

# Large-Scale Structure of the Universe – a powerful probe for fundamental physics

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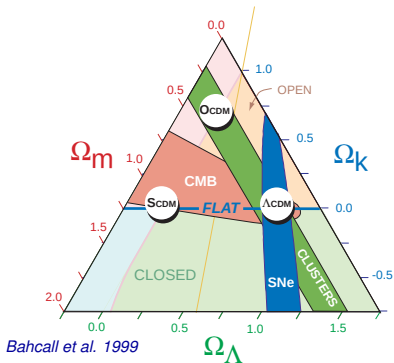


# Outline

- 1 **Concordance cosmology**
- 2 **LSS & fundamental physics**
- 3 **Initial conditions**
- 4 **Non-Gaussianity from inflation**
- 5 **Non-Gaussianity & LSS**

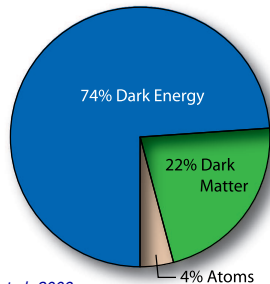


# $\Lambda$ CDM concordance cosmology

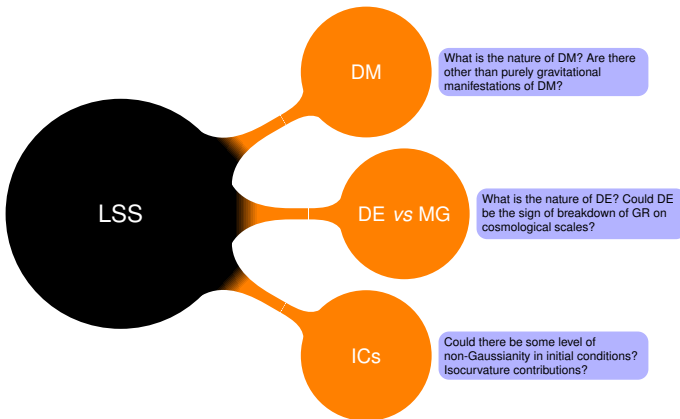


- What is DM?
- What is DE?
- Is there something more to be learned about the initial conditions?

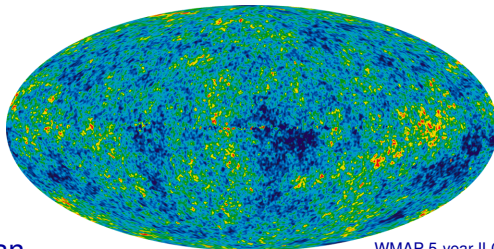
Quite remarkably, a model with only 6 free parameters ( $\Omega_m h^2$ ,  $\Omega_b h^2$ ,  $h$ ,  $A_s$ ,  $n_s$ ,  $\tau$ ) is able to accommodate a large body of diverse observational data.



# LSS & fundamental physics



# Initial conditions



WMAP 5-year ILC; *Hinshaw et al. 2008*

- **Gaussian**

All the information given by the 2pt correlator

- **Approximately scale invariant**

$$P_{\text{init}}(k) = A_s k^{n_s}, n_s \simeq 1$$

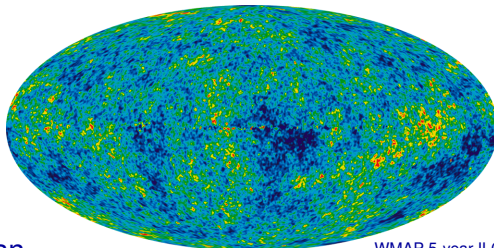
- **Adiabatic**

Pure curvature perturbation only. "Entropy perturbation" of a species  $i$ ,  $S_i \equiv 0$

$$S_i \equiv \frac{\delta(n_i/n_\gamma)}{n_i/n_\gamma} = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma} = \begin{cases} \delta_i - \frac{3}{4} \delta_\gamma & (\text{matter}) \\ \frac{3}{4} \delta_i - \frac{3}{4} \delta_\gamma & (\text{radiation}) \end{cases}$$



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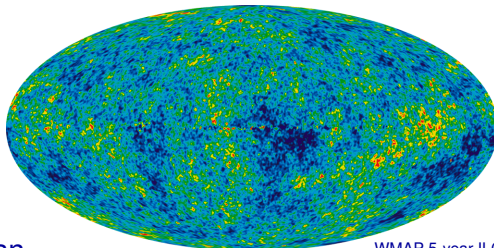
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Is that all that could be learned?



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Is that all that could be learned? **Hopefully NO!**



# Non-Gaussianity from inflation

A large, detectable amount of non-Gaussianity can be produced when any of the following conditions is violated:

(see, e.g., *Komatsu et al. 2009*, [arXiv:0902.4759](#))

- **Single Field.** There was only one quantum field responsible for driving inflation and for generating the primordial seeds for structures.
- **Canonical Kinetic Energy.** The kinetic energy of the quantum field is such that the speed of propagation of fluctuations is equal to the speed of light.
- **Slow Roll.** The evolution of the field was always very slow compared to the Hubble time during inflation.
- **Initial Vacuum State.** The quantum field was in the preferred adiabatic vacuum state (also sometimes called the “Bunch-Davies vacuum”) just before the quantum fluctuations were generated during inflation.

# Inflationary bispectra

- Perturbed metric in Newtonian gauge (scalar perturbations)

$$ds^2 = (1 + 2\Psi)dt^2 - a^2(t)(1 - 2\Phi)dx_idx^i$$

- Gaussian fluctuations fully determined by the power spectrum  $P_\Phi(k)$

$$\langle \delta_\Phi(\mathbf{k}_1) \delta_\Phi(\mathbf{k}_2) \rangle = (2\pi)^3 \delta_D^3(\mathbf{k}_1 + \mathbf{k}_2) P_\Phi(k_1)$$

- The lowest order statistic sensitive to non-Gaussian features is the bispectrum  $B_\Phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$

$$\langle \delta_\Phi(\mathbf{k}_1) \delta_\Phi(\mathbf{k}_2) \delta_\Phi(\mathbf{k}_3) \rangle = (2\pi)^3 \delta_D^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B_\Phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$

Some example forms:

- (A) Local or squeezed form can dominate in models involving multiple fields

$$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{\text{NL}}^{\text{loc}} \phi^2(\mathbf{x}) \implies B_\Phi^{\text{loc}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = 2f_{\text{NL}}^{\text{loc}} [P_\phi(k_1)P_\phi(k_2) + (\text{cyc.})]$$

- (B) Equilateral form can dominate in models with noncanonical kinetic terms

$$B_\Phi^{\text{eq}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) =$$

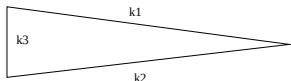
$$6f_{\text{NL}}^{\text{eq}} \left[ - (P_\phi(k_1)P_\phi(k_2) + (\text{cyc.})) - 2 (P_\phi(k_1)P_\phi(k_2)P_\phi(k_3))^{2/3} + (P_\phi^{1/3}(k_1)P_\phi^{2/3}(k_2)P_\phi(k_3) + (\text{perm.})) \right]$$

- (C) Flattened or folded form can dominate in models with non-vacuum initial conditions

$$B_\Phi^{\text{fol}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) =$$

$$6f_{\text{NL}}^{\text{fol}} \left[ (P_\phi(k_1)P_\phi(k_2) + (\text{cyc.})) + 3 (P_\phi(k_1)P_\phi(k_2)P_\phi(k_3))^{2/3} - (P_\phi^{1/3}(k_1)P_\phi^{2/3}(k_2)P_\phi(k_3) + (\text{perm.})) \right]$$

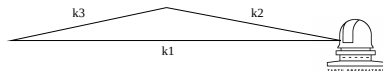
(a) Squeezed



(b) Equilateral



(c) Flattened/Folded



For more details and references see, e.g., [Desjacques & Seljak 2009, arXiv:1003.5020](#)

# $f_{\text{NL}}$ from large-scale structure

## Linear evolution

$$\begin{aligned}\delta(\mathbf{k}, z) &= \mathcal{M}(k, z) \Phi(\mathbf{k}) \\ \mathcal{M}(k, z) &= \frac{2}{3} \frac{k^2 T(k) D(z)}{\Omega_m H_0^2}\end{aligned}$$

... and so

$$\begin{aligned}P(k, z) &= \mathcal{M}^2(k, z) P_\Phi(k) \\ B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) &= \mathcal{M}(k_1, z) \mathcal{M}(k_2, z) \mathcal{M}(k_3, z) B_\Phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)\end{aligned}$$

If local form for  $B_\Phi$ , then

$$B^{\text{loc}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) = 2f_{\text{NL}}^{\text{loc}} \left[ \frac{\mathcal{M}(k_3, z)}{\mathcal{M}(k_1, z) \mathcal{M}(k_2, z)} P(k_1, z) P(k_2, z) + (\text{cyc.}) \right] \propto D^3(z)$$

Additional complications:

## Nonlinear evolution. From 2nd order Eulerian PT:

$$\begin{aligned}B_{\text{grav}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) &= \left[ 2F_2(\mathbf{k}_1, \mathbf{k}_2) P(k_1, z) P(k_2, z) + (\text{cyc.}) \right] \propto D^4(z) \\ F_2(\mathbf{k}_1, \mathbf{k}_2) &= \frac{5}{7} + \frac{\mu}{2} \left( \frac{k_1}{k_2} + \frac{k_2}{k_1} \right) + \frac{2}{7} \mu^2, \quad \mu \equiv \frac{\mathbf{k}_1 \cdot \mathbf{k}_2}{k_1 k_2}\end{aligned}$$

## Biasing. Assume deterministic quadratic local bias $\delta_g(\mathbf{x}) = b_1 \delta(\mathbf{x}) + \frac{1}{2} b_2 \delta^2(\mathbf{x})$ , then:

$$B_g(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) = 2P(k_1, z) P(k_2, z) b_1^3(z) \left[ f_{\text{NL}}^{\text{loc}} \frac{\mathcal{M}(k_3, z)}{\mathcal{M}(k_1, z) \mathcal{M}(k_2, z)} + F_2(\mathbf{k}_1, \mathbf{k}_2) + \frac{1}{2} \frac{b_2(z)}{b_1(z)} \right] + (\text{cyc.})$$

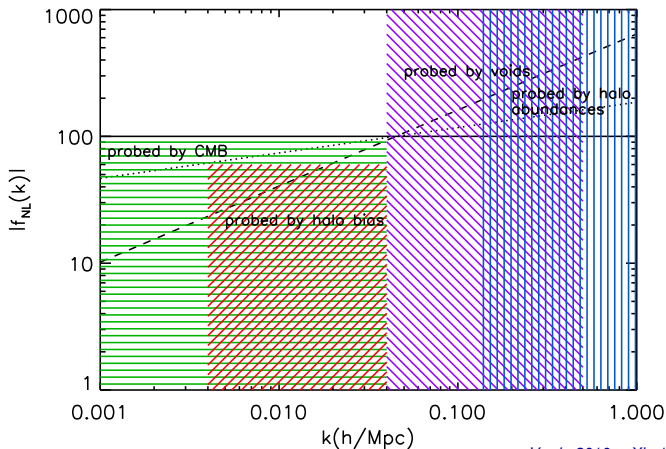
## Redshift-space distortions. Monopole spectra, i.e. spherically averaged over LOS:

$$\begin{aligned}P_g^z(k, z) &= \left[ 1 + \frac{2}{3} \beta + \frac{1}{5} \beta^2 \right] P_g(k), \quad \beta(z) \equiv \frac{d \ln D(z)}{d \ln a} \\ B_g^z(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) &= \left[ 1 + \frac{2}{3} \beta + \frac{1}{9} \beta^2 \right] B_g(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z)\end{aligned}$$

## Discrete sampling $\implies$ Poisson noise



# Other probes of NG



Verde 2010, arXiv:1001.5217

$$B_{\Phi}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = f_{\text{NL}} \left( \frac{K}{k_p} \right)^{n_{\text{ng}}} F(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3), \quad K \equiv \sqrt[3]{k_1 k_2 k_3}$$



# Halo abundances

$$\frac{dn_{\text{NG}}}{dM}(M, z, f_{\text{NL}}) = \mathcal{R}(M, z, f_{\text{NL}}) \times \frac{dn}{dM}(M, z)$$

$$\begin{aligned} \mathcal{R}(M, z, f_{\text{NL}}) &\simeq 1 + \frac{1}{6} \sigma S_3 (\nu^3 - 3\nu) \\ &- \frac{1}{6} \frac{d(\sigma S_3)}{d \ln \nu} \left( \nu - \frac{1}{\nu} \right) \end{aligned}$$

LoVerde et al. 2008, arXiv:0711.4126

Here:

$$\nu(M, z) = \frac{\delta_{\text{ec}}(z)}{\sigma(M)}, \quad \delta_{\text{ec}}(z) \simeq \frac{\delta_c(z)}{\sqrt{q}} \simeq \frac{1.68}{D(z)\sqrt{q}}, \quad (q \simeq 0.75)$$

$S_3$  is the normalized skewness:

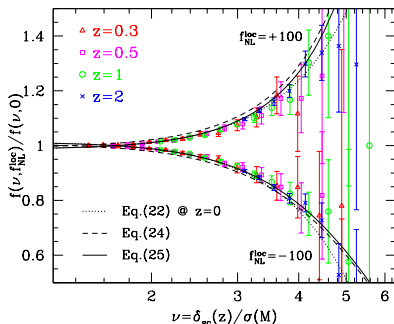
$$S_3 \equiv \frac{\langle \delta_R^3 \rangle_c}{\langle \delta_R^2 \rangle^2}$$

$$\langle \delta_R^3 \rangle_c = \int \frac{d^3 k_1}{(2\pi)^3} \int \frac{d^3 k_2}{(2\pi)^3} \int \frac{d^3 k_3}{(2\pi)^3} B_R(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) \delta_D^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)$$

$$\langle \delta_R^2 \rangle = \int \frac{d^3 k}{(2\pi)^3} P_R(k, z) \equiv \sigma^2(R)$$

$$B_R(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z) = W_R(k_1) W_R(k_2) W_R(k_3) B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, z)$$

$$P_R(k, z) = W_R^2(k) P(k, z)$$



Desjacques & Seljak 2009, arXiv:1006.4763

# Voids and superclusters

## • Voids

$$\begin{aligned} \frac{dn}{dR} &\simeq \frac{9}{2\pi^2} \sqrt{\frac{\pi}{2}} \frac{|\nu_v|}{R^4} e^{-\nu_v^2/2} \frac{d \ln |\nu_v|}{d \ln M} \left[ 1 - \frac{1}{6} \sigma \mathbf{S}_3 \left( |\nu_v|^3 - 3|\nu_v| \right) \right] \\ &+ \frac{1}{6} \frac{d(\sigma \mathbf{S}_3)}{d \ln |\nu_v|} \left( |\nu_v| - \frac{1}{|\nu_v|} \right) \\ \nu_v &\equiv \frac{\delta_v}{\sigma(M(R))}, \quad (\delta_v \leq 0) \end{aligned}$$

$f_{\text{NL}} \uparrow \implies$  number of large voids  $\downarrow$

*Kamionkowski et al. 2009, arXiv:0809.0506*

## • Superclusters

The formalism for voids is probably quite easily extendable for superclusters

$f_{\text{NL}} \uparrow \implies$  number large superclusters  $\uparrow$

# Halo bias

## Dominant NG contribution

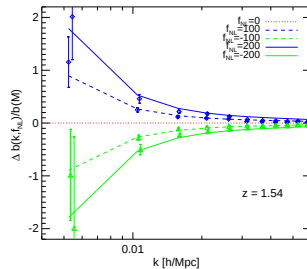
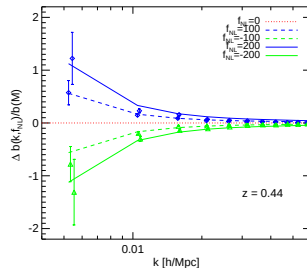
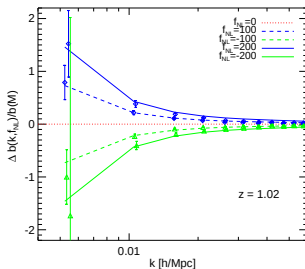
$$\Delta b(M, z, k, f_{\text{NL}}) = \frac{2 f_{\text{NL}} [b_1(M, z) - 1] \delta_{\text{sc}}(0)}{\mathcal{M}(k, z)}$$

$$\mathcal{M}(k, z) = \frac{2}{3} \frac{k^2 T(k) D(z)}{\Omega_m H_0^2}$$

Thus,  $\Delta b \propto \frac{f_{\text{NL}}}{k^2 T(k) D(z)}$ , and on large scales

$$\Delta b \propto f_{\text{NL}} k^{-2} D(z)^{-1}$$

$\Rightarrow$  suitable also for photo-z surveys



# Current $1\sigma$ and $2\sigma$ constraints on $f_{\text{NL}}^{\text{loc}}$

| Data/method             | $f_{\text{NL}}^{\text{loc}}$ | reference                  |
|-------------------------|------------------------------|----------------------------|
| Photometric LRG - bias  | $63^{+54+101}_{-85-331}$     | Slosar et al. 2008         |
| Spectroscopic LRG- bias | $70^{+74+139}_{-83-191}$     | Slosar et al. 2008         |
| QSO - bias              | $8^{+26+47}_{-37-77}$        | Slosar et al. 2008         |
| combined                | $28^{+23+42}_{-24-57}$       | Slosar et al. 2008         |
| NVSS–ISW                | $105^{+647+755}_{-337-1157}$ | Slosar et al. 2008         |
| NVSS–ISW                | $236 \pm 127 (2\sigma)$      | Afshordi&Tolley 2008       |
| WMAP3-Bispectrum        | $30 \pm 84$                  | Spergel et al. (WMAP) 2007 |
| WMAP3-Bispectrum        | $32 \pm 68$                  | Creminelli et al. 2007     |
| WMAP3-Bispectrum        | $87 \pm 60$                  | Yadav & Wandelt 2008       |
| WMAP-Bispectrum         | $38 \pm 42$                  | Smith et al. 2009          |
| WMAP5-Bispectrum        | $51 \pm 60$                  | Komatsu et al. (WMAP) 2008 |
| WMAP5-Minkowski         | $-57 \pm 121$                | Komatsu et al. (WMAP) 2008 |

Table from [Verde 2010, arXiv:1001.5217](#)

NROA VLA Sky Survey (NVSS) autocorrelation function:

$f_{\text{NL}}^{\text{loc}} = 62 \pm 27 (1\sigma \text{ CL}), 25 < f_{\text{NL}}^{\text{loc}} < 117 (2\sigma \text{ CL}),$  claimed detection of NG at  $\sim 3\sigma \text{ CL}$

[Xia et al. 2010, arXiv:1003.3451](#)



# Forecasts: $1\sigma$ constraints on $f_{\text{NL}}^{\text{loc}}$

| Data/method              | $\Delta f_{\text{NL}}^{\text{loc}} (1\sigma)$ | reference                |
|--------------------------|-----------------------------------------------|--------------------------|
| BOSS–bias                | 18                                            | Carbone et al. 2008      |
| ADEPT/Euclid–bias        | 1.5                                           | Carbone et al. 2008      |
| PANNStarrs –bias         | 3.5                                           | Carbone et al. 2008      |
| LSST–bias                | 0.7                                           | Carbone et al. 2008      |
| LSST-ISW                 | 7                                             | Afshordi & Tolley 2008   |
| BOSS–bispectrum          | 35                                            | Sefusatti & Komatsu 2008 |
| ADEPT/Euclid –bispectrum | 3.6                                           | Sefusatti & Komatsu 2008 |
| Planck-Bispectrum        | 3                                             | Yadav et al . 2007       |
| BPOL-Bispectrum          | 2                                             | Yadav et al . 2007       |

Table from [Verde 2010, arXiv:1001.5217](#)

- For a standard single-field slow-roll *etc* inflationary model  
 $f_{\text{NL}}^{\text{loc}} = \frac{5}{12} (1 - n_s) \simeq 0.017$ . That low level of NG would surely remain undetectable
- A convincing detection of  $f_{\text{NL}}^{\text{loc}}$  would **rule out all classes of inflationary models based on upon a single field**

[Creminelli & Zaldarriaga 2004, arXiv:astro-ph/0407059](#)

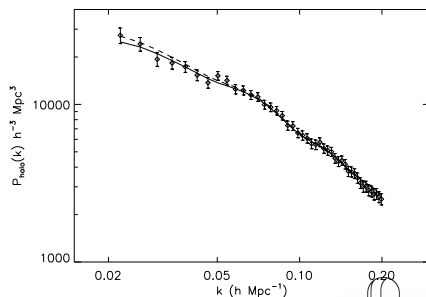
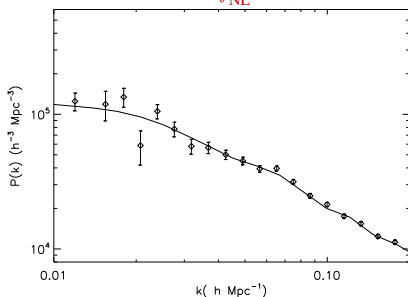


## Recent constraints from galaxy clusters

- *Jee et al. 2009*, arXiv:0908.3897 have reported a galaxy cluster **XMMU J2235.3–2557** at  $z \sim 1.4$  with an estimated weak lensing mass of  $M_{200} = (7.3 \pm 1.3) \times 10^{14} M_{\odot}$
- *Holz & Perlmutter 2010*, arXiv:1004.5349 have shown that finding object that massive is  $\sim 3\sigma$  **inconsistent** with  $\Lambda$ CDM
- *Cayón, Gordon & Silk 2010*, arXiv:1006.1950 have found that on cluster scales this implies a **92%** probability for  $f_{\text{NL}}^{\text{loc}} > 0$
- More recently *Brodwin et al. 2010*, arXiv:1006.5639 have reported an SZ-detected galaxy cluster **SPT-CL J0546-5345** at  $\langle z \rangle = 1.067$  with an estimated mass of  $M_{200} = 1.0^{+0.6}_{-0.4} \times 10^{15} M_{\odot}$

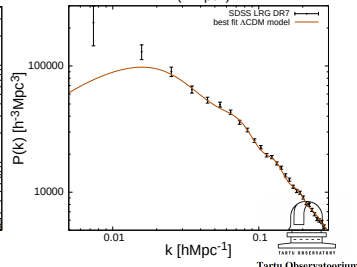
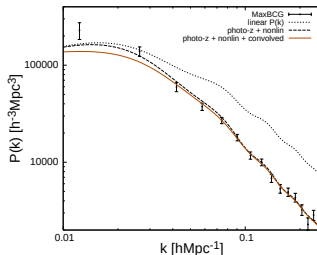
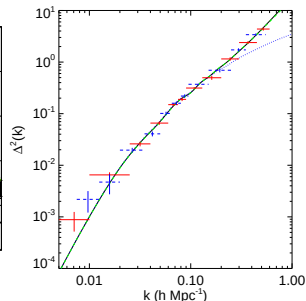
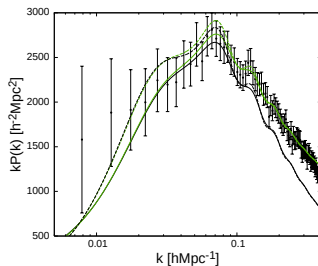
# Recent constraints from halo bias

- *De Bernardis et al. 2010*, [arXiv:1004.5467](https://arxiv.org/abs/1004.5467) have used the SDSS LRG **DR4** power spectrum of *Tegmark et al. 2006* and SDSS LRG **DR7** halo power spectrum data of *Reid et al. 2010* to constrain  $f_{\text{NL}}^{\text{loc}}$
- For the SDSS LRG **DR4** they find  $f_{\text{NL}}^{\text{loc}} = 171^{+140}_{-139}$  at  $1\sigma$  CL and  $-69 < f_{\text{NL}}^{\text{loc}} < +492$  at  $2\sigma$  CL
- Using the SDSS LRG **DR7** halo power spectrum they obtain  $f_{\text{NL}}^{\text{loc}} = -93 \pm 128$  at  $1\sigma$  CL and  $-327 < f_{\text{NL}}^{\text{loc}} < +177$  at  $2\sigma$  CL



# Excess large-scale power?

- SDSS LRG DR4  
*Hütsi 2006*  
[arXiv:astro-ph/0512201](#)
- SDSS LRG DR3 photo  
*Padmanabhan et al. 2007*  
[arXiv:astro-ph/0605302](#)
- SDSS maxBCG clusters  
*Hütsi 2010*  
[arXiv:0910.0492](#)
- See also  
*Blake et al. 2007*  
[arXiv:astro-ph/0605303](#)



## Conclusions

- Various observational results:
  - (i) the existence of unexpectedly massive galaxy clusters at  $z \sim 1$
  - (ii) the observed population of very rich superclusters
  - (iii) the possible excess of large-scale powerseem to support  $f_{\text{NL}} > 0$
- The observed supercluster-void network seems to have a higher degree of regularity than predicted by the standard  $\Lambda$ CDM
- Several future LSS surveys will have a power to constrain primordial NG at the level equal or even better than the forthcoming CMB experiments

Thanks!