The Quest for Primordial Non-Gaussianity

Overview and some recent developments

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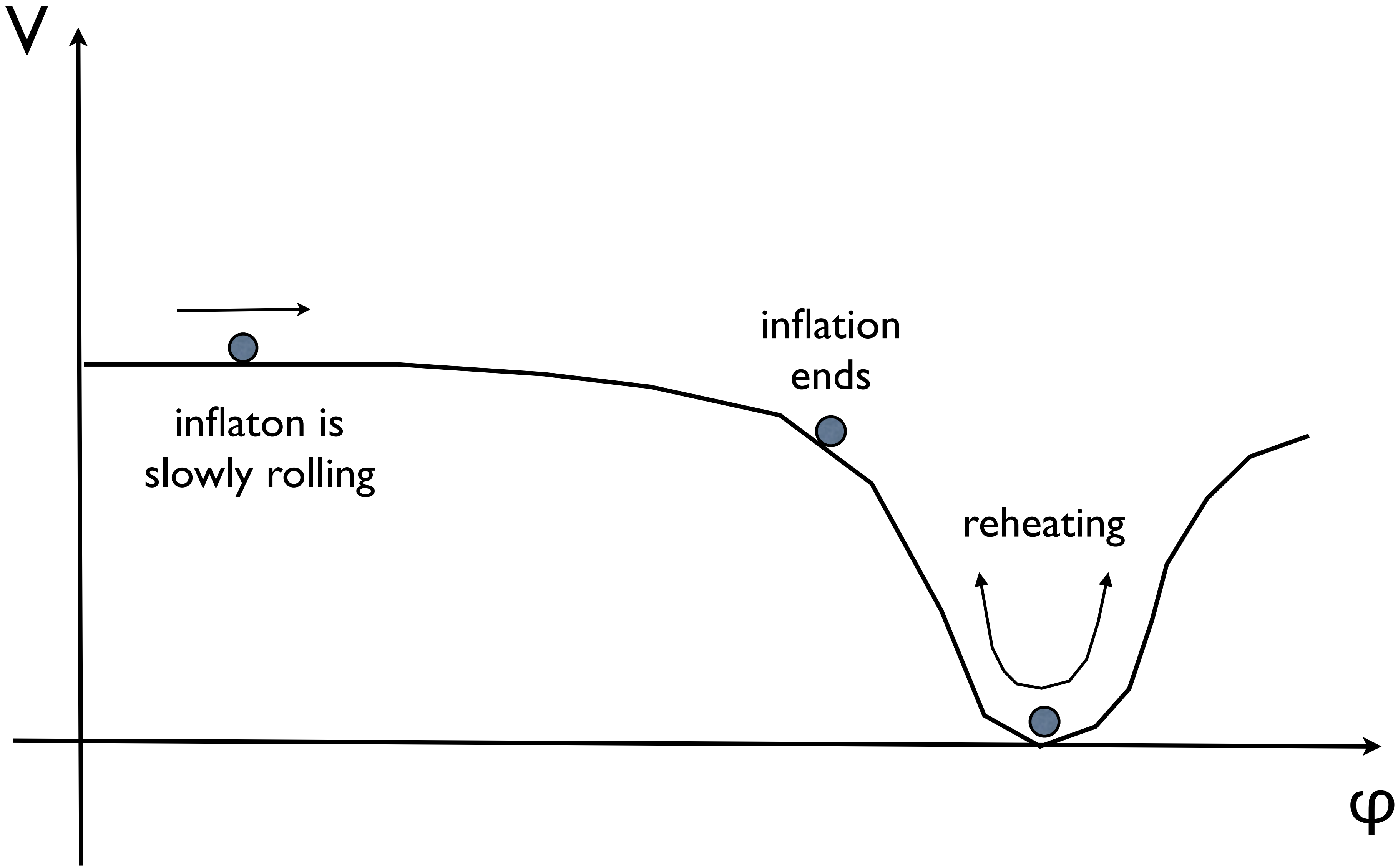
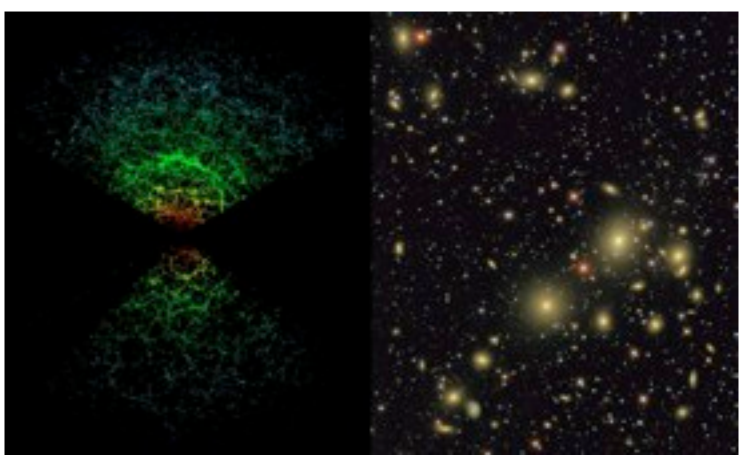
Motivation: testing Inflation

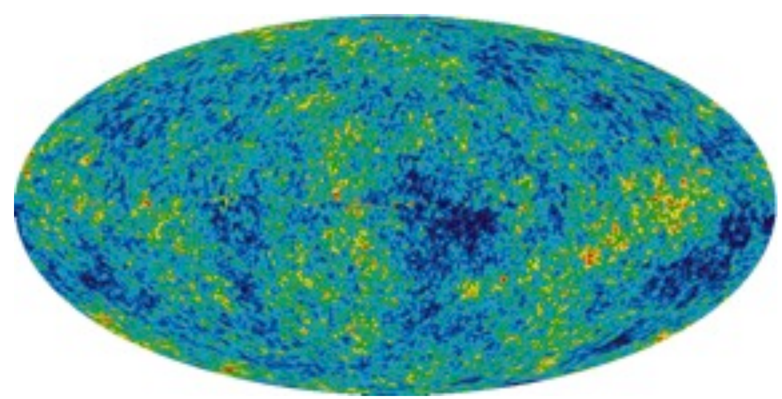


Why study non-Gaussianity (NG)?

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

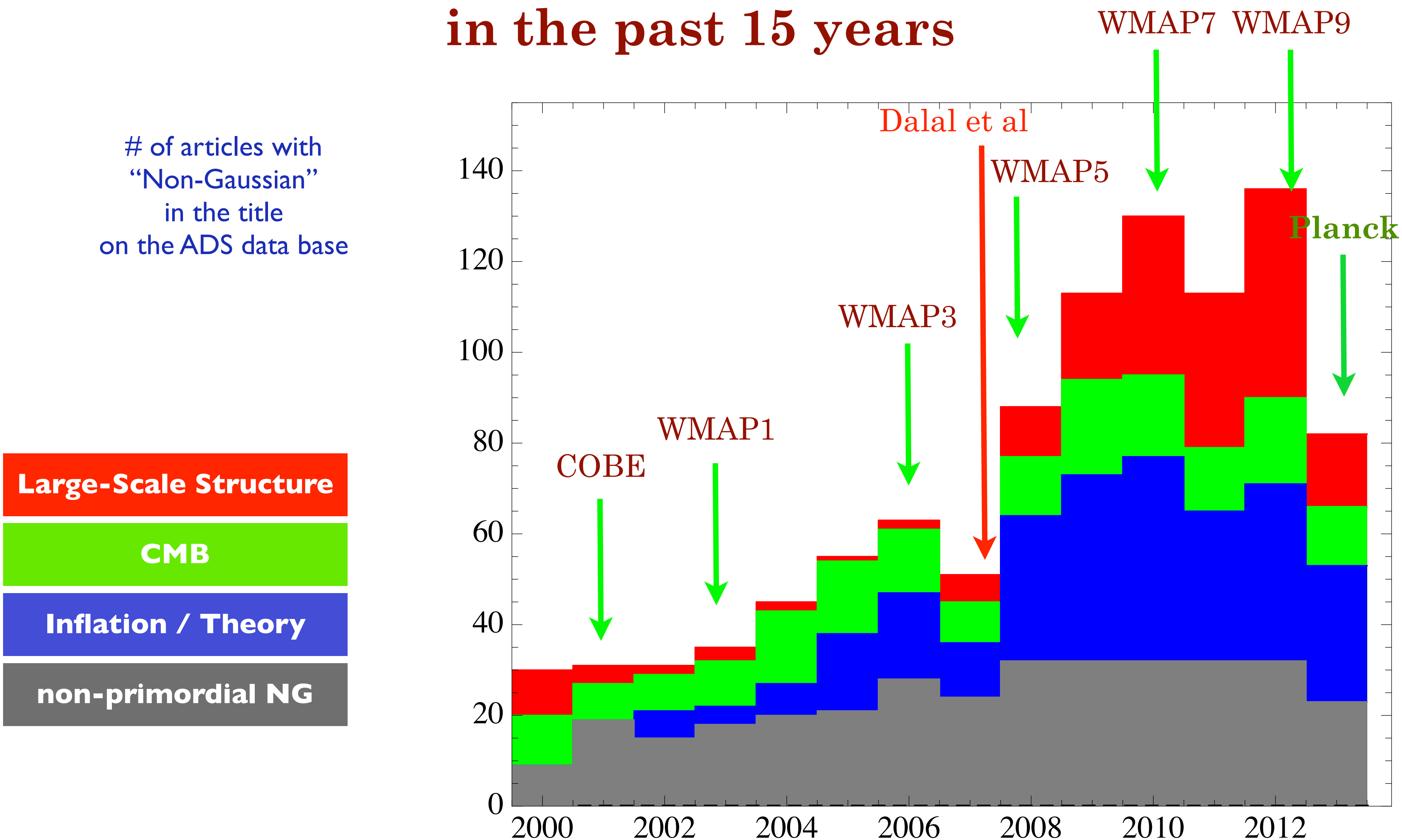
2. Conveniently, NG can be constrained/measured using CMB anisotropy maps and LSS. In particular, there is a rich set of observable quantities that are sensitive to primordial NG.





Non-Gaussianity papers in the past 15 years

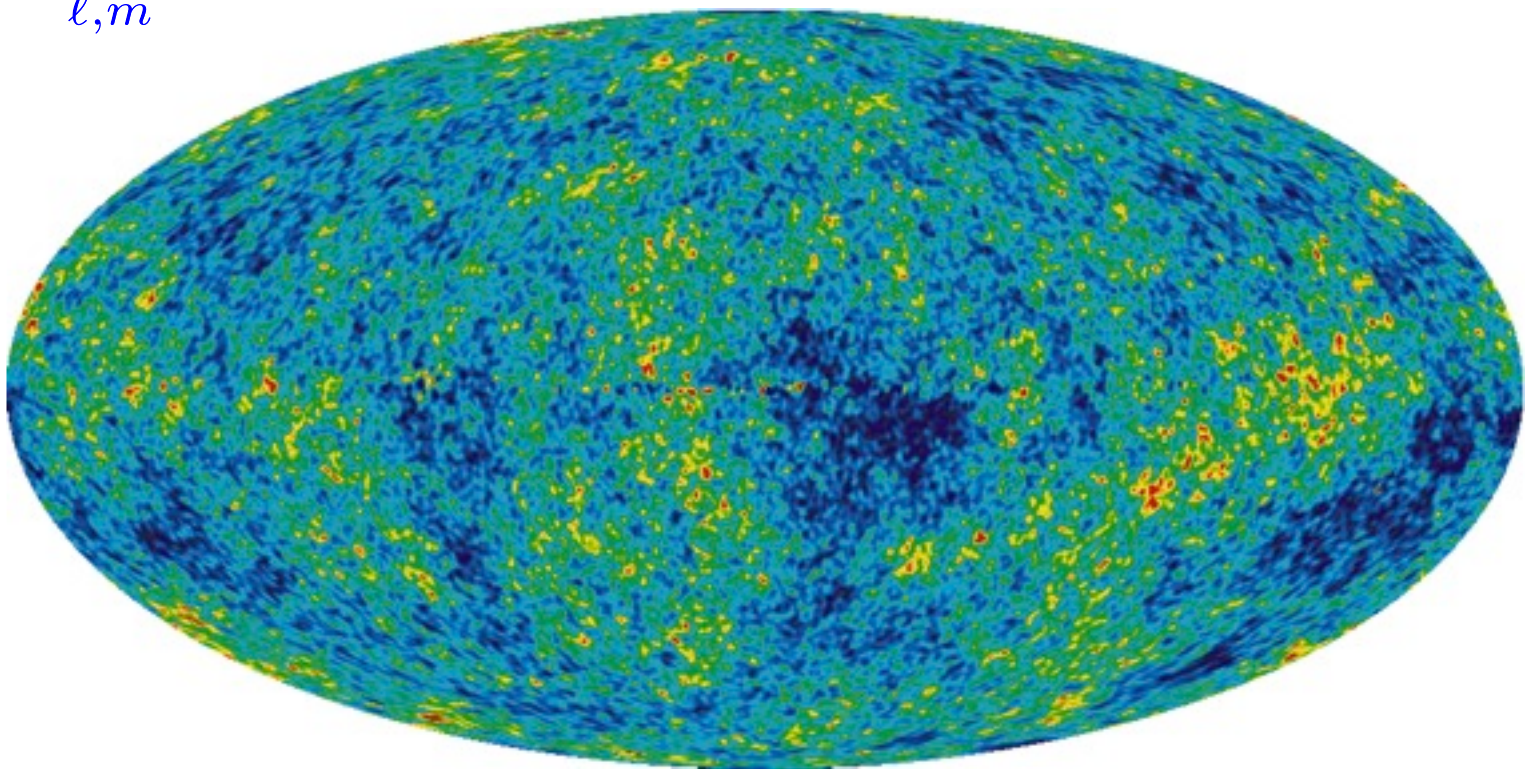
of articles with "Non-Gaussian" in the title on the ADS data base



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:

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

Statistical Isotropy:

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

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

Recall: power spectrum

Define Fourier transform of density fluctuation: $$\delta(\vec{r}) = \int \frac{d^3k}{(2\pi)^3}\, e^{-i\vec{k}\vec{r}}\, \delta_{\vec{k}}$$

Then the power spectrum P(k) is defined via

$$\langle \delta_{\vec{k}_1}\, \delta_{\vec{k}_2^*} \rangle = (2\pi)^3\, \delta^{(3)}(\vec{k}_1 + \vec{k}_2)\, P(k)$$

Sometimes it's nice to work in harmonic space

$$a_{\ell m} = 4\pi(-i)^\ell \int \frac{d^3k}{(2\pi)^3}\, T_\ell(k)\, \delta(\vec{k})\, Y_{\ell m}(\hat{k})$$

Then the angular power spectrum is defined as: $$\langle a_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'}\, C_\ell$$

The bispectrum:

similar, but for 3-pt function

Fourier space:

$$\langle \delta_{\vec{k}_1}\, \delta_{\vec{k}_2}\, \delta_{\vec{k}_3} \rangle = (2\pi)^3\, \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\, B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

Harmonic space:

$$\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle \equiv B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}$$

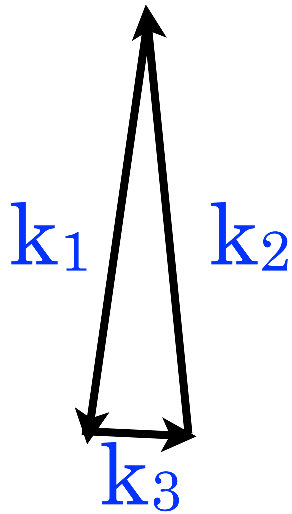
and the angle-averaged bispectrum is

$$B_{\ell_1\ell_2\ell_3} \equiv \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell+1)}{4\pi}} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}$$

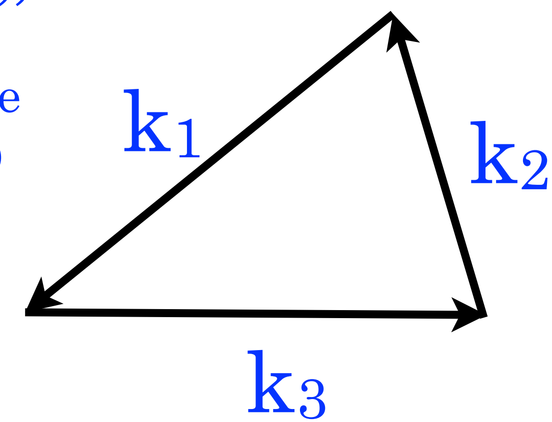
3-pt correlation function of CMB anisotropy
⇒ direct window into inflation

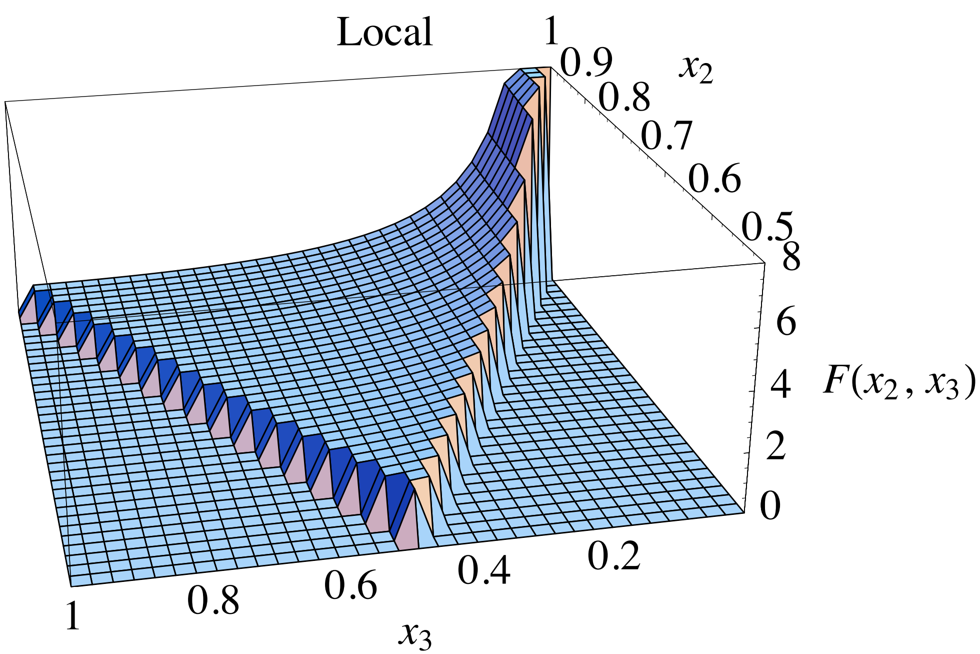
e.g. Luo & Schramm 1993

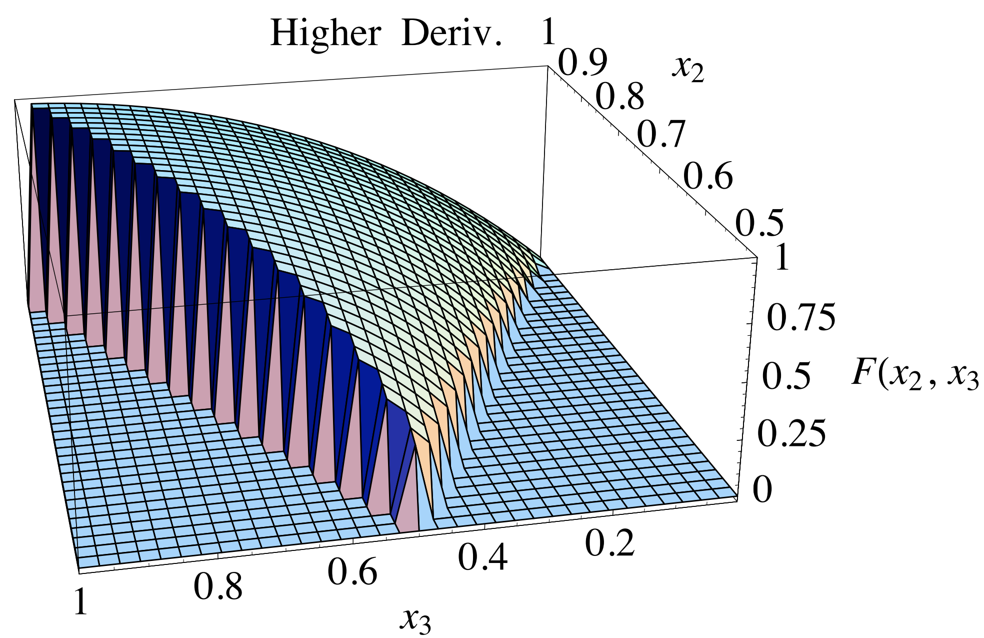
"local"
(eg. multi-field)



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

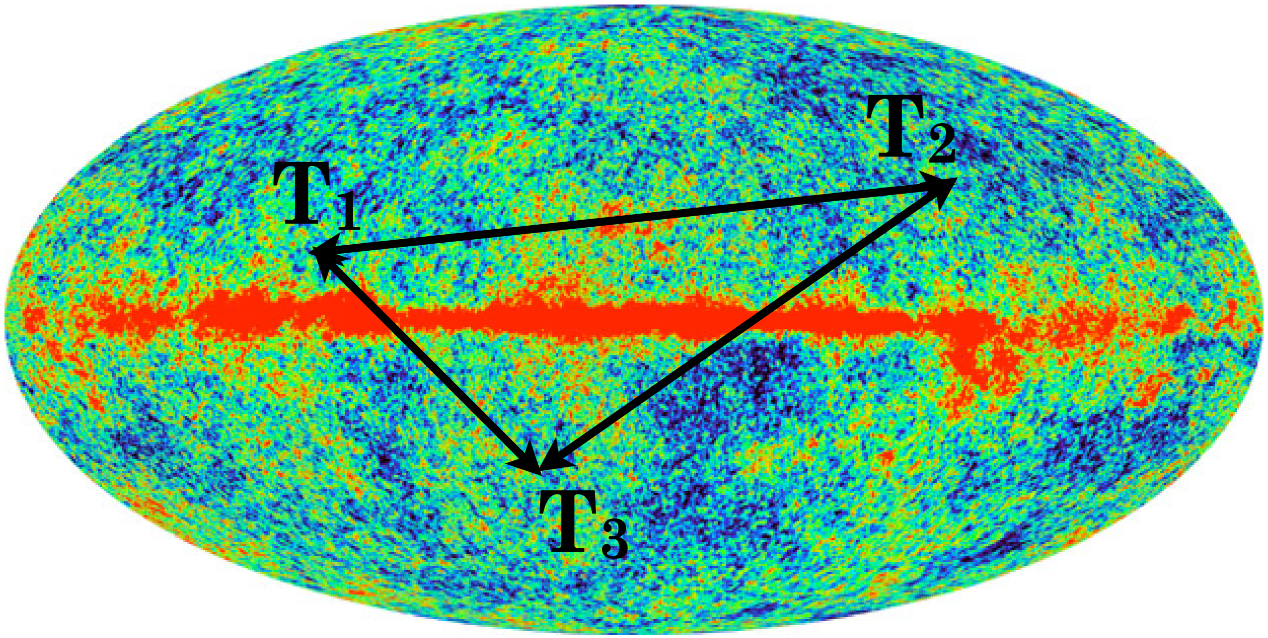






Babich, Creminelli & Zaldarriaga (2004)

NG from 3-point correlation function



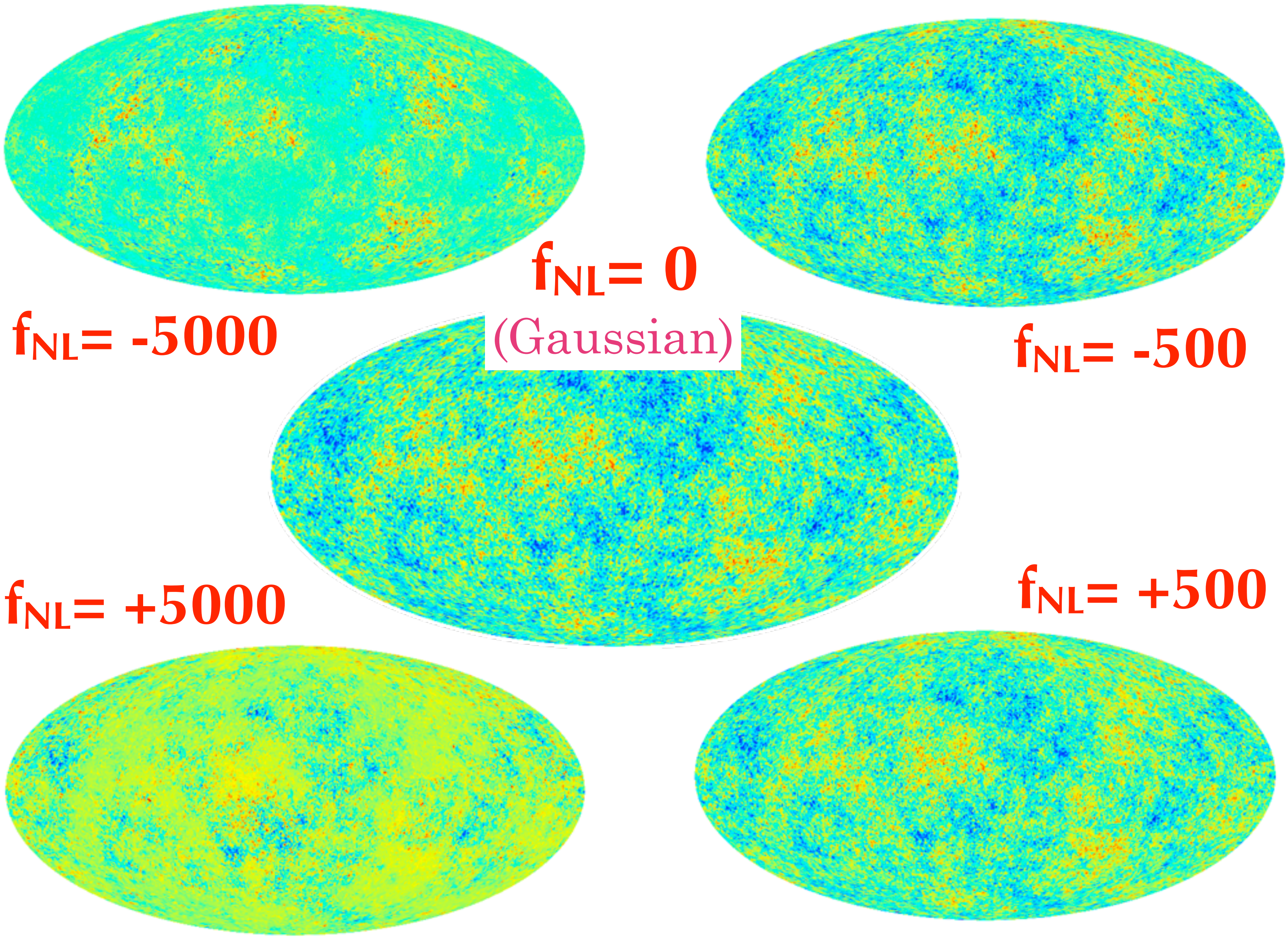
Local NG (squeezed triangles) - tests # inflationary fields

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

"Equilateral", "orthogonal" NG- tests inflationary interactions
tests interactions; parameter f_{NL}^{eq}, f_{NL}^{orth}

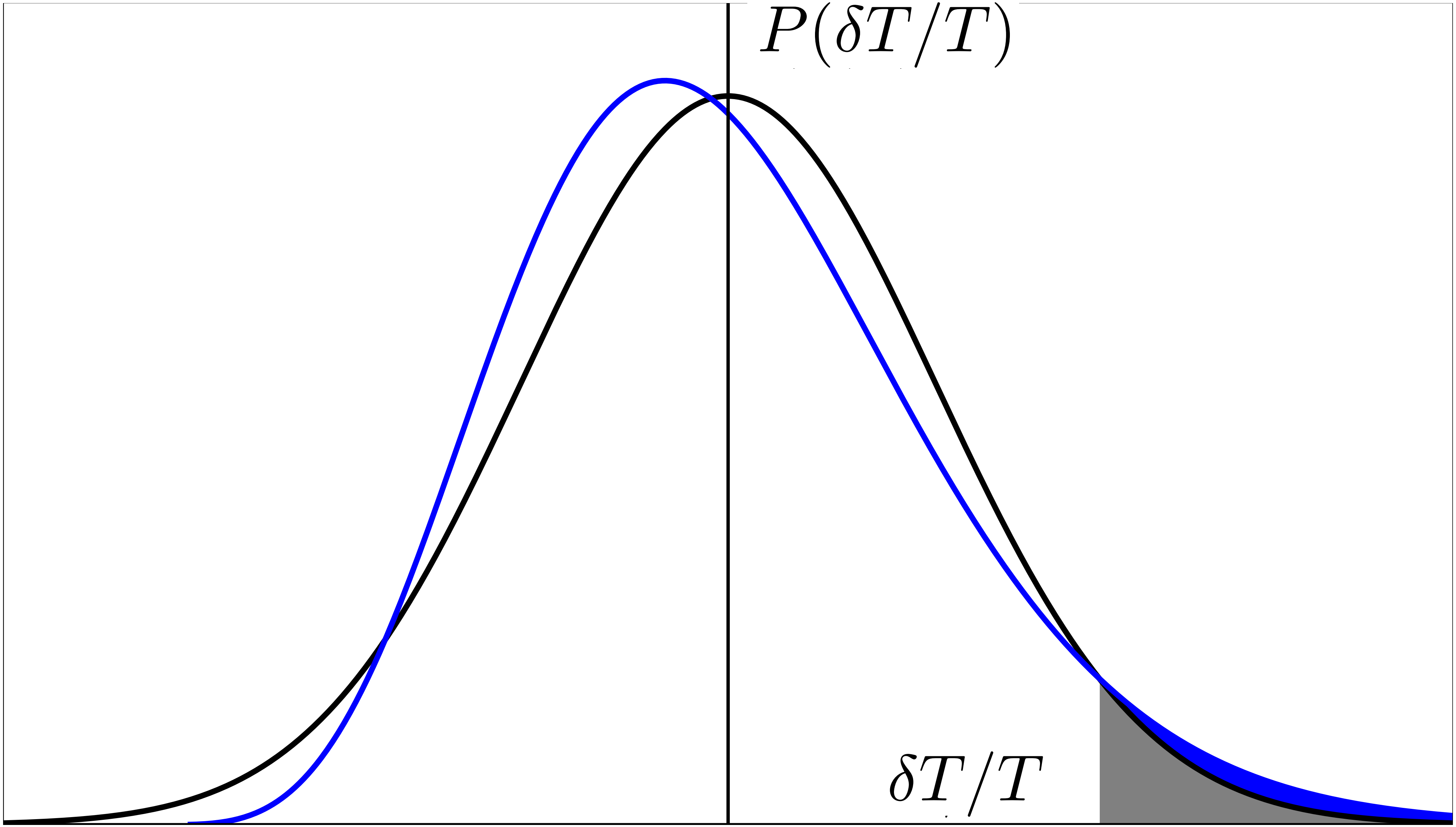
Threshold for new physics: $f_{NL}^{\text{any kind}} \gtrsim O(1)$

Alvarez et al, arXiv:1412.4671



Using publicly available NG maps by Elsner & Wandelt

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



Brief history of NG measurements: 1990's

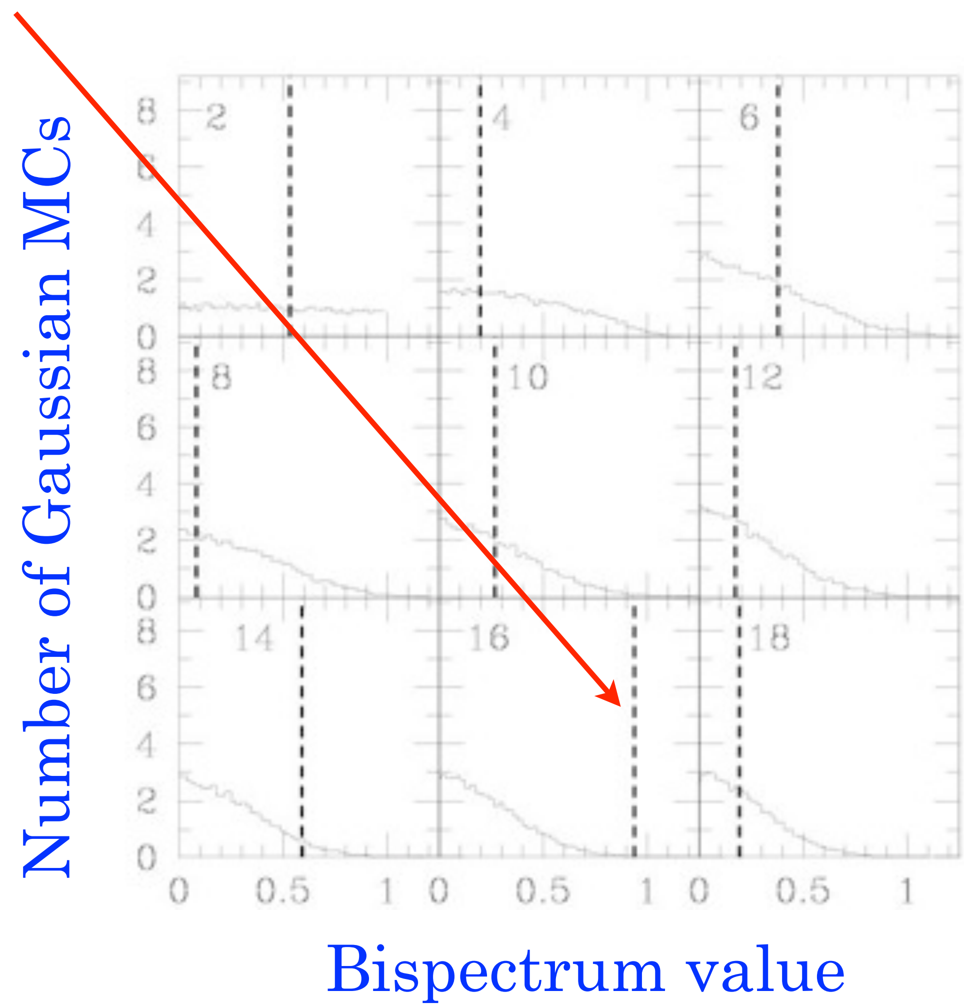
Early 1990s; COBE: Gaussian CMB sky (Kogut et al 1996)

$|f_{NL}| \lesssim 3000$ (Komatsu 2002)

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

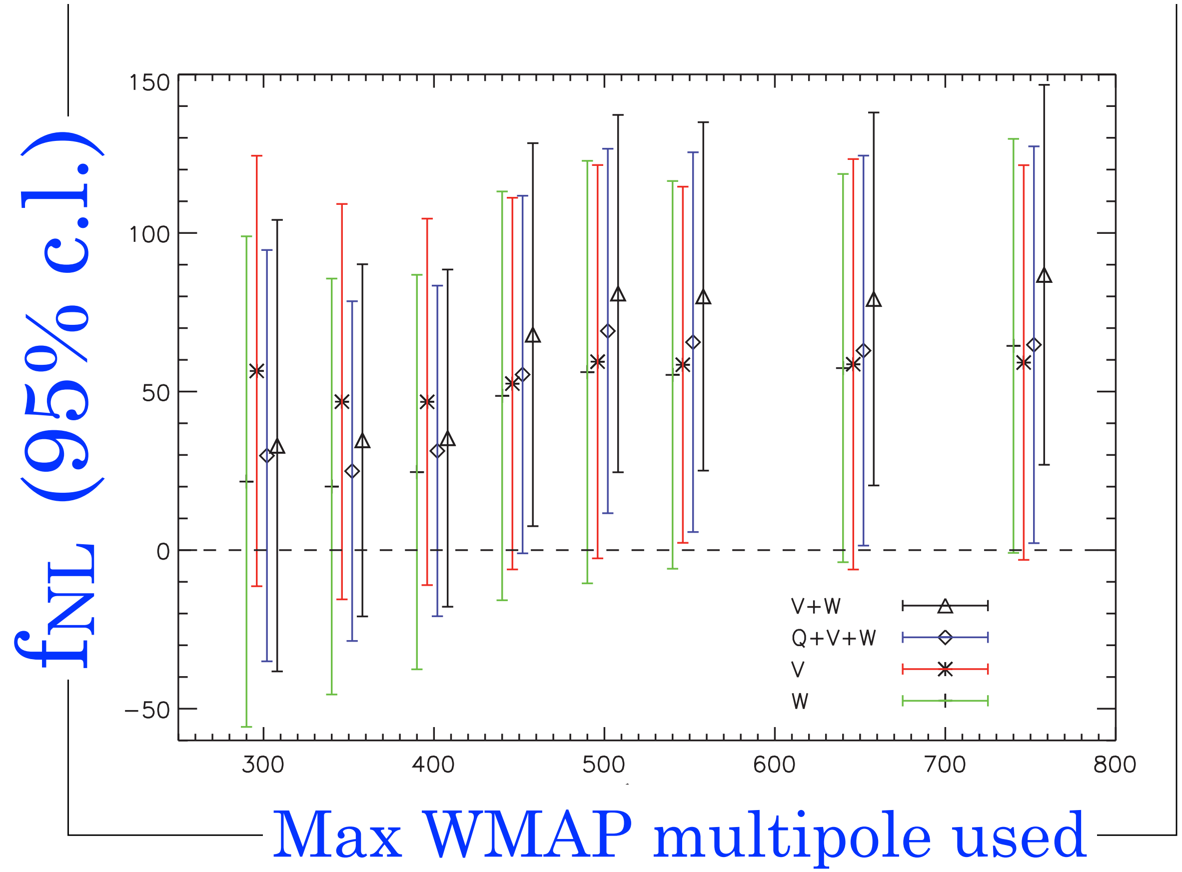
Pre-WMAP CMB: all is gaussian (e.g. MAXIMA; Wu et al 2001)

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 (7-yr)

Band	Foreground[b]	f_{NL}^{local}	f_{NL}^{equil}	f_{NL}^{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

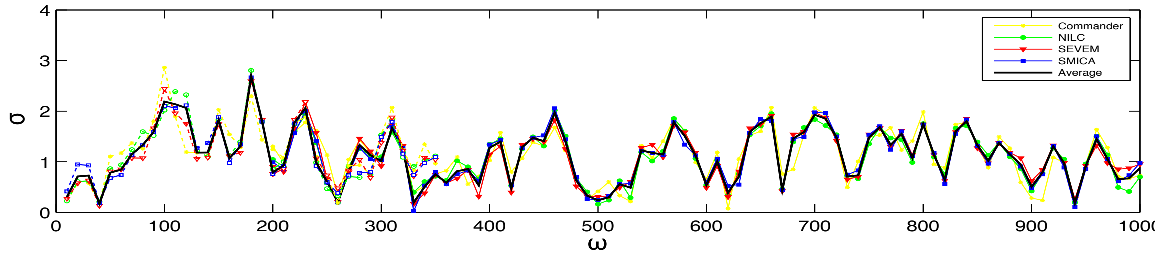
Komatsu et al. 2011

Constraints from Planck

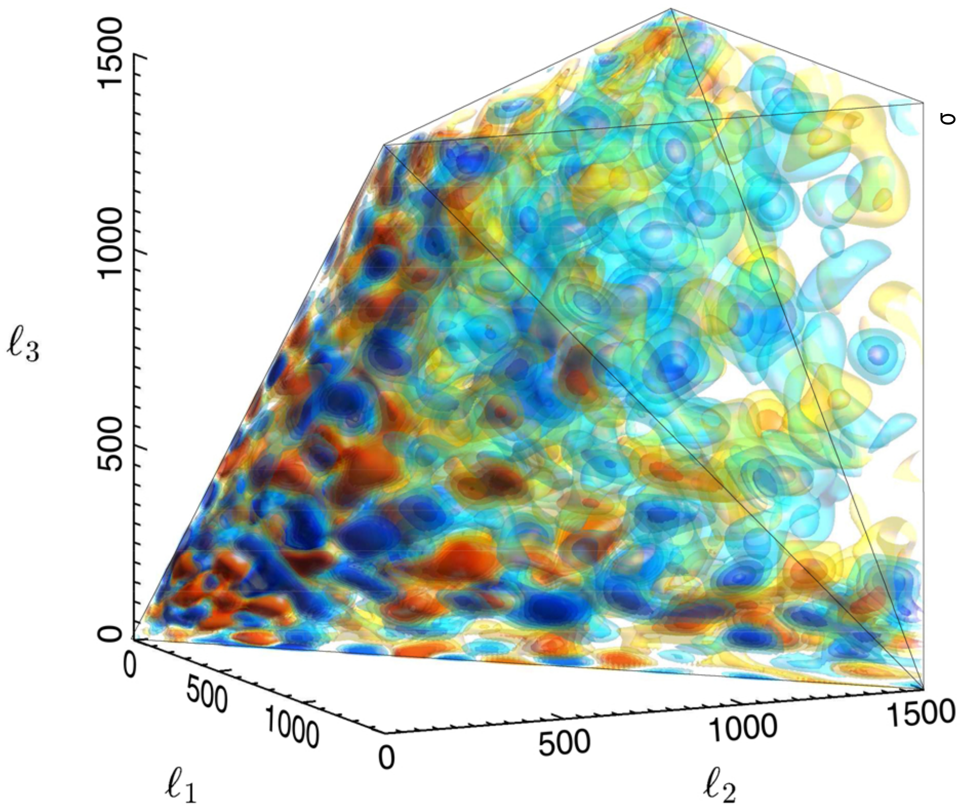
Shape and method	$f_{\rm NL}$(KSW) Independent	ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

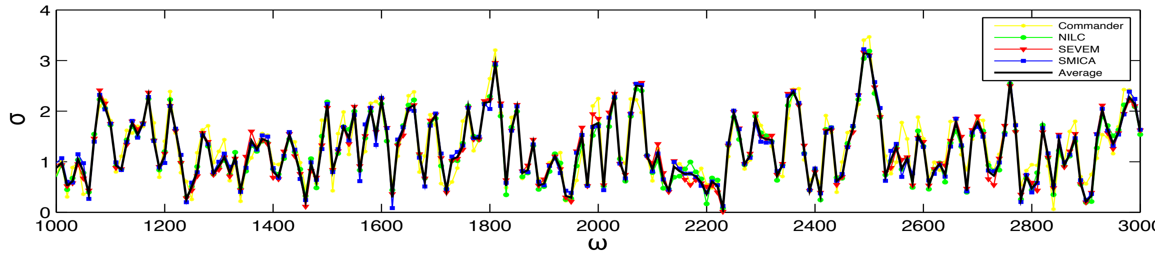
Planck collaboration XVII, 2015
(61 pages!)

Constraints from Planck: modal expansion



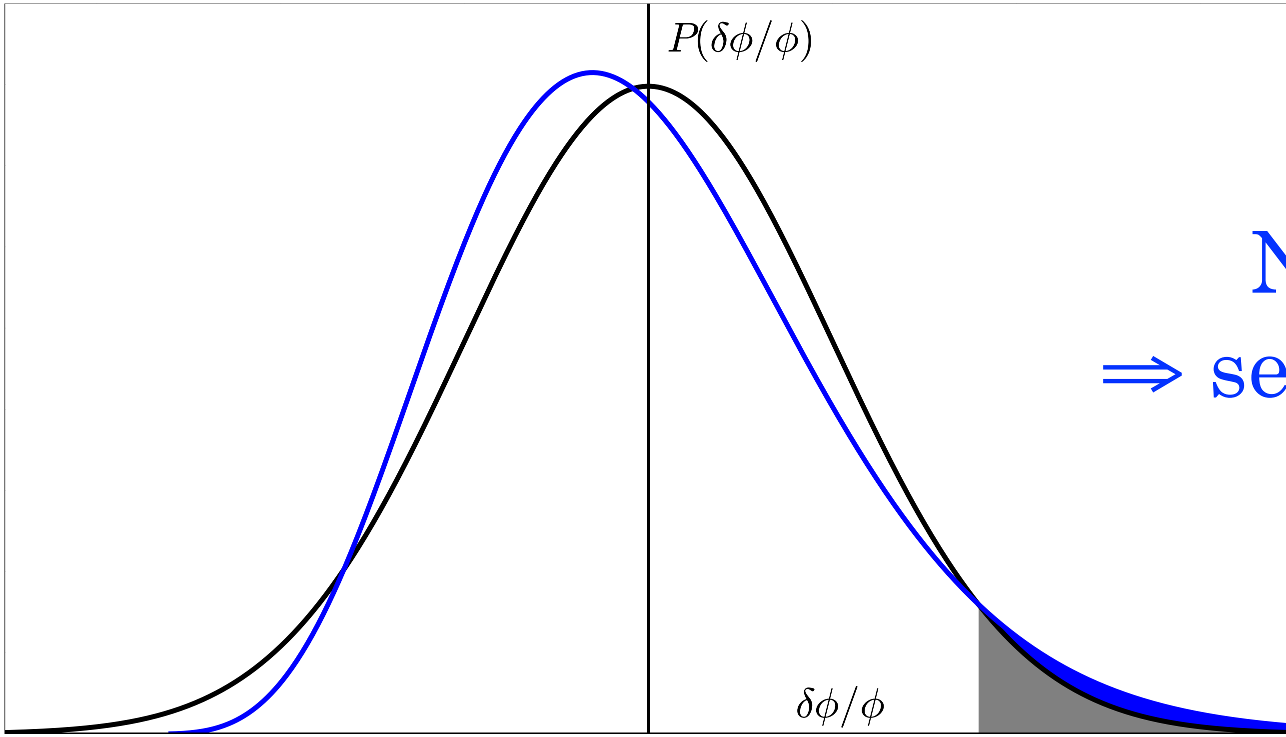
$$B(k_1, k_2, k_3) = \sum_{p,r,s} \alpha_{prs}\, q_p(k_1) q_r(k_2) q_s(k_3)$$





Planck collaboration XVII, 2015

Galaxy cluster counts' sensitivity to NG



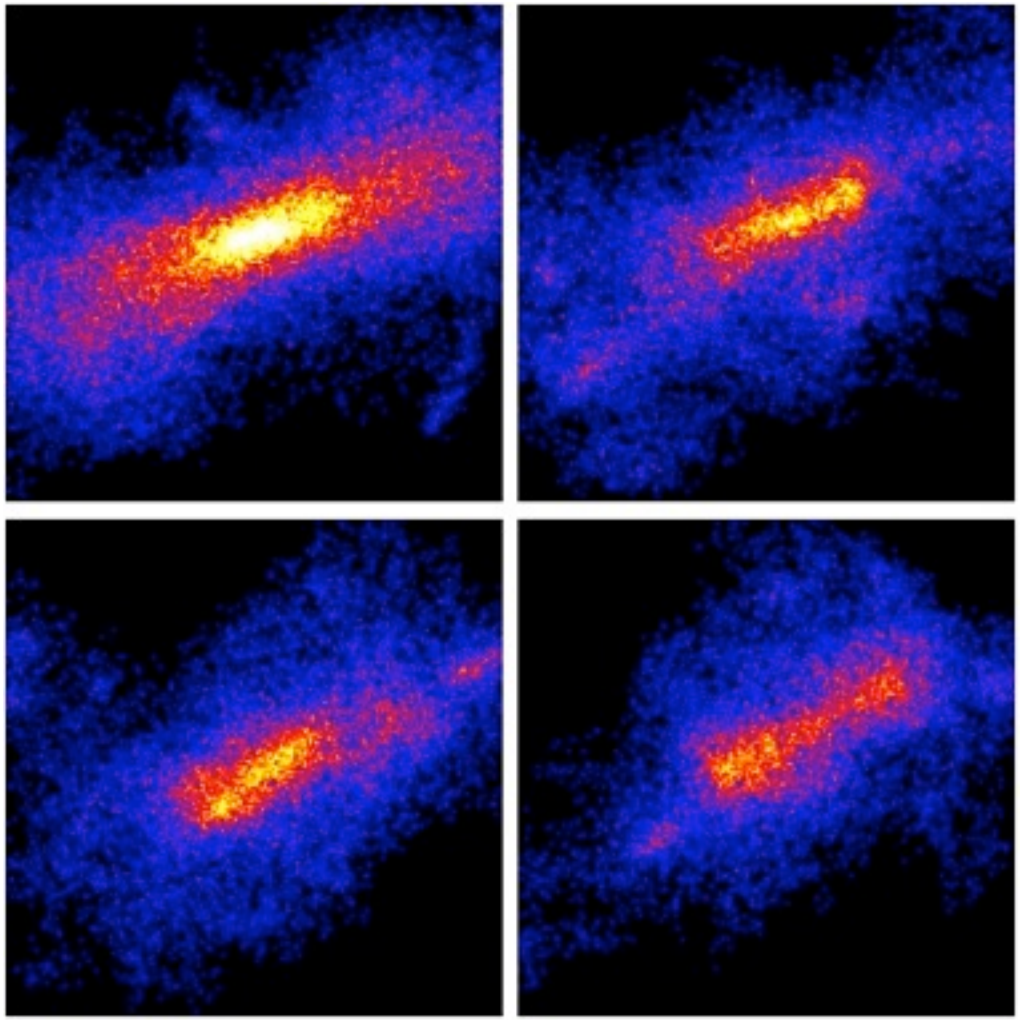
NG initial PDF
$\Rightarrow$ sensitivity to counts
"on the tail"

Lots of effort in the community to calibrate
the non-Gaussian mass function -
dn/dlnM(M, z) - of DM halos

A DM halo gets more massive with $f_{NL}>0$ (and v.v.)

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

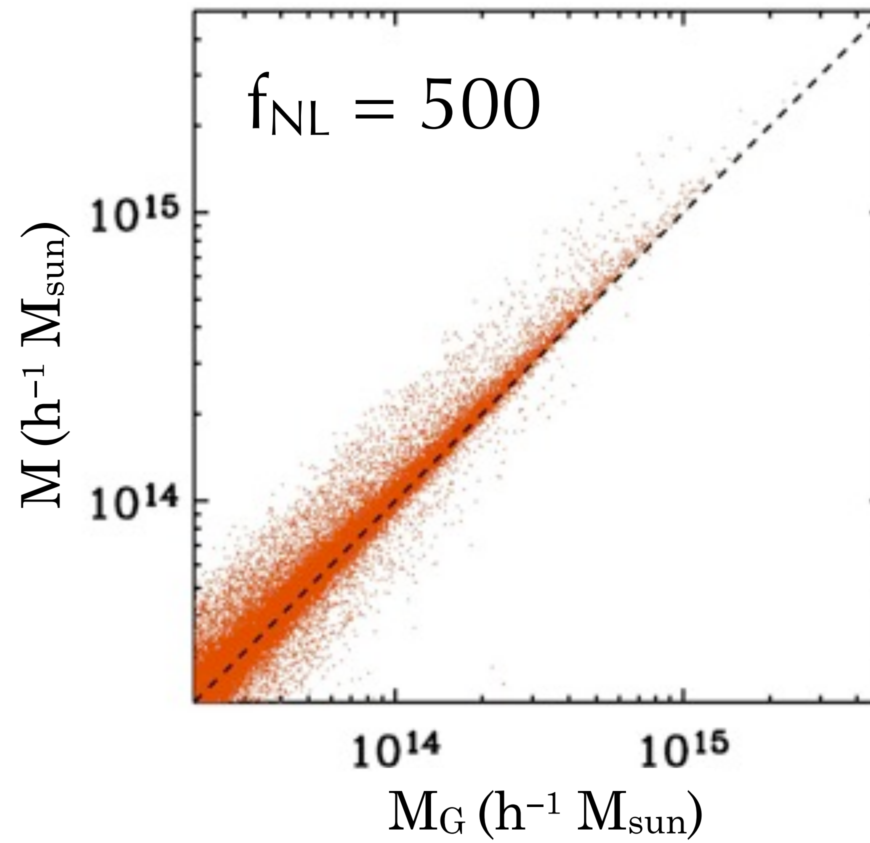
$f_{NL}=+500$
$M=5.9\ 10^{15}\ M_\odot$



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

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

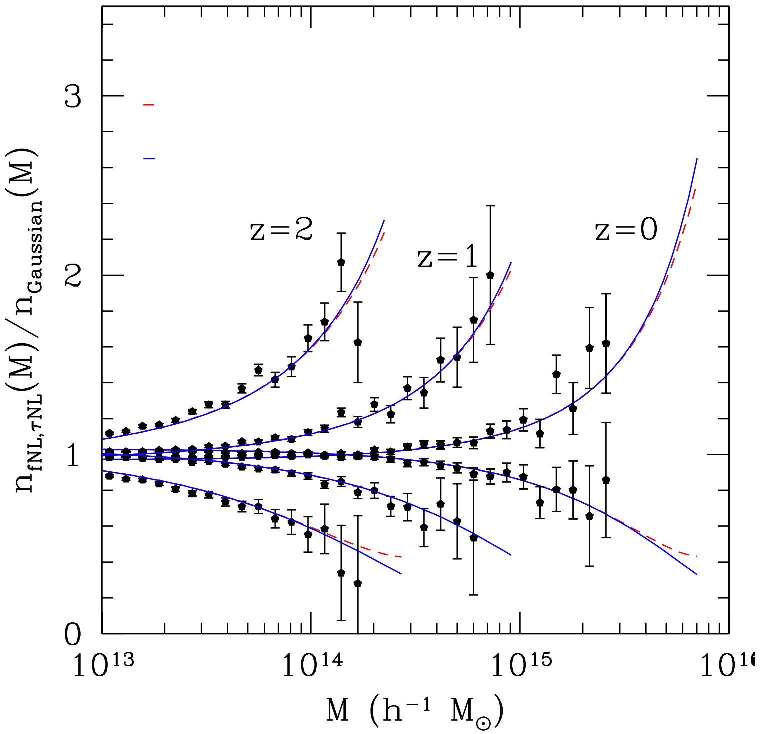
Mapping between M_G and $M \equiv M_{NG}$:



⇒ 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; many others going back to 1990s

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

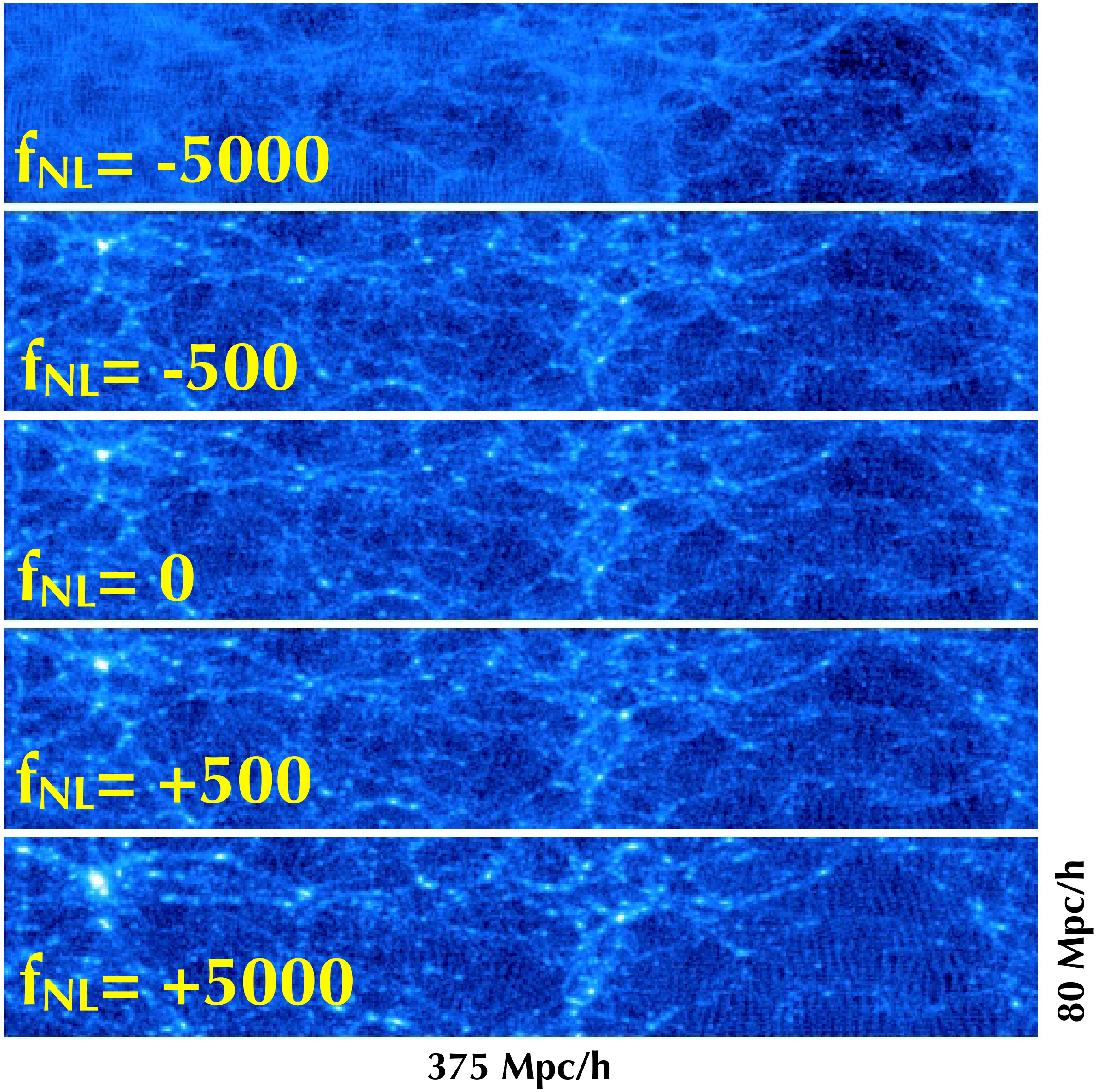
e.g. $\sigma(f_{NL})$=450 measured from SPT (Williamson et al 2010)

Nevertheless:

- cluster abundance is sensitive to ALL non-Gaussianity

Effects of primordial NG
on the bias of virialized objects

Simulations with non-Gaussianity (f_{NL})

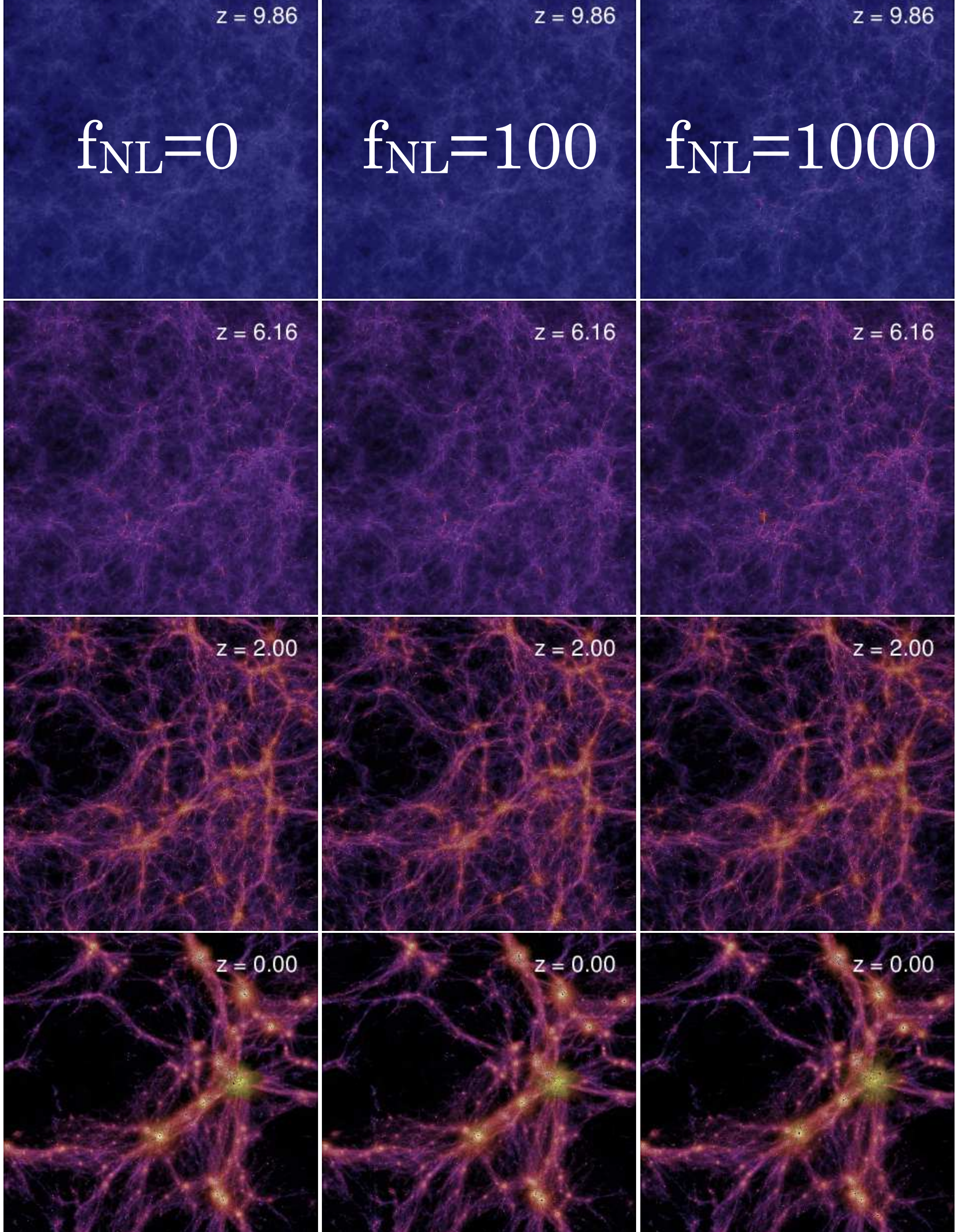


- Under-dense region evolution decrease with f_{NL}
- Over-dense region evolution increase with f_{NL}

- 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

...and now with baryons!



Zhao, Li,
Shandera & Jeong,
arXiv:1307.5051

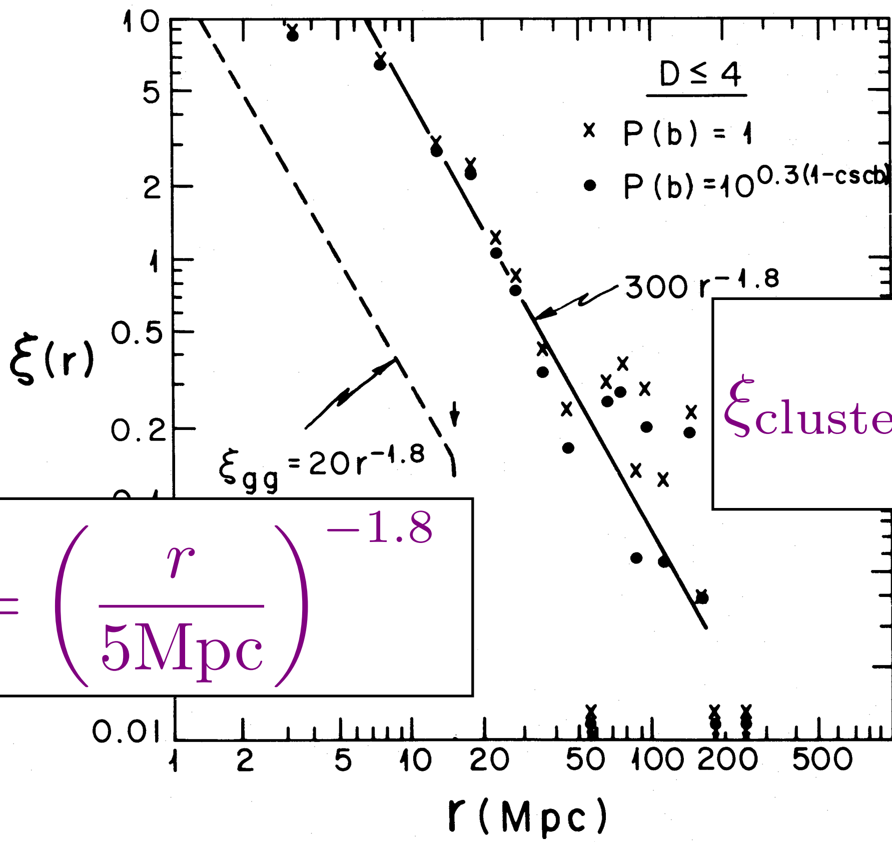
Does galaxy/halo bias depend on NG?

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

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

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

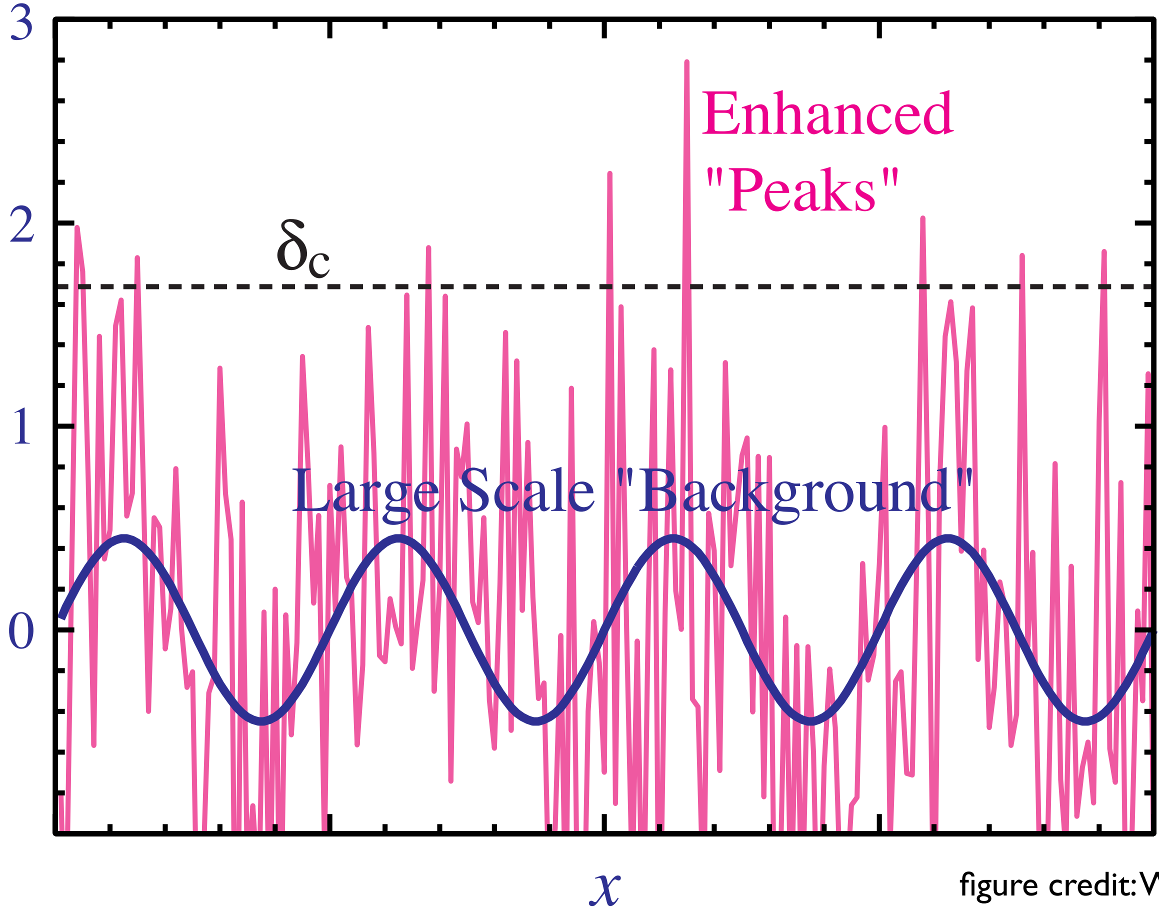
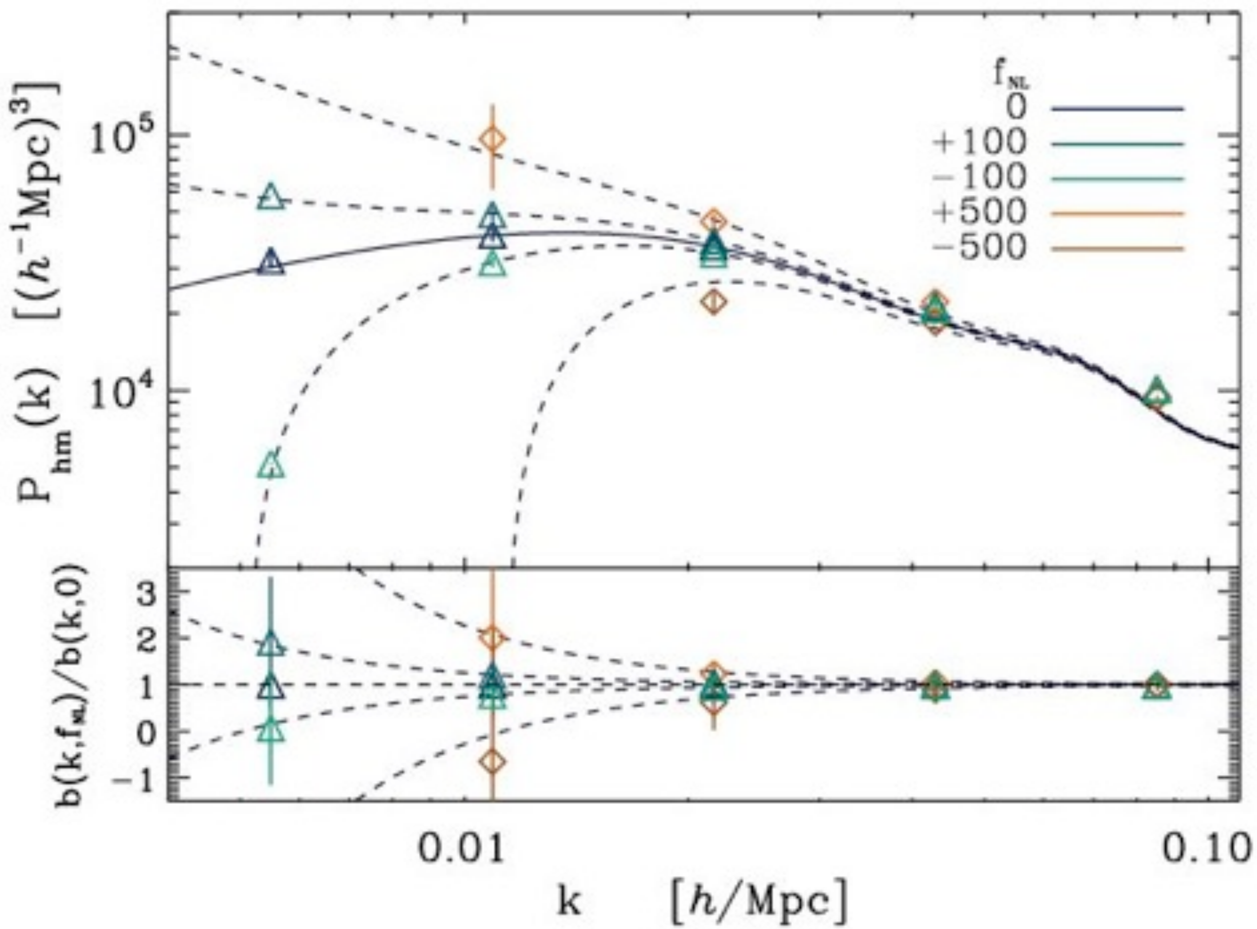


figure credit: Wayne Hu

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



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

Verified using a variety of theoretical derivations and numerical simulations.

Dalal, Doré, Huterer & Shirokov 2008

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

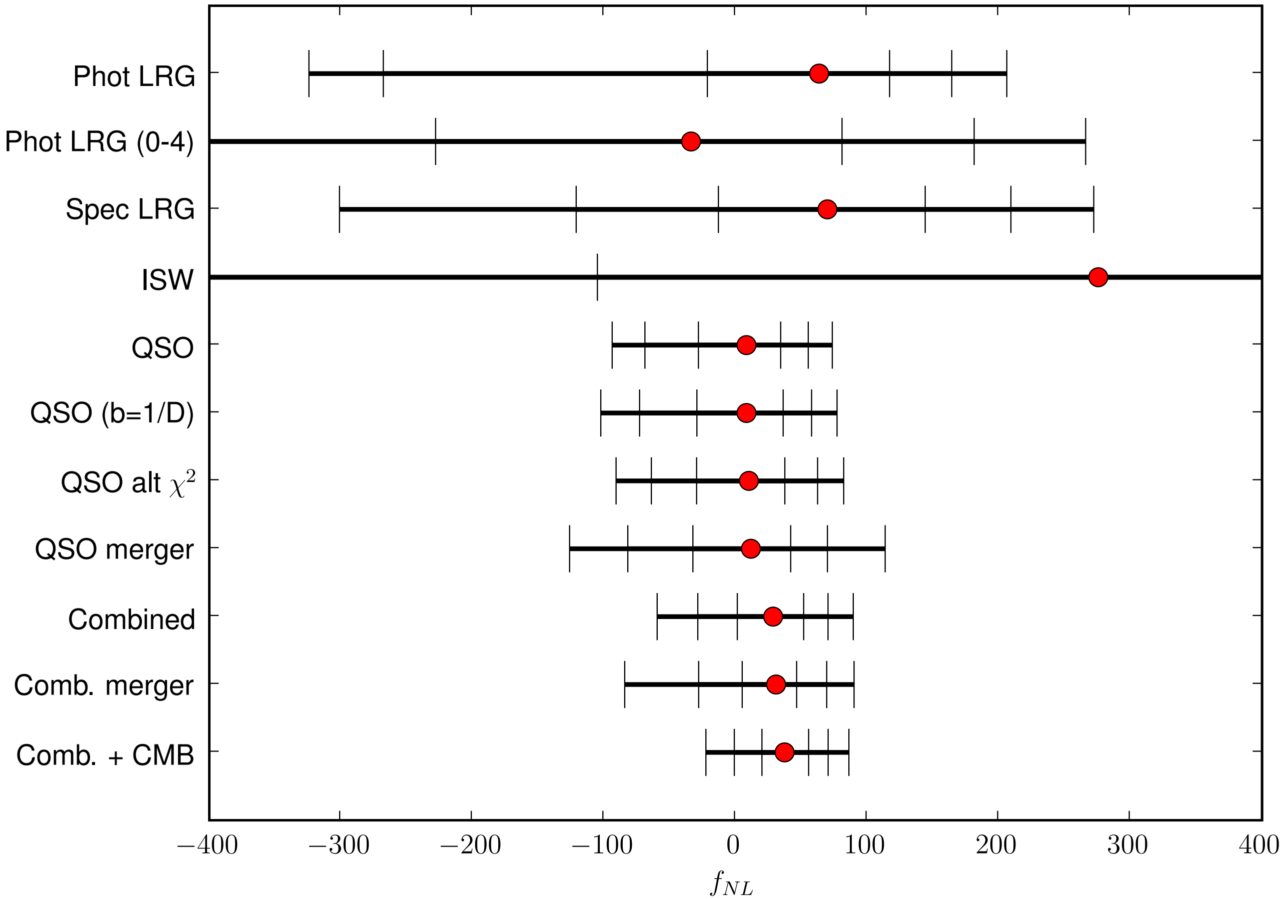
Implications:

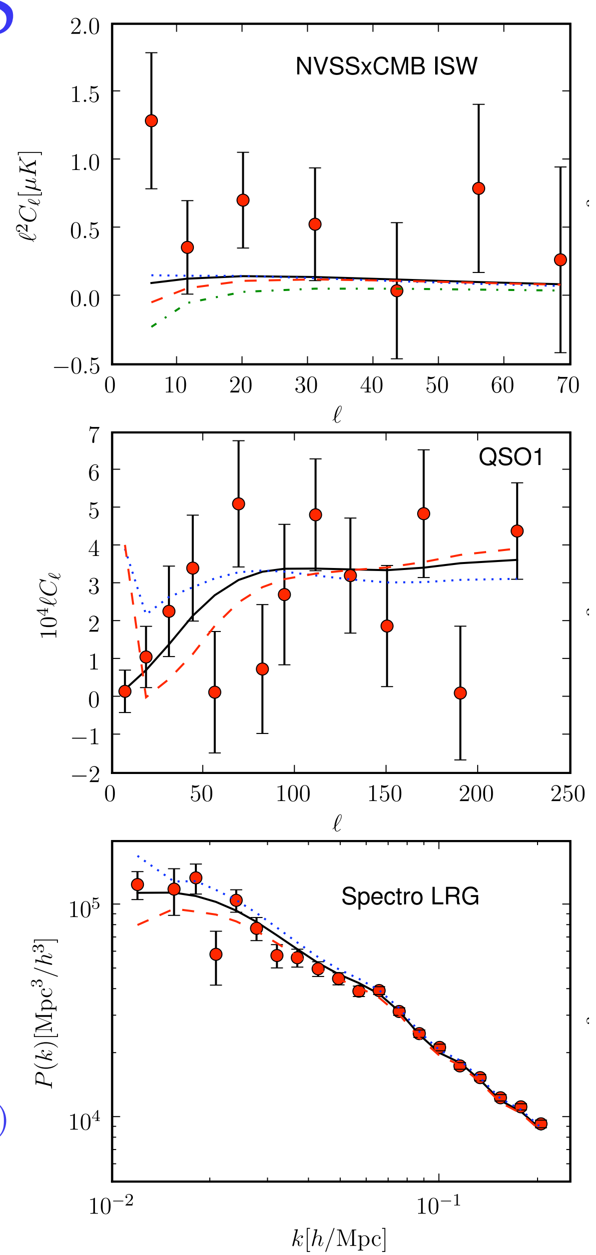
- Unique $1/k^2$ scaling of bias; no free parameters
- Distinct from effect of all other cosmo parameters
- Straightforwardly measured (g-g, g-T,...)
- Extensively tested with numerical simulations; good agreement found
- In general, LSS can probe:

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

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

Constraints from **current** data: SDSS



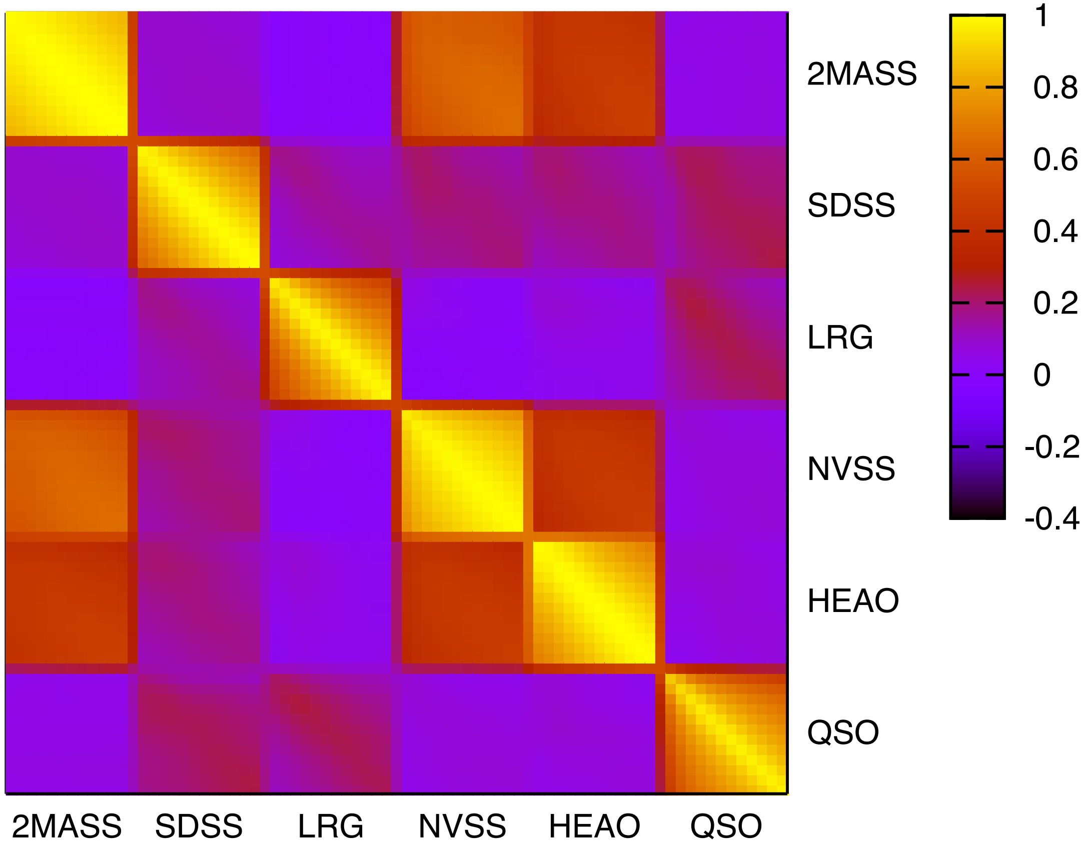


Slosar et al. 2008
(also Giannantonio et al 2013)

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

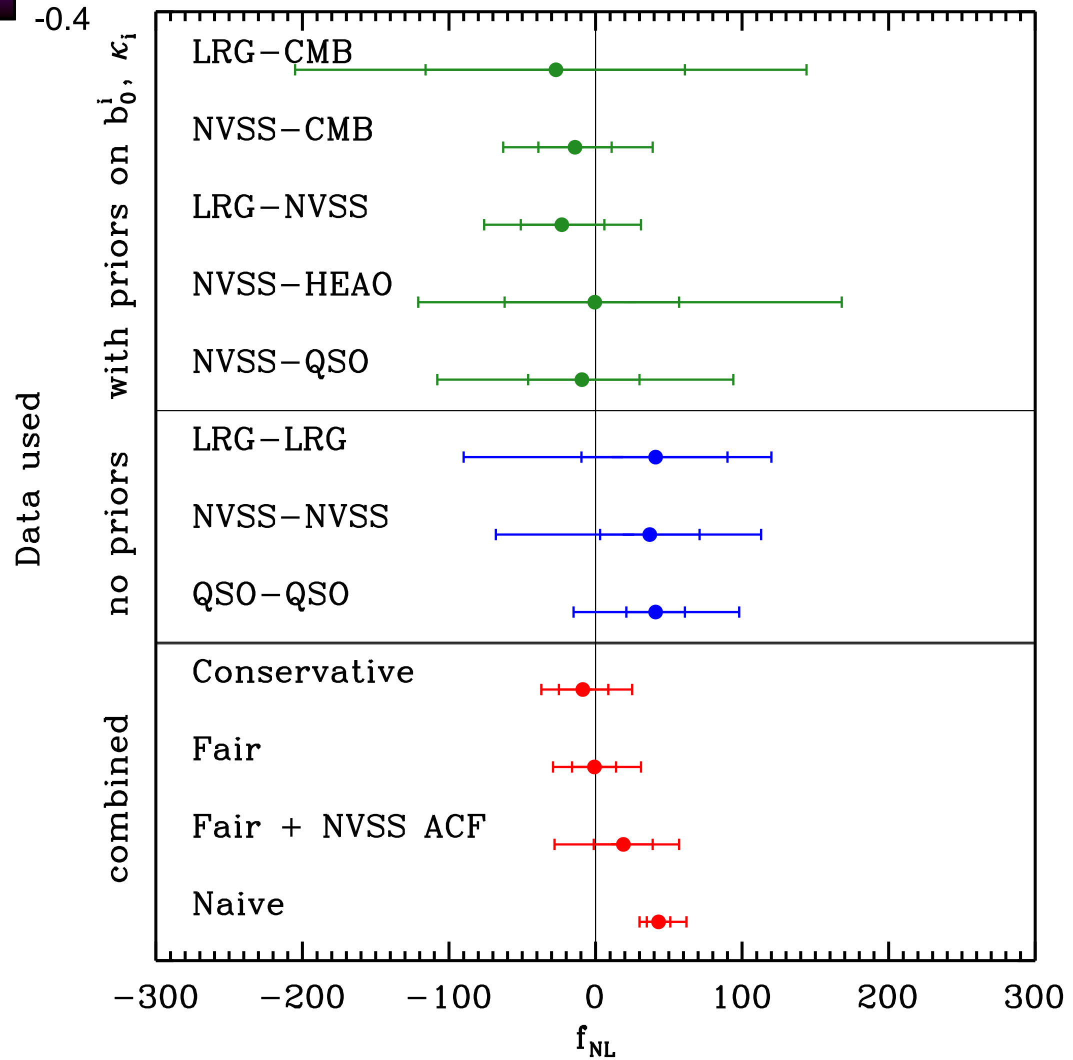
f_{NL} = 23 +/- 23 (68%, all)

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



Covariance matrix

Final constraints:



Giannantonio et al. 2013

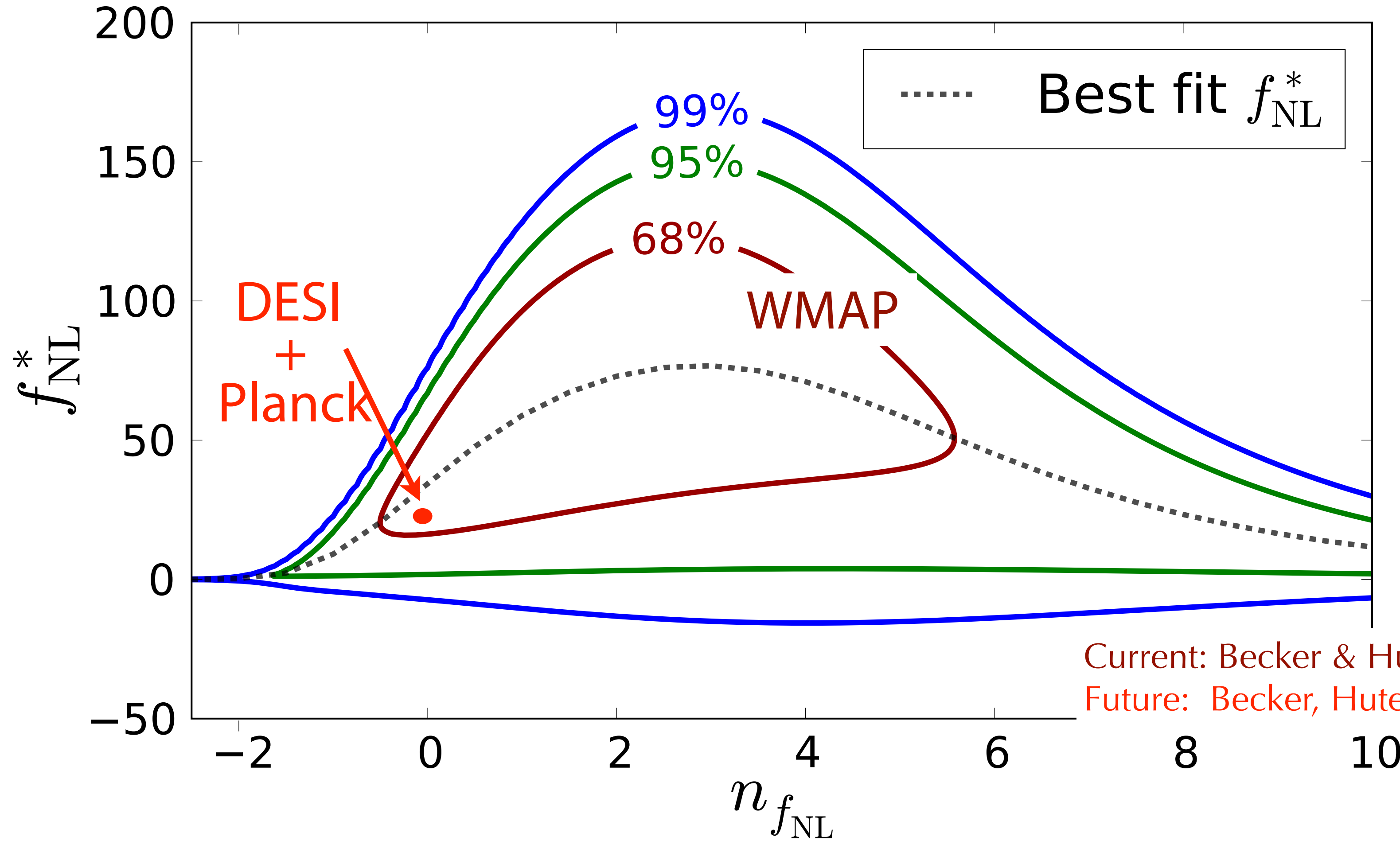
Next Frontier: **Large-Scale Structure**

	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...

More general NG models: beyond f_{NL}

Current and future constraints on:

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



Current: Becker & Huterer, PRL 2012
Future: Becker, Huterer & Kadota 2011

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

Shandera, Dalal & Huterer 2012

Dark Energy Survey Instrument (DESI)

- Huge spectroscopic survey on Mayall telescope (Arizona)
- ~5000 fibres, ~15,000 sqdeg, ~20 million spectra
- LRG in $0 < z < 1$, ELG in $0 < z < 1.5$, QSO $2.2 < z < 3.5$
- Great for dark energy (RSD, BAO)
- **Great for NG** - 3D P(k, z), bispectrum...
- start 2018, funding DOE + institutions

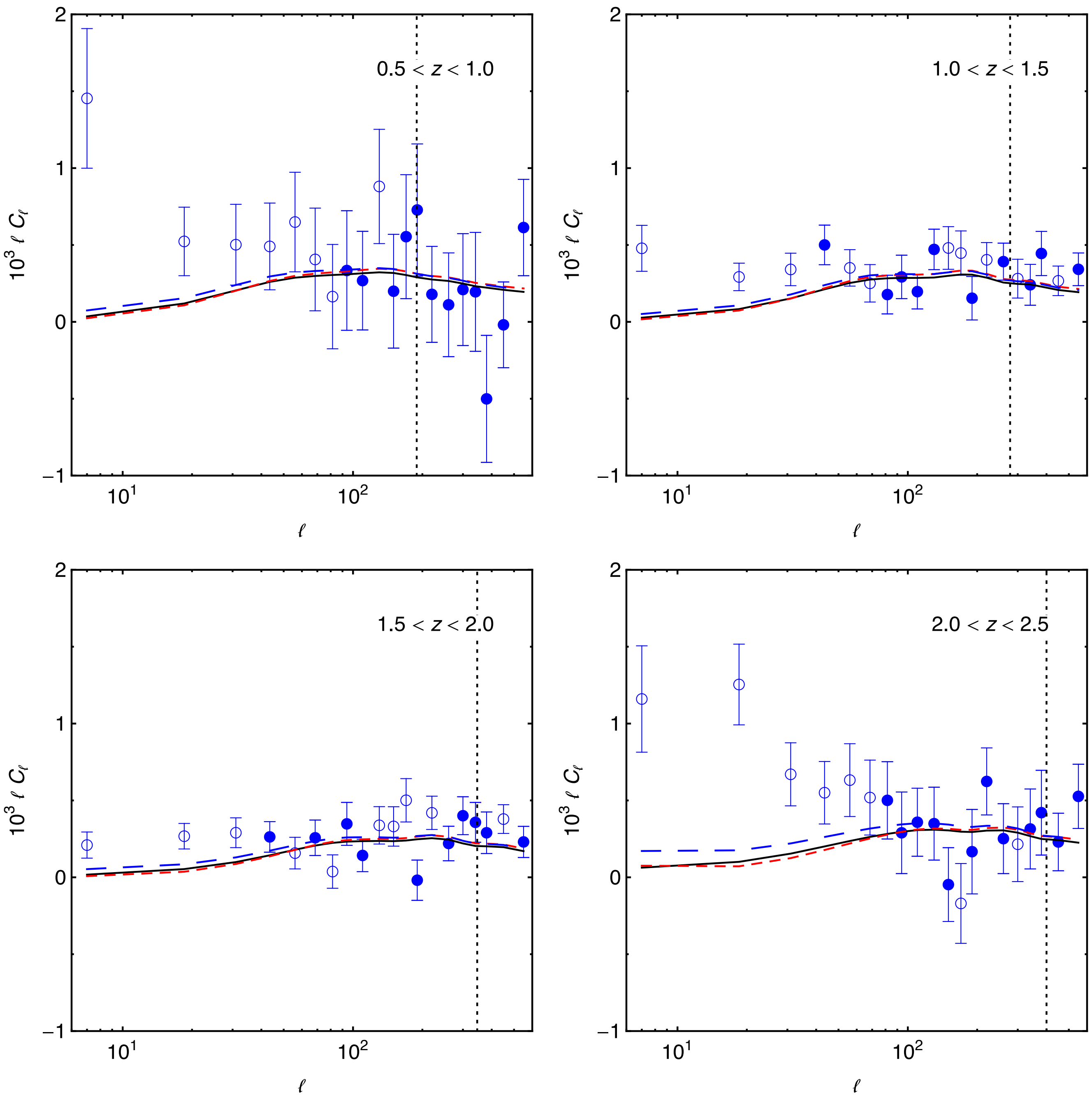
Systematic Errors:
(photometric) calibration errors

For the NG measurements, photo-z but also: (photometric) calibration errors

- **Detector sensitivity**: sensitivity of the pixels on the camera vary along the focal plane. Sensitivity of a given pixel can change with time.
- **Observing conditions**: spatial and temporal variations.
- **Bright objects**: The light from foreground bright stars and galaxies affects the sky subtraction procedure, which impairs the surveys' completeness near bright objects.
- **Dust extinction**: Dust in the Milky Way absorbs light from the distant galaxies.
- **Star-galaxy separation**: In photometric surveys, faint stars can be erroneously included in the galaxy sample. Conversely, galaxies are sometimes misclassified as stars and culled from the sample. Remember, stars are *not* randomly distributed across the sky.
- **Deblending**: Galaxy images can overlap, and it can be difficult to cleanly separate photometric and spectroscopic measurements for the blended objects.

Huterer, Cunha & Fang 2013

Calibration errors in SDSS DR8 power spectra

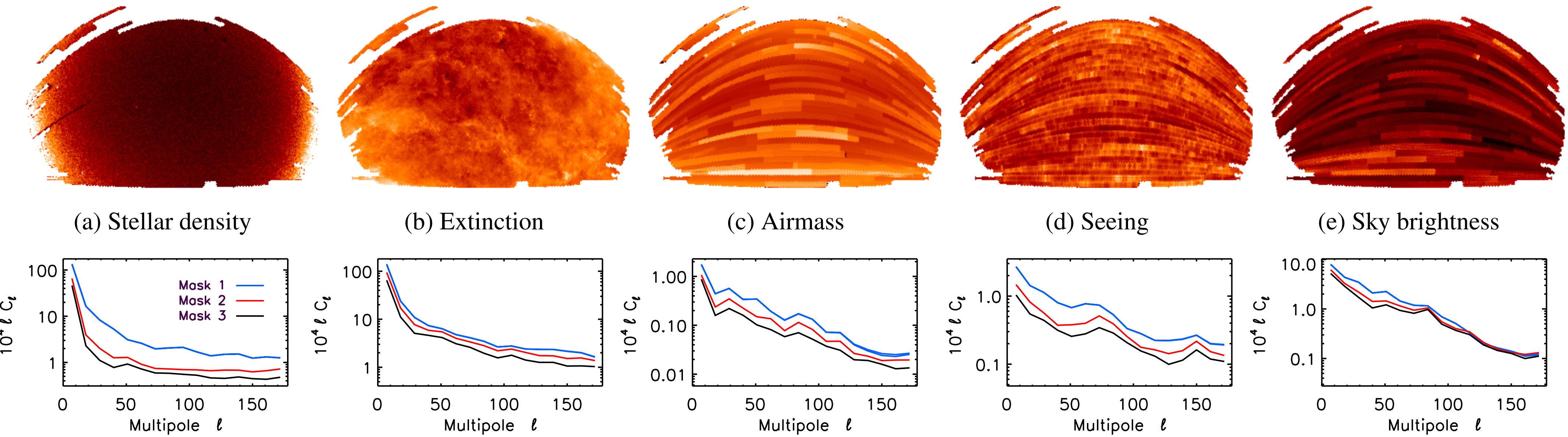


QSO power spectra from SDSS;
open circle points not used since they may be systematics-contaminated!

Similar results for LRGs (not shown)

Agarwal, Ho & Shandera, arXiv:1311.2606

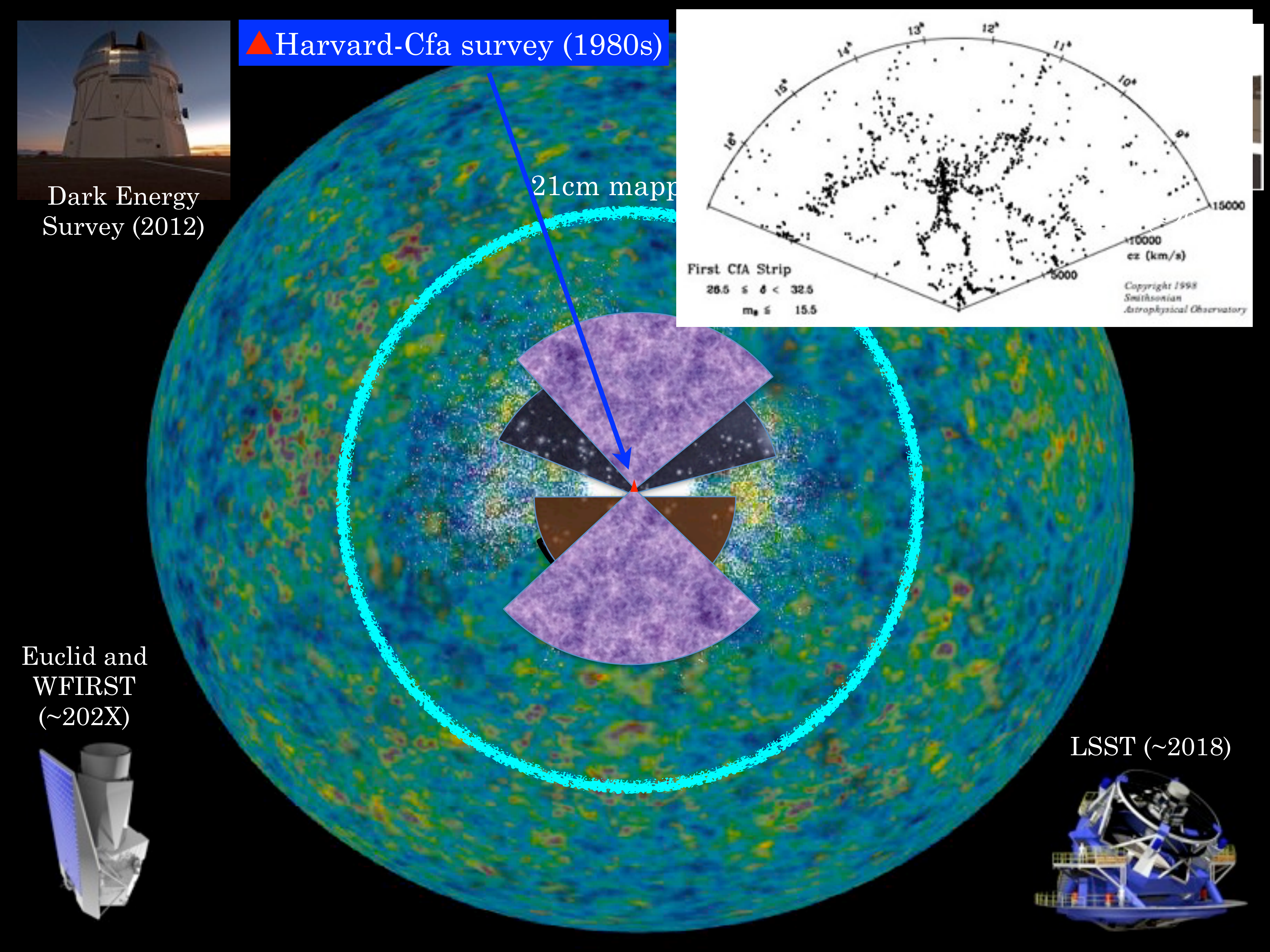
LSS calibration errors: example maps, power spectra



Leistedt et al 2013

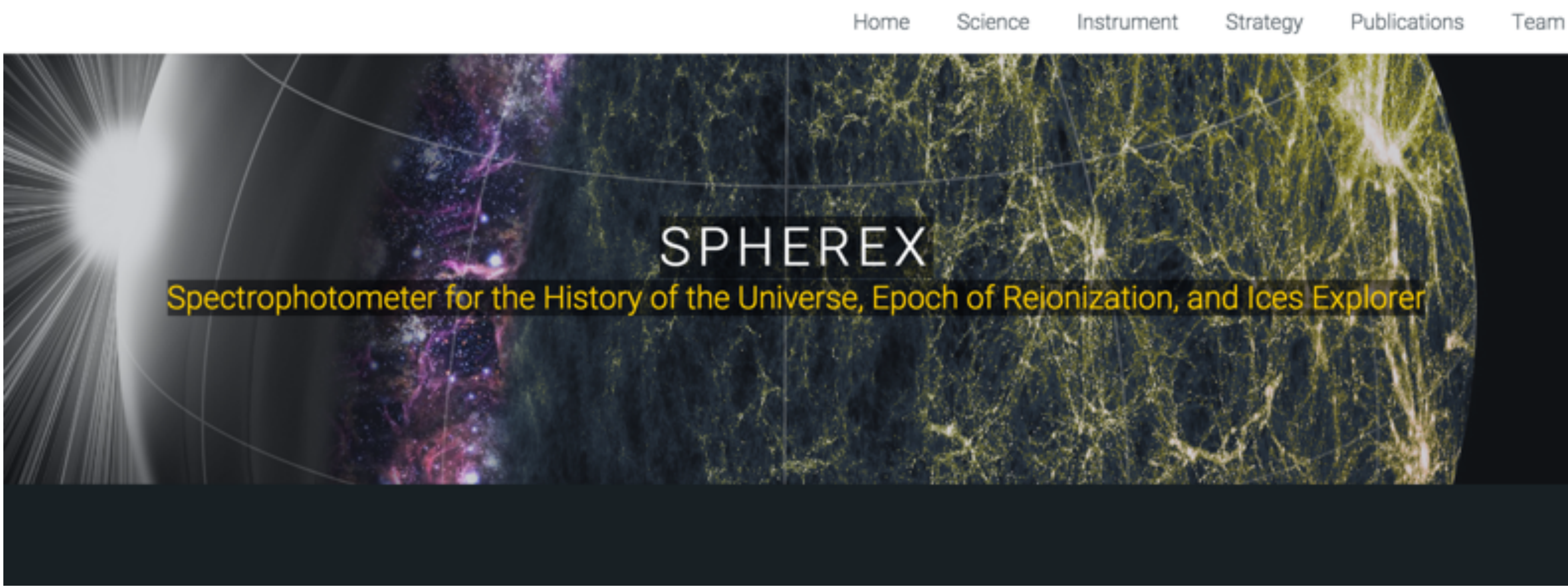
- dominate on large angular scales
- can be measured, removed using same or other data

Huterer, Cunha & Fang 2013;
Shafer & Huterer 2015


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

SPHEREx

proposal for telescope dedicated to measuring NG (and other science)



spherex.caltech.edu

- 97 bands (!) with Linearly Variable Filters (LVF)
- λ between 0.75 and 4 μm
- small (20cm) telescope, big field of view
- whole sky out to z~1
- **goal: $\sigma(f_{NL}) \lesssim 1$**

paper: Doré, Bock et al, arXiv:1412.4872

Conclusions:

- Primordial NG directly tests inflation:
  - How many fields
  - What interactions, couplings
- Constraints from WMAP, Planck are superb and consistent with zero NG
- Extremely good prospects for testing with galaxy surveys, at smaller scales than CMB

Advances in Astronomy special issue on

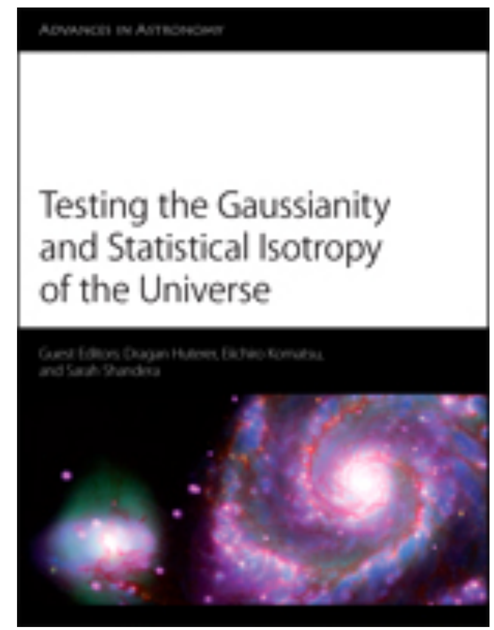
"Testing the Gaussianity and Statistical Isotropy of the Universe"

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,