Testing Statistical Isotropy and Primordial Non-Gaussianity with the CMB and LSS

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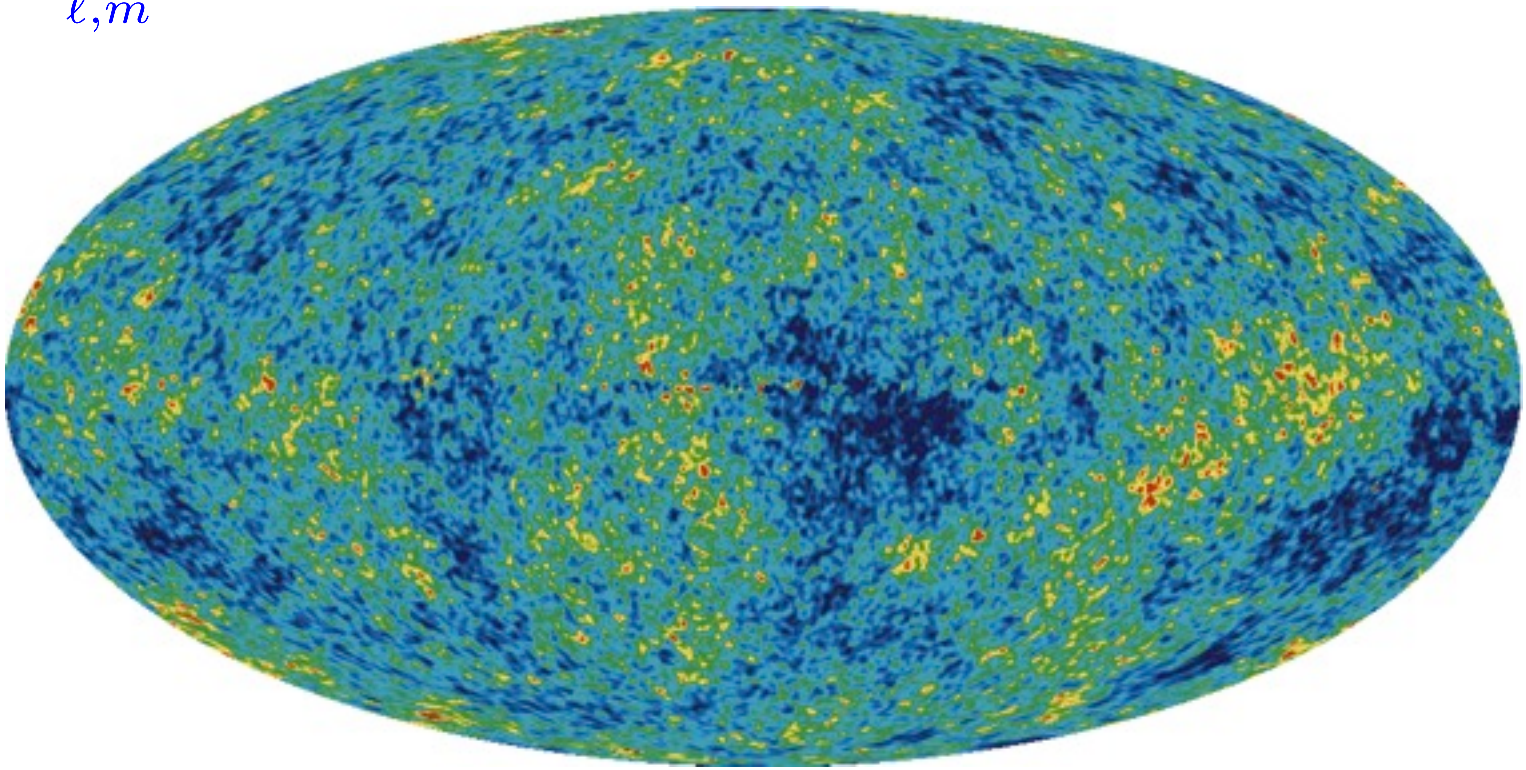
Initial conditions in the universe

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



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, statistically isotropic spectrum of density perturbations
- Background of gravity waves
- (Very nearly) gaussian initial conditions

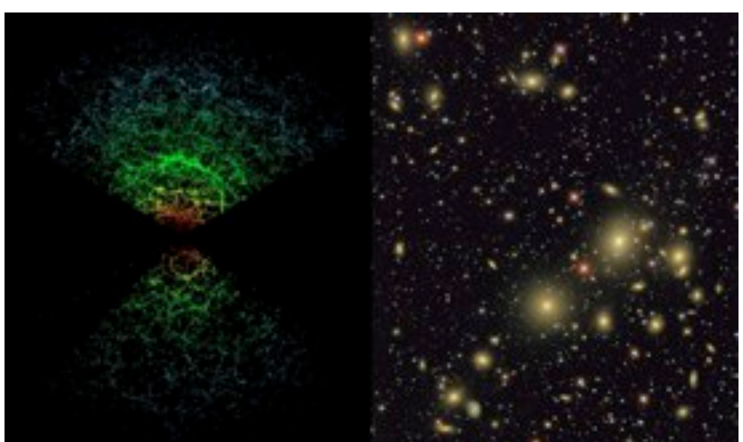
Gaussianity:

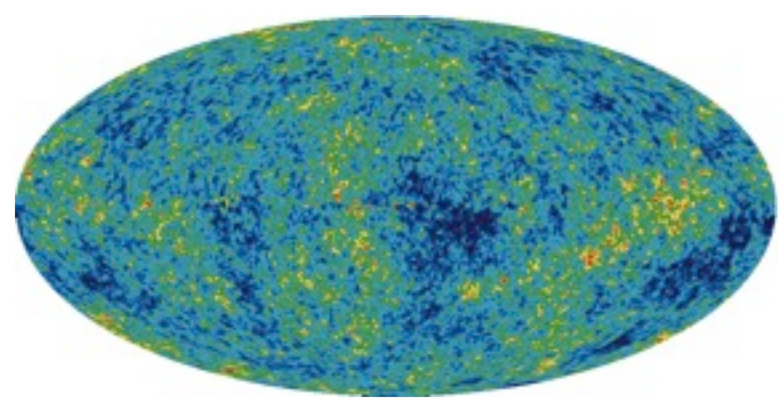
$$\langle a_{\ell m}\, a_{\ell' m'}\, a_{\ell'' m''} \rangle = 0$$

Why study statistical isotropy (SI) and primordial non-Gaussianity (NG)?

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

2. Conveniently, SI and 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 SI and NG.





1. Statistical Isotropy

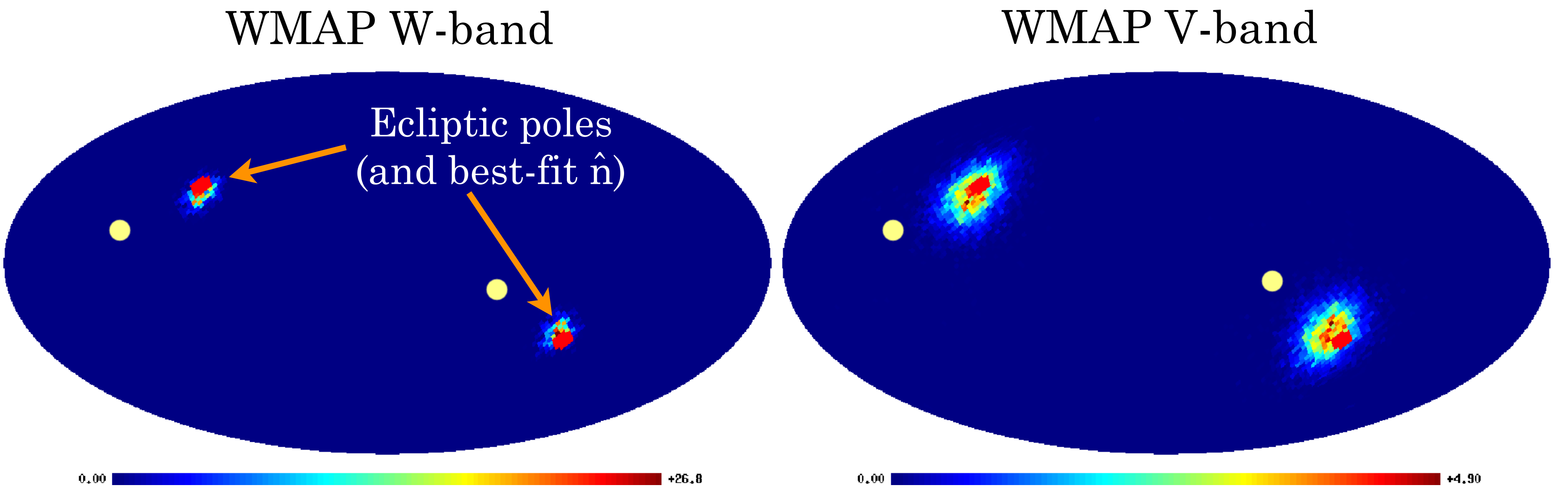
- So far, investigated in CMB much more than in LSS
- Despite hints of violation in SI at CMB's large scales...
- ...so far all observations are in good agreement with statistical isotropy
- Wider, deeper LSS surveys on the way will improve constraints by a lot

Hints of large-scale modulation (from higher-ℓ CMB)

Model:

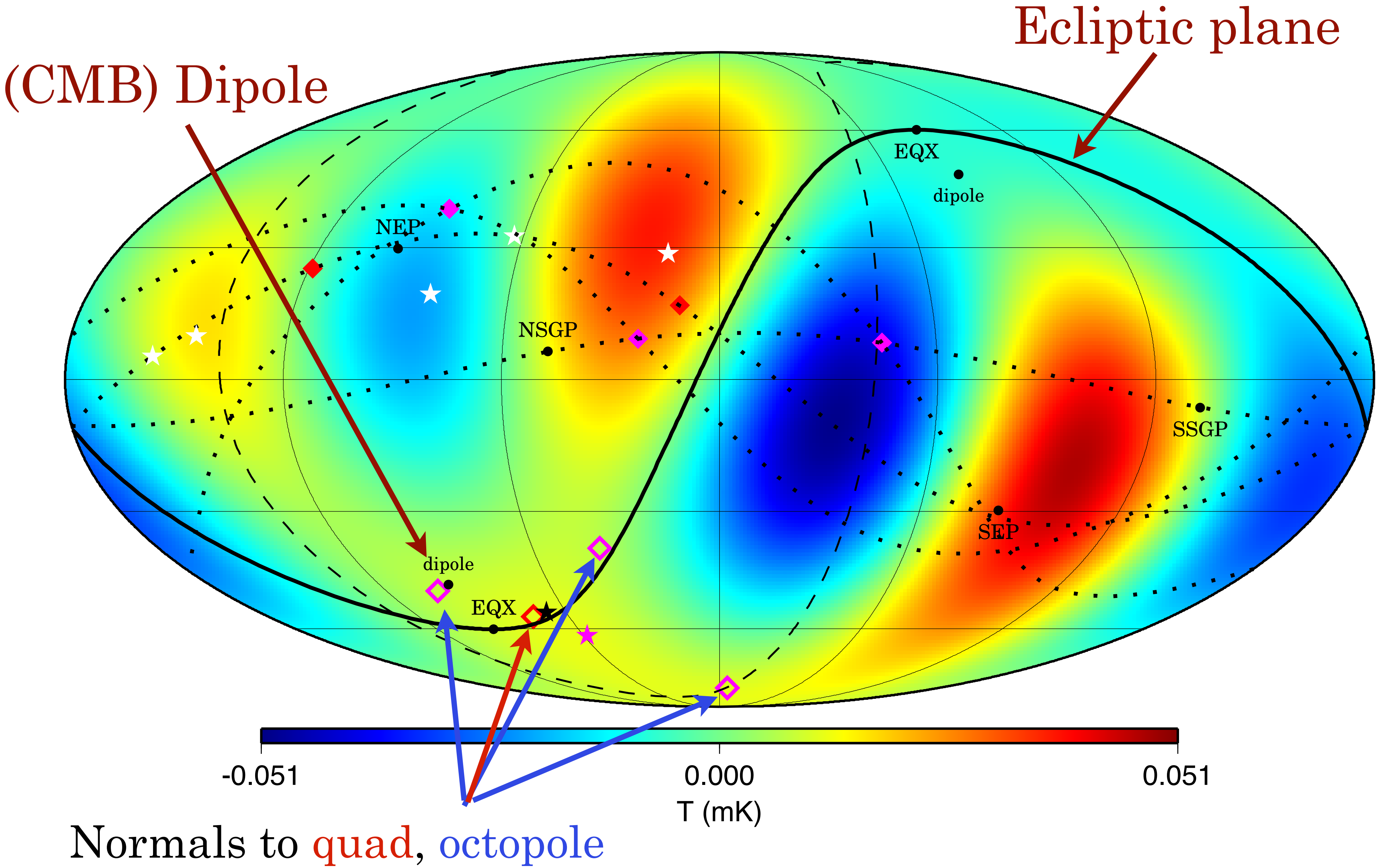
$$P(\mathbf{k}) = P(k)\left(1 + g\,(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2\right)$$

Ackerman, Carroll, Wise 2007



Groeneboom et al, arXiv:0911.0150

Hints of alignment of large-angle CMB (with the solar system geometry)



Schwarz, Starkman, Huterer & Copi 2004; review in 2010

Testing the statistical isotropy of large scale structure with multipole vectors

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(Dated: September 27, 2010)

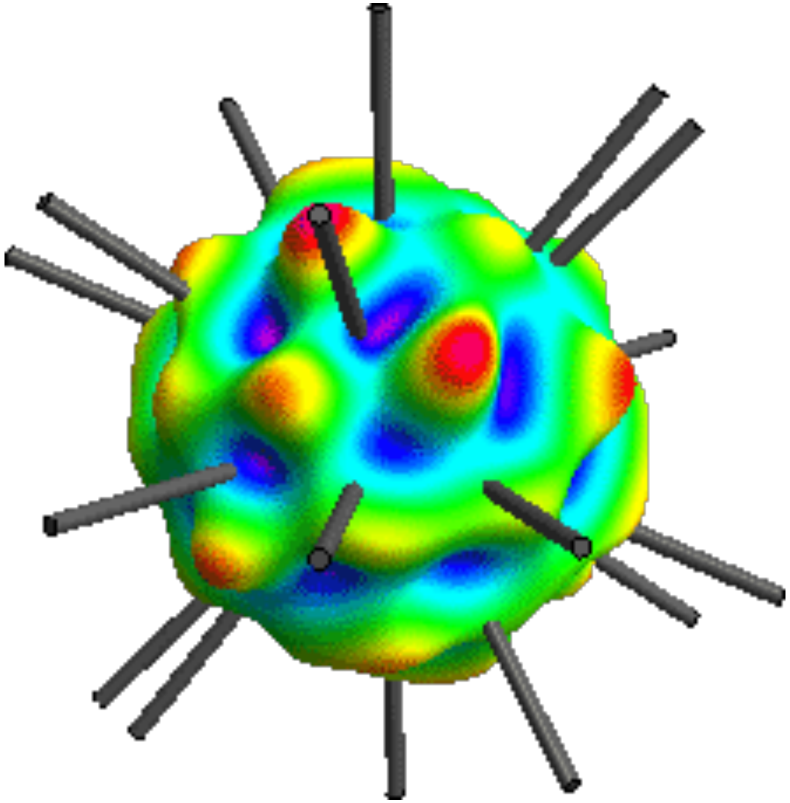
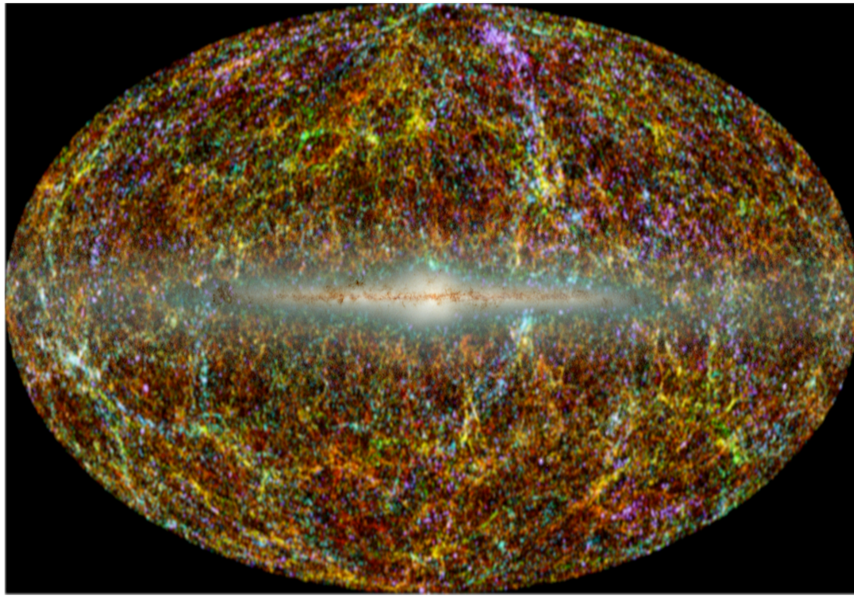
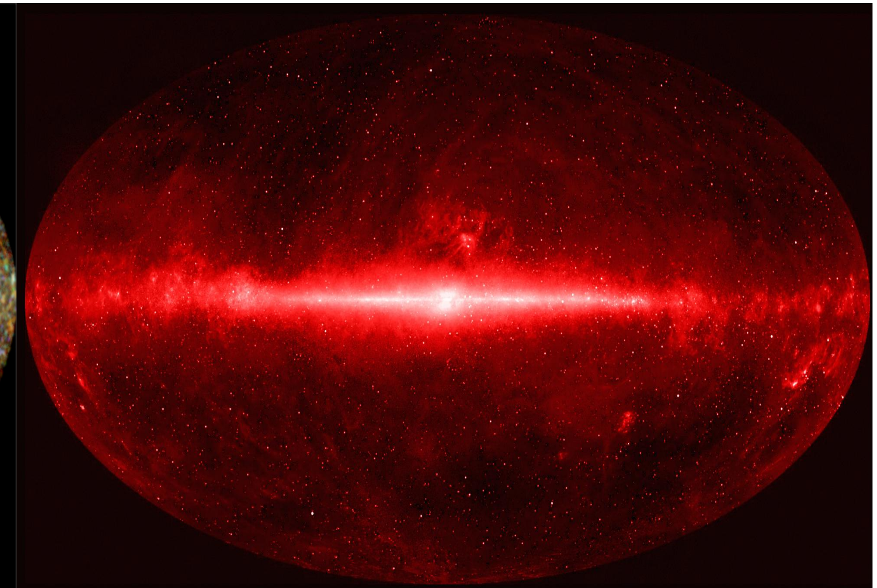


Image credit: Mark Dennis

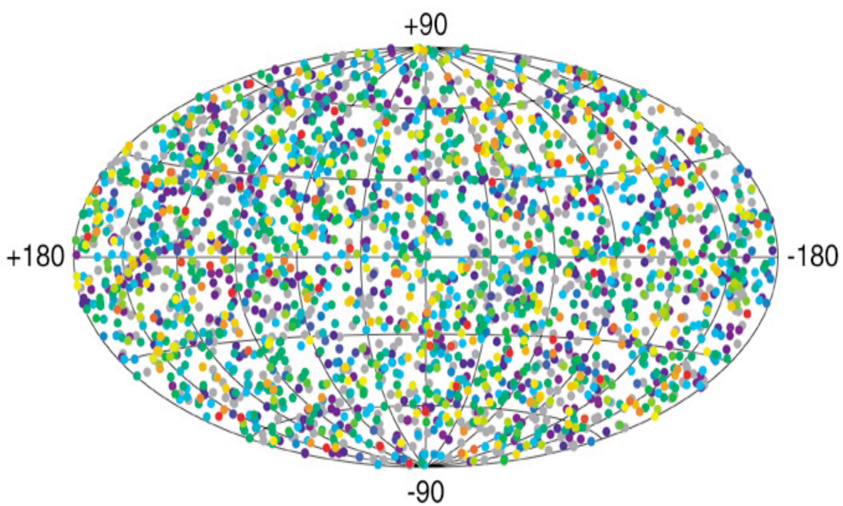
2MASS

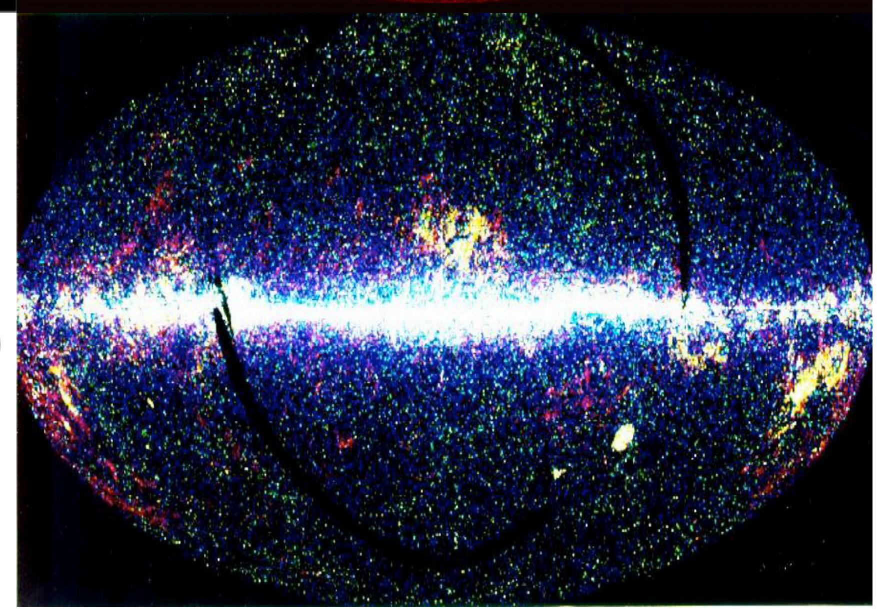


WISE



2704 BATSE Gamma-Ray Bursts





IRAS

And: DES, BigBOSS, LSST, ...

2. Primordial non-Gaussianity

Very popular topic recently

e.g. 56 talks at Michigan workshop on NG, May 2011:

Cosmological Non-Gaussianity Workshop May 2011 http://www.umich.edu/~mctp/SciPrgPgs/events/2011/CosmoNo...

Friday May 13th, 2011

8:30 AM	**Breakfast in 337 West Hall**	
9:00 AM	Gordon Kane (University of Michigan)	Welcome
9:10 AM	Sabino Matarrese (Universita di Padova)	Probing Primordial Non-Gaussianities with Large-Scale Structure Data
9:40 AM	Xingang Chen (Cambridge University)	Primordial features and non-Gaussianities as evidence for inflation
10:00 AM	Leonardo Senatore (Stanford University)	The effective field theory of Inflation and Multifield Inflation
10:20 AM	**Morning Coffee Break in 337 West Hall**	
10:50 AM	Misao Sasaki (Kyoto University)	Delta N Formalism and Superhorizon Curvature Perturbation
11:20 AM	Justin Khoury (University of Pennsylvania)	Scale Invariance from Conformal Invariance
11:40 AM	Daniel Chung (University of Wisconsin)	Isocurvature Perturbations and NG from Nonthermal Dark Matter
2:00 PM	Marco Peloso (University of Minnesota)	Large NG in Axion Inflation
12:20 PM	**Lunch**	
2:00 PM	Chris Byrnes (Bielefeld University)	Scale dependent Non-Gaussianity
2:20 PM	Paul Shellard (Cambridge University)	CMB Non-Gaussianity: Modal Methods
2:40 PM	James Fergusson (Cambridge University)	Applications of Modal Methods
3:00 PM	Michele Liguori (Cambridge University)	A Model Bispectrum Estimator for the CMB Bispectrum
3:20 PM	**Refreshments and Coffee in 337 West Hall**	
3:50 PM	Jun'ichi Yokoyama (University of Tokyo)	G-inflation and its Non-Gaussianity
4:10 PM	Kazuya Koyama (University of Portsmouth)	Non-Gaussianity from DBI Galileons
4:30 PM	**Canoeing @ Huron River**	

Saturday May 14th, 2011

8:30 AM	**Breakfast in 337 West Hall**	
9:00 AM	Licia Verde (Universitat de Barcelona)	General Non-Gaussian Shapes in Large-Scale Structure
9:30 AM	Fabian Schmidt (Caltech)	Peak-background Split and Primordial Non-Gaussianity

2 of 4 8/8/11 4:28 PM

Cosmological Non-Gaussianity Workshop May 2011 http://www.umich.edu/~mctp/SciPrgPgs/events/2011/CosmoNo...

10:00 AM	**Morning Coffee Break in 337 West Hall**	
10:30 AM	Roman Scoccimarro (New York University)	Probing Primordial Non-Gaussiani with Large-Scale Structure
10:50 AM	Shirley Ho (UC Berkeley)	Large-Scale Clustering, Systemati NG
11:10 AM	Carlos Cunha (University of Michigan)	The Dark Energy Survey and Prim Non-Gaussianity
11:30 AM	Kendrick Smith (Princeton University)	Halo Clustering with fNL, gNL, ar tau_NL
11:50 AM	Raphael Flauger (Yale University)	Resonant Non-Gaussianity
12:10 PM	Discussion	
12:20 PM	**Lunch**	
2:00 PM	**Machine-Gun session:** Anthony Pullen (Caltech) Emanuela Dimastrogiovanni (Padova) Tsz-Yan Lam (IPMU) Annalisa Pillepich (UC Santa Cruz) Tobias Baldauf (University of Zurich) Heike Modest (MPE) Peter Adshead (University of Chicago) Navin Sivanandam (University of Texas) Joel Meyers (University of Texas) Ivan Agullo (Penn State University) Jonathan Ganc (University of Texas) Guido d'Amico (New York University) Amjad Ashoorion (Uppsala University) Qingqing Mao (Vanderbilt University) Nico Hamaus (University of Zurich) Adam Becker (University of Michigan)	
3:10 PM	Discussion	
3:30 PM	**Refreshments and Coffee in 337 West Hall**	
4:00 PM	Donghui Jeong (Caltech)	Pg(k) near Horizon scales: galaxy general relativity and effective fNI
4:20 PM	Jaiyul Yoo (University of Zurich)	General Relativistic Description of Observed Galaxy Power Spectrum
4:40 PM	Paolo Creminelli (ICTP)	Galilean symmetry in the effective theory of inflation
5:00 PM	Eugene Lim (Cambridge University)	Can we ever detect tensor non-Gaussianities?
6:30 PM	**Reception and Dinner @ Art Museum**	

Sunday May 15th, 2011

Cosmological Non-Gaussianity Workshop May 2011 http://www.umich.edu/~mctp/SciPrgPgs/events/2011/CosmoNo...

8:30 AM	**Breakfast in 337 West Hall**	
9:00 AM	Emiliano Sefusatti (Institut de Physique Theorique)	Primordial Non-Gaussianity & the Galaxy Bispectrum
9:20 AM	Vincent Desjacques (University of Zurich)	Non-Gaussian bias from peak-background split
9:40 AM	Eiichiro Komatsu (University of Texas)	Non-Gaussianity Consistency Relation for Multi-field Inflation
10:00 AM	**Morning Coffee Break in 337 West Hall**	
10:30 AM	Sarah Shandera (Perimeter Institute)	New observational power from halo bias
10:50 AM	Cristiano Porciani (University of Bonn)	Primordial Non-Gaussianity and the Large-Scale Structure of the Universe
11:10 AM	Marilena Loverde (Institute for Advanced Study)	Halo Mass Function with fNL, gNL, and tau_NL Loverde
11:30 AM	Naoshi Sugiyama (Nagoya University)	Effect of Kurtosis-Type of Primordial NG on Halo Mass Function
11:50 AM	Christophe Ringeval (Universite Catholique de Louvain)	Non-Gaussianities from cosmic strings in scaling
12:10 PM	Discussion	
12:20 PM	**Lunch**	
2:00 PM	Gary Shiu (University of Wisconsin)	Effective Field Theory and Decoupling in Multifield Inflation
2:20 PM	Aashay Kumar (University of Michigan)	Non-Gaussianity and Scale Dependence Kumar
2:40 PM	Enrico Pajer (Cornell University)	Dante's Inferno
3:00 PM	**Refreshments and Coffee in 337 West Hall**	
3:30 PM	Neil Barnaby (U. of Minnesota)	Probing the Inflaton Coupling to Matter with NG
3:50 PM	Louis LeBlond (Perimeter Institute)	Beyond the Bispectrum: N-point functions for large N
4:10 PM	Takahiro Tanaka (Kyoto University)	IR Effects on Cosmological Perturbation
4:30 PM	Christoph Raeth (MPE)	Probing Scale-dep NG in the WMAP Data Using Surrogates
4:50 PM	Scott Watson (Syracuse)	Summary and Closing Remarks
5:00 PM	**End of workshop**	

Sponsored by MCTP *and* KICP

Standard Inflation, with...

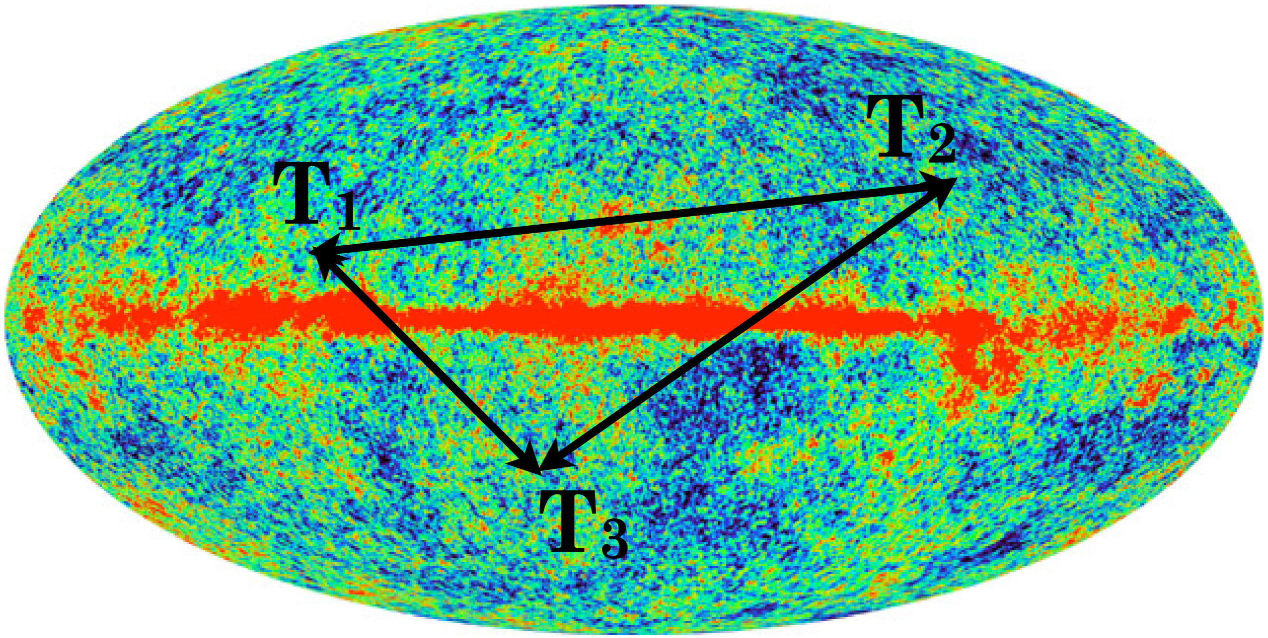
1. a single scalar field
2. the canonical kinetic term
3. always slow rolls
4. in Bunch-Davies vacuum
5. in Einstein gravity

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



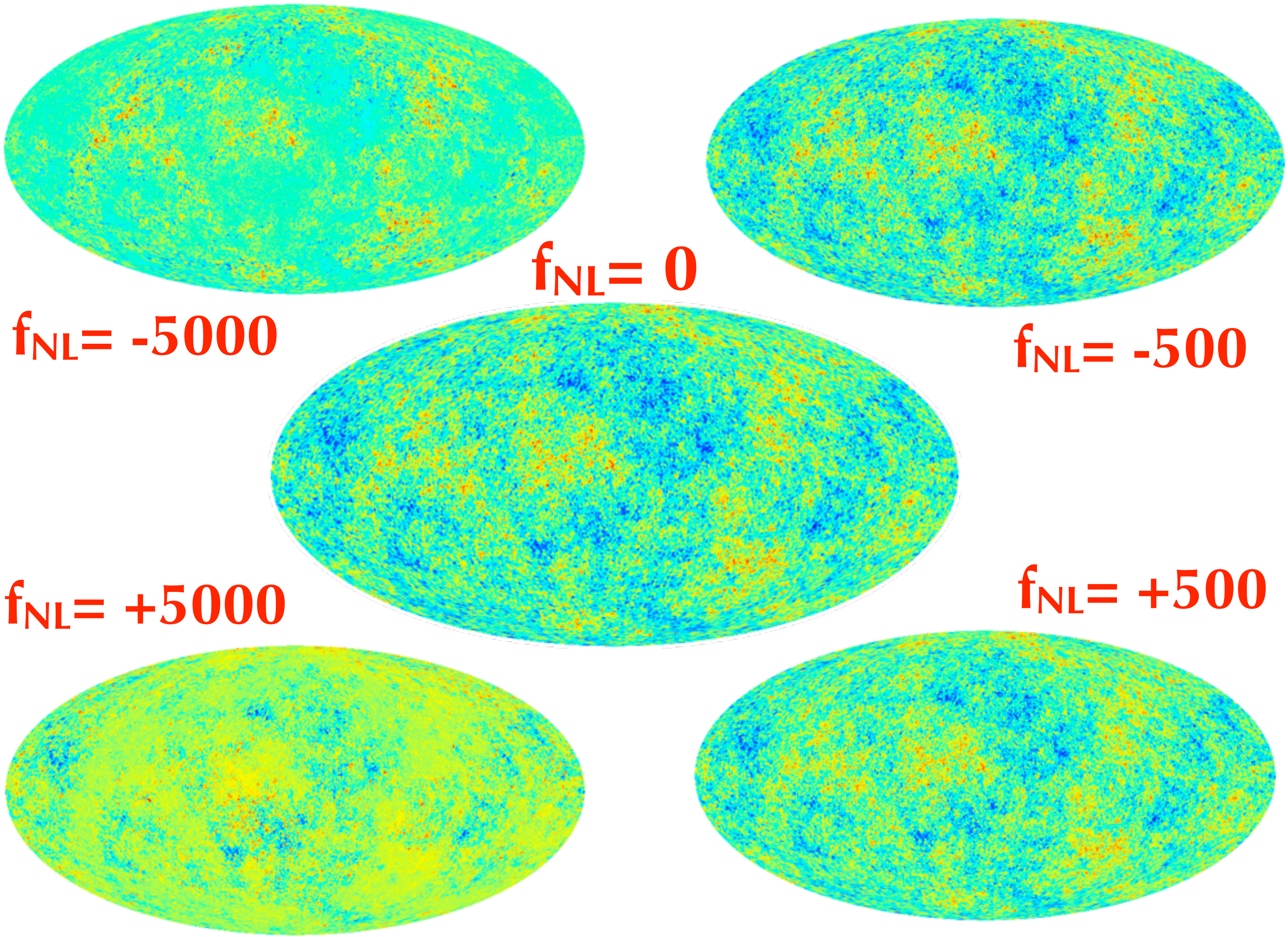
Commonly used "local" model of NG

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

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)

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



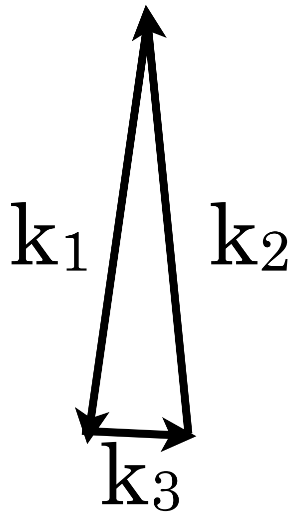
Using publicly available NG maps by Elsner & Wandelt

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

e.g. Luo & Schramm 1993

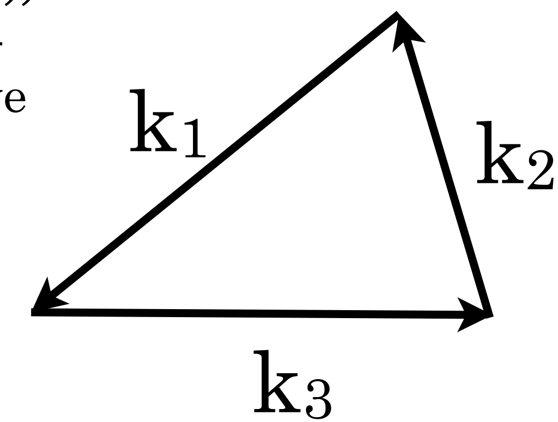
"local"

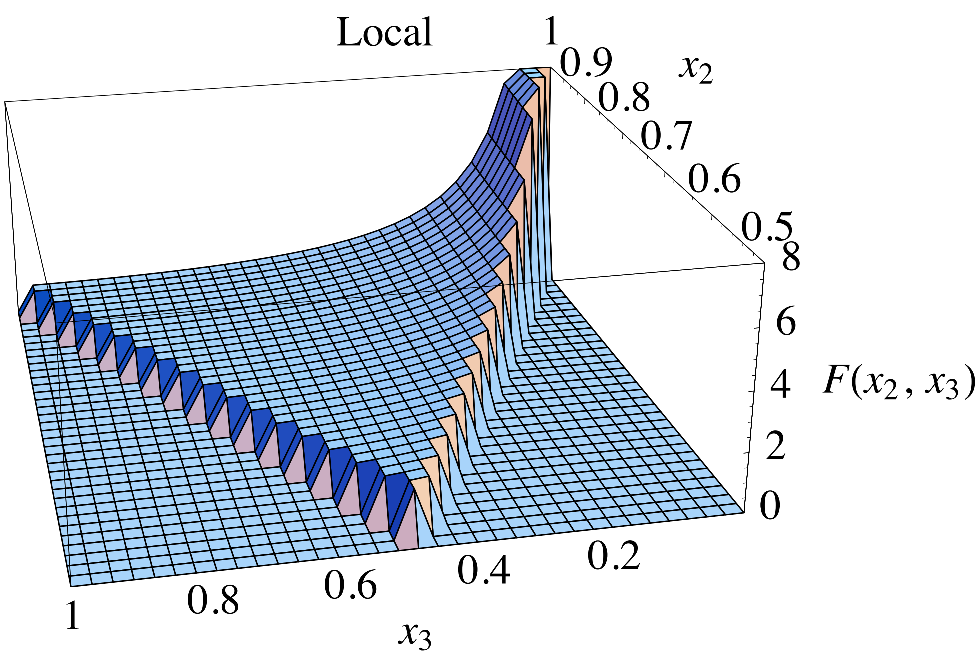
(eg. from sharp features in V(ϕ))

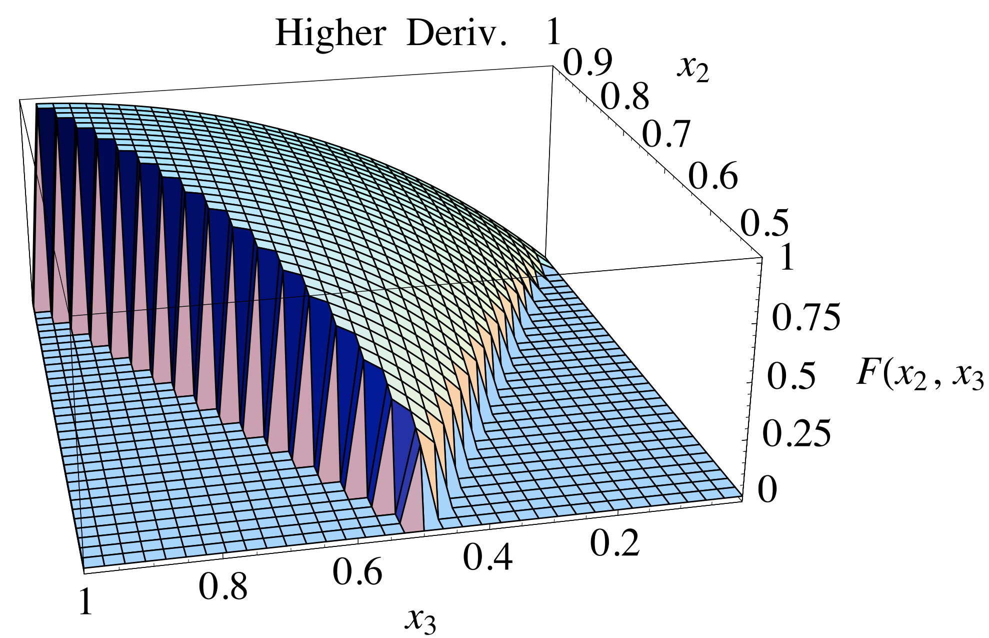


"equilateral"

(eg. higher-derivative action)







Babich, Creminelli & Zaldarriaga 2004

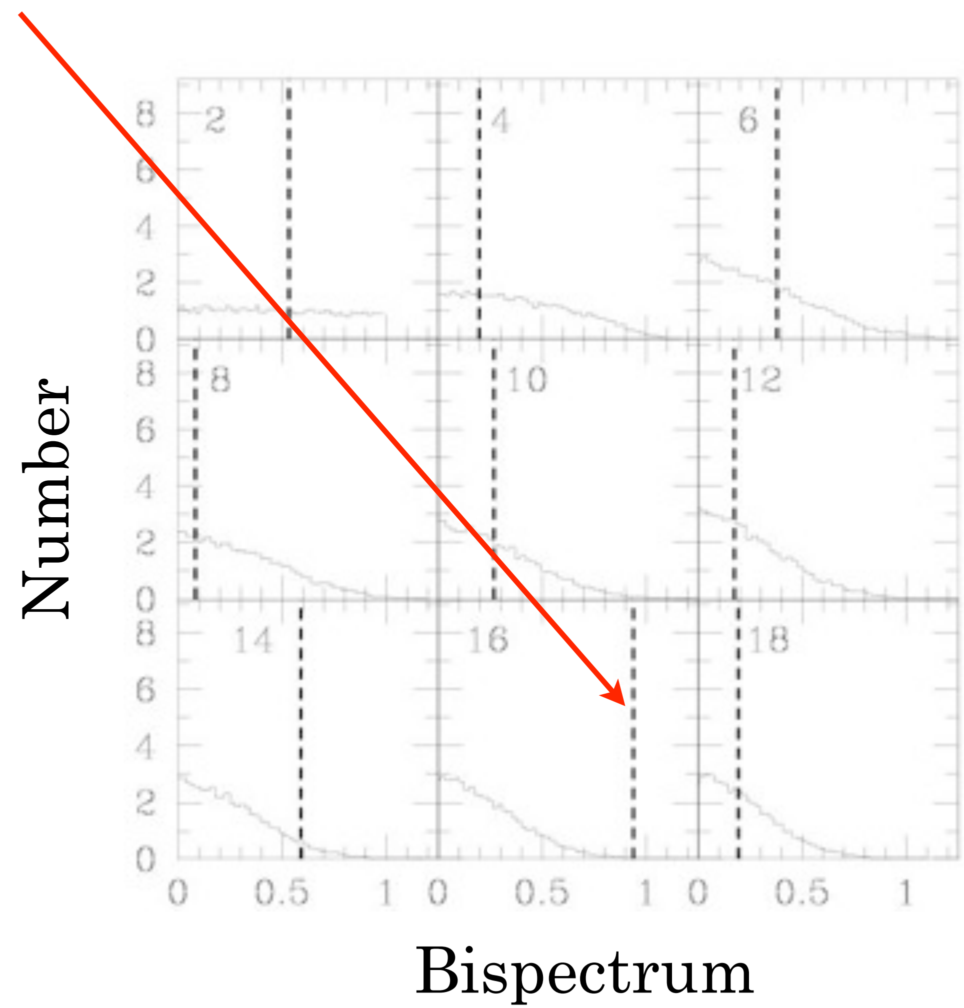
Brief history of NG measurements: 1990's

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

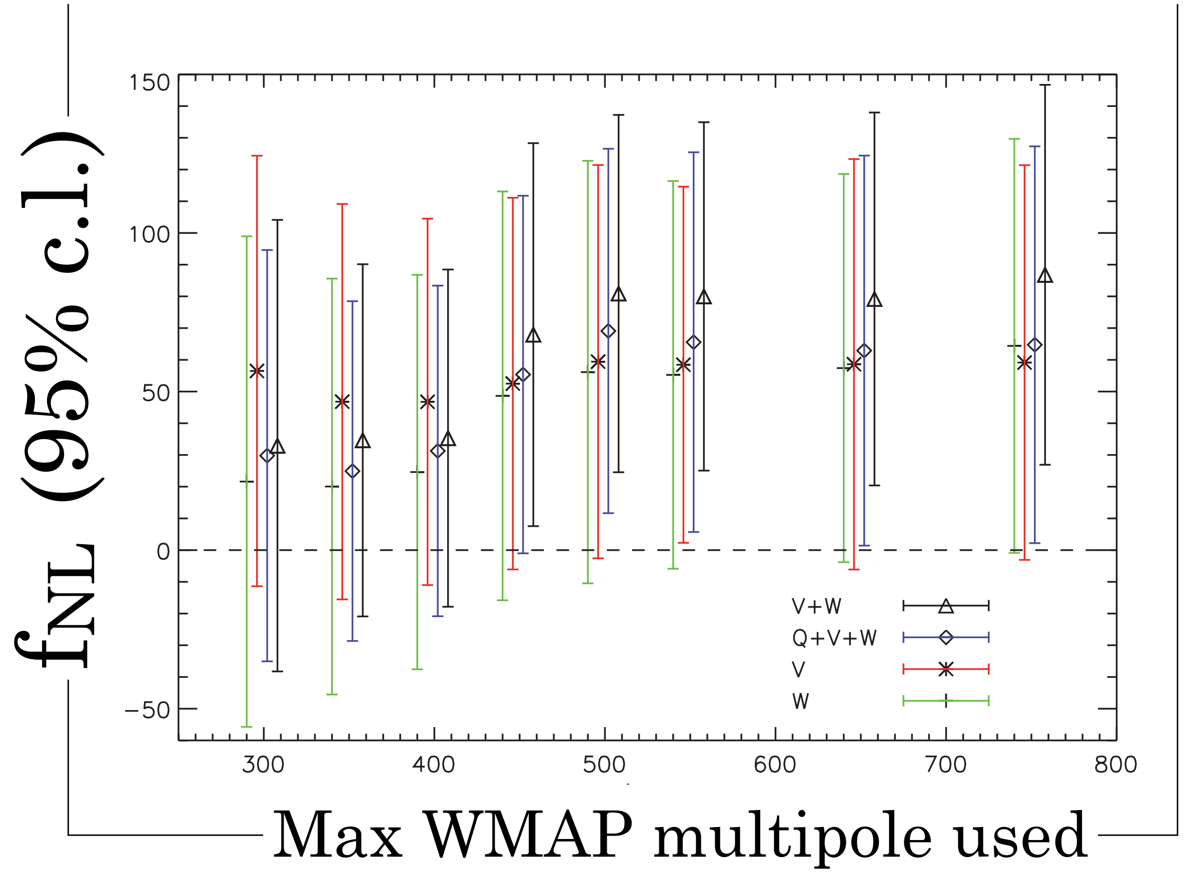
Pre-WMAP CMB: all is gaussian (e.g. MAXIMA; Wu et al 2001)

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)



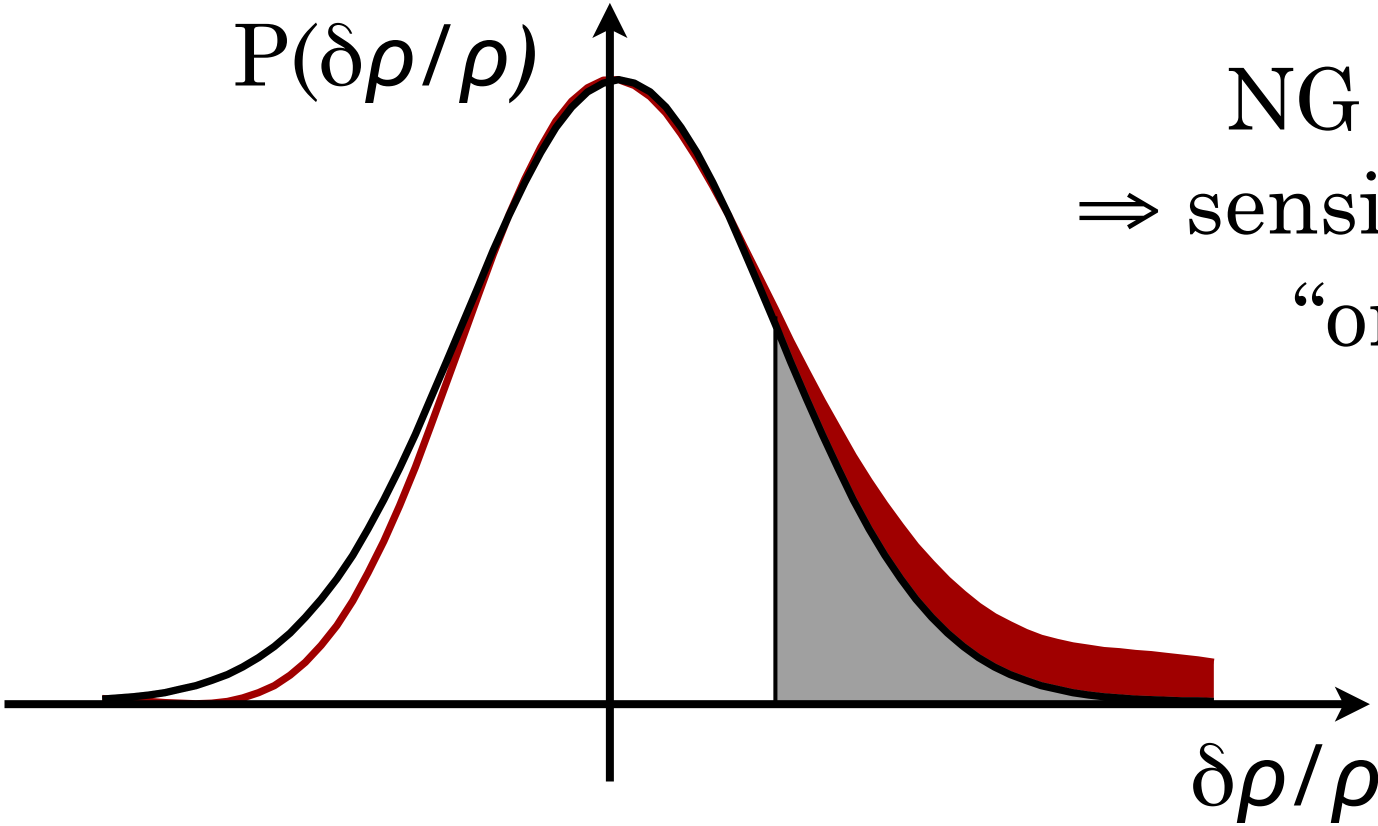
Current constraints from WMAP

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

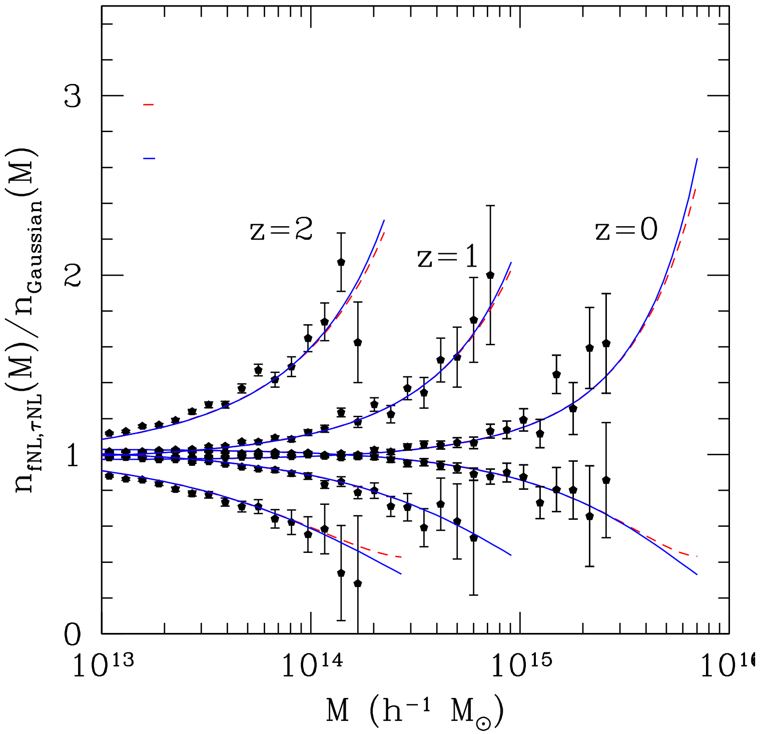
Future: much better constraints expected, $\sigma(f_{NL})$<O(10) with Planck

Galaxy 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 -
dn/dlnM(M, z) - of DM halos
(analytic extensions of Press-Schechter + simulations)



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

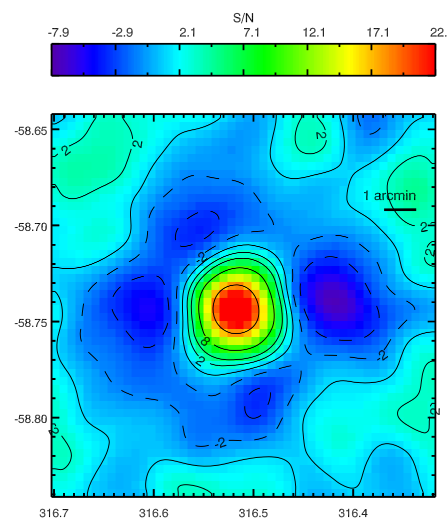
e.g. Sefusatti et al. 2007 forecasted the depressing $\sigma(f_{NL})=145$ from SDSS
e.g. $\sigma(f_{NL})=450$ measured from SPT (Williamson et al 2010)

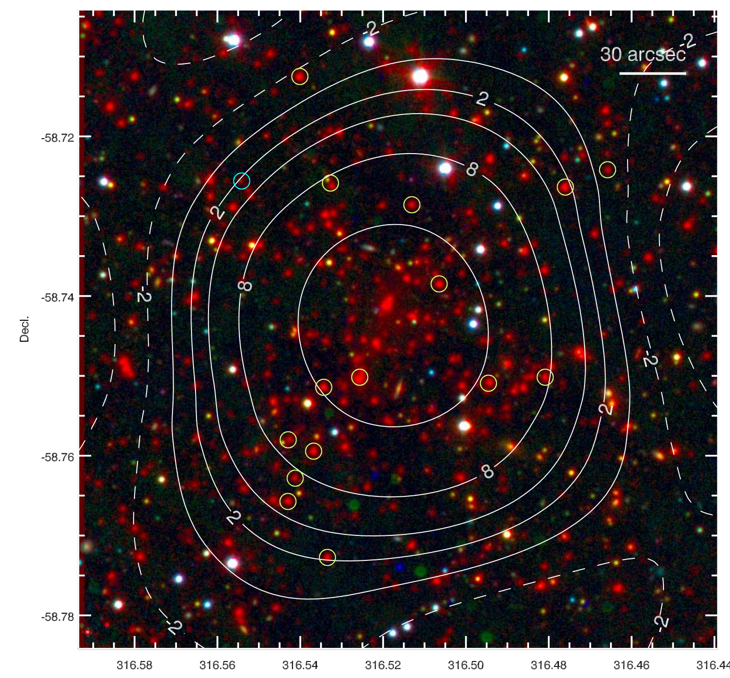
Nevertheless, it is true that a (large) amount of (local model) NG can boost the number of 'pink elephant' clusters

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

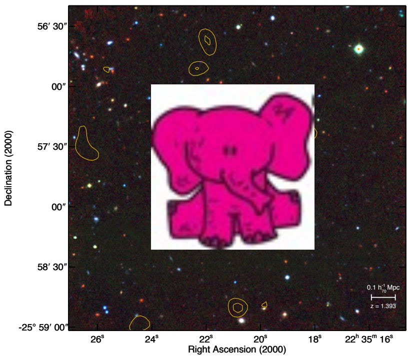
- SPT-CL J0546-5045: $z=1.067$, $M \approx (8.0 \pm 1.0) \cdot 10^{14}\,M_{sun}$
- XMMU J2235.3-2557: $z=1.39$, $M \approx (8.5 \pm 1.7) \cdot 10^{14}\,M_{sun}$
- SPT-CL J2106-8544: $z=1.132$, $M \approx (1.3 \pm 0.2) \cdot 10^{15}\,M_{sun}$

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 (2010);
Cayon, Gordon & Silk (2010);
Holz & Perlmutter 2010



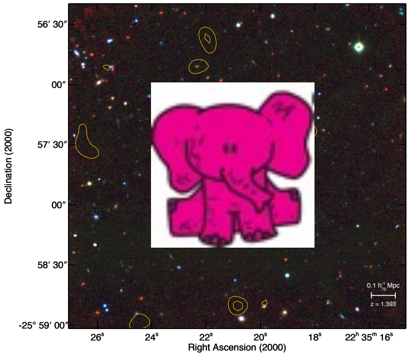
Are the pink elephants in conflict with LCDM?!

4 things to account for:

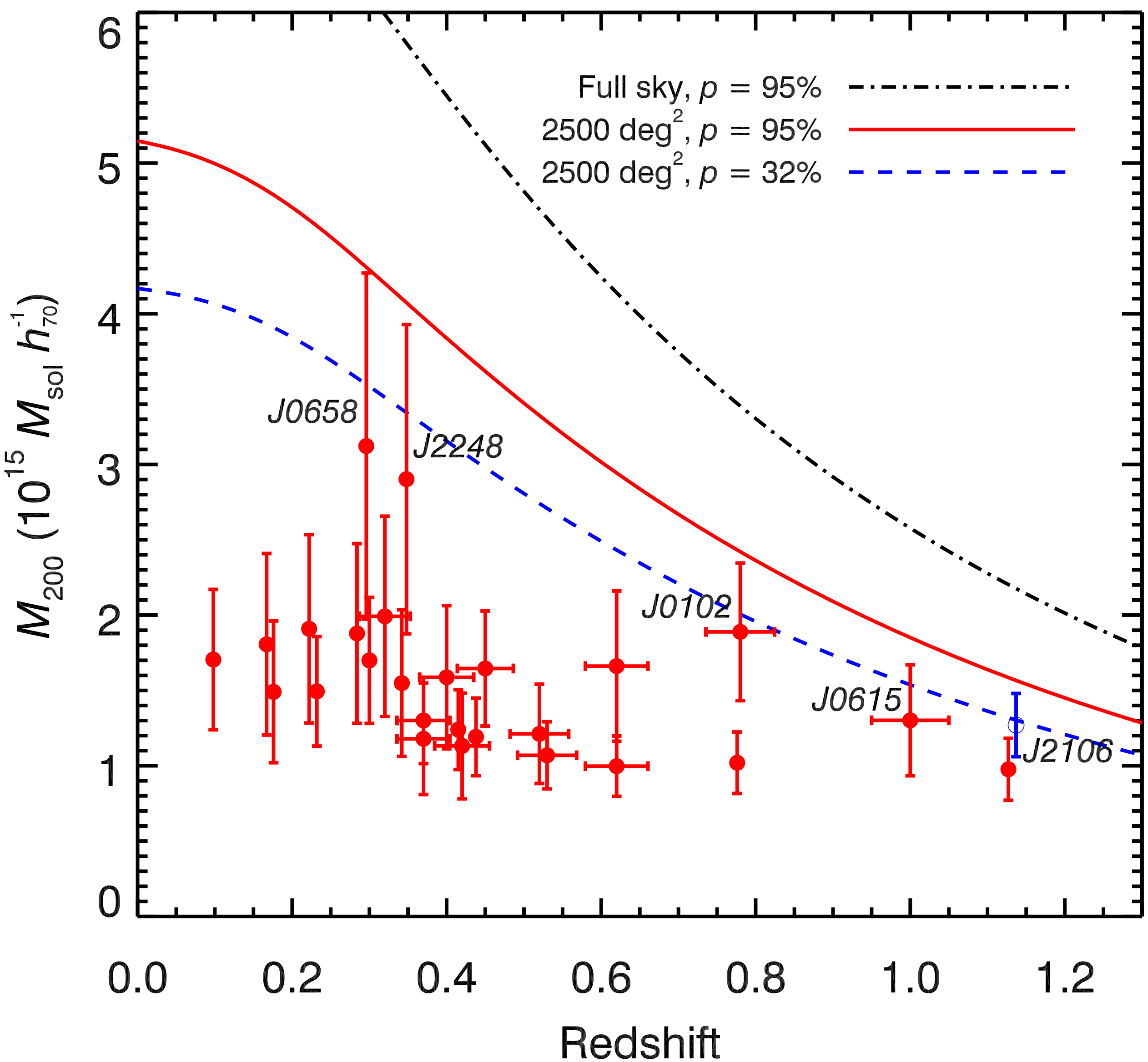
1. **Sample variance** - the Poisson noise in counting rare objects in a finite volume
2. **Parameter variance** - uncertainty due to fact that current data allow cosmological parameters to take a range of values
3. **Eddington bias** - mass measurement error will preferentially ‘scatter’ the cluster 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: arXiv:1004.0236



No conflict - for now.



Foley et al 2011 arXiv:1101.1286 (SPT team);
Mortonson, Hu & Huterer: arXiv:1004.0236

Effects of primordial NG
on the bias of virialized objects

Simulations with nongaussianity (f_{NL})

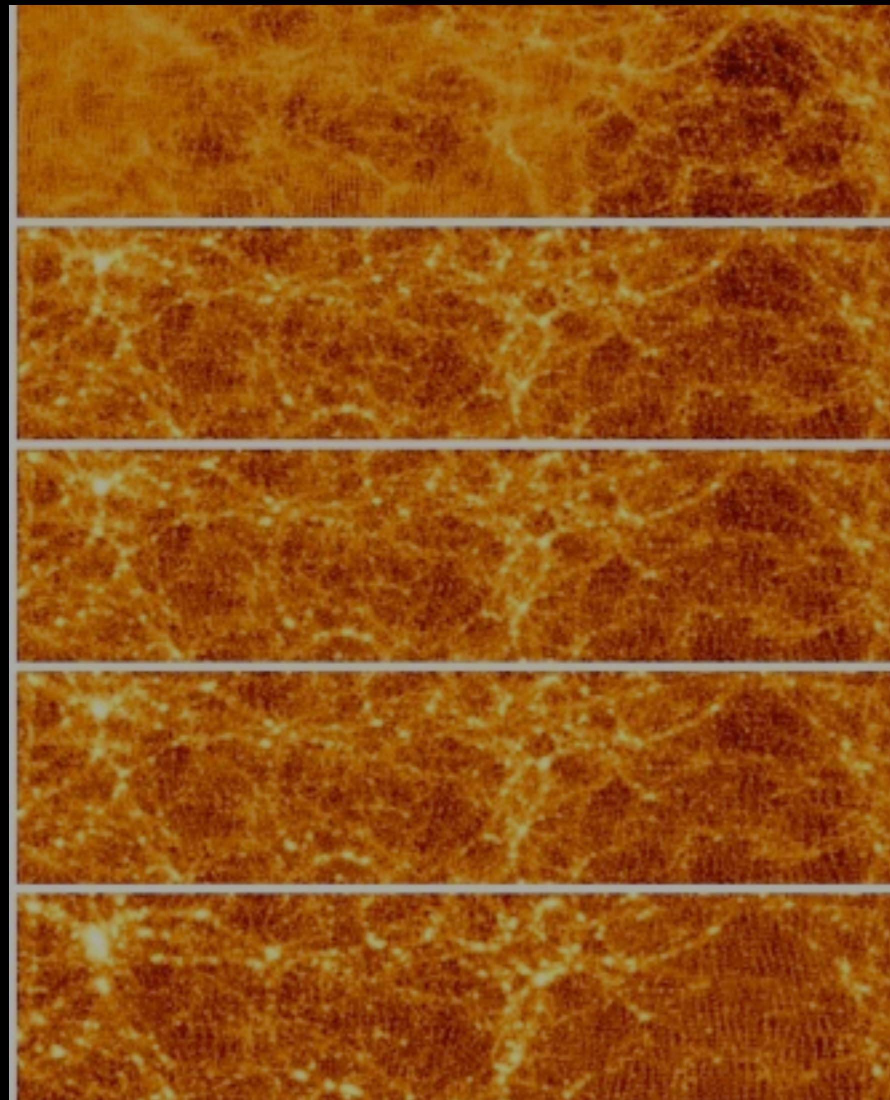
f_{NL}=-5000

f_{NL}=-500

f_{NL}=0

f_{NL}=+500

f_{NL}=+5000



80 Mpc/h

375 Mpc/h

- 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

Does galaxy/halo bias depend on NG?

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

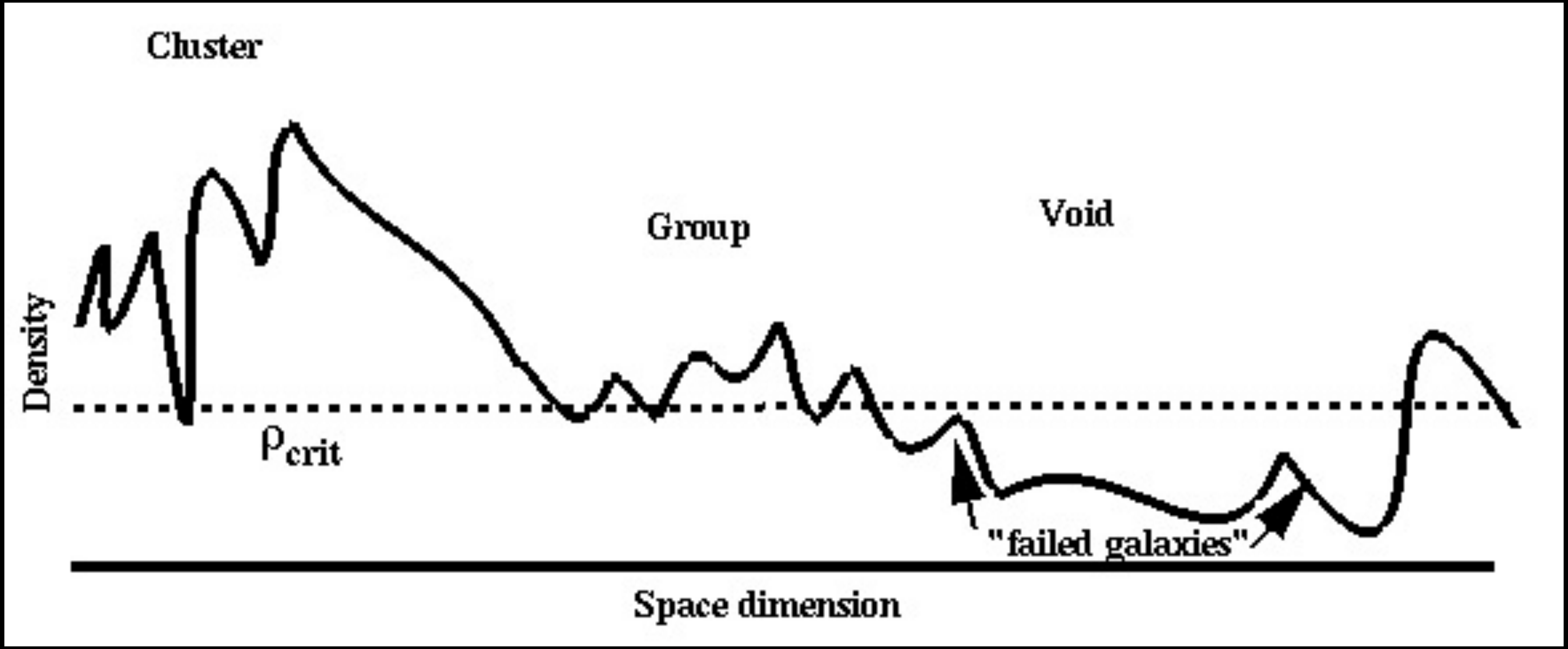
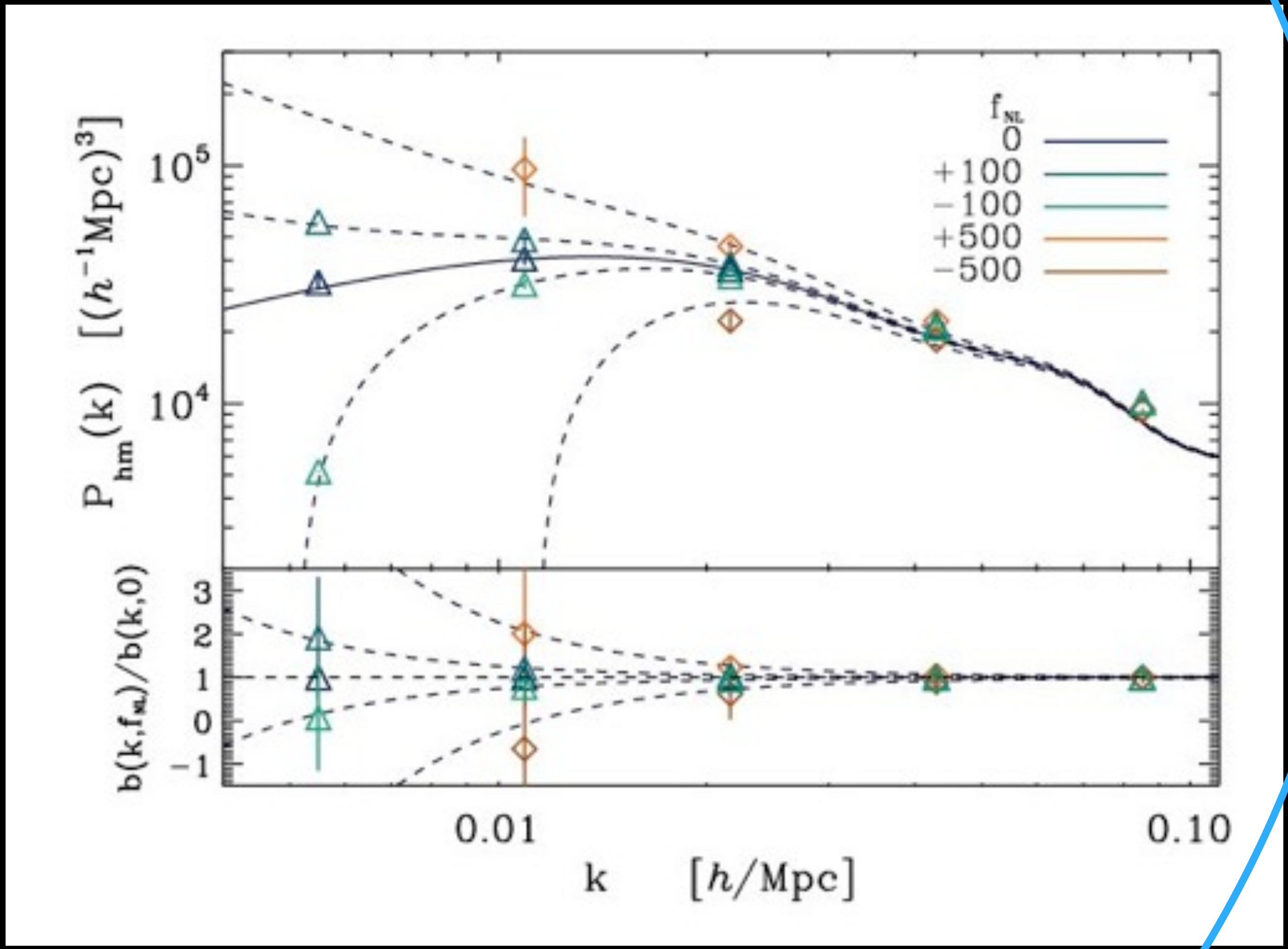


figure credit: Bill Keel

Simulations and theory both say: large-scale bias is scale-independent
(theorem if halo abundance is function of local density)

Scale dependence of NG halo bias!



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

Dalal, Doré, Huterer & Shirokov 2008

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

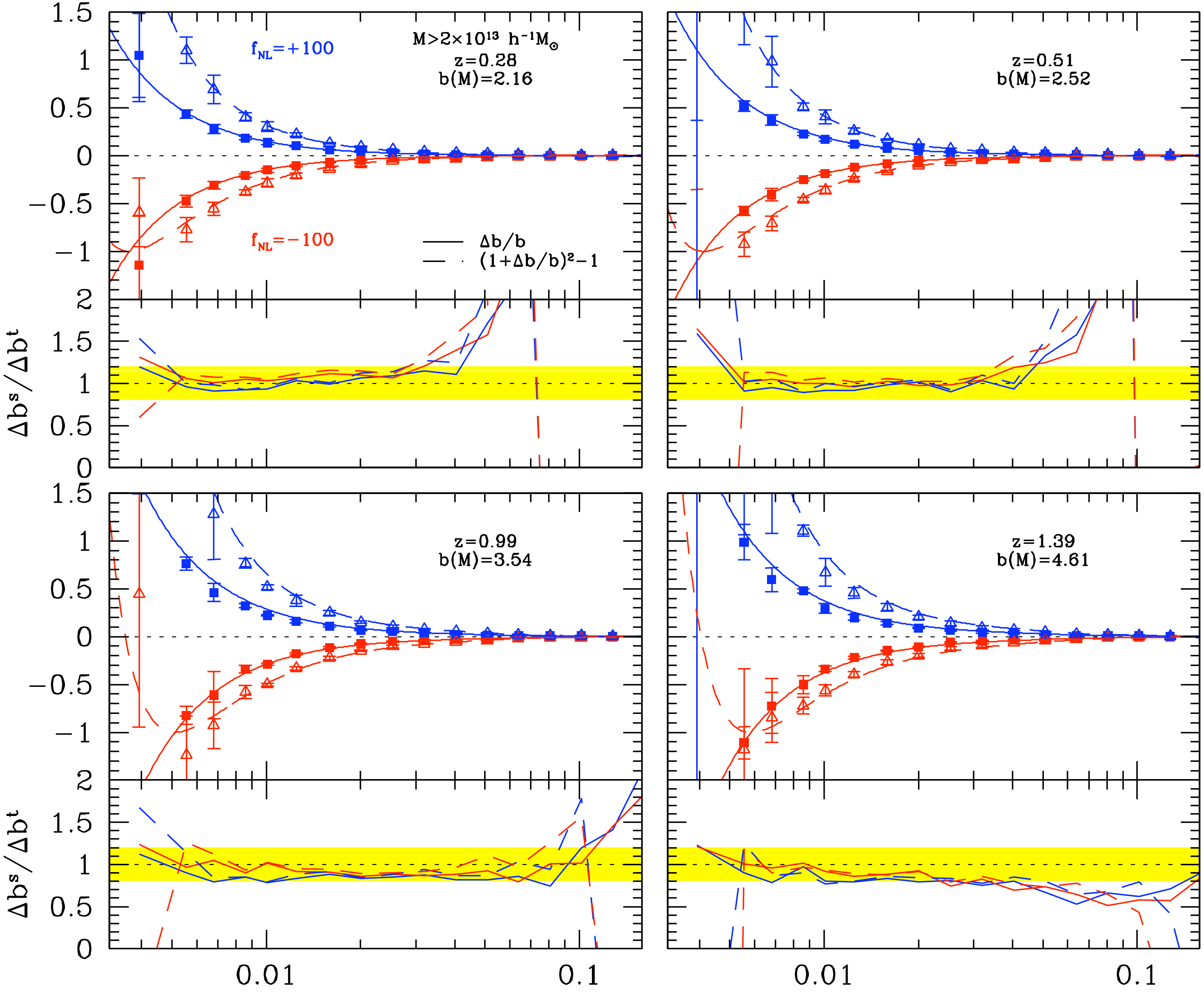
Implications:

- Unique $1/k^2$ scaling of bias; no free parameters
- Distinct from effect of 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; Grossi et al; McDonald; Desjacques, Jeong & Schmidt 2011

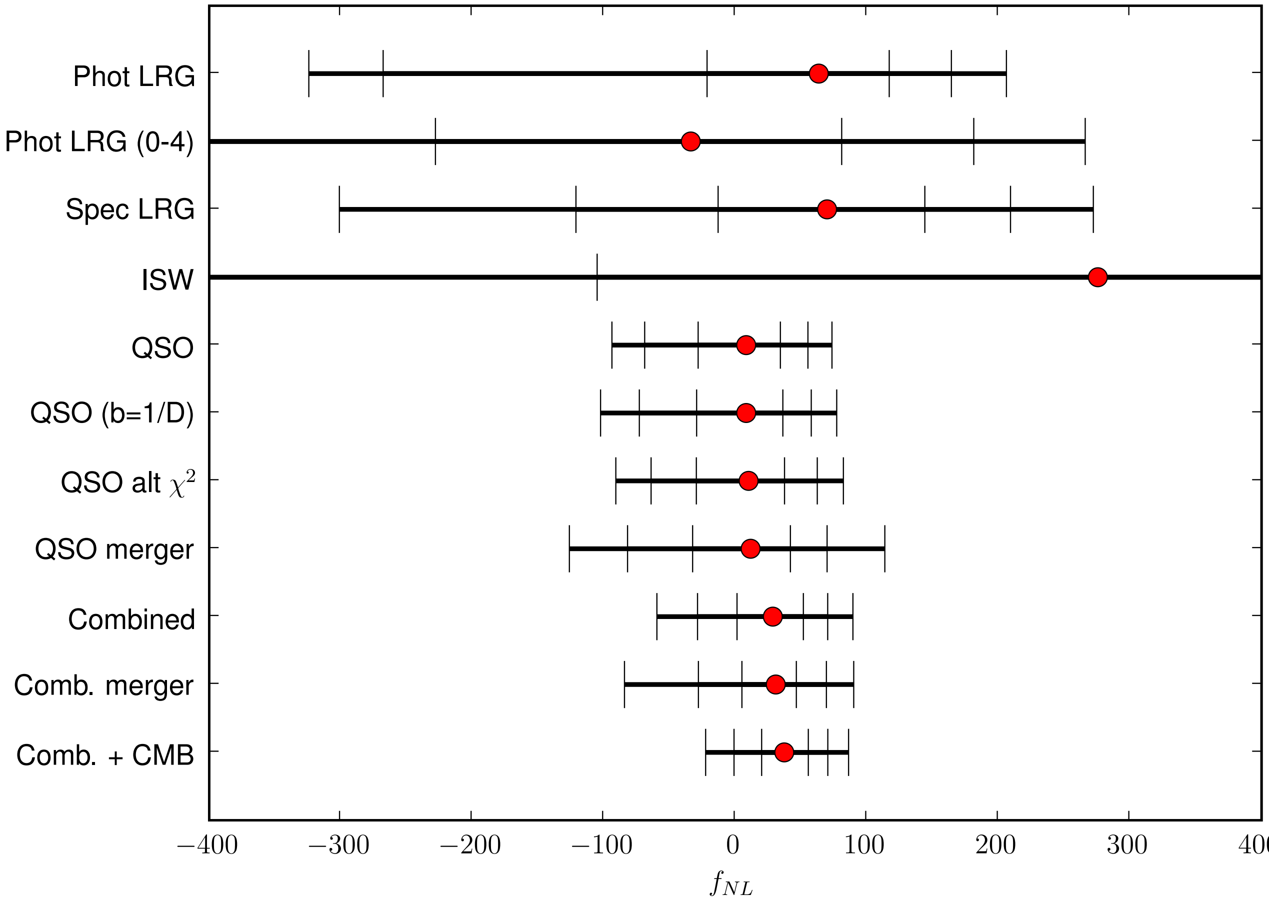
Analytic and numerical results agree:

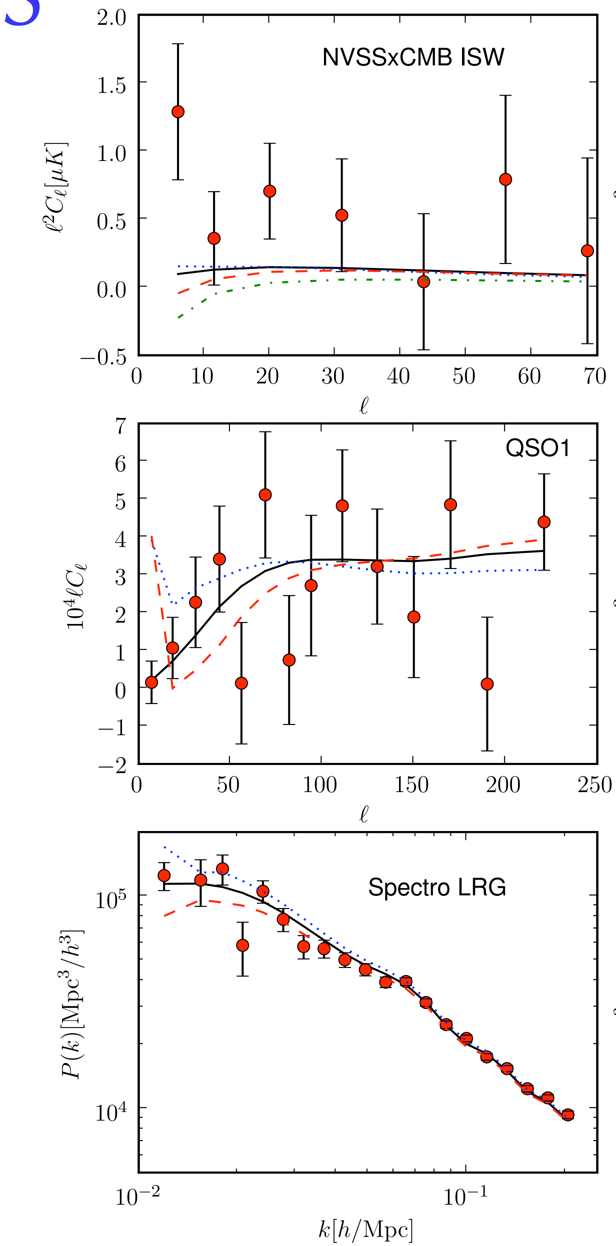
$$\Delta b(k) = 2\, b_L f_{\rm NL} \delta_c \, \frac{3}{2} \, \frac{\Omega_M H_0^2}{T(k) D(a) k^2}$$



Dalal et al 2008
Desjacques et al 2009
Grossi et al. 2009

Constraints from **current** data: SDSS





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

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

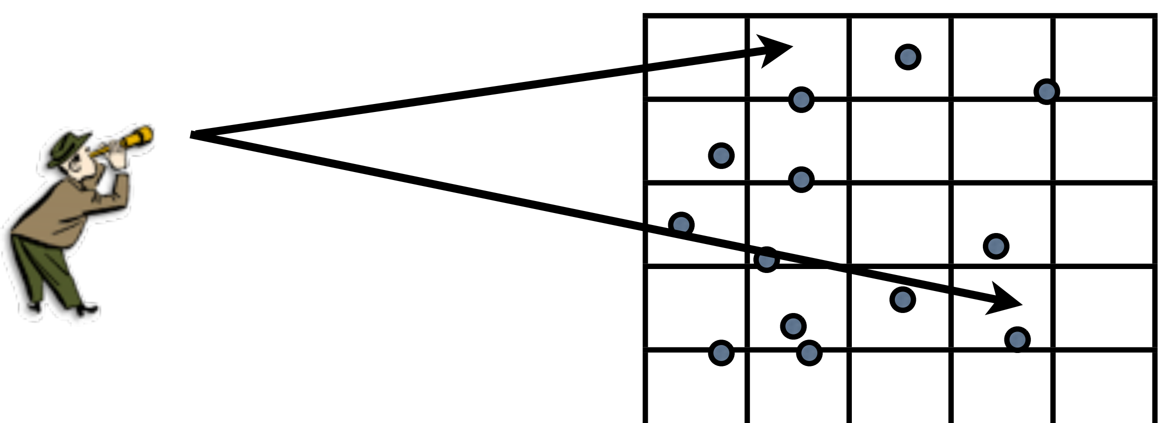
Slosar et al. 2008

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

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**

NG can survive marginalization over numerous systematic effects e.g:

- relation of mass of cluster and its observable quantity (T, flux, etc)
- redshift evolution of bias

Dark Energy Survey cluster forecasts

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	**2.1×10^3**	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**

Marginalized errors—Full Covariance

Counts (1-pt function) mainly probe DE parameters
Covariance (2-pt function) mainly probes f_{NL}

Cunha, Huterer & Doré 2010

Scale-dependent nongaussianity? Generalized local ansatz

Becker, Huterer & Kadota,2011 + in prep.

- Motivated by single- and multi-field inflation ⇒ **see Shandera talk**
- In general, even if you are considering standard single-field inflation, interactions may lead to scale-dependence of f_{NL}

(Usual) local model...

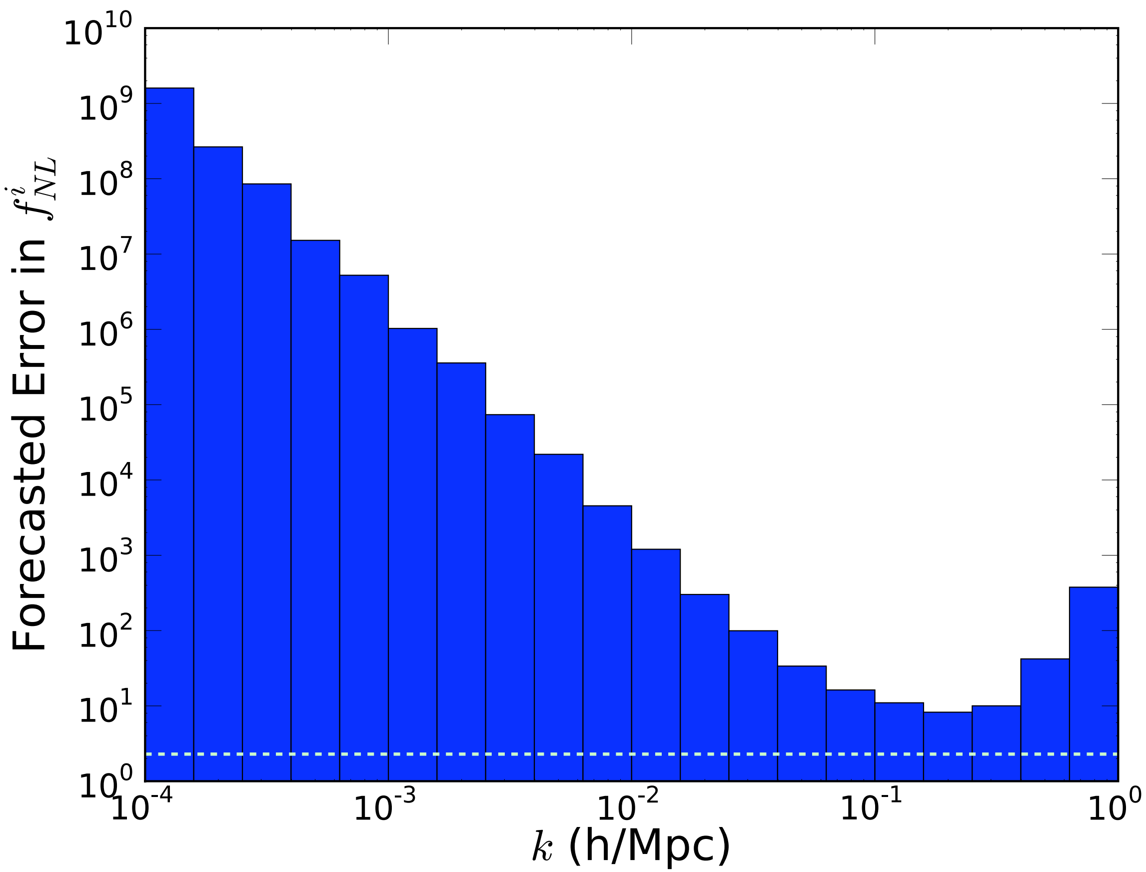
$$\Phi(x) = \phi_G(x) + f_{\rm NL}\left[\phi_G^2(x) - \langle\phi_G^2\rangle\right]$$

...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

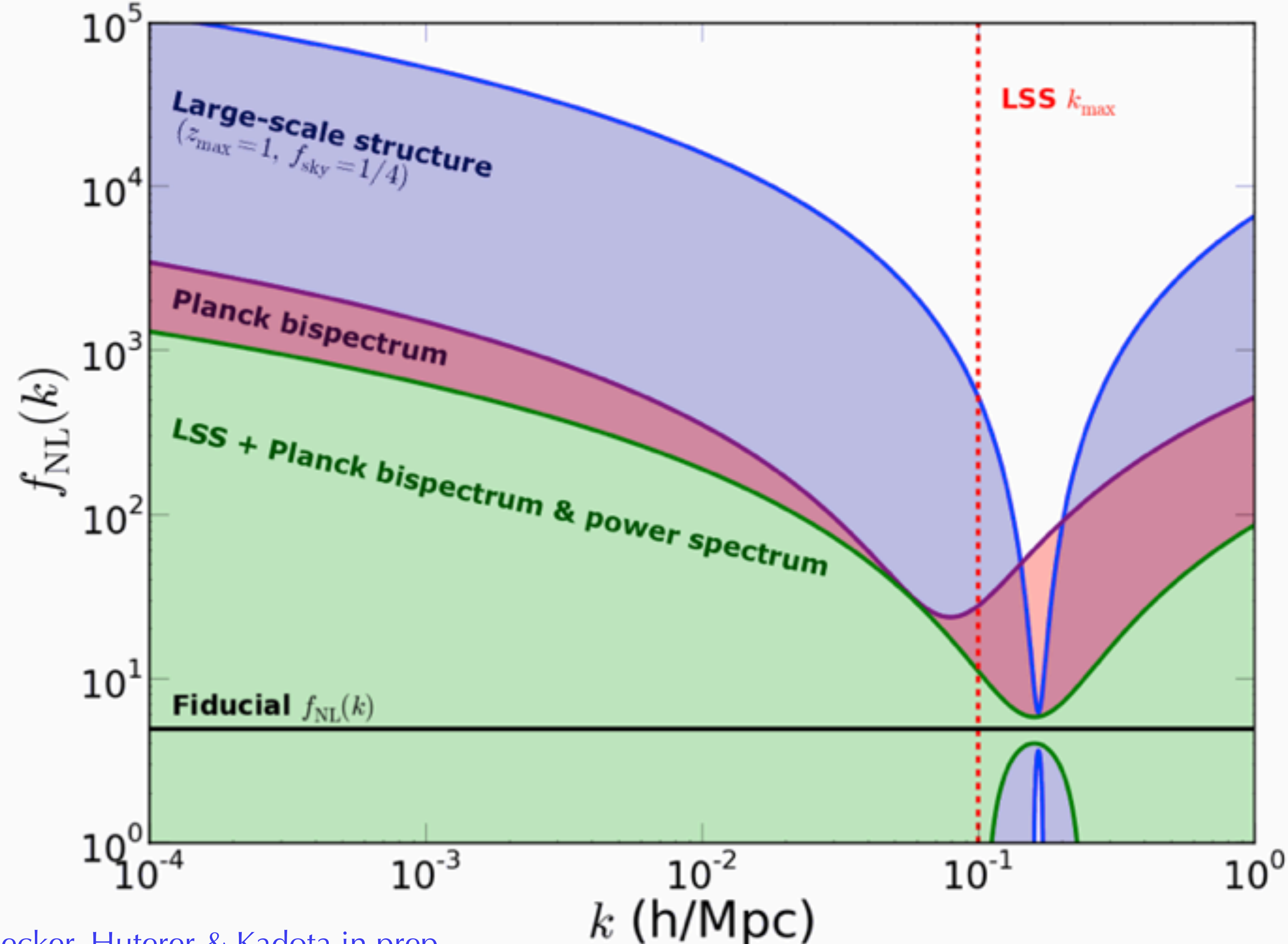
Given this basis, projecting forecasts onto any parametrized $f_{NL}(k)$ model is now trivial

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

Becker, Huterer & Kadota 2011

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

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

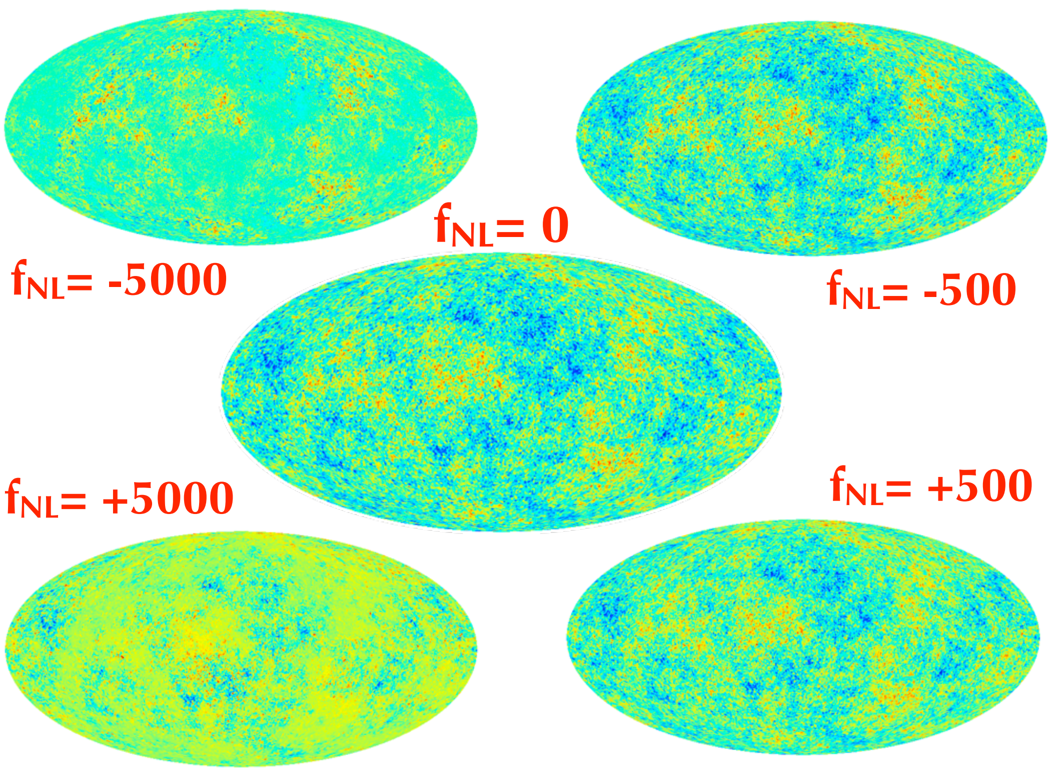


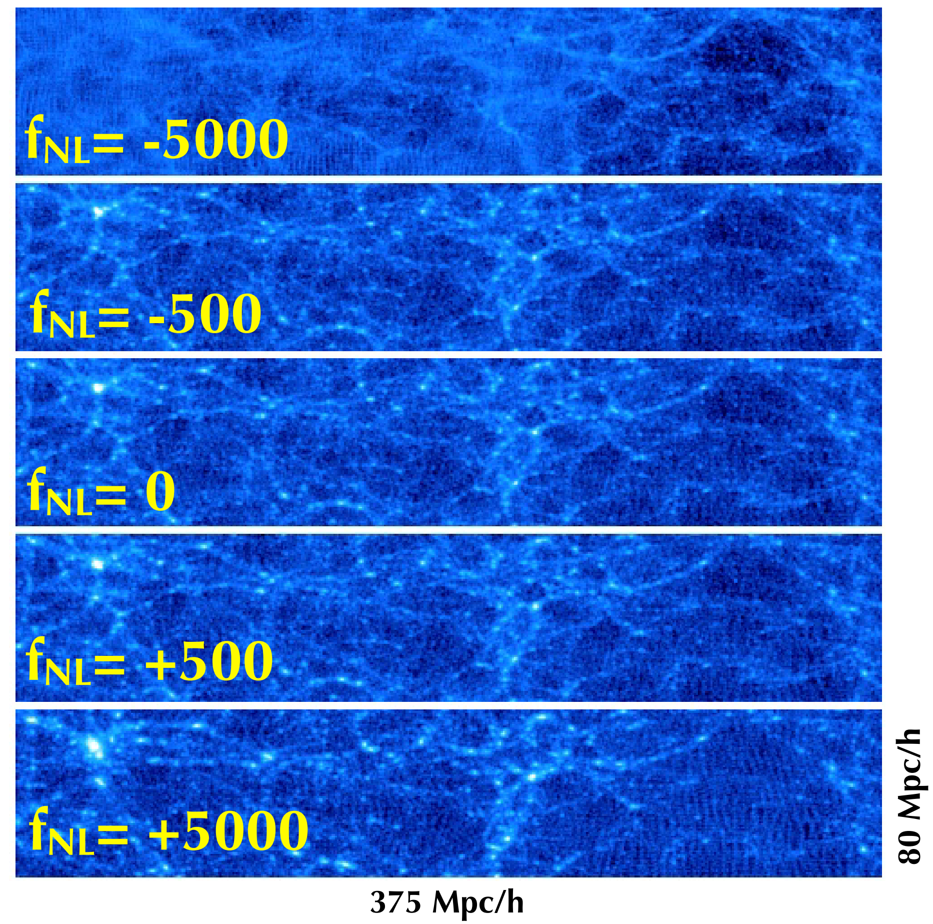
Becker, Huterer & Kadota in prep.

CMB+LSS: Cosmic Complementarity

different observations on different scales with different systematics

but measuring the same fundamental quantities





CMB

LSS

Advances in Astronomy special issue on

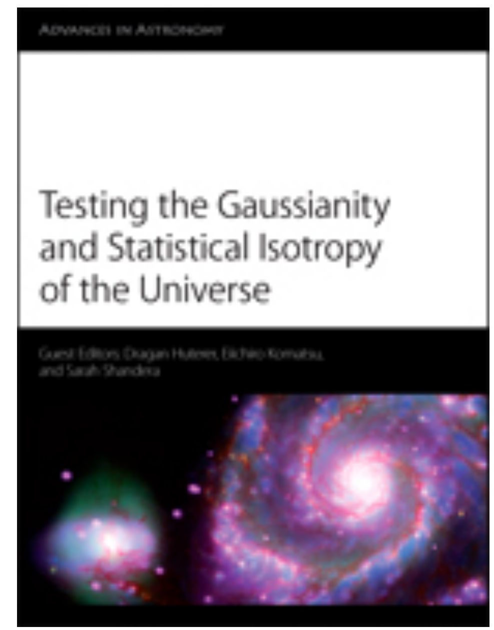
“Testing the Gaussianity and Statistical Isotropy of the Universe”

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,


Looking for jobs!
Adam Becker (PhD)
Wenjuan Fang (postdoc)
Cameron Gibelyou (PhD)