Testing Early Universe Physics with non-Gaussianity of the Cosmic Microwave Background

Michele Liguori
Univ. Padova. Dipartimento di Fisica e Astronomia
INFN-Padova. INAF-OAPD

with inputs from the Italian CMB community and CORE teams

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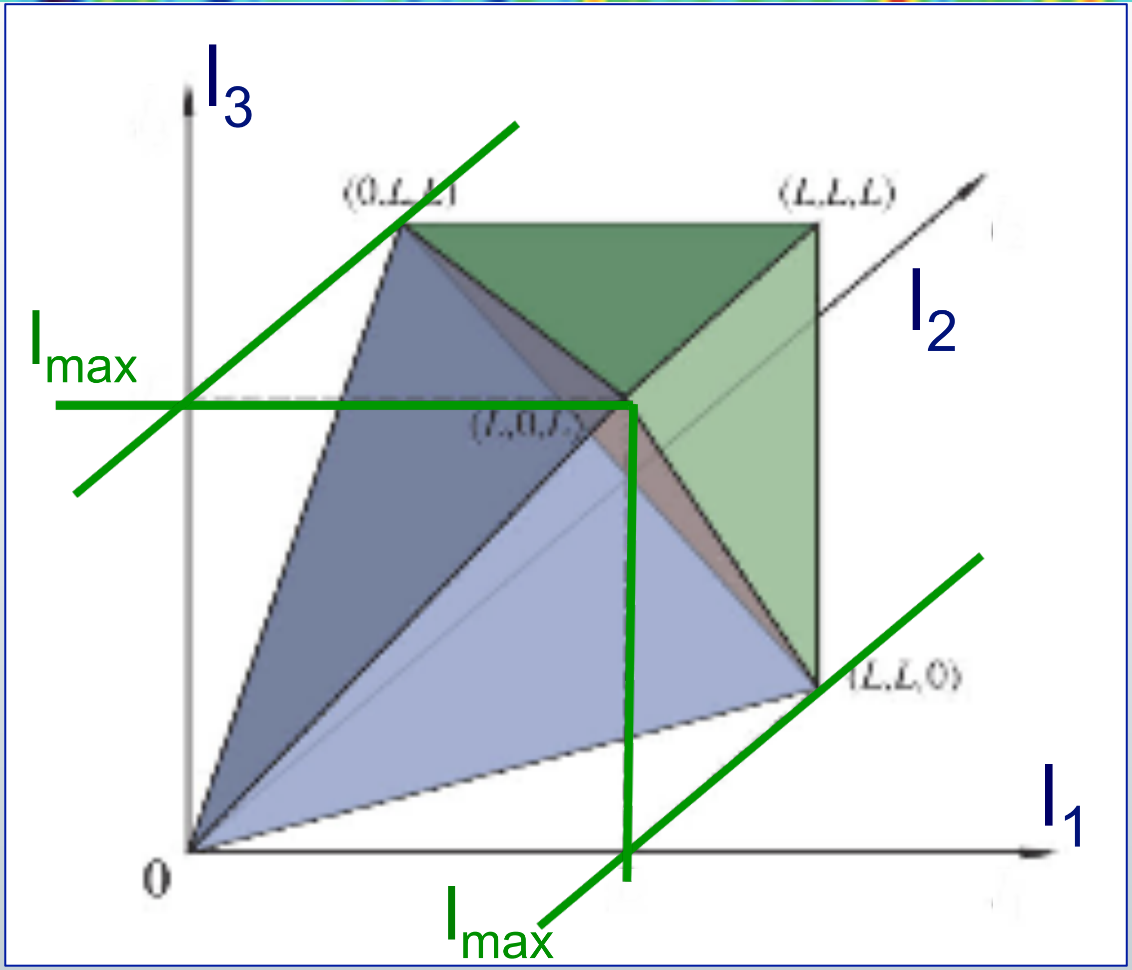
Why do we study primordial NG?

- One of the most accurately tested predictions of Inflation is that primordial perturbations are *nearly* Gaussian
- Most inflationary models predict small but model dependent deviations from Gaussianity
- Also alternative Early Universe scenarios predict specific NG signatures

Primordial non-Gaussianity provides a powerful way to constrain different Early Universe scenarios, and discriminate between them

CMB reduced bispectrum



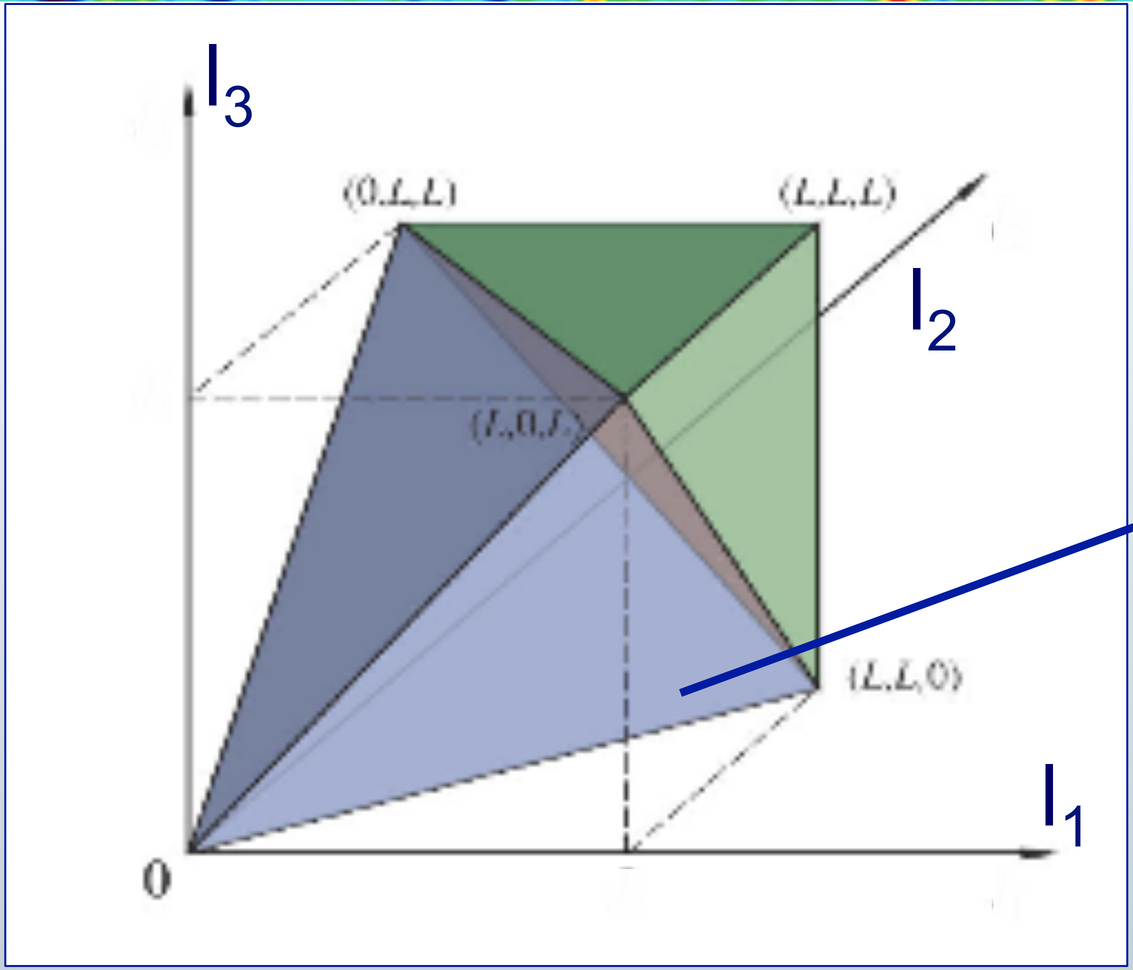
Non-Gaussianity:

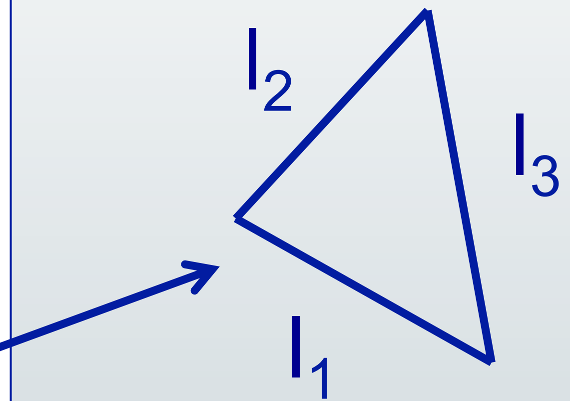
Information beyond Power spectrum.

Most important for Inflation: 3-point function ***(bispectrum)***

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

CMB reduced bispectrum





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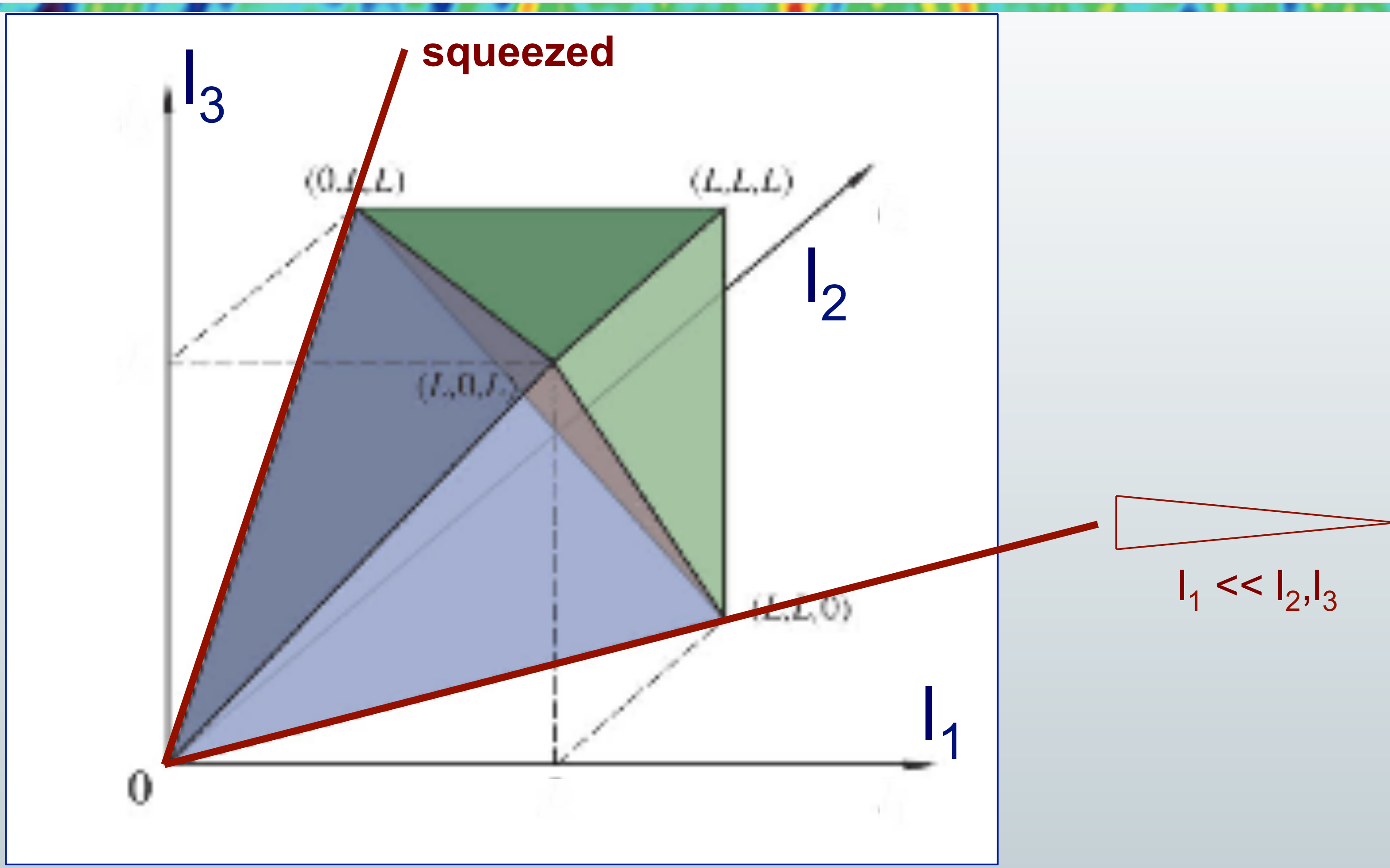

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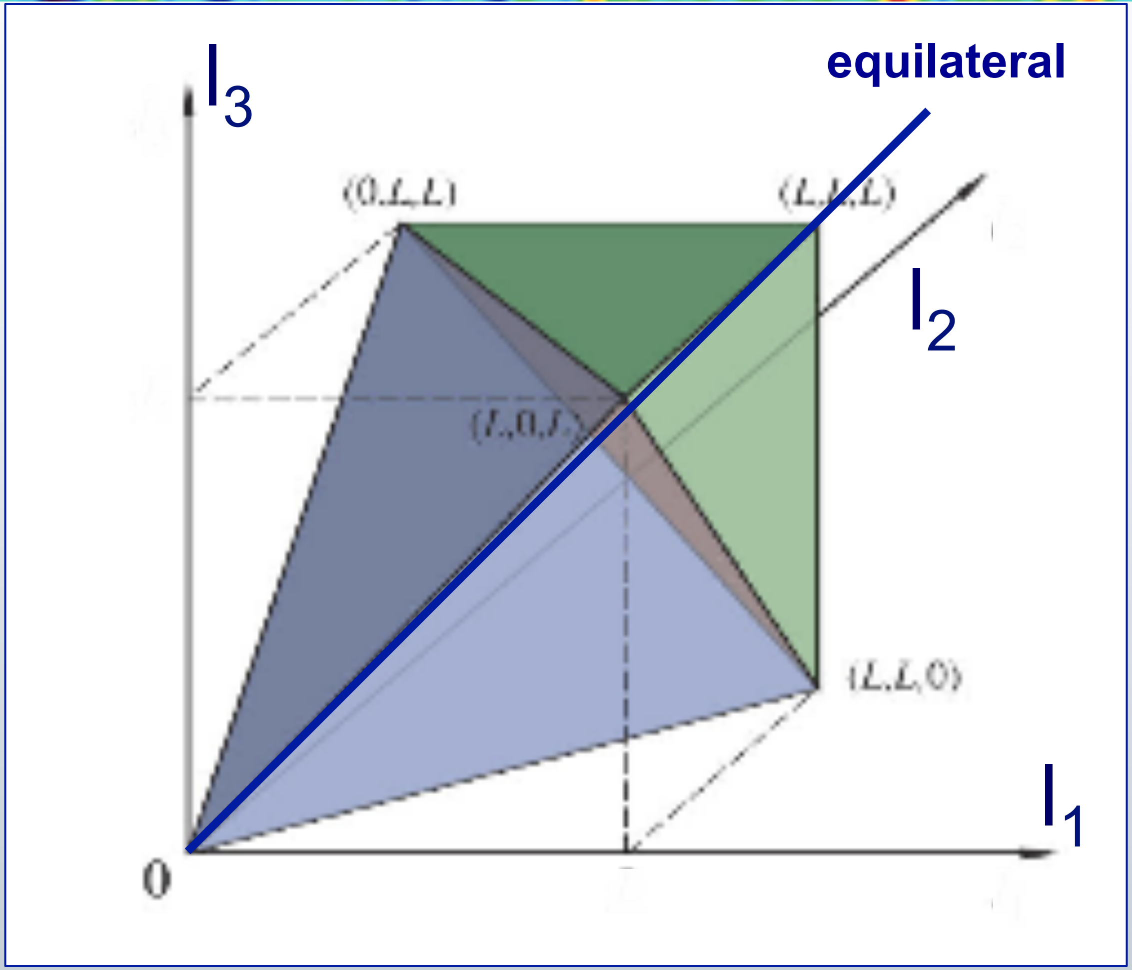
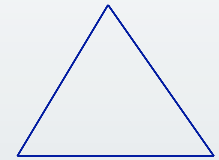
CMB reduced bispectrum

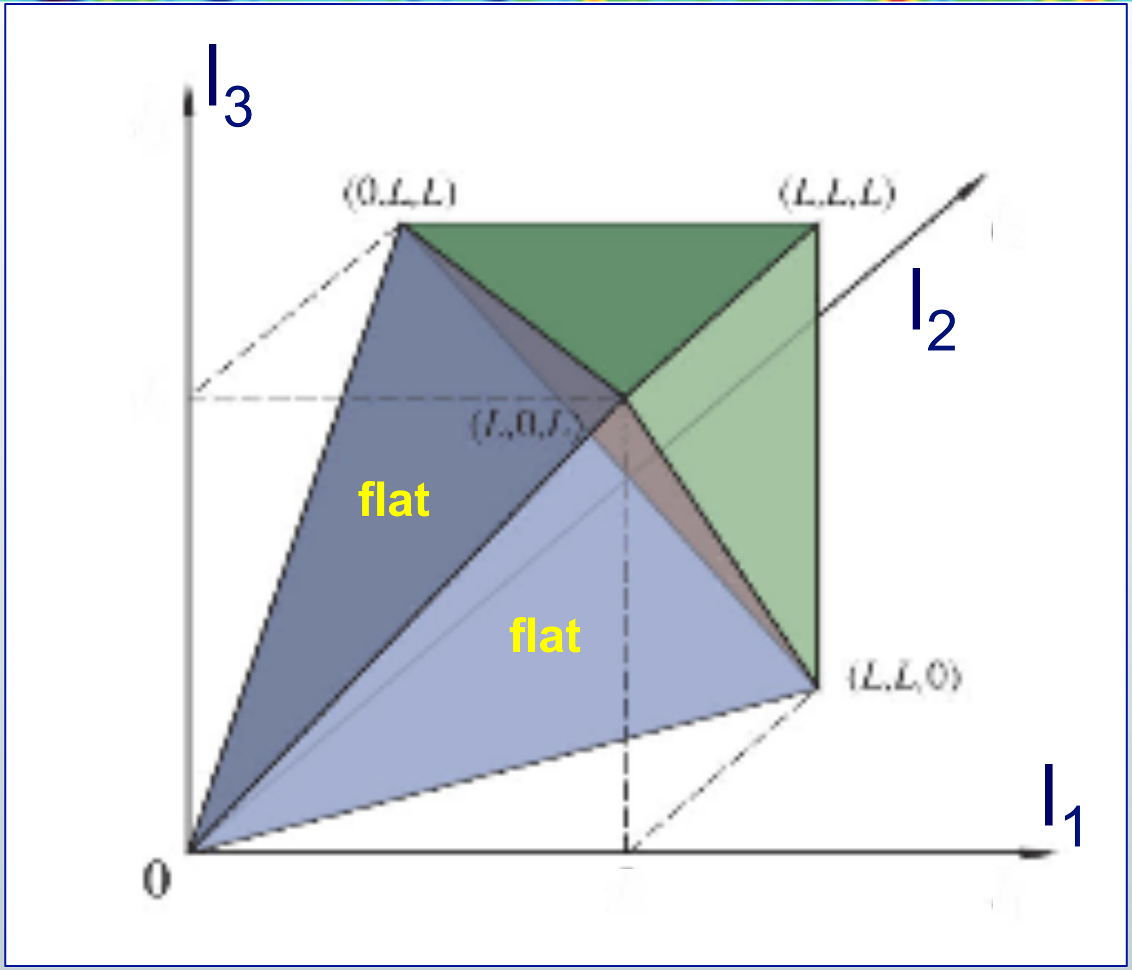




$l_1 \sim l_2 \sim l_3$

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

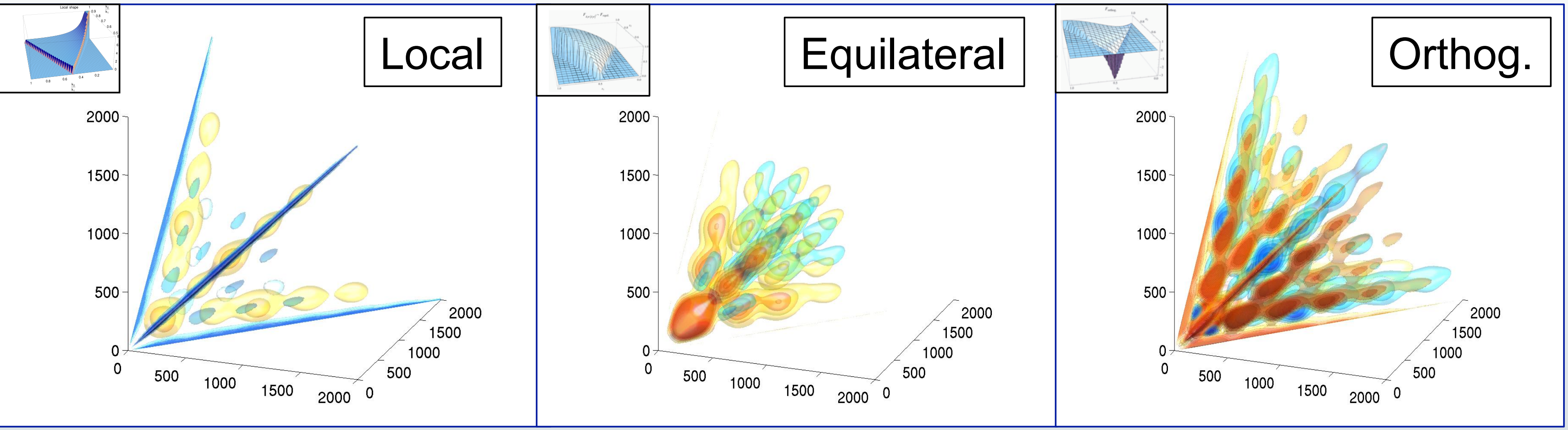
CMB reduced bispectrum



$l_2 \sim l_3$

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

Main primordial shapes



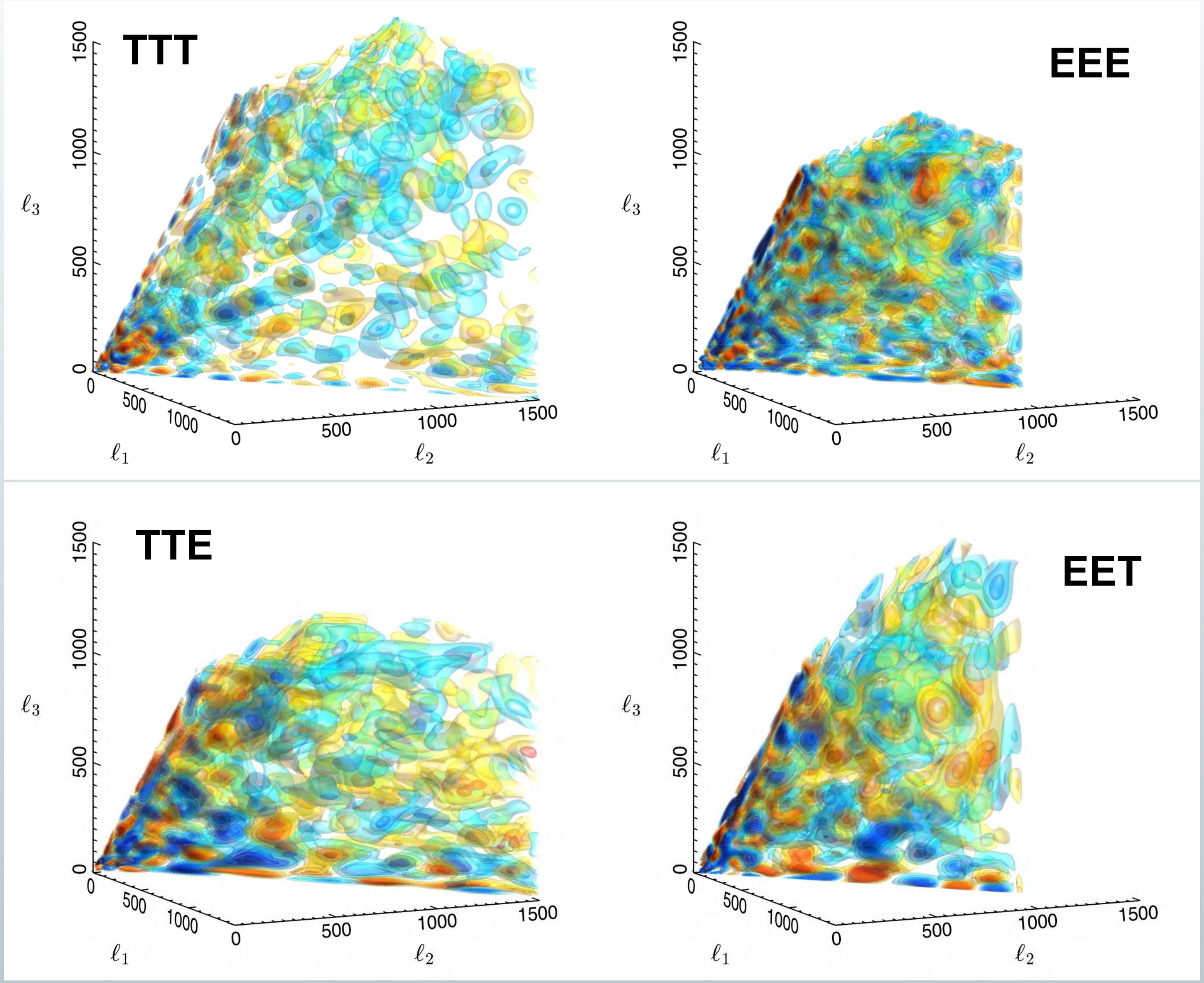
- <u>Local shape</u>: peaked on squeezed triangles. Multifield Inflation and Ekpyrotic models.

- <u>Equilateral shape</u>: single-field models with non-standard kinetic/higher-derivative terms, effective field theory

- <u>Flat shape</u>: linear combination of equilateral. and orthogonal. Non bunch Davies vacuum

- *Standard single field slow-roll: negligible NG*

The 2015 *Planck* full bispectrum



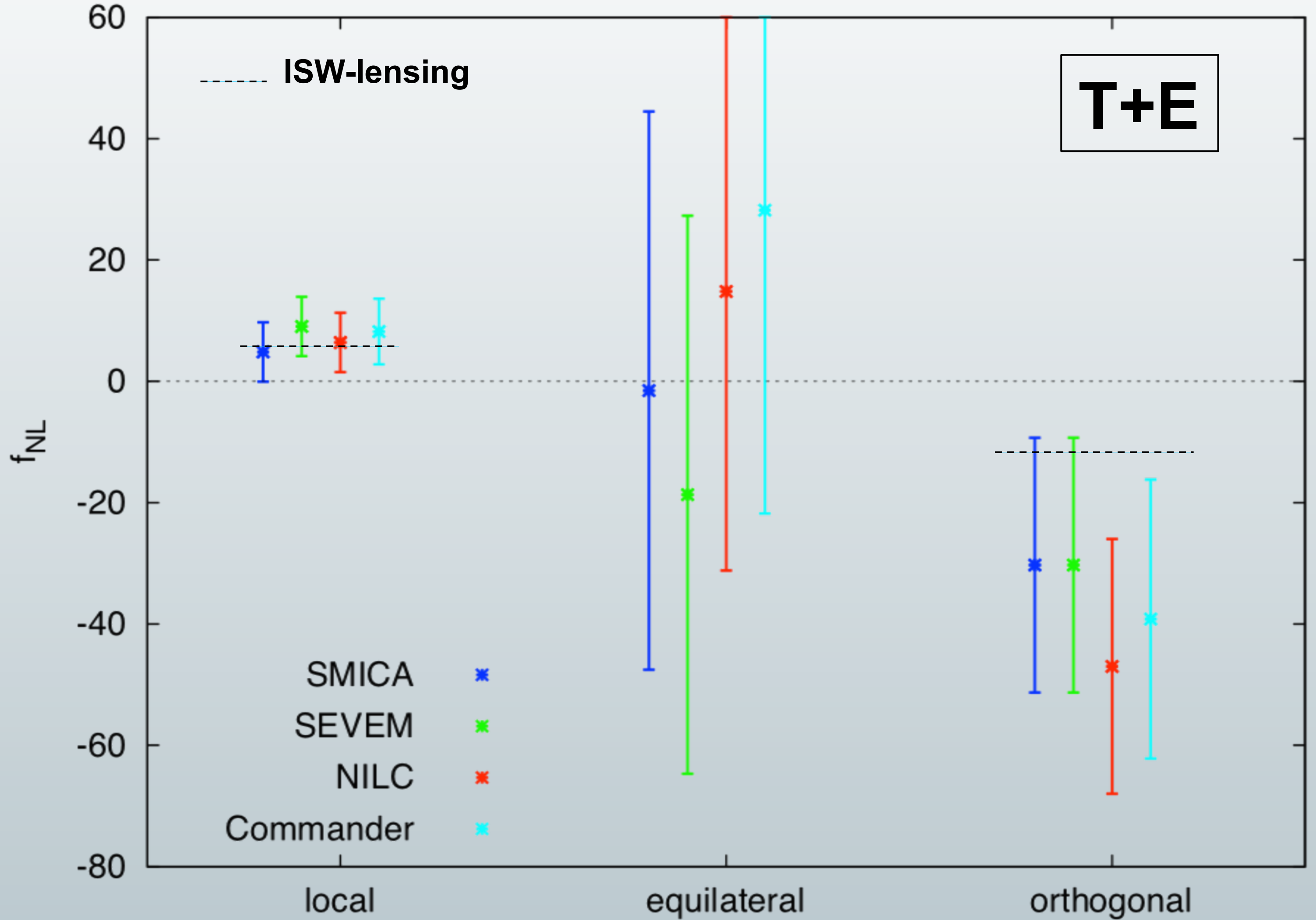
(S/N weighted)

f_{NL} from *Planck* bispectrum (KSW)

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

- We fit theoretical templates ("shapes") to data. The degree of correlation is measured by the dimensionless parameter $\mathbf{f_{NL}}$
- Large f_{NL} => detection of NG with a *specific* shape. It would rule out many inflationary scenarios at once

f_{NL}, cleaned maps comparison (modal)



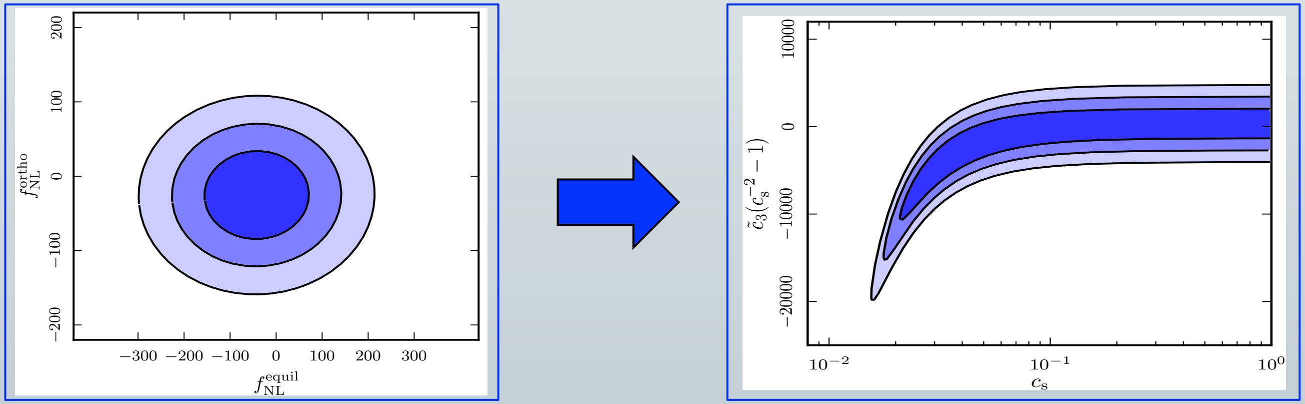
Some implications for inflation

- No evidence for primordial NG of the local, equilateral, orthogonal type. consistent with the simplest scenario: standard single-field slow roll.

- Other possibilities are however not ruled out. Constraints on f_{NL} are converted into constraints on relevant model parameters, for example:

  - Curvaton decay fraction $r_D > 19\%$ (from local f_{NL}, T+E)

  - Speed of sound in Effective Field Theory $c_S > 0.024$ (from equil. + ortho. f_{NL})



  - DBI inflation: $c_S > 0.087$ (T+E)

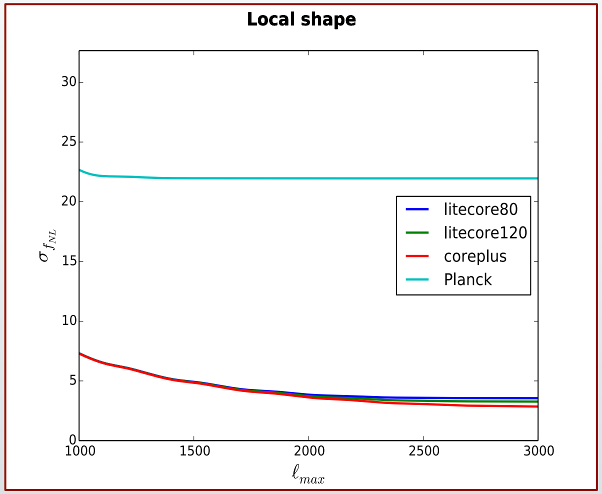
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

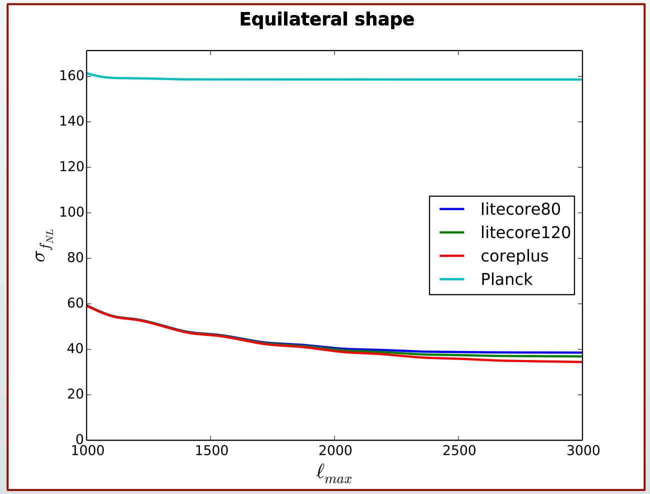
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

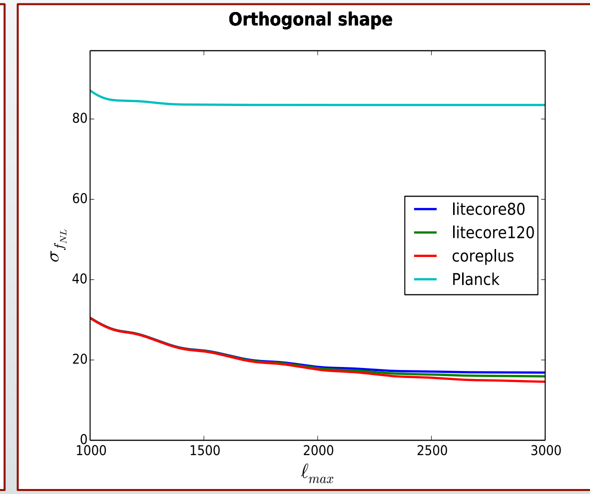
CMB bispectrum, beyond *Planck*

	LiteCOrE-120	COrE+	Planck 2015	LiteBird	ideal
T local	3.7	3.4	5.7	9.4	2.7
T equil.	59	56	70	92	46
T ortho.	25	25	33	58	20
E local	4.5	3.9	32	11	2.4
E equil.	46	43	141	76	31
E ortho.	21	19	72	42	13
T+E local	2.2	**1.9**	**5.0**	5.6	1.4
T+E equil.	22	**20**	**43**	40	15
T+E ortho.	10	**9.1**	**21**	23	6.7

- All forecasts for l_{max} = 3000, f_{sky} = 0.7 except LiteBird (l_{max} = 1350) and "ideal" (f_{sky} = 1)
- Planck 2015 refers to actual error bars (l_{max}= 2500, f_{sky}= 0.76), Planck local stil suboptimal (l_{min}-E = 40)


Local shape
litecore80
litecore120
coreplus
Planck
$\sigma_{f_{NL}}$
ℓ_{max}


Equilateral shape
litecore80
litecore120
coreplus
Planck
$\sigma_{f_{NL}}$
ℓ_{max}


Orthogonal shape
litecore80
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$\sigma_{f_{NL}}$
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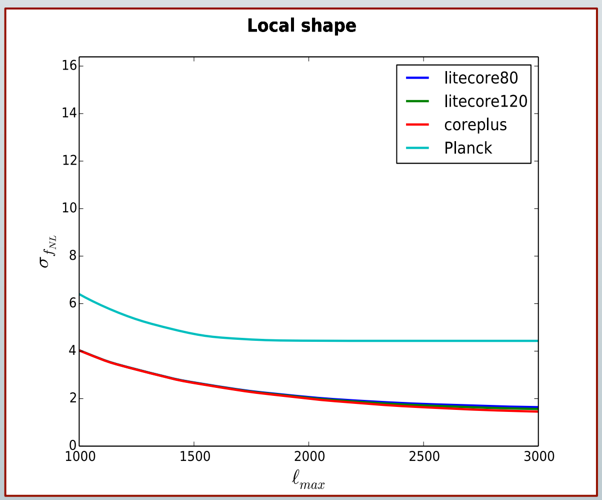
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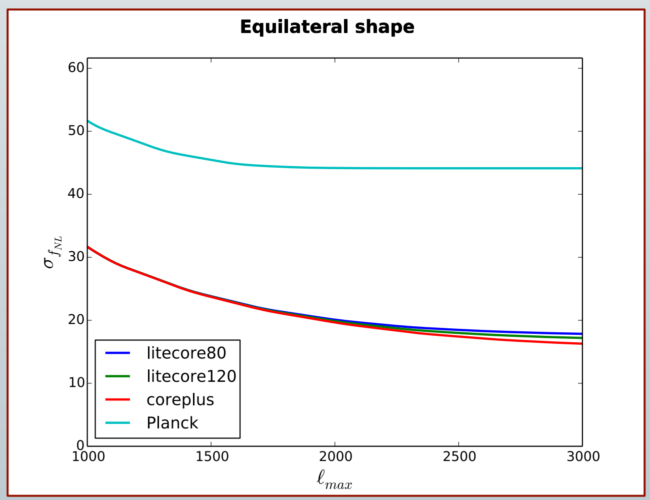
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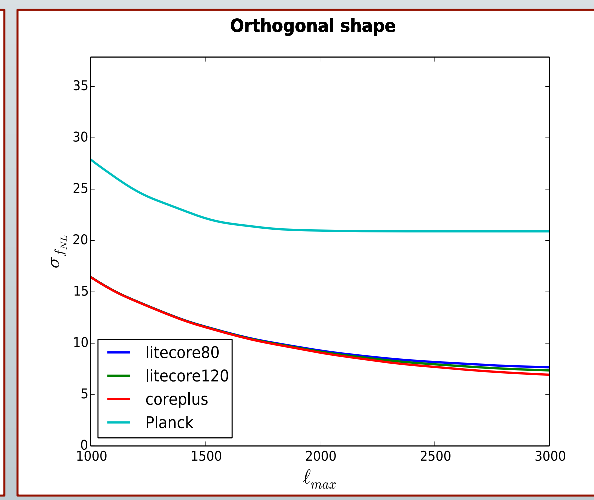
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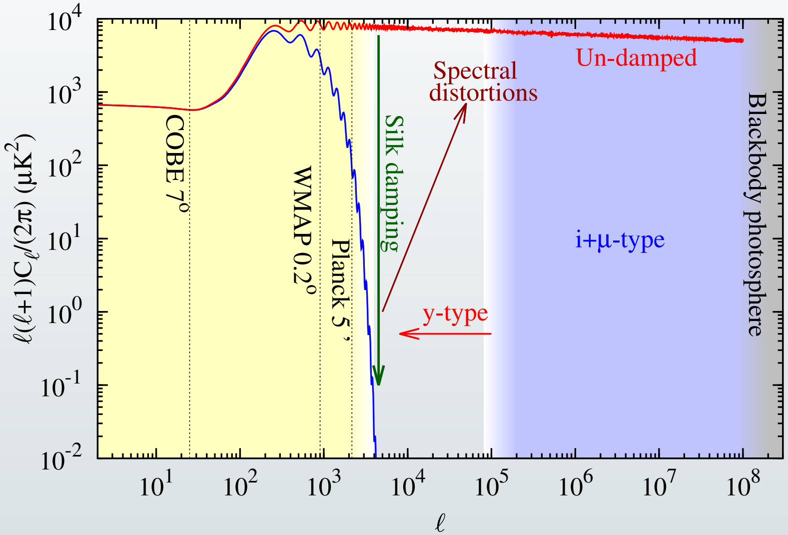
NG with CMB spectral distortions



CMB spectral distortions from acoustic wave dissipation probe a large range of scales, much smaller than CMB/LSS

Many additional modes!

Kathri and Sunyaev 2013, arXiv: 1303.7212

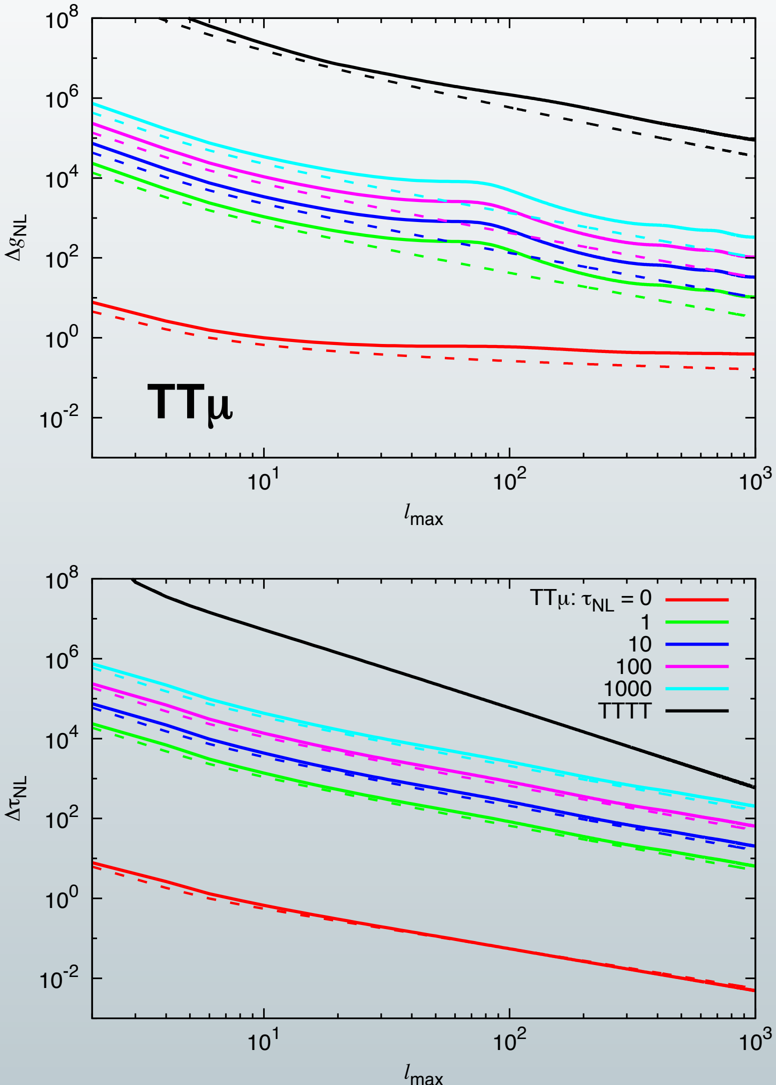
- If μ-*<u>anisotropies</u>* are measured (<u>no absolute calibration needed</u>):

  ✓ Tμ correlation: primordial local f_{NL} **(Pajer and Zaldarriaga 2013)**, or other squeezed shapes, and scale dependent NG **(Biagetti et al 2013, Emami et al. 2015)**

  ✓ μμ correlation: primordial local trispectrum, τ_{NL}

  ✓ TTμ bispectrum: primordial local trispectrum, g_{NL} (Bartolo, ML, Shiraishi 2016)

Generally requires futuristic, high levels of sensitivity. **However some models (excited initial states, *Ganc and Komatsu 2013*) produce enhanced signal. Very interesting to look at and include in forthcoming forecasts.**



Bartolo, ML, Shiraishi 2016

For G initial conditions, dissipated power in small patches is isotropically distributed

If local NG => large scale modulation of small scale power => Tμ correlations (**Pajer, Zaldarriaga 2013**)

Enhanced bispectrum on squeezed configurations (e.g. excited initial states) produces potentially detectable Tμ with PIXIE-like survey **(Ganc, Komatsu 2013)**

Anisotropic primordial signature produce Characteristic off-diagonal terms in Tμ (**Shiraishi, ML, Bartolo 2015**)

…and more (Ty, scale depndence, PMF)

Conclusions

- Primordial NG (even when not detected) is a powerful tool to constrain Inflation. It provides complementary information to the power spectrum CMB is the ideal observable (perturbations in linear regime)

- Current status: no primordial NG detected. Consistent with single-field slow-roll. Tight constraints on other scenarios.

- Main goal for the future: achieve $f_{NL} \sim 1$ sensitivity (can rule out multi-field)

- COrE+: expected error bars improvement ~2 over Planck *for all shapes*. Close to saturating ideal limit for CMB.

- CMB spectral distortions have a strong potential (many modes!). Many orders of magnitude improvement on local NG possible with an ideal experiment (futuristic). Significant improvements expected in the near future already for specific models (NBD)

With B-mode and NG measurements in the (near?) future we could:

1. **Find definitive confirmation of Inflation.**
2. **Understand inflationary Physics in detail.**