Structure Formation from primordial non-Gaussianity

non-local scale-dependent bias and future constraints

TG & Porciani,
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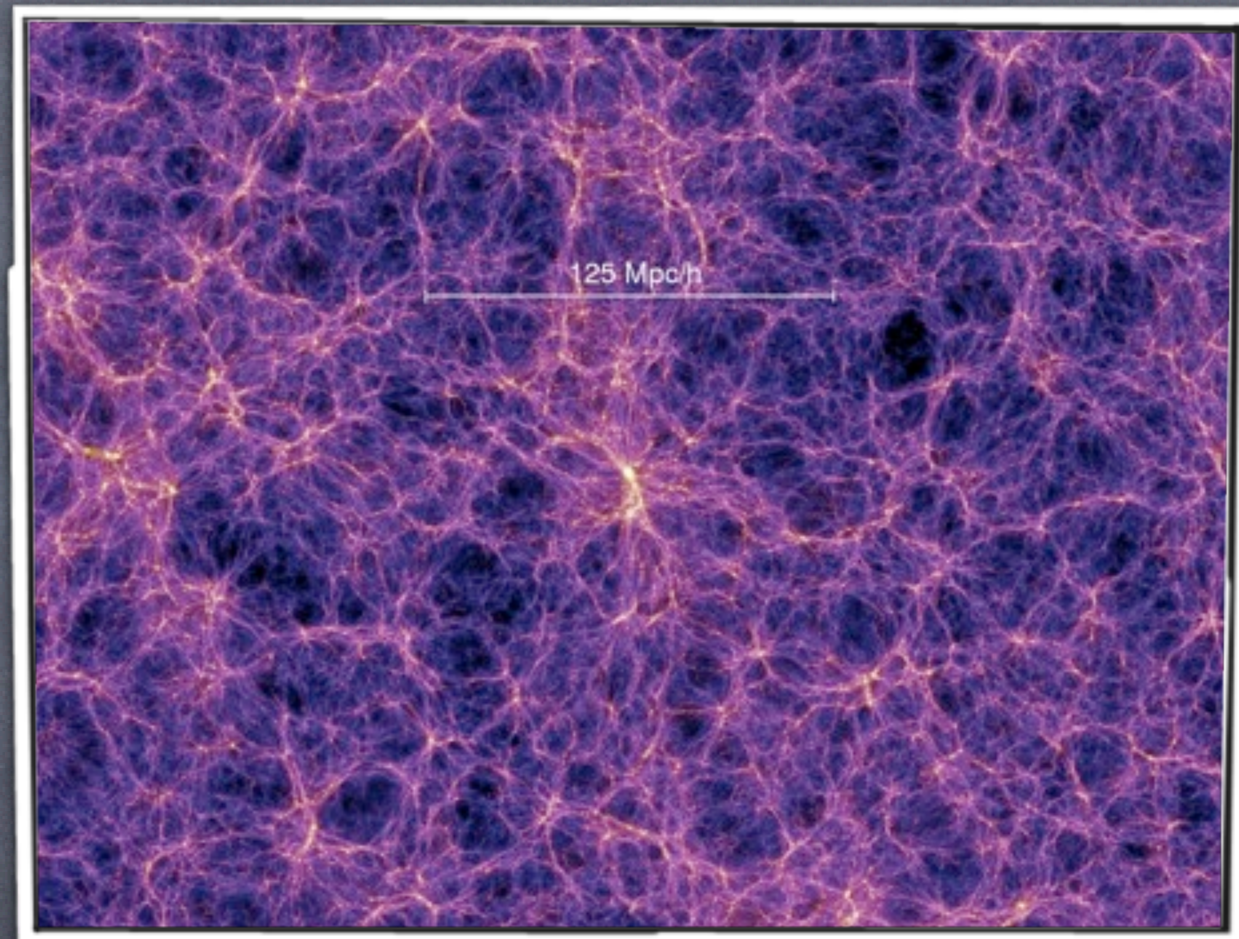
TG, Porciani, Amara,
Pillepich, Carron
in prep.



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in collaboration with C. Porciani, A. Amara, A. Pillepich, J. Carron

Benasque, 18th August 2010

Outline

- Introduction: how to measure non-Gaussianity
- Non-Gaussian halo mass functions
- Scale-dependent bivariate (or non-local) bias
- Statistics: Power spectra and Bispectra
- Comparison with N-body simulations
- How to measure NG from future surveys
- Conclusion

Measuring NG

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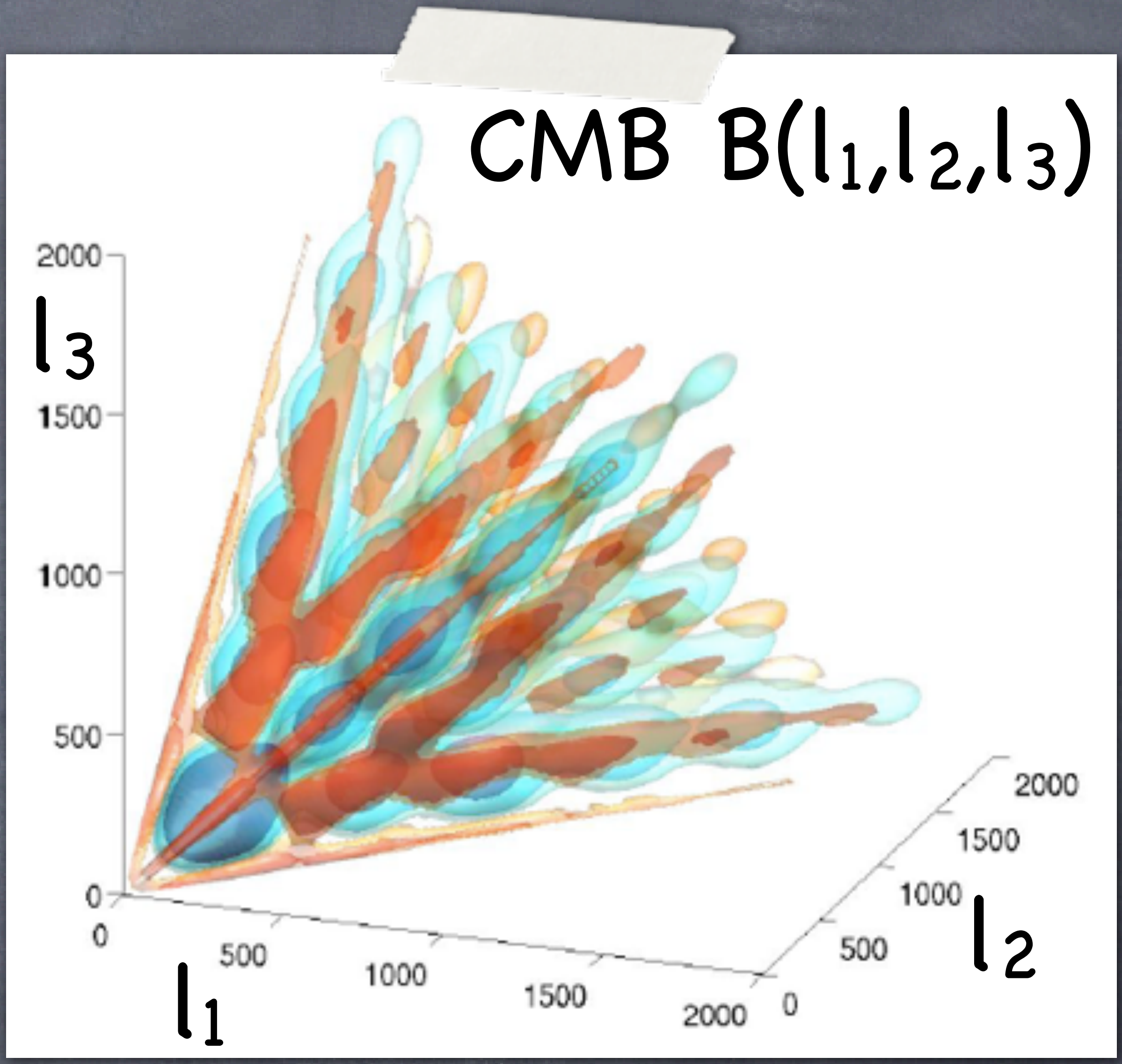
- 3- and 4-point correlation functions of the CMB $\Theta \equiv \delta T/T$
  - $\langle\Theta\Theta\Theta\rangle = 0$, $\langle\Theta\Theta\Theta\Theta\rangle = PP$ if Gaussian;
  - WMAP: $-10 < f_{NL} < 74$ (95%) [Komatsu et al 10]
  - $-3.80 \cdot 10^6 < g_{NL} < 3.88 \cdot 10^6$ [Smidt et al. 10]
  - Planck will have $\sigma(f_{NL}) = 5$



[Ferguson et al. 09]

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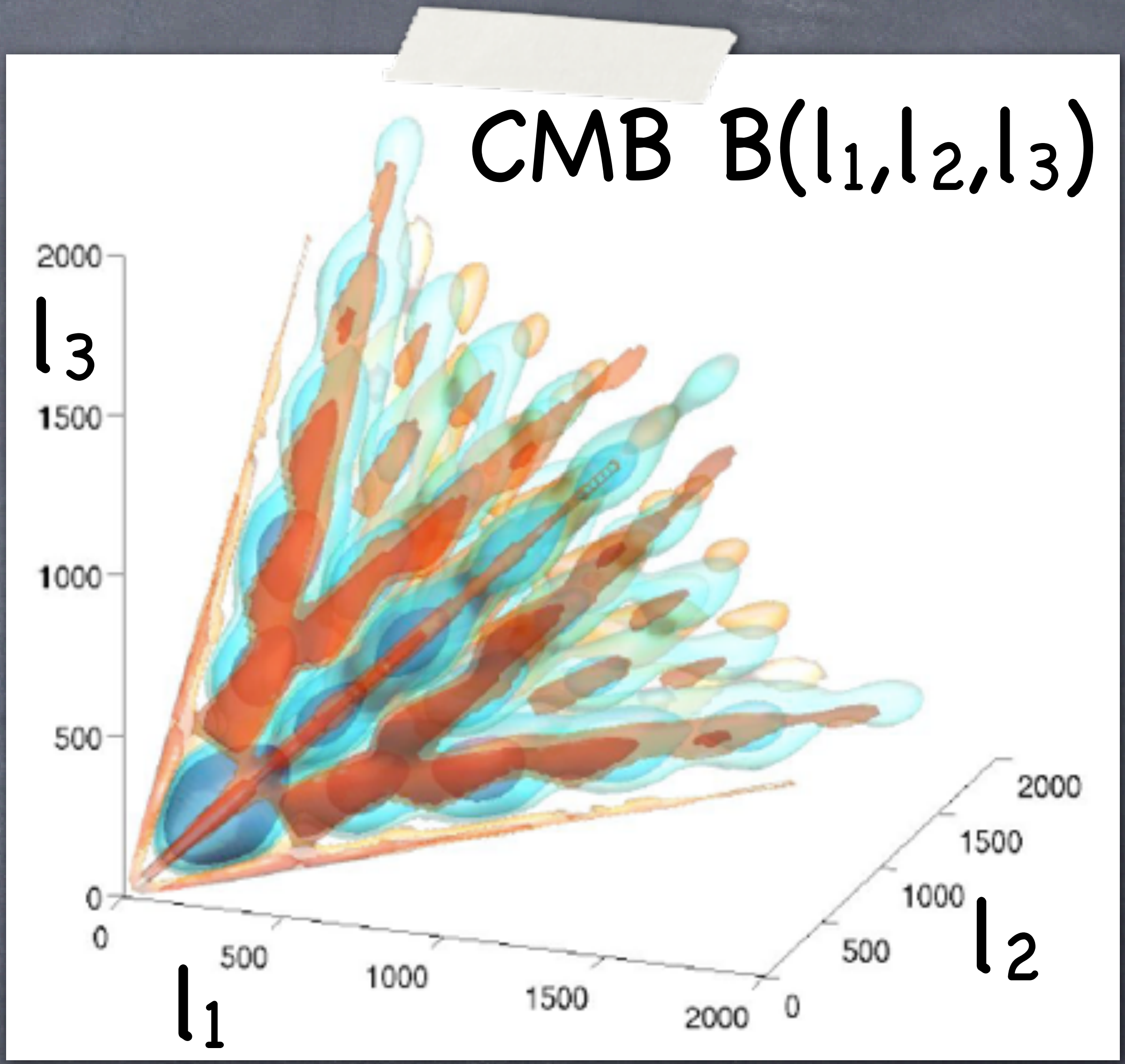
- same for Large-scale structure (LSS):
  - how to distinguish from late-time NG?
  - mass distribution at high z [Scoccimarro et al. 04]
  - very massive objects at low z [LoVerde et al. 08]
  - will need PanSTARRS, DES, EUCLID!



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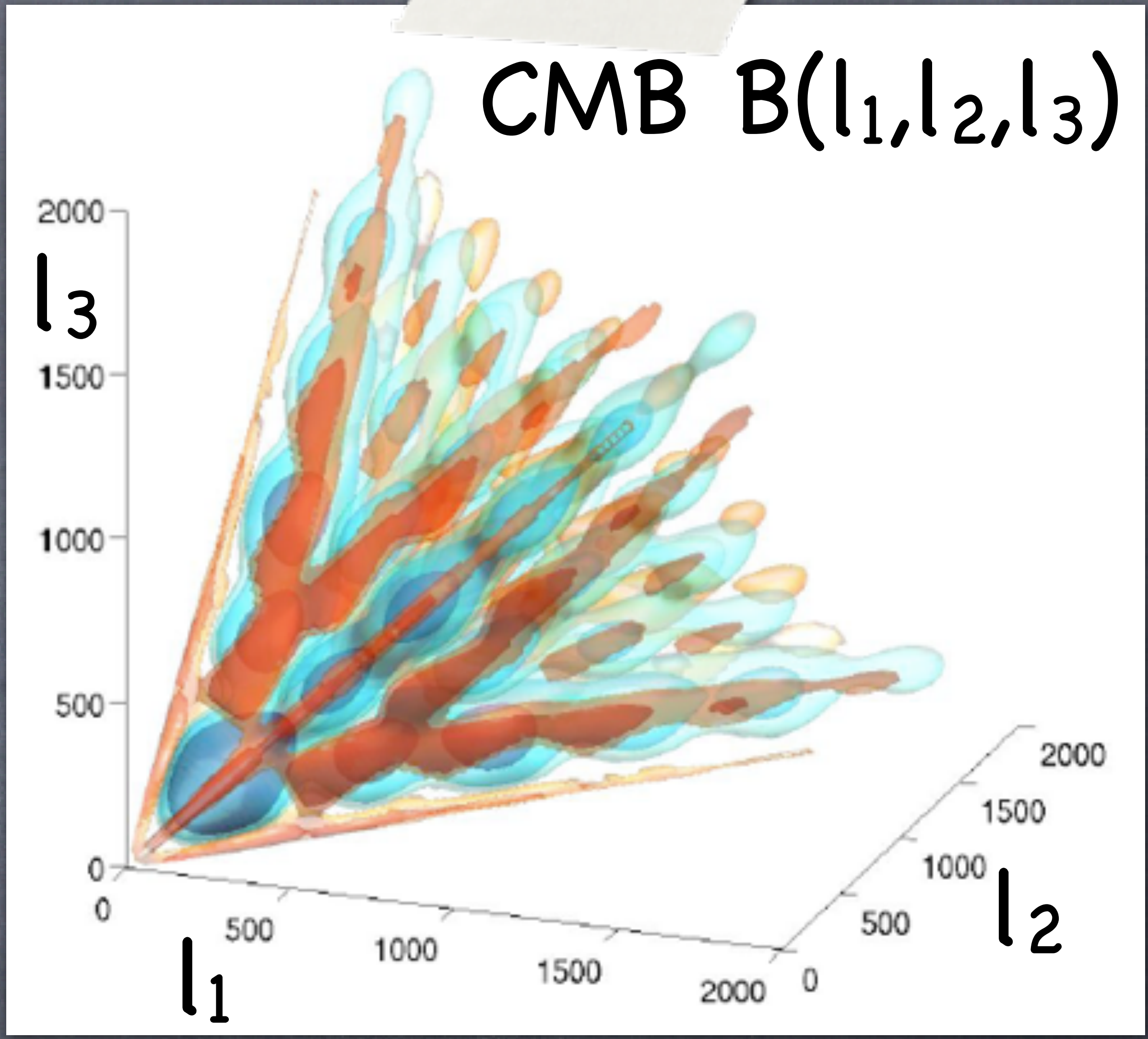

[Ferguson et al. 09]

An additional LSS technique:

scale-dependent bias

[Dalal et al. 07, Afshordi et al. 08, Slosar et al. 08, Taruya et al 08, Matarrese & Verde 08, ...]

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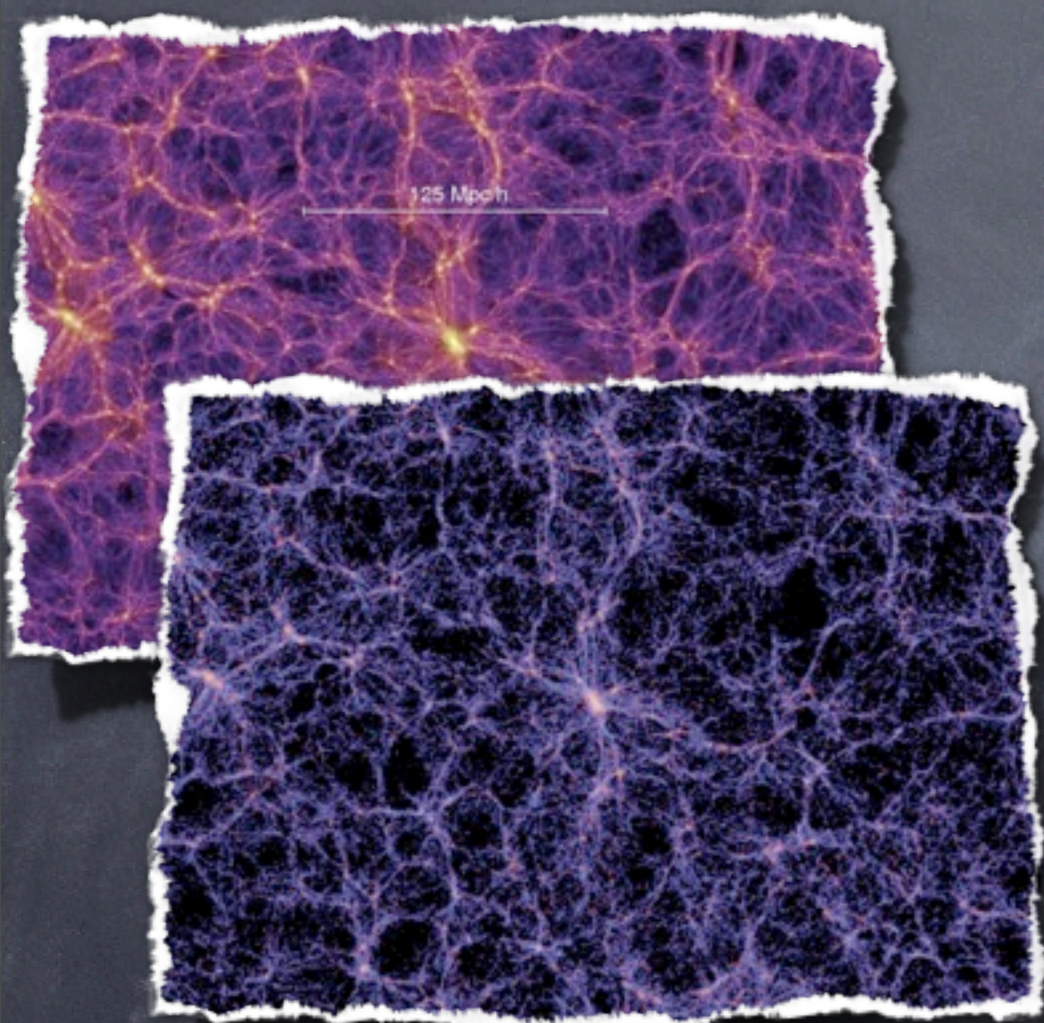

[Millennium run, Springel et al.

- D.m. perturbations δ_m > d.m. haloes δ_h > galaxies δ_g: in increasing high-density
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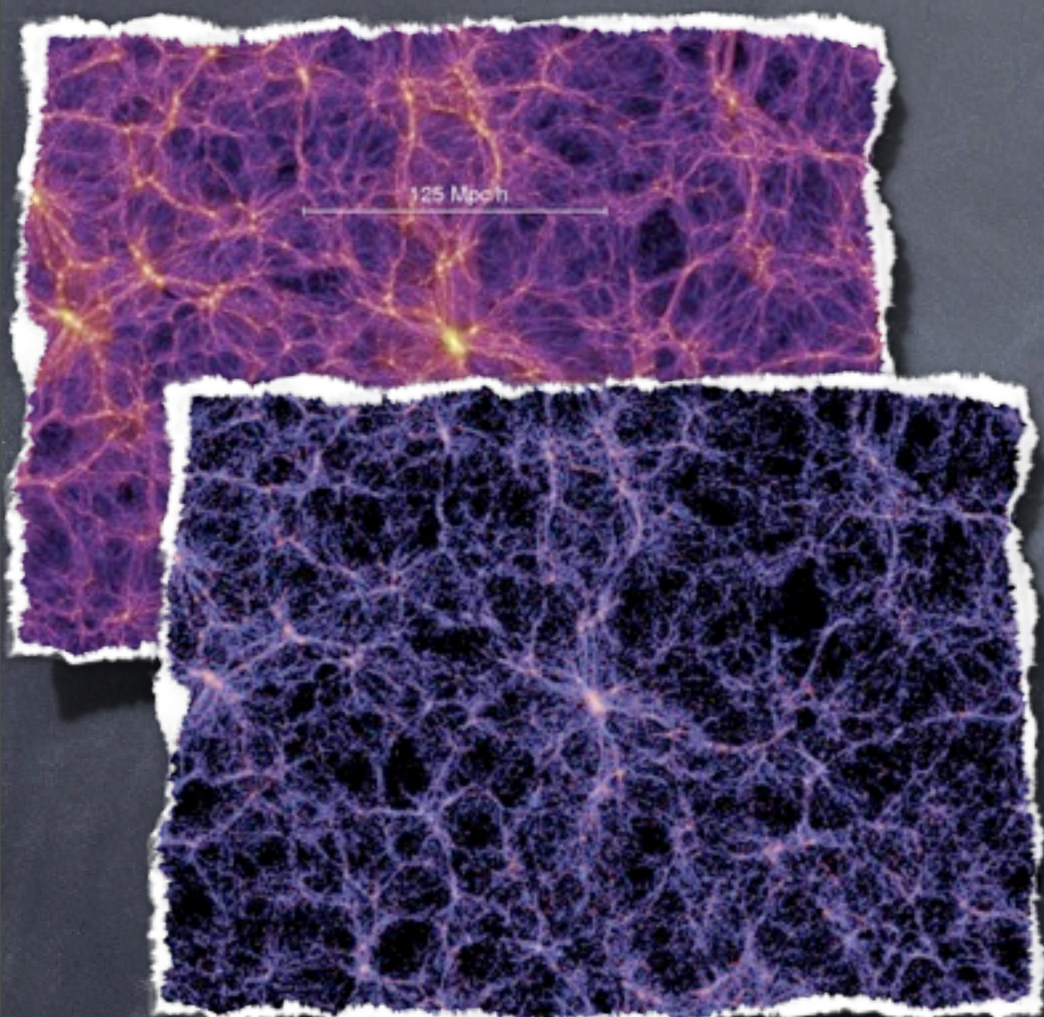

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- with NG: strongly scale-dependent! [Dalal et al. 07, Afshordi et al. 08, Slosar et al. 08]
  - $b \rightarrow b' = b_{Gau} + \Delta b(k)$ for **both** halo & gal !
    - $b_g \propto \int b_h\ n\ (M)\ HOD(M)\ dM$
- spectra <gal-gal> ~ b^2 and <gal-CMB> ~ b: constraints on NG!
  - $-29 < f_{NL} < 69$ (95%) [Slosar et al 08]
  - $-3.5\cdot10^5 < g_{NL} < 8.2\cdot10^5$ [Desjacques et al. 10]

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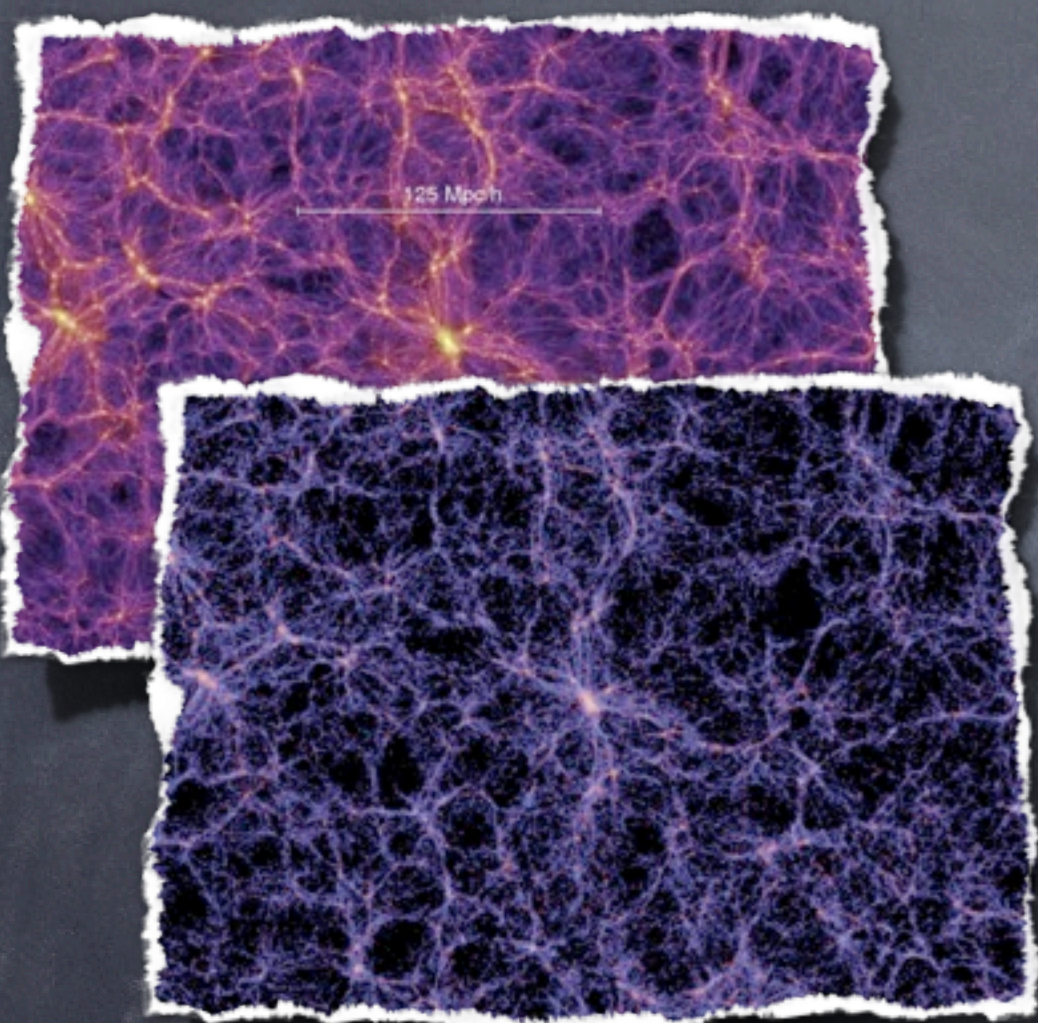

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Agreement with simulations not excellent
Theoretical derivation not fully consistent

Comparison with simulations

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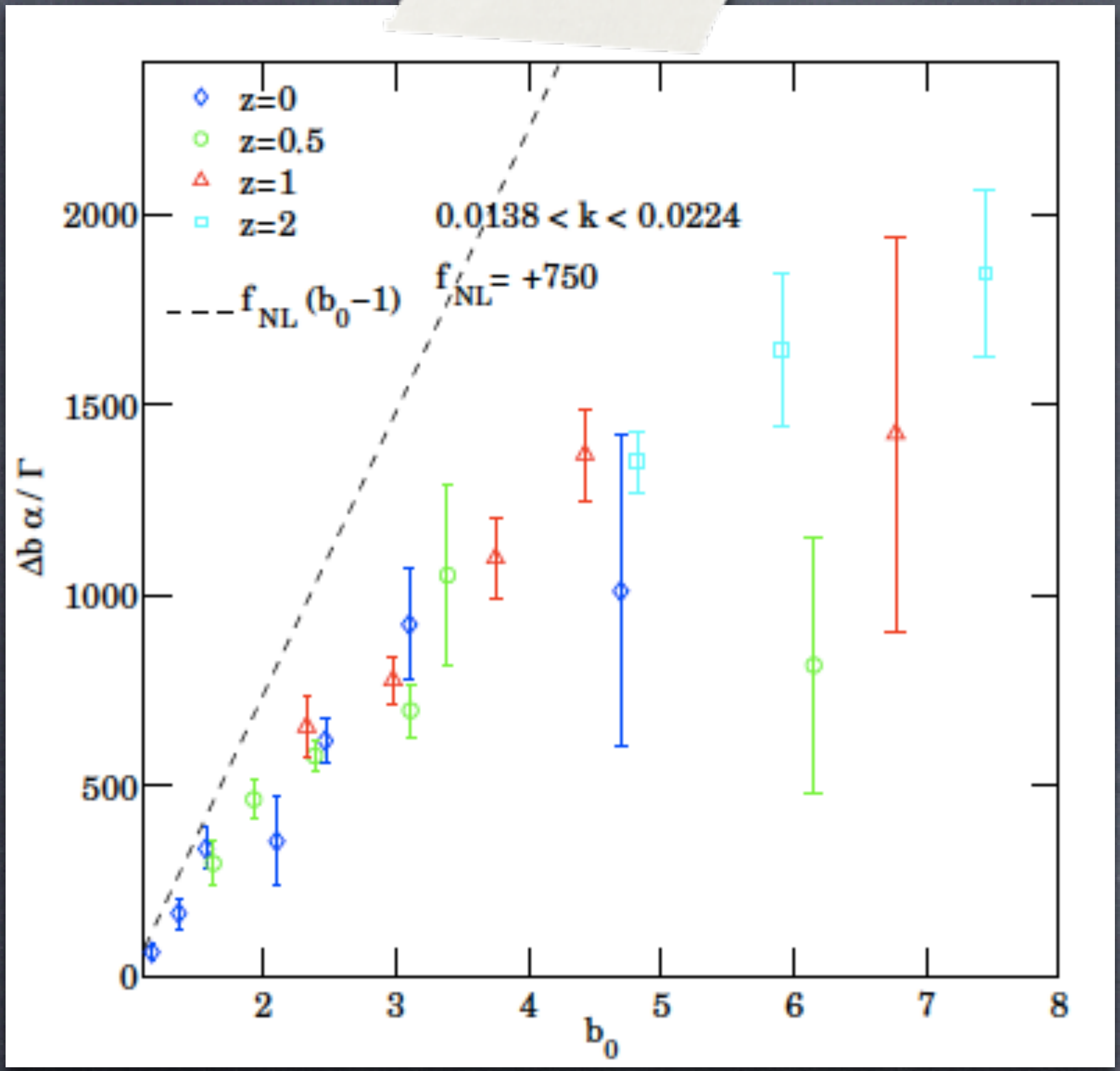

[Pillepich et al. 08]

- Simple prediction for local NG:
- $\Delta b(k) = f_{NL}\ (b_0 - 1) / k^2 \times \text{const.}$

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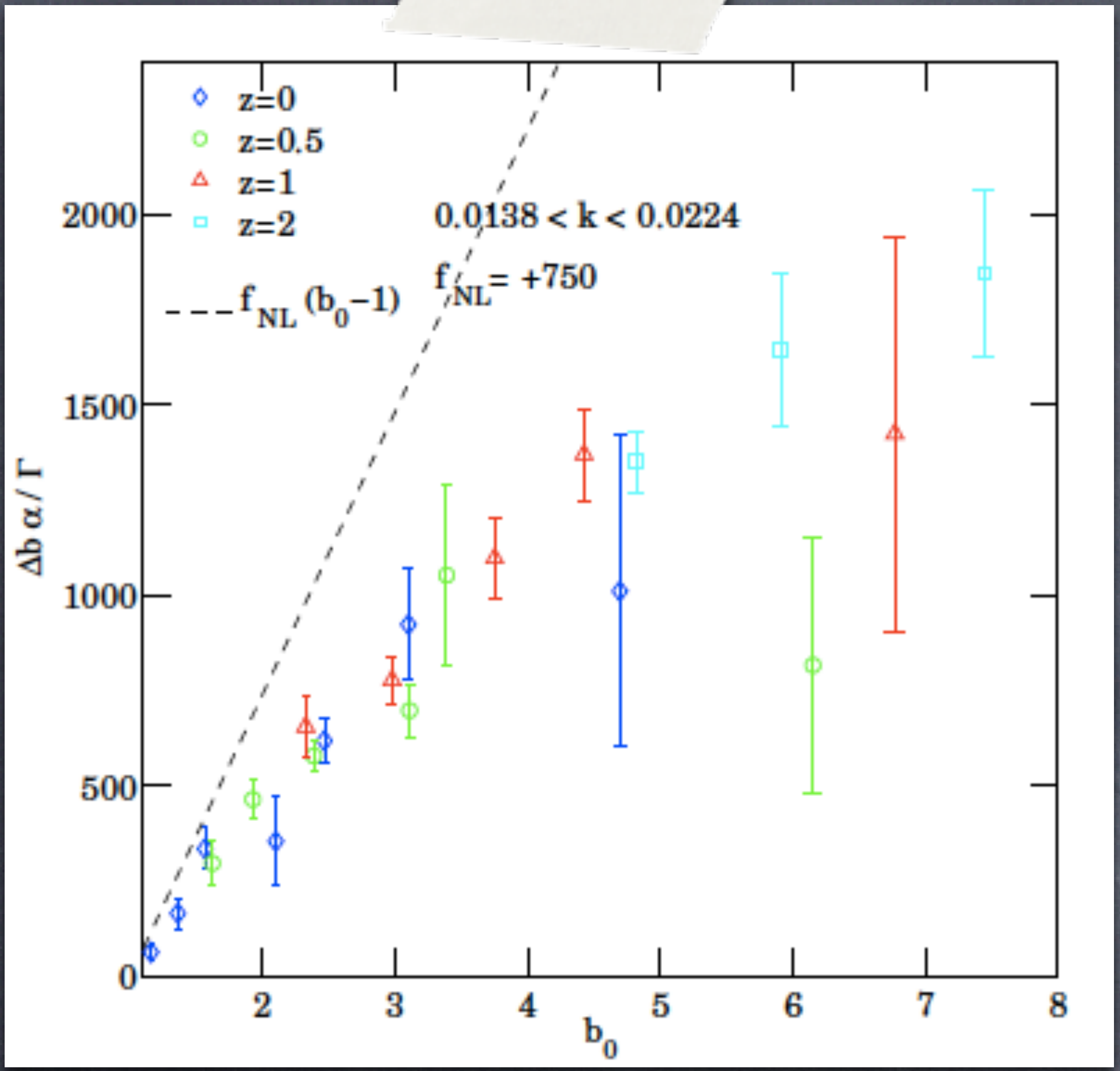

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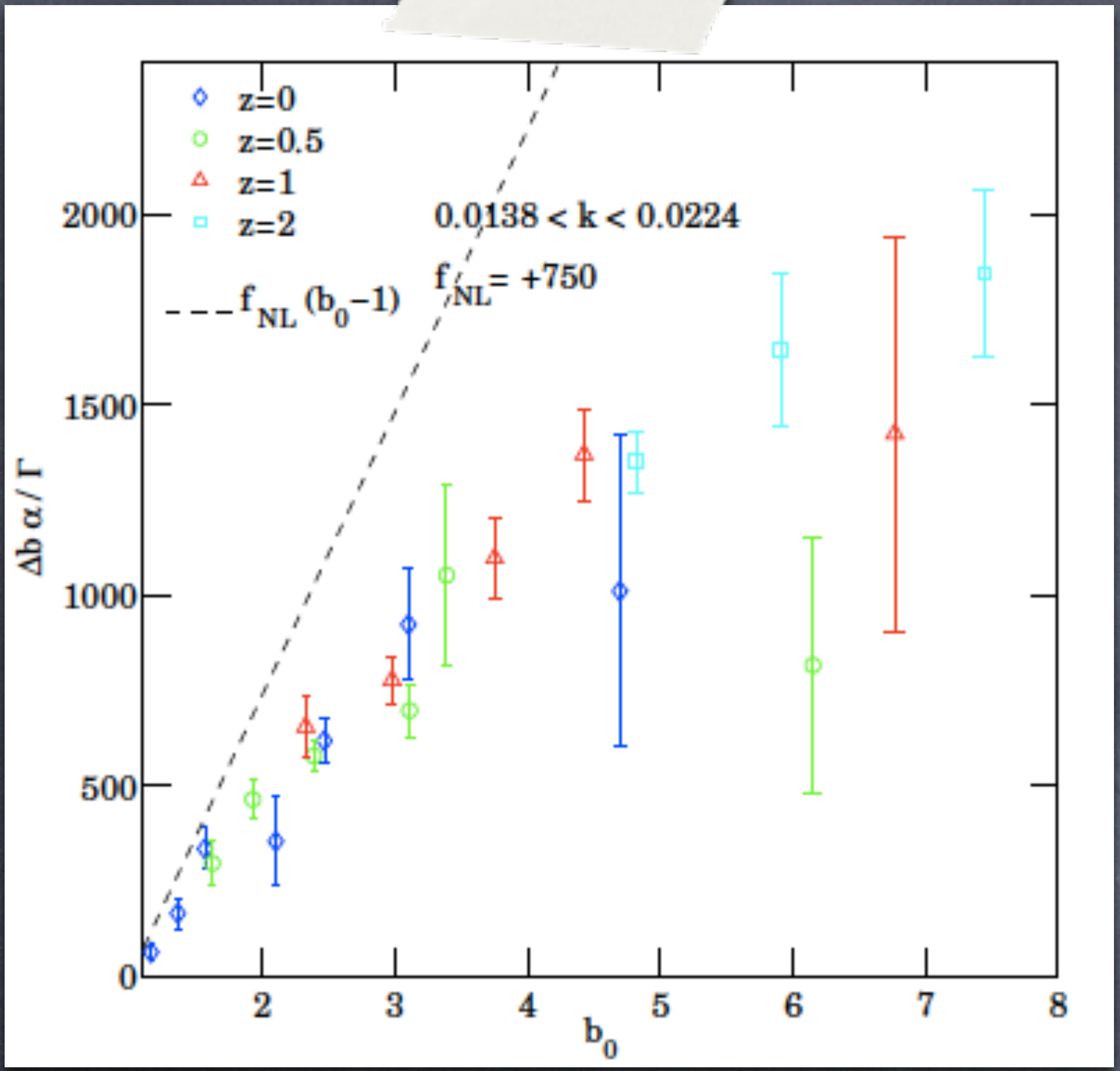

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We calculate full one-loop corrections in a new, fully predictive and consistent way!

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- Expand real-space (Eulerian) perturbations to 3rd order...
  - $\delta_h(x) = b_0 + b_1\,\delta(x) + b_2\,\delta^2(x)\,/\,2 + b_3\,\delta^3(x)\,/\,3! + \ldots$
    [Fry & Gaztanaga 93]
  - δ smoothed at scale R: (R ≈ 10 Mpc/h, must be in this range)
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All this in the non-Gaussian case. Locality won't hold!

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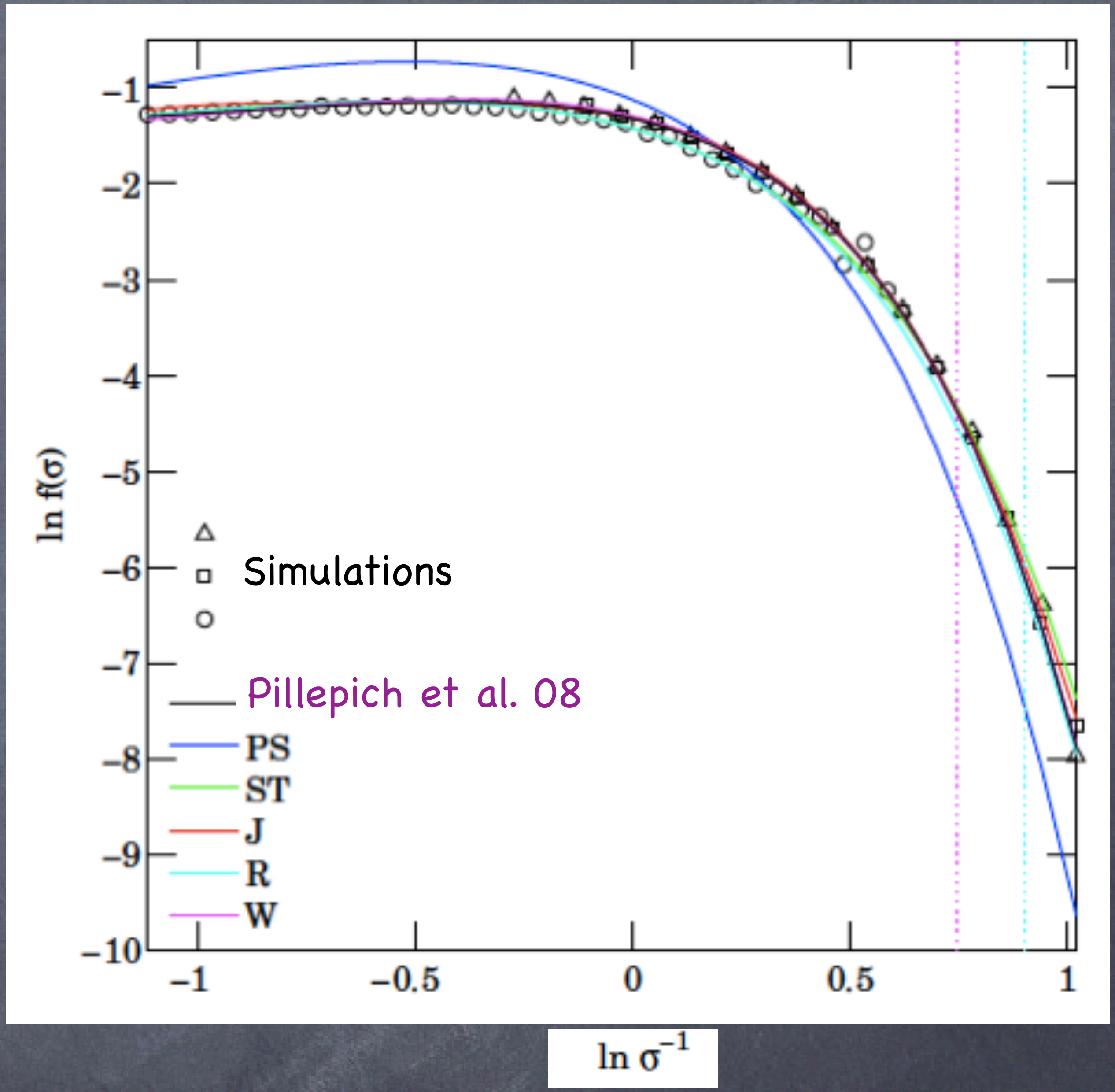
  - $dn/dM \propto f(\sigma, f_{NL})$
  - $\sigma(M)$: variance of the linear δ smoothed at a scale $R_f(M)$



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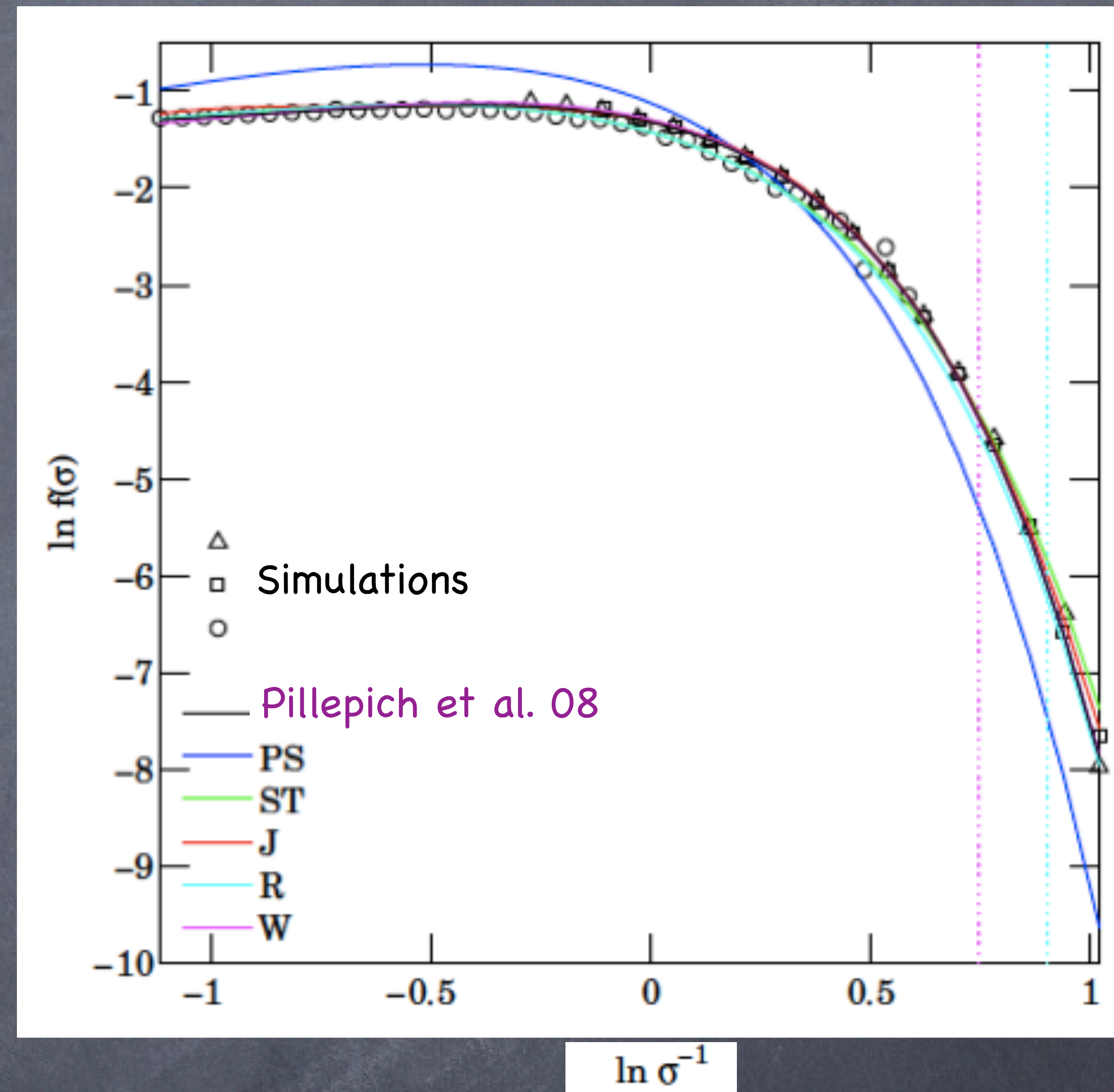
spherical collapse threshold

$$f_{\rm PS} = \sqrt{\frac{2}{\pi}}\frac{\delta_c}{\sigma}e^{-\frac{\delta_c^2}{2\sigma^2}}$$

  - Sheth-Tormen (ST), Jenkins, Warren: extra parameters fit from simulations



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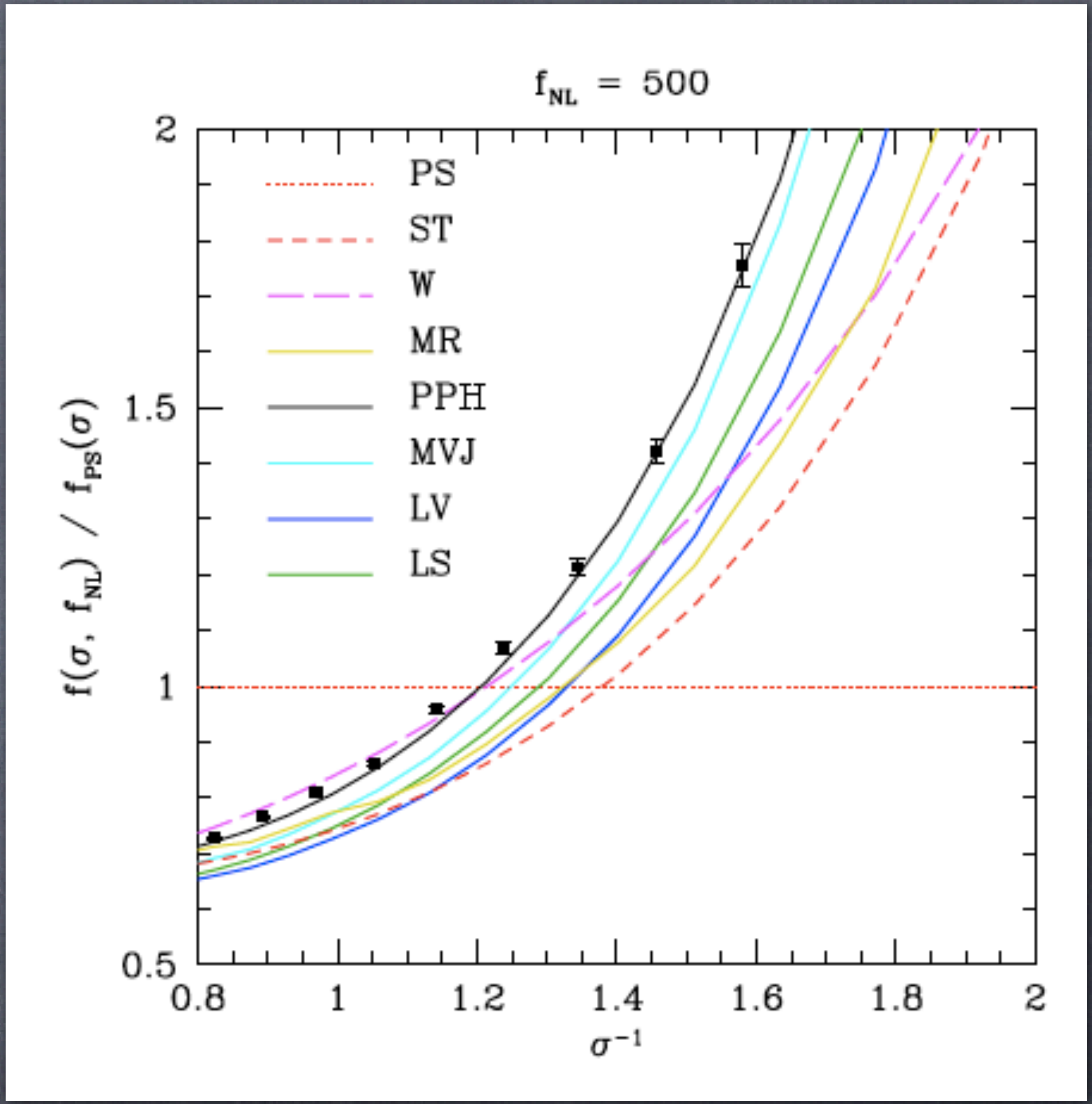
$$f_{\rm MVJ} = \sqrt{\frac{2}{\pi}}e^{-\delta_\star^2/(2\sigma^2)}\left|\frac{\delta_c^3}{6\,\sigma\,\delta_\star}\,\frac{dS_3(\sigma)}{d\ln\sigma}+\frac{\delta_\star}{\sigma}\right|,$$

  - LoVerde (LV), Maggiore-Riotto (MR) Lam-Sheth (LS)
- Or just a fit to our simulations! (PPH)[Pillepich et al. 08]



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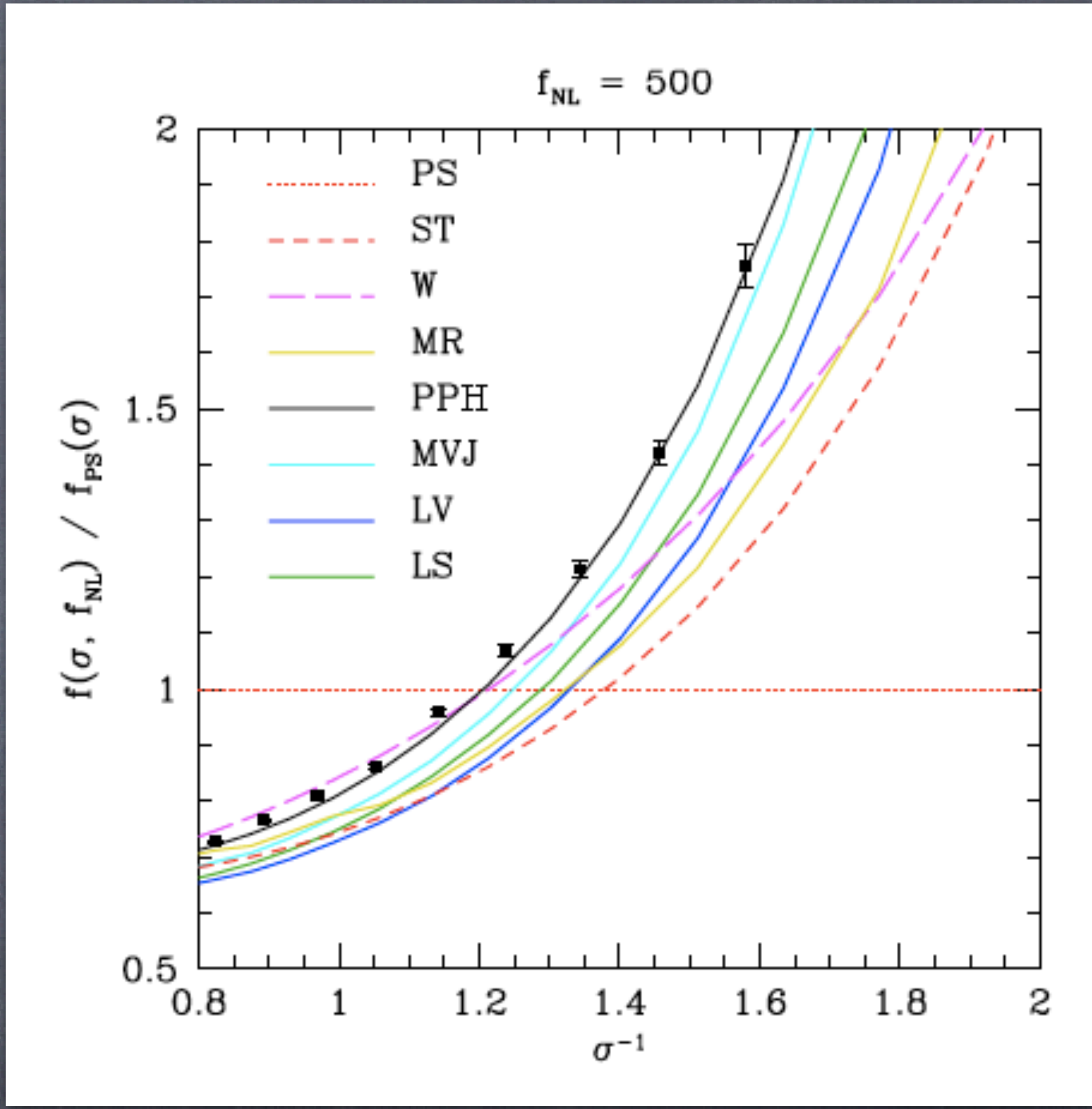

Accuracy ~ 10%
We will use LV, PPH fit

Peak-background split

[Bardeen et al 86, Cole & Kaisers 89]

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- Gaussian potential, Lagrange space: $\varphi(q) = \varphi_l(q) + \varphi_s(q)$
- From NG definition: $\Phi = \varphi + f_{\rm NL}\left[\varphi^2 - \langle\varphi^2\rangle\right]$
  - $\Phi_l = \varphi_l + f_{NL}\,\varphi_l^2 - \langle\varphi^2\rangle$
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- Fourier space: Poisson equation: $\nabla^2\Phi(k) = A\delta(k)$, $\nabla^2\varphi(k) = A\delta_G(k)$
  - $\delta_l = \delta_{G,l}\,(1 + 2f_{NL}\,\varphi_l) + \ldots$ modulate counts, large-scale motions
  - $\delta_m = 2\, f_{NL}\,(\delta_{G,s}\,\varphi_l + \delta_{G,l}\,\varphi_s) + \ldots$ collapse to form d.m. haloes
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  - $\delta_s = \delta_{G,s}\,(1 + 2f_{NL}\,\varphi_l) + \ldots$ collapse to form d.m. haloes
- $\delta_{G,s}$ can be eliminated
- Halo formation: when $\delta_s + \delta_m > \delta_c$
  - $\delta_s + \delta_m \approx \delta_s\,(1 + 2f_{NL}\,\varphi_l)$
  - with r.m.s. $\sigma\,(1 + 2f_{NL}\,\varphi_l)$

$\ldots + 3\, g_{NL}\,\varphi_l^2 + \ldots + j\, Q_{NLj}\,\varphi_l^{j-1}$

With NG, extra bias from the potential!

Bias from a mass function

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- halo density Lagrangian perturbation: $\delta_h^L = \dfrac{n(M) - \bar{n}}{\bar{n}}$, $n \propto f(\delta_c/\sigma)$
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- Gaussian case: f = f (M, δ_l)

$$\delta_h^L(\mathbf{q}) = \frac{f\left(\frac{\delta_c - \delta_l(\mathbf{q})}{\sigma}\right)}{f\left(\frac{\delta_c}{\sigma}\right)} - 1 \longrightarrow \delta_h^L(\mathbf{q}) = \sum_{j=0}^{\infty} \frac{b_j^L}{j!}\, \delta_l^j(\mathbf{q})$$

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- Non-Gaussian case: f = f (M, δ_l, φ_l)

$$\delta_h^L(\mathbf{q}) = \frac{f\left(\frac{\delta_c - \delta_l(\mathbf{q})}{[1+2f_{\rm nl}\varphi_l(\mathbf{q})]\sigma}\right)}{f\left(\frac{\delta_c}{\sigma}\right)} - 1 \longrightarrow \delta_h^L(\mathbf{q}) = \sum_{j=0}^{\infty}\sum_{m=0}^{\infty} \frac{b_{jm}^L}{j!m!}\,\delta_l^j(\mathbf{q})\,\varphi_l^m(\mathbf{q})$$

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$\boxed{\text{NG correcting the rms by } 1+2f_{NL}\varphi_l \quad [+\ 3\ g_{NL}\ \varphi_l^2 + \ldots + j\ Q_{NLj}\ \varphi_l^{j-1}]}$

- obviously δ_l, φ_l related by Poisson eq, but non-local

Lagrangian bias

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- Third-order NG expansion:

$$\begin{aligned}\delta_h^L(\mathbf{q}) &= b_0^L + b_{10}^L\,\delta + b_{01}^L\,\varphi + \\ &+ \frac{1}{2!}\left(b_{20}^L\,\delta^2 + 2\,b_{11}^L\,\delta\varphi + b_{02}^L\,\varphi^2\right) + \\ &+ \frac{1}{3!}\left(b_{30}^L\,\delta^3 + 3\,b_{21}^L\,\delta^2\varphi + 3\,b_{12}^L\,\delta\varphi^2 + b_{03}^L\,\varphi^3\right)\end{aligned}$$

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e.g.: $b_{01} = 2\, f_{NL}\, \delta_c\, b_{10}$

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e.g.: $b_{01} = 2\, f_{NL}\, \delta_c\, b_{10}$

- If also g_{NL}: extra terms in b_{02}, b_{12}

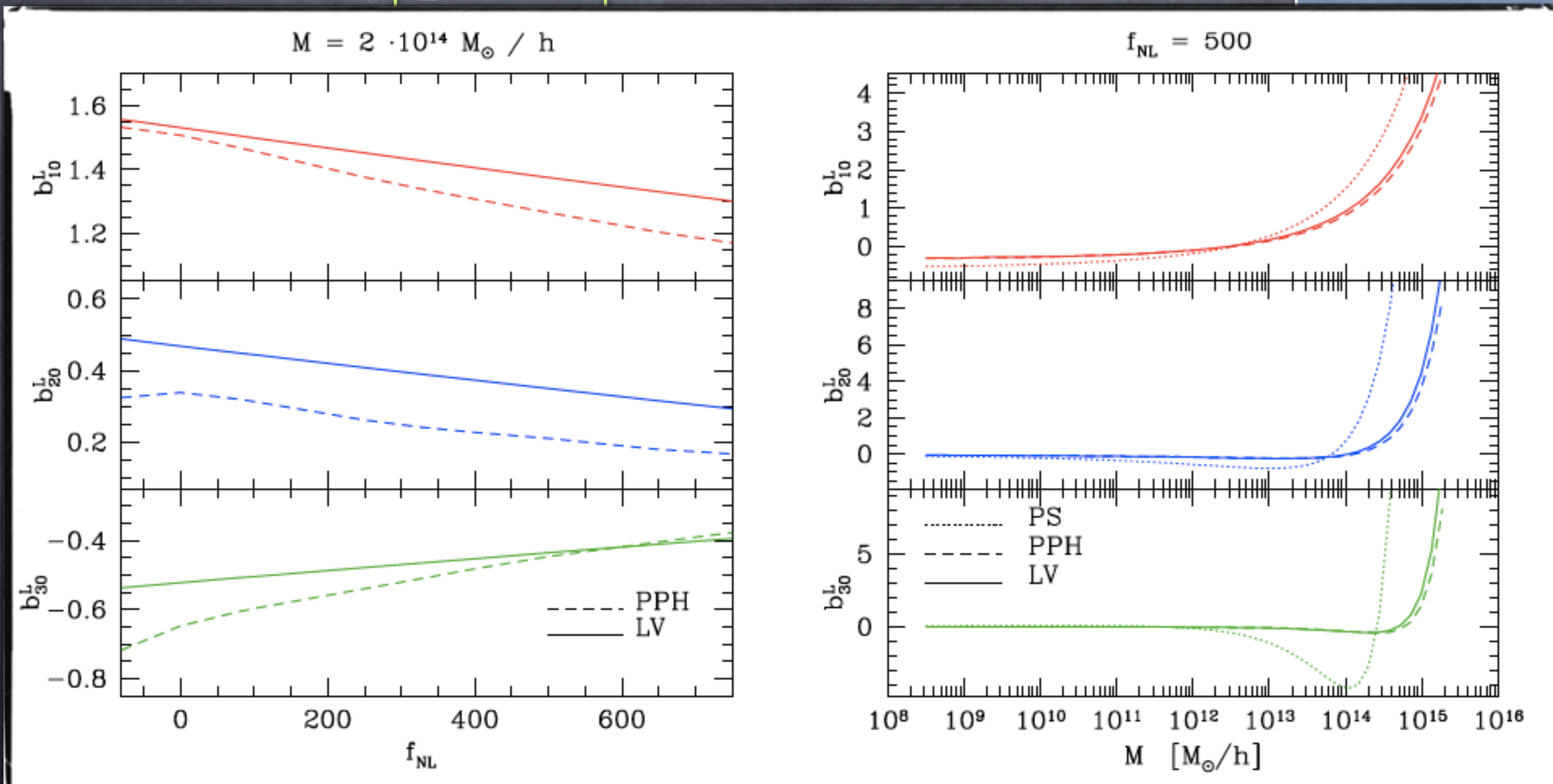
- can be computed from any mass function (PS, LV, PPH, ...)

Lagrangian bias

- Third-order NG expansion:

$$\delta_h^L(\mathbf{q}) = \boxed{b_0^L + b_{10}^L\,\delta + b_{01}^L\,\varphi} + \frac{1}{2!}\left(b_{20}^L\,\delta^2 + 2\,b_{11}^L\,\delta\varphi + b_{02}^L\,\varphi^2\right) +$$

1st-order NG: recovers Dalal et al. 07, etc



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- Observables are **Eulerian**: structure has evolved

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- 3rd order perturbations expansion: $\delta = \delta_1 + \delta_2 + \delta_3$; $\varphi = \varphi_1$

$$\tilde{\delta}_n(\mathbf{k}) = \int \frac{d^3\mathbf{q}_1}{(2\pi)^3} \ldots \frac{d^3\mathbf{q}_n}{(2\pi)^3}\, \delta_D\left(\mathbf{k} - \sum_{i=1}^{n} \mathbf{q}_i\right)\, J_n(\mathbf{q}_1, \ldots, \mathbf{q}_n)\, \tilde{\delta}_1(\mathbf{q}_1) \ldots \tilde{\delta}_1(\mathbf{q}_n)$$

Finally: rewrite δ_h only in terms of δ_1, φ_1

Statistics: Power spectra

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- To harmonic space $\Phi(x) \to \Phi(k)$
- Spectra of $\Phi(k)$: spectra of φ + small corrections
  - $(2\pi)^3 P_\Phi(k)\, \delta_D(k+k') = \langle\Phi(k)\Phi(k')\rangle$ $\approx P_\varphi$
  - $(2\pi)^3 B_\Phi(k)\, \delta_D(k+k'+k'') = \langle\Phi(k)\,\Phi(k')\,\Phi(k'')\rangle$ $\approx 2f_{NL}\,[P_\varphi\, P_\varphi + \mathrm{cyc.}]$
  - $(2\pi)^3 T_\Phi(k)\, \delta_D(k+k'+k''+k''') = \langle\Phi(k)\,\Phi(k')\,\Phi(k'')\,\Phi(k''')\rangle$ $\approx 4f_{NL}^2\,[P_\varphi\, P_\varphi\, (P_\varphi+P_\varphi)+\mathrm{c.}]$

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  - ΔP_Φ small,
  - $\Delta T_\Phi = 6\, g_{NL}\, P_\varphi\, P_\varphi\, P_\varphi + \text{cyc.}$
- linear density perturbations $\delta_1(k) = \alpha(k)\,\Phi(k)$
  - $P_0(k) = \alpha^2(k)\, P_\Phi(k) \approx \alpha^2(k)\, P_\varphi(k)$
  - $B_0(k)$, $T_0(k)$ similar

$$\alpha(k) = \frac{2c^2k^2T(k)D(z)}{3\Omega_m H_0^2}$$

- we can now move on to density full spectra...

Matter spectra [Taruya et al. 08]

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- <δδ>, with $\delta = \delta_1 + \delta_2 + \delta_3$
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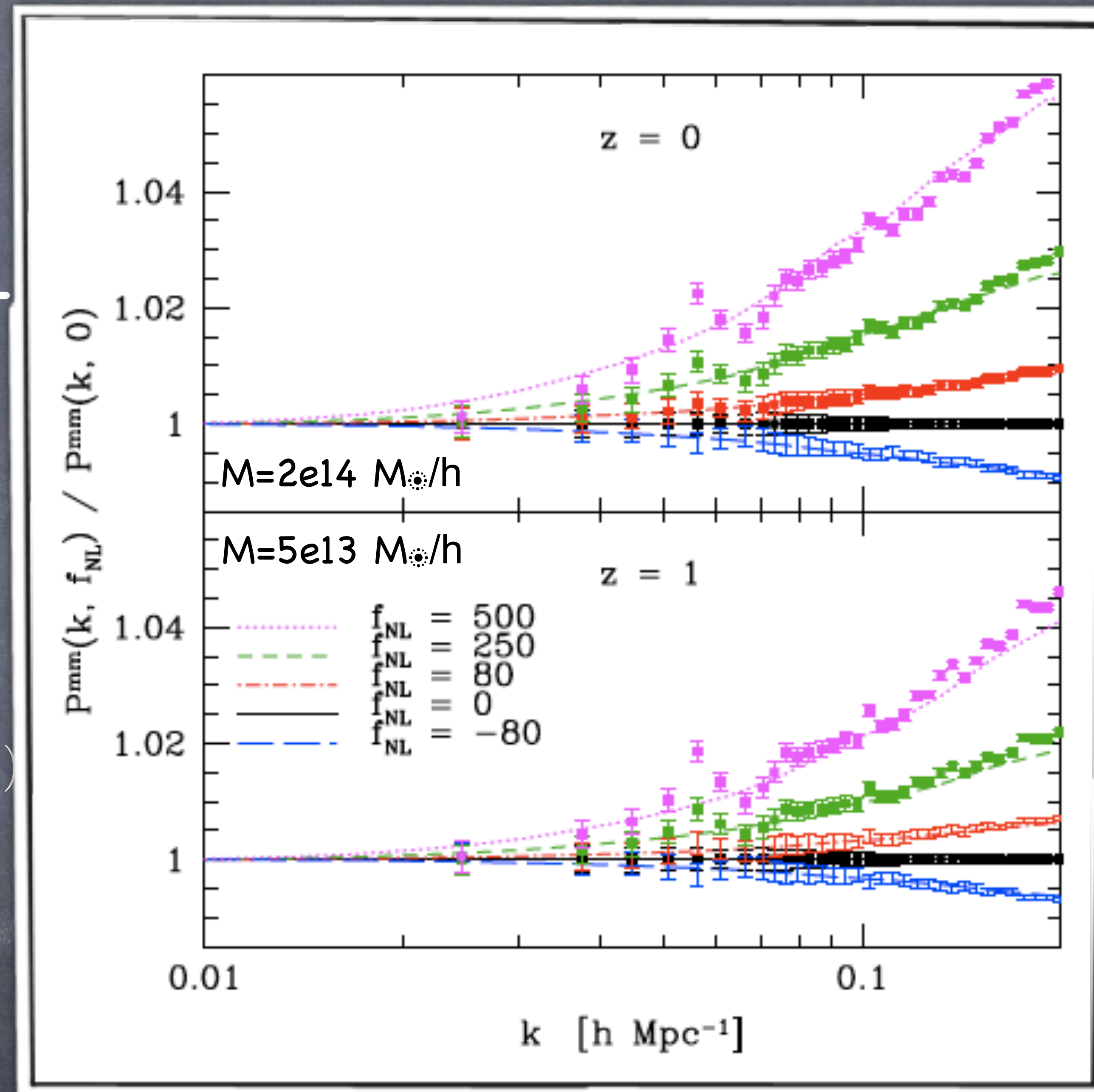

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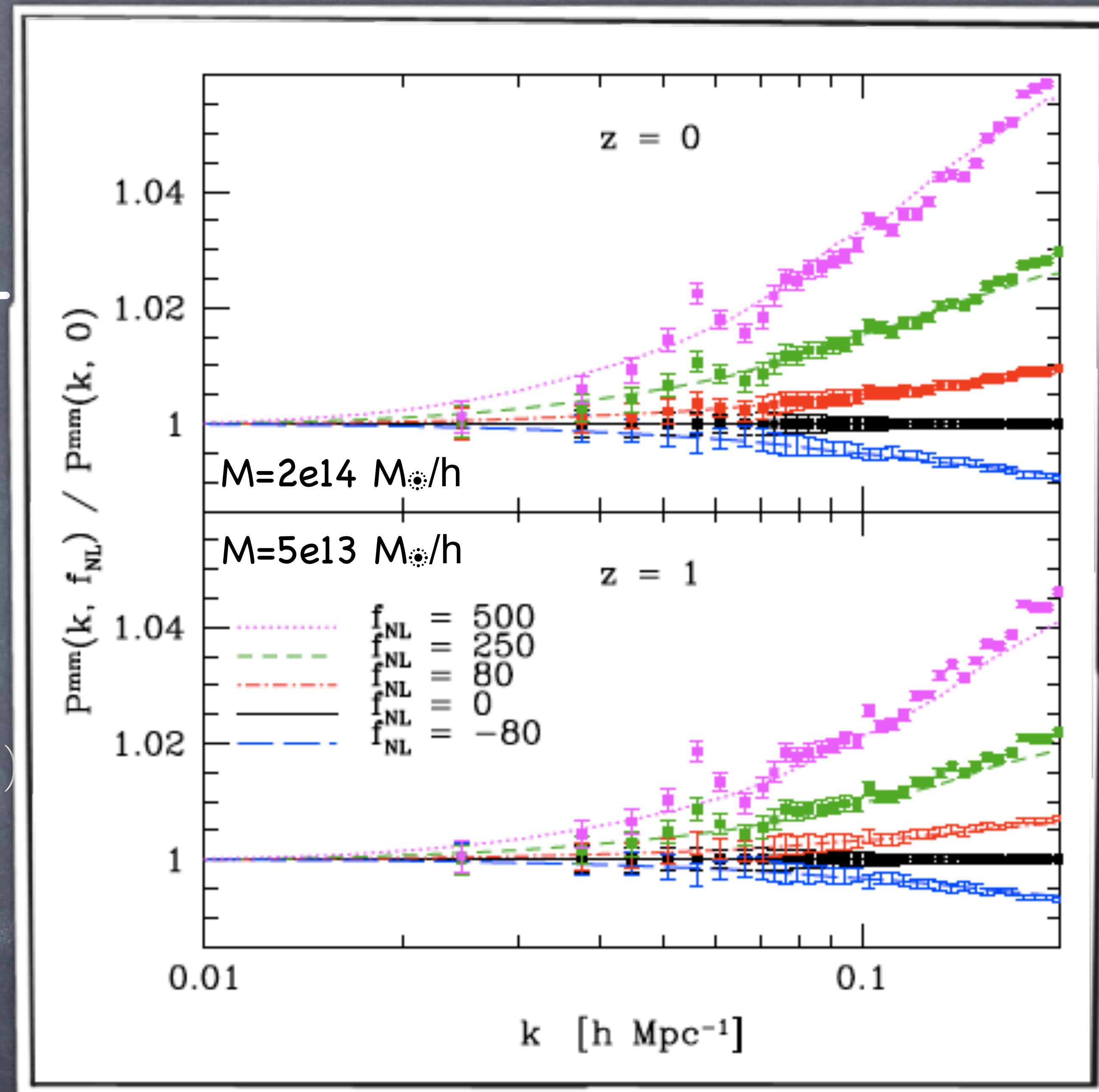


Excellent agreement with Taruya et al up to k = 0.2 h/Mpc

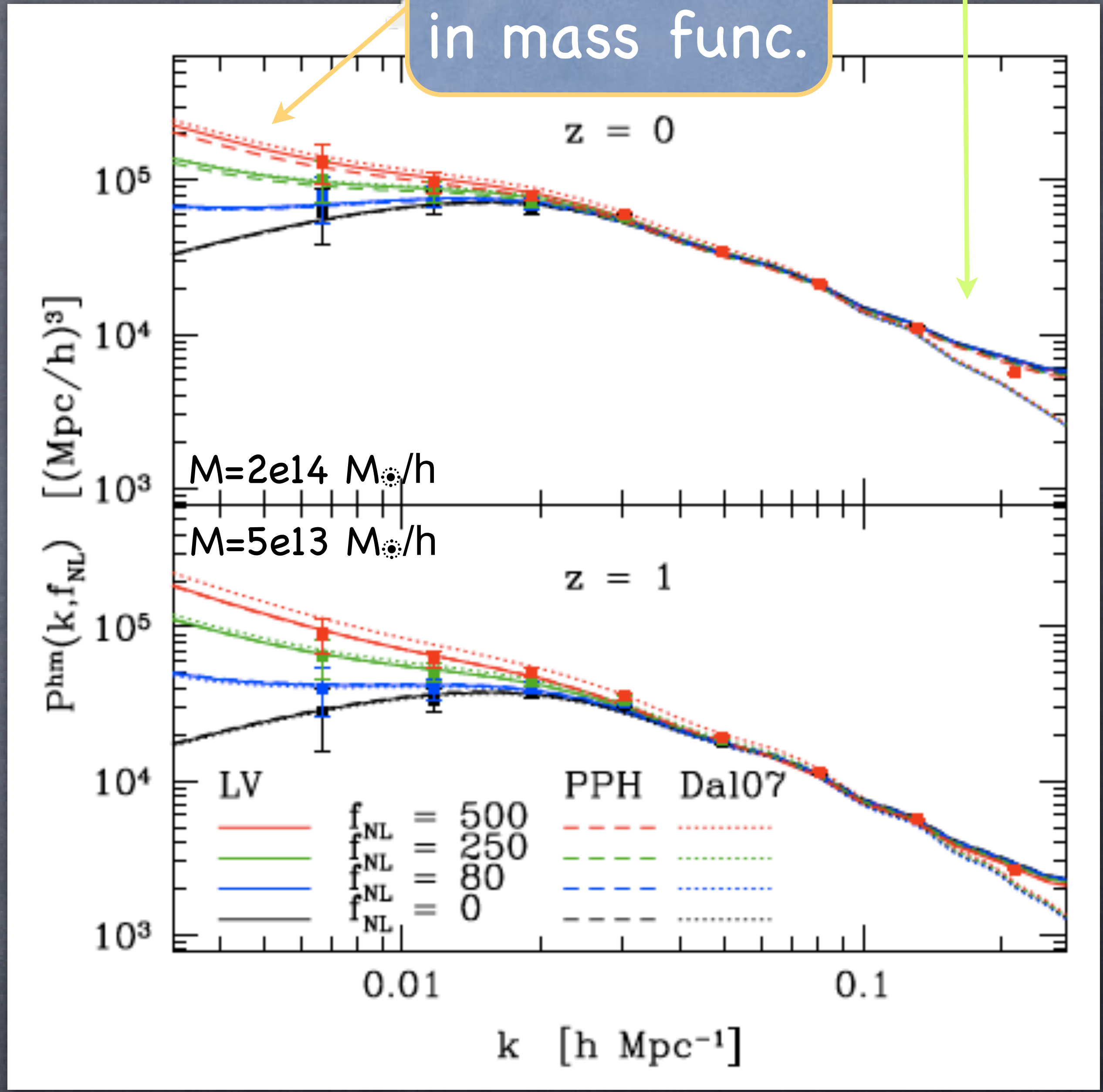
Halo spectra

Halo spectra

Non-linearity

- $\langle\delta_i\delta_j\rangle$ (i,j = halo or matter)
  - δ_h = full expansion (δ,φ)
- $P^{ij}(k, z) = D^2 P^{ij}_{11} + D^3 P^{ij}_{12} + D^4 (P^{ij}_{22} + P^{ij}_{13})$
  - **MANY** terms now, of the types
  - $\langle\delta_1\delta_1\rangle \rightarrow P_0$
  - $\langle\delta_2\delta_2\rangle \rightarrow F_2 T_0 \approx F_2 P_0 P_0$
  - $\langle\delta_1\delta_3\rangle \rightarrow F_3 T_0 \approx F_3 P_0 P_0$
  - $\langle\delta_1\delta_2\rangle \rightarrow F_2 B_0$
  - for haloes some δ_1 replaced by $\varphi=\delta_1/\alpha$

Offset: f_{NL} in mass func.



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  - for haloes some δ_1 replaced by $\varphi=\delta_1/\alpha$
- Our result:
  - ✓ reproduces Dalal et al. 07 at linear order
  - ✓ gives standard 1-loop theory if f_{NL} = 0
  - ✓ contains all terms by Taruya et al. 08, Sefusatti 09 + extra terms
  - ✓ is fully consistent and complete

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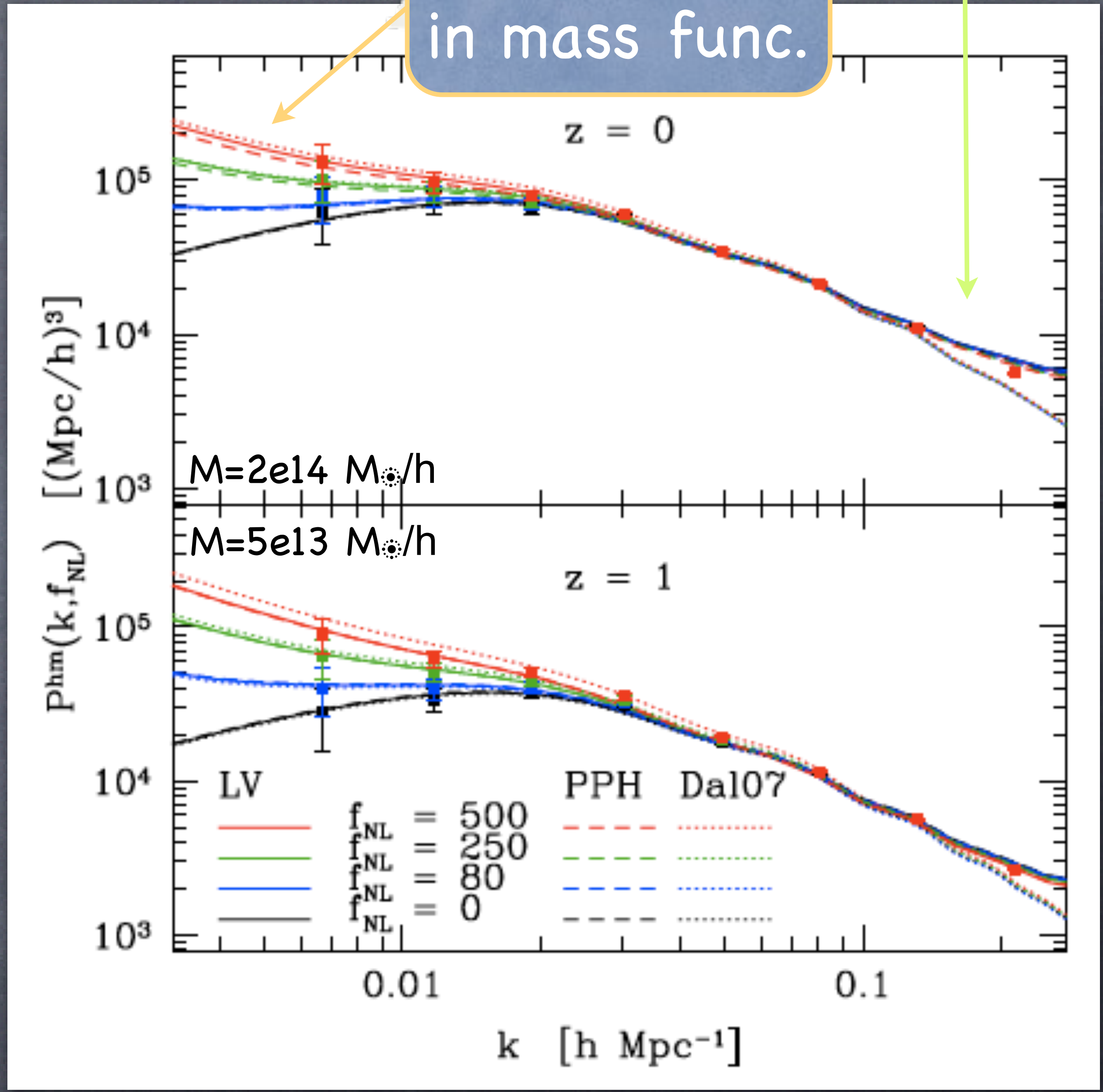

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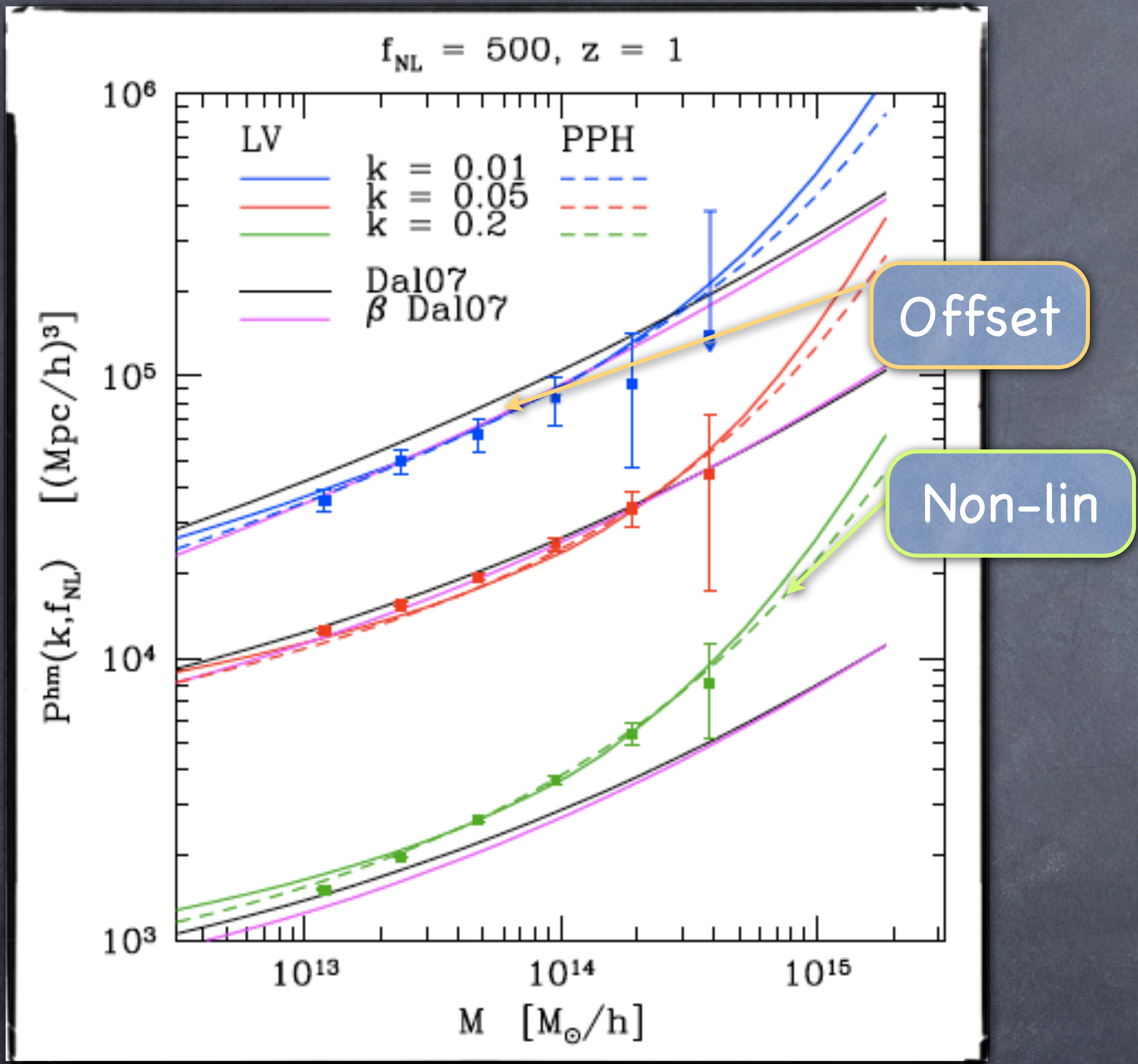
Mass dependency



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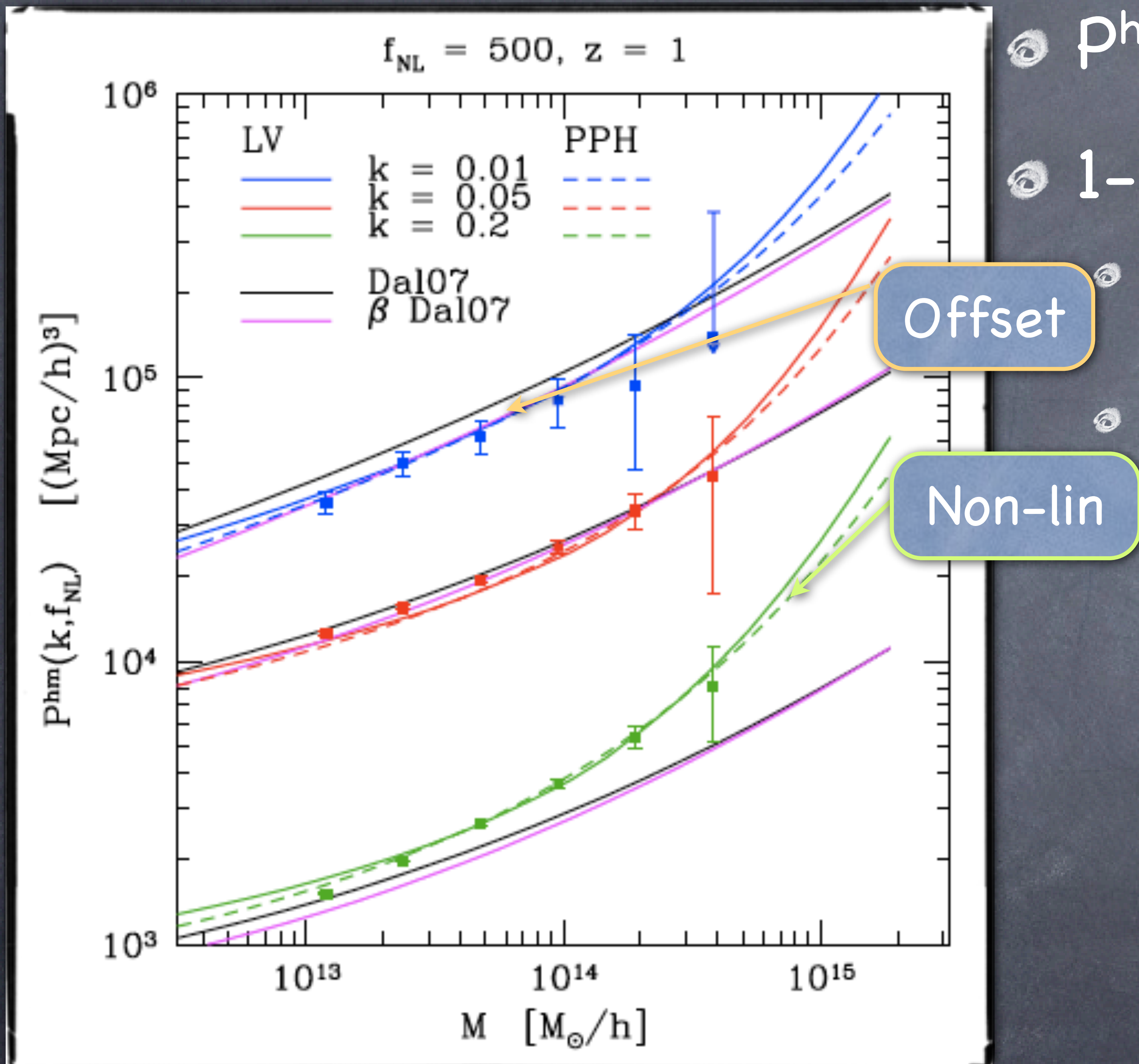

- $P^{hm}(M)$ at 3 scales
- 1-loop: superior accuracy
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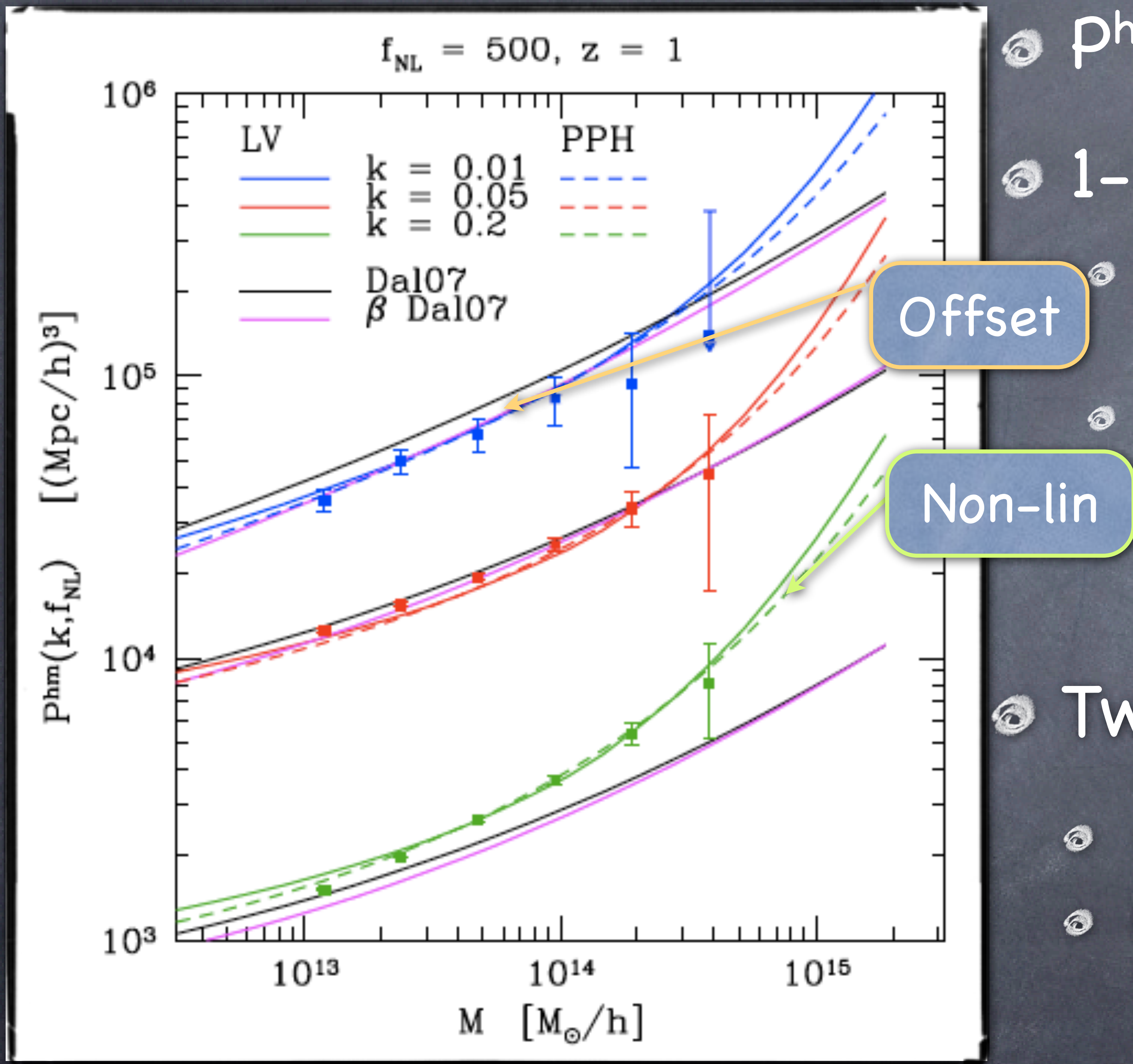

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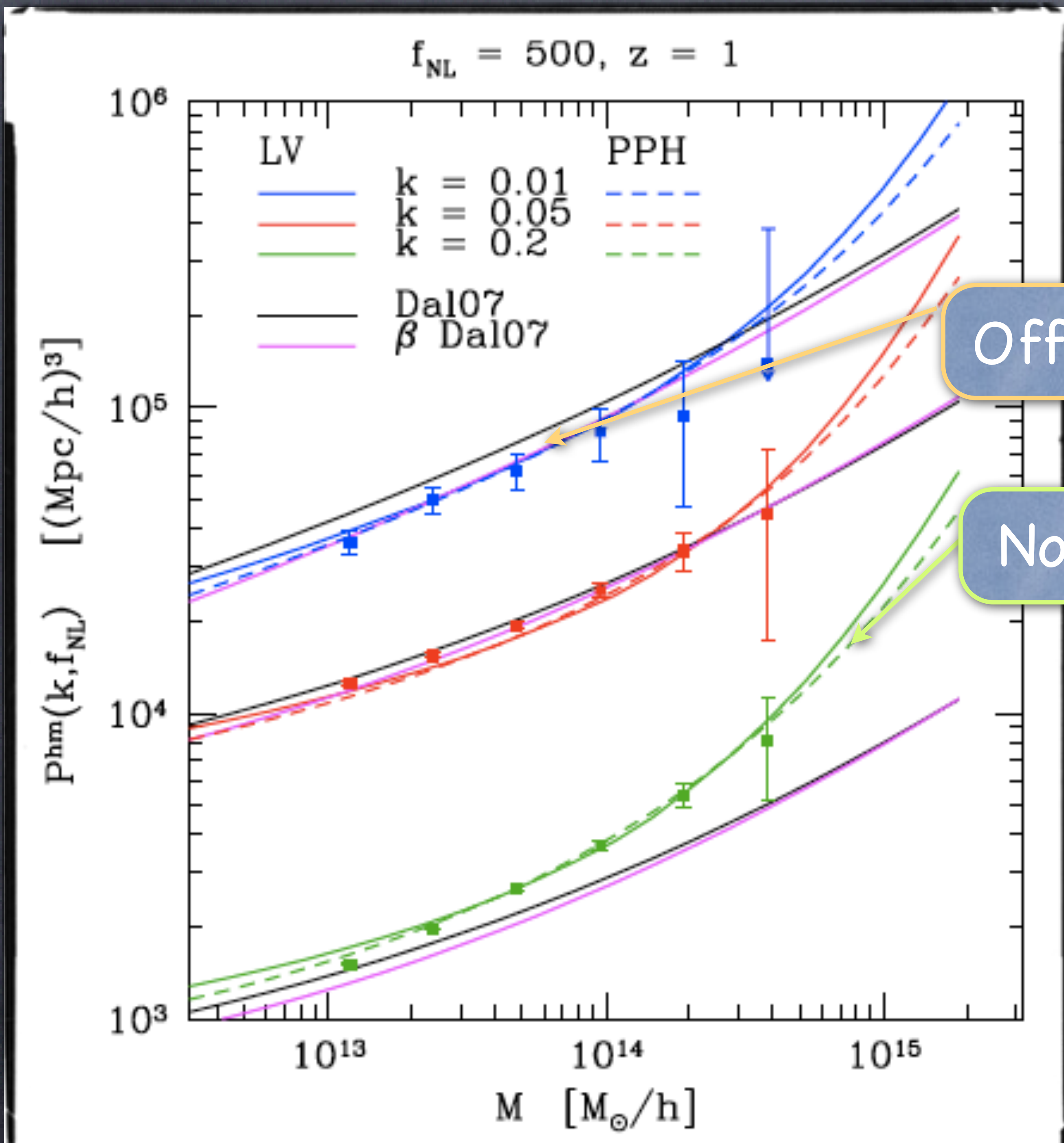
Mass dependency



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$$\Delta b_{\rm lin}(k) = \boxed{b_{10}(f_{\rm NL}) - b_{10}(f_{\rm NL}=0)} + \boxed{2 f_{\rm NL}\delta_c \left[b_{10}(f_{\rm NL}) - 1\right]/\alpha(k)}$$

The effect of g_{NL}

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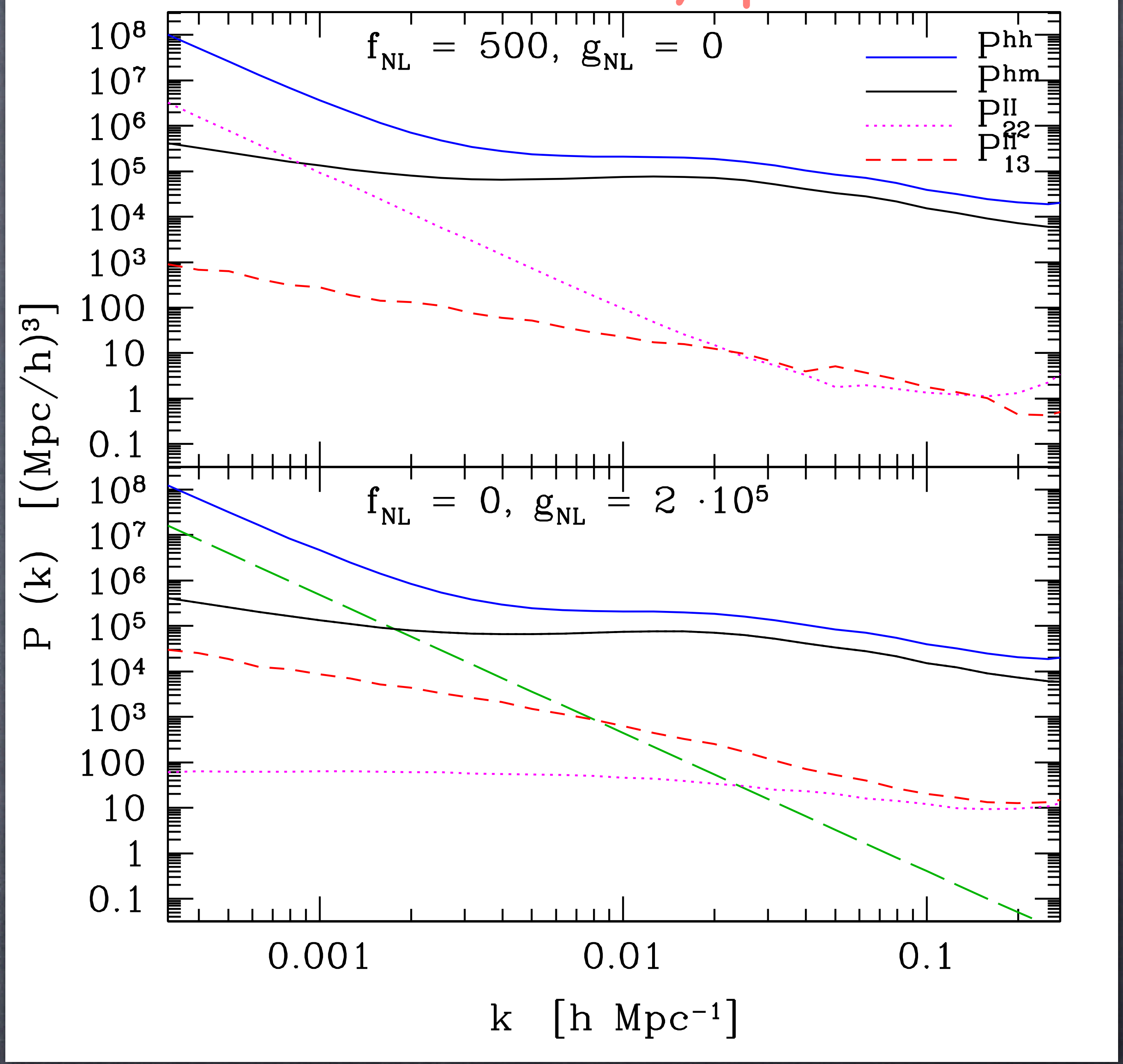
- New terms from two sources:
  - Trispectrum correction $\Delta T \propto g_{NL}$
  - bias corrections $\propto g_{NL}$

Preliminary plot!



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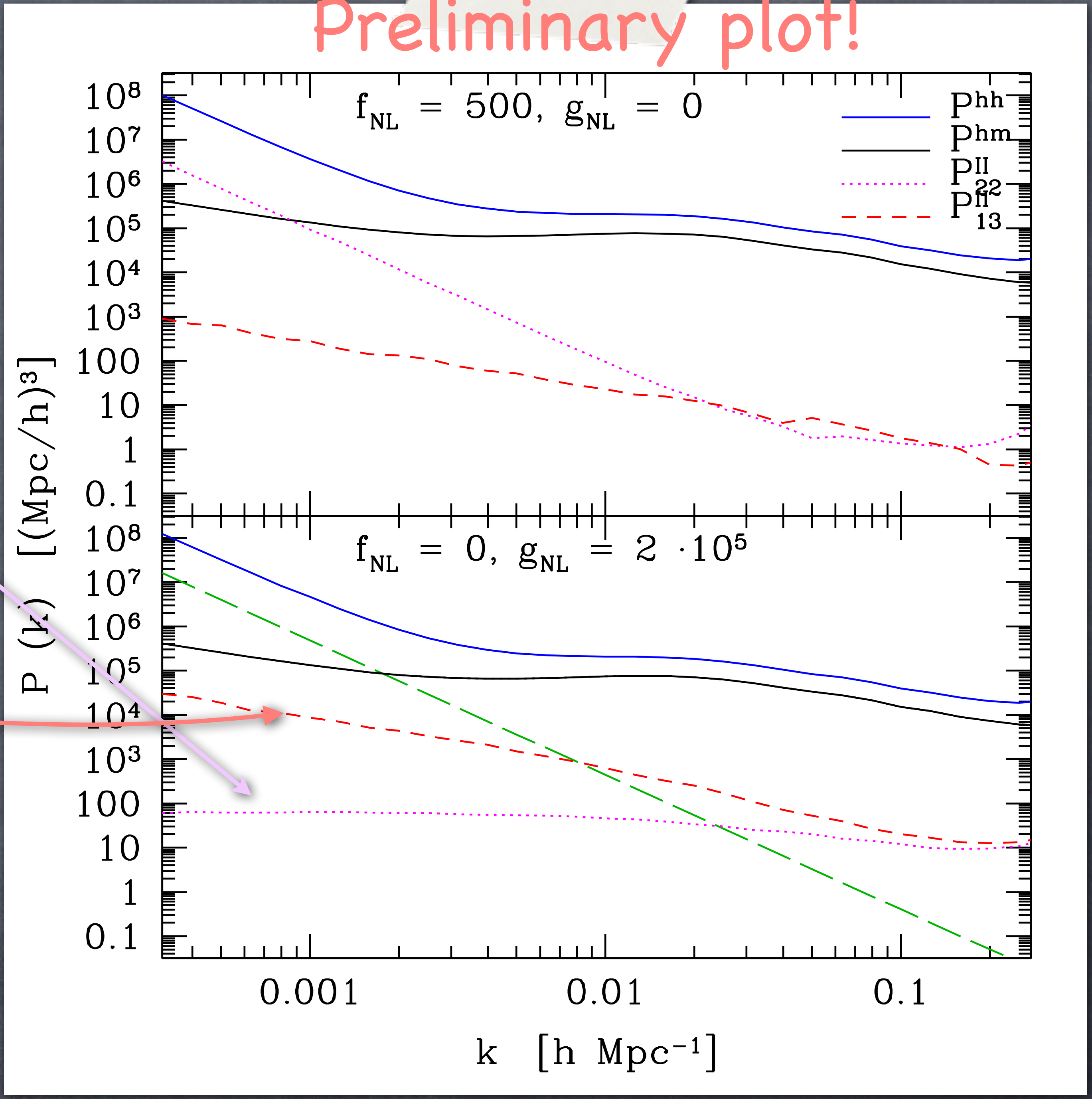

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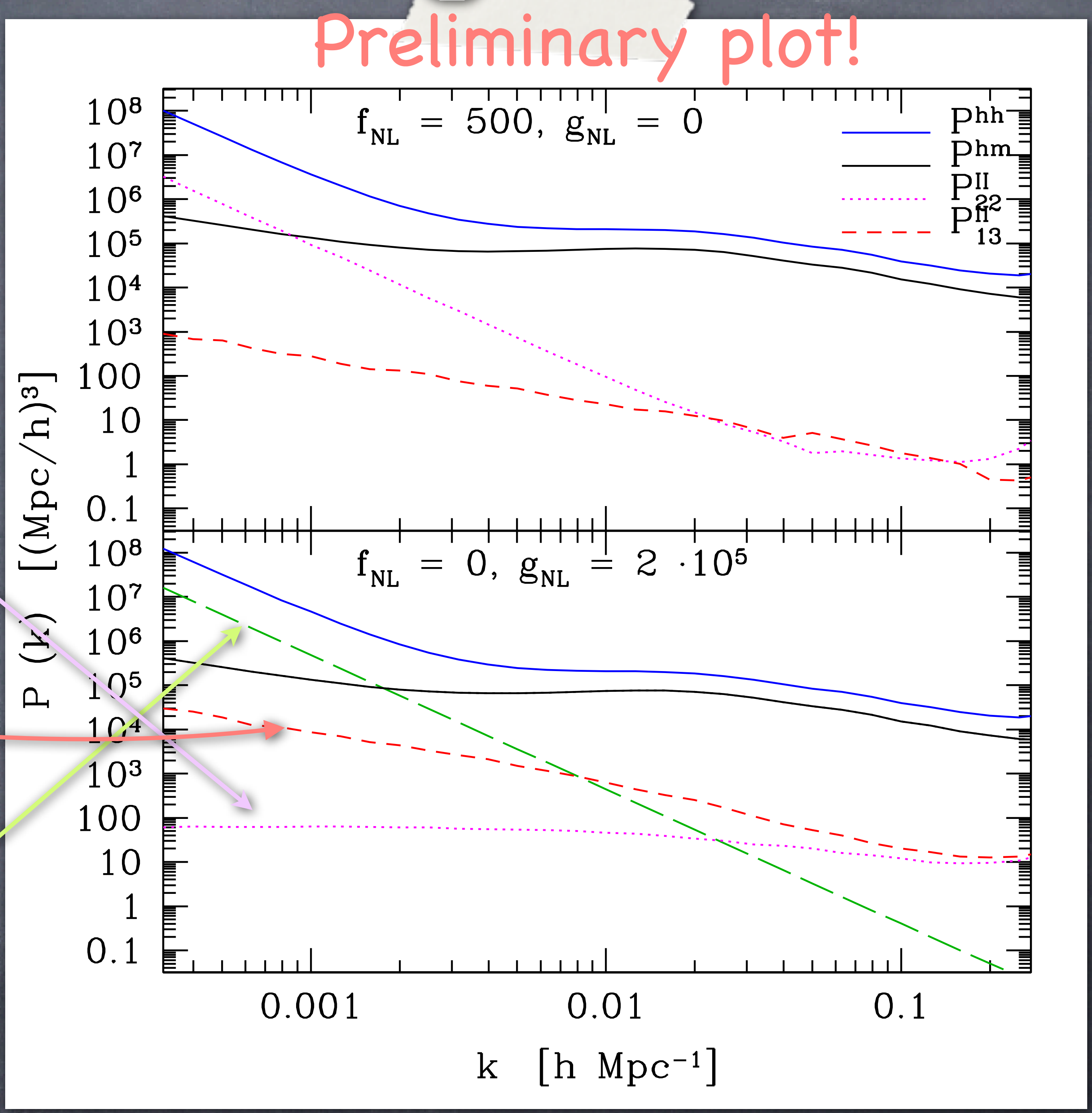
  - In halo-halo only: add terms to P^{ij}_{22} (subdominant)
  - and to P^{ij}_{13} (can be dominant for large g_{NL})
- Bias corrections $\propto g_{NL}$
  - Only b_{02}, b_{12} are altered
  - In halo-matter, subdominant
  - In halo-halo, term in $b_{02}^2 \propto g_{NL}^2$ can be dominant for large g_{NL}, small f_{NL}



Differences from local approach

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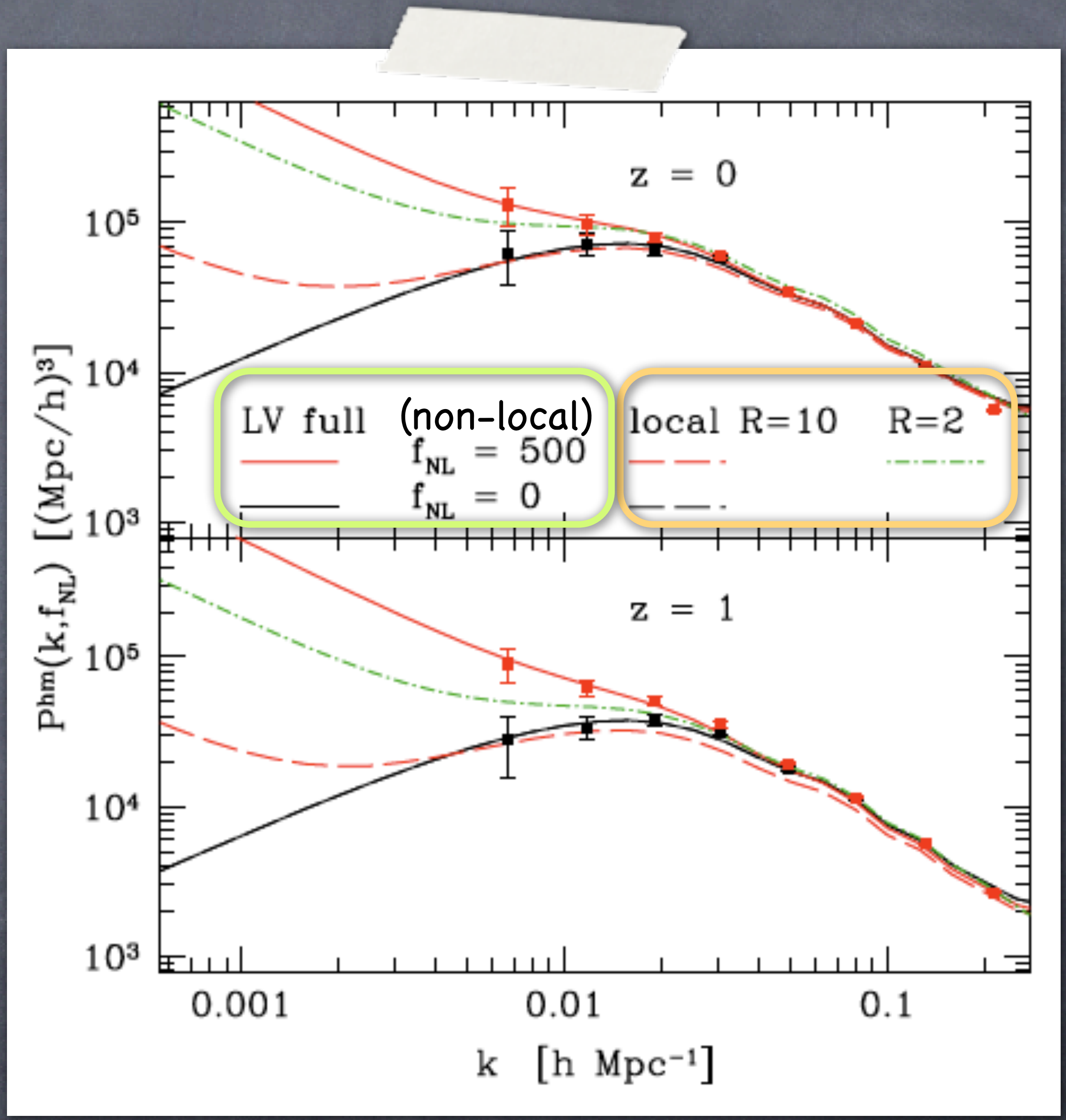
Bivariate (or non-local) b vs. local b [Taruya et al. 08, Sefusatti 09, Matarrese & Verde 08]



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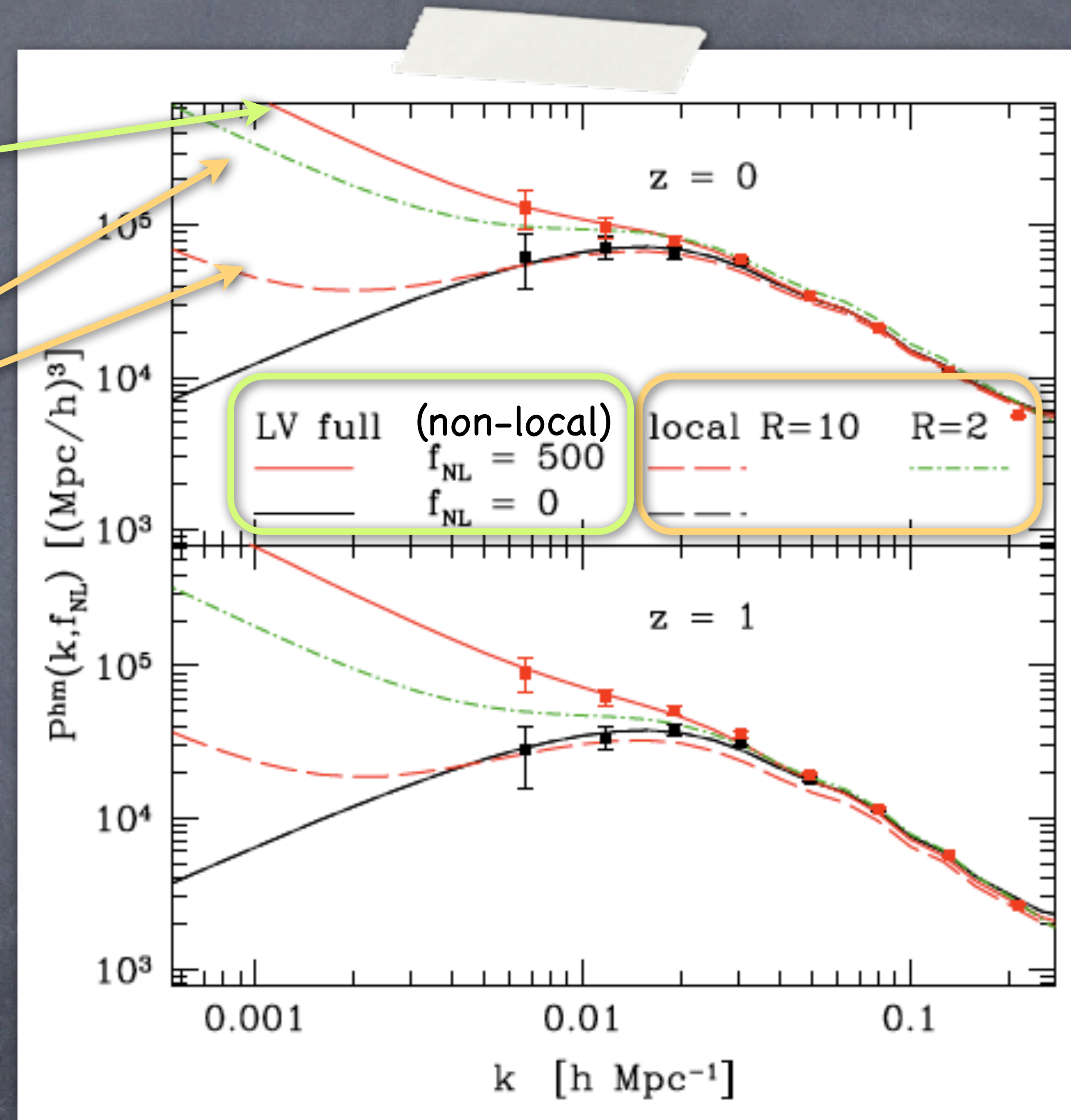
- At leading order:
- we recover $\Delta b \propto b_{10}-1$ from $\langle\delta_1\varphi\rangle$
- No strong dependence on R smoothing at leading order
- in local approach is found $\Delta b \propto b_{20}\,\sigma^2(R)$ from $\langle\delta_1\delta_1^2\rangle$
- This is ∝ R smoothing
  - equivalent only if: high peaks ($\delta_c\, b_{10}^{L2} \sim b_{10}^{L}\, b_{20}^{L} \sim \delta_c^3$), smoothing R = halo Lagrangian R
  - but then $\sigma \sim 1$, so pert. theory problematic



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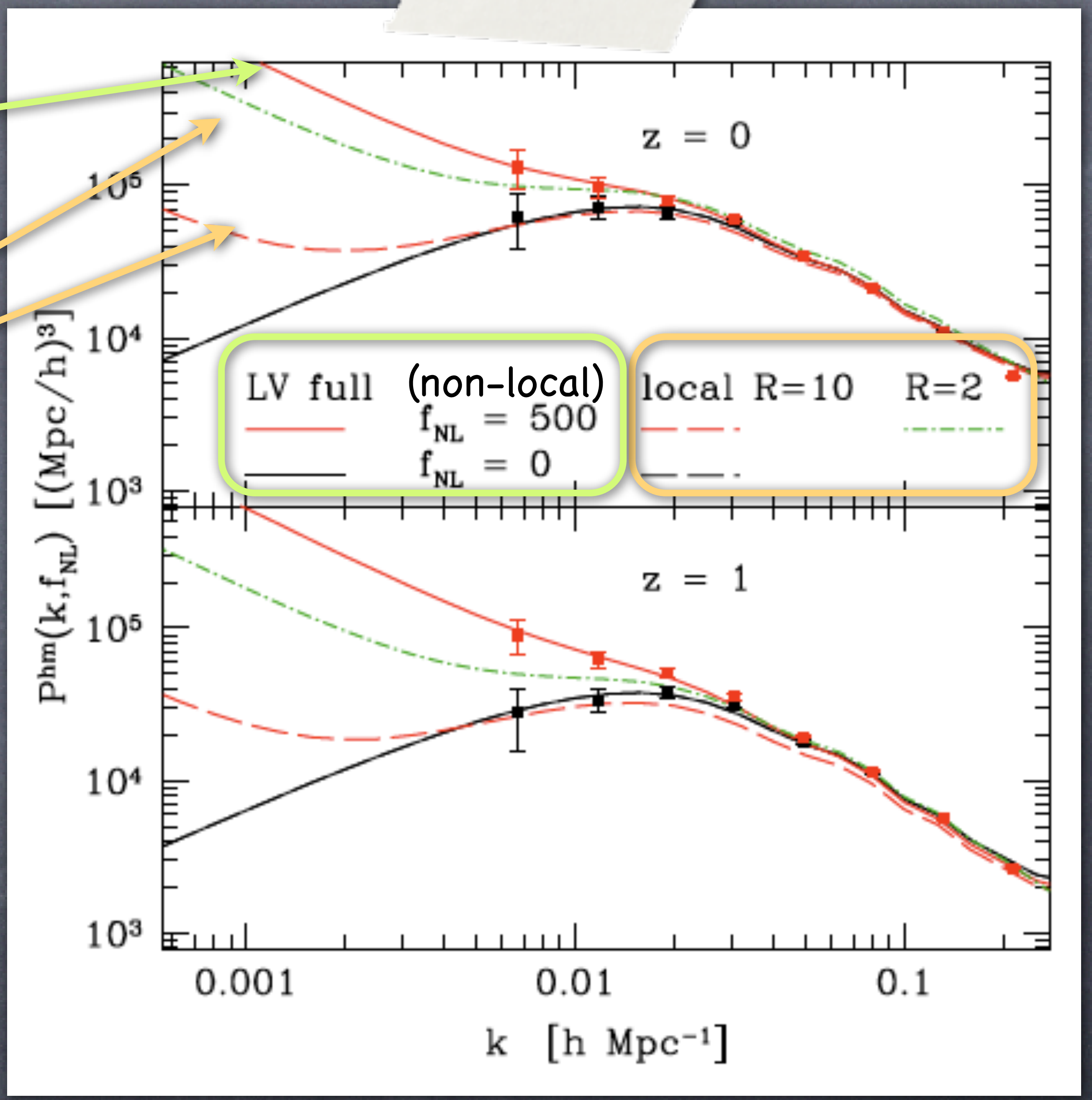
  - but then $\sigma \sim 1$, so pert. theory problematic
- Asymptotic k-dependence identical
  - so no problem if b's are free fitting parameters, or renormalised a la McDonalds 08
- but non-local (bivariate) method needed for predictive bias theory



Physical meaning: large-scale δ_h trace φ, not δ!

Bispectra

from

Sefusatti talk

Isosceles triangles

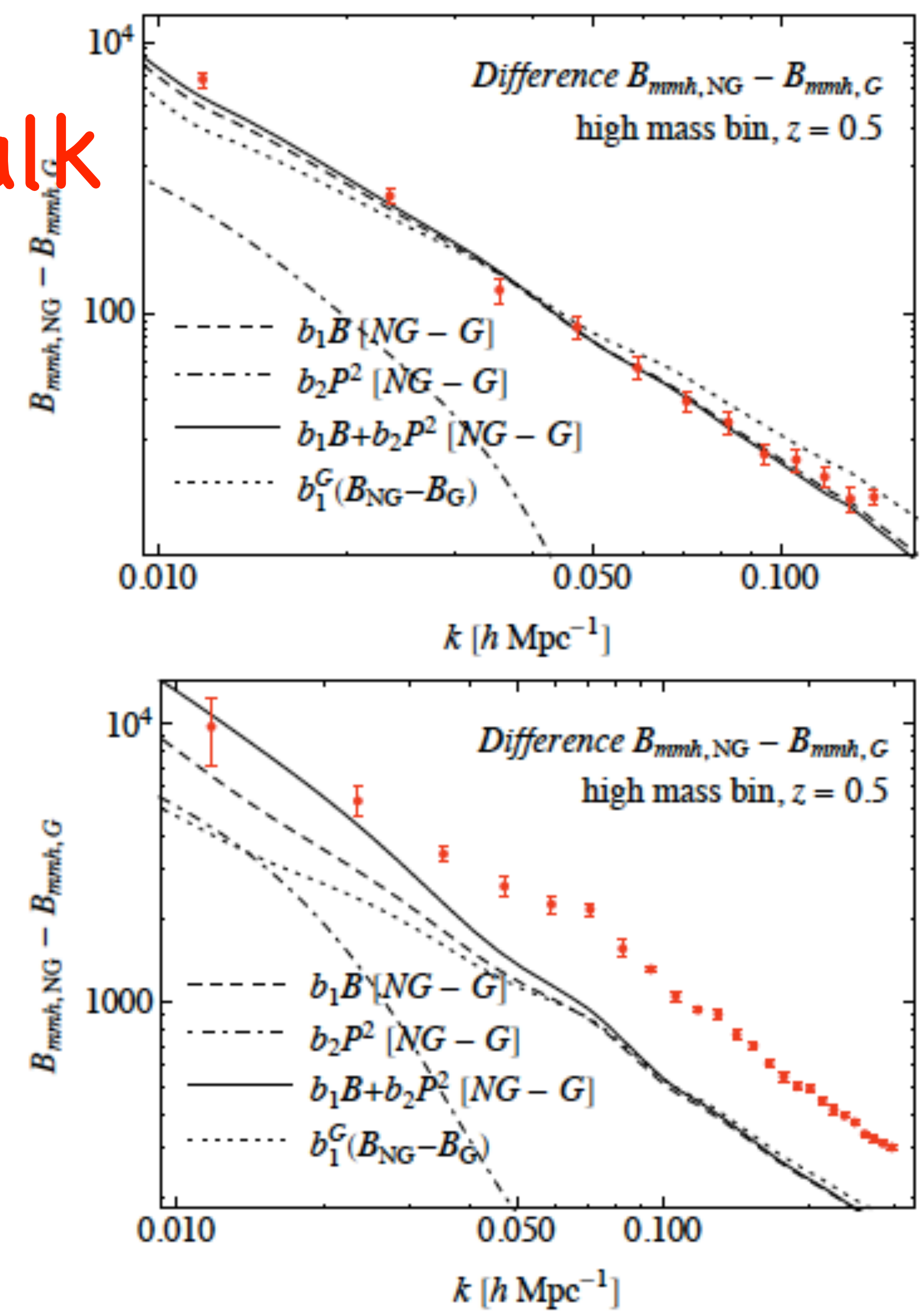
$B(2k, 2k, k)$ vs k

(Non-Gaussian IC)

Squeezed triangles

$B(k, k, \Delta k)$ vs k

(Non-Gaussian IC)



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Bispectra

- $\langle\delta_h\delta_h\delta_h\rangle$ in local bias [Sefusatti 09, Jeong & Komatsu 09]:
    - $B_h(k,k,k) = b_1^3\, B_\delta(k,k,k) + b_1^2\, b_2\, [P_\delta(k)\, P_\delta(k) + \text{cyc.} + \int T_\delta]$
- Non-local approach:
    - many new terms!
- SEE TALKS BY Sefusatti & Baldauf! (last week)
- Higher-order terms depend on all f_{NL}, g_{NL}, τ_{NL}: interesting!

from Sefusatti talk

Isosceles triangles

$B(2k, 2k, k)$ vs k

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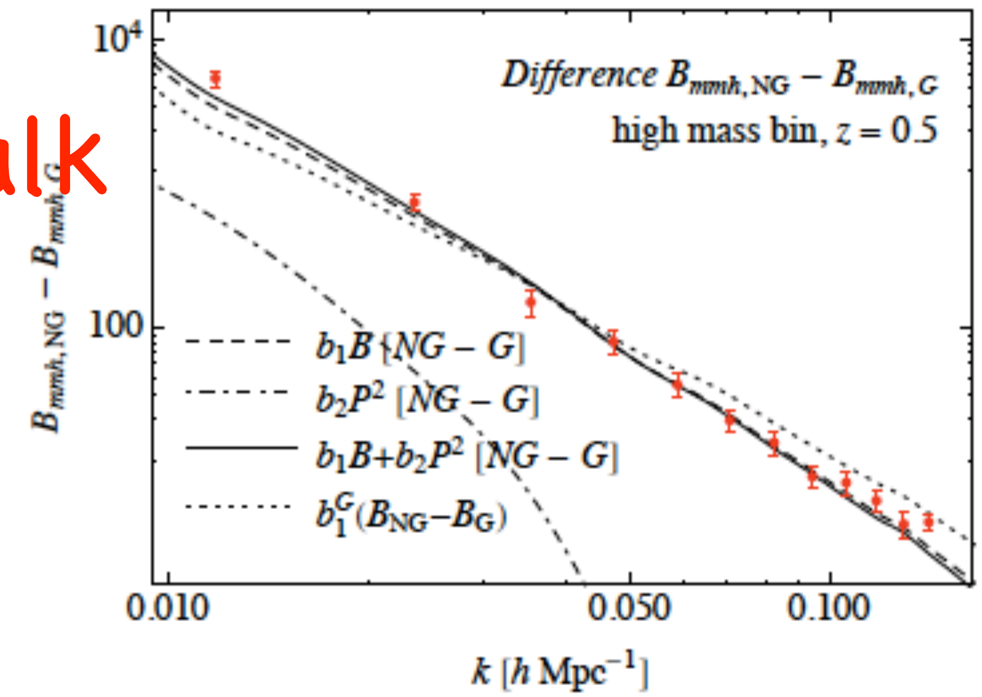

Squeezed triangles

$B(k, k, \Delta k)$ vs k

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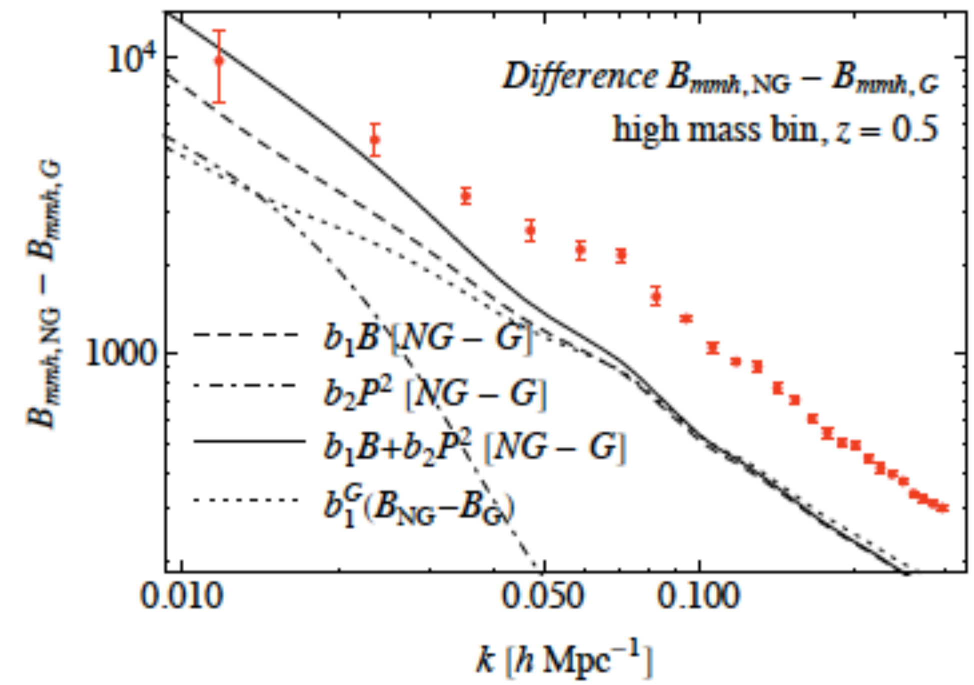

Measuring NG with future surveys

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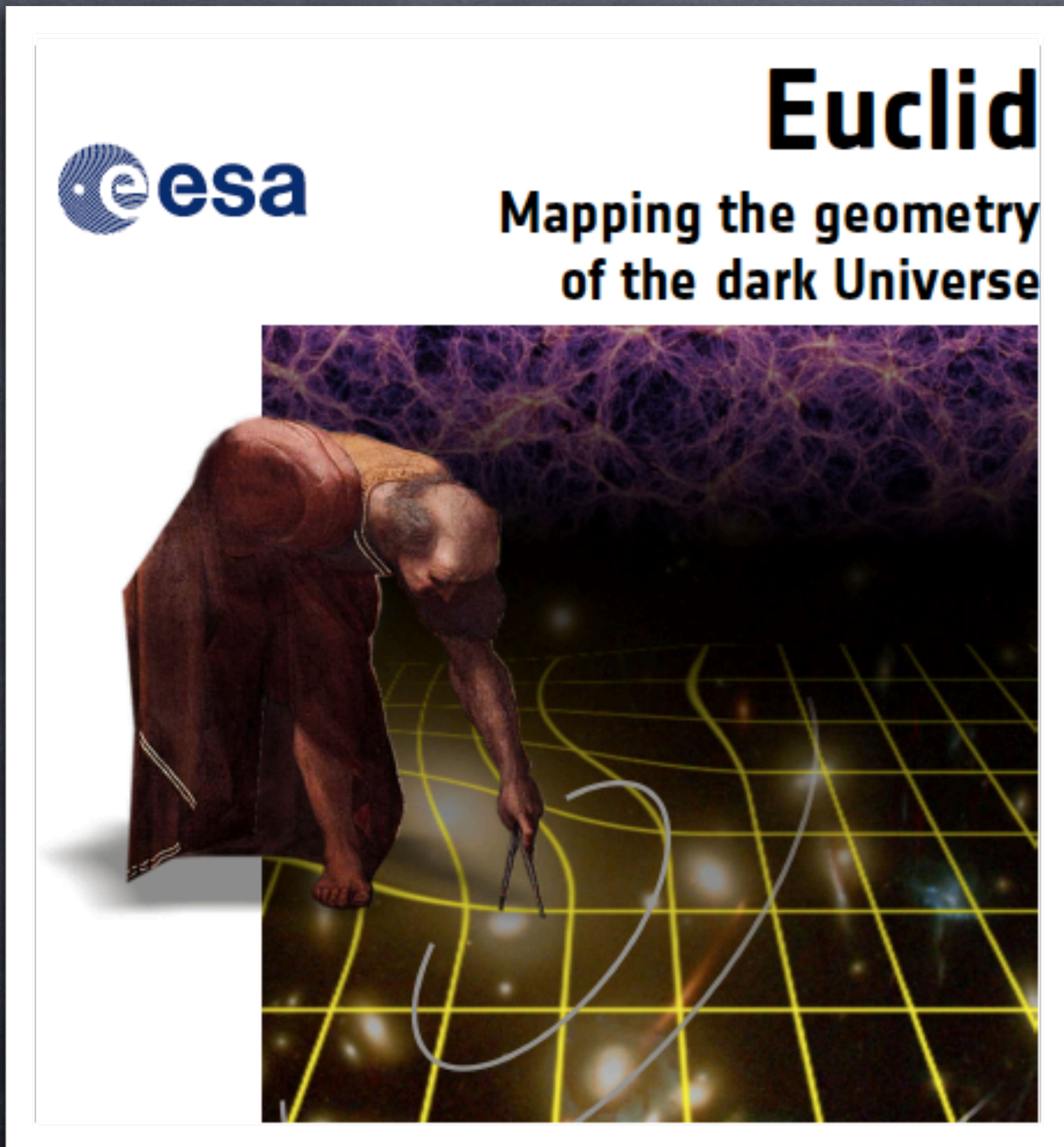

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- L2 orbiter, launch: 2018?
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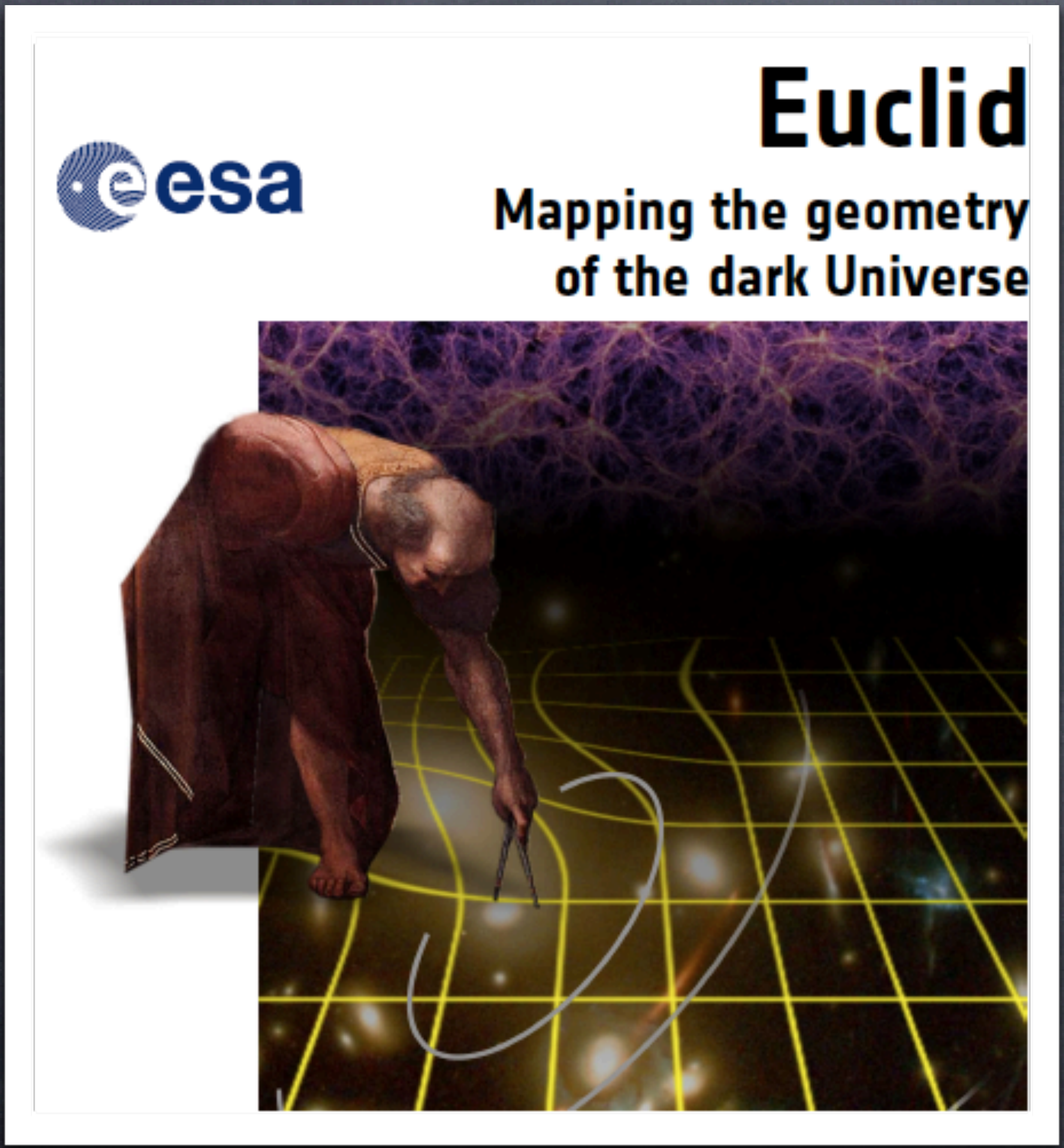

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- Key probes: weak lensing, BAO and full P(k)
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  - measure w_0 @ 2%, w_a @ 10%
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  - improving Planck constraints 20x
  - testing LSS and DM paradigm
  - and non-Gaussianity?

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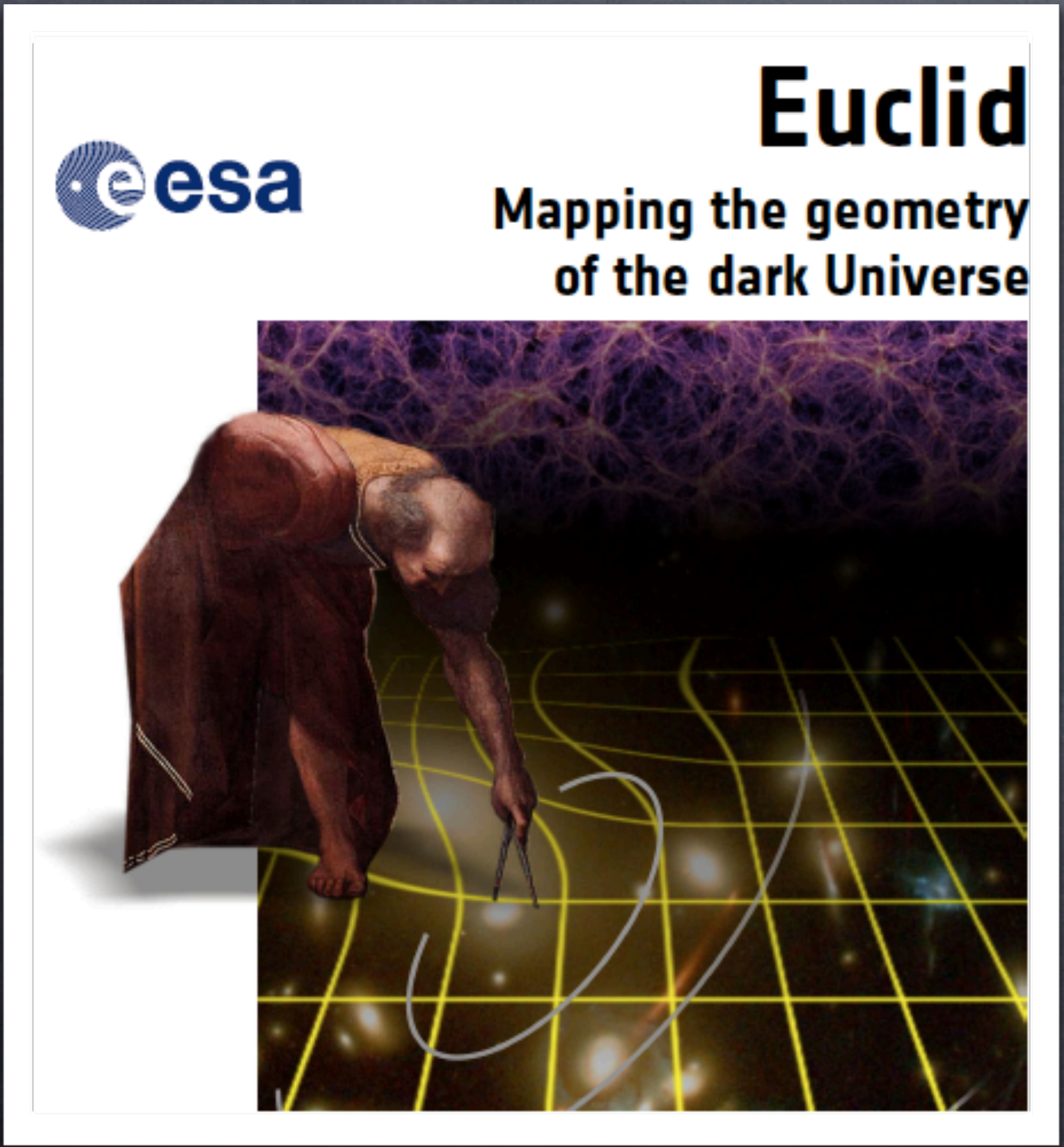

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Fisher matrix forecasts for NG [TG et al, in prep]

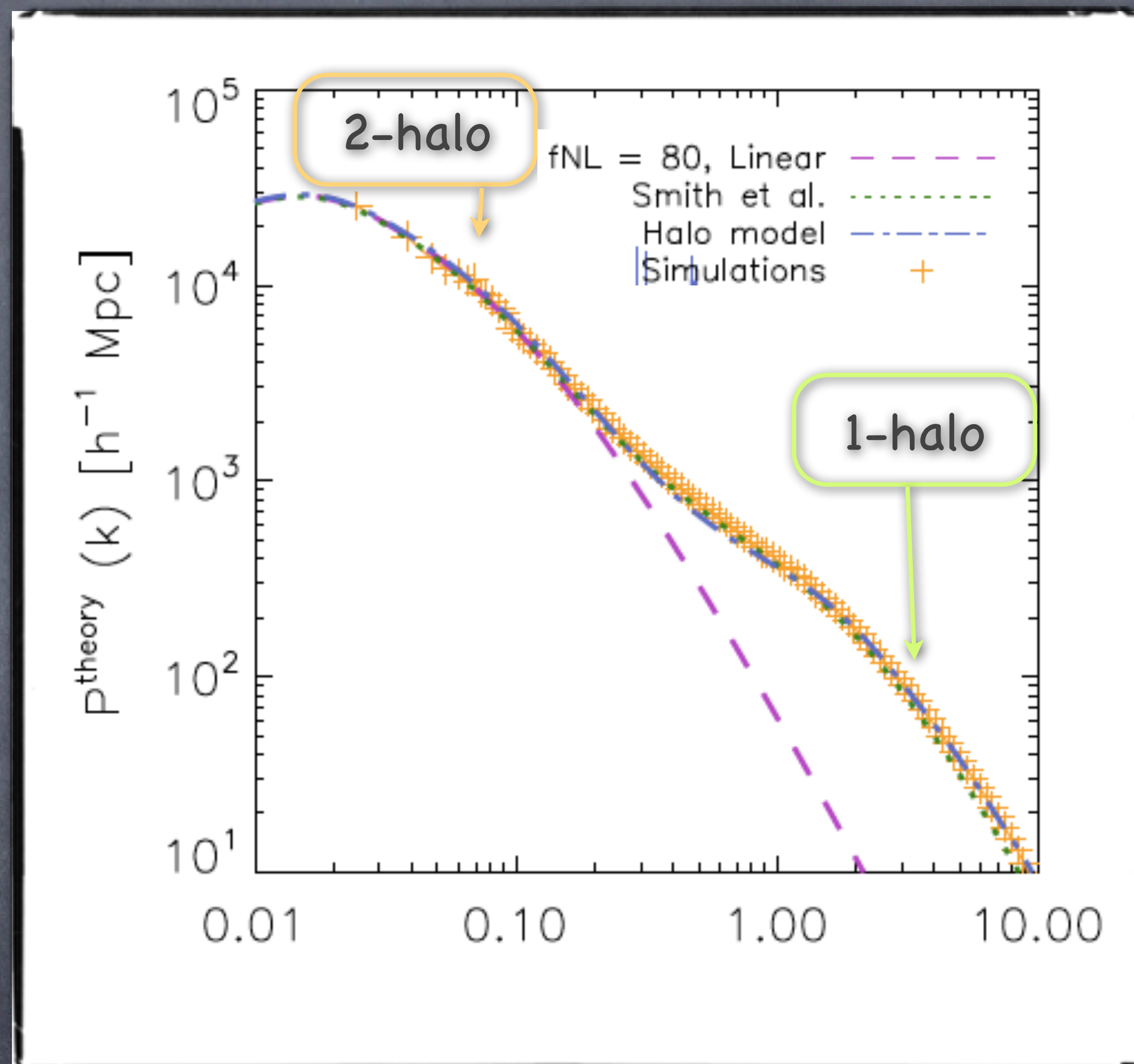
(See also Fedeli & Moscardini 09, Carbone Verde et al. 08, 10)

The non-linear regime

k [h/Mpc]

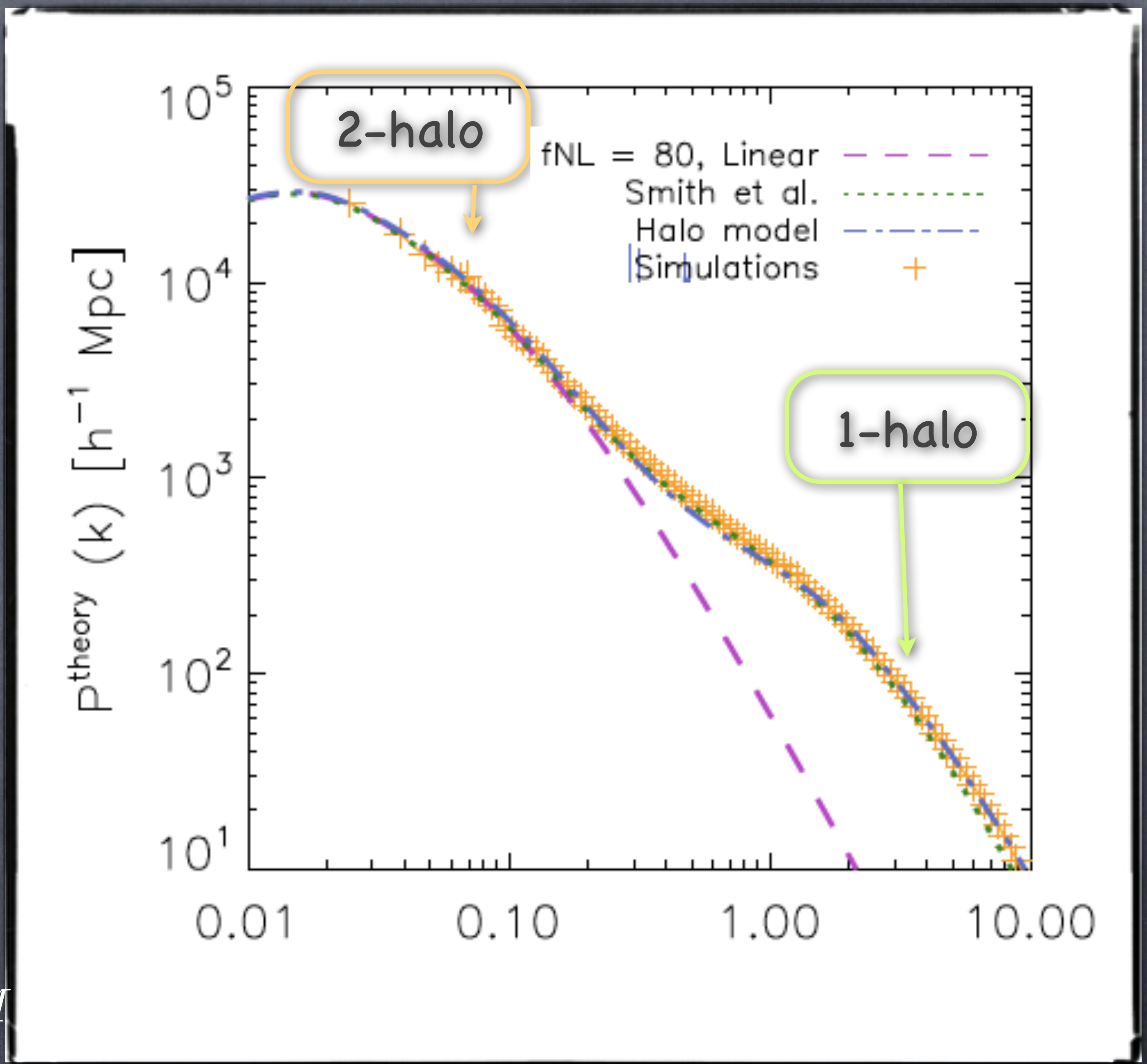
The non-linear regime

- For lensing, deep into non-lin.



The non-linear regime

- For lensing, deep into non-lin.
- Halo model: P(k) = P_1 + P_2
  [Ma & Fry 00, Seljak 00]
  - within one halo and 2-haloes
- Mass function:
  - LoVerde, as correction to PPH fit
- Bias:
  - Linear theory:
  - b (k) = b_{10} + $\Delta b_{\rm lin}$ (k)
- Halo profile
  - NFW fitting concentration from simul

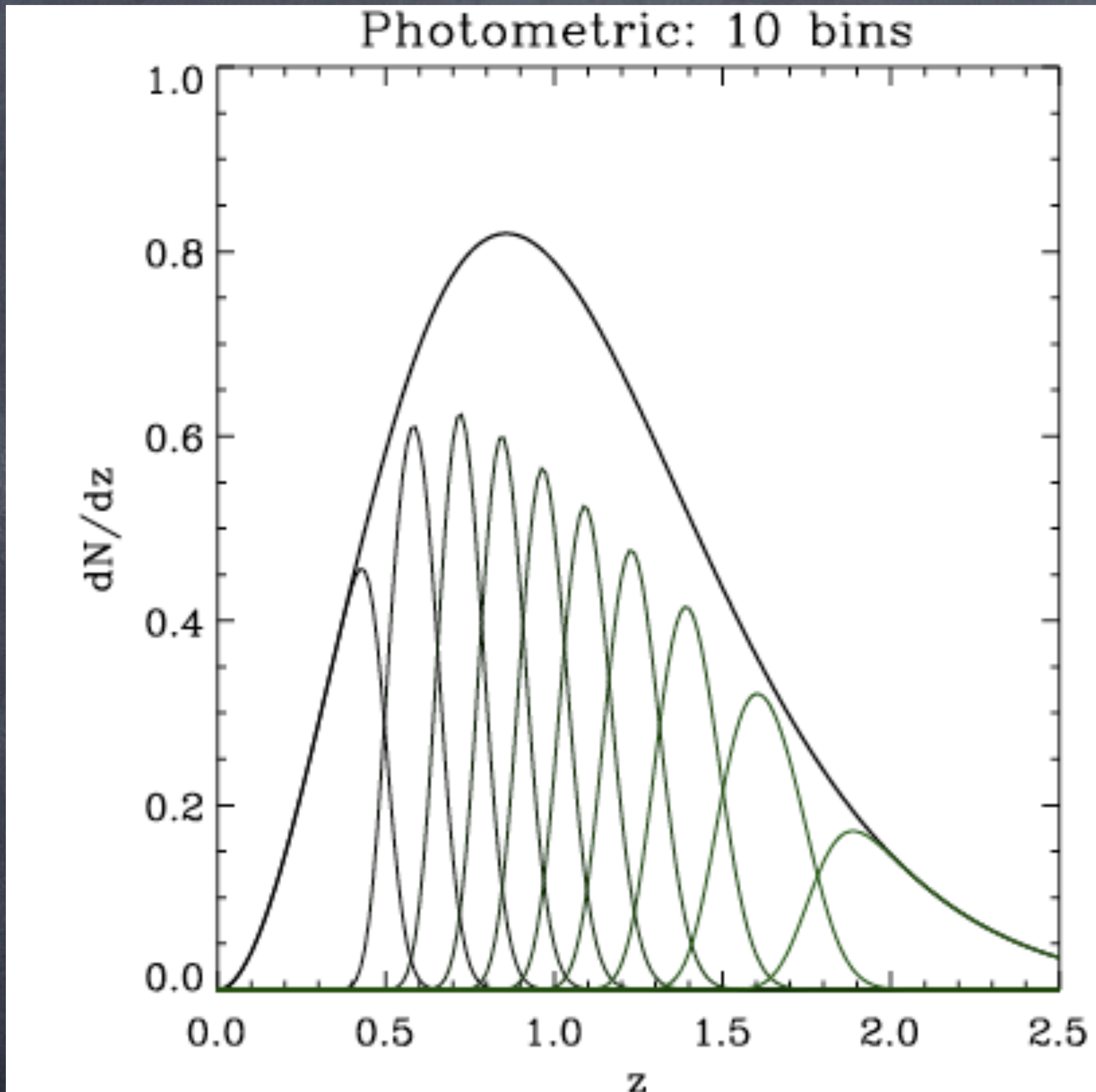


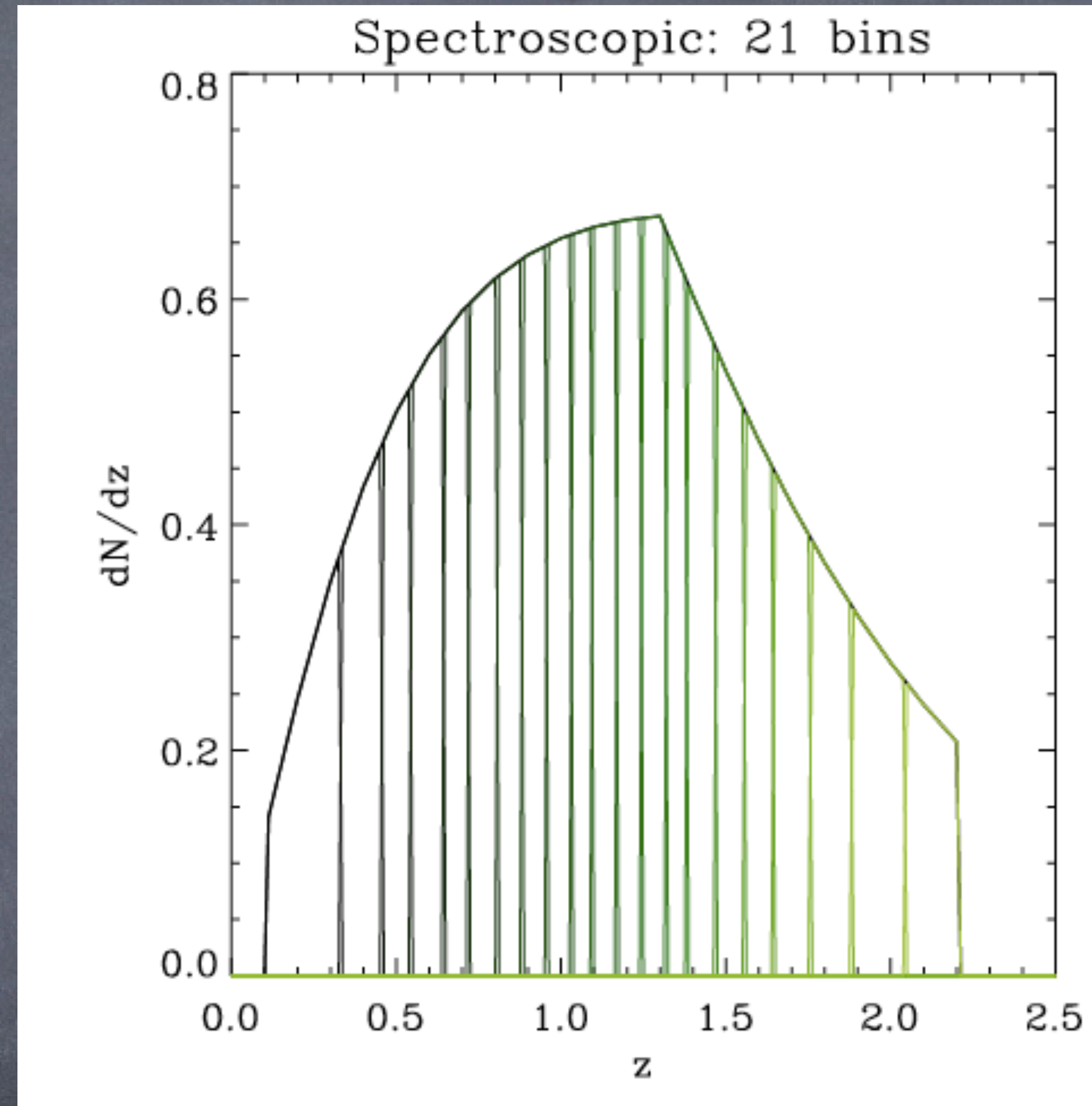
$$P_1(k,z,f_{\rm NL}) = \int n(M,z,f_{\rm NL}) \left[\frac{\tilde\rho(M,z,k)}{\rho_m}\right]^2 dM$$

$$P_2(k,z,f_{\rm NL}) = \left[\int n(M,z,f_{\rm NL})\, b(M,z,k,f_{\rm NL}) \frac{\tilde\rho(M,z,k)}{\rho_m} dM\right]^2 P_0(k,z)$$

Agreement to 10% level up to k = 10 h/Mpc

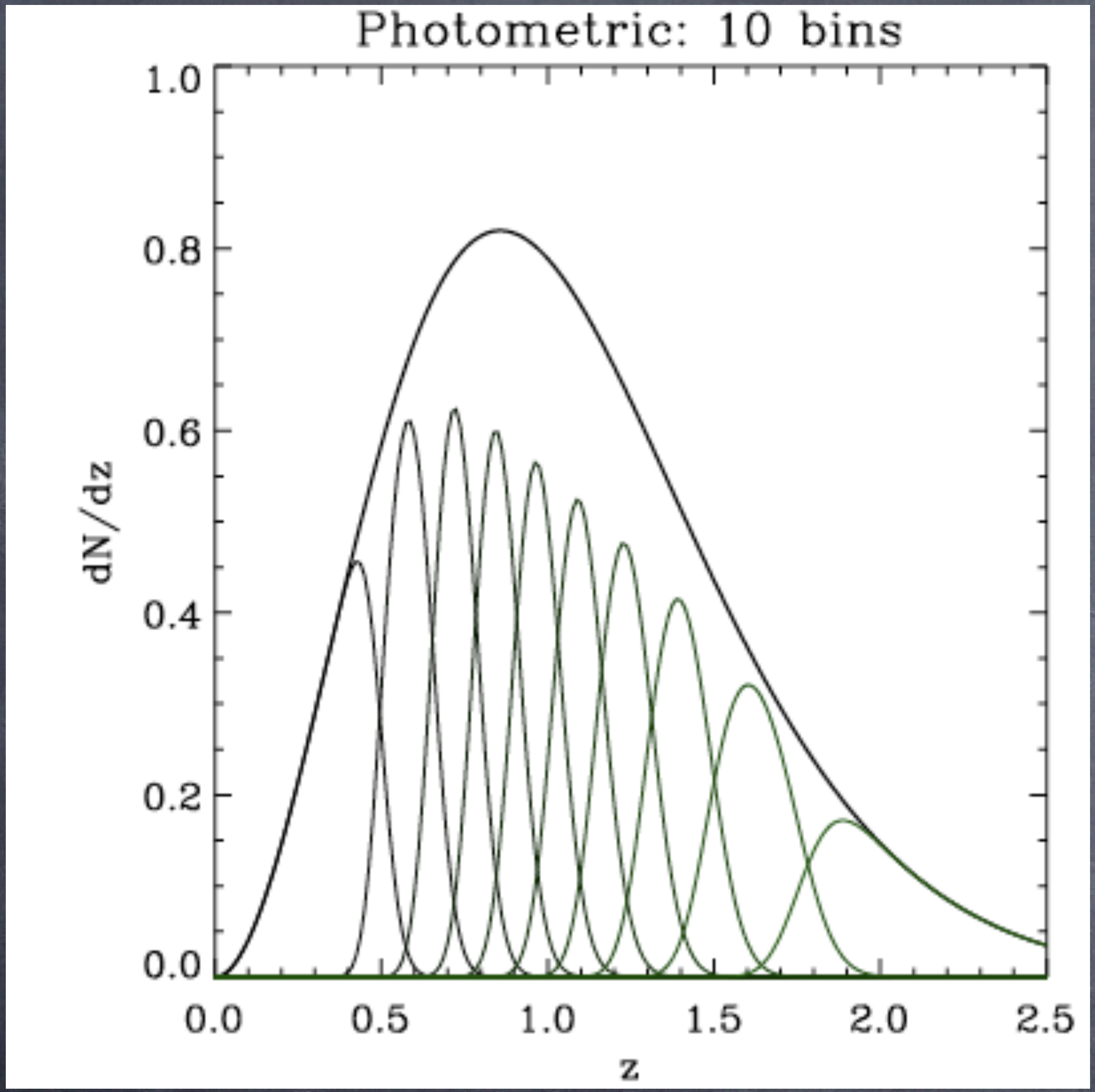
Redshift distributions

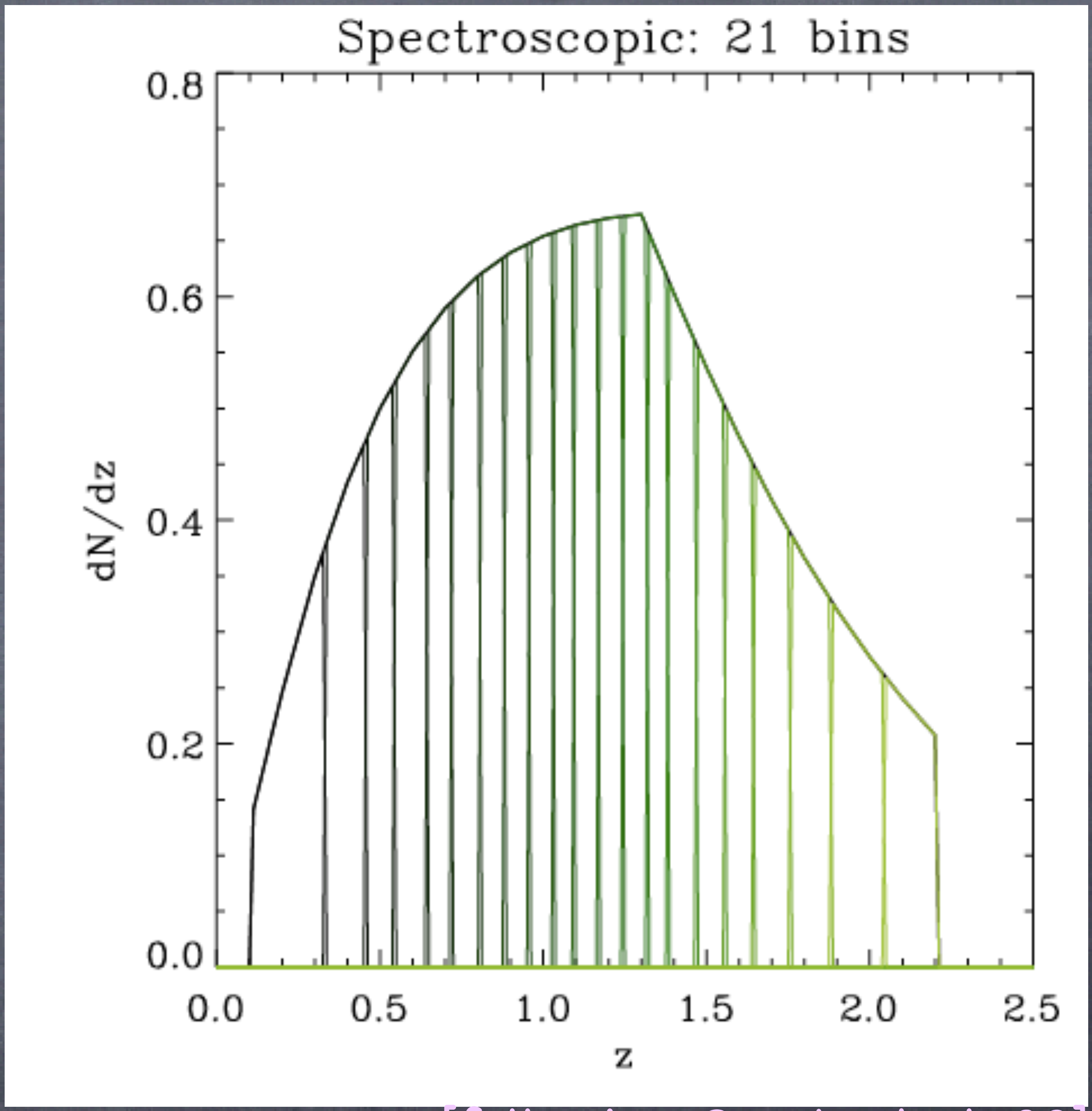




[following Geach et al, 09]

Redshift distributions

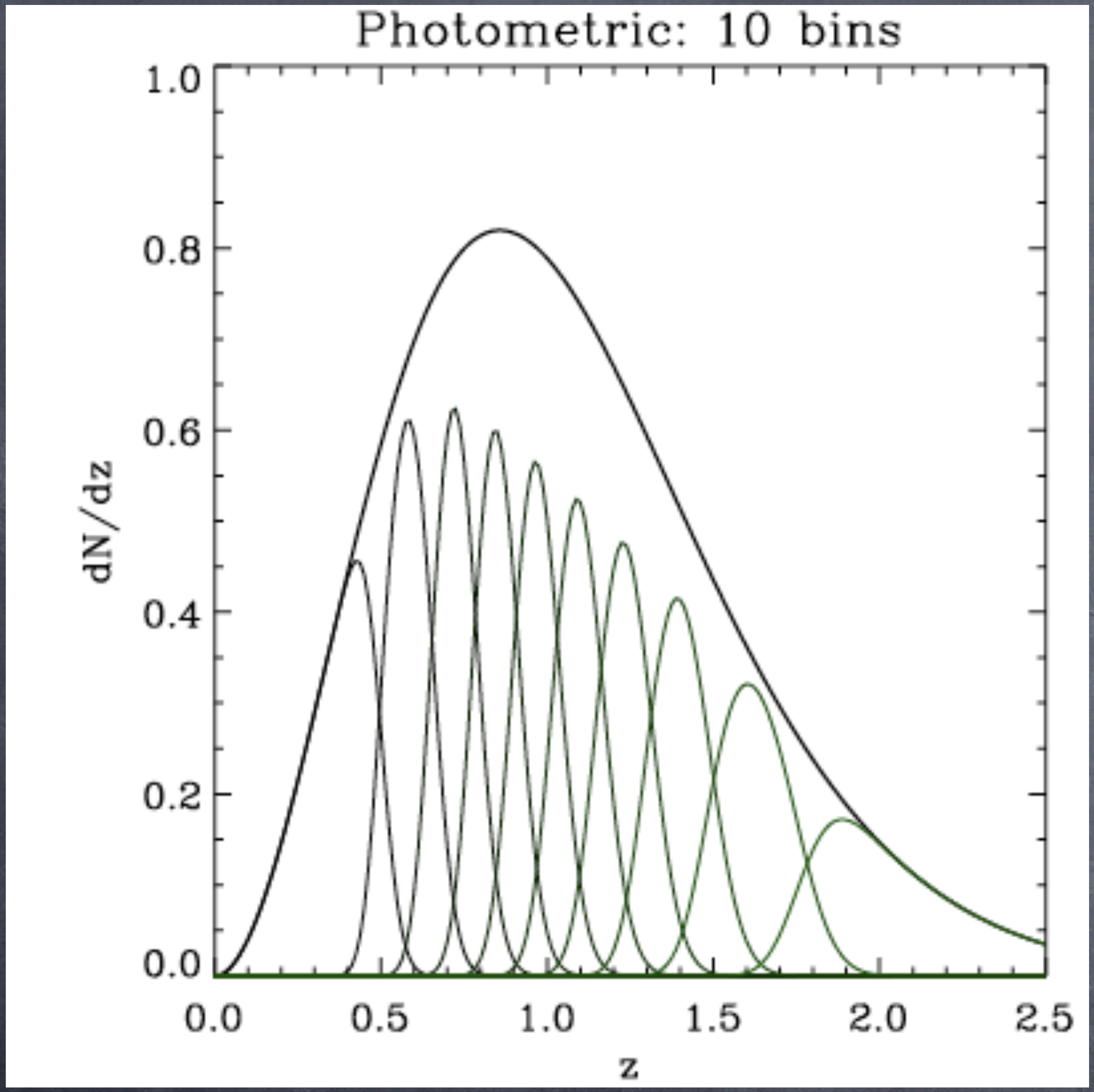


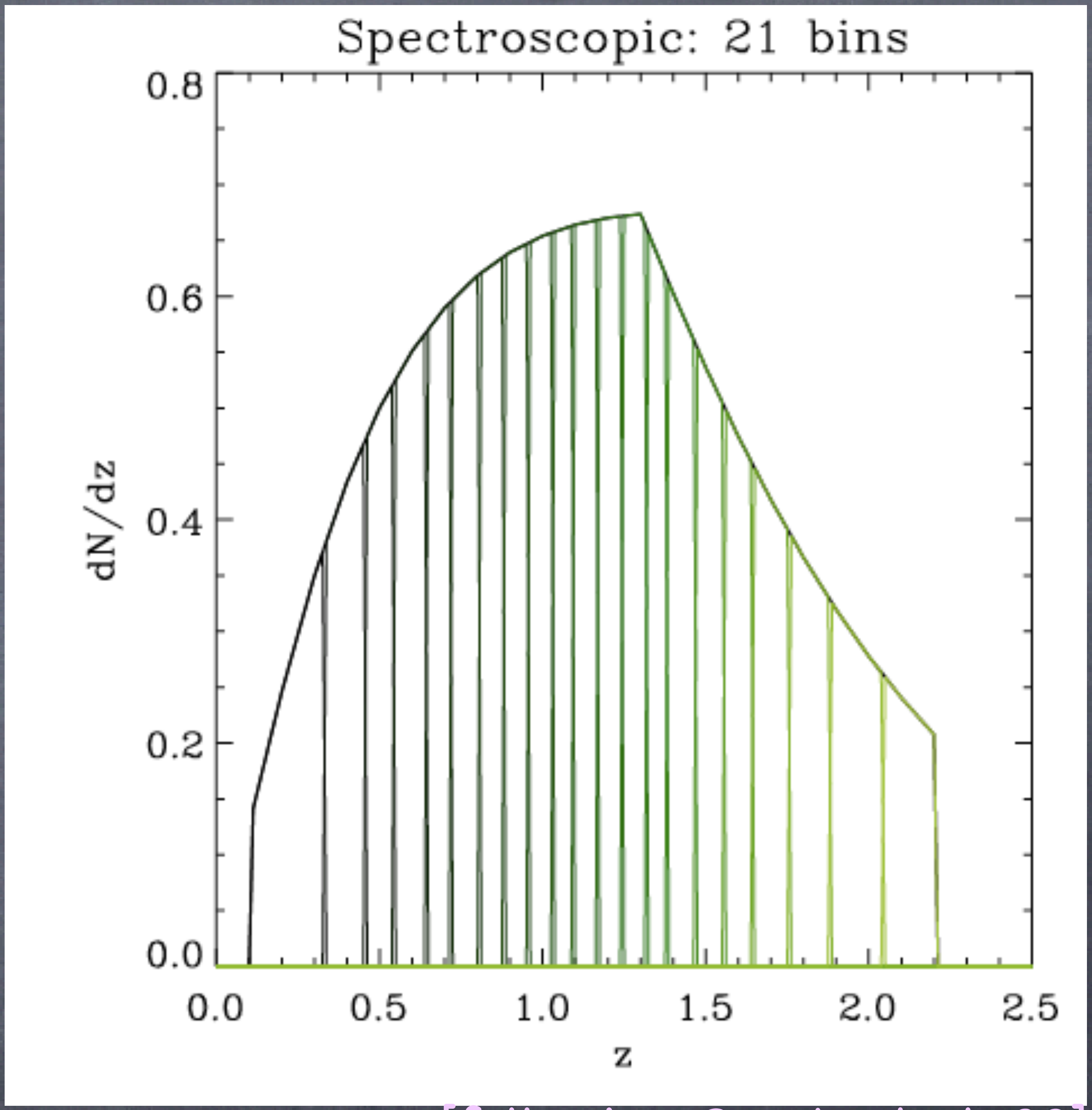


[following Geach et al, 09]

- Photometric
  - for WL and 2D galaxy spectrum
  - 10 z bins and nuisance bias parameters

Redshift distributions





[following Geach et al, 09]

- Photometric
  - for WL and 2D galaxy spectrum
  - 10 z bins and nuisance bias parameters
- Spectroscopic
  - for 2D and 3D galaxy spectrum
  - 21 z bins and nuisance bias parameters

Fisher matrix

Preliminary!

Fisher matrix

Preliminary!

- Weak lensing
  - 10 z bins, photo-z: 2D lensing spectra: $\left[C_l^{\rm lens}\right]_{ij}$
  - + errors (intrinsic ellipticities + shot noise): $\left[\tilde{C}_l^{\rm lens}\right]_{ij}$
  - derivatives: $\left[D_{l\alpha}^{\rm lens}\right]_{ij} = \frac{\partial \left[C_l^{\rm lens}\right]_{ij}}{\partial \Theta_\alpha}$
  - Fisher matrix: $F_{\alpha\beta}^{\rm lens} = f_{\rm sky} \sum_{l=l_{\rm min}}^{l_{\rm max}} \frac{(2l+1)\Delta l}{2} \,{\rm Tr}\left[D_{l\alpha}^{\rm lens} \left(\tilde{C}_l^{\rm lens}\right)^{-1} D_{l\beta}^{\rm lens} \left(\tilde{C}_l^{\rm lens}\right)^{-1}\right]$
    [Hu & Jain 04, Amara ea 07]

Fisher matrix

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  - 10 z bins, photo-z: 2D lensing spectra: $\left[C_l^{\rm lens}\right]_{ij}$
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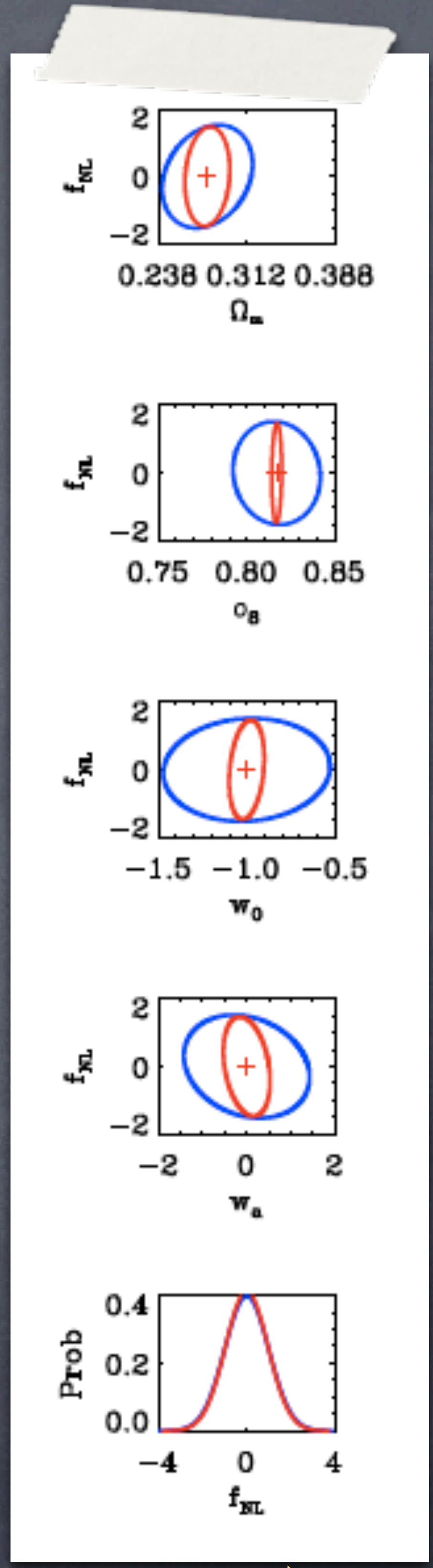
    [Hu & Jain 04, Amara ea 07]
- 2D galaxy clustering
  - as with lensing for photo-z, + 21 z bins for spectroscopic
  - l_{max} = 1200 (→ k_{max} = 0.5 h/Mpc at z = 1)

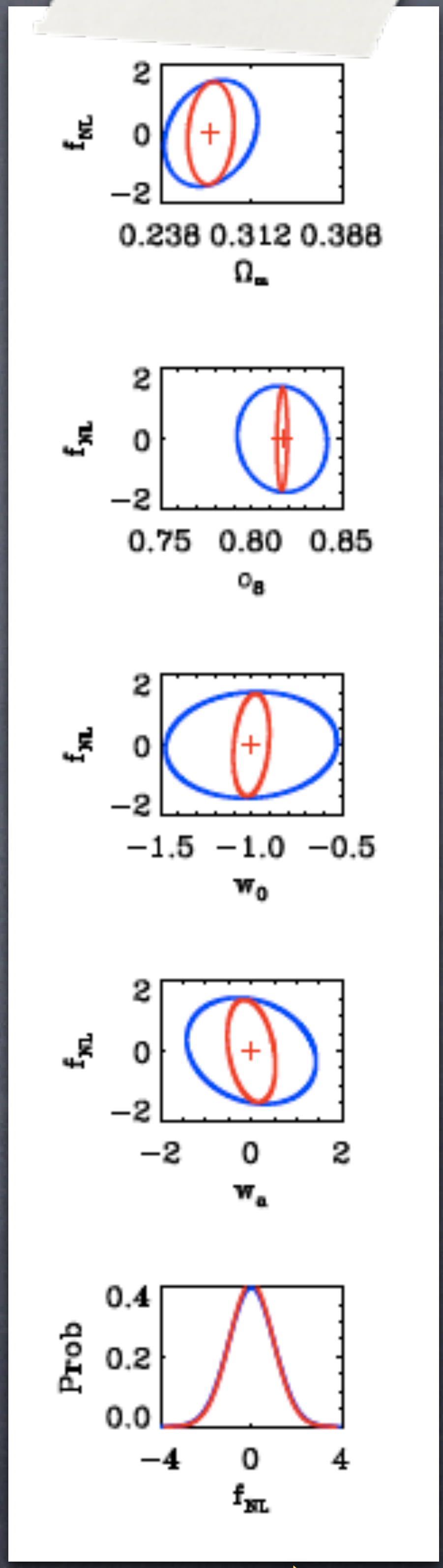


2D gal, spectro

Fisher matrix

Preliminary!

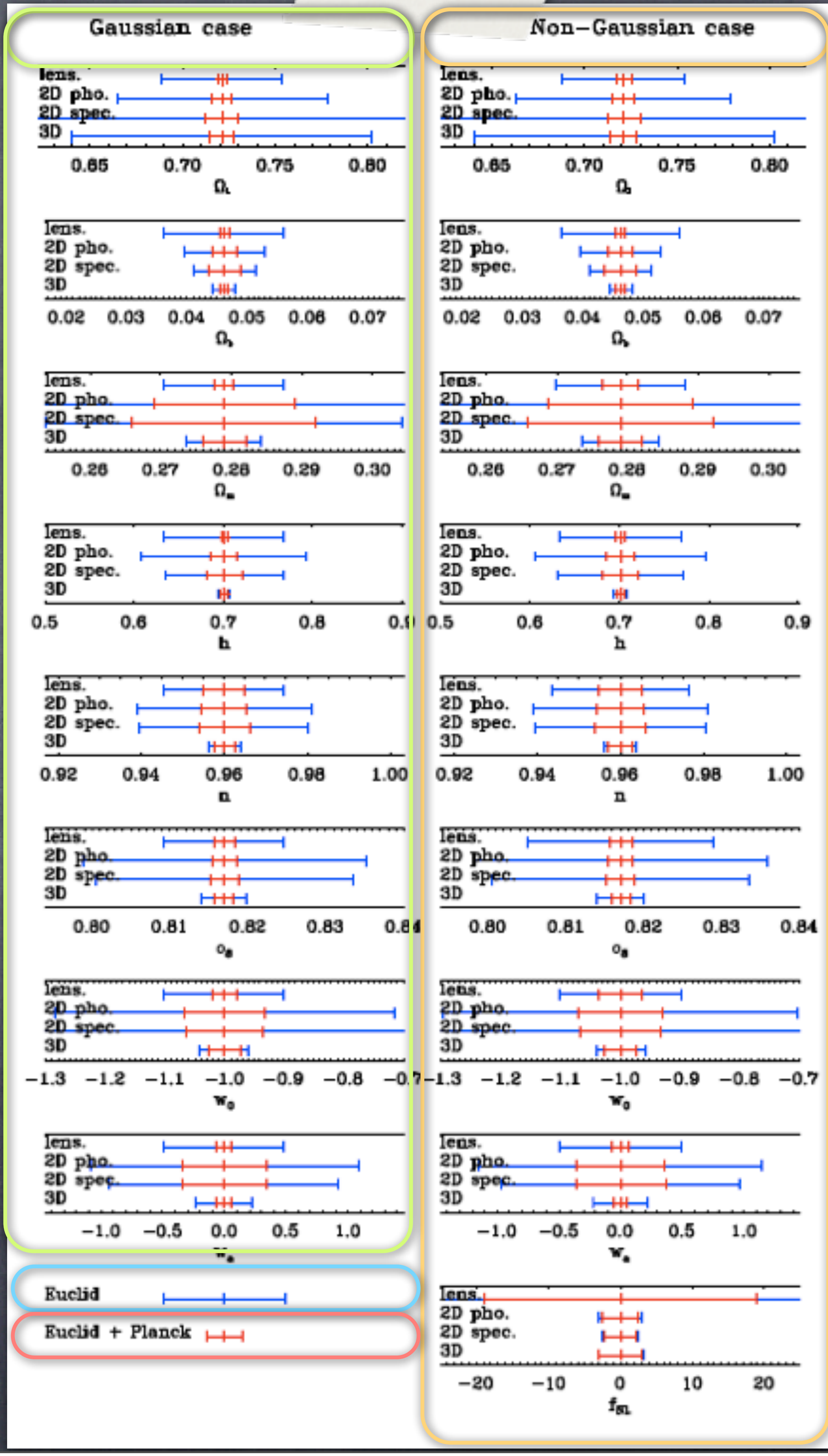
- Weak lensing
  - 10 z bins, photo-z: 2D lensing spectra: $\left[C_l^{\text{lens}}\right]_{ij}$
  - + errors (intrinsic ellipticities + shot noise): $\left[\tilde{C}_l^{\text{lens}}\right]_{ij}$
  - derivatives: $\left[D_{l\alpha}^{\text{lens}}\right]_{ij} = \dfrac{\partial \left[C_l^{\text{lens}}\right]_{ij}}{\partial \Theta_\alpha}$
  - Fisher matrix: $F_{\alpha\beta}^{\text{lens}} = f_{\text{sky}} \sum_{l=l_{\min}}^{l_{\max}} \dfrac{(2l+1)\Delta l}{2} \operatorname{Tr}\left[D_{l\alpha}^{\text{lens}} \left(\tilde{C}_l^{\text{lens}}\right)^{-1} D_{l\beta}^{\text{lens}} \left(\tilde{C}_l^{\text{lens}}\right)^{-1} \right]$
    [Hu & Jain 04, Amara ea 07]
- 2D galaxy clustering
  - as with lensing for photo-z, + 21 z bins for spectroscopic
  - l_{max} = 1200 (→ k_{max} = 0.5 h/Mpc at z = 1)
- 3D galaxy clustering
  - redshift-space distorsions + Alcock-Pacinsky effect
  - k_{max} = 0.5 h/Mpc at z = 1
  - Fisher matrix: $F_{\alpha\beta}^{\text{3D}} = \pi \int_{-1}^{1} \int_{k_{\min}}^{k_{\max}} \dfrac{\partial \ln P(k,\mu)}{\partial \Theta_\alpha} \dfrac{\partial \ln P(k,\mu)}{\partial \Theta_\beta} w(k,\mu)\, d\ln k\, d\mu$
    [Tegmark 97, Song ea 08]



2D gal, spectro

Forecasts

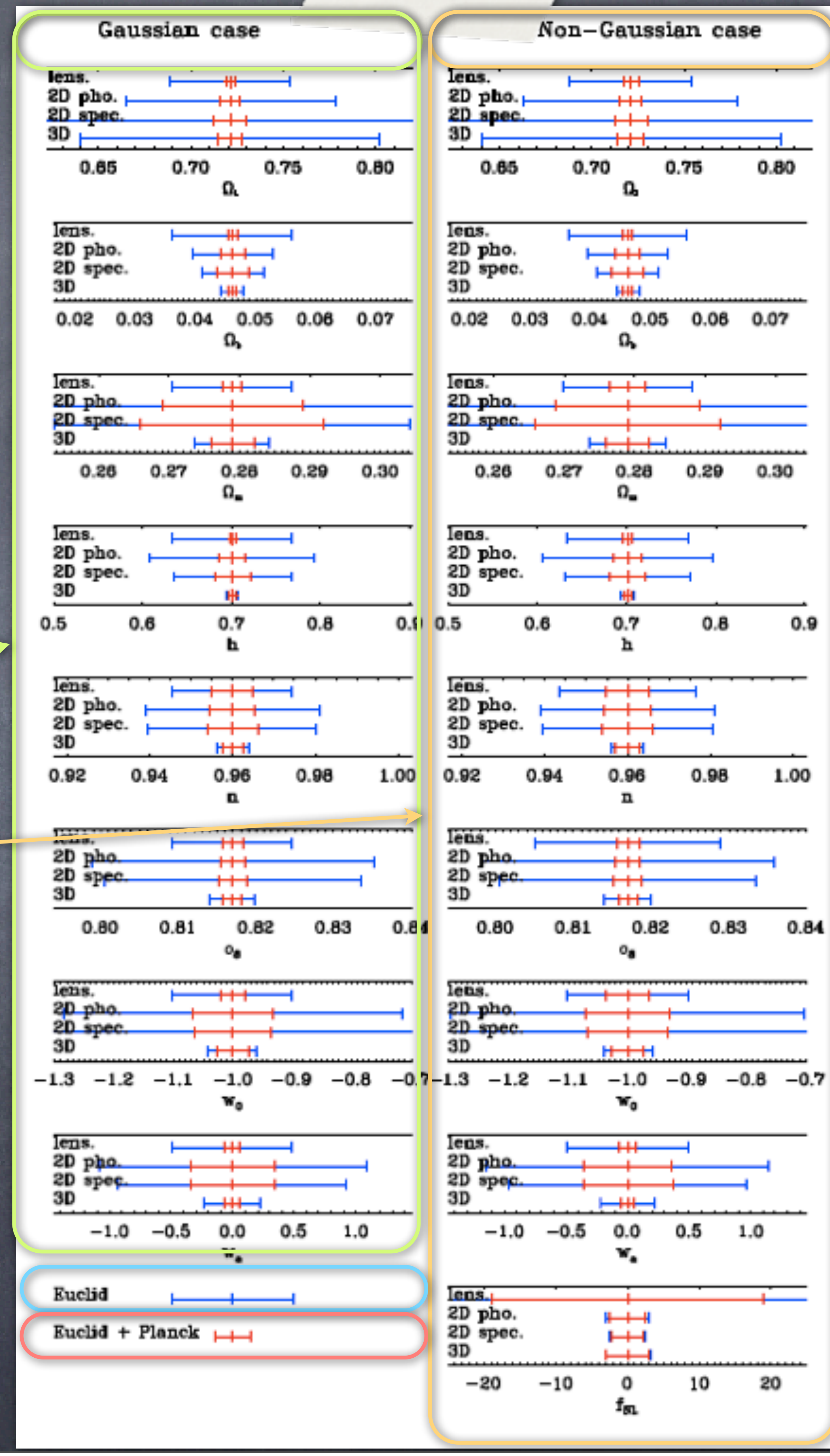
Preliminary!



Forecasts

Preliminary!

- 1D-marginalised forecasts
  - lensing
  - 2D galaxy clustering, photo & spectro
  - 3D galaxy clustering
- Euclid, Euclid+Planck
- Gaussian, non-Gaussian
- f_{NL} less constrained by lensing
- with P spectrum: $\boxed{\sigma(\mathrm{fNL}) = 3}$
- not very degenerate with other parameters
- Combining WL+P(k): $\boxed{\sigma(\mathrm{fNL}) = 2}$



Scale-dependent fNL

- In many models of inflation, fNL is scale-dependent [e.g. Byrnes, Wands 09]
- spectral index of fNL: nfNL

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

- additional parameter in Fisher forecasts

IF scale dependency simply applied to final b(k)...

- preliminary result: if $f_{NL} = 50$

$$\boxed{\sigma\left(n_{f_{\rm NL}}\right) \simeq 0.08}$$

- marginalised over all other parameters

Polynomial bias fit

- Instead of one b parameter for each bin
- bias is expected to be smooth
- polynomial fit:

$$b(z) = b_0 + b_1(z-1) + b_2(z-1)^2 + b_3(z-1)^3$$

- Fisher forecasts improve
- preliminary result:
- up to 30% improvement in the parameter constraints

Conclusions

- Non-Gaussianity: a very important imprint of the early Universe
- Scale-dependent bias: an additional powerful probe of NG
- Bias becomes non-local or bivariate
- 1-loop calculation SPT
- Good agreement with simulations
- Very accurate LSS measurements of NG soon possible!