Testing Inflation with Dark Matter Halos

Primordial non-Gaussianity in large-scale structure

Marilena Loverde (Institute for Advanced Study)

K. M. Smith & ML arXiv: 1010.0055, ML & K.M. Smith arXiv:1102.1439
K. M. Smith, S. Ferraro, & ML arXiv:1106.0503

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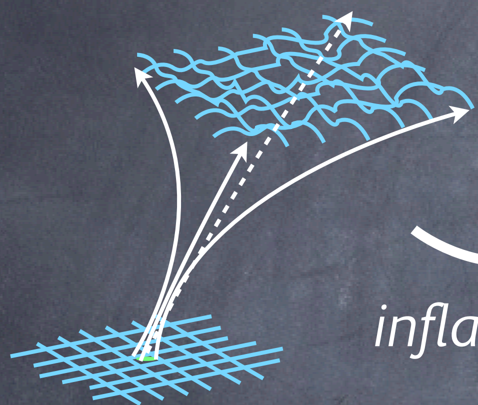
Outline

- Inflation as the origin of structure
- Statistics of primordial perturbations
- Impact of (primordial) non-Gaussian statistics on large-scale structure: Analytics & N-body simulations
- Conclusion & Outlook

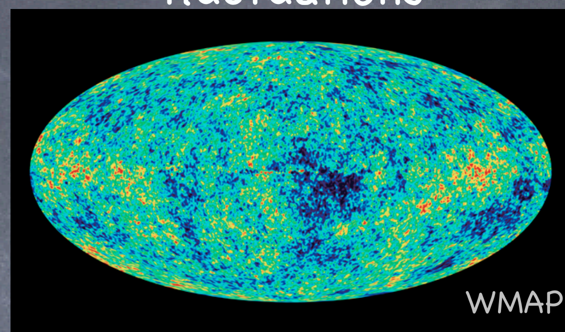
Inflation as the origin of structure

quantum fluctuations

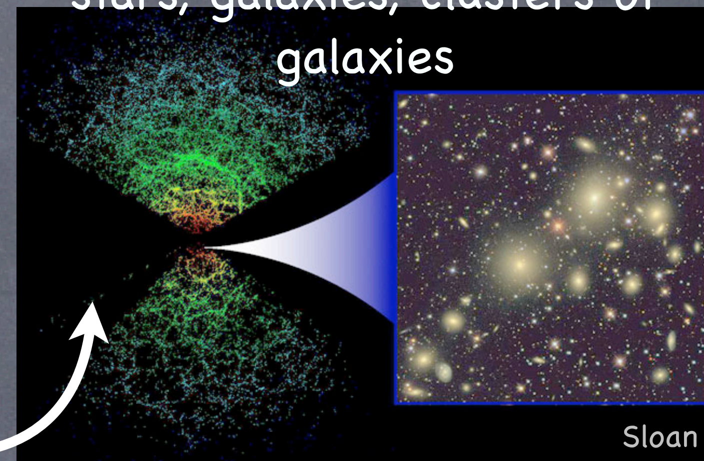


inflation

small matter & energy fluctuations



stars, galaxies, clusters of galaxies

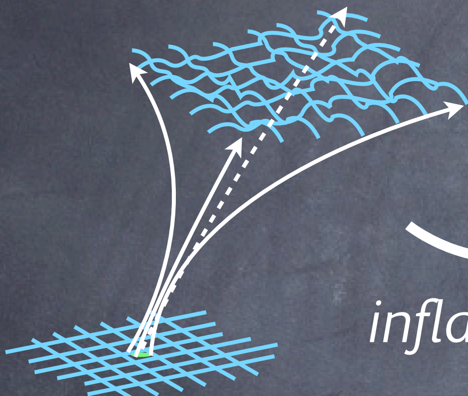


gravitational collapse

$$\delta\varphi_{\text{inflaton}} \longrightarrow \Phi_{\text{curvature}} \rightsquigarrow \begin{matrix} \delta T_{\text{CMB}} \\ \delta\rho_{\text{matter}} \\ \delta n_{\text{galaxies}} \end{matrix}$$

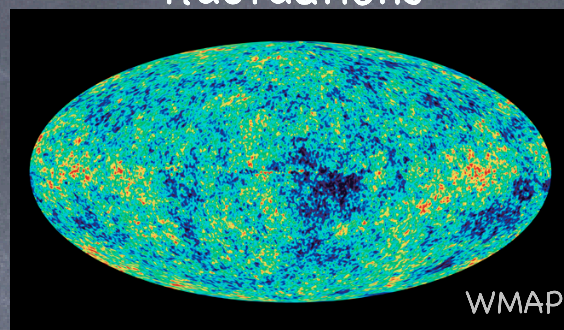
Inflation as the origin of structure

quantum fluctuations



inflation

small matter & energy fluctuations



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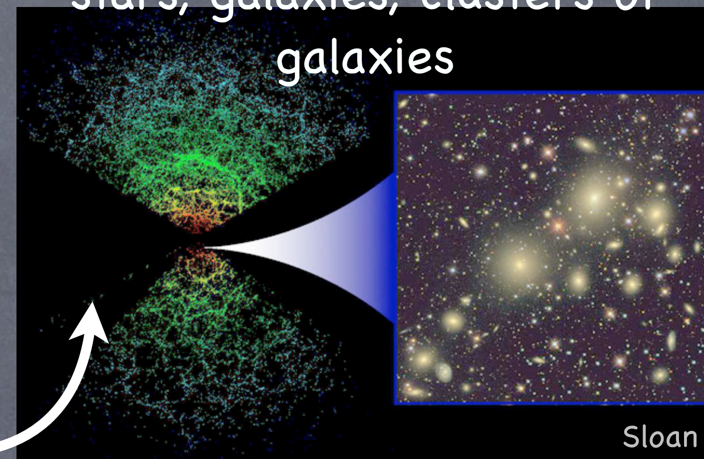


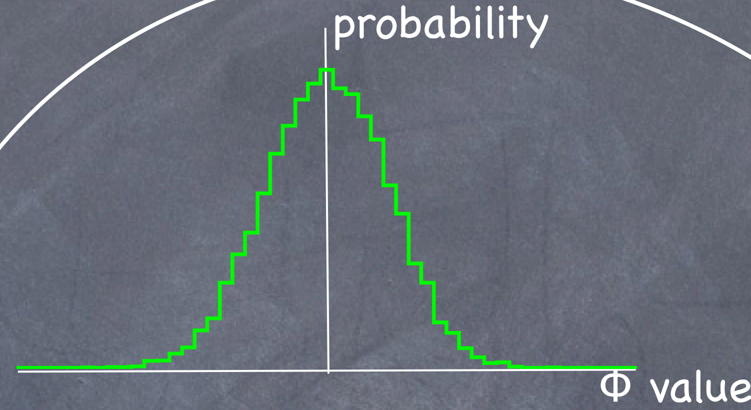
gravitational collapse

statistics of these

probe of this era

$$\delta\varphi_{\mathrm{inflaton}} \longrightarrow \Phi_{\mathrm{curvature}} \rightsquigarrow \begin{array}{l} \delta T_{\mathrm{CMB}} \\ \delta\rho_{\mathrm{matter}} \\ \delta n_{\mathrm{galaxies}} \end{array}$$

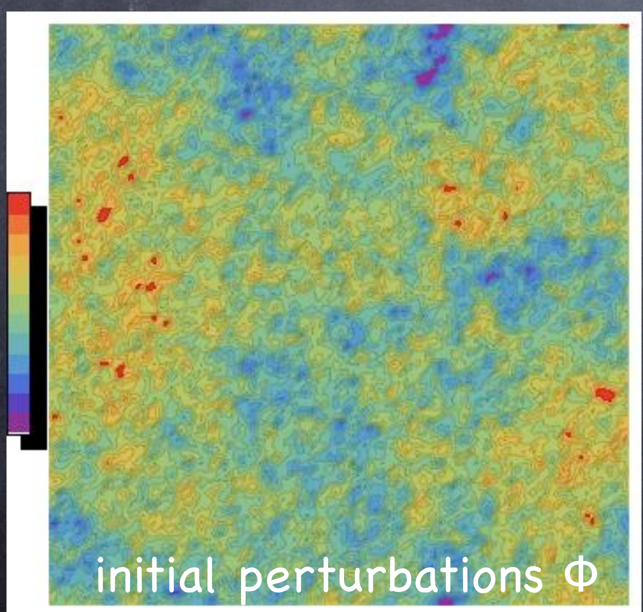
What can we learn from the statistics of perturbations?



$$\langle \Phi(x)\Phi(y) \rangle \leftrightarrow P_\Phi(k)$$

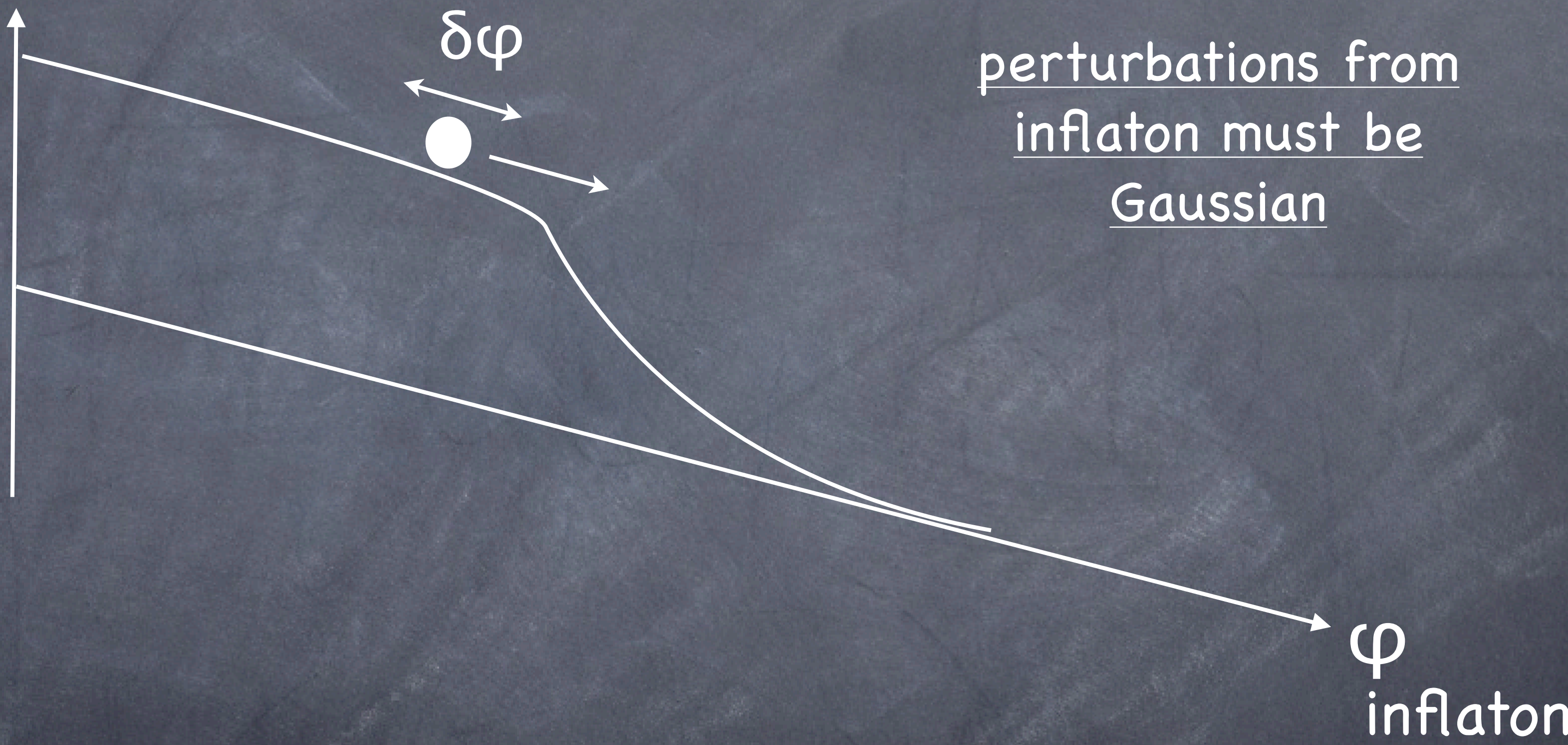
$$\langle \Phi(x)\Phi(y)\Phi(z) \rangle \leftrightarrow B_\Phi(k_1,k_2,k_3)$$

. . .



For instance

potential ~ $V(\varphi)$



total energy dominated by inflaton:

$$H^2 = 8\pi G/3\ V(\varphi,\sigma)$$

<u>perturbations from inflaton must be Gaussian</u>

Acquaviva, Bartolo, Matarrese, Riotto 2003; Maldacena 2003;

For instance

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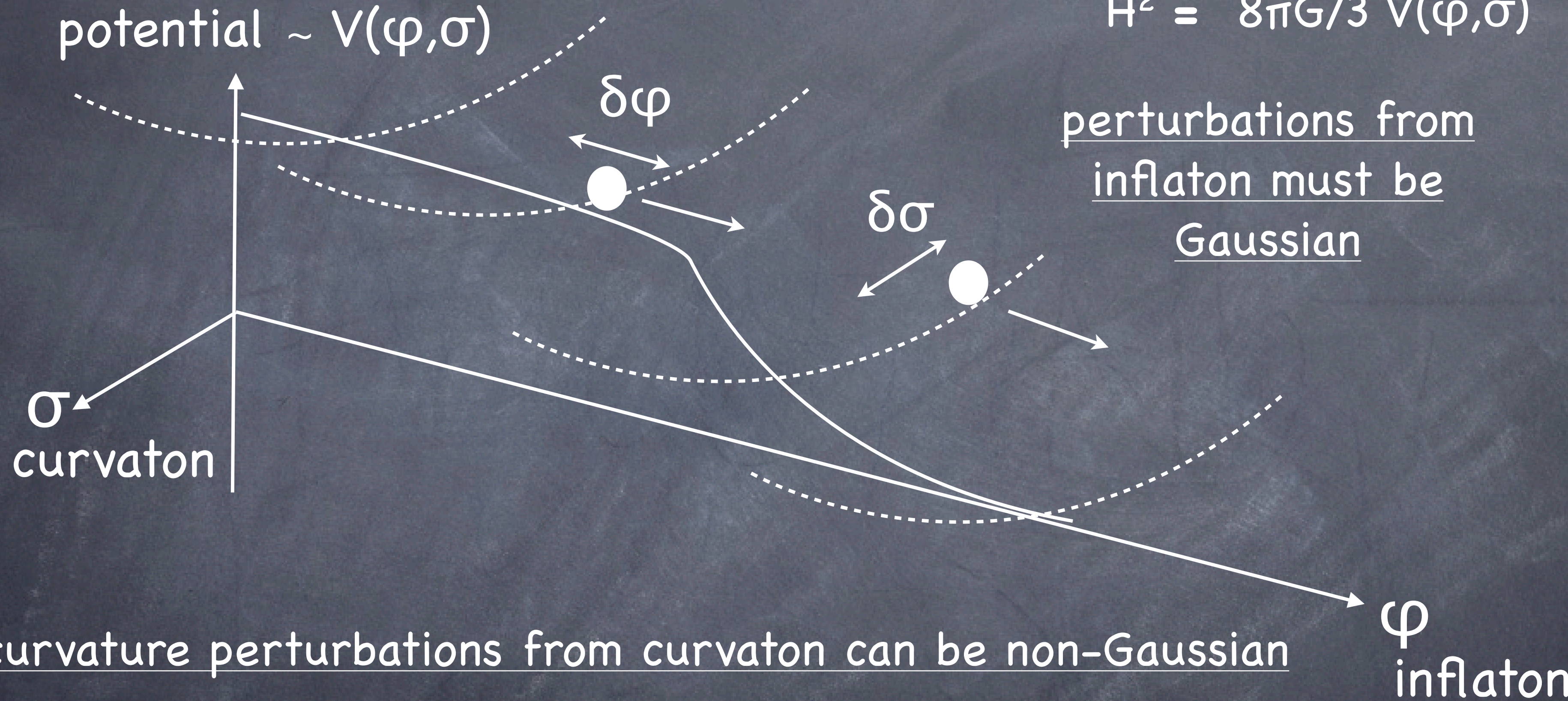


perturbations from inflaton must be Gaussian

curvature perturbations from curvaton can be non-Gaussian

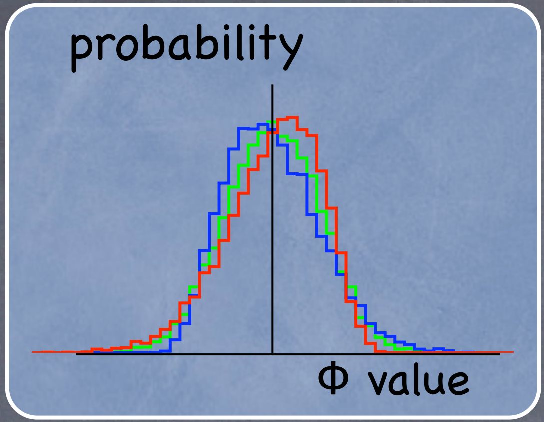
$$\Phi \sim \delta\sigma + \delta\sigma^2$$

$$\Phi \sim \delta\sigma + \delta\sigma^3 + \ldots$$

$$\Phi \sim \delta\varphi + \delta\sigma + \delta\sigma^2 + \ldots$$

Linde and Mukhanov 1997; Lyth and Wands 2002

"f_{NL}" $\Phi \sim \delta\sigma + f_{NL}\, \delta\sigma^2$



skewness ~ f_{NL}

kurtosis ~ $f_{NL}{}^2$

. . .

Φ value

(Φ=primordial gravitational potential)

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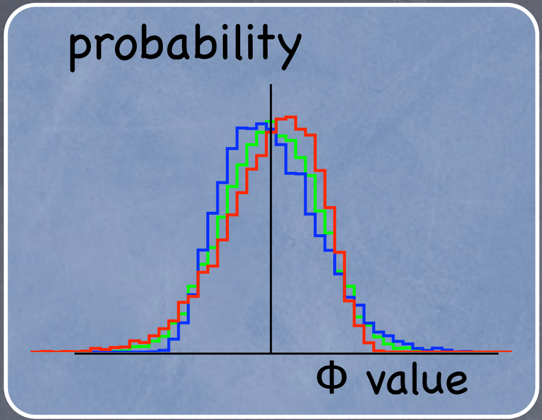

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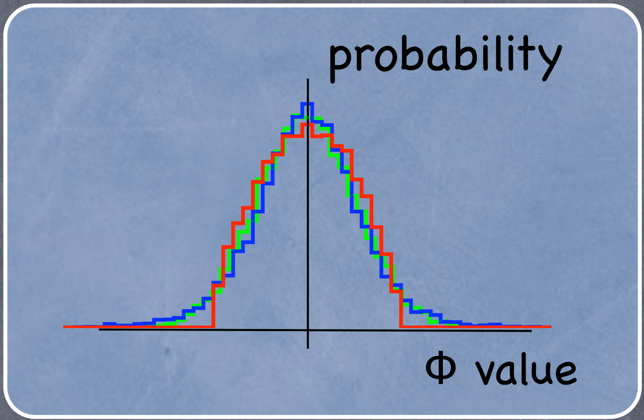
. . .

"g_{NL}" $\Phi \sim \delta\sigma + g_{NL}\delta\sigma^3 + \ldots$



skewness ~ 0

kurtosis ~ g_{NL}

. . .

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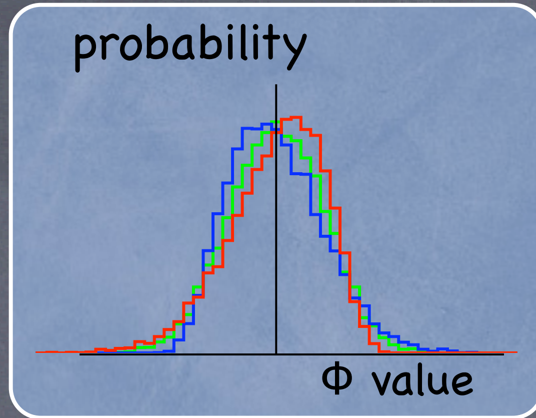

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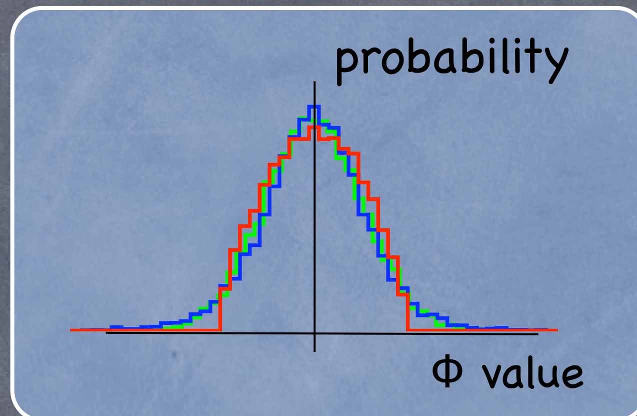


skewness ~ 0

kurtosis ~ g_{NL}

. . .

"τ_{NL}" $\Phi \sim \delta\varphi + \delta\sigma + \tilde{f}_{NL}\delta\sigma^2 + \ldots$

$\tilde{f}_{NL} = f_{NL}(1 + P_{\varphi\varphi}/P_{\sigma\sigma})^2$

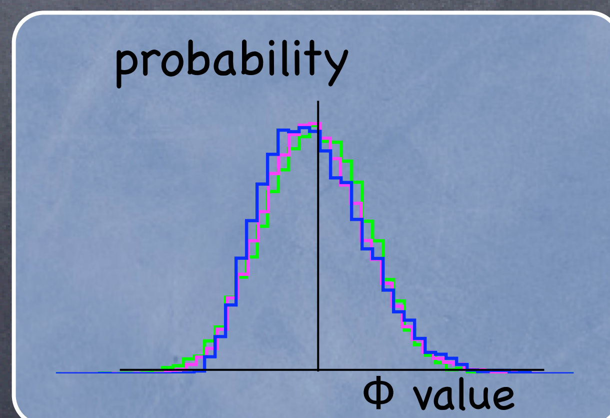
$\tau_{NL} = f_{NL}{}^2(1 + P_{\varphi\varphi}/P_{\sigma\sigma})$

and $P_{\varphi\sigma} = 0$

(Φ=primordial gravitational potential)

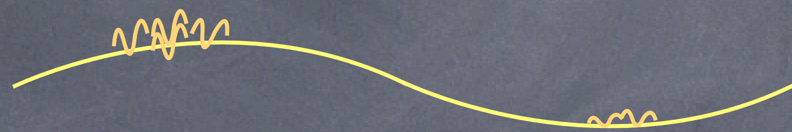
skewness ~ f_{NL}

kurtosis ~ τ_{NL}



"f_{NL}" $\Phi \sim \delta\sigma + f_{NL}\,\delta\sigma^2$

$$\langle \Phi_{short}{}^2 \rangle = \langle \sigma_{G,short}{}^2 \rangle \, (1 + 4\, f_{NL}\, \sigma_{G,long}(x))$$



small-scale power depends on large-scale fluctuations!

(Φ=primordial gravitational potential)

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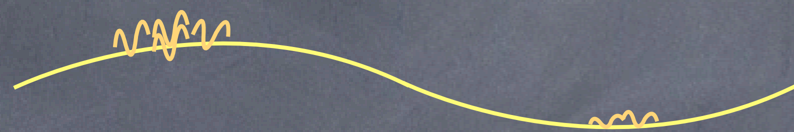
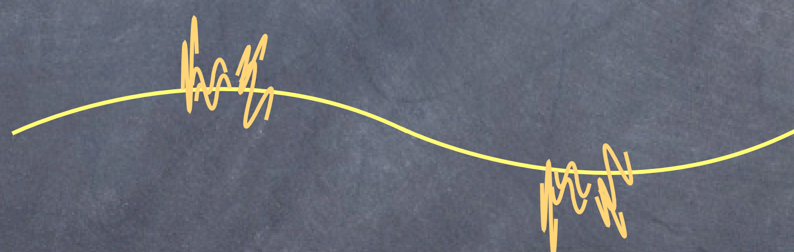


"g_{NL}" $\Phi \sim \delta\sigma + g_{NL}\delta\sigma^3 + \ldots$

$$\langle \Phi_{short}{}^3 \rangle = 18\, g_{NL}\, \langle \sigma_{G,short}{}^2 \rangle^2 \sigma_{G,long}(x) \equiv f_{NL}{}^{eff}(x) \langle \sigma_{G,short}{}^2 \rangle^2$$



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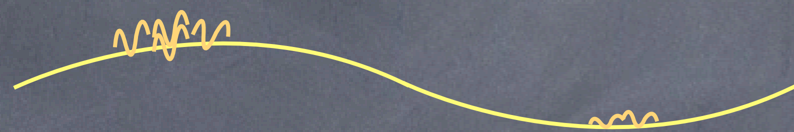

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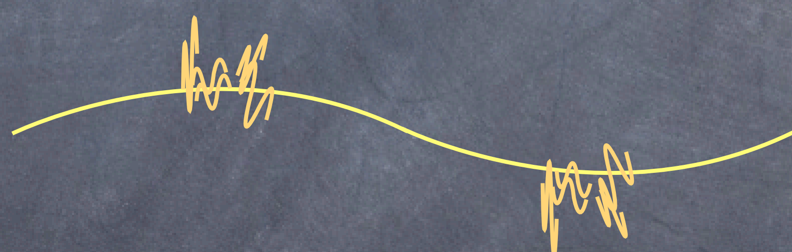

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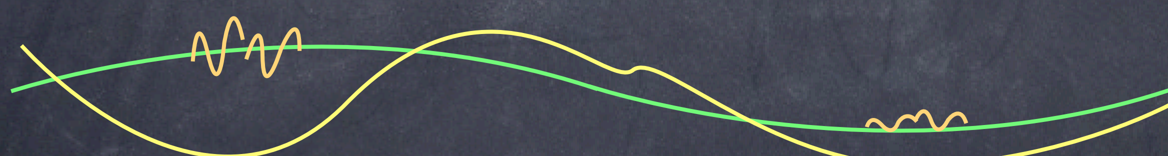

$\Phi = \varphi + \sigma$

(Φ=primordial gravitational potential)

These “local” models (i.e. $\Phi_{NG}(x)=F(\sigma_G(x))$) of non-Gaussianity are just some examples

Can also get non-Gaussianity from self interactions of inflaton (e.g. k-inflation, DBI, . . .)

but not with such extreme couplings of perturbations on short and long length scales

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BUT, single-field inflation requires

$$\langle\Phi(\mathbf{k})\Phi(\mathbf{k}')\Phi(\mathbf{k}''\text{-->}0)\rangle \approx f_{NL}(2\pi)^3\delta(\mathbf{k}+\mathbf{k}')\, P_\Phi(k)\, P_\Phi(k'') \approx 0$$

so $f_{NL} \gtrsim$ few rules out single field inflation

Acquaviva, Bartolo, Matarrese, Riotto 2003; Maldacena 2003; Creminelli & Zaldarriaga 2004

(similar arguments hold for g_{NL}, τ_{NL})

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$-10 < f_{NL} < 74$

WMAP, Komatsu et al 2010

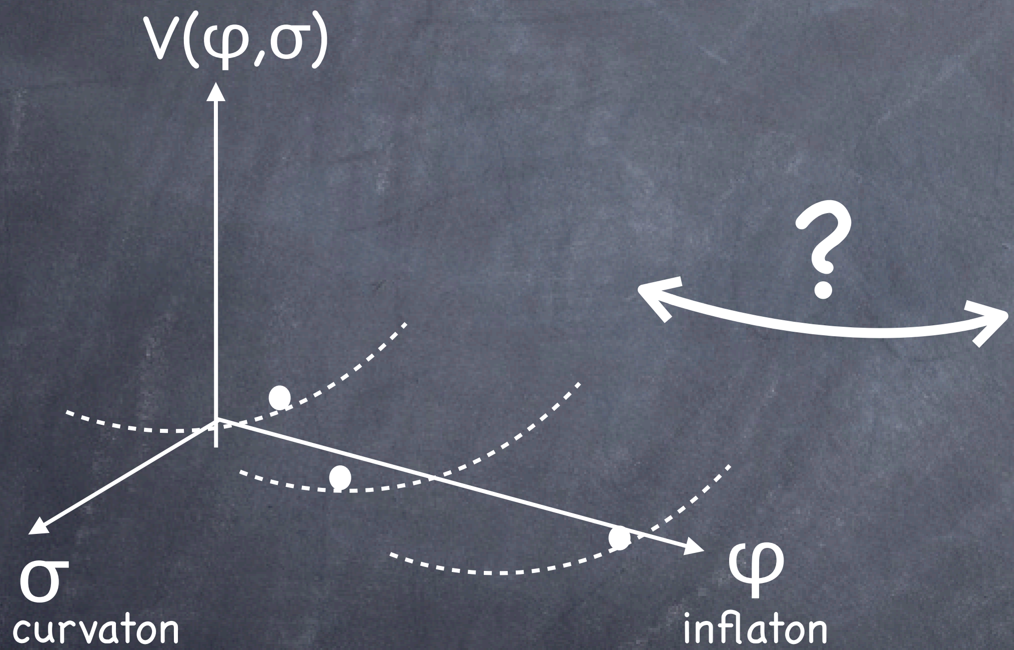
$-12 < g_{NL} /10^5 < 16$

(WMAP, Fergusson et al 2010)

$-6000 < \tau_{NL} < 33{,}000$

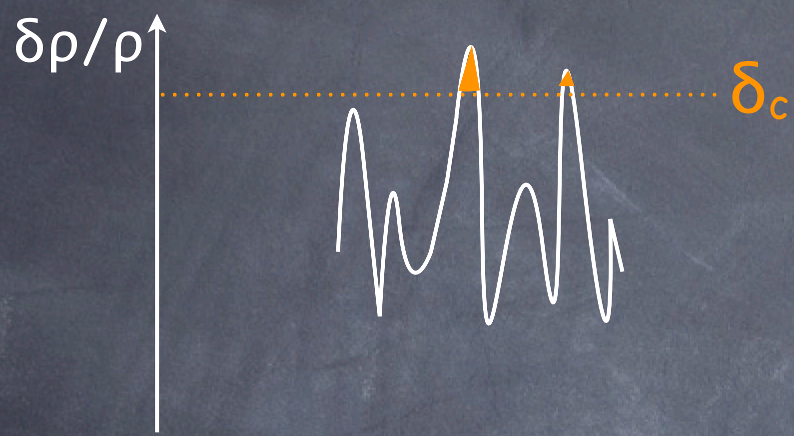
(WMAP, Smidt et al 2010)

How does the large-scale halo distribution see primordial non-Gaussianity?



Signatures in LSS I: more/fewer massive halos

dark matter halos form in peaks of the density field



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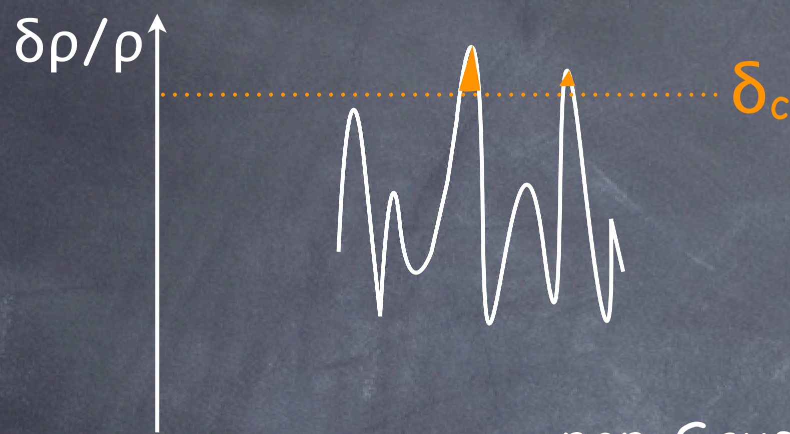
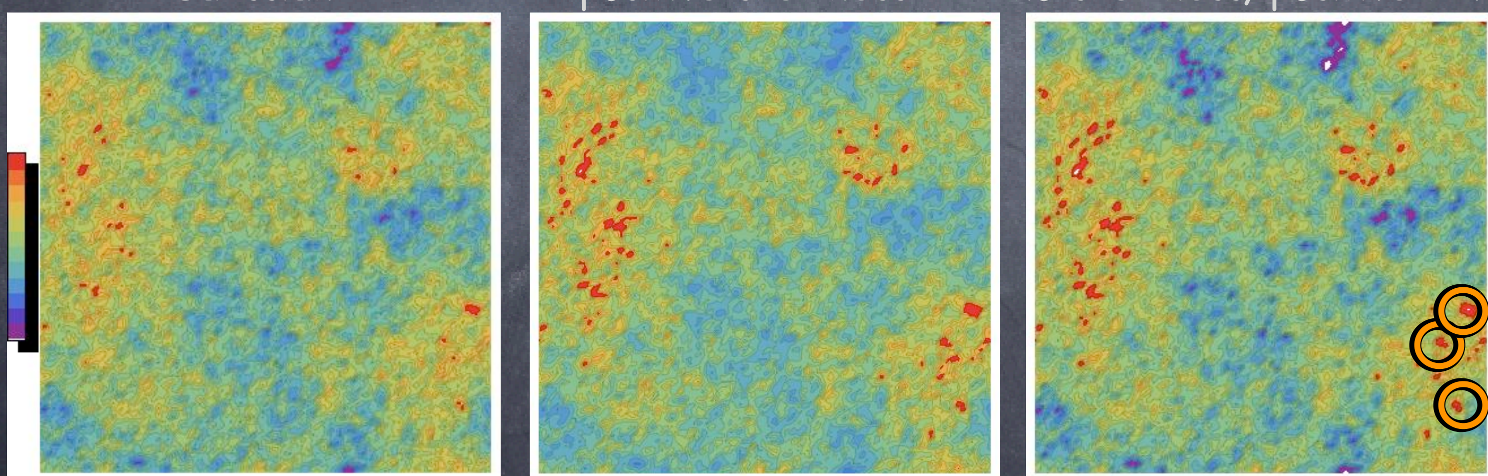


non-Gaussianity changes the number density of peaks

Gaussian | positive skewness | no skewness, positive kurtosis



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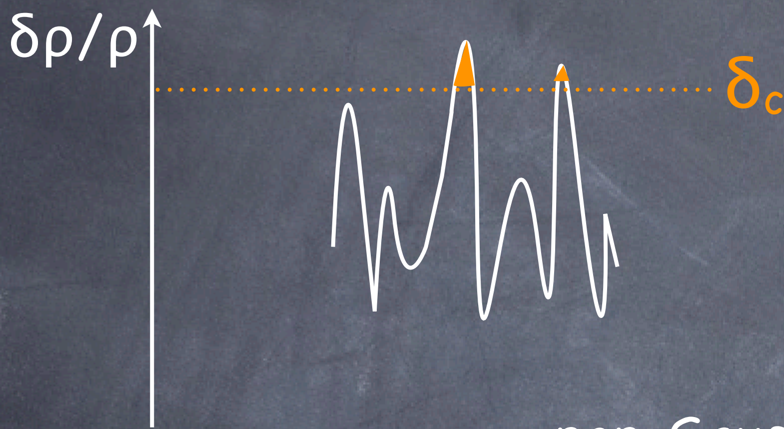

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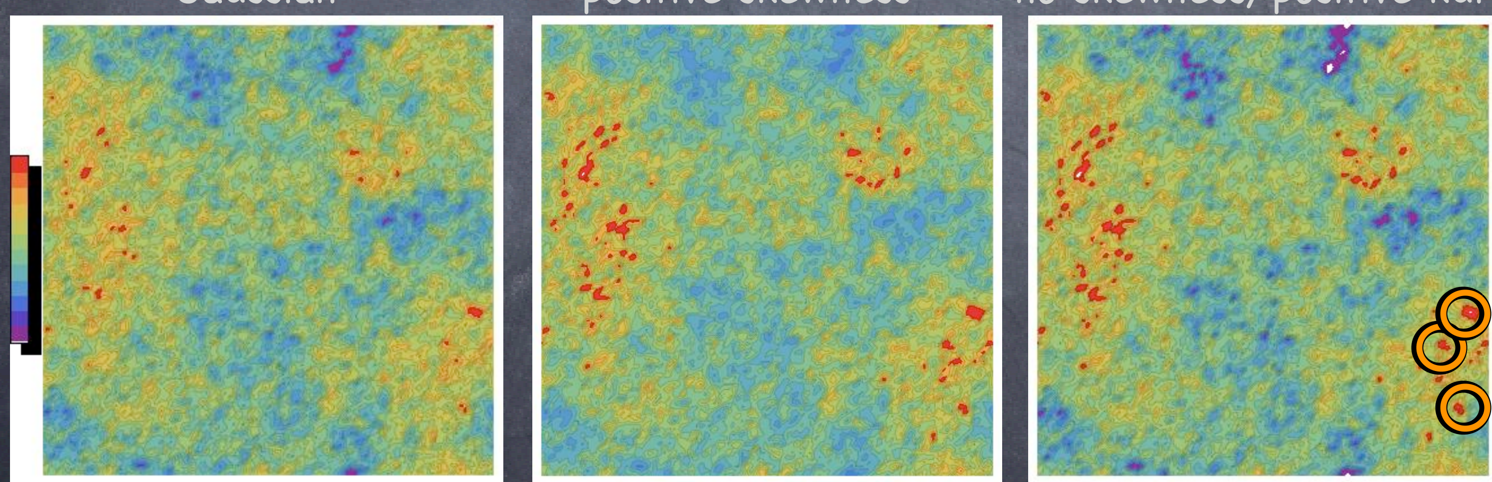
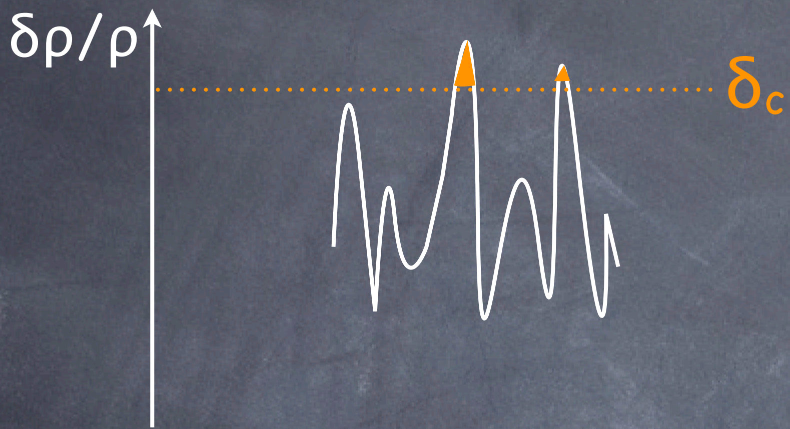


number of peaks ⇆ number of dark matter halos

Lucchin & Matarrese 1988; Chiu, Ostriker, Strauss 1998; Robinson, Gawiser, Silk 2000

Signatures in LSS II: scale-dependent halo bias

a dark matter halo forms when $\delta\rho/\rho$ is larger than the collapse threshold



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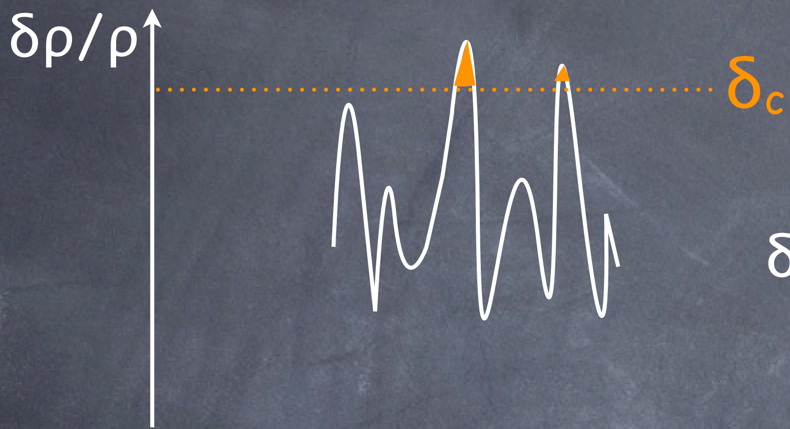
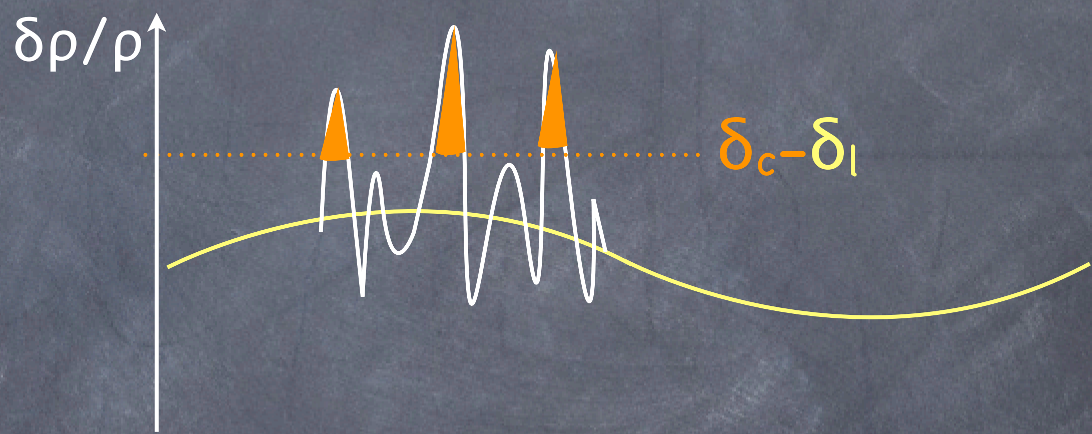


which is easier to reach on top of a long wavelength density perturbation



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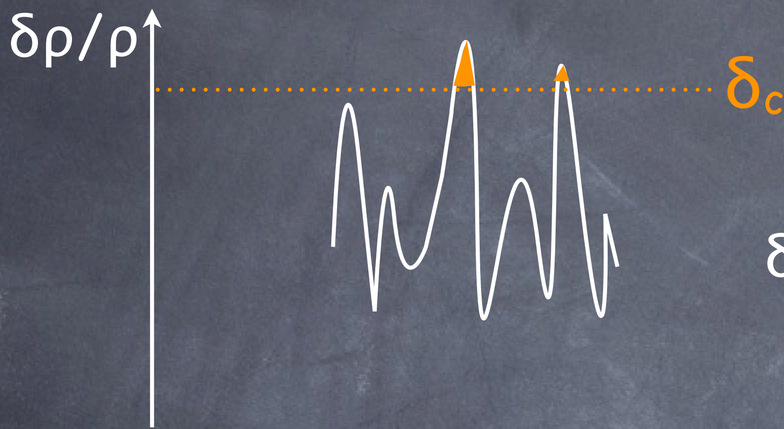

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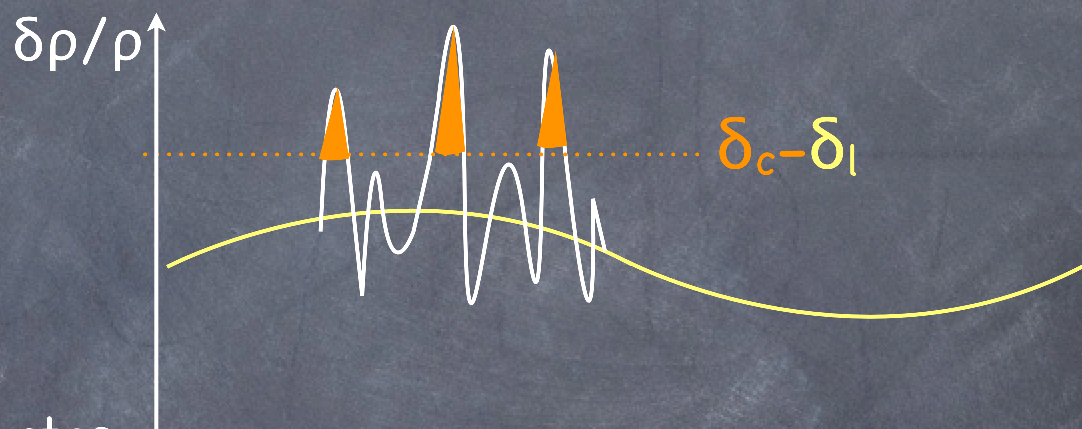

so the number of halos fluctuates depending on δ_l

$$\delta n = \frac{\partial n}{\partial \delta} \delta_l \; . \; . \; .$$

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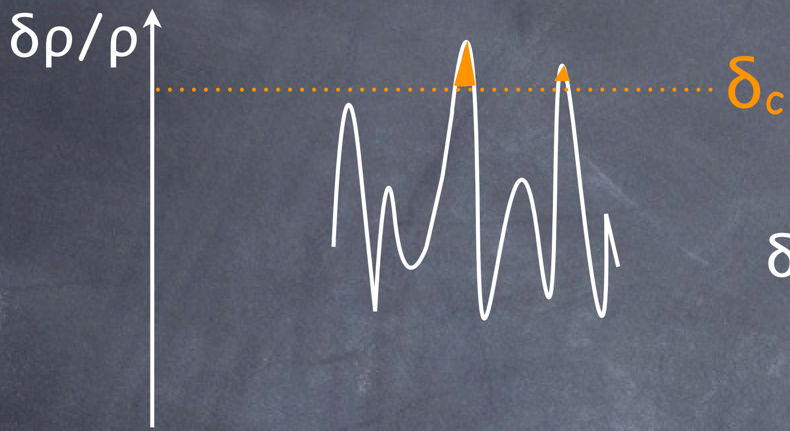

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"halo bias"

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Signatures in LSS II: scale-dependent halo bias

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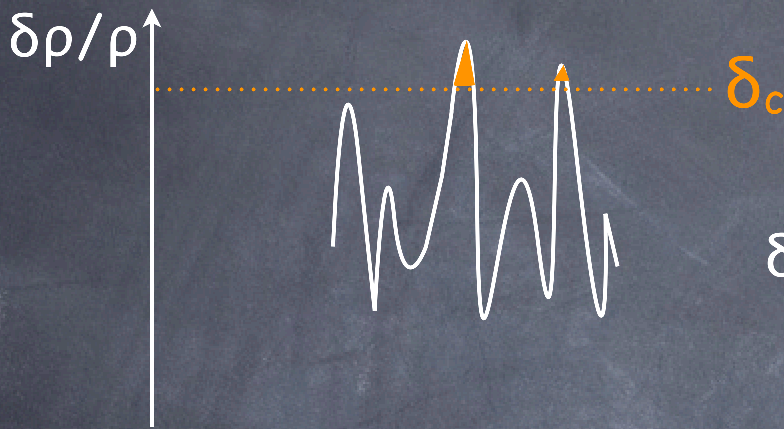

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"halo bias"

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so the number of halos fluctuates depending on δ_l

but with f_{NL} non-Gaussianity, the small-scale power also fluctuates depending on Φ_l

Signatures in LSS II: scale-dependent halo bias

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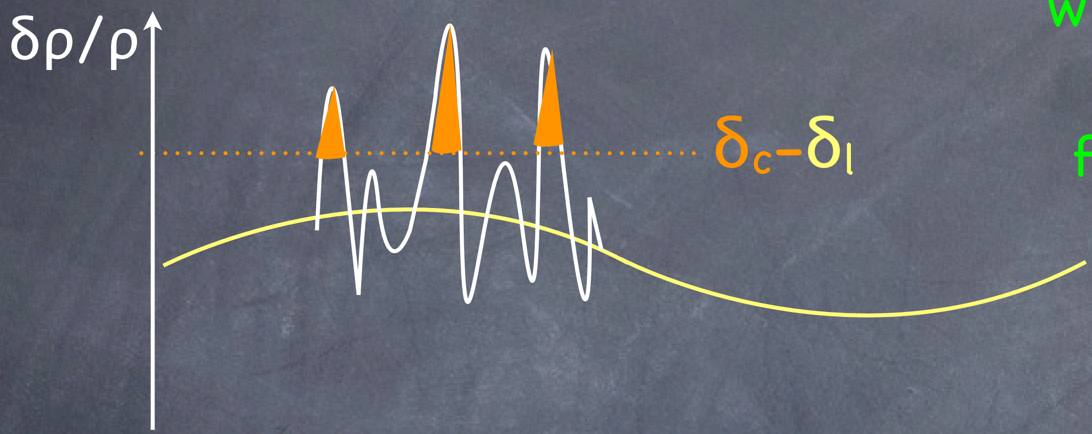

with f_{NL} non-Gaussianity, the small-scale power P_s also fluctuates depending on Φ_l

so the number of halos fluctuates depending on δ_l and Φ

$$\delta n = \frac{\partial n}{\partial \delta}\delta_l + 4 f_{NL}\frac{\partial n}{\partial P_s}\Phi_l \ldots$$

Dalal, Doré, Huterer, Shirokov 2007

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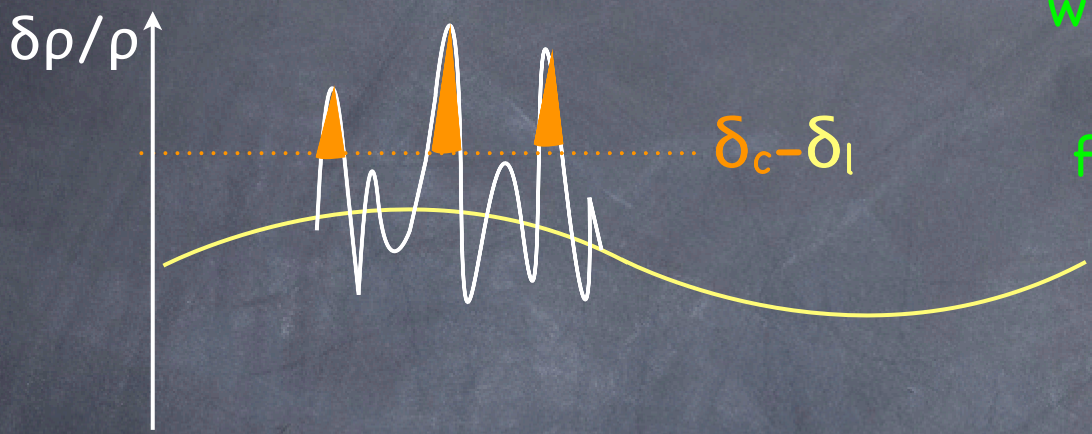

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$$\delta n = \frac{\partial n}{\partial \delta}\delta_l + 4f_{NL}\frac{\partial n}{\partial P_s}\Phi_l \ldots$$

$$\nabla^2\Phi_l \sim 4\pi G\,\delta_l \quad \longrightarrow \quad \approx \underbrace{\left(\frac{\partial n}{\partial \delta} + 4f_{NL}\frac{\partial n}{\partial P_s}/k^2\right)}_{\text{bias depends on Fourier scale } k}\delta_l(k) \ldots$$

Matarrese & Verde 2008; Slosar, Hirata, Seljak, Ho, Padmanabhan 2008; Afshordi & Tolley 2008; McDonald 2008

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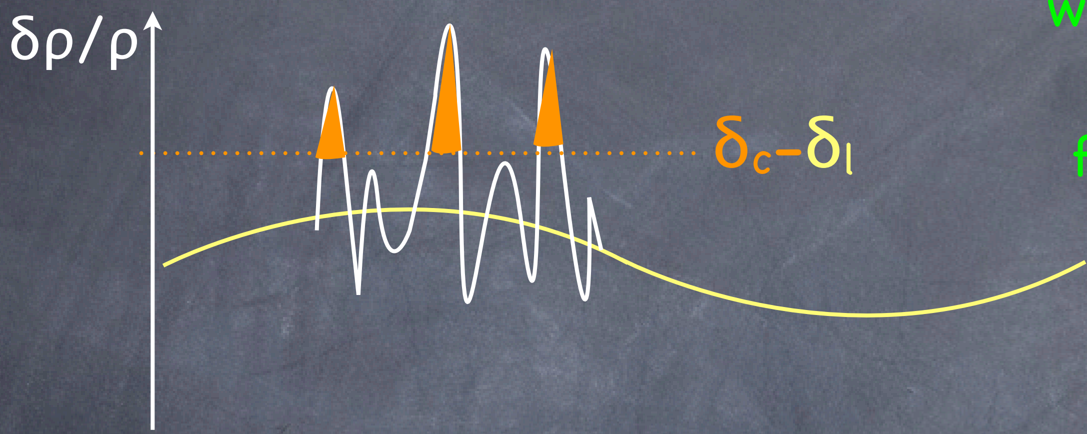

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$$\approx \left(\frac{\partial n}{\partial \delta} + 4f_{NL}\frac{\partial n}{\partial P_s}/k^2\right)\delta_l(k)\ldots$$

this $1/k^2$ scaling is hard to generate with local (post-inflationary) processes

Matarrese & Verde 2008; Slosar, Hirata, Seljak, Ho, Padmanabhan 2008; Afshordi & Tolley 2008; McDonald 2008

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Signatures in LSS II: scale-dependent halo bias

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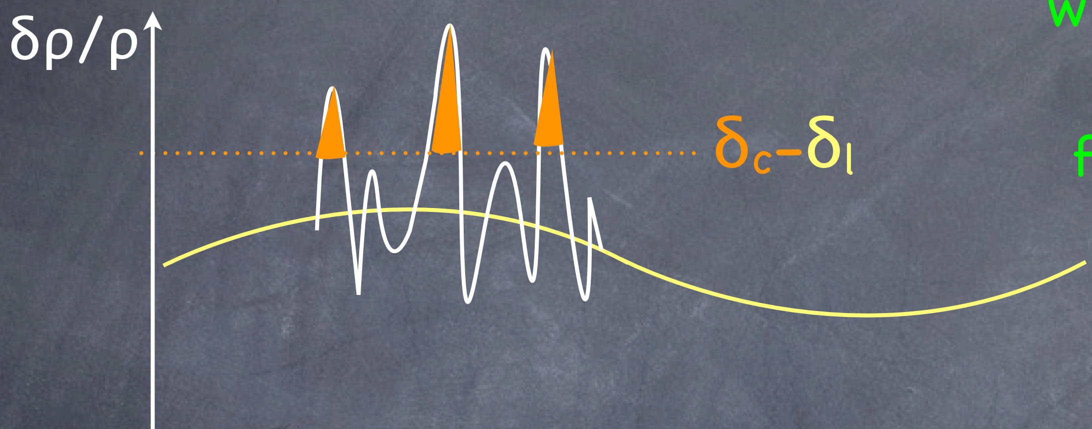

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so the number of halos fluctuates depending on δ_l and Φ

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$\nabla^2\Phi_l \sim 4\pi G\, \delta_l$

this $1/k^2$ scaling is hard to generate with local (post-inflationary) processes ⟶ powerful test!

Matarrese & Verde 2008; Slosar, Hirata, Seljak, Ho, Padmanabhan 2008; Afshordi & Tolley 2008; McDonald 2008

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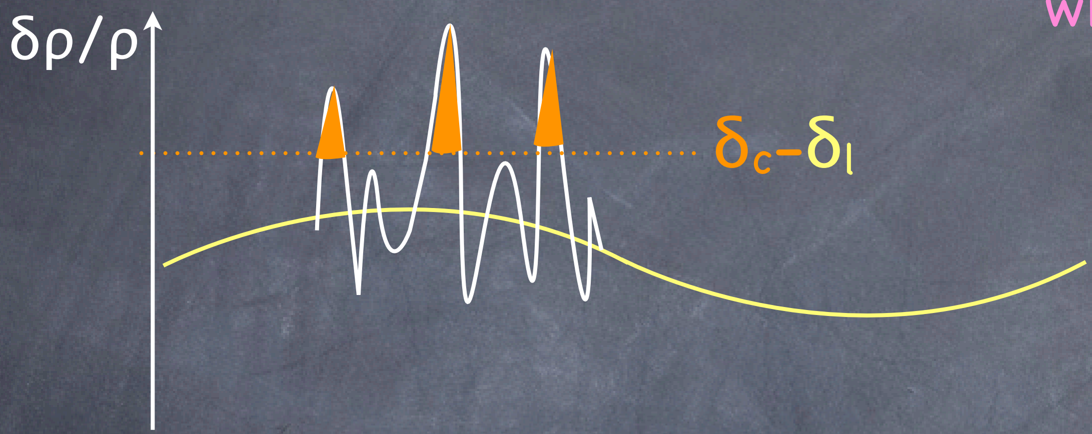


with g_{NL} non-Gaussianity, the small-scale skewness fluctuates with Φ_l

so the number of halos fluctuates depending on δ_l and Φ

$$\delta n = \frac{\partial n}{\partial \delta}\,\delta_l + 18 g_{NL}\,\frac{\partial n}{\partial S_3}\,\Phi_l \ldots$$

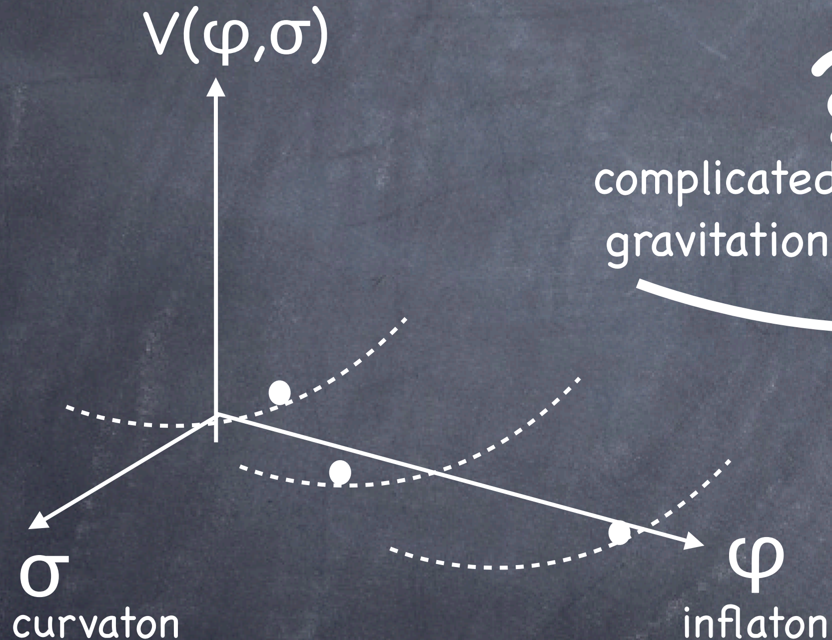
$$\approx \left(\frac{\partial n}{\partial \delta} + 18 g_{NL} \frac{\partial n}{\partial S_3} / k^2 \right) \delta_l(k) \ldots$$

$\nabla^2 \Phi_l \sim 4\pi G\, \delta_l$

bias depends on Fourier scale k

Desjacques & Seljak 2009; Smith, Ferraro, ML 2011

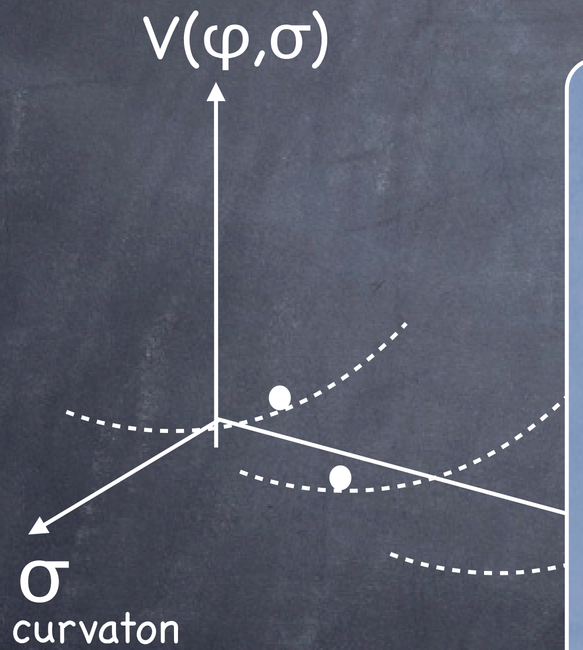
Can we model the non-Gaussian effects on halos reliably?



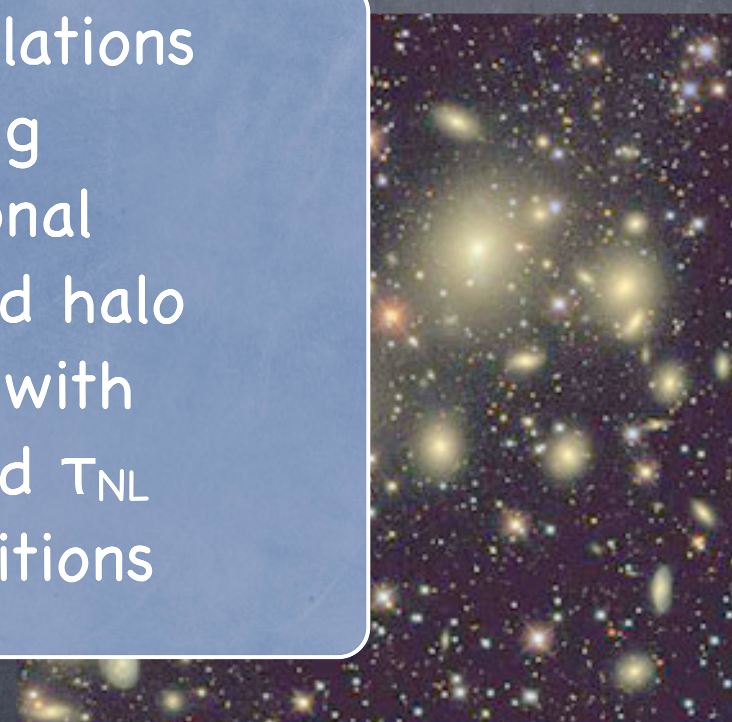
?

complicated, non-linear
gravitational evolution

Can we model the non-Gaussian effects on halos reliably?



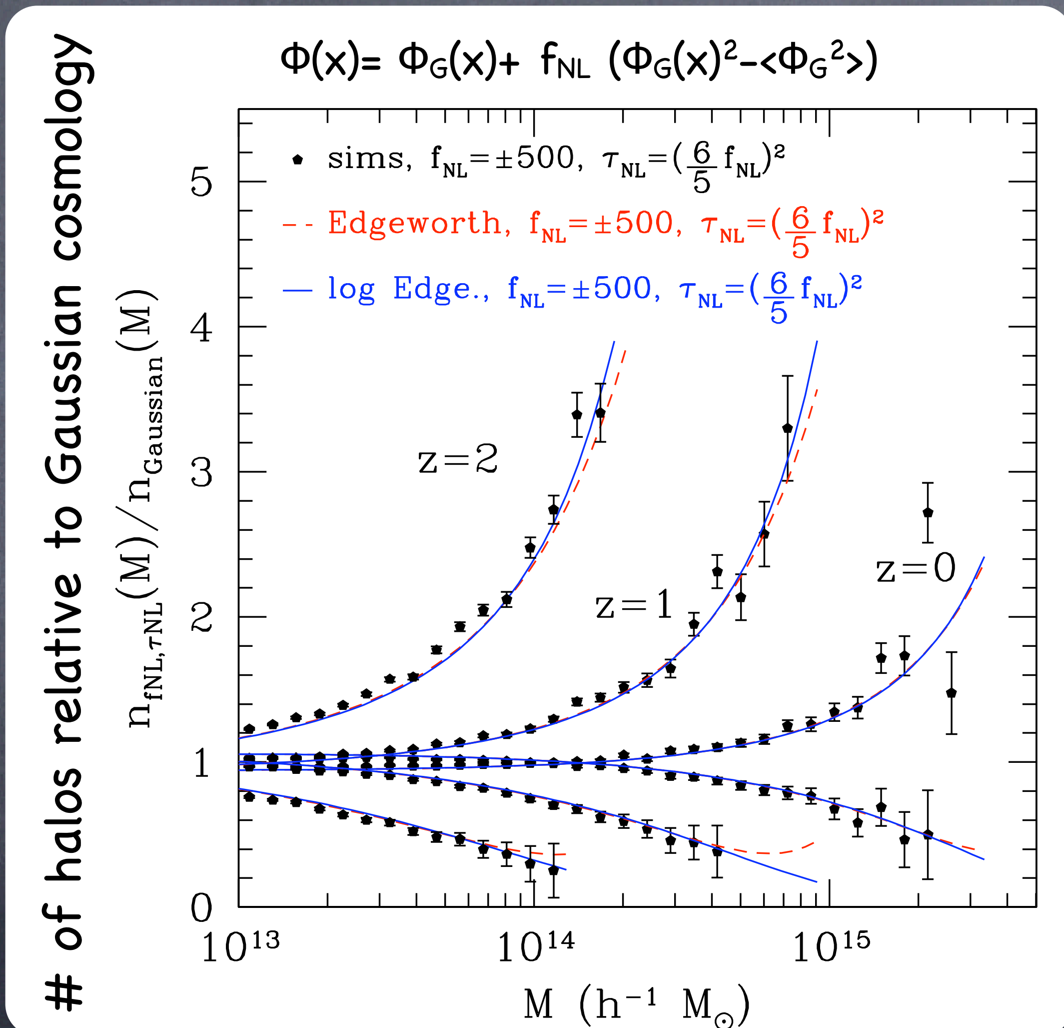
N-body simulations modeling gravitational evolution and halo formation with f_{NL}, g_{NL}, and τ_{NL} initial conditions



Signatures in LSS I: more/fewer massive halos

N-body simulations with f_{NL}, g_{NL}, and τ_{NL}

f_{NL}



curves are simple models of halo abundance (Press-Schechter + spherical collapse + approximate expressions for P.D.F. of δ)

see also Dalal, Dore, Huterer, Shirokov 2007; Grossi et al 2009; Kang, Norberg, Silk 2009; Pillepich, Porciani, Hahn 2009 ; many others

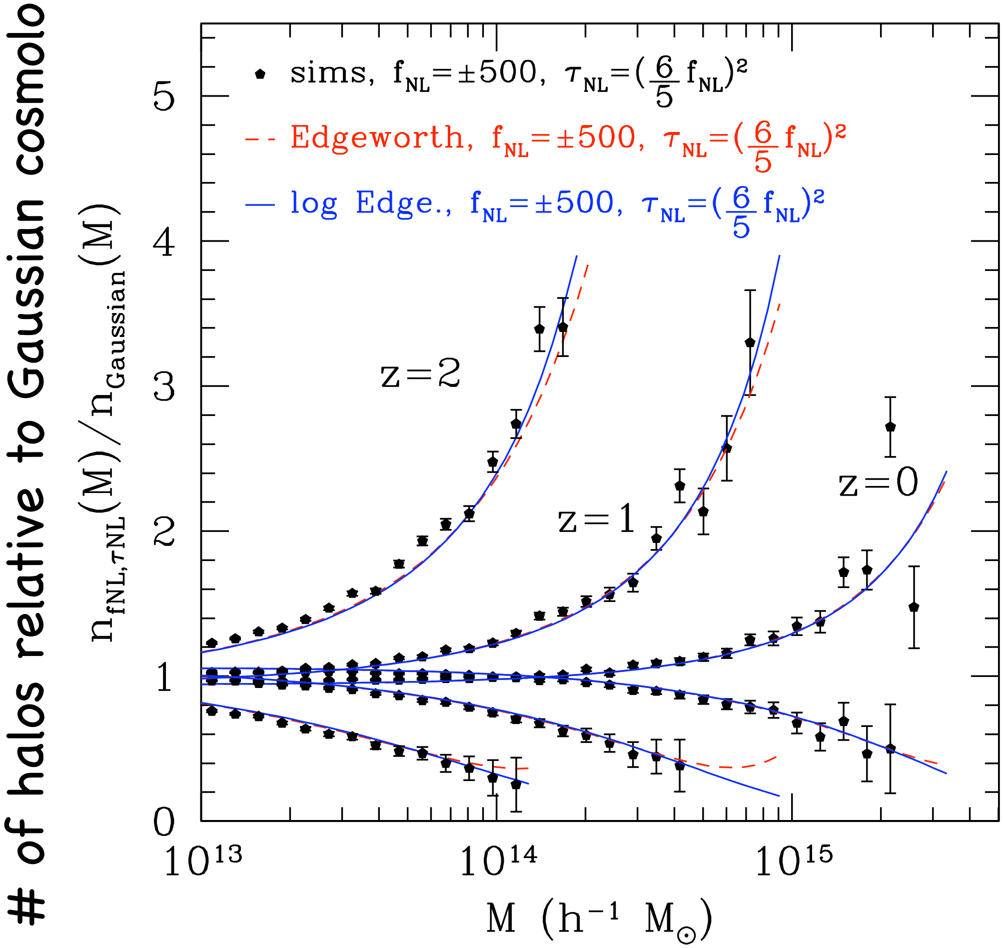
ML & K.M. Smith 2011

Signatures in LSS I: more/fewer massive halos

N-body simulations with f_{NL}, g_{NL}, and τ_{NL}

f_{NL}

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



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ML & K.M. Smith 2011

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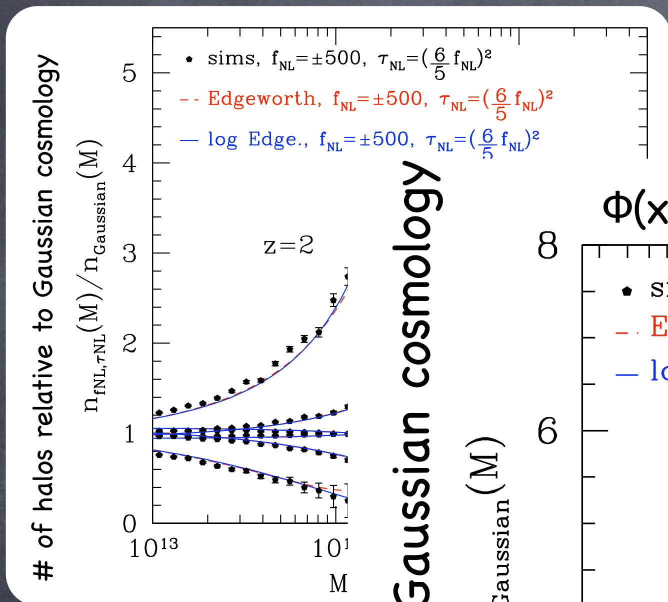
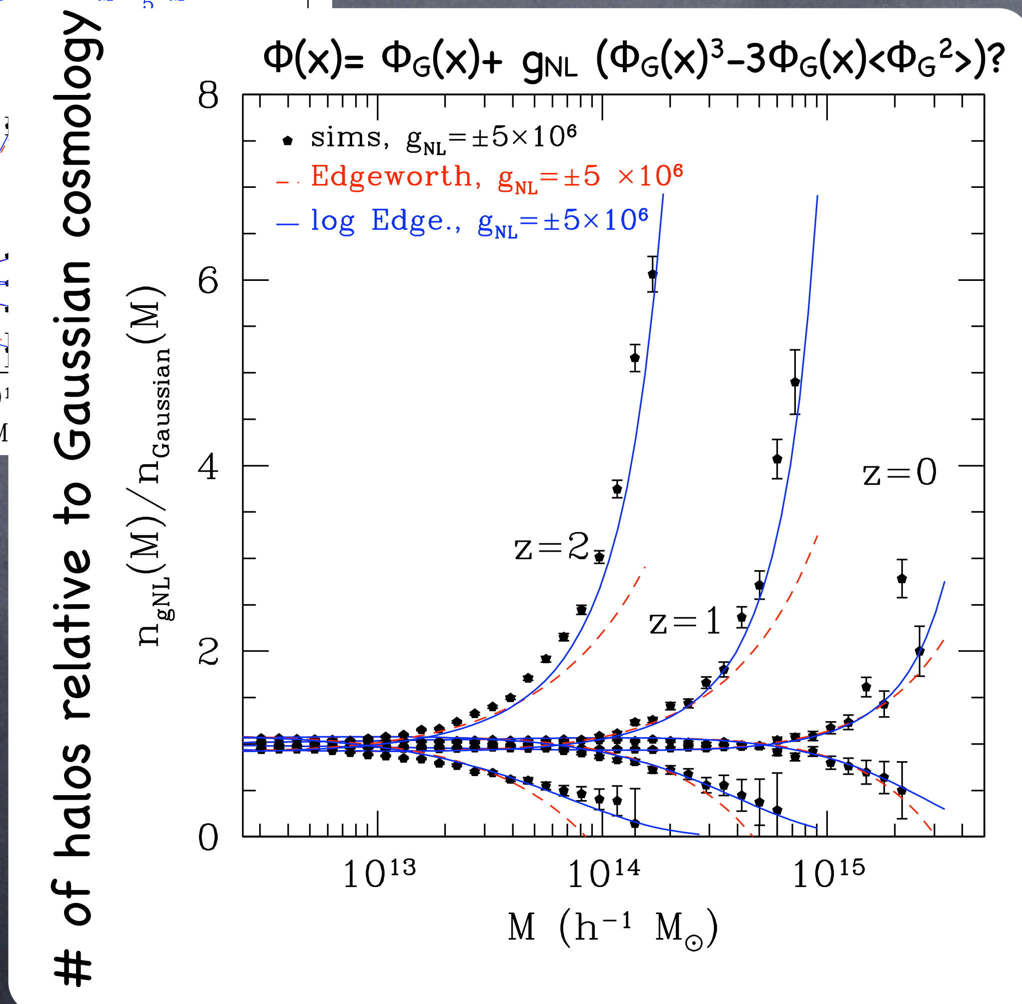


g_{NL}



curves are simple models of halo abundance (Press-Schechter + spherical collapse + approximate expressions for P.D.F. of δ)

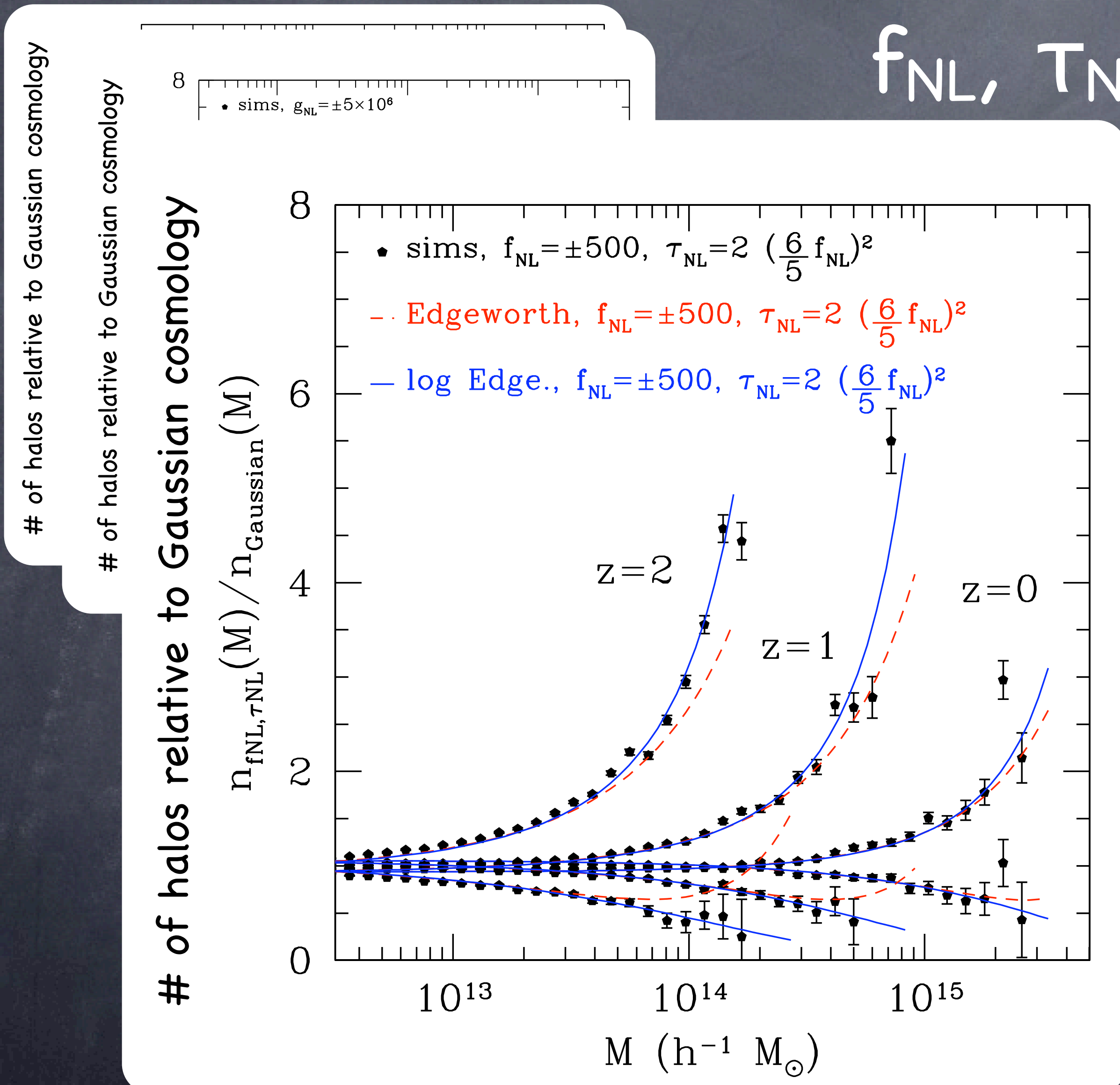
yes!

ML & K.M. Smith 2011

(see also Desjacques and Seljak 2010)

Signatures in LSS I: more/fewer massive halos

N-body simulations with f_{NL}, g_{NL}, and τ_{NL}



f_{NL}, τ_{NL} independent

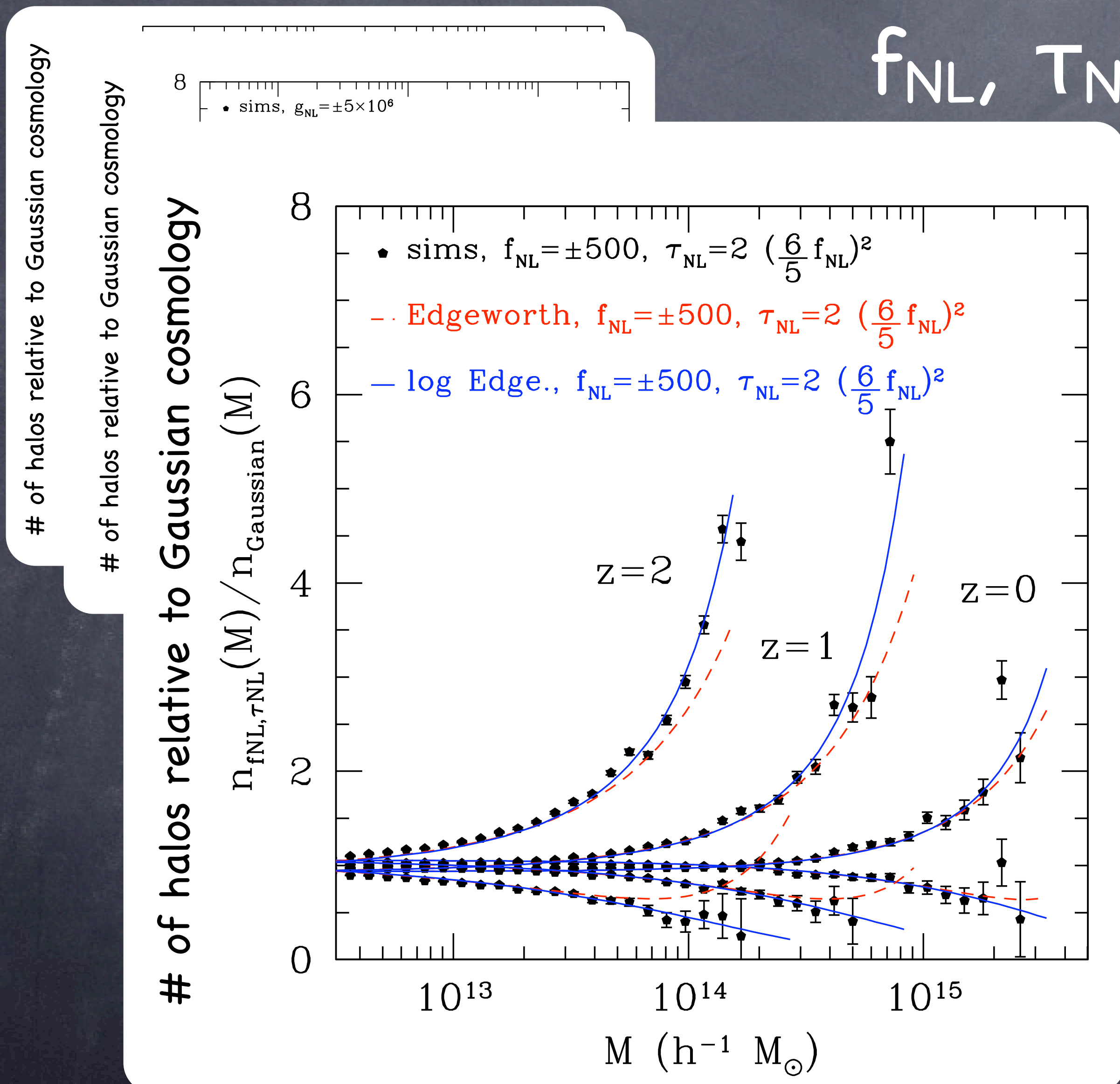
curves are simple models of halo abundance (Press-Schechter + spherical collapse + approximate expressions for P.D.F. of δ)

yes!

ML & K.M. Smith 2011

Signatures in LSS I: more/fewer massive halos

N-body simulations with f_{NL}, g_{NL}, and τ_{NL}



f_{NL}, τ_{NL} independent

the old mass function is ok for f_{NL}

the new mass function works for f_{NL}, g_{NL}, and τ_{NL} types of non-Gaussianity

ML & K.M. Smith 2011

Signatures in LSS II: scale-dependent halo bias

Recall, $\nabla^2 \Phi_l \sim 4\pi G\, \delta_l$ or $k^2 \Phi_l(k) \sim 4\pi G \delta_l(k)$

so on large scales $\delta n \approx \left(\frac{\partial n}{\partial \delta} + 4 f_{NL} \frac{\partial n}{\partial P_s} / k^2 \right) \delta_l(k) \ldots$

OR

$$P_{n\delta}(k) \approx \left(\frac{\partial n}{\partial \delta} + 4 f_{NL} \frac{\partial n}{\partial P_s} / k^2 \right) P_{\delta\delta}(k) \ldots$$

Dalal, Doré, Huterer, Shirokov 2007

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given a Gaussian mass function, we can calculate these derivatives and predict the coefficients

Dalal, Doré, Huterer, Shirokov 2007

Signatures in LSS II: scale-dependent halo bias

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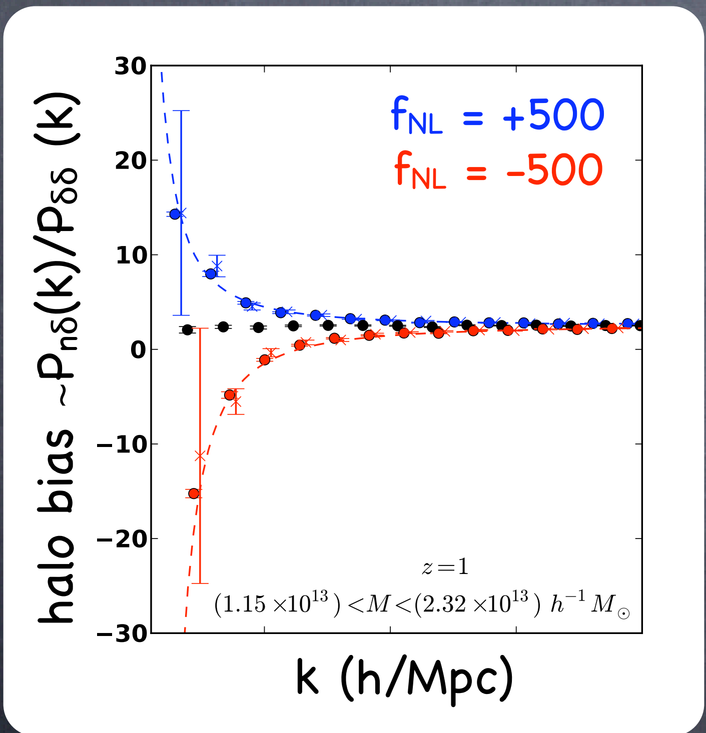
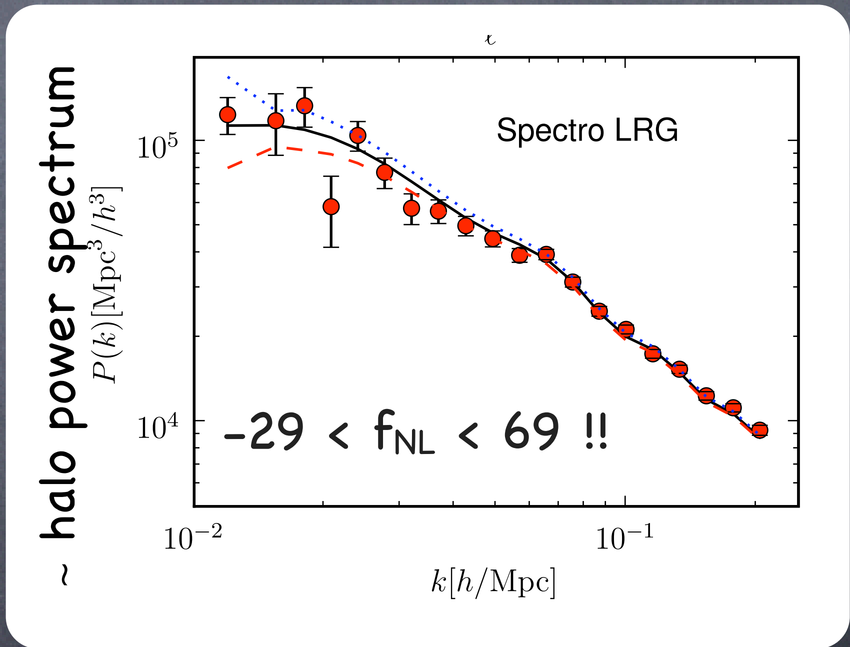
AND IT WORKS!



example data



Slosar, Hirata, Seljak, Ho, Padmanabhan 2008

Dalal, Doré, Huterer, Shirokov 2007

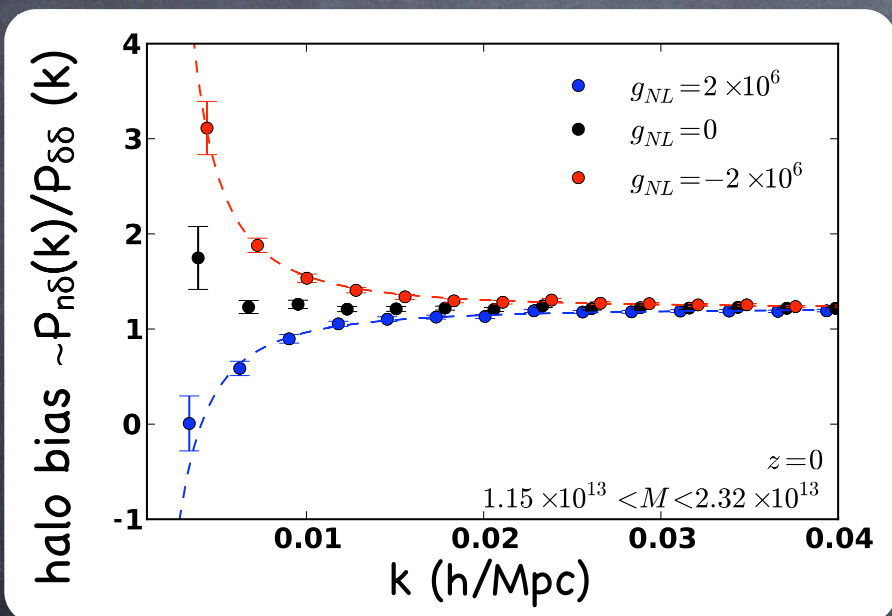
Pillepich, Porciani, Hahn 2008; Desjacques, Seljak, Iliev 2008; Grossi et al 2009

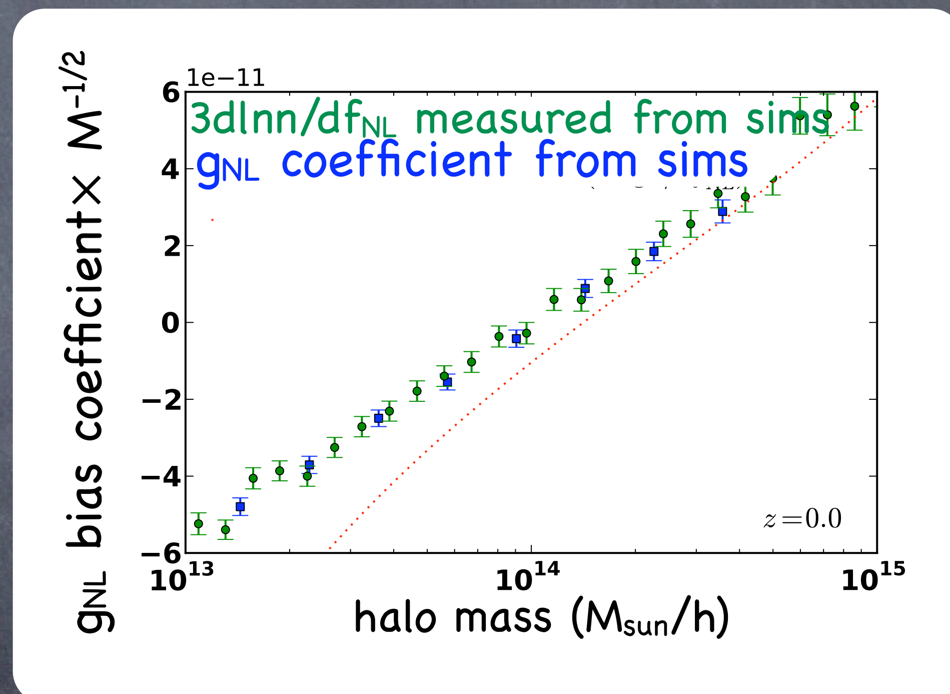
Signatures in LSS II: scale-dependent halo bias

And for g_{NL}: $$\delta n \approx \left(\frac{\partial n}{\partial \delta} + 18 g_{NL} \frac{\partial n}{\partial S_3} / k^2 \right) \delta_l(k) \ldots$$

$$= \left(\frac{\partial n}{\partial \delta} + 3 g_{NL} \frac{\partial n}{\partial f_{NL}} / k^2 \right) \delta_l(k) \ldots$$

AND IT WORKS AGAIN!



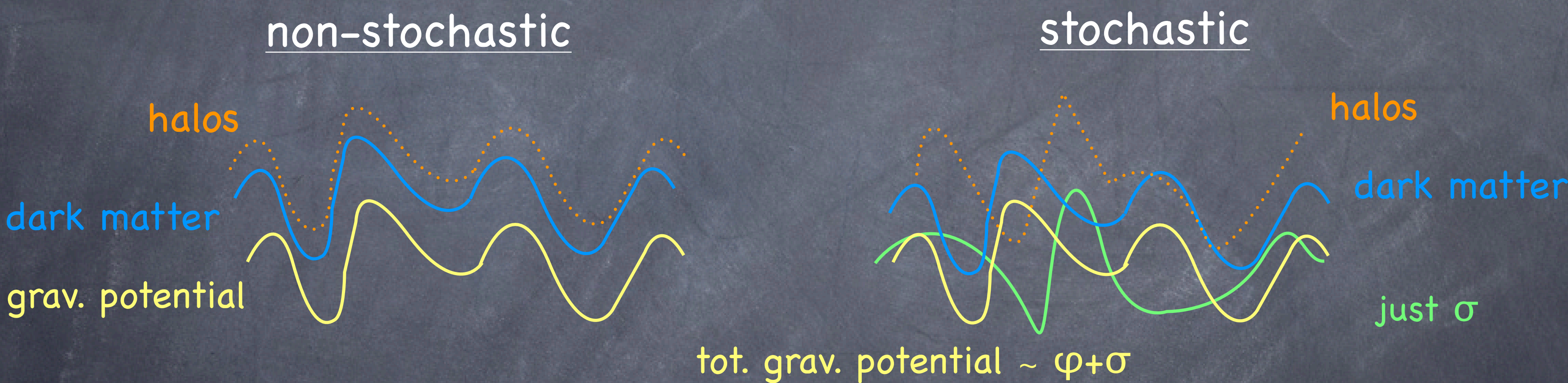


Smith, Ferraro, ML 2011

(see also Desjacques and Seljak 2010)

Signatures in LSS III: stochastic halo bias

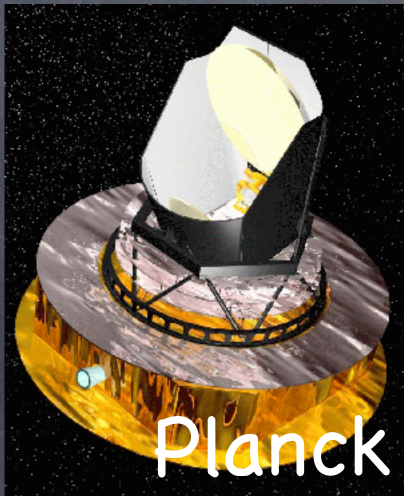
f_{NL} , τ_{NL} non-Gaussianity gives both scale dependent bias and makes halo # fluctuations stochastic w.r.t. dark matter fluctuations



Tseliakhovich, Hirata, Slosar 2010

τ_{NL} dependent stochasticty is present in N-body sims! But the predicted amplitude is not as accurate as f_{NL} and g_{NL} biases . . .

Smith & ML 2010



lots of large-scale structure data!

SPT

ACT

. . . and more

see e.g. Shandera, Dalal, Huterer 2010
Oguri and Takada 2010
Carbone, Verde, Matarrese 2009 many more . . .

Summary

- Non-Gaussian initial conditions significantly change the abundance and clustering of dark matter halos
- We have an analytic description for the halo mass function that compares well to N-body for f_{NL}, g_{NL} and τ_{NL} -- perhaps it works for more general forms of NG?
- Analytic descriptions of halo bias agree well with sims, for f_{NL} and g_{NL} too!
- *Large-scale structure is a promising probe of the early universe*

Signatures in LSS III: stochastic halo bias

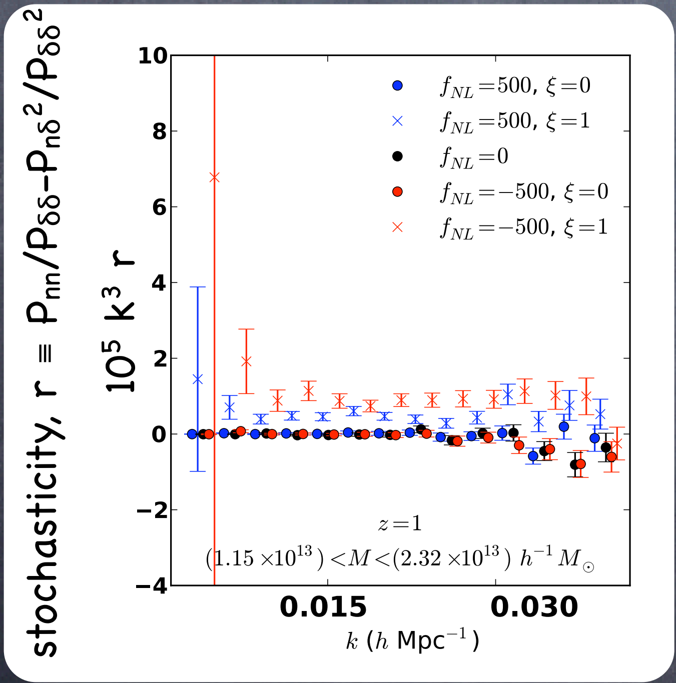
$$P_{n\delta}(k) \sim \left(\frac{\partial n}{\partial \delta} + 4f_{NL}\frac{\partial n}{\partial P_s} / k^2 \right) P_{\delta\delta}$$

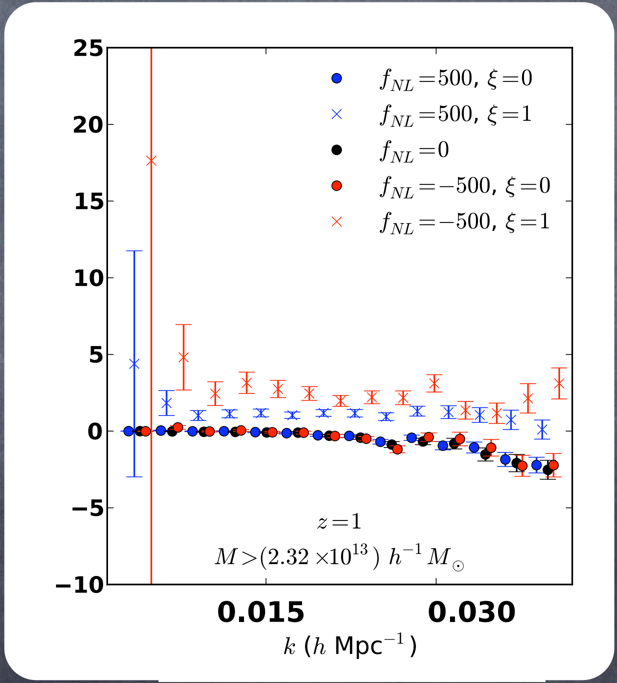
stochasticity

$$P_{nn}(k) \sim \left(\frac{\partial n}{\partial \delta} + 4f_{NL}\frac{\partial n}{\partial P_s} / k^2 \right)^2 P_{\delta\delta} + \left(4f_{NL}\frac{\partial n}{\partial P_s}\right)^2 \xi^2 P_{\delta\delta}$$

$$\xi^2 = P_{\varphi\varphi}(k)/P_{\sigma\sigma}(k)$$

$$\tau_{NL} = (1+\xi^2)\, f_{NL}^2$$





N.B. the bias factor in $P_{n\delta}$ is unchanged from f_{NL}-only model

Signatures in LSS III: stochastic halo bias

$$P_{n\delta}(k) \sim \left(\frac{\partial n}{\partial \delta} + 4 f_{NL} \frac{\partial n}{\partial P_s} / k^2 \right) P_{\delta\delta}$$

$$P_{nn}(k) \sim \left(\frac{\partial n}{\partial \delta} + 4 f_{NL} \frac{\partial n}{\partial P_s} / k^2 \right)^2 P_{\delta\delta} + \left(4 f_{NL} \frac{\partial n}{\partial P_s}\right)^2 \xi^2 P_{\delta\delta}$$

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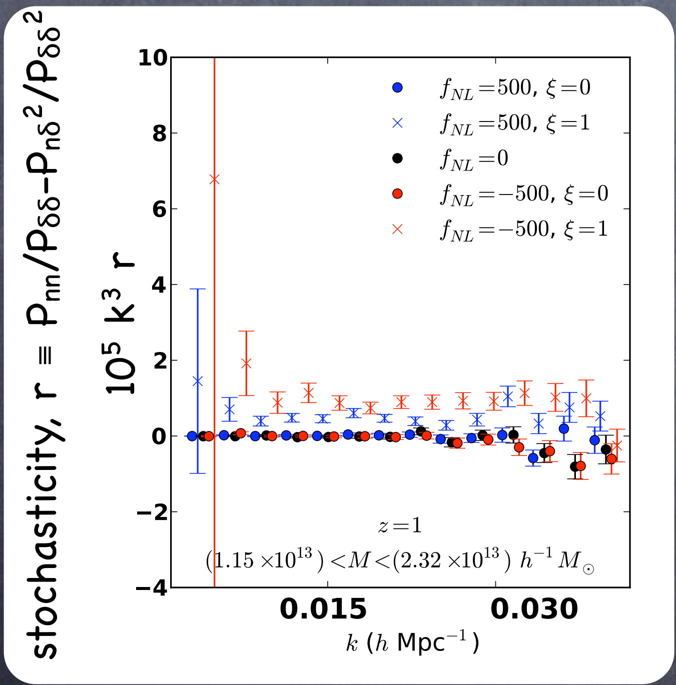
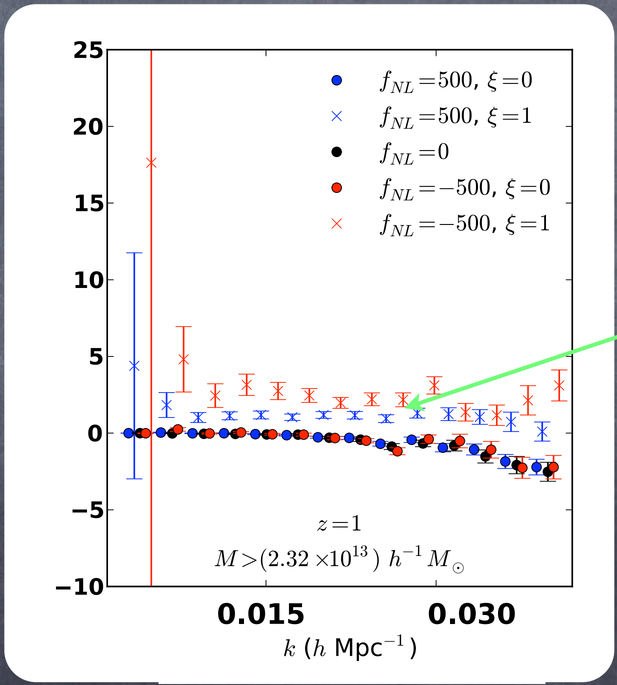




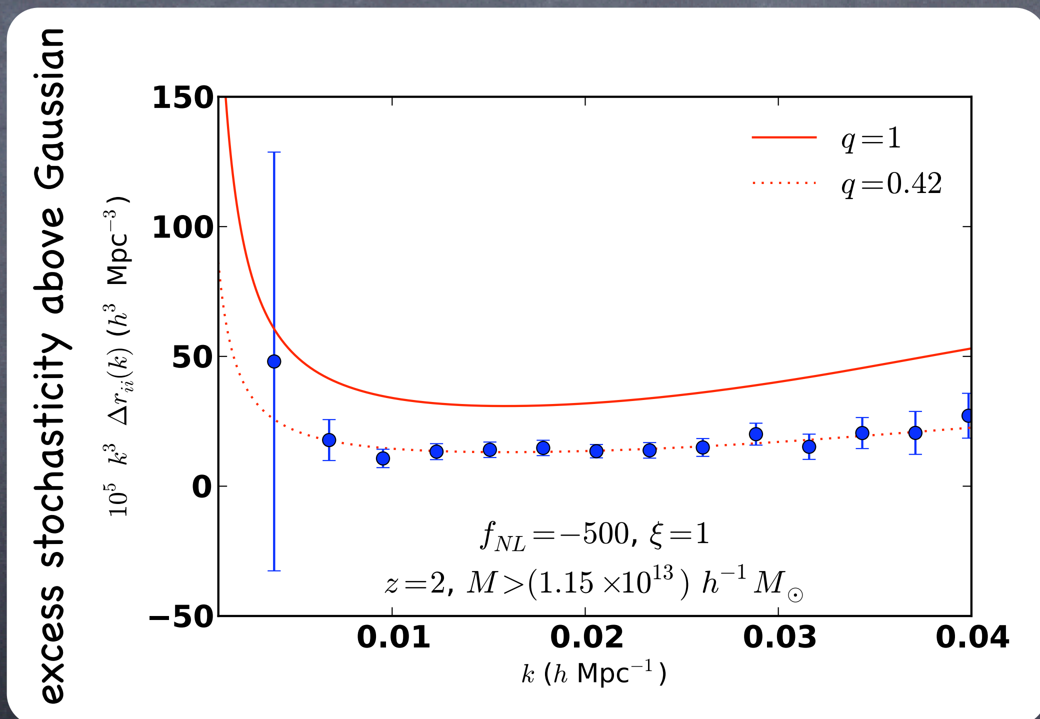
models with $\xi \neq 0$ indeed stochastic

N.B. the bias factor in $P_{n\delta}$ is unchanged from f_{NL}-only model

Signatures in LSS III: stochastic halo bias

does stochasticity agree with predictions?

$$P_{nn}(k) \sim \left(\frac{\partial n}{\partial \delta} + 4 f_{NL} \frac{\partial n}{\partial P_s} / k^2 \right)^2 P_{\delta\delta} + \left(4 f_{NL} \frac{\partial n}{\partial P_s}\right)^2 \xi^2 P_{\delta\delta}$$



Signatures in LSS III: stochastic halo bias

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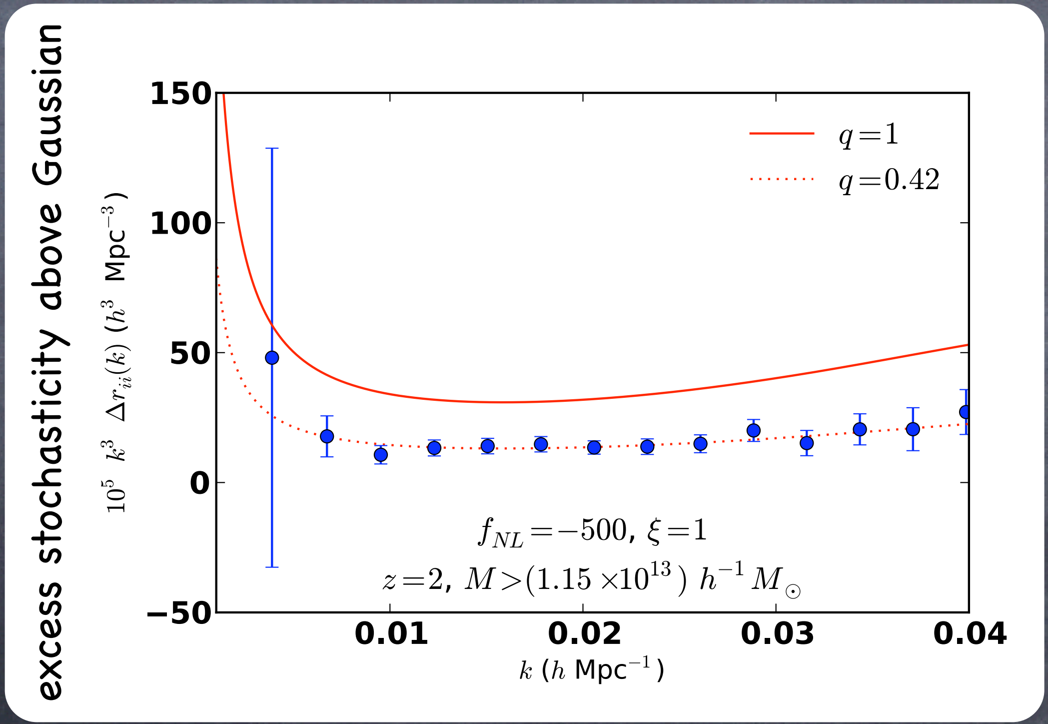

um, shape looks good but not amplitude

tends to look better at low masses, low f_{NL}