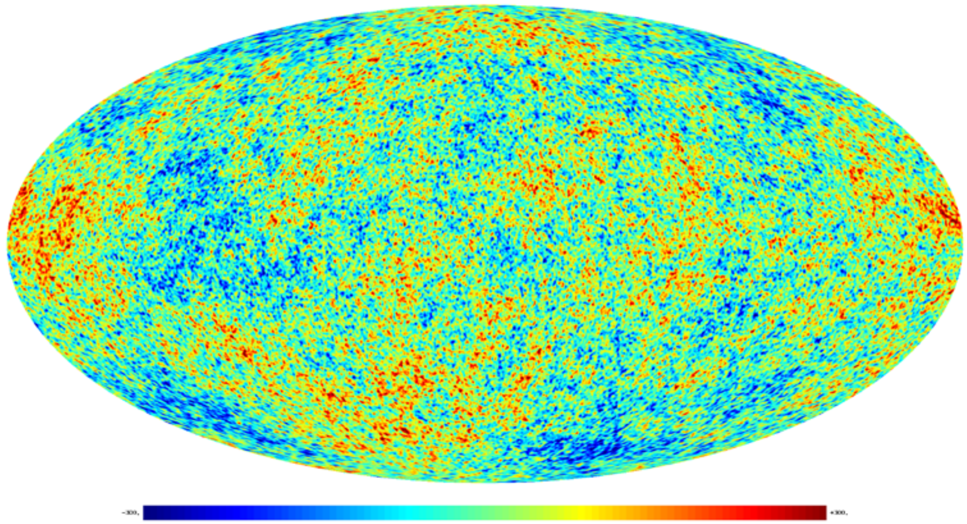


Beauty and Blemishes in the Universe

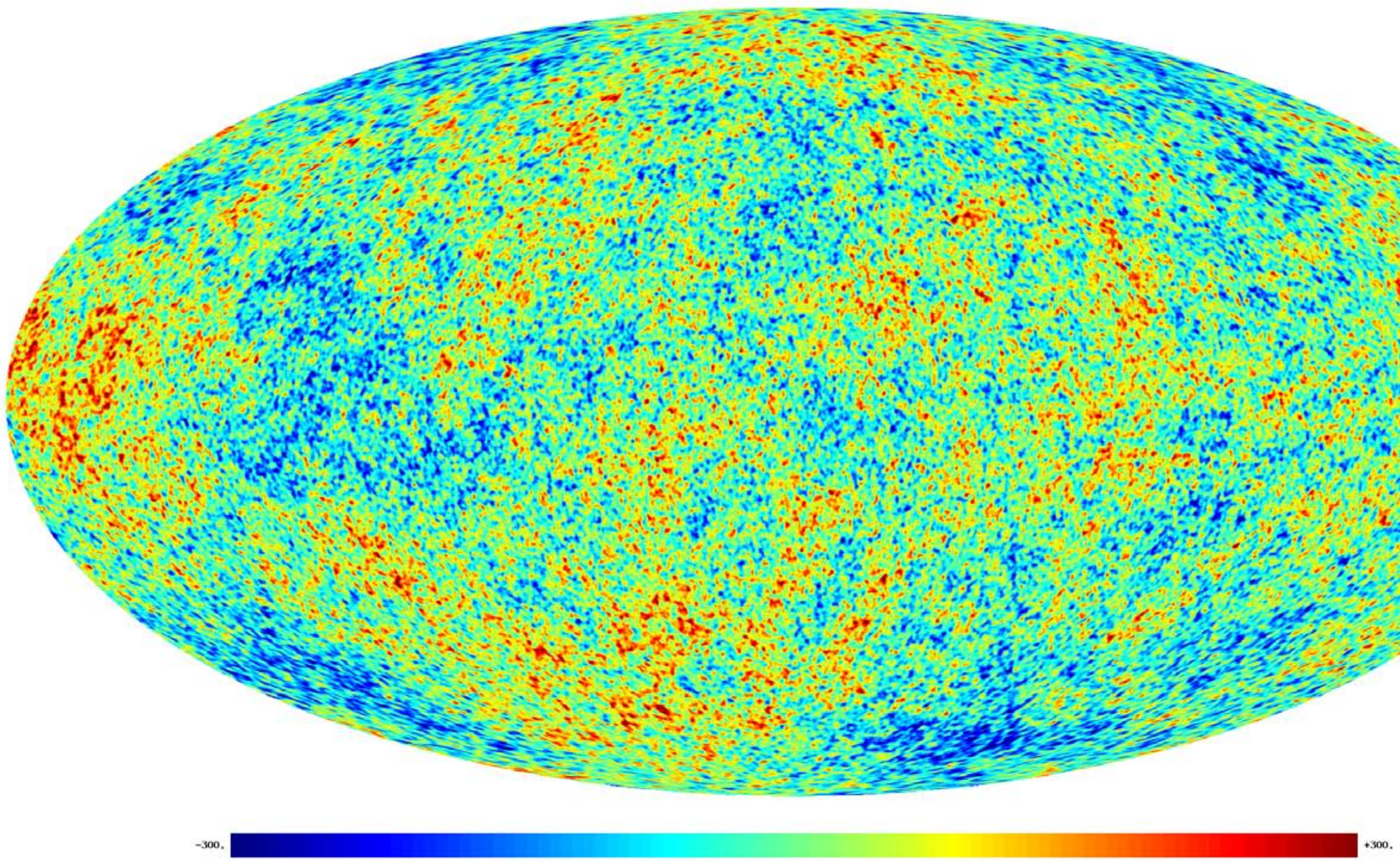
Marc Kamionkowski

(Johns Hopkins University)

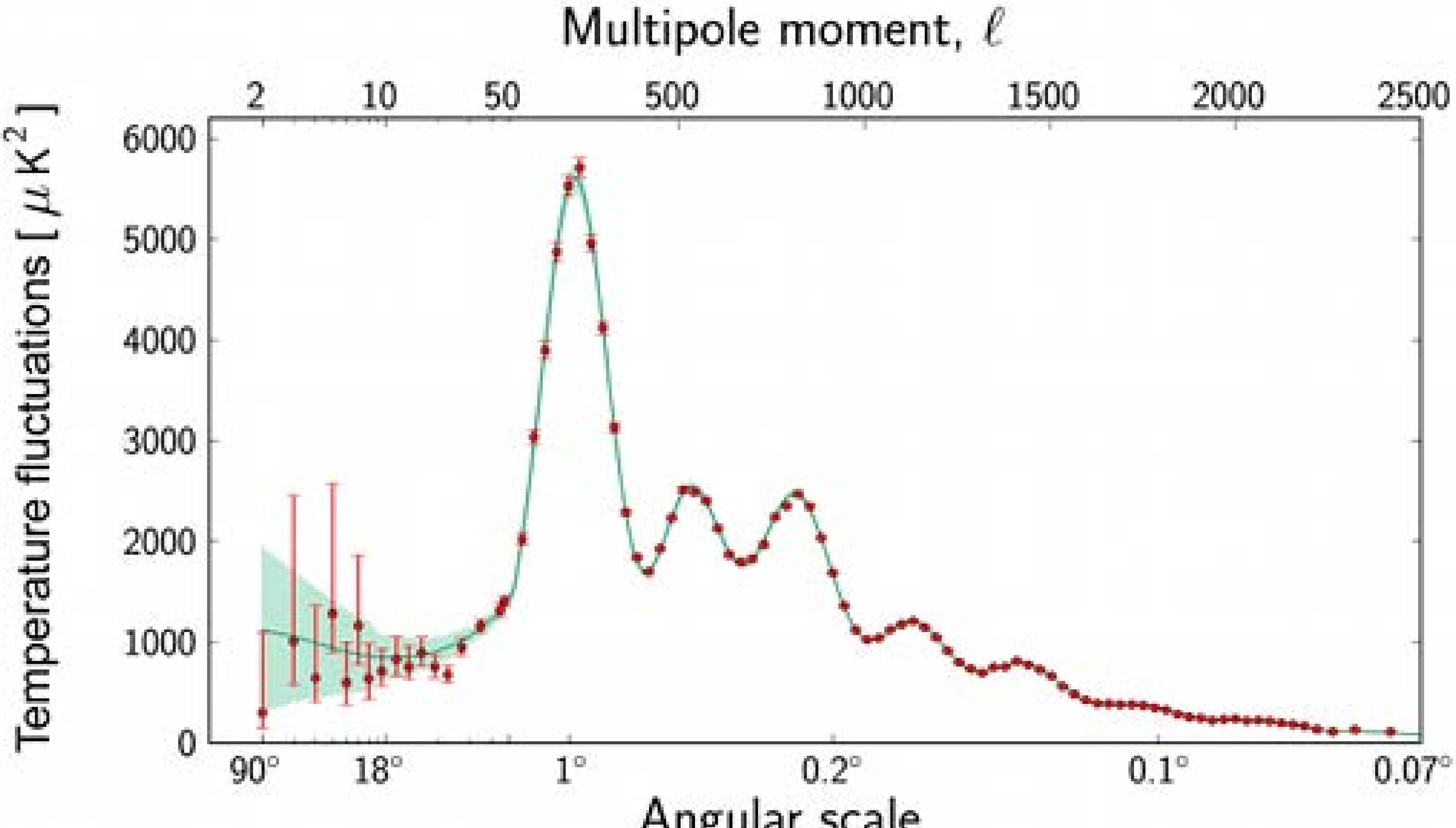
IAP, 14 November 2013

Outline

- CMB review
- Departures from statistical isotropy
- A hemispherical power asymmetry?
- New 3d probes of inflation
- Cosmic bandits?

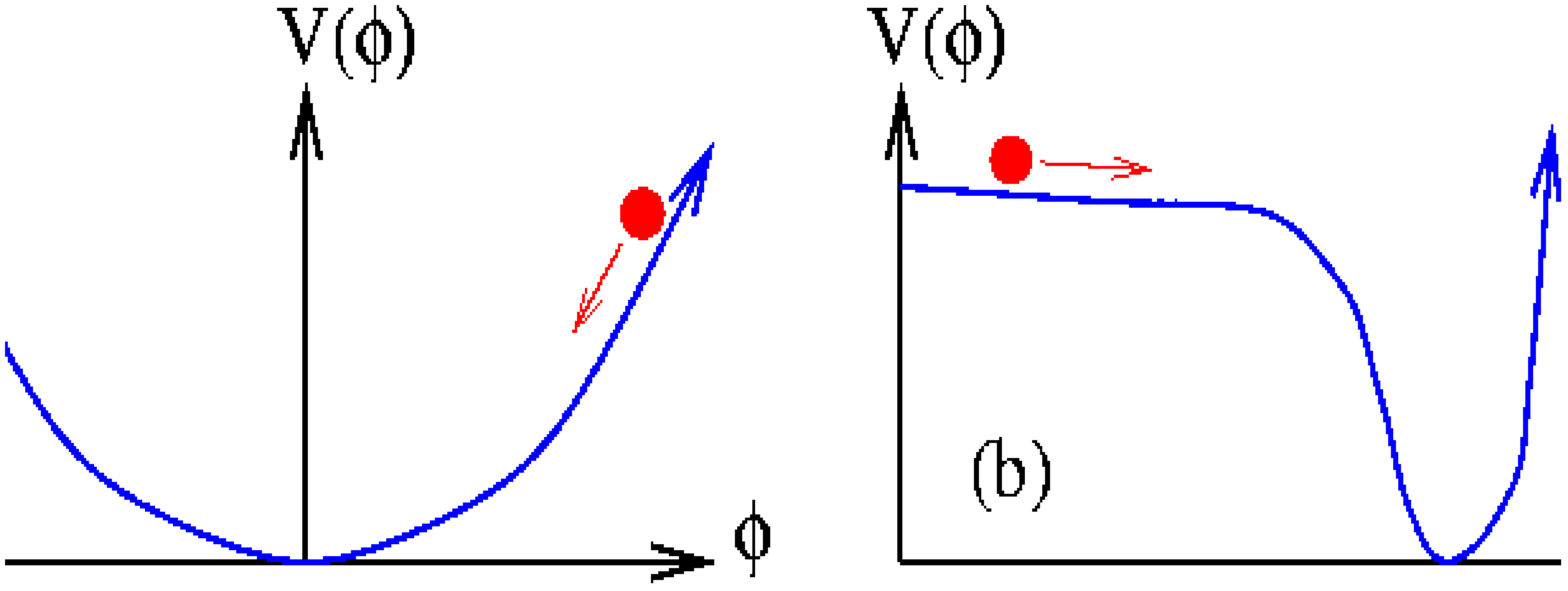


-300.
+300.


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

Interpretation: Temperature fluctuations from primordial density perturbations from inflation

The mechanism: Vacuum energy associated with new ultra-high-energy physics (e.g., grand unification, strings, supersymmetry, extra dimensions….)



Every Fourier mode of inflaton field satisfies SHO-like equation of motion:

$$\ddot{\phi}_{\vec{k}} + k^2 \phi_{\vec{k}} = 0$$

Then imprinted as primordial density perturbations

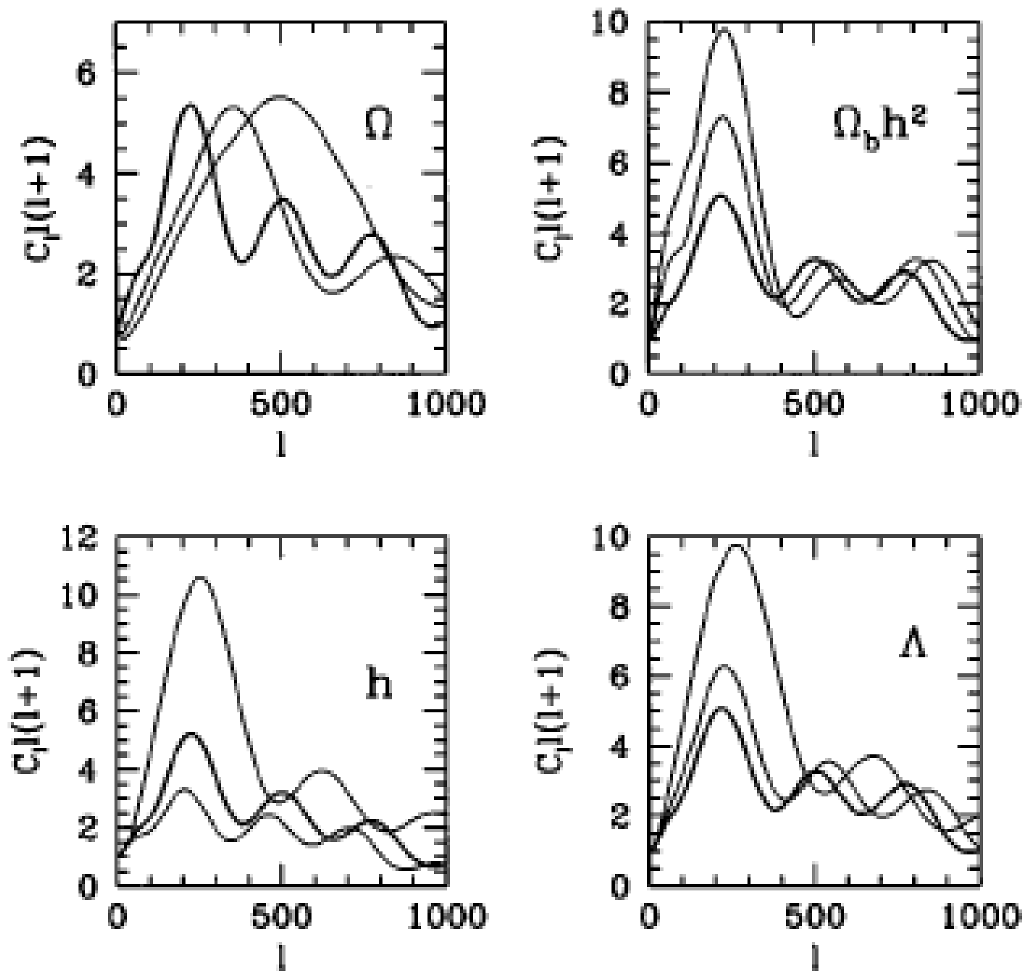
➔ Amplitude of each Fourier mode selected from Gaussian random distribution (the ground-state SHO wave function)

Inflationary prediction is that CMB is realization of statistically isotropic Gaussian random field: each a_{lm} is statistically independent and there is no *m* dependence

$$\langle a^*_{lm} a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

Power-spectrum predictions straightforward given values of cosmological parameters; e.g.,

$$\{\Omega_{\rm m}, \Omega_{\rm de}, w, \Omega_{\rm b}, \Omega_\nu, H_0, \tau_{\rm reion}, n_s, \cdots\}$$



Measurement of power spectrum allows precise determination of cosmological parameters (Jungman, MK, Kosowsky, Spergel, 1996)

As has now been done……

Planck 2013 results. XVI. Cosmological parameters

Abstract: This paper presents the first cosmological results based on *Planck* measurements of the cosmic microwave background (CMB) temperature and lensing-potential power spectra. We find that the *Planck* spectra at high multipoles ($\ell \gtrsim 40$) are extremely well described by the standard spatially-flat six-parameter ΛCDM cosmology with a power-law spectrum of adiabatic scalar perturbations. Within the context of this cosmology, the *Planck* data determine the cosmological parameters to high precision: the angular size of the sound horizon at recombination, the physical densities of baryons and cold dark matter, and the scalar spectral index are estimated to be $\theta_* = (1.04147 \pm 0.00062) \times 10^{-2}$, $\Omega_b h^2 = 0.02205 \pm 0.00028$, $\Omega_c h^2 = 0.1199 \pm 0.0027$, and $n_s = 0.9603 \pm 0.0073$, respectively (68% errors). For this cosmology, we find a low value of the Hubble constant, $H_0 = 67.3 \pm 1.2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and a high value of the matter density parameter, $\Omega_m = 0.315 \pm 0.017$. These values are in tension with recent direct measurements of H_0 and the magnitude-redshift relation for Type Ia supernovae, but are in excellent agreement with geometrical constraints from baryon acoustic oscillation (BAO) surveys. Including curvature, we find that the Universe is consistent with spatial flatness to percent level precision using *Planck* CMB data alone. We use high-resolution CMB data together with *Planck* to provide greater control on extragalactic foreground components in an investigation of extensions to the six-parameter ΛCDM model. We present selected results from a large grid of cosmological models, using a range of additional astrophysical data sets in addition to *Planck* and high-resolution CMB data. None of these models are favoured over the standard six-parameter ΛCDM cosmology. The deviation of the scalar spectral index from unity is insensitive to the addition of tensor modes and to changes in the matter content of the Universe. We find a 95% upper limit of $r_{0.002} < 0.11$ on the tensor-to-scalar ratio. There is no evidence for additional neutrino-like relativistic particles beyond the three families of neutrinos in the standard model. Using BAO and CMB data, we find $N_{\mathrm{eff}} = 3.30 \pm 0.27$ for the effective number of relativistic degrees of freedom, and an upper limit of 0.23 eV for the sum of neutrino masses. Our results are in excellent agreement with big bang nucleosynthesis and the standard value of $N_{\mathrm{eff}} = 3.046$. We find no evidence for dynamical dark energy; using BAO and CMB data, the dark energy equation of state parameter is constrained to be $w = -1.13^{+0.13}_{-0.10}$. We also use the *Planck* data to set limits on a possible variation of the fine-structure constant, dark matter annihilation and primordial magnetic fields. Despite the success of the six-parameter ΛCDM model in describing the *Planck* data at high multipoles, we note that this cosmology does not provide a good fit to the temperature power spectrum at low multipoles. The unusual shape of the spectrum in the multipole range $20 \lesssim \ell \lesssim 40$ was seen previously in the *WMAP* data and is a real feature of the primordial CMB anisotropies. The poor fit to the spectrum at low multipoles is not of decisive significance, but is an "anomaly" in an otherwise self-consistent analysis of the *Planck* temperature data.

What else can we do?

Departures from Gaussianity and Statistical Isotropy

Inflationary prediction,

$$\langle a_{lm}^* a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

can be modified by

- late-time effects (e.g., gravitational lensing)
- Inflationary physics beyond vanilla inflation
- Exotica

Any such effects can be parametrized as

$$\langle a^*_{lm} a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'} + \sum_{L \geq 0} \sum_{M=-L}^{L} \mathcal{C}^{LM}_{lml'm'} A^{LM}_{ll'}$$

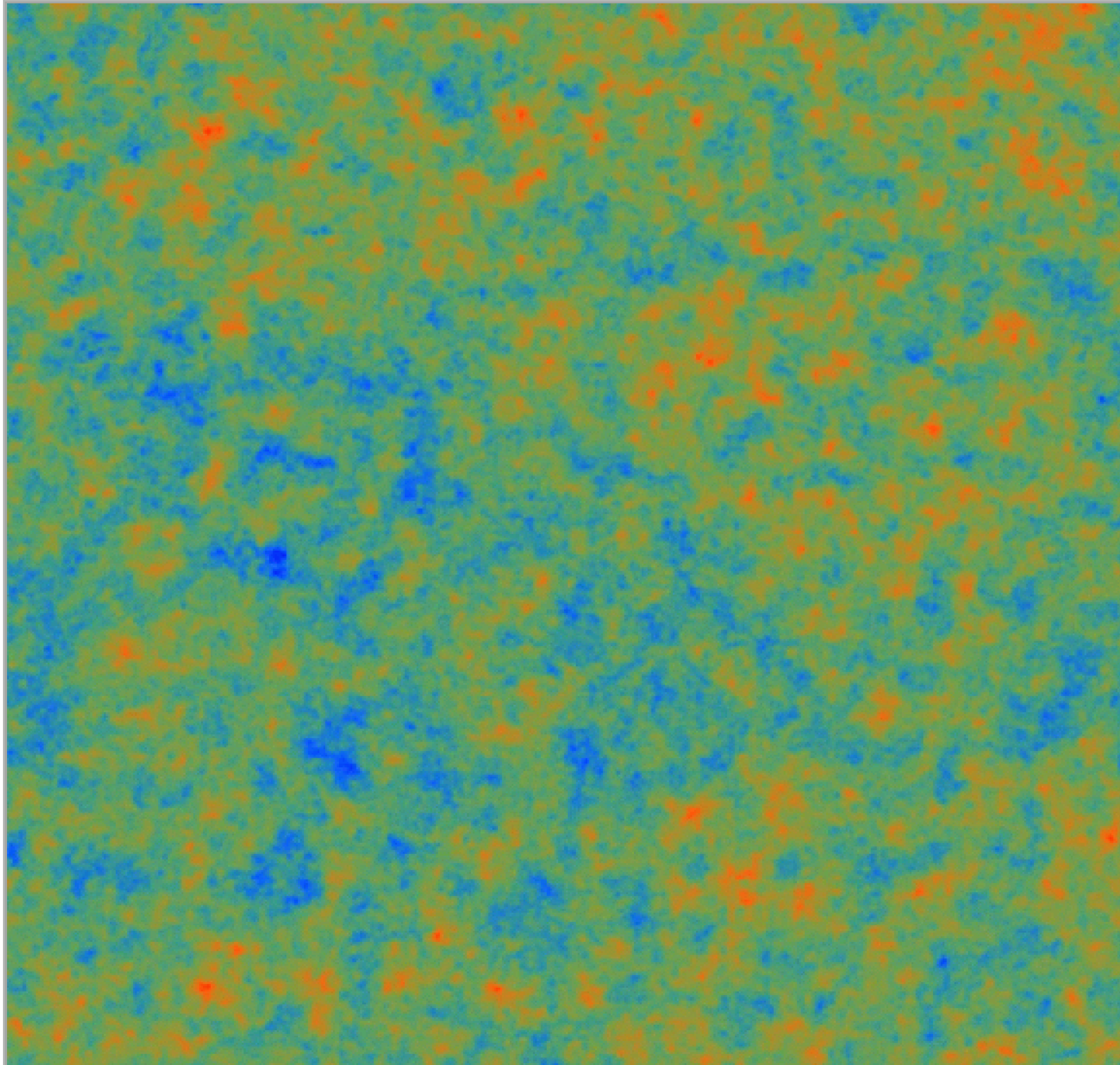
Clebsch-Gordan coefficients

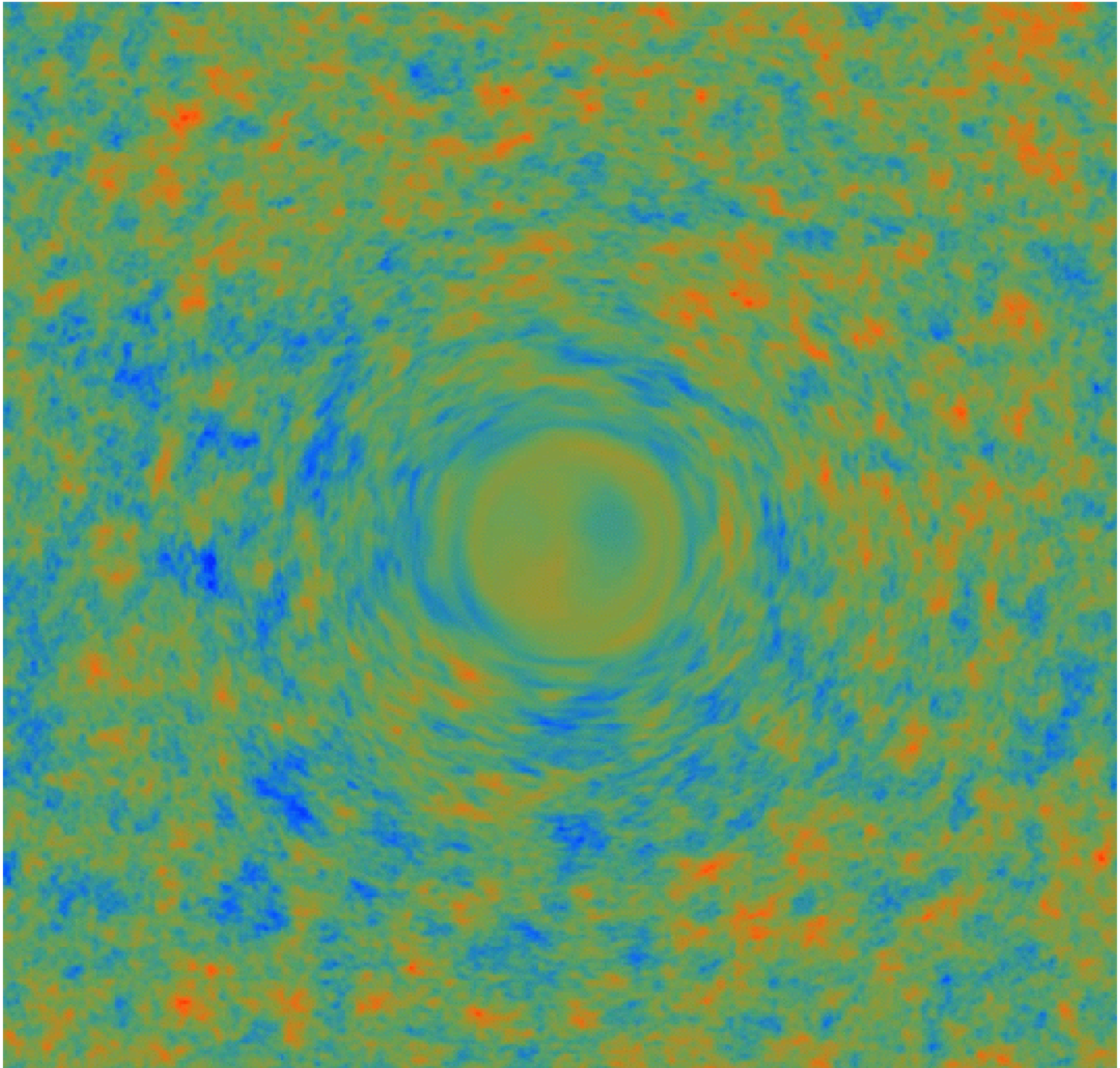
Bipolar spherical harmonics (BiPoSHs)
(Hajian & Souradeep 2004; Book, MK, Souradeep 2011)

Recipe for measuring BiPoSHs (generalizations of power spectrum to direction-dependent fluctuations):

$$\widehat{A_{ll'}^{LM}} = \sum_{mm'} \mathcal{C}_{lml'm'}^{LM} a_{lm}^{*} a_{l'm'}$$

Example 1: Weak gravitational lensing of CMB





$$A^{\oplus LM}_{ll'} = \frac{\phi_{LM}}{\sqrt{2L+1}}\left[\frac{C_l G^L_{l'l}}{\sqrt{l'(l'+1)}} + \frac{C_{l'} G^L_{ll'}}{\sqrt{l(l+1)}}\right] = Q^{\oplus L}_{ll'}\phi_{LM}$$

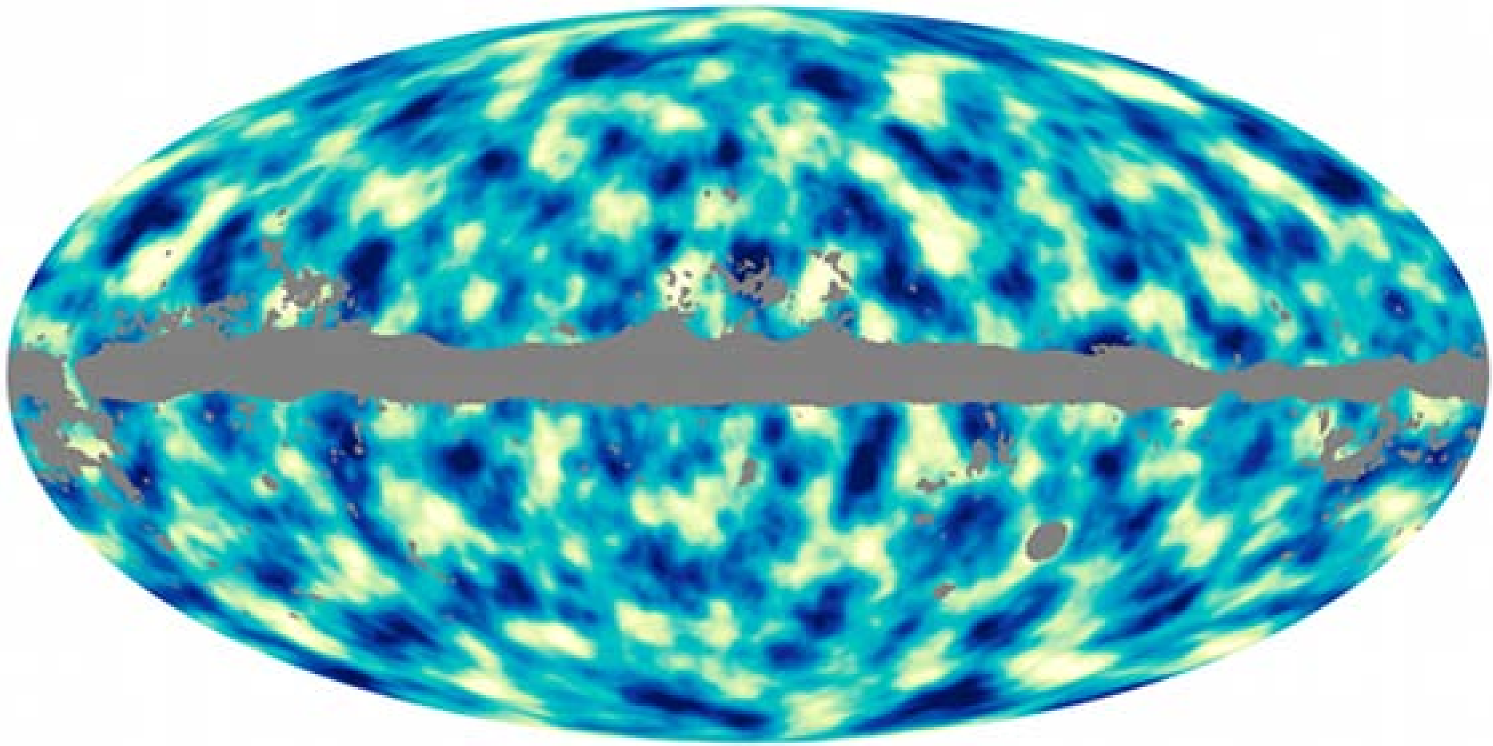
where deflection angle is $\vec{\alpha} = \vec{\nabla}\phi$

Lensing of CMB recently detected!
through cross-correlation with galaxy surveys

(Smith, Zahn, Dore 2007; Hirata et al. 2008)

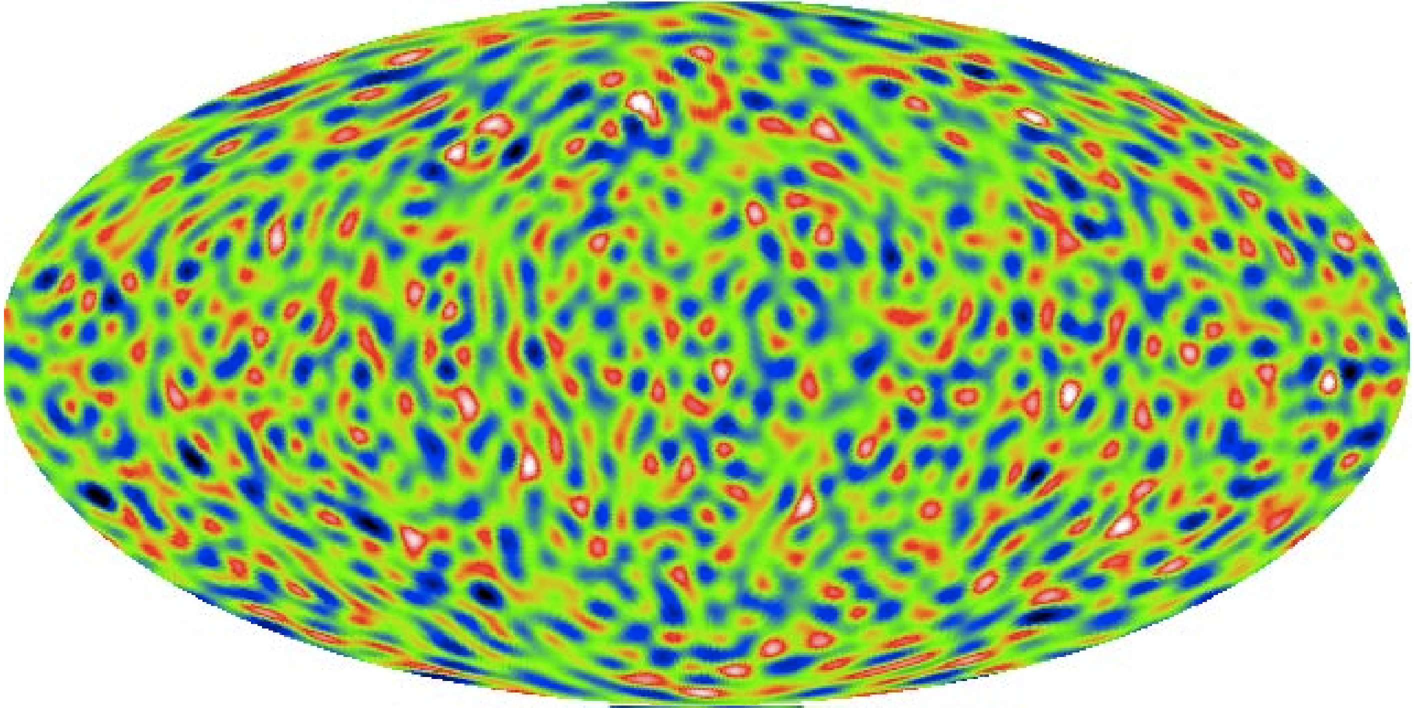
And now without galaxies (Das et al. (ACT) 2010)

And in Planck!!!

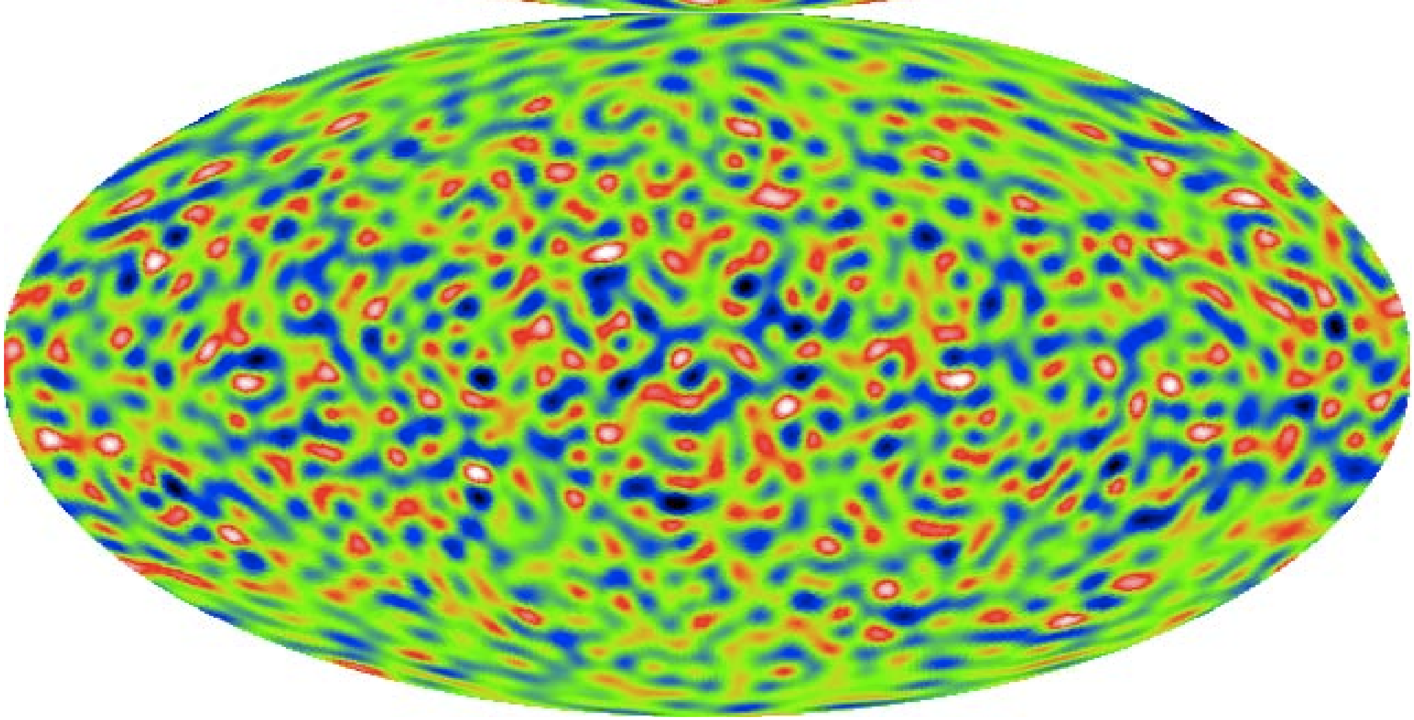


Example II (Exotica): Departures from Statistical Isotropy (Pullen,MK, 2007)

- Inflation: Universe statistically isotropic and homogeneous
- Statistical isotropy: Power spectrum does not depend on direction



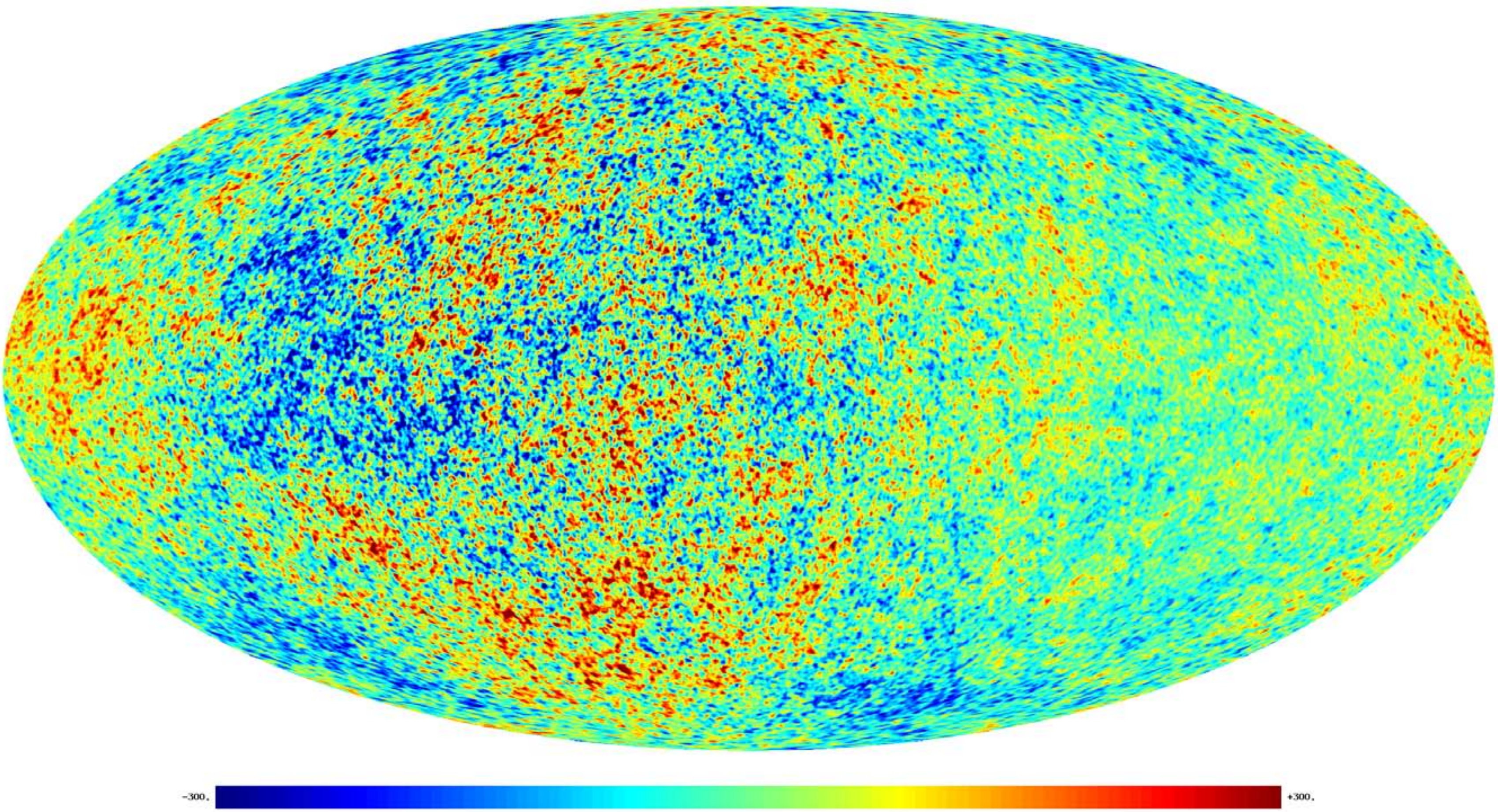
Statistically isotropic



A power quadrupole

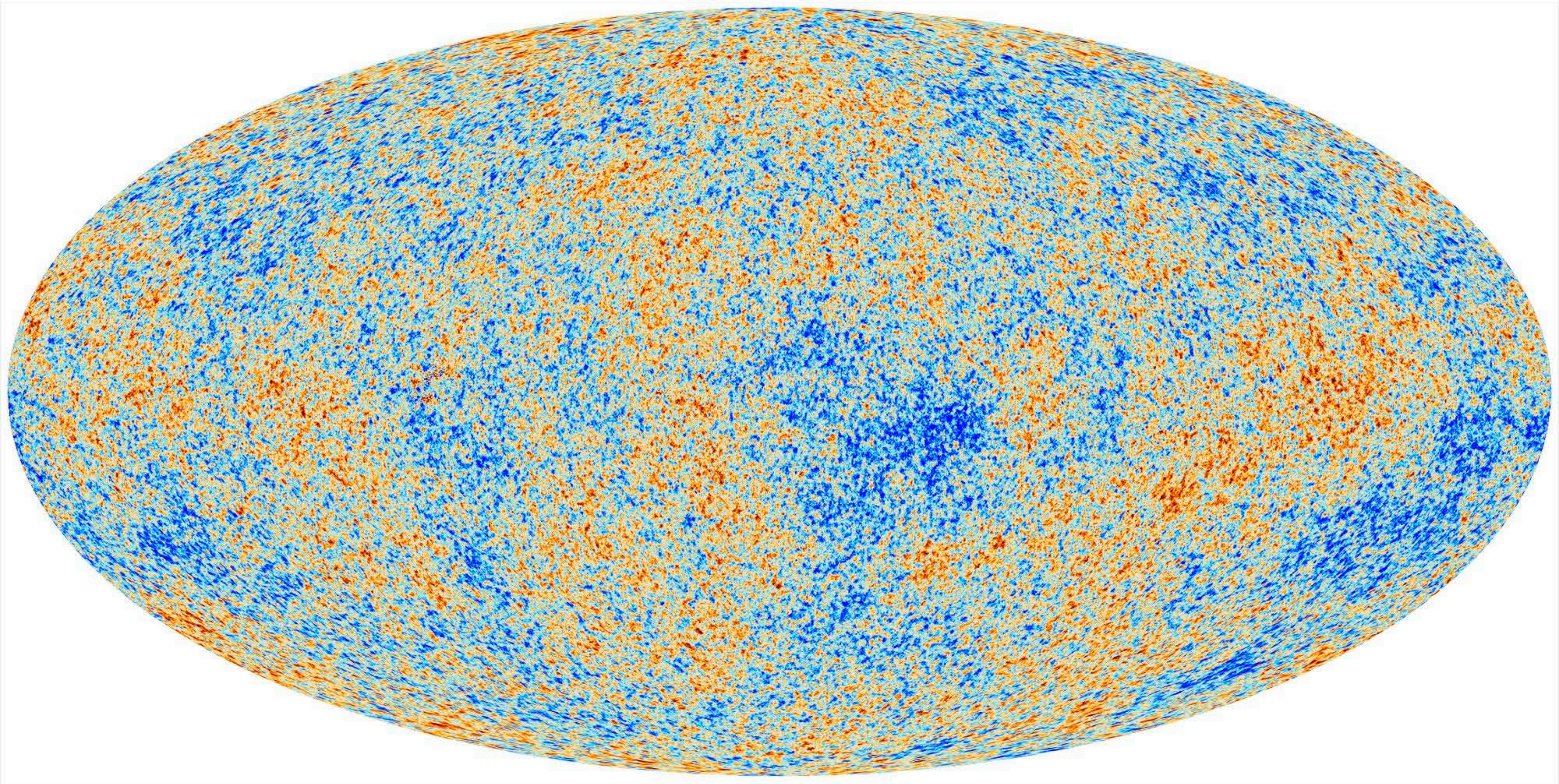
Such a quadrupolar power asymmetry arises even in SFSR inflation from the tensor-scalar-scalar three-point function!
(Dai, Jeong, MK, 2013)

A power asymmetry?



Erickcek, MK, Carroll 2008; Erickcek, Carroll, MK 2008; Erickcek, Hirata, MK 2009; Dai, Jeong, MK, Chluba, 2013

Has been seen (???) in WMAP and now in Planck



The claim

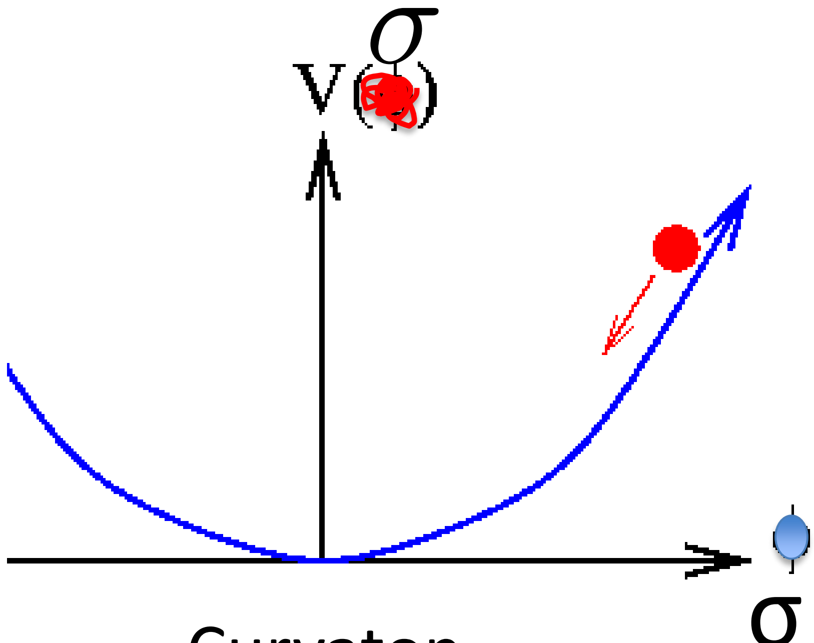
Power at l<100 on one side of sky differs at >3sigma level from other side
What happens at smaller scales (higher l) still unclear

Problem for single-field inflation:

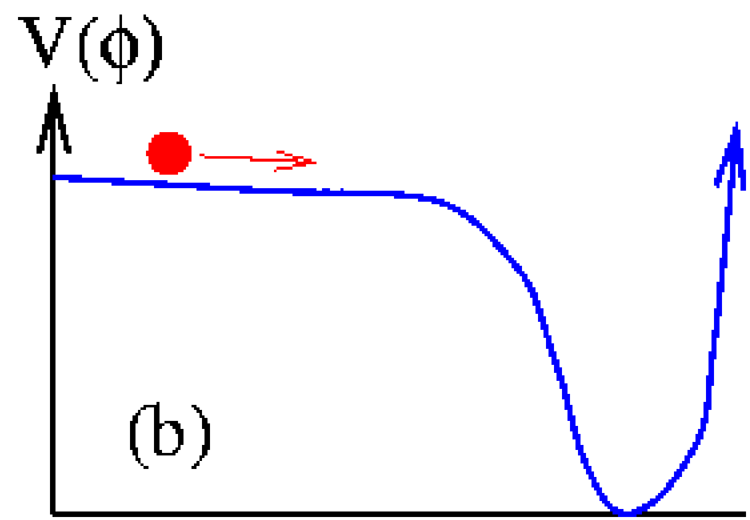
- If ϕ varies, then $V(\phi)$ varies
  ➔ large-scale density fluctuation, which is constrained to be very small by CMB quadrupole/octupole (Erickcek, MK, Carroll, arXiv:0806.0377; Erickcek, Carroll, MK, arXiv:0808.1570, Zibin-Scott 2008)
- Real problem: One scalar field (inflaton) controls density perturbations (which we want to vary across Universe) and the total density (which can*not* vary)

Solution (Erickcek, MK, Carroll 2008)

- Add second scalar field (curvaton); energy density generated by one and perturbations generated by other (or both by some combination)



Curvaton

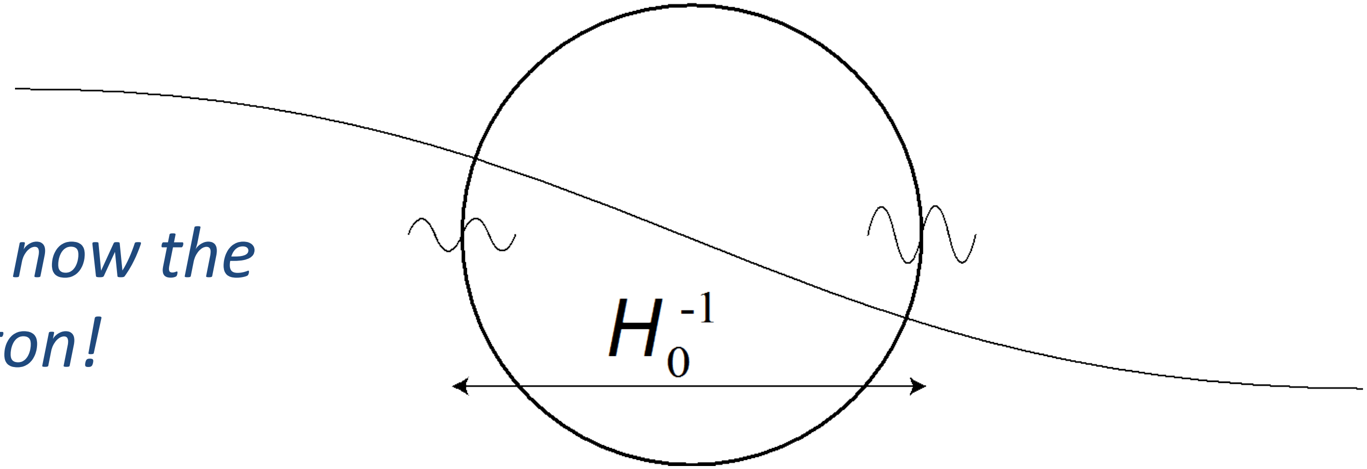


Inflaton

Explaining the power asymmetry

- Postulate long-wavelength curvaton fluctuation $\Delta\sigma$
- Keep inflaton smooth

This is now the curvaton!



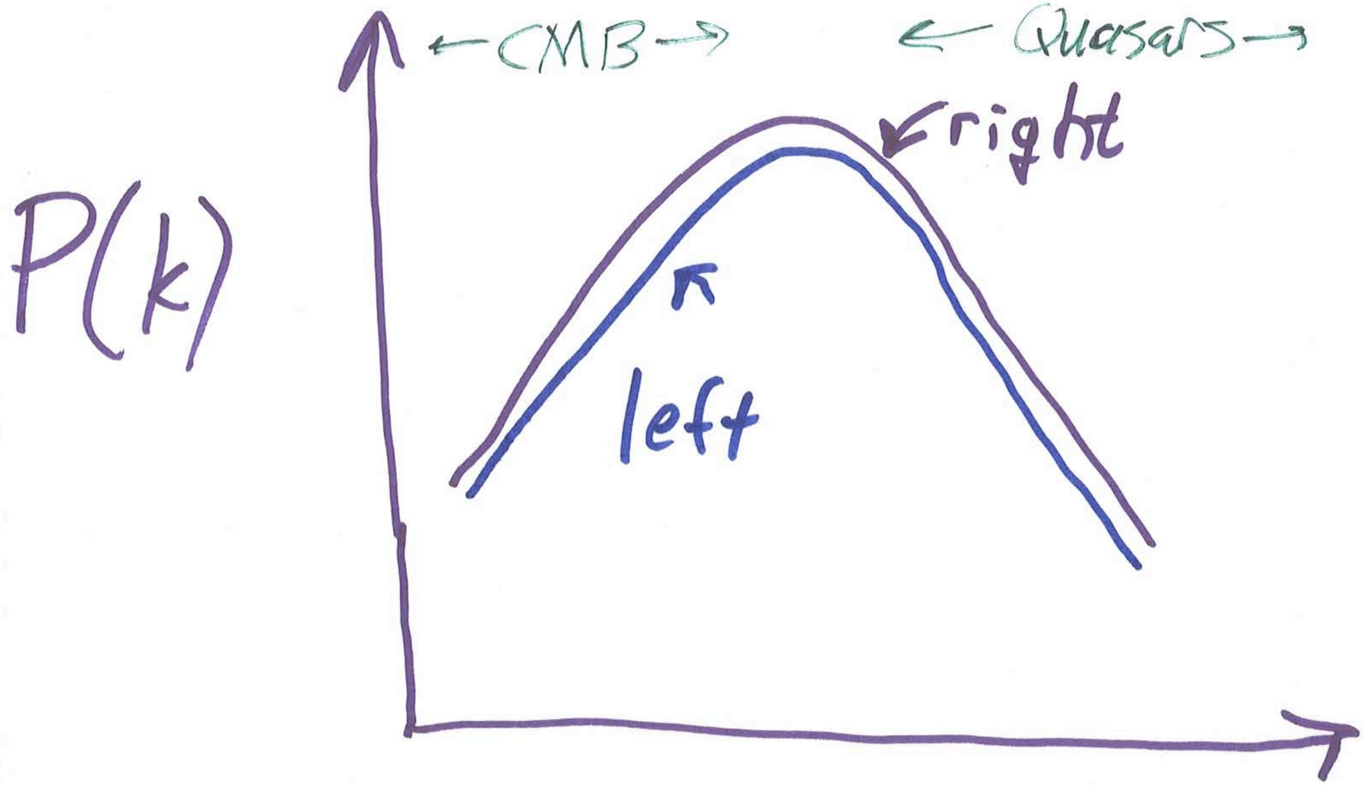
Model prediction: non-Gaussianity

- Predicts non-Gaussianity, with $f_{\rm nl} > 50$ which is now ruled out by Planck
- And that power asymmetry is scale-invariant

Afterwards….

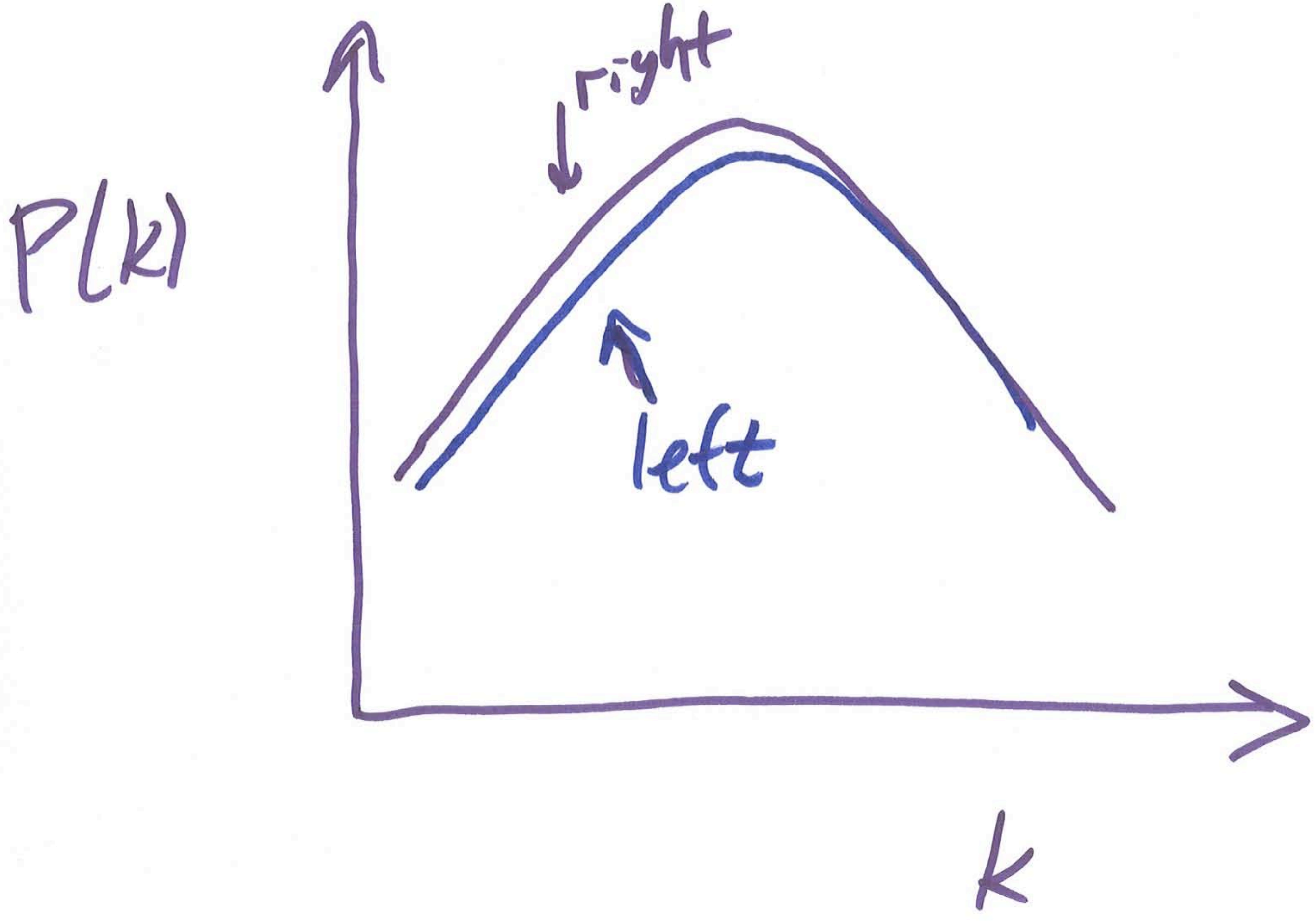
- SDSS quasar distribution/clustering restricts asymmetry to be small on smaller distance scales (Hirata 2009)

Power Spectrum



Erickcek, MK, Carroll
Prediction

The data

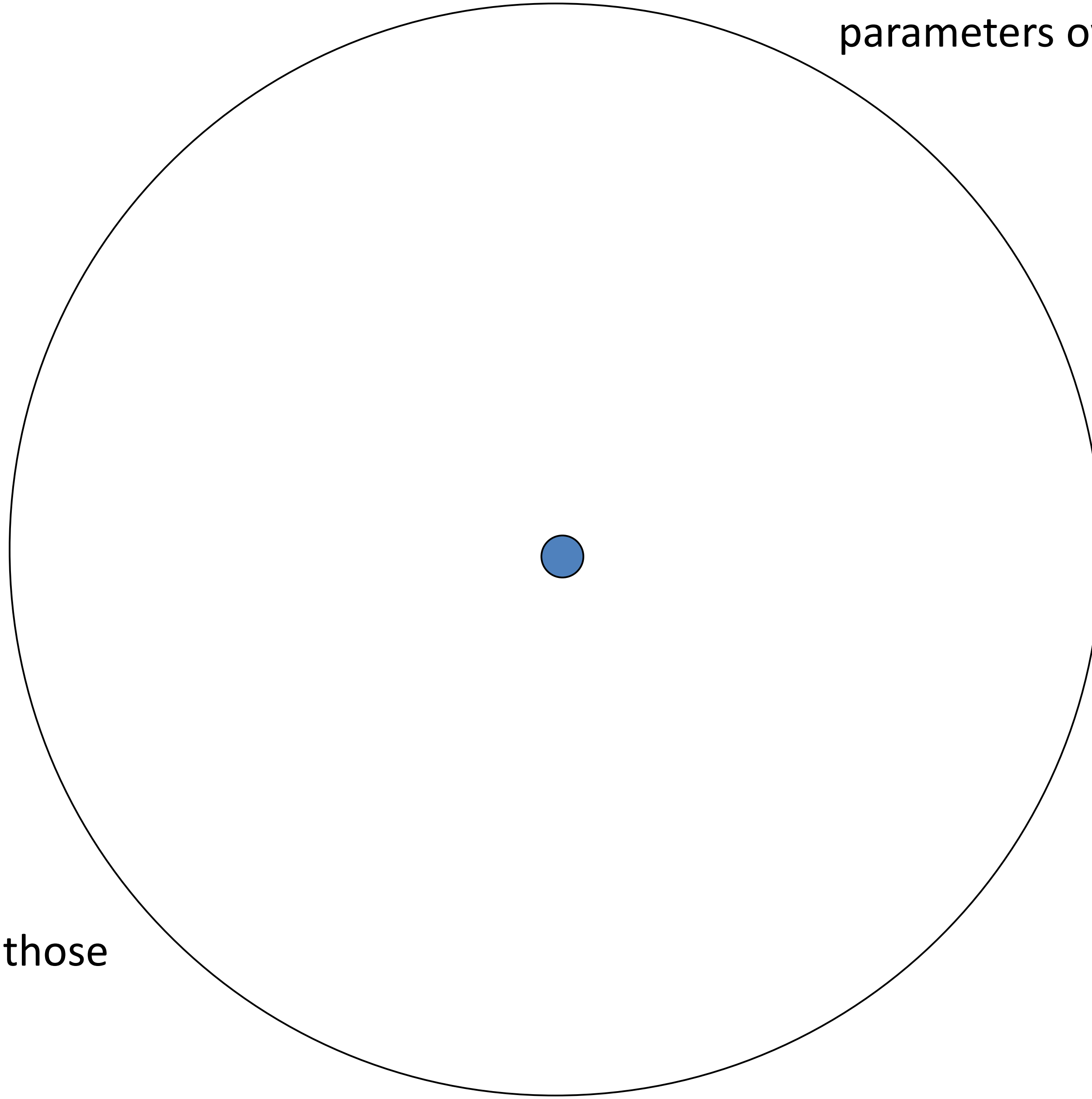


Two possible explanations

(Dai, Jeong, MK, Chluba 2013)

- Scale-dependent power asymmetry (e.g., with two-field inflation model; Erickcek, Hirata, MK, 2009)
- Modulation of parameters that affect CMB without affecting mass distribution (Dai et al. 2013). If energy-density distribution (and/or geometry) is modulated, will also induce departures from homogeneity

What if cosmological parameters over here……

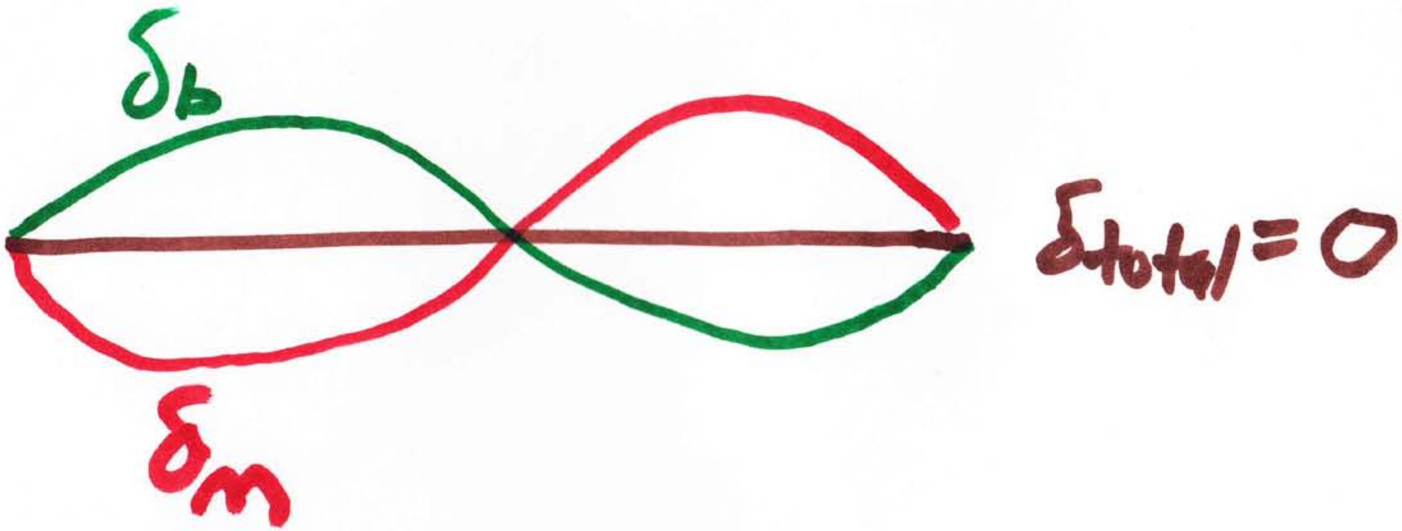


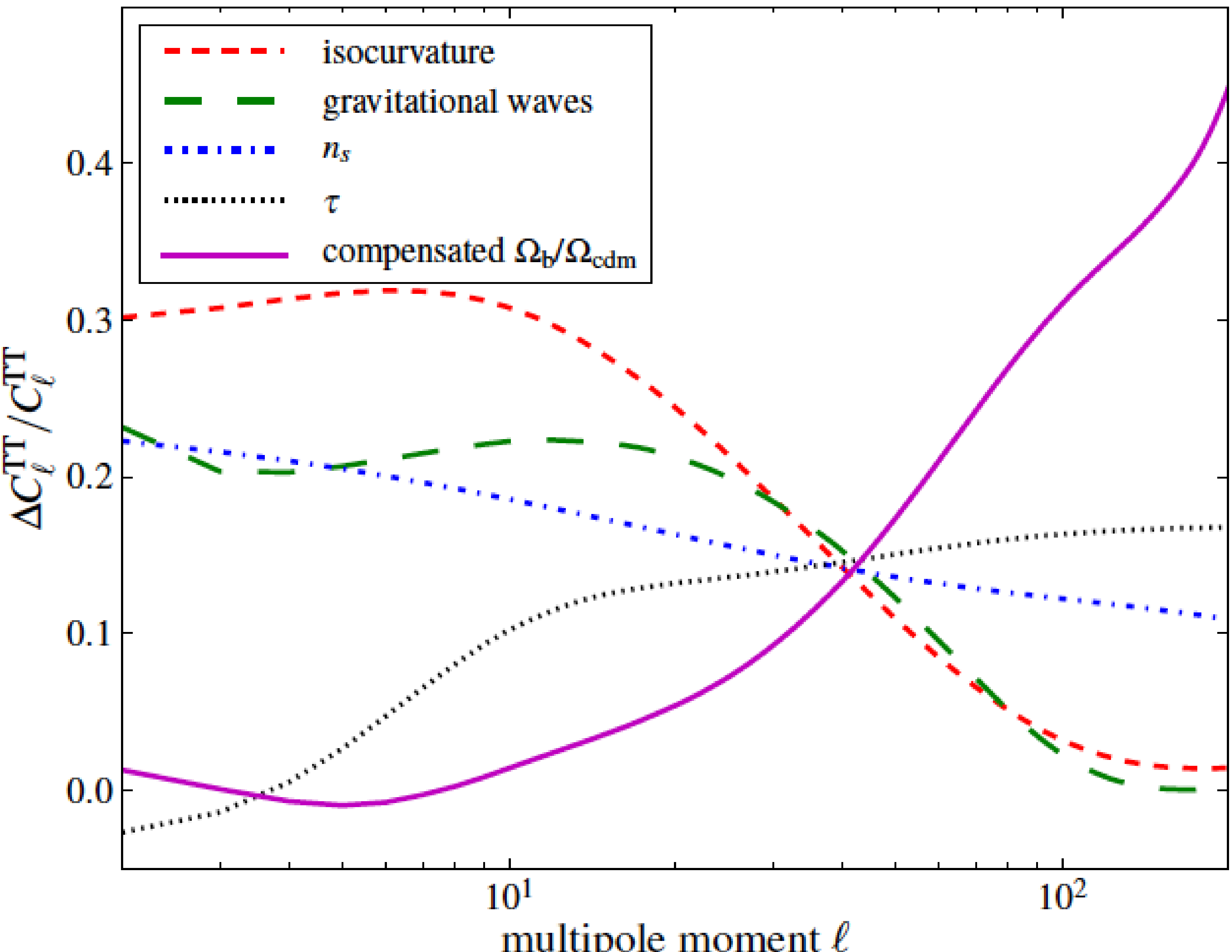
differ from those over here?

We tried:

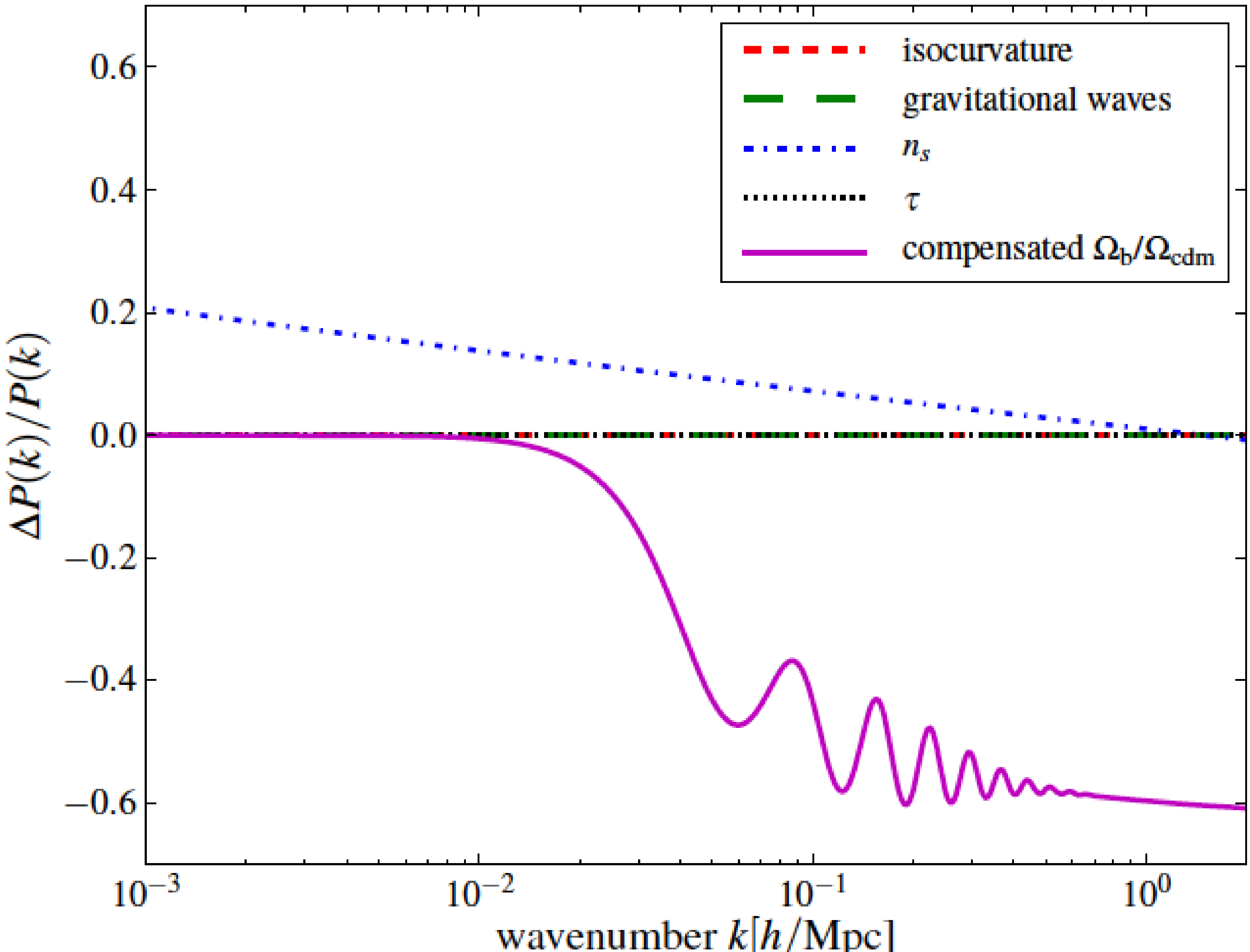
- Compensated isocurvature perturbation (DM and baryon densities balance out so that total-density is constant; Gordon & Pritchard 2009; Holder, Nollett, van Engelen 2010; Grin et al., 2011, 2011, 2013)
- Variation in tensor-to-scalar ratio r
- Variation in scalar spectral index n_s
- Variation in reionization optical depth

Compensated isocurvature perturbation





isocurvature
gravitational waves
n_s
τ
compensated Ω_b/Ω_{cdm}
0.0
0.1
0.2
0.3
0.4
10^1
10^2
multipole moment ℓ
$\Delta C_\ell^{TT}/C_\ell^{TT}$


isocurvature
gravitational waves
n_s
τ
compensated Ω_b/Ω_{cdm}
$\Delta P(k)/P(k)$
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
10^{-3}
10^{-2}
10^{-1}
10^{0}
wavenumber $k[h/\mathrm{Mpc}]$

CMB polarization

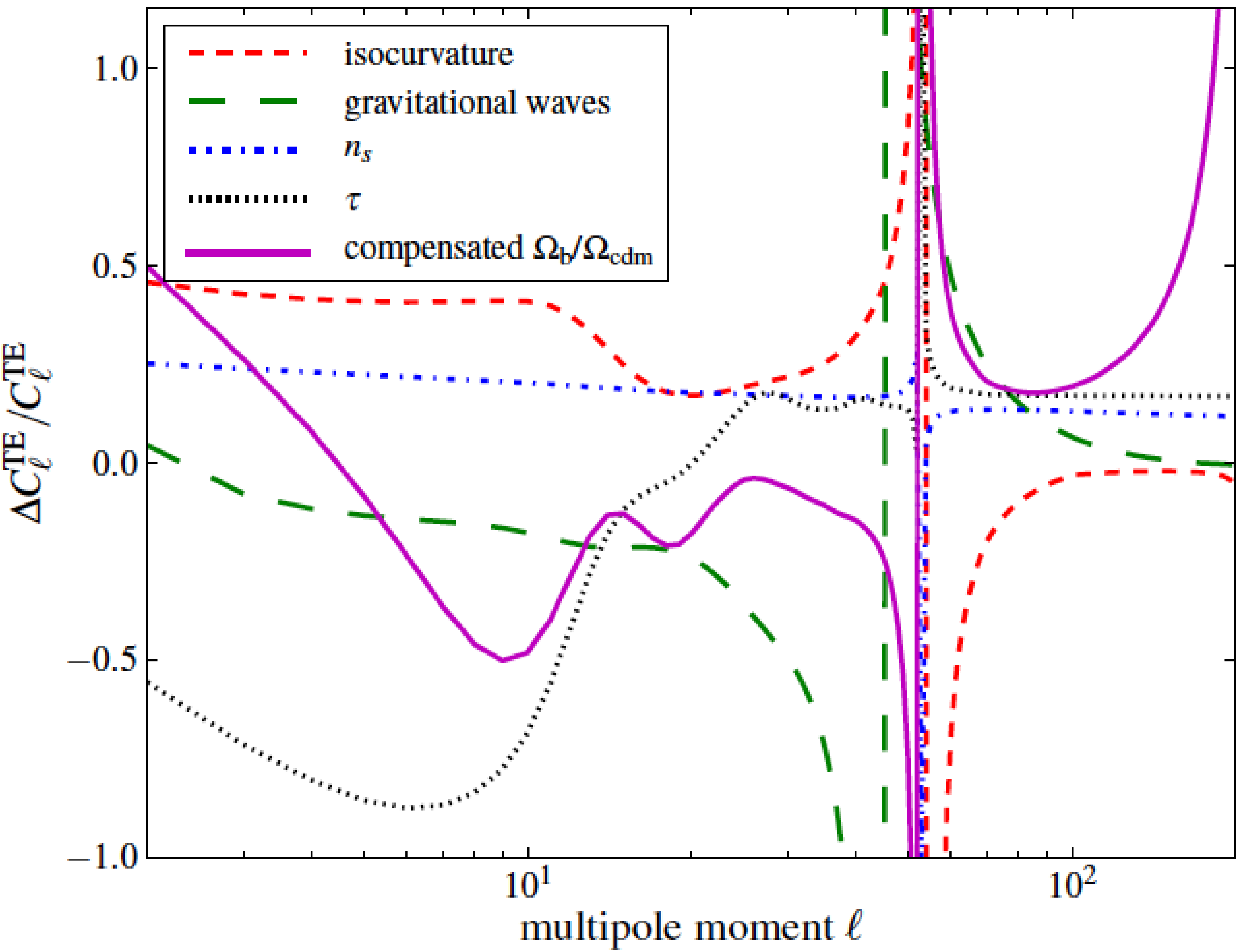
"E modes"

"B modes"

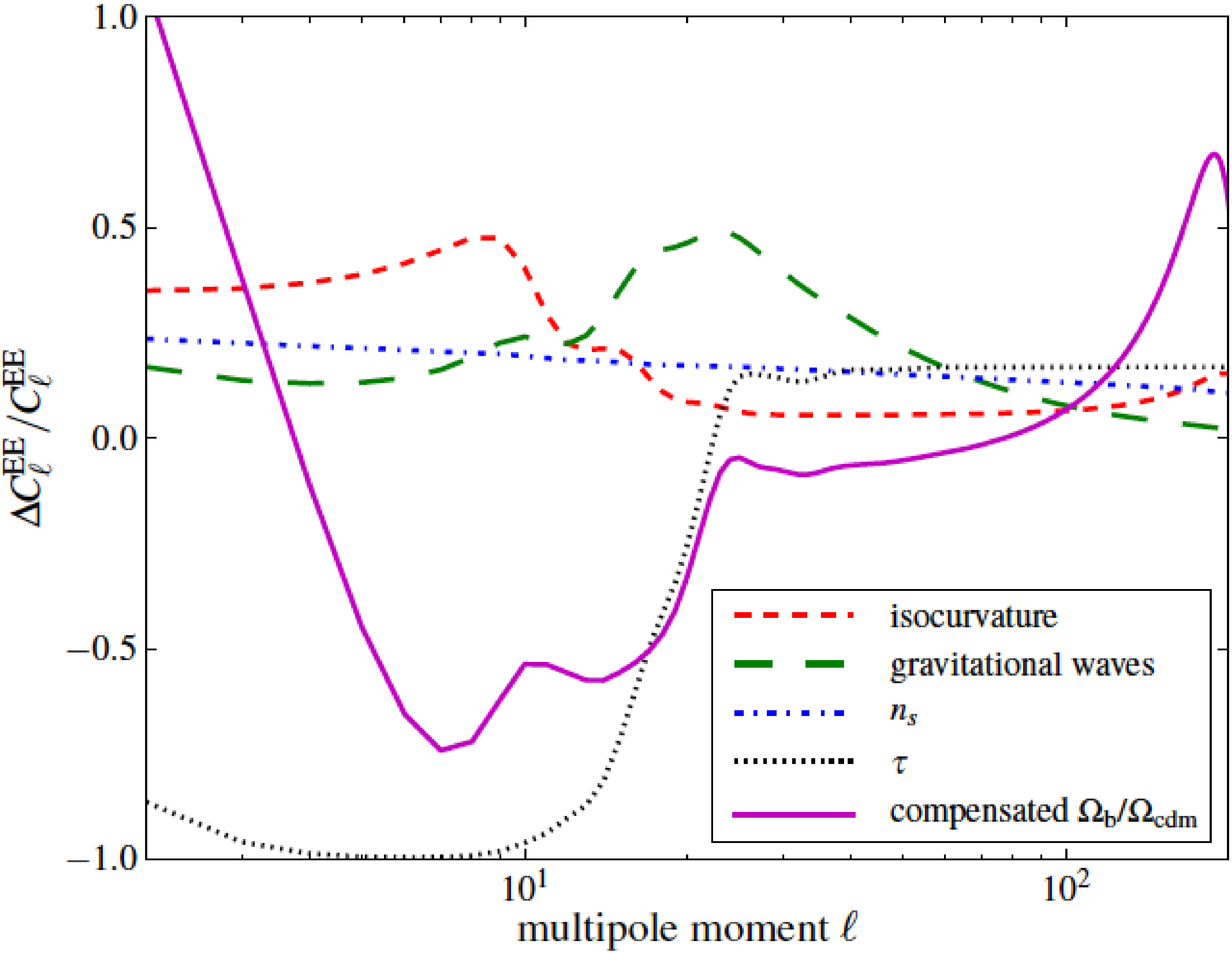
Temperature map: $$T(\hat{n})$$

Polarization Map: $$\vec{P}(\hat{n}) = \vec{\nabla} A + \vec{\nabla} \times \vec{B}$$

(MK, Kosowsky, Stebbins 1996; Seljak, Zaldarriaga 1996)



isocurvature
gravitational waves
n_s
τ
compensated Ω_b/Ω_{cdm}
1.0
0.5
0.0
−0.5
−1.0
$\Delta C_\ell^{TE}/C_\ell^{TE}$
10^1
10^2
multipole moment ℓ



1.0
0.5
0.0
−0.5
−1.0
$\Delta C_\ell^{\mathrm{EE}} / C_\ell^{\mathrm{EE}}$
10^1
10^2
multipole moment ℓ
isocurvature
gravitational waves
n_s
τ
compensated $\Omega_{\mathrm{b}}/\Omega_{\mathrm{cdm}}$

“Frequently nature does not knock with a very loud sound but rather a very soft whisper, and you have to be aware of subtle behavior which may in fact be a sign that there is interesting physics to be had.”

---Douglass Osheroff

Planck needs to measure ALL of these power differences if we are to figure out what to make of this $l<60$ asymmetry!!!

Galaxy Surveys and Fossil Fields from Inflation (Jeong, MK 2012, Dai, Jeong, MK, 2013)

Galaxy-clustering signatures of coupling of inflaton to new field

Can distinguish spin (scalar, vector, tensor) of new field

Can distinguish couplings to fields of right- and left-handed spins

But there is more!

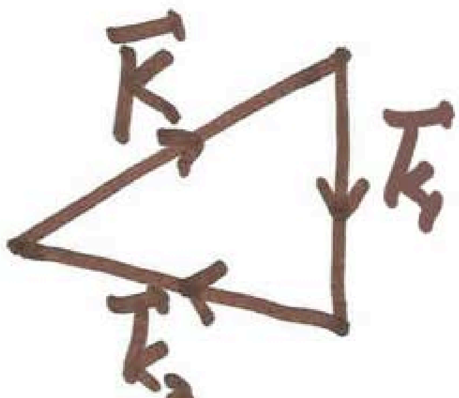
$$\mathcal{L} \subset g^{\mu\nu}(\nabla_\mu \phi)(\nabla_\nu \phi)$$

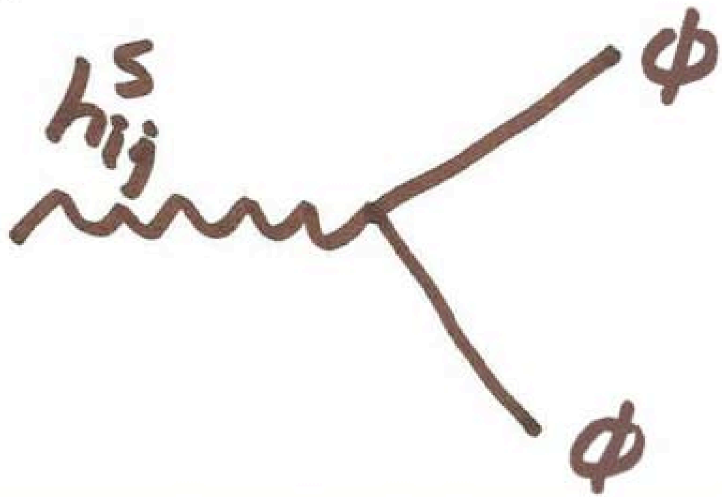
$$\Longrightarrow \quad h^{ij}(\partial_i \phi)(\partial_j \phi)$$

$\Longrightarrow$ tensor-scalar-scalar bispectrum (Maldacena 2002
(GW)

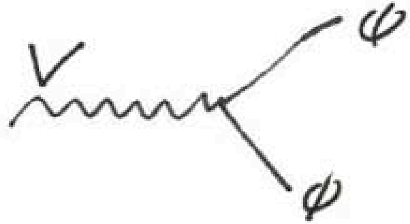
$$\langle h^s_{\vec{K}} \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle \propto \delta_D(\vec{k}_1+\vec{k}_2+\vec{k}_3) \epsilon^s_{ij} k_1^i k_2^j \, B_{tss}(K, k_1, k_2)$$

$s = +, \times$

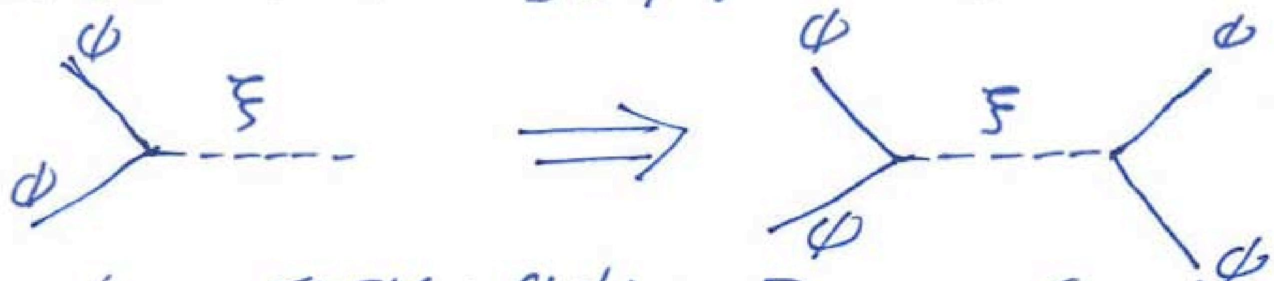




A vector field V^μ ? $(\partial_\mu\phi)(\partial_\nu\phi)\,\partial^{(\mu}V^{\nu)}$



A spectator scalar $\xi(\vec{x})$? $\xi\phi^2$



(e.g., SUSY inflation; Baumann-Green)

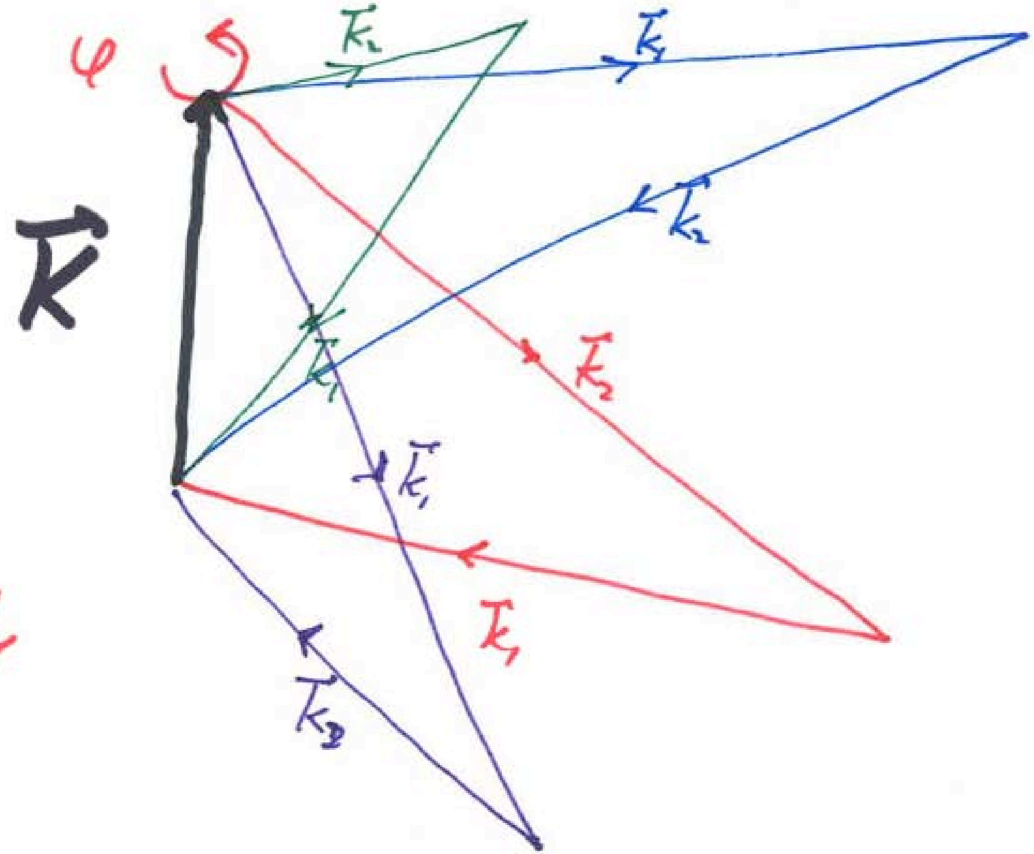
Some spectator spin-2 fields $T^{\mu\nu}$? $T^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi$

minimum-variance

Estimator for $h_p(\vec{K})$

$$\sum_{\vec{k}_1+\vec{k}_2=\vec{K}} \delta(\vec{k}_1)\,\delta(\vec{k}_2)\left[f_p(\vec{k}_1,\vec{k}_2)\,\epsilon^p_{ij}\,k_1^i k_2^j\right]$$

with inverse-variance weighting



Azimuthal (φ) dependence distinguishes scalar, from vector from tensor geometrically

Cosmic bandits: Adaptive survey strategies for inflationary B-mode searches and cosmic survey more generally (Kovetz & MK 2013)

- Sensitivity to B modes optimized in experiment with fixed detector sensitivity with deep integration on small patch of sky (Jaffe,MK 2000)
- But sensitivity limited by foregrounds and relevant foreground amplitude cannot be determined without making the measurement

The Multi-Armed-Bandit Problem

- Goal:

  Facing slots with different odds, maximize winnings.
- With infinite funds, this is easy. You *learn* the odds.
- With a finite number of plays, problem is unsolved.
- Heuristics have been developed and compared.

ion: But this then takes tim
deep integration??

Cosmic bandits

- We have developed bandit-like adaptive-survey strategies to optimize sensitivity to inflationary B modes in a small-sky experiment (like, EBEX, ABS, PolarBear, SPTPol, etc.)
- Conclusion: *Adaptive strategy can improve sensitivity to inflationary B modes by ~2-3, and maybe more, with an experiment of fixed detector sensitivity and observation time*