Title: Constraining the Physics of Inflation with the CMB

Date: Jan 18, 2012 12:45 PM

URL: http://pirsa.org/12010127

Abstract: The observational search for non-Gaussian statistics in the initial conditions of the universe is a powerful,

Outline

Inflation overview

Non-Gaussian models

CMB phenomenology and statistics

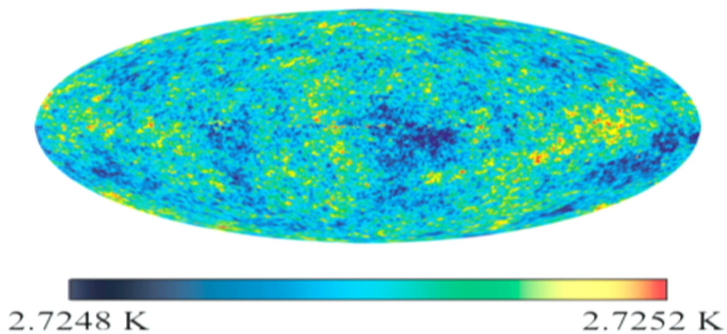
WMAP results

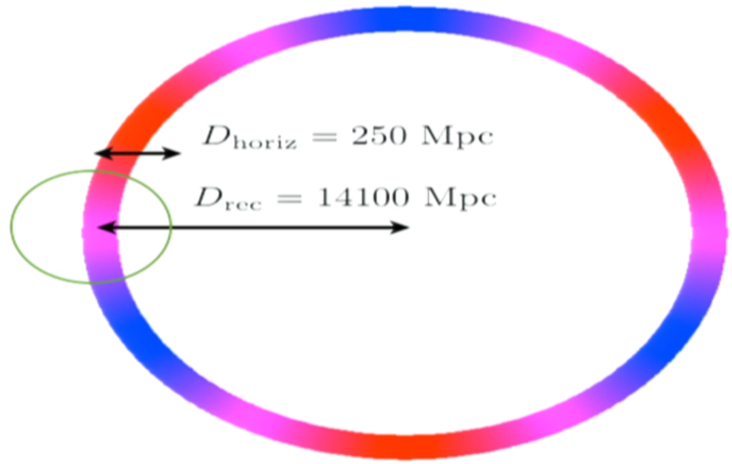
Large-scale structure (time permitting)

Horizon problem

Surface of last scattering is nearly isothermal, suggesting that all parts of the last scattering surface were once in causal contact

However, the causal horizon at last scattering is much smaller: points separated by $> 1^\circ$ have never been in causal contact





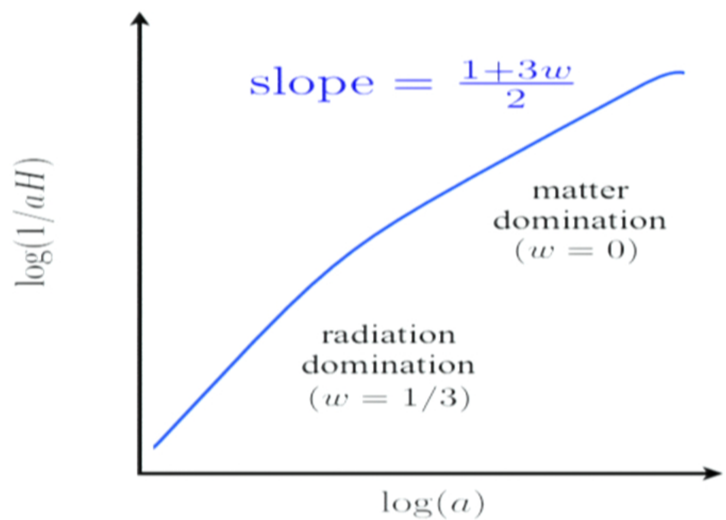
Horizon problem

$(aH)^{-1}$ = comoving distance light travels in an e-folding

Evolution with scale factor a:

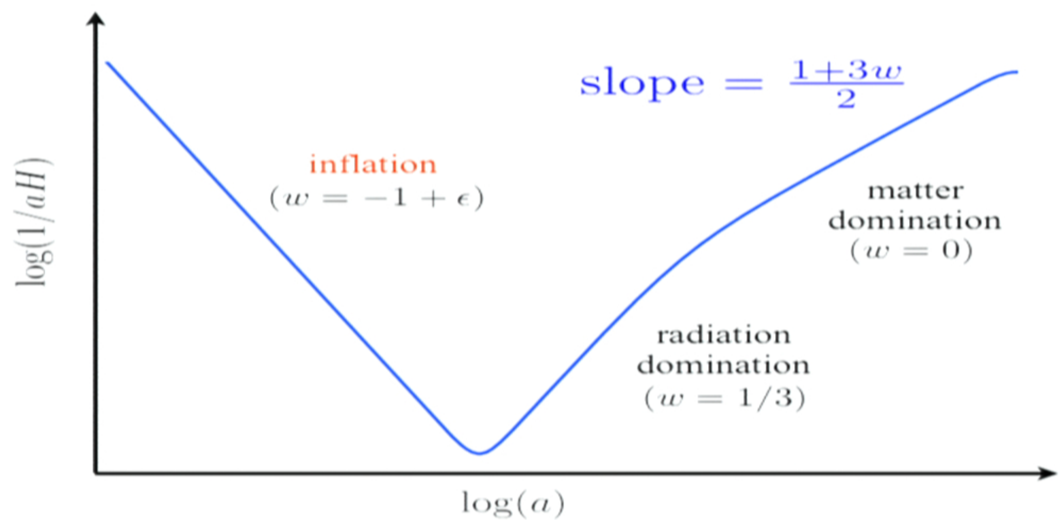
$$\frac{d\log(aH)^{-1}}{d\log a} = \frac{1+3w}{2} \qquad (w = p/\rho)$$

In a universe filled with nonrelativistic $(w=0)$ or relativistic $(w=1/3)$ matter, the horizon is small at early times



Inflation

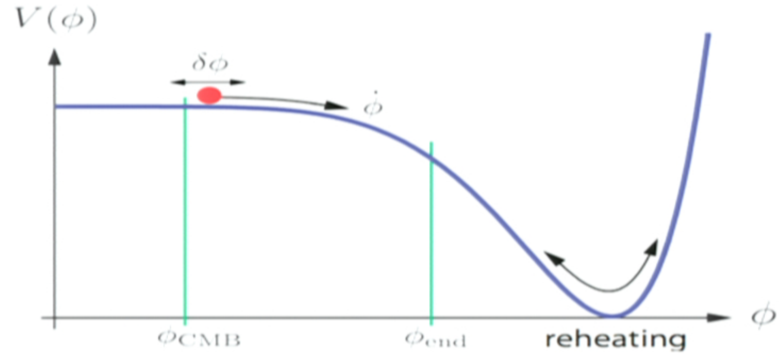
To get a large horizon at early times, ΛCDM expansion history must be preceded by an "inflationary" epoch with $w < -\frac{1}{3}$, i.e. negative pressure



Single-field slow-roll inflation

Example model: scalar field ϕ slowly rolling down potential $V(\phi)$

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2}(\partial\phi)^2 - V(\phi) \right)$$



Flatness: $\epsilon = \frac{M_{\rm Pl}^2}{2} \left(\frac{V'(\phi)}{V(\phi)} \right)^2 \ll 1$ (WMAP7: $\epsilon \leq 0.015$)

Negative pressure: $w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \approx -1 + \frac{2}{3}\epsilon$

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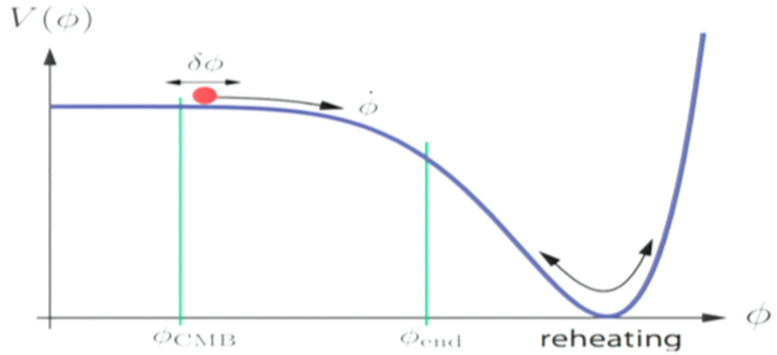

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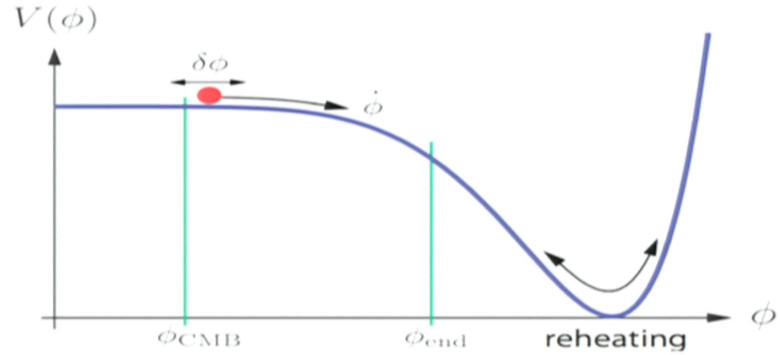

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Generation of perturbations

Amazing fact: inflation naturally generates perturbations

In an expanding background, microscopic degrees of freedom are quantum mechanically excited

Toy example: massless test scalar field $(-\infty < \eta < 0)$

$$S_\pi = \frac{1}{2}\int d\eta\, d^3x\, a(\eta)^2 \left[\left(\frac{d\sigma}{d\eta}\right)^2 - (\partial_i\sigma)^2\right]$$

time dependence

Each Fourier mode $\sigma_{\mathbf{k}}$ behaves as a 1D harmonic oscillator with time dependent Hamiltonian

$$H = \frac{1}{2}\left[(H\eta)^2 p^2 + \frac{k^2}{(H\eta)^2}x^2\right]$$

Generation of perturbations

Toy example: Fourier modes evolve w/Hamiltonian

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Assume wavefunction in ground state at start of inflation ($\eta = -\infty$)

$\eta \ll 1/k$: wavefunction stays in ground state (adiabatic)

$\eta \gg 1/k$: wavefunction "frozen": $\psi(x) \propto \exp\left(-\frac{k^3}{4H^2}x^2\right)$

At all times, the wave function is Gaussian

$\Rightarrow$ At the end of inflation, the scalar field σ is a Gaussian field with scale-invariant power spectrum $\langle \sigma^*_{\mathbf{k}} \sigma_{\mathbf{k}} \rangle \propto 1/k^3$

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Reheating: fluctuations in inflationary sector convert to fluctuations in Standard Model particles

Simplest scenario: inflaton decays to SM particles, source of initial density fluctuations is the inflaton itself

Non-Gaussianity is unobservably small (Maldacena 2002), given the following assumptions:

1. single-field (initial fluctuations come only from inflaton)
2. reheating is homogeneous
3. inflaton Lagrangian is $\frac{1}{2}(\partial\phi)^2 - V(\phi)$

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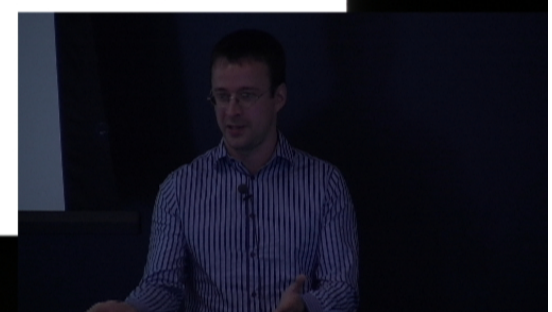

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WMAP results

Large-scale structure (time permitting)

A non-Gaussian model: modulated reheating

Suppose:

1) Decay rate Γ of inflaton is controlled by auxiliary field σ

$$\Gamma(\mathbf{x}) = \Gamma_0 + \Gamma_1\,\sigma(\mathbf{x}) + \Gamma_2\,\sigma(\mathbf{x})^2 + \cdots$$

2) σ acquires Gaussian fluctuations via the standard mechanism

This setup leads to an adiabatic curvature fluctuation of the form

$$\zeta(\mathbf{x}) = A(\delta\sigma(\mathbf{x})) + B(\delta\sigma(\mathbf{x}))^2 + \cdots$$

or equivalently:

$$\zeta(\mathbf{x}) = \zeta_G(\mathbf{x}) + \frac{3}{5} f_{NL}^{\rm loc} \zeta_G(\mathbf{x})^2 + \cdots$$

where ζ_G is a Gaussian field and $f_{NL}^{\rm loc}$ is a free parameter.

Non-Gaussianity: "local model"

$$\zeta(\mathbf{x}) = \zeta_G(\mathbf{x}) + \frac{3}{5} f_{NL}^{\rm loc} \zeta_G(\mathbf{x})^2$$

non-Gaussian

Arises if non-G is generated by local physics after horizon crossing

- modulated reheating (inflaton decay mediated by spectator field)
- curvaton model (spectator field with non-flat potential generates ζ)
- "New" Ekpyrosis (two-field model; second field generates ζ)

Natural values in these models: $f_{NL}^{\rm loc} = 1$–100

Observational errors (1σ):

$\Delta f_{NL}^{\rm loc} = 21$ (WMAP7)

$\Delta f_{NL}^{\rm loc} \approx 5$ (Planck)

$\Delta f_{NL}^{\rm loc} \approx 1$ (futuristic LSS)

Local non-Gaussianity requires multiple fields; observation of $f_{NL}^{\rm loc} \neq 0$ would rule out all single-field models

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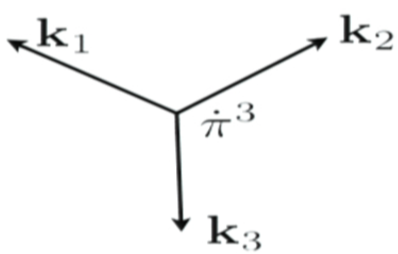
Non-Gaussianity via cubic interactions

Add interaction terms to Lagrangian
Toy example: massless test scalar with $\dot{\sigma}^3$ interaction

$$S = \frac{1}{2}\int d\eta\ d^3x\ a(\eta)^2 \left[\left(\frac{d\sigma}{d\eta}\right)^2 - (\partial_i \sigma)^2 \right] + f\ a(\eta) \left(\frac{d\sigma}{d\eta}\right)^3$$

small coupling constant

To first order in f, non-Gaussianity shows up in the 3-point function



$$\langle \sigma_{\mathbf{k}_1} \sigma_{\mathbf{k}_2} \sigma_{\mathbf{k}_3} \rangle \propto f \int_0^\infty d\eta \frac{\eta^2 e^{-(k_1+k_2+k_3)\eta}}{k_1 k_2 k_3}$$
$$= \frac{2f}{k_1 k_2 k_3 (k_1 + k_2 + k_3)^3}$$

Non-Gaussianity in single-field inflation

Classification theorem: if

1. the inflaton is the source of the initial curvature perturbations
2. the inflaton Lagrangian does not have rapid explicit time dependence (e.g. oscillatory potentials or transient "features")

Then the most general curvature 3-point function is:

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = f_{\dot\sigma^3} F_{\dot\sigma^3}(k_1, k_2, k_3) + f_{\dot\sigma(\partial\sigma)^2} F_{\dot\sigma(\partial\sigma)^2}(k_1, k_2, k_3)$$

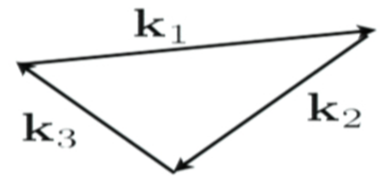
where $F_{\dot\sigma^3} =$ same 3-point function as test scalar with $\dot\sigma^3$

$F_{\dot\sigma(\partial\sigma)^2} =$ same 3-point function as test scalar with $\dot\sigma(\partial_i\sigma)^2$

Senatore, Smith & Zaldarriaga 2009

"Shapes" of non-Gaussianity

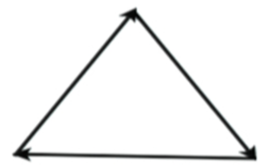
Curvature 3-point function $\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle$
defined for closed triangles



Single field shapes

$F_{\dot{\sigma}^3}(k_1, k_2, k_3)$

$F_{\dot{\sigma}(\partial\sigma)^2}(k_1, k_2, k_3)$



peaked on equilateral

small for squeezed

Local shape $F_{\rm loc}(k_1, k_2, k_3) = \frac{6}{5} f_{NL}^{\rm loc} P_\zeta(k_1) P_\zeta(k_2) + \text{cyc.}$

signal-to-noise dominated by squeezed triangles

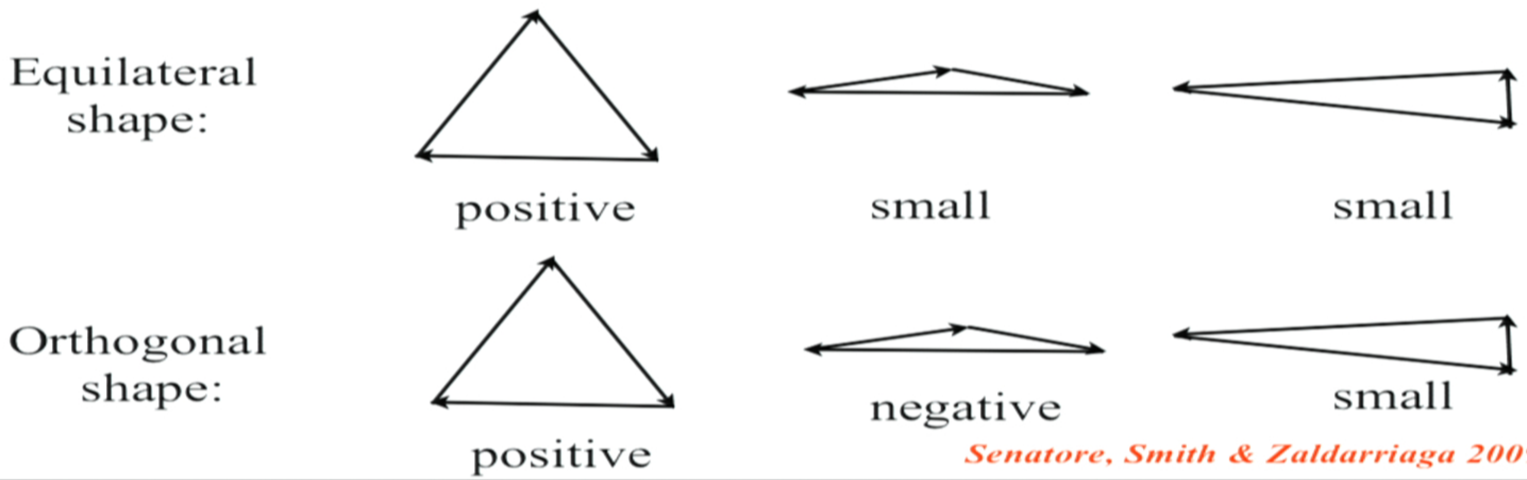
Orthogonal shape

Single-field shapes $F_{\dot\sigma^3}(k_1, k_2, k_3)$, $F_{\dot\sigma(\partial\sigma)^2}(k_1, k_2, k_3)$ are very similar (highly correlated)

Orthogonalize: define new basis

$$F_{\rm equil} = 1.21\, F_{\dot\sigma^3} + 1.04\, F_{\dot\sigma(\partial\sigma)^2}$$

$$F_{\rm orthog} = 0.108\, F_{\dot\sigma^3} - 0.068\, F_{\dot\sigma(\partial\sigma)^2}$$



Senatore, Smith & Zaldarriaga 2009

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Data analysis

Diagram

$\downarrow$

Curvature bispectrum $\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle$

$\downarrow$

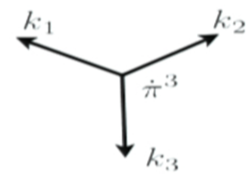
CMB bispectrum $\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$

$\downarrow$

Optimal estimator $\widehat{f}_{NL}$

$\downarrow$

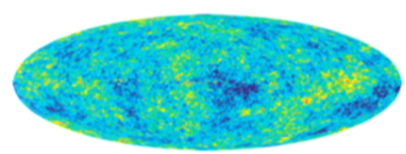
WMAP constraint



$$\int d\eta \frac{\eta^2 e^{-(k_1+k_2+k_3)\eta}}{k_1 k_2 k_3}$$

$$\sqrt{\frac{\prod(2\ell_i+1)}{4\pi}} \int d\eta\, dr\, \eta^2 r^2 \prod \mu_{\ell_i}(\eta, r) \times \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix}$$

$$\int \eta^2\, d\eta \int r^2\, dr \int \left(\sum_{\ell m} \mu_\ell(\eta, r) (C^{-1} a)_{\ell m} \right)^3$$



General case is computationally intractible

Calculating CMB bispectrum from curvature bispectrum:

$$\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle = \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)}{4\pi}} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix}$$

$$\times \int dr\, dk_1\, dk_2\, dk_3 \left(\prod_{i=1}^{3} \frac{2k_i^2}{\pi} j_{\ell_i}(k_i r) \Delta_{\ell_i}(k_i) \right) \langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle$$

CMB transfer function (computed numerically)

4D oscillatory integral for each (ℓ_1, ℓ_2, ℓ_3): too slow

Computing optimal estimator from data ($a_{\ell m}$):

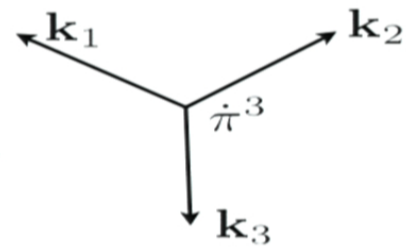
$$\widehat{f}_{NL} = \sum_{\ell_i m_i} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle \; (C^{-1}a)_{\ell_1 m_1} (C^{-1}a)_{\ell_2 m_2} (C^{-1}a)_{\ell_3 m_3}$$

Number of terms in sum is $\approx \ell_{\max}^5$: too slow

Smith & Zaldarriaga

Physical shapes are tractable!

Example: $\dot{\pi}^3$ interaction



$$\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle = \int_0^\infty d\eta\, \eta^2 \frac{1}{k_1 k_2 k_3} e^{-(k_1+k_2+k_3)\eta}$$

Specialized to this case, estimator can be written in tractable form:

$$\hat{f}_{NL} = \int_0^\infty \eta^2 d\eta \int_0^\infty r^2\, dr \int d^2\mathbf{n} \left(\sum_{\ell m} \mu_\ell(\eta, r) (C^{-1} a)_{\ell m} \right)^3$$

Generalizes to any tree diagram, e.g. 4-point estimators:

Smith, Senatore & Zaldarriaga, to appear

Computational problem 1: large number of terms

$$\hat{f}_{NL} = \sum_i \eta_i^2(\Delta\eta) \sum_j r_j^2(\Delta r) \int d^2\mathbf{n} \left(\sum_{\ell m} \mu_\ell(\eta_i, r_j)(C^{-1}a)_{\ell m} \right)^3$$

Sum of many terms, corresponding to points in (η, r) plane

Proposed optimization algorithm to reduce computational cost

General form:

Given estimator $\hat{X} = \sum_{i=1}^{N} \hat{X}_i$ and covariance matrix $\mathrm{Cov}(\hat{X}_i, \hat{X}_j)$

Find minimal (in sense defined by Cov) subset $\{\hat{X}_{i_1}, \hat{X}_{i_2}, \cdots, \hat{X}_{i_M}\}$

Original $\hat{X}$ can be written w/fewer terms: $w_1 \hat{X}_{i_1} + \cdots + w_M \hat{X}_{i_M}$

Specialized to $\hat{f}_{NL}$: Start with many points in the (η, r) plane

Optimization algorithm gives small number of points, weights

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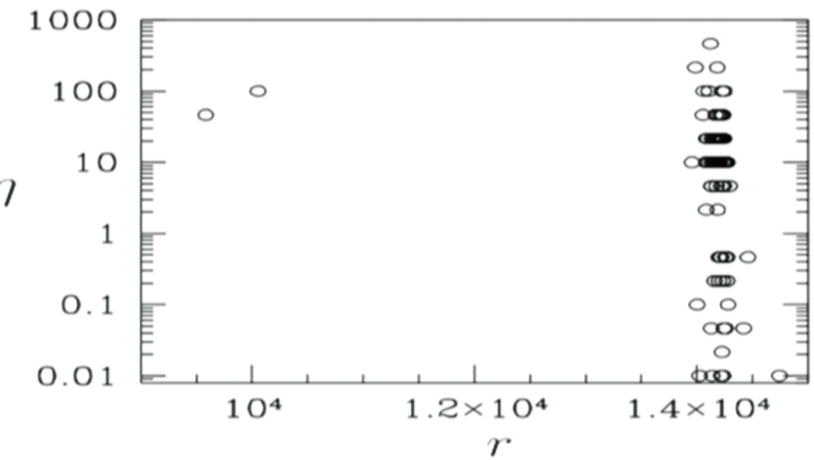
Optimization algorithm: example

$$\hat{f}_{NL} = \int_0^\infty \eta^2 d\eta \int_0^\infty r^2\, dr \int d^2\mathbf{n} \left(\sum_{\ell m} \mu_\ell(\eta, r)(C^{-1}a)_{\ell m} \right)^3$$

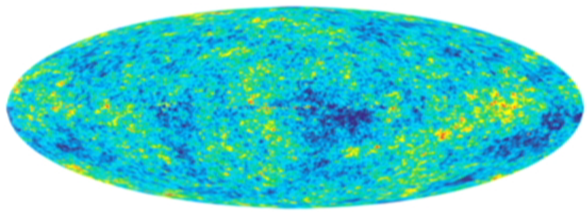
"Unoptimized" estimator: 80000 terms corresponding to dense sampling in the (r, η) plane



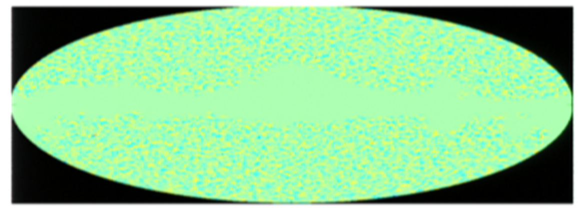
Applying optimization algorithm reduces number of integration points (or terms in the estimator) to 86

Smith & Zaldarriaga

Computational problem 2: $\mathbf{C}^{-1}$



$\Rightarrow$



CMB map = vector a

$C^{-1}a = (S+N)^{-1}a$

$N =$ Noise covariance matrix (diagonal in pixel space)
$S =$ Signal covariance matrix (diagonal in harmonic space)

Appears to require inverting 10^6-by-10^6 matrix!

Proposed fast multigrid algorithm for solving $(S+N)x = a$ iteratively (similar to elliptic PDE such as $\nabla^2 x = a$)

WMAP: ~15 core-min   Planck: ~4 core-hours

Smith, Zahn, Dore & Nolta 2008

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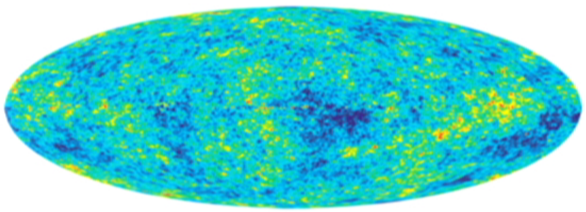

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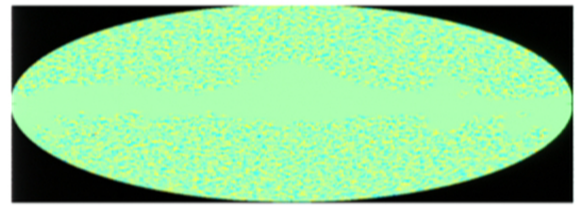

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WMAP results: local shape

First optimal analysis: $f_{NL}^{\mathrm{loc}} = 38 \pm 21 \ (1\sigma)$ *(Smith, Senatore & Zaldarriaga)*

At the time, results in the literature were difficult to interpret...

$$f_{NL}^{\mathrm{loc}} = 32 \pm 34$$ *(Creminelli et al)*

$$f_{NL}^{\mathrm{loc}} = 87 \pm 30$$ *(Yadav & Wandelt)*

$$f_{NL}^{\mathrm{loc}} = 55 \pm 30$$ *(Komatsu et al)*

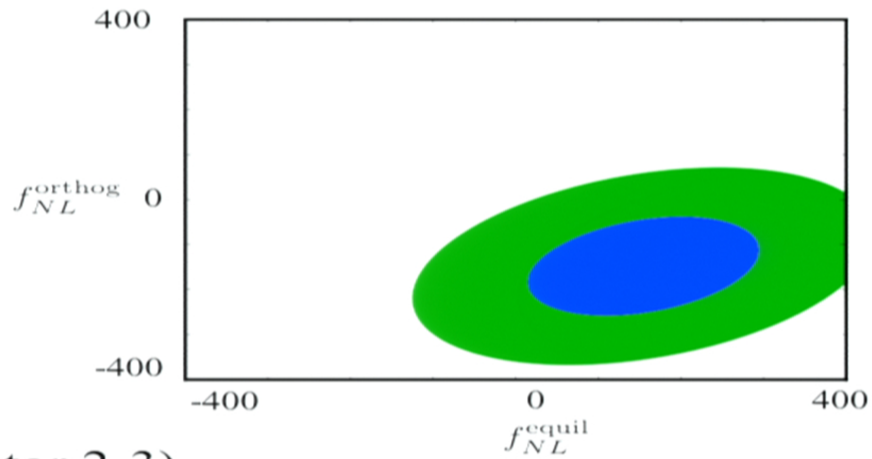
Optimal estimator achieves smallest error bars and ensures uniqueness of result by removing "choices" in data analysis

Current data is consistent with single-field inflation ($f_{NL}^{\mathrm{loc}} = 0$);
Planck will reduce error bar by factor $\sim$4

WMAP results: single-field shapes

First optimal constraints:

$$f_{NL}^{\text{equil}} = 155 \pm 140$$
$$f_{NL}^{\text{orthog}} = -149 \pm 110$$



(Planck: errors smaller by factor 2-3)

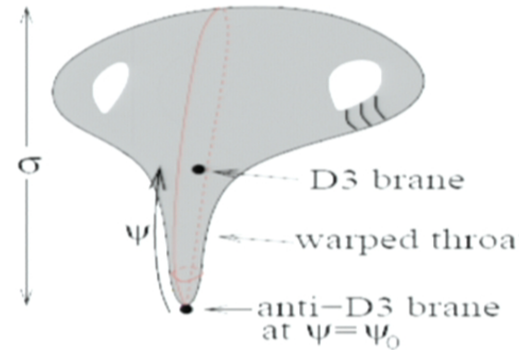
"Master result" which can be compared to all single-field models

Senatore, Smith & Zaldarriaga 2009

Case study: DBI inflation

String-motivated model of inflation
(Alishahiha, Silverstein & Tong)

$$\mathcal{L} = -\frac{1}{g_s}\left(\frac{\sqrt{1+f(\phi)(\partial\phi)^2}}{f(\phi)} + V(\phi)\right)$$



Single field model, classification theorem applies....

$$f_{NL}^{\rm equil} = -\frac{0.35}{c_s^2} \qquad f_{NL}^{\rm orthog} = -\frac{0.024}{c_s^2}$$

From WMAP results we get: $c_s \gtrsim 0.054$ (95% CL)

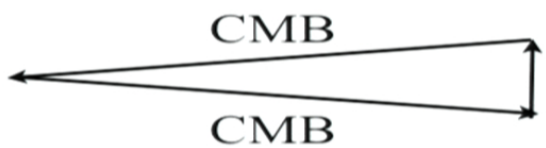
Senatore, Smith & Zaldarriaga 2009

WMAP results: gravitational lensing

Different CMB power spectrum when looking through large-scale overdense/underdense region:

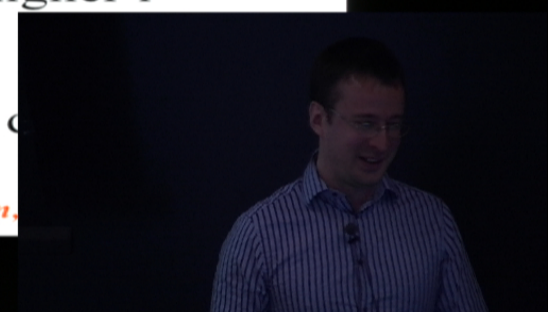
- overdense: magnifies, acoustic peaks shift to lower l
- underdense: demagnifies, acoustic peaks shift to higher l

Three-point function:



matter c

Smith, Zahn,



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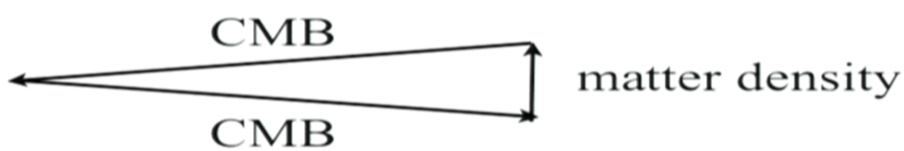
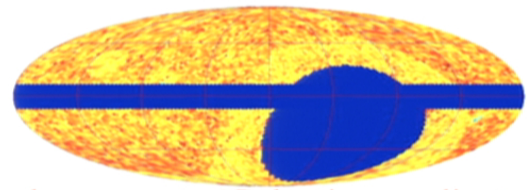


Smith, Zahn, Dore & Nolta 2008

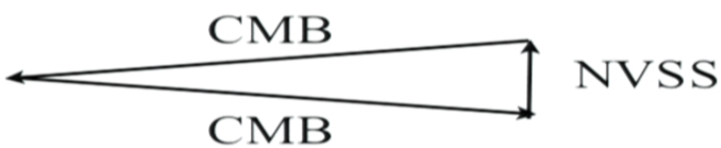
WMAP results: gravitational lensing

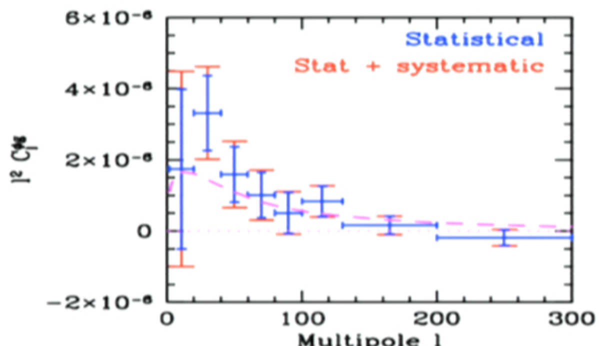
NVSS: 1.4 GHz all-sky radio survey

Use galaxy counts as tracer for CMB lenses



galaxy counts (Galactic coordinates)





Three-point signal detected at 3.4σ
First detection of CMB lensing!

Smith, Zahn, Dore & Nolta 2008

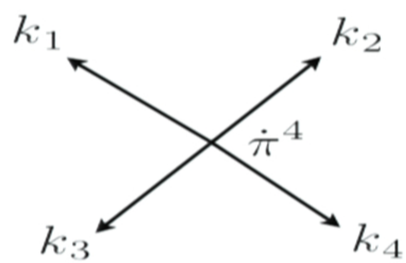
Analyses in progress...

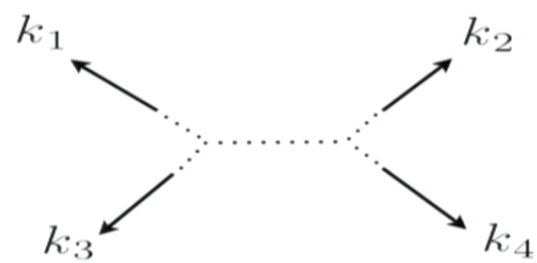
WMAP9: Optimal power spectrum using C^{-1} weighting

Improves errors on most parameters by 10-20%
(more than WMAP7 to WMAP9 improvement)

Planck: Error bars on primordial shapes reduced by factor 2-4
Gravitational lensing: 30 sigma (!)

Four-point shapes (coming soon)





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