Testing primordial non-Gaussianity with CMB and LSS data.

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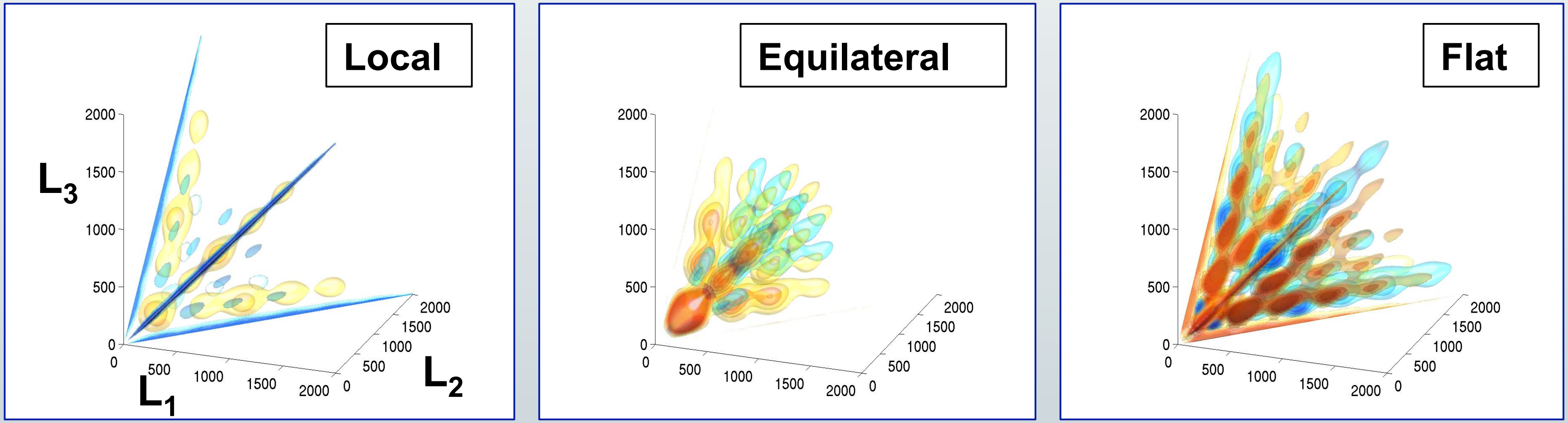
Beyond power spectra: non-Gaussianity

Primordial non-Gaussianity. Many inflationary scenarios (notably, multi-field Inflation) predict small, model-dependent deviations from Gaussianity.
Additional information in 3-point (bispectrum) and 4-point (trispectrum) correlation functions.



- Fit primordial bispectrum (trispectrum) template to the data and measure the degree of correlation via a dimensionless parameter f_{NL} (g_{NL}, τ_{NL}).
- Large f_{NL} for a given shape selects specific scenarios. E.g. **large local f_{NL} would rule out standard single-field models**.

Primordial and CMB bispectrum

Non-Gaussianity: higher order correlators of the primordial curvature perturbation field are non-vanishing

- Largest correlator (in most cases): the primordial bispectrum

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

$$f_{NL} \equiv \frac{k^6 F(k,k,k)}{6\Delta_\Phi^2(k)}$$

Primordial potential

Shape

Translation invariance

Amplitude

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- What we measure is the CMB angular bispectrum :

$$B_{\ell_1\ell_2\ell_3}^{m_1m_2m_3} = \left\langle a_{\ell_1}^{m_1} a_{\ell_2}^{m_2} a_{\ell_3}^{m_3}\right\rangle$$

Primordial and CMB bispectrum

Non-Gaussianity: higher order correlators of the primordial curvature perturbation field are non-vanishing

- Largest correlator (in most cases): the primordial bispectrum

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

$$\underbrace{f_{NL}}_{\text{Amplitude}} \equiv \frac{k^6 F(k,k,k)}{6\Delta_\Phi^2(k)}$$

Primordial potential

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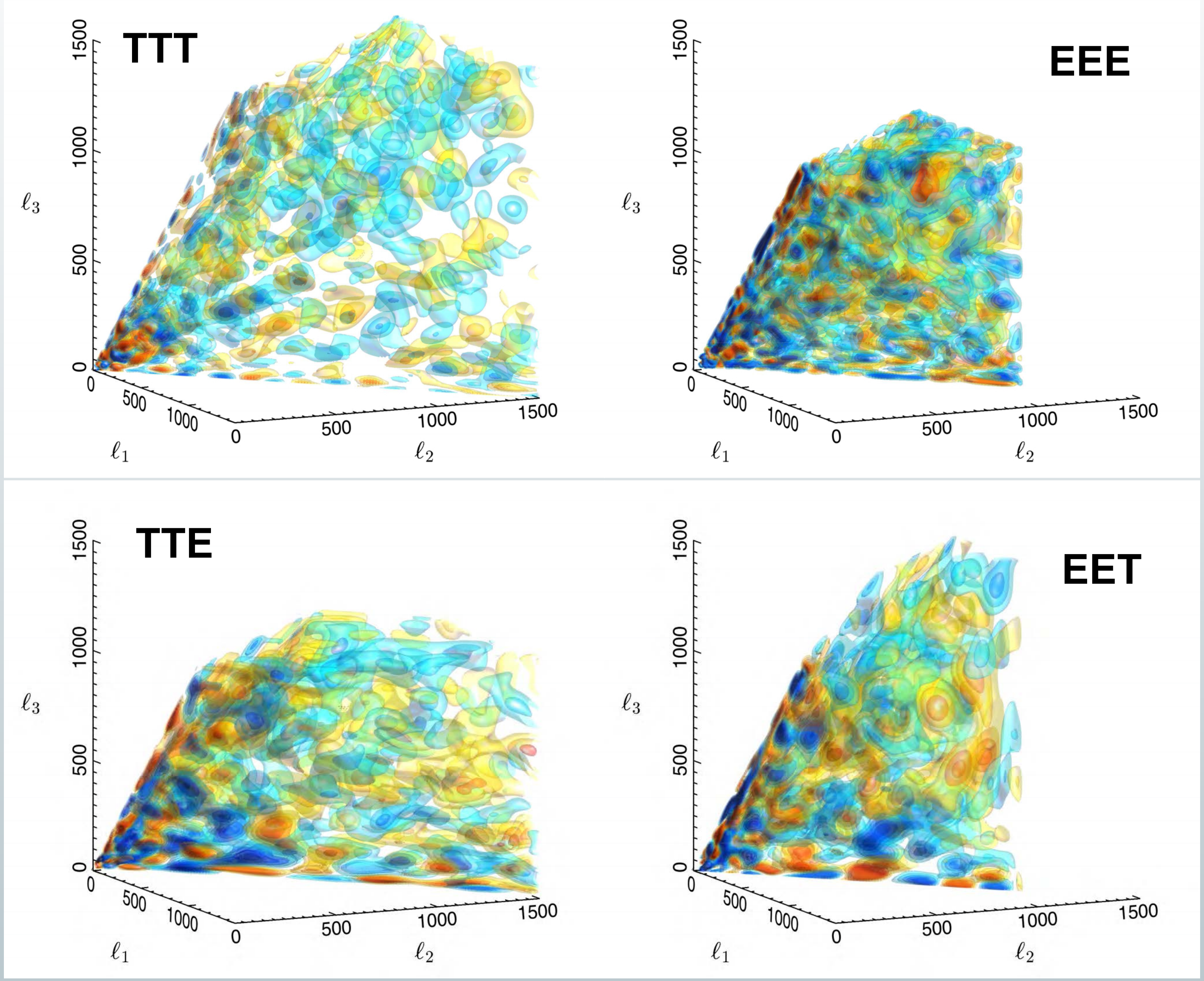
- What we measure is the CMB angular bispectrum : $B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} = \langle a^{m_1}_{\ell_1} a^{m_2}_{\ell_2} a^{m_3}_{\ell_3}\rangle$

- Primordial and CMB bispectra are linked through linear radiative transfer effects (same as for power spectrum)

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

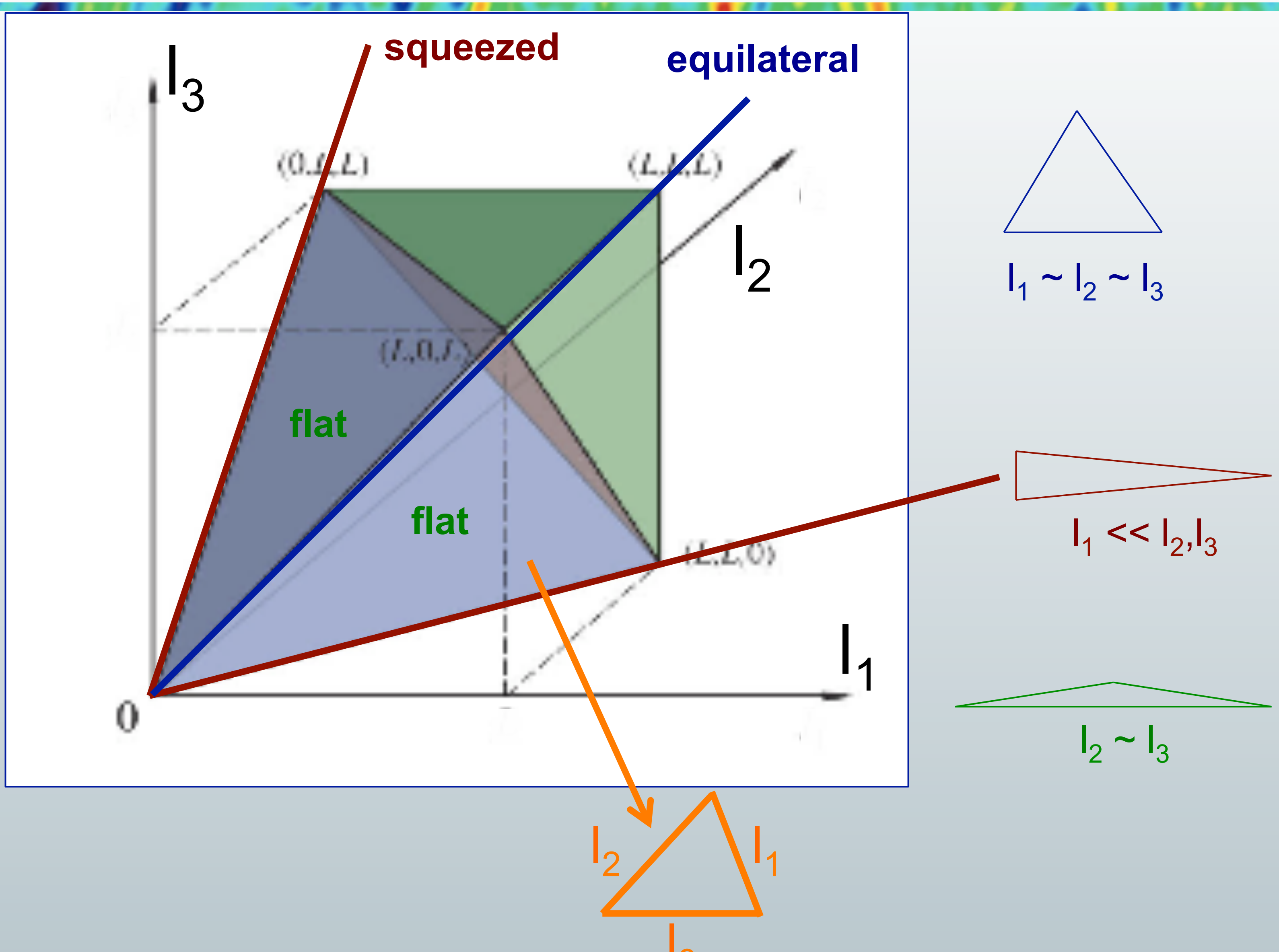
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

The 2015 *Planck* bispectrum (modal)



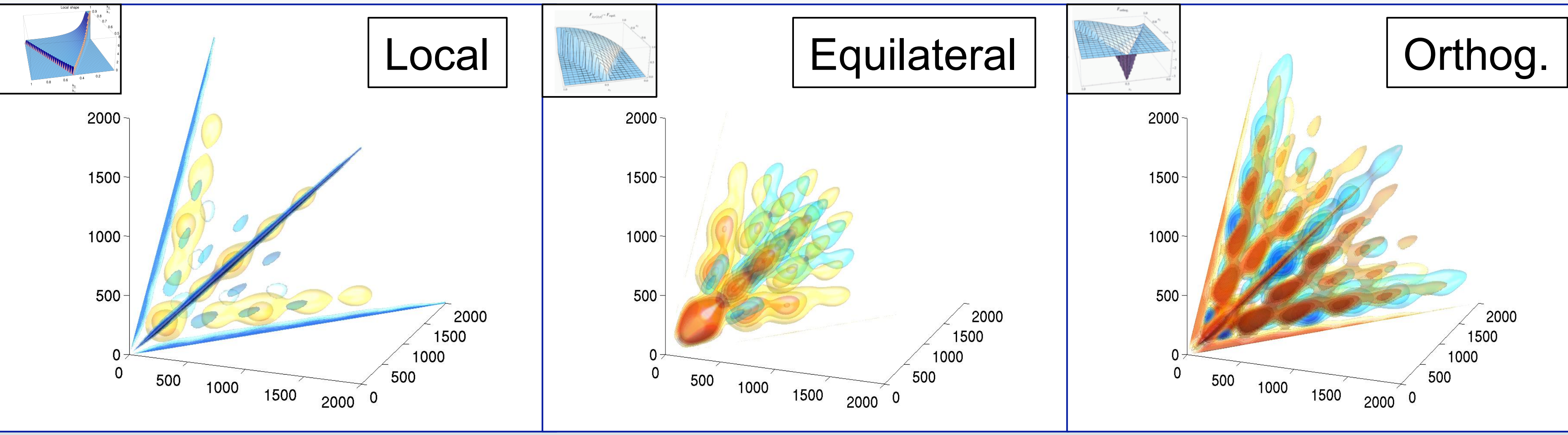
(S/N weighted)

Bispectrum



squeezed
equilateral
l_3
l_2
l_1
0
(0,L,L)
(L,L,L)
(L,0,L)
(L,L,0)
flat
flat
$l_1 \sim l_2 \sim l_3$
$l_1 << l_2,l_3$
$l_2 \sim l_3$
l_2
l_1
l_3

Main primordial shapes



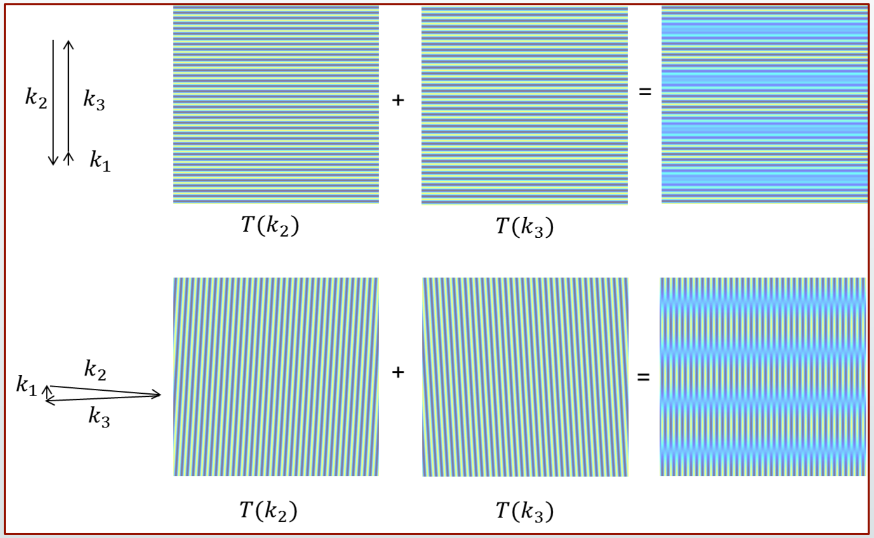
- Local shape: peaked on squeezed triangles. Multifield Inflation and Ekpyrotic models.

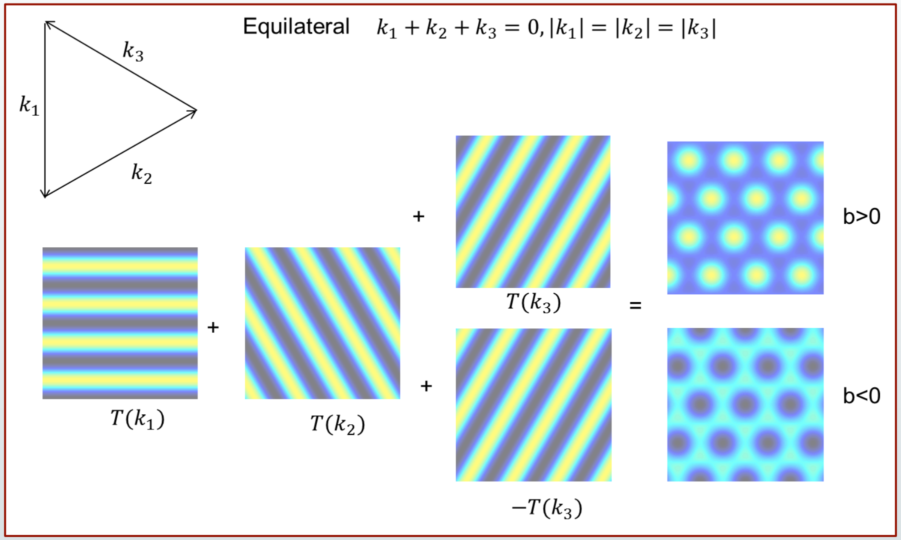
- Equilateral shape: single-field models with non-standard kinetic/higher-derivative terms, effective field theory

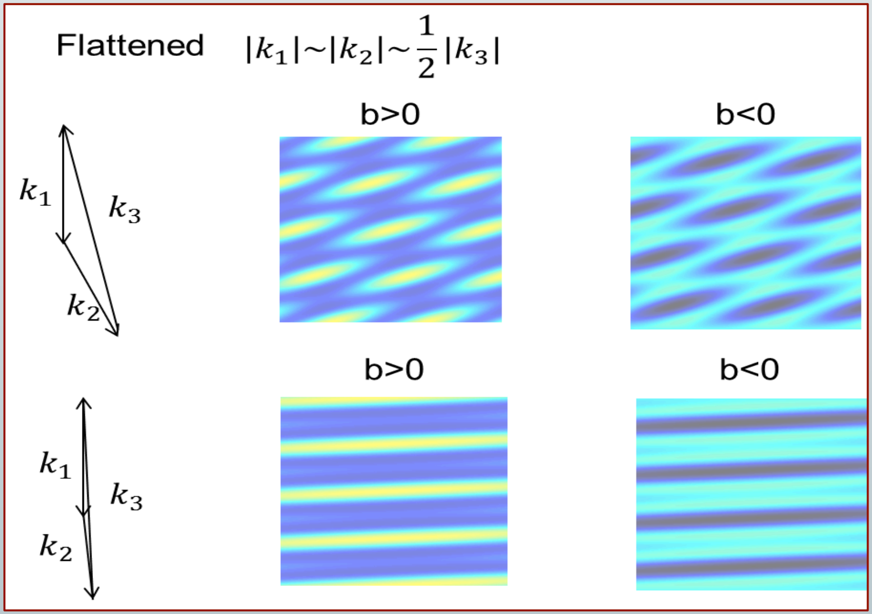
- Flat shape: linear combination of equilateral. and orthogonal. Non bunch Davies vacuum

- *Standard single field slow-roll: negligible NG (given current sensitivity)*

NG fields in real space







Local: large scale modulation of small scale power (more/less small scale structure in large scale overdense regions)

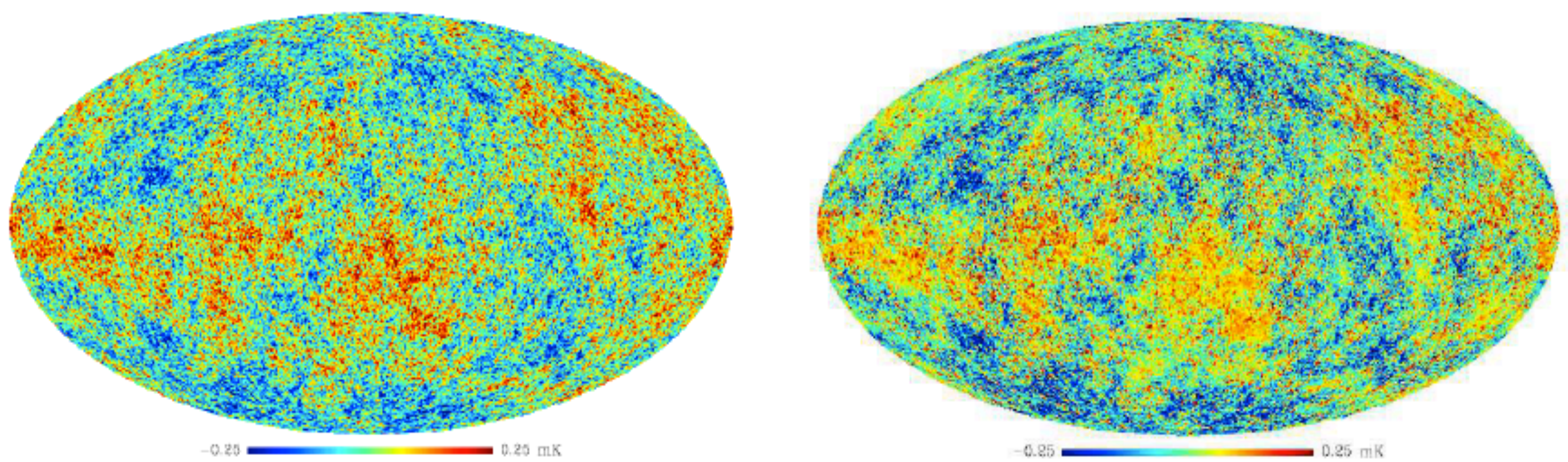
Equilateral: filamentary structure of over/underdense regions

Flattened: pancake structure

Lewis 2012

CMB local-type NG simulations

$$\Phi\left(\vec{x}\right) = \Phi_L\left(\vec{x}\right) + f_{NL}\left(\Phi_L^2\left(\vec{x}\right) - \left\langle \Phi^2\left(\vec{x}\right)\right\rangle\right) + g_{NL}\Phi_L^3\left(\vec{x}\right)$$



Liguori et al. 2007

$f_{NL} = 0$, $g_{NL} = 0$ **$f_{NL} = 3000$, $g_{NL} = 0$**

Optimal f_{NL} bispectrum estimator

$$\hat{f}_{NL} = \frac{1}{N}\sum B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}\left(C^{-1}a\right)^{m_1}_{\ell_1}\left(C^{-1}a\right)^{m_2}_{\ell_2}\left(C^{-1}a\right)^{m_3}_{\ell_3} - 3C^{-1}_{\ell_1 m_1 \ell_2 m_2}\left(C^{-1}a\right)^{m_3}_{\ell_3}$$

Leaving aside complications coming from breaking of statistical isotropy (sky-cut, noise…), one can see that we are extracting the three point Function from the data and fitting theoretical bispectrum templates to it

$$\boxed{\hat{f}_{NL} = \frac{1}{N}\sum_{\ell_i m_i} B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}\frac{a^{m_1}_{\ell_1}}{C_{\ell_1}}\frac{a^{m_2}_{\ell_2}}{C_{\ell_2}}\frac{a^{m_3}_{\ell_3}}{C_{\ell_3}}}$$

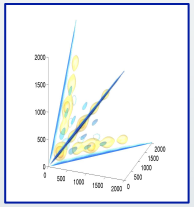
A brute force implementation scales like $\ell^5_{\max}$. Unfeasible at Planck (or WMAP) resolution.

Can achieve massive speed improvement ($\ell^3_{\max}$ scaling) if the reduced bispectrum is *separable* (Komatsu, Spergel, Wandelt 2003). KSW method.

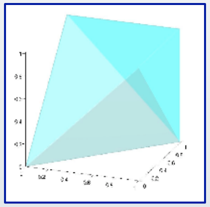
$$b_{\ell_1\ell_2\ell_3} = \sum_{ijk} X^i_{\ell_1} Y^j_{\ell_2} Z^k_{\ell_3} \Rightarrow B^{m_1 m_2 m_3}_{\ell_1\ell_2\ell_3} = b_{\ell_1\ell_2\ell_3}\int Y^{m_1}_{\ell_1}(\Omega) Y^{m_2}_{\ell_2}(\Omega) Y^{m_3}_{\ell_3}(\Omega)$$

Modal expansion in figures

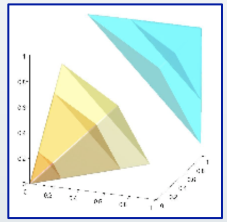
Expansion



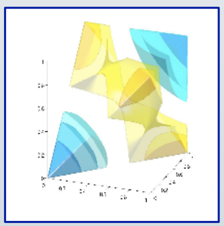
$= \alpha_0$



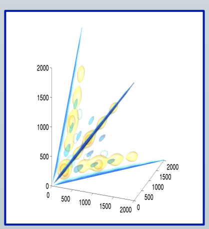
$+ \alpha_1$



$+ \alpha_2$

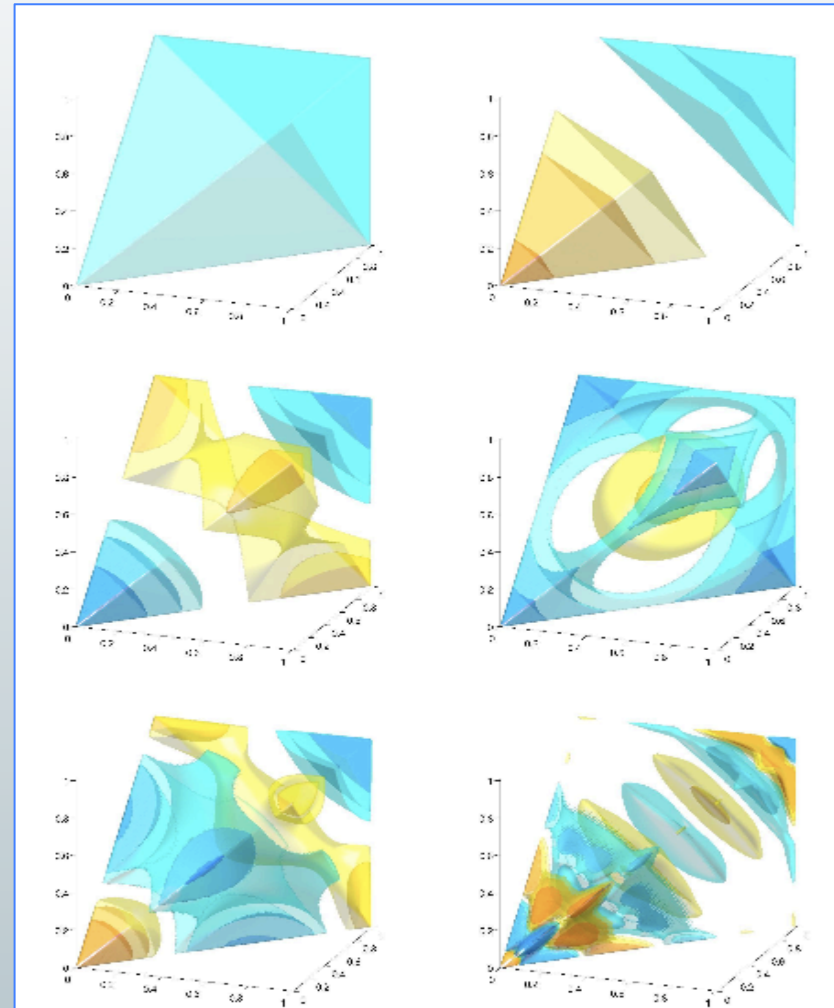


$+ \ldots$

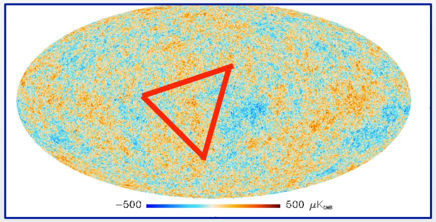


$$\Rightarrow \left(\alpha_0, \alpha_1, \ldots, \alpha_n\right)$$

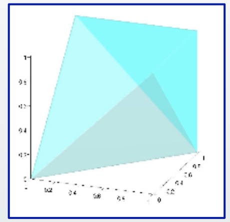
Basis modes



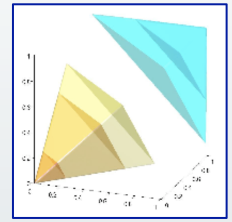
Bispectrum estimation



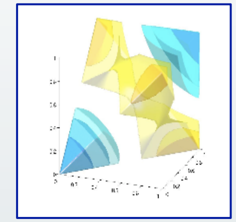
$= \beta_0$



$+ \beta_1$



$+ \beta_2$



$+ \ldots$

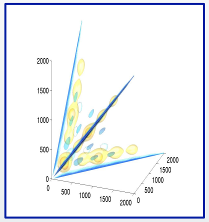
For a given dataset, extract best-fit β_i, i=1,…,n

- The basis elements pictured on the right *are by construction factorizable*

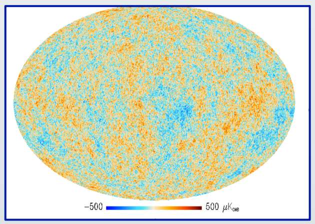
- Apply position space cubic statistics, KSW, to each separable template on the right to estimate the amplitudes β_i

- Orthonormal basis ➔ β_i uncorrelated (in first approx.)

f_{NL} and bispectrum reconstruction



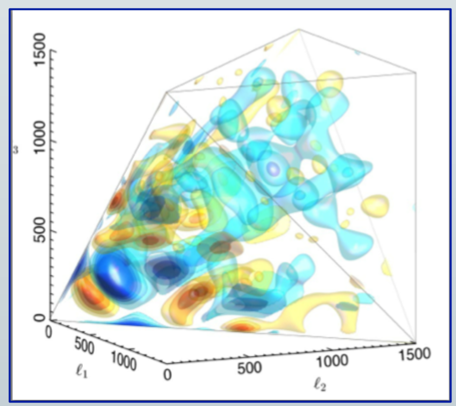
$$\left(\alpha_0, \alpha_1, \ldots, \alpha_n\right)$$ Theory



$$\left(\beta_0, \beta_1, \ldots, \beta_n\right)$$ Data (“mode spectrum”)

$$f_{NL} = \frac{1}{N} \sum_n \alpha_n \beta_n$$

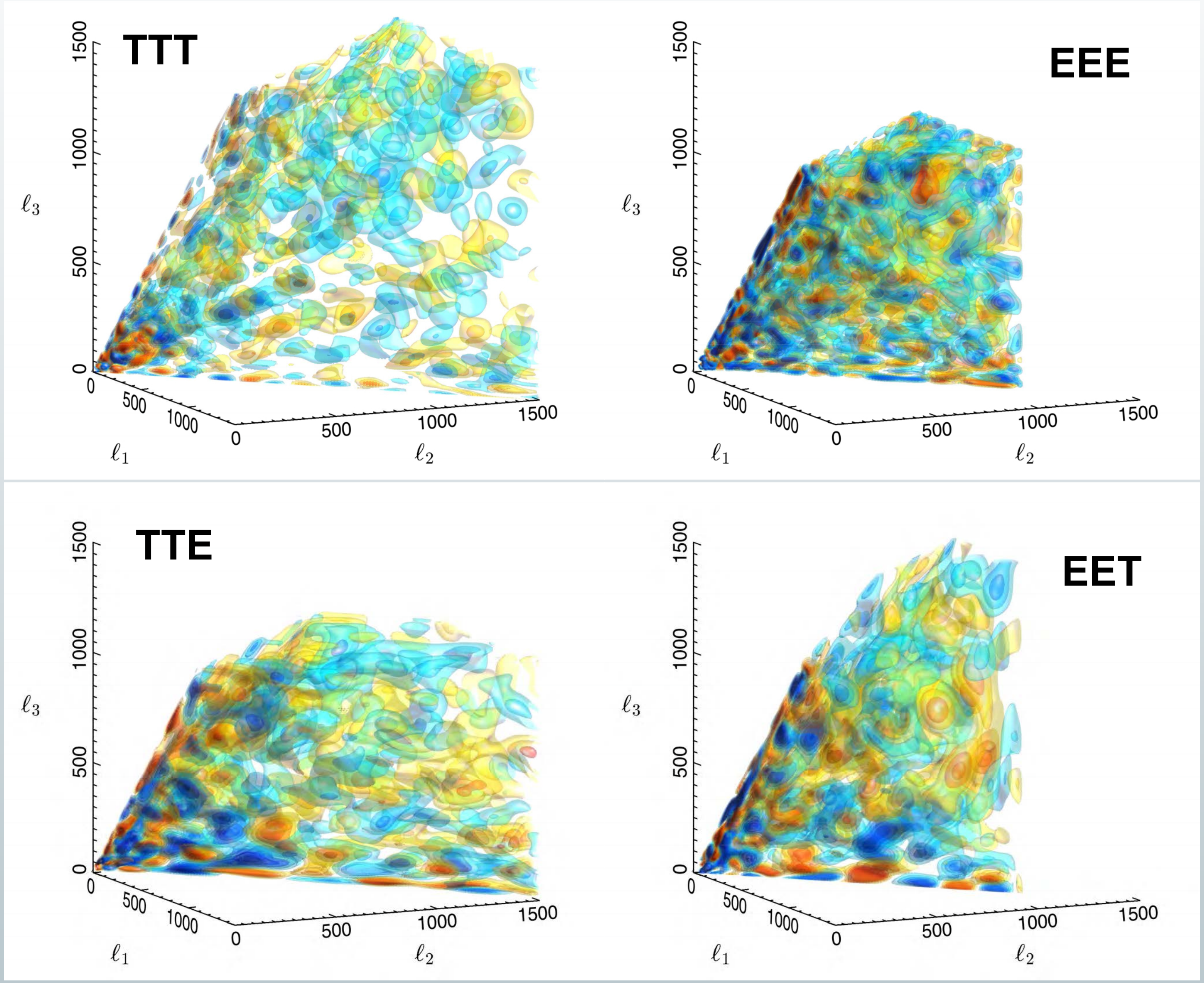
$$N = \frac{1}{6} \sum_n \alpha_n^2$$



$$= \sum_n \beta_n \Re_n$$

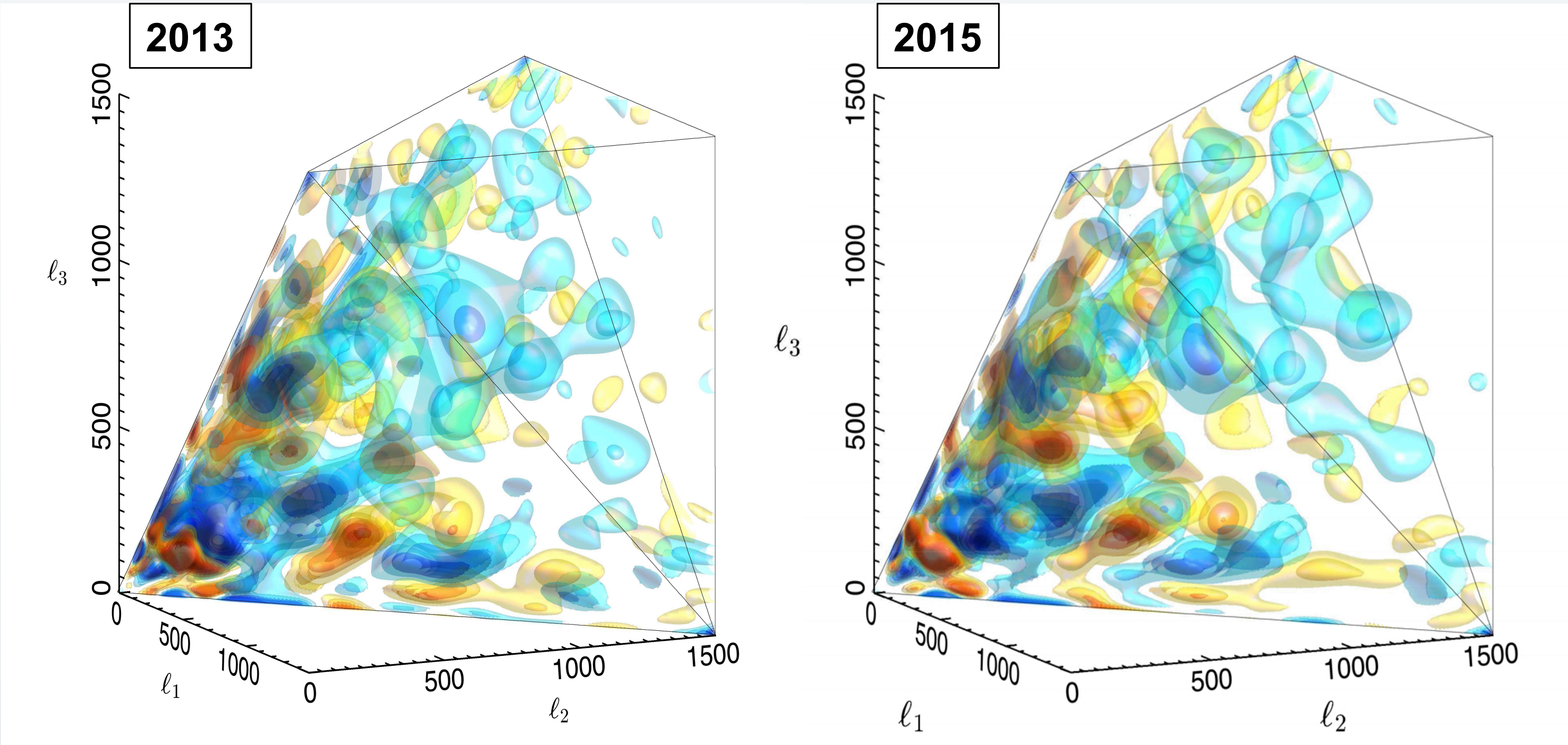
J. Fergusson, ML, P. Shellard 2009, 2010, arXiv: 0912.5516, 1006.1642
J. Fergusson, P. Shellard, 2011, arXiv: 1105.2791,
M. Shiraishi, ML, J. Fergusson 2014, arXiv: 1403.4222, 1409.0265
J. Fergusson 2014, arXiv:1403.7949

The 2014 *Planck* bispectrum (modal)



(S/N weighted)

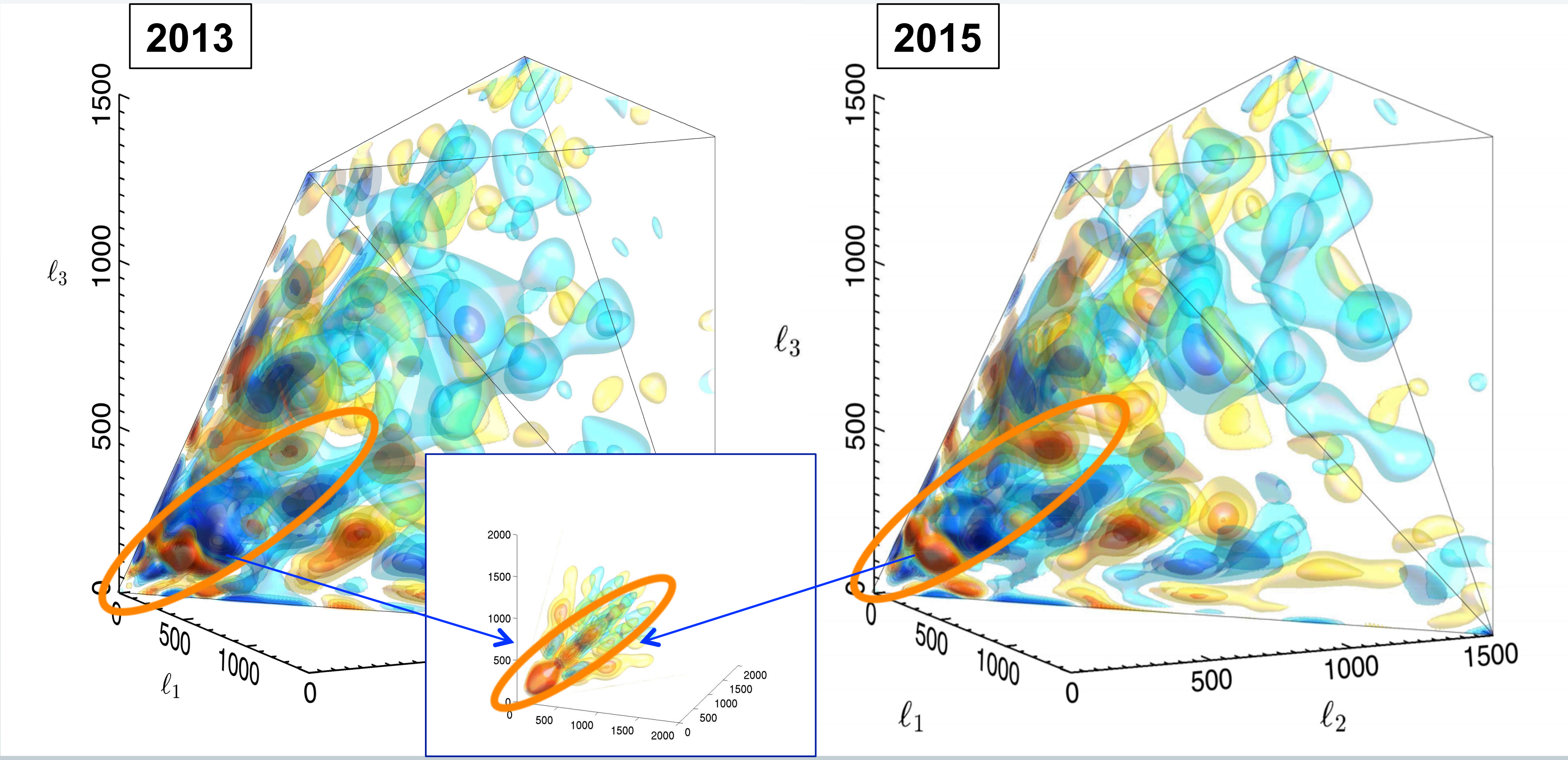
Planck TTT: 2013 vs Planck 2015



Primordial NG Planck results:
Ade et al., Planck 2015 results. XVII

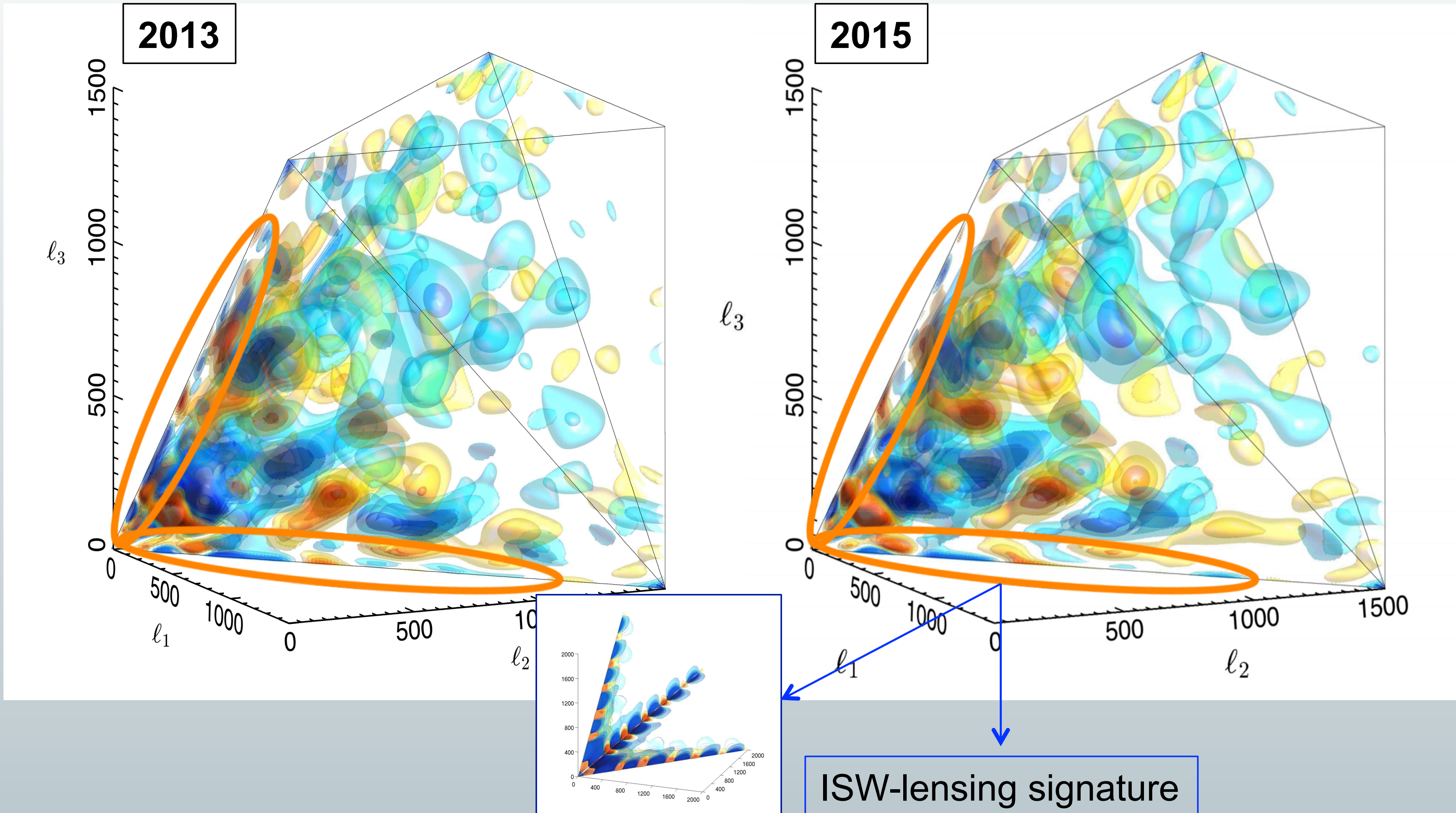
Modal bispectrum reconstruction:
Fergusson, ML, Shellard 2010, 2011

Planck TTT: 2013 vs Planck 2015



Does not match period of acoustic oscillations for primordial bispectra

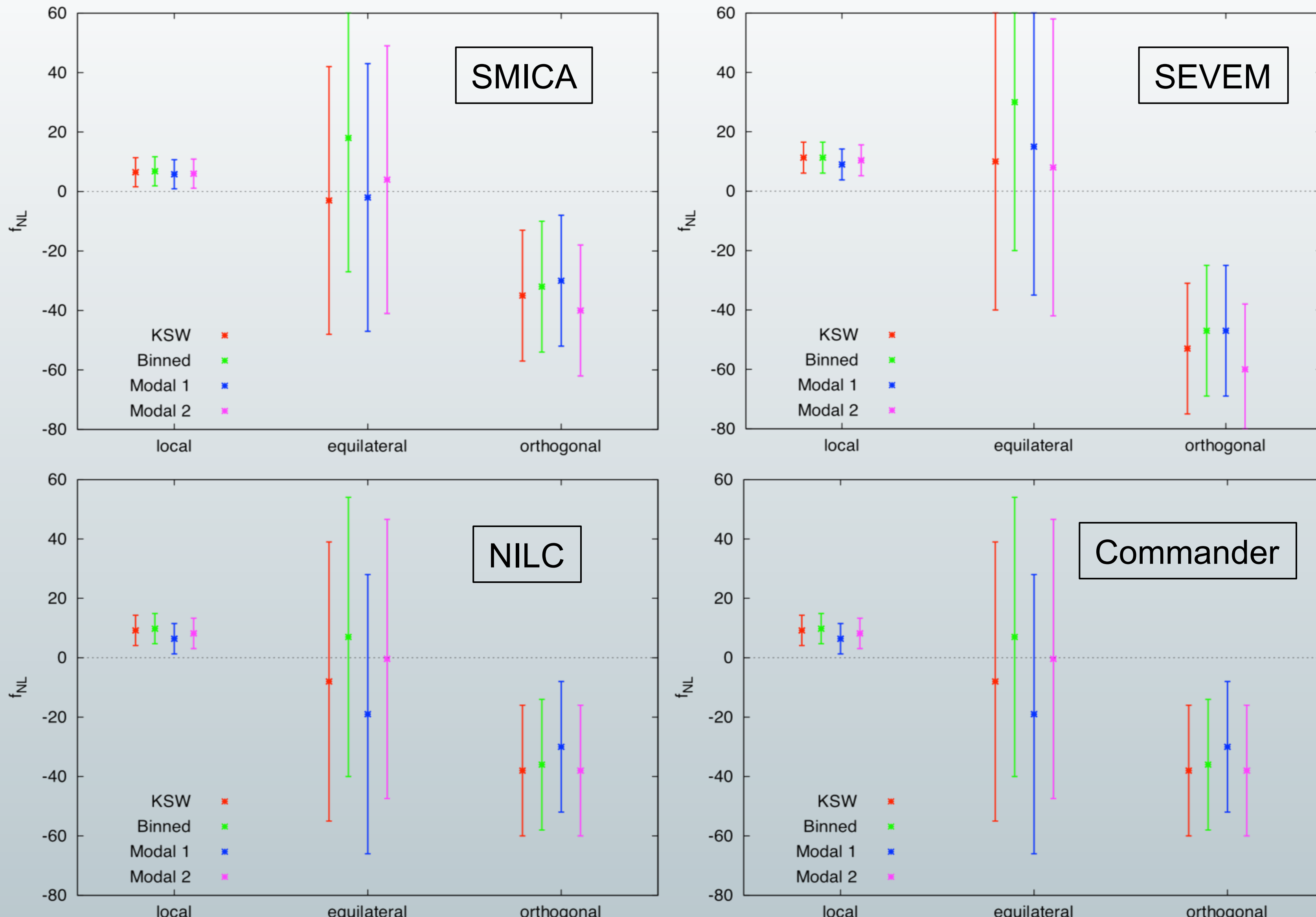
Planck TTT: 2013 vs Planck 2015



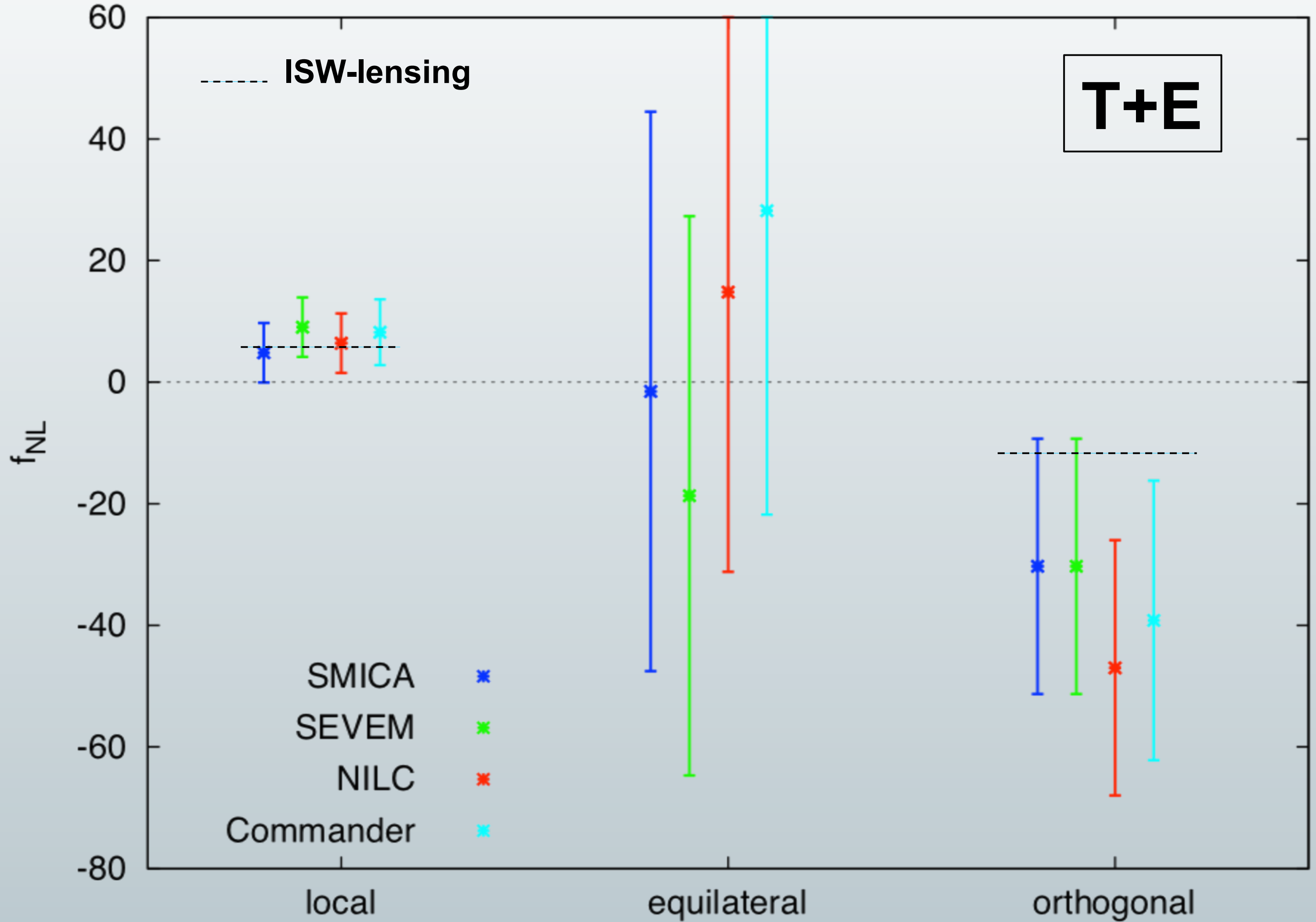
f_{NL} from *Planck* bispectrum (KSW)

Shape and method	f_{NL}(KSW) Independent	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	$\mathbf{-26 \pm 21}$

f_{NL}, estimators comparison



f_{NL}, cleaned maps comparison (modal)



Beyond "standard" shapes

- We compute f_{NL} for a large number of primordial models beyond the standard local, equilateral, orthogonal shapes, including

  - ✓ Equilateral family (DBI, EFT, ghost)
  - ✓ Flattened shapes (non-Bunch Davies)
  - ✓ Feature models (oscillatory bispectra, scale-dependent)
  - ✓ Direction dependence
  - ✓ Quasi-single-field
  - ✓ Parity-odd models

- **No evidence for NG found, constraints on parameters from the models above**

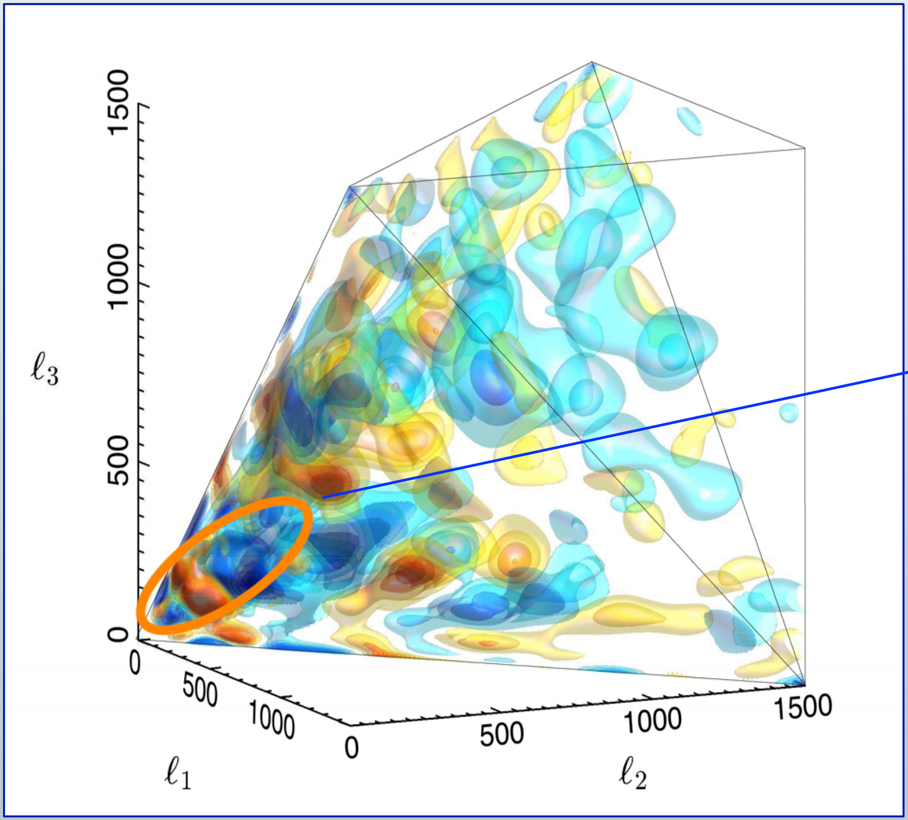
- **Extended survey of feature models with respect to 2013, 600 -> 2000 modes, including polarization.**

All primordial NG *Planck* results in ***Planck*** **2015 results. XVII.**

Feature models

$$S \sim f_{NL}^{feat.} \sin\left(\frac{K}{k_*} + \phi\right)$$

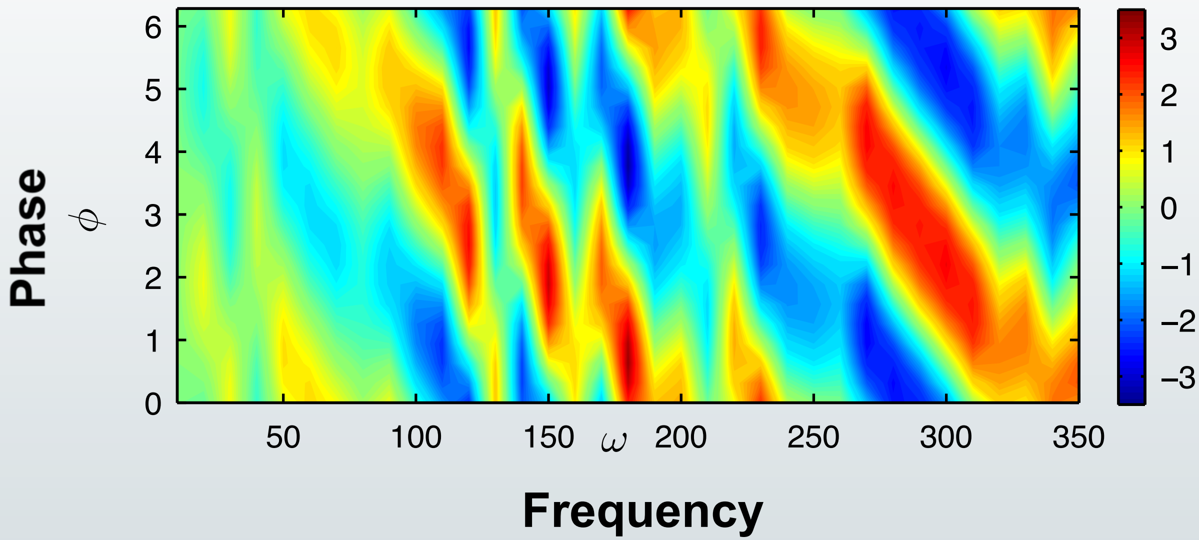
$$S_{flat-feat.} = S_{flat} \times S_{feat}$$
$$S_{equil-feat} = S_{equil} \times S_{feat}$$

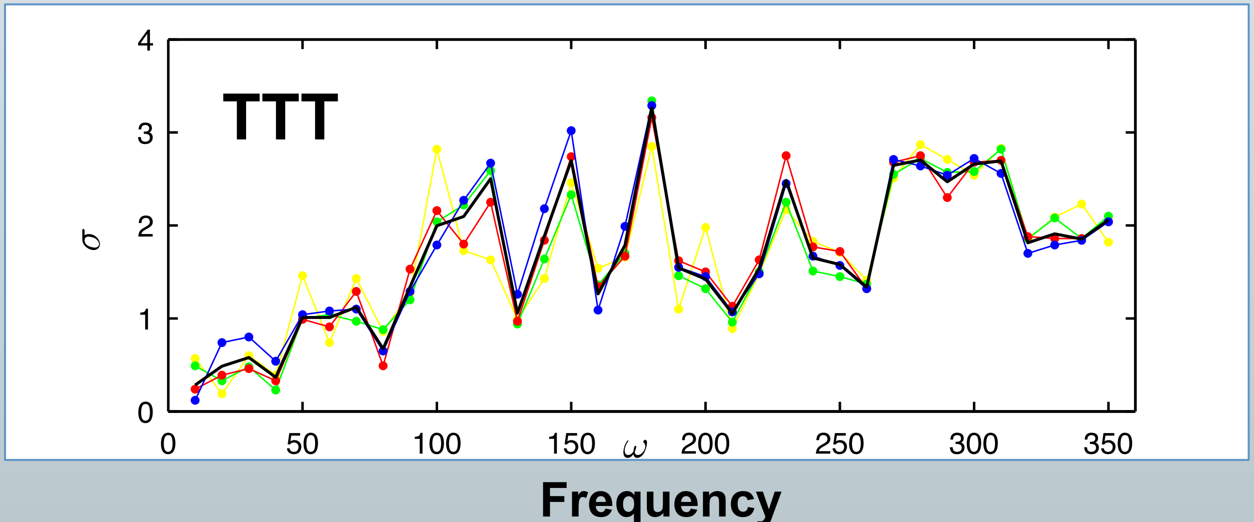


Change of sign does not match acoustic peak

Can be captured by oscillating features

Features x Equilateral

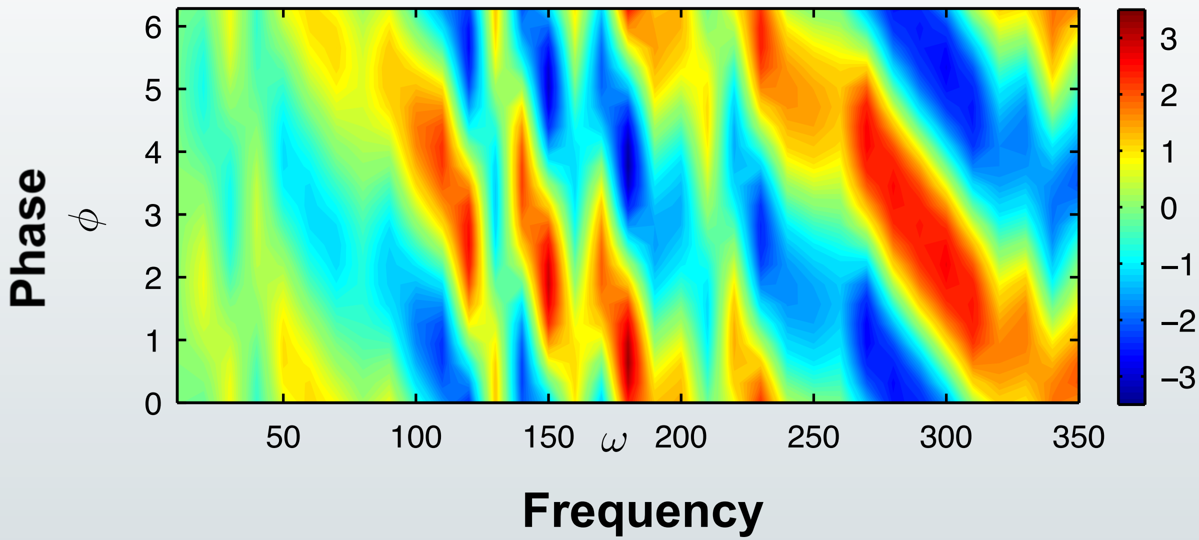


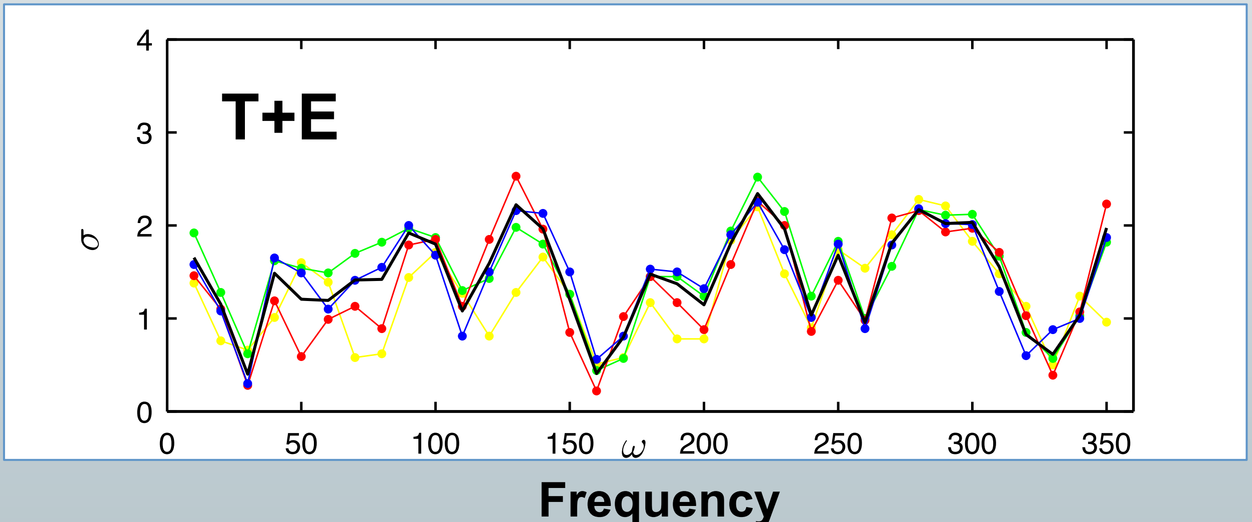


Marginalizing over phase

“Look elsewhere” accounted for

Features x Equilateral

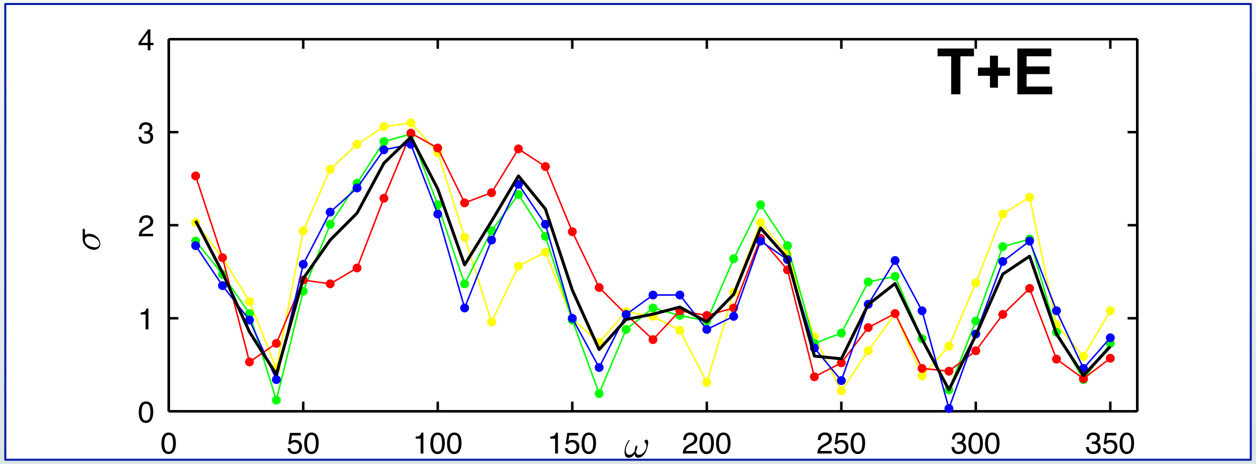




Marginalizing over phase

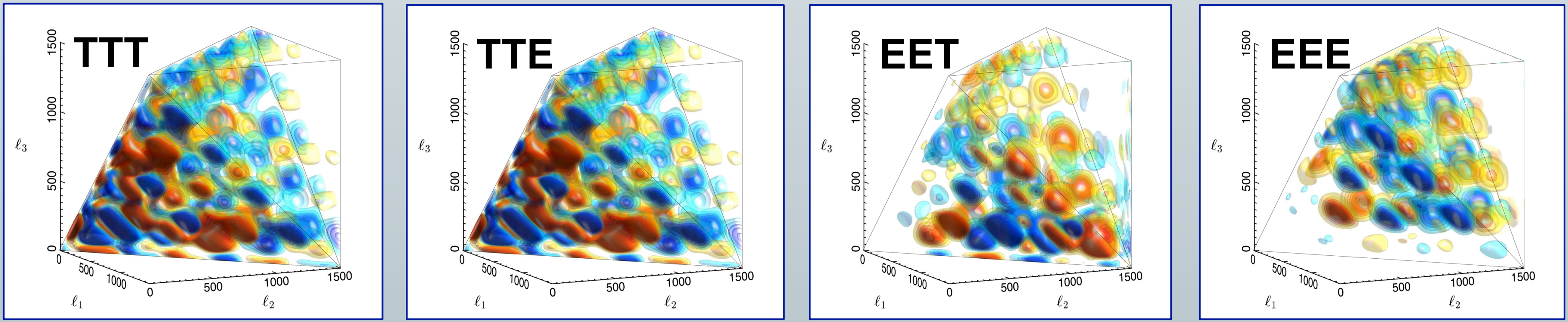
“Look elsewhere” not accounted for

Features x Flat

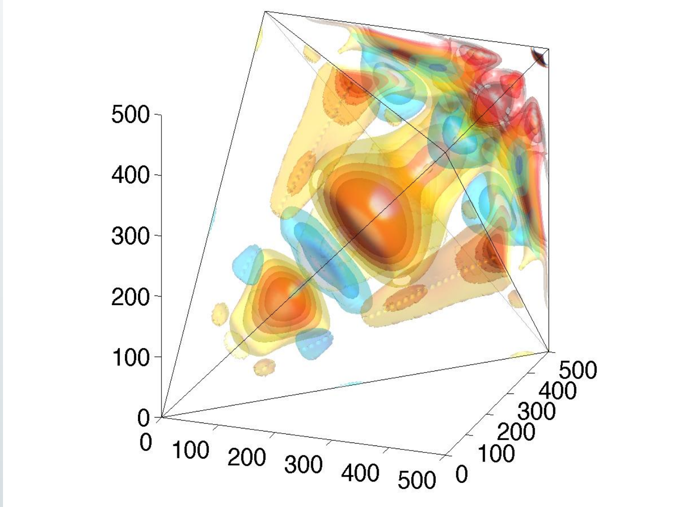
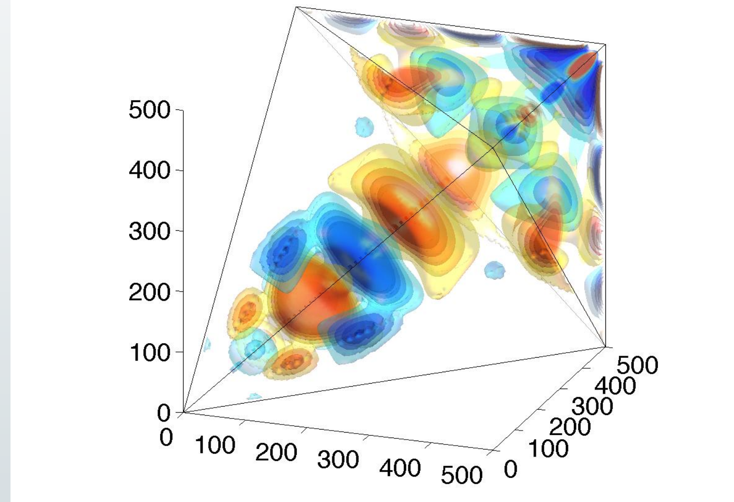
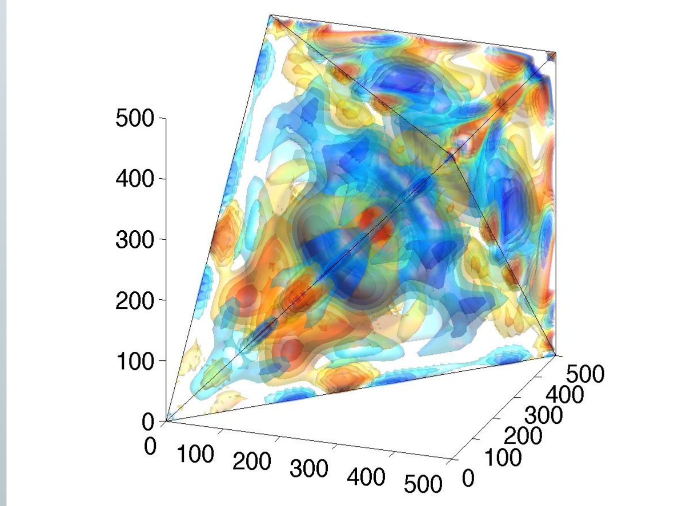
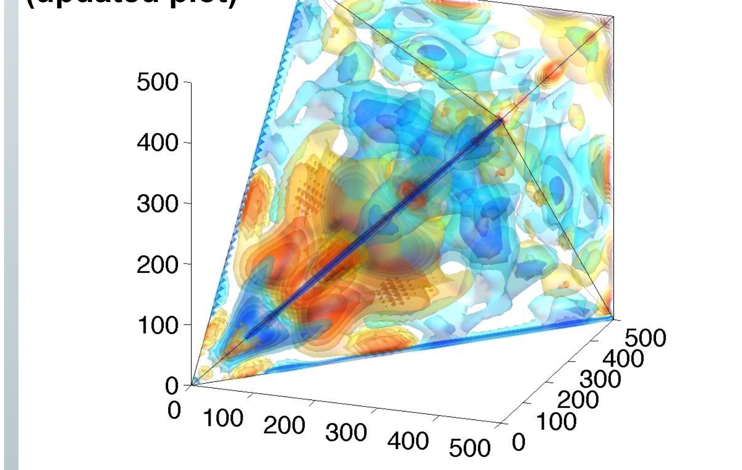


Largest significance obtained for feature models with "Flat" envelope

Best-fit Feature x Flat

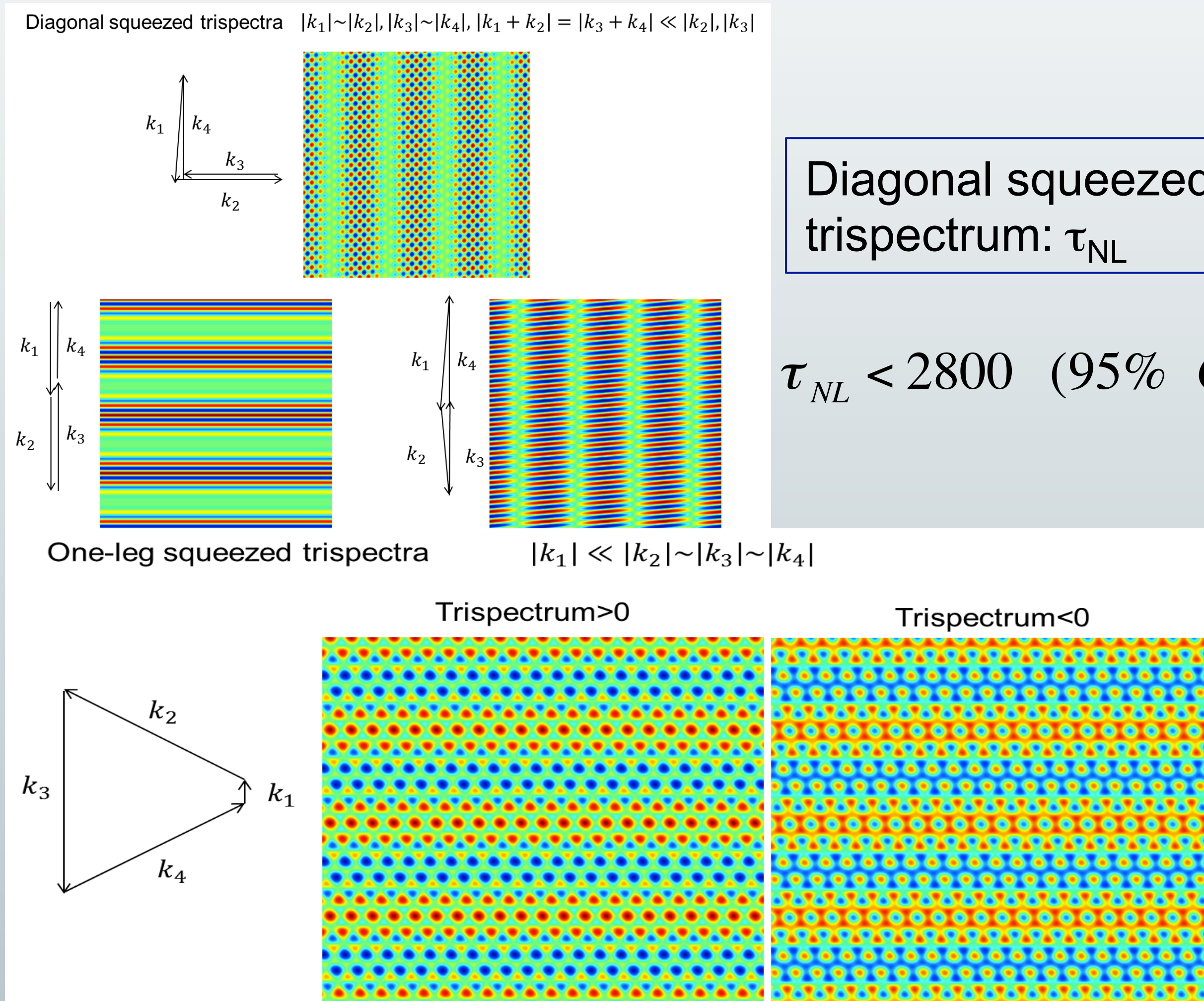


Planck vs WMAP

	Planck	WMAP
Parity-odd		M. Shiraishi, ML, J. Fergusson 2014 
Parity-even		J Fergusson, ML, P. Shellard 2009, 2010 (updated plot) 

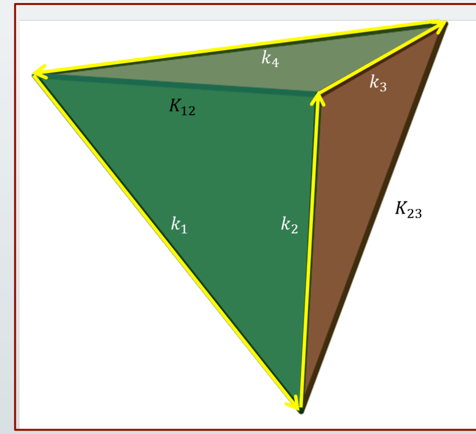
Trispectrum

$$\left\langle \Phi(k_1)\Phi(k_2)\Phi(k_3)\Phi(k_4)\right\rangle \propto F\left(k_1,k_2,k_3,k_4,K_{12},K_{23}\right)\delta\left(\vec{k}_1+\vec{k}_2+\vec{k}_3+\vec{k}_4\right)$$



Diagonal squeezed trispectrum: τ_{NL}

$$\tau_{NL} < 2800 \quad (95\% \ \ C.L.)$$



Pictures from Lewis 2012

Leg squeezed trispectrum: g_{NL}

$$g_{NL}^{local} = \left(-9.0 \pm 7.7\right) \times 10^{-4}$$

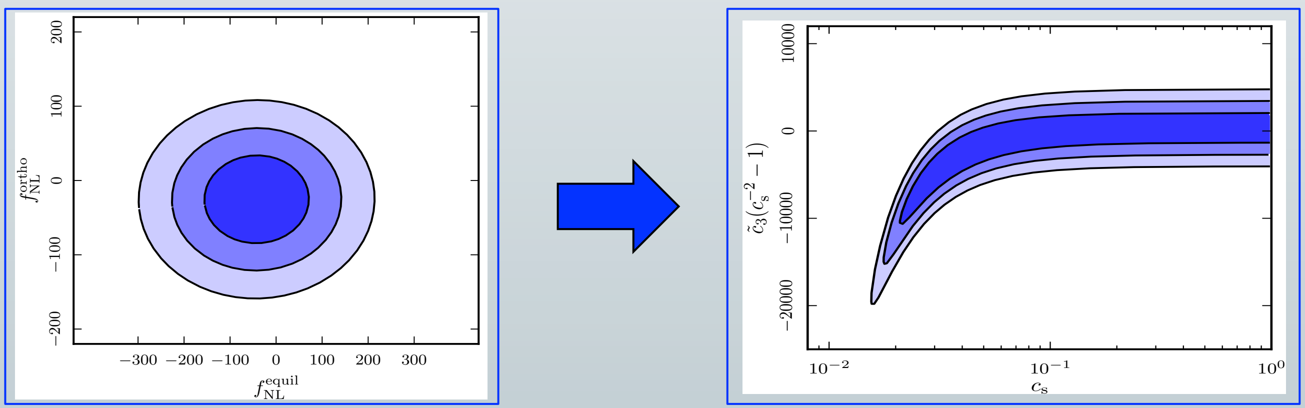
Implications for inflation (examples)

- 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)

Future prospects

What else can be done with the CMB bispectrum?

- ✓ Planck is very close to saturating the theoretical limit on f_{NL} sensitivity, which is achievable using CMB observations (a cosmic-variance-limited T+E full sky survey, up to l~3000, could still improve by a factor ~2)
- ✓ The current level of sensitivity is amazing, but with these error bars we are still unable to directly probe predictions from standard single field models (fnl ~ 10^{-2} !!), or rule out multi-field (e.g. curvaton, $|f_{NL}| > 5/4$)

For the required large improvements in sensitivity, we need other cosmological probes

LSS

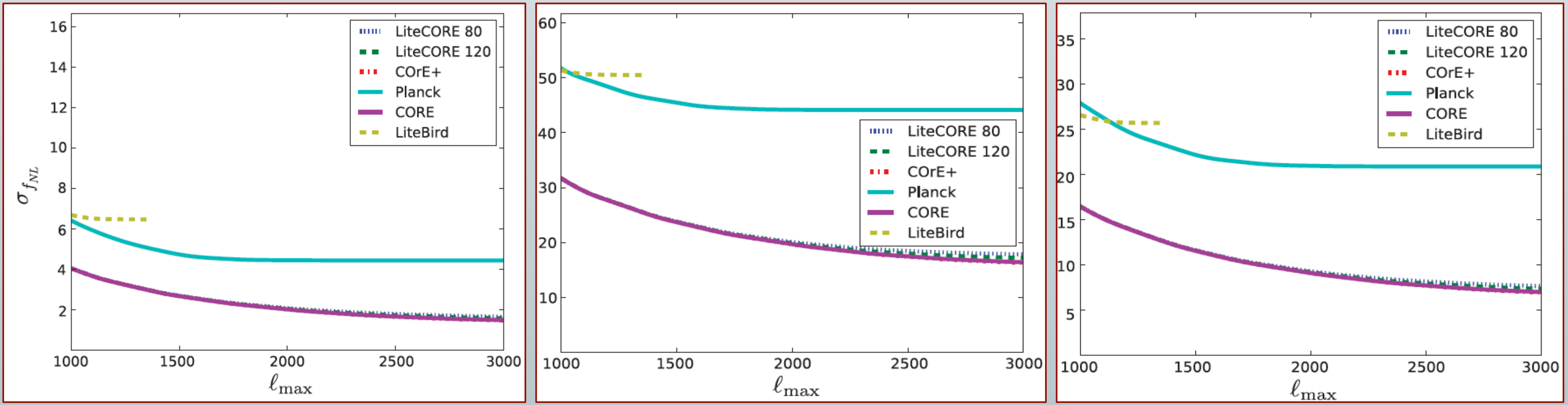
- ✓ Scale dependent halo bias (*local* Δf_{NL} ~ 1 with Euclid). Control of systematics will be crucial. *Both in galaxy surveys and CIB*.
- ✓ Bispectrum of galaxies. Sensitive to *all* shapes. *Needs small scales.* Gravitational bispectrum, bias and other non-linear effects pose a serious challenge.

Other observables (futuristic)

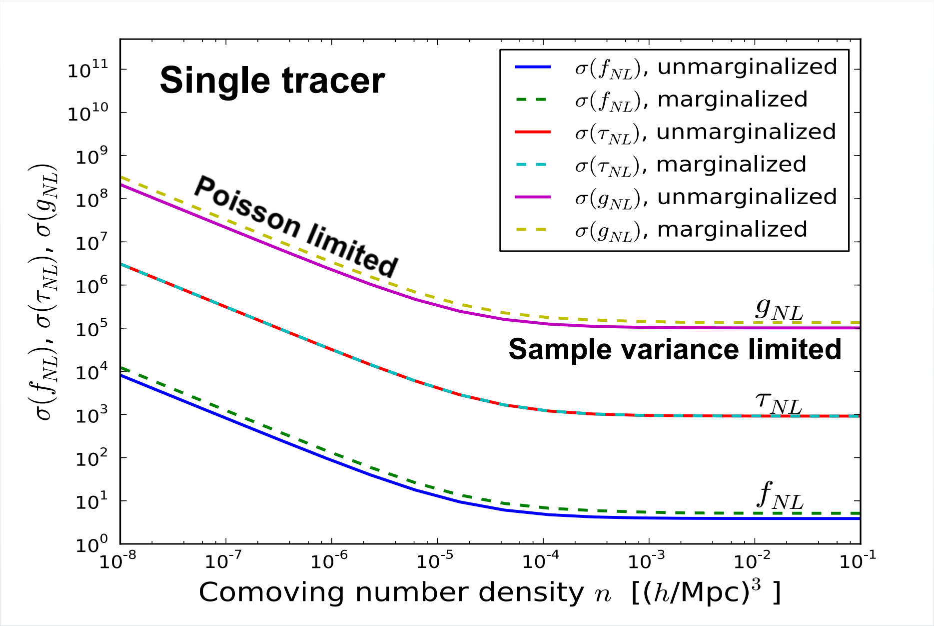
- ✓ CMB (μ-type) spectral distorsions (only squeezed bispectra/trispectra)
- ✓ 21 cm bispectrum

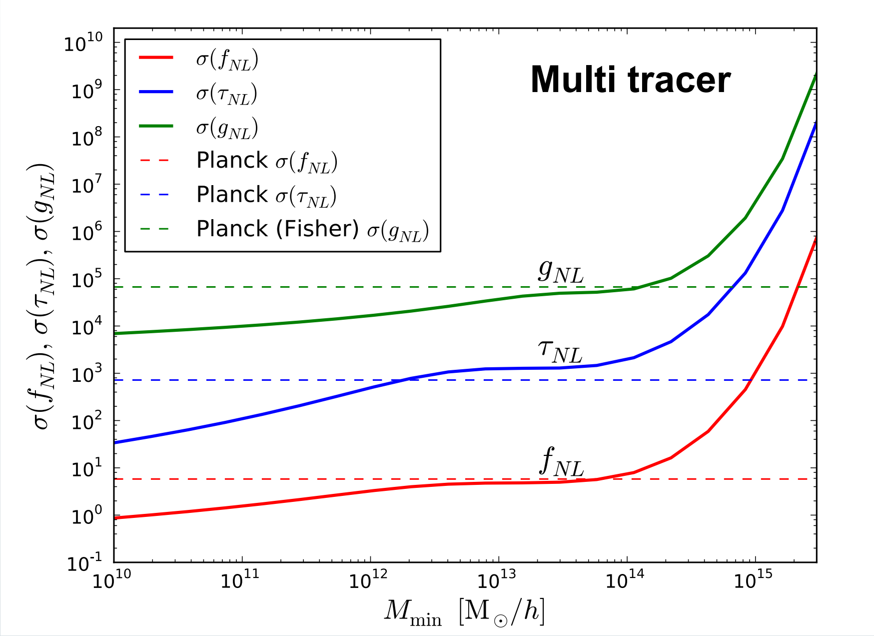
CORE. CMB bispectrum forecasts

	LiteCORE 80	LiteCORE 120	**CORE M5**	COrE+	Planck 2015	LiteBIRD	ideal 3000
T local	4.5	3.7	**3.6**	3.4	(5.7)	9.4	2.7
T equilat	65	59	**58**	56	(70)	92	46
T orthog	31	27	**26**	25	(33)	58	20
T lens-isw	0.15	0.11	**0.10**	0.09	(0.28)	0.44	0.07
E local	5.4	4.5	**4.2**	3.9	(32)	11	2.4
E equilat	51	46	**45**	43	(141)	76	31
E orthog	24	21	**20**	19	(72)	42	13
E lens-isw	0.37	0.29	**0.27**	0.24		1.1	0.14
T+E local	2.7	2.2	**2.1**	1.9	(5.0)	5.6	1.4
T+E equilat	25	22	**21**	20	(43)	40	15
T+E orthog	12	10.0	**9.6**	9.1	(21)	23	6.7
T+E lens-isw	0.062	0.048	**0.045**	0.041		0.18	0.027



NG with LSS. 2-point function





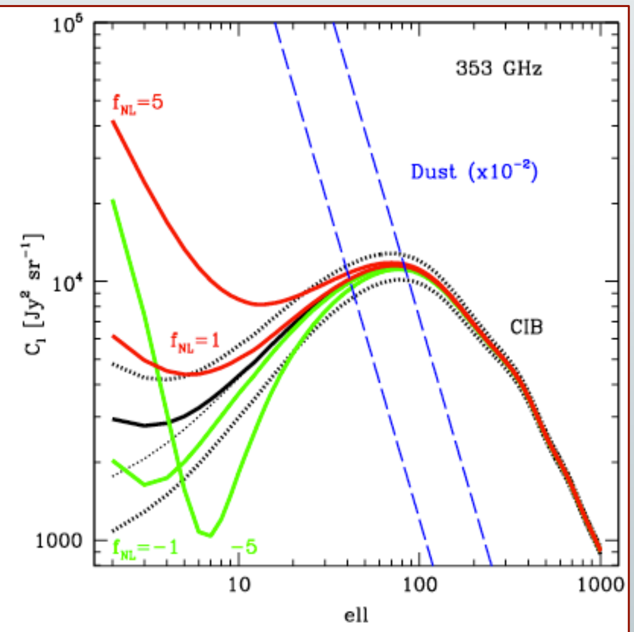
Ferraro and Smith 2014

$$\Delta b(k) = 2(b-1) f_{\rm NL} \delta_c \frac{3\Omega_m}{2a\, g(a) r_H^2 k^2}$$

- Single tracer, V = 25 Gpc^3 h^{-3}, statistical power ~ Planck
- Multi-tracer techniques have the power to reach $\sigma_{f\rm NL}$ ~ 1 (local)
- Significant degeneracies between f_{NL}, g_{NL}, τ_{NL}

CIB power spectrum

- CIB power spectrum is integrated over a large volume. Ideal for scale dependent bias **(Tucci et al. 2016)**
- Seriously contaminated by dust, but future full-sky satellite B-mode experiments with many (high-)frequency channels allow very accurate component separation.



				COrE+					$\sigma(f_{NL})$
ν [GHz]	220	255	295	340	390	450	520	600	
fwhm [arcmin]	3.82	3.29	2.85	2.47	2.15	1.87	1.62	1.40	
w^{-1} [Jy^2 sr^{-1}]	0.654	1.43	5.20	8.31	13.50	22.98	39.88	69.26	
$\Sigma^2_{\rm CIB}$ [Jy^2 sr^{-1}]	–	8.04	–	47.3	–	212.	382.	–	**1.6**
				COrE+ with *Planck*					
$\Sigma^2_{\rm CIB}$ [Jy^2 sr^{-1}]	–	1.97	–	10.8	–	45.6	90.2	163.6	**0.6**
				CORE					$\sigma(f_{NL})$
ν [GHz]	220	255	295	340	390	450	520	600	
fwhm [arcmin]	5.23	4.57	3.99	3.49	3.06	2.65	2.29	1.98	
w^{-1} [Jy^2 sr^{-1}]	0.29	0.57	0.77	1.08	2.16	3.55	6.2	11.0	
$\Sigma^2_{\rm CIB}$ [Jy^2 sr^{-1}]	–	1.8	–	8.8	–	42.9	80.1	–	**0.7**
				CORE with *Planck*					
$\Sigma^2_{\rm CIB}$ [Jy^2 sr^{-1}]	–	1.03	–	5.2	–	23.3	43.9	68.9	**0.34**

(Tucci et al. 2016) **(Finelli et al. 2016)**

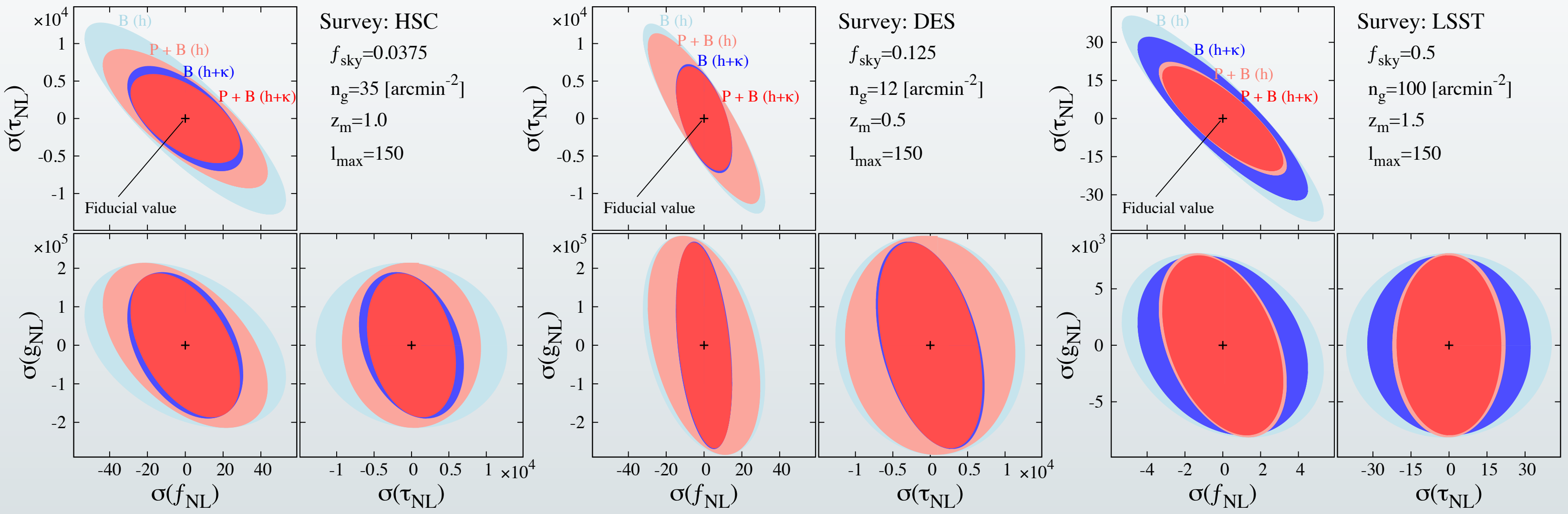
NG with LSS. Bispectrum

Sample	Power Spectrum $\sigma_{f_{\rm NL}}$ bias float	Power Spectrum $\sigma_{f_{\rm NL}}$ bias fixed	Bispectrum $\sigma_{f_{\rm NL}}$ bias float	Bispectrum $\sigma_{f_{\rm NL}}$ bias fixed
BOSS	21.30	13.28	$1.04^{(0.65)}_{(2.47)}$	$0.57^{(0.35)}_{(1.48)}$
eBOSS	14.21	11.12	$1.18^{(0.82)}_{(2.02)}$	$0.70^{(0.48)}_{(1.29)}$
Euclid	6.00	4.71	$0.45^{(0.18)}_{(0.71)}$	$0.32^{(0.12)}_{(0.35)}$
DESI	5.43	4.37	$0.31^{(0.17)}_{(0.48)}$	$0.21^{(0.12)}_{(0.37)}$
BOSS + Euclid	5.64	4.44	$0.39^{(0.17)}_{(0.59)}$	$0.28^{(0.11)}_{(0.34)}$

Tellarini et al. 2016

- Fisher matrix forecast. Tree level bispectrum. Local NG initial conditions. In redshift space. Covariance between different triangles neglected (optimistic).
- Bispectrum could do better than power spectrum.
- f_{NL} ~ 1 achievable with forthcoming surveys?
- Many issues, e.g. full covariance, accurate bias model, GR effects, survey geometry, estimator implementation… Still, great potential: 3D vs 2D (CMB).

Galaxy + Lensing

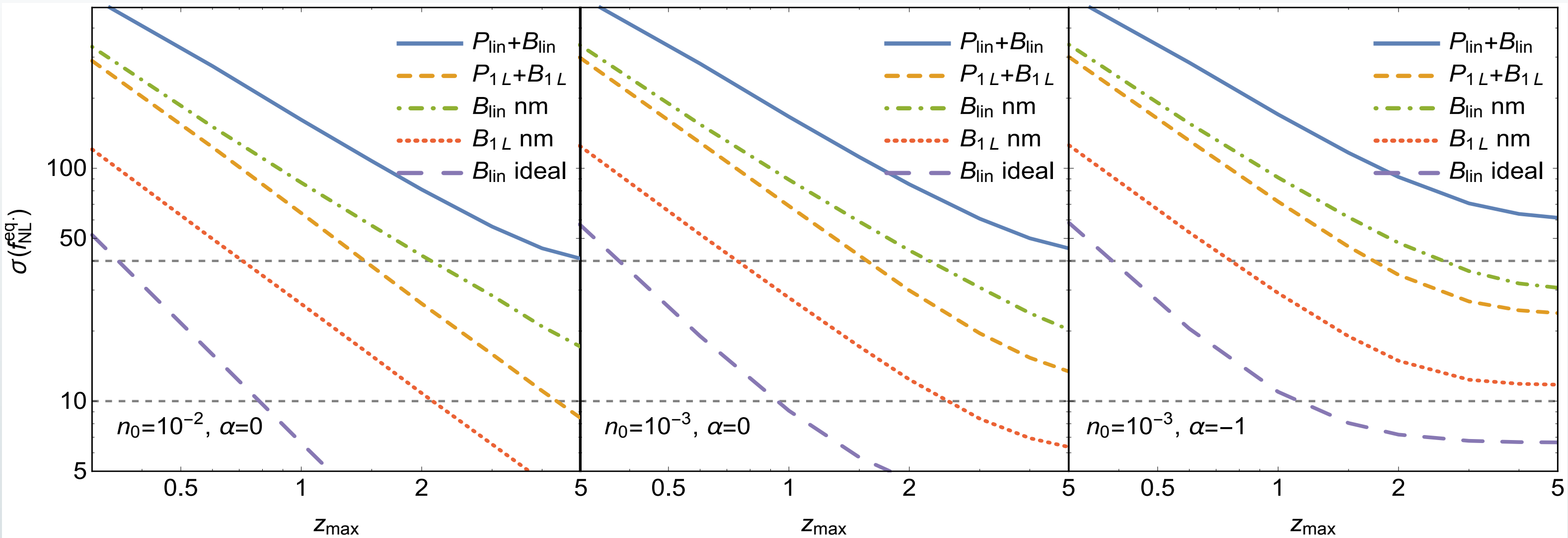


Hashimoto et al. 2016

Combining power spectra and bispectra, clustering and weak lensing, can help to break degeneracies between local NG parameters

	HSC	DES	LSST	current CMB
$\sigma(f_{NL})$	19 (9.2)	9.8 (5.2)	2.1 (0.89)	(5.1)
$\sigma(g_{NL})$	1.2×10^5 (7.1×10^4)	1.8×10^5 (1.0×10^5)	5.3×10^3 (3.8×10^3)	(1.4×10^5)
$\sigma(\tau_{NL})$	3.9×10^3 (2.1×10^3)	4.6×10^3 (2.5×10^3)	14 (6.2)	(1.4×10^3)

Equilateral NG. Theoretical uncertainties



Baldauf et al. 2016

- The LSS bispectrum allows in principle tight constraints also on non-local shapes e.g. equilateral
- Naive mode counting suggest σ_{fNL} ~ 1 for equilateral might be achievable by pushing k_{max} high enough
- However, in the non-linear regime we have to model the gravitational bispectrum with high accuracy. Very challenging. Equilateral is more correlated than local to non-linear gravitational bispectrum, so bigger problem.

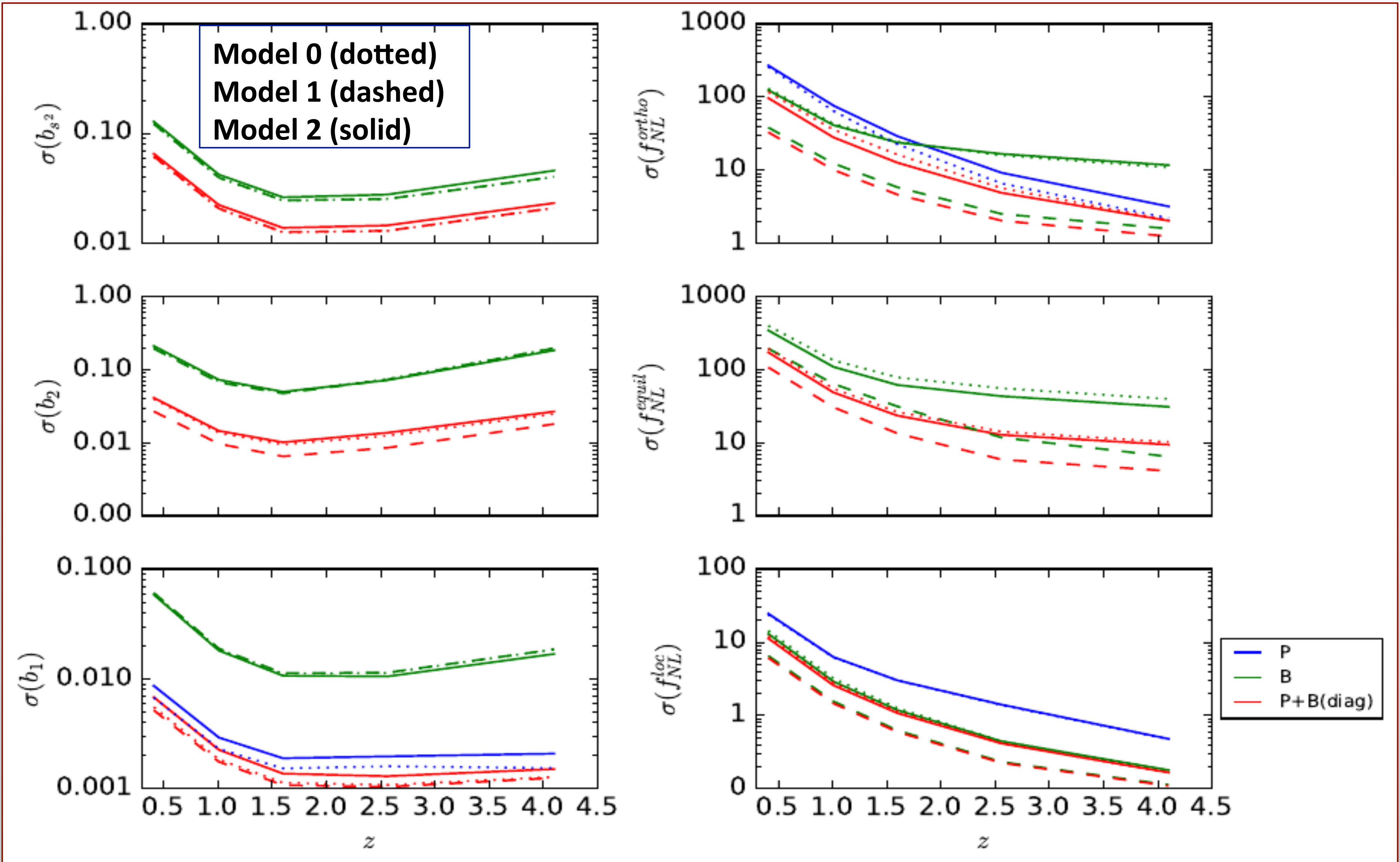
Radio surveys

- Wide radio surveys, reaching high-z can produce very interesting constraints in principle. High-z allows to reach higher k, while remaining in linear regime (but careful to theoretical errors)

Forecasts (D. Karagiannis, ML, A. Raccanelli, N. Bartolo, in prep.):

- Joint power spectrum/bispectrum prediction for local, equilateral,
- orthogonal + bias coefficients
- Use cross-correlation method between radio continuum surveys and
- spectroscopic datasets to derive redshift information on point sources (Schneider et al 2006, Newman et al 2008)
- Effective halo bias expansion up to 2[nd] order (Mirbabayi et al. 2014) parameters b_1, b_2, b_{s2}.
- Bivariate bias expansion for local shape
- $k_{max} = 0.1/D(z)$
- Including trispectrum correction term (NG contrib. to tree-level bispectrum).
- RSD accounted for up to 2[nd] order (excluding trispectrum)
- Neglecting PB covariance
- Theoretical errors not included yet (should worsen forecast by a factor 3-4)
- **Model 0: Real space, no trispectrum. Model 1: Real space + trispectrum. Model 2: Redshift space, no trispectrum**

Forecasts: SKA



Model 0

	SKA ($1\mu Jy$)			ASKAP/EMU ($10\mu Jy$)		
	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$
Power spectrum	0.44	-	2.0	0.94	-	5.43
Bispectrum	0.16	29	8.2	0.42	55.34	16.9
P+B (diagonal)	0.15	7.8	1.9	0.38	17	4.91

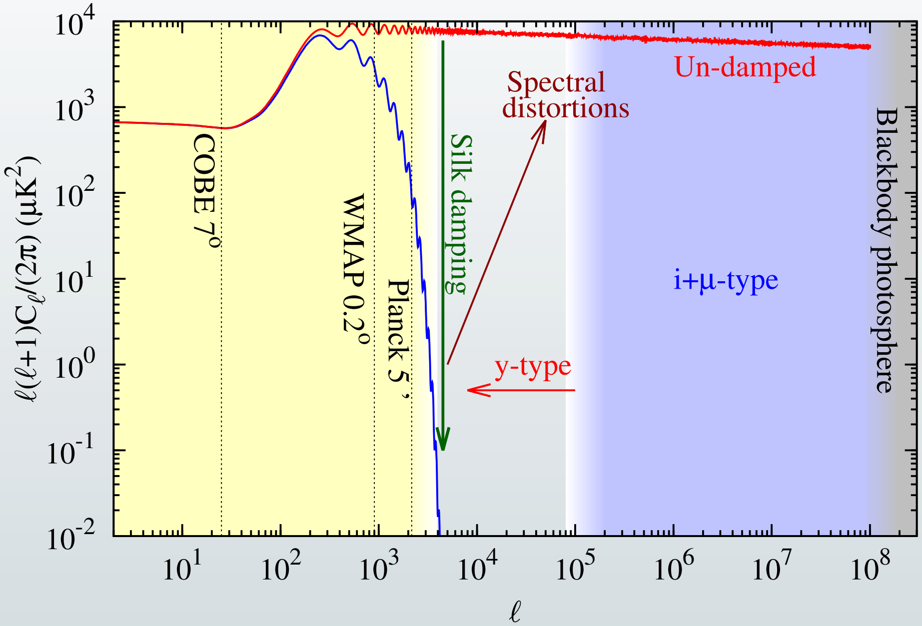
Model 1

	SKA ($1\mu Jy$)			ASKAP/EMU ($10\mu Jy$)		
	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$
Power spectrum	0.44	-	2.0	0.94	-	5.43
Bispectrum	0.1	5.53	1.28	0.22	10.37	2.1
P+B (diagonal)	0.096	3.24	1.0	0.21	5.96	1.78

Model 2

	SKA ($1\mu Jy$)			ASKAP/EMU ($10\mu Jy$)		
	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$
Power spectrum	0.44	-	2.97	0.96	-	7.73
Bispectrum	0.16	22.7	8.62	0.43	46.5	17.3
P+B (diagonal)	0.15	7.12	1.84	0.39	15.5	4.62

NG with CMB spectral distorsions



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

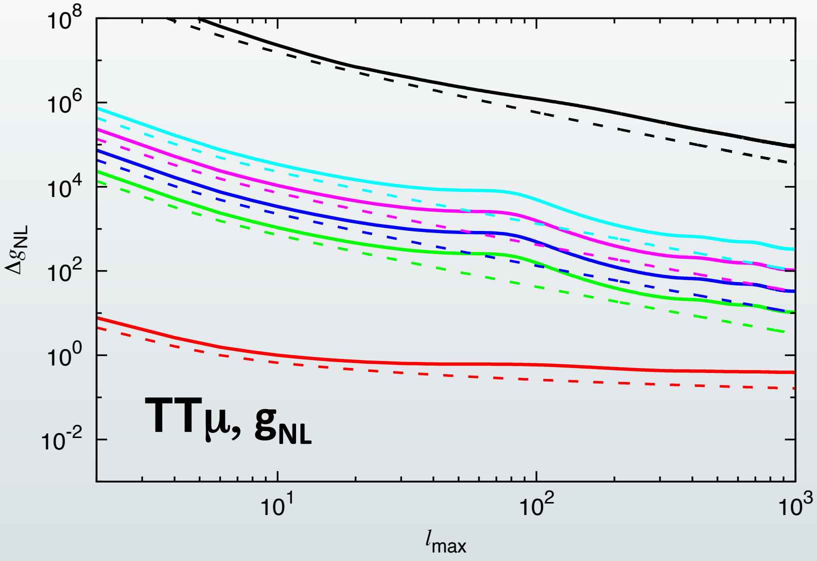
Many additional modes!

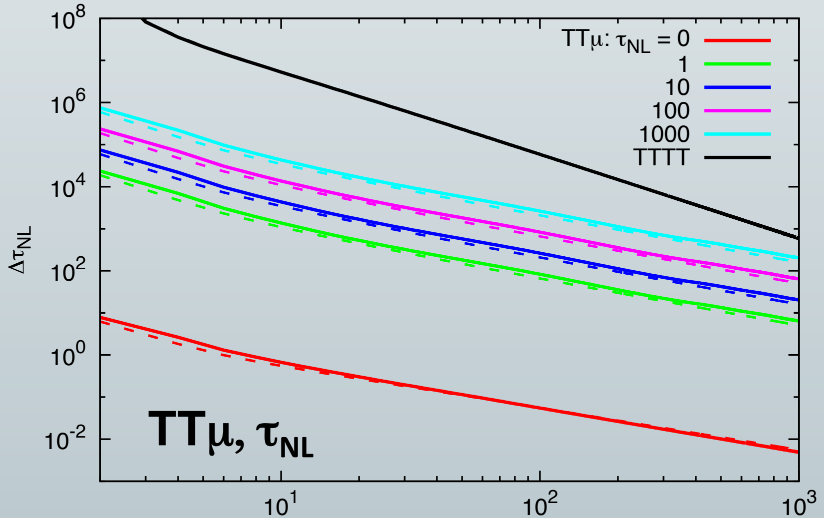
Kathri and Sunyaev 2013, arXiv: 1303.7212

If μ-*anisotropies* are measured ($\delta\mu \sim \Phi^2$):

- ✓ Tμ correlation: primordial local f_{NL} **(Pajer and Zaldarriaga 2013)** or other squeezed shapes, e.g. excited initial states **(Ganc and Komatsu 2013)**
- ✓ μμ correlation: primordial local trispectrum, τ_{NL}
- ✓ TTμ bispectrum: primordial local trispectrum, g_{NL} **(Bartolo, ML, Shiraishi 2016)**

NG with CMB spectral distorsions





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, Emami et al. 2015**)

$$\Phi = \Phi_G + \Phi_{NG} = \Phi_G + f_{NL}\Phi_G^2,$$

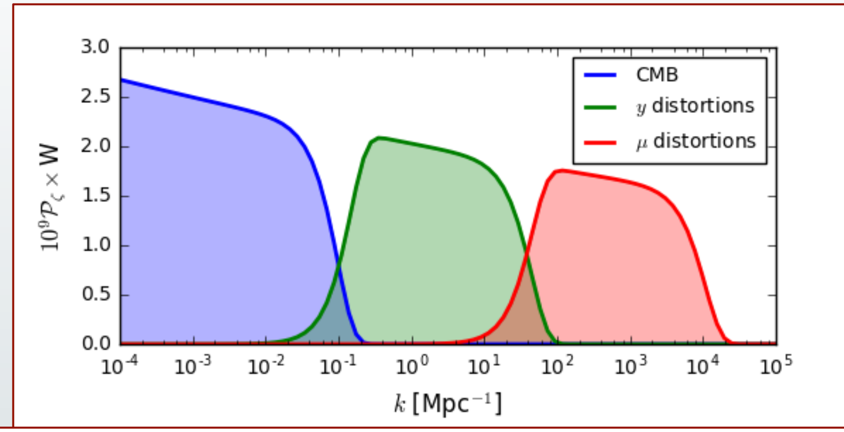
$$\Phi_G = \Phi_S + \Phi_L \Rightarrow \Phi_{NG} = \Phi_S^2 + \Phi_L^2 + 2 f_{NL}\Phi_S\Phi_L$$

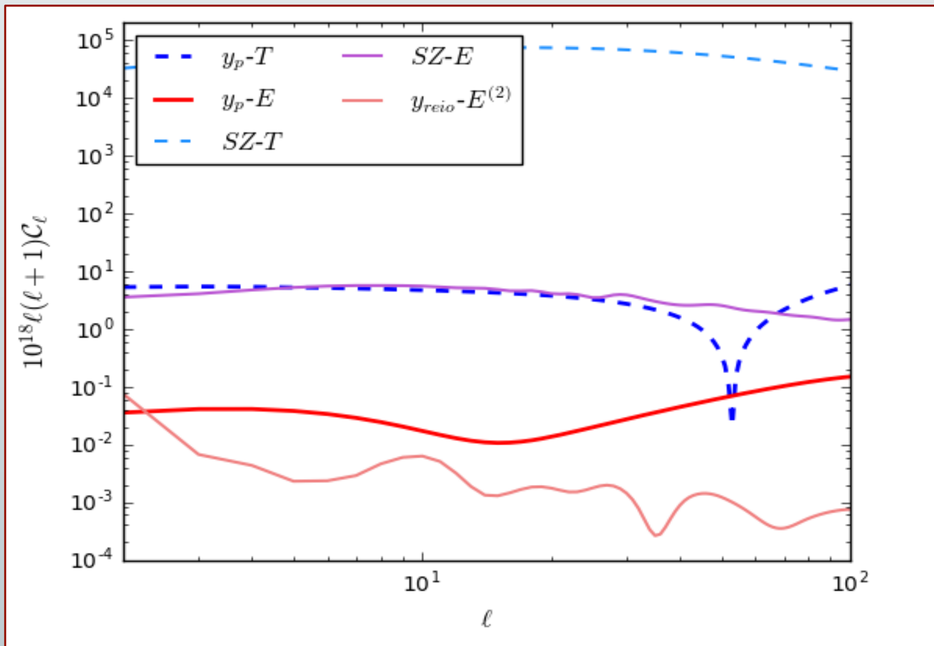
$$\Phi \propto \Phi_S\left(1 + 2f\Phi_L\right) \Rightarrow \frac{\delta\left\langle\Phi^2\right\rangle}{\Phi^2} = \frac{\delta\mu}{\mu} \sim 4 f_{NL}\Phi_L$$

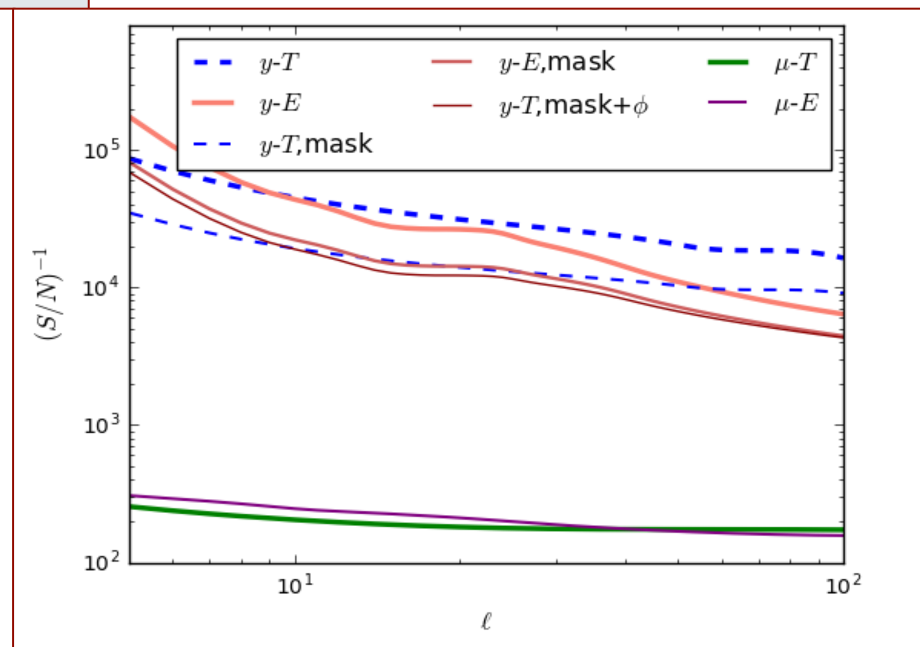
$$\Rightarrow \left\langle \left.\frac{\delta T}{T}\right|_L \frac{\delta\mu}{\mu}\right\rangle \propto f_{NL}C_\ell$$

Scale dependent NG with μ and y

- T, μ and y-dist. probe different scales. Can be used to test NG scale dependence. **(Biagetti et al. 2013, Emami et al. 2015**)
- yT is strongly contaminated by SZ. Can improve by correlating with polarization **(Ravenni et al. 2017 in prep.)**





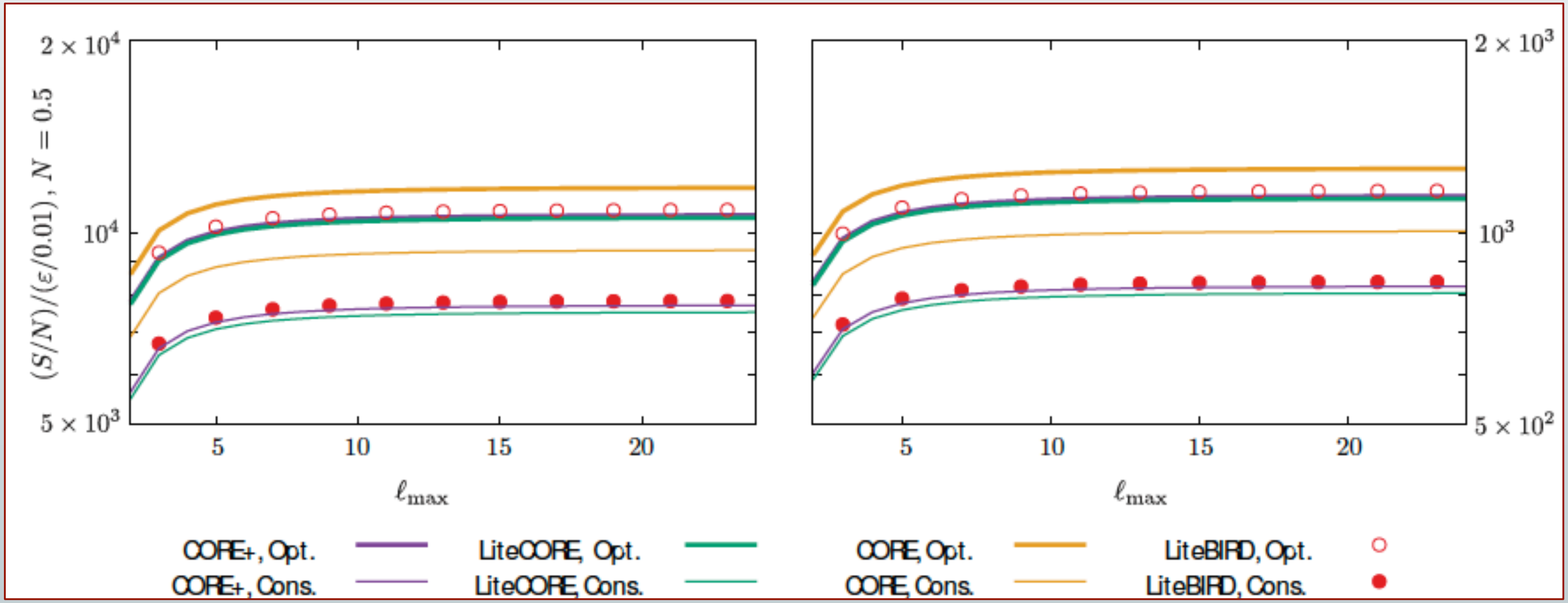


A. Ravenni, ML, N. Bartolo, M. Shiraishi in prep.

$$f_{NL}^{\mu}(\mu T) \gtrsim 175 \rightarrow f_{NL}^{\mu}(\mu T, E) \gtrsim 126 \qquad f_{NL}^{y}(yT) \gtrsim 10^4 \rightarrow f_{NL}^{y}(yT, E) > 4300$$

Excited initial states

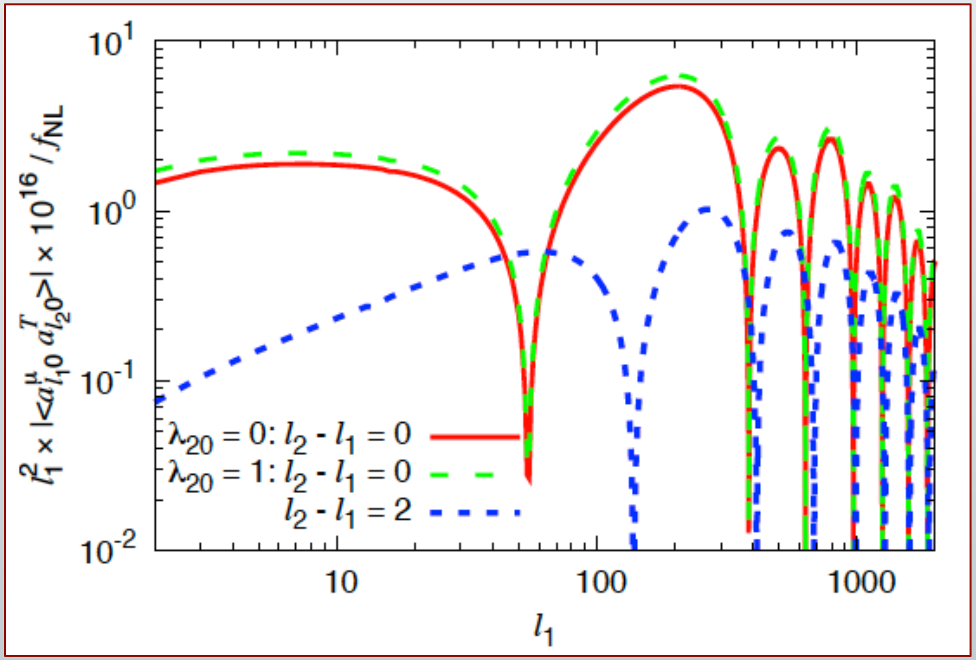
- Specific models with excited initial states predict enhanced signals in the squeezed limit (Agullo and Parker 2011).
- This can generate high S/N in μT tests (Ganc and Komatsu 2012)

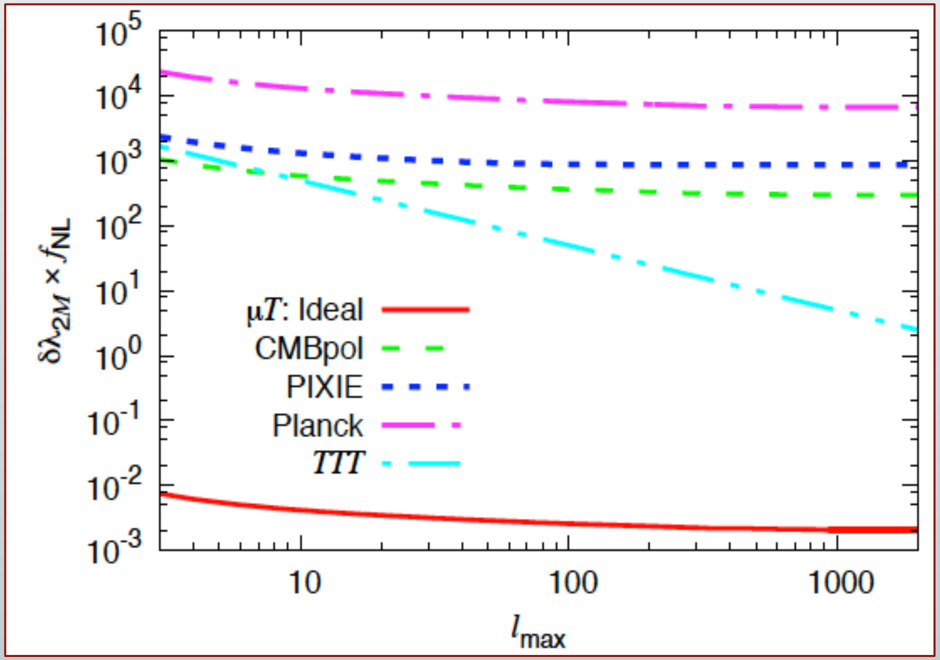


Finelli et al. 2016

Anisotropic models

- The $\mu\mu$ auto-spectrum measures τ_{NL} type trispectra i.e. power spectrum modulation signals
- Anisotropic models produce distinctive off-diagonal entries in the $\mu\mu$ covariance



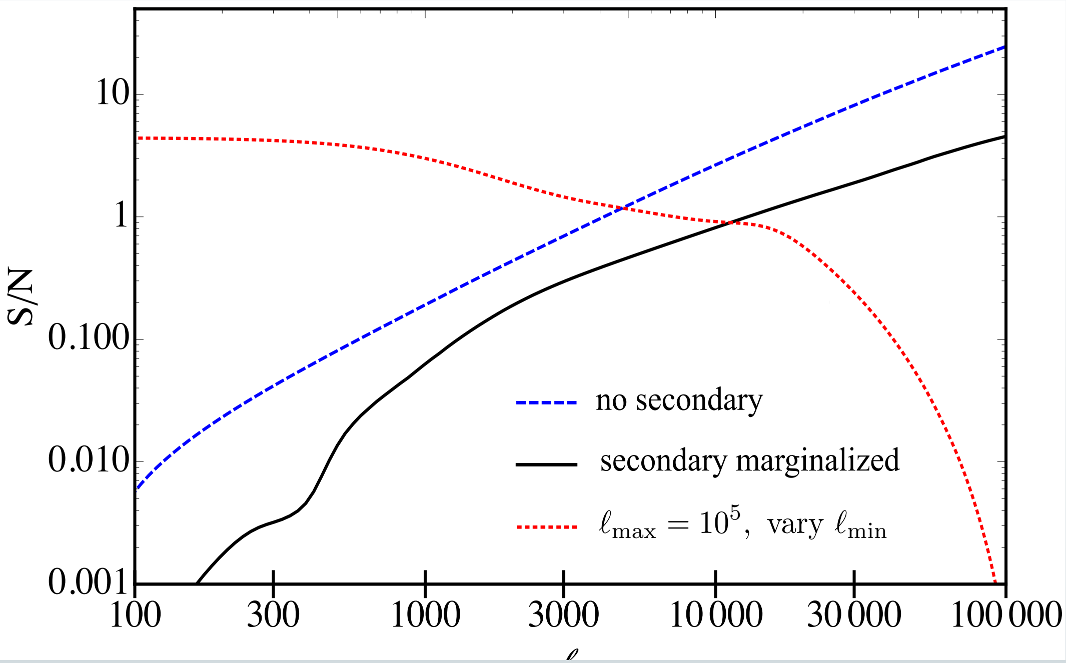


Shiraishi, ML, N. Bartolo 2015

21cm bispectrum

PNG type	$\sigma_{f_{\rm NL}}$ (1 MHz)	$\sigma_{f_{\rm NL}}$ (0.1 MHz)
Local	0.12	0.03
Equilateral	0.39	0.04
Orthogonal	0.29	0.03
$J = 1$	1.1	0.1
$J = 2$	0.33	0.05
$J = 3$	0.85	0.09

Munoz, Haimoud and Kamionkowski, 2015



- 21cm full-sky measurments reach very high l_{max} => many modes and high S/N, even after marginalization of secondary effects + redshift tomography.

Conclusions

- Primordial NG probes interaction terms in the Inflationary action Therefore it is a powerful test to discriminate between different scenarios

- *Planck* NG results are consistent with predictions by the simplest inflationary models. However, we need more sensitivity to reach critical fNL thresholds. Local fNL=1 is the next goal

- CMB anisotropies have nearly saturated ideal limit

- Next: scale-dependent halo bias and LSS bispectrum. 3-point function very challenging but sensitive to all shapes

- CIB can be a very powerful local fNL probe, via large-scale power spectrum

- Very powerful but futuristic: spectral distortions, 21 cm

- Specific shapes are already interesting with spectral distortions.

- Multiple approaches to local shape. Only bispectrum for the rest.

NG forecasts: future radio surveys

- We consider a SKA and ASKAP/EMU like surveys.
- Use cross-correlation method between radio continuum surveys and spectroscopic datasets to derive redshift information of point sources (Schneider et al 2006, Newman et al 2008).

ASKAP/EMU ($10\mu Jy$)			SKA ($1\mu Jy$)		
z	V	n	z	V	n
0.86	12.41	2.61	0.41	4.26	2.18
1.45	28.63	2.11	1.01	18.4	6.01
2.3	32.41	1.32	1.6	32.06	9.56
3.46	50.33	0.45	2.56	48.56	4.76
5.48	55.55	0.059	4.1	167.42	1.23

Table 2. The basic numbers for the two surveys considered here per redshift bin. The shell volume is in units of $(\mathrm{Gpc/h})^3$ and the mean number density in $10^{-4}(\mathrm{h/Mpc})^3$.

Bias

Effective halo bias expansion up to second order (N=2), of the form (Mirbabayi et al 2014)

$$\delta_h^L(\mathbf{q}) = \sum_{n=1}^{N} \frac{b_n^L}{n!}[\delta_R^{(1)}(\mathbf{q})]^n + \sum_{n=2}^{N} \frac{b_{sn}^L}{n!}\mathrm{Tr}[s_1^n(\mathbf{q})]$$

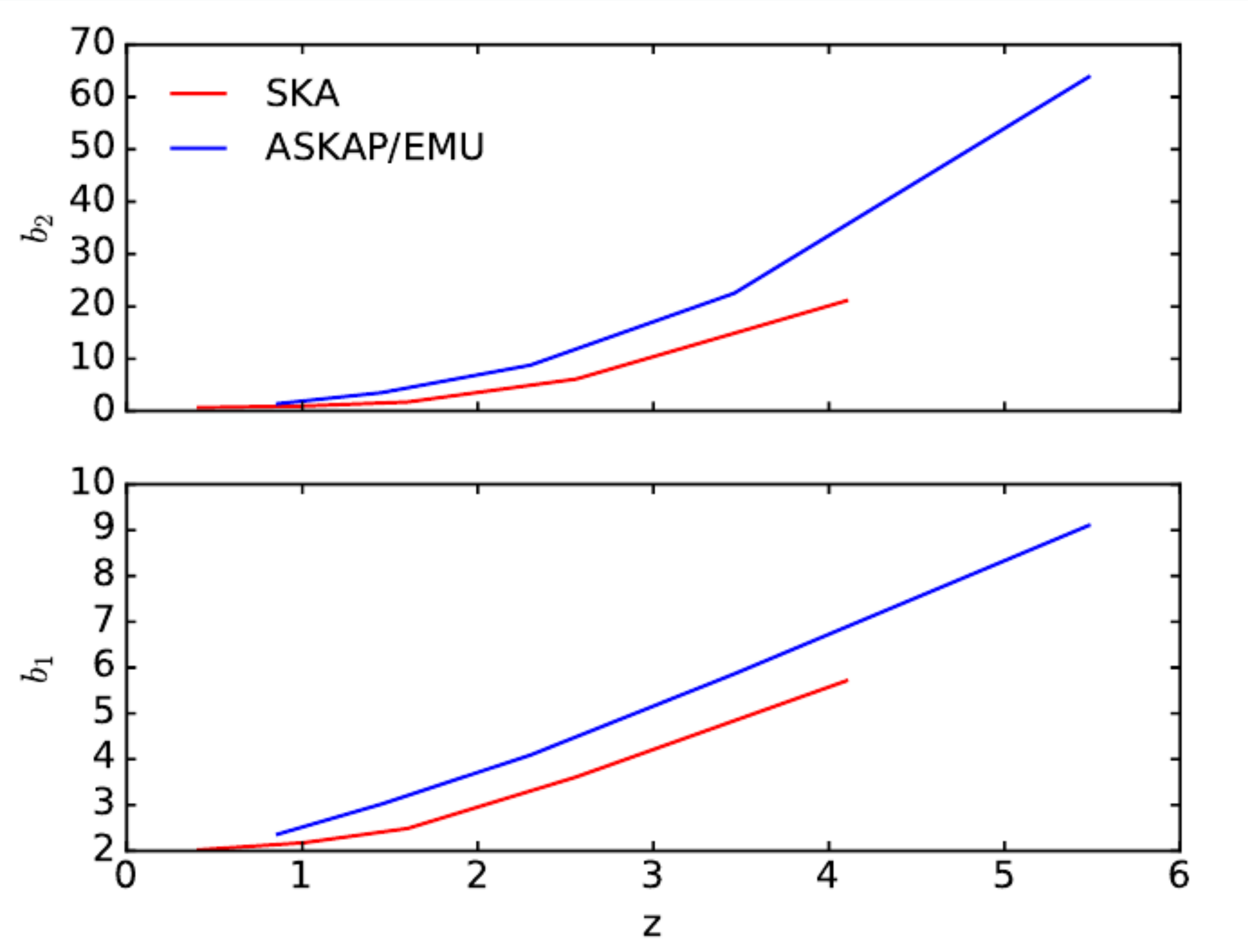
Stay in large-intermediate scales, hence we exclude stohastic bias.

λSecond part of the expansion are the tidal field terms. For n=2 the tidal term bias is a simple function of linear bias.

Use a weighted average with respect to a simple HOD to derive galaxy bias from the PBS halo model.

$$\langle N(M)\rangle = \begin{cases} 1 + \dfrac{M}{M_1}\exp\left(-\dfrac{M_{cut}}{M}\right), & \text{if } M \geqslant M_{min} \\ 0, & \text{otherwise,} \end{cases}$$

Bias



Model

We use the fisher matrix formalism to derive prediction on assumed free parameters from the two and three point statistics.
In fourier space power spectrum and bispectrum of the galaxies is:

$$P_g(k,z) = (b_1 + \delta b_1(f_{NL}) + \Delta b_1(k, f_{NL}))^2 P_m^L(k,z)$$

$$\begin{aligned}
B_g(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) &= b_1^3 (B_G(k_1,k_2,k_3,z) + B_I(k_1,k_2,k_3,z)) \\
&+ \frac{b_1^2 b_2}{2}\Bigg(2(P_m^L(k_1,z)P_m^L(k_2,z) + 2\mathrm{perm}) \\
&+ \left(\int \frac{d^3q}{(2\pi)^3} T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{q}, \mathbf{k}_3 - \mathbf{q}) + 2\mathrm{perm} \right) \Bigg) \\
&+ b_{s^2} b_1^2 \Bigg(2(S_2(\mathbf{k}_1, \mathbf{k}_2) P_m^L(k_1,z) P_m^L(k_2,z) + 2\mathrm{perm}) \\
&+ \left(\int \frac{d^3q}{(2\pi)^3} S_2(\mathbf{q}, \mathbf{k}_3 - \mathbf{q}) T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{q}, \mathbf{k}_3 - \mathbf{q}) + 2\mathrm{perm} \right) \Bigg)
\end{aligned}$$

For the trispectrum term in bispectrum we consider only the non-Gaussian contribution to the tree level trispectrum.

We exclude primordial trispectrum since $O(f_{NL}^2)$.

For the local PNG we consider a bivariate bias expansion (Giannantonio et al 2009) .

Finally we test the effect of RSD up to second order in the predicted variables, excluding trispectrum contributions from the bispectrum.

The Fisher matrix for the two correlators will be:

$$F^P_{\alpha\beta} = \sum_{k=k_f}^{k_{\max}} \frac{\partial P_g(k)}{\partial p_\alpha} \frac{\partial P_g(k)}{\partial p_\beta} \frac{1}{\Delta P^2}$$

$$F^B_{\alpha\beta} = \sum_{k_1 \le k_2 \le k_3 = k_f}^{k_{\max}} \frac{\partial B_g(k_1,k_2,k_3)}{\partial p_\alpha} \frac{\partial B_g(k_1,k_2,k_3)}{\partial p_\beta} \frac{1}{\Delta B^2}$$

Fisher matrix predictions

- We consider as free parameters p={f_{NL},b_1,b_2,b_s} and for the RSD model p={f_{NL},b_1,b_2,b_s,σ_P,f}.
- k_{max}=0.1/D(z), k_{min}=k_f
- For the powerspecttrum bispectrum joint predictions we neglect off-diagonal terms in the covariance,
- We neglect for now theoretical errors, although they can increase the errors 3-4 times.

$$F^{P+B}_{\alpha\beta} = F^{P}_{\alpha\beta} + F^{B}_{\alpha\beta}$$

- 3 models for the galaxy bispectrum are used for the prediction.

1)Model 0: Redshift space bispectrum (monopole only) excluding trispectrum loop correction.
2)Model 1: Redshift space bispectrum (monopole only) including trispectrum correction.
3)Model 2: Redshift space bispectrum (RSD 2^{nd} order), without including trispectrum.

Fisher matrix predictions

Model 0

	SKA ($1\mu Jy$)			ASKAP/EMU ($10\mu Jy$)		
	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$
Power spectrum	0.44	-	2.0	0.94	-	5.43
Bispectrum	0.16	29	8.2	0.42	55.34	16.9
P+B (diagonal)	0.15	7.8	1.9	0.38	17	4.91

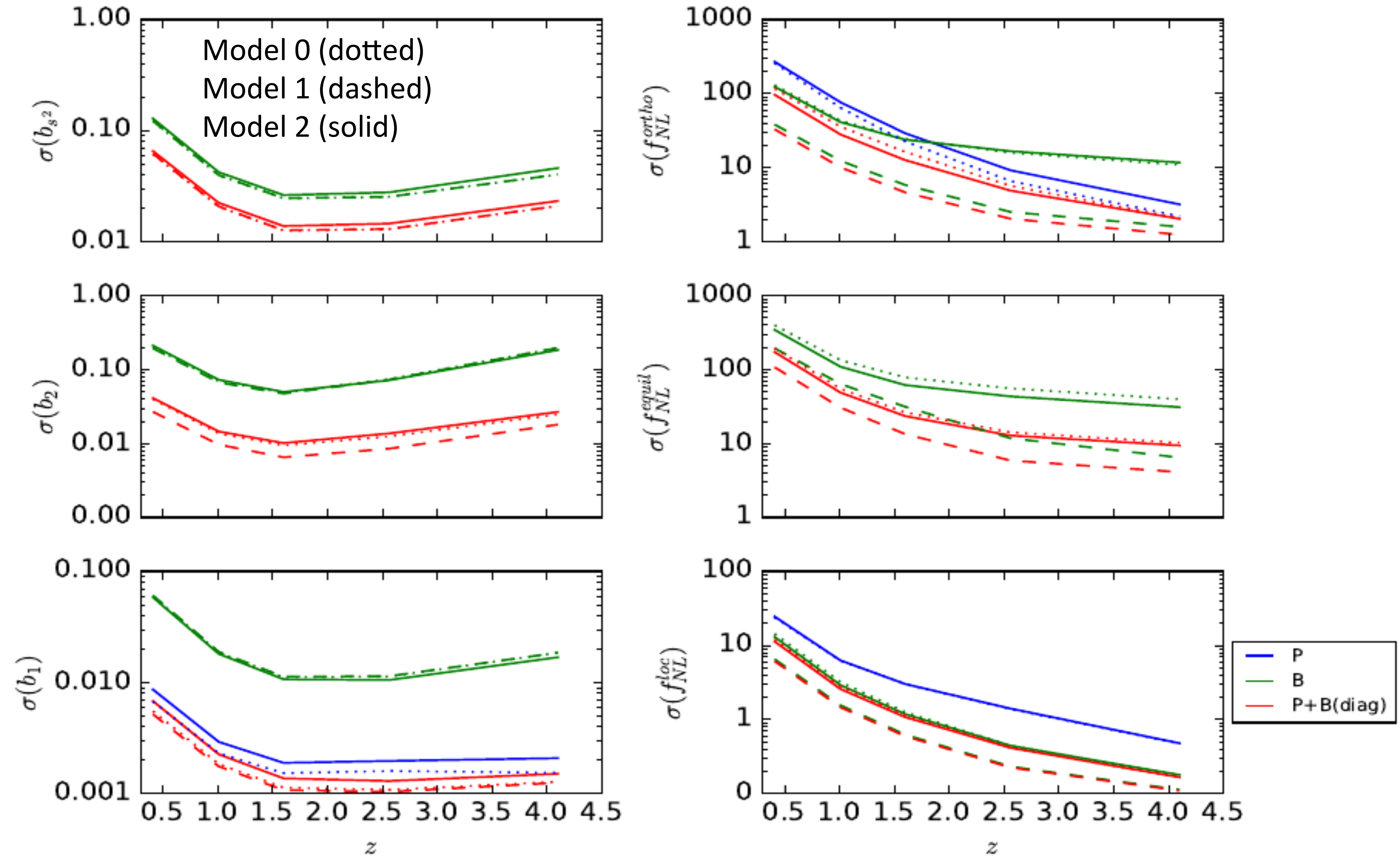
Model 1

	SKA ($1\mu Jy$)			ASKAP/EMU ($10\mu Jy$)		
	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$
Power spectrum	0.44	-	2.0	0.94	-	5.43
Bispectrum	0.1	5.53	1.28	0.22	10.37	2.1
P+B (diagonal)	0.096	3.24	1.0	0.21	5.96	1.78

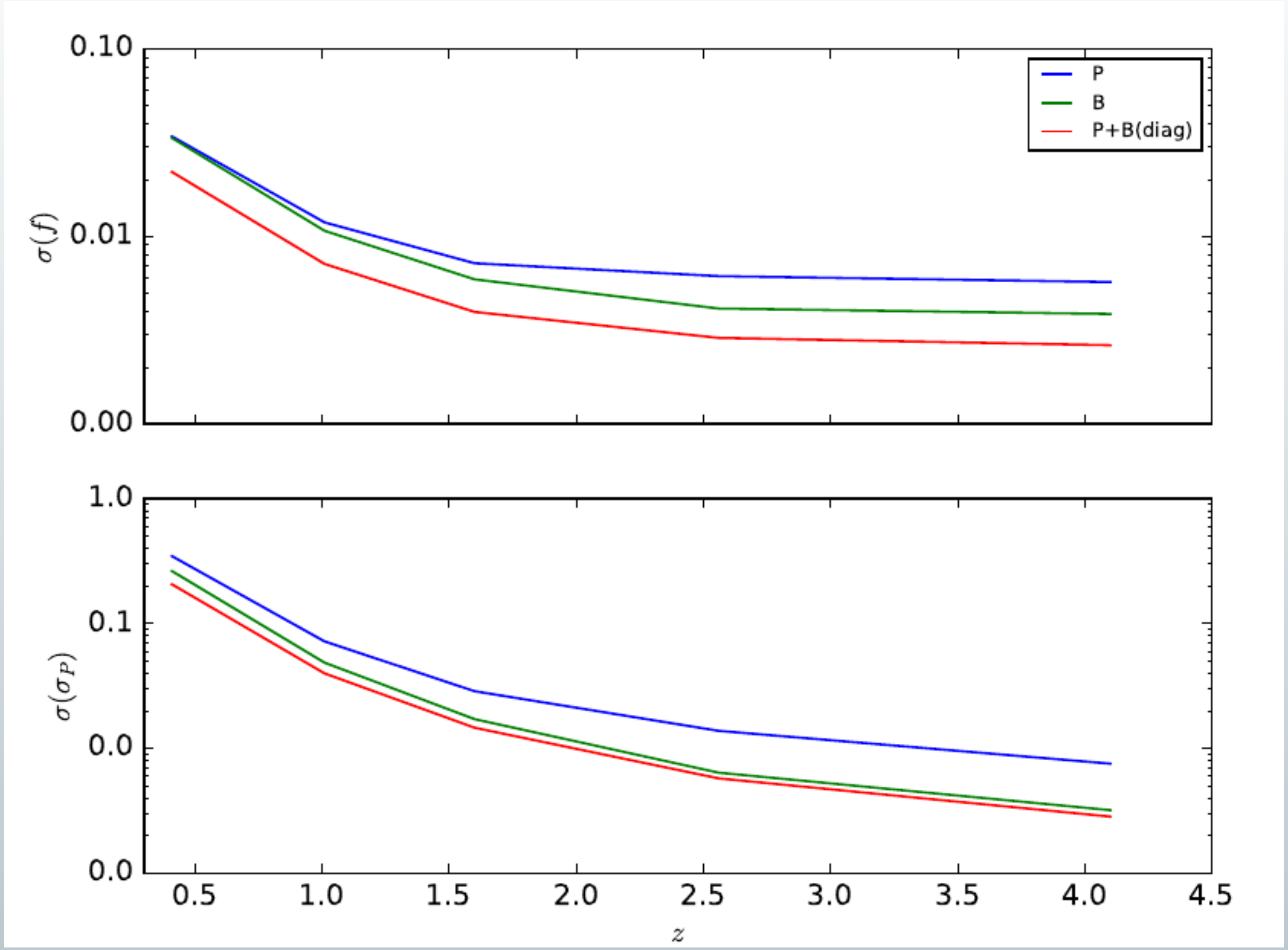
Model 2

	SKA ($1\mu Jy$)			ASKAP/EMU ($10\mu Jy$)		
	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$	$\sigma(f_{NL}^{loc})$	$\sigma(f_{NL}^{equil})$	$\sigma(f_{NL}^{orth})$
Power spectrum	0.44	-	2.97	0.96	-	7.73
Bispectrum	0.16	22.7	8.62	0.43	46.5	17.3
P+B (diagonal)	0.15	7.12	1.84	0.39	15.5	4.62

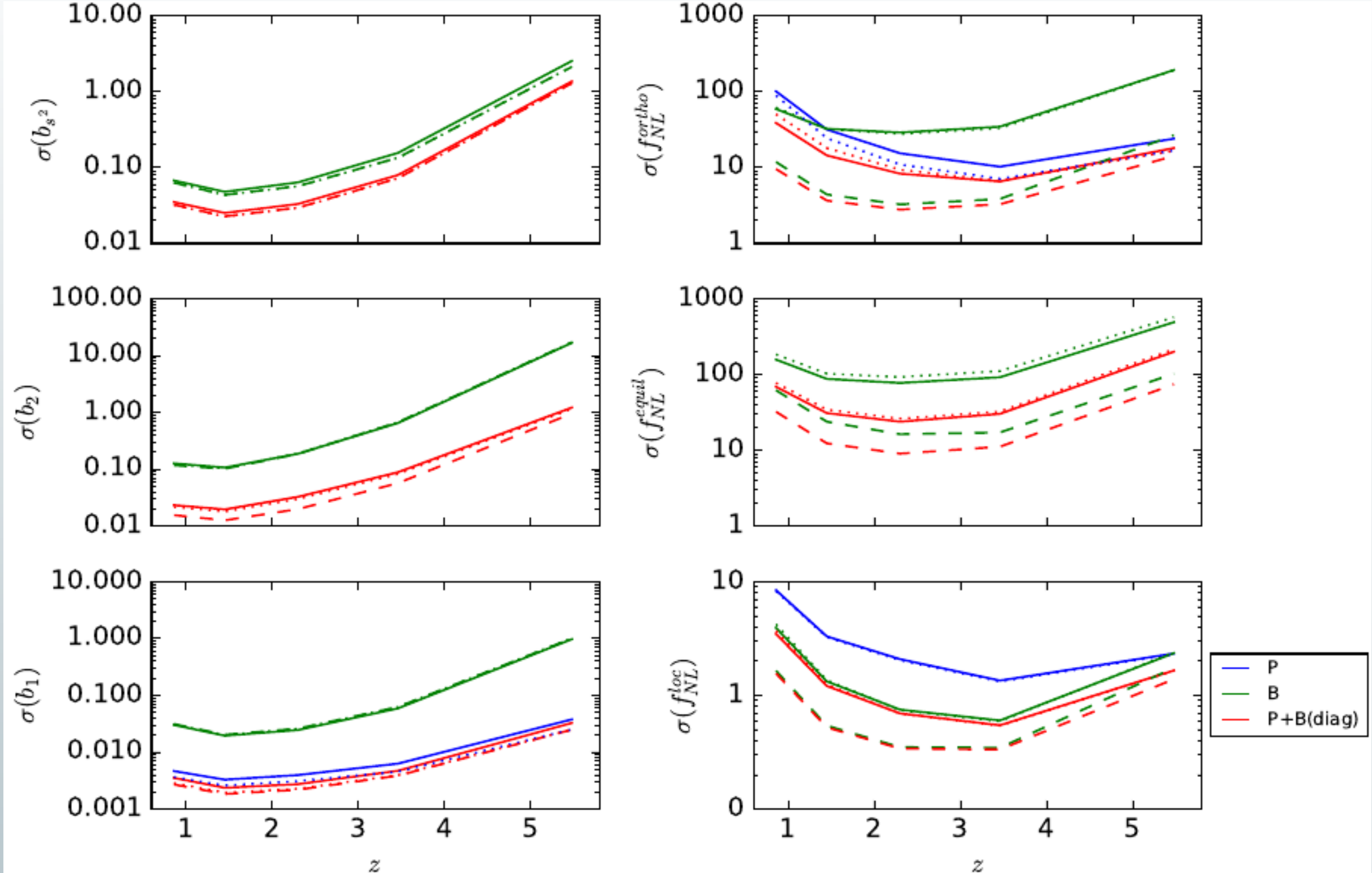
Predictions for SKA



Predictions for SKA



Predictions for ASKAP/EMU



Predictions for ASKAP/EMU