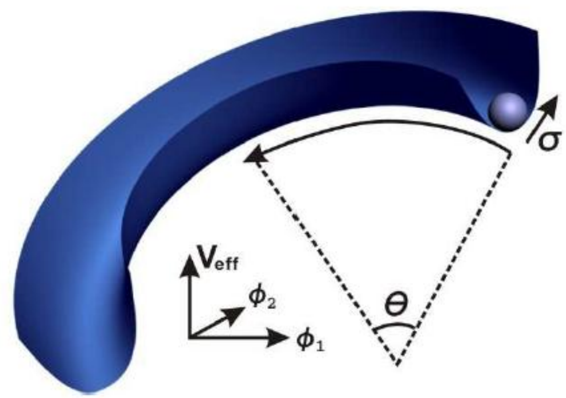
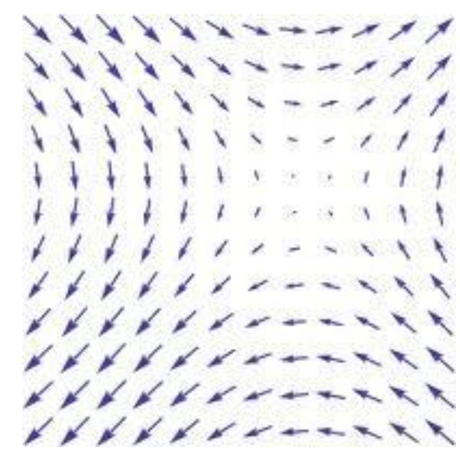


image credit:
X. Chen & Y. Wang

Scalar fossil:
Multi-field
Quasi-single field
Curvaton, etc…

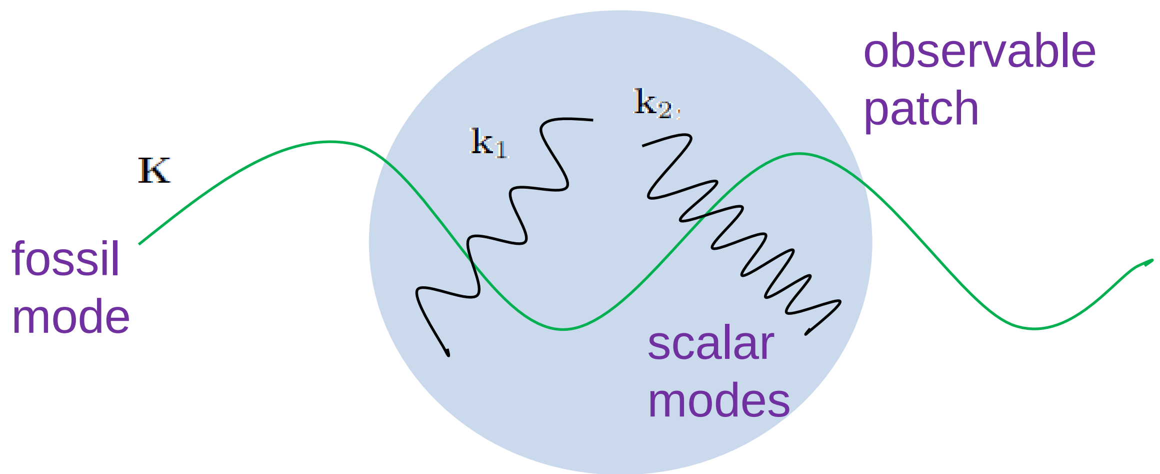


vector fossil:
Primordial magnetic field,
Modified gravity,
Vector-field driven inflation
etc…

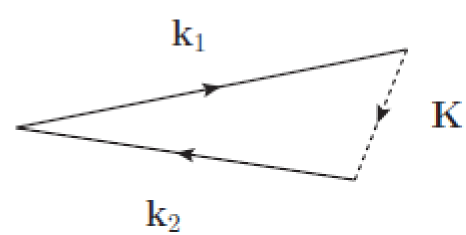
Generic imprints of inflation fossils

Primordial scalar-scalar-fossil bispectrum

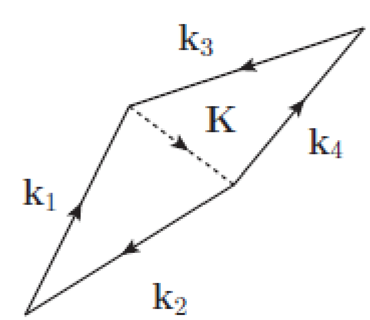
$$\langle \Phi(\mathbf{k}_1)\, \Phi(\mathbf{k}_2)\, h^p(\mathbf{K}) \rangle = (2\pi)^3\, \delta_D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{K})\, B_{\Phi\Phi h}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{K}, \epsilon^p(\mathbf{K}))$$



Fixed fossil configuration → off-diagonal two-scalar correlation



Stochastic fossil background→ connected four-scalar correlation



A parameterizaton for fossils

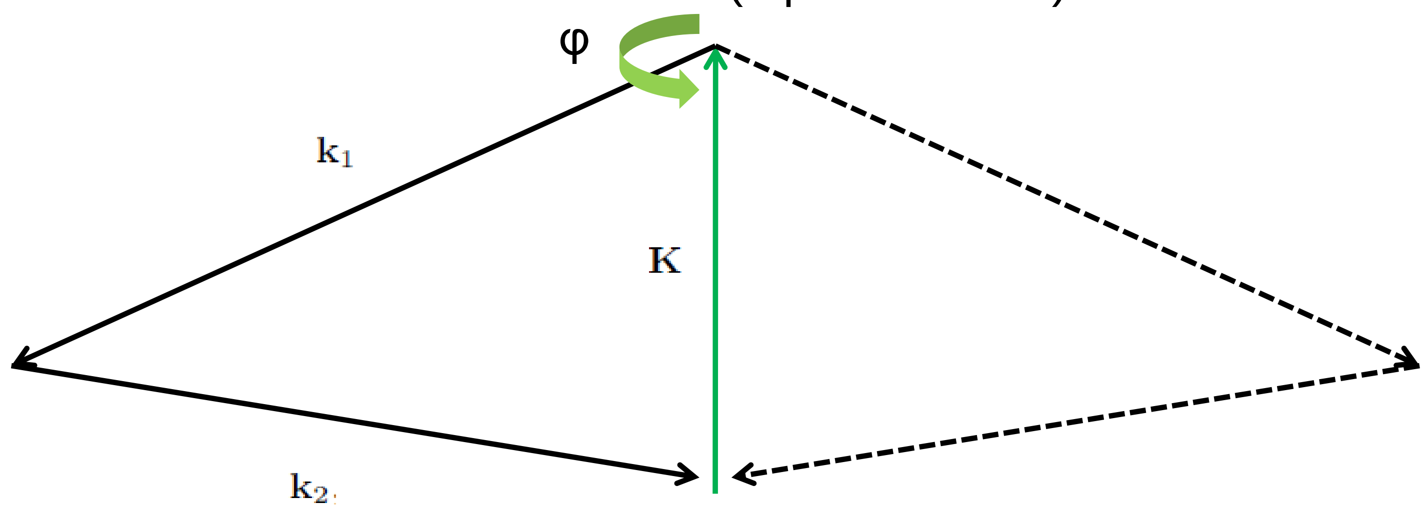
Generic effect of a primordial scalar-scalar-fossil correlation

Described by a three-by–three symmetric tensor (Jeong & Kamionkowski 12')

$$
\begin{aligned}
\langle \Phi(\mathbf{k}_1)\,\Phi(\mathbf{k}_2)\rangle_{h^p(\mathbf{K})} &= (2\pi)^3\,\delta_D(\mathbf{k}_1+\mathbf{k}_2)\,P_\Phi(k_1) \\
&\quad + (2\pi)^3\,\delta_D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{K})\,f_h^p(k_1,k_2,K)\,[h^p(\mathbf{K})]^*\,\epsilon^p_{ij}(\mathbf{K})\,\hat{k}_1^a\hat{k}_2^b
\end{aligned}
$$

Symmetric polarization tensor **ε(K)** encodes:

- 2 scalars (trace + longitudinal)
- 1 transverse vector (2 polarizations)
- 1 transverse traceless tensor (2 polarizations)

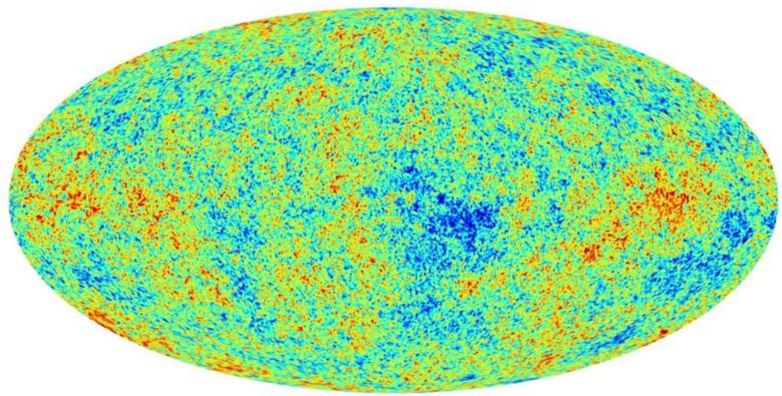


Distinguish spin via the azimuthal dependence from galaxy clustering surveys (Jeong & Kamionkowski 12')

Outline

- ✓ Motivation: inflation and inflation fossils
- ☐ Fossil signatures in CMB
- ☐ Numerical results: prospects for detection
- ☐ Summary

Fossils also leave signature in the CMB



Φ sources temperature anisotropies

$$\frac{\delta T}{T_0}(\hat{n}) = \sum_{lm} a^T_{lm} Y_{(lm)}(\hat{n})$$

$$a^T_{lm} = \frac{1}{2\pi^2}(-i)^l \int k^2 dk g^T_l(k) \Phi_{lm}(k)$$

Given a **fixed** realization of a fossil field:

Off-diagonal correlations for **Φ**
(violation of **statistical homogeneity**)

$$\langle \Phi(\mathbf{k}_1)\, \Phi(\mathbf{k}_2) \rangle_{h^p(\mathbf{K})} = (2\pi)^3 \delta_D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{K})\, f^p_h(k_1, k_2, K)\, [h^p(\mathbf{K})]^* \epsilon^p_{ij}(\mathbf{K})\, \hat{k}^a_1 \hat{k}^b_2$$

Off-diagonal correlations for CMB temperature multipoles
(violation of **statistical isotropy**)

$$\langle a^T_{l_1 m_1} a^{T*}_{l_2 m_2} \rangle_h \neq 0, \qquad for \quad l_1 \neq l_2, m_1 \neq m_2$$

CMB bipolar spherical harmonic analysis (BiPoSH)

(Hajian, Souradeep and Cornish 04')

General two-point correlation on the sky

$$\boxed{A^{JM}_{l_1 l_2}} = (-1)^{l_1+l_2+M}\sqrt{2J+1} \times \sum_{m_1 m_2} (-1)^{m_2} \mathcal{W}^{l_1 l_2 J}_{m_1,-m_2,-M} \left\langle a^T_{l_1 m_1} a^{T*}_{l_2 m_2} \right\rangle_h$$

- BiPoSH multipole **J,M** → angular scale of the variation of statistics
- power multipoles **l_1,l_2** → angular scale of fluctuations

Even-parity BiPoSHs **$l_1 + l_2 + J$ = even** can be induced by

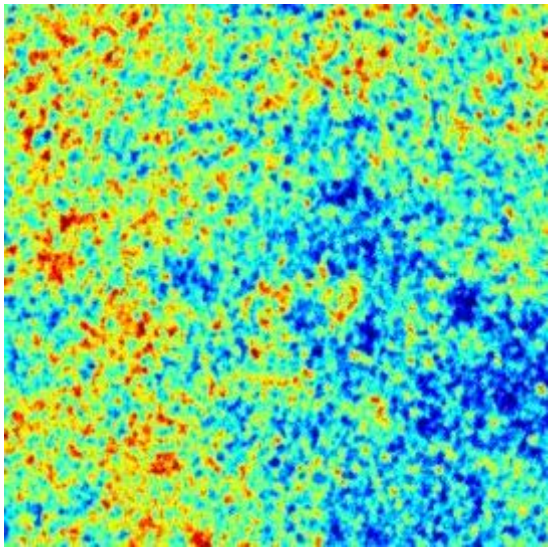
- scalar fossils
- E-type spherical modes of vector fossils
- E-type spherical modes of tensor fossils

Odd-parity BiPoSHs **$l_1 + l_2 + J$ = odd** can only be induced by

- B-type spherical modes of vector fossils
- B-type spherical modes of tensor fossils ⬅ **Probe fossils with higher spins**

Meaning of BiPoSHs in real space

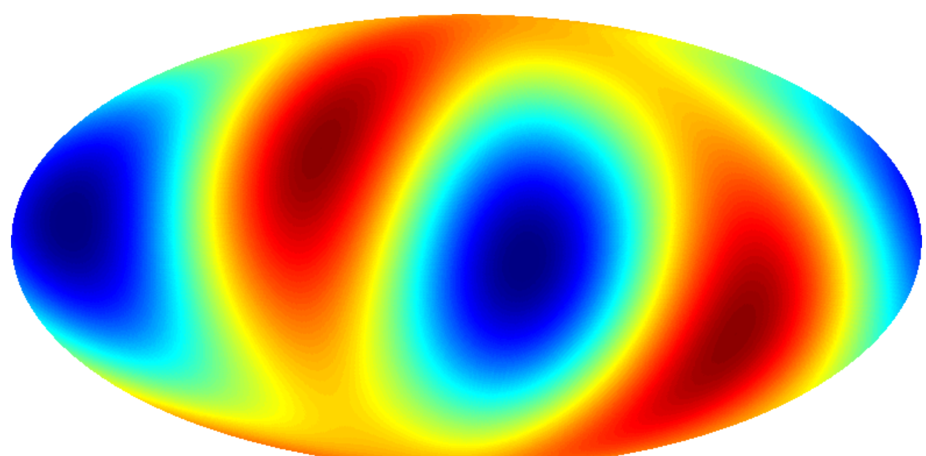
In the limit $J << l_1, l_2$:
Modulations of small scale anisotropies



hot/cold contrast

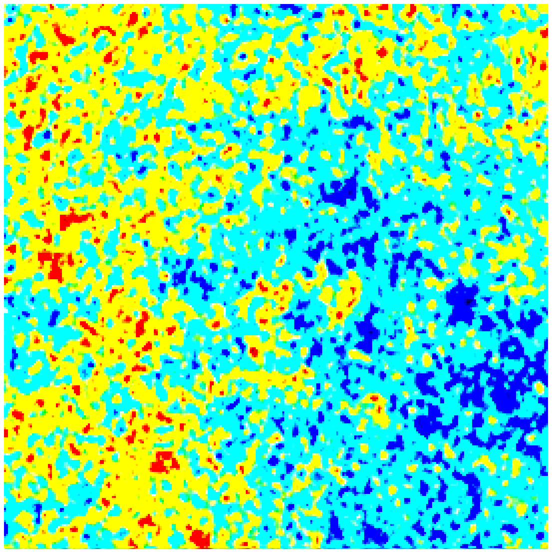
Distortions are modulated over large angular scales characterized by **J,M**

Example:
quadrupolar BiPoSH



Meaning of BiPoSHs in real space

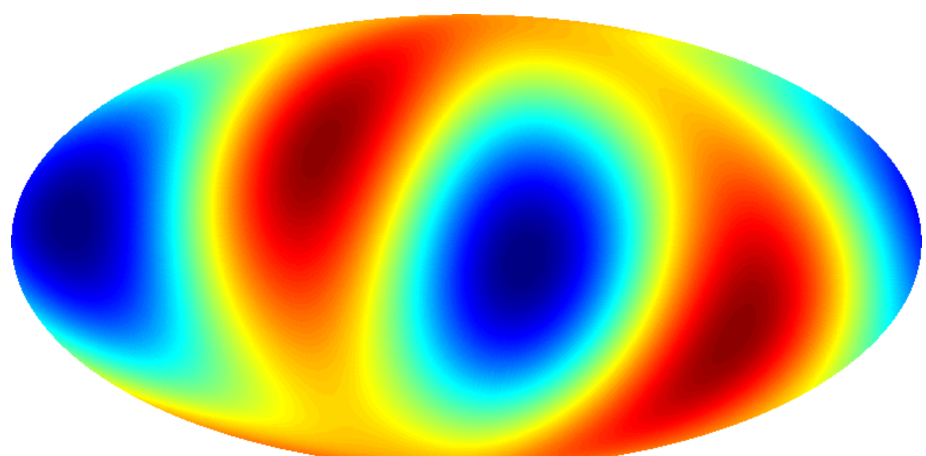
In the limit $J << l_1, l_2$:
Modulations of small scale anisotropies



hot/cold contrast

Distortions are modulated over large angular scales characterized by **J,M**

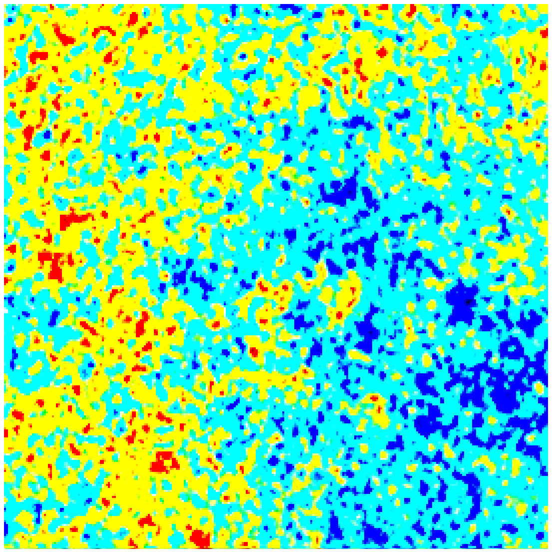
Example:
quadrupolar BiPoSH



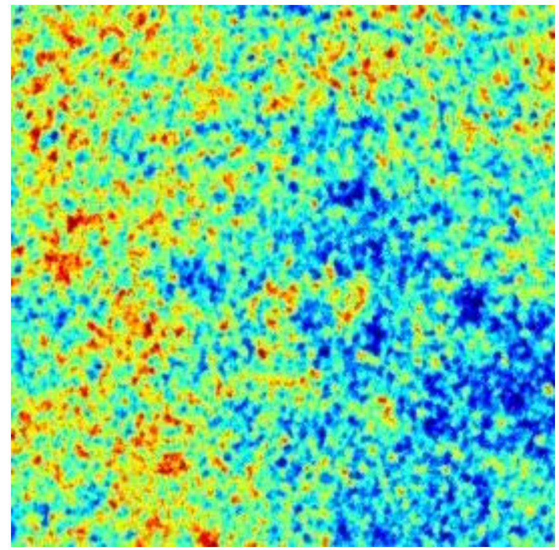
Meaning of BiPoSHs in real space

In the limit $J \ll l_1, l_2$:

Modulations of small scale anisotropies



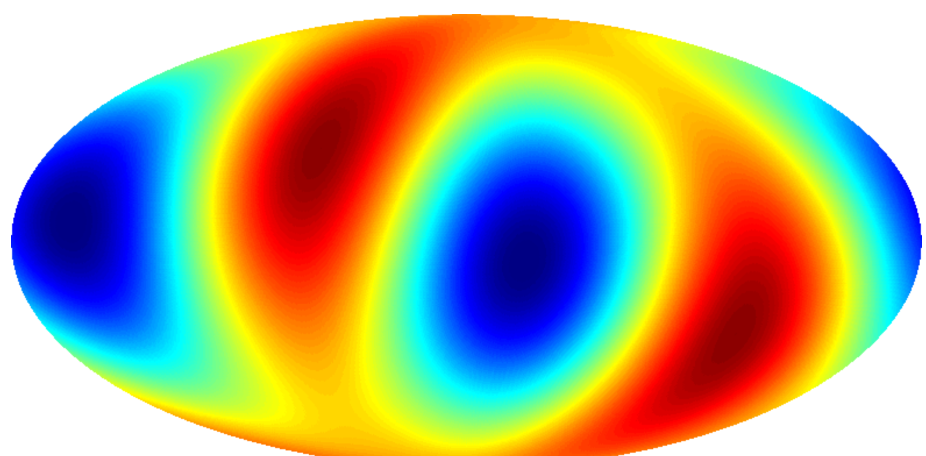
hot/cold contrast



displacement

Distortions are modulated over large angular scales characterized by **J,M**

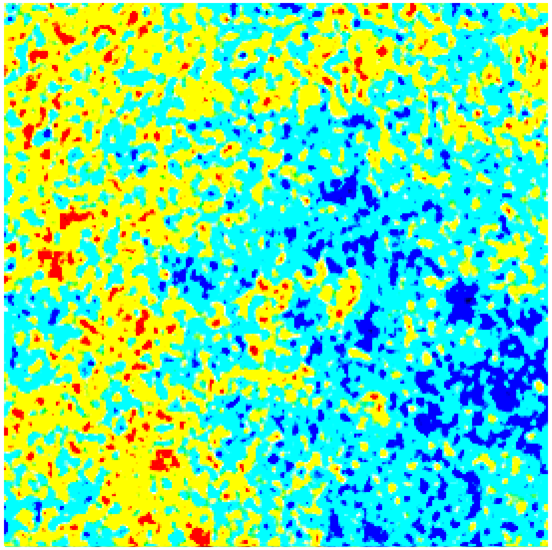
Example:
quadrupolar BiPoSH



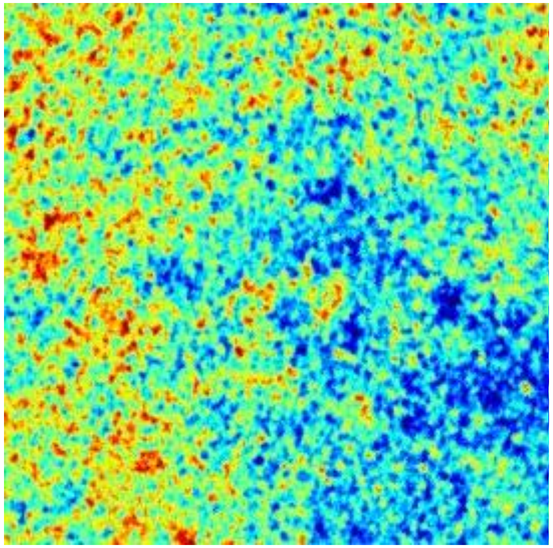
Meaning of BiPoSHs in real space

In the limit $J \ll l_1, l_2$:

Modulations of small scale anisotropies



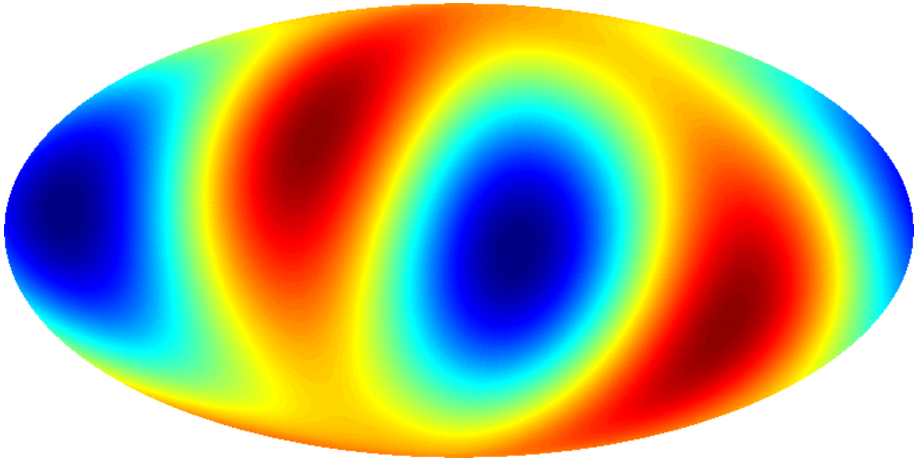
hot/cold contrast



displacement

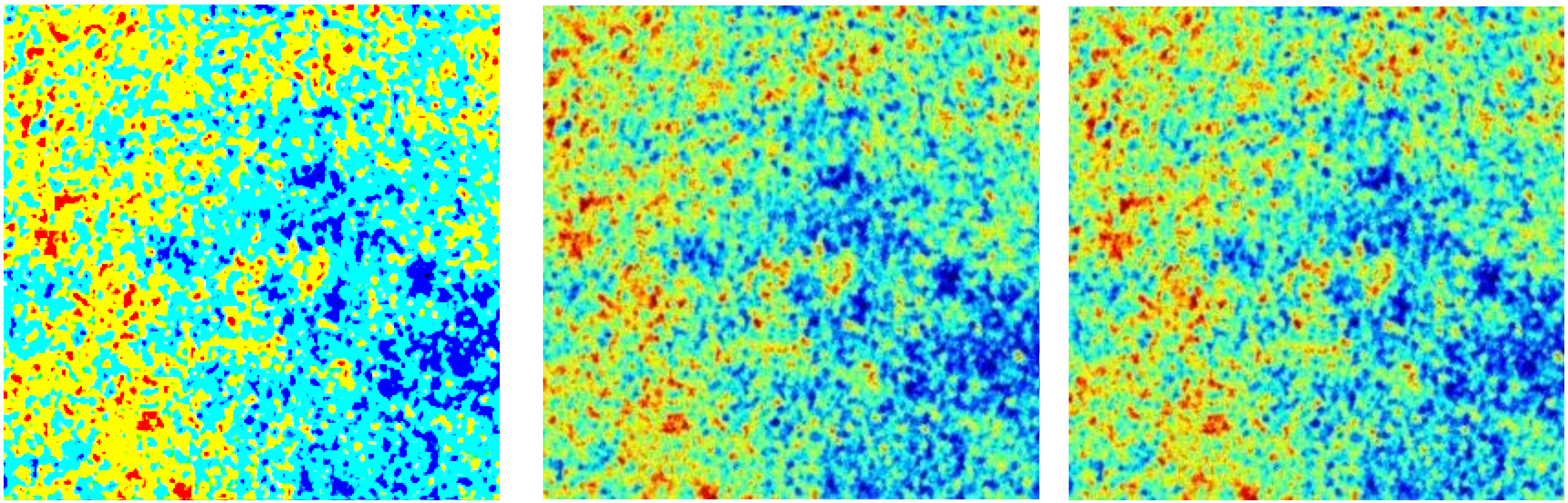
Distortions are modulated over large angular scales characterized by **J,M**

Example:
quadrupolar BiPoSH



Meaning of BiPoSHs in real space

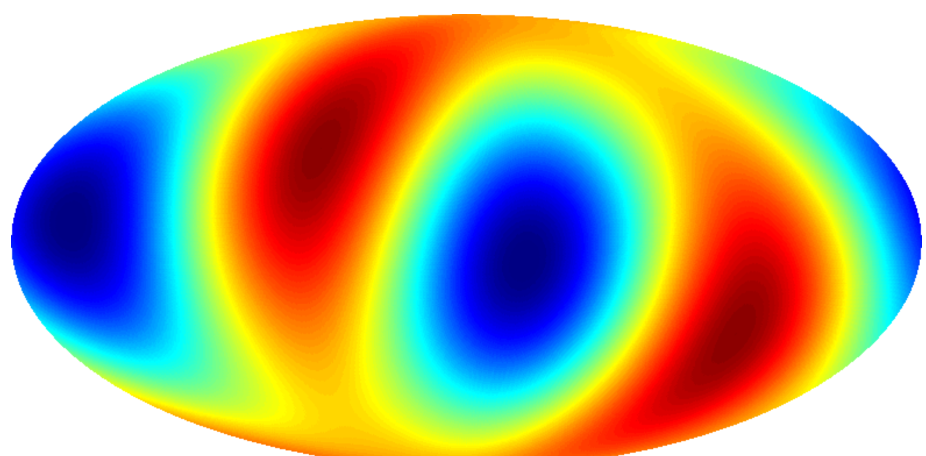
In the limit $J << l_1, l_2$:
Modulations of small scale anisotropies



hot/cold contrast   displacement   ellipticity

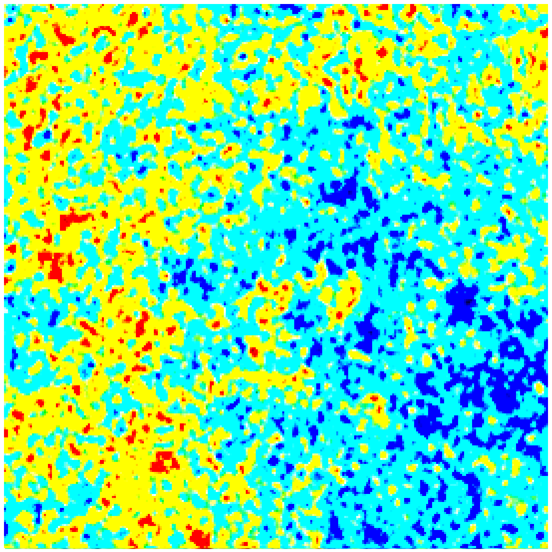
Distortions are modulated over large angular scales characterized by **J,M**

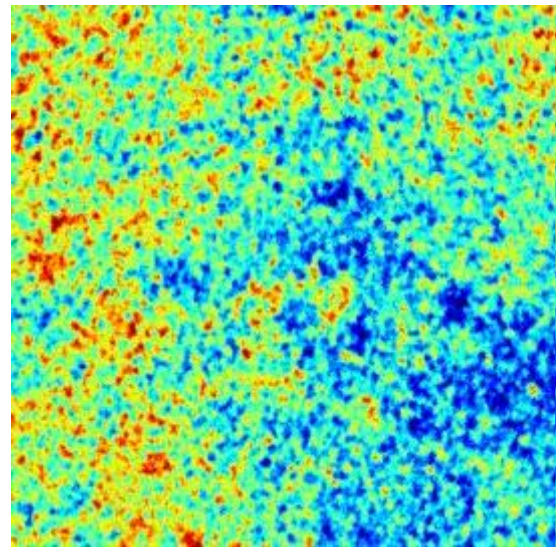
Example:
quadrupolar BiPoSH

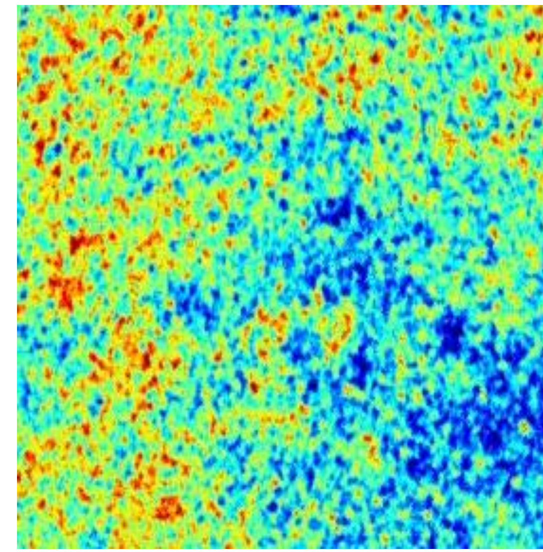


Meaning of BiPoSHs in real space

In the limit $J \ll l_1,l_2$:
Modulations of small scale anisotropies



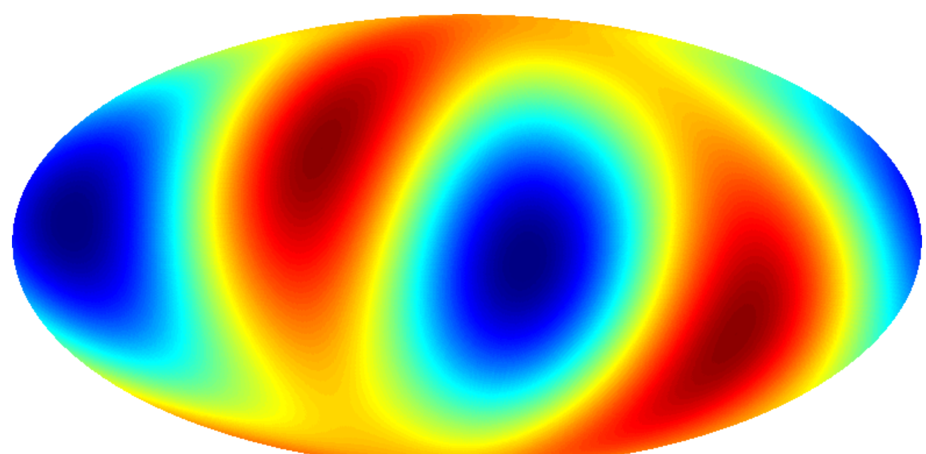




hot/cold contrast displacement ellipticity

Distortions are modulated over large angular scales characterized by **J,M**

Example:
quadrupolar BiPoSH



Bipolar power spectrum

For a **stochastic** fossil-field background, we can only predict the **variance** of BiPoSHs

$$C^{J}_{l_1 l_2, l_3 l_4} = \frac{1}{2J+1} \left\langle \sum_{M=-J}^{J} A^{JM}_{l_1 l_2} \left[A^{JM}_{l_3 l_4} \right]^* \right\rangle$$

Assume fiducial forms for fossil power spectrum and scalar-scalar-fossil bispectrum

$$P_h^Z(K) = \mathcal{P}_h^Z \tilde{P}_h^Z(K) \qquad f_h^Z(k_1, k_2, K) = \mathcal{B}_h^Z \tilde{f}_h^Z(k_1, k_2, K).$$

$$C^{J}_{l_1 l_2, l_3 l_4} = \mathcal{A}_h^Z \mathcal{F}^{J,Z}_{l_1 l_2, l_3 l_4}$$

We can measure the reduced fossil amplitude $\mathcal{A}_h^Z = \mathcal{P}_h^Z \left(\mathcal{B}_h^Z \right)^2$

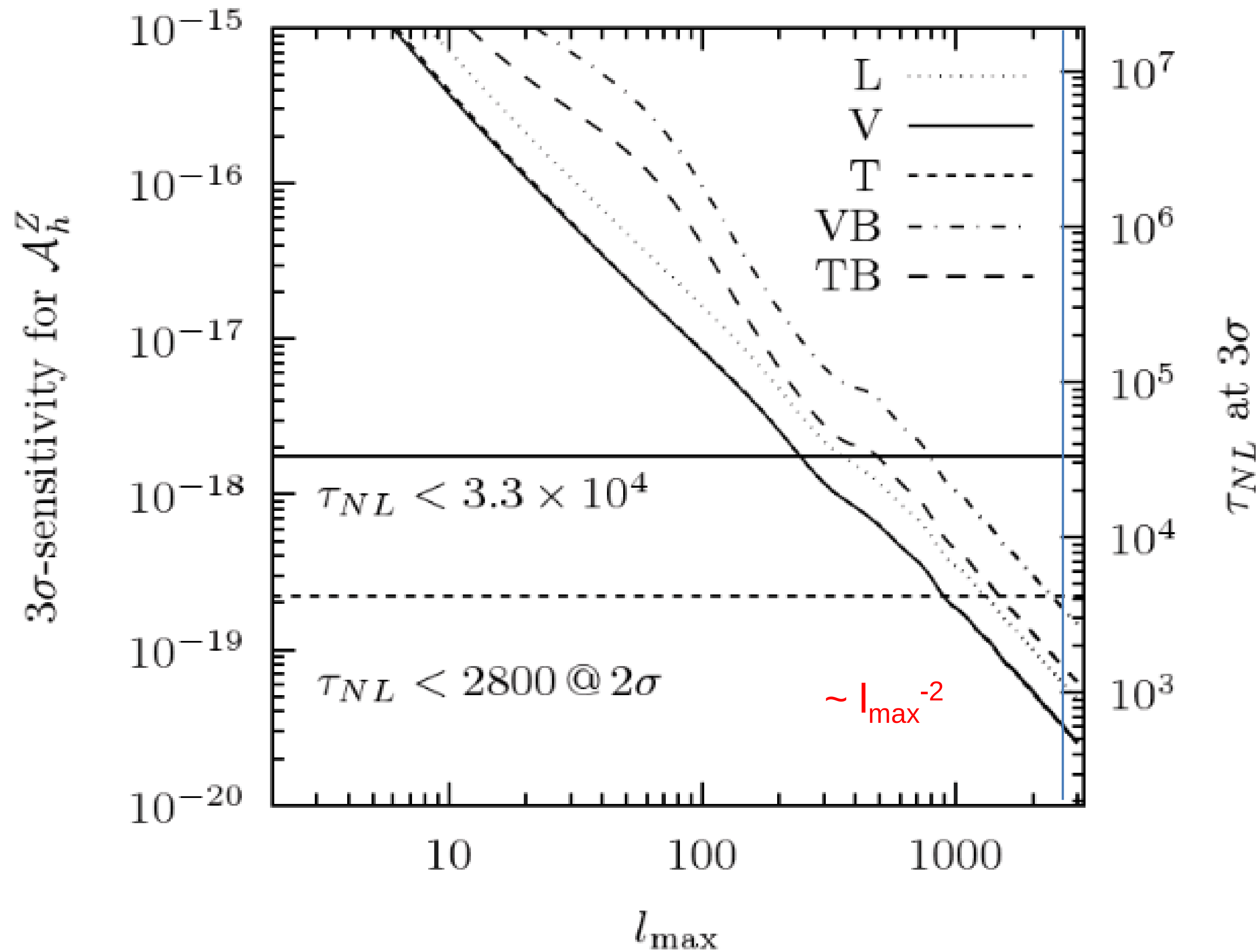
Outline

- ✓ Motivation: what are inflation fossils?
- ✓ Fossil signatures in CMB: bipolar power spectrum
- ☐ Numerical results: prospects for detection
- ☐ Summary

Cumulative sensitivity

Local-type bispectrum: $\tilde{f}_h^Z(k_1, k_2, K) = 1/(k_1 k_2)^{3/2}$

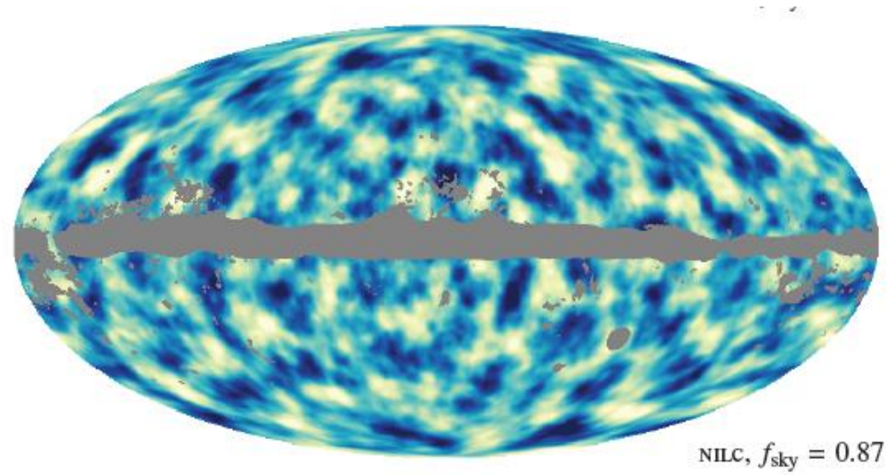
Scale-free fossil power spectrum: $\tilde{P}_h^Z(K) = 1/K^3$



Degeneracy with lensing?

Lensing by potential does not induce odd-parity BiPoSHs

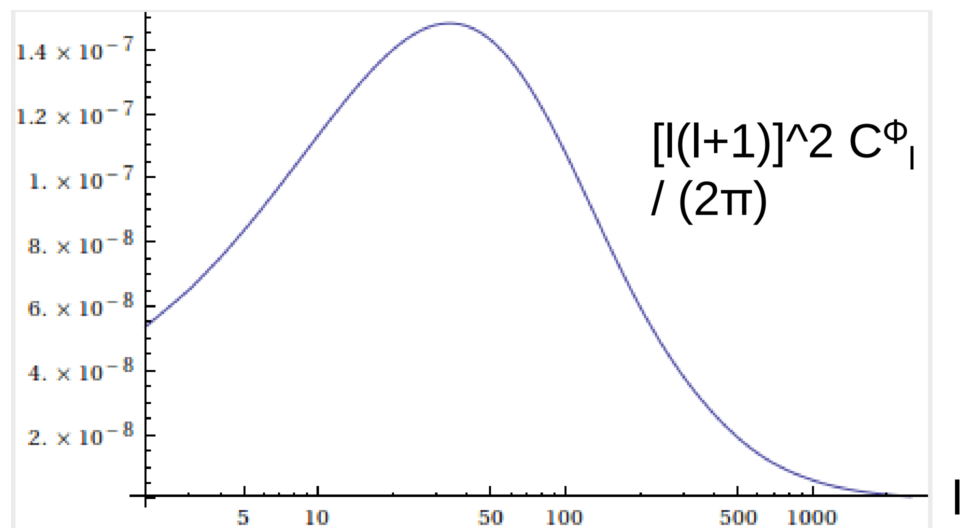
Lensing induces B-mode polarization, while fossil does not



Planck's lensing map

Lensing BiPoSHs peaks at J~50.

Local-type fossil BiPoSH is dominated by J~ a few



Outline

- ✓ Motivation: what are inflation fossils?
- ✓ Fossil signatures in CMB: bipolar power spectrum
- ✓ Numerical results: prospects for detection
- ☐ Summary

Summary

✓ Inflation fossils can leave observable trace through a primordial scalar-scalar-fossil bispectrum.

✓ In the CMB, inflation fossils might induce non-zero bipolar power spectrum. Particularly, odd-parity BiPoSHs are clean probes of vector/tensor fossil field.

✓ We constructed an optimal quadratic estimator for the reduced fossil amplitude, and predicted the sensitivity in a full-sky CMB experiment such as Planck. Room for detection still exists given current constraints on primordial trispectrum.

✓ Forthcoming CMB polarization data can be used to further improve the sensitivity.

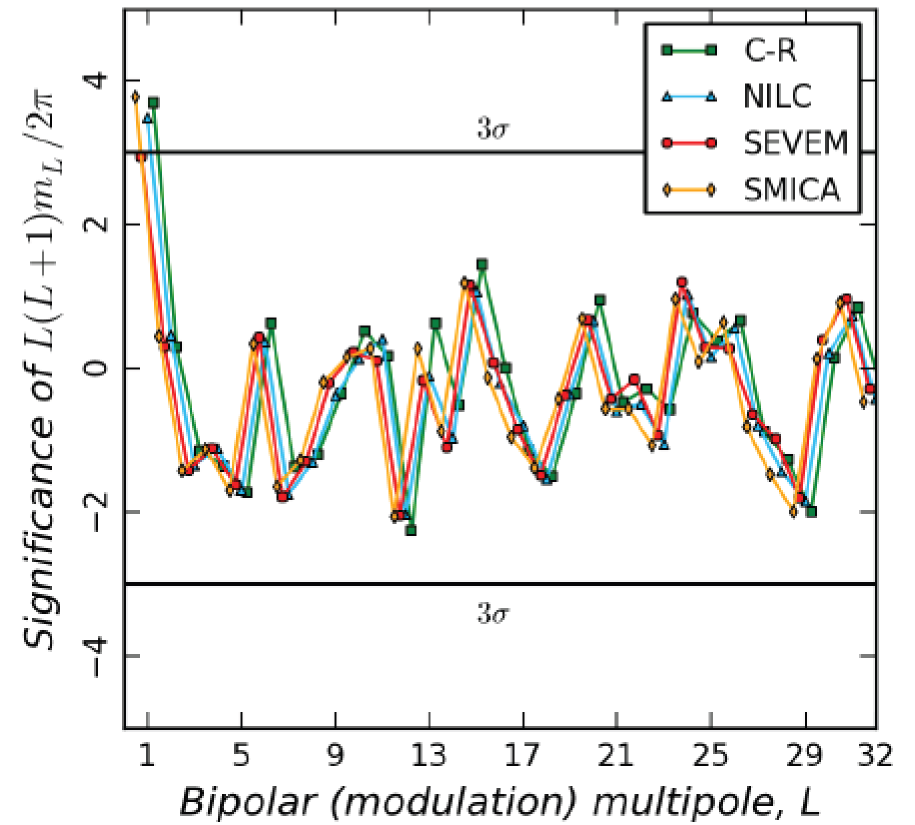
Thank you !

What does Planck say?

- Large dipolar BiPoSH confirmed! But not seeing higher-multipole BiPoSHs.

Scalar/vector fossil might explain the dipole modulation,

But probably not local type?



- Optimal estimator might be needed to reveal vector/tensor fossils.

.Call for more data analysis.

- Fossil produces primordial (scalar) trispectrum without bispectrum

$$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$$