Inflation

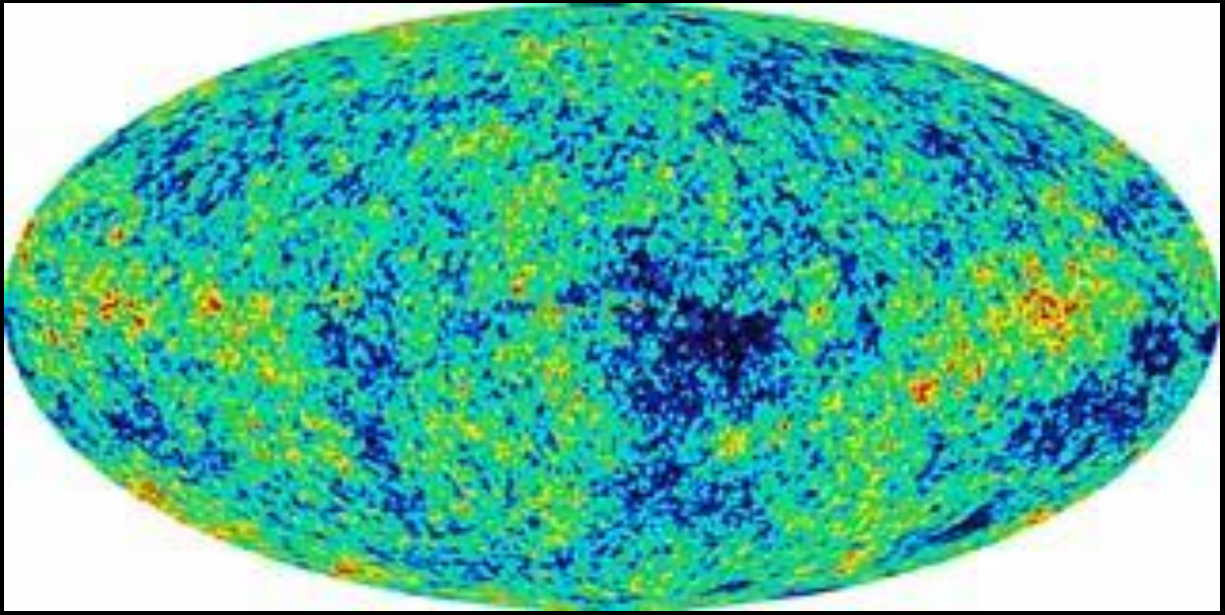
Evidence

Gravitational Waves

Non-Gaussianity

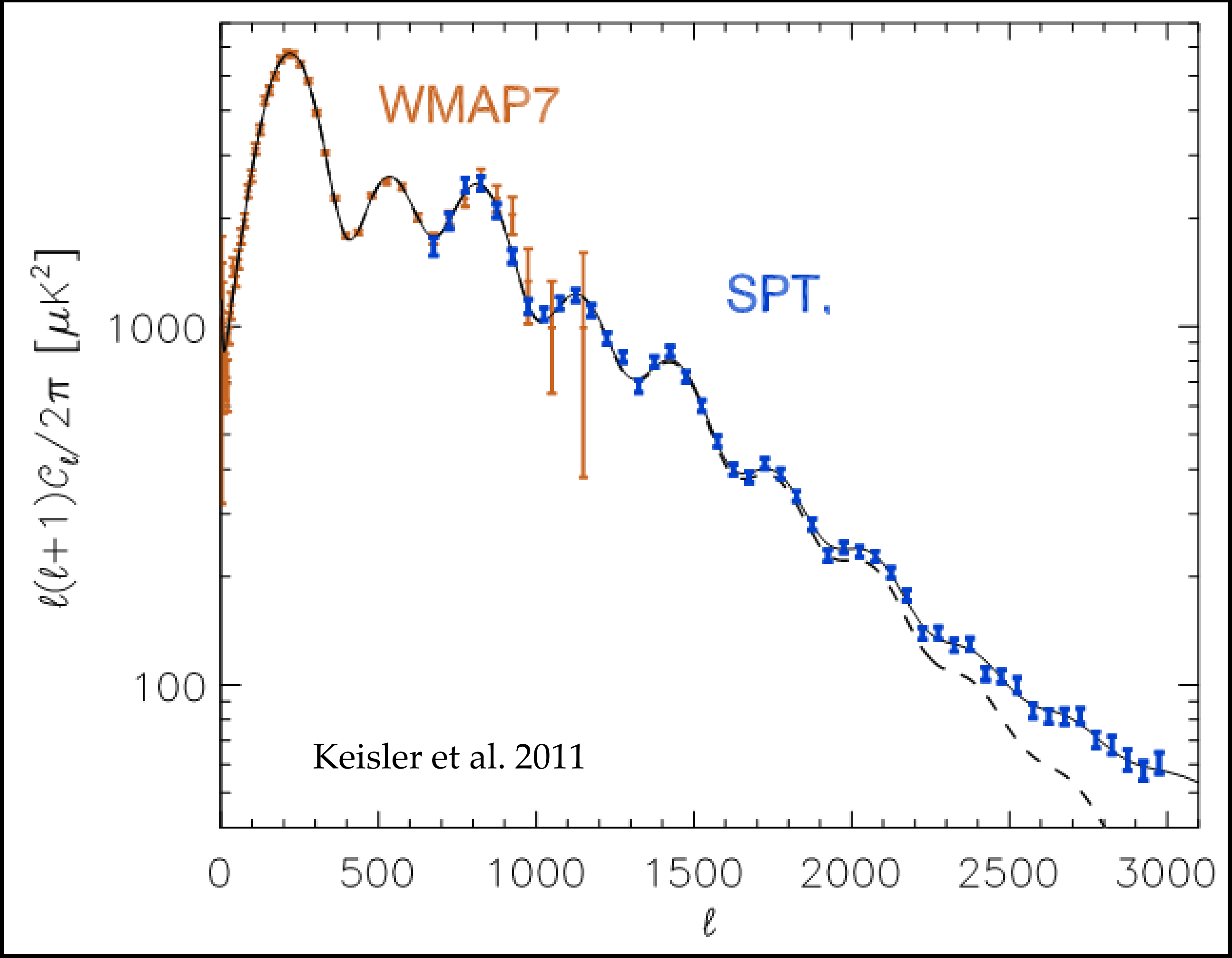
Evidence

- 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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Astronomical Society-o
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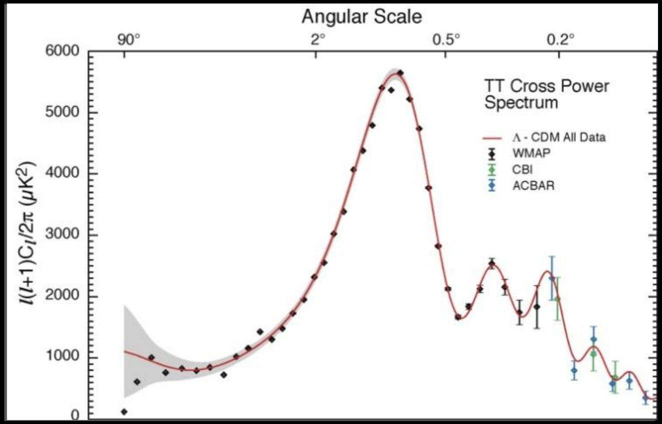
Evidence

<u>Dialog</u>

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

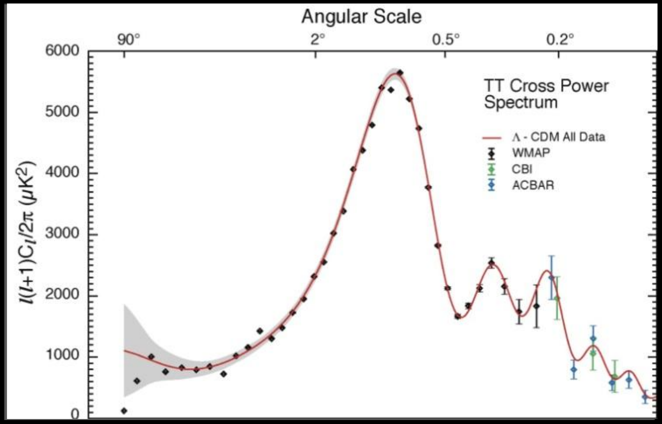


Evidence

<u>Dialog</u>

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

Rocky: 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

<u>Dialog</u>

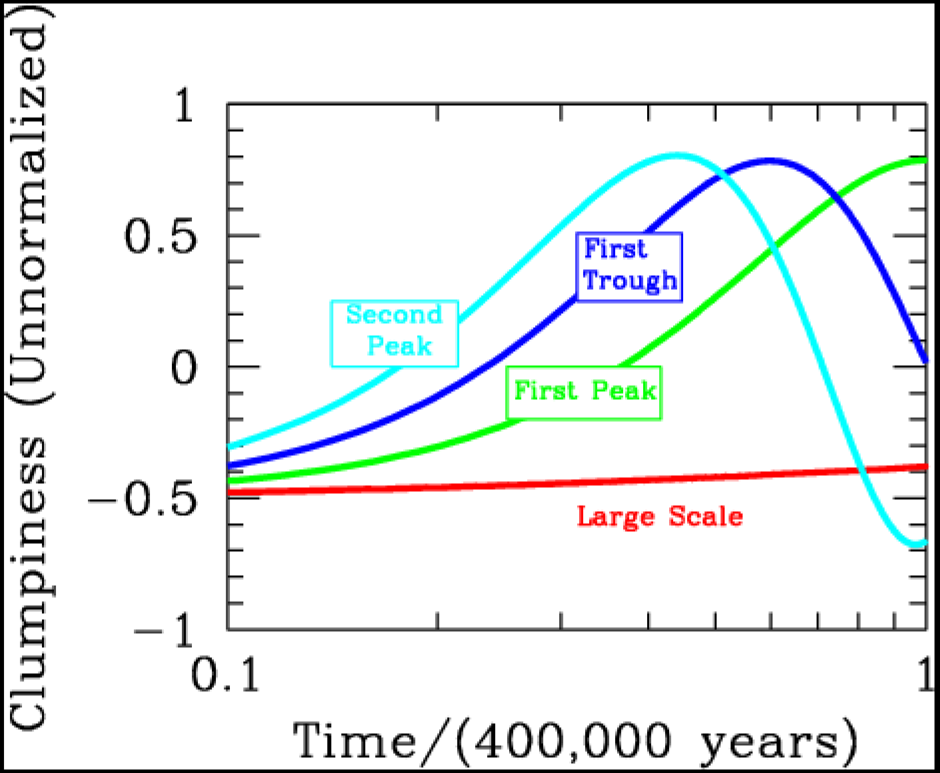
Mike: But you get a fundamental mode and harmonics in musical spectra because the ends of the strings are tied down; the Universe is not tied down!

Evidence

<u>Dialog</u>

Mike: 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!

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

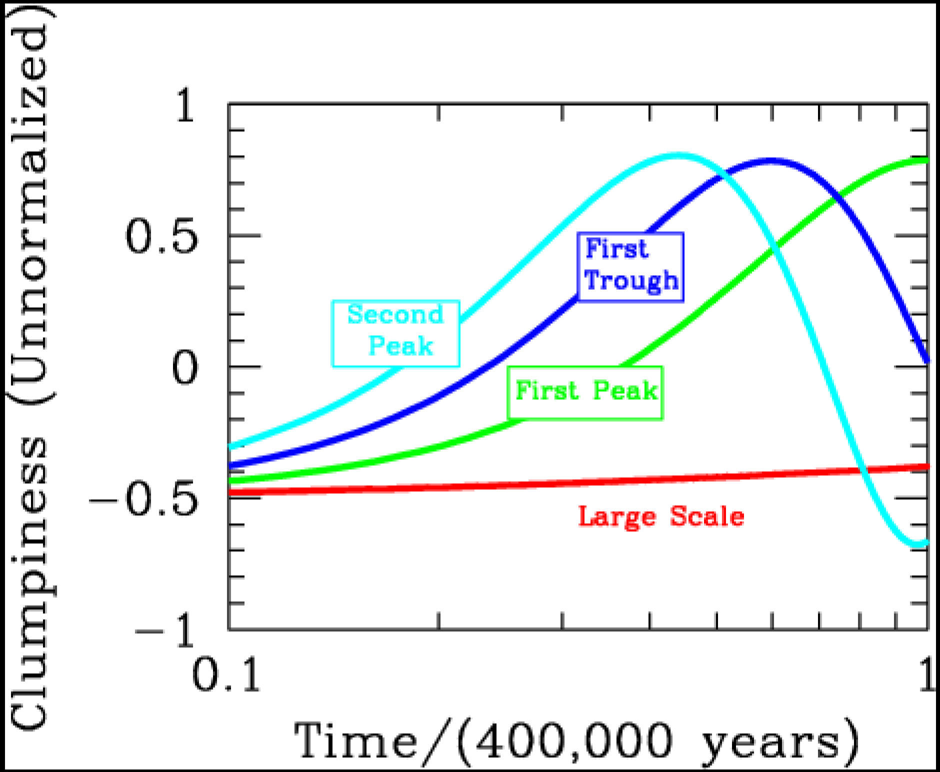


Evidence

<u>Dialog</u>

Mike: So what?

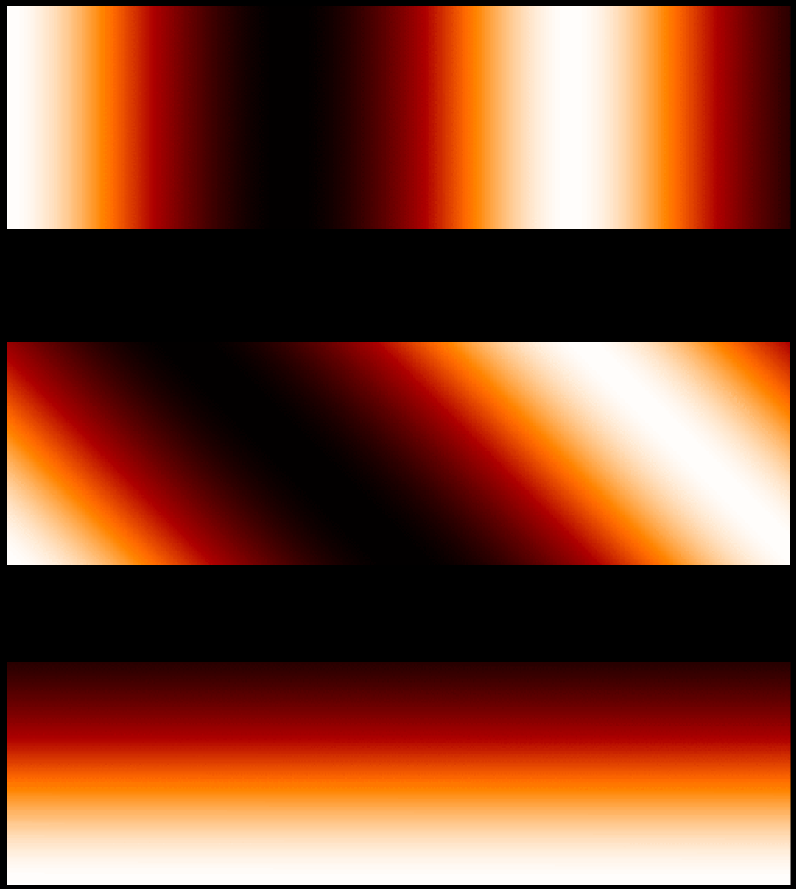
Rocky: Some modes have reached maximal amplitude at recombination. We see these as peaks. Others (“Michelle Bachmann” modes) peaked too soon; we see these as troughs. All modes exist: in our single snapshot, we see only some of them!



Evidence

Dialog

Mike: 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.

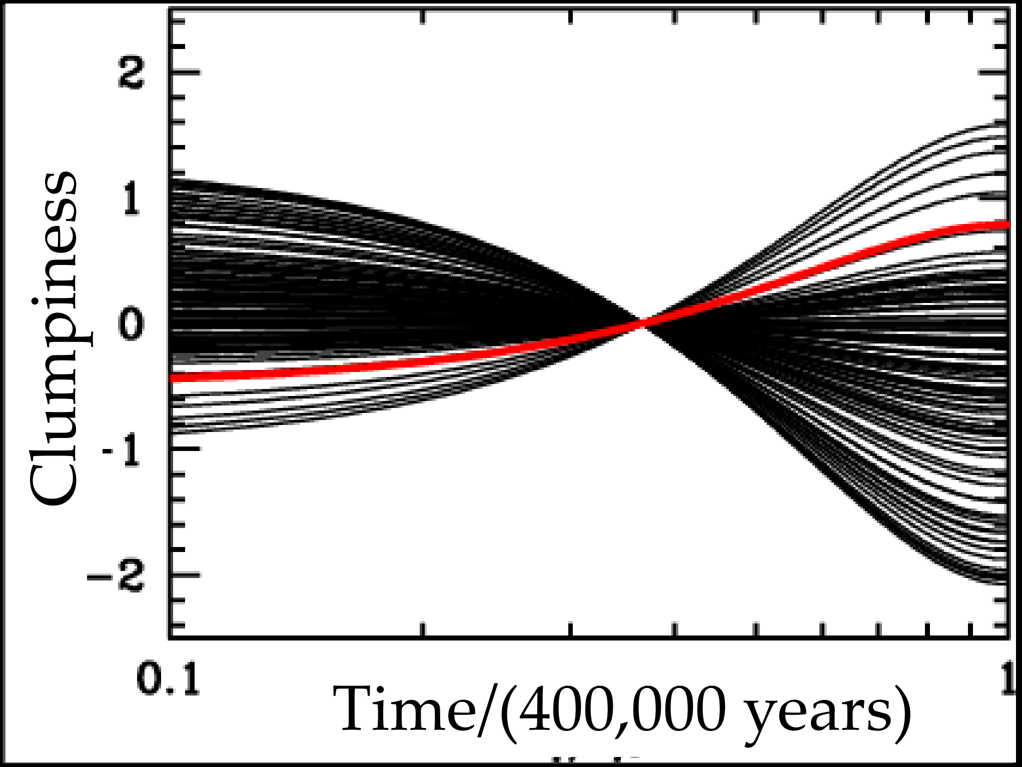


Rocky: So what?

Evidence

Dialog

Mike: 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?

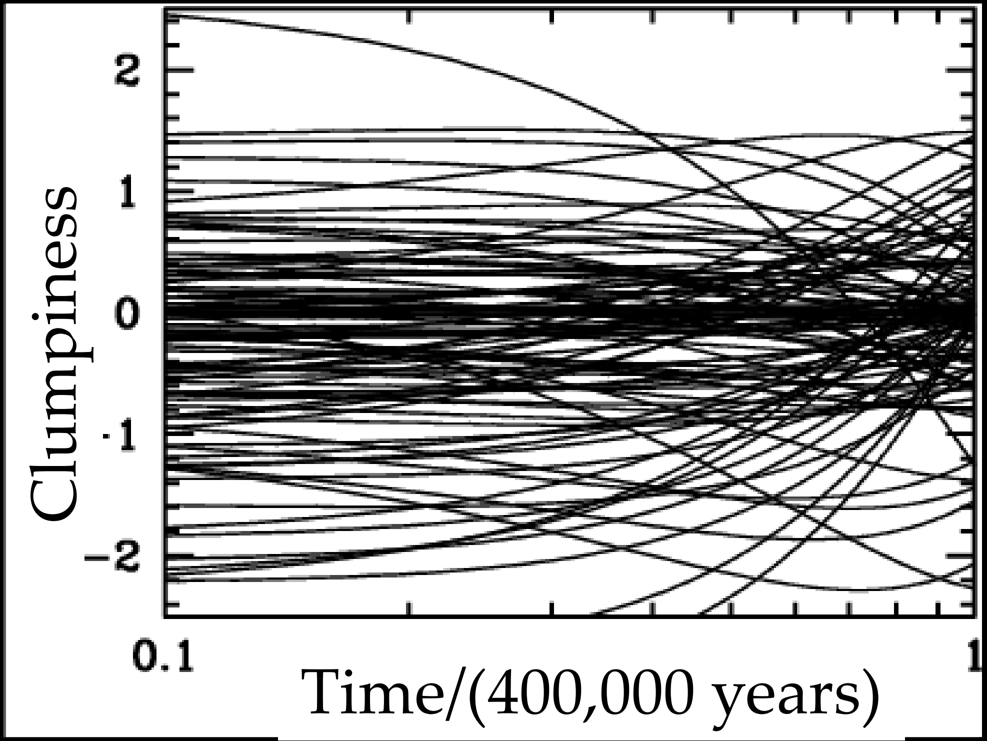


Rocky: Hmm

Evidence

<u>Dialog</u>

Mike: 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.

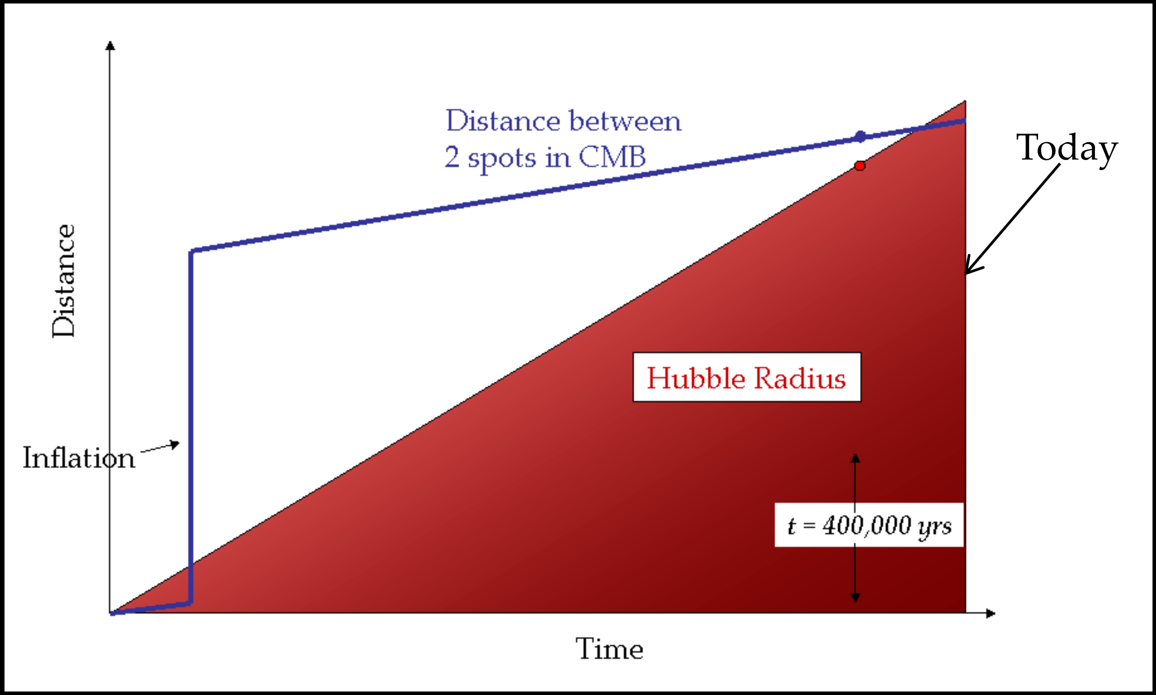


Evidence

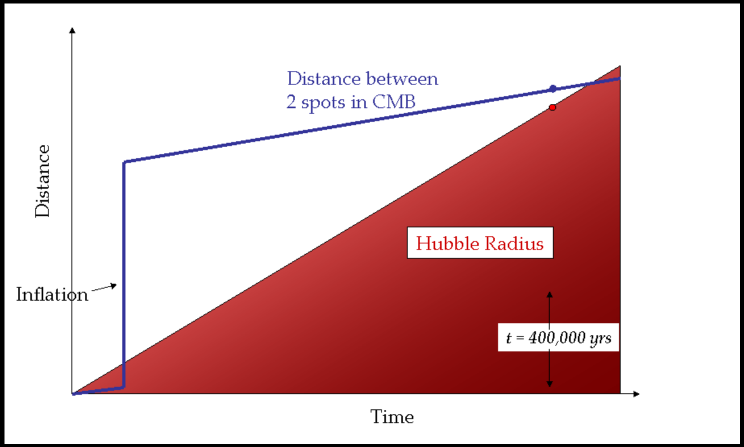
Dialog

Rocky: Remember the diagram we made famous in the 80's?

Mike: You remember the 80's?



Evidence



__Dialog__

Rocky: 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

Evidence

Dialog

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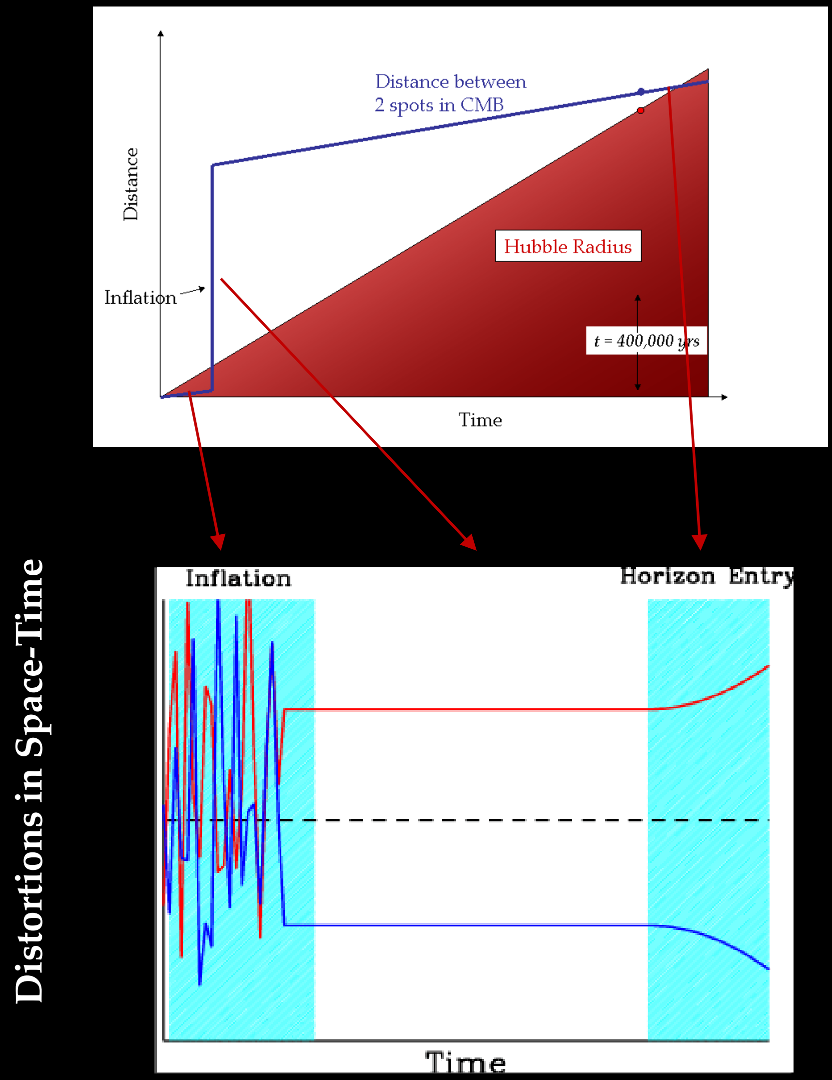
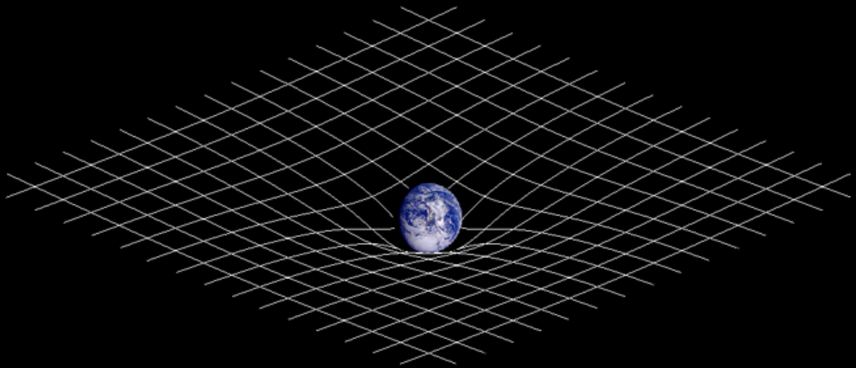


Physics Behind Inflation

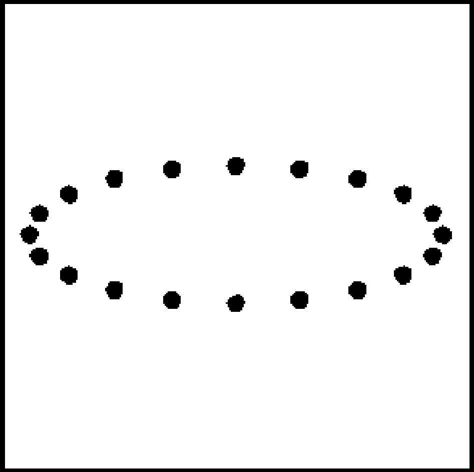
- Inflation has passed tests
- Challenge to understand underlying physics
- Gravitational Waves: Focus of Heroic Experimental Effort
- Non-Gaussianity: Exciting Recent Theoretical Developments

Gravitational Waves

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

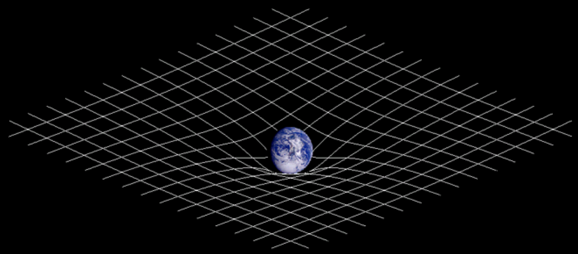


Scalar/Density

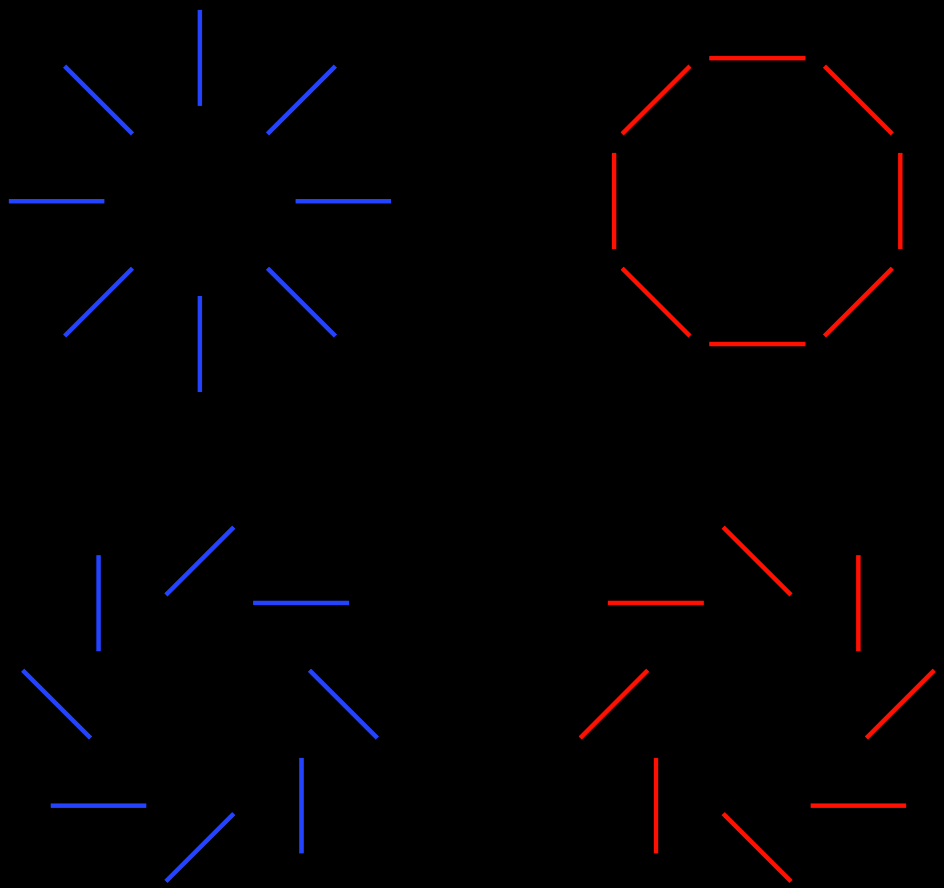


Tensor/Gravitational Waves

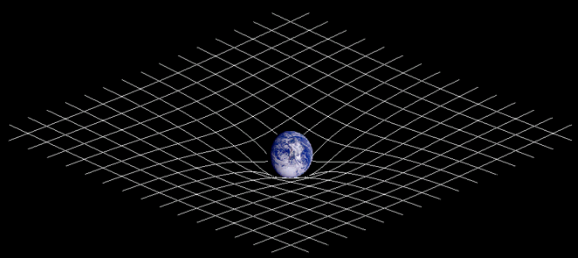
Gravitational Waves



Density perturbations
produce only E-modes



Gravitational Waves



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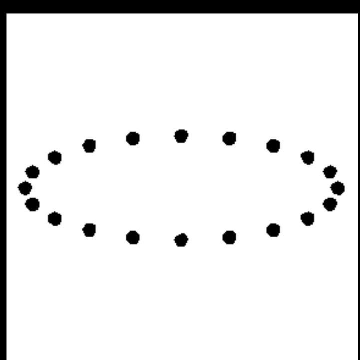
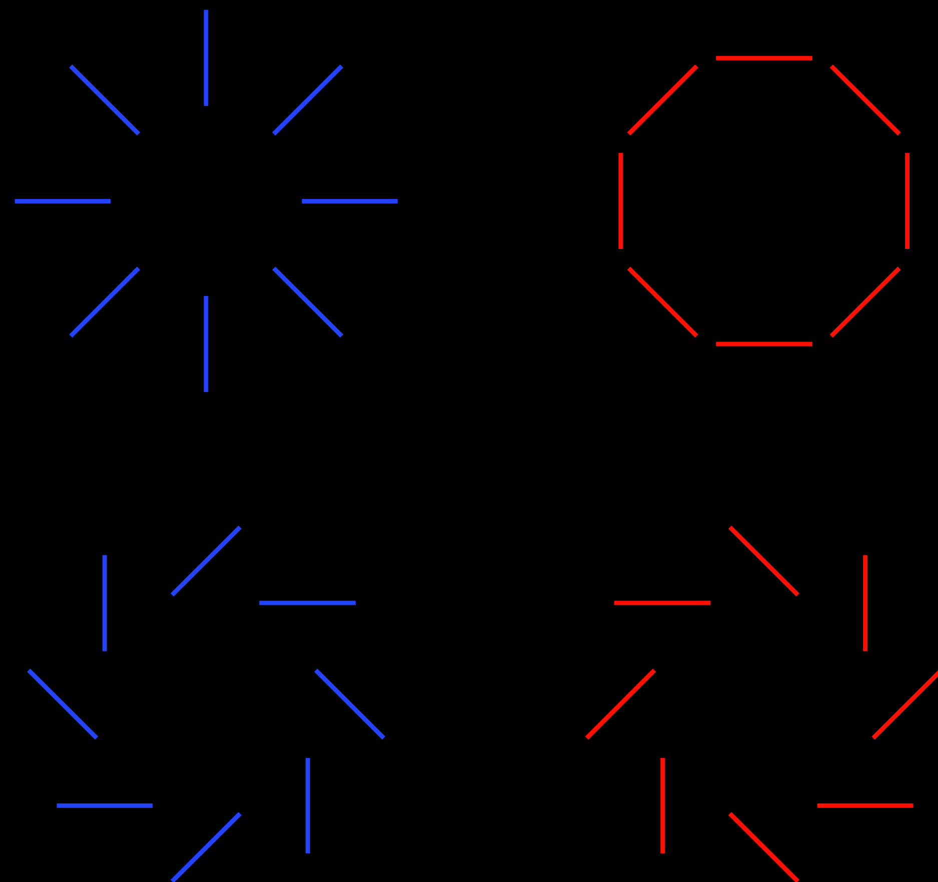
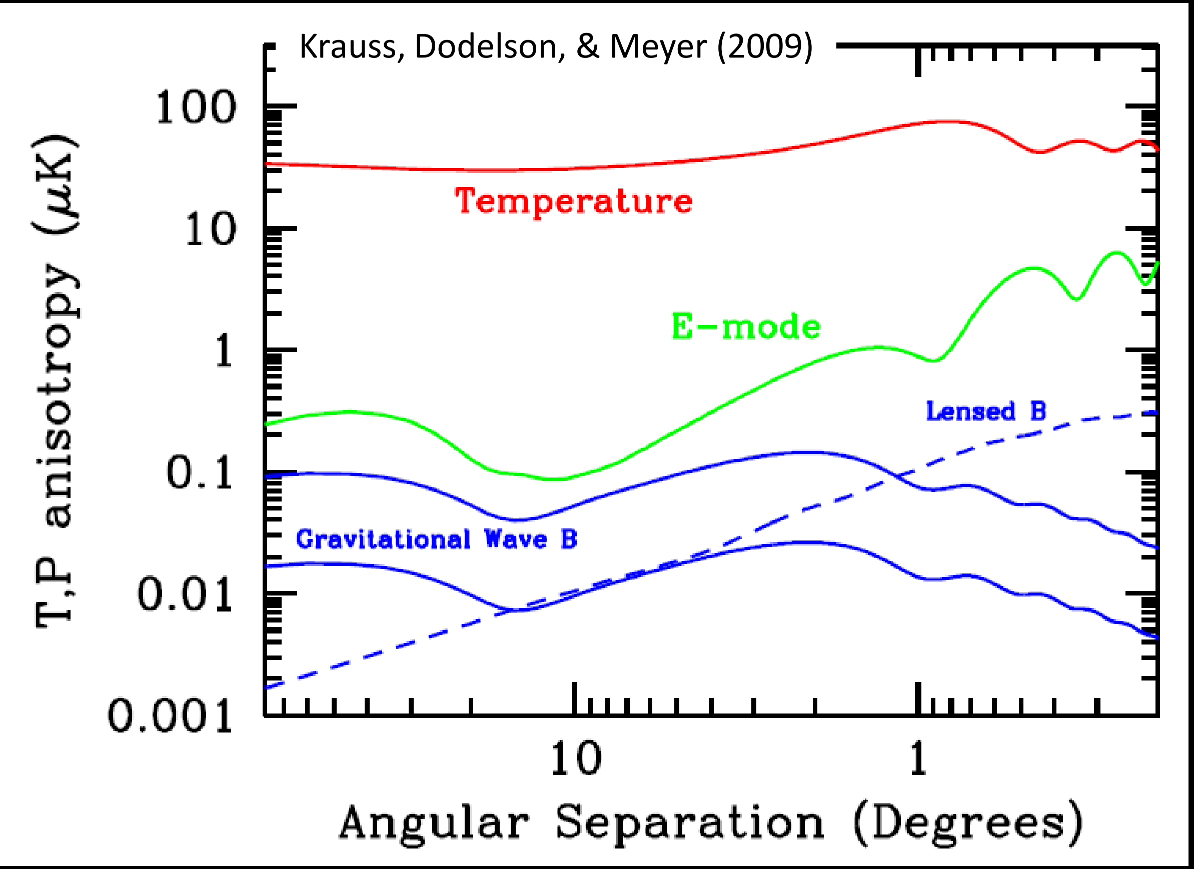


Gravity waves produce E- and B- modes

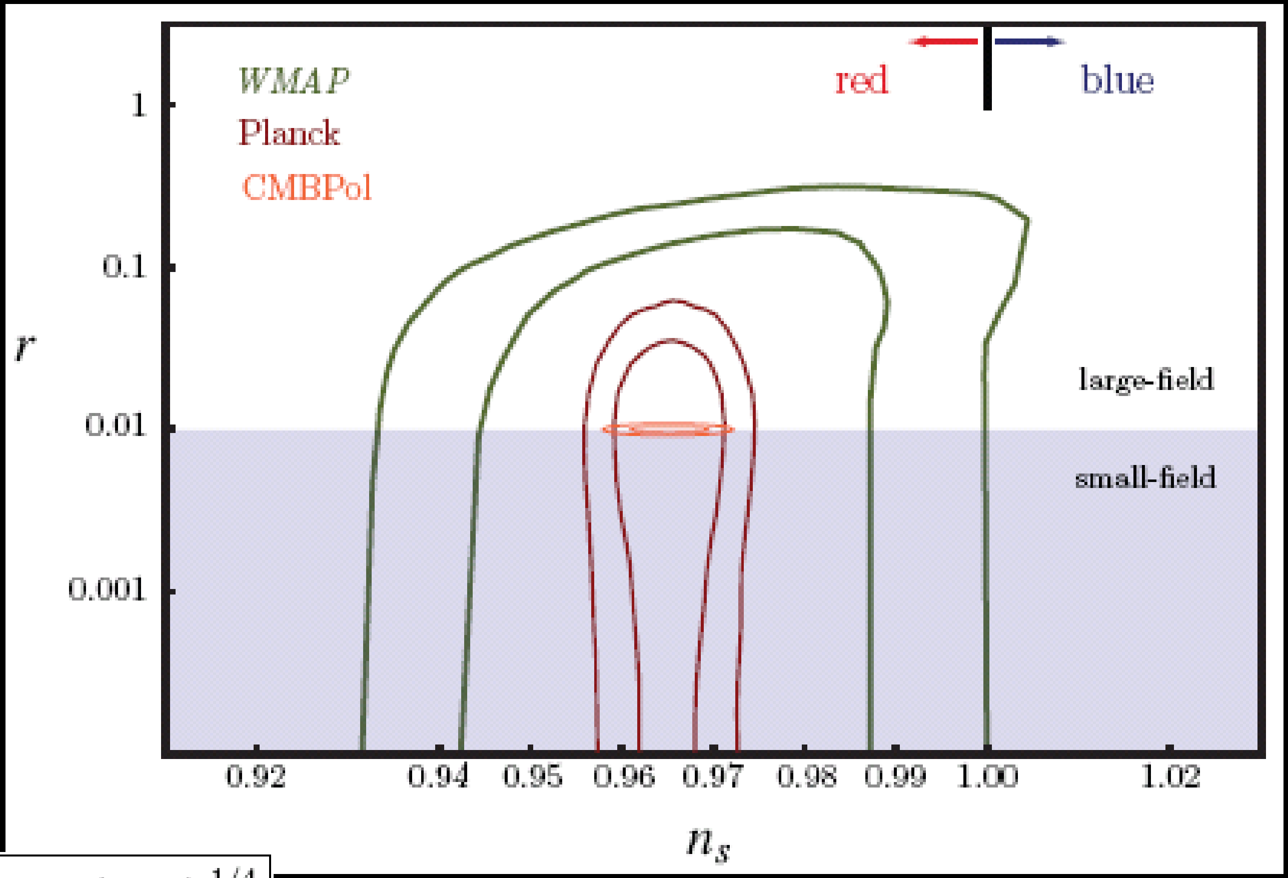


Gravitational Waves

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



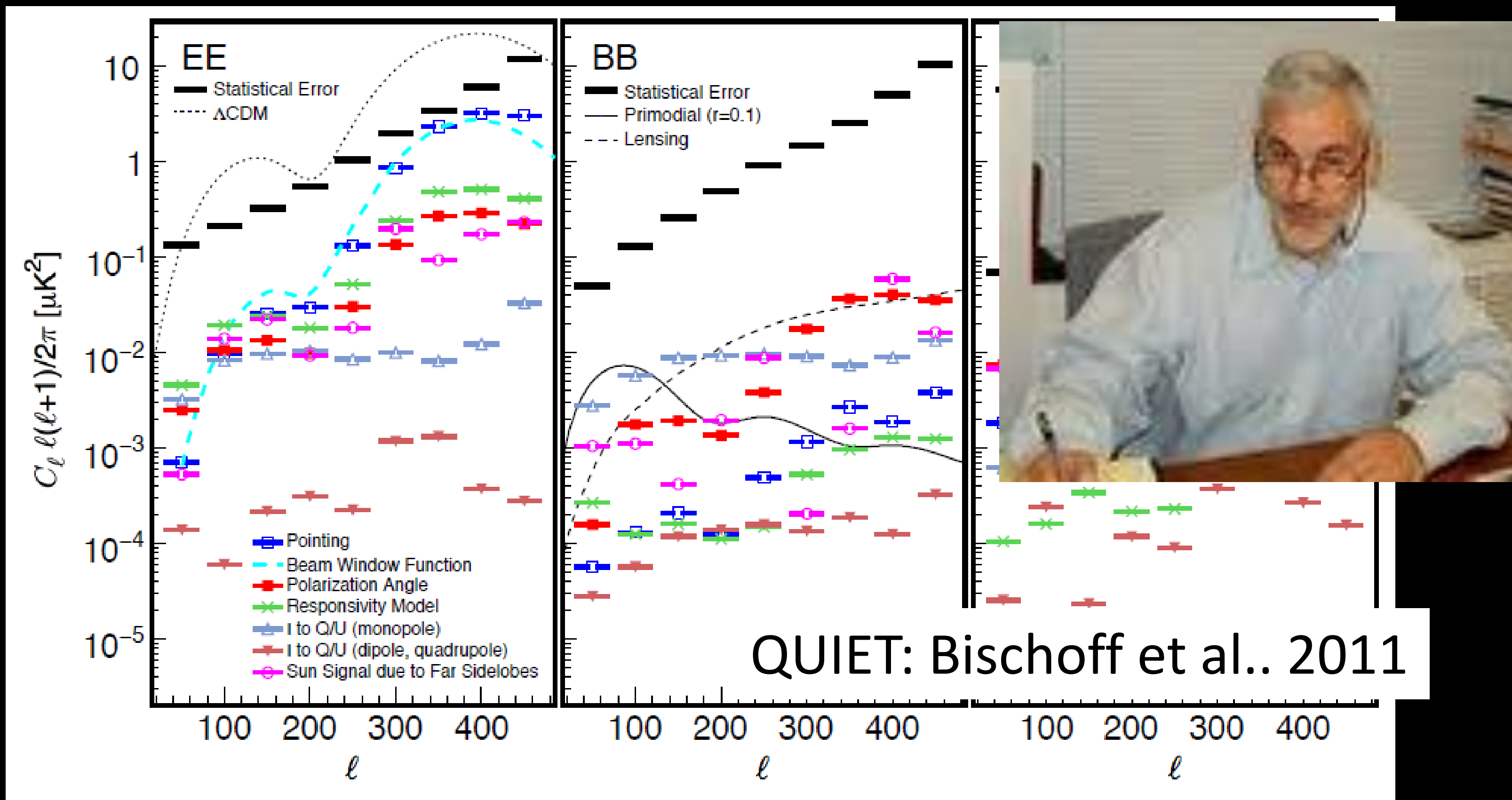
Gravitational Waves



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

*

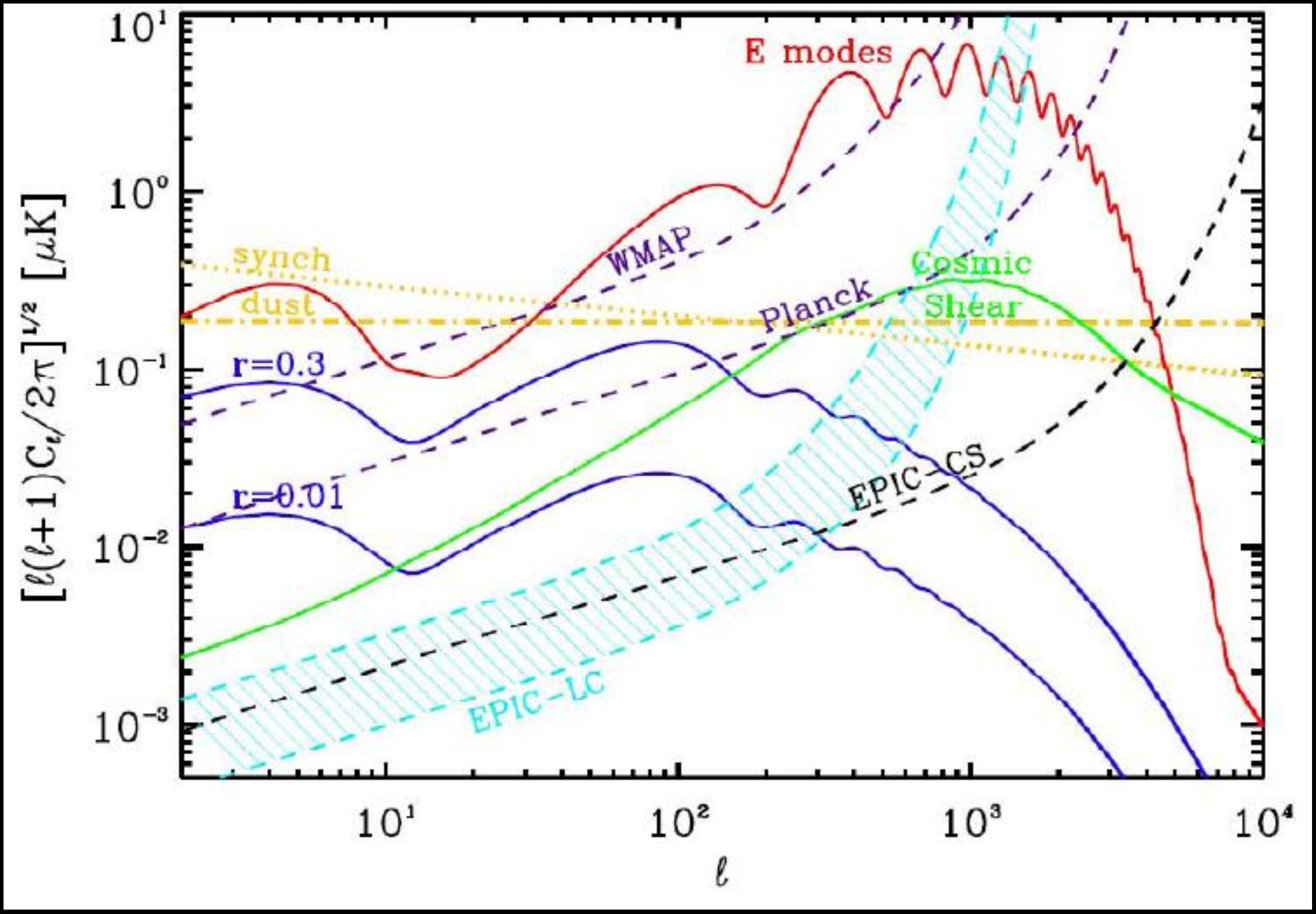
Gravitational Waves



QUIET: Bischoff et al.. 2011

Gravitational Waves

Ambitious plans for the future



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):*

$$\lim_{k_1 \to 0} \left\langle \zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3) \right\rangle = (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) P(k_1) P(k_2)(n-1)$$

Squeezed limit

Power spectra of long and short wavelength modes

Deviation from scale invariance (n=1); amplitude constrained by observations to be at most ~0.05

So $4f_{NL}=n-1$ is generically 0.01 in single field models

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

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

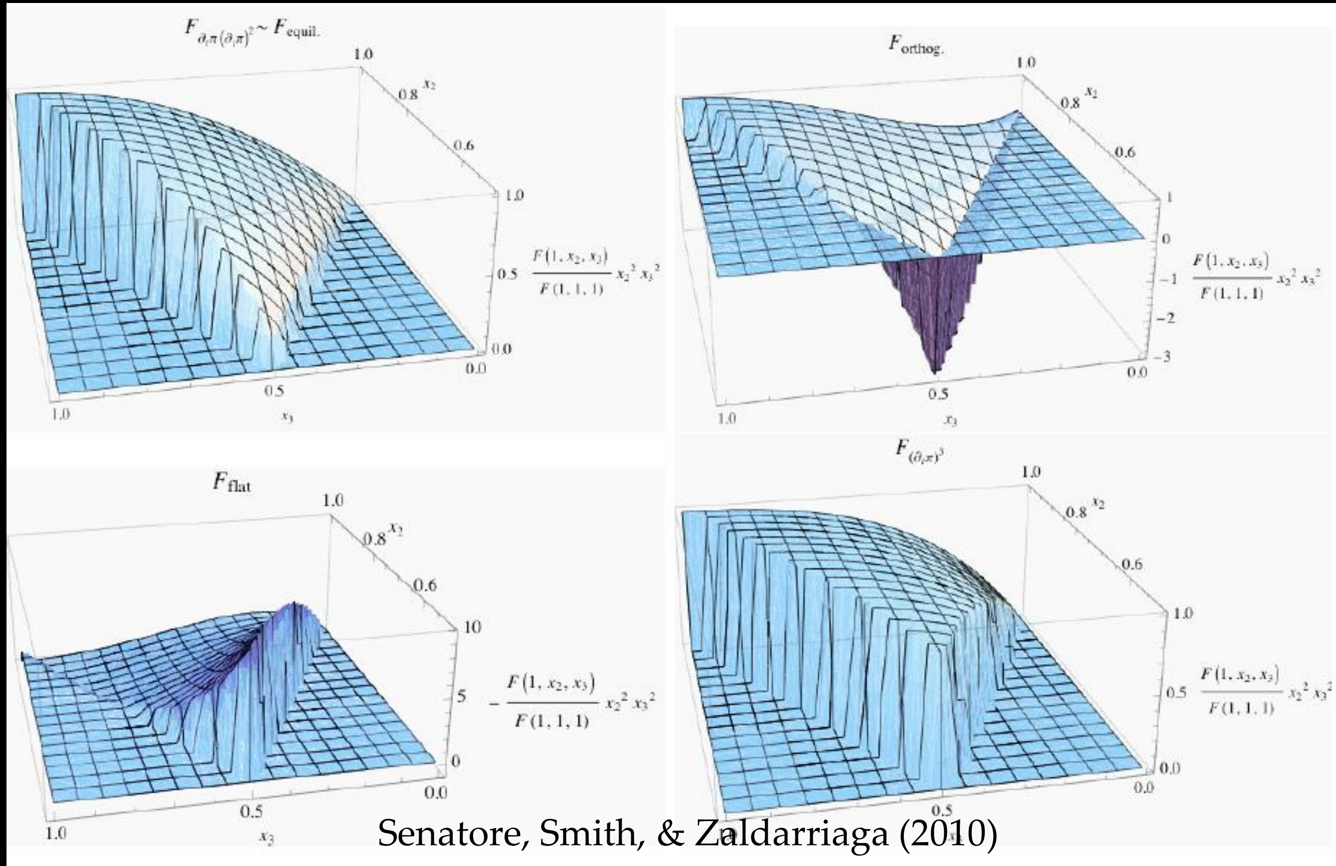
$$S_\pi = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{1}{a^2}(\partial_i\pi)^2\right)\right.$$
$$\left. + \frac{\dot{H}M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\dot{\pi}\frac{1}{a^2}(\partial_i\pi)^2 - \frac{\dot{H}M_{\rm Pl}^2}{c_s^2}(1-c_s^2)\left(1+\frac{2}{3}\frac{\tilde{c}_3}{c_s^2}\right)\dot{\pi}^3\right.$$

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

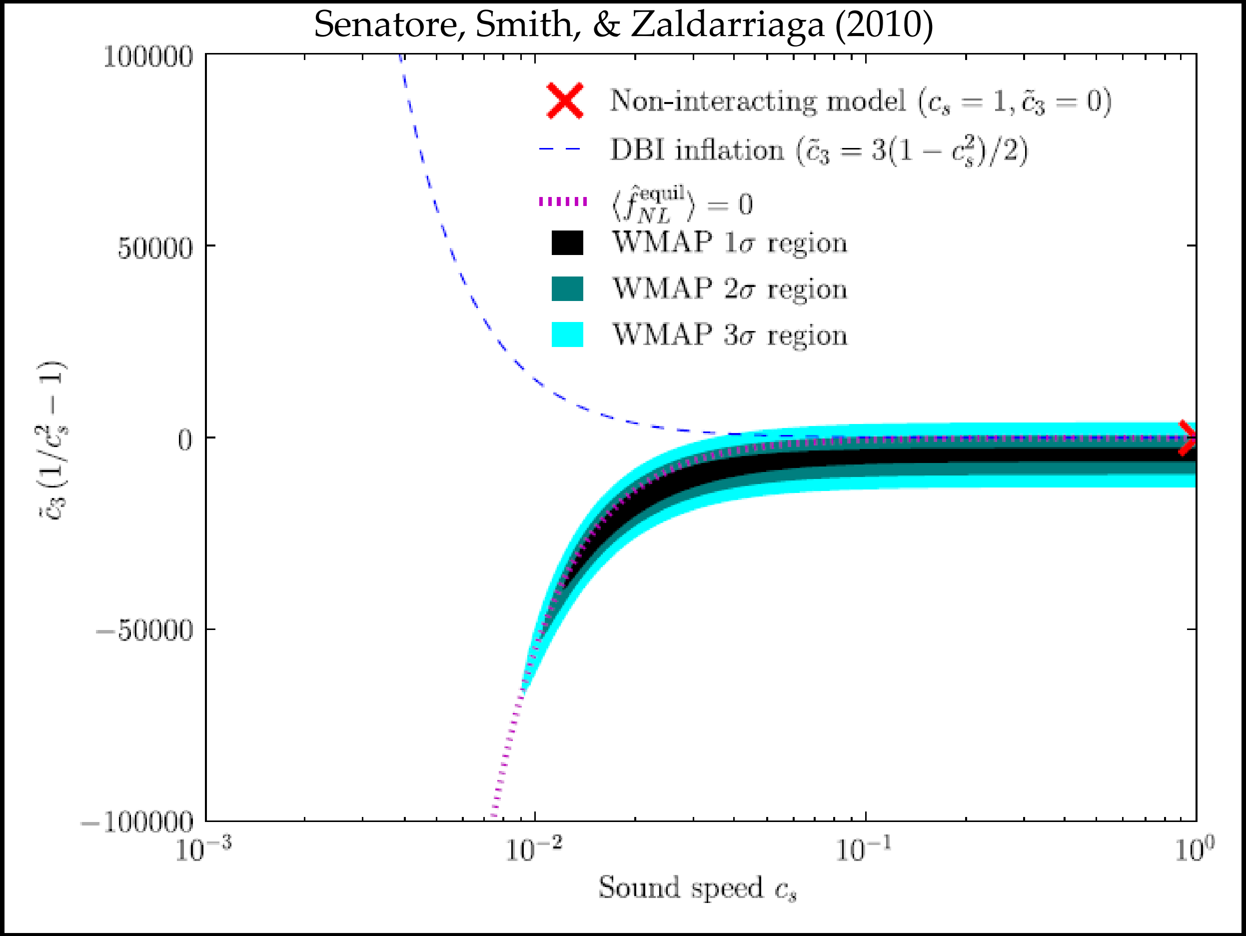
Each term in the action corresponds to a distinctive bispectrum *F*



Senatore, Smith, & Zaldarriaga (2010)

Non-Gaussianity

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



Non-Gaussianity

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

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

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

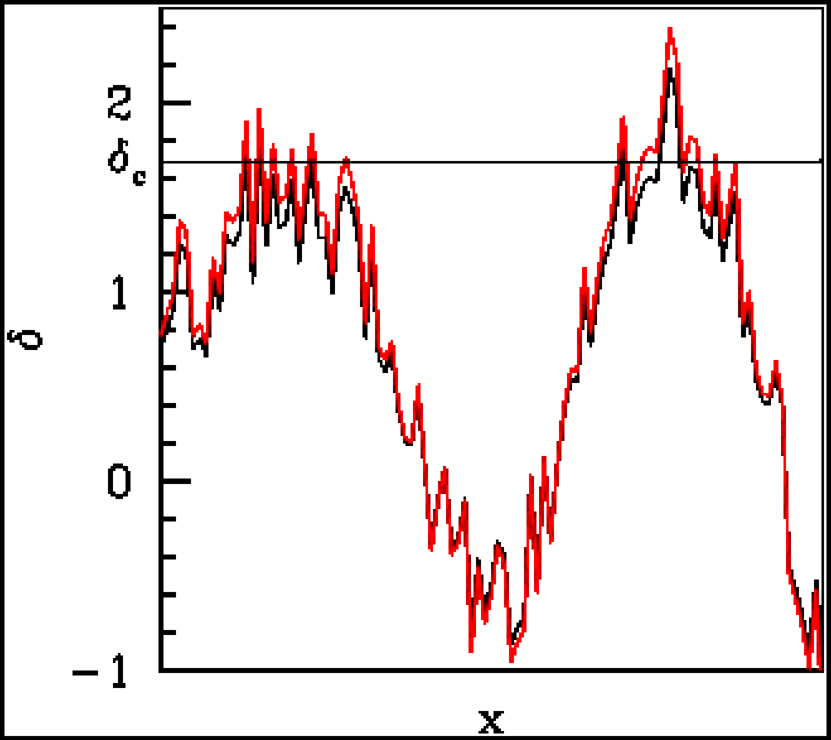
Apply Poisson Equation

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

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

Non-Gaussianity

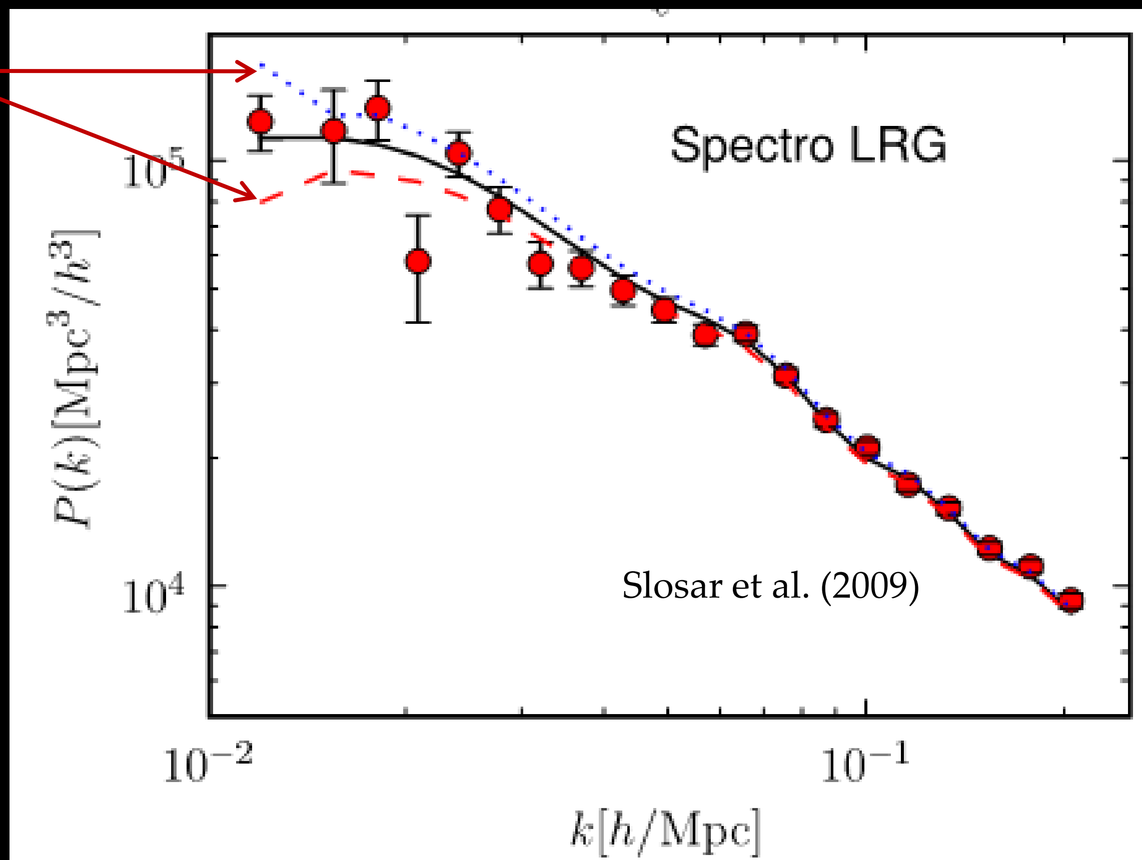
NG term leads to enhancement in overdensity near peaks for positive f_{NL}



$$\delta_{peaks} = \delta_G + 2 f_{NL} \Phi_G \delta_G \Rightarrow \Delta\delta_{peaks} \propto \frac{f_{NL}}{k^2}$$

Non-Gaussianity

$$f_{NL} = \pm 100$$



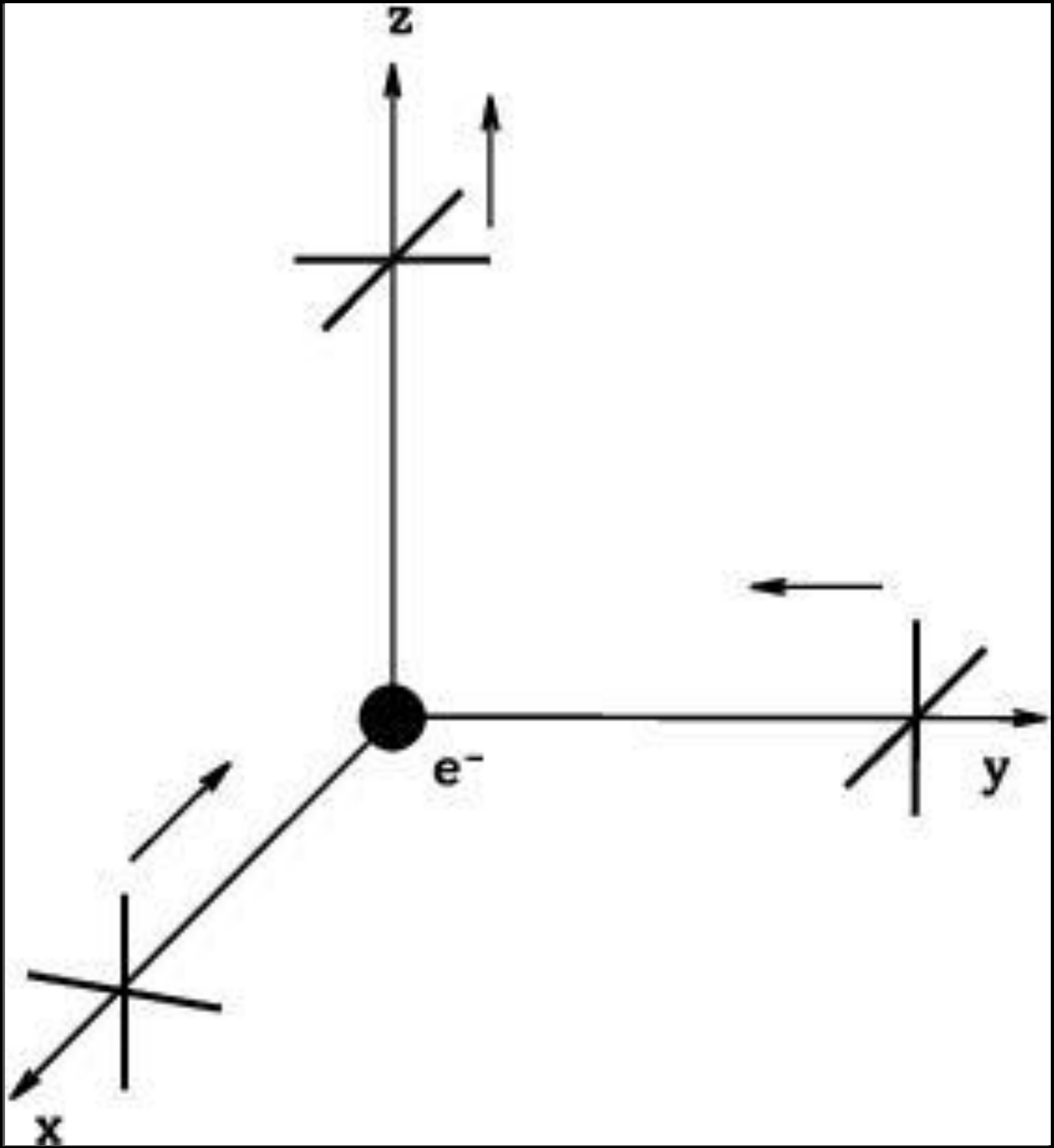
2020: Scenario I

- 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

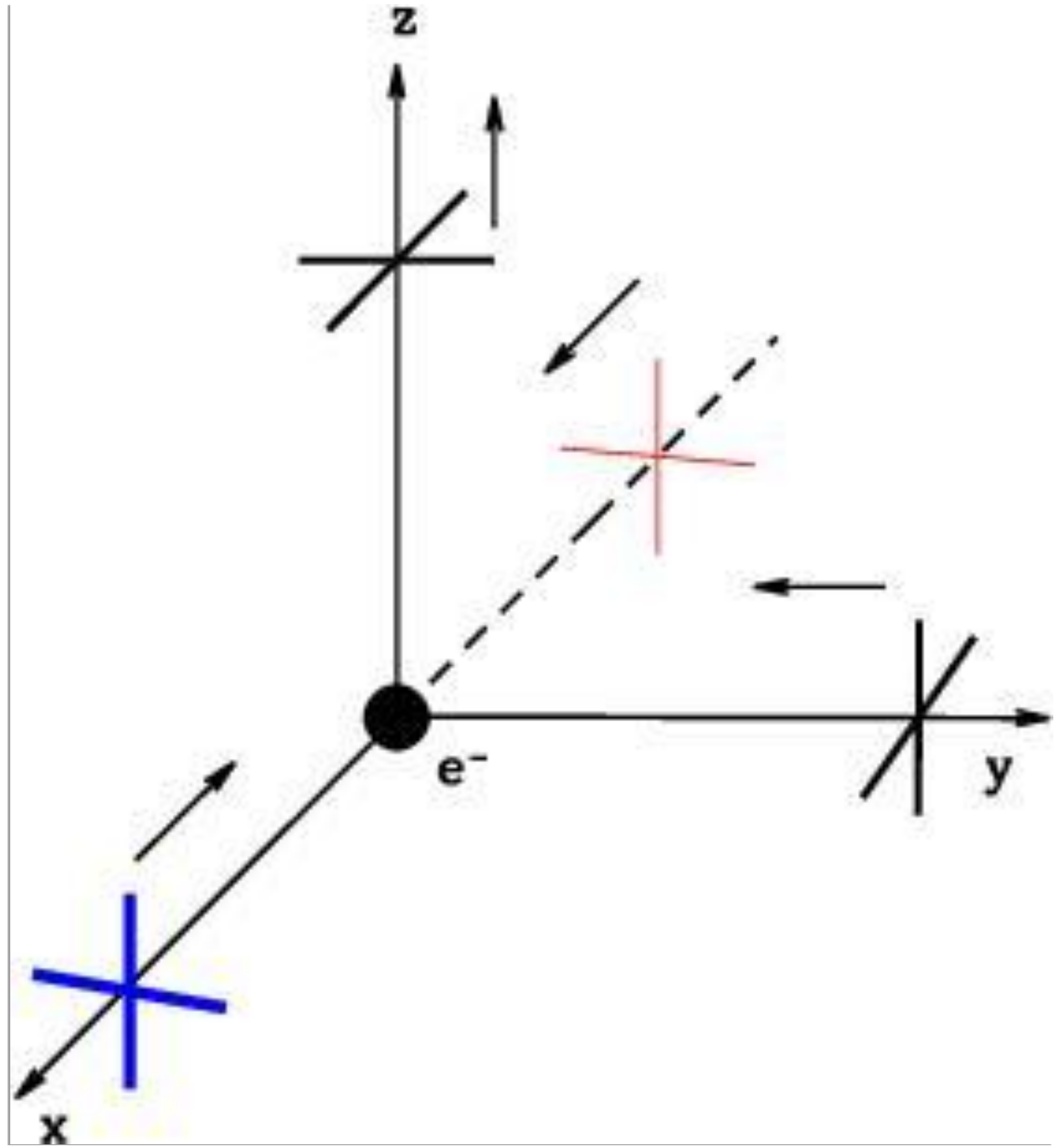
2020: Scenario II

- No B-modes detected
- Primordial Non-Gaussianity detected
- Cosmology in disarray: Is inflation right? Alternatives?

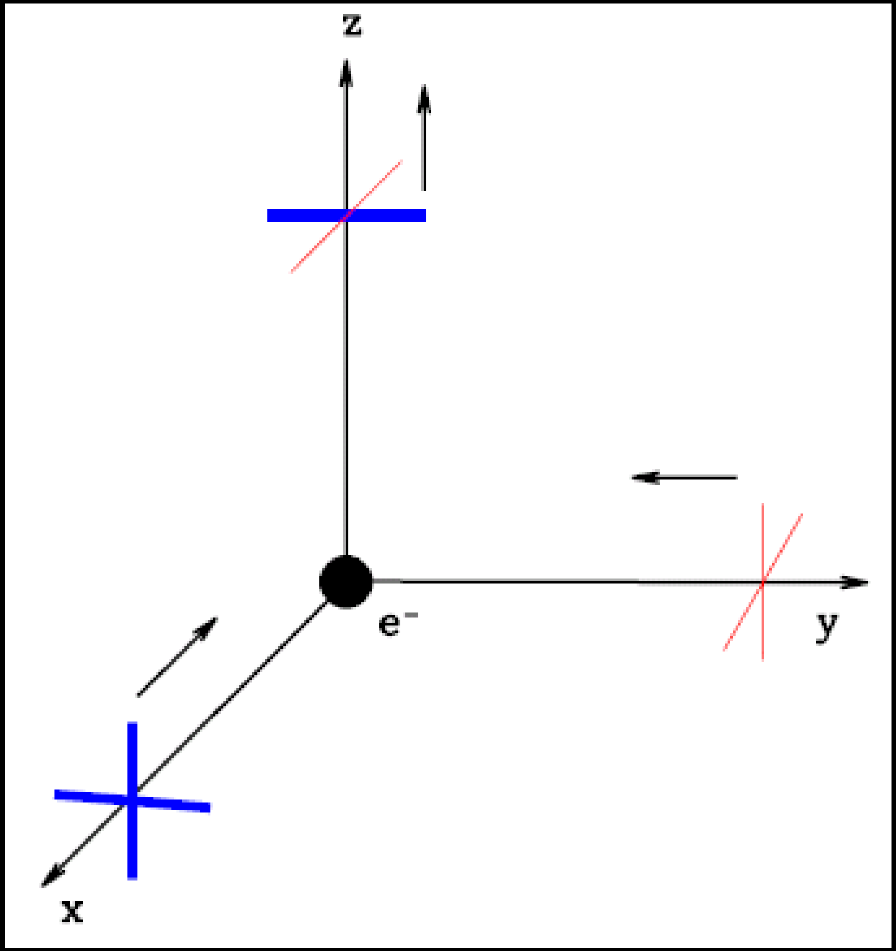
Isotropic radiation field produces no polarization after Compton scattering



Radiation with a dipole produces no polarization



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