Primordial non-Gaussianity after *Planck* 2015:
looking for new observational tests and new signatures

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Outline

- *Inflation and NG: current status*
- *Some prospects for the future:*
  primordial NG and CMB spectral distortions
- *New signatures:*
  NG from modified gravity

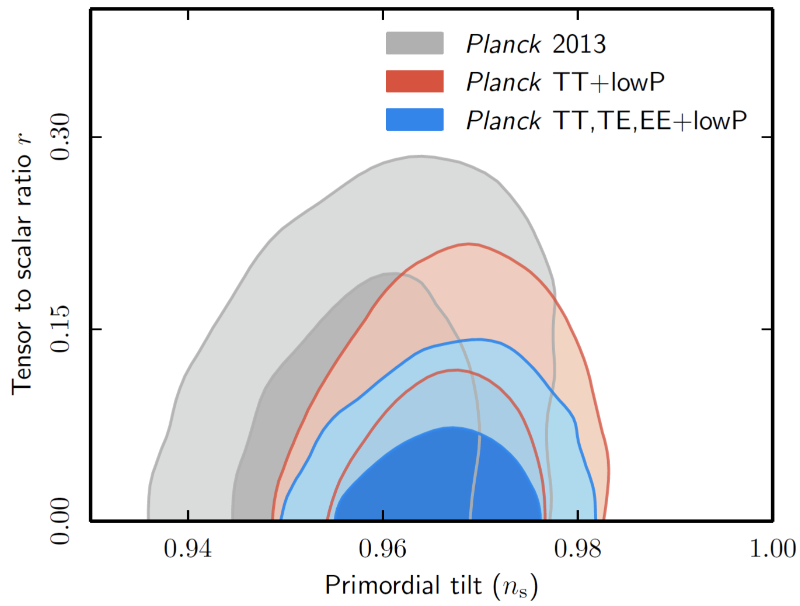
Based on
N.B., M. Liguori, M. Shiraishi, JCAP 1603, 29 (2016)
M. Shiraishi,M. Liguori, N.B., S. Matarrese Phys.Rev. D92, 083502 (2015)
N.B, M. Liguori, M. Shiraishi in preparation
N.B., G. Orlando, M. Shiraishi, in preparation

Current status of inflation

Inflation is in a very good status

$$n_s = 0.968 \pm 0.006 \ \ (68\% \text{ CL})$$

$r_{0.05} < 0.09 \ \ (95\% \text{ CL})$ from latest measurements of B-modes BICEP2/Keck array



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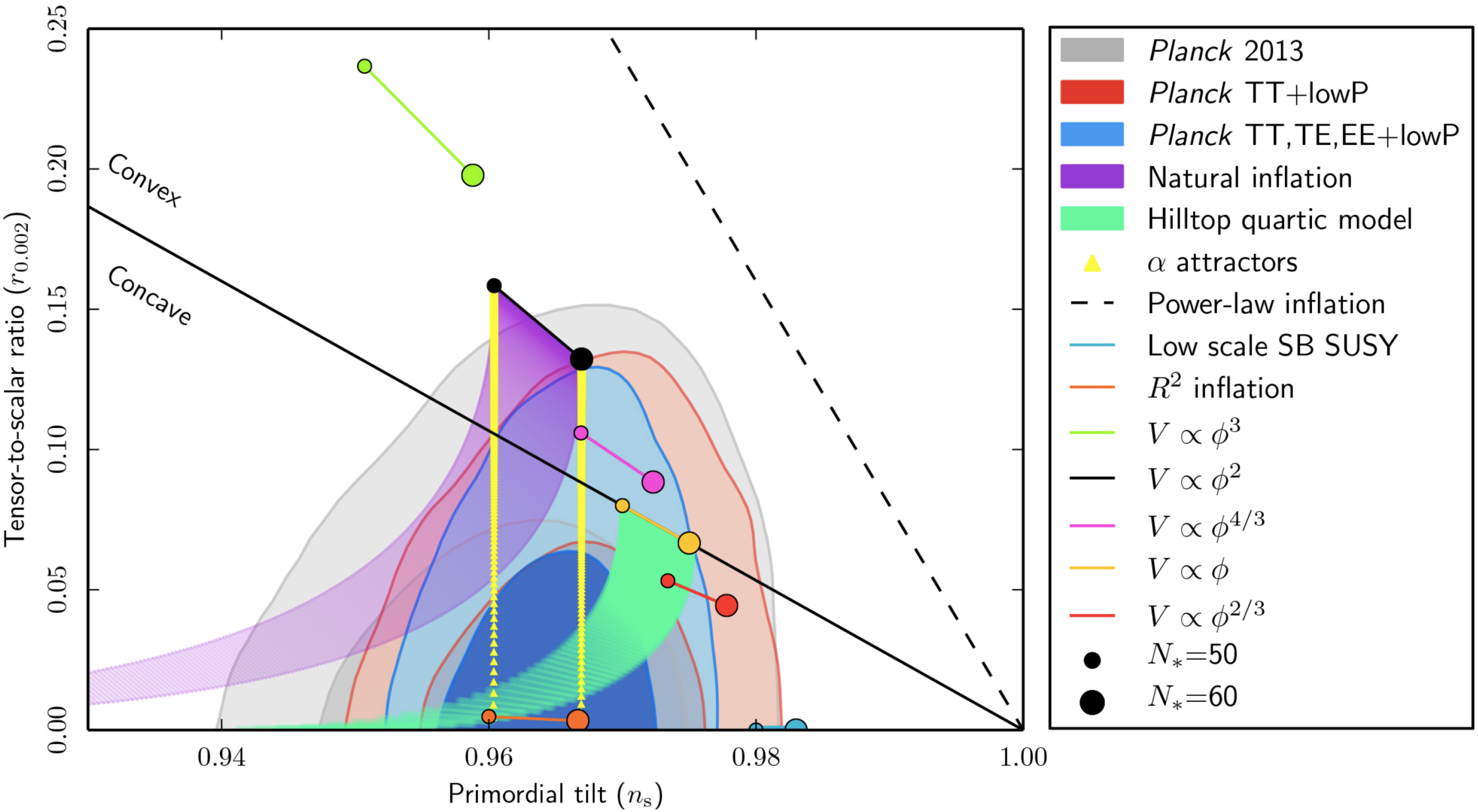


Primordial non-Gaussianity

Primordial NG

$\zeta(\mathbf{x})$: primordial perturbations

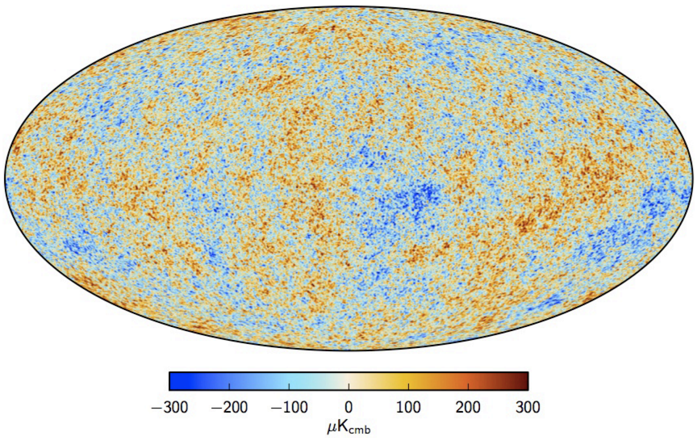
If the fluctuations are Gaussian distributed then their statistical properties are completely characterized by the two-point correlation function, $\langle\zeta(\mathbf{x}_1)\zeta(\mathbf{x}_2)\rangle$ or its Fourier transform, the power-spectrum.

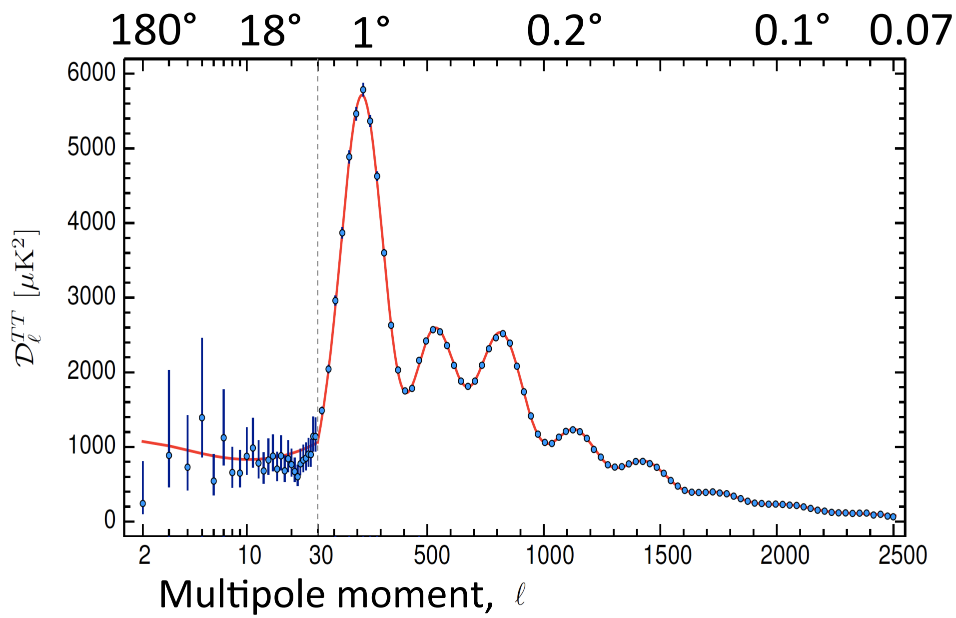
Thus a non-vanishing ***three point function***, or its Fourier transform, the ***bispectrum is an indicator of non-Gaussianity***

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

$$\rightarrow \quad \left\langle \frac{\Delta T}{T}(n_1)\frac{\Delta T}{T}(n_2)\frac{\Delta T}{T}(n_3) \right\rangle$$

Bispectrum vs power spectrum information



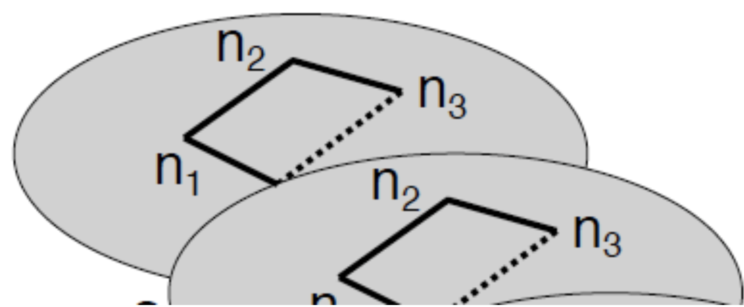


Planck 2015 Results. I. Overview of products and scientific results

5×10⁶ pixels compressed into ~2500 numbers: O.K. only if gaussian

If not we could miss precious information

Measure 3 point-function and higher-order



Primordial NG

Gaussian $\Longleftrightarrow$ free (i.e. non-interacting) field, linear theory

Collection of independent harmonic oscillators
(no mode-mode coupling)

Physical origin of primordial NG:
self-interactions of the inflaton field, e.g. $\lambda\,\phi^3$,
interactions between different fields,
non-linear evolution of the fields during inflation,
gravity itself is non linear…..

Why primordial NG is important?

One (among many) good reason:

f_{NL} and shape are model dependent:

e.g.: standard single-field models of slow-roll inflation predict

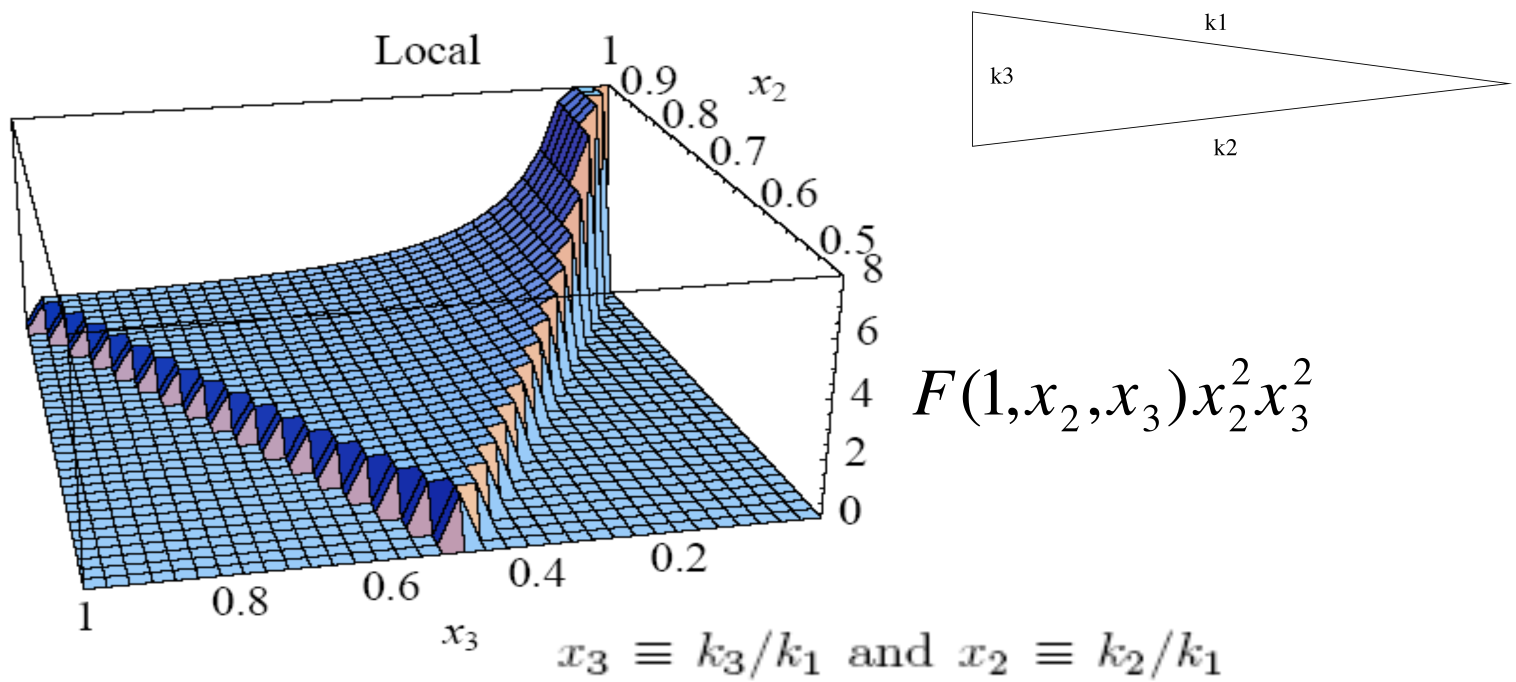
$$f_{NL} \sim O(\varepsilon,\eta) << 1$$

(Acquaviva, Bartolo, Riotto, Matarrese 2002; Maldacena 2002)

A detection of a primordial $|f_{NL}| \sim 1$ would rule out *all* standard single-field models of slow-roll inflation

SHAPES OF NG: LOCAL NG

Bispectrum peaks for squeezed triangles $k_1 << k_2 \sim k_3$



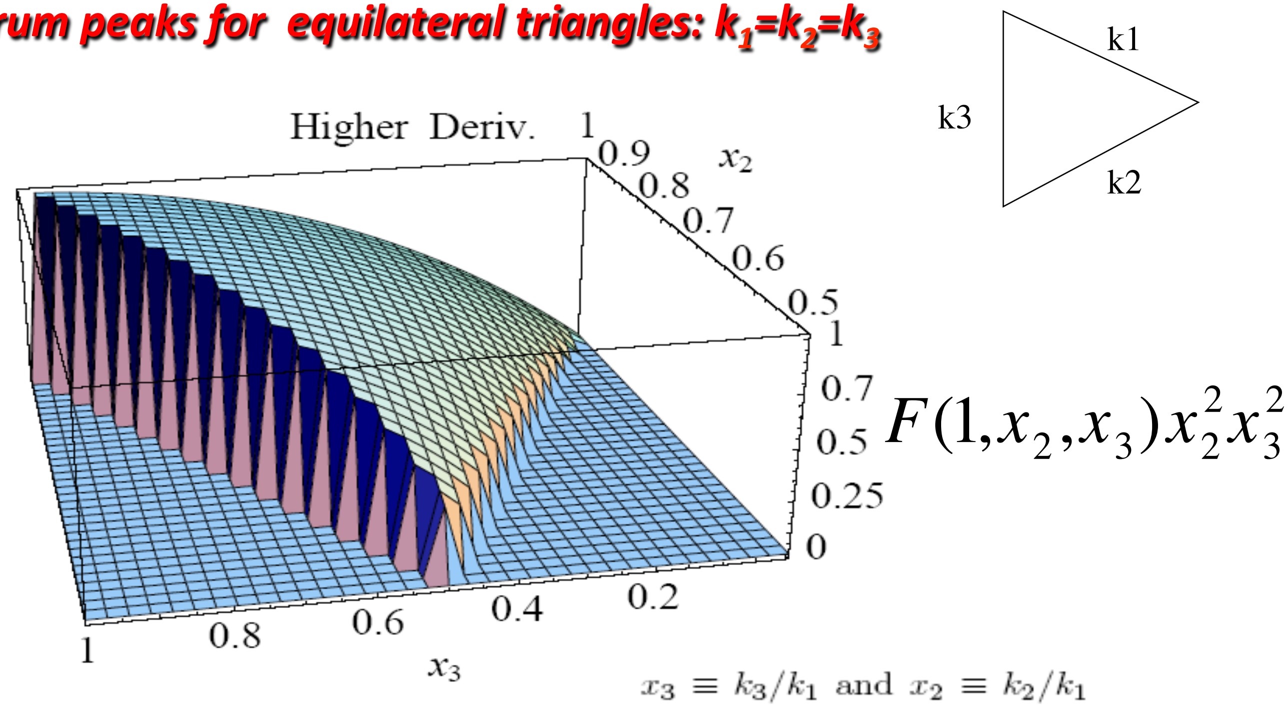
Babich et al. astro-ph/0405356

$$\zeta(\mathbf{x}) = \zeta^{\mathrm{G}}(\mathbf{x}) + \frac{3}{5} f_{\mathrm{NL}} \left(\zeta^{\mathrm{G}}(\mathbf{x})\right)^2$$

Non-linearities develop outside the horizon during or immediately after inflation (e.g. ***multifield models of inflation***)

EQUILATERAL NG

Bispectrum peaks for equilateral triangles: $k_1=k_2=k_3$



Babich et al. (2004)

Single field models of inflation with non-canonical kinetic term L=P(φ, X) where X=(∂ φ)^2 (DBI or K-inflation) where NG comes from higher derivative interactions of the inflaton field

Example: $\dot{\delta\phi}(\nabla\delta\phi)^2$

Limits set by Planck

See Planck 2015 results. XVII. Constraints on primordial non-Gaussianity

Observational limits set by Planck

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
`SMICA` (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
`SMICA` (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

e.g. models with non-standard kinetic terms

e.g. multi-field models of inflation

Planck 2015 results. XVII. Constraints on primordial non-Gaussianity.

Implications for inflation models

- The standard models of single-field slow-roll inflation has survived the most stringent tests of Gaussianity to-date: ***deviations from primordial Gaussianity are less than 0.01% level. This is a fantastic achievement, one of the most precise measurements in cosmology!***

$$\Phi(\mathbf{x}) = \Phi^{(1)}(\mathbf{x}) + f_{\mathrm{NL}} \left(\Phi^{(1)}(\mathbf{x}) \right)^2 + \ldots\ldots$$

$\sim 10^{-5}$ $\sim$few $\sim 10^{-10}$

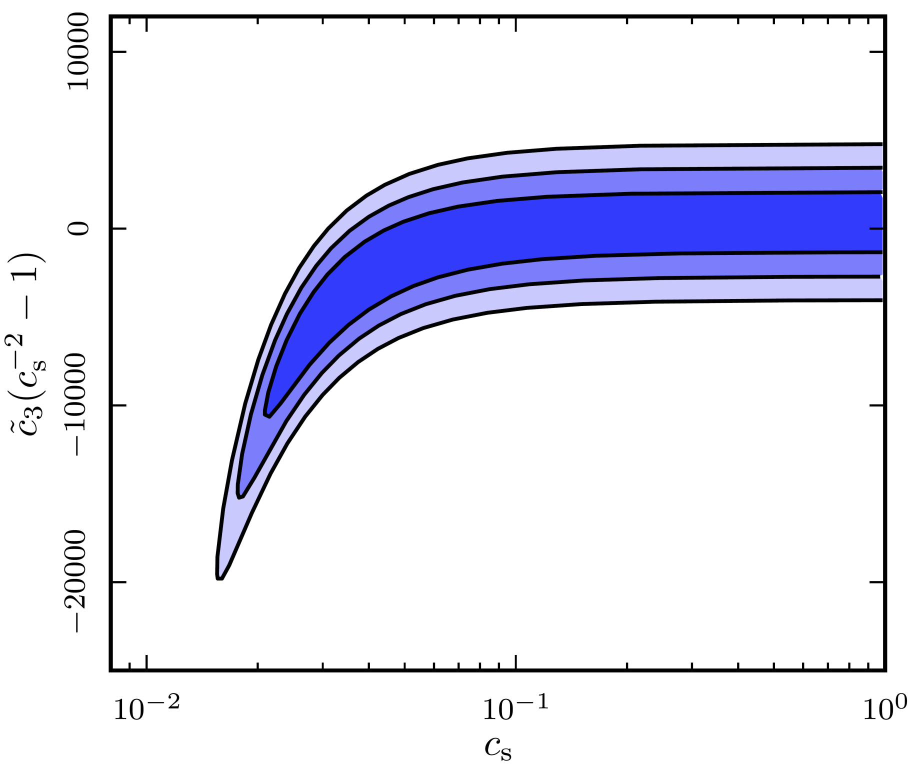
- ***The NG constraints*** on different primordial bispectrum shapes ***severly limit/rule out specific key (inflationary) mechanisms alternative to the standard models of inflation***

General single-field models of inflation: Implications for Effective Field Theory of Inflation

$$S = \int d^4x \sqrt{-g}\Big[-\frac{M_{\rm Pl}^2 \dot{H}}{c_{\rm s}^2}\left(\dot{\pi}^2 - c_{\rm s}^2\frac{(\partial_i\pi)^2}{a^2}\right) - M_{\rm Pl}^2\dot{H}(1-c_{\rm s}^{-2})\dot{\pi}\frac{(\partial_i\pi)^2}{a^2} + \left(M_{\rm Pl}^2\dot{H}(1-c_{\rm s}^{-2}) - \frac{4}{3}M_3^4\right)\dot{\pi}^3\Big]$$

$$f_{\rm NL} \propto \frac{1}{c_s^2}$$

(Cheung et al. 08; Weinberg 08)
for extensions see also N.B., Fasiello, Matarrese, Riotto 10)



Constraints obtained from

$$f_{\rm NL}^{\rm equil} = -16 \pm 70 \quad (68\%\ {\rm CL})$$

$$f_{\rm NL}^{\rm ortho} = -34 \pm 33 \quad (68\%\ {\rm CL})$$

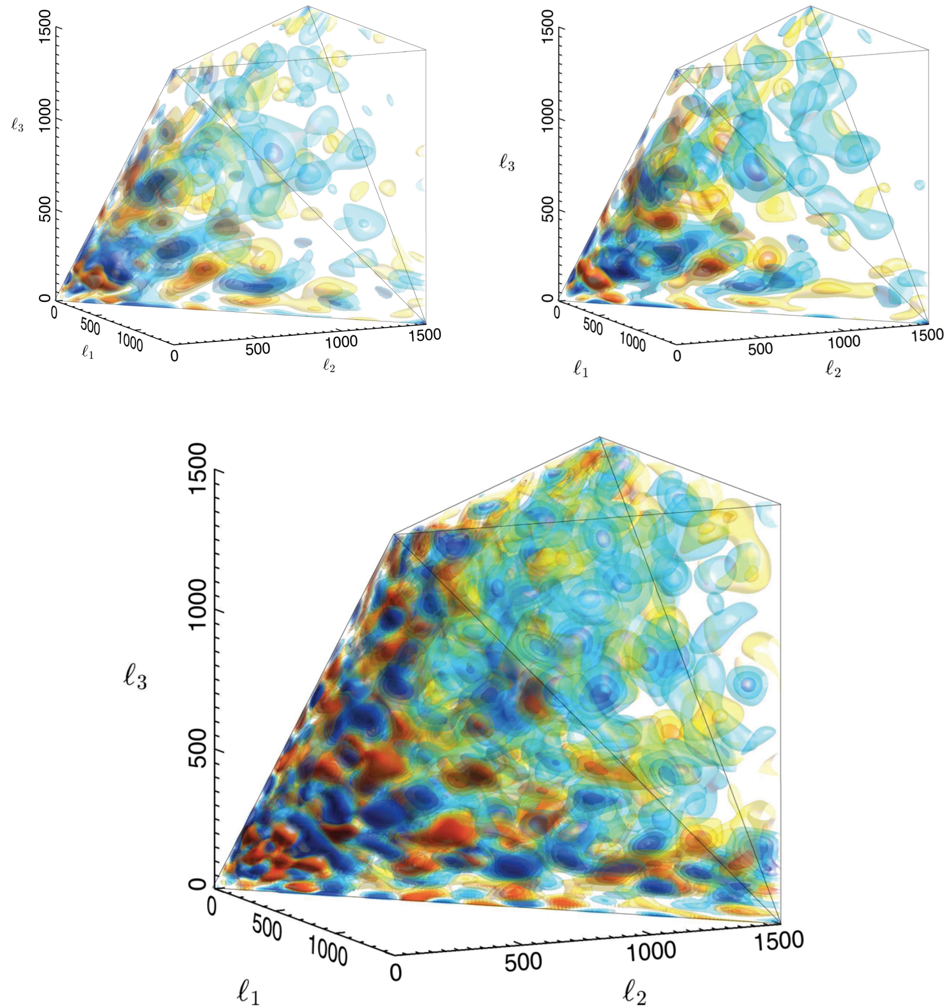
$$\boxed{c_s \geq 0.02 \ \text{ at } 95\%\ \text{CL}}$$

The CMB bispectrum as seen by Planck

$$\frac{\Delta T}{T}(\vartheta,\phi) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vartheta,\phi)$$

$$B_{\ell_1\ell_2\ell_3} = \sum_m \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \left\langle a_{\ell_1}^{m_1} a_{\ell_2}^{m_2} a_{\ell_3}^{m_3} \right\rangle;$$

$$B_{\ell_1\ell_2\ell_3} = h_{\ell_1\ell_2\ell_3} b_{\ell_1\ell_2\ell_3}$$



So…… what next for NG?
(or next to next)

Significant thresholds

- ***multiple field models of inflation generically predict f_{NL}(local)≥ 1.***
  e.g curvaton models

$$f_{\rm NL}^{\rm local} = \frac{5}{4r_{\rm D}} - \frac{5r_{\rm D}}{6} - \frac{5}{3}$$

  with minimum value –(5/3) (N.B, Matarrese, Riotto 2004).

- ***also for equilateral NG a motivated threshold is f_{NL}(equil)≥ 1***
  (see Marcelo Alvarez et al . arXiv:1412.4671).

- Of course a clear distinction between. e.g., single and multiple field inflation, requires to improve current sensitivities by at least one order of magnitude, thus probing a range of amplitudes which is at the level of the standard single-field slow-roll prediction

$f_{NL} \sim O(\varepsilon,\eta) \ll 1$ (Acquaviva, Bartolo, Riotto, Matarrese 2002; Maldacena 2002)

New observational strategies

CMB is a priviliged laboratory for cosmic inflation.

Improvements are possible thanks to CMB polarization.

An experiment like PRISM or CMBpol, cosmic variance dominated in E-mode up to to l_max ~ 3000 can improve by a factor of 3 the error bars on f_NL for ***all shapes.***

New observational strategies

CMB is a priviliged laboratory for cosmic inflation. However different observables can be competitive, and in the future, have a better sensitivity to, e.g., primordial non-Gaussianity

- Large-Scale-Structure Surveys
- CMB spectral distortions
- Future high-redshift large radio surveys
- High-redshift 21cm fluctuations

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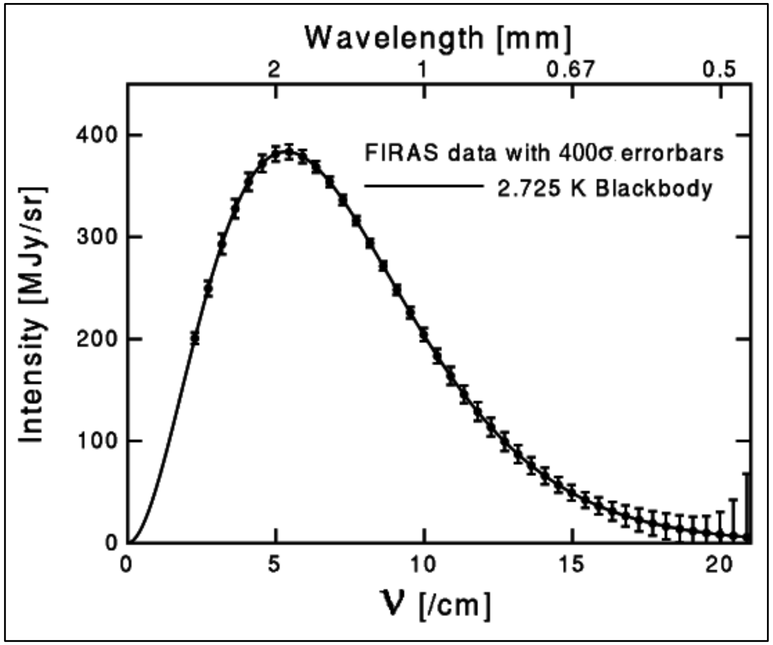
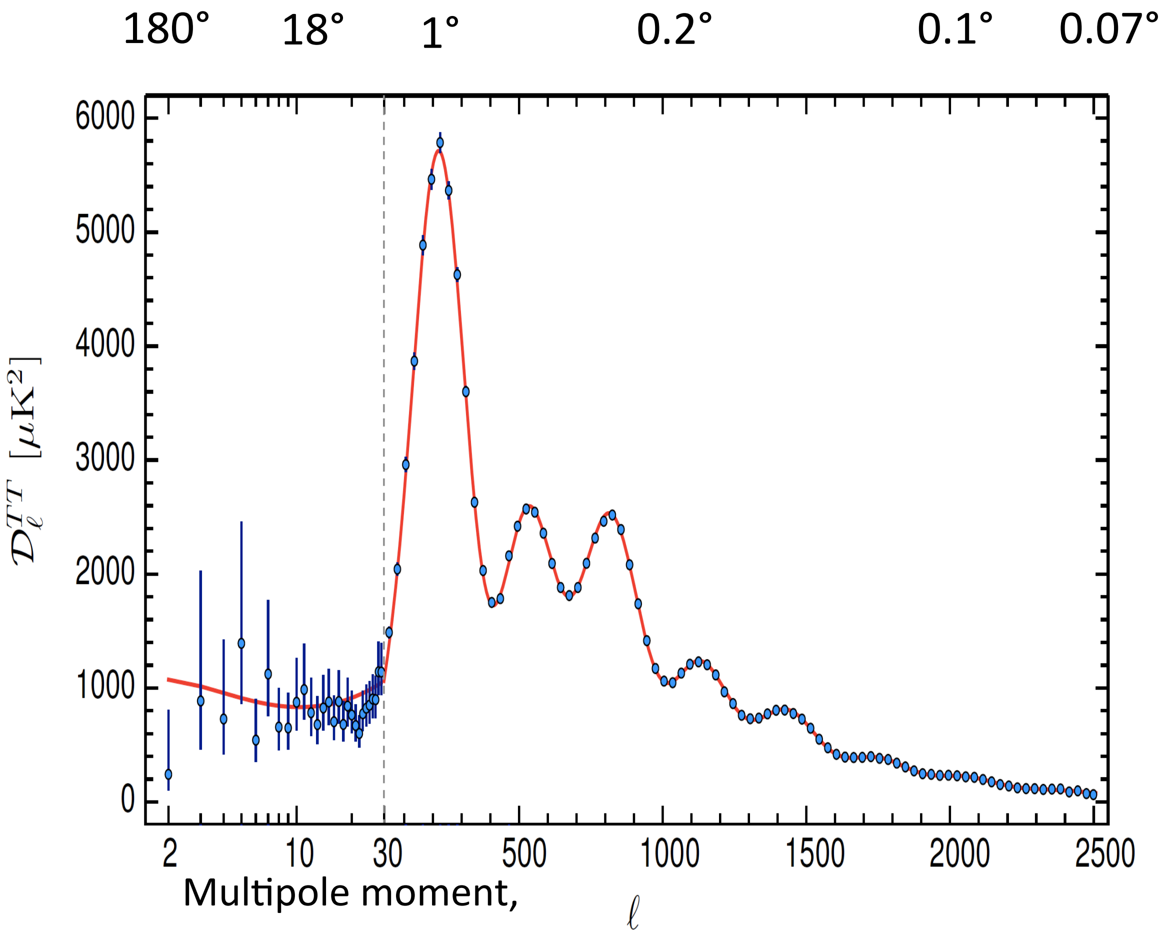
- Large-Scale-Structure Surveys
- **CMB spectral distortions**
- Future high-redshift large radio surveys
- High-redshift 21cm fluctuations

CMB spectral distortions

- We know there must be tiny deviations from a perfect black body of the CMB spectrum in the frequency domain
- Not detected yet (apart y-distortions from Sunyaev-Zel'dovich effect)
- $\dfrac{\Delta I_\nu}{I_\nu} < 10^{-4} \qquad \mu < 9 \times 10^{-5} \qquad y < 1.5 \times 10^{-5} \quad (95\%\ \mathrm{C.L})$

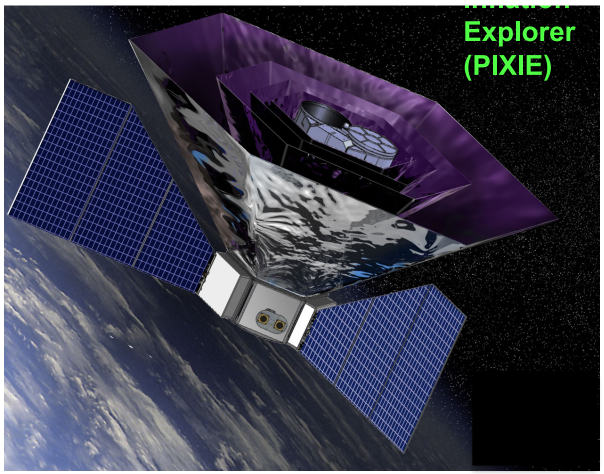
FROM COBE/FIRAS



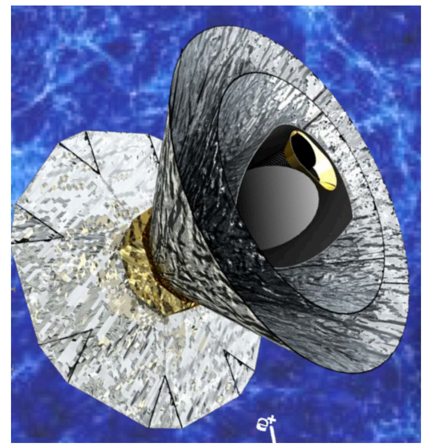

180°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
2
10
30
500
1000
1500
2000
2500
Multipole moment, ℓ

CMB spectral distortions

- Various planned and proposed satellite missions can achieve the required sensitivity to measure the primordial μ and y spectral distortions: these are predicted to be $\langle\mu\rangle \approx 1.9\times10^{-9}$ and $\langle y\rangle \approx 4.2\times10^{-8}$



Sensitive to a minimum $\langle\mu\rangle_{min} \approx 10^{-9}$



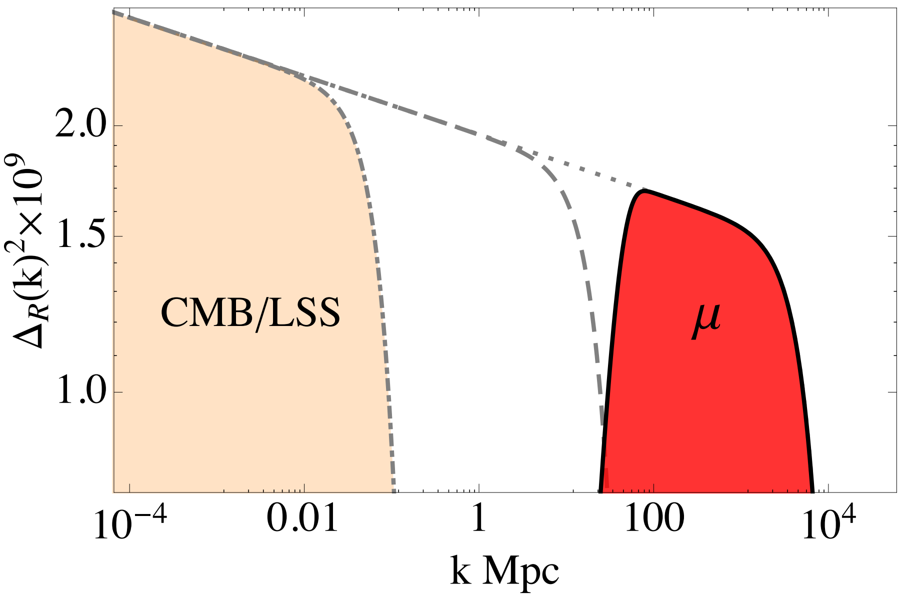
PRISM

Sensitive to a minimum $\langle\mu\rangle_{min} \approx 10^{-8}$

- Besides being a probe of the standard ΛCDM model (including inflation) it can unveil new physics, e.g. about
  - decaying and annihilating dark matter particles
  - black holes and cosmic strings

  and it can allow to measure a whole series of signals like y-distortions from re-ionized gas

A powerful source of information



(From Pajer & Zaldarriaga 2012)

- CMB spectral distortions expected in the standard ΛCDM modeL: AN ALMOST UNEXPLOITED OBSERVATIONAL WINDOW
  (see, e.g., Kathri and Sunyaev 2013, arXiv: 1303.7212;
  Chluba 2016, arXiv: 1603.02496)

- **In particular can probe very small scales 10^{-4} - 0.02 Mpc!**

CMB μ distortions

- Energy injection from dissipation of acoustic waves due to Silk damping
  The relevant redshit range is
  $5\times10^4 = z_f < z < z_i = 2\times10^6$
  and the relevant scales are $k_D(z_i) = 12000\ \mathrm{Mpc}^{-1}$ and $k_D(z_f) = 46\ \mathrm{Mpc}^{-1}$

$$\mu \approx \frac{1.4}{4}\left[\langle\delta_\gamma^2(x)\rangle_p\right]_{z_f}^{z_i} \qquad \Delta_\gamma(k) \simeq 3\cos(kr)\exp[-k^2/k_D^2(z)]$$

- Transfer functions

$$\mu(\mathbf{x}) \simeq \left[\prod_{n=1}^{2}\int\frac{d^3\mathbf{k}_n}{(2\pi)^3}\zeta_{\mathbf{k}_n}\right]\int d^3\mathbf{k}_3\delta^{(3)}\left(\sum_{n=1}^{3}\mathbf{k}_n\right)f(k_1,k_2,k_3)e^{-i\mathbf{k}_3\cdot\mathbf{x}}$$

$$f(k_1,k_2,k_3) \equiv \frac{9}{4}W\left(\frac{k_3}{k_s}\right)\left[e^{-(k_1^2+k_2^2)/k_D^2(z)}\right]_{z_f}^{z_i}$$

Selects squeezed config. $k_1, k_2 > k_D(z_f) > k_3$

- The monopole

$$\langle\mu\rangle \simeq \int d\ln k\,\Delta_\zeta^2(k)\left[e^{-2k^2/k_D^2}\right]_f^i$$

It is predicted to be 1.9×10^{-8} for the best fit ΛCDM

CMB spectral distortions and NG

- Pajer & Zaldarriaga (2012) and Ganc & Komatsu (2012) pointed out that the cross-correlation between CMB μ-distortion and CMB temperature fluctuations can be a diagnostic very sensitive to local-type bispectra peaking in the squeezed configuration: a cosmic variance limited experiment can achieve f_{NL}~0.001

Local primordial non-Gaussianity correlates short- with long-mode perturbations, so it induces a correlation between the dissipation process on small scales

$$\mu \sim \delta_\gamma^2 \sim \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}}$$

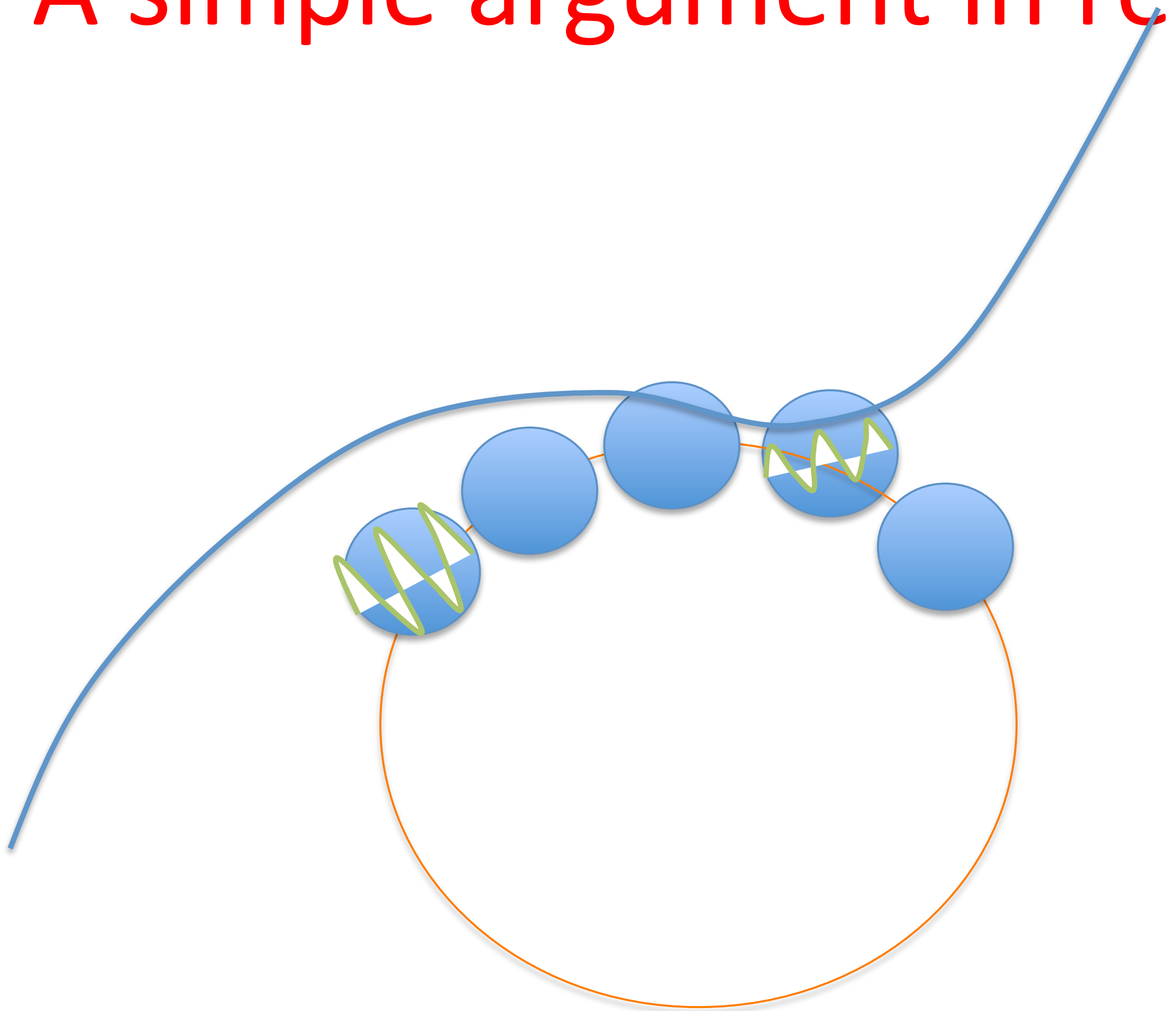
and the long-mode fluctuations in the CMB

$$\delta T/T \sim \zeta_{\mathbf{k}}$$

$$\downarrow$$

$$C_\ell^{\mu T} \sim \langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle$$

A simple argument in real space



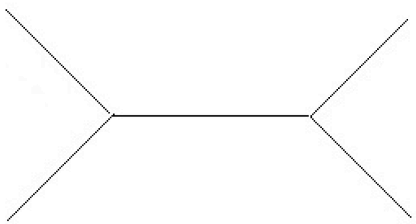
If there is a local model of non-Gaussianity, then the small scale power spectrum of curvature perturbation $\Delta^2_\varsigma(k,x)$ will be modulated from patch to patch, by the long-wavelength curvature fluctuation and correlated to it

Looking at the inflationary trispectra (4-point correlation functions)

Looking at the inflationary trispectra

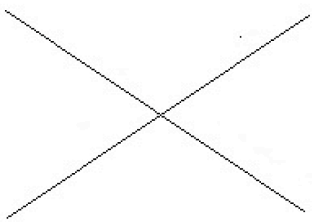
$$\langle \hat{\zeta}_{\vec{k}_1} \hat{\zeta}_{\vec{k}_2} \hat{\zeta}_{\vec{k}_3} \hat{\zeta}_{\vec{k}_4} \rangle = (2\pi)^3 \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3 + \vec{k}_4) T_\zeta(\vec{k}_1, \vec{k}_2, \vec{k}_3, \vec{k}_4)$$

Scalar exchange:
comes from terms in the 3-oder action, e.g. $(\delta\phi)^3$



$\tau_{NL} \propto f^2_{NL}$

Contact interaction: e.g. $\lambda\, (\delta\phi)^4$ (intrinsic contributions from the 4-th order action)



g_{NL}

Looking at the inflationary trispectra

Motivations:

- It can also provide crucial information to further distinguish between competing models (or alternatives to inflation)

- Sizeable amplitudes can arise only in multi-field models (or in models with higher derivative interations of the inflaton field)

- Testing consistency relations
  e.g. Suyama-Yamaguchi relation $\tau_{\rm NL} \geq (6 f_{\rm NL}^{\rm loc}/5)^2$

- Scenarios where the trispectrum has larger S/N ratio than the bispectrum (e.g. some curvaton models, some multifield models; technically natural models do exist (e.g., Senatore & Zaldarriaga 2012; N.B., Fasiello, Matarrese, Riotto 2012).

Local trispectra

Possible models

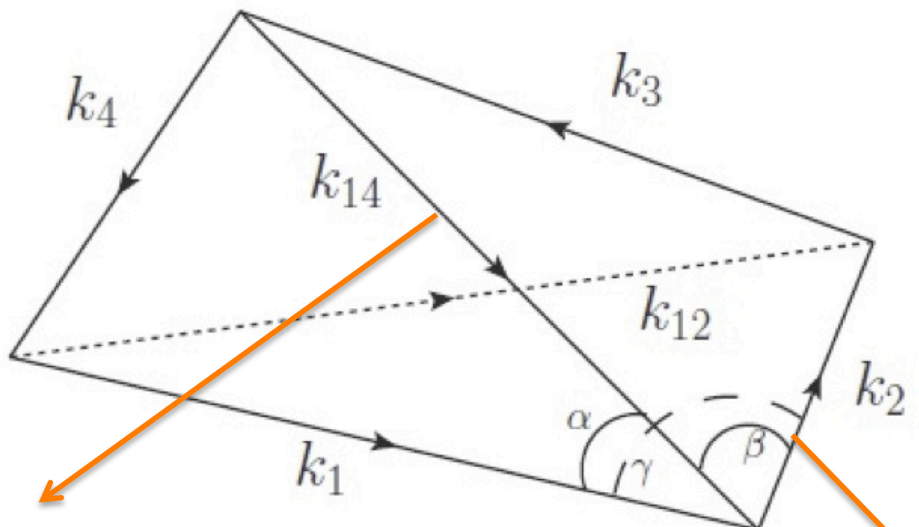
$$\zeta(\mathbf{x}) = \zeta^{\mathrm{G}}(\mathbf{x}) + \frac{3}{5} f_{\mathrm{NL}} \left(\zeta^{\mathrm{G}}(\mathbf{x})\right)^2 + \frac{9}{25} g_{\mathrm{NL}} \left(\zeta^{\mathrm{G}}(\mathbf{x})\right)^3$$

or

$$\zeta(\mathbf{x}) = \zeta^{\mathrm{G}}(\mathbf{x}) + \sqrt{\tau_{\mathrm{NL}}}\sigma(\mathbf{x})\zeta^{\mathrm{G}}(\mathbf{x})$$

Typically arising in multi-field models of inflation

Looking at the inflationary trispectra



e.g. k_14 -> 0
corresponds to τ_NL:
a modulation of power spectra

e.g. k_2 -> 0
corresponds to g_NL:
a modulation of the bispectrum

Observational limits set by Planck

$$\tau_{\rm NL}^{\rm loc} < 2800 \quad (95\%\ {\rm CL})$$

$$\begin{aligned} g_{\rm NL}^{\rm local} &= (-9.0 \pm 7.7) \times 10^4; \\ g_{\rm NL}^{\dot\sigma^4} &= (-0.2 \pm 1.7) \times 10^6; \\ g_{\rm NL}^{(\partial\sigma)^4} &= (-0.1 \pm 3.8) \times 10^5. \quad (68\%\ {\rm CL}) \end{aligned}$$

Also From LSS

$-4.5 \times 10^5 < g_{\rm NL} < 1.6 \times 10^5 \;\; 95\%{\rm CL}$ *(Giannantonio et al. 2013)*

A warning

- ***Tμ (and μμ) cross-correlation is not able to determine the g_{NL} parameter***

- the TTμ *bispectrum* is a potential powerful way to measure g_{NL}
- An ideal, cosmic variance dominated experiment can reach g_{NL}~0.1

(N.B., Liguori and Shiraishi 2015)

A simple guide argument

- Why Tμ cross-correlation is sensitive to f_{NL}?

Local primordial non-Gaussianity correlates small and long wavelengths, so that it modulates the small-scale monopole <μ> from patch to path on the last scattering surface: <μ> is an (integrated) power spectrum on small scales which gets modulated by $f_{NL.}$

- By the same token: <μ μ> depends on two power spectra. τ_{NL} is a modulation of two power spectra

- So where the idea of TTμ came from?
  Tμ is a bispectrum and T(Tμ) is a modulation of a bispectrum (exactly what g_{NL} does).

A simple computation

A local non-Gaussianity modulates the small scale power spectrum and hence the μ-distortions

$$\langle \mu \rangle \simeq \int d\ln k\, \Delta_\zeta^2(k)\, F(k)$$

Take as a model $\zeta(\mathbf{x}) = \zeta^{\mathrm{G}}(\mathbf{x}) + \frac{9}{25} g_{\mathrm{NL}} \left(\zeta^{\mathrm{G}}(\mathbf{x})\right)^3$

Split into short and long fluctuation parts $\zeta(\mathbf{x}) = \zeta_S(\mathbf{x}) + \zeta_L(\mathbf{x})$

$$\zeta_S(\mathbf{x}) = \zeta_S^{\mathrm{G}}(\mathbf{x}) \left[1 + \frac{27}{25} g_{\mathrm{NL}} \left(\zeta_L^{\mathrm{G}}(\mathbf{x})\right)^2\right] \Longrightarrow \frac{\delta\langle\zeta^2\rangle}{\langle\zeta^2\rangle} \simeq \frac{\delta\mu}{\mu} \simeq \frac{54}{25} g_{\mathrm{NL}} \left(\zeta_L^{\mathrm{G}}(\mathbf{x})\right)^2$$

A simple computation

$$\left\langle \frac{\delta T_1}{T}\frac{\delta T_2}{T}\frac{\delta \mu_3}{\mu}\right\rangle \simeq \frac{54}{25} g_{\rm NL} \left\langle \frac{\zeta_1}{5}\frac{\zeta_2}{5}\left(\zeta^{\rm G}_{L3}\right)^2\right\rangle = 108\, g_{\rm NL} \left\langle \frac{\delta T_1}{T}\frac{\delta T_3}{T}\right\rangle \left\langle \frac{\delta T_2}{T}\frac{\delta T_3}{T}\right\rangle$$

$$b^{TT\mu}_{\ell_1\ell_2\ell_3} \simeq 108\, g_{\rm NL}\, \underbrace{\frac{9}{4} A_S \ln\left(\frac{k_i}{k_f}\right)}_{} C^{TT}_{\ell_1} C^{TT}_{\ell_2}$$

This corresponds to the monopole
<μ> for a scale-invaraint power spectrum

Forecasts

Simple Fisher matrix analysis

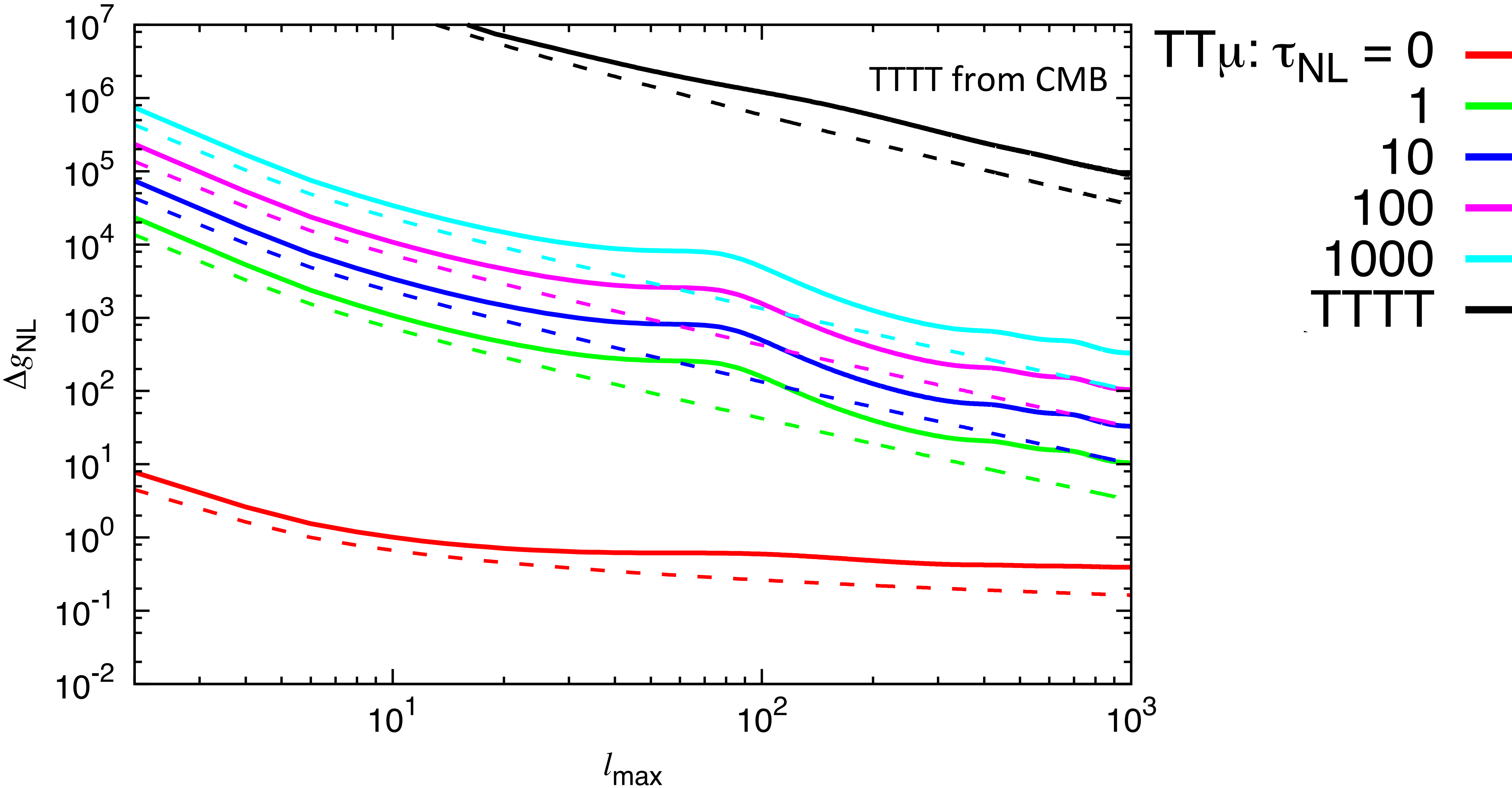
$$F^{TT\mu} = \sum_{\ell_1\ell_2\ell_3} \frac{\left(h_{\ell_1\ell_2\ell_3}\hat{b}^{TT\mu}_{\ell_1\ell_2\ell_3}\right)^2}{2C^{TT}_{\ell_1}C^{TT}_{\ell_2}C^{\mu\mu}_{\ell_3}}$$

Some subtleties:

- $C_\ell^{T\mu} = 0$ taking f_NL=0
- Also: $C_\ell^{\mu\mu}$ receives a contribution from τ_NL if τ_NL≠0.

Forecasts for g_{NL}

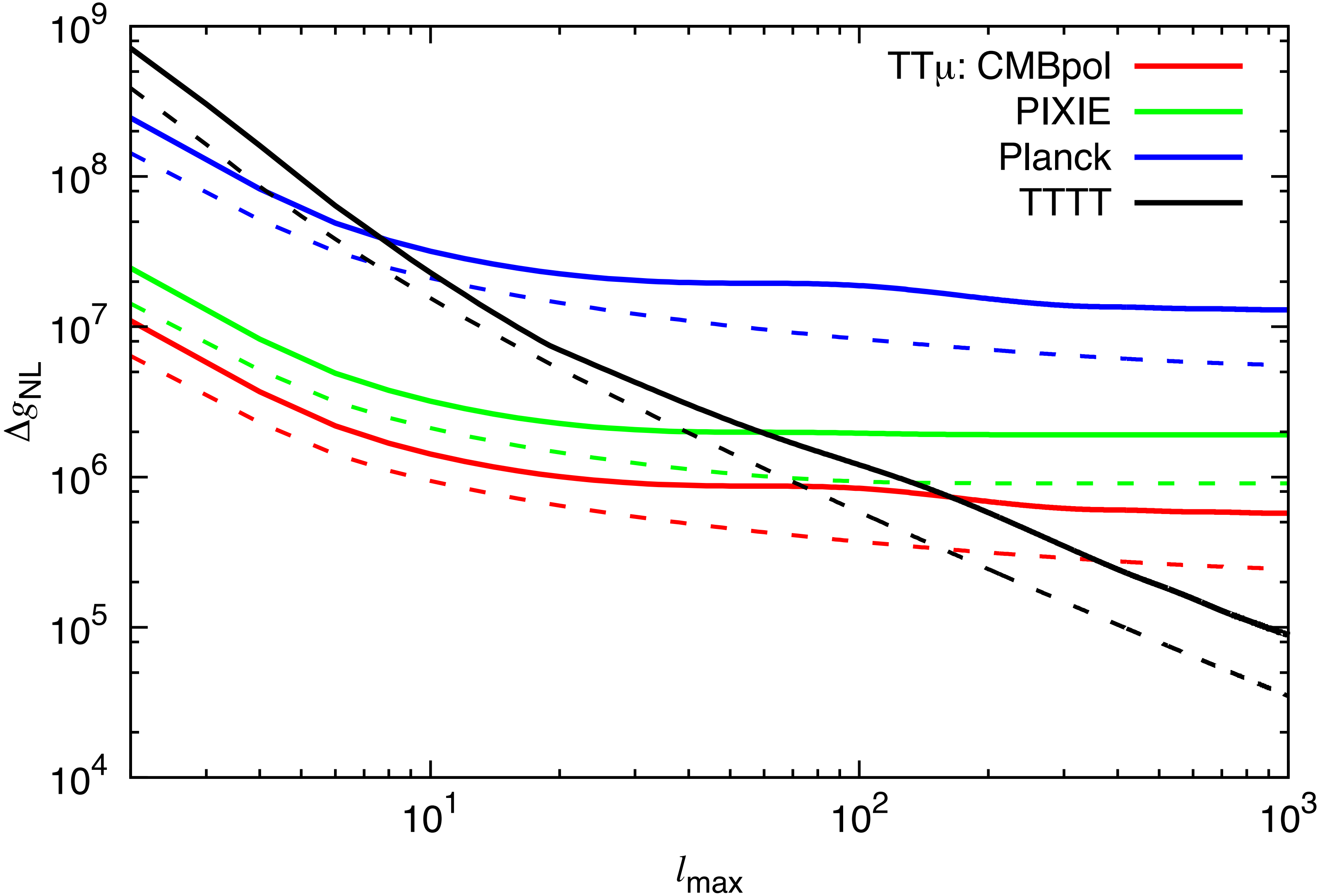
Cosmic variance dominated case



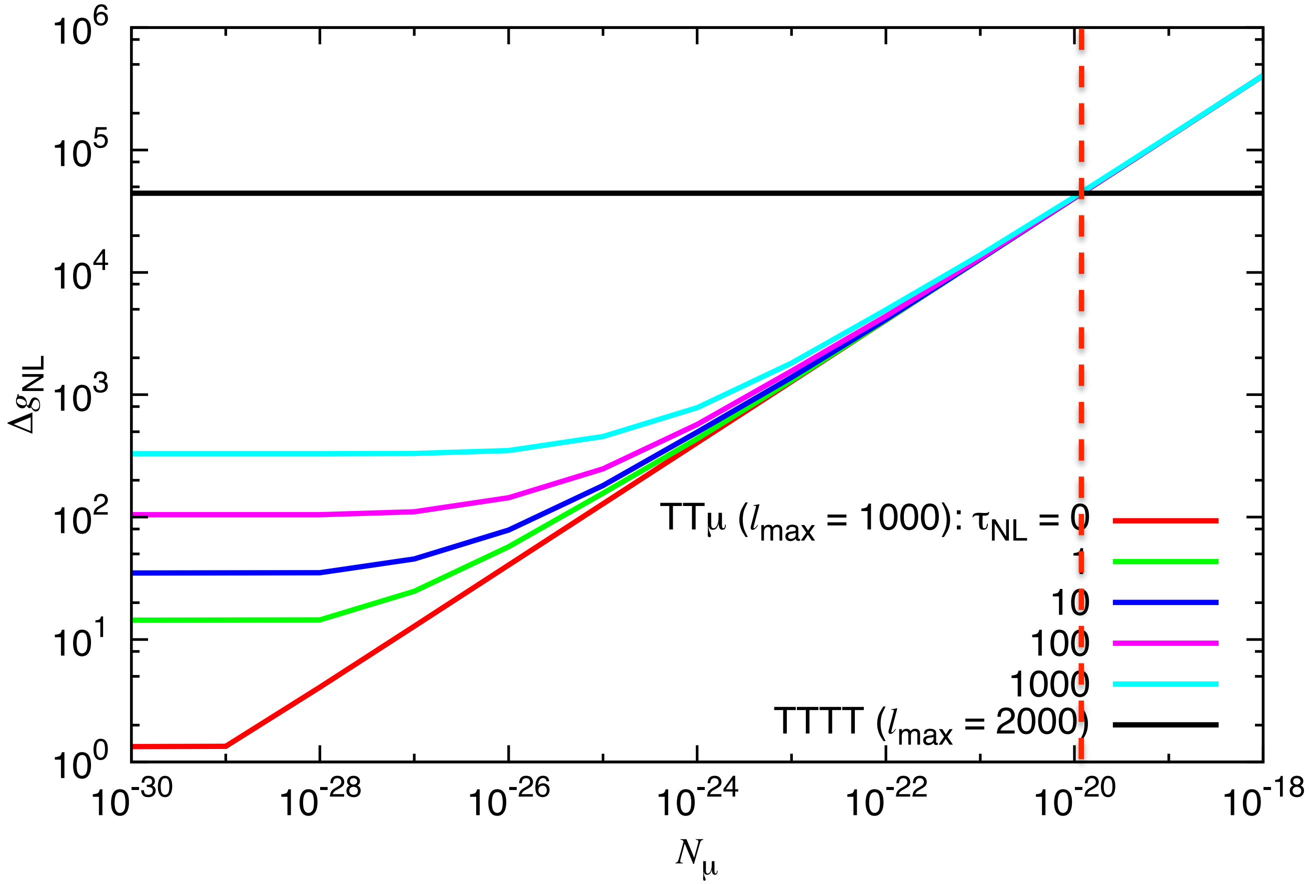
You can reach Δg_{NL}~0.4:

5 orders of magnitude improvement w.r.t to current constraints

g_{NL} forecasts for experiments



Effect of experimental noise



$$C_\ell^{\mu\mu} = C_\ell^{\mu\mu,\mathrm{sig}} + N_\ell^{\mu\mu} \quad N_\ell^{\mu\mu} = N_\mu \mathrm{exp}\left(\ell^2/\ell_\mu^2\right)$$

$$(N_\mu, \ell_\mu) = (10^{-15}, 861)\ (\mathit{Planck}),\ (10^{-17}, 84)\ (\mathrm{PIXIE})$$
$$(2 \times 10^{-18}, 1000)\ (\mathrm{CMBpol})$$

So why CMB spectral distortions are interesting in this context?

Among the many reasons:

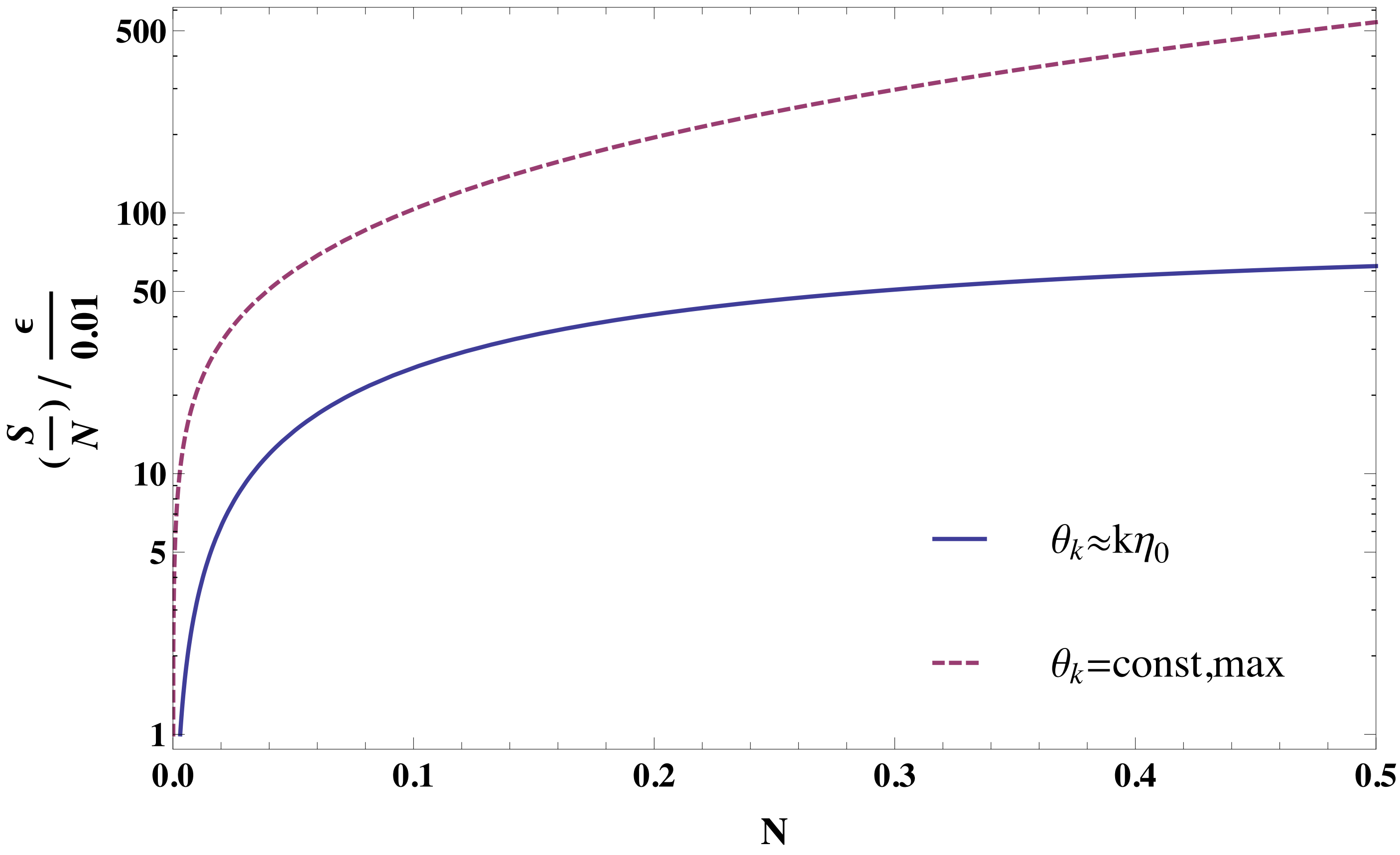
1. There is an enormous wealth of information that can be potentially exploited through new and original applications

2. We are testing the predictions of the standard cosmological model: ΛCDM+standard models of inflation

3. The specific signal in Tμ, TTμ depends on the specific inflationary models considered (e.g. imprints from primordial vector fields, non-Bunch Davies vacuum states).
Also: can test alternative models of inflation, like ekpyrotic models which predict g_{NL} <-1700 a or -1000 < g_{NL} <-100.

4. Our TTμ provides an unbiased estimator for the local trispectrum g_{NL}

3.Some models can already be at reach of present sensitivities



Deviations from a Bunch-Davies vacuum state during inflation could be already detected by Planck via CMB μ-spectral distortions; for sure at reach of a PIXIE like experiment

4. An unbiased estimator for TTμ

- We have verified that the *Gaussian component of* TTμ is largely suppresed
- This is particularly interesting, and very different w.r.t to the CMB trispectrum estimator, where a miscalibration of the Gaussian part can produce a strong bias
- So it is actually already worth to carry on an analysis with present *Planck* CMB data (N.B.: we do not need absolute measurements of the distortions)
- An analysis of *Planck* data for Tμ and μμ already exists (see Khatri)

The exact shape of the TTμ bispectrum depends on the primordial inflationary scenario under exam

e.g. CMB spectral distortions
(+ CMB anisotropies and some LSS observables)
can be efficient also in constraining anisotropic sources during inflation, related e.g. to the presence of vector fields

New signatures (I): anisotropic sources of inflation

Preliminary considerations

Typically when vector fields are present during inflation with a non-vanishing vev $\langle \vec{A} \rangle \neq 0$ the power spectrum of primordial curvature perturbations get a quadrupolar correction

e.g. $\mathcal{L} = -\frac{I^2(\varphi)}{4} F_{\mu\nu} F^{\mu\nu}$

$$P'(\mathbf{k}) = P(k)\left(1 + g(k)(\hat{\mathbf{k}} \cdot \mathbf{n})^2\right)$$

breaking of statistical isotropy

$$\textit{Planck} \;\; 95\% \; \mathrm{CL}$$

$$-0.0225 \leq g_* \leq 0.0363$$

Preliminary considerations

- Vector fields produce a ***statistical anisotropic bispectrum*** typically of the form (N.B., Dimastrogiovanni, Liguori, Matarrese, Riotto 2012)

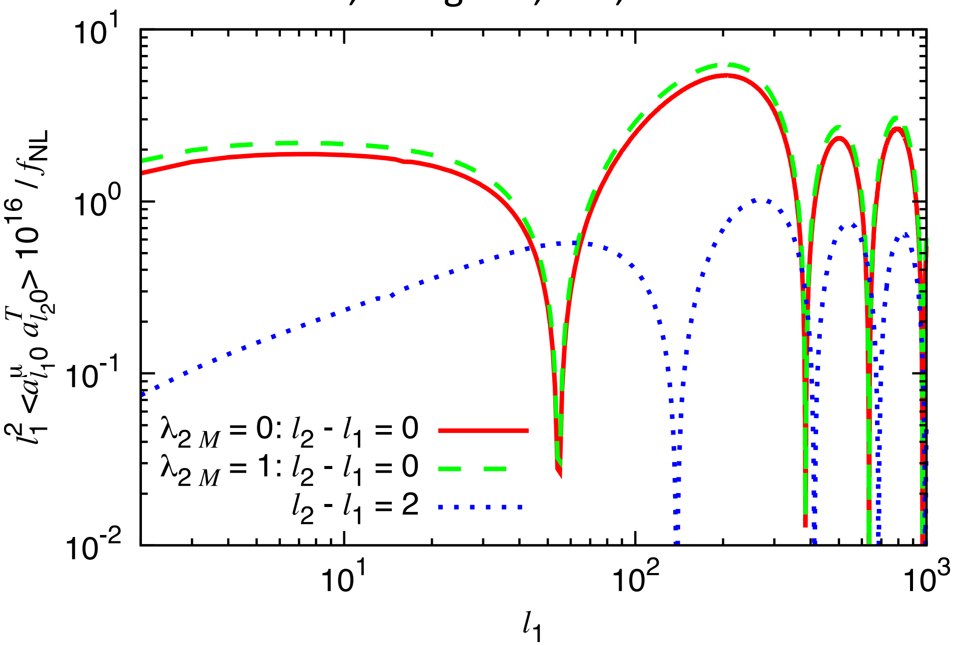
$$B_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3} = \frac{6}{5} f_{\rm NL} P(k_1) P(k_2) \left[1 + \sum_M \lambda_{2M} \left(Y_{2M}(\hat{\mathbf{k}}_1) + Y_{2M}(\hat{\mathbf{k}}_2)\right)\right] + (2 \text{ perm})$$

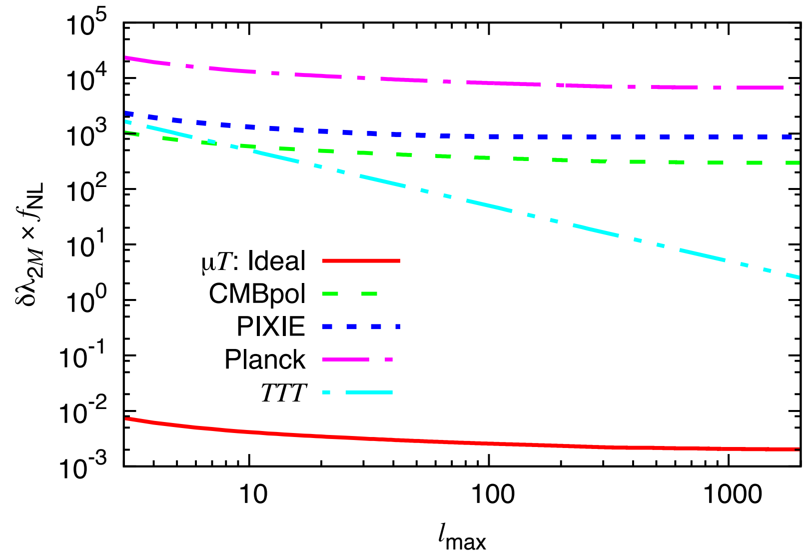
- For the vast majority these bispectra peaks in the squeezed configuration

- We therefore expect that CMB spectral distortions to be sensitive also to this kind of anisotropic bispectra

CMB spectral distortions: Tμ

M. Shiraishi, M.Liguori, N.B, S. Matarrese 2015





- Distinctive off-diagonal signals in the μ-T correlation coupling l_1 with $l_2 \pm 2$ $\langle a^{\mu}_{\ell_1 m_1} a^{T}_{\ell_2 m_2} \rangle$

- What is achievable for an ideal cosmic variance limited experiment?

$$\delta\lambda^{\mu T}_{2M} \approx \frac{5 \cdot 10^{-3}}{f_{\rm NL}} \left(\frac{\bar{C}^{\mu\mu}_{\ell}}{10^{-28}} \right)^{1/2} (\ln \ell_{\max})^{-1/2}$$

For $f_{NL} \sim 1$ can be sensitive to λ_{2M} of 0.1% improving of 2 order of magnitudes w.r.t. to the TTT CMB bispectrum estimators

Preliminary considerations

- Vector fields with a non-vanishing vev produce a ***statistical anisotropic bispectrum*** typically of the form (N.B., Dimastrogiovanni, Liguori, Matarrese, Riotto 2012)

$$B_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3} = \frac{6}{5} f_{\rm NL} P(k_1) P(k_2) \left[1 + \sum_M \lambda_{2M} \left(Y_{2M}(\hat{\mathbf{k}}_1) + Y_{2M}(\hat{\mathbf{k}}_2) \right) \right] + (2 \text{ perm})$$

- Estimators for anisotropic bispectra has been proposed in N.B., E. Dimastrogiovanni, M.Liguori, S. Matarrese, A. Riotto. Not yet appllied to the real data.

- So, to connect to what is actually constrained with the data one usually makes an angle-average of the anisotropic bispectrum (only isotropic bispectra have been constrained so far).

Prediction for primordial NG: bispectrum

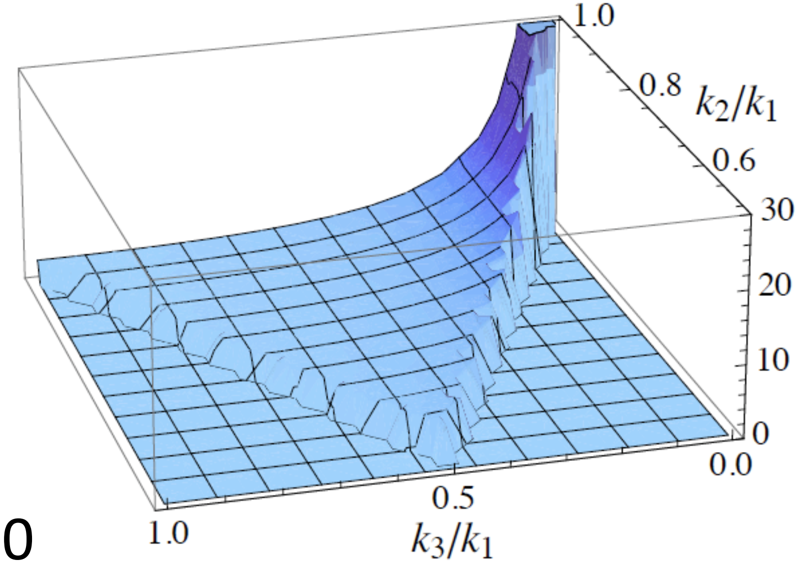
$$\left\langle \prod_{n=1}^{3} \zeta_{\mathbf{k}_n} \right\rangle = \frac{\delta^{(3)}\left(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3\right)}{(2\pi)^{3/2}} \sum_L c_L P(k_1) P(k_2) P_L(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2) + 2 \text{ perms}$$

C_0 corresponds to the so called local non-Gaussianity

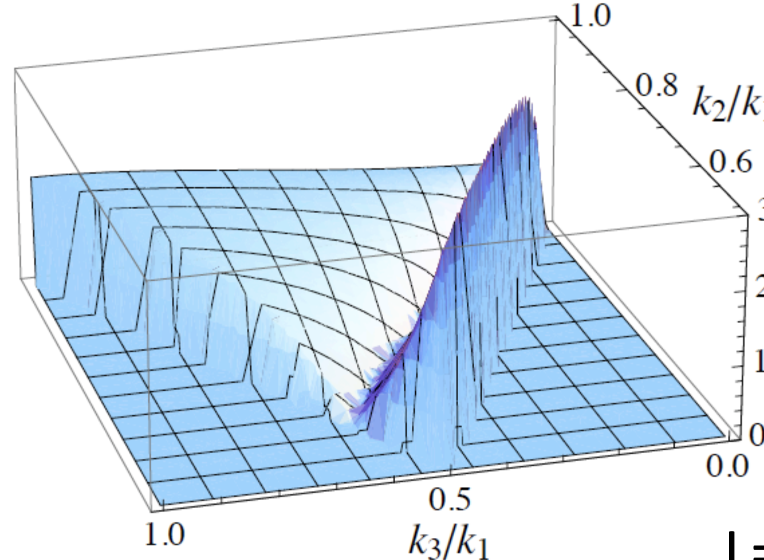
Why Looking for c_L with L>0? They are sensitive to vector fields or to non-trivial Symmetry of the inflaton field

- $I^2(\phi)F^2$ producing c_0 and $c_2=c_0/2$
  (N.B., S. Matarrese, M. Peloso, A.Ricciardone, 2013; M. Shiraishi, E. Komatsu, M. Peloso, N. Barnaby 2013)
- models with an axion inflaton field $\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + I^2(\phi)\left(-\frac{1}{4}F^2 + \frac{\gamma}{4}F\tilde{F}\right)$
  (N.B., S. Matarrese, M. Peloso, M. Shiraishi, 2015)
- Solid inflation with $c_2 \gg c_0$ (S. Endlich, A. Nicolis, and J. Wang, 2013)
- Large-scale magnetic fields generate c_0, c_1, and c_2 at the radiation era
  (M. Shiraishi 2012)

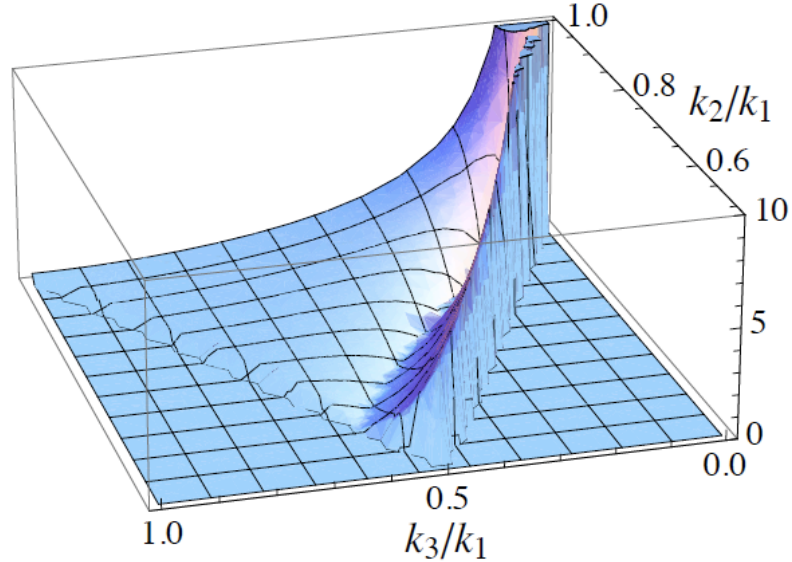
Prediction for primordial NG: bispectrum



L=0



L=1



L=2

Taken from M. Shiraishi, E. Komatsu, M. Peloso, N. Barnaby 2013

Prediction for primordial NG: trispectrum

$$\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\zeta_{\mathbf{k}_4}\rangle = (2\pi)^3\delta^{(3)}\left(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4\right)\times$$
$$d_L\left[\mathcal{P}_L(\hat{k}_1\cdot\hat{k}_3)+\mathcal{P}_L(\hat{k}_1\cdot\hat{k}_{12})+\mathcal{P}_L(\hat{k}_3\cdot\hat{k}_{12})\right]P(k_1)P(k_3)P(k_{12})+(23\text{ perm})$$

- e.g. $I^2(\phi)F^2$ Models produce d_0 and d_2

Planck 2015 results. XVII. Constraints on primordial non-Gaussianity

Planck Collaboration: P. A. R. Ade[92], N. Aghanim[63], M. Arnaud[77], F. Arroja[70,83], M. Ashdown[73,6], J. Aumont[63], C. Baccigalupi[91], M. Ballardini[51,53,32], A. J. Banday[103,9], R. B. Barreiro[69], N. Bartolo[31,70*], E. Battaner[104,105], K. Benabed[64,102], A. Benoît[61], A. Benoit-Lévy[24,64,102], and other 216 authors not shown

ABSTRACT

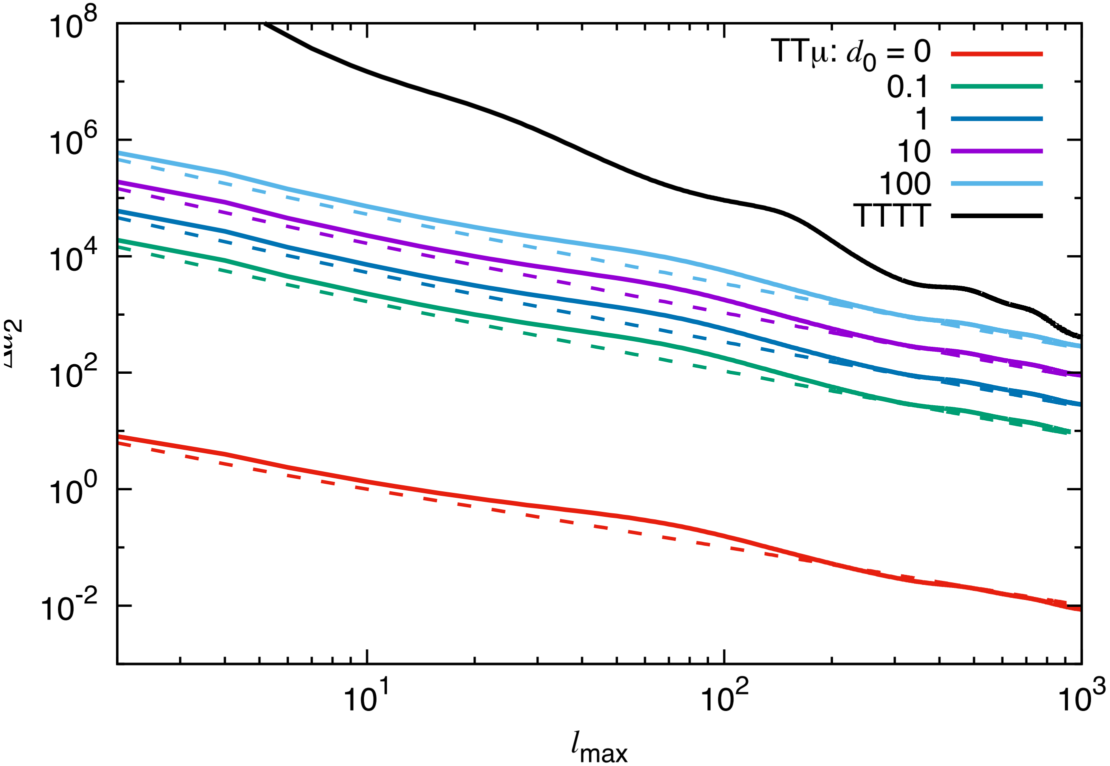
The *Planck* full mission cosmic microwave background (CMB) temperature and *E*-mode polarization maps are analysed to obtain constraints on primordial non-Gaussianity (NG). Using three classes of optimal bispectrum estimators — separable template-fitting (KSW), binned, and modal — we obtain consistent values for the primordial local, equilateral, and orthogonal bispectrum amplitudes, quoting as our final result from temperature alone $f_{\rm NL}^{\rm local} = 2.5 \pm 5.7$, $f_{\rm NL}^{\rm equil} = -16 \pm 70$ and $f_{\rm NL}^{\rm ortho} = -34 \pm 33$ (68 % CL statistical). Combining temperature and polarization data we obtain $f_{\rm NL}^{\rm local} = 0.8 \pm 5.0$, $f_{\rm NL}^{\rm equil} = -4 \pm 43$ and $f_{\rm NL}^{\rm ortho} = -26 \pm 21$ (68 % CL statistical). The results are based on comprehensive cross-validation of these estimators on Gaussian and non-Gaussian simulations, are stable across component separation techniques, pass an extensive suite of tests, and are consistent with estimators based on measuring the Minkowski functionals of the CMB. The effect of time-domain de-glitching systematics on the bispectrum is negligible. In spite of these test outcomes we conservatively label the results including polarization data as preliminary, due to a known mismatch of the noise model in simulations and the data. Beyond estimates of individual shape amplitudes, we present model-independent, three-dimensional reconstructions of the *Planck* CMB bispectrum and derive constraints on early universe scenarios that generate primordial NG, including general single-field models of inflation, axion inflation, initial state modifications, models producing parity-violating tensor bispectra, and directionally-dependent vector models. We present a wide survey of scale-dependent feature and resonance models, accounting for the "look-elsewhere" effect in estimating the statistical significance of features. We also look for isocurvature NG, finding no signal but obtaining constraints that improve significantly with the inclusion of polarization. The primordial trispectrum amplitude in the local model is constrained to be $g_{\rm NL}^{\rm local} = (-9.0 \pm 7.7) \times 10^4$ (68 % CL statistical), and we perform an analysis of trispectrum shapes beyond the local case. The global picture that emerges is one of consistency with the premises of the ΛCDM cosmology, namely that the structure we observe today was sourced by adiabatic, passive, Gaussian, and primordial seed perturbations.

Constraints on c_L bispectra from *Planck*

	Commander		NILC		SEVEM		SMICA	
	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N
$L = 1$								
Modal2 T-only	-41 ± 43	-0.9	-58 ± 42	-1.4	-51 ± 43	-1.2	-49 ± 43	-1.1
KSW T-only	-8 ± 46	-0.2	-62 ± 46	-1.3	-34 ± 45	-0.8	-26 ± 45	-0.6
Modal2 T+E	-28 ± 29	-1.0	-30 ± 27	-1.1	-49 ± 28	-1.7	-31 ± 26	-1.2
KSW T+E	-57 ± 33	-1.7	-62 ± 32	-1.9	-79 ± 32	-2.5	-54 ± 32	-1.7
$L = 2$								
Modal2 T-only	0.7 ± 2.8	0.2	0.8 ± 2.8	0.4	1.1 ± 2.7	0.3	0.5 ± 2.7	0.2
KSW T−only	1.5 ± 5.1	0.3	-3.9 ± 5.1	-0.8	-0.4 ± 5.1	-0.1	0.1 ± 5.0	0.0
Modal2 T+E	1.1 ± 2.4	0.5	0.5 ± 2.4	0.2	1.3 ± 2.4	0.6	-0.2 ± 2.3	-0.1
KSW T+E	-3.0 ± 4.1	-0.7	-3.6 ± 4.0	-0.9	-3.8 ± 4.0	-1.0	-1.3 ± 3.9	-0.3

CMB spectral distortions: TTμ

$$\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\zeta_{\mathbf{k}_4}\rangle = (2\pi)^3\delta^{(3)}\left(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4\right)\times$$
$$d_L\left[\mathcal{P}_L(\hat{k}_1\cdot\hat{k}_3)+\mathcal{P}_L(\hat{k}_1\cdot\hat{k}_{12})+\mathcal{P}_L(\hat{k}_3\cdot\hat{k}_{12})\right]P(k_1)P(k_3)P(k_{12})+(23\ \mathrm{perm})$$



- a minimun value d_2~0.01 is in principle detectable for a CVL exp. (4-orders of magnitude better than CMB TTTT can do)
- The signal from d_2 is very low correlated to the standard local g_{NL} and τ_{NL} signals

N.B, Shiraishi, Liguori, 2016, in preparation

New signatures (II)

Modified gravity during inflation: gravitational waves and non-Gaussianity

Modifying gravity during inflation and non-Gaussianity

- Example 1: ***graviton non-Gaussianities beyond ordinary Einstein*** considered in Madacena & Pimentel (2011); Soda, Kodama, Nozawa (2011); Shiraishi, Nitta, Yokoyama (2011)

$\langle\gamma\gamma\gamma\rangle$ from higher derivative corrections

$$S = \int d\tau d^3 x \lambda^{-2} \left(\sqrt{-g}C^3 + \tilde{C}C^2\right)$$

$$C^3 = C^{\alpha\beta}{}_{\gamma\delta} C^{\gamma\delta}{}_{\sigma\rho} C^{\sigma\rho}{}_{\alpha\beta}$$

$$\widetilde{C}C^2 = \epsilon^{\alpha\beta\mu\nu} C_{\mu\nu\gamma\delta} C^{\gamma\delta}{}_{\sigma\rho} C^{\sigma\rho}{}_{\alpha\beta}$$

however such primordial NG is unobservably small.

Modifying gravity during inflation and non-Gaussianity

- Example 2: an effective field theory approach to inflation

Weinberg Phys. Rev. D77 (2008): Lagrangian with all general covariant terms sup to 4 derivatives

Take Ψ to be the inflaton

EQUILATERAL NG

$$
\begin{aligned}
L = \sqrt{-g}\Bigg[& \frac{1}{2} M_{Pl}^2 \Omega(\psi)^2 R - \frac{1}{2} h(\psi) g^{\mu\nu} \partial_\mu \psi \partial^\mu \psi - U(\psi) \\
& + f_1(\psi)\Big(g^{\mu\nu}\partial_\mu\psi\partial_\nu\psi\Big)^2 + \cancel{f_2(\psi) g^{\rho\sigma}\partial_\rho\psi\partial_\sigma\psi\Box\psi} \\
& + \cancel{f_3(\psi)\Big(\Box\psi\Big)^2} + f_4(\psi) R^{\mu\nu}\partial_\mu\psi\partial_\nu\psi \\
& + f_5(\psi) R\, g^{\mu\nu}\partial_\mu\psi\partial_\nu\psi + \cancel{f_6(\psi) R\Box\psi} + f_7(\psi) R^2 \\
& + \cancel{f_8(\psi) R^{\mu\nu} R_{\mu\nu}} + \cancel{f_9(\psi) C^{\mu\nu\rho\sigma} C_{\mu\nu\rho\sigma}} \Bigg] \\
& + f_{10}(\psi) \epsilon^{\mu\nu\rho\sigma} C_{\mu\nu}{}^{\kappa\lambda} C_{\rho\sigma\kappa\lambda} \,. \qquad (1)
\end{aligned}
$$

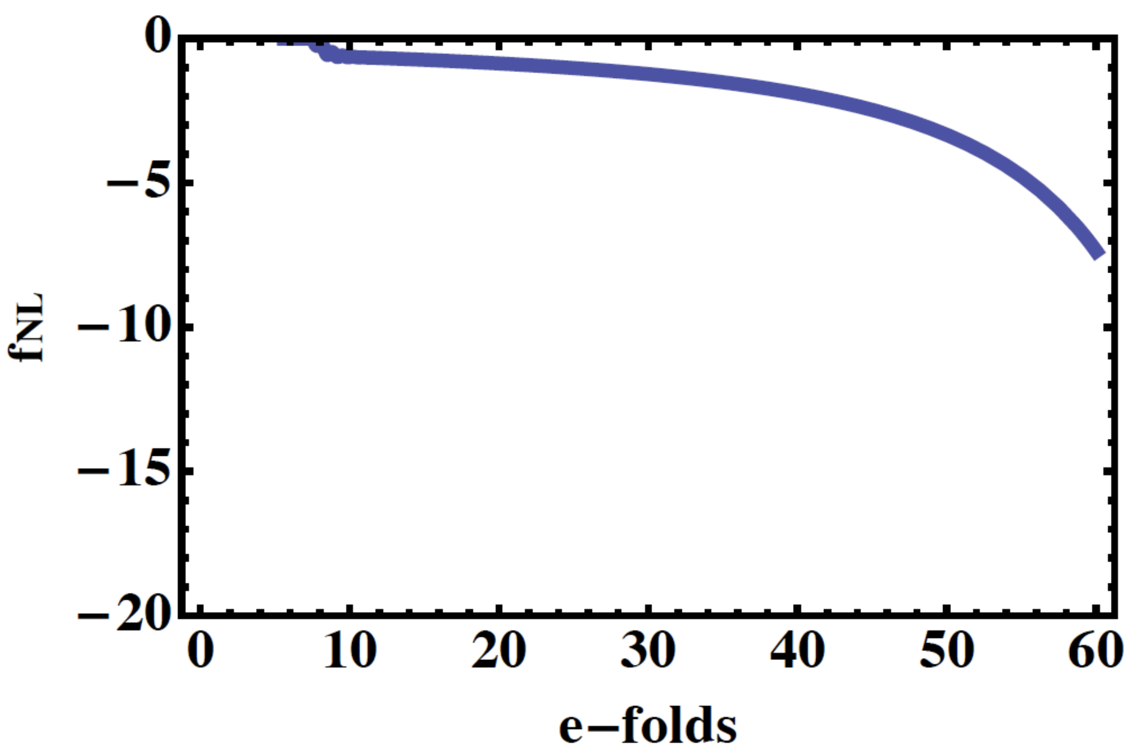
Modifying gravity during inflation and non-Gaussianity

- Example 3: an effective field theory approach to inflation

``scalaron'' field

Inflaton field

$$\mathcal{L} = \sqrt{-g}\left[f(R) - \frac{1}{2}g^{\mu\nu}\partial_\mu\psi\partial_\nu\psi - U(\psi)\right]$$



f_{NL} of order -1 up to -30 can be generated (quasi-local NG).

N.B., Cannone, Jimenez, Matarerse, Verde, PRL 2014

WHERE NG COMES FROM?

- modifications of gravity → extra scalar degree of freedom associated to R^2
  → its non-Gaussianities can be transferred to the inflaton field

a well known mechanism can take place here (N.B., Matarrese, Riotto 2002) :
if both fields contribute to the background then NG very low (slow-roll constraints);
but if one of the two (e.g. in our case the one associated to R^2) is subdominant then slow-roll is no longer requires and an efficient transfer of NG from the isocurvature to the adiabatic (inflaton) field can take place

Slow-roll inflation with Chern-Simons term

$$S = \frac{1}{2}\int d^4x \, \sqrt{g} \, \left[M_{pl}^2 R - g_{\mu\nu} D^\mu \phi D^\nu \phi - 2V(\phi)\right] + f(\phi)\epsilon^{\mu\nu\rho\sigma} C_{\mu\nu}{}^{\kappa\lambda} C_{\rho\sigma\kappa\lambda}$$

$C_{\mu\nu\rho\sigma}$: Weyl tensor, traceless component of the Riemann tensor
$\epsilon_{\mu\nu\rho\sigma}$: Levi-Civita pseudotensor

Features of the Chern-Simons term

- zero on the background ($C^{(0)}_{\mu\nu\rho\sigma} = 0$)
- parity breaking
- surface term if $f(\phi)=$ const. (total time derivative term)

Quadratic analysis of the Chern-Simons term

- quadratic action of the scalar modes does not change
- use right (R) and left (L) polarization states of gravitational waves (GW) γ_{ij}

$$\epsilon_{ij}^{R} = \frac{1}{\sqrt{2}}(\epsilon_{ij}^{+} + i\epsilon_{ij}^{\times}) \qquad \epsilon_{ij}^{L} = \frac{1}{\sqrt{2}}(\epsilon_{ij}^{+} - i\epsilon_{ij}^{\times})$$

Quadratic action for tensor modes with C-S term

$$S_{\gamma\gamma} = \frac{1}{2}\sum_{s=L,R}\int d\tau \, \frac{d^3k}{(2\pi)^3} \, A_{T,s}^2 \left[\, |\gamma_s'(\tau,k)|^2 - k^2|\gamma_s(\tau,k)|^2 \, \right]$$

$$A_{T,s}^2 = \frac{M_{pl}^2 a^2}{2}\left(1 - \alpha_s \frac{k}{a}\frac{1}{M_{C-S}}\right) \qquad \begin{cases} \alpha_R = 1 \\ \alpha_L = -1 \end{cases} \qquad M_{C-S} = \frac{M_{pl}^2}{8\dot{f}(\phi)}$$

Right (R) polarization modes with $k_{phys} > M_{C\text{-}S}$ (Chern-Simons mass) become ghosts

➔ need to introduce a an UV- cut-off $\Lambda < M_{C\text{-}S}$

See, e.g., Alexander & Martin, 2005; Satoh, 2010; Dyda, Flanagan, Kamionkowksi 2012.

Left and Right tensor power spectra

$\tilde{\gamma}_s = \mathcal{A}_T \gamma_s$ $\qquad$ $\tilde{\gamma}^s_{\vec{k}} = z_s(\vec{k},\tau)\hat{a}_s(\vec{k}) + z_s^*(-\vec{k},\tau)\hat{a}_s{}^\dagger(-\vec{k})$

New equation of motion for the mode function z_s

$$z''_{\vec{k},s} + \left(k^2 - \frac{\nu_T^2 - \frac{1}{4}}{\tau^2} + \alpha_s \frac{k}{\tau}\frac{H}{M_{C-S}}\right) z_{\vec{k},s} = 0$$

- $\frac{H}{M_{C-S}} << 1$
- assumptions: $M_{C-S}, H \simeq$ constant $\longrightarrow$ Whittaker equation

L and R power spectra

$$P_T^L = P_T \times exp\left(-\frac{\pi}{2}\frac{H}{M_{C-S}}\right)$$
$$P_T^R = P_T \times exp\left(\frac{\pi}{2}\frac{H}{M_{C-S}}\right)$$

Polarized primordial gravitational waves

Asymmetry in the power spectrum of the primordial gravitational waves

$$\Theta_{R-L} = \frac{P_T^R - P_T^L}{P_T^R + P_T^L} = \frac{\pi}{2} \frac{H}{M_{C-S}}$$

- Θ_{R-L} quantifies the degree of parity breaking in the power spectrum of the tensor modes
- $\Theta_{R-L} << 1$ for the approximation made in the theory

Modification to consistency relation

$$r_{C-S} = -8 n_T \left(1 + \Theta_{R-L}^2\right)$$

CMB anisotropies: primordial symmetry breakings and resulting CMB correlations $\langle a^X_{\ell_1 m_1} a^{Y*}_{\ell_2 m_2}\rangle$

Parity	Rotation	Examples	$\ell_1 = \ell_2$	$\ell_1 = \ell_2 \pm 1$	$\ell_1 = \ell_2 \pm 2$
○	○	Standard inflation	XX, TE	-	-
×	○	$f(\phi)R\tilde{R}$, $f(\phi)F\tilde{F}$	all	-	-
○	×	$f(\phi)F^2$ with $\langle\vec{A}\rangle$	XX, TE	TB, EB	XX, TE
×	×	$f(\phi)F\tilde{F}$ with $\langle\vec{A}\rangle$	all	all	all

N.B., S. Matarrese, M. Peloso, M. Shiraishi, JCAP 1501 (2015) 01, 027

X,Y=T,E,B

Specific signatures:

- TT, TE, EE and BB correlations between ℓ_1 and $\ell_1 = \ell_2 \pm 1$ $(\ell_1 + \ell_2 = odd)$
- TB and EB correlations between ℓ_1 and $\ell_1 = \ell_2 \pm 2$ $(\ell_1 + \ell_2 = even)$

These signals cannot be realized if one of parity and isotropy is preserved

Constraints and forecasts for future experiments

arXiv:1605.09357v1 [astro-ph.CO] 30 May 2016

Testing chirality of primordial gravitational waves with Planck and future CMB data: no hope from angular power spectra

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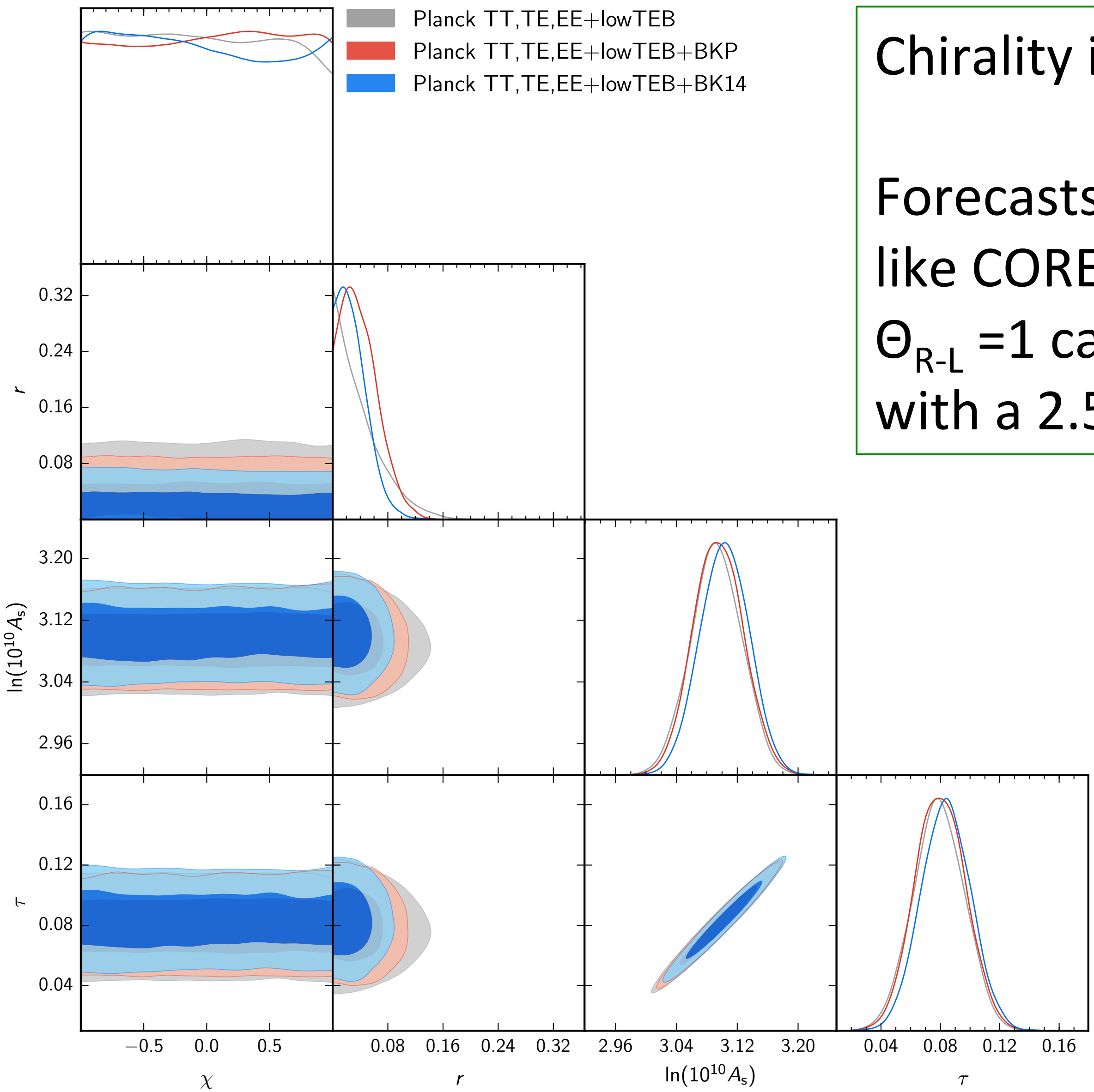
Abstract. We use the 2015 Planck likelihood in combination with the Bicep2/Keck likelihood (BKP and BK14) to constrain the chirality, χ, of primordial gravitational waves in a scale-invariant scenario. In this framework, the parameter χ enters theory always coupled to the tensor-to-scalar ratio, r, e.g. in combination of the form $\chi \cdot r$. Thus, the capability to detect χ critically depends on the value of r. We find that with present data set χ is *de facto* unconstrained. We also provide forecasts for χ from future CMB experiments, as COrE+, exploring several fiducial values of r. We find that the current limit on r is tight enough to disfavor a neat detection of χ. For example in the unlikely case in which $r \sim 0.1(0.05)$, then the maximal chirality case, i.e. $\chi = \pm 1$, could be detected with a significance of $\sim 2.5(1.5)\sigma$ at best. We conclude that the two-point statistics at the basis of CMB likelihood functions is currently unable to constrain chirality and may only provide weak limits on χ in the most optimistic scenarios. Hence, it is crucial to investigate the use of other observables, e.g. provided by higher order statistics, to constrain these kind of parity violating theories with the CMB.

Constraints and forecasts for future experiments



Chirality is unconstrained

Forecasts: for an experiment like CORE+ if r=0.1 (0.05) then $\Theta_{R\text{-}L}$ =1 can be detected at best with a 2.5(1.5) sigma significance

Non-Gaussianities from the Chern-Simons term[*]

[*](N.B., G. Orlando and M. Shiraishi in preparation)

Non-Gaussianities from the Chern-Simons term

$\langle\zeta(\vec{k_1})\zeta(\vec{k_2})\zeta(\vec{k_3})\rangle_{C-S} = 0 \longrightarrow$ scalar perturbations are parity invariant

Idea: computation of the bispectrum $\langle\gamma_{r_1}(\vec{k_1})\gamma_{r_2}(\vec{k_2})\zeta(\vec{k_3})\rangle_{C-S}$

- The dominant interaction term between 2 gravitons and 1 scalar in the slow-roll limit is

$$S_{\varphi\gamma\gamma} = \int d^4x\ \epsilon^{\mu\nu\rho\sigma} \left[\left(\frac{\partial}{\partial\phi} f(\phi) \right) \delta\phi\ C^{(1)\ \kappa\lambda}_{\mu\nu}|_T\, C^{(1)}_{\rho\sigma\kappa\lambda}|_T \right]$$

$\left(\frac{\partial}{\partial\phi} f(\phi)\right)\delta\phi$ comes from the Taylor expansion of the function $f(\phi)$

→We can compute the interaction term computing the Weyl tensor only up to first-order in tensor perturbations

Computation of the bispectrum

Computation of the bispectrum $\langle \gamma_{s_1}(\vec{k}_1)\gamma_{s_2}(\vec{k}_2)\delta\phi(\vec{k}_3)\rangle$:

In-In formalism

$$\langle \gamma_{s_1}(\vec{k}_1)\gamma_{s_2}(\vec{k}_2)\delta\phi(\vec{k}_3)\rangle = i\int_{-\infty}^{0} d\tau' a \langle 0|[\gamma^I_{s_1}(\vec{k}_1)\gamma^I_{s_2}(\vec{k}_2)\delta\phi^I(\vec{k}_3),\ L^{\varphi\gamma\gamma}_{int}(\tau')]|0\rangle$$

At leading order in slow-roll parameters:

$$L^{\varphi\gamma\gamma}_{int}(\tau) = -\alpha_s \int d^3K \frac{\delta^3(\sum_i K_i)}{(2\pi)^6}\Bigg[\left(\frac{\partial}{\partial\phi}f(\phi)\right) p\delta\phi'(\vec{k})\gamma'^{s}_{ij}(\vec{p})\gamma'^{ij}_{s}(\vec{q}) +$$

$$+\left(\frac{\partial}{\partial\phi}f(\phi)\right) p\,(\vec{p}\cdot\vec{q})\,\delta\phi'(\vec{k})\gamma^{s}_{ij}(\vec{p})\gamma^{ij}_{s}(\vec{q}) + \left(\frac{\partial}{\partial\phi}\dot{f}(\phi)\right) p\delta\phi(\vec{k})\gamma'^{s}_{ij}(\vec{p})\gamma'^{ij}_{s}(\vec{q})$$

$$+a\left(\frac{\partial}{\partial\phi}\dot{f}(\phi)\right) p\,(\vec{p}\cdot\vec{q})\,\delta\phi(\vec{k})\gamma^{s}_{ij}(\vec{p})\gamma^{ij}_{s}(\vec{q})\Bigg]$$

Main results I

$$\langle\gamma_R(\vec{k}_1)\gamma_R(\vec{k}_2)\delta\phi(\vec{k}_3)\rangle = (2\pi)^3\delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)\frac{\dot{\phi}_*}{H_*}F'(k_i)\left(H^2\frac{\partial^2}{\partial^2\phi}f(\phi)\right)^* \times$$
$$\times\,(P_T(k_1)P_T(k_2) + sym)$$

$F'(k_i) \sim \mathcal{O}(1)$
$* \equiv$ horizon crossing of the overall momentum $K = \frac{k_1+k_2+k_3}{3}$

$$\langle\gamma_L(\vec{k}_1)\gamma_L(\vec{k}_2)\delta\phi(\vec{k}_3)\rangle = -\langle\gamma_R(\vec{k}_1)\gamma_R(\vec{k}_2)\delta\phi(\vec{k}_3)\rangle$$

$$\langle\gamma_L(\vec{k}_1)\gamma_R(\vec{k}_2)\delta\phi(\vec{k}_3)\rangle = \langle\gamma_R(\vec{k}_1)\gamma_L(\vec{k}_2)\delta\phi(\vec{k}_3)\rangle = 0$$

$$P_T = 8\frac{H_*^2}{M_{Pl}^2 k^3}\left(\frac{k}{k_*}\right)^{n_T}$$

Main results I-bis

switch to the variable ζ on super-horizon scales

- $\zeta = -\frac{H}{\dot\phi}\delta\phi - \frac{\eta_V}{2}\frac{H^2}{\dot\phi^2}\delta\phi^2$
- non linear correction gives a disconnected contribution

$$\langle\gamma_R(\vec{k}_1)\gamma_R(\vec{k}_2)\zeta(\vec{k}_3)\rangle_{C-S} = -\left(H^2\frac{\partial^2}{\partial^2\phi}f(\phi)\right)^* \left(\sum_{i<j} P_T(k_i)P_T(k_j)\right) F'(k_i)$$

$$F'(k_i) = 8\ \frac{(k_1+k_2)(k_3^2-k_2^2-k_1^2)\left(1-\frac{k_3^2-k_2^2-k_1^2}{2k_1k_2}\right)^2}{\left(\sum_i k_i^3\right)}$$

Shape of the bispectrum

The bispectrum peaks for squeezed configuration when $k_3 << k_1 \sim k_2$

Main results II

$$\langle \gamma_R(\vec{k}_1)\gamma_R(\vec{k}_2)\zeta(\vec{k}_3)\rangle_{C-S} = -\left(H^2\frac{\partial^2}{\partial^2\phi}f(\phi)\right)^* \left(\sum_{i<j} P_T(k_i)P_T(k_j)\right) F'(k_i)$$

$$\langle \gamma_L(\vec{k}_1)\gamma_L(\vec{k}_2)\zeta(\vec{k}_3)\rangle_{C-S} = -\langle \gamma_R(\vec{k}_1)\gamma_R(\vec{k}_2)\zeta(\vec{k}_3)\rangle_{C-S}$$

$$\langle \gamma_s(\vec{k}_1)\gamma_s(\vec{k}_2)\zeta(\vec{k}_3)\rangle_{Einstein} = \left(\sum_{i>j} P_T(k_i)P_T(k_j)\right) F(k_i)$$

$F(k_i) \sim \mathcal{O}(1)$

coefficent of parity violation in the bispectrum $\langle\gamma\gamma\zeta\rangle$

$$B^{\gamma\gamma\zeta}_{R-L} = \frac{\langle\gamma_R\gamma_R\zeta\rangle_{TOT} - \langle\gamma_L\gamma_L\zeta\rangle_{TOT}}{\langle\gamma_R\gamma_R\zeta\rangle_{TOT} + \langle\gamma_L\gamma_L\zeta\rangle_{TOT}} \sim -2\left(H^2\frac{\partial^2}{\partial^2\phi}f(\phi)\right)^*$$

A preliminary estimate of $B_{R\text{-}L}$

$$H \frac{\partial}{\partial \phi} f(\phi) \simeq \frac{\Theta_{R-L}}{\sqrt{\epsilon_V}} \frac{M_{Pl}}{H}$$

Requirement for small time dependence of M_{C-S}

$$H^2 \frac{\partial^2}{\partial^2 \phi} f(\phi) < \frac{H}{M_{Pl}\sqrt{\epsilon_V}} \left(H \frac{\partial}{\partial \phi} f(\phi) \right)$$

$$\longrightarrow \left| B_{R-L}^{\gamma\gamma\zeta} \right| < \mathcal{O}\left(\frac{\Theta_{R-L}}{\epsilon_V} \right)$$

- in the slow-roll limit a priori a large parity breaking is possible also with small Θ_{R-L}

Issues under investigation

- CMB estimators targeted to measure these parity-violating effects in the tensor sector
  (e.g. measuring the parity violation amplitude in the <ζγγ> correlator)

- What are the effects for GW interferometers?

- How to measure these effects at interferometers?

Conclusions

- CMB polarization can improve constraints on primordial NG.
- However to make a real breakthrough new observational tests must be pursed
- CMB spectral distortions can be one of these.
- In particular TTμ can offer an unbiased estimator for the primordial 4-point functions
- As an example of new signatures to be investigated: parity violation and NG in the primordial gravitational waves