The Quest for Primordial Non-Gaussianity

Overview and some recent developments;
skewed toward observations

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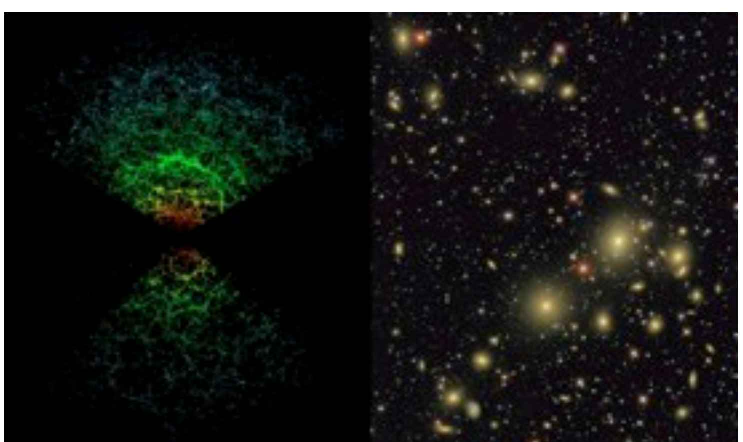
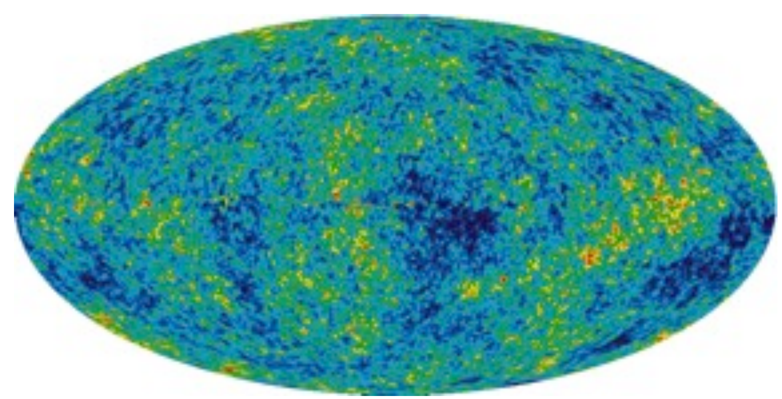
Why study non-Gaussianity (NG)?

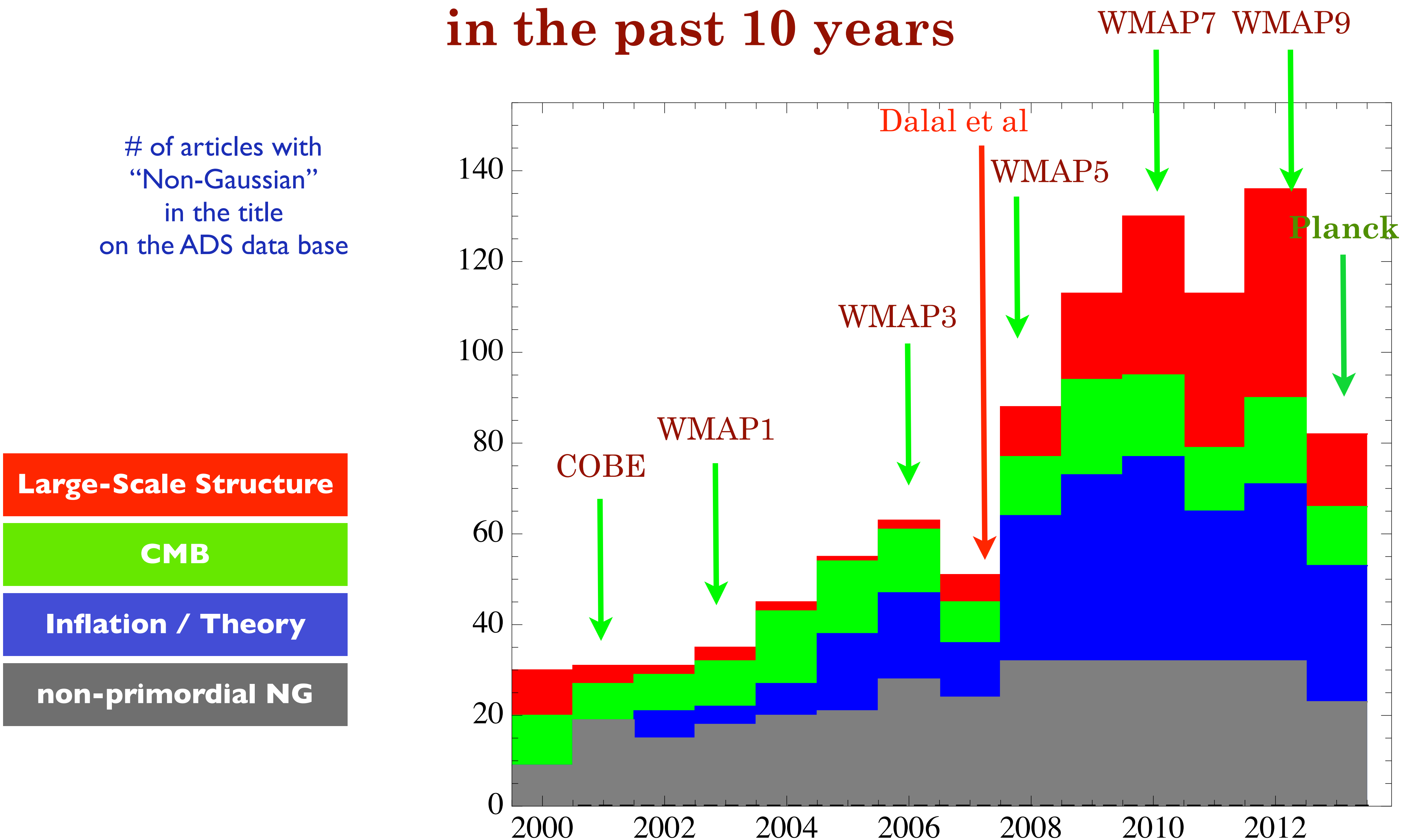
1. NG presents a window to the very early universe. For example, NG can distinguish between physically distinct models of inflation.

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.





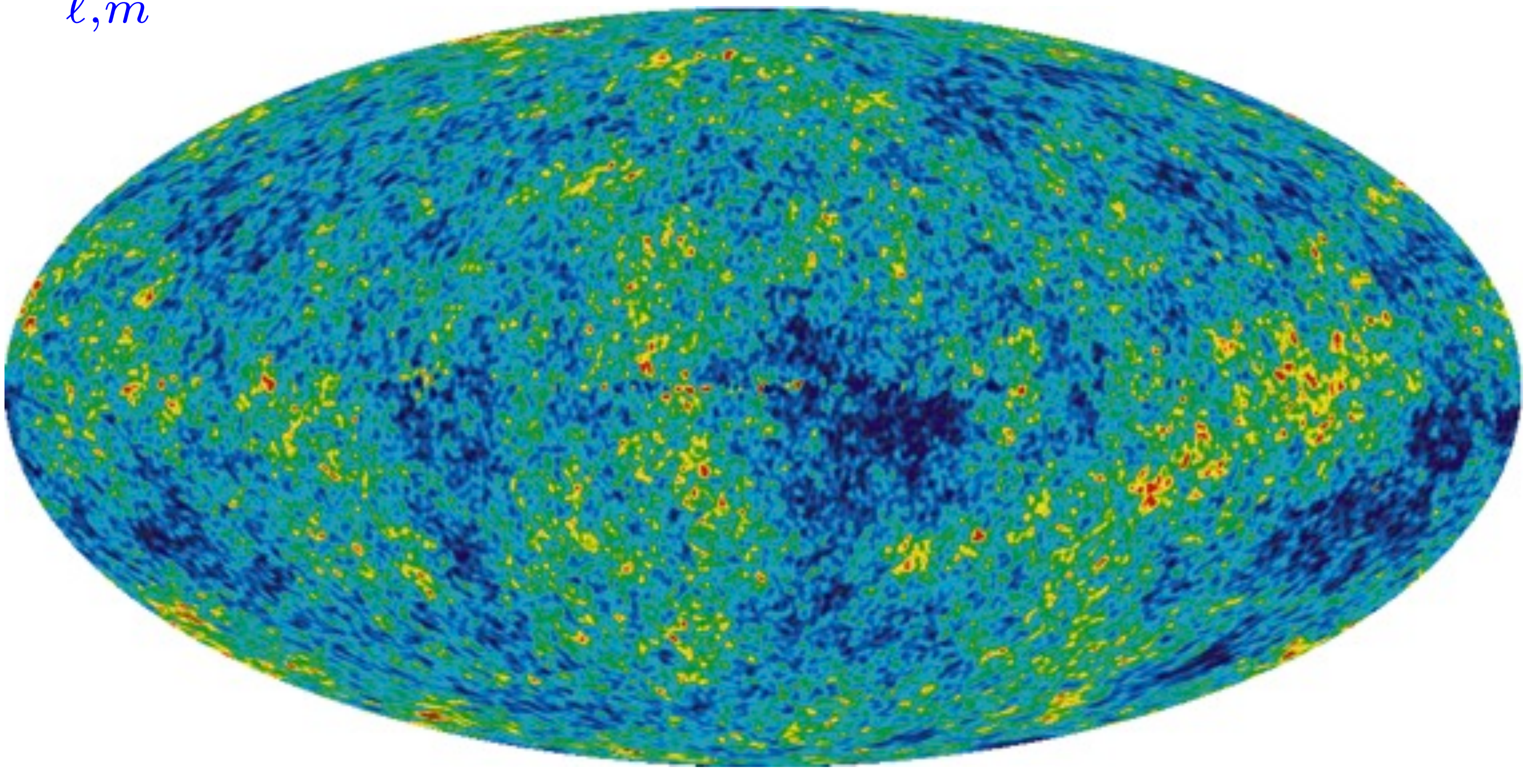
Non-Gaussianity papers
in the past 10 years



Produced by Emiliano Sefusatti

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:

Statistical Isotropy:

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

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

Gaussianity:

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

Standard Inflation, with...

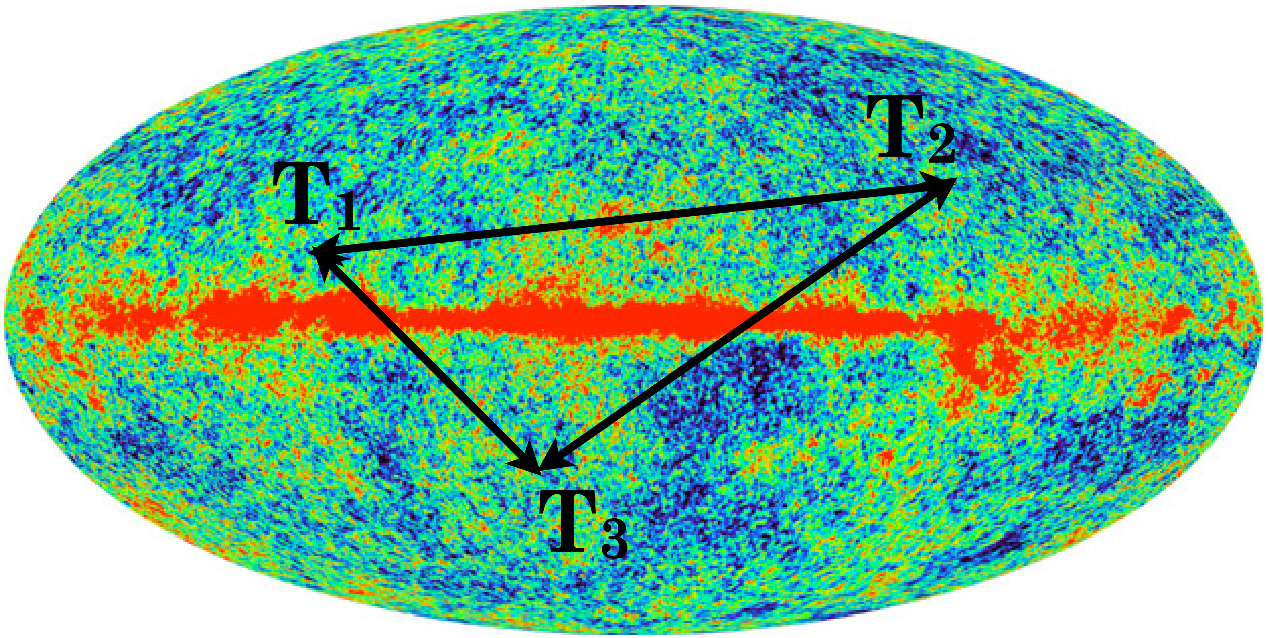
1. a single scalar field
2. the canonical kinetic term
3. always slow rolls
4. in Bunch-Davies vacuum
5. in Einstein gravity

produces **unobservable** NG

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

e.g. Maldacena 2003, X. Chen, Adv. Astronomy, 2010; Komatsu et al, arXiv:0902.4759

NG from 3-point correlation function



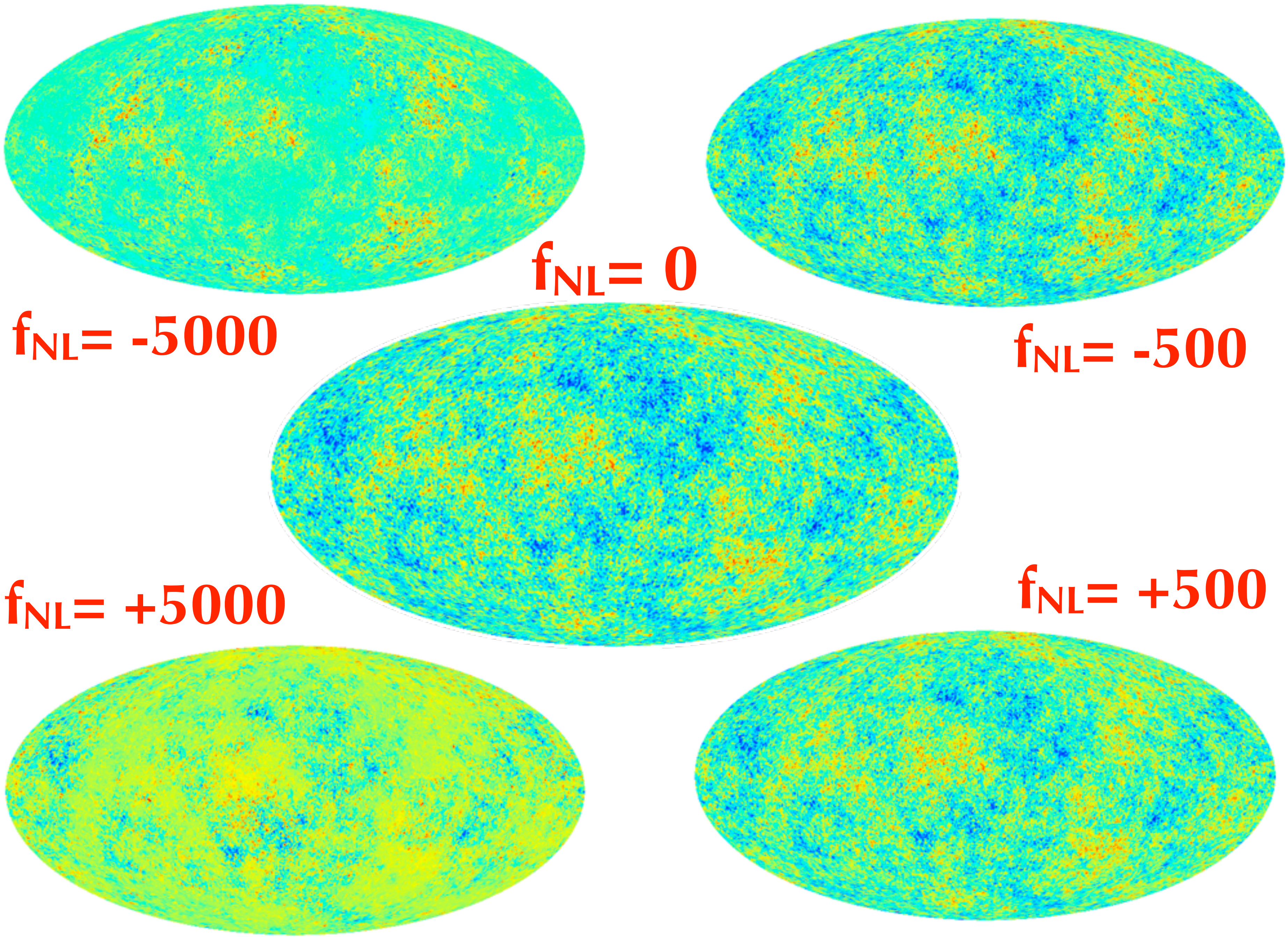
Commonly used "local" model of NG

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

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

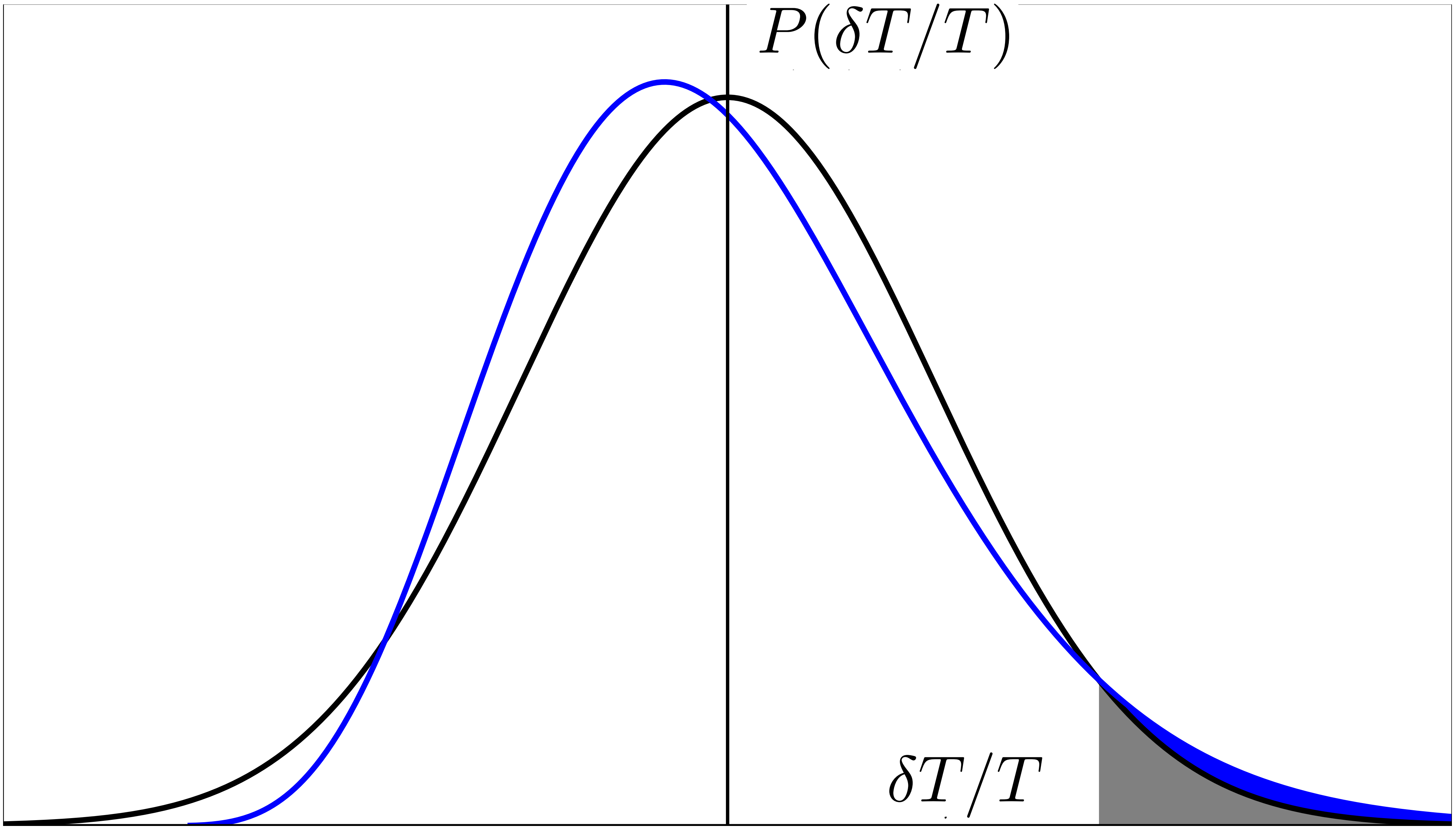
Then the 3-point function is related to $f_{\rm NL}$ via (in k-space)

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



Using publicly available NG maps by Elsner & Wandelt

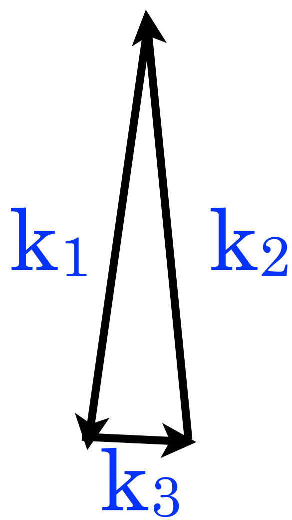
Current upper bound on NG is ~1000 times smaller than this:



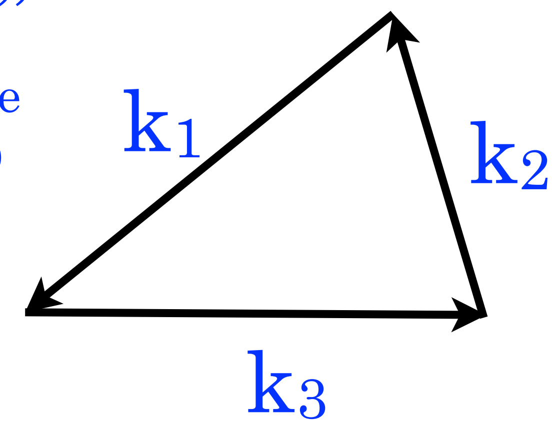
3-pt correlation function of CMB anisotropy ⇒ direct window into inflation

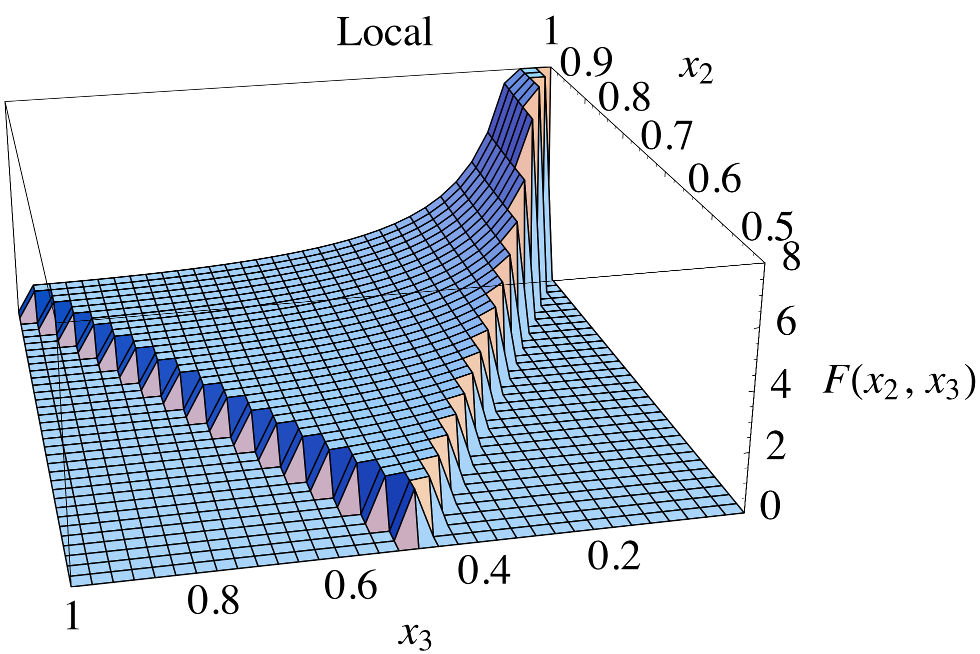
e.g. Luo & Schramm 1993

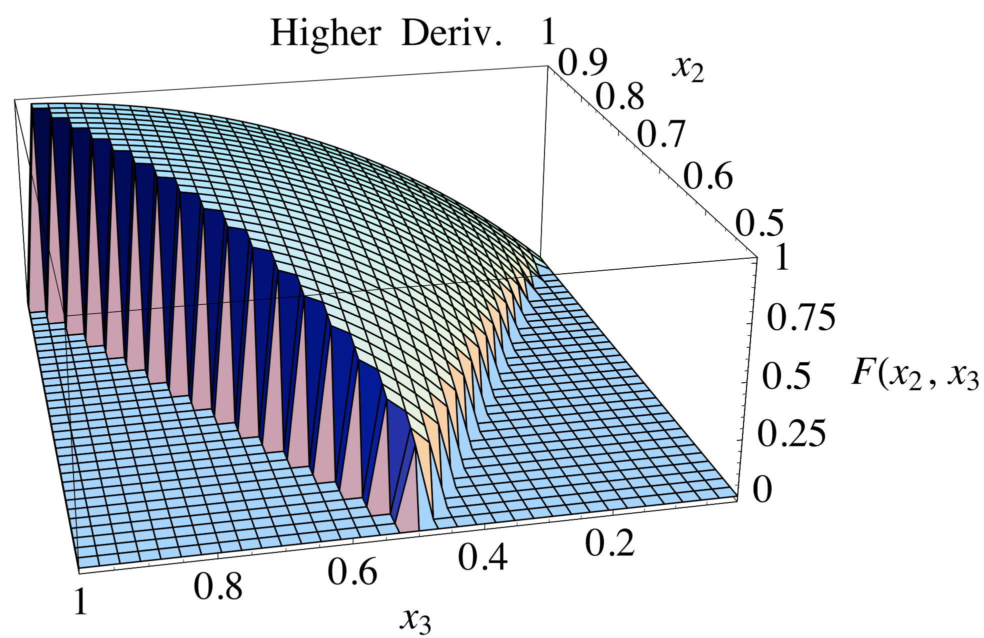
"local"
(eg. multi-field)



"equilateral"
(eg. higher-derivative action; interactions)







Babich, Creminelli & Zaldarriaga 2004

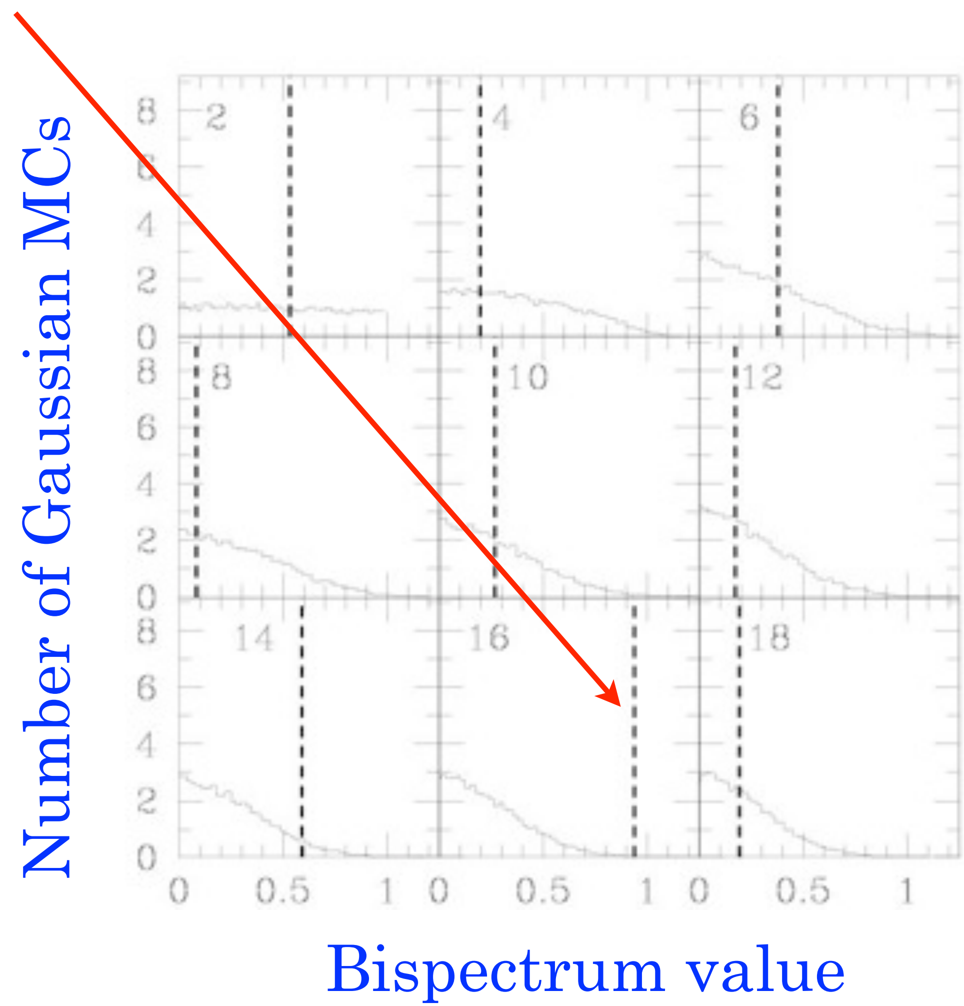
Brief history of NG measurements: 1990’s

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

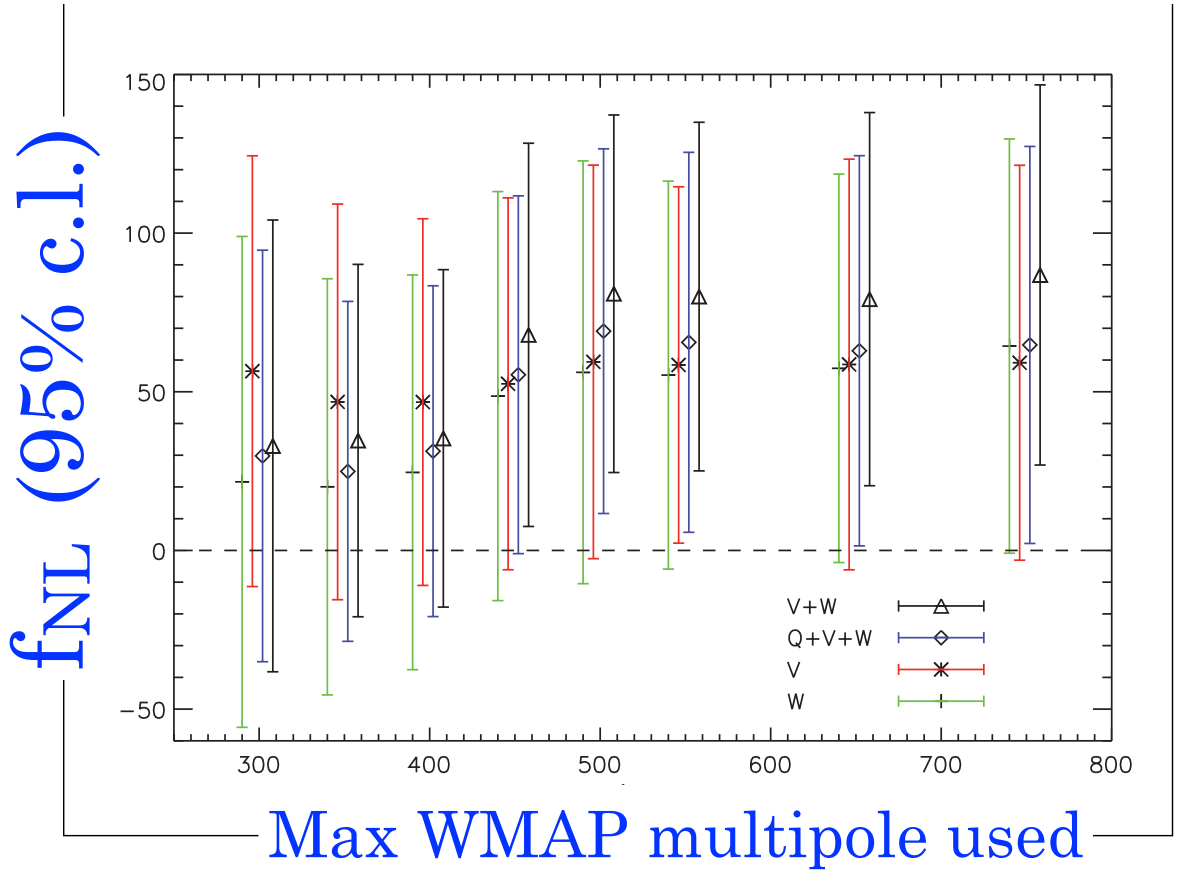
Pre-WMAP CMB: all is gaussian (e.g. MAXIMA; Wu et al 2001)

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)



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

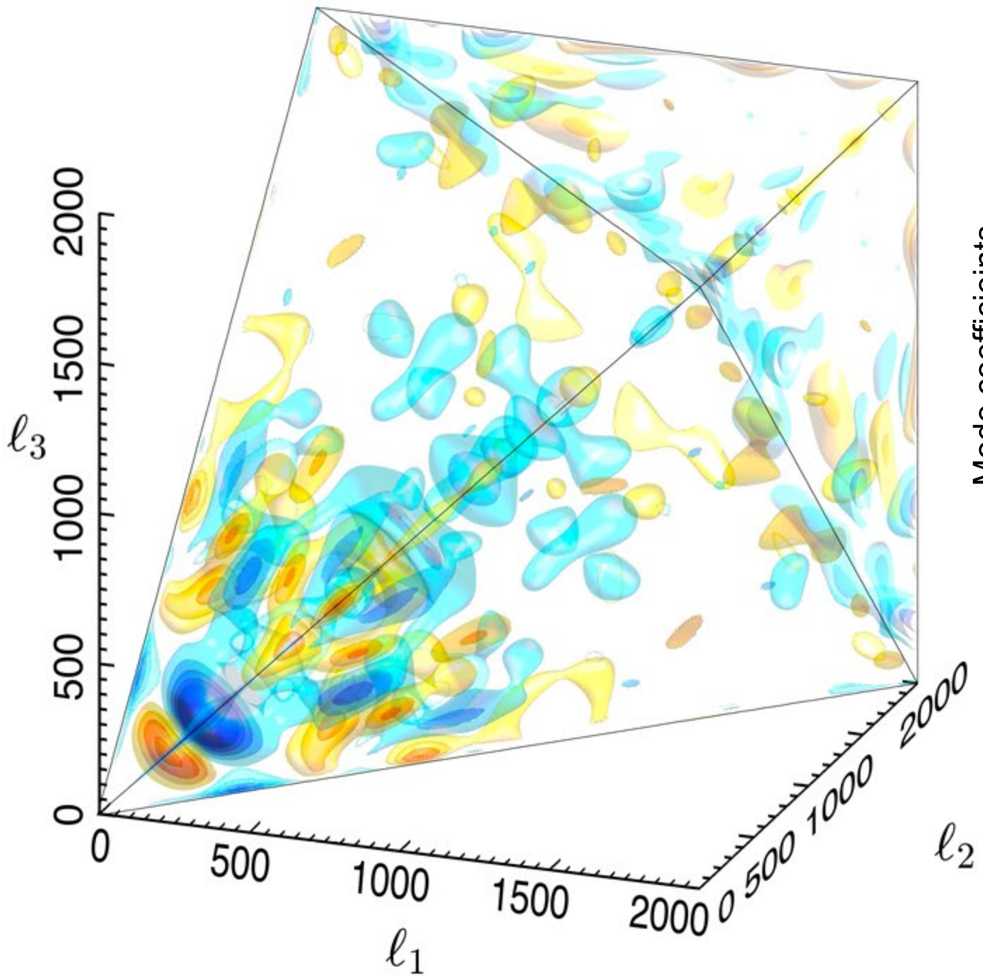
Constraints from Planck

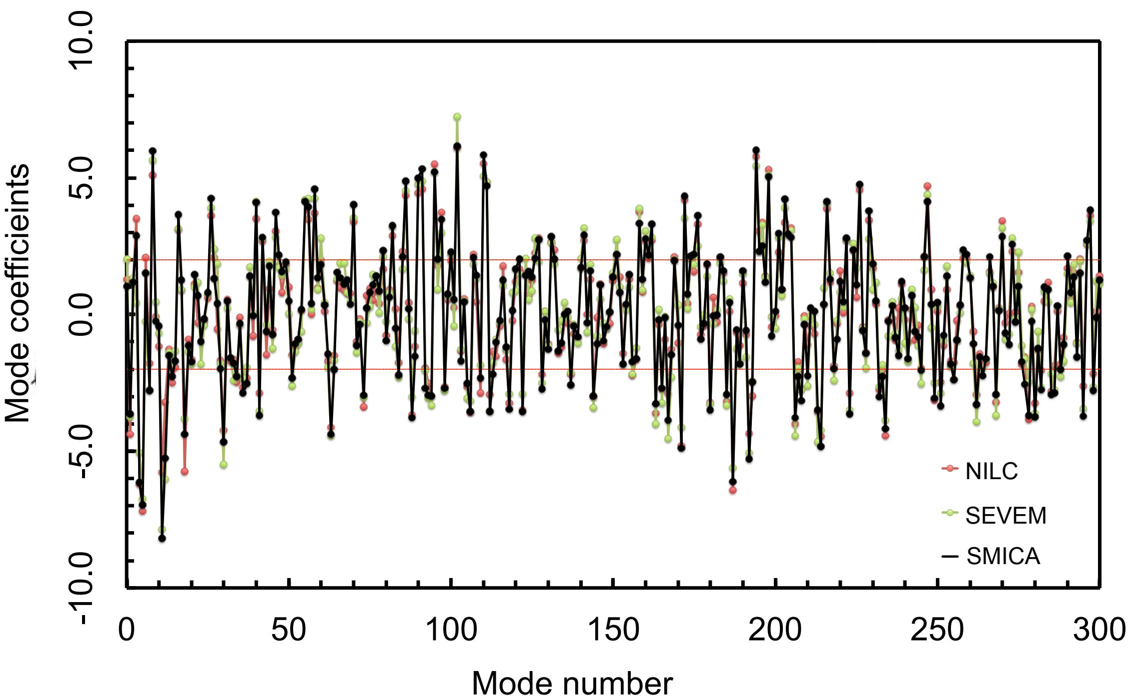
	ISW-lensing subtracted		
	KSW	Binned	Modal
SMICA			
Local	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	**−25 ± 39**	−17 ± 41	−14 ± 42
NILC			
Local	4.5 ± 5.8	3.6 ± 5.8	2.7 ± 6.0
Equilateral	−48 ± 76	−38 ± 73	−20 ± 78
Orthogonal	−53 ± 40	−41 ± 41	−37 ± 43
SEVEM			
Local	3.4 ± 5.9	3.2 ± 6.2	2.6 ± 6.0
Equilateral	−36 ± 76	−25 ± 73	−13 ± 78
Orthogonal	−14 ± 40	−9 ± 42	−2 ± 42
C-R			
Local	6.4 ± 6.0	5.5 ± 5.9	5.1 ± 5.9
Equilateral	−62 ± 79	−55 ± 74	−32 ± 78
Orthogonal	−57 ± 42	−41 ± 42	−42 ± 42

Planck collaboration XXIV, 2013

Constraints from Planck: modal expansion

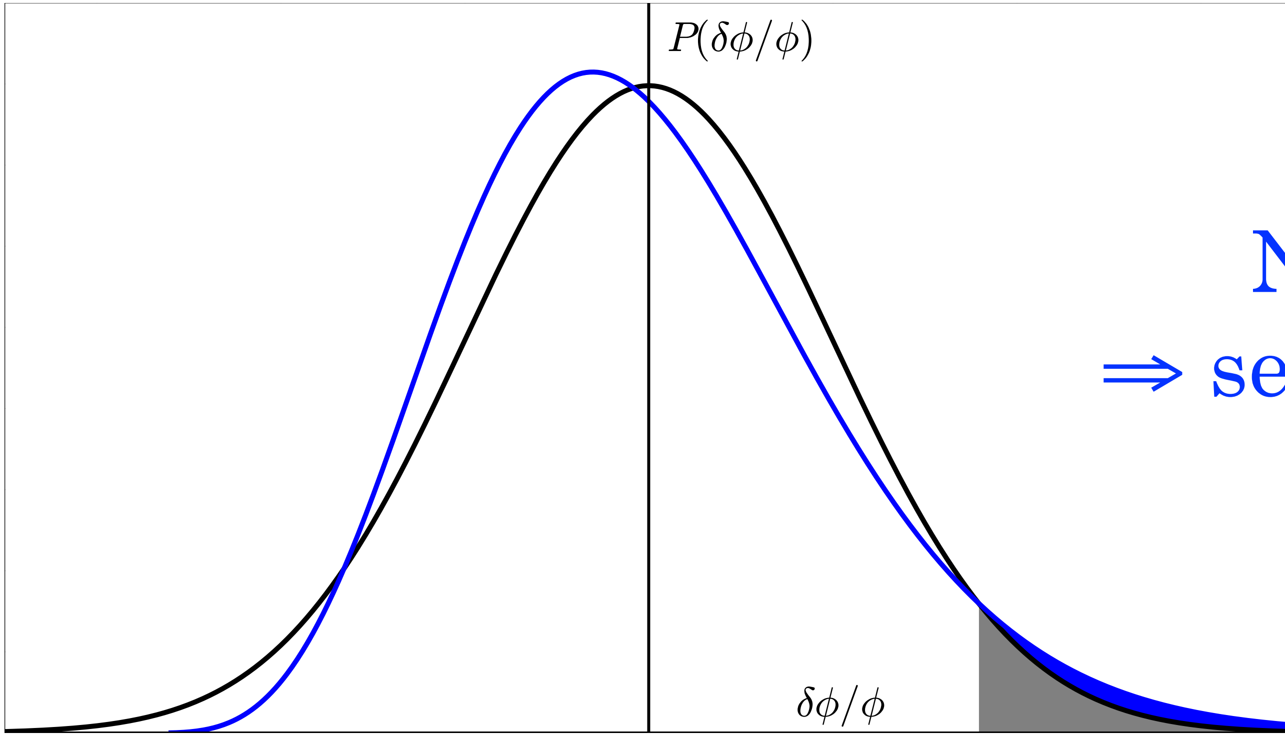
$$B(k_1, k_2, k_3) = \sum_{p,r,s} \alpha_{prs}\, q_p(k_1) q_r(k_2) q_s(k_3)$$





Planck collaboration XXIV, 2013

Galaxy cluster counts' sensitivity to NG



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

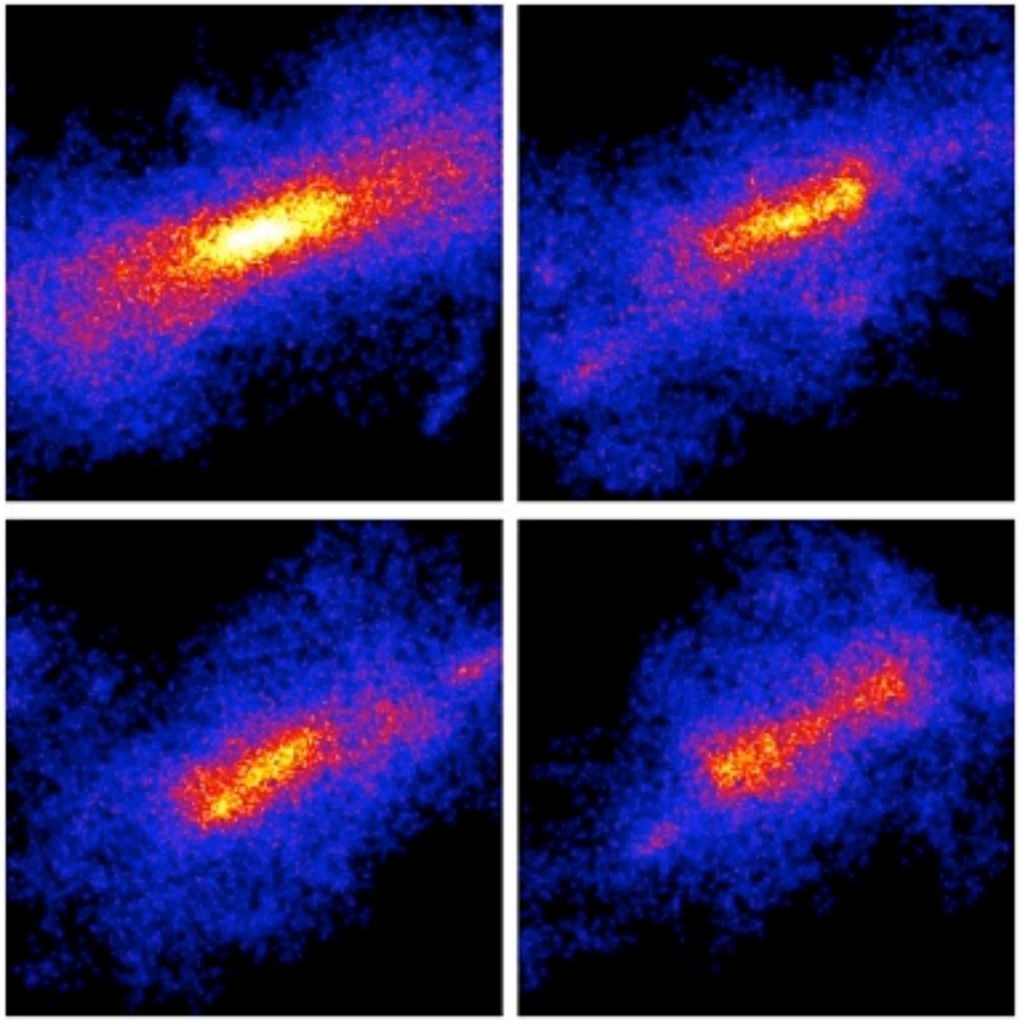
(amount of NG shown is >100× bigger than allowed by data!)

Lots of effort in the community to calibrate
the non-Gaussian mass function -
dn/dlnM(M, z) - of DM halos
(analytic extensions of Press-Schechter + simulations)

DM halo gets more massive with fNL>0 (and v.v.)

f_{NL}=+5000
M=1.2 10^{16} $M_\odot$

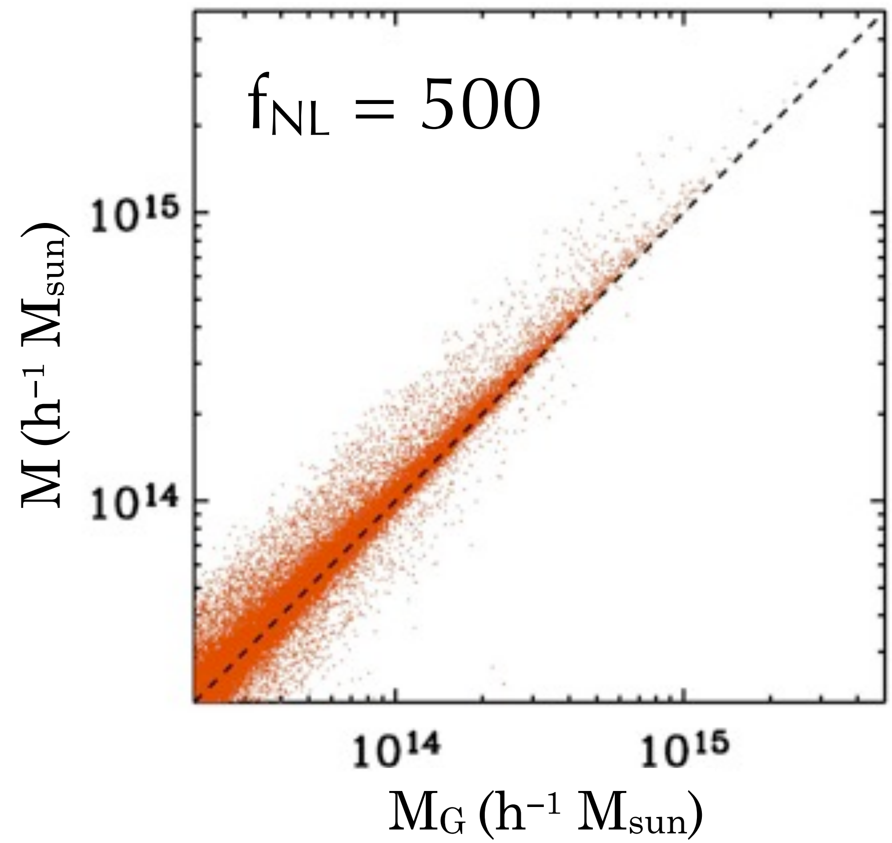
f_{NL}=+500
M=5.9 10^{15} $M_\odot$



f_{NL}=0
M=5.1 10^{15} $M_\odot$

f_{NL}=-500
M=4.3 10^{15} $M_\odot$

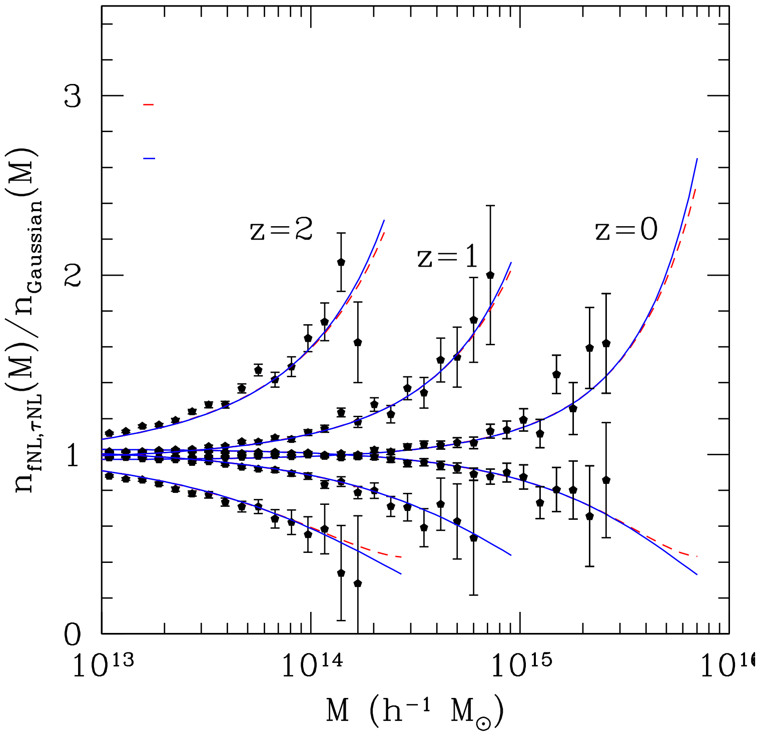
Mapping between
M_G and $M \equiv M_{NG}$:



$\Rightarrow$ NG mass function:

$$\frac{dN}{dM} = \int \frac{dP(M|M_G)}{dM} \frac{dN}{dM_G} dM_G$$

Dalal, Doré, Huterer & Shirokov 2008



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. $\sigma(f_{NL})$=450 measured from SPT (Williamson et al 2010)

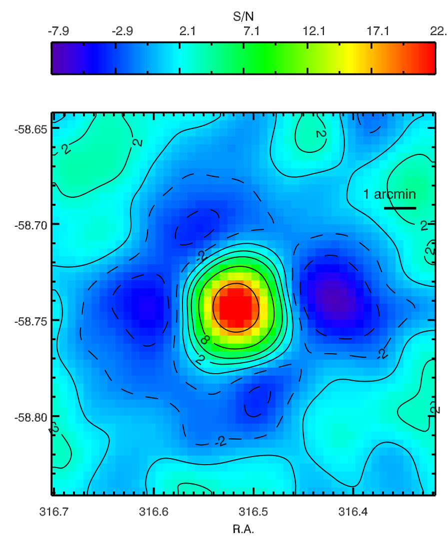
Nevertheless:

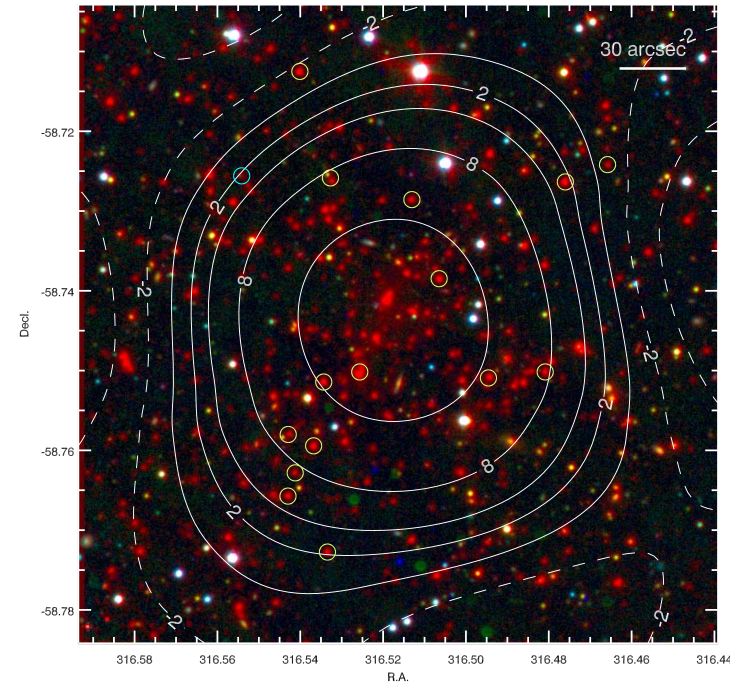
- cluster abundance is sensitive to ALL non-Gaussianity
- (large) amount of (local model) NG can boost the number of ‘pink elephant’ clusters

High-z, high-M - "pink elephant" - clusters of galaxies

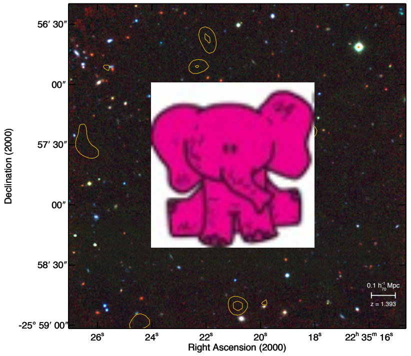
- SPT-CL J0546-5045: $z=1.067$, $M \approx (8.0 \pm 1.0) \cdot 10^{14}\, M_{sun}$
- XMMU J2235.3-2557: $z=1.39$, $M \approx (8.5 \pm 1.7) \cdot 10^{14}\, M_{sun}$
- SPT-CL J2106-8544: $z=1.132$, $M \approx (1.3 \pm 0.2) \cdot 10^{15}\, M_{sun}$

Some authors have claimed the existence of these clusters is in conflict with LCDM, but can be explained with (huge; $f_{NL} \sim 500$) **non-Gaussianity**





Hoyle, Jimenez & Verde (2011);
Cayon, Gordon & Silk (2011);
Holz & Perlmutter 2011



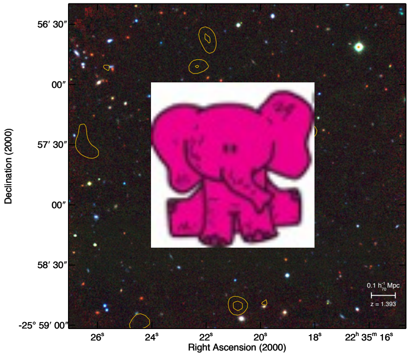
Are the pink elephants in conflict with LCDM?!

4 things to account for:

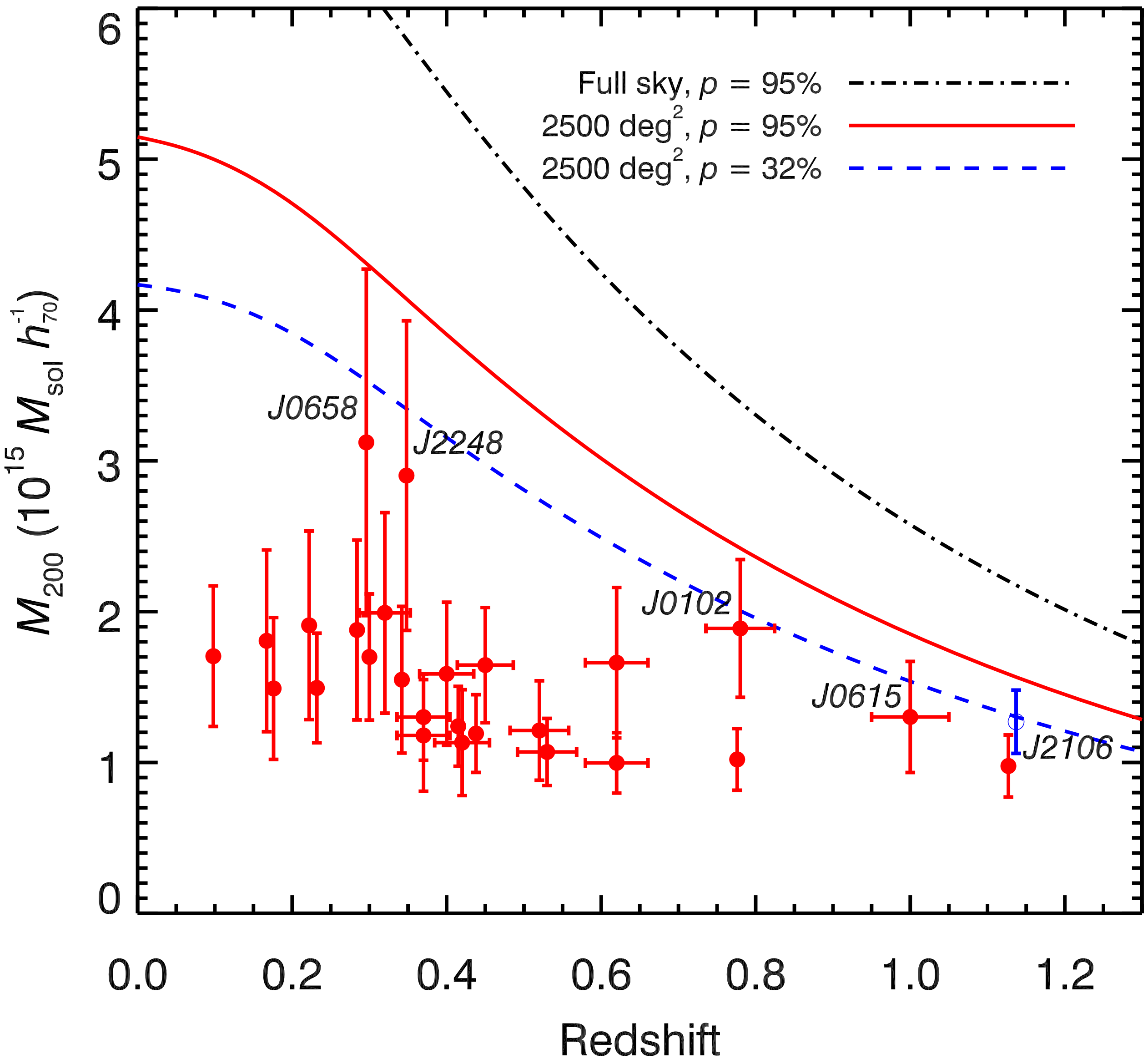
1. **Sample variance** - the Poisson noise in counting rare objects in a finite volume
2. **Parameter variance** - uncertainty due to fact that current data allow cosmological parameters to take a range of values
3. **Eddington bias** - mass measurement error will preferentially ‘scatter’ the cluster 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 2011



No conflict - for now.



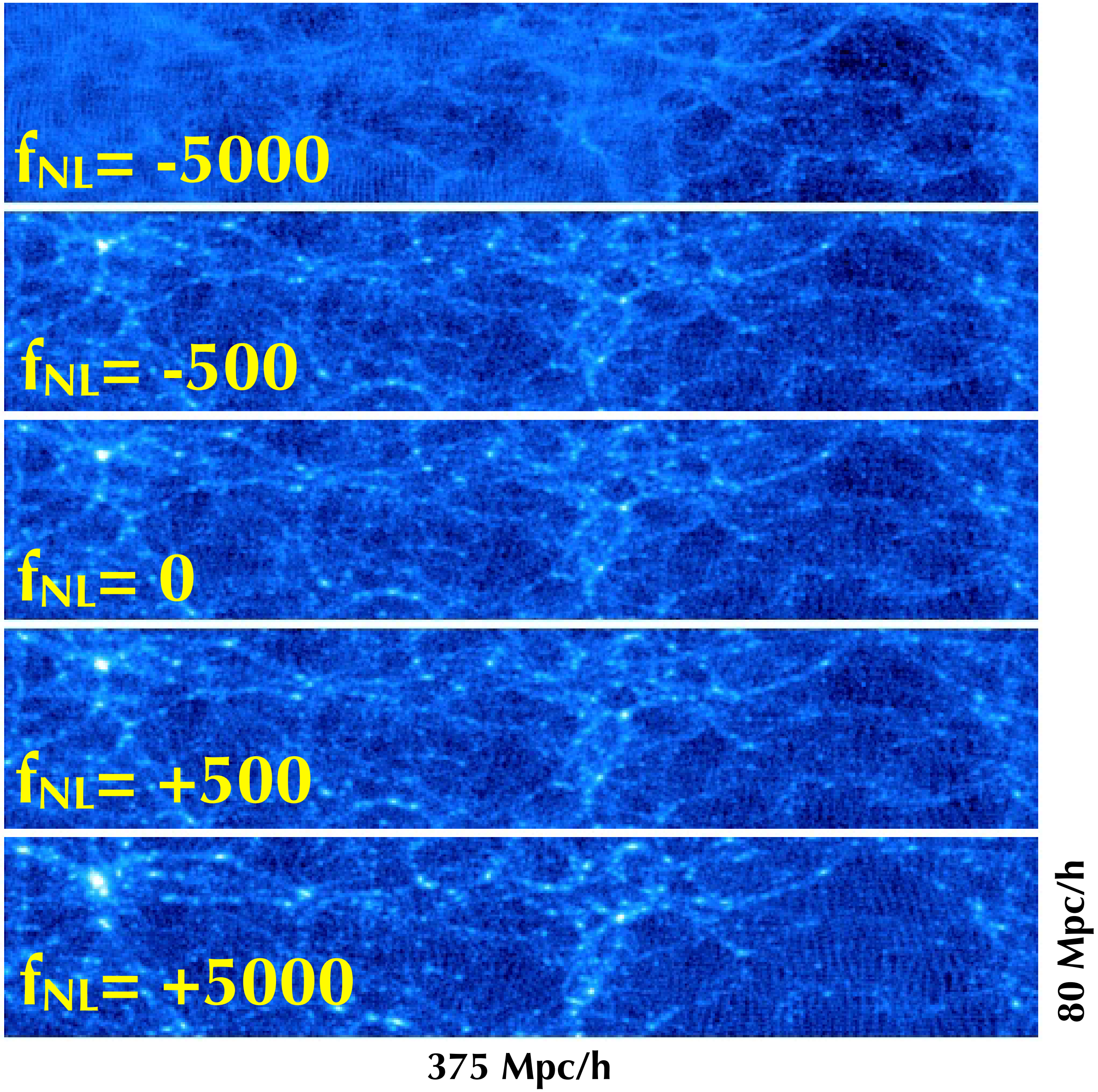
Foley et al 2011 arXiv:1101.1286 (SPT team);
Mortonson, Hu & Huterer 2011

Next Frontier: Large-Scale Structure

	CMB	LSS
dimension	2D	3D
# modes	$\propto l_{max}{}^2$	$\propto k_{max}{}^3$
systematics & selection func.	relatively clean	relatively messy
temporal evol.	no	yes
can slice in	λ only	λ, M, bias...

Effects of primordial NG
on the bias of virialized objects

Simulations with non-Gaussianity (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 2008

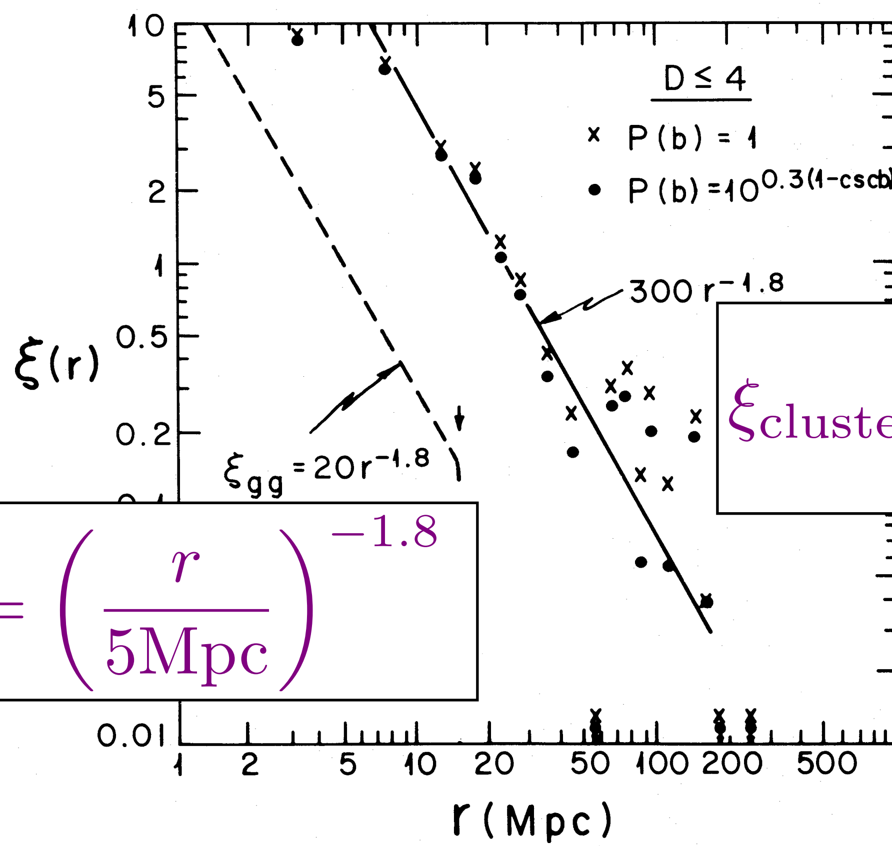
Does galaxy/halo bias depend on NG?

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

cosmologists measure

theory predicts

usually nuisance parameter(s)



$$\xi_{\text{clusters}}(r) = \left(\frac{r}{25\text{Mpc}}\right)^{-1.8}$$

$$\xi_{\text{galaxies}}(r) = \left(\frac{r}{5\text{Mpc}}\right)^{-1.8}$$

Bahcall & Soneira 1983

Bias of dark matter halos

$$P_h(k,z) = \boxed{b^2(k,z)}\, P_{\rm DM}(k,z)$$

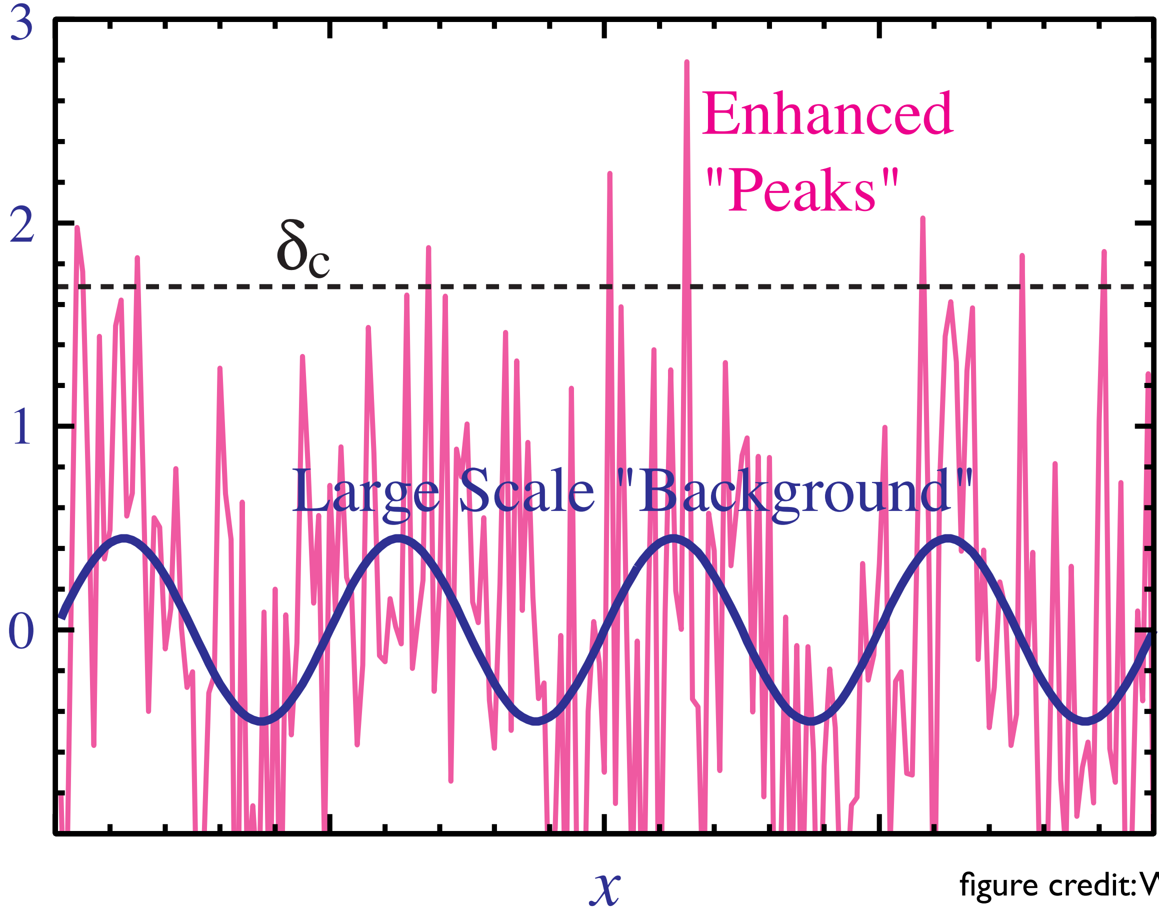
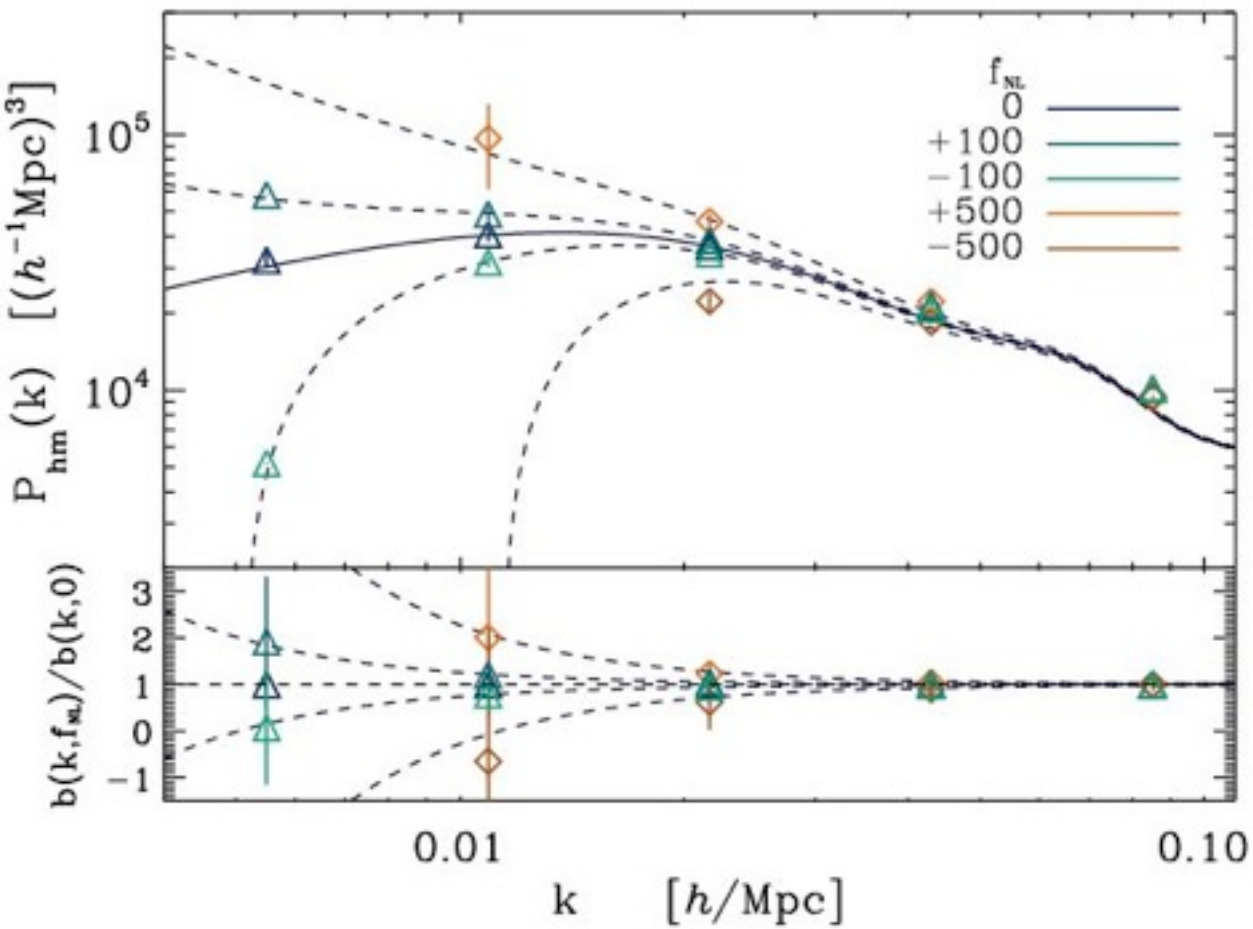


figure credit: Wayne Hu

Simulations and theory both say: large-scale bias is scale-independent
(theorem if halo abundance is function of local density
and if the short and long modes are uncorrelated)

Scale dependence of NG halo bias



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

Verified using a variety of theoretical derivations and numerical simulations.

Dalal, Doré, Huterer & Shirokov 2008

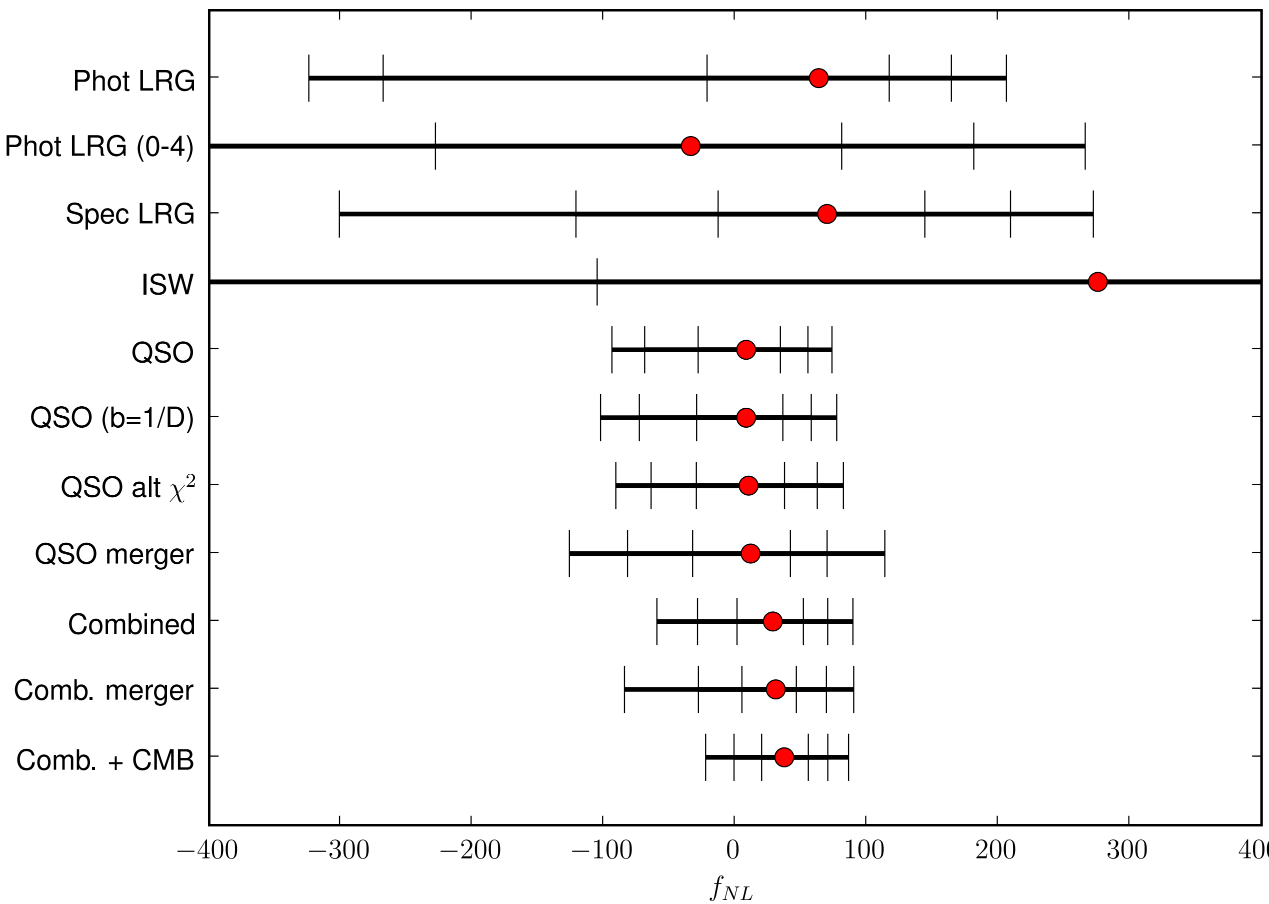
$$\Delta b(k) = f_{\rm NL}(b_G - 1)\,\delta_c\,\frac{3\,\Omega_M H_0^2}{T(k)D(a)k^2}$$

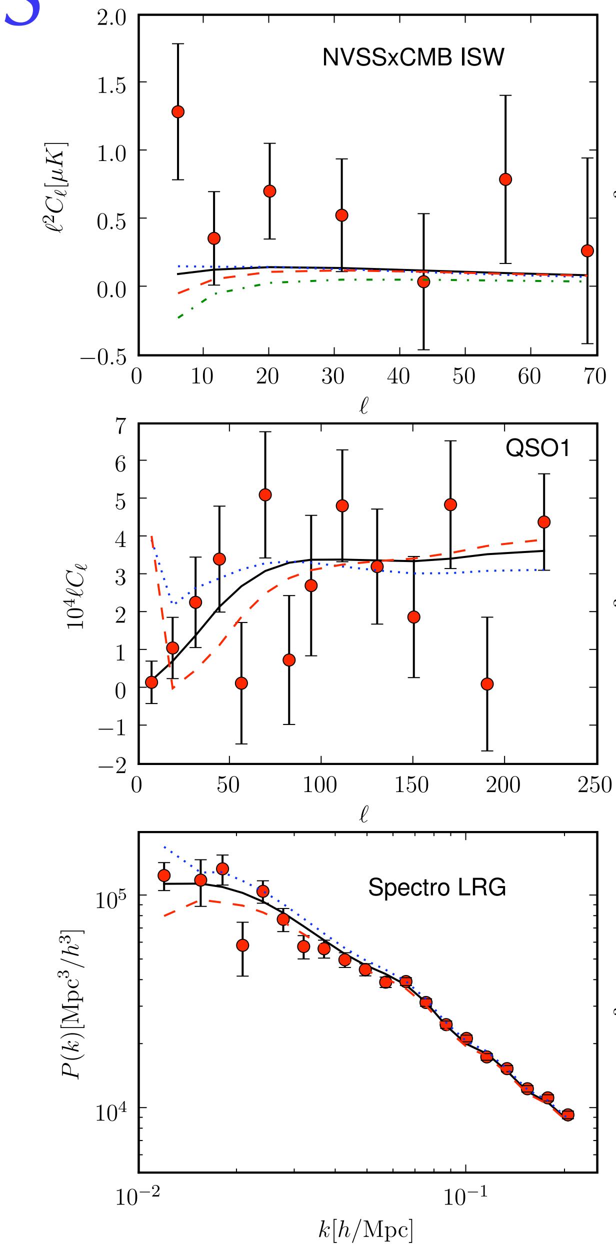
Implications:

- Unique $1/k^2$ scaling of bias; no free parameters
- Distinct from effect of all other cosmo parameters
- Straightforwardly measured (g-g, g-T,...)
- Derived theoretically several different ways
- Extensively tested with numerical simulations; good agreement found

Dalal et al.; 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

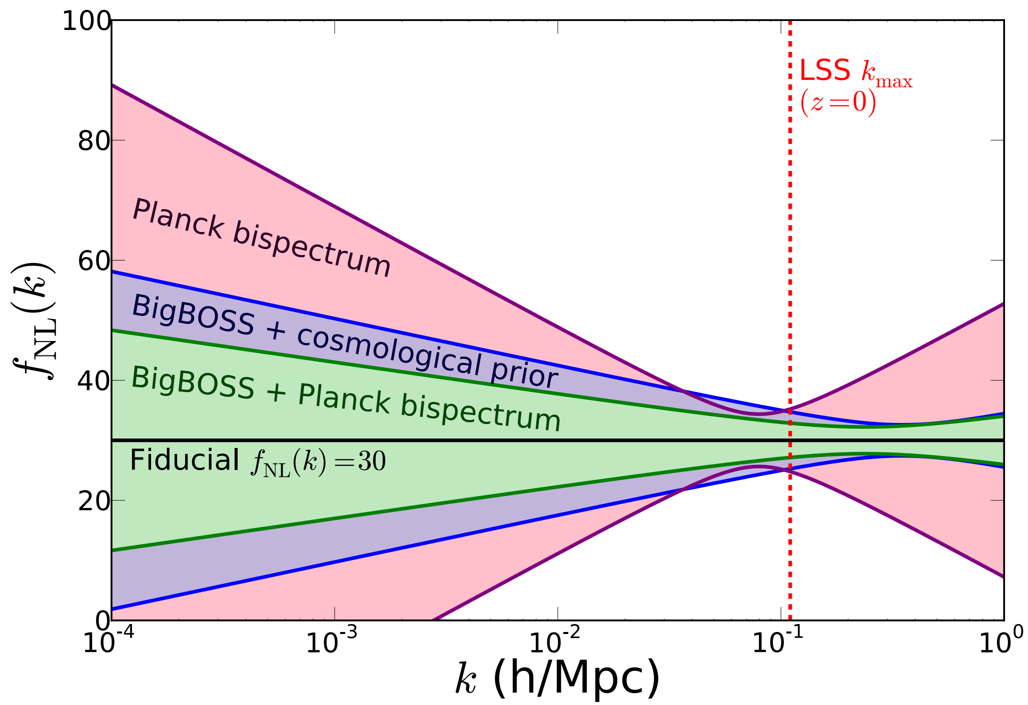
Future data forecasts for LSS: $\sigma(f_{NL}) \approx O(\text{few})$
(at least?) as good as, and highly complementary, to Planck CMB

More general NG models: beyond f_{NL}

More generic NG: $f_{NL}(k)$ forecasts

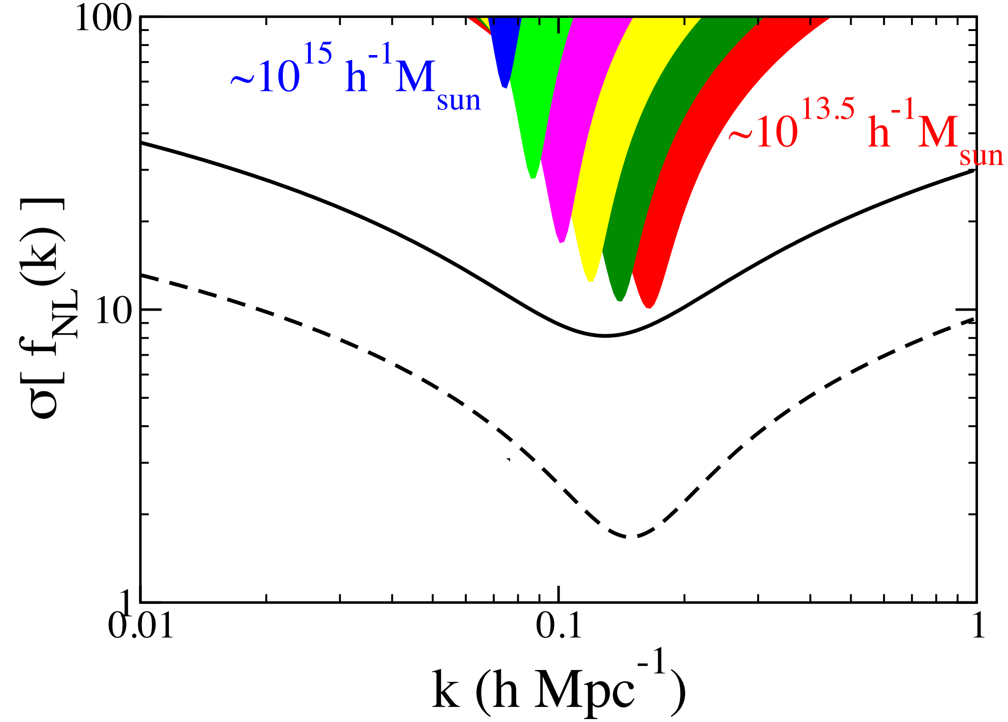
$$f_{\rm NL}(k) = f^*_{\rm NL}\left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

CMB and LSS are very complementary



Becker, Huterer & Kadota 2012, Shandera, Dalal & Huterer 2012

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



In general, LSS can probe:

$$\Delta b_{NG} \propto \begin{cases} k^{-2} \text{ (local)} \\ k^{-1} \text{ (folded)} \\ k^{0} \text{ (equilateral)} \\ k^{-\alpha} \text{ (generic); } 0 \le \alpha \le 3 \end{cases}$$

Forecasts for $f_{NL}(k)$

$$f_{\rm NL}(k) = f_{\rm NL}^{*} \left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

Projected errors $\sigma(f_{\rm NL}^*)$ and $\sigma(n_{f_{\rm NL}})$, and the corresponding pivots

Variable	BigBOSS	BigBOSS+Planck C_ℓs	Planck bispec	**BigBOSS+all Planck**
$\sigma(f_{\rm NL}^*)$	3.0	2.6	4.4	2.2
$\sigma(n_{f_{\rm NL}})$	0.12	0.11	0.29	0.078
$\mathrm{FoM}^{(\mathrm{NG})}$	2.7	3.4	0.78	5.8
k_{piv}	0.33	0.35	0.080	0.24

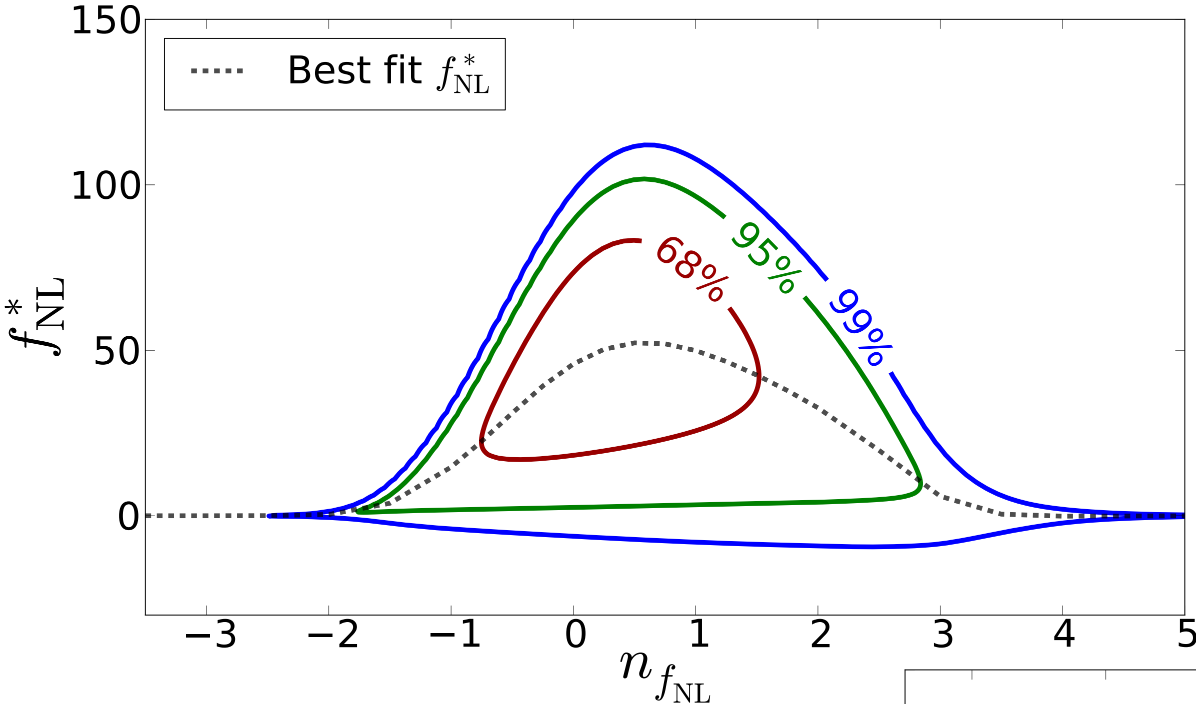
area in f_{NL}^*-n_{fNL} plane

NB: The LSS forecasts are very uncertain, much more so than the CMB

Becker, Huterer & Kadota, 2012

First constraints on the running of NG

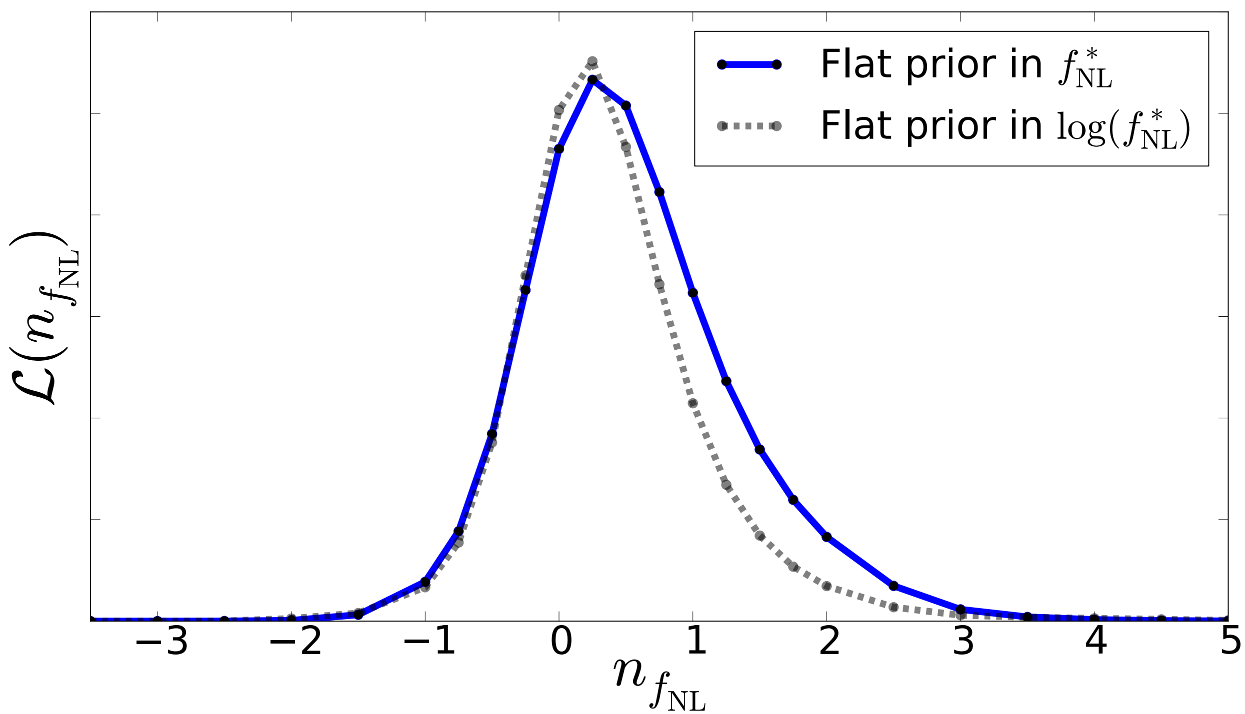
WMAP7 data, modified KSW estimator



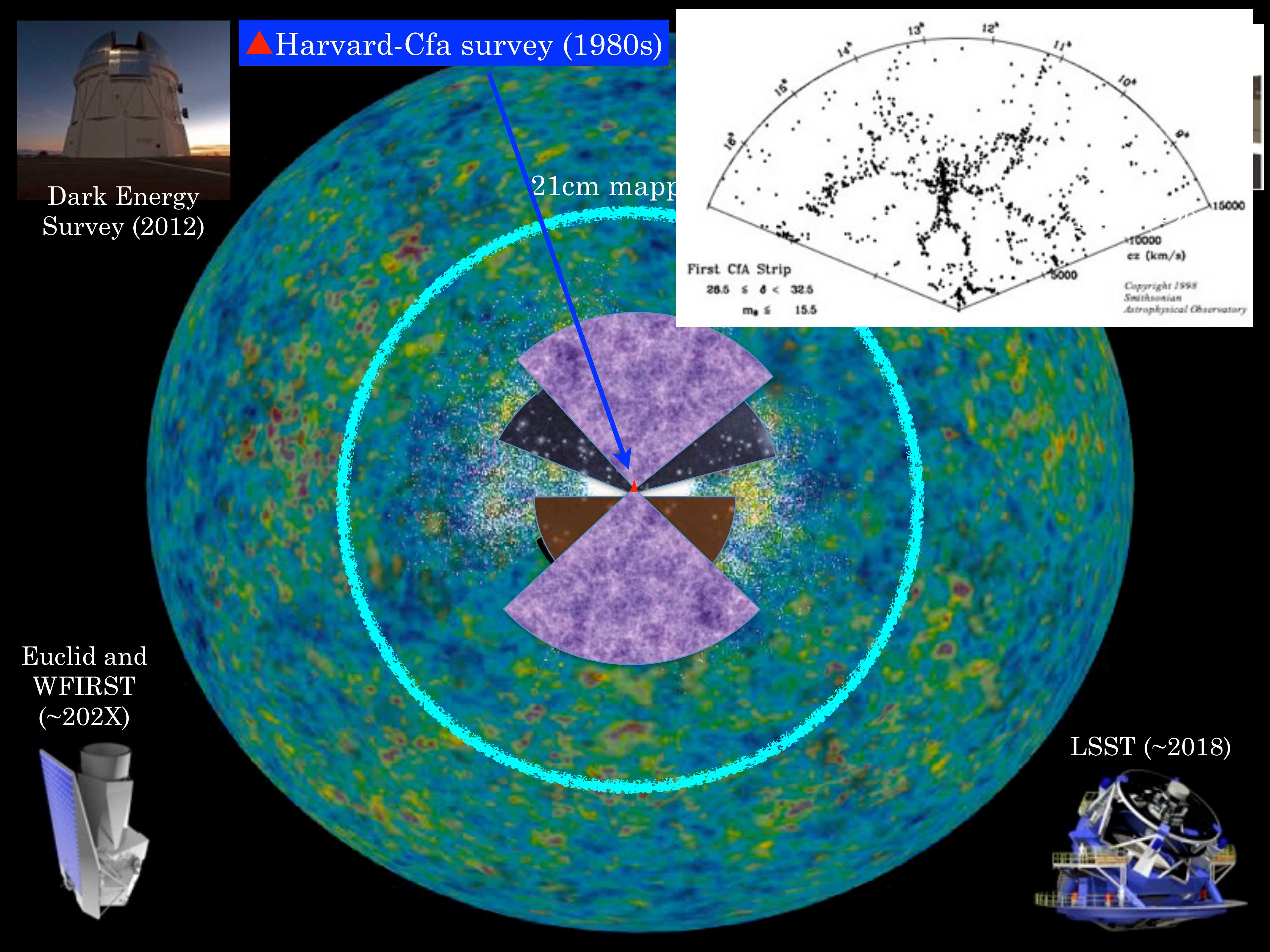
$$f_{\rm NL}(k) = f^*_{\rm NL}\left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

$$n_{f_{\rm NL}} = 0.3^{+1.9}_{-1.2}$$

at 95% CL



Becker & Huterer, PRL 2012


Harvard-Cfa survey (1980s)
Dark Energy Survey (2012)
21cm mapp
First CfA Strip
26.5 ≤ δ < 32.5
m$_B$ ≤ 15.5
15000
10000
5000
cz (km/s)
Copyright 1998 Smithsonian Astrophysical Observatory
Euclid and WFIRST (~202X)
LSST (~2018)

Challenges for NG program

... and approximate current status

- Motivate simple and more complicated NG models
✓ (single-field, multiple fields, self-interactions)
- Utilize a variety of observables in LSS and CMB to get at NG ✓
- Develop fast, near-optimal estimators to extract NG from the CMB ✓
- Develop theory to relate NG models to LSS observables ✓✗ (messy; still need to check with sims)
- Develop theory to use LSS info from quasi-linear scales ($k \lesssim 0.1\ h^{-1}$ Mpc) ✓✗
- Control the systematic errors, esp large-scale LSS ✓✗
- Use LSS bispectrum to get at primordial NG ✗

Advances in Astronomy special issue on

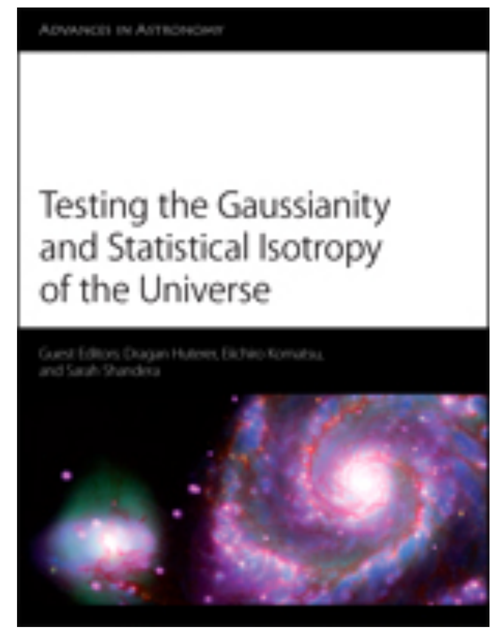
“Testing the Gaussianity and Statistical Isotropy of the Universe”

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,

EXTRA SLIDES

Scale-dependent nongaussianity? Generalized local ansatz

Becker, Huterer & Kadota 2011, 2012
theory motivation: **Byrnes et al**, etc

- 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...

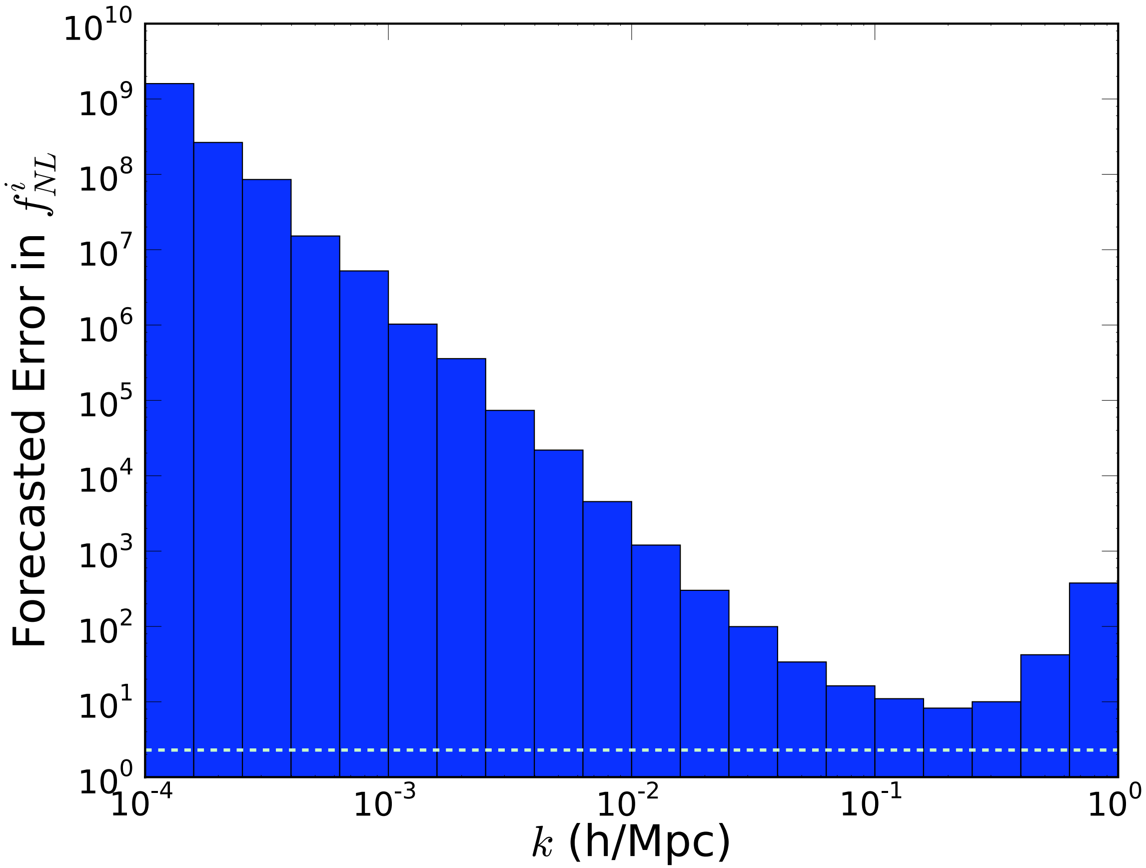
$$\Phi(x) = \phi_G(x) + f_{\rm NL}\left[\phi_G^2(x) - \langle\phi_G^2\rangle\right]$$

...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, 2011, 2012

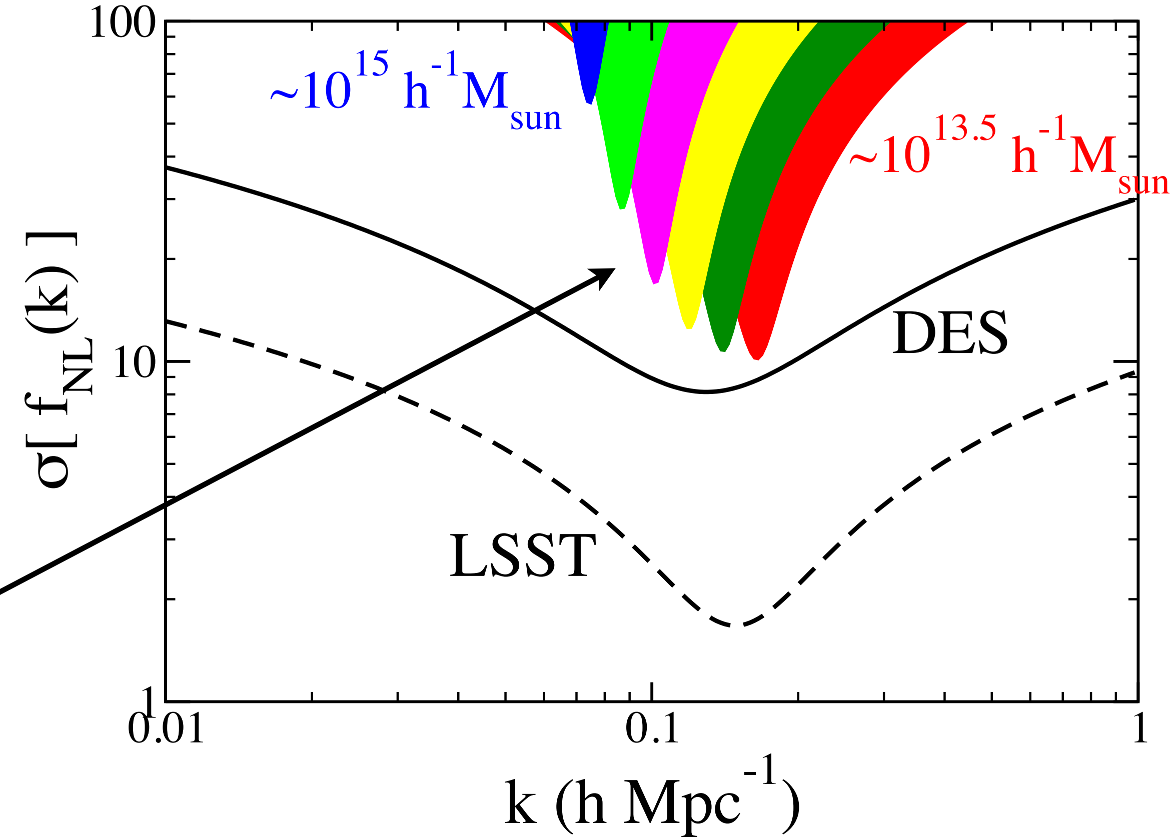
Future: using LSS to probe scale-dependent NG

- Scale-dep NG models are motivated by particle theory (single-field inflation with self-interaction; mixed curvaton-inflaton models)
- Effects on LSS are significant, but theory predictions are uncertain ⇒ ongoing theoretical and simulation work
- Understanding of astrophysics (of DM halos, etc) required in order to probe fundamental physics

Scale-dependent NG ansatz:

$$f_{\rm NL}(k) = f^*_{\rm NL}\left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

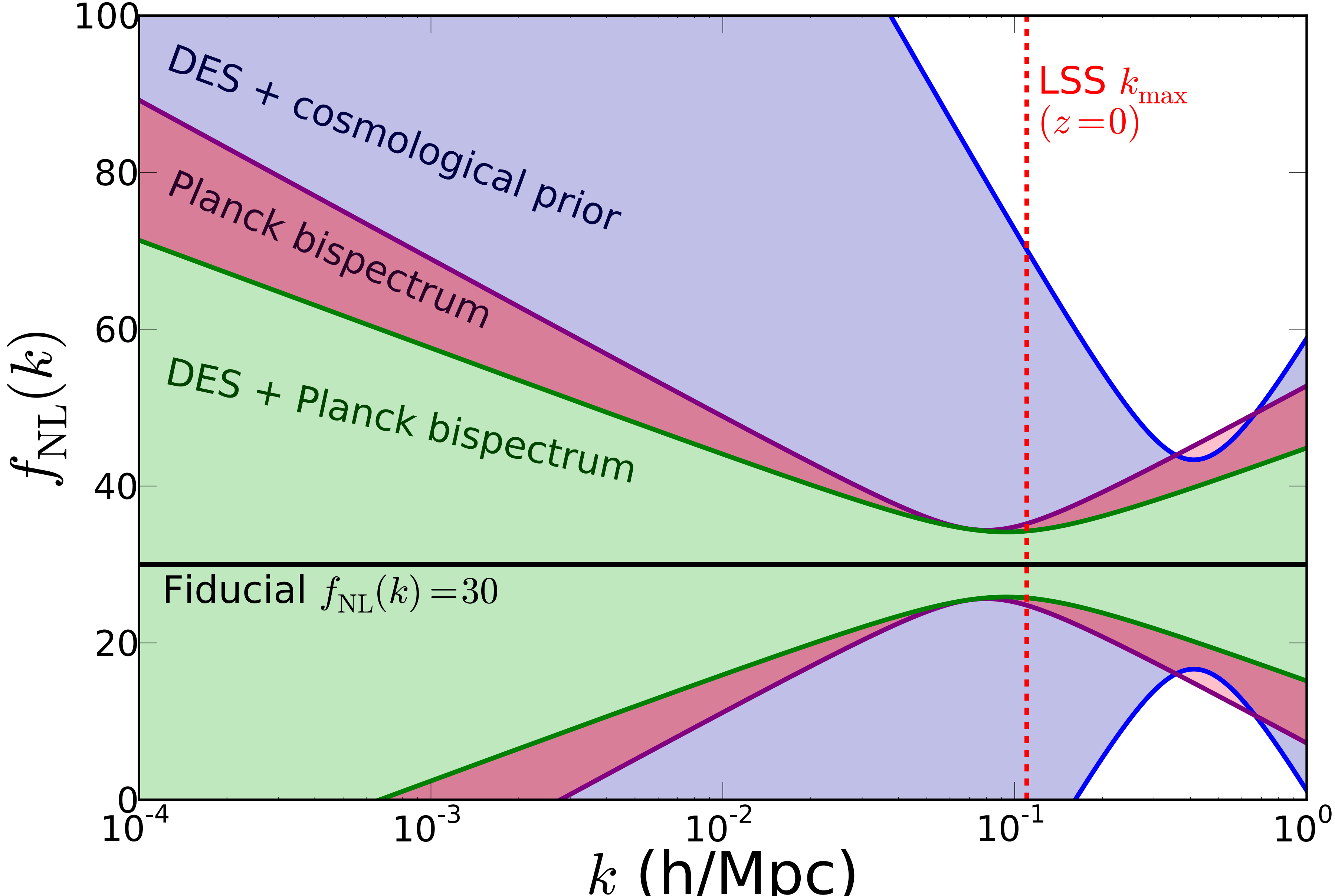
Halos of mass M probe NG on scale $k \sim M^{-1/3}$



Shandera, Dalal & Huterer, 2011

CMB, LSS, and CMB+LSS **forecasts**

$$f_{\rm NL}(k) = f^*_{\rm NL}\left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$



Becker, Huterer & Kadota, 2012