Inflation

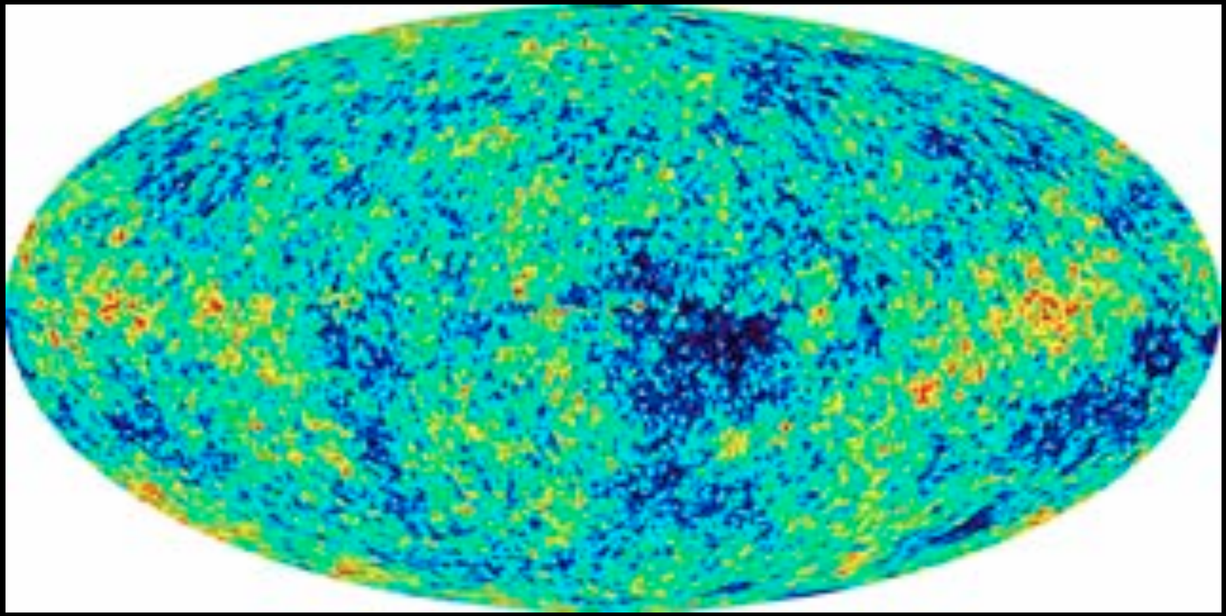
Evidence

Gravitational Waves

Non-Gaussianity

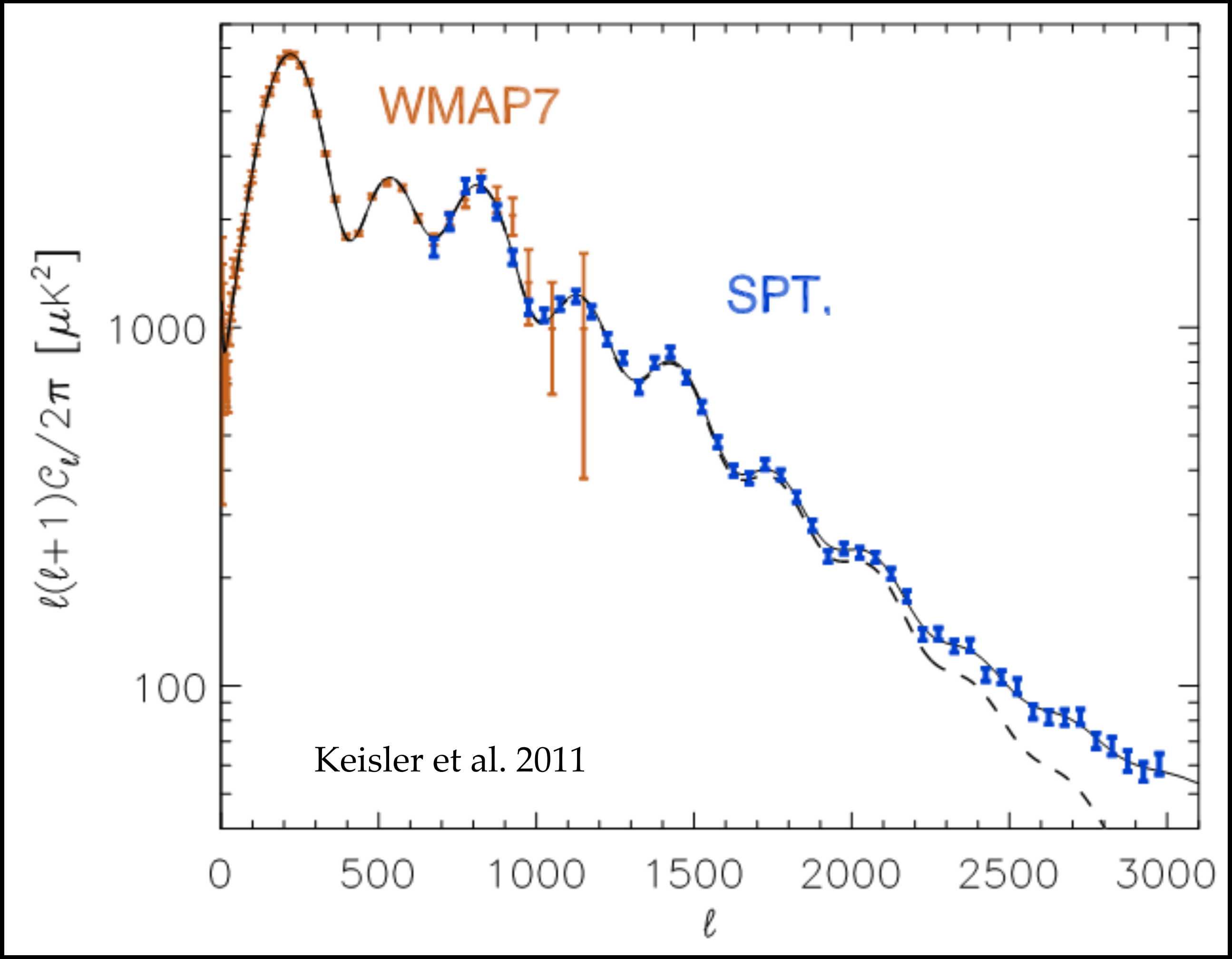
Evidence

- Flatness (remember the 80's and 90's)
- Nearly Scale Invariant Spectrum
- Nearly Gaussian Perturbations
- Acoustic peaks (in CMB T, CMB E, LSS)



Evidence

Observed series of peaks and troughs in temperature spectrum



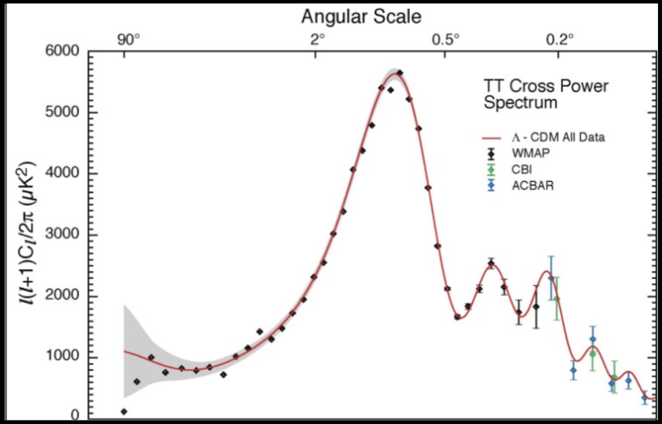
Evidence

DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congressi di quattro giornate si discorre sopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filosofiche, e Naturali tanto per l'una, quanto per l'altra parte.
CON PRI VILEGI.
IN FIORENZA, Per Gio: Batista Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

Evidence

<u>Dialog</u>

Sage 1: Why do we observe peaks and troughs in the temperature spectrum?



Sage 2: Perturbations in the pre-recombination plasma (electrons, protons, photons) were governed by the wave equation. So there were acoustic oscillations, similar to those produced by musical instruments.

Evidence

Dialog

S1: But you get a fundamental mode and harmonics in musical spectra because the ends of the strings are tied down; the Universe is not tied down!

Evidence

Dialog

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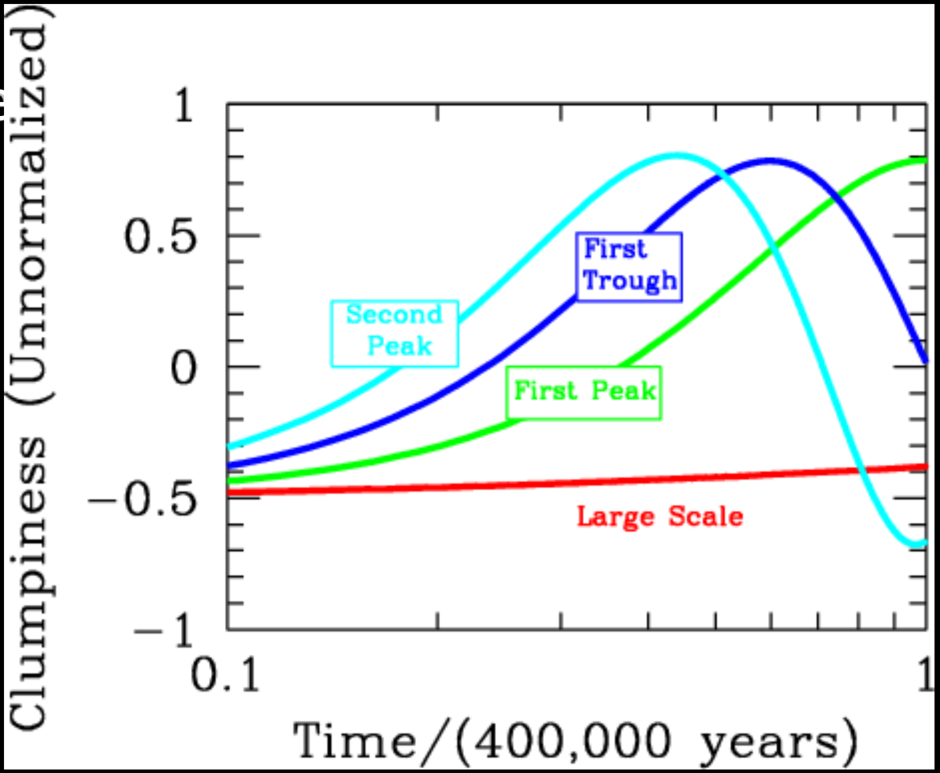


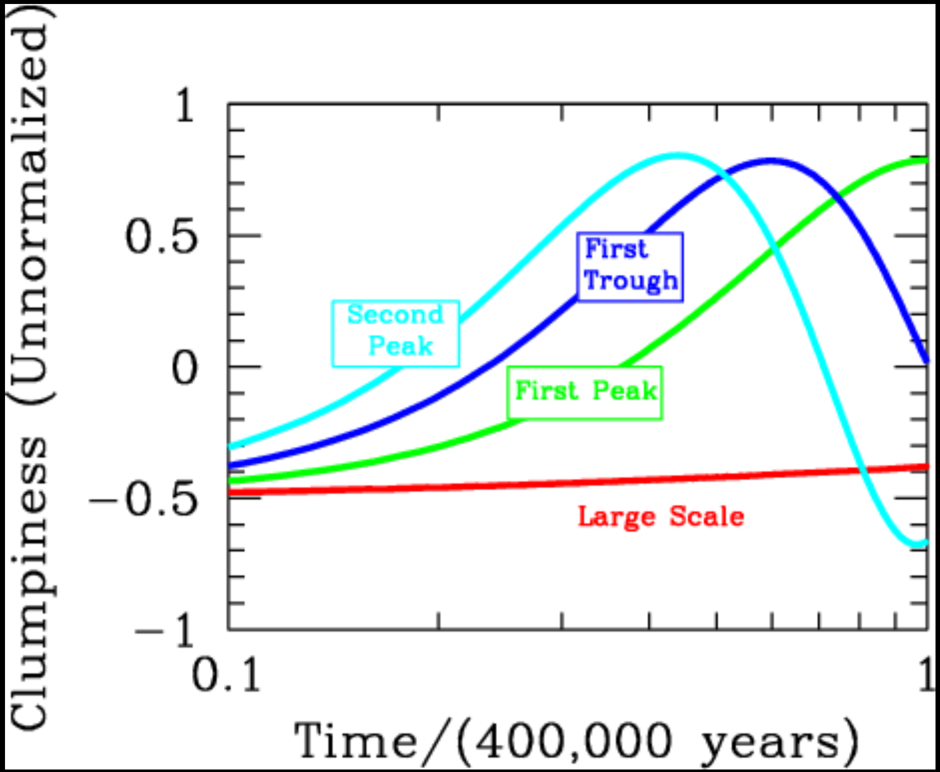
S2: Modes of different wavelengths start evolving at different times (short wavelength earlier; long wavelength later)

Evidence

<u>Dialog</u>

S1: So what?

S2: Some modes have reached maximal amplitude at recombination. We see these as peaks. Others peaked too soon; we see these as troughs. All modes exist: in our single snapshot, we see only some of them!

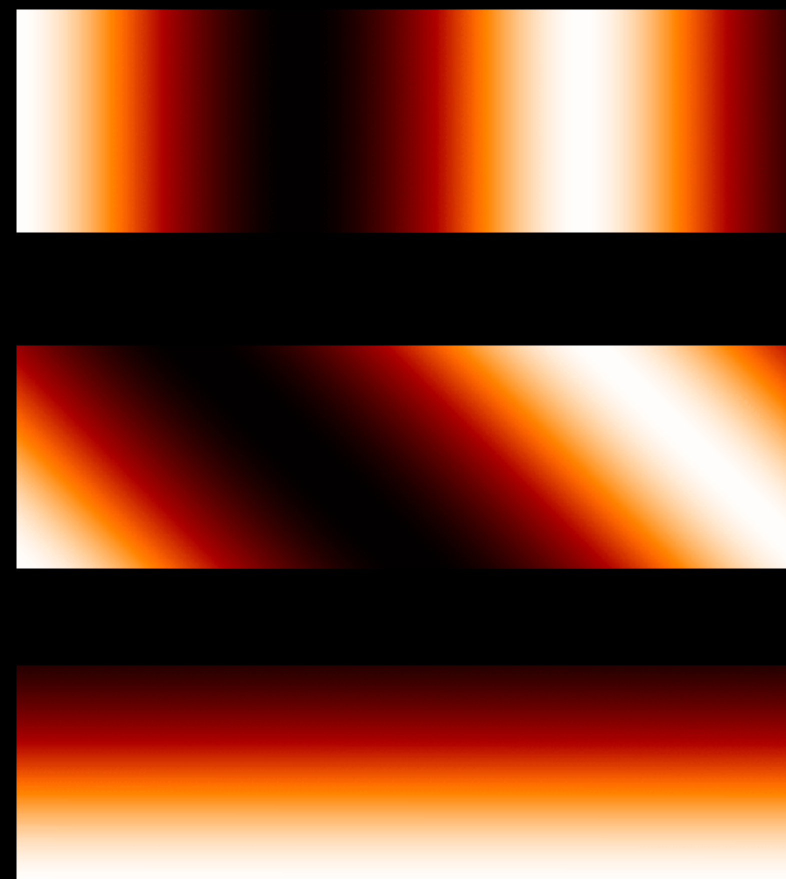


Evidence

<u>Dialog</u>

S1: Well, that is a beautiful answer, but it neglects one key thing. A given wavelength has an infinite number of modes. The CMB first peak, first example, comes from a sum over an infinite number of Fourier modes, each with a different orientation.

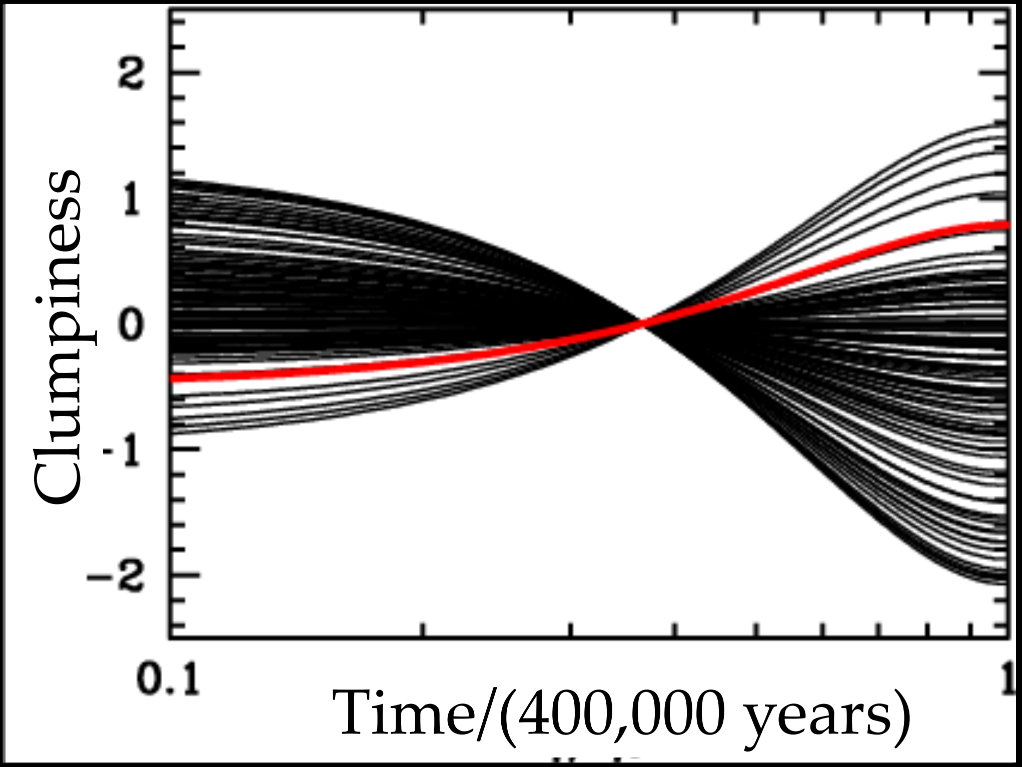
S2: So what?



Evidence

Dialog

S1: You assumed in your plot that the first peak mode started with constant amplitude. Now, you' ve got to assume that *all* of the inifinite modes start with constant amplitude. Who organized the phases so they were all the same?

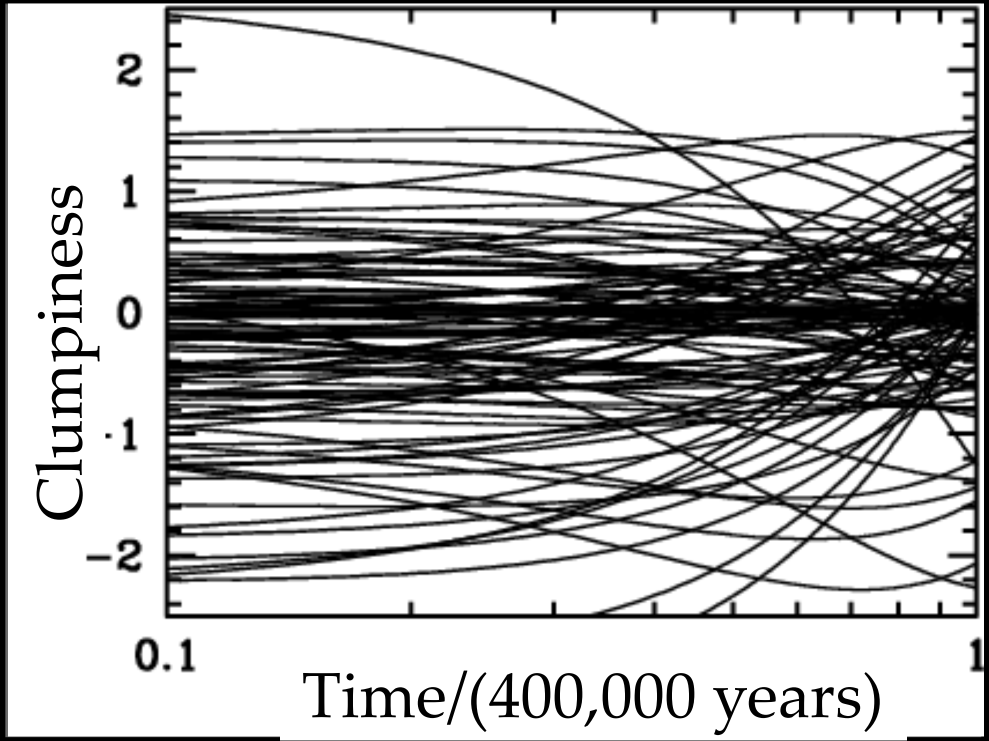


S2: Hmm

Evidence

Dialog

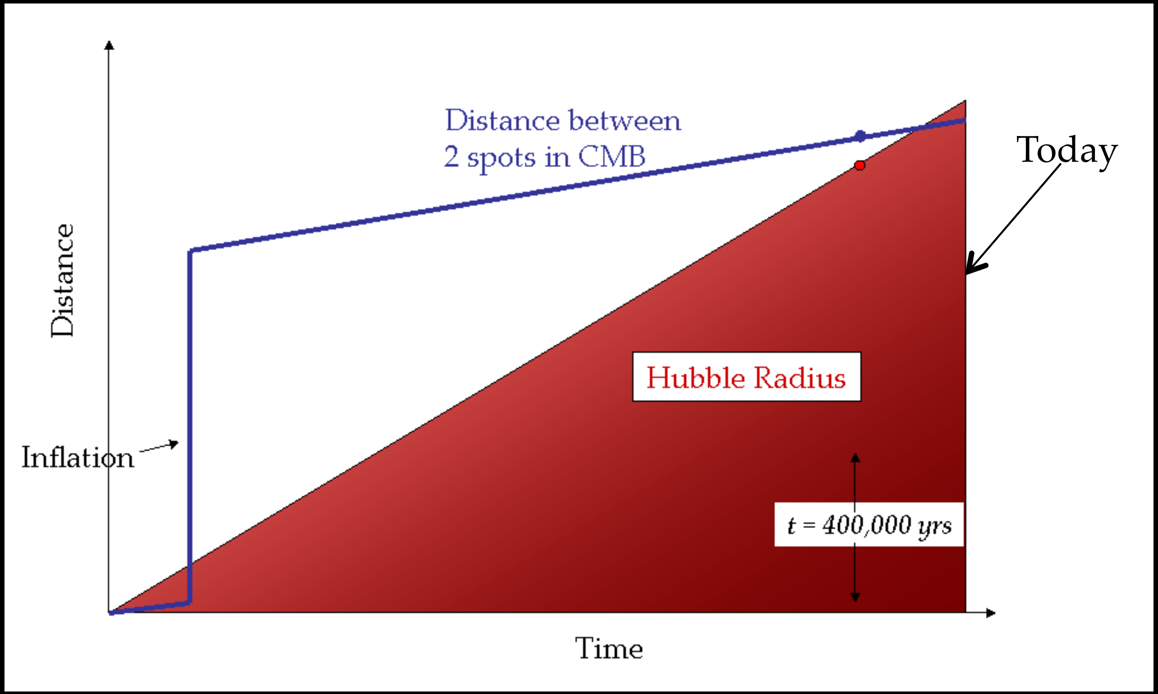
S1: If the phases were random, the amplitudes of the first peak modes would look like this. Same with "first trough" modes, and we wouldn't get a coherent series of peaks and trough. We'd just see noise.



Evidence

Dialog

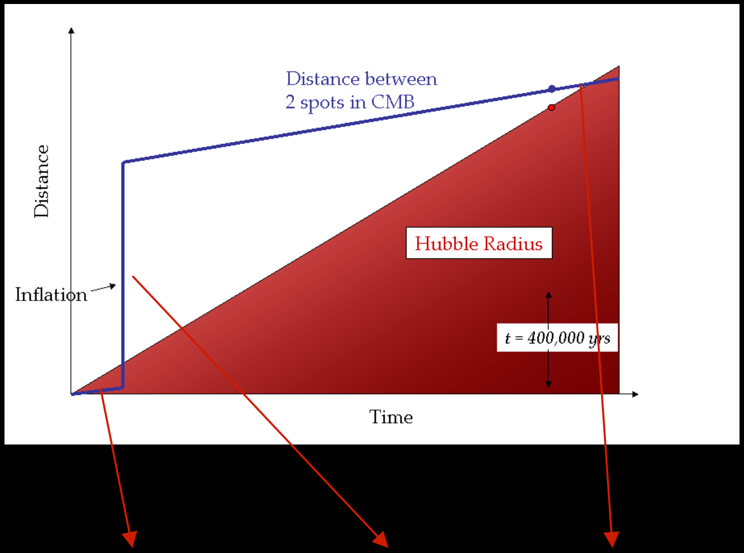
S1: Remember the diagram from the 1980's that shows when modes leave and then re-enter the horizon?

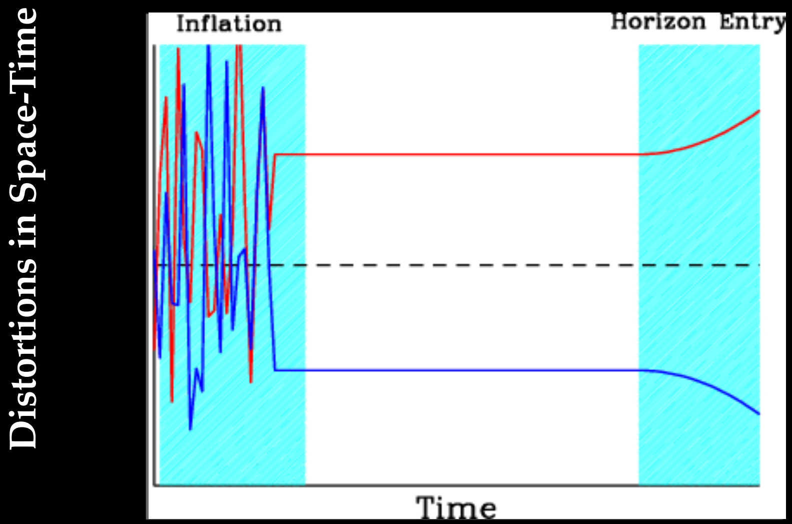


Evidence

Dialog

S1: Inflation sets the phases automatically. Quantum fluctuations during inflation freeze out as they leave the horizon and then begin oscillating much later when they re-enter. So all modes enter the horizon with constant amplitude





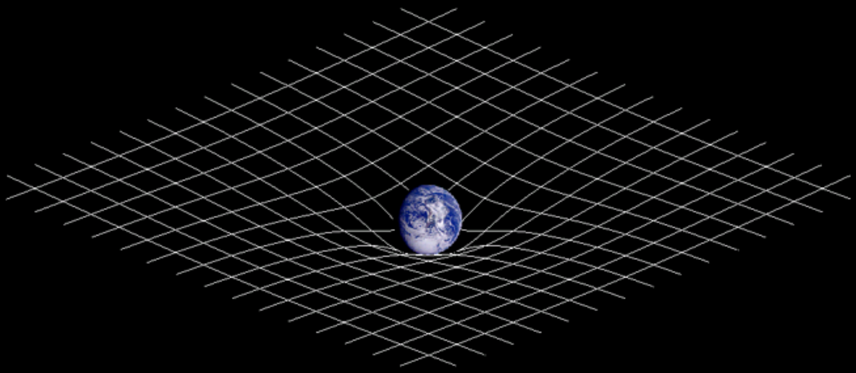
Physics Behind Inflation

Inflation has passed all observational tests. The challenge now is to understand the underlying physics. Two tools have emerged:

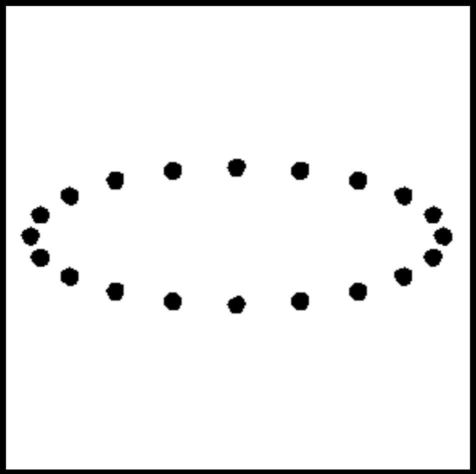
- Gravitational Waves: Focus of Heroic Experimental Effort
- Non-Gaussianity: Exciting Recent Theoretical Developments

Gravitational Waves

Inflation produces both *scalar* and *tensor* perturbations. The former have been produced: the goal is to detect the latter

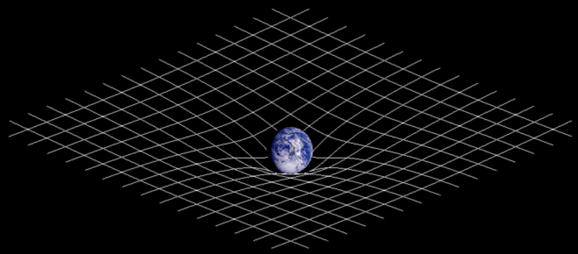


Scalar/Density

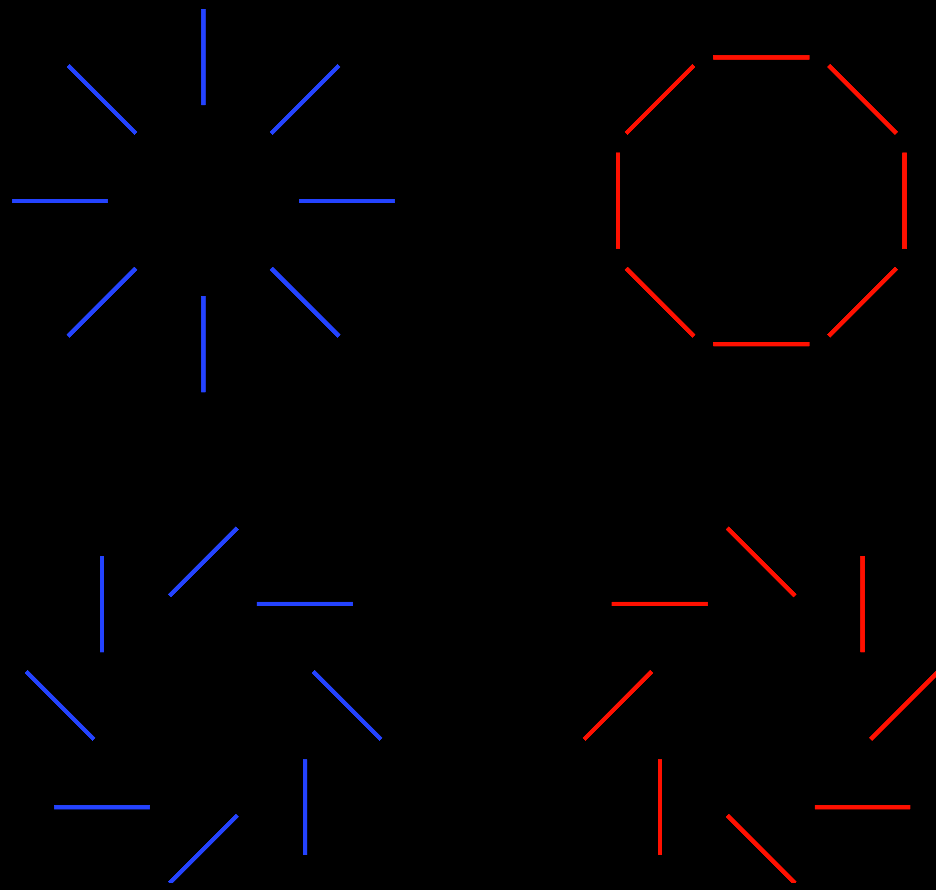


Tensor/Gravitational Waves

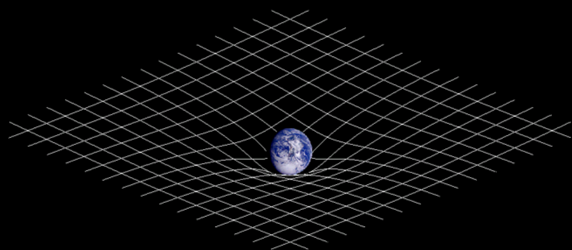
Gravitational Waves

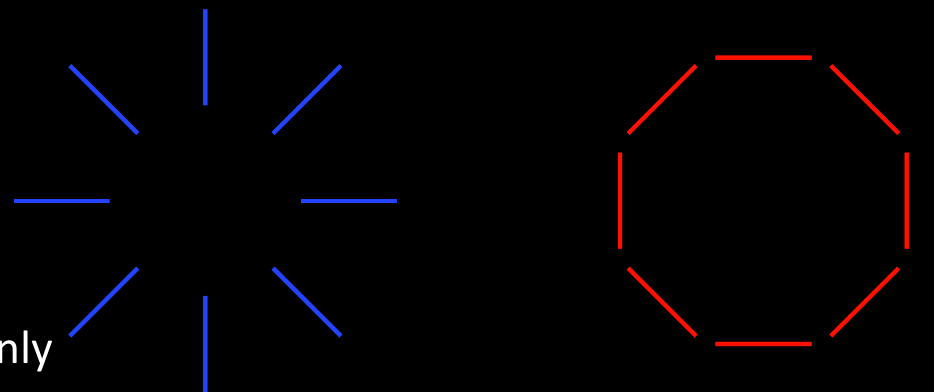


Density perturbations
produce only E-modes

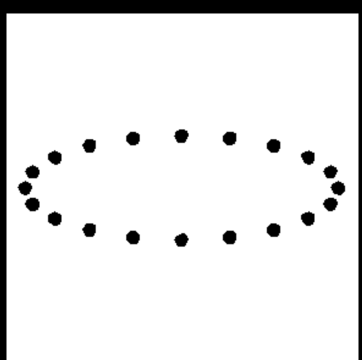


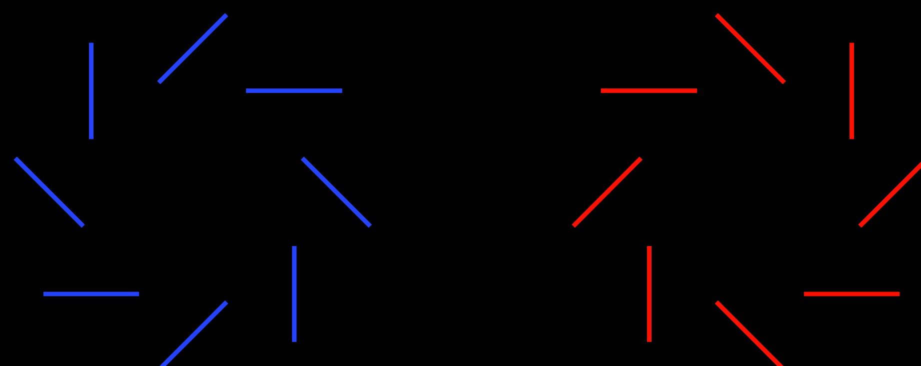
Gravitational Waves





Density perturbations produce only E-modes of polarization

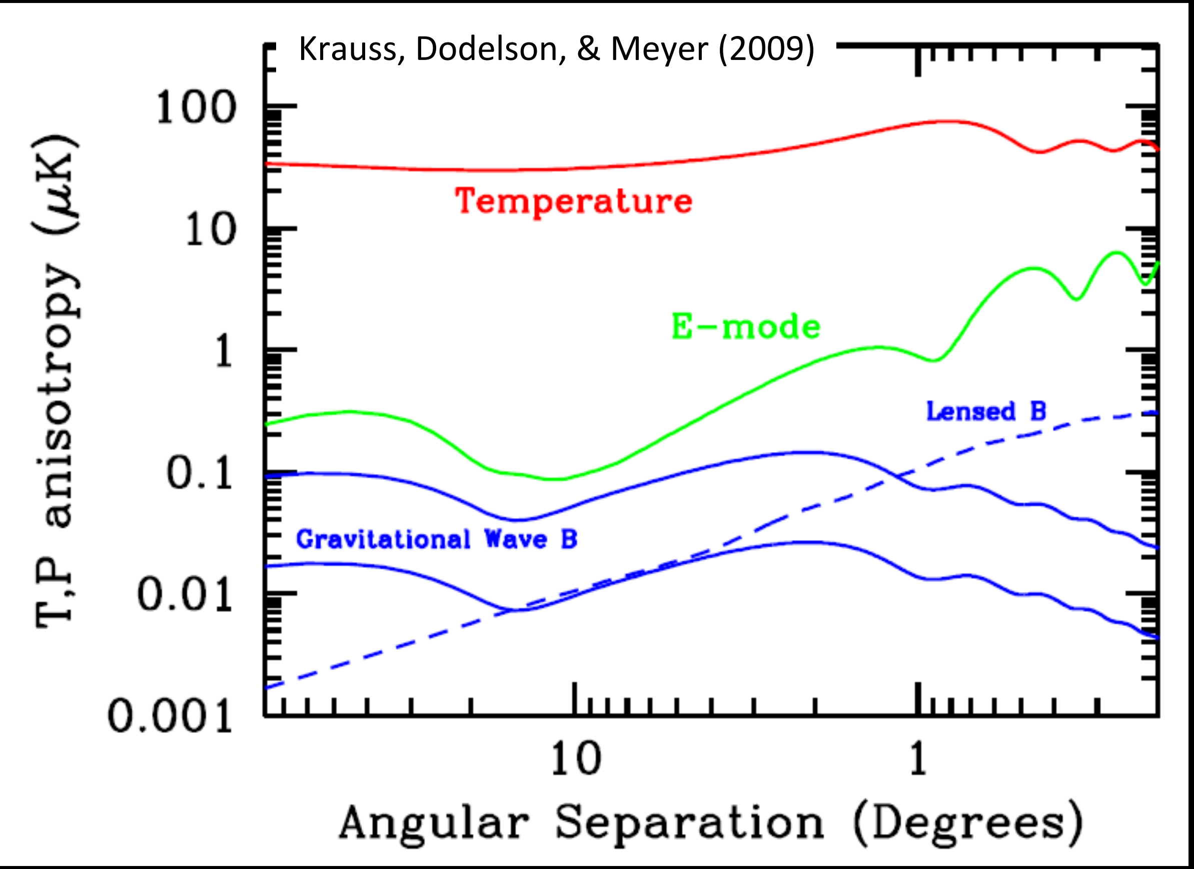




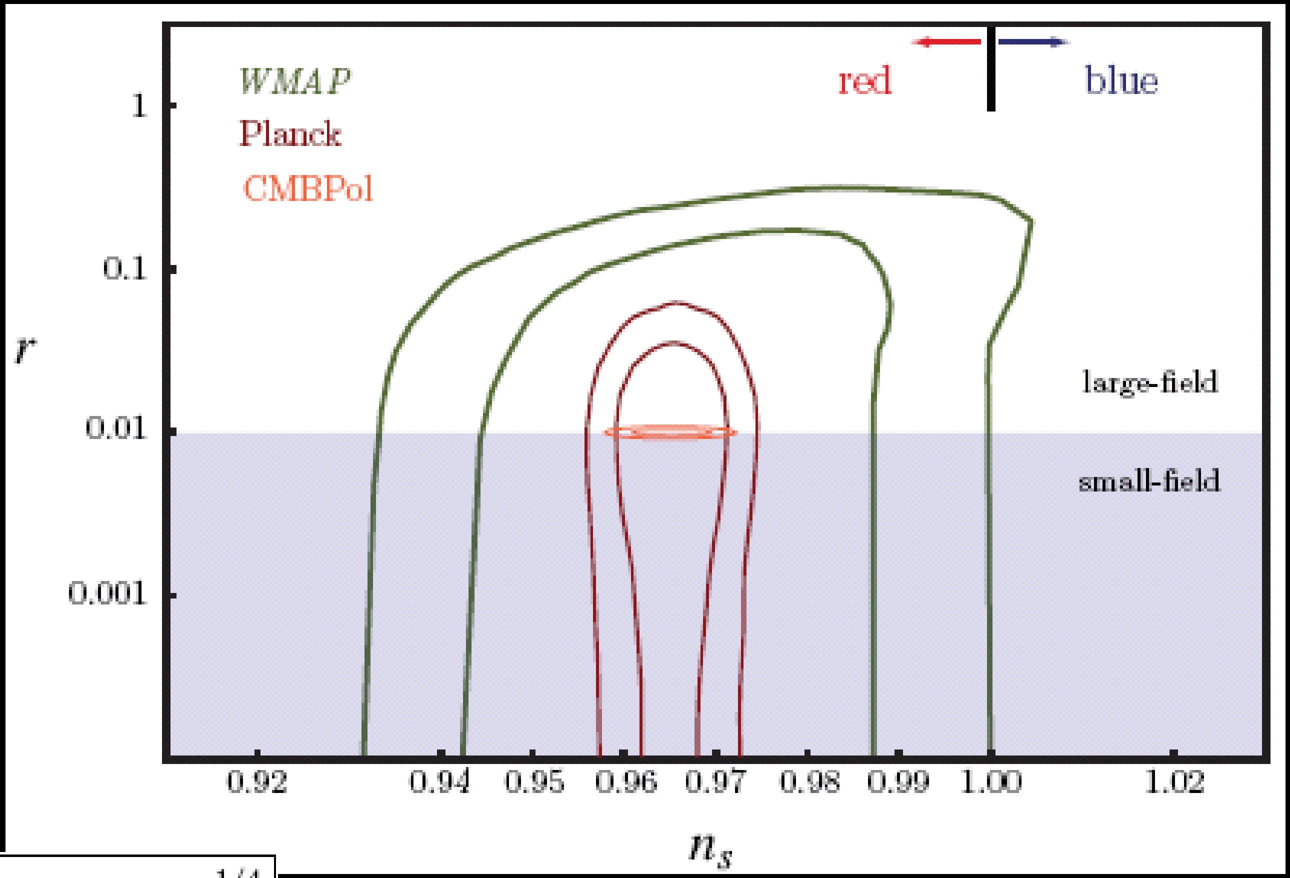
Gravity waves produce E- and B- modes

Gravitational Waves

Amplitude of B-mode spectrum model-dependent, but characteristic spectral shape

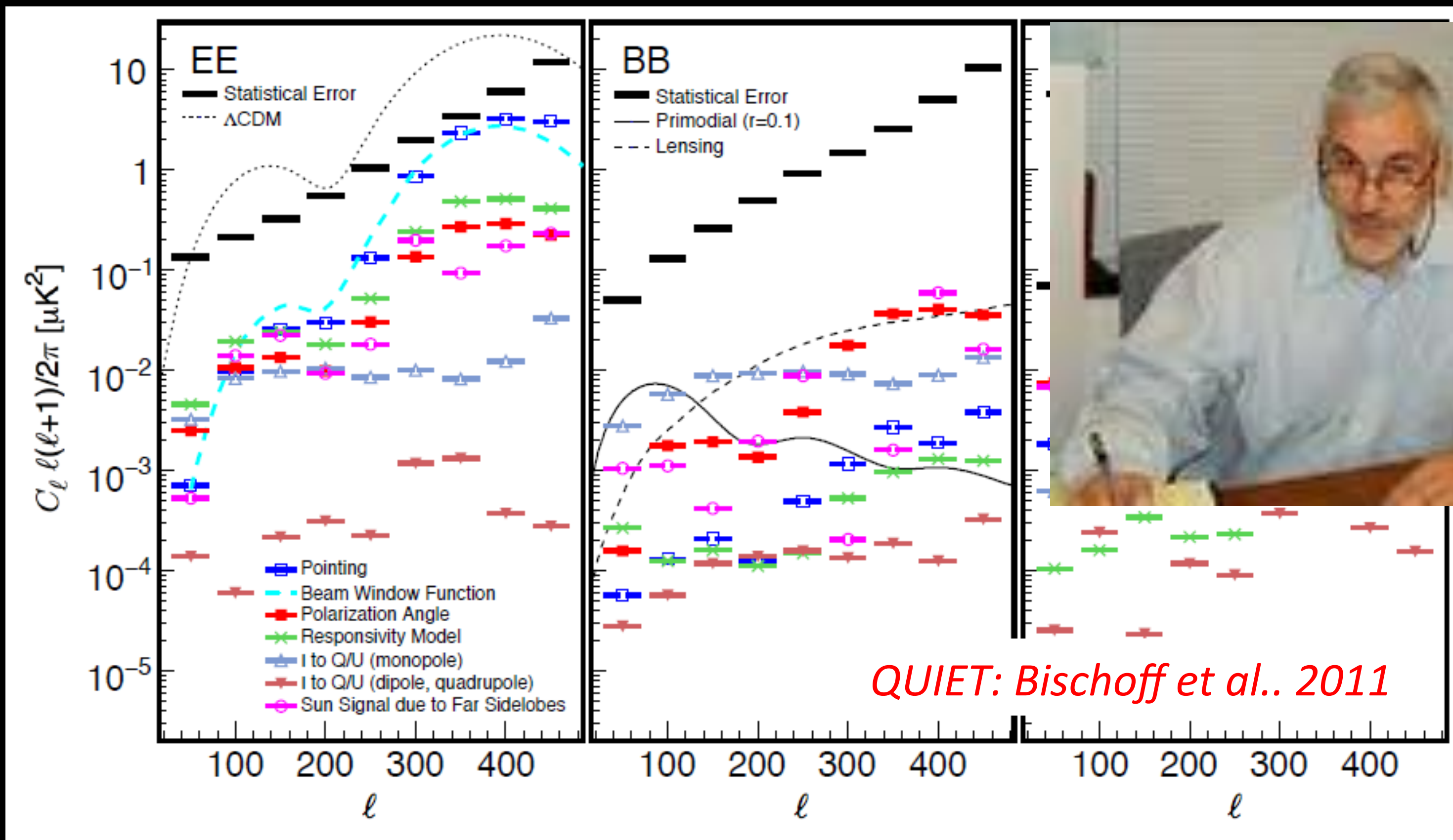


Gravitational Waves



$$V^{1/4} = 1.06 \times 10^{16}\ \text{GeV} \left(\frac{r_\star}{0.01}\right)^{1/4}$$

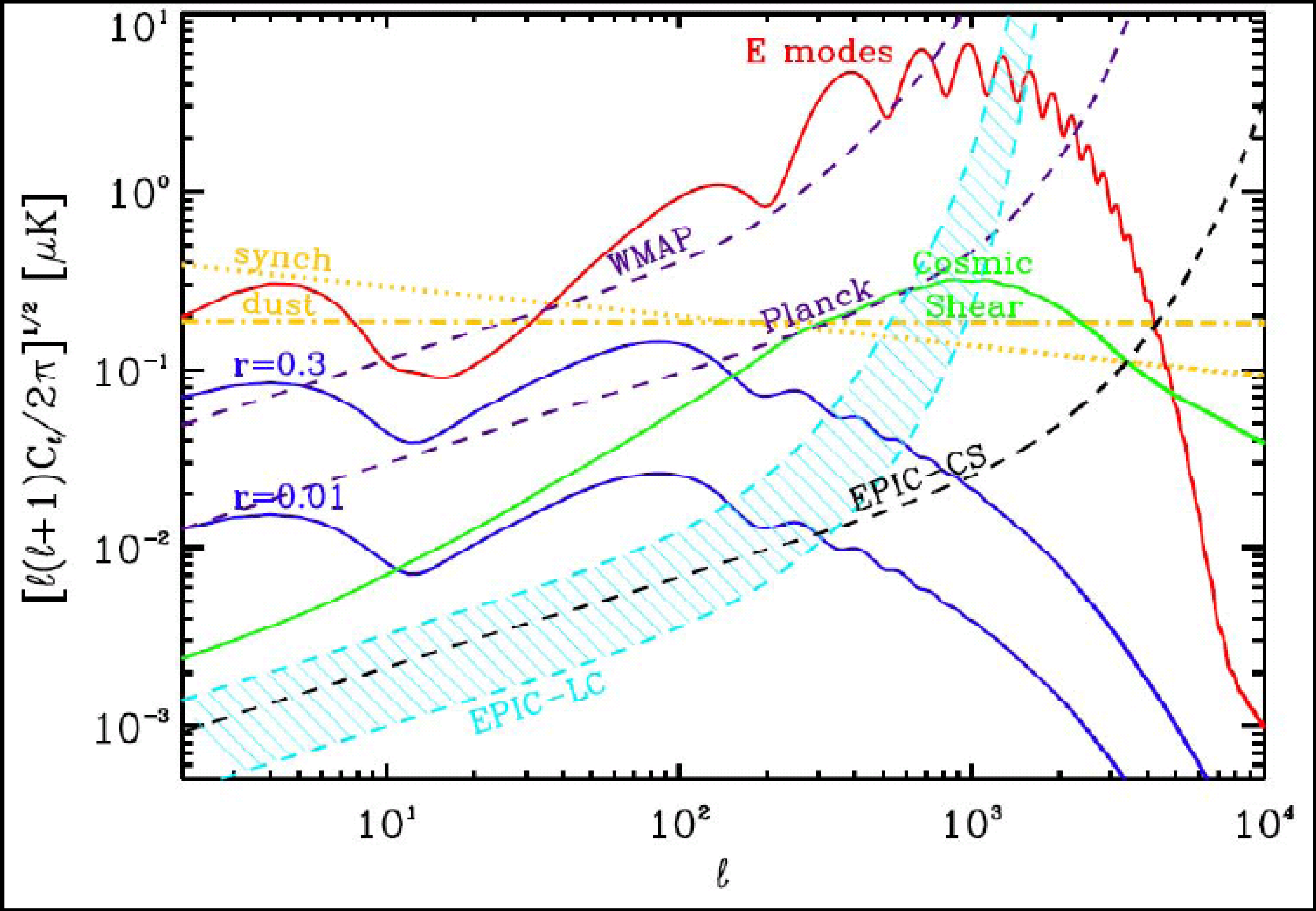
Gravitational Waves



QUIET: Bischoff et al.. 2011

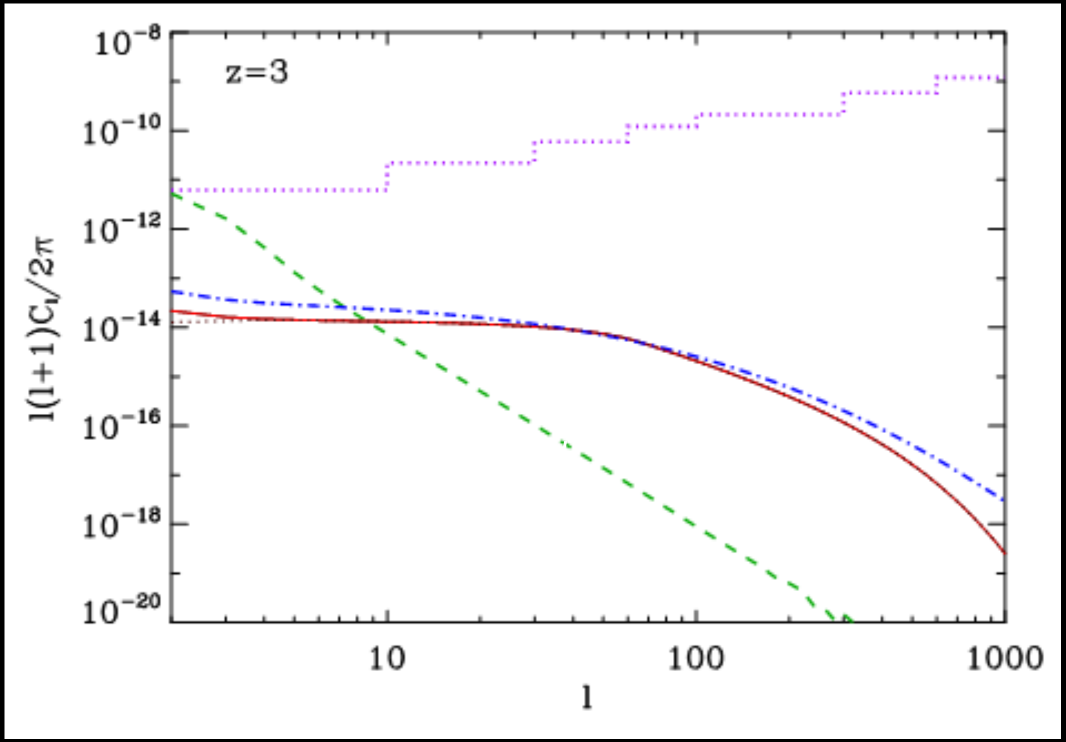
Gravitational Waves

Ambitious plans for the future



Gravitational Waves Elsewhere

Primordial Gravitational Waves also produce **lensing** B-modes. B-mode lensing (call it ω) spectrum peaks on the largest scales*

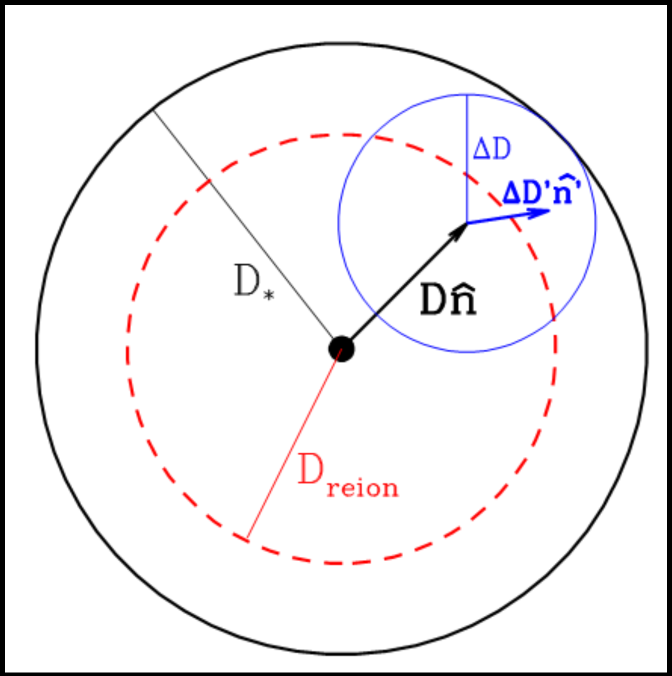


Dodelson, Rozo, & Stebbins (2003)
Sarkar et al. (2008)
Dodelson (2010)
Masui & Pen (2010)
Book, Kamionkowski, & Schmidt (2011)

*Might be good way to test for bubble collisions predicted by eternal inflation

Gravitational Waves Elsewhere

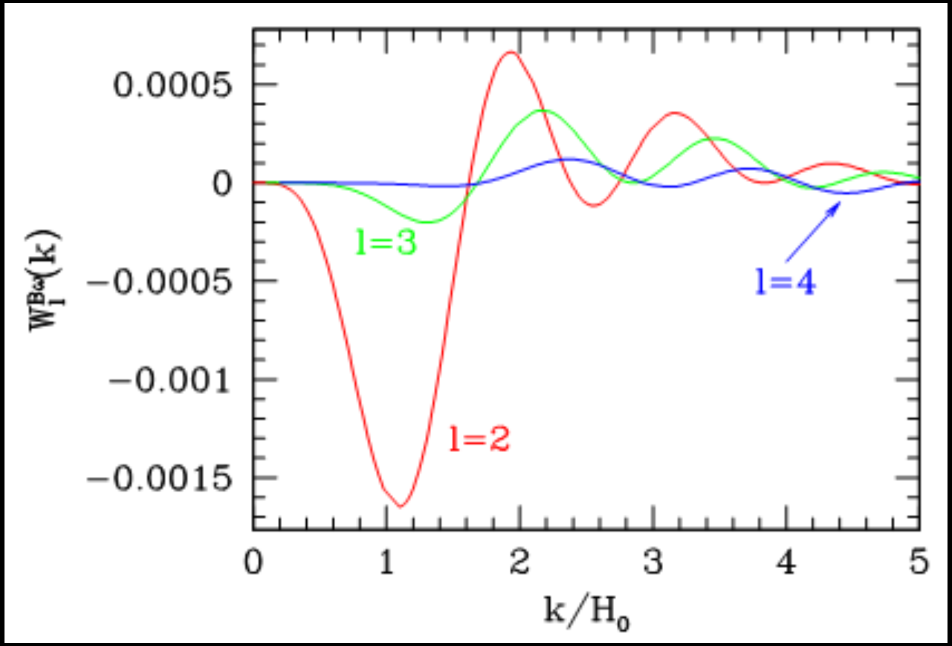
The same gravitational wave that sources polarization after reionization also transforms the shapes of galaxies: these two signals are correlated!



Cross-Correlation is non-negligible

$$C_l^{\omega B} = \int dk W_l^{\omega B}(k) P_{GW}(k)$$

Depends on l and redshift of source galaxies; might devise weighting scheme to optimize signal. Detection would eliminate systematics.



Non-Gaussianity

Choose a gauge

$$ds^2 = -dt^2 + a(t)^2 e^{2\zeta(x)} dx_i dx_i$$

ζ describes perturbations *(5/3)Φ*

$$\left\langle \zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3) \right\rangle = (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) F(k_1, k_2, k_3)$$

3-point function basic measure of NG

Translation invariance implies k's form a triangle

Shape/amplitude depends on 3 variables

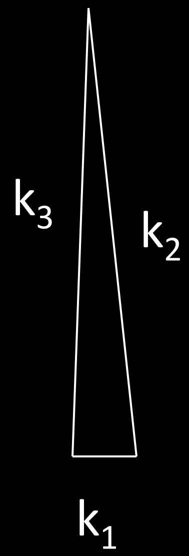
Non-Gaussianity

Generic prediction of single-field inflation *(consistency relation):*

$$\lim_{k_1 \to 0}\left\langle \zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3)\right\rangle = 4 f_{NL}(2\pi)^3\delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)P(k_1)P(k_2)$$

Squeezed limit

Power spectra of long and short wavelength modes



Amplitude of NG determined by Deviation from scale invariance (n=1)

$$f_{NL} = \frac{n-1}{4} \sim 1\%$$

Non-Gaussianity

Current observations

WMAP	$-4 < f_{NL} < 80\,(95\%CL)$	Smith, Senatore, & Zaldarriaga (2009)
SDSS	$-1 < f_{NL} < 63\,(95\%CL)$	Slosar et al. (2008)

Upcoming observations

Planck	$f_{NL} < 3-5$
DES	$f_{NL} < 5-20$

If local NG is found in the next decade, single field models of inflation will be falsified

Non-Gaussianity: Effective Field Theory

Over the last several years, theorists have imported Effective Field Theory techniques to analyze perturbations generated during inflation

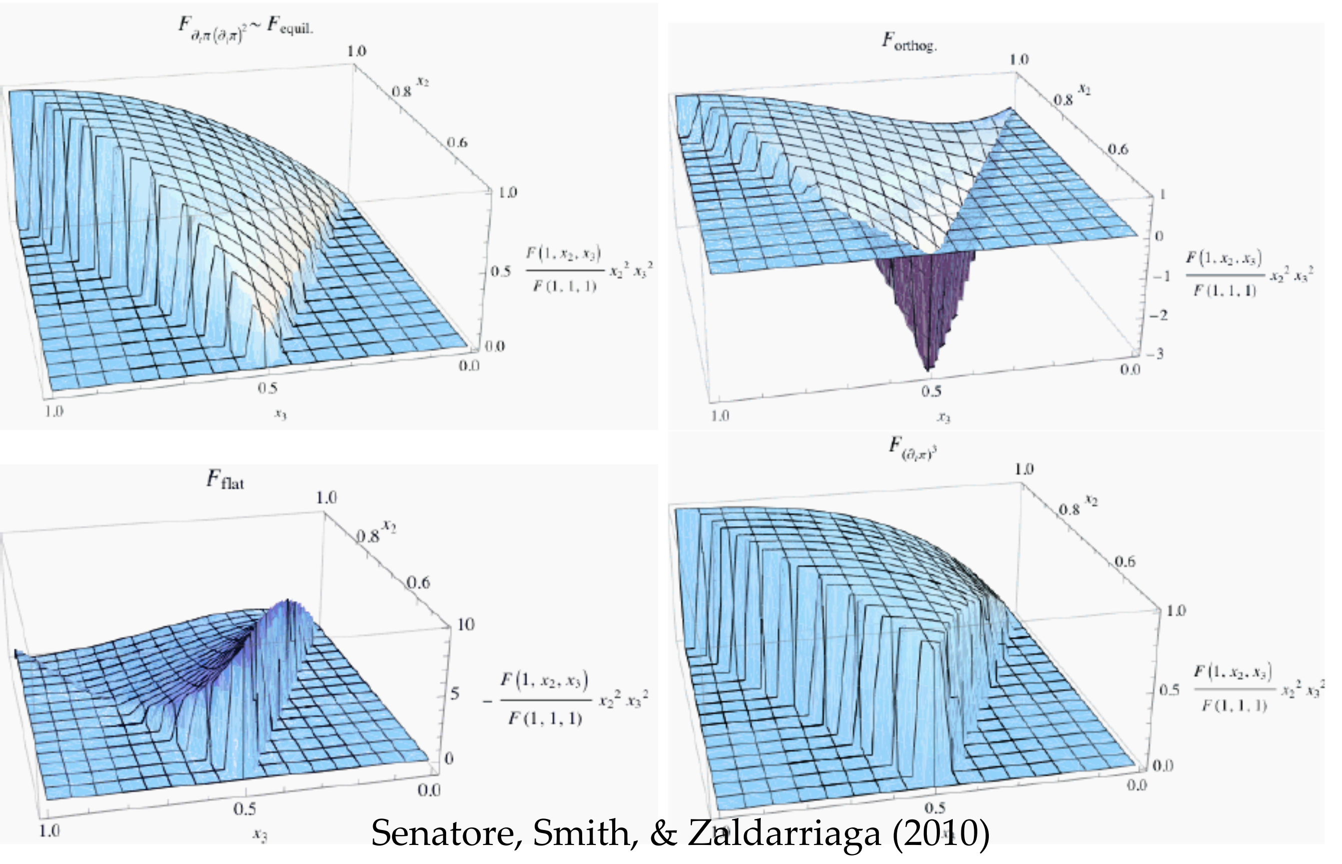
$$S_\pi = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{1}{a^2}(\partial_i\pi)^2\right)\right.$$
$$\left. + \frac{\dot{H}M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\dot{\pi}\frac{1}{a^2}(\partial_i\pi)^2 - \frac{\dot{H}M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\left(1+\frac{2}{3}\frac{\tilde{c}_3}{c_s^2}\right)\dot{\pi}^3\right.$$

Time diffeomorphisms are broken (because inflation ends), leading to a Goldstone boson (π) whose interactions are dictated by symmetry (spatial diffeomorphisms). This is the field whose fluctuations give rise to scalar perturbations.

Cheung, Creminelli, Fitzpatrick, Kaplan, & Senatore (2007)

Non-Gaussianity: Effective Field Theory

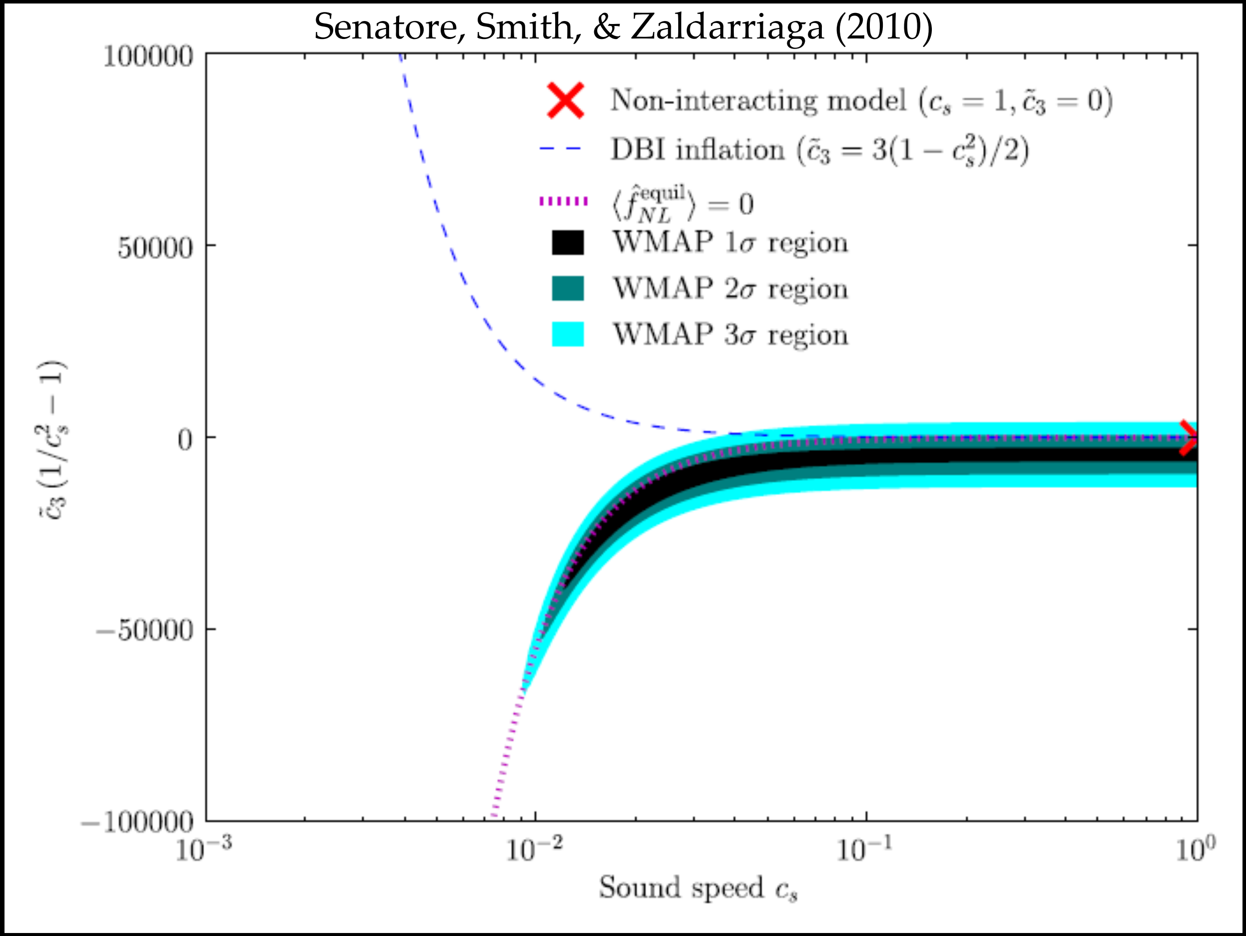
Each term in the action corresponds to a distinctive bispectrum *F*



Senatore, Smith, & Zaldarriaga (2010)

Non-Gaussianity: Effective Field Theory

Use template fitting to extract constraints on each coefficient using, e.g., CMB data



Non-Gaussianity: Large Scale Bias

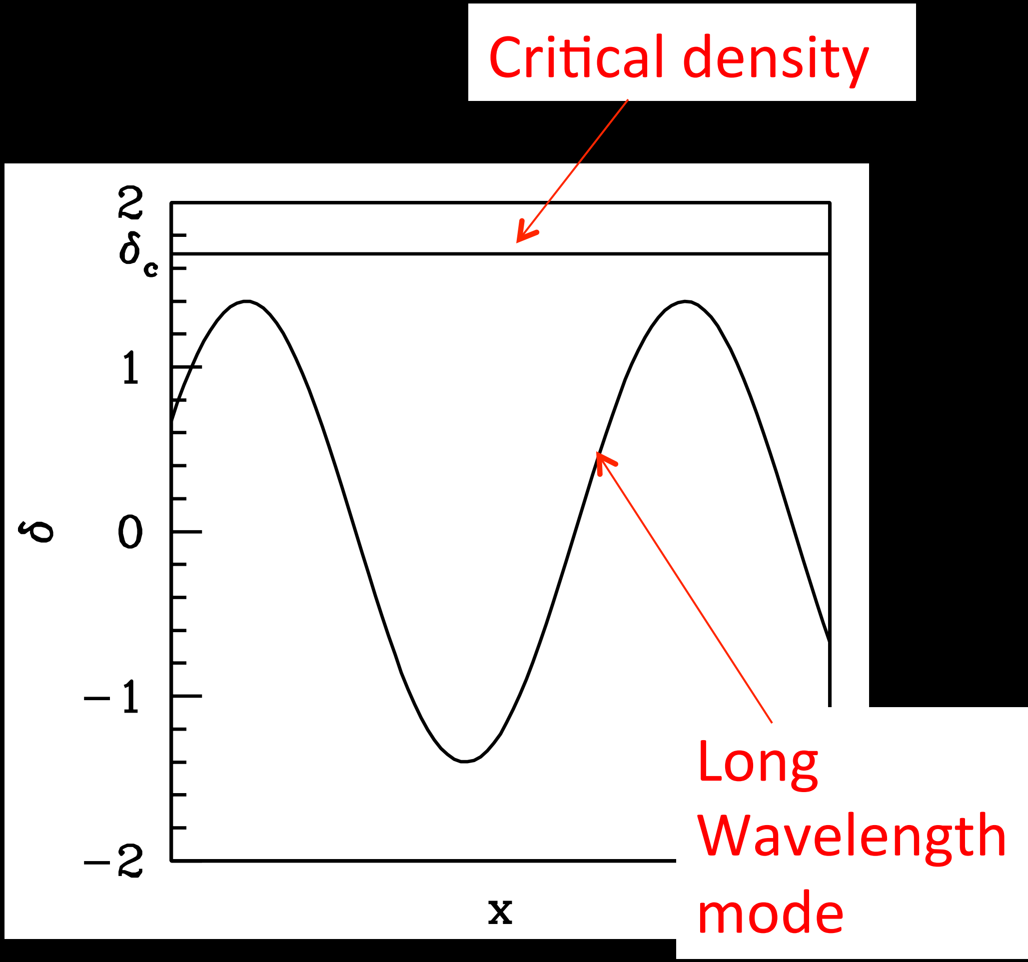
Local Non-Gaussianity corresponds to:

$$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G{}^2(x)$$

Dalal et al. (2008) showed that this leaves a characteristic imprint on large scale structure

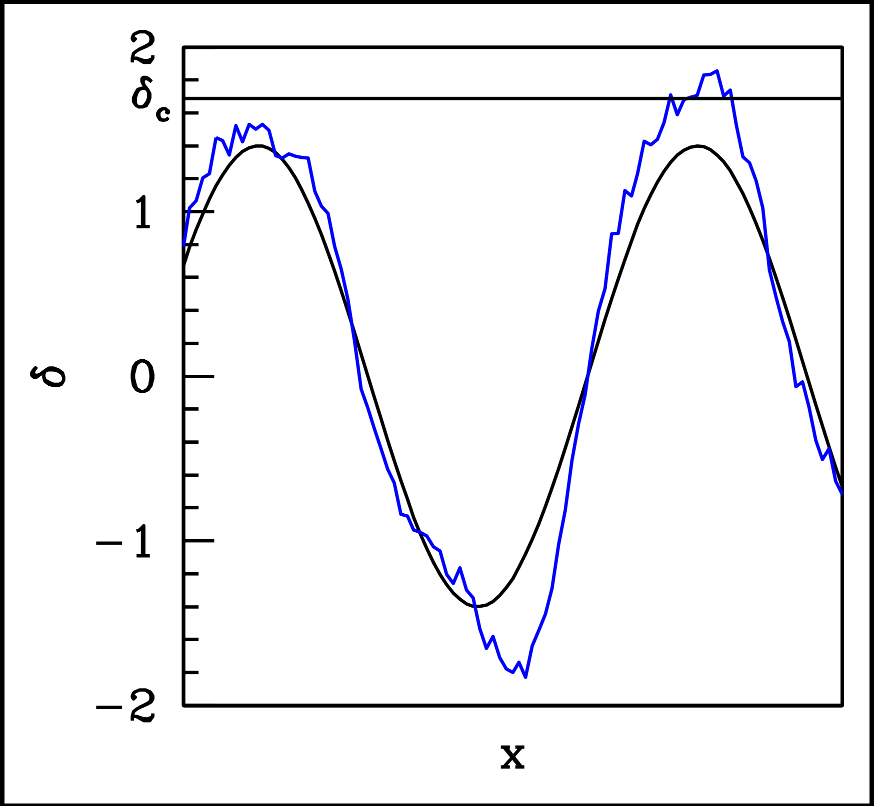
Non-Gaussianity: Large Scale Bias

Consider the density field in 1D. A given region is *collapsed* (i.e. forms a halo) if the density is larger than a critical value.



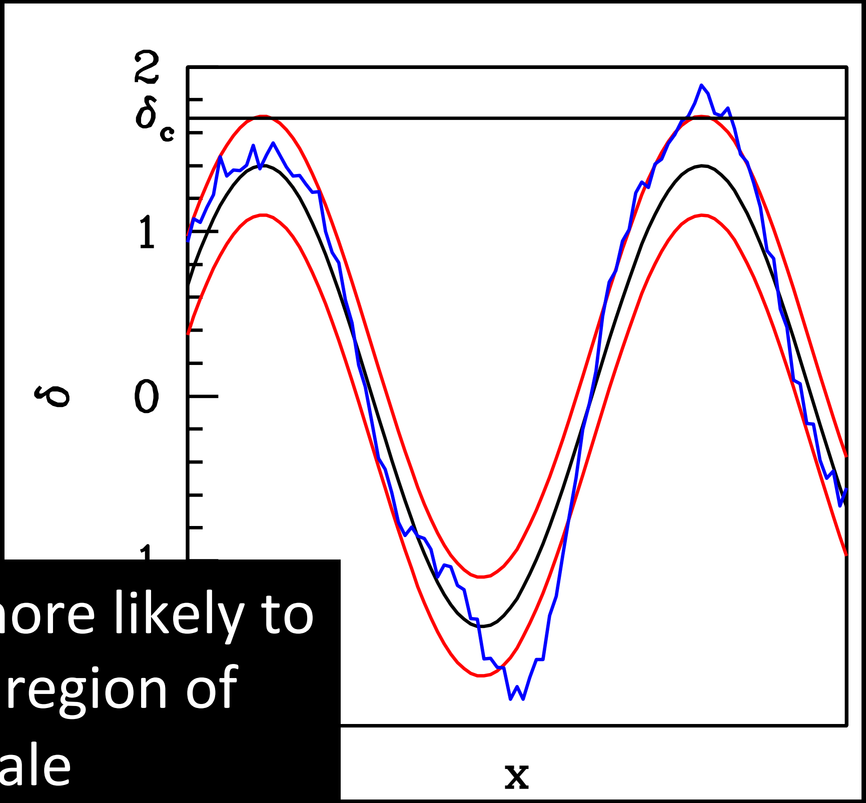
Non-Gaussianity: Large Scale Bias

Add in short wavelength modes. For this one realization, the second peak has collapsed into a halo.



Non-Gaussianity: Large Scale Bias

More generally, short wavelength modes drawn from a distribution with given rms (red curves)

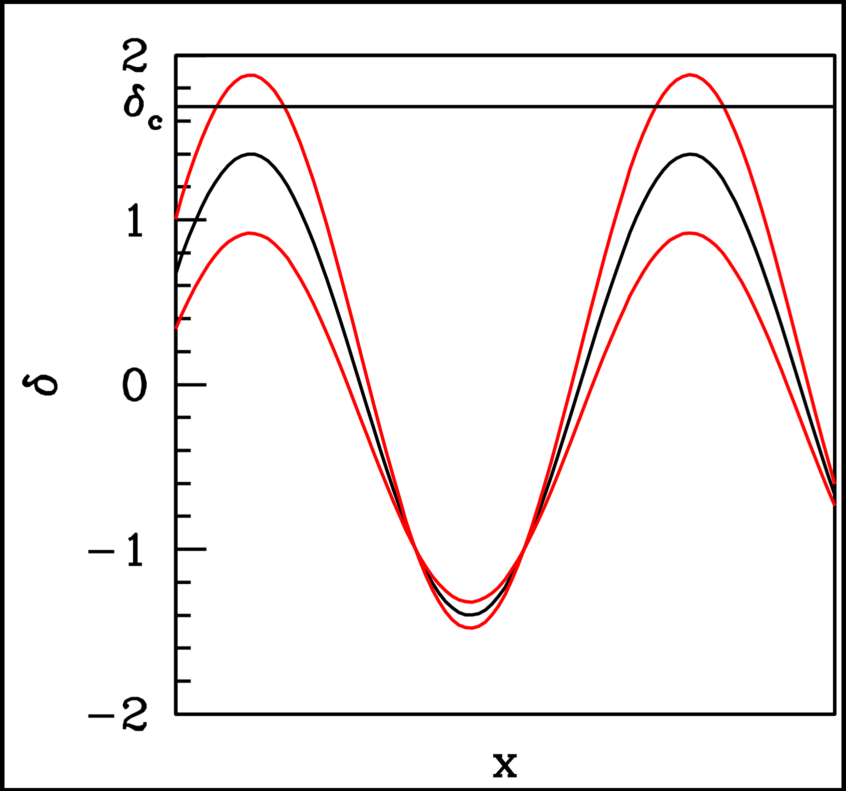


Halos more likely to form in region of large scale overdensity = *bias*

Non-Gaussianity: Large Scale Bias

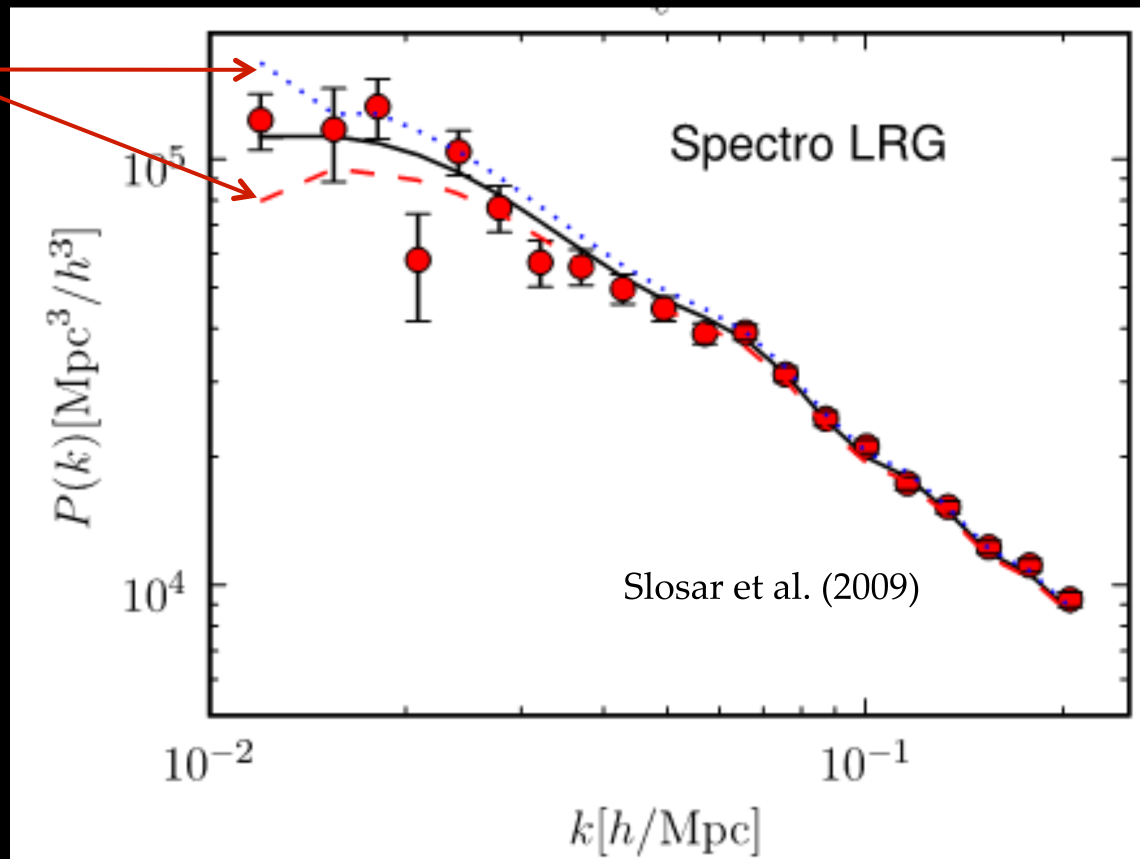
$$\delta_s(x) \propto k^2 \Phi_s (1 + 2 f_{NL} \Phi_l)$$

Change with primordial NG: more small-scale fluctuations in region of large scale over-density → more bias on large scale



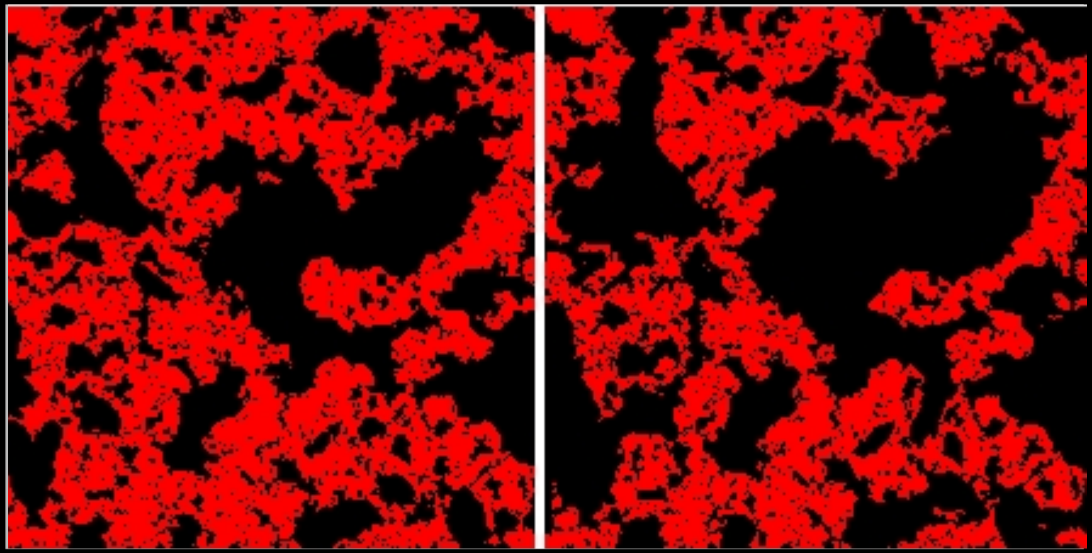
Non-Gaussianity: Large Scale Bias

$f_{NL} = \pm 100$

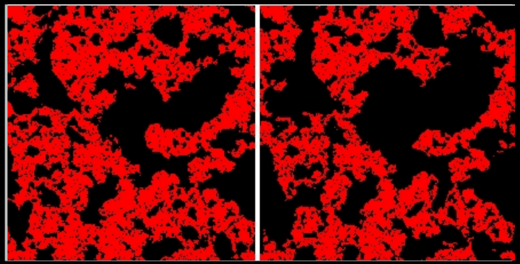


Non-Gaussianity Elsewhere

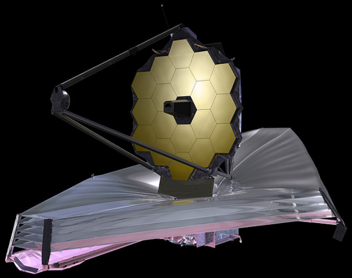
Reionization proceeds more rapidly in NG models (Adshead, Baxter, Dodelson, Lidz 2012)



Non-Gaussianity Elsewhere



May learn about inflation from surveys from infrared or 21 cm observations



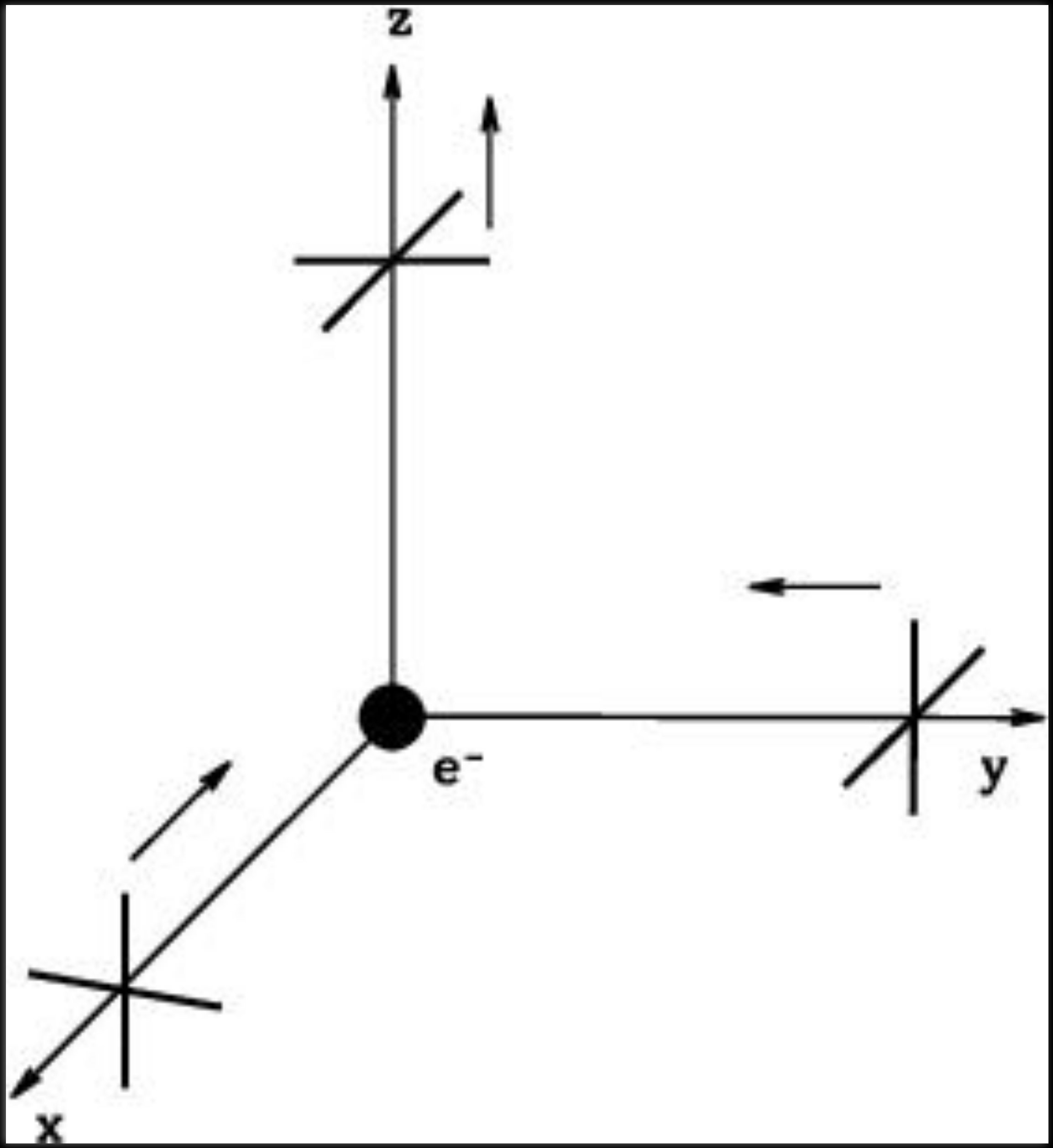
2020: Scenario I

- B-modes detected by ground-based experiments
- Gravitational wave amplitude precisely determined by 3 CMB experiments
- Scale of inflation together with SUSY discovery at LHC leads to unified model for dark matter and inflation

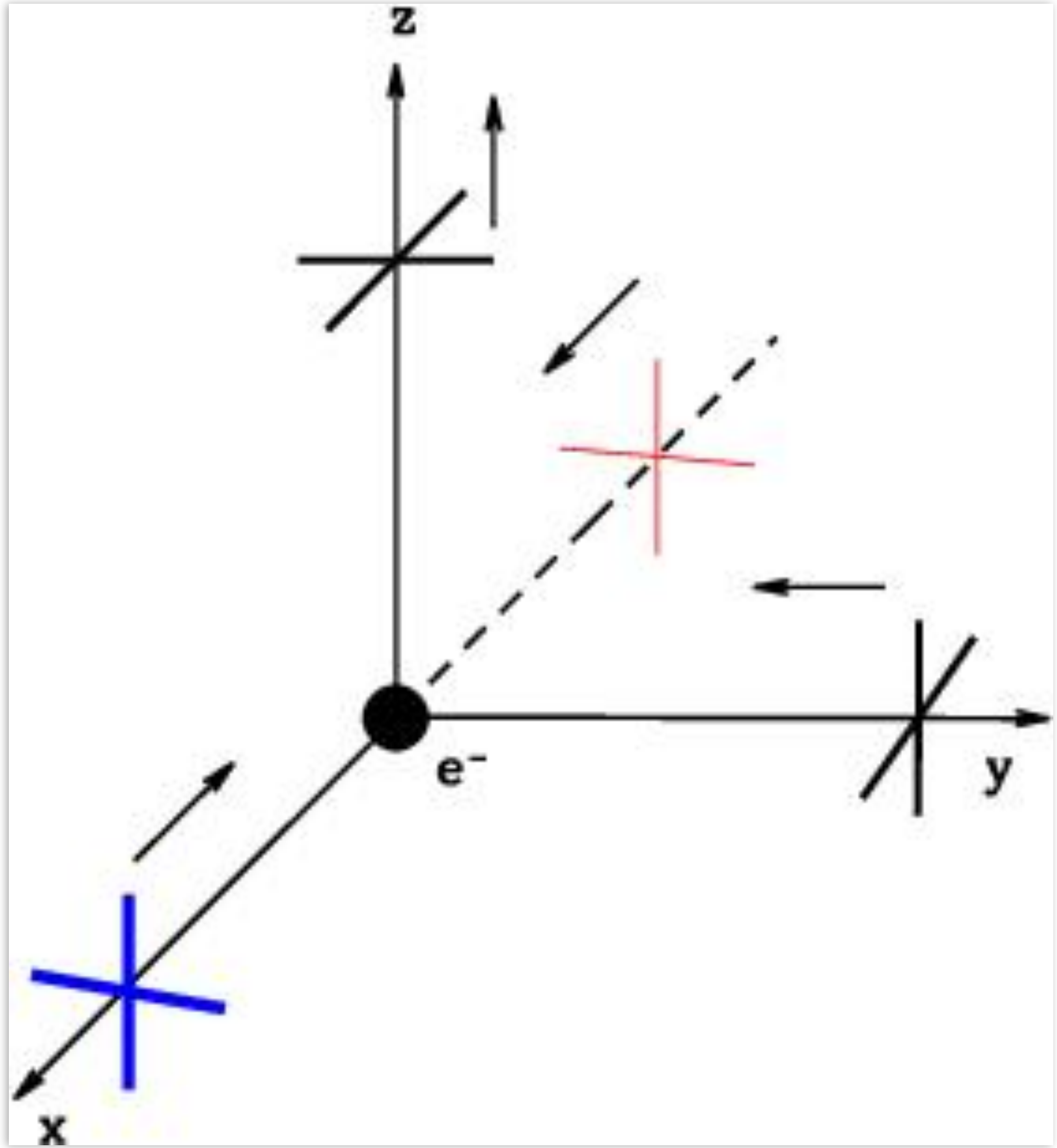
2020: Scenario II

- No B-modes detected
- Primordial Non-Gaussianity detected by Planck, in galaxy distribution of Dark Energy Survey, and in 21 cm Epoch of Reionization experiment LOFAR
- Cosmology in disarray: Is inflation right? Alternatives?

Isotropic radiation field produces no polarization after Compton scattering



Radiation with a
dipole produces
no polarization



Non-Gaussianity

Start from

$$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G{}^2(x)$$

Take the Laplacian and consider potential well troughs

$$\nabla^2\Phi = \nabla^2\Phi_G + 2f_{NL}\left[\Phi_G\nabla^2\Phi_G + \left|\nabla\Phi_G\right|^2\right]$$

$$\rightarrow \nabla^2\Phi_G + 2f_{NL}\Phi_G\nabla^2\Phi_G$$

Non-Gaussianity

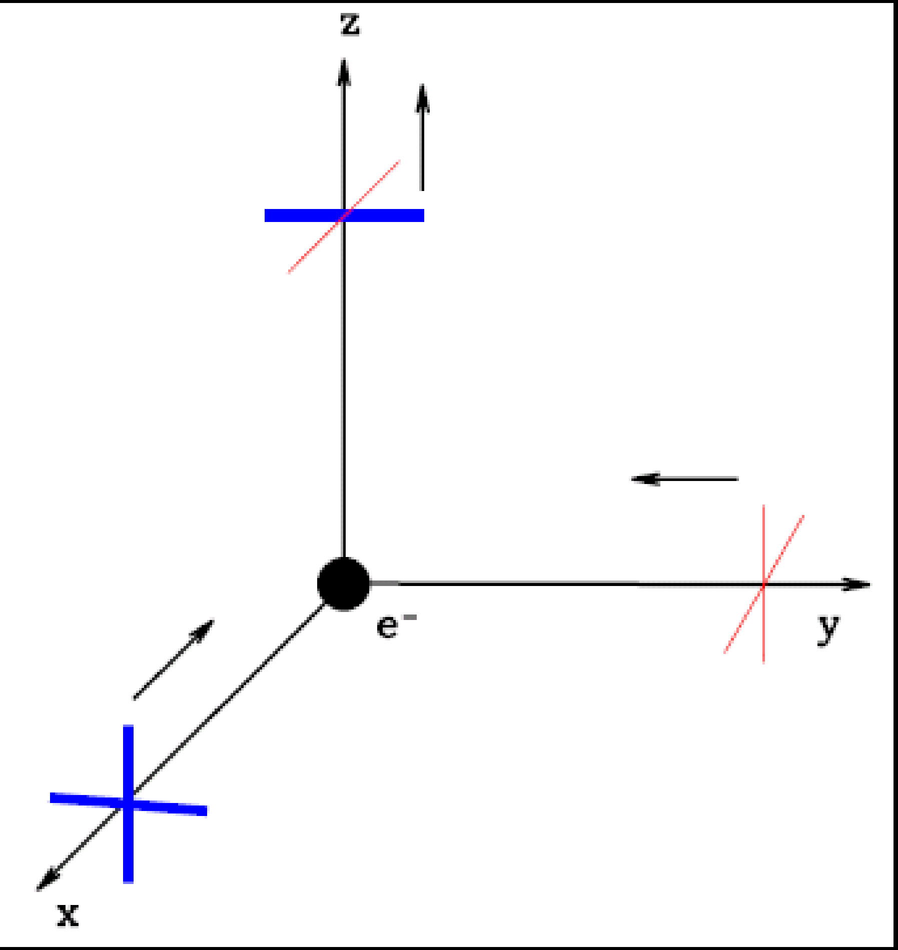
$$\nabla^2\Phi = \nabla^2\Phi_G + 2 f_{NL}\Phi_G\nabla^2\Phi_G$$

Apply Poisson Equation

$$\delta = \delta_G + 2 f_{NL}\Phi_G\delta_G$$

NG term leads to enhancement in overdensity near peaks for positive f_{NL}

Compton scattering of unpolarized anisotropic radiation produces polarization



- Require Quadrupole (small before *t=400,000* yrs)
- Require Compton scattering (rare after *t=400,000* yrs)
- Signals factor of 10 smaller than temperature anisotropies