New Observational Power from Halo Bias

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Cornell
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The Plan:

- Non-Gaussianity and Large Scale Structure
- A bigger family for the local ansatz
- Theory information in the new ansatz
- Analytic expectation for halo bias
- Simulation results
- What it might mean...

I. Non-Gaussianity and Large Scale Structure

Inflation: Our current knowledge:

$$\mathcal{P}_\zeta = \frac{H^2}{(2\pi)^2 M_p^2 \epsilon}$$
$$= A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$$

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Amplitude

$\mathcal{O}(10^{-9})$

Spectral index

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Amplitude

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Spectral index

$n_s - 1 = -6\epsilon + 2\eta \approx -0.04$

* Two numbers to fit: Can change the model radically

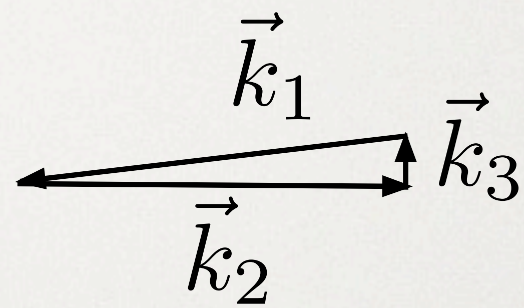
Beyond the power spectrum

- *Non-Gaussianity*: any higher order connected correlation different from zero
- Interactions: $S = S_0 + S_2 + S_3 + \dots$

* Gravity
* Self-interactions
* Multiple fields

} Qualitatively distinguishable!

Summary of NG properties:

	Power Spectrum	Bispectrum	N-point
Information	$\lvert\vec{k}\rvert$		N-gon
Amplitude	$\mathcal{P}_\zeta$	$f_{NL}\mathcal{P}_\zeta^2$	$\langle\zeta^n\rangle \propto \frac{(\langle\zeta^2\rangle)^{n-1}}{(c_s^2)^{n-2}}$
Sign	—	$f_{NL} > 0$ More Structure	N=4: wide/narrow distribution
Scale Dependence	$n_s - 1$	?	?

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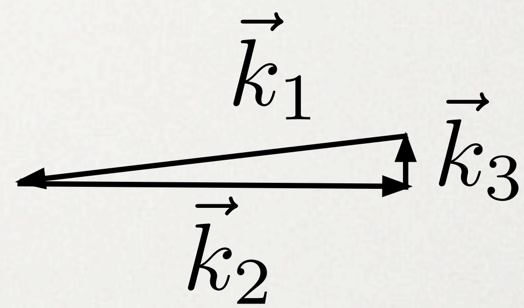
Information	$\lvert\vec{k}\rvert$		N-gon
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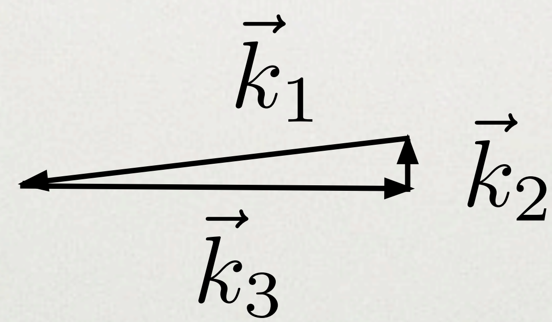
CMB: check specific bispectra

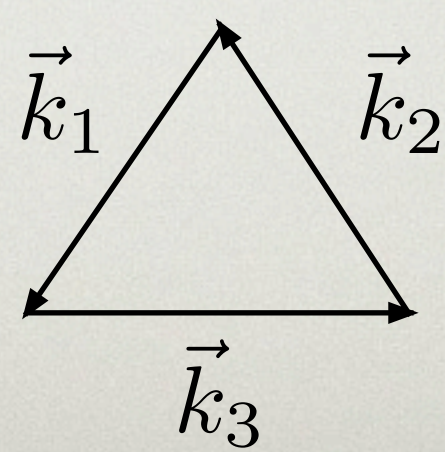
- Given a shape, limit the amplitude:
- Computationally intensive

* Squeezed:



"Local" type; multiple fields, slow roll

* Equilateral:



Derivative interactions

How Non-Gaussian is Non-Gaussian?

$$f_{NL} \sim 0.05 \ll 5 \sim 5 \ll \mathcal{O}(100) \ll 10^{9/2}$$

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Gravitational Evolution

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Planck potential

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Slow-roll

Very non-Gaussian

Gravitational Evolution

Good News for Planck...

(Hero)

Good News for Planck...

* Lots of room for discovery
* Detection now rules out 99% of models

(Hero)

Large scale structure

Inflaton $\longrightarrow$ Curvature

$$\delta\phi \longrightarrow \zeta$$

Curvature $\longrightarrow$ Density

$$\zeta \longrightarrow \delta$$

Density $\longrightarrow$ Structure

$$\delta \longrightarrow$$

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Large scale structure

Inflaton ⟶ Curvature
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Density ⟶ Structure
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- Different statistics:
  - Cluster number counts
  - power spectra of collapsed objects
- Initial conditions + Grav. evolution
- Smaller scales

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Density ⟶ Structure

Simulations!

$\delta \longrightarrow$

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A favorite cosmologist's ansatz...

- "Local Ansatz" (Salopek, Bond; Komatsu, Spergel)

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

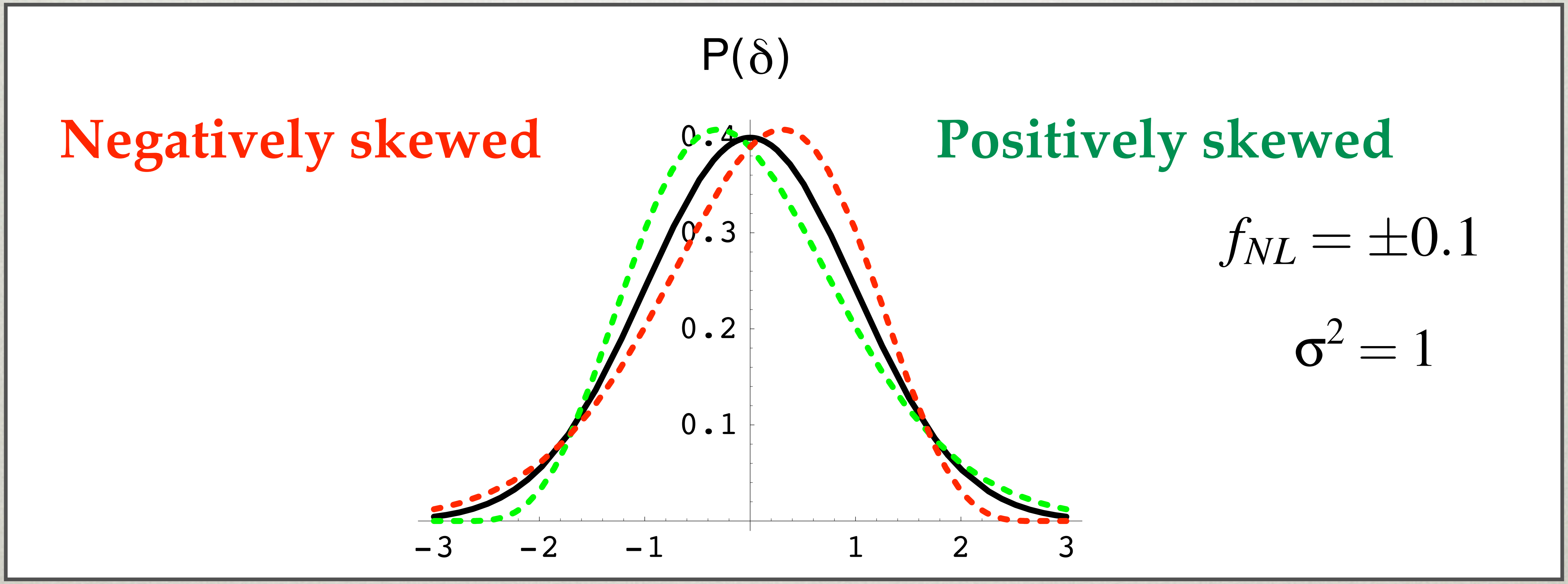
- Nearly Gaussian?

$$|f_{NL}| < 10^{9/2}$$

- Positive skewness (**$f_{NL} > 0$**) means more structure

Why the Local Ansatz is nice (I)

- Easy for N-body simulations (defined from a real space Gaussian)
- One parameter: $\langle \Phi^n \rangle \propto f_{NL}^{n-2} (\Delta_\Phi^2)^{(n-1)}$



Why the Local Ansatz is nice (II)

- Exciting signal in the power spectrum of collapsed objects
- Constraints competitive with CMB!

(Dalal et al; Slosar et al; McDonald; Afshordi, Tolley; Matarrese, Verde; Carbone et al)

Halo/Galaxy Bias

- Statistics of collapsed objects are different from underlying matter fluctuations
- Assume: collapsed objects form from peaks in the initial density field

Peak-Background Split: Gaussian Case

- Long wavelength background mode:
- Perturb it:
- Poisson eqn (no mode coupling):

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- Long wavelength background mode: $\Phi(\mathbf{k}_l)$
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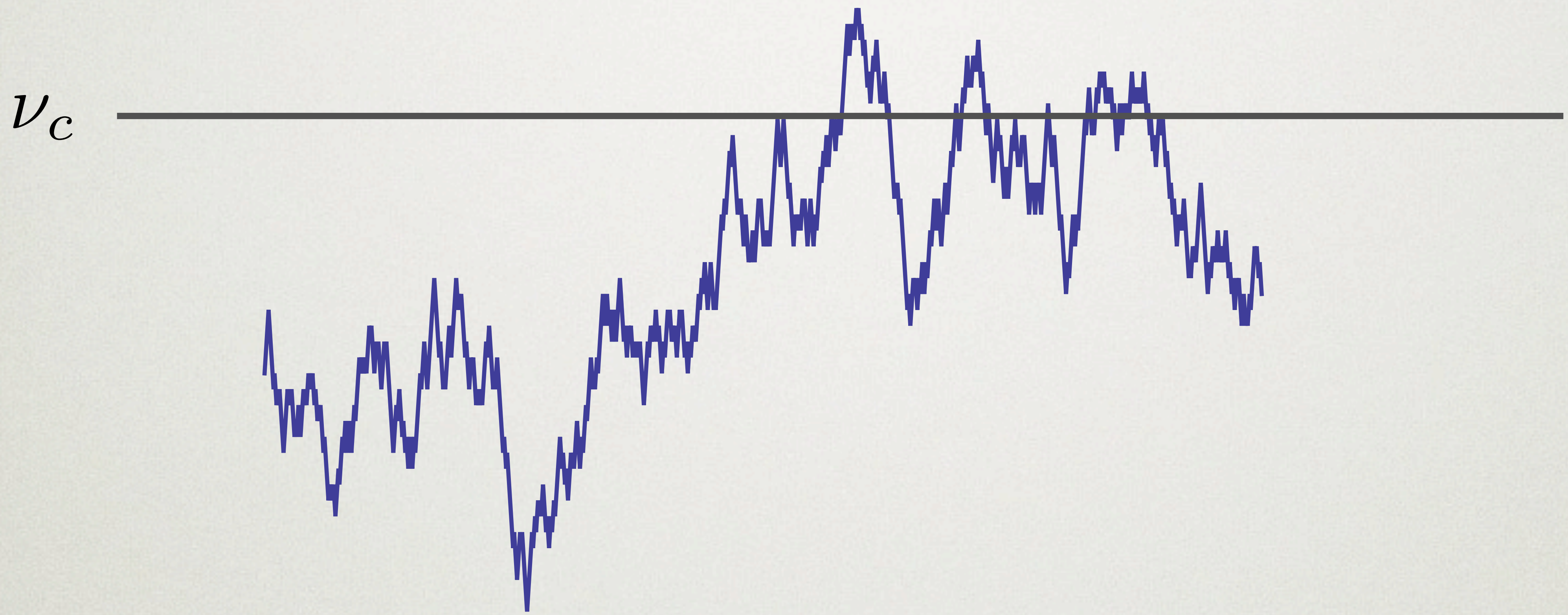
$$\Delta\delta(\mathbf{k}_l) \propto k_l^2 \Delta\Phi(\mathbf{k}_l)$$

* Shift background density up/down

Gaussian Case: peaks are more clustered



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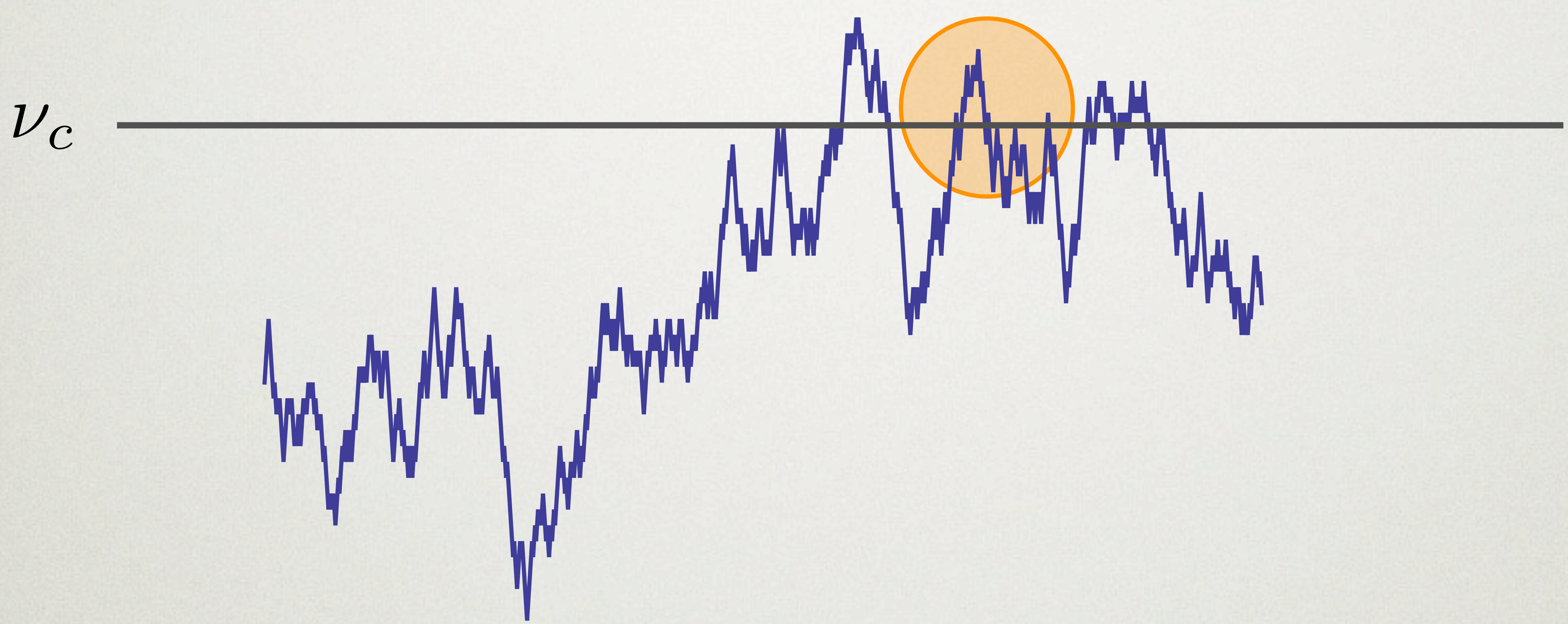

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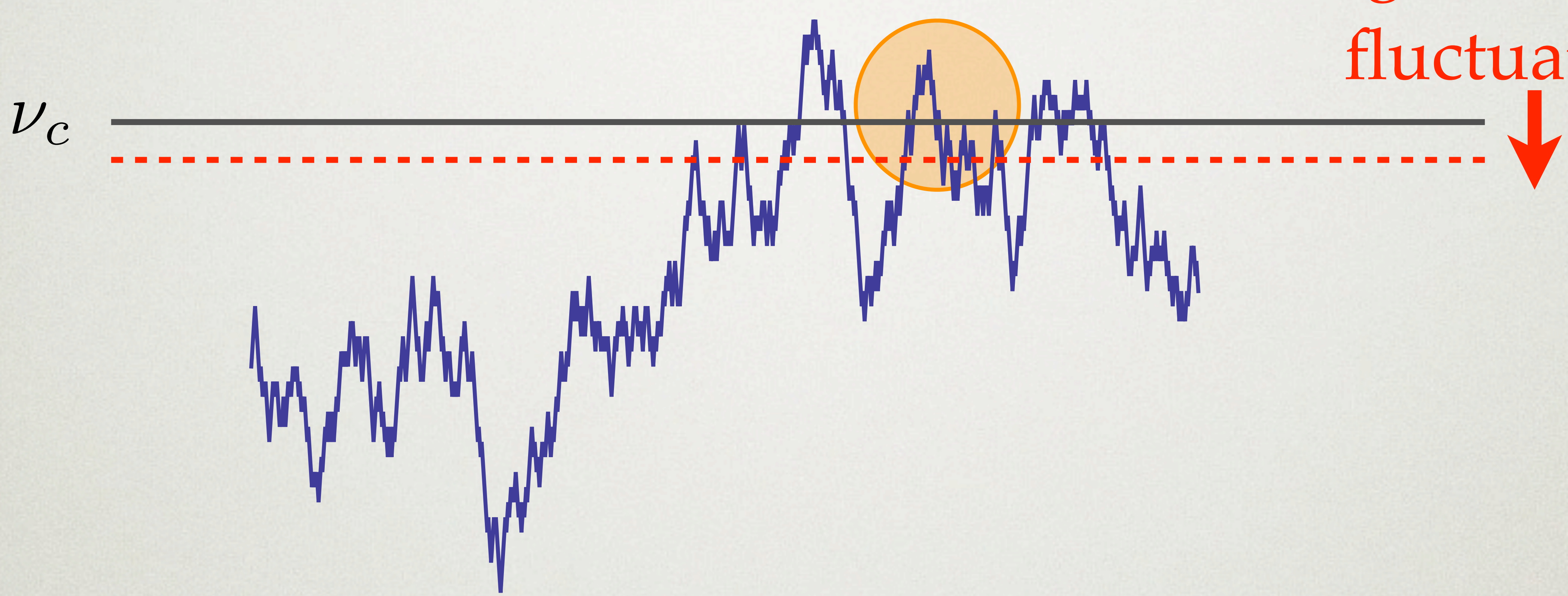

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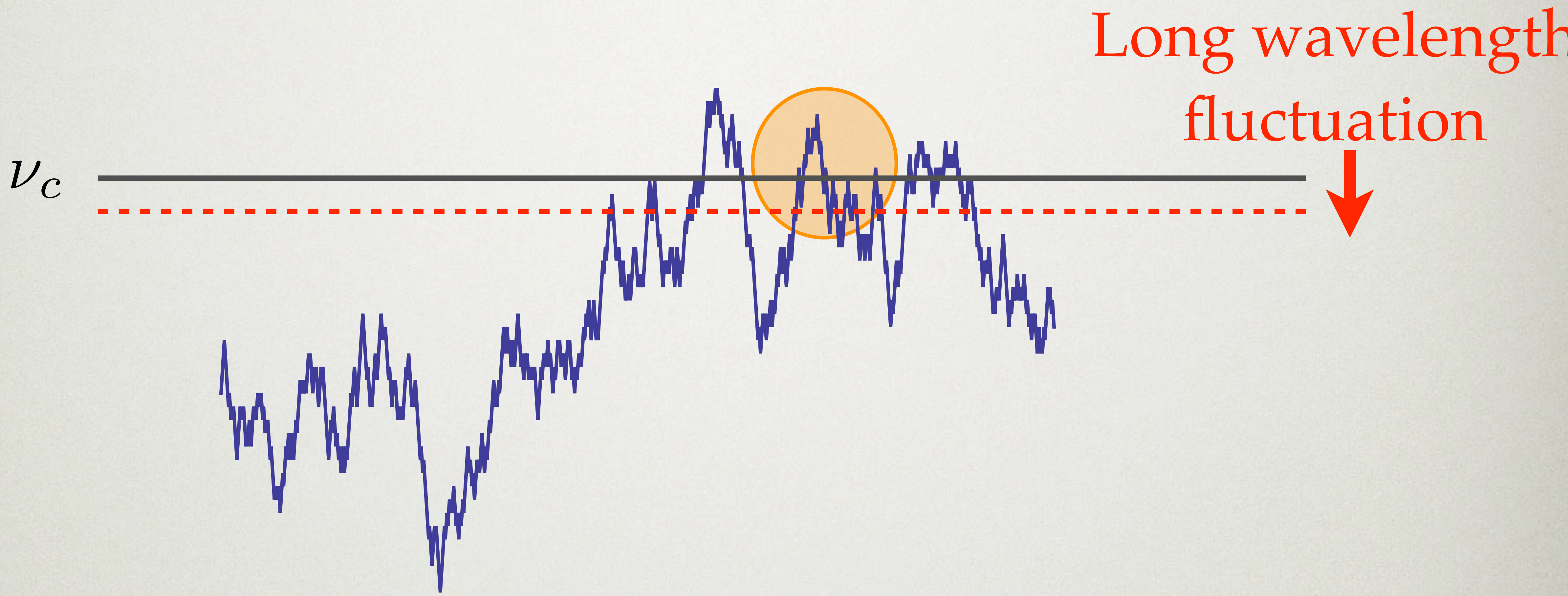

$$P_{hm}(k) = b(M)P_{mm}(k)$$

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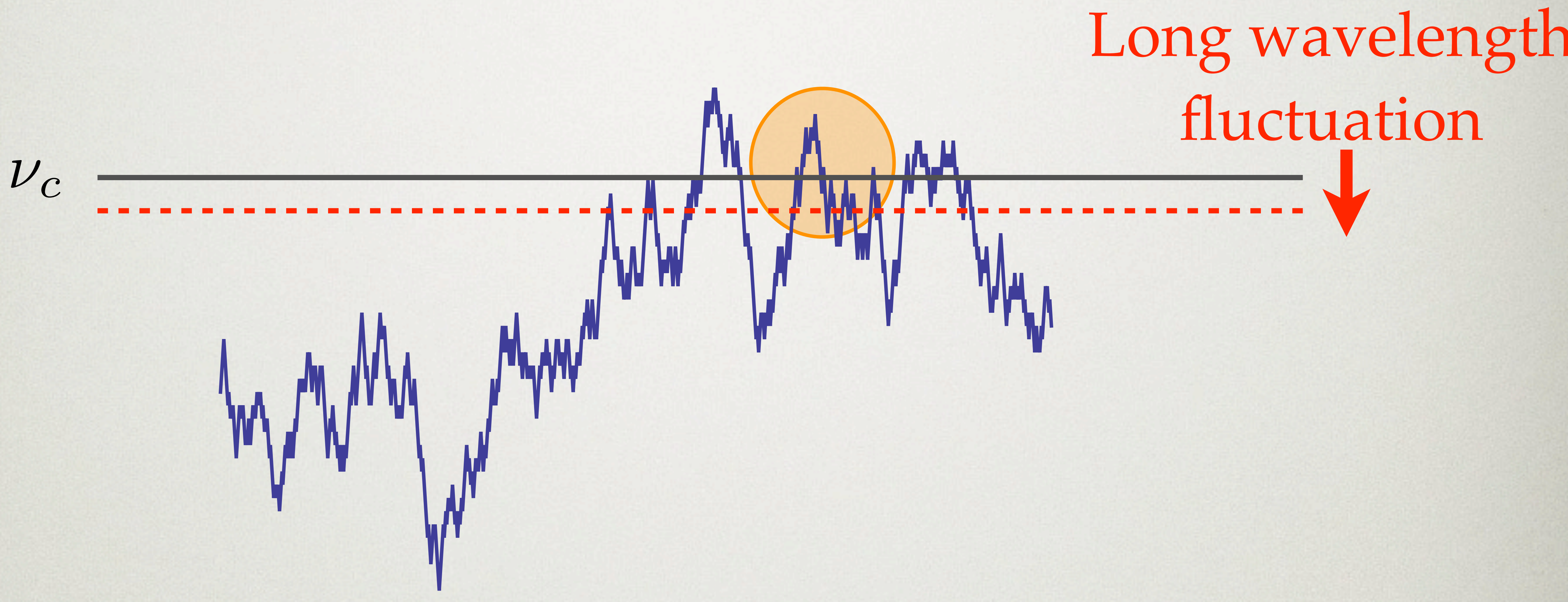

$$P_{hm}(k) = b(M) P_{mm}(k)$$

Naively, from the mass function

Local Non-Gaussianity

- *Correlation* between long and short modes → enhanced clustering

- Peak-Background split:

(Slosar et al)

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- Peak-Background split:

$$\Phi_{NG}(\mathbf{k}_s) \approx \Phi_G(\mathbf{k}_s)[1 + 2 f_{NL} \Phi(\mathbf{k}_l)]$$

(Slosar et al)

Bias, cont'd

- Poisson Equation:

$$\delta_s \propto -\nabla^2 \Phi_{NG,s}$$
$$\delta_s \propto -\nabla^2 \Phi_{G,s}(1 + 2 f_{NL} \Phi_{G,l})$$
$$\delta_s \propto \delta_{G,s}(1 + 2 f_{NL} \Phi_{G,l})$$

✱ Physically: local σ_8 depends on $\Phi(k_l)$

(McDonald; Afshordi, Tolley)

- So, on *large scales* the shift is

$$\Delta b(M, f_{NL}, k) \propto b_G(M) f_{NL} \frac{1}{k^2 T(k) D(z)}$$

Bias, cont'd

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Constraints and Forecasts

Table 1 Current recent 2 − *sigma* constraints on local fnl

Data/method	f_{NL}	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 ± 84	Spergel et al. (WMAP) 2007
WMAP3-Bispectrum	32 ± 68	Creminelli et al. 2007
WMAP3-Bispectrum	87 ± 60	Yadav & Wandelt 2008
WMAP-Bispectrum	38 ± 42	Smith et al. 2009
WMAP5-Bispectrum	51 ± 60	Komatsu et al. (WMAP) 2008
WMAP5-Minkowski	-57 ± 121	Komatsu et al. (WMAP) 2008

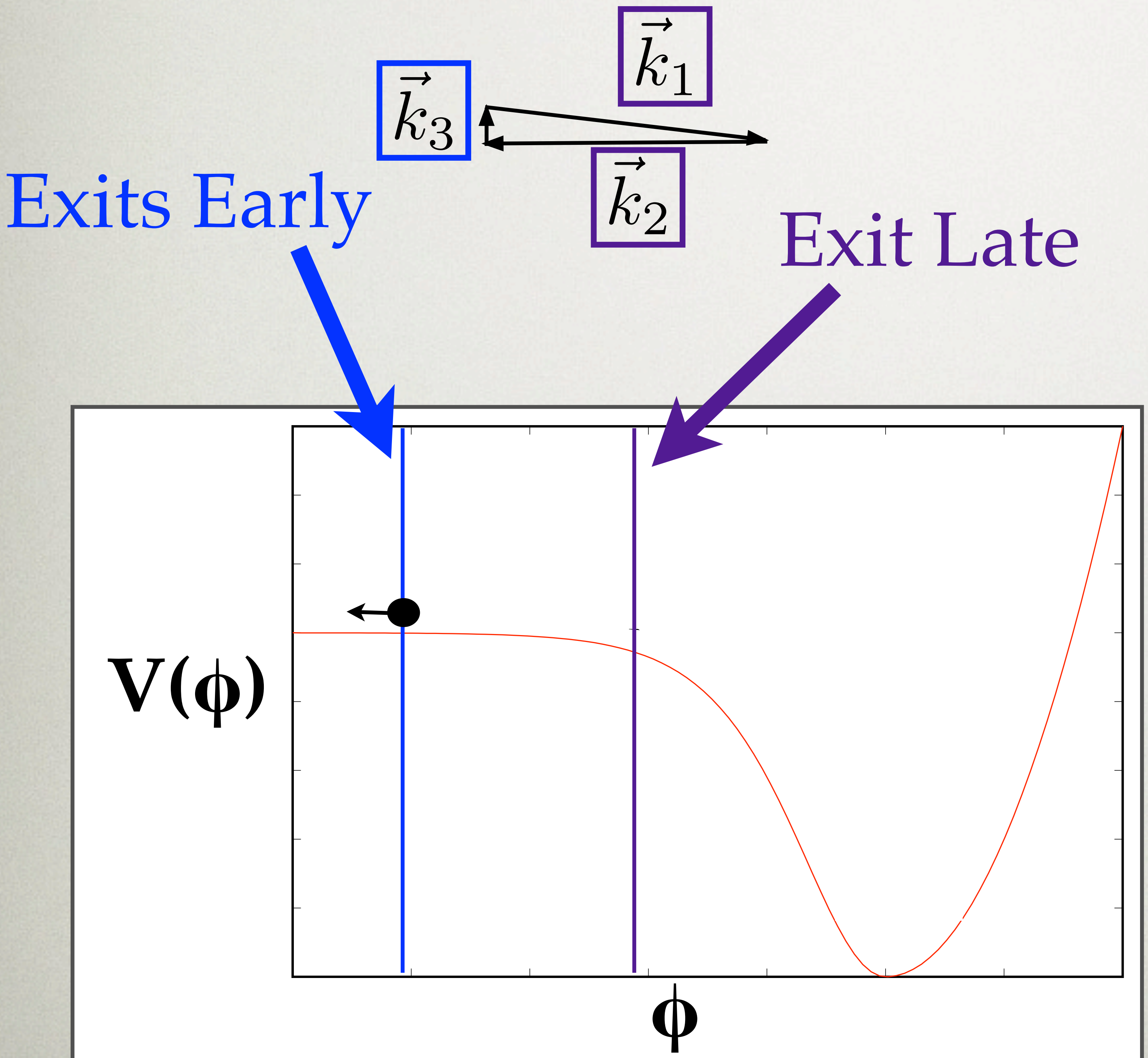
Tables compiled by
Licia Verde

Table 2 Forecasts 1 − *sigma* constraints on local f_{NL}

Data/method	Δf_{NL} $(1-\sigma)$	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

II. A Bigger Family for the Local Ansatz

Single fields and the squeezed limit

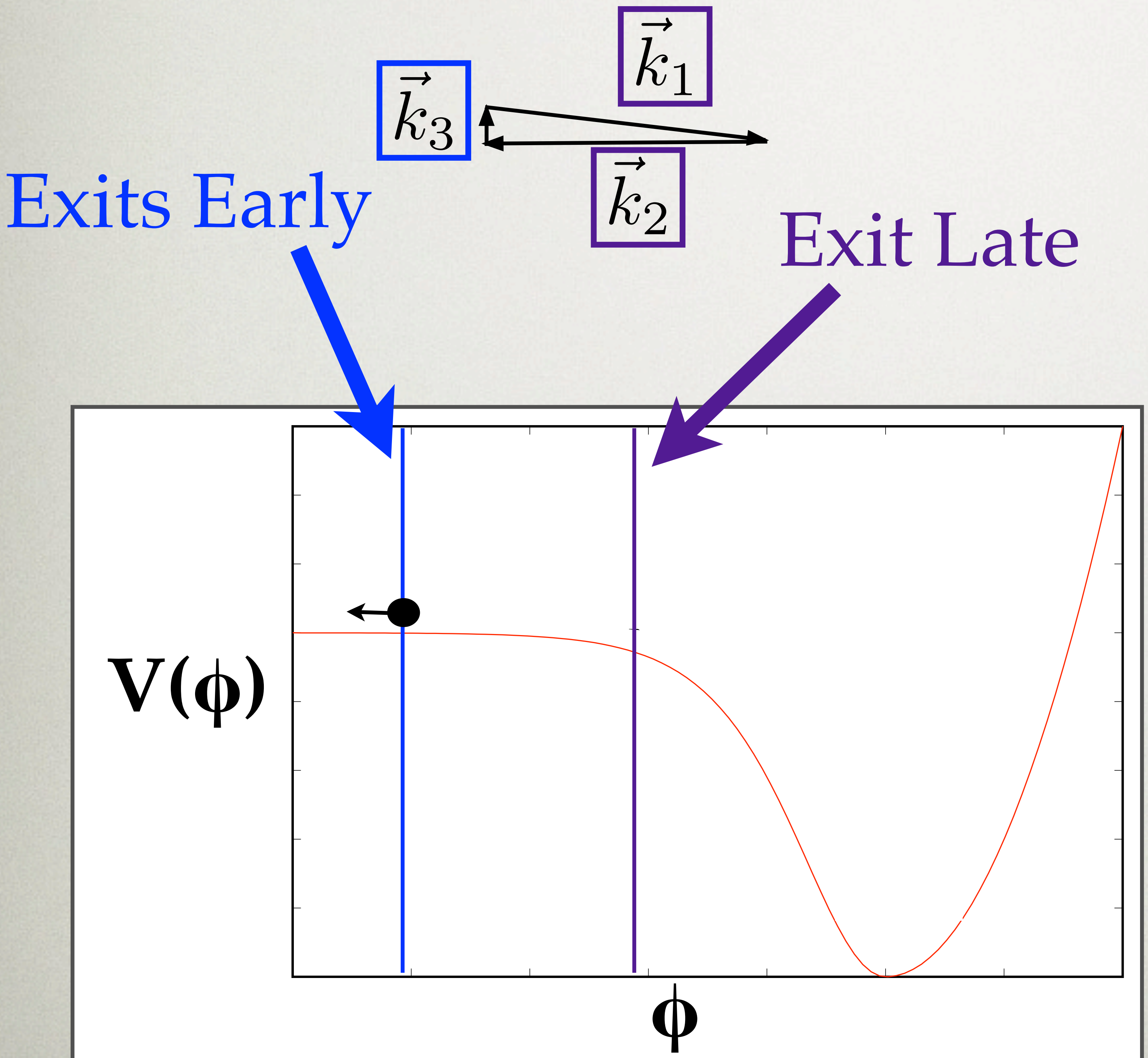


$$|\vec{k}_1| = |\vec{k}_2| = a(t)H(t)$$

First jump resets the clock:

$$\Delta t = \frac{\delta\phi}{\dot{\phi}}$$

Single fields and the squeezed limit



$$|\vec{k}_1| = |\vec{k}_2| = a(t)H(t)$$

$$f_{NL} \propto -(n_s - 1)$$

(Maldacena; Creminelli, Zaldarriaga)

So...Local type NG is necessarily multi-field

- One field sources inflation; a second field sources curvature fluctuation: "curvaton" (Lyth, Ungarelli, Wands)
- Mixed curvaton/inflaton contributions to curvature
- Multi-field inflation (Linde, Mukhanov)

(Many! modern references, see paper)

Local Ansatz?

- What information does the local ansatz contain? *(eg, where is multi-field information?)*
- How closely does it match the theory possibilities?
- Many multi-field scenarios...*distinguishable?*
  - Needs to be generalized...

Other reasons to Generalize

- Test the properties of the observable (bias)
- Test analytic understanding: simulations

A Generalization...

- Factorizable, symmetric extension:

$$B_\Phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \qquad P_\Phi(k_1) P_\Phi(k_2) + 5 \text{ perm} \; .$$

- Mild scale-dependence:

A Generalization...

- Factorizable, symmetric extension:

$$B_\Phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \quad \xi_m(k_1)\xi_m(k_2)P_\Phi(k_1)P_\Phi(k_2) + 5\,\mathrm{perm}\,.$$

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- Mild scale-dependence:

$$\xi_{s,m}(k) = \xi_{s,m}(k_p)\left(\frac{k}{k_p}\right)^{n_f^{(s),(m)}}$$

Note...

- One of these functions is familiar:

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

$$f_{NL}^{\mathrm{eff}}(k) = f_{NL}^{\mathrm{eff},0}\left(\frac{k}{k_0}\right)^{n_f}$$

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III. Information in the generalized ansatz

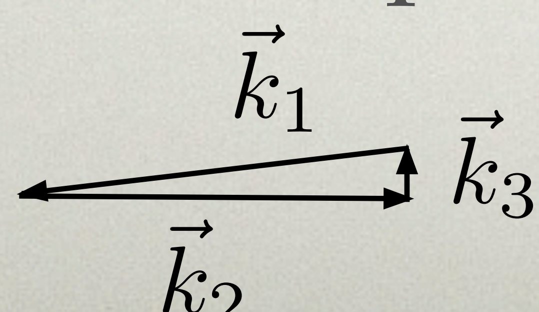
Scale-dependence, physically

- Power Spectrum:

$$\dot{H} \neq 0 \Rightarrow n_s \neq 1$$
$$\dot{H} < 0 \Rightarrow n_s < 1$$

Red spectrum is encouraging!

- Bispectrum?
  - Single field slow roll: amplitude and scale dependence linked: (Maldacena; Creminelli)



$$f_{NL} \propto -(n_s - 1)$$

Scale-Dependence? Type I (multi-field)

- Two or more fields contribute to curvature:

(Wands et al; Byrnes et al; Byrnes, Wands)

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$$\xi = \frac{\mathcal{P}_{\zeta,\sigma}(k)}{\mathcal{P}_{\zeta,\phi}(k) + \mathcal{P}_{\zeta,\sigma}(k)}$$

$$f_{NL}(k) = \tilde{f}_{NL}\xi^2(k)$$

Scale-dependence from changing ratio of contribution to $\mathcal{P}_\zeta$

(Wands et al; Byrnes et al; Byrnes, Wands)

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$$\Bigg\} \quad n_f \leq -(n_s - 1) \sim 0.1$$

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$$B_\Phi^m(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \xi_m(k_1)\xi_m(k_2)P_\Phi(k_1)P_\Phi(k_2) + 5\,\mathrm{perm}$$

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- A non-Gaussian (non-inflaton!) field alone generates curvature perturbations:

- and -

- The field has self-interactions beyond quadratic

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- and -

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Quadratic curvaton → constant f_{NL}

$$\Phi \propto \delta\rho \sim \frac{1}{2}(2m^2\sigma\delta\sigma + m^2\delta\sigma^2)$$

Beyond quadratic → scale-dependent f_{NL}

(Byrnes, Enqvist, Takahashi; Huang)

Both in one go...

- Multiple field inflation

$$\zeta(k) = N_{,\phi}(k)\delta\phi(k) + N_{,\sigma}(k)\delta\sigma(k) + \frac{1}{2}N_{,\sigma\sigma}(k)[\delta\sigma\star\delta\sigma](k) \ + \ldots$$

- Mixed generic curvaton/inflaton

Generally:

$$B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) \equiv \xi_s(k_3)\xi_m(k_1)\xi_m(k_2)\, P_\Phi(k_1)P_\Phi(k_2) + 5\,\text{perm.},$$

How Natural?

- Theoretically, are multiple fields likely?? Hard to say, but:
- IF we find observably large local non-Gaussianity, as natural as the spectral index different from one
- IF we are constraining local non-Gaussianity, this possibility matters!

(theory) Caveats for our Model

- We will check only approx. local NG

(THEORY) CAVEATS

- We will check only local NG (equilateral more compelling?)

- Constant scale-dependence can't be exact

Analog of Local ansatz constraint:

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

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→ $$|f_{NL}^{\text{eff}}(k)| < 10^{9/2}$$

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- Statement about perturbation theory of the inflaton

(THEORY) CAVEATS

- We will check only local NG (equilateral more compelling?)

- Constant scale-dependence can't be exact

- Expect more terms in the series

Beyond the bispectrum

- Higher orders = more work (only up to S_4 done in some cases)

$$S = S_0 + S_2 + S_3 + \ldots$$

- *Expect* new terms/parameters at each order

$$\Phi(\mathbf{x}) = \Phi_G(\mathbf{x}) + f_{NL} * \left[\Phi_G^2(\mathbf{x}) - \langle\Phi_G^2(\mathbf{x})\rangle\right] + g_{NL} * \Phi_G^3 + \ldots$$

(eg, simulations by Desjacques, Seljak)

(THEORY) CAVEATS

- We will check only local NG (equilateral more compelling?)

- Constant scale-dependence can't be exact

- Expect more terms in the series

- k-space form not exact (?)
- Restricted to $n_f \sim \mathcal{O}(\epsilon, \eta)$?

IV.Analytic Expectations for Bias

Expect...

- Background is defined by scale of object
- Scale-dependent non-Gaussianity: relevant f_{NL} is at the scale of object

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- Scale-dependent non-Gaussianity: relevant f_{NL} is at the scale of object

For $$f_{NL}(k) = f_{NL}(k_p)\left(\frac{k}{k_p}\right)^{n_f^{(s)}}$$

If $$n_f^{(s)} > 0$$

Then $$\Delta b_{NG}(M_{small}) > \Delta b_{NG}(M_{large})$$

Two effects...

$$B_\Phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \equiv \xi_s(k_3)\xi_m(k_1)\xi_m(k_2)\, P_\Phi(k_1)P_\Phi(k_2) + 5\,\text{perm.},$$

- Effective f_{NL} depending on mass (scale) of object $\xi_s(k), \xi_m(k)$
- Shift in k-dependence on large scales $\xi_m(k)$

$$\Delta b_{NG}(k, M) \propto \frac{f_{NL}^{\rm eff}(M)}{k^{2-n_f^{(m)}}}$$

Peak-Background split

- Bispectrum in squeezed limit:

$$k_1, k_2 = k_s \gg k_3 = k_l$$

$$B(k_1, k_2, k_3) \approx 2\xi_s(k_1)\xi_m(k_2)\xi_m(k_3)P(k_2)P(k_3)$$

Peak-Background split

- Bispectrum in squeezed limit:

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$$B(k_1, k_2, k_3) \approx 2\xi_s(k_1)\xi_m(k_2)\xi_m(k_3)P(k_2)P(k_3)$$

$$B(k_1, k_2, k_3) \approx 2\xi_s(k_s)\xi_m(k_s)\xi_m(k_l)P(k_s)P(k_l)$$

Bias, Cont'd

- The result, *summing* over short wavelength modes

Bias, Cont'd

- The result, *summing* over short wavelength modes

$$\Delta b \propto b_G \left[\frac{2\delta_c}{k^2 T(k)} \left(\frac{k}{k_p}\right)^{n_f^{(m)}} \xi_s(k_p)[\xi_m(k_p)]^2 \mathcal{F}_R(k, n_f^{(s)}, n_f^{(m)}) \right]$$

Bias, Cont'd

- The result, *summing* over short wavelength modes

$$\Delta b \propto b_G \left[\frac{2\delta_c}{k^2 T(k)} \left(\frac{k}{k_p} \right)^{n_f^{(m)}} \xi_s(k_p)[\xi_m(k_p)]^2 \overbrace{\mathcal{F}_R(k, n_f^{(s)}, n_f^{(m)})} \right]$$

Bias, Cont'd

- The result, *summing* over short wavelength modes

$$\Delta b \propto b_G \left[\frac{2\delta_c}{k^2 T(k)} \left(\frac{k}{k_p} \right)^{n_f^{(m)}} \overbrace{\xi_s(k_p)[\xi_m(k_p)]^2 \mathcal{F}_R(k, n_f^{(s)}, n_f^{(m)})} \right]$$

$$\underbrace{\xi_s(k_p)[\xi_m(k_p)]^2 \mathcal{F}_R(k, n_f^{(s)}, n_f^{(m)})}_{f_{NL}^{eff}(M, n_f^{(s)}, n_f^{(m)}, k_p)}$$

$f_{NL}^{eff}(M, n_f^{(s)}, n_f^{(m)}, k_p)$

The Sum

- Small k limit:

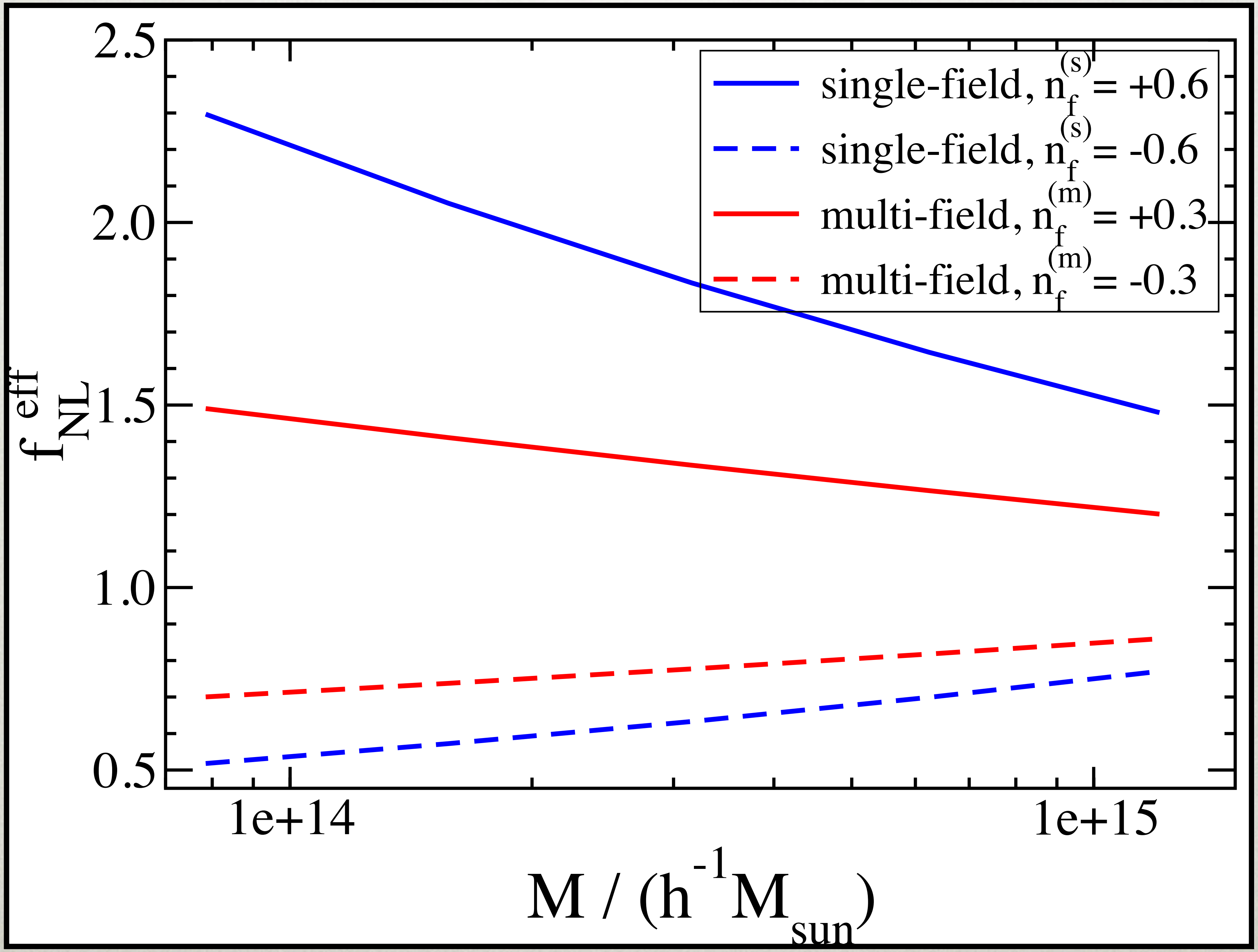
$$\mathcal{F}_R(k, n_f^{(s)}, n_f^{(m)}) \approx \frac{1}{2\pi^2\sigma(M)^2}\int_0^\infty dk_1\; k_1^2 P_\Phi(k_1) M_R^2(k_1)\left(\frac{k_1}{k_p}\right)^{n_f^{(s)}+n_f^{(m)}}$$

Text

Window function

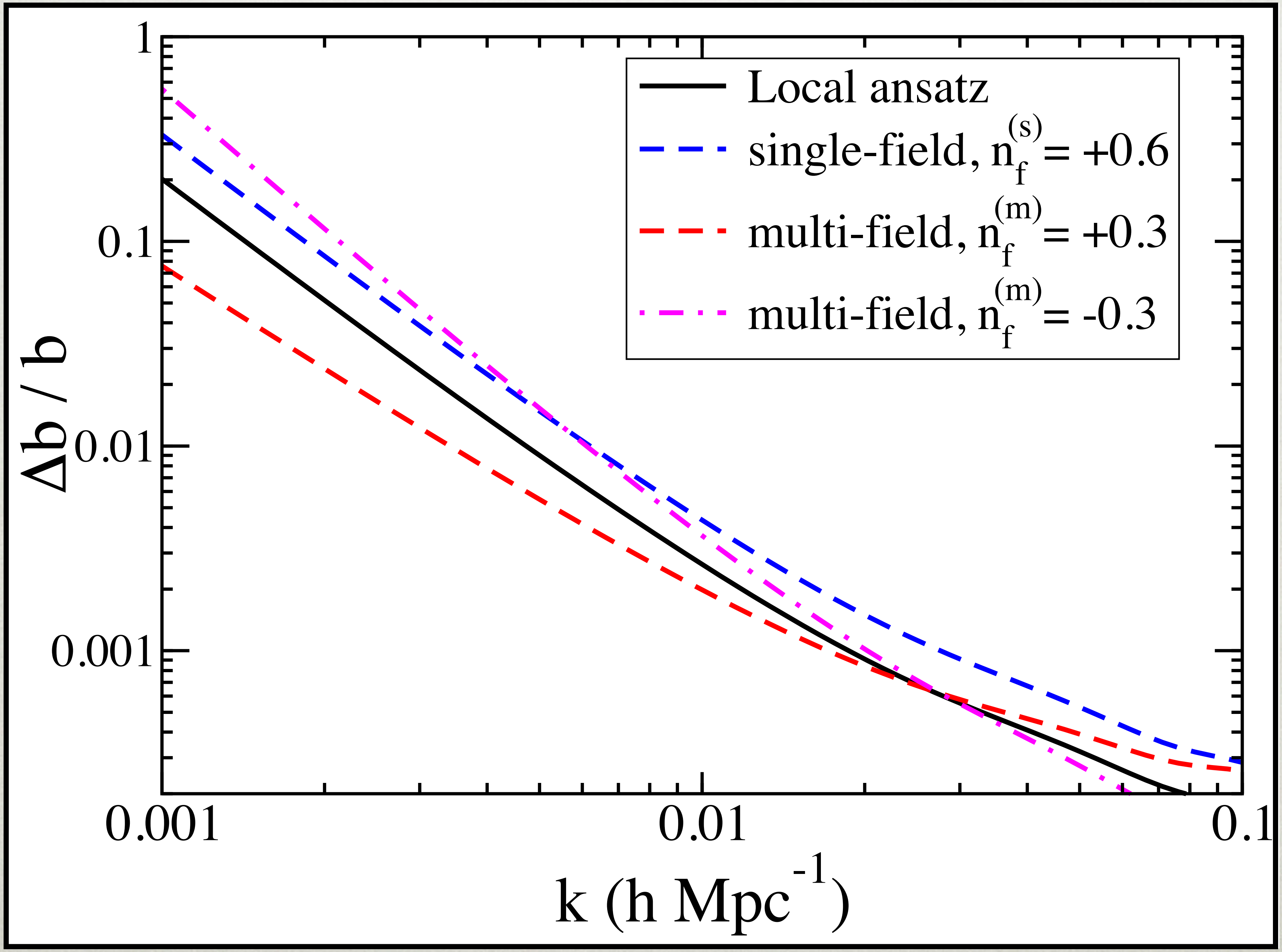
✱ Normalized to 1 if NG constant

I. Mass-dependent amplitude



Shandera, 17 Nov 2010, Cornell

Predicted Effect on Bias



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Forecasts

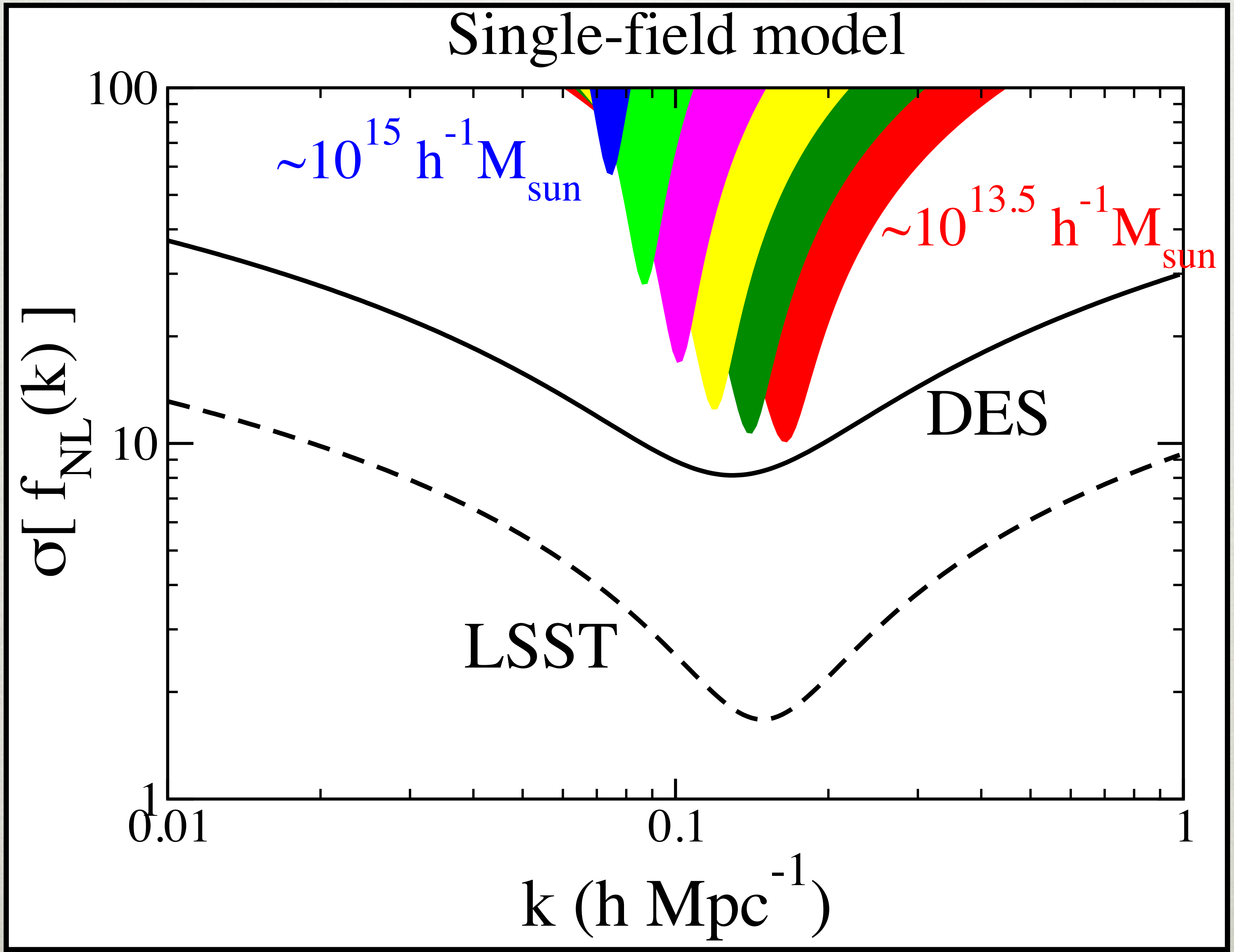
- We report constraints on:

$$f_{NL}(k) = \xi_s(k_p)[\xi_m(k_p)]^2 \left(\frac{k}{k_p}\right)^{n_f^{(s)}+n_f^{(m)}}$$

- Fiducial values:

$$f_{NL}(k_p) \equiv \xi_s(k_p)\xi_m^2(k_p) = 30,\ n_f^{(s),(m)} = 0$$

Single Field Model



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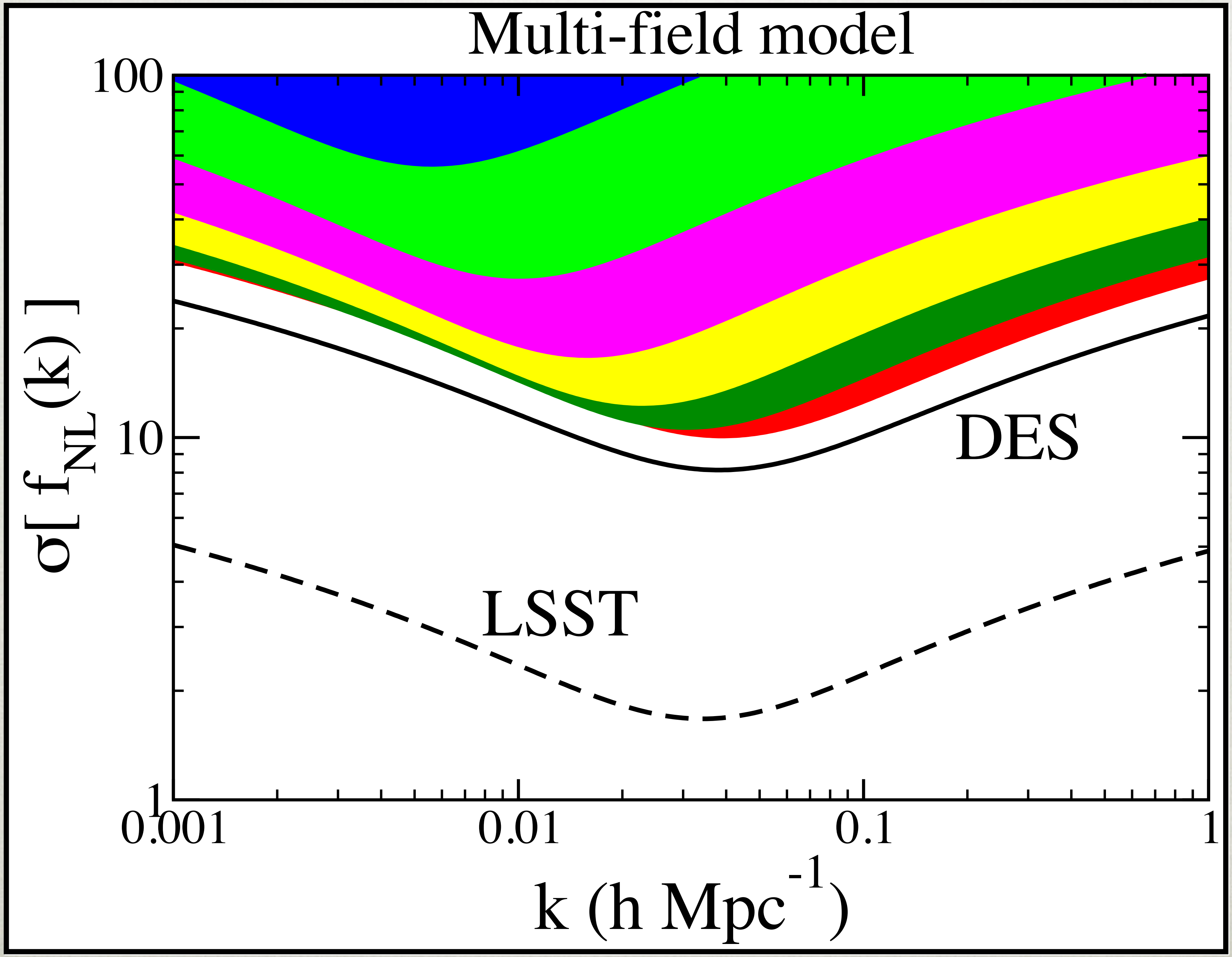
Multi-Field Model



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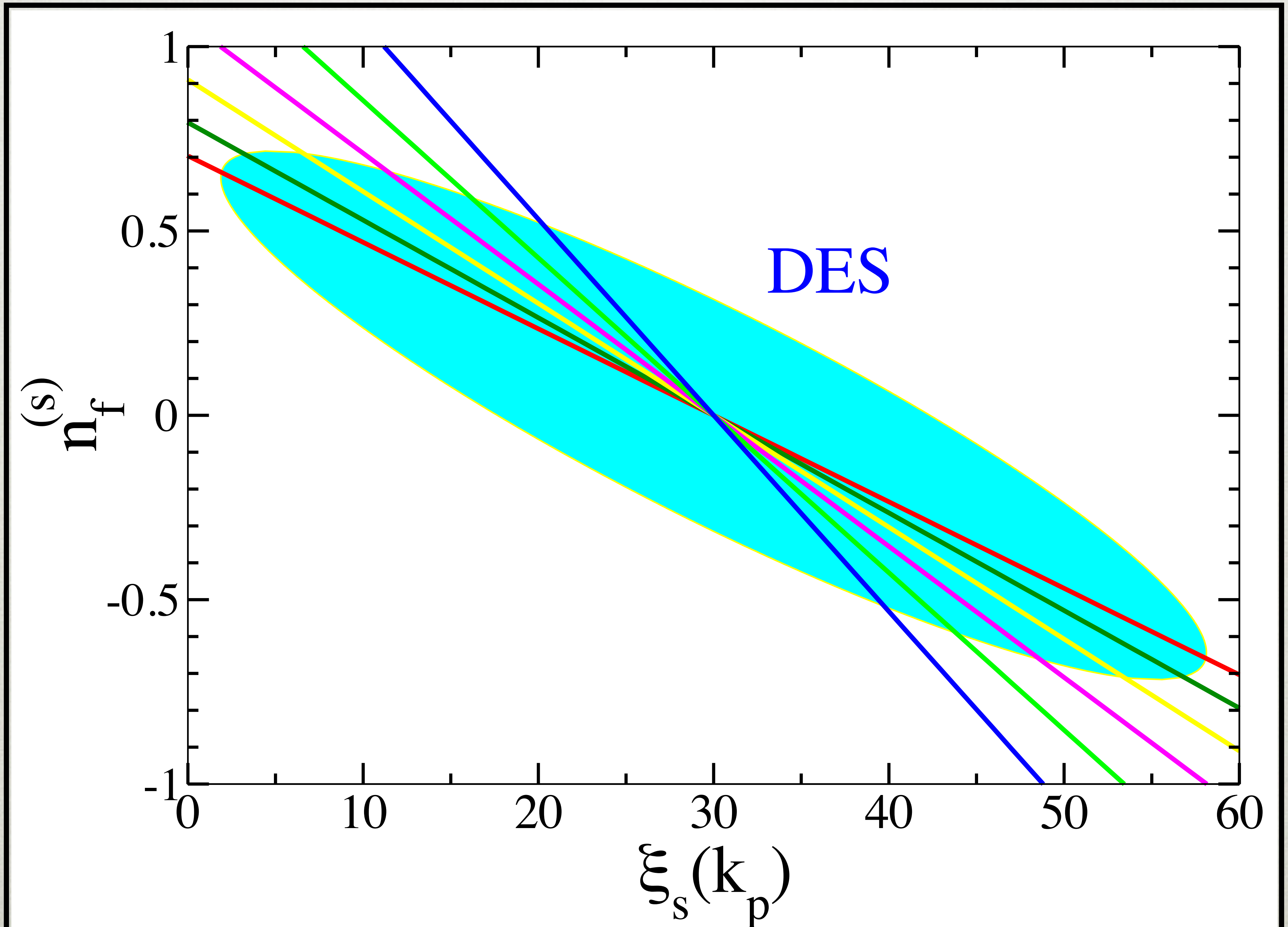
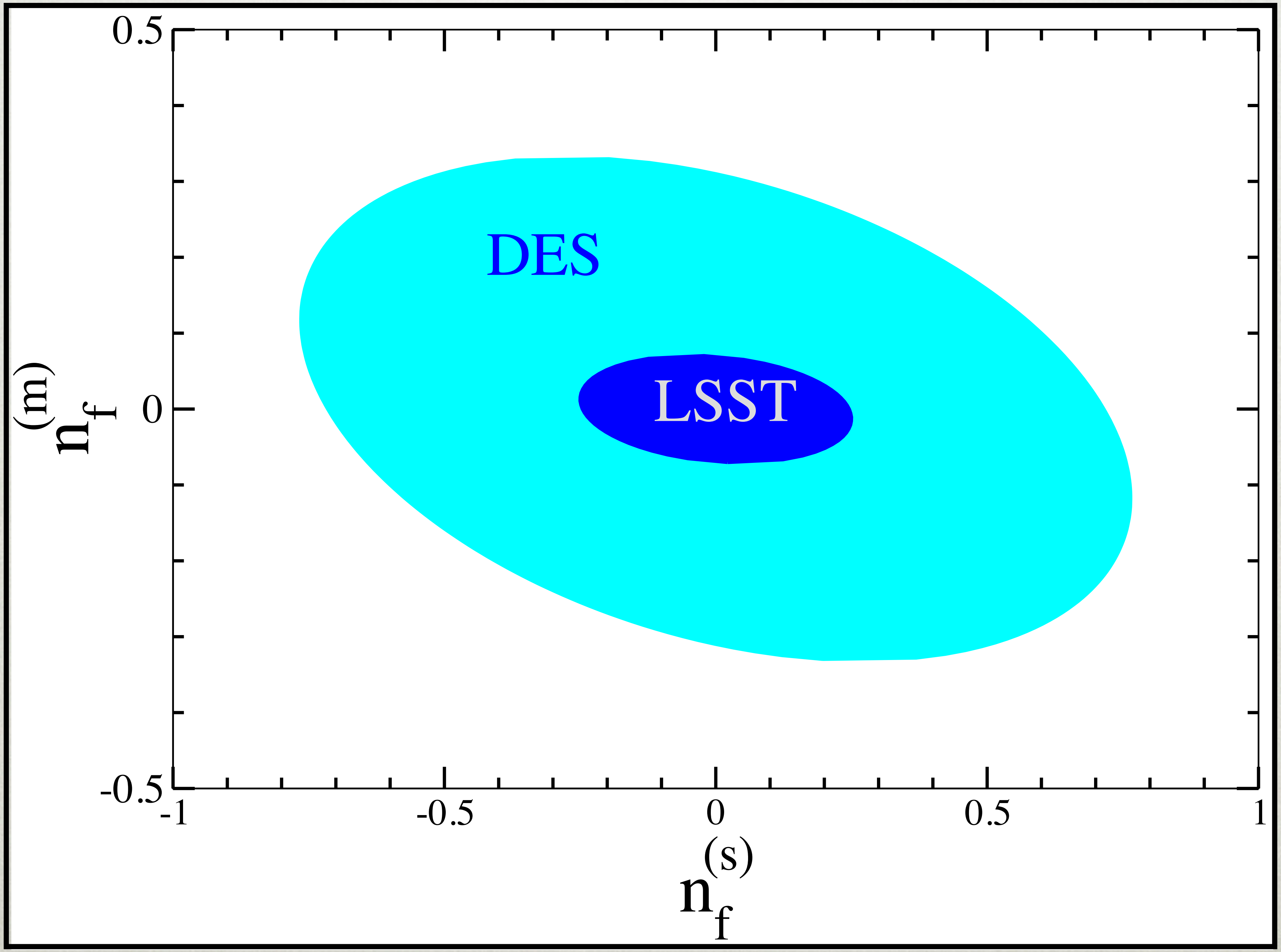
Single-Field Again



Distinguishing Between the effects



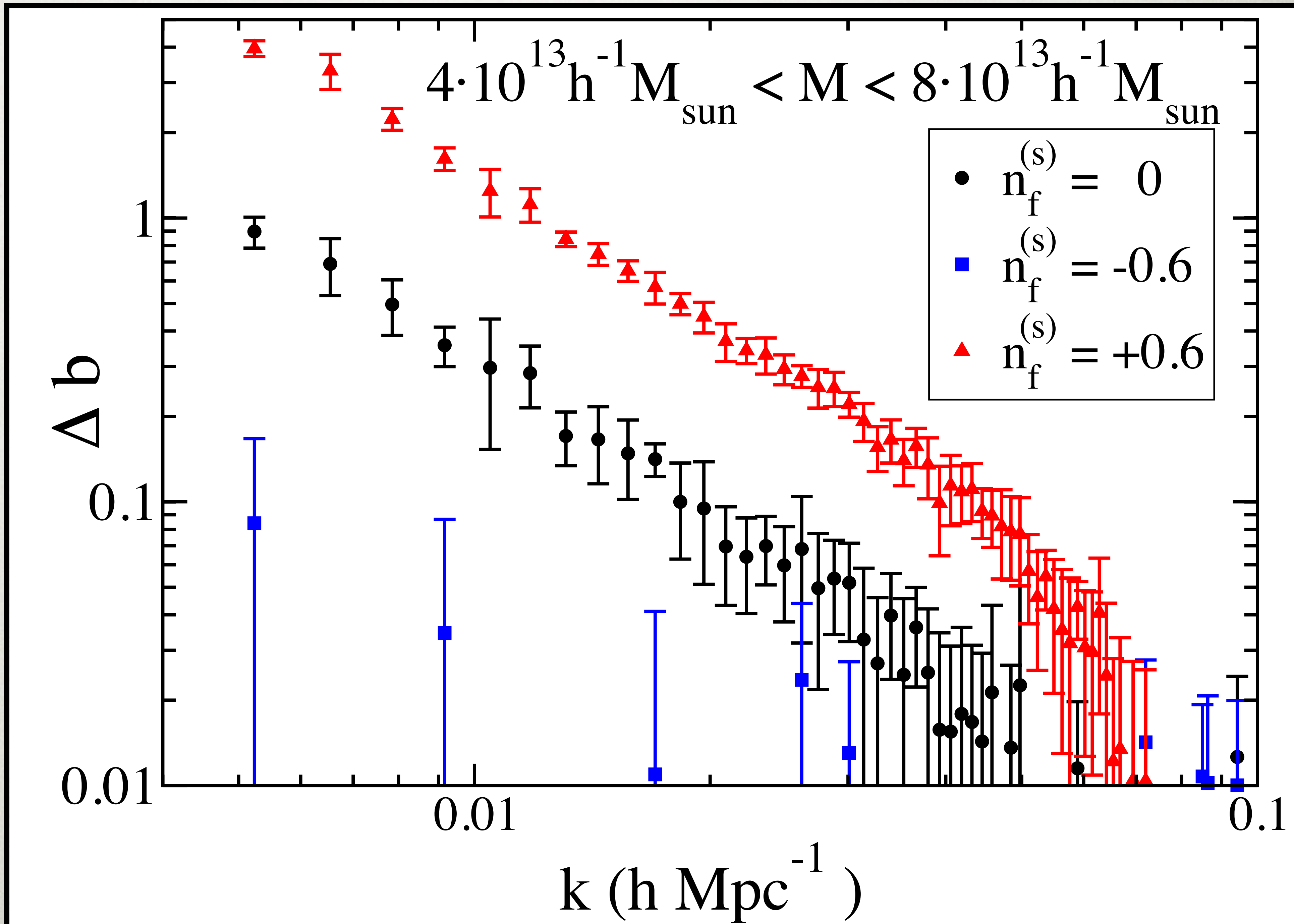
V. Simulation Results

N-body simulations

- Results for single-field model
- Simulation stats:
  - $(1024)^3$ particles
  - L_{box}= 2400 h^{-1} Mpc
  - M_p=9.65 x 10^{11} h^{-1} M_{sun}
  - 8 realizations (Gaussian, non-Gaussian)

Results: low mass

$f_{NL}(k_p) = 300$



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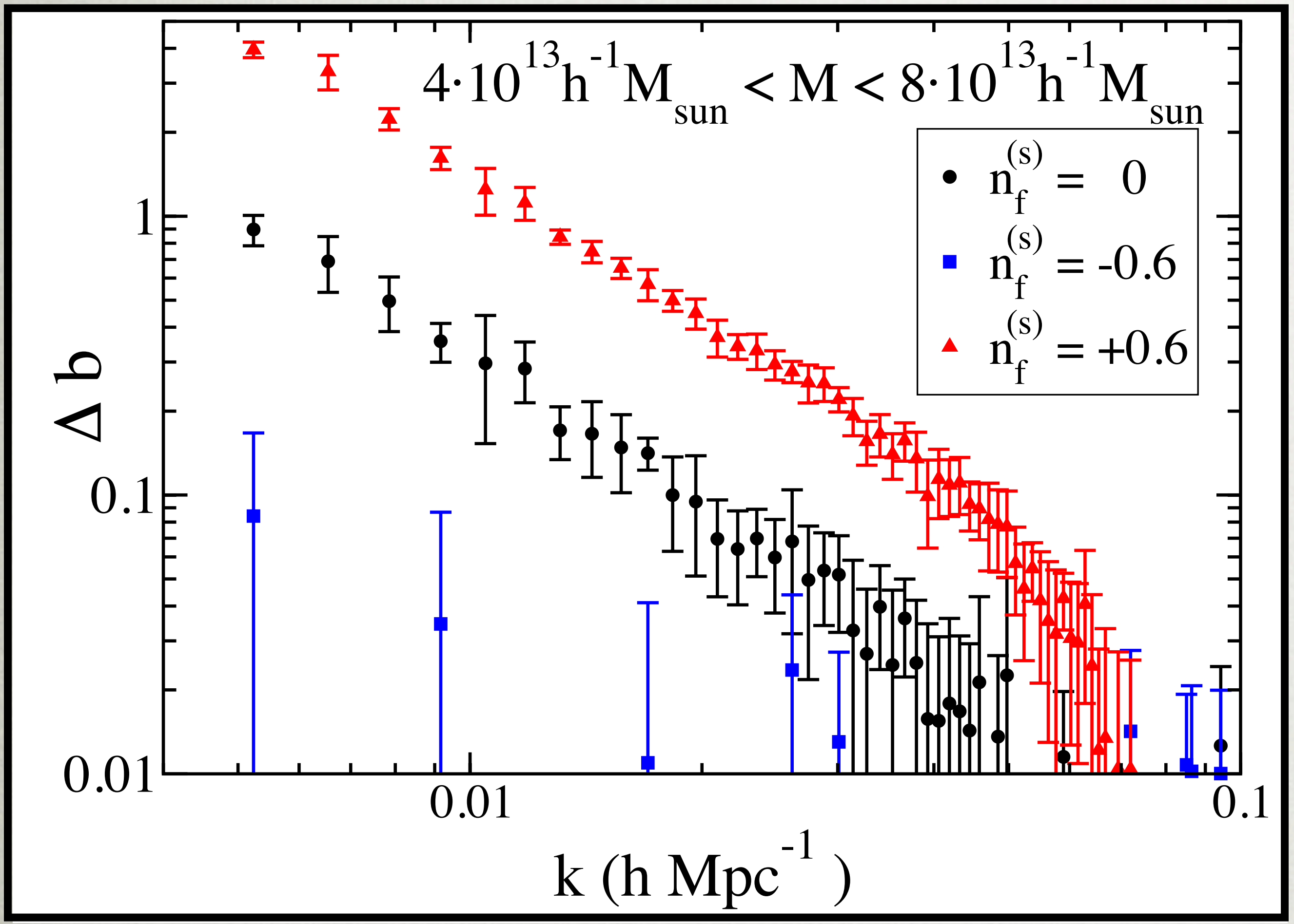
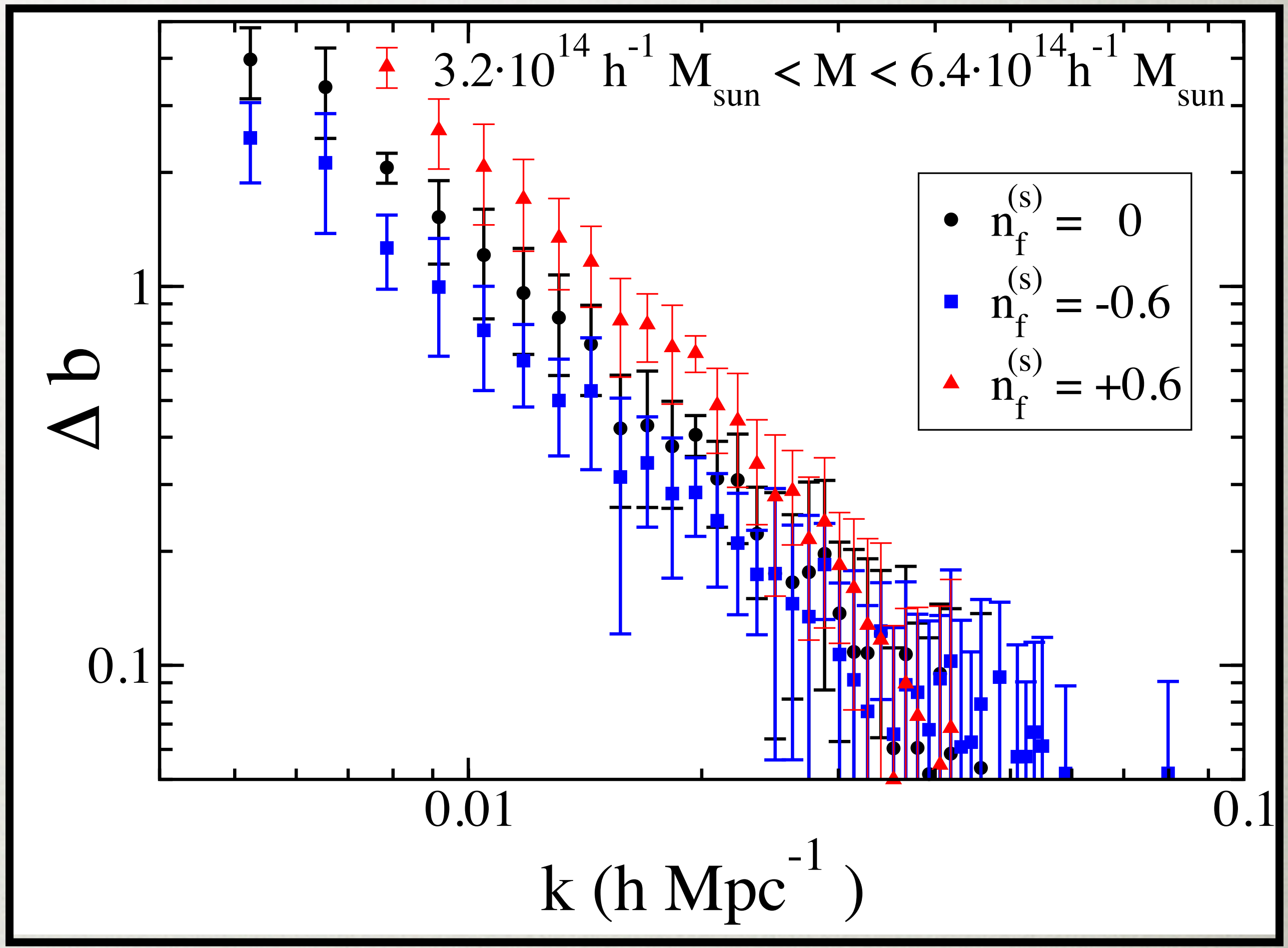
Compare High Mass





$$f_{NL}(k_p) = 300$$

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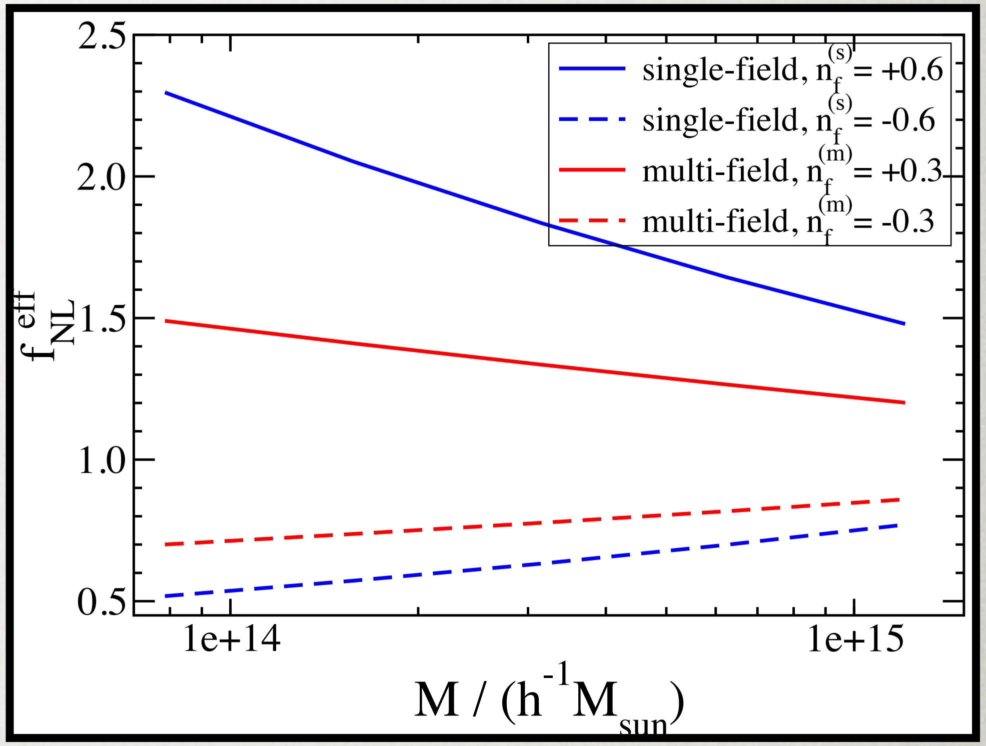
VI. Putting it all together

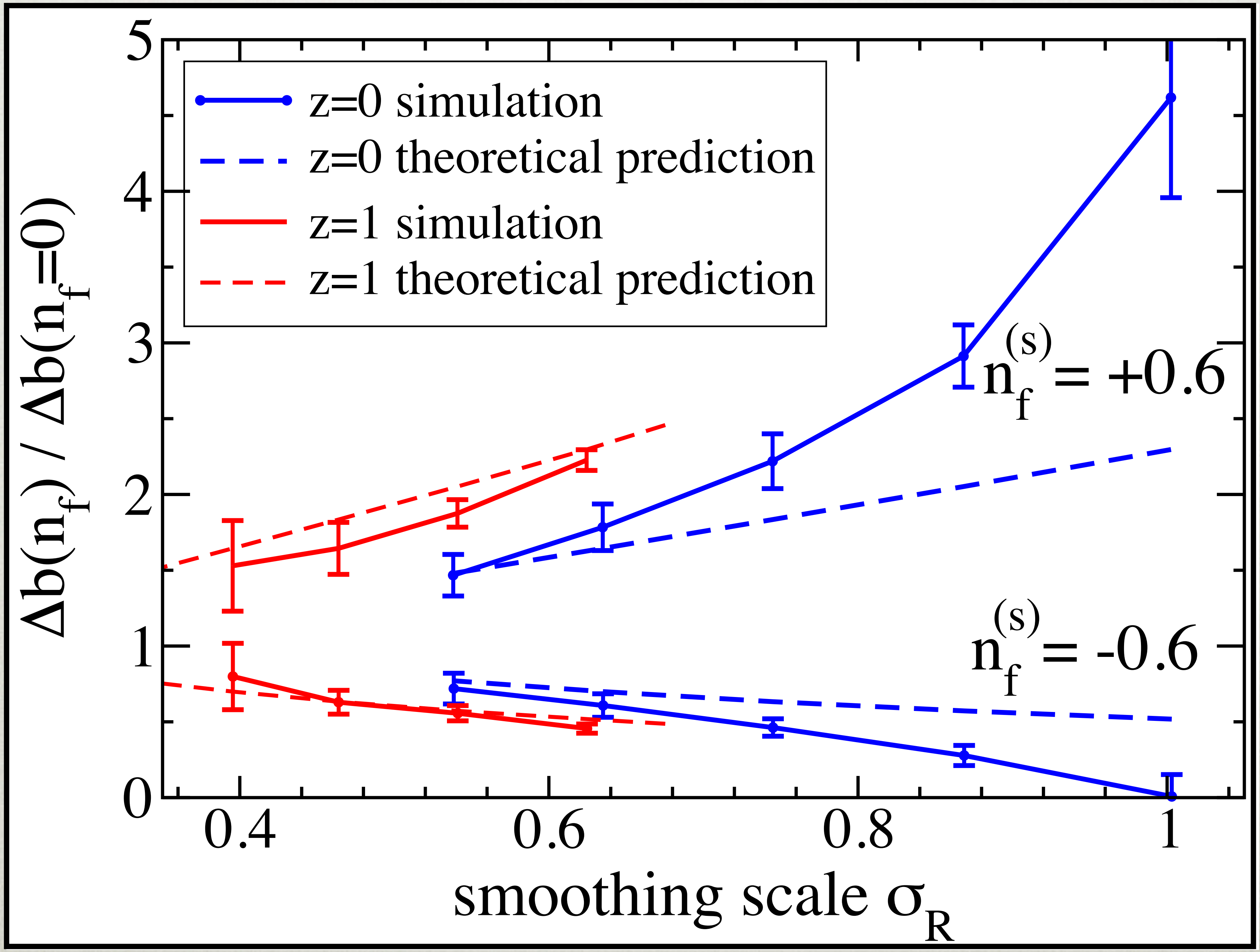
Qualitative effect is there...but...

- Compare with theory
- Plot from the simulations:



$$\mathcal{F}^{\rm sim} \equiv \frac{b(f_{NL}=300, n_f^{(s)}=0.6) - b(f_{NL}=0)}{b(f_{NL}=300, n_f^{(s)}=0) - b(f_{NL}=0)} = \frac{\Delta b(n_f^{(s)})}{\Delta b(n_f^{(s)}=0)}$$

Agreement?



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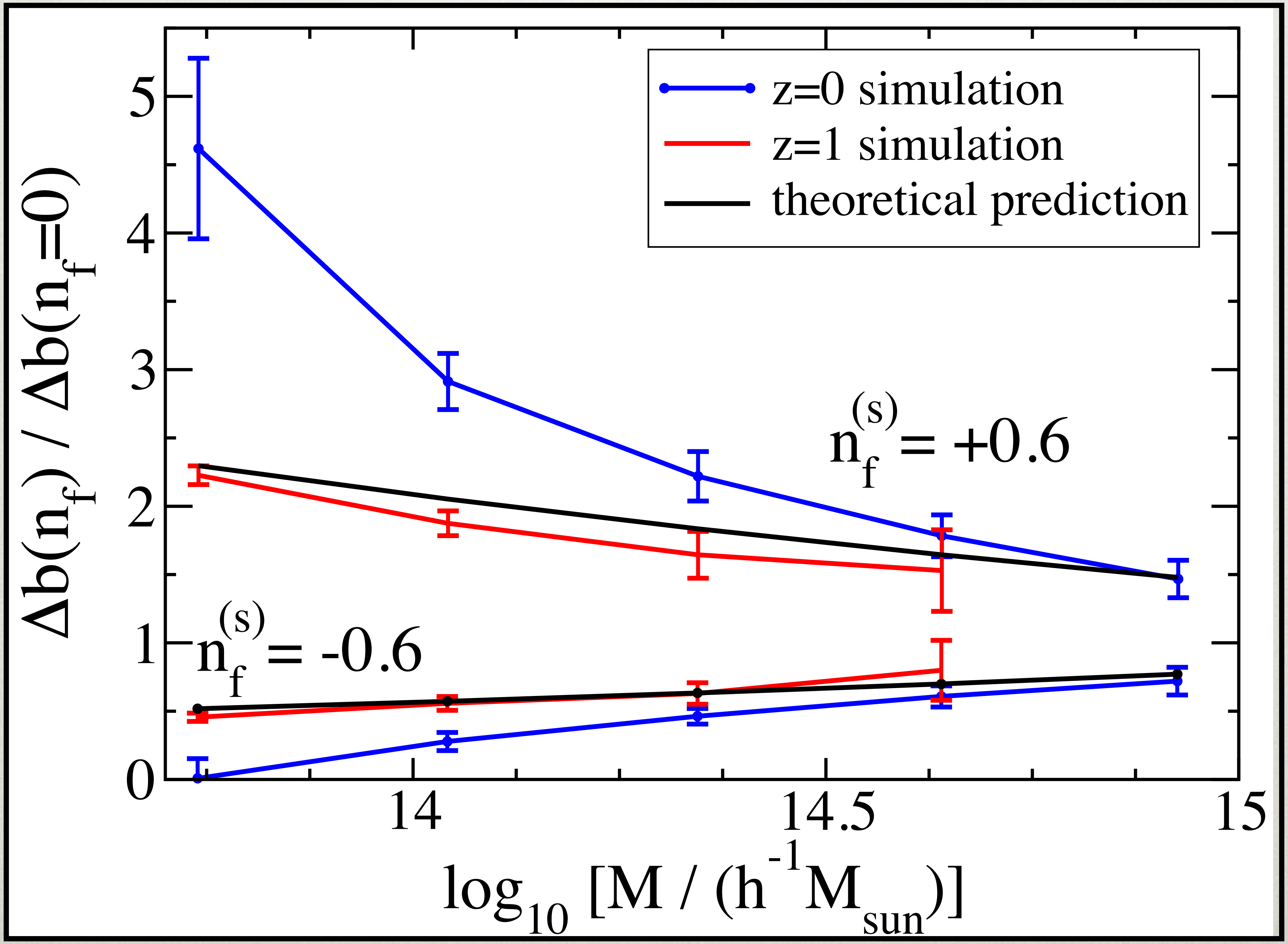
A different View



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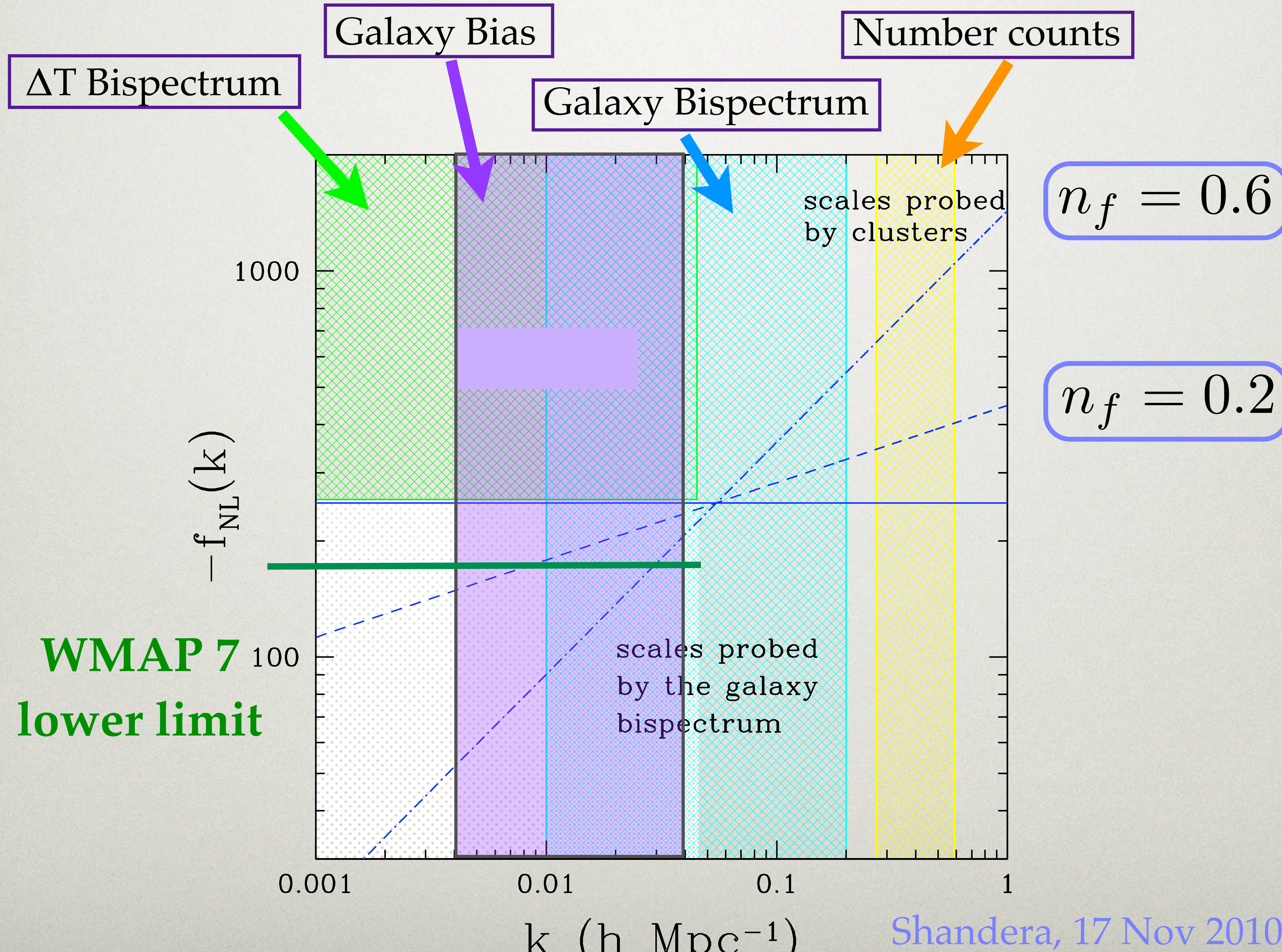
Future

- Encouraging for observations if correct
- Overlap with CMB (Planck!)
  - Previous analysis (different ansatz); CMB (Planck) alone: (Sefusatti et al)

$$f_{NL}^{\text{local}} = 50 \qquad \Delta n_f = 0.1$$

NG on Smaller scales



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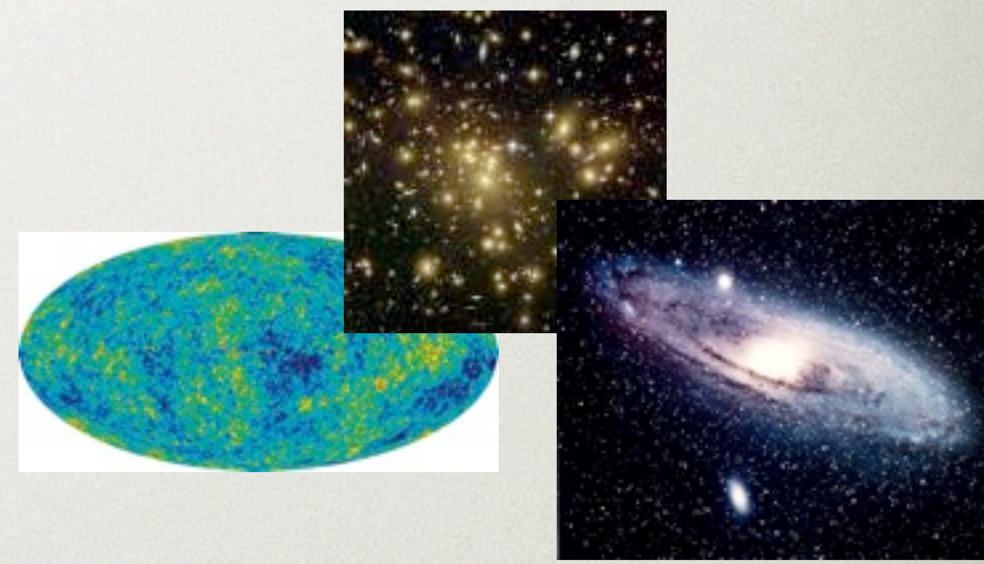
Future

- Encouraging for observations if correct
- Overlap with CMB (Planck?)
- Important to use different mass tracers!
- Explanation related to initial peak profile?
    - Peaks at high $\sigma(M)$ are peakier (so sensitive to smaller scales than naive expectation) (BBKS; Dalal, Lithwick, Kuhlen)

Conclusions

- Much to look forward to from LSS!
- Fundamental theory can better inform cosmologists' approach
- Beyond the tree-level 2-point! Theorists rejoice!



- Coming soon: Properties of NG!