Title: Primordial nongaussianity and large-scale structure

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Abstract: Standard inflationary theory predicts that primordial fluctuations in the universe were nearly Gaussian random. Therefore, searches for, and limits on, primordial nongaussianity are some of the most fundamental tests of inflation and the early universe in general. I first briefly review the history of its measurements from the cosmic microwave background anisotropies and large-scale structure in the universe. I then present results from recent work where effects of primordial nongaussianity on the distribution of largest virialized objects was studied numerically and analytically. We found that the bias of dark matter halos takes strong scale dependence in nongaussian cosmological models. Therefore, measurements of scale dependence of the bias, using various tracers of large-scale structure, can - and do - constrain primordial nongaussianity more than an order of magnitude better than previously thought.

Primordial Nongaussianity and Large-scale Structure

Dragan Huterer
(University of Michigan)

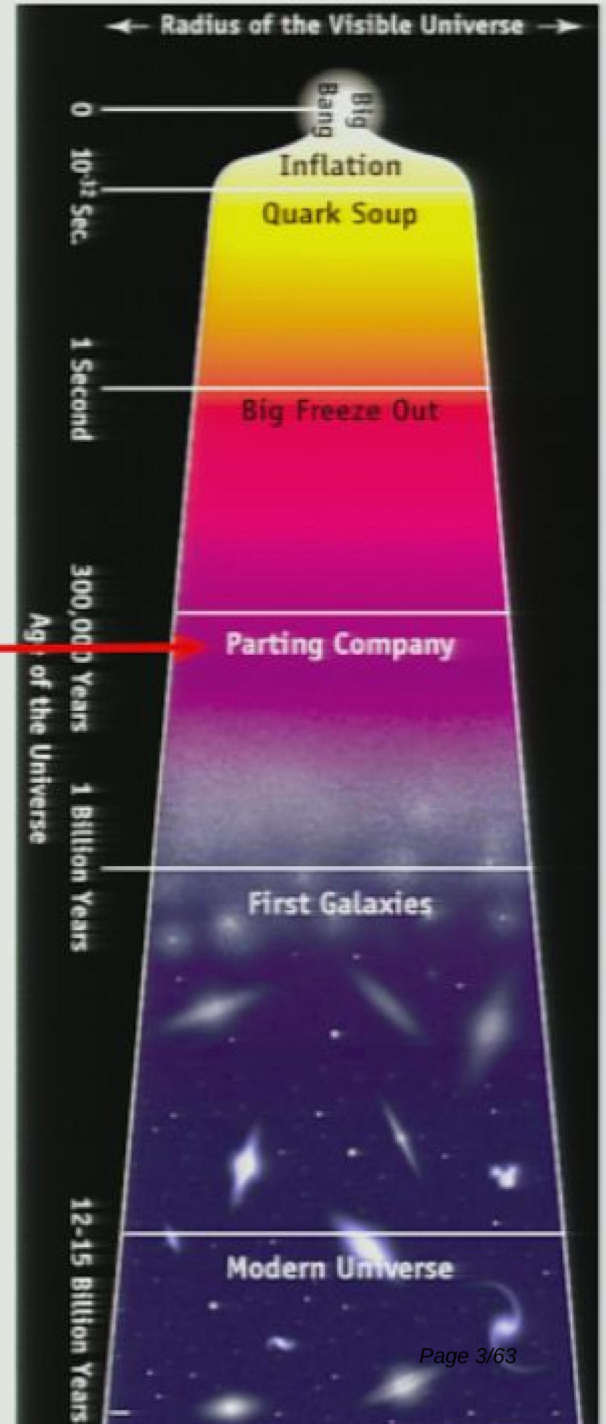
with Neal Dalal (CITA), Olivier Doré (JPL),
Carlos Cunha (Michigan), and others

work principally based on
arXiv:0710.4560 (PRD 2008)

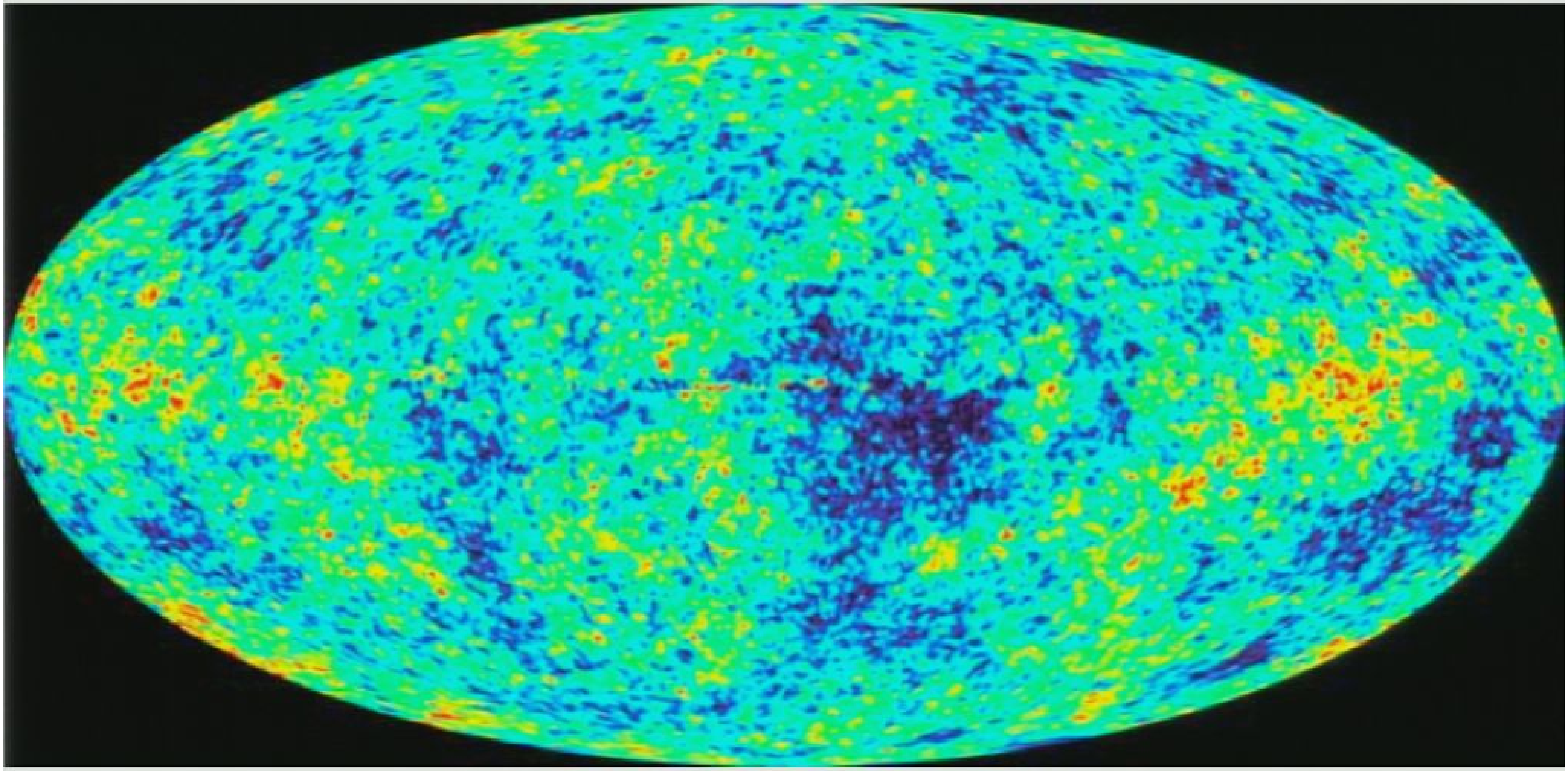
Some slides courtesy of O. Doré

Universe becomes transparent (t=380,000 yrs)

- Radiation finally free to propagate - universe has become cool enough for atoms to form
- The Cosmic Microwave Background radiation we observe has been released at this time
- Temp = 3000 Kelvin (2.725 Kelvin today)
- Uniform to one part in 100,000



Fluctuations 1 part in 100,000 (of 2.725 Kelvin)



As seen by Wilkinson Microwave Anisotropy Probe (2003-present)

The cosmic Rosetta Stone

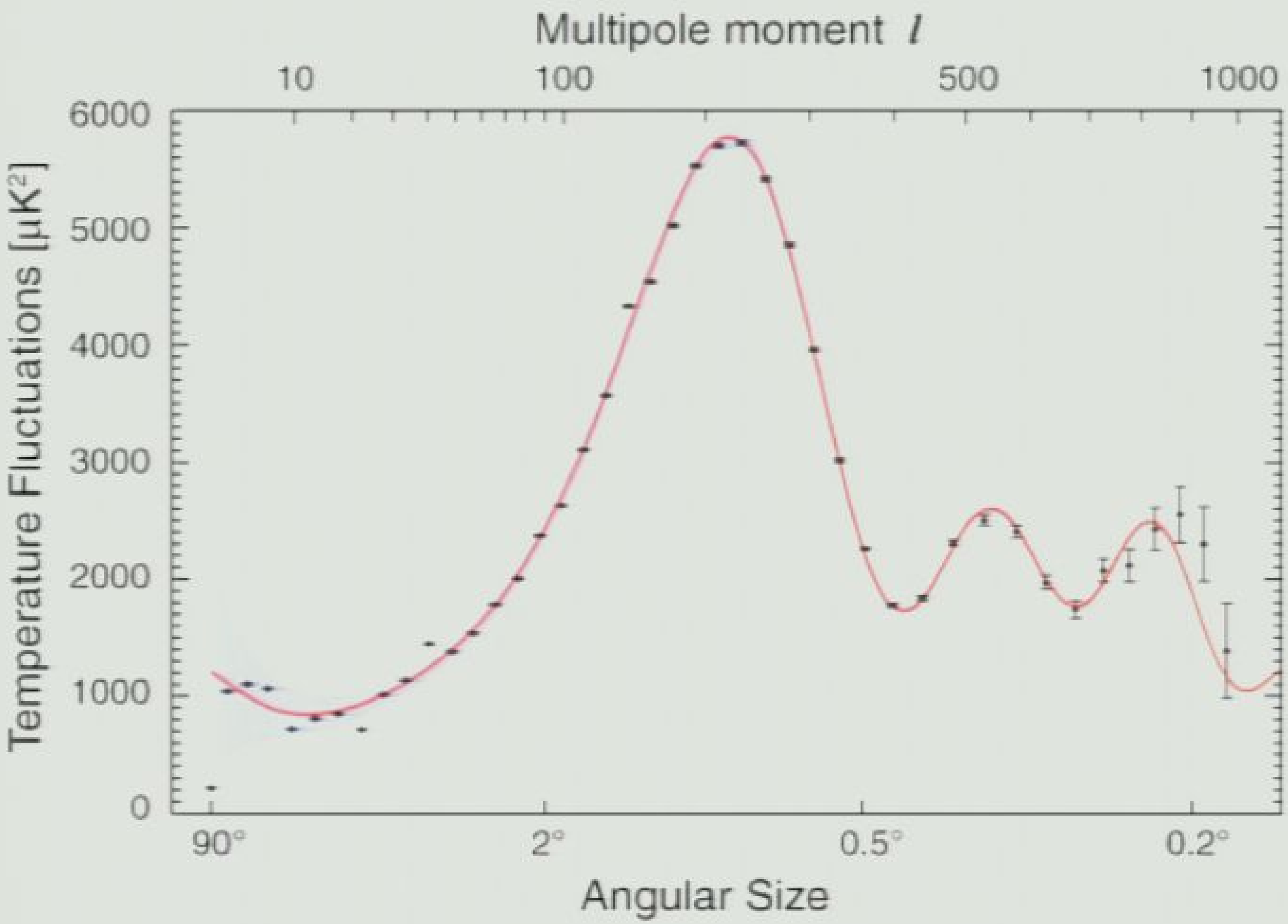


Image From http://map.gsfc.nasa.gov

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l\,m} a_{lm} Y_{lm}(\theta,\phi), \qquad C_\ell \equiv \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*–BAO–SN ML	*WMAP* 5-year Mean[b]	*WMAP*–BAO–SN Mean
Primary	$100\Omega_b h^2$	2.268	2.263	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1081	0.1136	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.751	0.724	0.742 ± 0.030	0.721 ± 0.015
	n_s	0.961	0.961	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.089	0.080	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.42×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.787	0.811	0.796 ± 0.036	0.817 ± 0.026
	H_0	72.4 km/s/Mpc	70.3 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0458	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.206	0.230	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1308	0.1363	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{reion}{}^f$	11.2	10.5	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

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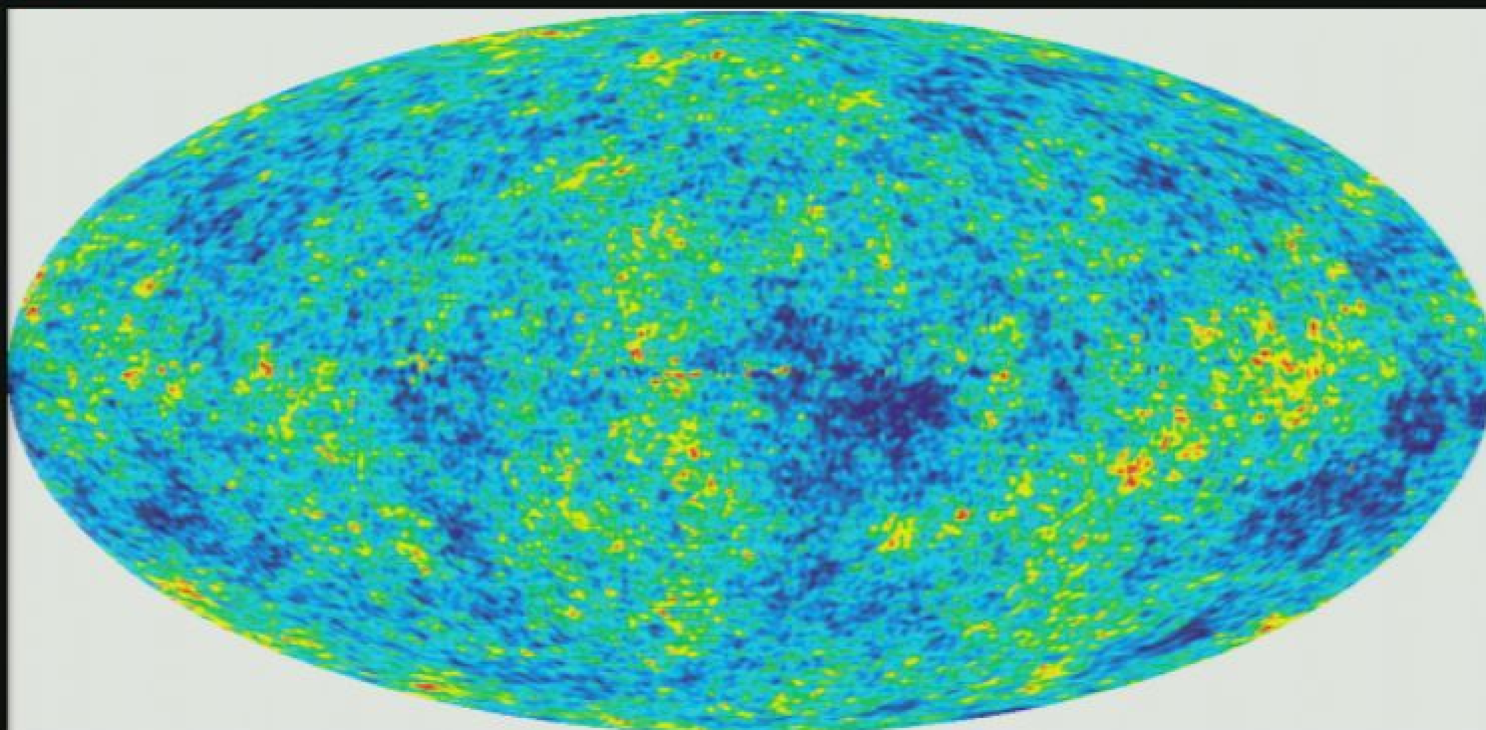
Section	Name	Type	*WMAP* 5-year	*WMAP*+BAO+SN
§ 3.2	Gravitational Wave[a]	No Running Ind.	$r < 0.43$[b]	$r < 0.20$
§ 3.1.3	Running Index	No Grav. Wave	$-0.090 < dn_s/d\ln k < 0.019$[c]	$-0.0728 < dn_s/d\ln k < 0.0087$
§ 3.4	Curvature[d]		$-0.063 < \Omega_k < 0.017$[e]	$-0.0175 < \Omega_k < 0.0085$[f]
	Curvature Radius[g]	Positive Curv.	$R_{\rm curv} > 12\ h^{-1}$Gpc	$R_{\rm curv} > 23\ h^{-1}$Gpc
		Negative Curv.	$R_{\rm curv} > 23\ h^{-1}$Gpc	$R_{\rm curv} > 33\ h^{-1}$Gpc
§ 3.5	Gaussianity	Local	$-9 < f_{NL}^{\rm local} < 111$[h]	N/A
		Equilateral	$-151 < f_{NL}^{\rm equil} < 253$[i]	N/A
§ 3.6	Adiabaticity	Axion	$\alpha_0 < 0.16$[j]	$\alpha_0 < 0.067$[k]
		Curvaton	$\alpha_{-1} < 0.011$[l]	$\alpha_{-1} < 0.0037$[m]
§ 4	Parity Violation	Chern-Simons[n]	$-5.9^\circ < \Delta\alpha < 2.4^\circ$	N/A
§ 5	Dark Energy	Constant w[o]	$-1.37 < 1 - w < 0.32$[p]	$-0.11 < 1 - w < 0.14$
		Evolving $w(z)$[q]	N/A	$-0.38 < 1 + w_0 < 0.14$[r]
§ 6.1	Neutrino Mass[s]		$\sum m_\nu < 1.3$ eV[t]	$\sum m_\nu < 0.61$ eV[u]
§ 6.2	Neutrino Species		$N_{\rm eff} > 2.3$[v]	$N_{\rm eff} = 4.4 \pm 1.5$[w] (68%)

Initial conditions in our universe

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

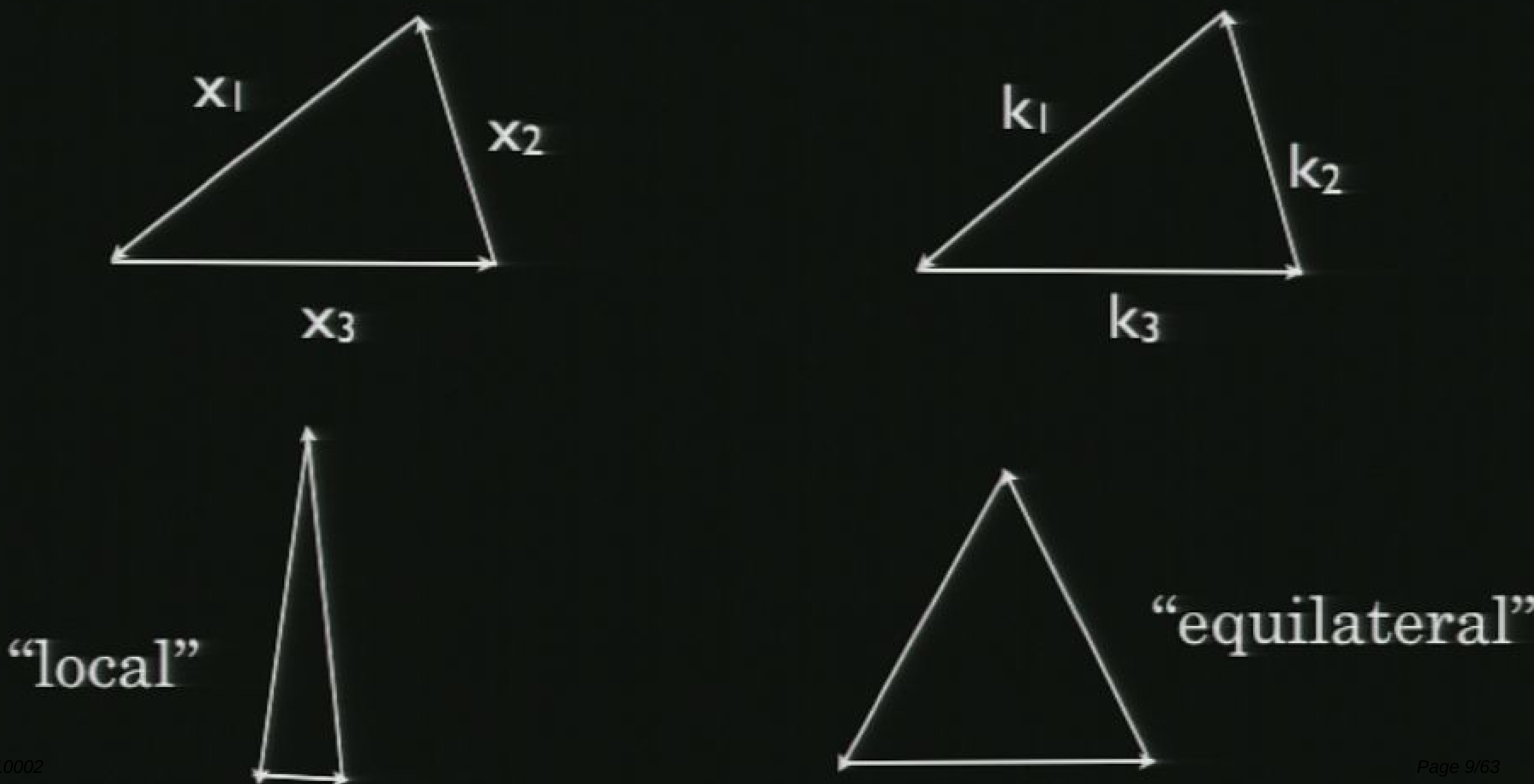


Generic inflationary predictions:

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

3-pt function as a measure of cosmological NonGaussianity (NG)

- Principal measure of NG: three-pt correlation function



e.g. Luo & Schramm 1993

Inflation generically predicts (very nearly) gaussian random fluctuations

- Nongaussianity is proportional to slow-roll parameters, V′/V and V″/V

- Reasonable and commonly used approximation: the "local" model of primordial nongaussianity

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

- Inflation predicts f_{NL}~O(0.1), which is basically extremely small

- More exotic inflationary models can produce observable NG, however

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

Brief history of NG measurements: 1990's

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

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1998; COBE: claim of NG at l=16 equilateral bispectrum
(Ferreira, Magueijo & Gorski 1998)

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)

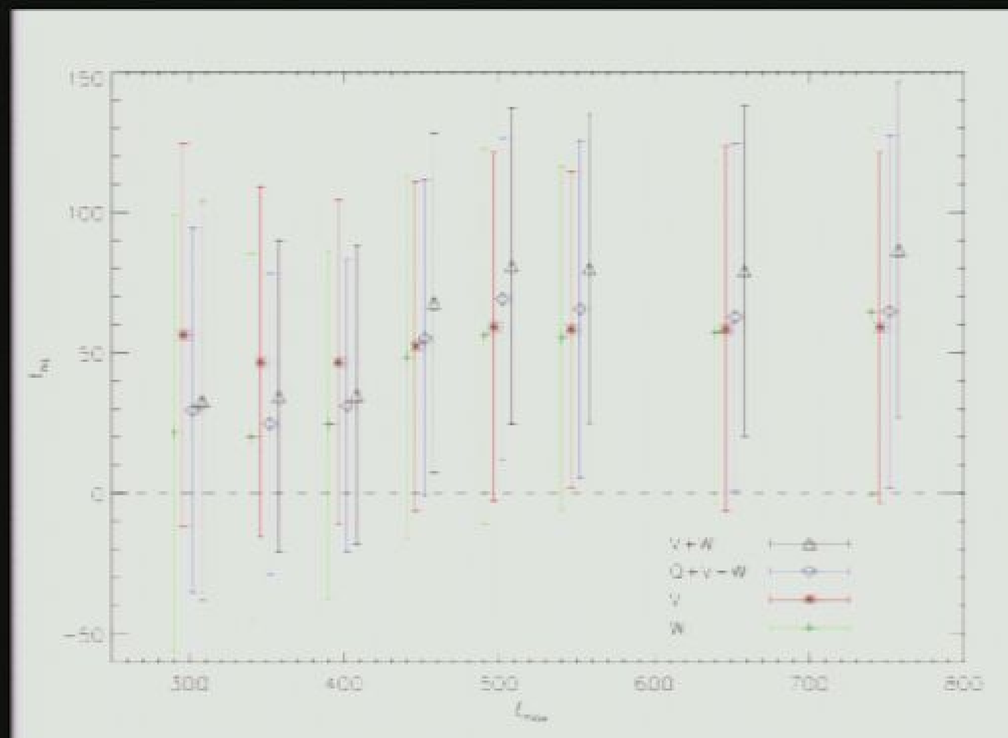


TABLE 6

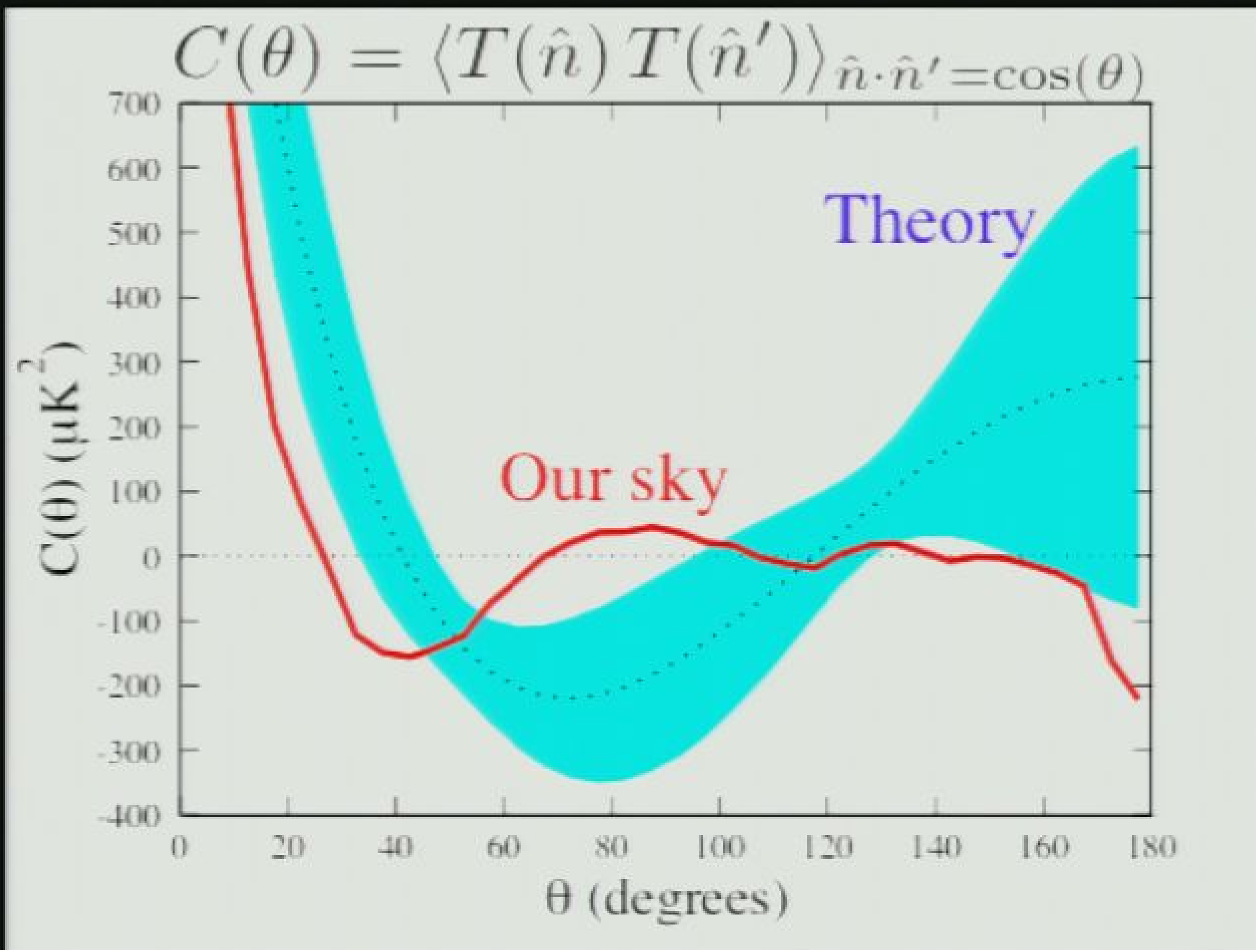
NULL TESTS, FREQUENCY DEPENDENCE, AND RAW-MAP ESTIMATES OF THE LOCAL FORM OF PRIMORDIAL NON-GAUSSIANITY, $f_{NL}^{\rm local}$, FOR $l_{\rm max} = 500$

Band	Foreground	Mask	$f_{NL}^{\rm local}$
Q−W	Raw	*KQ75*	-0.53 ± 0.22
V−W	Raw	*KQ75*	-0.31 ± 0.23
Q−W	Clean	*KQ75*	0.10 ± 0.22
V−W	Clean	*KQ75*	0.06 ± 0.23
Q	Raw	*KQ75p1*[a]	-42 ± 45
V	Raw	*KQ75p1*	38 ± 34
W	Raw	*KQ75p1*	43 ± 33
Q	Raw	*KQ75*	-42 ± 48
V	Raw	*KQ75*	41 ± 35
W	Raw	*KQ75*	46 ± 35
Q	Clean	*KQ75p1*	9 ± 45
V	Clean	*KQ75p1*	47 ± 34
W	Clean	*KQ75p1*	60 ± 33
Q	Clean	*KQ75*	10 ± 48
V	Clean	*KQ75*	50 ± 35
W	Clean	*KQ75*	62 ± 35
V+W	Raw	*KQ85*	9 ± 26
V+W	Raw	*Kp0*	48 ± 26
V+W	Raw	*KQ75p1*	41 ± 28
V+W	Raw	*KQ75*	43 ± 30

[a]This mask replaces the point-source mask in *KQ75* with the one that does not mask the sources identified in the *WMAP* K-band data

Komatsu et al. 2008

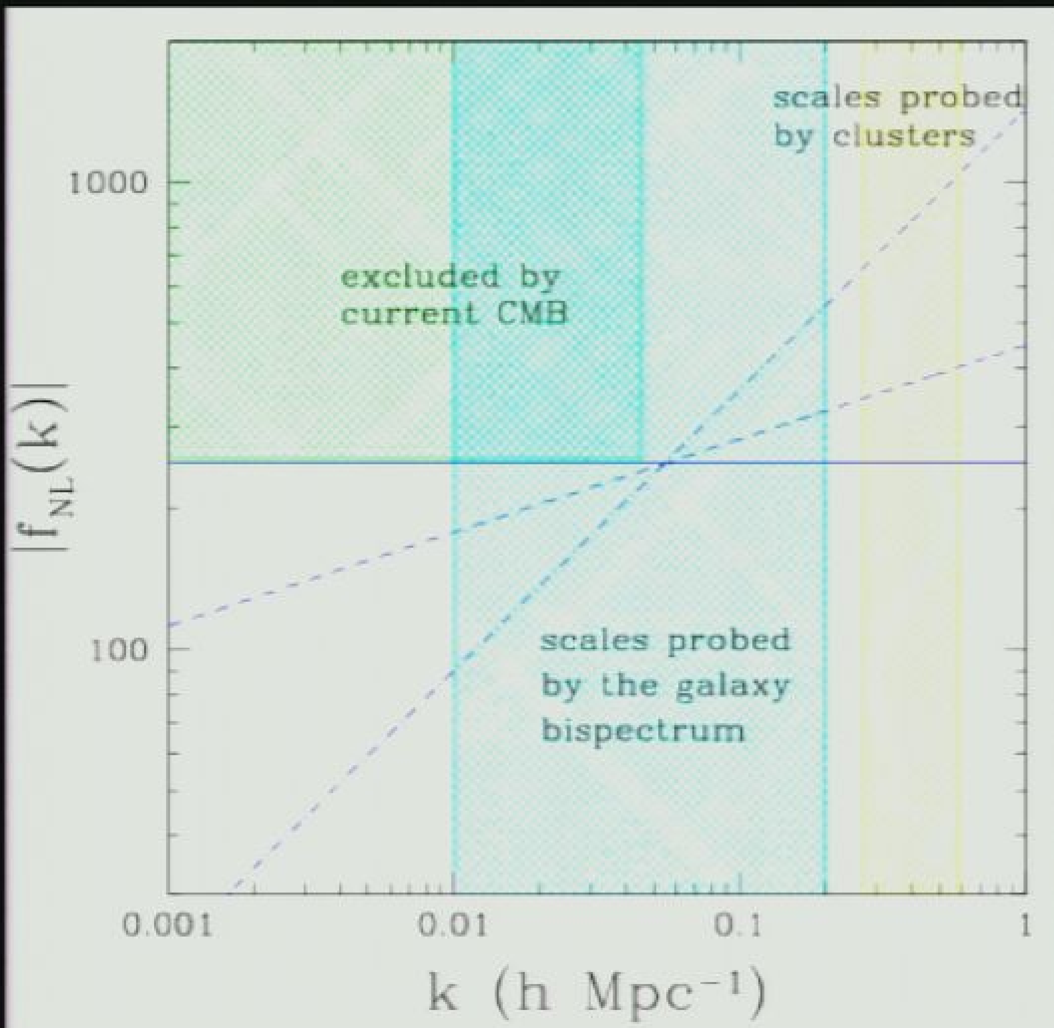
... and also "large-scale anomalies"



lack of power at >60 deg; significant at 99.97%

Hinshaw et al. 1996 (COBE)
Spergel et al. 2003 (WMAP 1)
Copi, Huterer, Schwarz & Starkman 2007, 08 (WMAP 3, 5)

Constraints from future LSS surveys



LoVerde, Miller, Shandera & Verde, arXiv:0711.4126

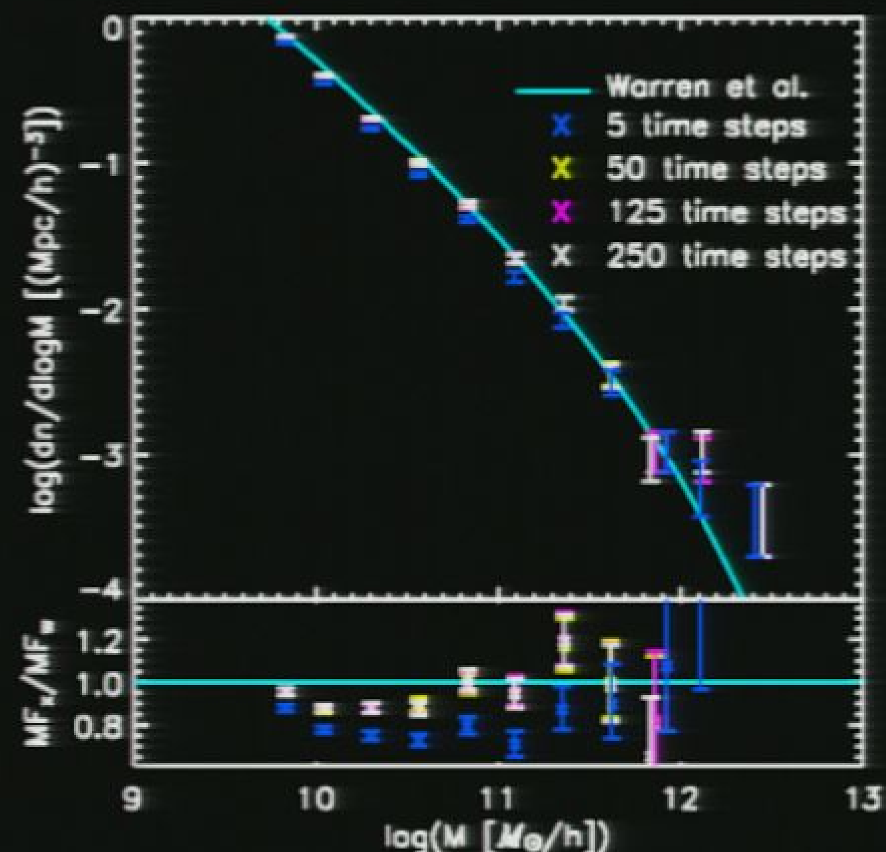
Abundance of halos: the mass function

Lots of interest in using halo counts as a cosmological probe.

- Mass function can be computed precisely (~5%) and robustly for standard cosmology (Jenkins et al. 01, Warren et al. 03)

- dN/dM appears universal — i.e. f(σ) — for standard cosmologies

$$\sigma^2(M,z) = \frac{1}{2\pi^2}\int_0^\infty k^2 P(k) W^2(k,M)\, dk$$



Mass function, usual analytic approach

Press & Schechter 1974:

$$\frac{dn}{dM}dM = \frac{\rho_M}{M}\left|\frac{dF}{dM}\right|dM \qquad F(>M) = 2\int_{\delta_c/\sigma(M)}^{\infty} P_G(\nu)d\nu$$

therefore $$\left(\frac{dn}{d\ln M}\right)_{\rm PS} = 2\,\frac{\rho_M}{M}\frac{\delta_c}{\sigma}\left|\frac{d\ln\sigma}{d\ln M}\right| P_{\rm G}(\delta/\sigma)$$

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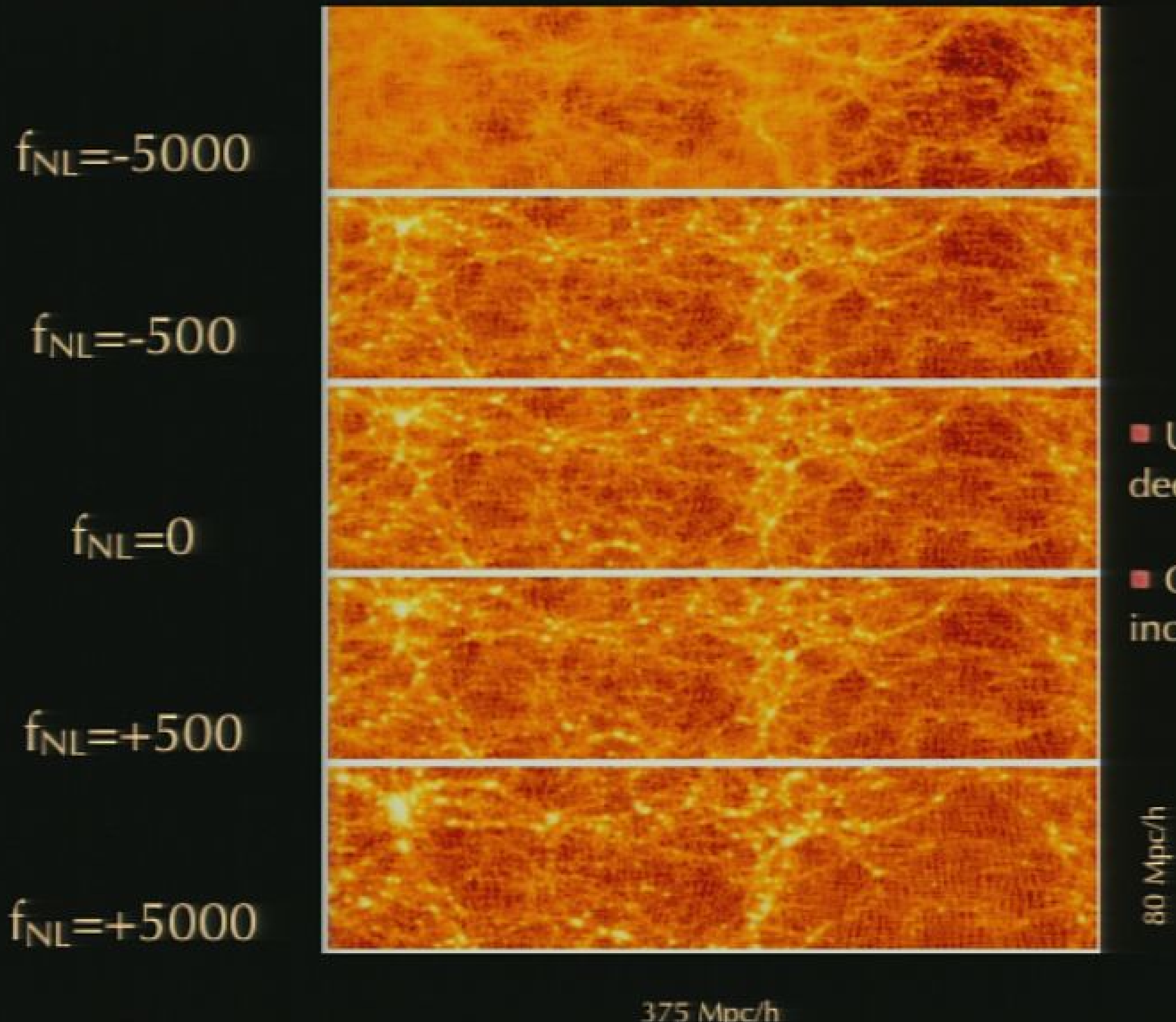
"Extended Press-Schechter" (EPS): $P_G(\nu) \rightarrow P_{NG}(\nu)$

Matarrese, Verde & Jimenez (2000; MVJ):
follow EPS, then expand P_{NG} in terms of skewness, do the integral
(also LoVerde, Miller, Shandera & Verde 2008)

However, no convincing reason why either should work!
Need to check these formulae with simulations

Simulations with nongaussianity (f_{NL})

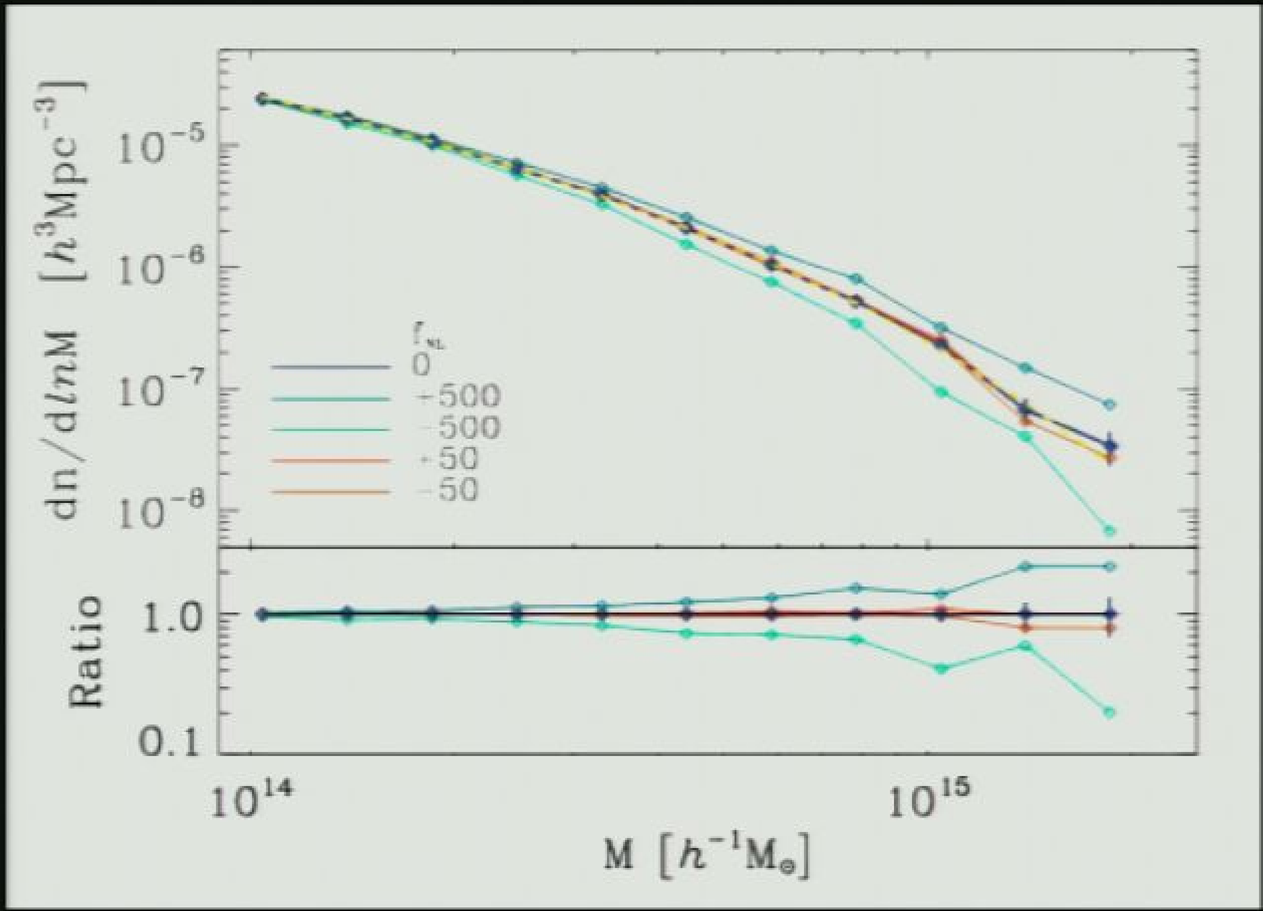


- Under-dense region evolution decrease with f_{NL}
- Over-dense region evolution increase with f_{NL}

- 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, arXiv:0710.4560, PRD 2008

The measured halo mass function

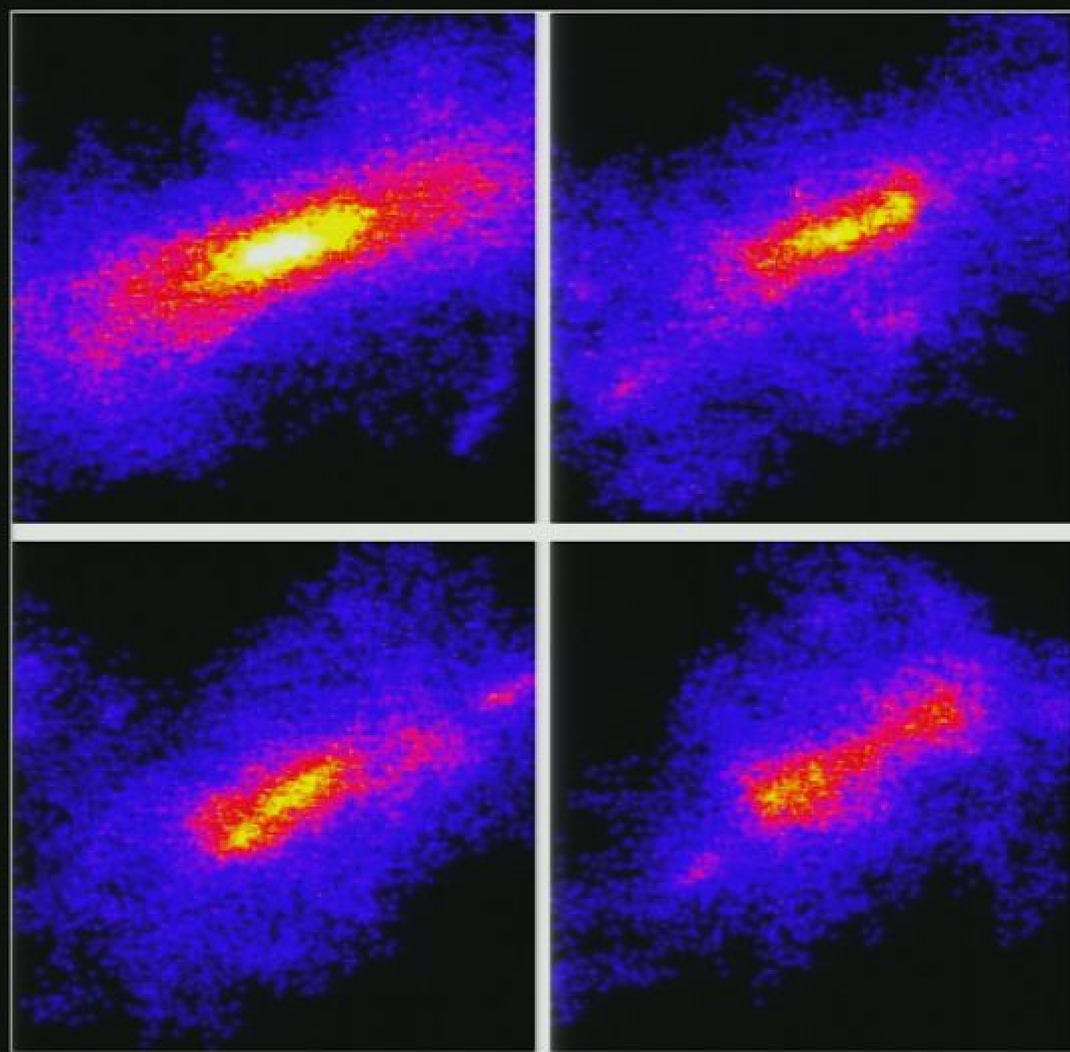


- 512^3 (1024^3) particle simulations with box size 800 (1600) Mpc/h
- Gracos code (www.gracos.com); add quadratic Phi term in real space; apply transfer function in Fourier space

Looking at one individual cluster

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

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

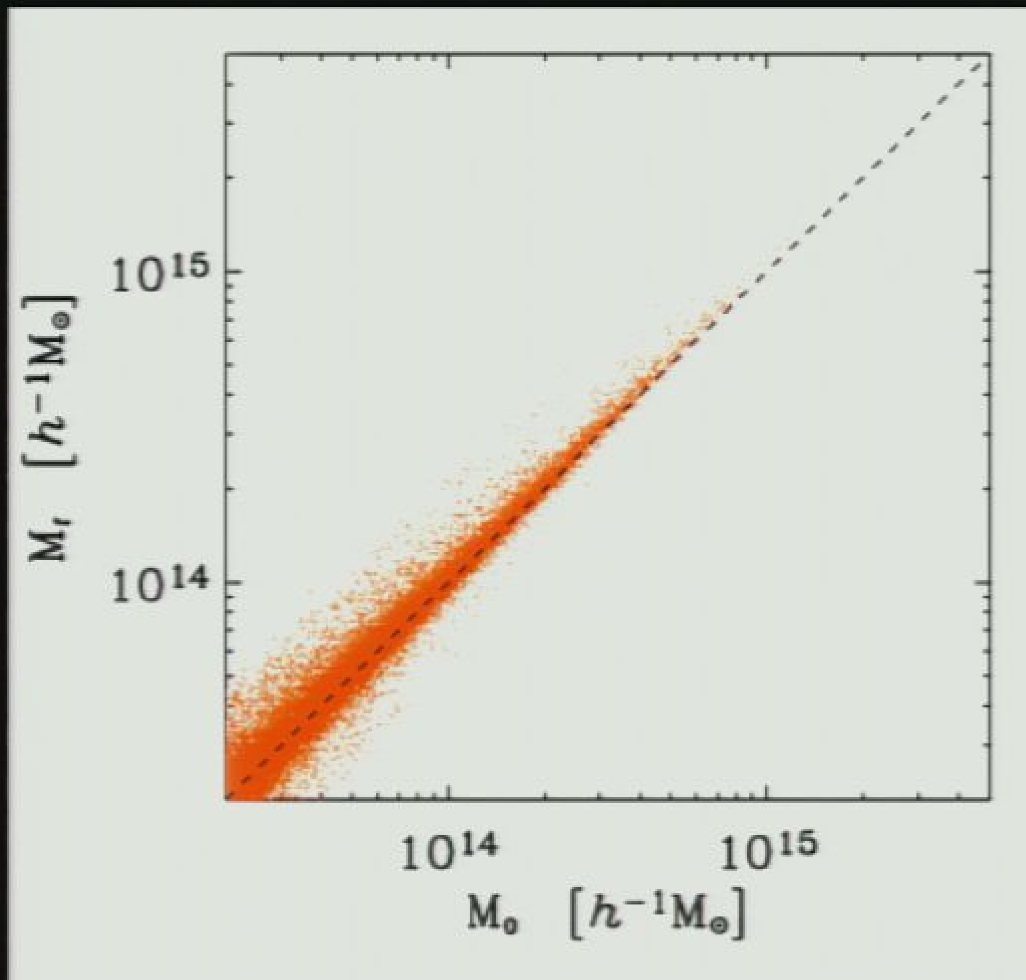


f_{NL}=0
M=5.1 10^{15} $M_\odot$

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

- Most massive cluster in our simulation
- For small enough f_{NL}, same peaks arise, with different heights (implying different masses)
- Can we extend to any cluster?

Building the $P(M_f|M_0)$ distribution



$f_{NL} = 500$

- Idea: identify the *same* cluster for different f_{NL}, keep track how its mass changed!
- Significantly saves computational expenses

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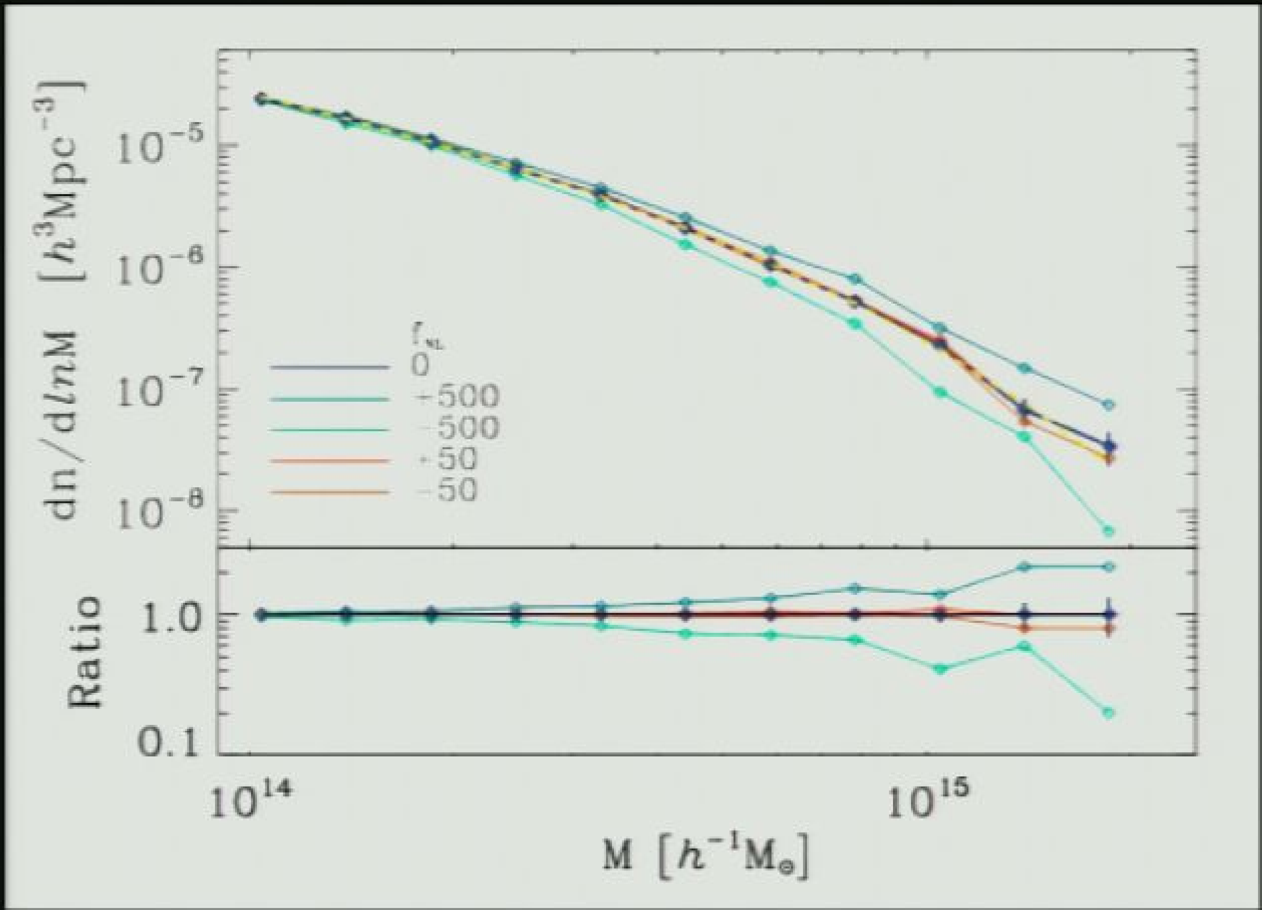

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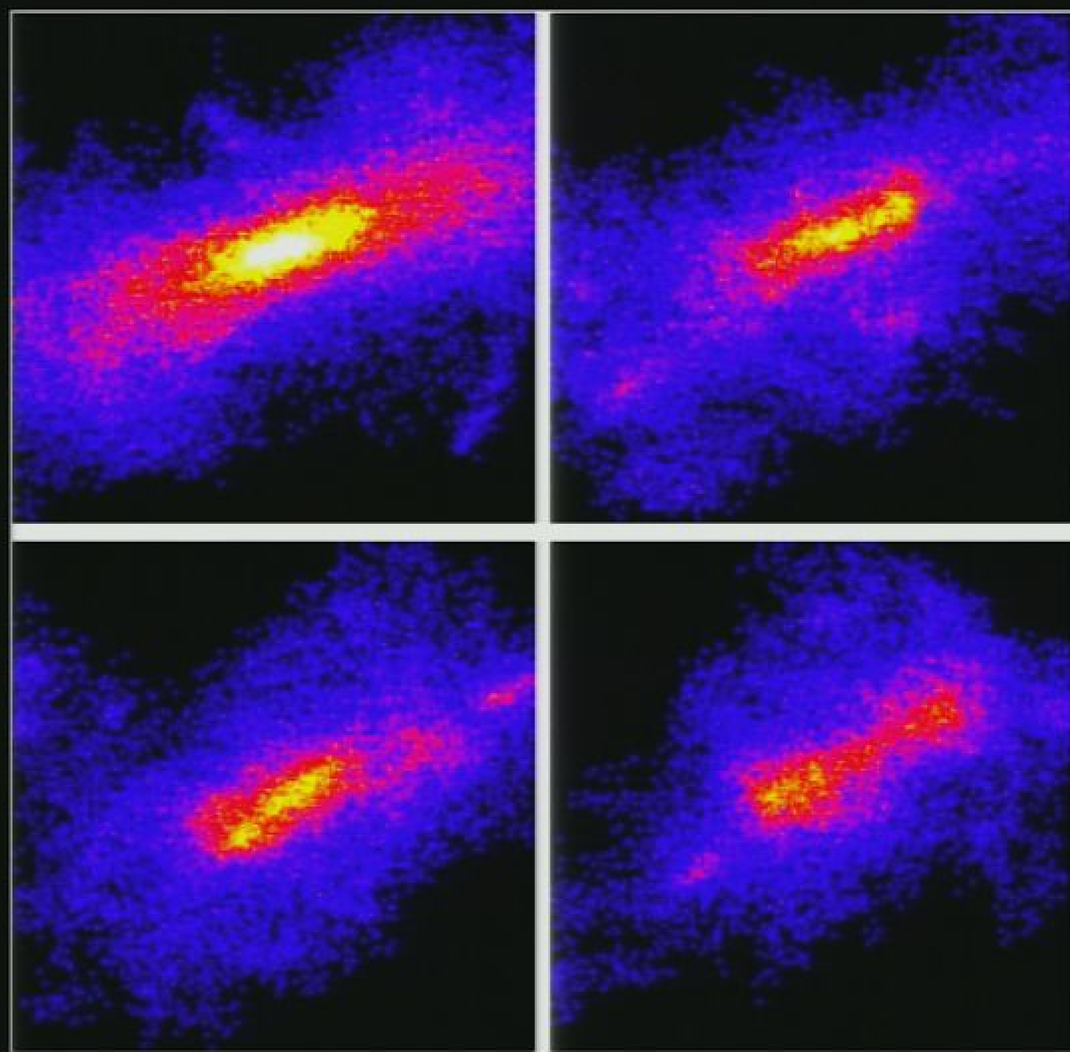

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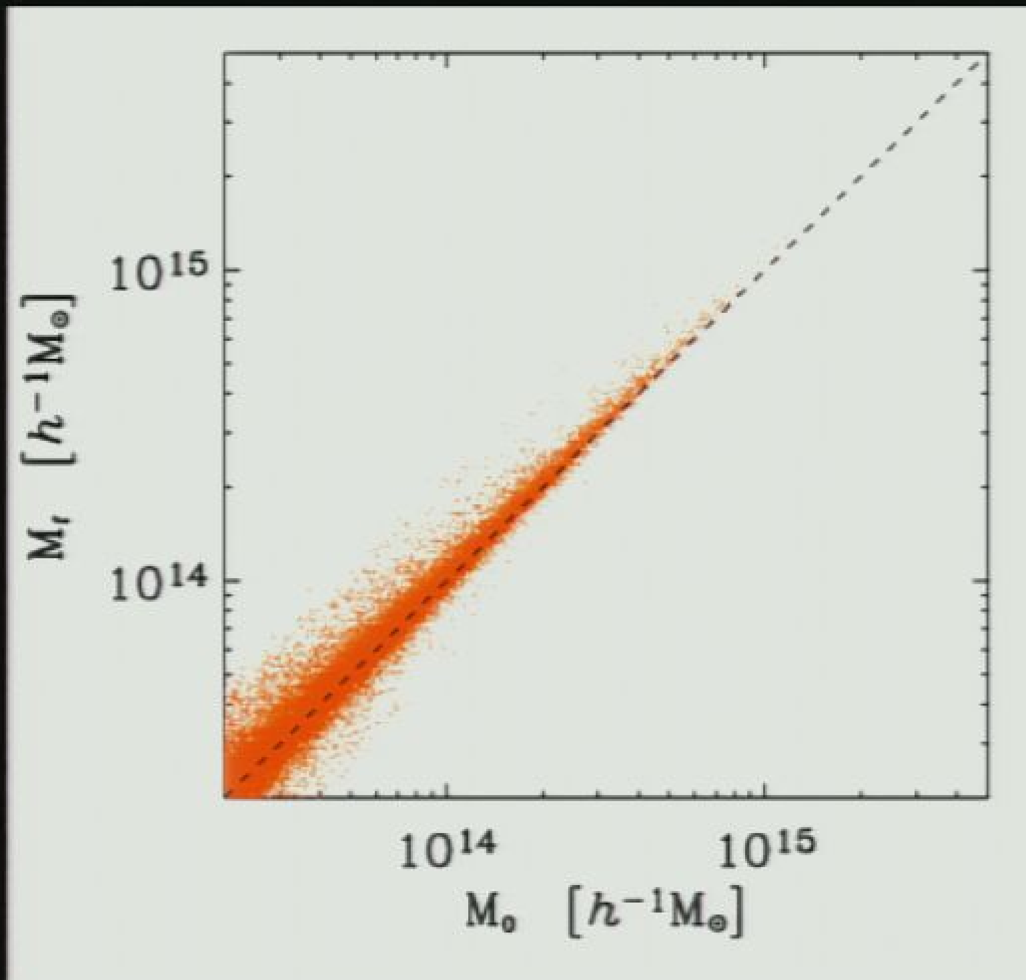

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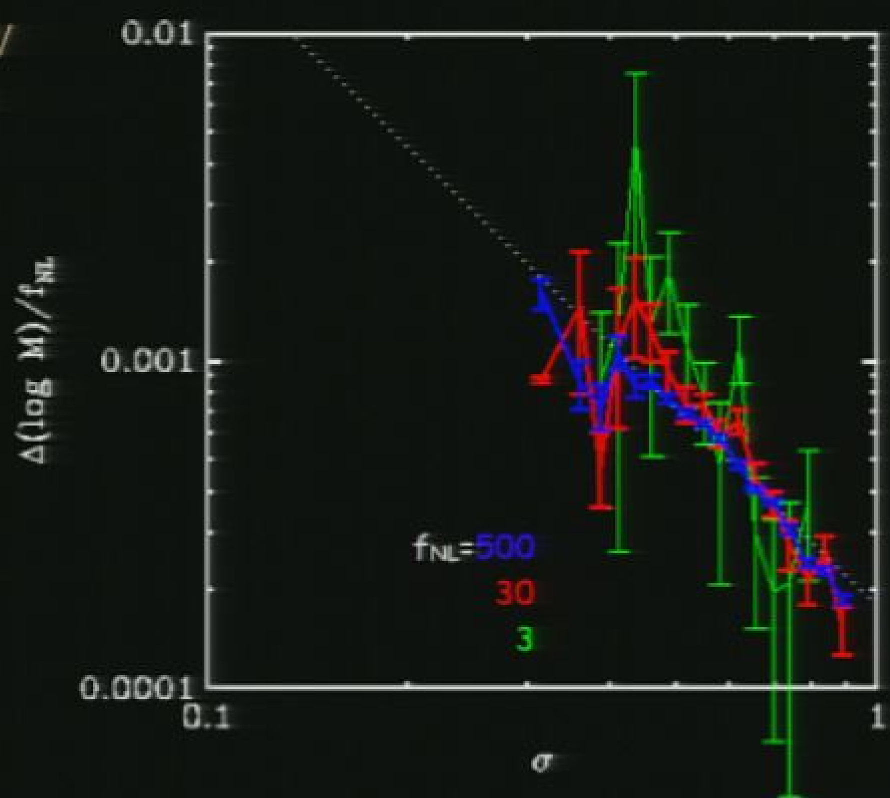
Towards a fitting function

- If the mapping $M_0 \rightarrow M_f$ is described by a PDF $dP/dM_f(M_0)$, then the non-gaussian mass function is a convolution over the (known) gaussian mass function

$$\frac{dN}{dM} = \int \frac{dP(M_f|M_0)}{dM_f} \frac{dN}{dM_0} dM_0$$

usual Gaussian mass function (e.g. Jenkins et al)

non-Gaussian mass function



Mean and variance of $P(M_f/M_0)$ are well fit by:

$$\left[\frac{\bar{M}_f}{M_0}\right] - 1 = 6.\ 10^{-5} f_{NL} \sigma_8\ \sigma(M_0, z)^{-2}$$

$$\sigma\left(\left[\frac{\bar{M}_f}{M_0}\right] - 1\right) = 0.012\ (f_{NL}\sigma_8)^{0.4}\ \sigma(M_0, z)^{-0.5}$$

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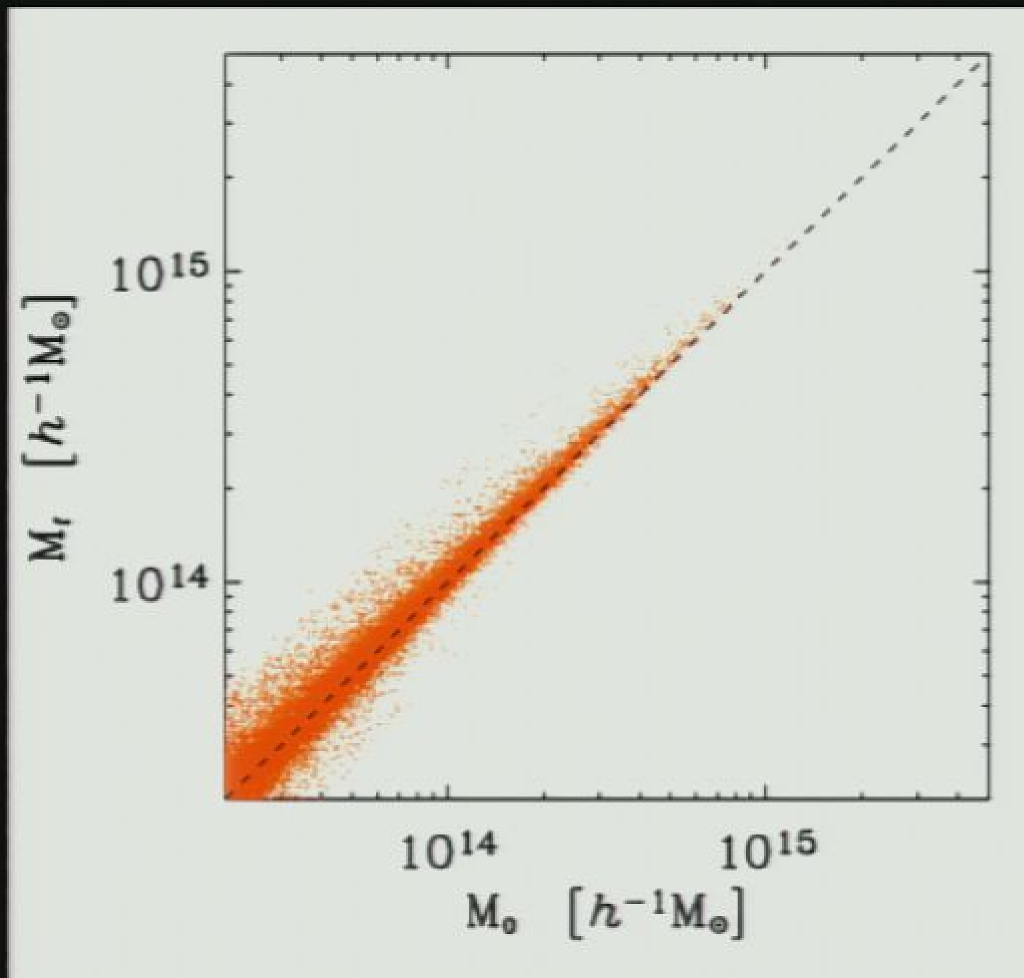

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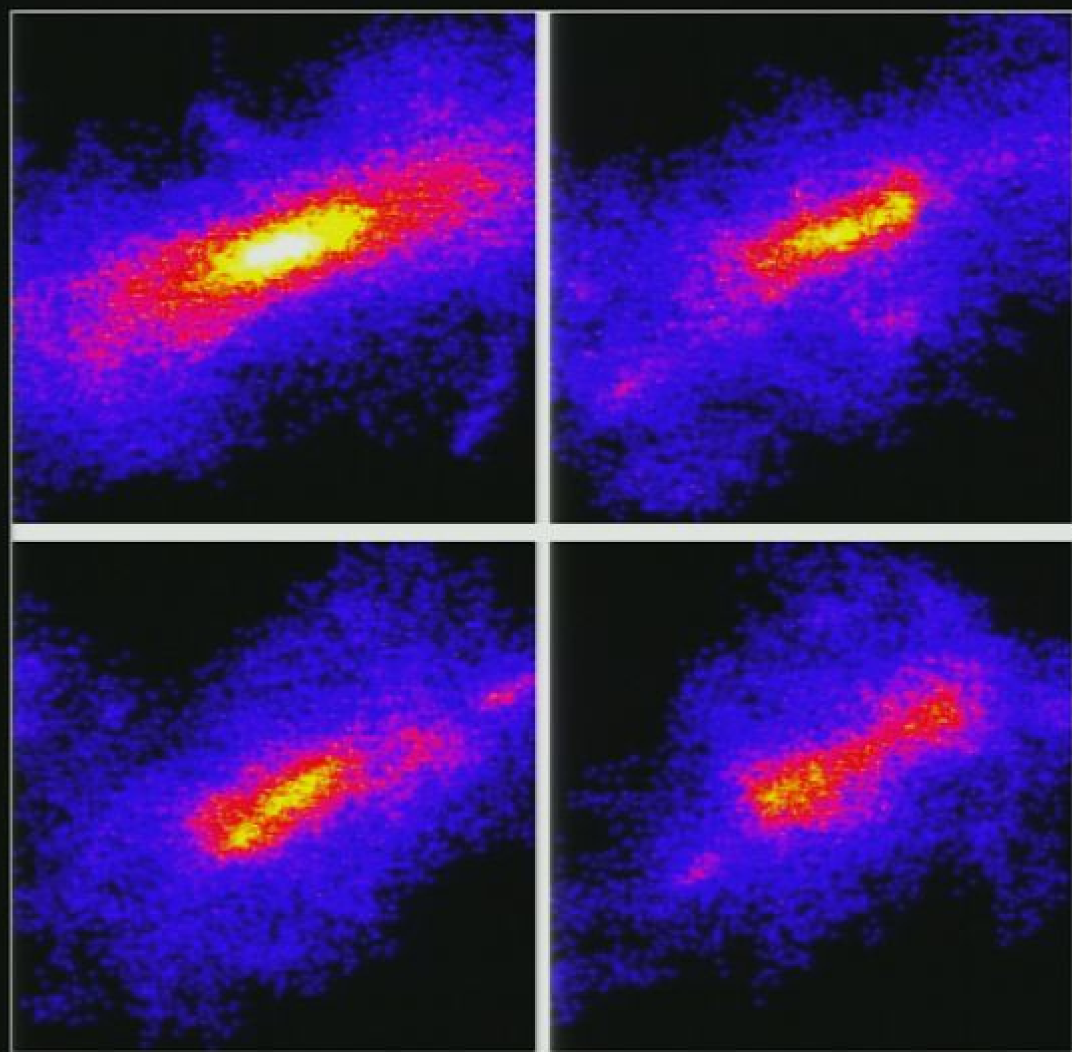

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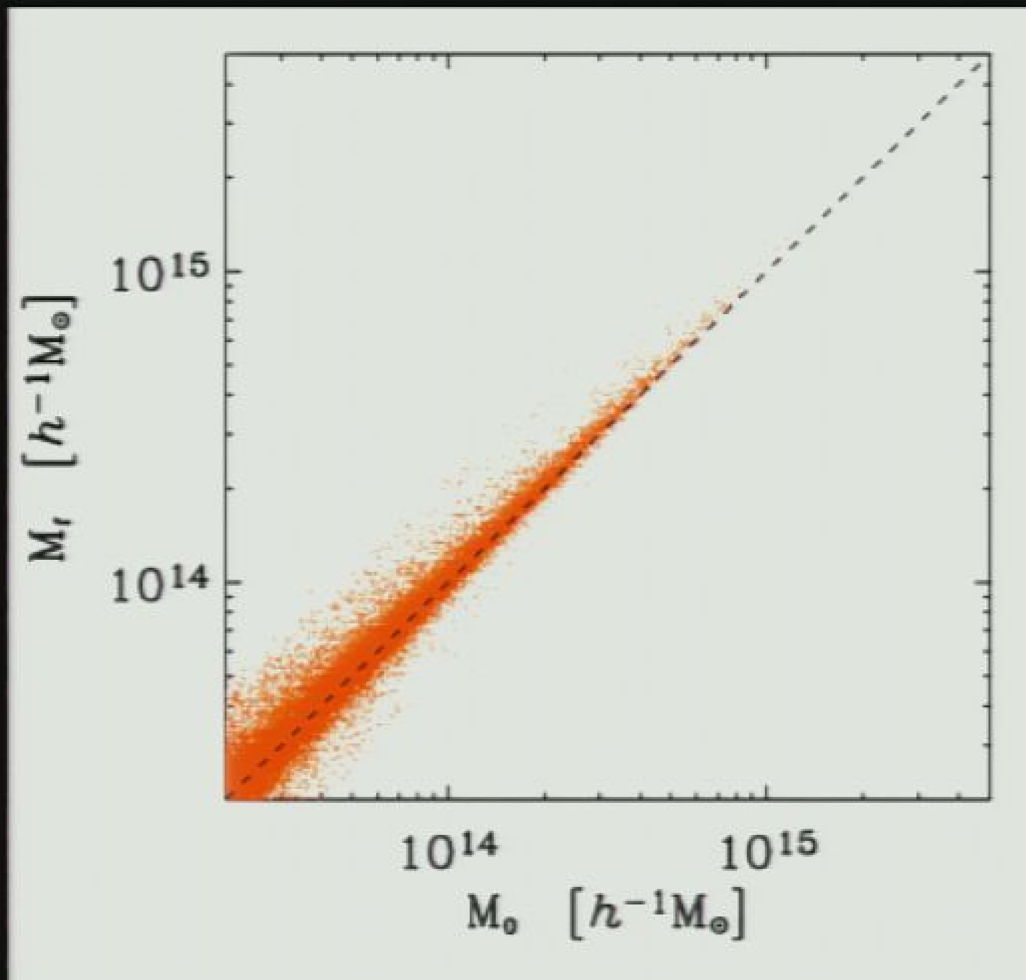

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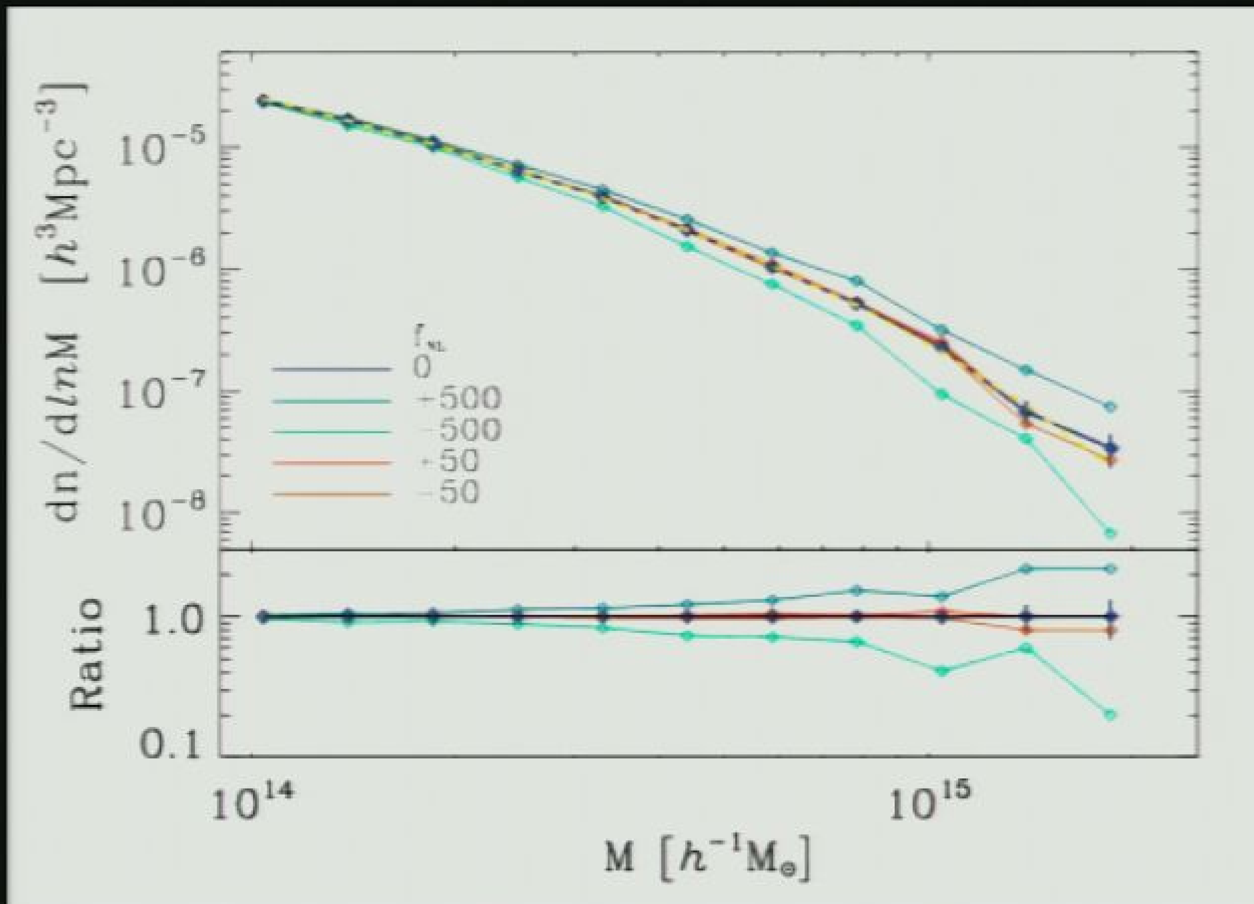

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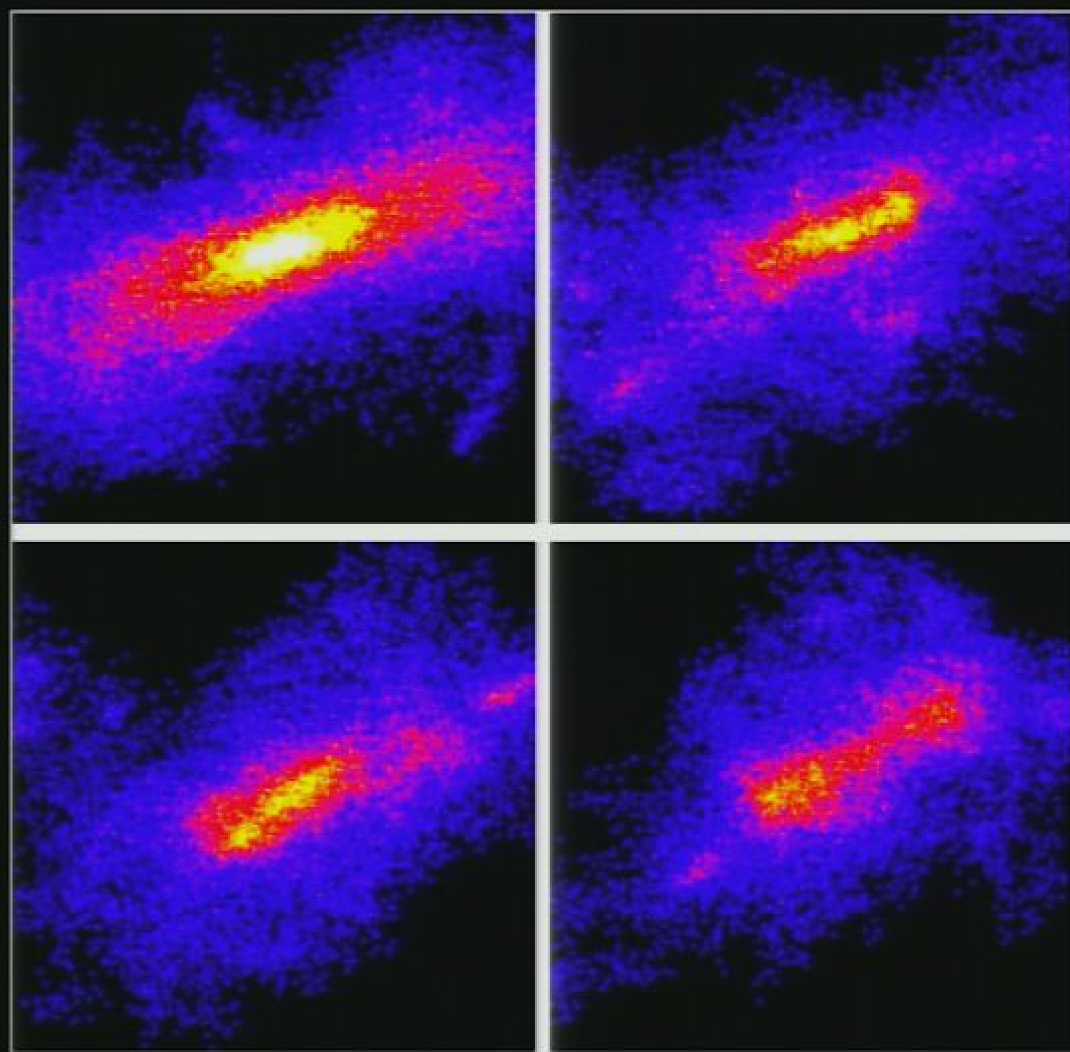

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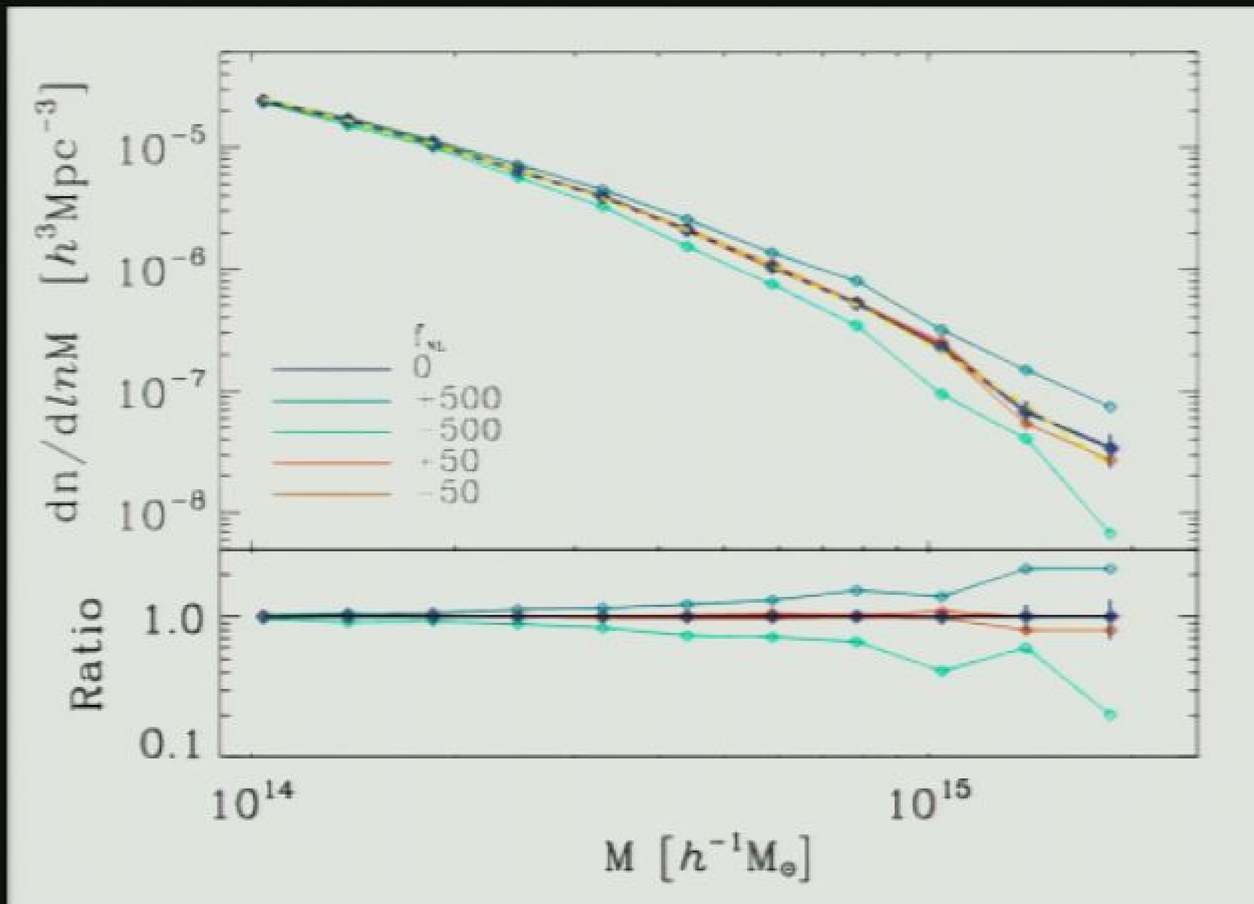

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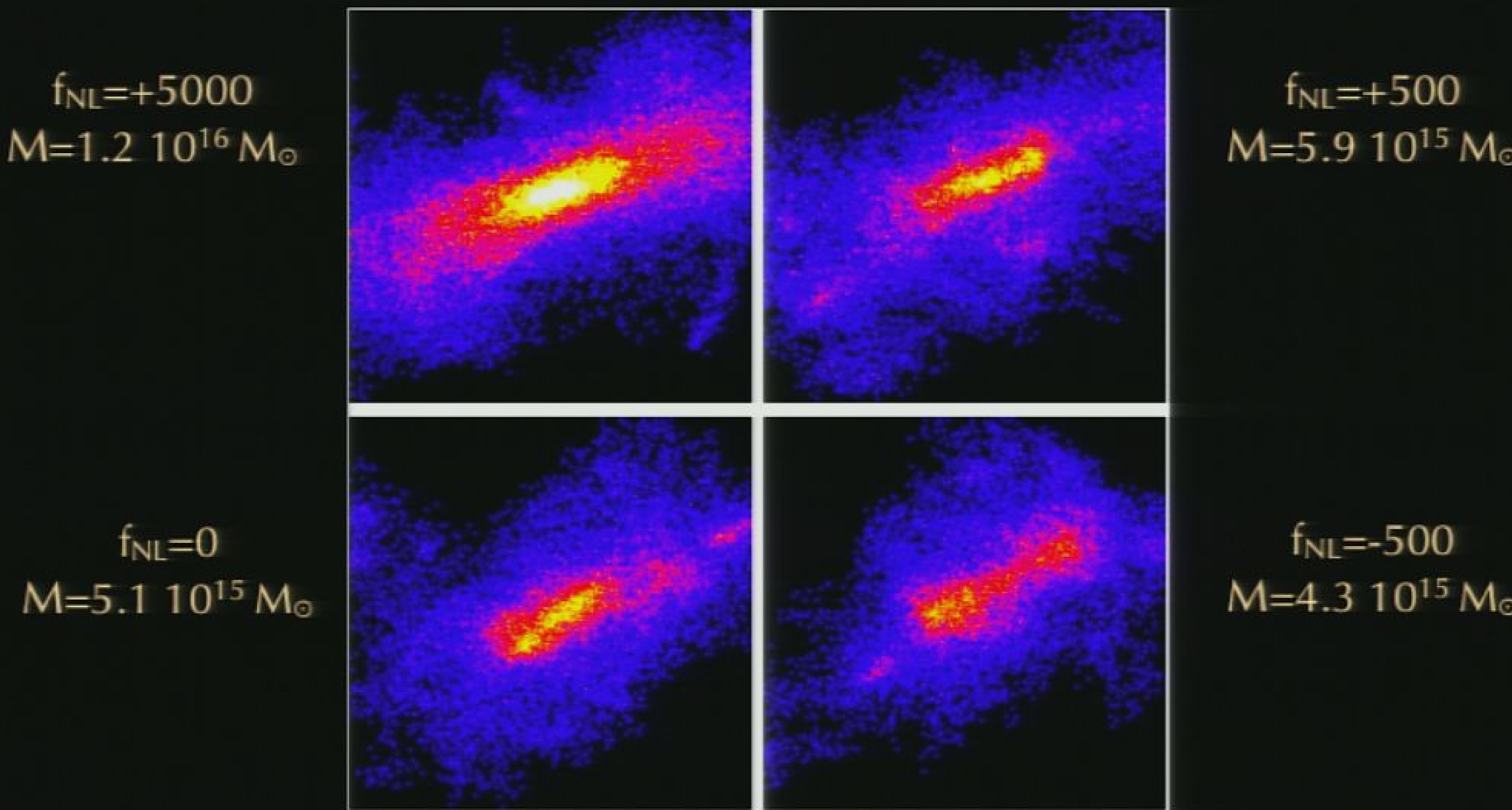

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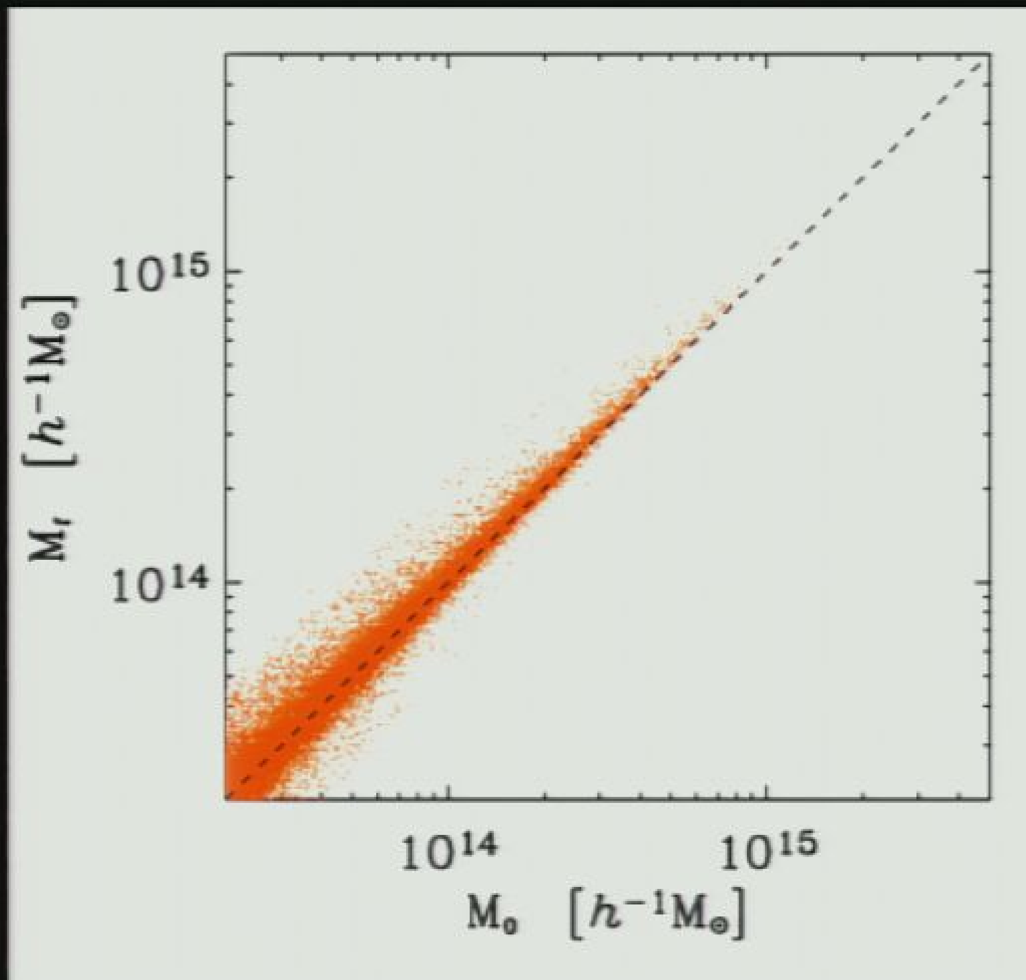

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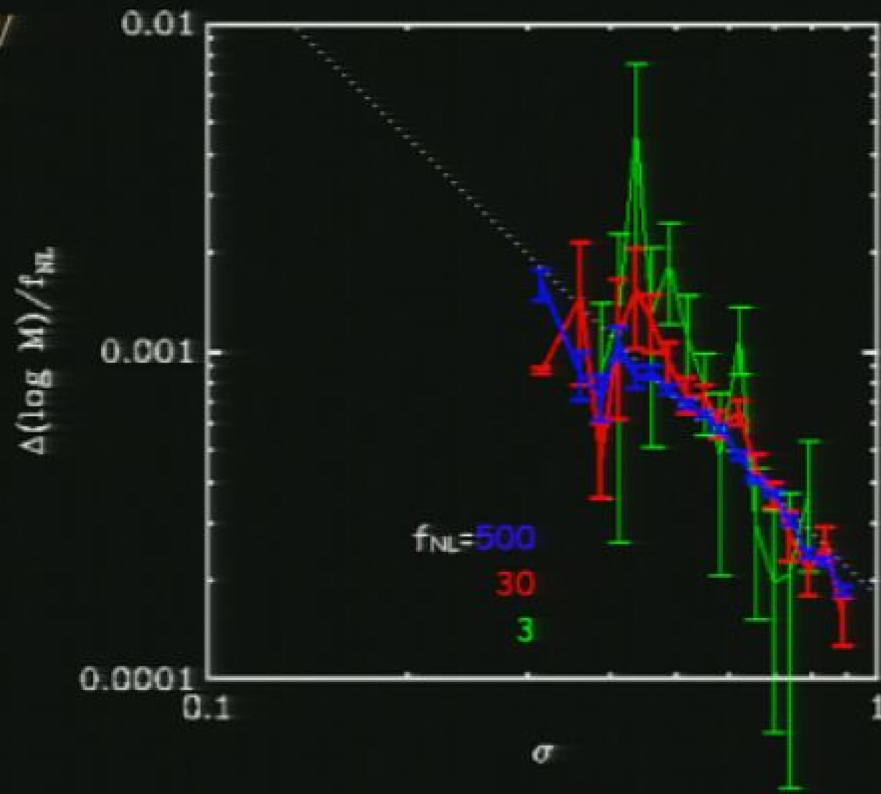
non-Gaussian mass function

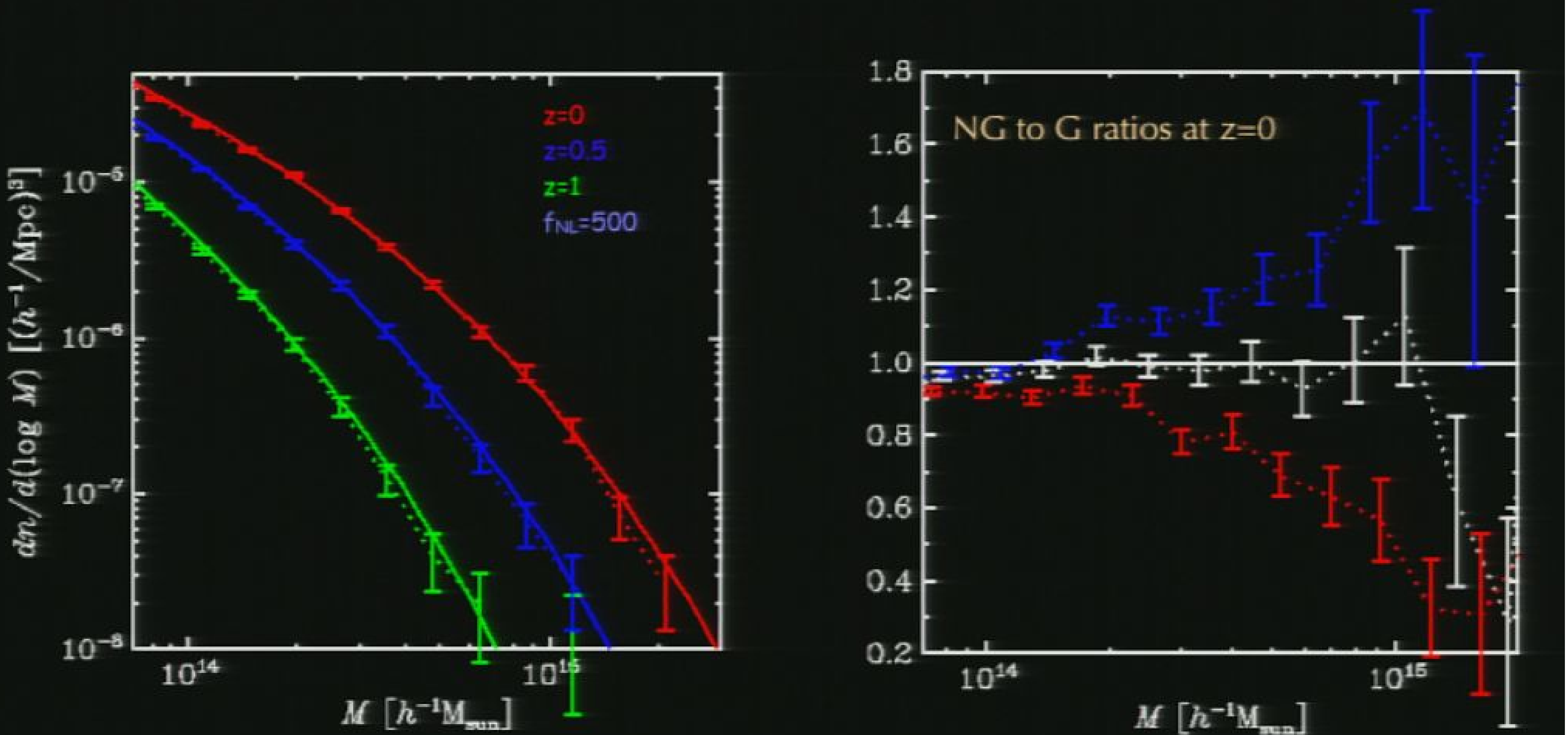


Mean and variance of $P(M_f/M_0)$ are well fit by:

$$\left[\frac{\bar{M}_f}{M_0}\right] - 1 = 6.\ 10^{-5} f_{NL} \sigma_8\ \sigma(M_0, z)^{-2}$$

$$\sigma\left(\left[\frac{\bar{M}_f}{M_0}\right] - 1\right) = 0.012\ (f_{NL}\sigma_8)^{0.4}\ \sigma(M_0, z)^{-0.5}$$

Mass function from N-body simulation and our fitting formula



Dalal, Doré, Huterer & Shirokov, arXiv:0710.4560, PRD 2008

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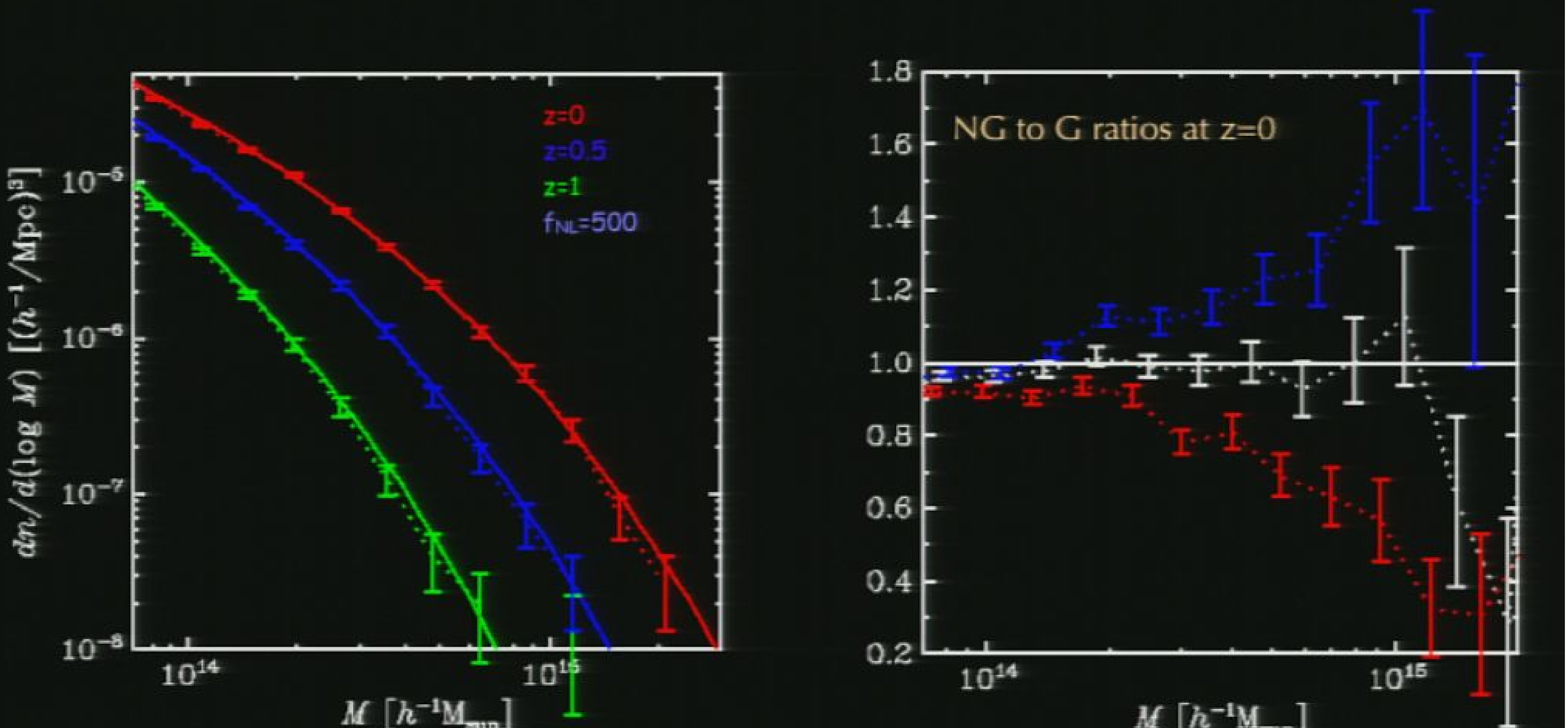

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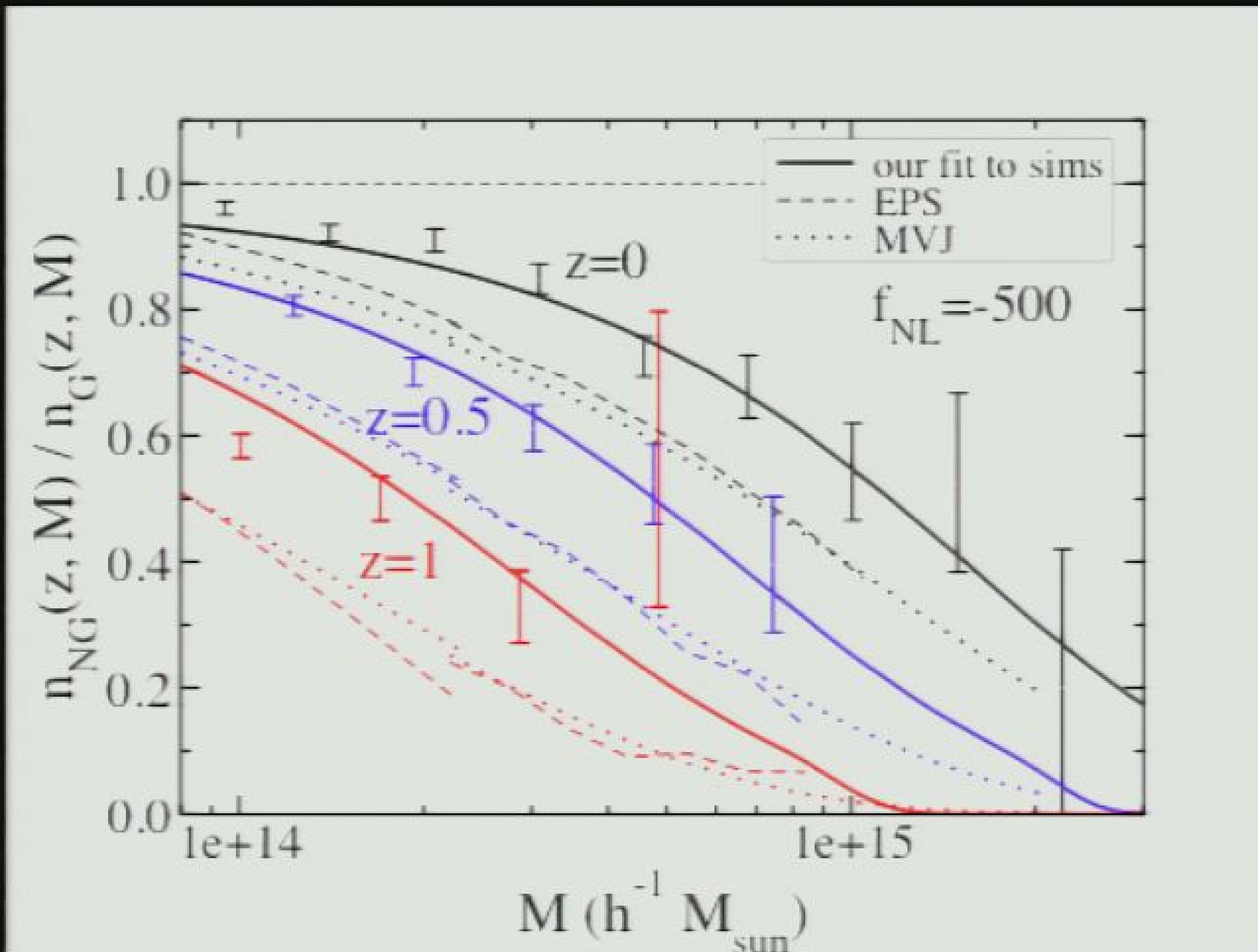
Old fitting functions are discrepant; off by O(100%) wrt truth



Moreover, it is not much harder to run a simulation than evaluate Extended Press-Schechter n(M)

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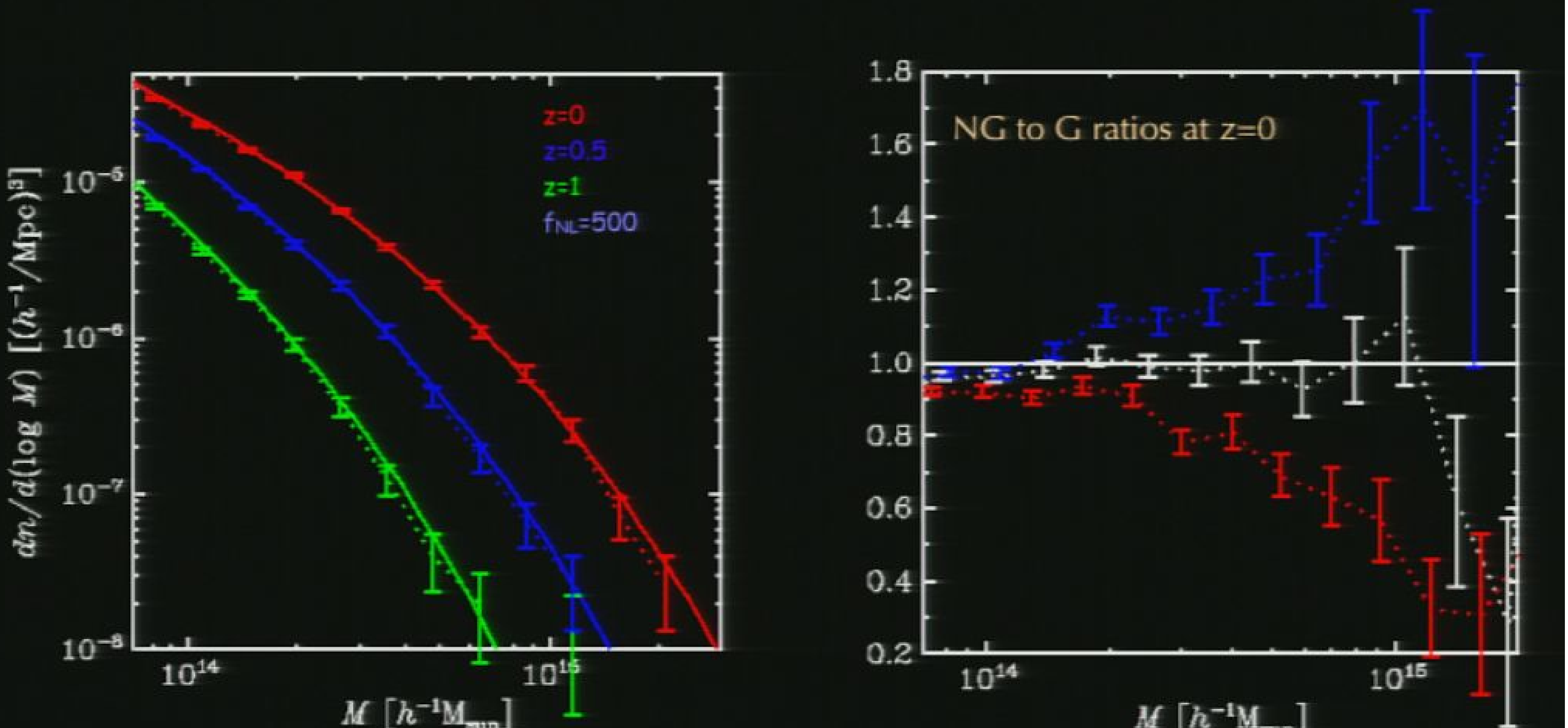

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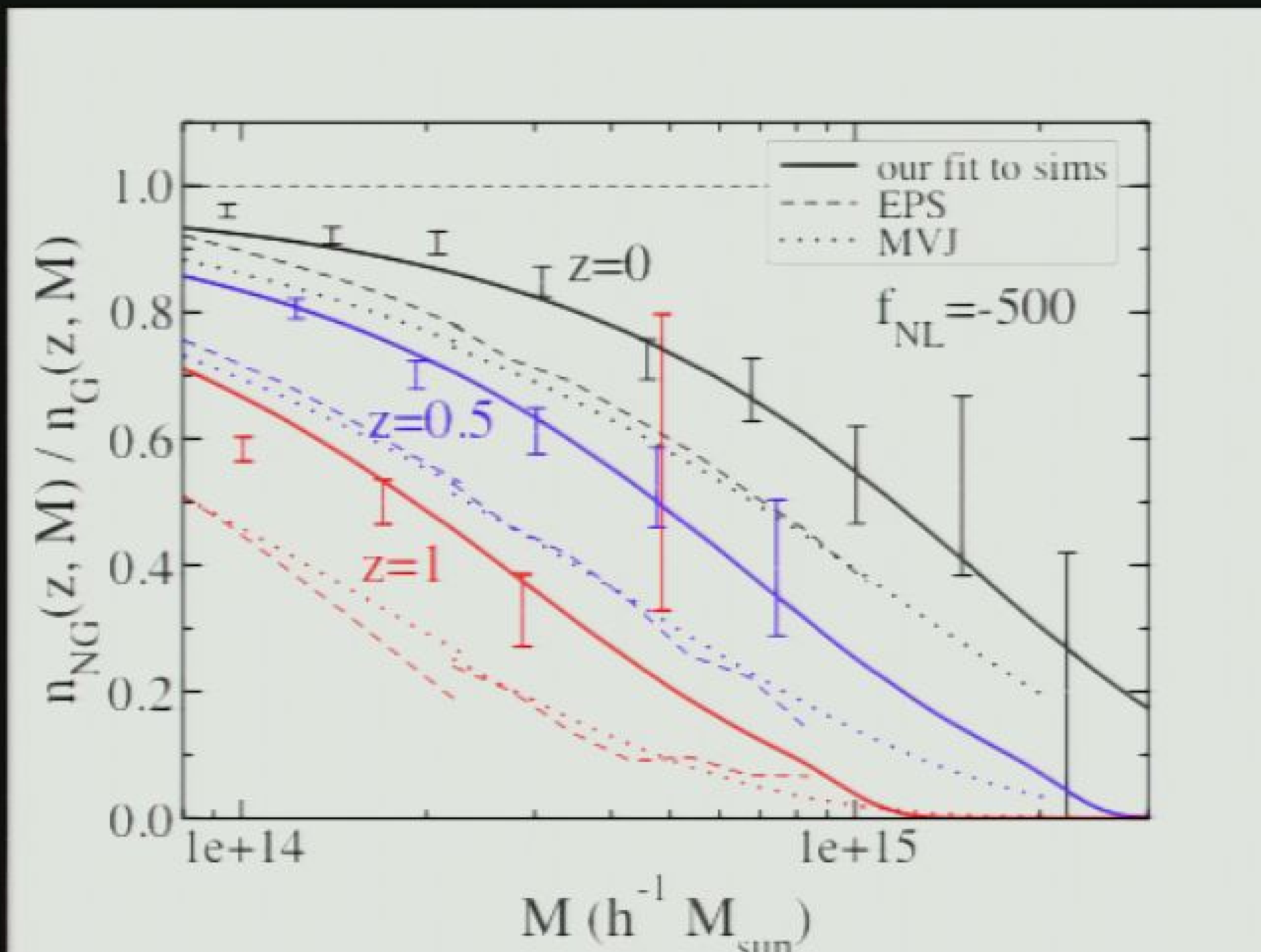

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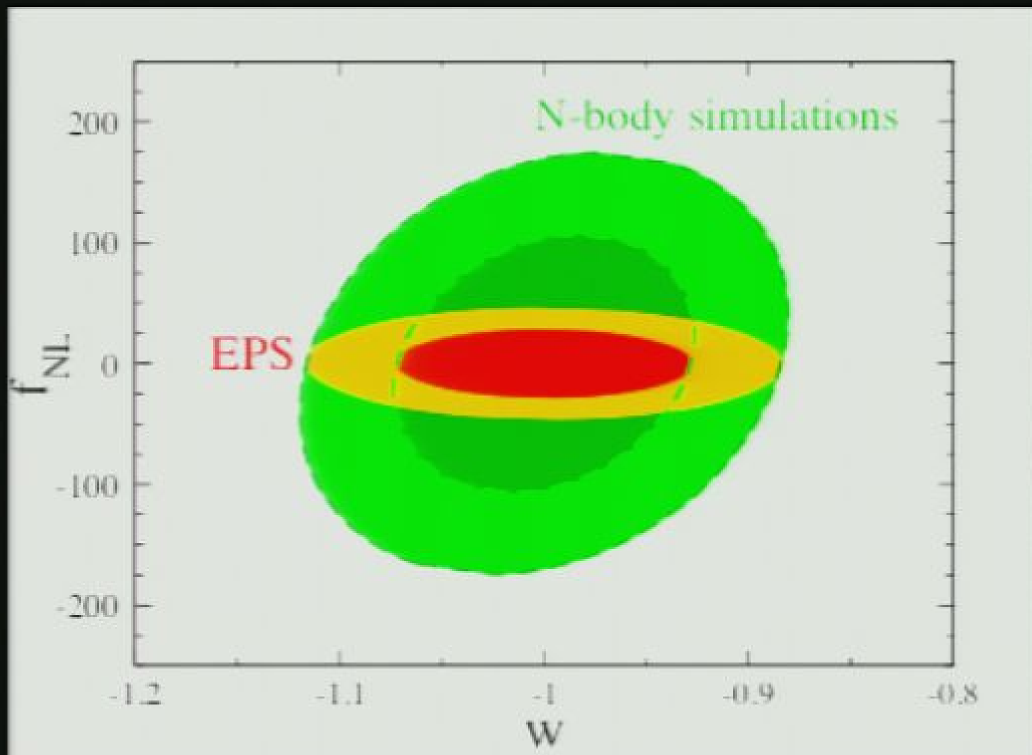
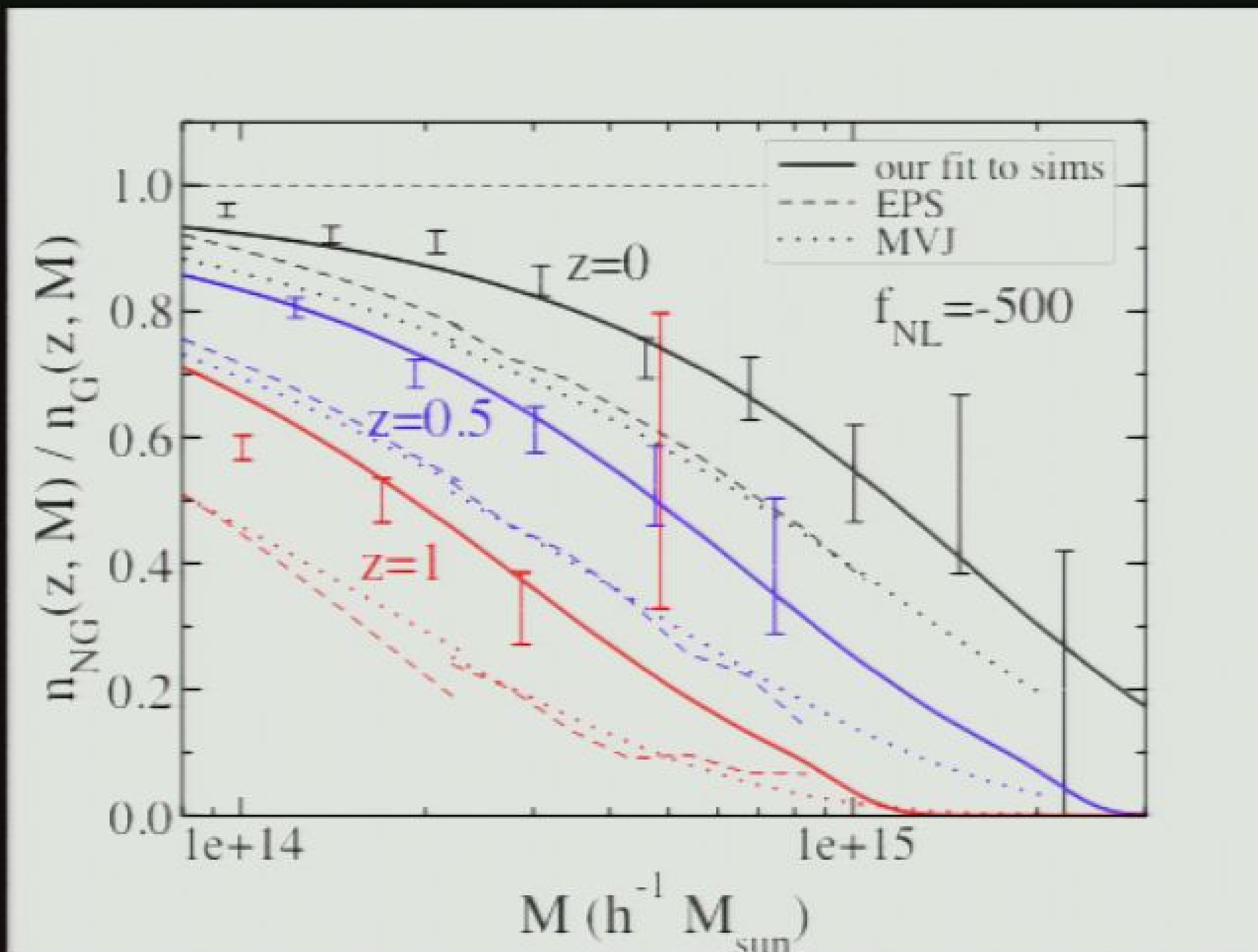
Cosmological constraints - dark energy and NG



SPT-type survey, ~7,000 clusters, 4000 sq.deg., 0.1<z<1.5
Planck prior

Recall, this is just from the cluster counts;
CMB provides stronger constraints

Old fitting functions are discrepant; off by O(100%) wrt truth



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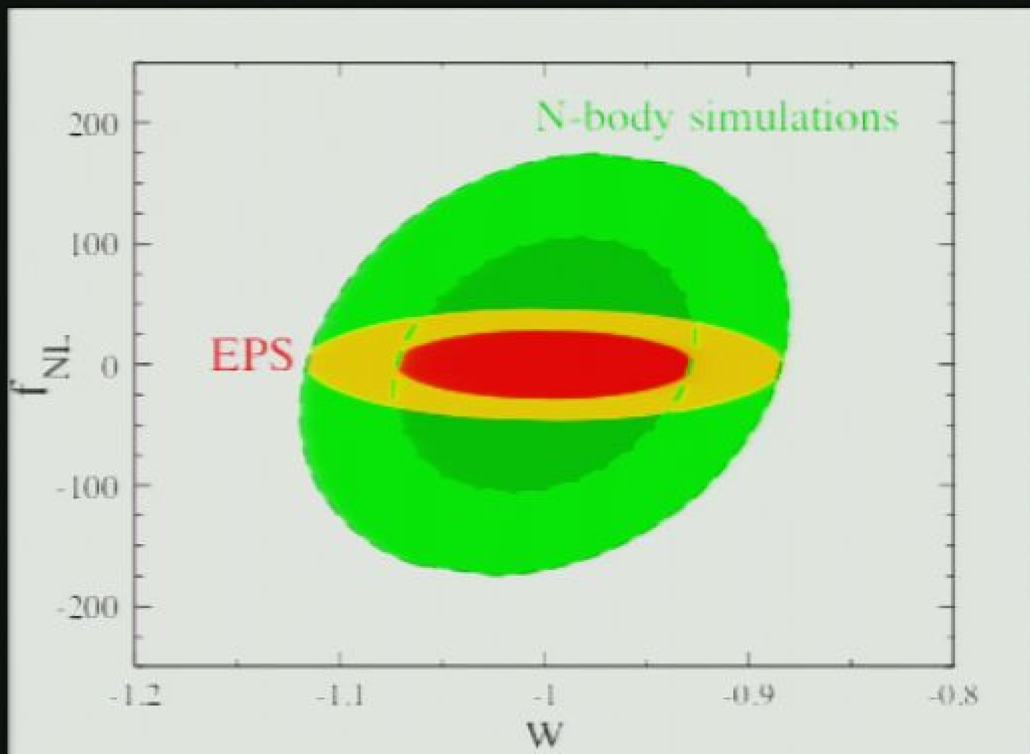


SPT-type survey, ~7,000 clusters, 4000 sq.deg., 0.1<z<1.5
Planck prior

Recall, this is just from the cluster counts;
CMB provides stronger constraints

Recent exciting developments (2007-present):

how to constrain primordial NG
much more accurately
from the LSS

We looked at the galaxy bias

cosmologists measure

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

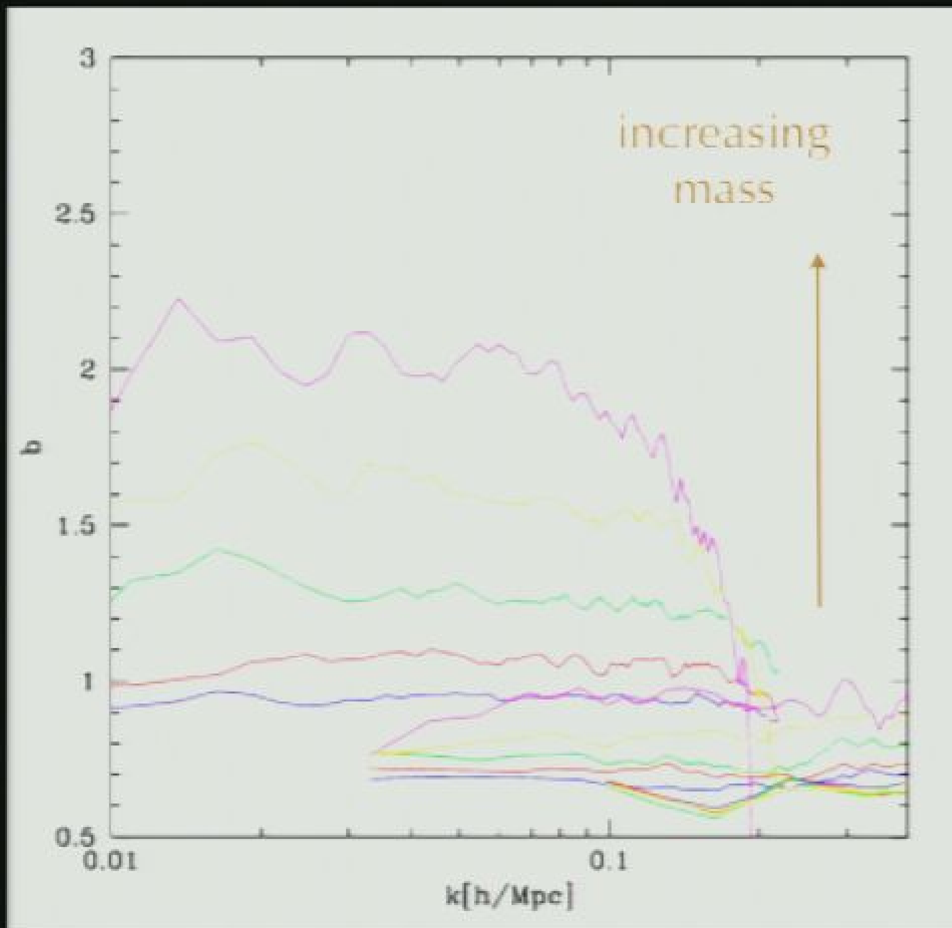
usually nuisance parameter(s)

theory predicts

Simulations and theory both say:
large-scale bias is scale-independent

Bias of dark matter halos - Gaussian case

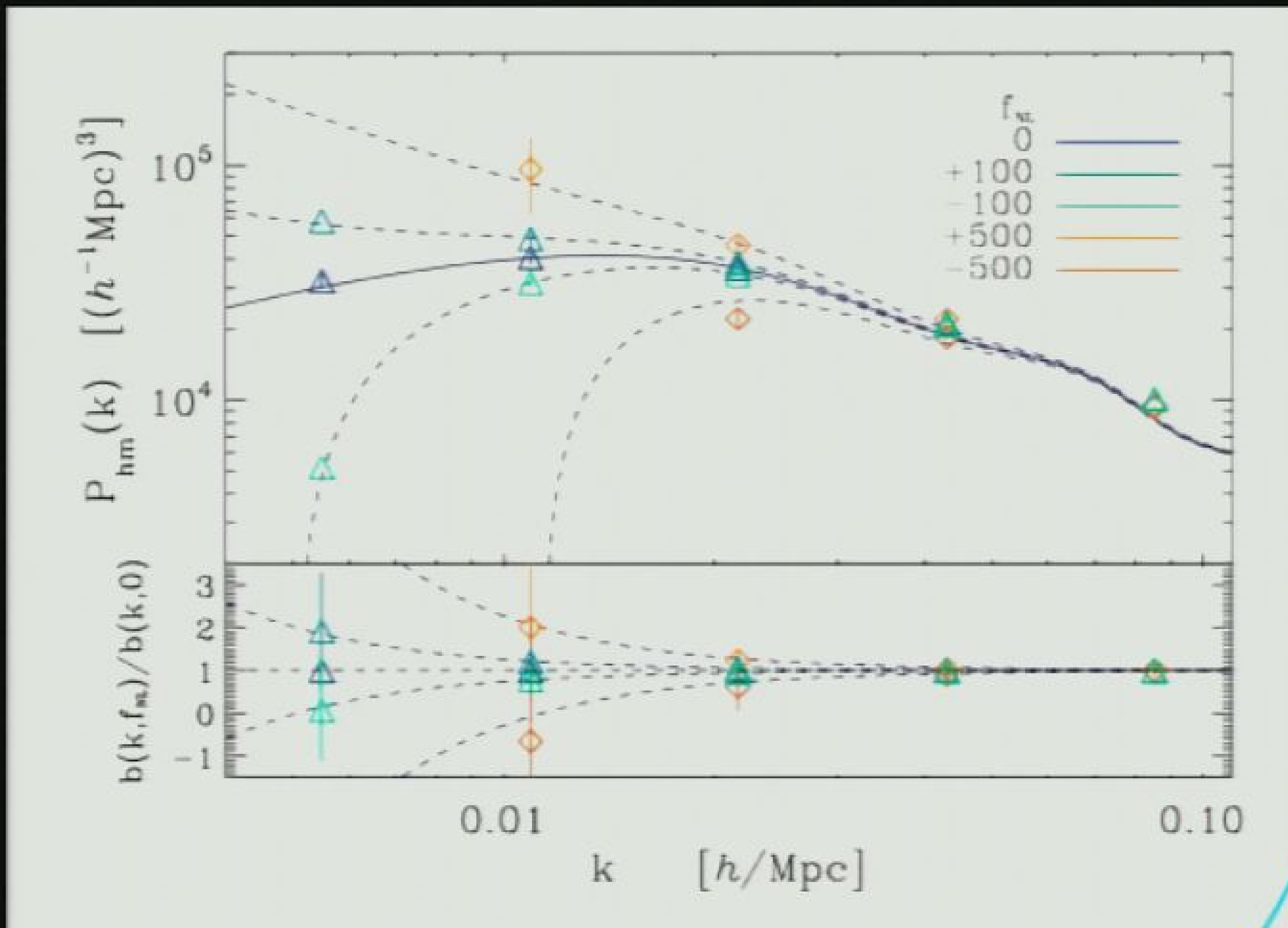
$b \equiv \delta_h/\delta_{\mathrm{DM}}$



Seljak & Warren 2004

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!



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

Dalal, Doré, Huterer & Shirokov, arXiv:0710.4560, PRD 2008

Halo clustering with NG: Analytic confirmation

Rigorous derivations exist, but here's back-of-envelope:

$$\Phi_{\rm NG} = \phi + f_{\rm NL}(\phi^2 - \langle\phi^2\rangle)$$

Then, near the peaks of the potential

$$\begin{aligned} \nabla^2\Phi_{\rm NG} &= \nabla^2\phi + 2f_{\rm NL}\left(\phi\nabla^2\phi + |\nabla\phi|^2\right) \\ &\approx \nabla^2\phi\,(1 + 2f_{\rm NL}\phi) \end{aligned}$$

And in particular $\delta_{\rm NG} = \delta(1 + 2f_{\rm NL}\phi)$

Halo clustering with NG: Analytic confirmation

Definition of bias: $$\delta_h = b_L \, \delta$$

With NG, for peaks: $$\delta \longrightarrow \delta + 2 f_{\rm NL} \phi \, \delta$$

Reinterpreting as change in bias $$\delta_h = b_L \, (\delta + 2 f_{\rm NL} \phi \, \delta) = (b_L + \Delta b) \, \delta$$

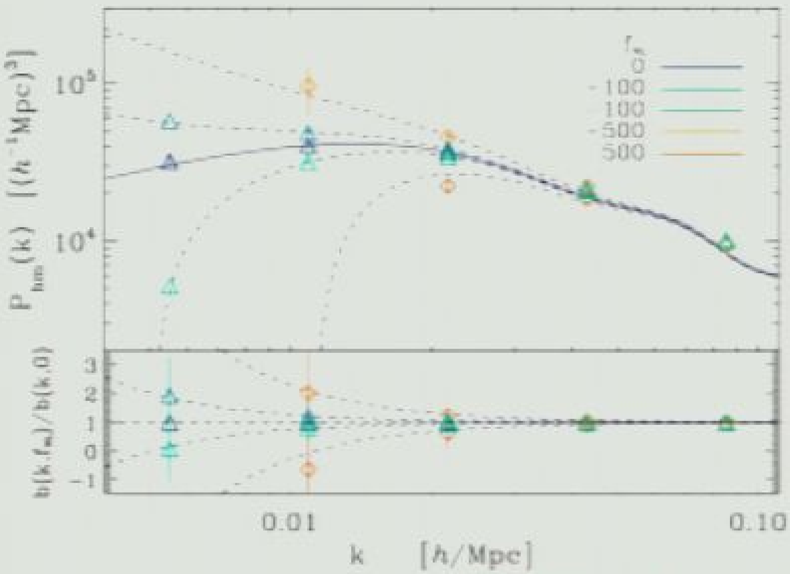
Using Poisson Eq. (to replace ϕ with δ) and including late-time perturbation evolution, you immediately get

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

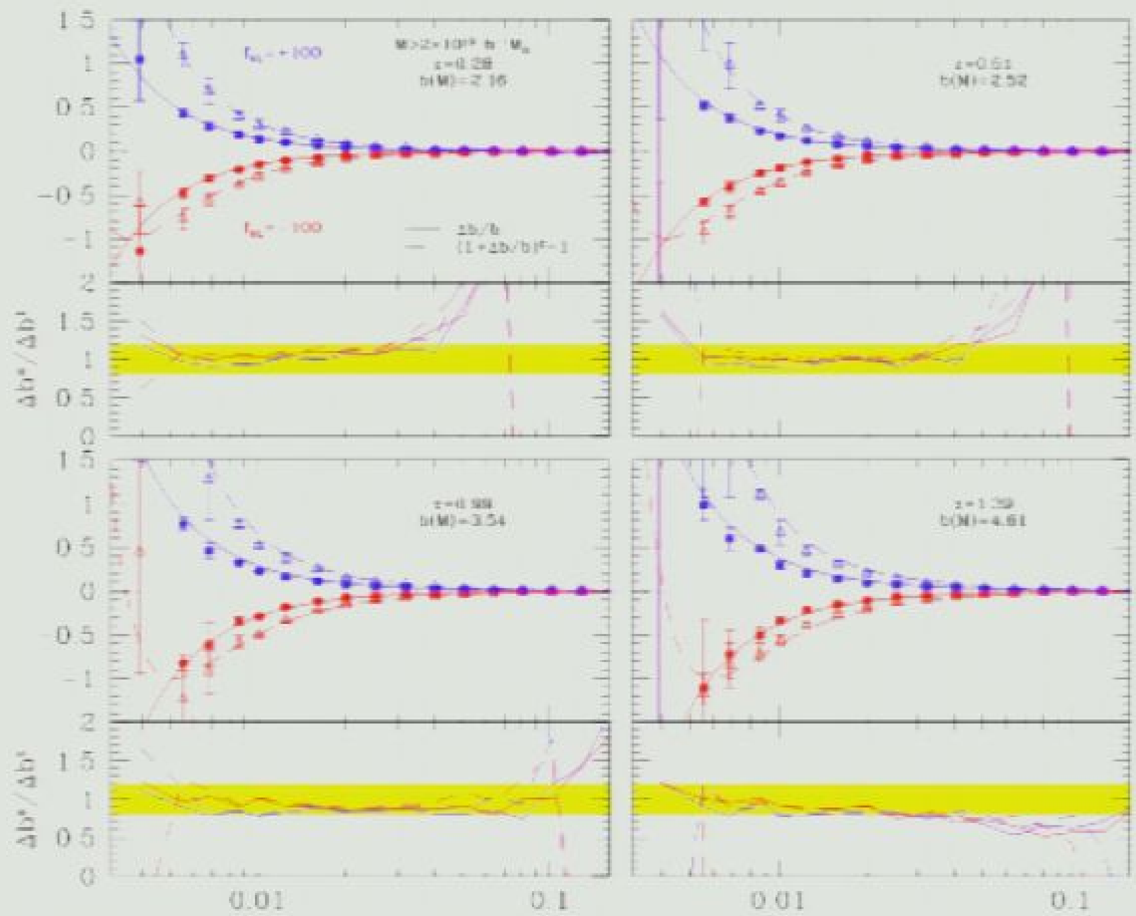
Dalal, Doré, Huterer & Shirokov, arXiv:0710.4560

see also Matarrese & Verde 2008; Afshordi & Tolley 2008; Slosar et al. 2008; McDonald 2008

Analytic and numerical results agree



Dalal et al 2008

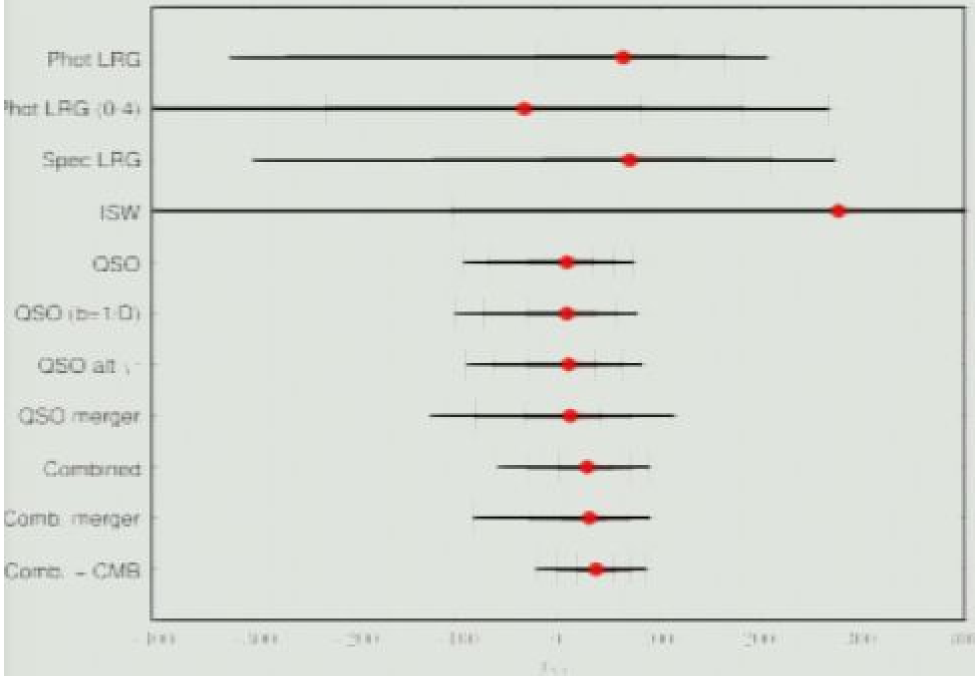


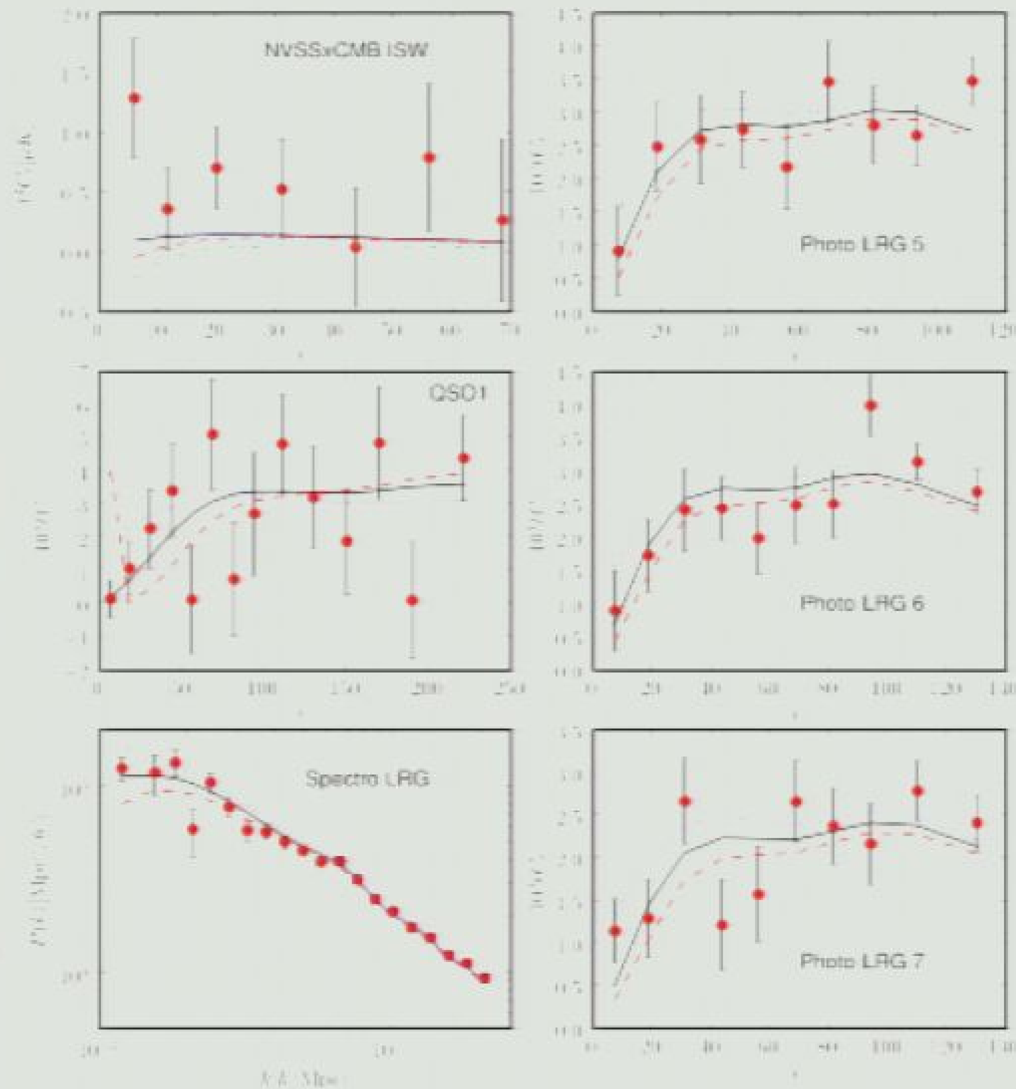
Desjacques, Seljak & Iliev 2009

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

Constraints from the bias of DM halos

Constraints from *current* data - west coast team



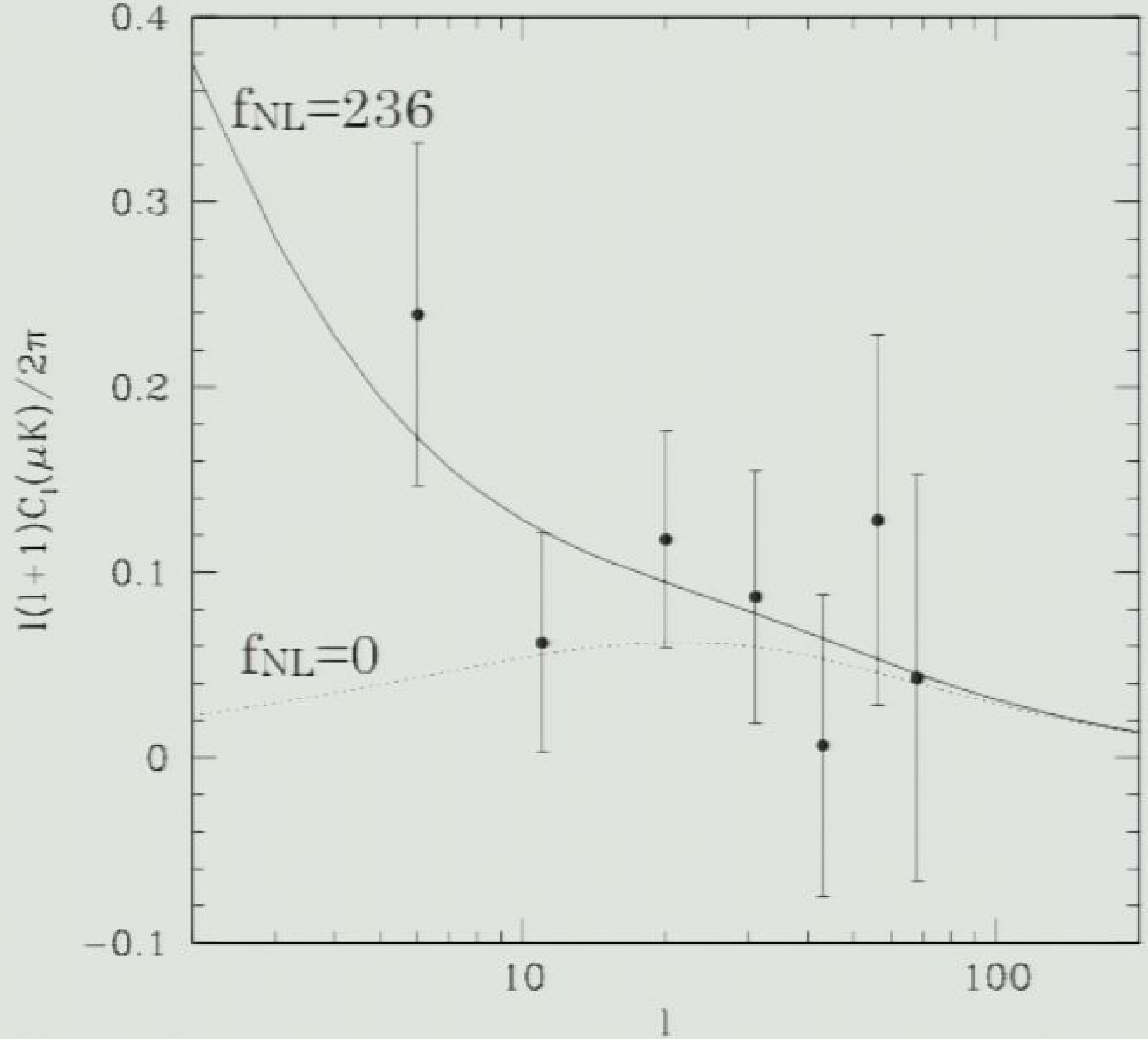


$f_{NL} = 8 +/- 30$ (68%, QSO)

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

Slosar, Hirata, Seljak, Ho & Padmanabhan 2008

Constraints from *current* data - Canada team



$f_{NL} = 236$ +/- 127 (68%)

Afshordi & Tolley 2008

Future NG from measurements of b(k)

- Numerous cosmological probes, such as the baryon acoustic oscillations (BAO) or probes of Integrated Sachs-Wolfe effect (galaxy-CMB cross-corr) can be used to measure b(k)

- The effect (going as k^{-2}) provides a fairly unique signature and a clear target; almost no degeneracy with other cosmological parameters

- Expect accuracy of order sigma(f_{NL})<10 or even ~1 in the future

TABLE 1
GALAXY SURVEYS CONSIDERED

survey	z range	sq deg	mean galaxy density $(h/Mpc)^3$	$\Delta f_{NL}/q'$ LSS
SDSS LRG's	$0.16 < z < 0.47$	7.6×10^3	1.36×10^{-4}	40
BOSS	$0 < z < 0.7$	10^4	2.66×10^{-4}	18
WFMOS low z	$0.5 < z < 1.3$	2×10^3	4.88×10^{-4}	15
WFMOS high z	$2.3 < z < 3.3$	3×10^2	4.55×10^{-4}	17
ADEPT	$1 < z < 2$	2.8×10^4	9.37×10^{-4}	1.5
EUCLID	$0 < z < 2$	2×10^4	1.56×10^{-3}	1.7
DES	$0.2 < z < 1.3$	5×10^3	1.85×10^{-3}	8
PanSTARRS	$0 < z < 1.2$	3×10^4	1.72×10^{-3}	3.5
LSST	$0.3 < z < 3.6$	3×10^4	2.77×10^{-3}	0.7

!

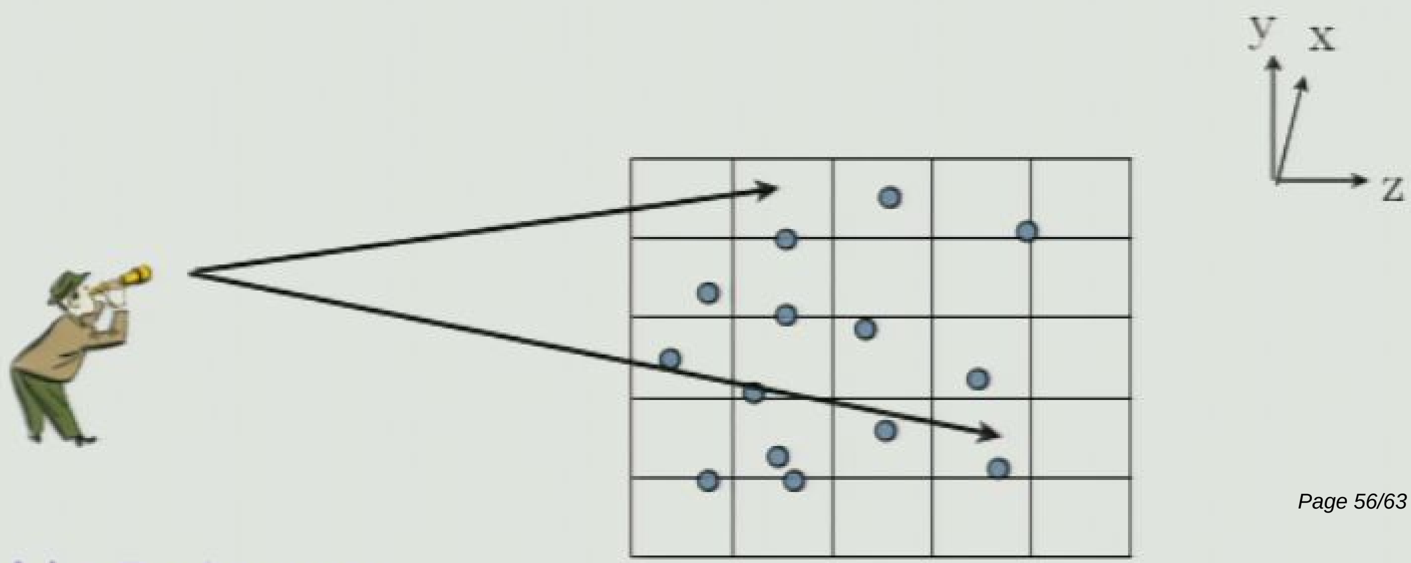
Carbone, Verde & Matarrese 2008; Afshordi & Tolley 2008

Nongaussianity form galaxy clusters

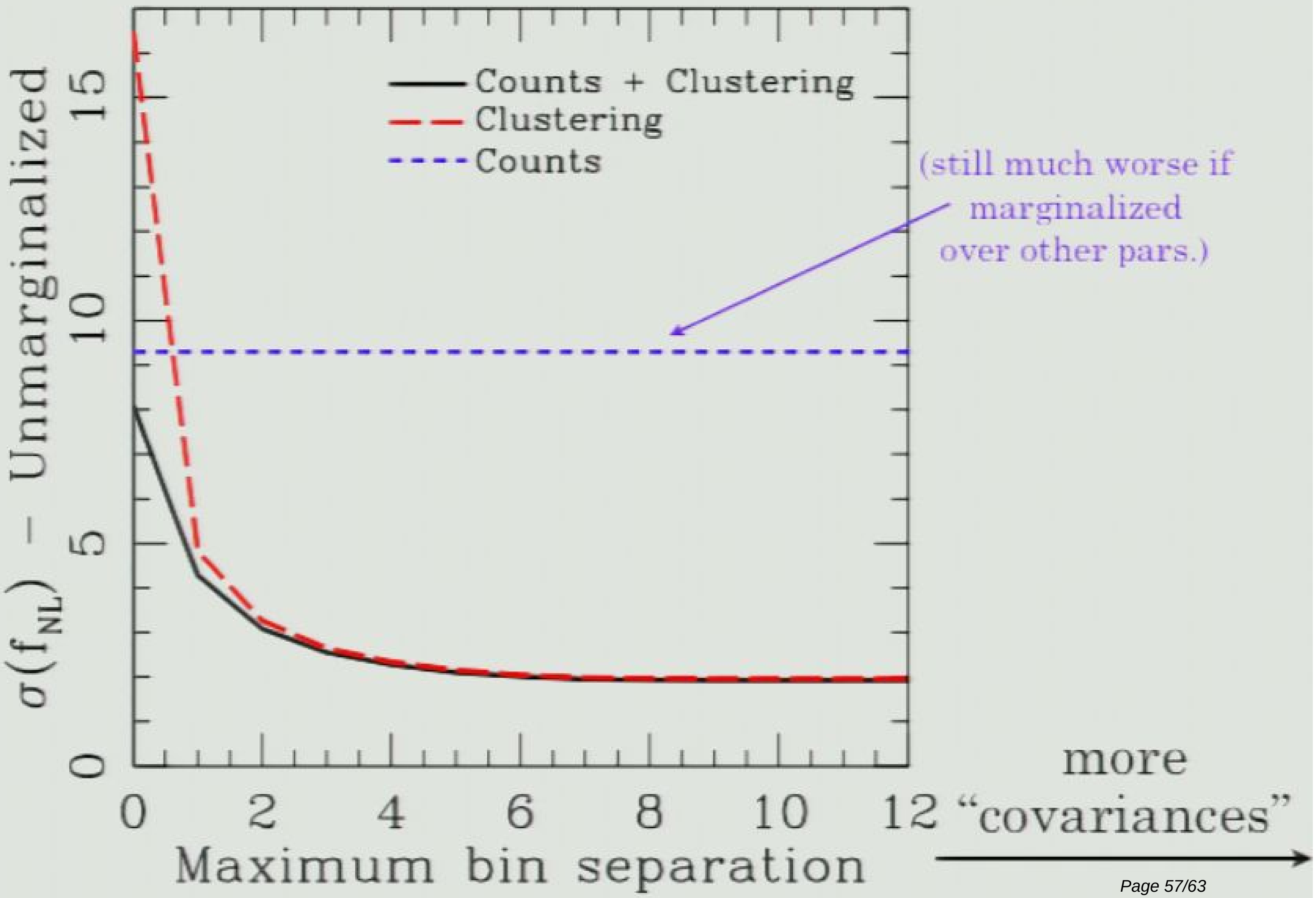
- For dark energy/dark matter constraints, counts of clusters are most important; probe the volume and distance; $d^2N/dzd\Omega = r^2(z)/H(z)$

- For nongaussianity, variance of cluster counts improves constraints on NG by an order of magnitude, since it is proportional to (integral over) power spectrum $P_{cluster}(k)=b^2(k)P(k)$.

- However, we found that **covariance** of cluster counts improves those constraints by nearly **another order of magnitude**, since basically covariance you get correlation across large distances (or small k); recall, the effect goes as $b^2(k) \propto k^{-4}$



NG form **covariance** of galaxy clusters



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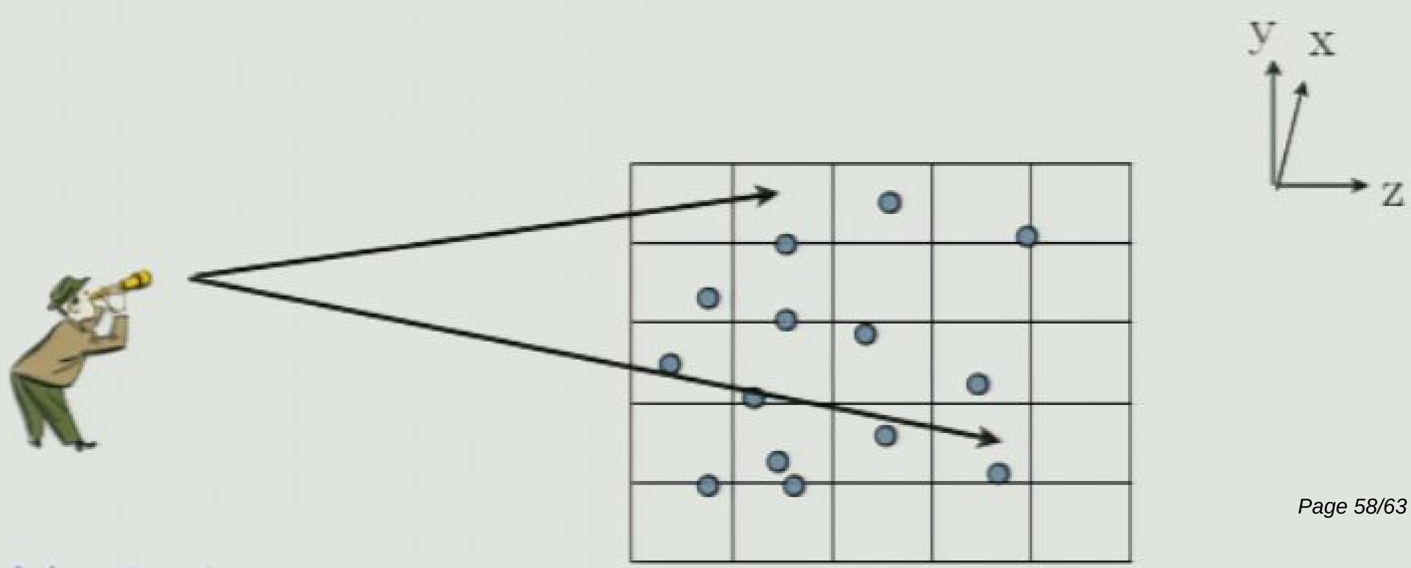

Cunha, Huterer, Dalal & Doré, in prep

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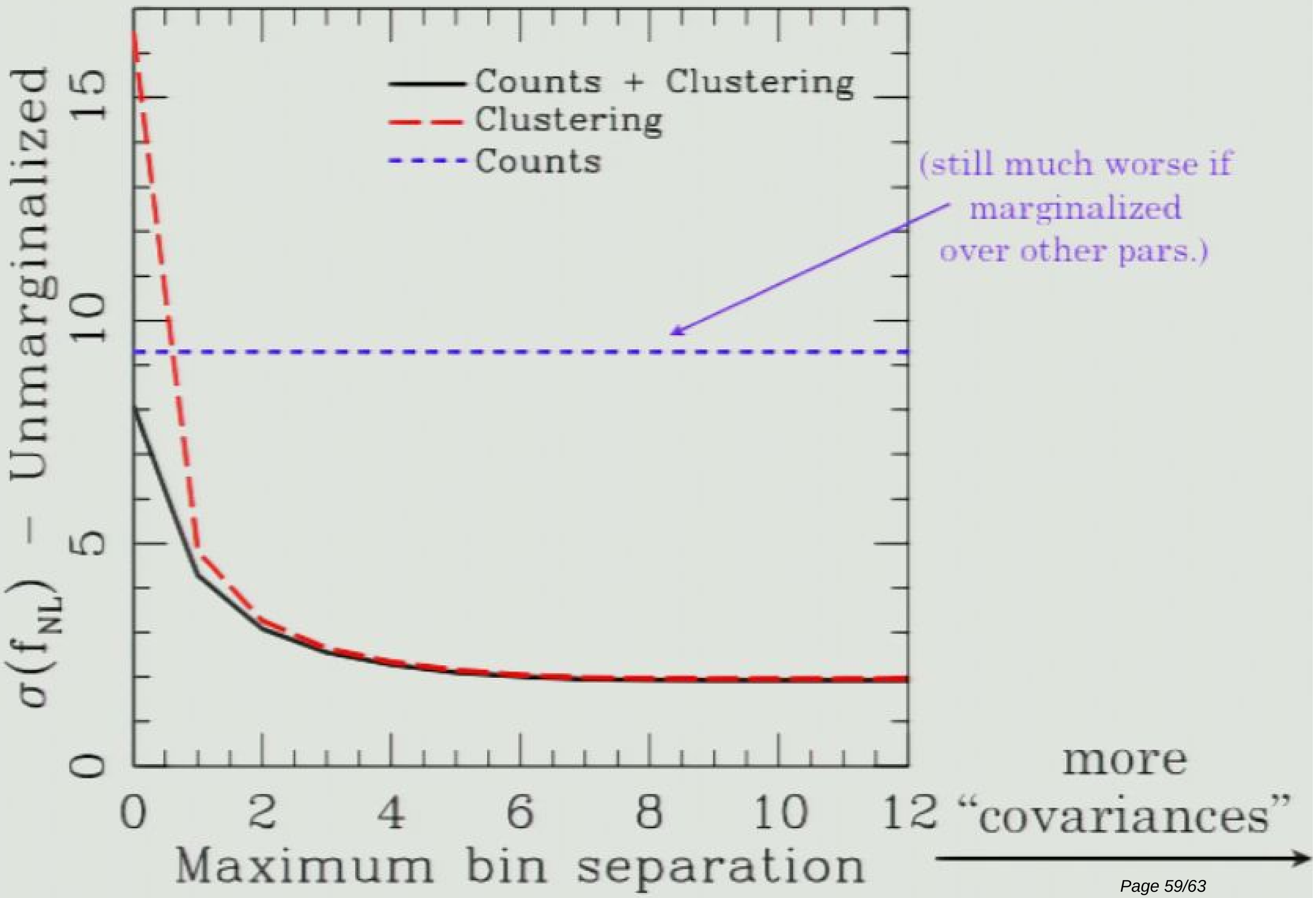

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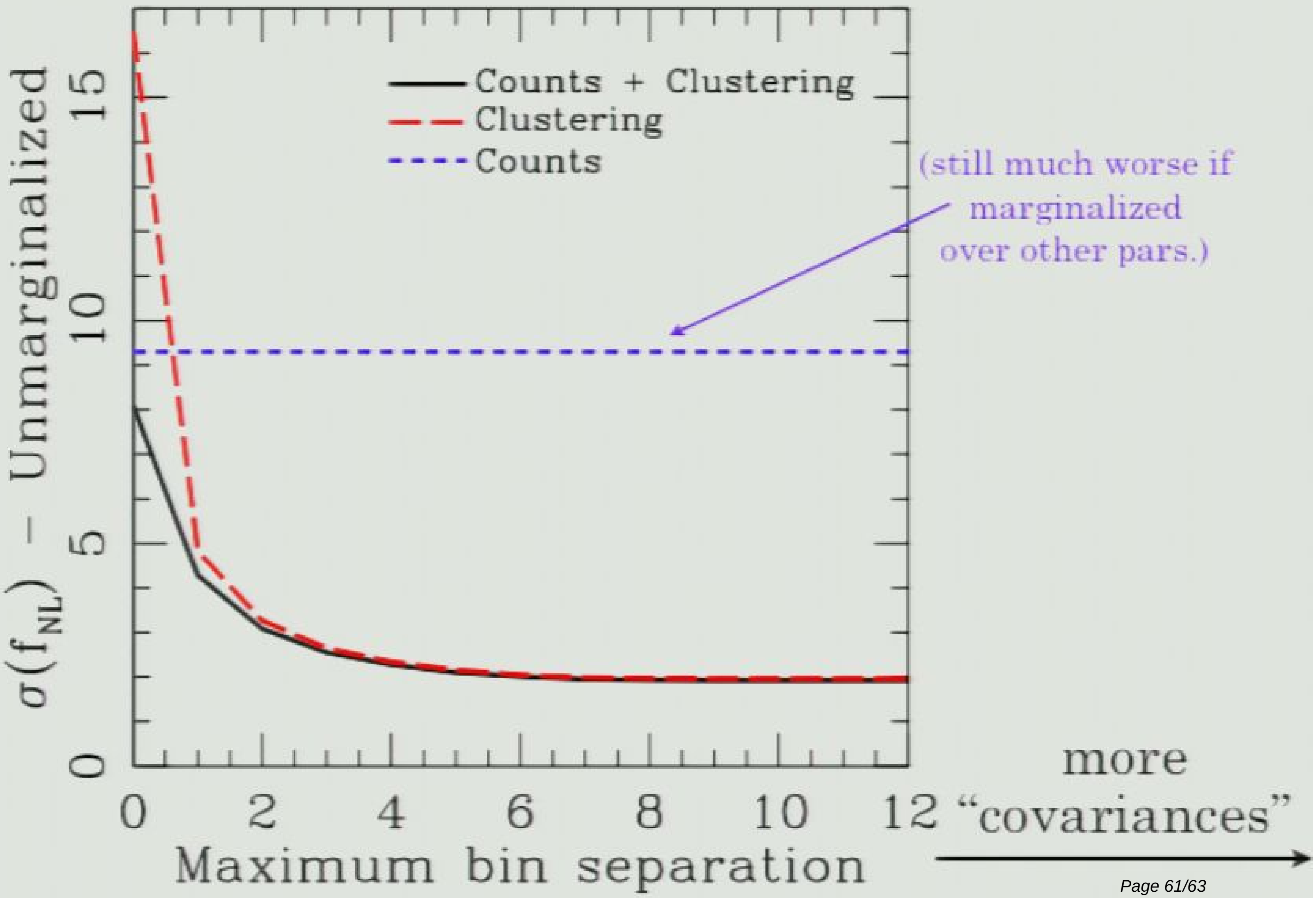

Open questions ⇒ current research

- What is the effect on large-scale structure (and bias) of other models of nongaussianity? (problem: NG = "non-dog"; could be anything)
- What systematic error control (e.g. atmospheric blurring; pixel response; astrophysical effects) is required not to degrade the projected future constraints?
- How best to design a survey to measure primordial nongaussianity?
- What galaxies and clusters are best to use (mass, color, etc)?
- Do you still get the same theoretical b(k) result as $k^{-1} \rightarrow H_0^{-1}$?
- What about the f_{NL} model where f_{NL} depends on scale, $f_{NL}=f_{NL}(k)$?

Conclusions

- Searching for primordial nongaussianity is one of the most fundamental tests of the early universe cosmology

- CMB bispectrum traditionally most promising tool; current results favor $f_{NL}>0$ but only at 1-2 sigma

- Mass function of cluster counts is in principle sensitive to NG, but not competitive with the CMB

- Cosmological models with (local) primordial NG lead to significant scale dependence of halo bias; theory and simulations appear to be in remarkable agreement on this

- Therefore, LSS probes (baryon oscillations, galaxy-CMB cross-correlations, etc) are likely to lead to constraints on NG nearly 2 orders of magnitude stronger than previously thought

- sigma(f_{NL})~few expected from future LSS surveys (DES, LSST, JDEM etc)