Primordial Non-Gaussianity and Galaxy Clusters

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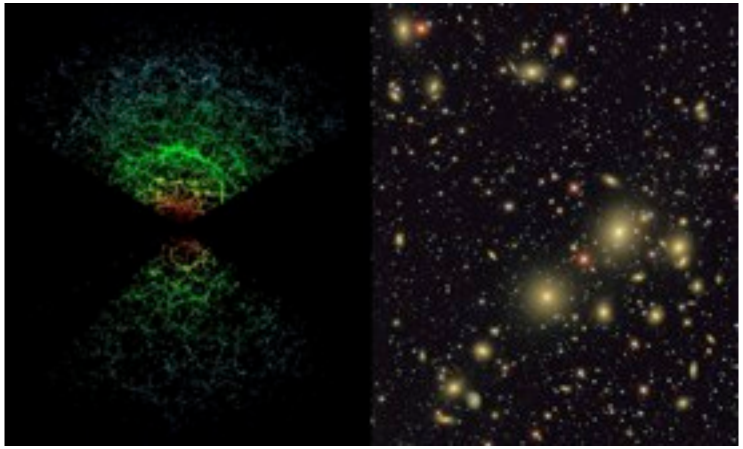
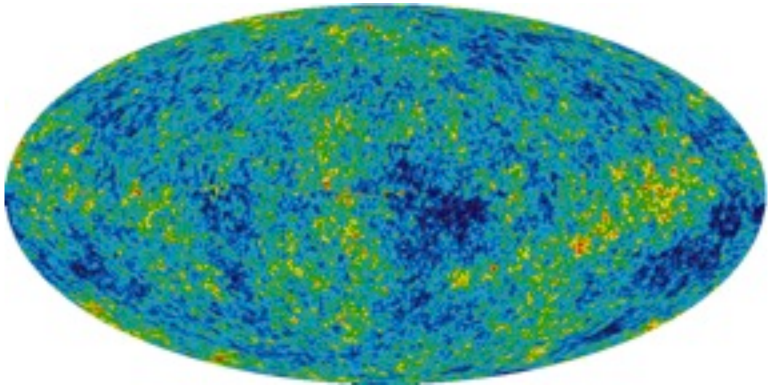
Why study non-Gaussianity (NG)?

1. NG presents a window to the very early universe ($t \sim 10^{-35}$ seconds after Big Bang). For example, NG can distinguish between physically distinct models of inflation.

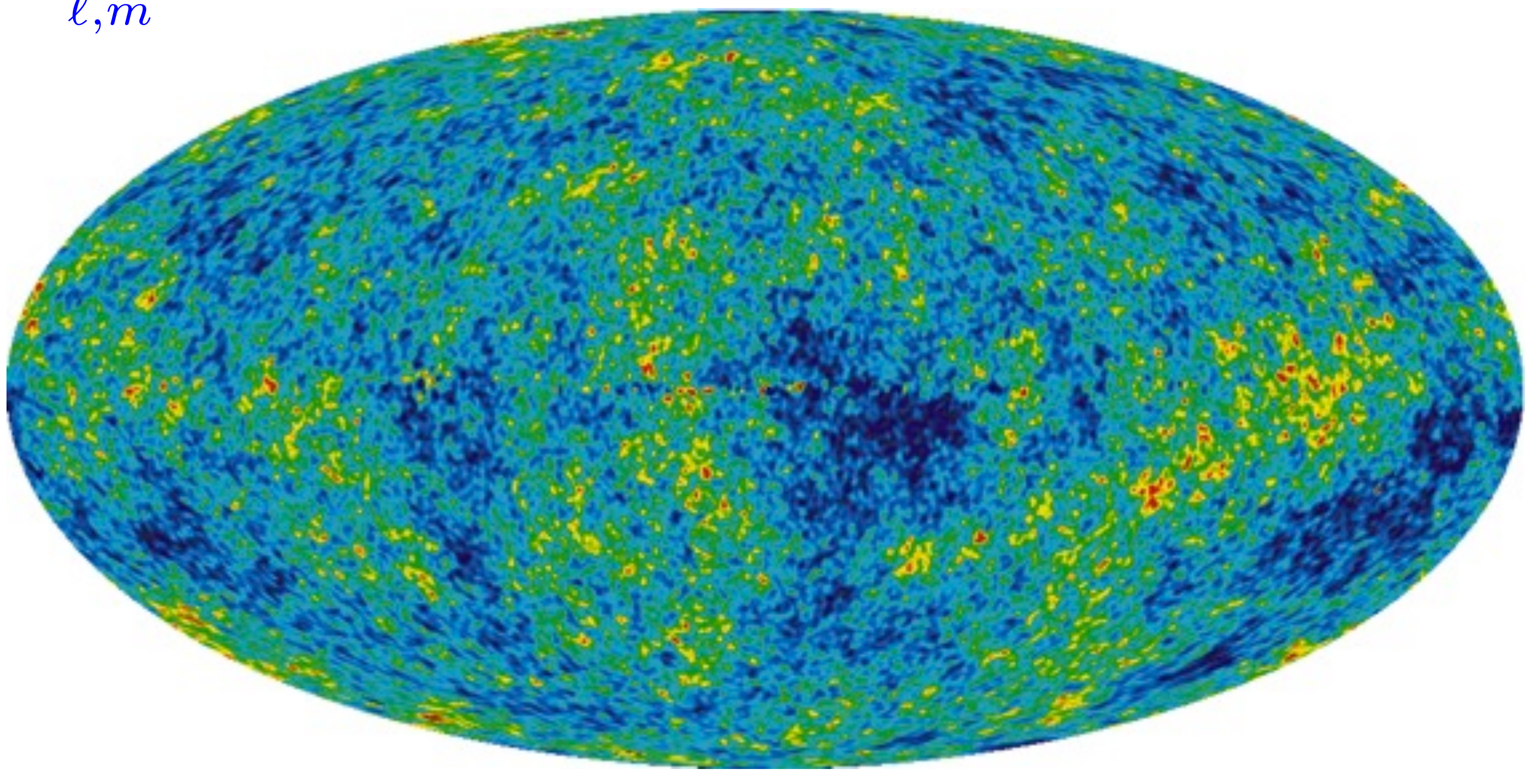
2. Conveniently, NG can be constrained/measured using CMB anisotropy maps and LSS. In particular, there is a rich set of observable quantities that are sensitive to primordial NG.





Initial conditions in the universe

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\phi) \qquad \ell \simeq \frac{180^\circ}{\theta}$$



Generic inflationary predictions:

- Nearly scale-invariant spectrum of density perturbations
- Background of gravity waves
- (Very nearly) gaussian initial conditions:

Statistical Isotropy:

$$\langle a_{\ell m}\, a_{\ell' m'} \rangle \equiv C_{\ell \ell' m m'} = C_\ell \delta_{\ell \ell'} \delta_{m m'}$$

Gaussianity:

$$\langle a_{\ell m}\, a_{\ell' m'}\, a_{\ell'' m''} \rangle = 0$$

Standard Inflation, with...

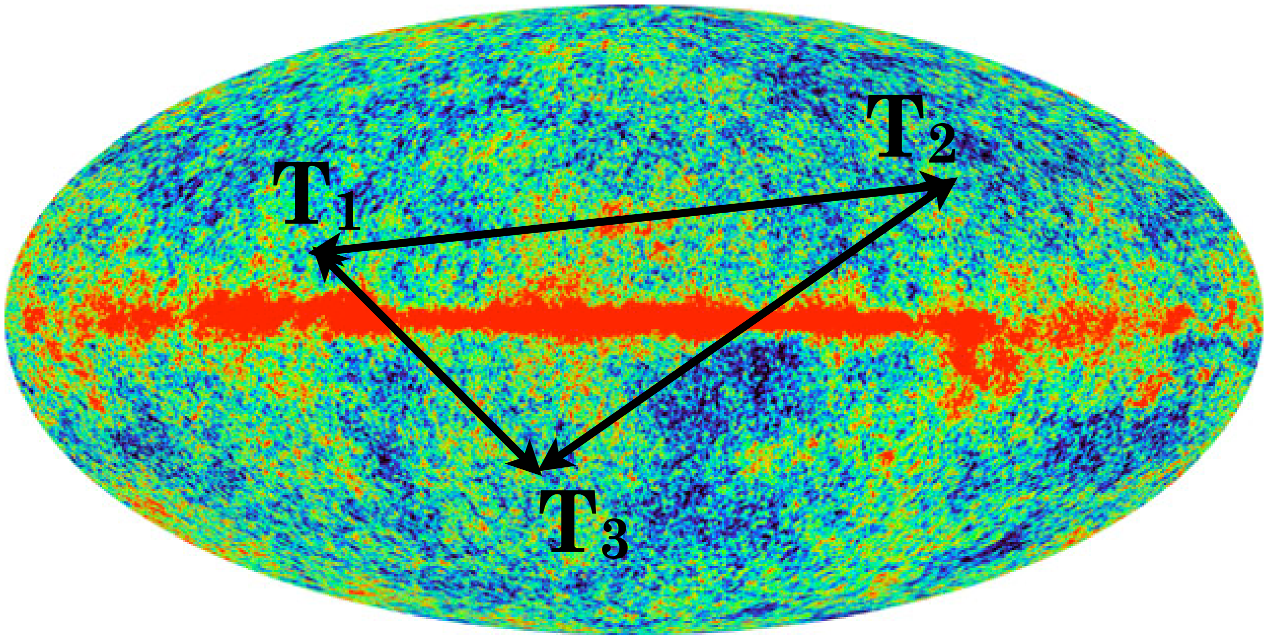
1. a single scalar field
2. the canonical kinetic term
3. always slow rolls
4. in Bunch-Davies vacuum
5. in Einstein gravity

produces **unobservable** NG

Therefore, measurement of nonzero NG would point to a **violation** of one of the assumptions above

e.g. X. Chen, Adv. Astronomy, 2010; Komatsu et al, arXiv:0902.4759

NG from 3-point correlation function



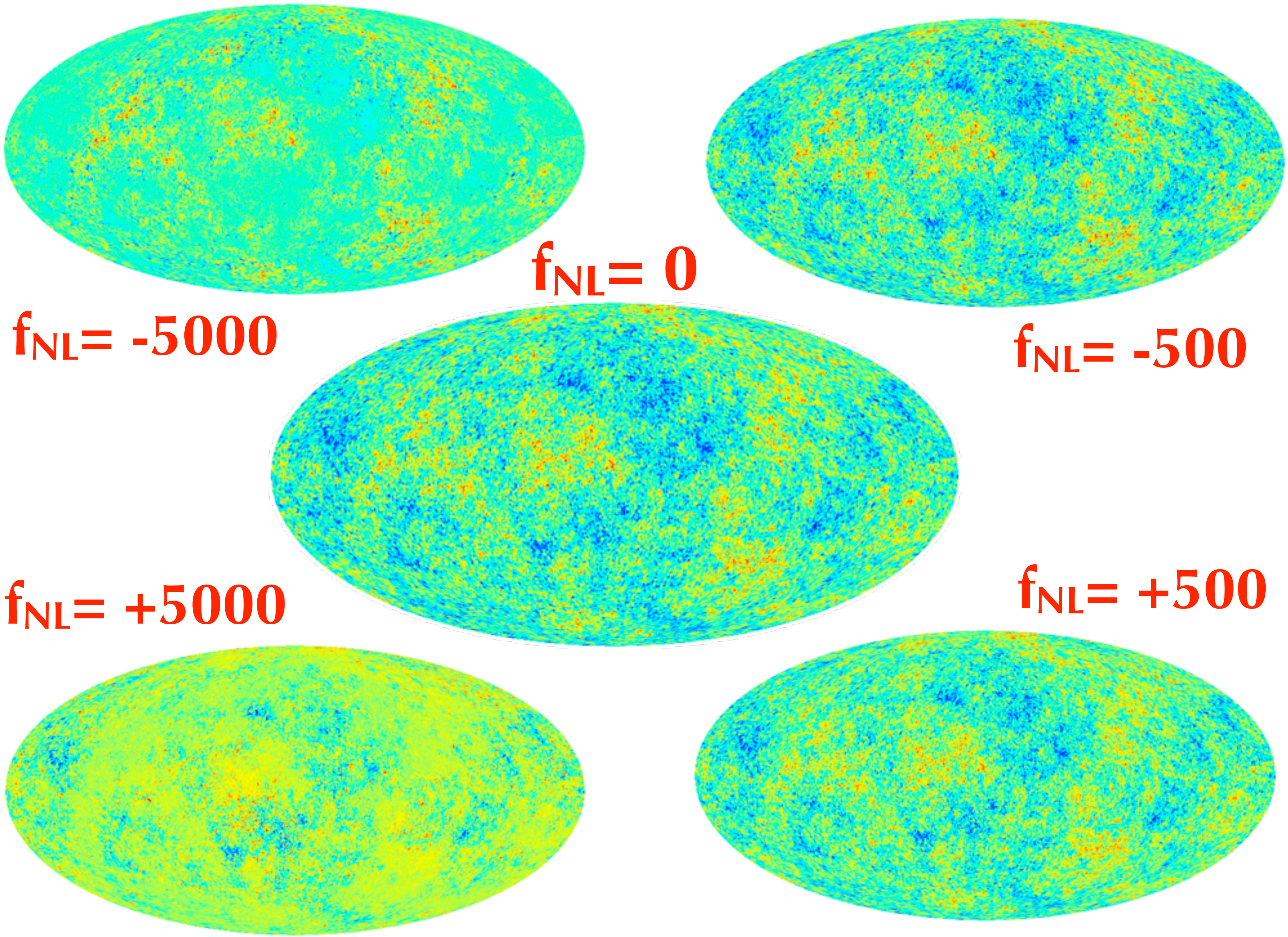
Commonly used "local" model of NG

$$\Phi = \Phi_G + f_{\rm NL}\left(\Phi_G^2 - \langle\Phi_G^2\rangle\right)$$

Salopek & Bond 1990; Verde et al 2000; Komatsu & Spergel 2001; Maldacena 2003

Then the 3-point function is related to $f_{\rm NL}$ via (in k-space)

$$B(k_1, k_2, k_3) \sim f_{\rm NL}\left[P(k_1)P(k_2) + \text{perm.}\right]$$

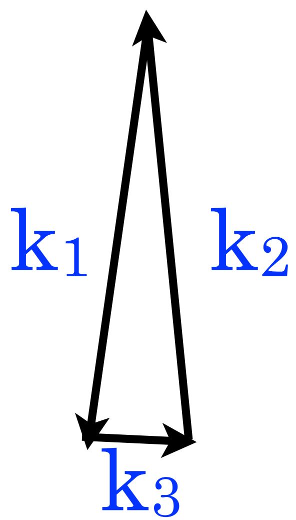


Using publicly available NG maps by Elsner & Wandelt

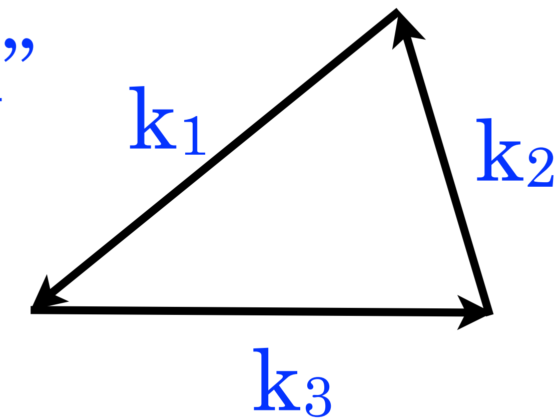
3-pt correlation function of CMB anisotropy
⇒ direct window into inflation

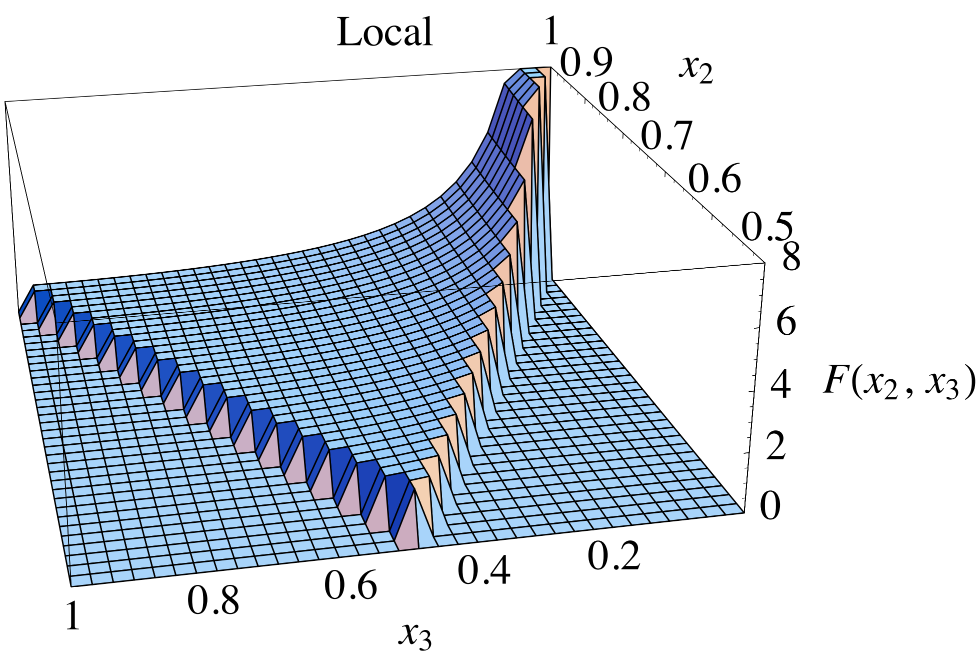
e.g. Luo & Schramm 1993

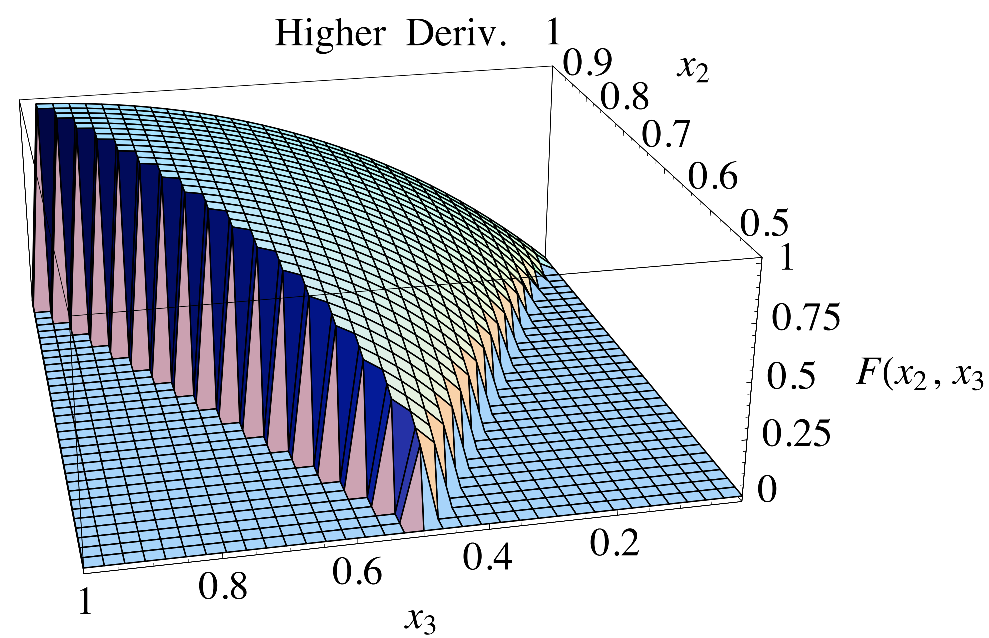
"local"
(eg. from sharp features in)



"equilateral"







Babich, Creminelli & Zaldarriaga 2004

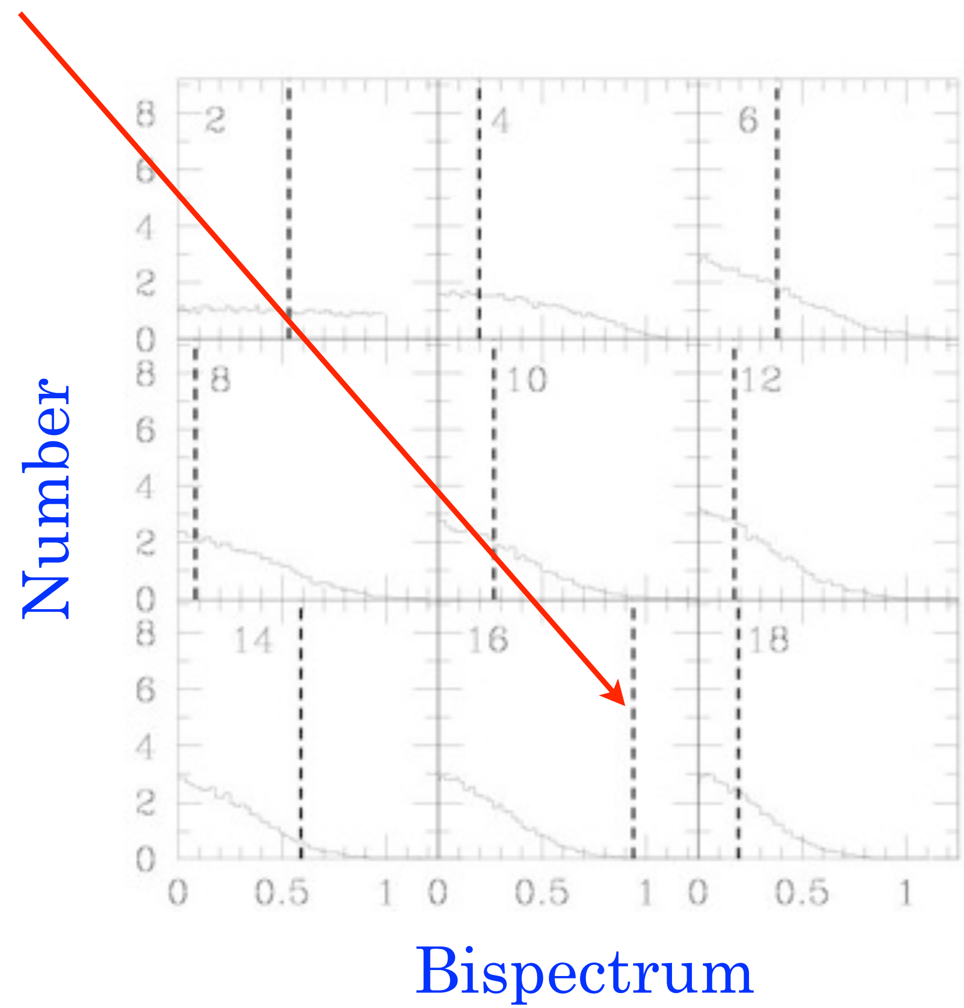
Brief history of NG measurements: 1990's

Early 1990s; COBE: Gaussian CMB sky (Kogut et al 1996)

1998; COBE: claim of NG at l=16 equilateral bispectrum
(Ferreira, Magueijo & Gorski 1998)

but explained by a known systematic effect!
(Banday, Zaroubi & Gorski 1999)

(and anyway isn't unexpected given all bispectrum configurations you can measure; Komatsu 2002)



Brief history of NG measurements: 2000's

Pre-WMAP CMB: all is gaussian (e.g. MAXIMA; Wu et al 2001)

WMAP pre-2008: all is gaussian

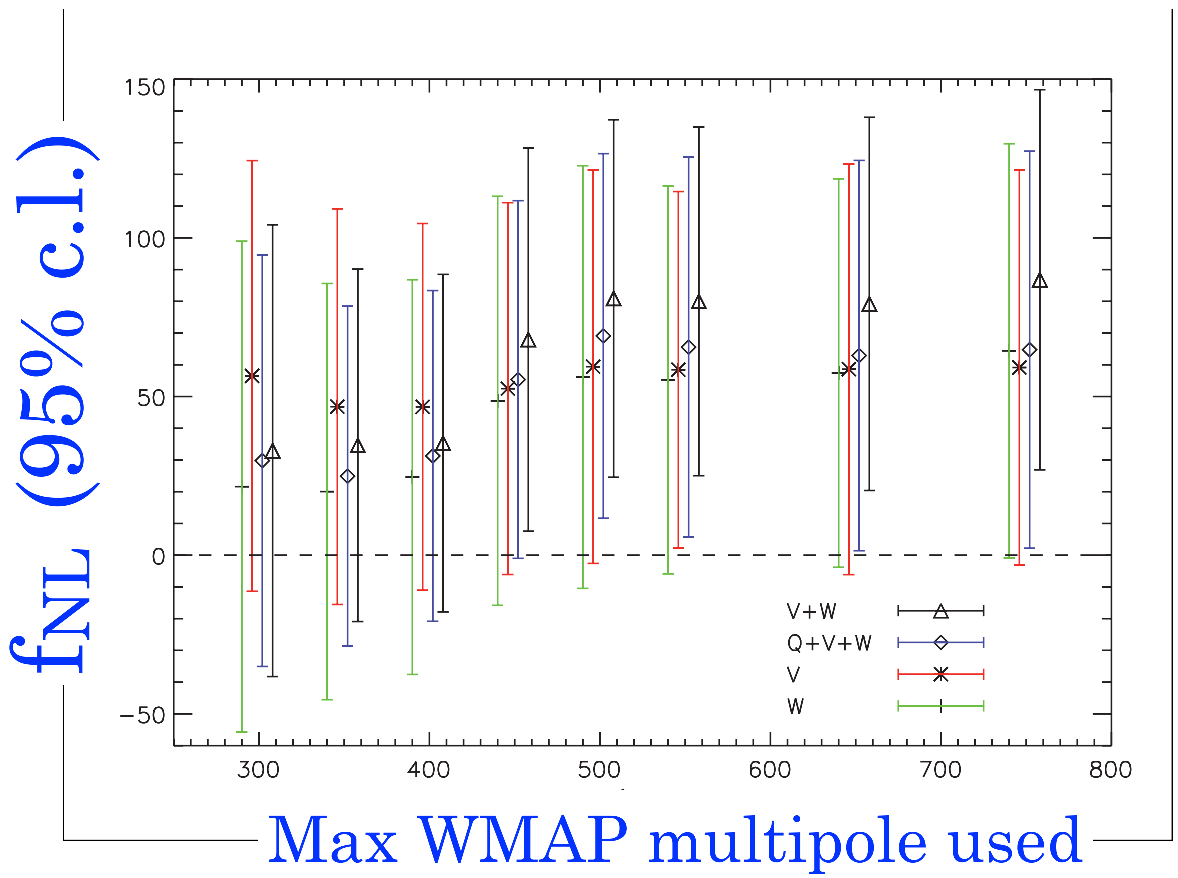
(Komatsu et al. 2003; Creminelli, Senatore, Zaldarriaga & Tegmark 2007)

$-36 < f_{NL} < 100$ (95% CL)

Dec 2007, claim of NG in WMAP

(Yadav & Wandelt arXiv:0712.1148)

$27 < f_{NL} < 147$ (95% CL)



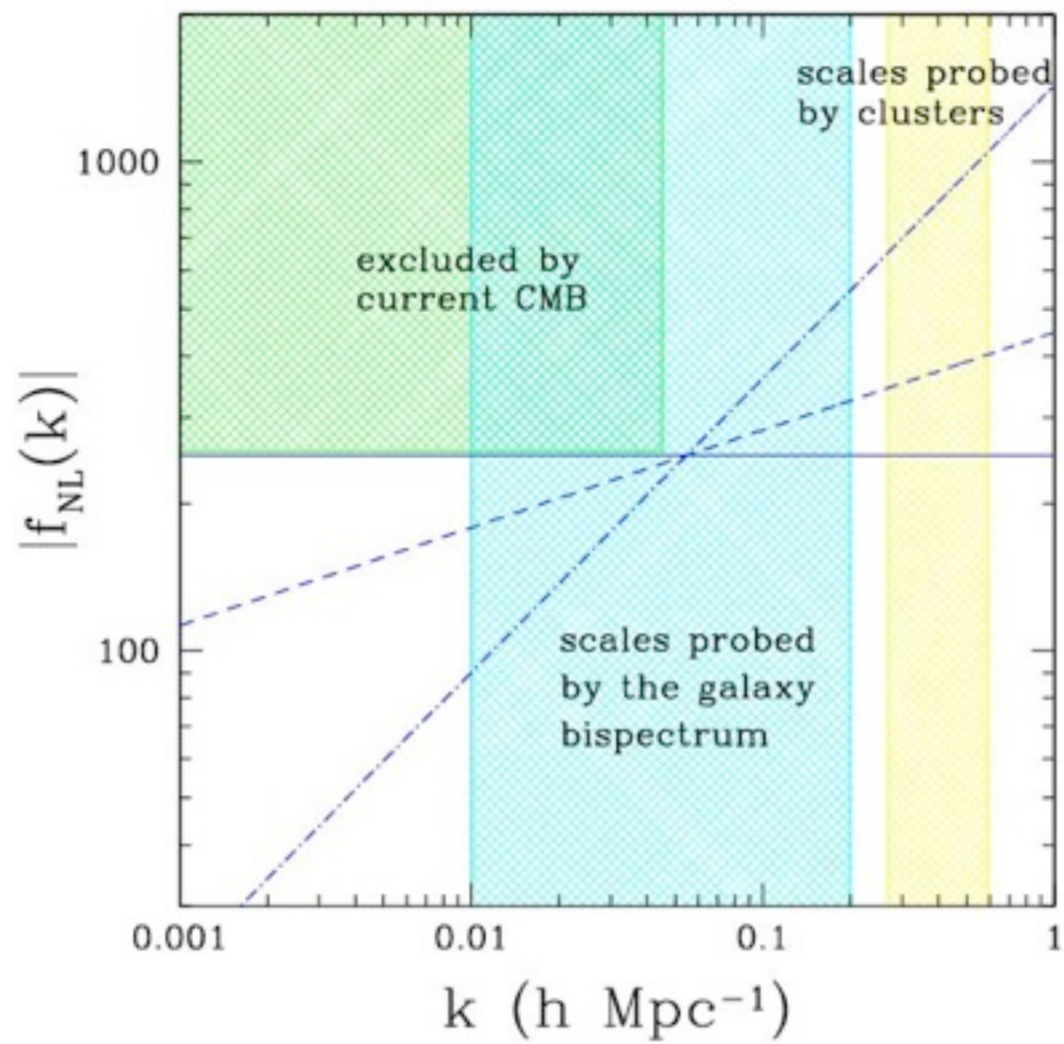
Current constraints from WMAP

Band	Foreground[b]	$f_{NL}^{\rm local}$	$f_{NL}^{\rm equil}$	$f_{NL}^{\rm orthog}$	b_{src}
V+W	Raw	59 ± 21	33 ± 140	-199 ± 104	N/A
V+W	Clean	42 ± 21	29 ± 140	-198 ± 104	N/A
V+W	Marg.[c]	32 ± 21	26 ± 140	-202 ± 104	-0.08 ± 0.12
V	Marg.	43 ± 24	64 ± 150	-98 ± 115	0.32 ± 0.23
W	Marg.	39 ± 24	36 ± 154	-257 ± 117	-0.13 ± 0.19

Komatsu et al. 2010

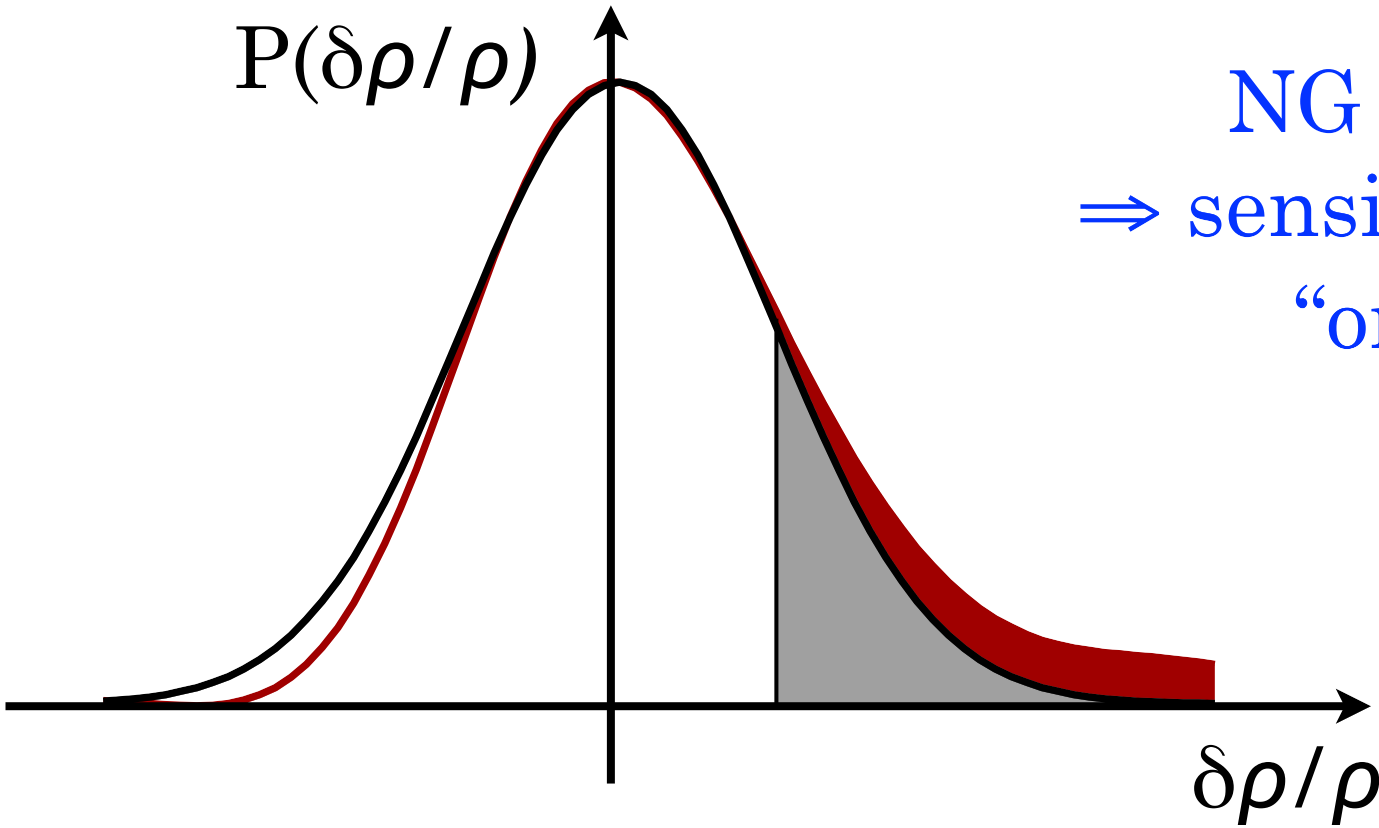
Future: much better constraints expected, $\sigma(f_{NL})<O(10)$ with Planck

NG can be measured at different scales



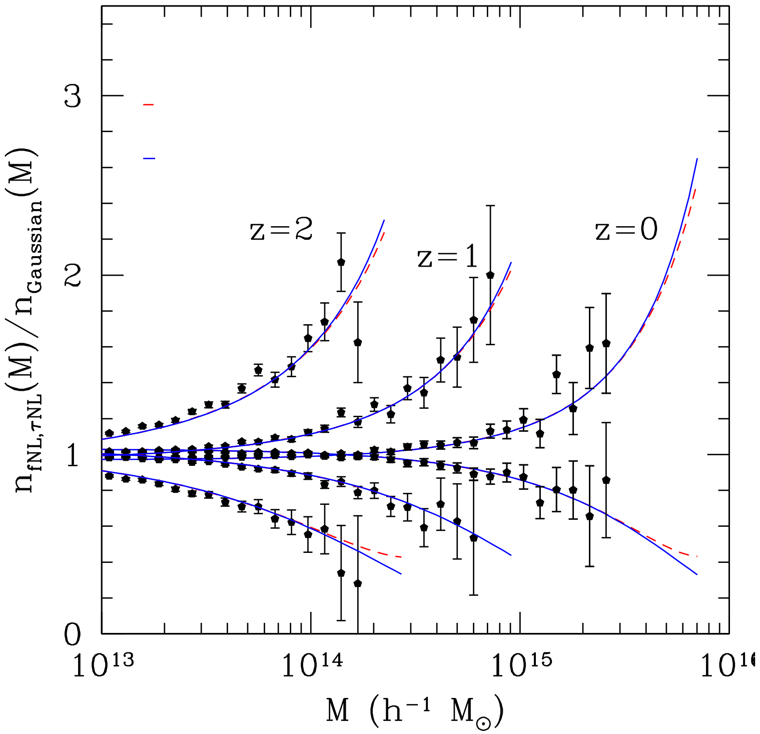
LoVerde, Miller, Shandera & Verde, 2008

Cluster counts' sensitivity to NG



NG initial PDF
⇒ sensitivity to counts
"on the tail"

Lots of effort in the community to calibrate the non-Gaussian mass function of DM halos



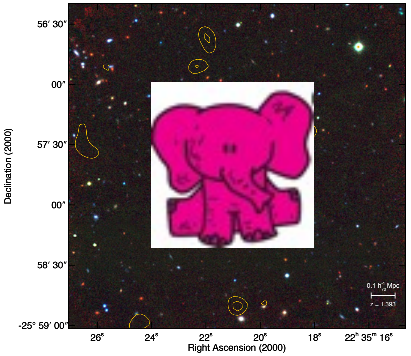
NG/Gaussian mass function ratios: for fixed M, more sensitivity at higher redshift

Smith & LoVerde 2011; Pillepich, Porciani and Hahn 2009; many others going back to 1990s

Unfortunately, cluster counts are **weakly** sensitive to NG

e.g. Sefusatti et al. 2007 forecasted the depressing $\sigma(f_{NL})=145$ from SDSS
e.g. $\sigma(f_{NL})=450$ measured from SPT (Williamson et al 2010)

Nevertheless, it is true that a (large) amount of (local model) NG can boost the number of ‘pink elephant’ clusters



Is the existence of 1 (or more) high-z, high-M clusters in conflict with LCDM?

4 things to account for:

1. **Sample variance** - the Poisson noise in counting rare objects in a finite volume

2. **Parameter variance** - uncertainty due to fact that current data allow cosmological parameters to take a range of values

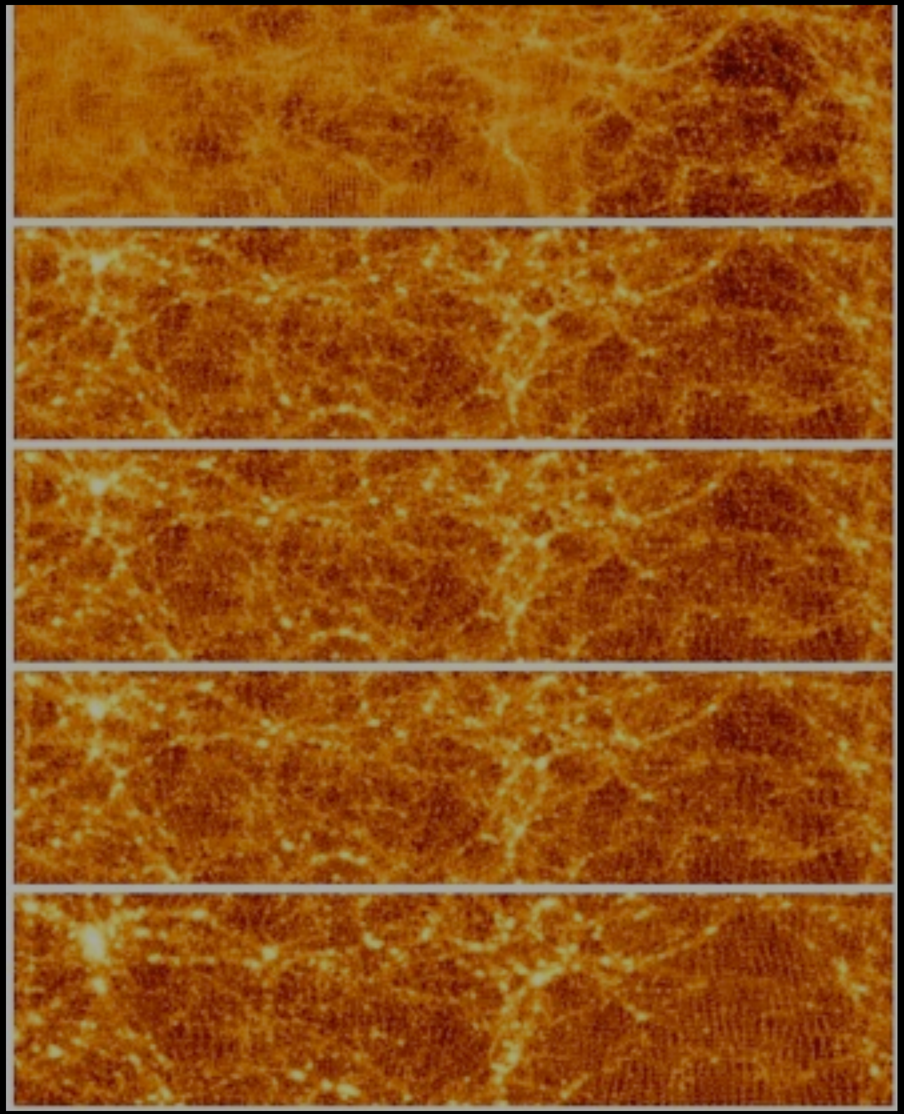
3. **Eddington bias** - mass measurement error will preferentially ‘scatter’ the cluster into higher mass

4. **Survey sky coverage** - needs to be fairly assessed

N.B. If a cluster rules out LCDM, it will rule out quintessence too!

Mortonson, Hu & Huterer: arXiv:1004.0236
also see Foley talk

Simulations with nongaussianity (f_{NL})



- Under-dense region evolution decrease with f_{NL}
- Over-dense region evolution increase with f_{NL}

- Same initial conditions, different f_{NL}
- Slice through a box in a simulation $N_{part}=512^3$, L=800 Mpc/h

Dalal, Doré, Huterer & Shirokov, arXiv:0710.4560, PRD 2008

Effects of primordial NG
on the bias of virialized objects

Does galaxy/halo bias depend on NG?

cosmologists measure

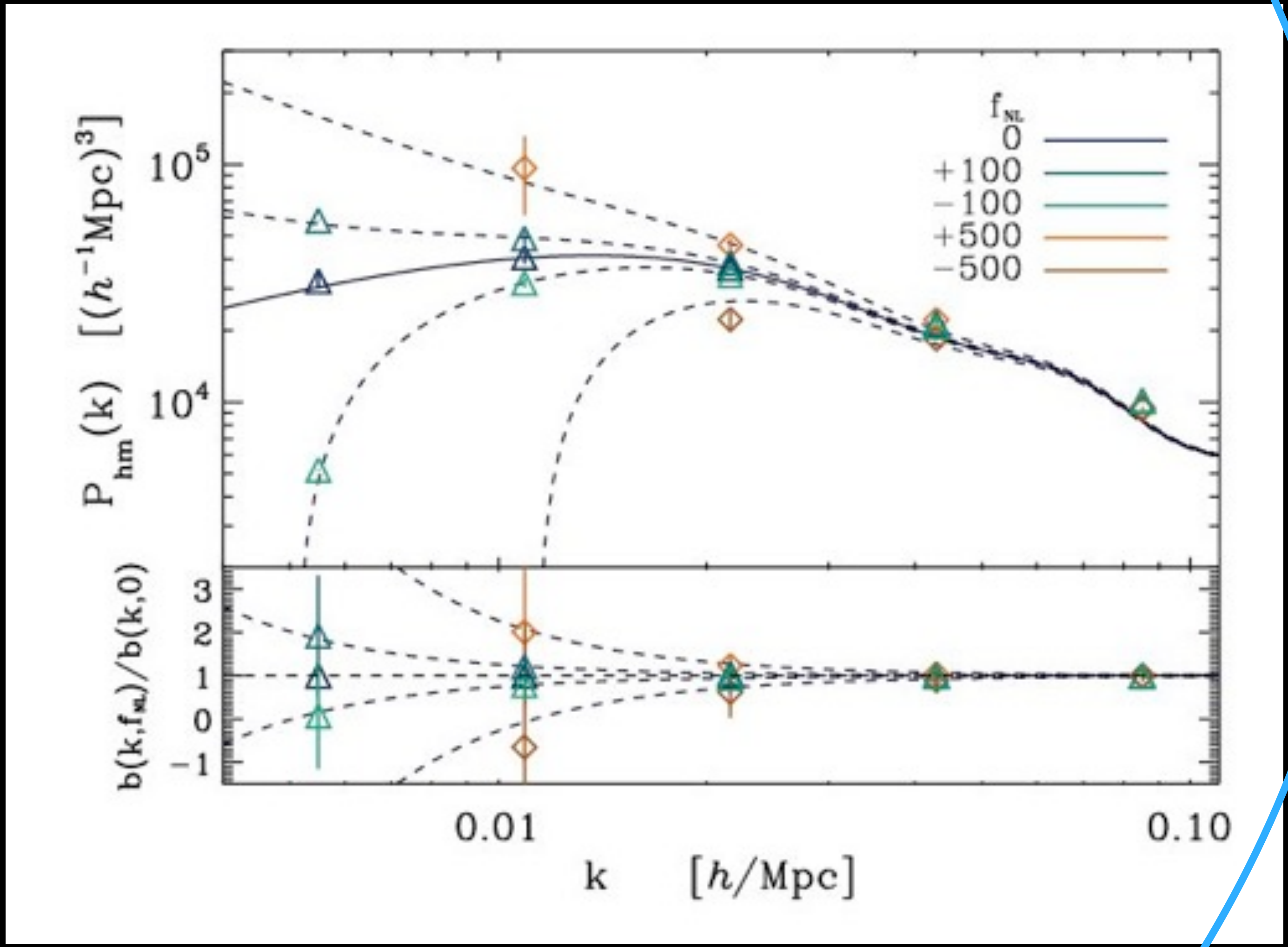
$$\text{bias} \equiv \frac{\text{clustering of galaxies}}{\text{clustering of dark matter}} = \frac{\left(\frac{\delta\rho}{\rho}\right)_{\text{halos}}}{\left(\frac{\delta\rho}{\rho}\right)_{\text{DM}}}$$

usually nuisance parameter(s)

theory predicts

Simulations and theory both say:
large-scale bias is scale-independent

Scale dependence of NG halo bias!



$$b(k) = b_{\mathrm{G}} + f_{\mathrm{NL}} \frac{\mathrm{const}}{k^2}$$

Dalal, Doré, Huterer & Shirokov, arXiv:0710.4560, PRD 2008

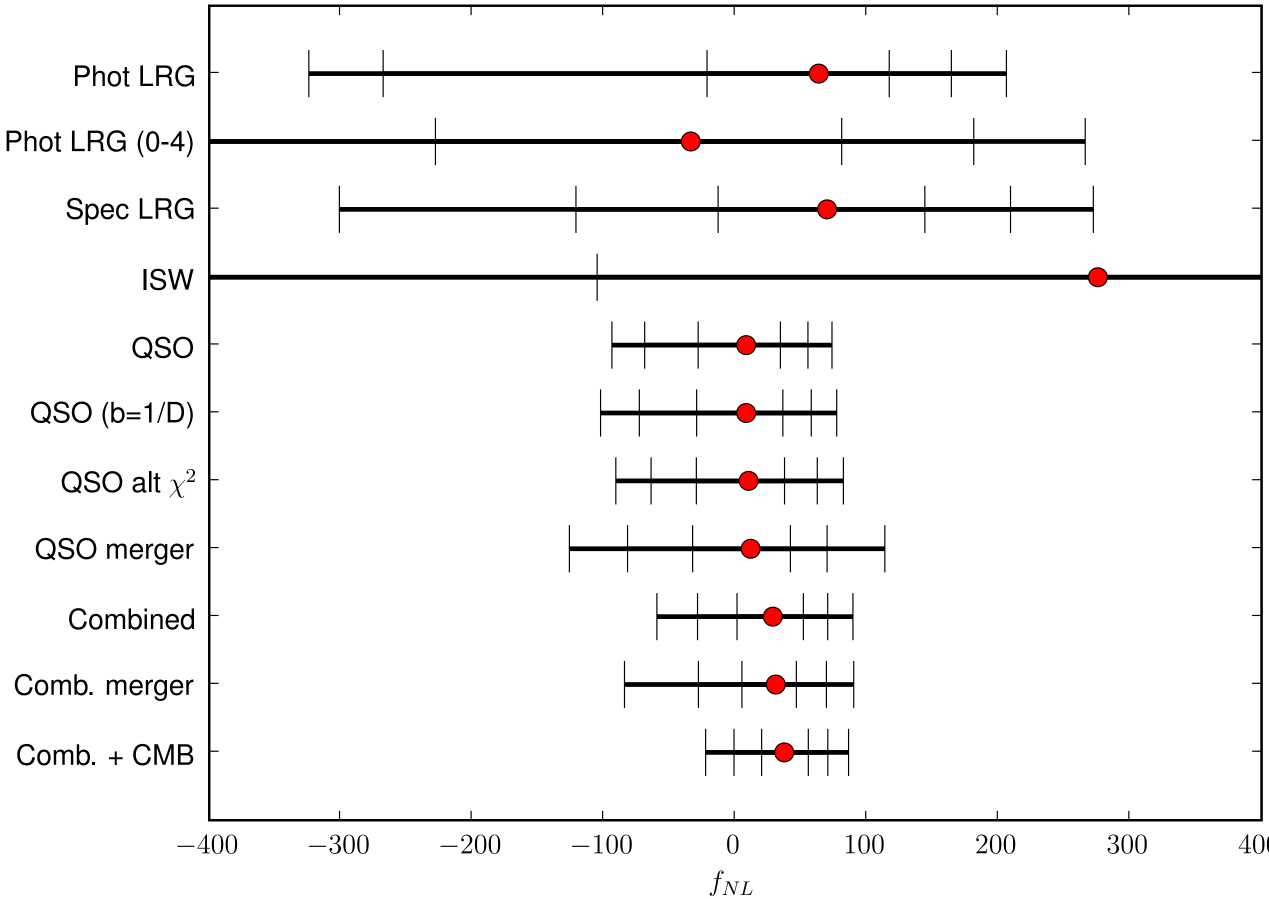
$$\Delta b(k) = f_{\rm NL}(b_G - 1)\,\delta_c\,\frac{3\,\Omega_M H_0^2}{T(k)D(a)k^2}$$

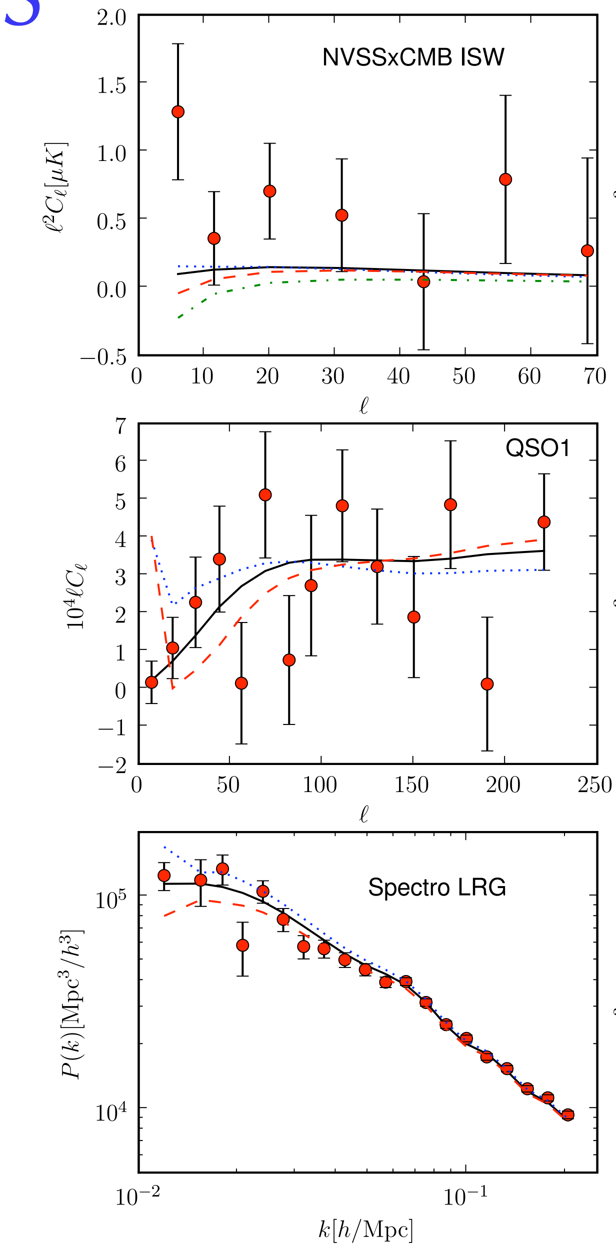
Implications:

- Unique $1/k^2$ scaling of bias; no free parameters
- Distinct from effect of other cosmo parameters
- Straightforwardly measured (clustering of any type of halo autocorrelation, cross-correlation with CMB,...
- Derived theoretically several different ways
- Extensively tested with numerical simulations; good agreement found

Dalal et al. 2008; Matarrese & Verde; Slosar et al; Afshordi & Tolley; Desjacques et al; Giannantonio & Porciani; Grossi et al; McDonald; ....

Constraints from **current** data: SDSS





f_{NL} = 8 +/- 30 (68%, QSO)

f_{NL} = 23 +/- 23 (68%, all)

Slosar et al. 2008

Future data forecasts for LSS: $\sigma(f_{NL}) \approx O(\text{few})$

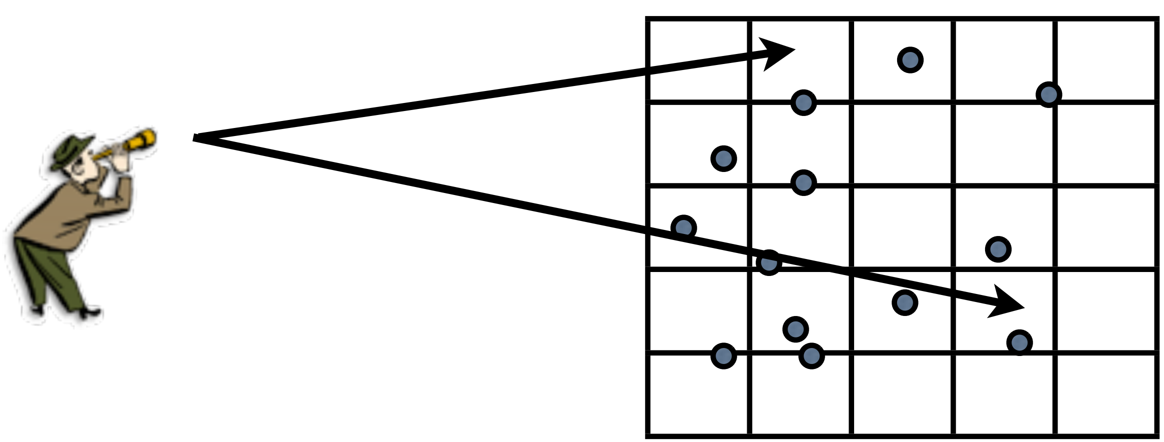
(at least?) as good as, and highly complementary, to Planck CMB

(see A. Pillepich talk)

Nongaussianity form clustering of galaxy **clusters**

Cunha, Huterer & Doré 2010

- **Covariance** (i.e. clustering) between very distant clusters of galaxies is especially sensitive to primordial nongaussianity
- Improvement relative to counts alone: **2-3 orders of magnitude** in accuracy
- Improvement relative to *variance* of counts: >1 order of magnitude in accuracy
- In other words:
  - **Good**: Counts ($d^2N/dzd\Omega = r^2(z)/H(z)$)
  - **Better**: Variance (of counts in cells)
  - **Best: Covariance** (of counts in cells)



N.B. calculation is numerically demanding even at the Fisher matrix level

Nongaussianity form clustering of galaxy **clusters**

Encouraging sign:
NG can survive marginalization over numerous nuisance parameters

DES cluster survey forecasts

Marginalized errors—Full Covariance										
Nuisance parameters		Counts			Covariance			Counts + Covariance		
Halo bias	$M_{\rm obs}$	$\sigma(\Omega_{\rm DE})$	$\sigma(w)$	$\sigma(f_{\rm NL})$	$\sigma(\Omega_{\rm DE})$	$\sigma(w)$	$\sigma(f_{\rm NL})$	$\sigma(\Omega_{\rm DE})$	$\sigma(w)$	$\sigma(f_{\rm NL})$
Marginalized	Marginalized	∞	∞	∞	∞	∞	∞	0.069	0.23	**6.0**
Known	Marginalized	0.097	0.33	$\mathbf{2.1 \times 10^3}$	0.13	0.43	**12**	0.065	0.22	**5.4**
Marginalized	Known	∞	∞	∞	0.099	0.34	**7.0**	0.0036	0.014	**3.8**
Known	Known	0.0051	0.023	**94**	0.042	0.13	**5.1**	0.0036	0.014	**1.8**

Counts mainly probe DE parameters
Covariance mainly probes $f_{\rm NL}$

Cunha, Huterer & Doré 2010
see also Sartoris et al 2010

Scale-dependent nongaussianity? Generalized local ansatz

Becker, Huterer & Kadota, arXiv:1009:4189

- Motivated by multi-field inflationary models
- In general, even if you are considering standard single-field inflation, interactions may lead to scale-dependence of f_{NL}

(Usual) local model...

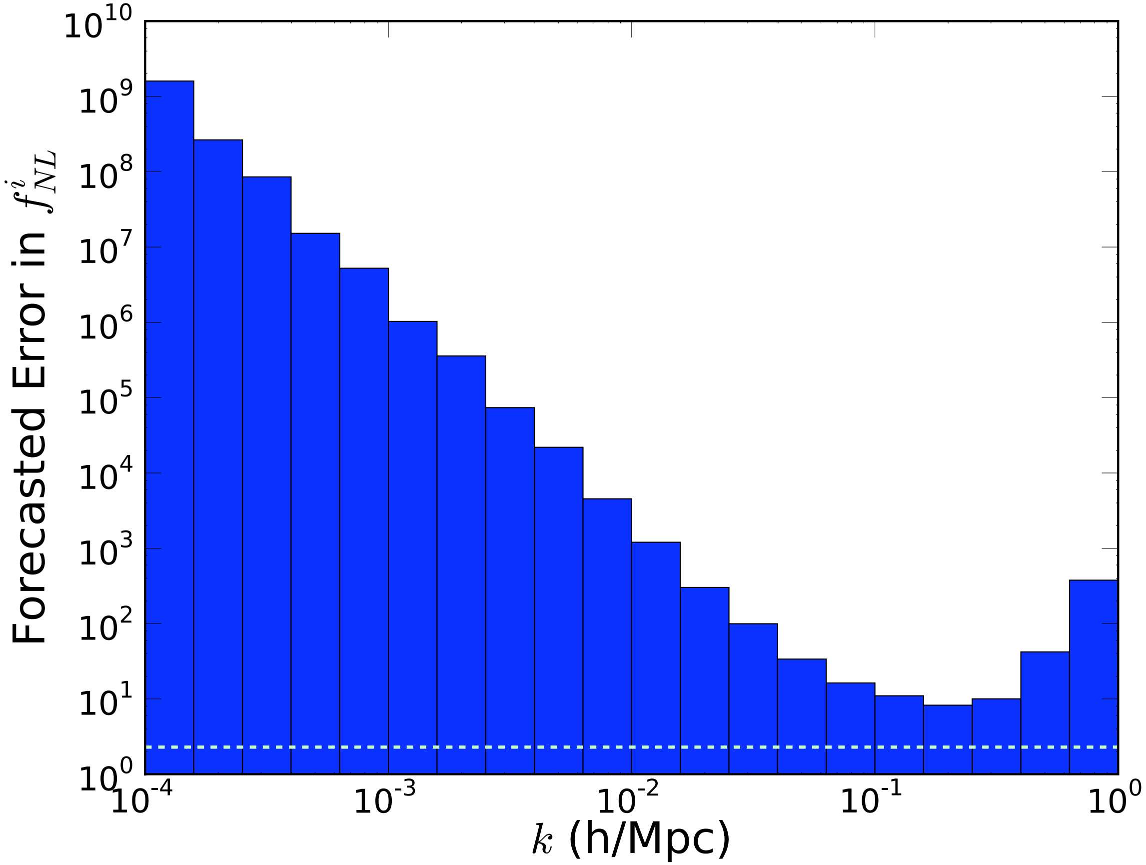
$$\Phi(x) = \phi_G(x) + f_{\rm NL}\left[\phi_G^2(x) - \langle\phi_G^2\rangle\right]$$

...we generalize to a scale dependent (non-local) model

$$\Phi(x) = \phi_G(x) + f_{\rm NL}(x) * \left[\phi_G^2(x) - \langle\phi_G^2\rangle\right]$$

$$\Phi(k) = \phi_G(k) + f_{\rm NL}(k)\int\frac{d^3k'}{(2\pi)^3}\phi_G(k')\phi_G(k-k')$$

A complete basis for $f_{NL}(k)$: piecewise-constant bins



Measurement forecasts from DES-type survey

Given this basis, projecting forecasts onto any parametrized $f_{NL}(k)$ model is now trivial

Warning, however: theoretical predictions are uncertain and (always!) have to be checked with simulations first

Becker, Huterer & Kadota, arXiv:1010:3772

Scale-dependent non-Gaussianity: comparison with simulations

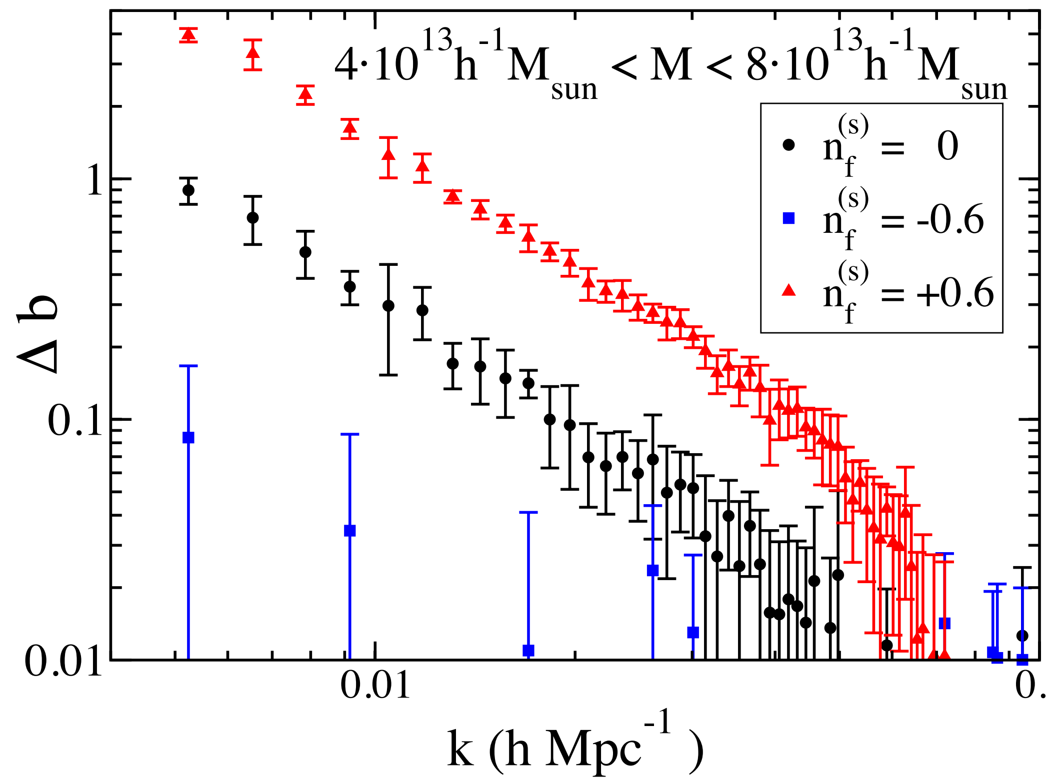
Shandera, Dalal & Huterer, arXiv:1010:3722

- Scale-dependent NG meets numerical simulations - 1st time
- Two models considered:
  - 1. Single-field inflaton with self-interaction
  - 2. Mixed curvaton-inflaton model

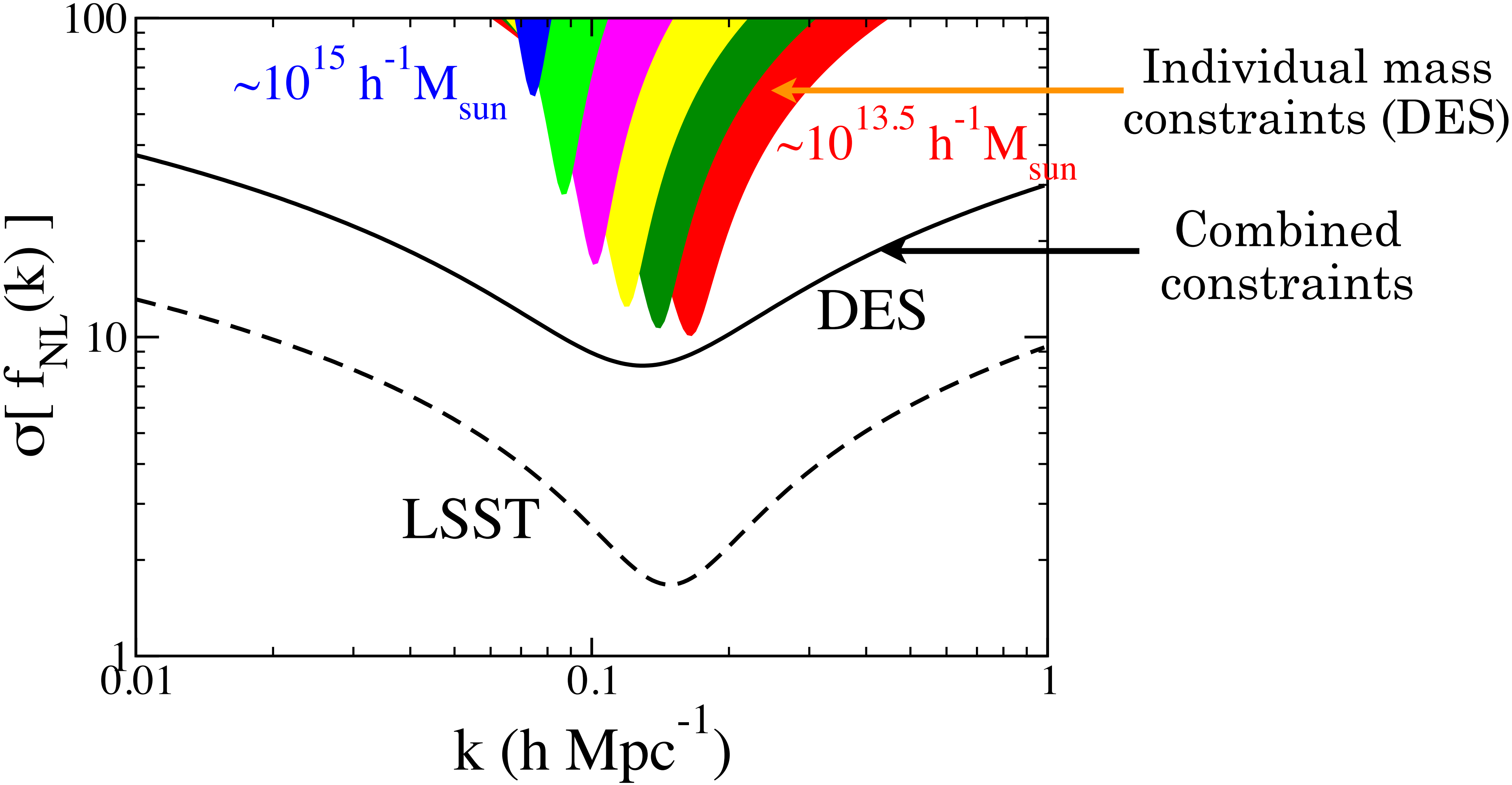
theoretical ansatz:

$$f_{\rm NL}(k) = f_{\rm NL}(k_p)\left(\frac{k}{k_p}\right)^{n_f}$$

in numerical simulations →



Halos of mass M probe NG on scale $k \sim M^{-1/3}$



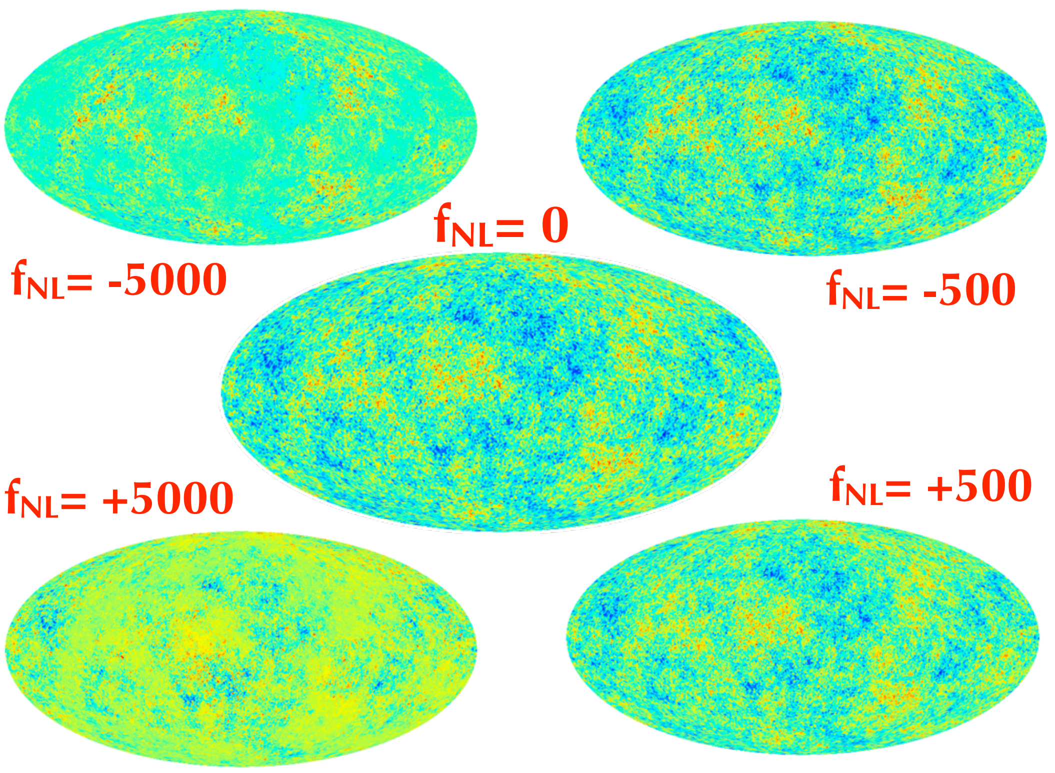
NB. 1. Theory predictions are uncertain
NB. 2. More sim comparisons needed

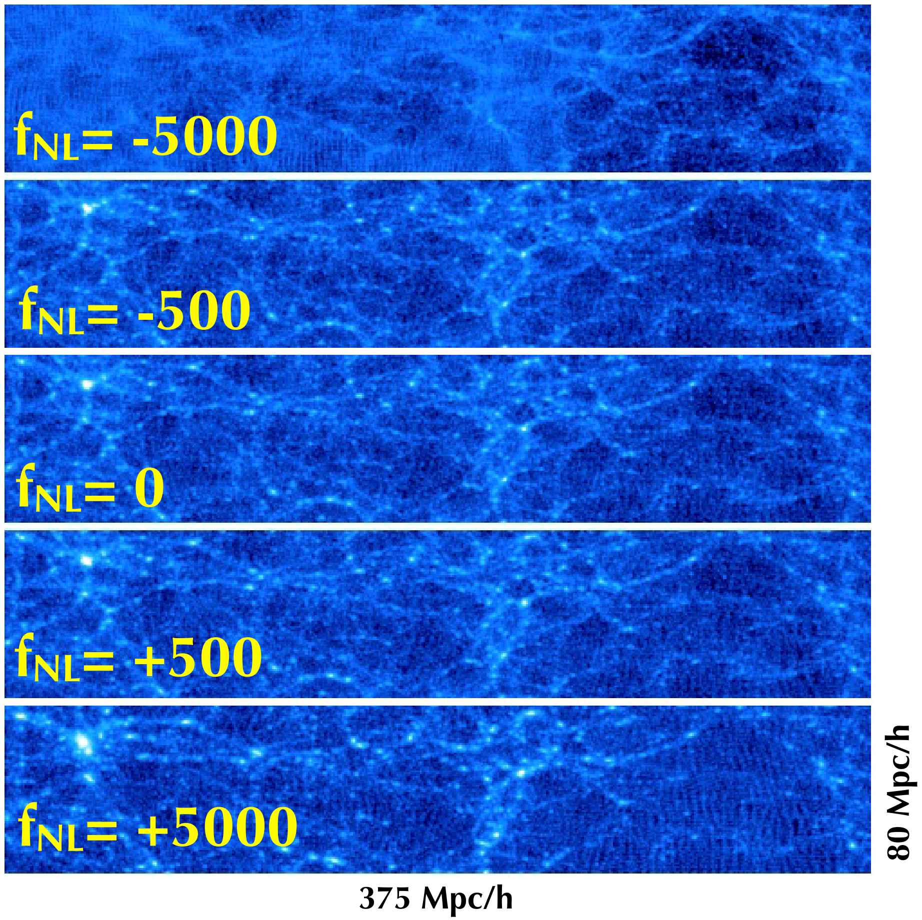
Shandera, Dalal & Huterer, arXiv:1010:3722

CMB+LSS: Cosmic Complementarity

different observations on different scales with different systematics

but measuring the same fundamental quantities





CMB

LSS

Conclusions

- Constraining or measuring primordial non-Gaussianity directly probes the physics of inflation

- CMB bispectrum traditionally most promising tool; current results consistent with f_{NL}=0 at 2 sigma

- Cluster counts are in principle sensitive to NG, but not competitive with the CMB (huge amount needed to explain 'pink elephant' clusters)

- Cosmological models with (local) primordial NG lead to significant scale dependence of halo bias; theory and simulations are in remarkable agreement on this

- Therefore, LSS probes (baryon oscillations, galaxy-CMB cross-correlations, etc) are likely to lead to constraints on NG ~2 orders of magnitude better than previously thought from LSS.

- Using this (bias) method, current constraints from SDSS are comparable to those from WMAP

- Excellent prospects for upcoming LSS measurements, even in the presence of systematic errors

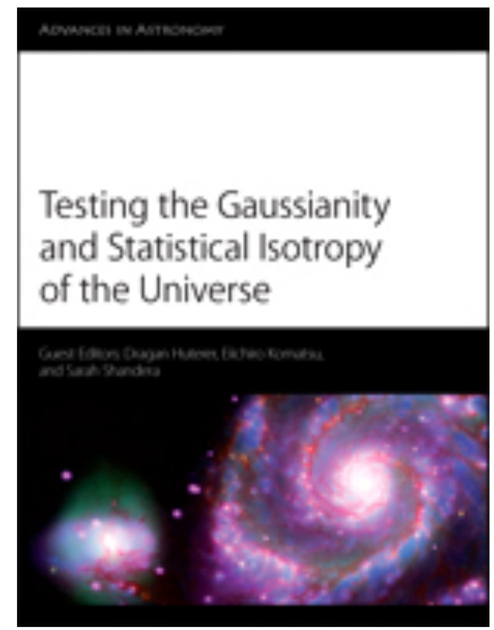
Advances in Astronomy special issue on
"Testing the Gaussianity and Statistical Isotropy of the Universe"

http://www.hindawi.com/journals/aa/2010/si.gsiu/

15 review articles (all also on arXiv)

Testing the Gaussianity and Statistical Isotropy of the Universe

Guest Editors: Dragan Huterer, Eiichiro Komatsu, and Sarah Shandera



Non-Gaussianity from Large-Scale Structure Surveys, Licia Verde
Volume 2010 (2010), Article ID 768675, 15 pages

Non-Gaussianity and Statistical Anisotropy from Vector Field Populated Inflationary Models, Emanuela Dimastrogiovanni, Nicola Bartolo, Sabino Matarrese, and Antonio Riotto
Volume 2010 (2010), Article ID 752670, 21 pages

Cosmic Strings and Their Induced Non-Gaussianities in the Cosmic Microwave Background,