Testing Inflation with Large-Scale Structure (LSS)

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Vanilla* inflation predicts:

- Flat universe (Ω_K=1) with nearly scale-invariant fluctuation spectrum ($n_s \approx 1-6\varepsilon+2\eta$)
- Stochastic background of gravity waves
- Nearly gaussian density fluctuations
- Homogeneous and isotropic universe

Any departures (as well as measurements of n_s) shed direct light on inflation

*Single scalar field, canonical kinetic term, in Bunch-Davies vacuum, always slow-rolls, in Einstein GR

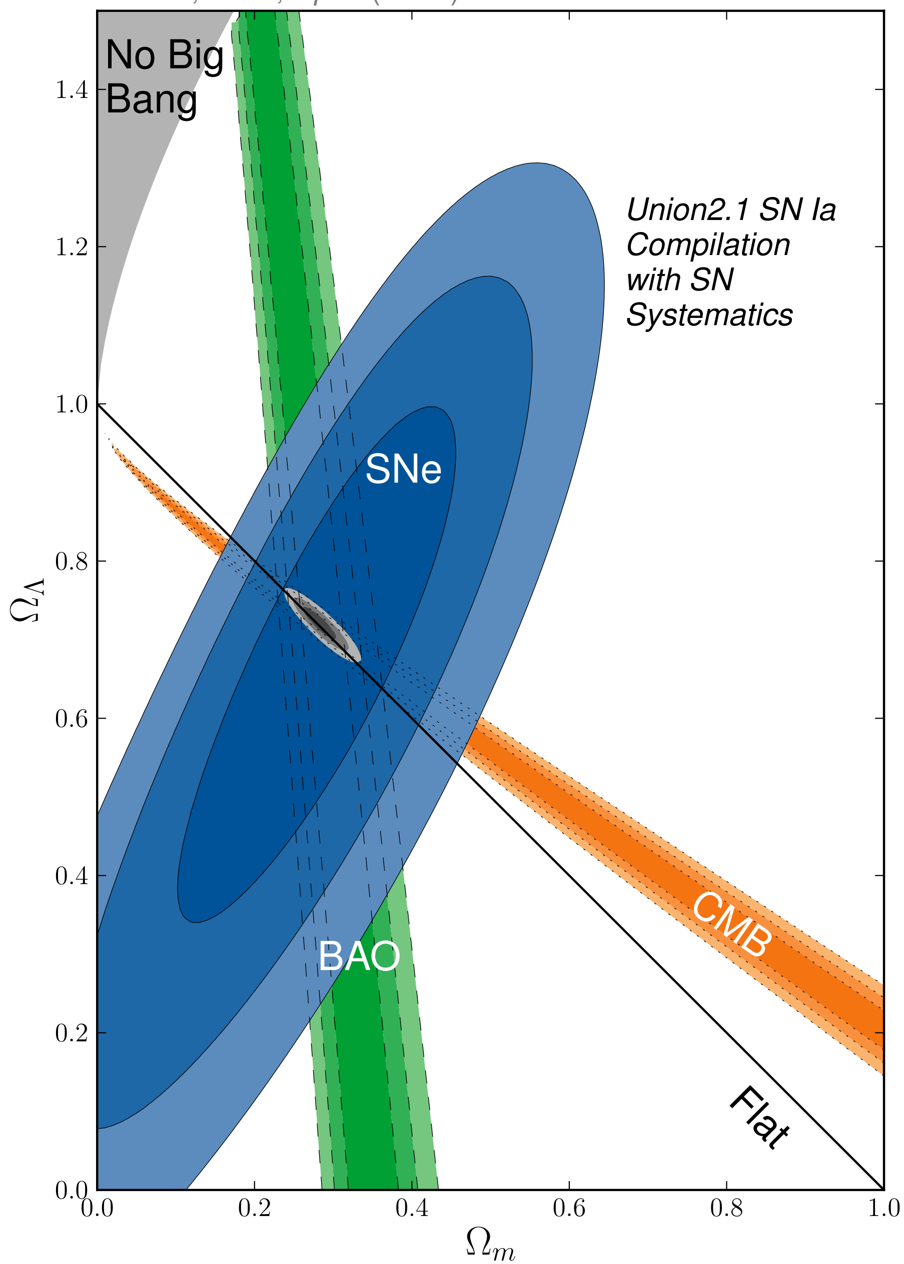
LSS: an under-utilized probe of the early universe

	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
slice vs. color, M, bias...	no	yes

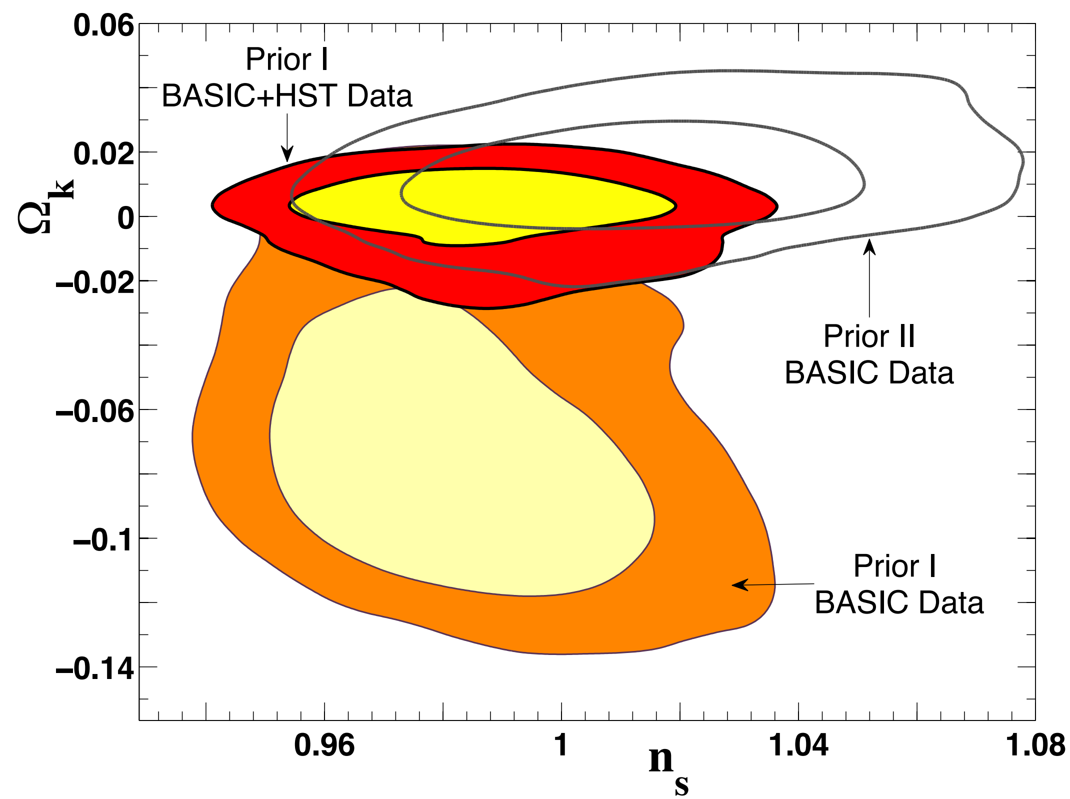
LSS and
inflationary cosmological parameters

Spatial Curvature:
LSS helps break parameter degeneracies

Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)

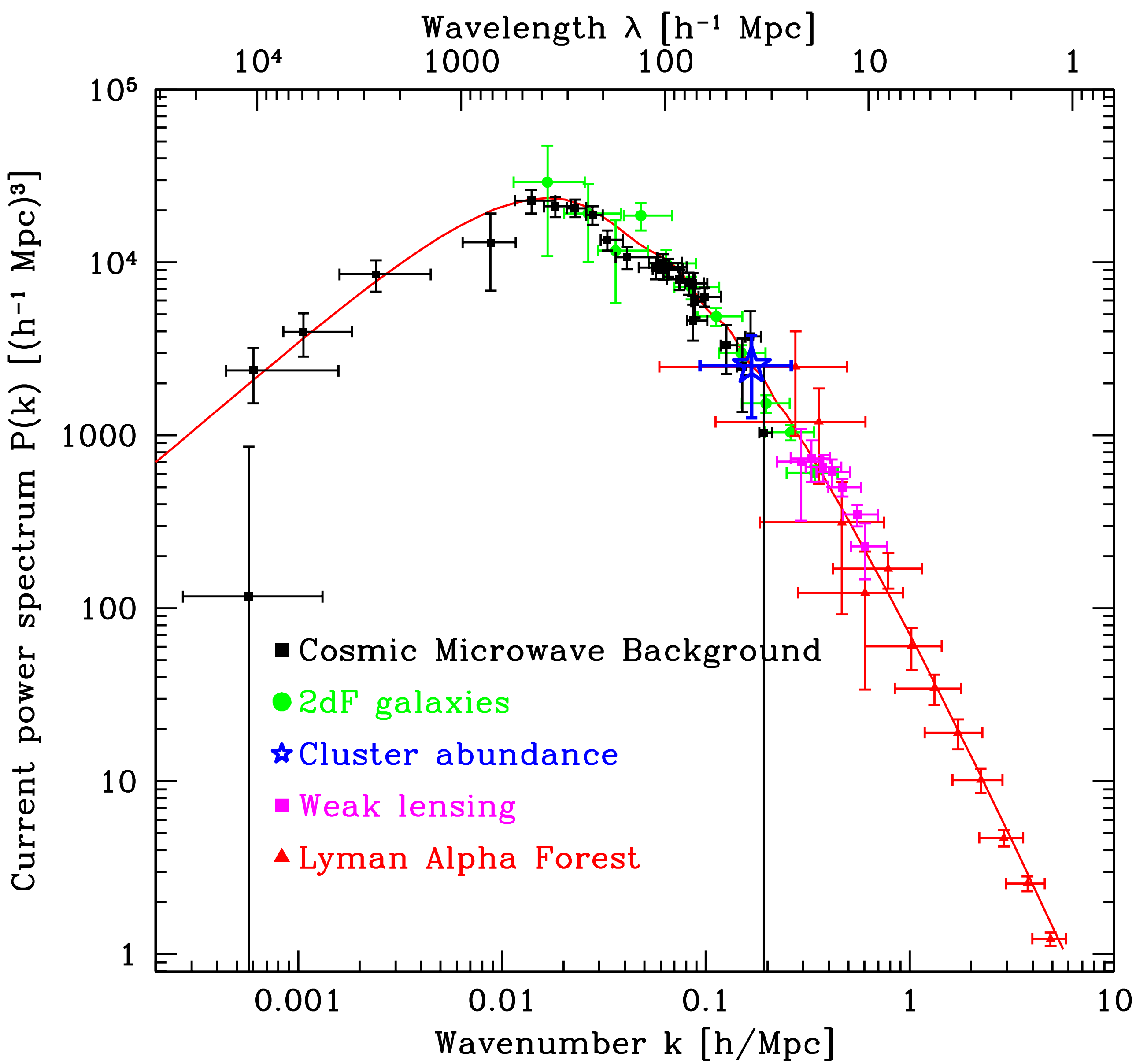


More complicated if $w \neq -1$, or if $w(a)$ allowed, but general picture still holds:

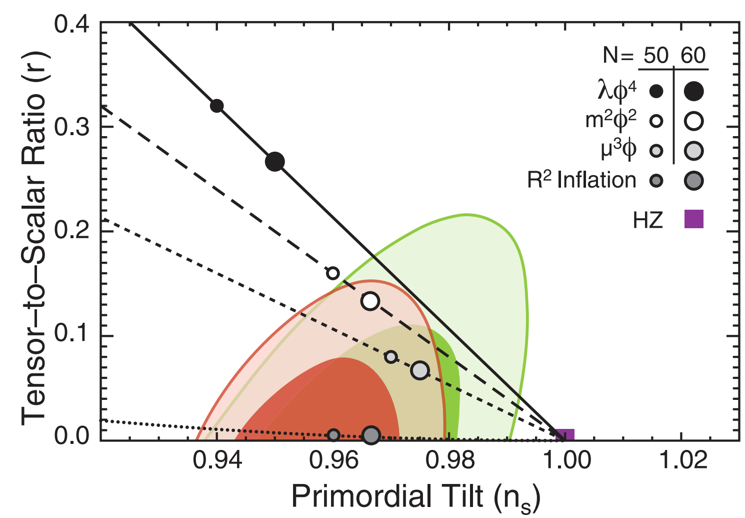


Okouma, Fantaye & Bassett 2012

Scalar spectral index: LSS extends the lever arm in k



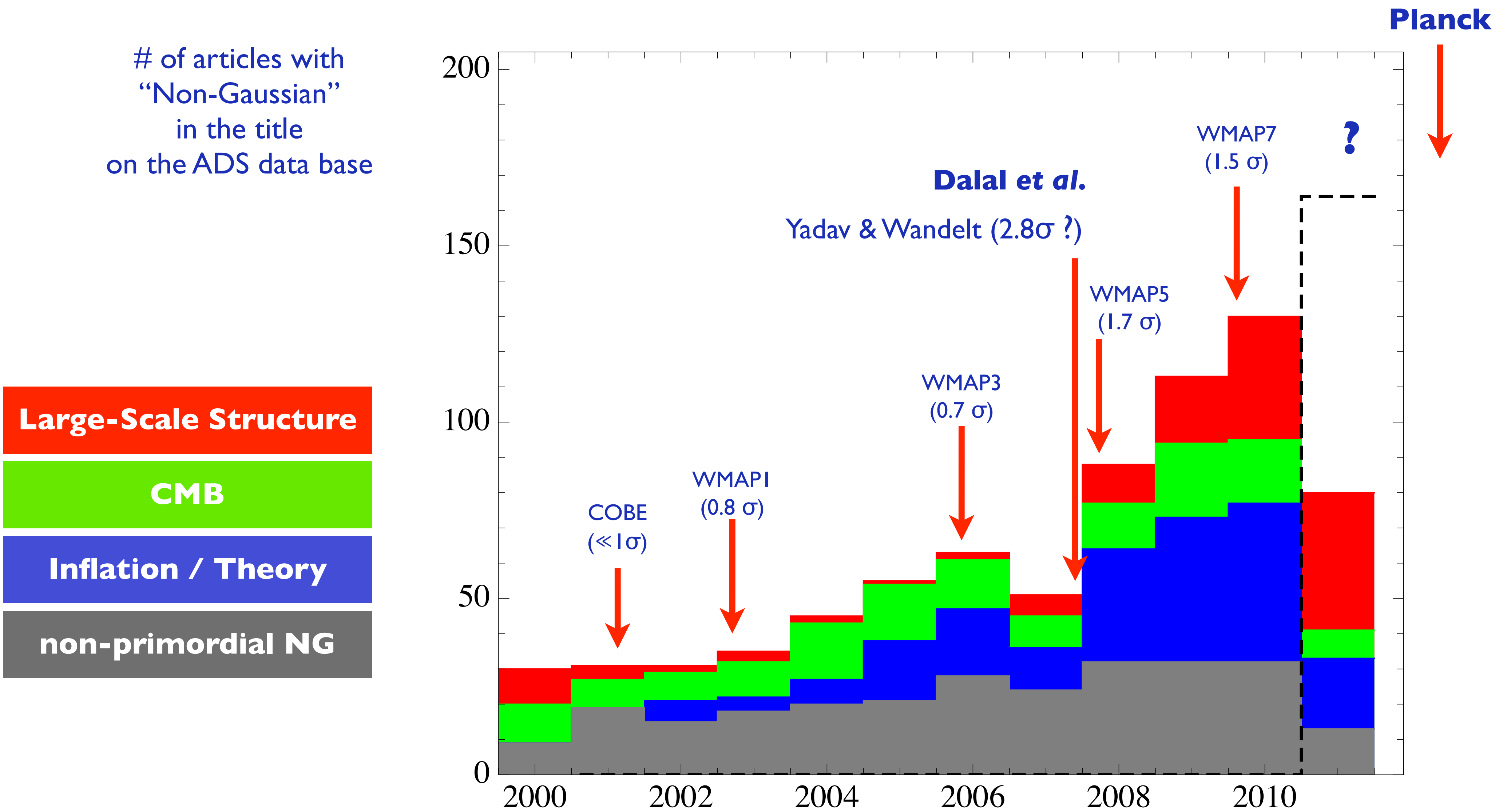
Tegmark & Zaldarriaga 1998



Hinshaw et al (WMAP9) 2013

LSS and primordial non-Gaussianity

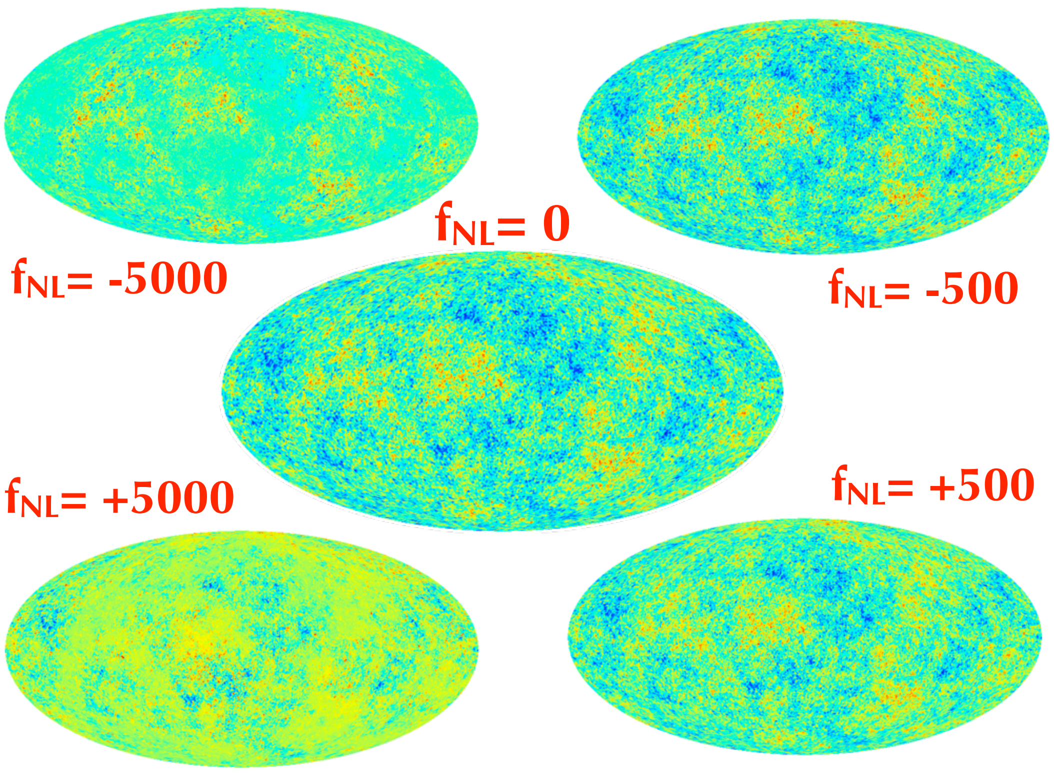
Non-Gaussianity papers in the past 10 years



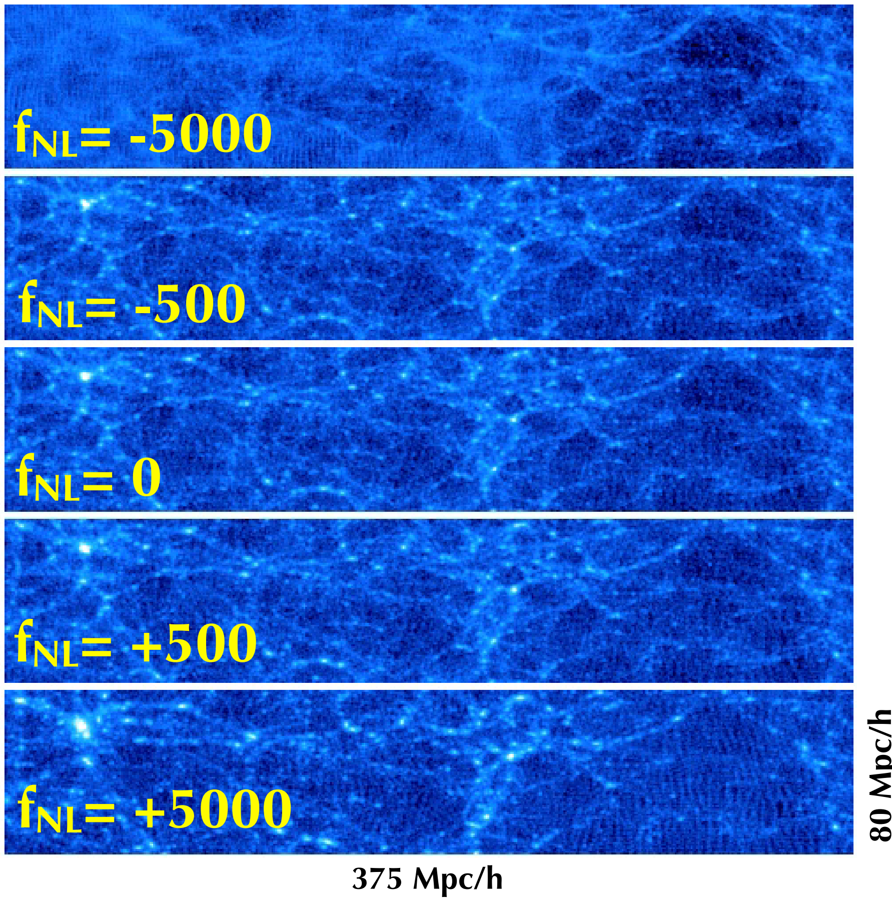
Produced by Emiliano Sefusatti

Effects of primordial non-Gaussianity of local type

CMB: 3-point function is non-zero

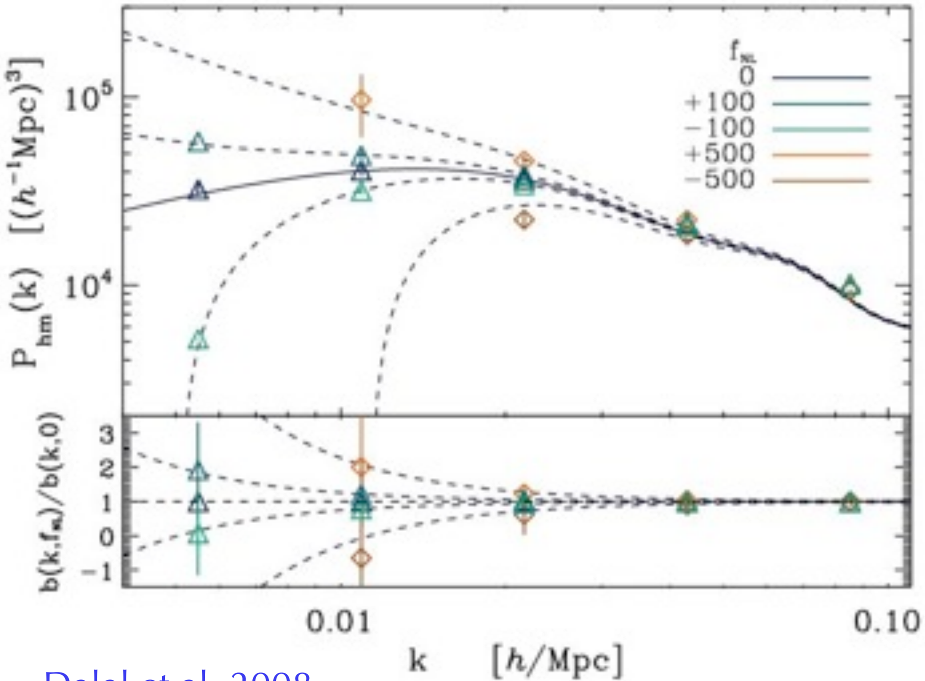


LSS: over/under accentuation of density peaks



Using publicly available NG maps by Elsner & Wandelt

Dalal, Doré, Huterer & Shirokov 2008

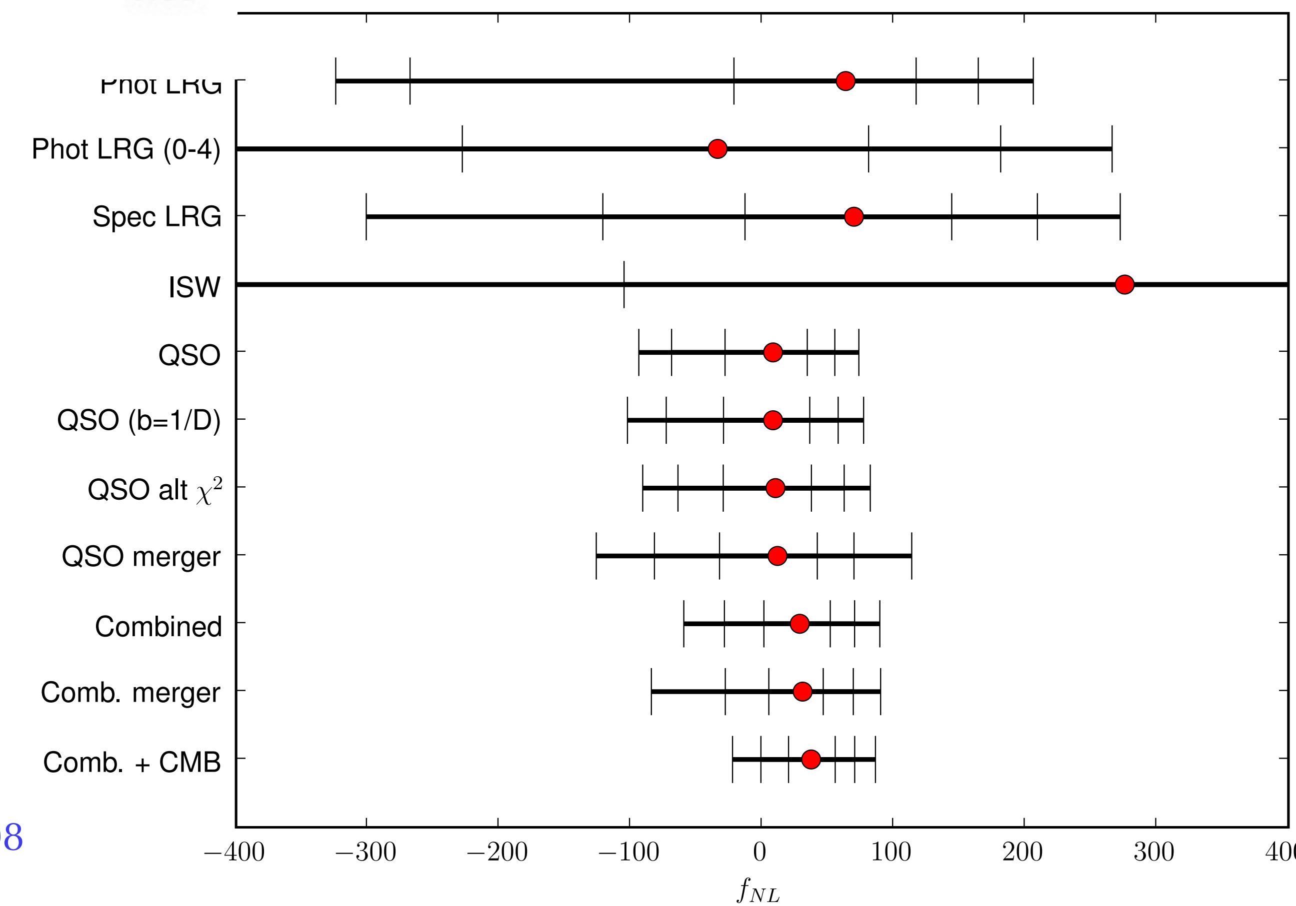


Dalal et al. 2008

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

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

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

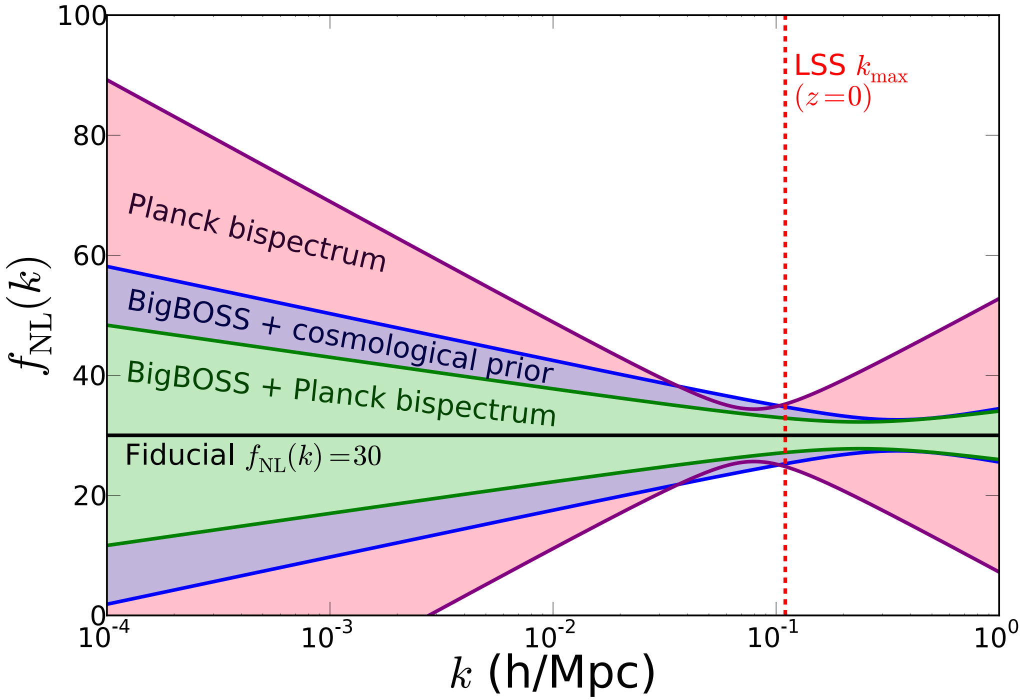


Slosar et al. 2008

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

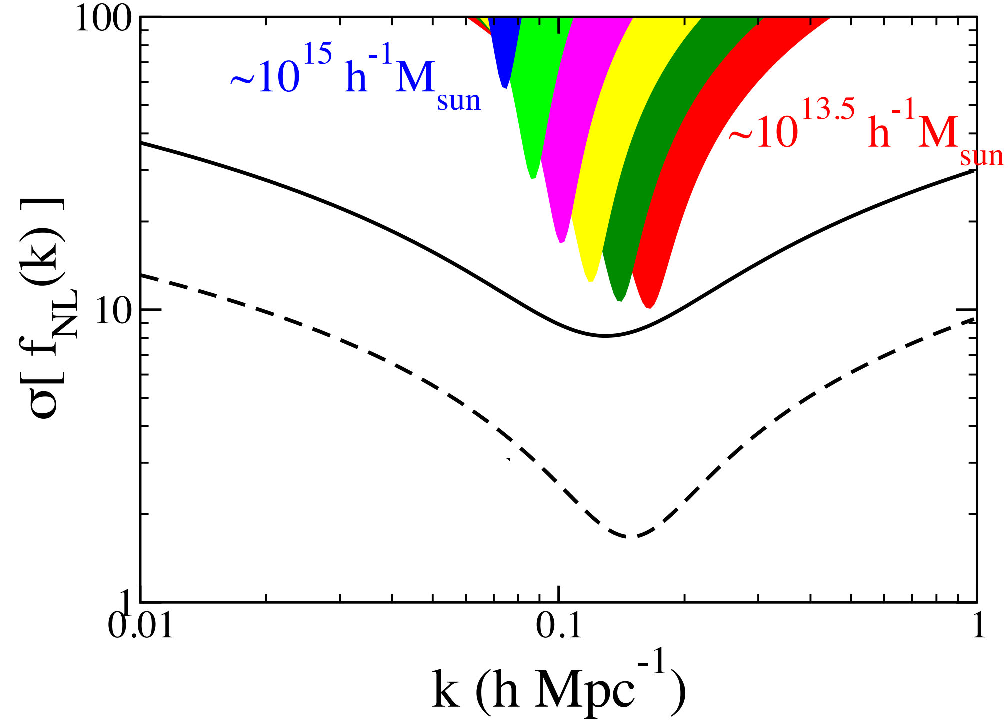
$$f_{\rm NL}(k) = f^*_{\rm NL}\left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

CMB and LSS are very complementary



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

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



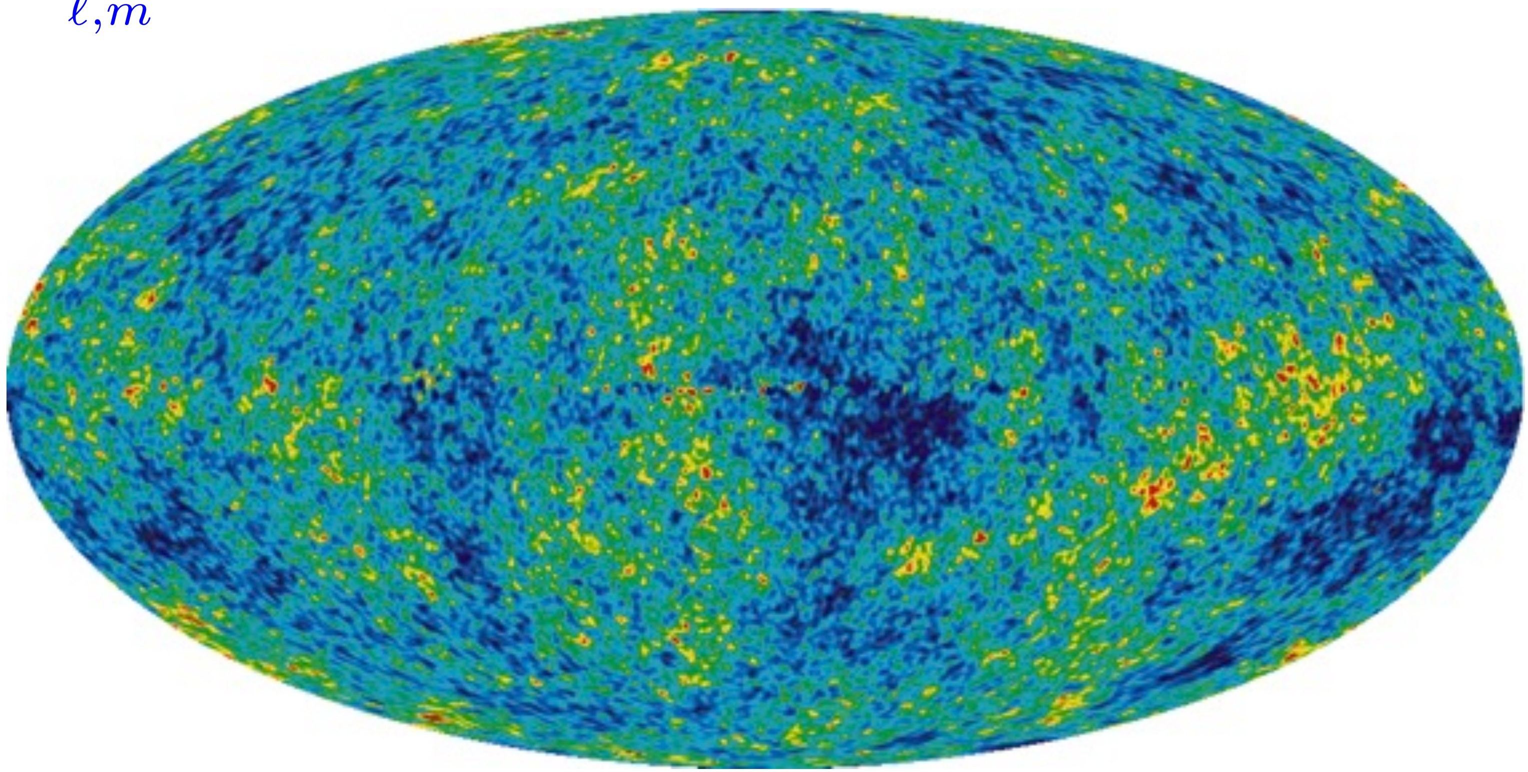
In general, LSS can probe:

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

LSS and statistical isotropy + homogeneity

Initial conditions in the universe

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



Statistical Isotropy:

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

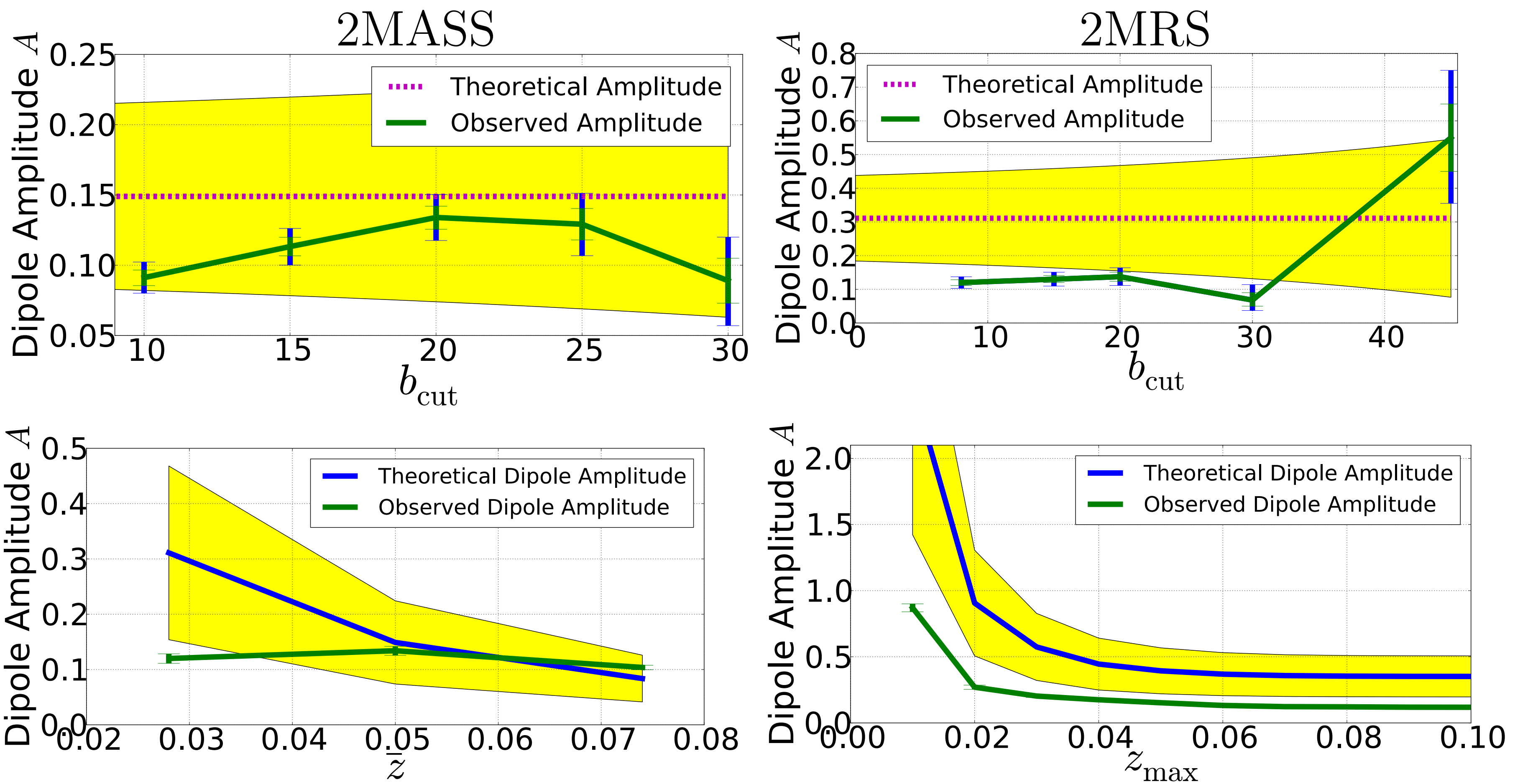
Gaussianity:

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

Testing homogeneity and statistical isotropy with the LSS

Example I: dipole modulations in number counts:

$$N(\hat{\mathbf{n}}) = \bar{N}(\hat{\mathbf{n}})\left[1 + A\left(\hat{\mathbf{d}} \cdot \hat{\mathbf{n}}\right)\right]$$

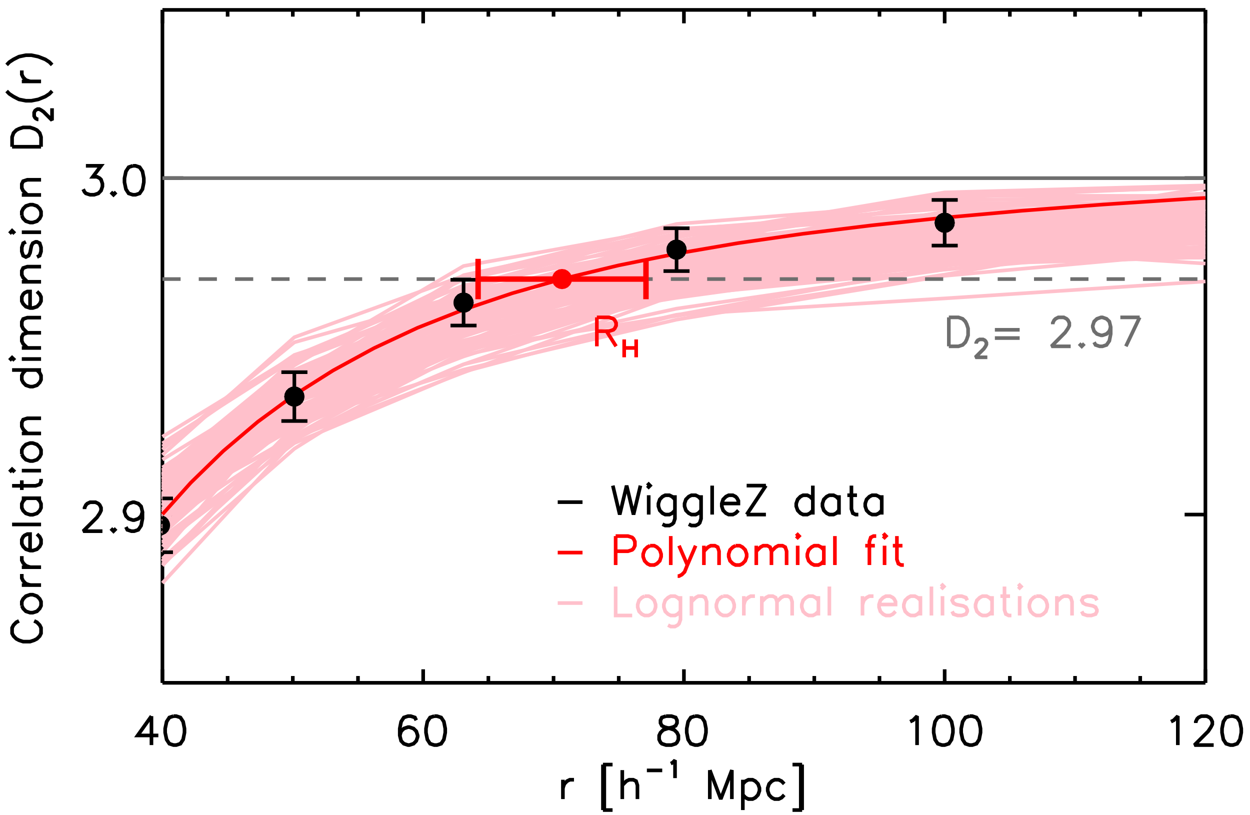


Gibelyou & Huterer (2012); method from Hirata (2009)

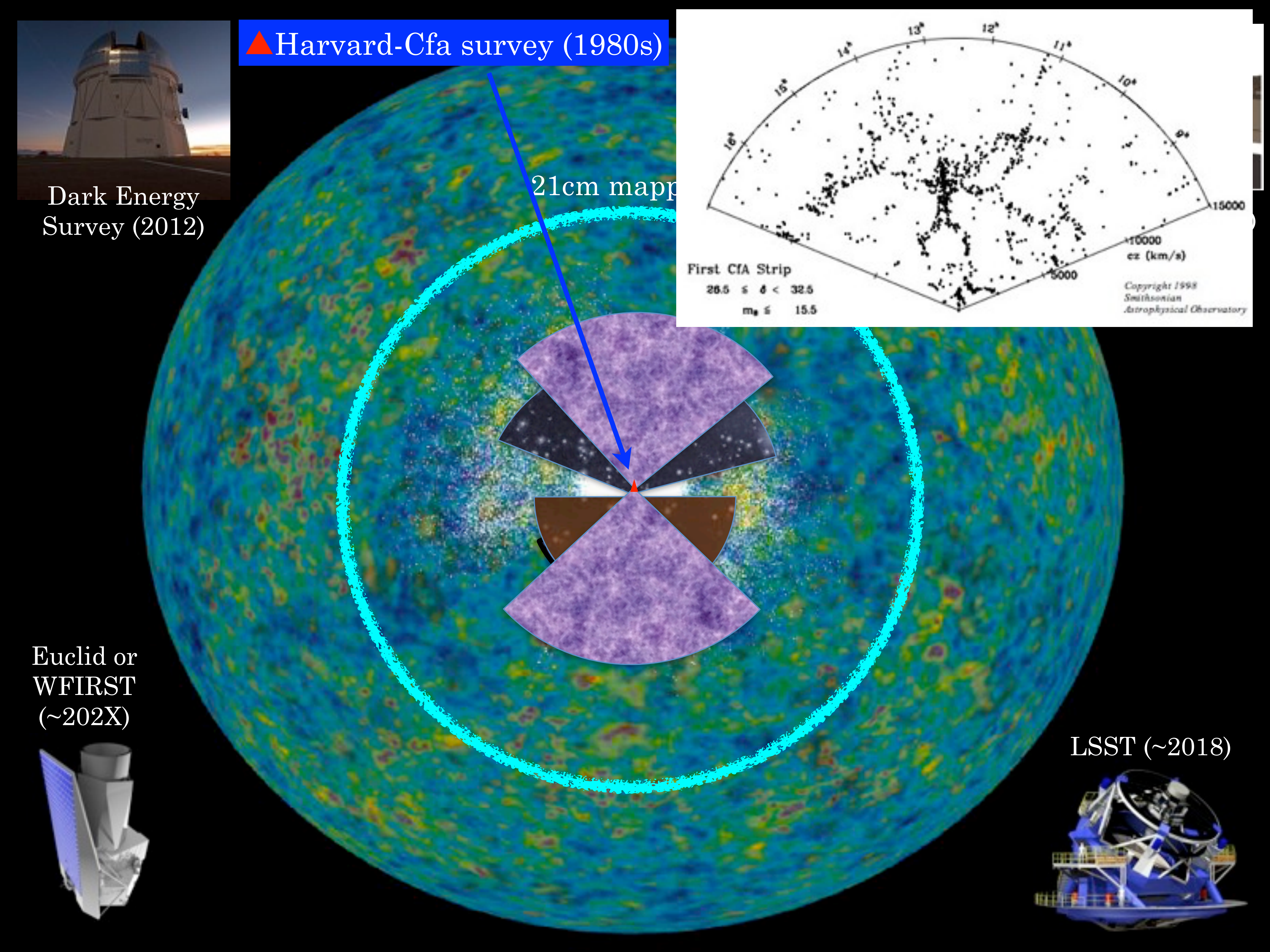
Testing homogeneity and statistical isotropy with the LSS

Example II: testing homogeneity with galaxies:

$$N(< r) \propto r^{D_2}$$



Wigglez (Scrimgeour et al, 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 or WFIRST (~202X)
LSST (~2018)

Desiderata for future LSS surveys

Large volume: at large spatial scales, errors on cosmological parameters go as $V^{-1/2}$

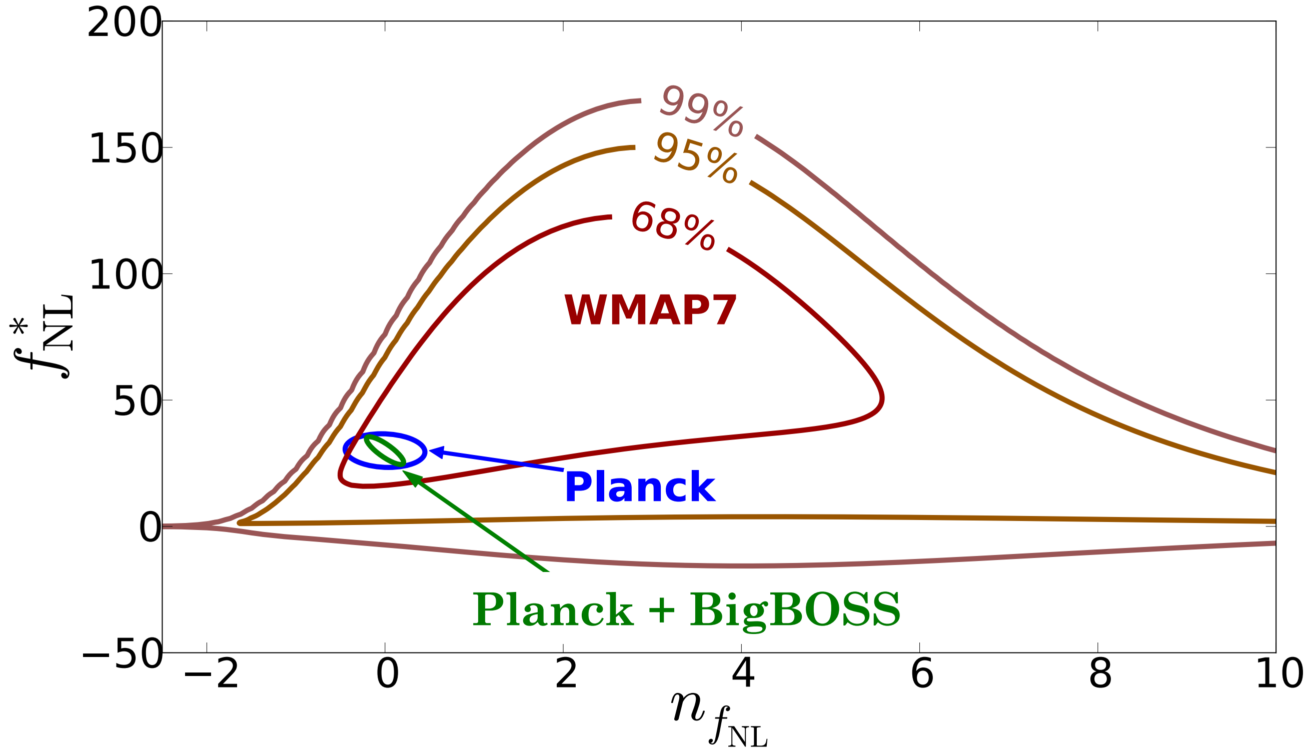
Redshifts: enormous amount doable with photometric info alone, but the photo-zs are inherently messy; accurate knowledge of the full $P(z_s | z_p)$ is required (or: spectra).

Well-characterized selection: helps pin down masses of halos, and their other properties such as bias

....

EXTRA SLIDES

Forecasts for $f_{NL}(k)$ with BigBOSS



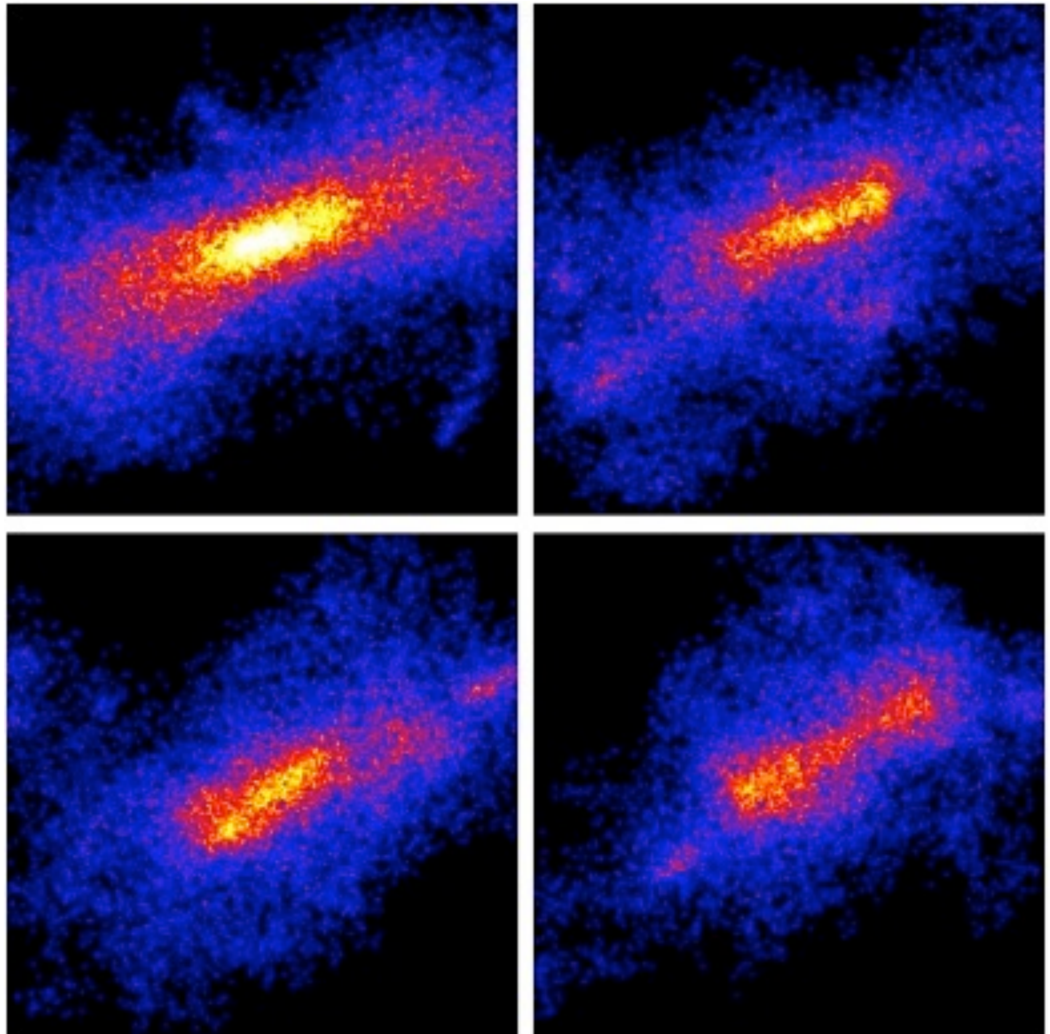
Projected errors $\sigma(f^*_{\rm NL})$ and $\sigma(n_{f_{\rm NL}})$, and the corresponding pivots				
Variable	BigBOSS	BigBOSS+Planck C_ℓs	Planck bispec	**BigBOSS+all Planck**
$\sigma(f^*_{\rm NL})$	3.0	2.6	4.4	2.2
$\sigma(n_{f_{\rm NL}})$	0.12	0.11	0.29	0.078
$\mathrm{FoM}^{(\mathrm{NG})}$	2.7	3.4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

Becker, Huterer & Kadota, arXiv:1206.6165

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} $M_\odot$

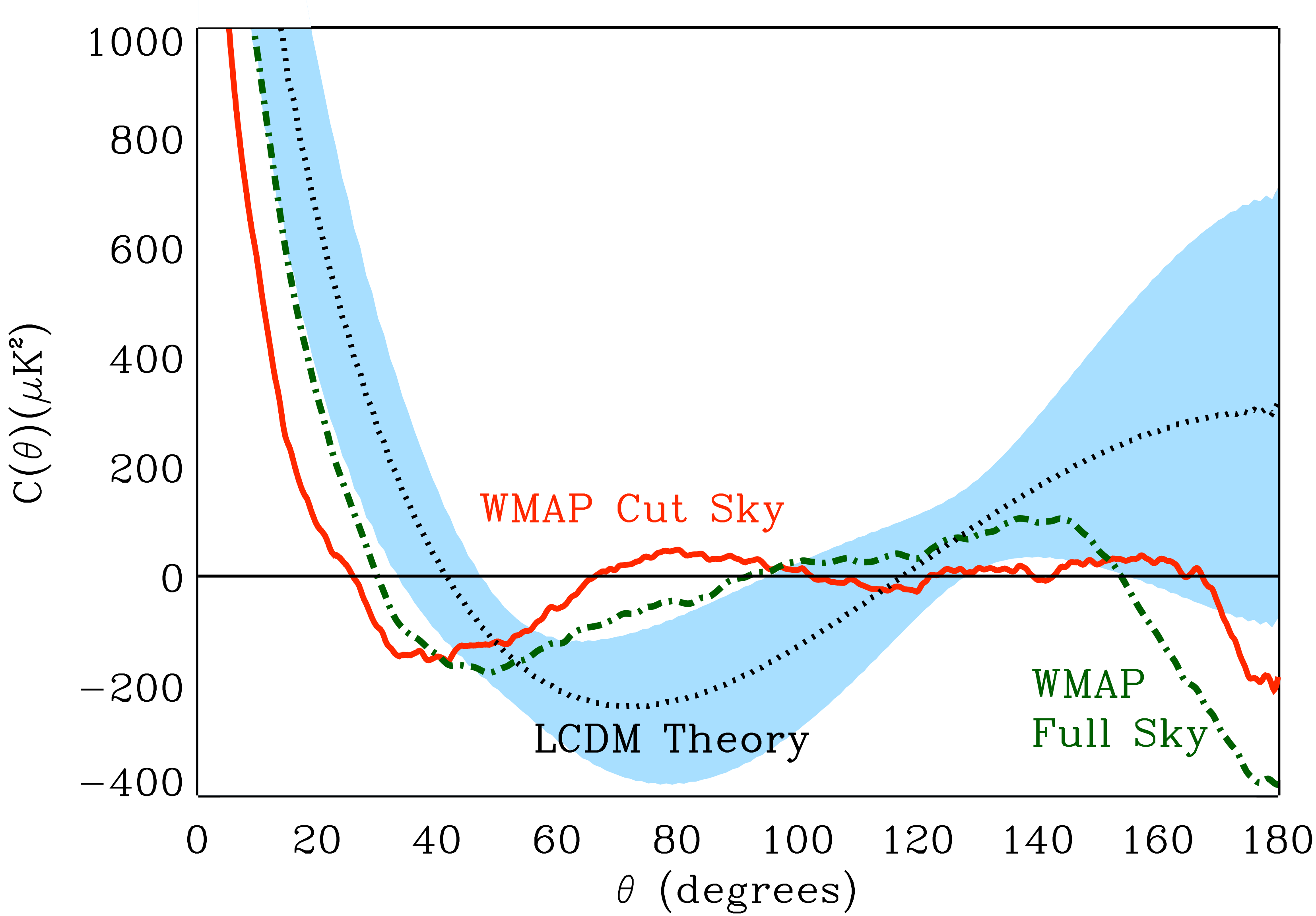


f_{NL}=0
M=5.1 10^{15} $M_\odot$

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

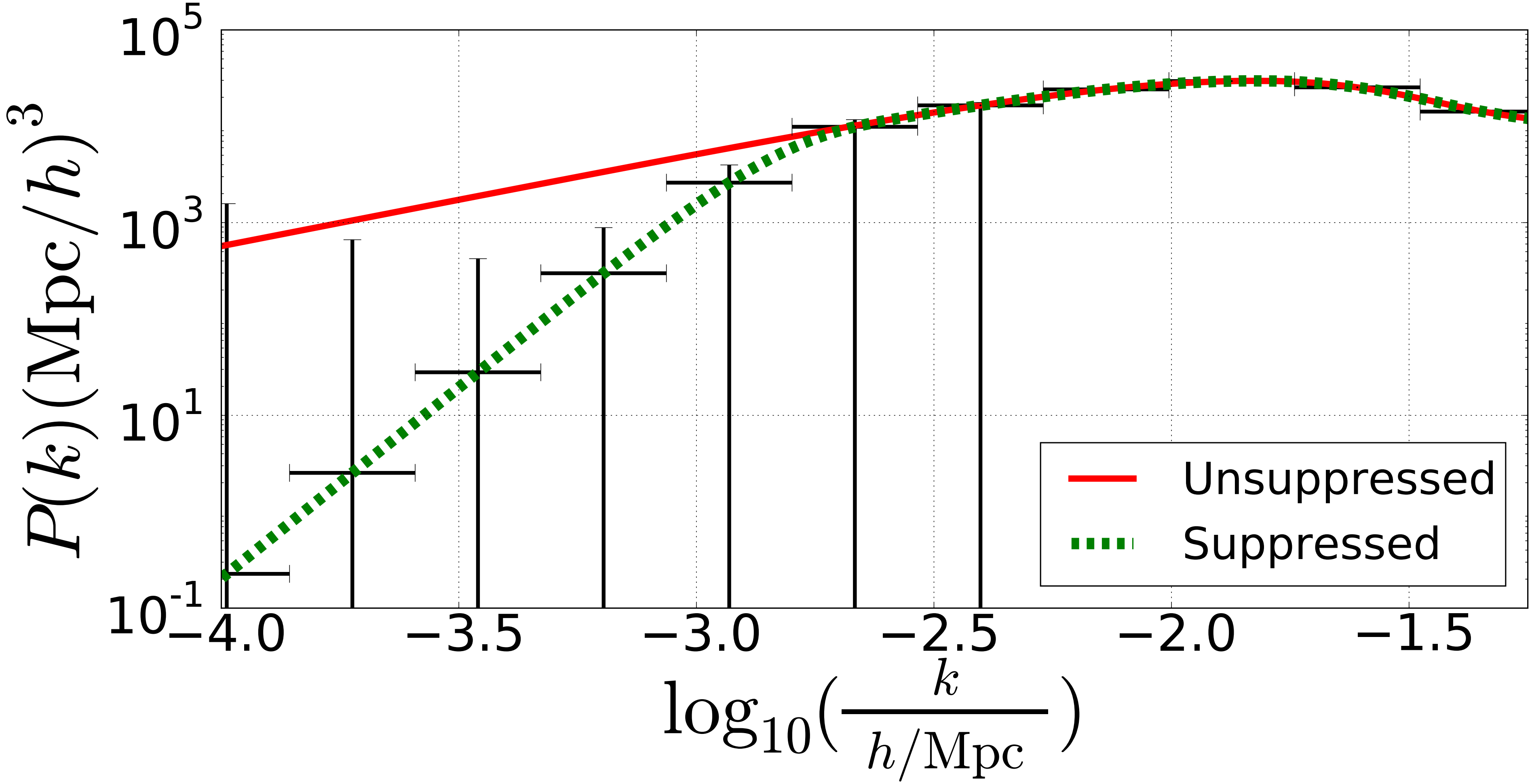
Dalal, Doré, Huterer & Shirokov 2008

Missing power above 60°



Hinshaw et al 1996 (COBE);
Spergel et al 2003 (WMAP)
Copi et al 2007, 2009; Sarkar et al 2010

Using LSS to test whether low P(k) is the cause of low C(θ)



Can do this with LSS if you have a HUGE number of galaxy redshifts, as assumed in plot above

(LSST with gazillion redshifts)

Gibelyou, Huterer & Fang 2010