UNIVERSITÉ DE GENÈVE

Center for Astroparticle Physics GENEVA

Looking for primordial non-Gaussianity in the LSS

a new insight from the peak approach to halo clustering

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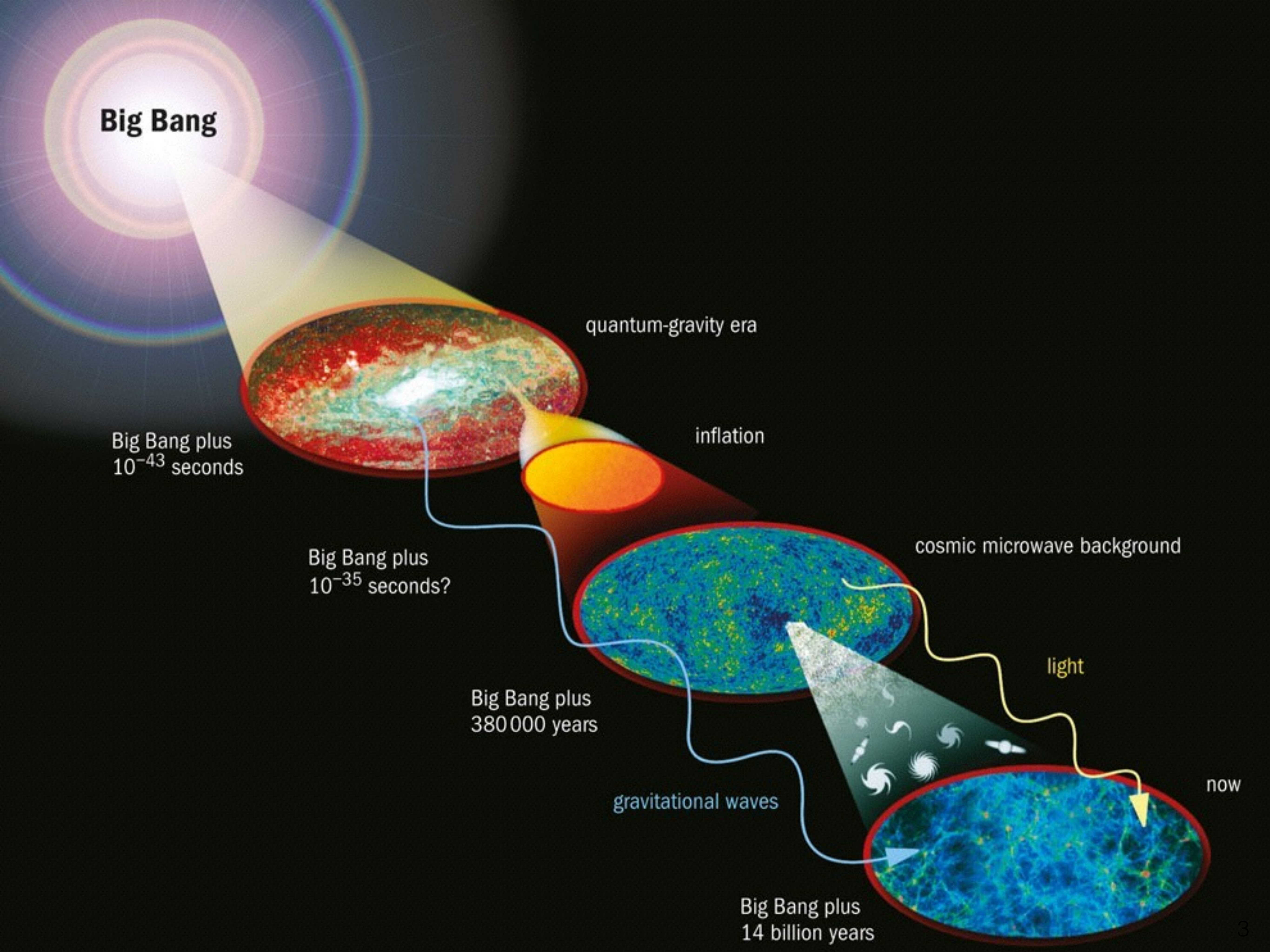
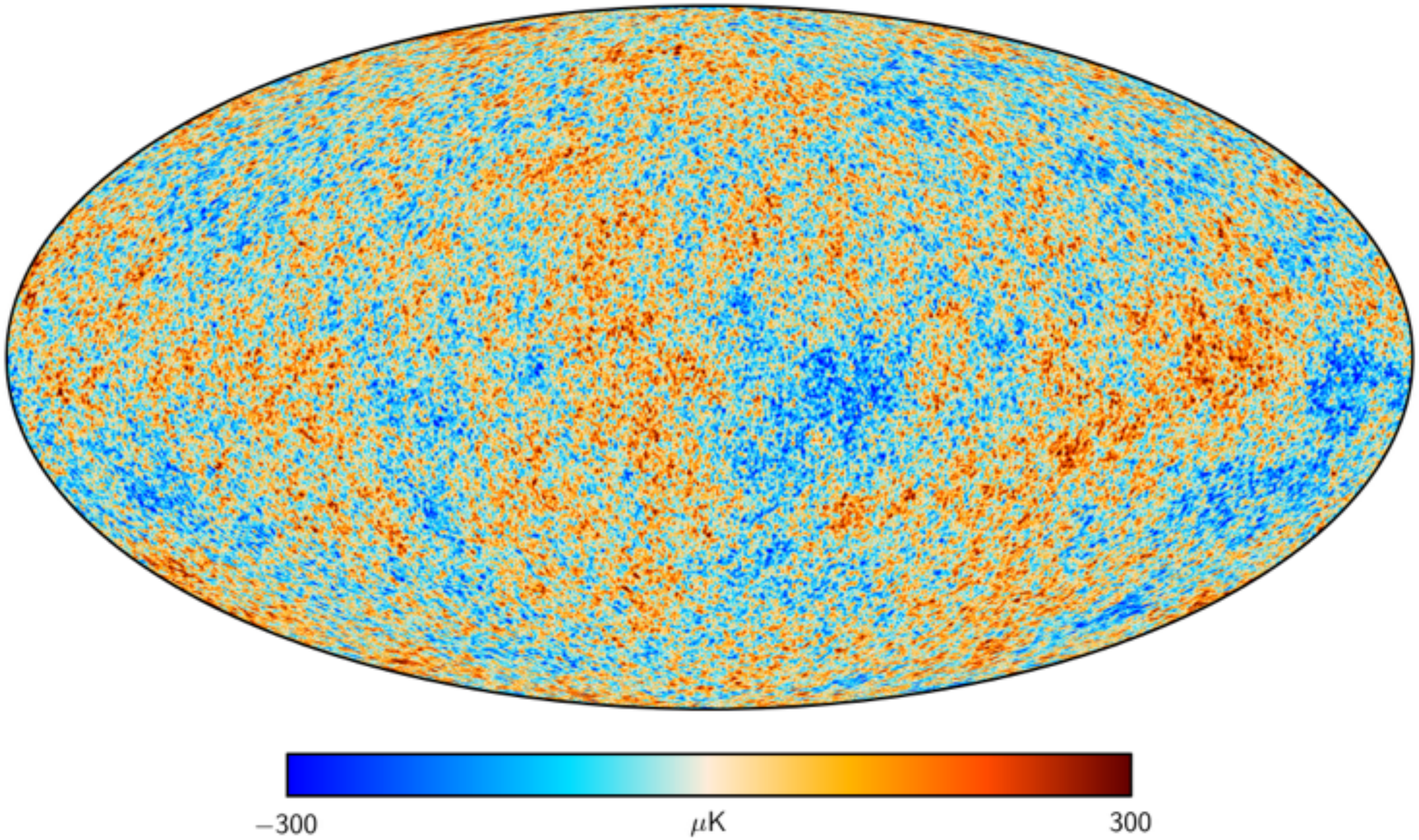
MB & Desjacques, MNRAS ***451*** *(2015) 3643 [arXiv:1501.04982]*
work in preparation with Vincent Desjacques, Fabian Schmidt, Tobias Baldauf, Titouan Lazeyras

Motivation


Big Bang
quantum-gravity era
Big Bang plus
10^{-43} seconds
inflation
Big Bang plus
10^{-35} seconds?
cosmic microwave background
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years

What is the mechanism for primordial perturbations?

Perturbations at the surface of last scattering are observable as temperature anisotropies in the CMB

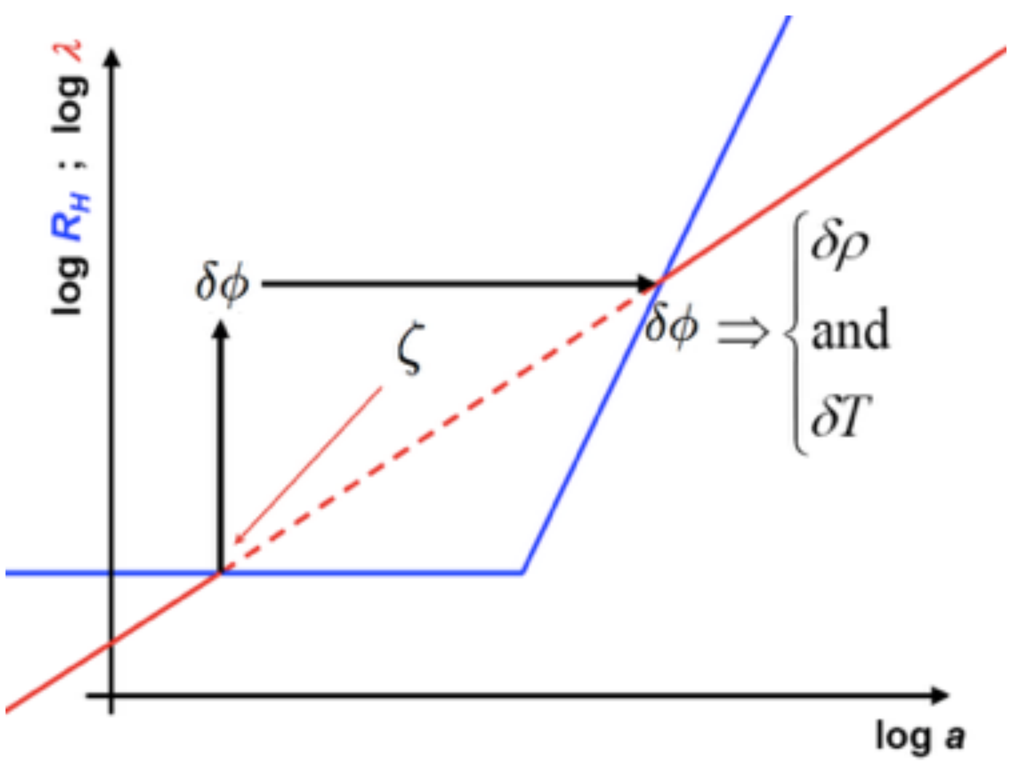


Planck Collaboration (2015)

What is the mechanism for primordial perturbations?

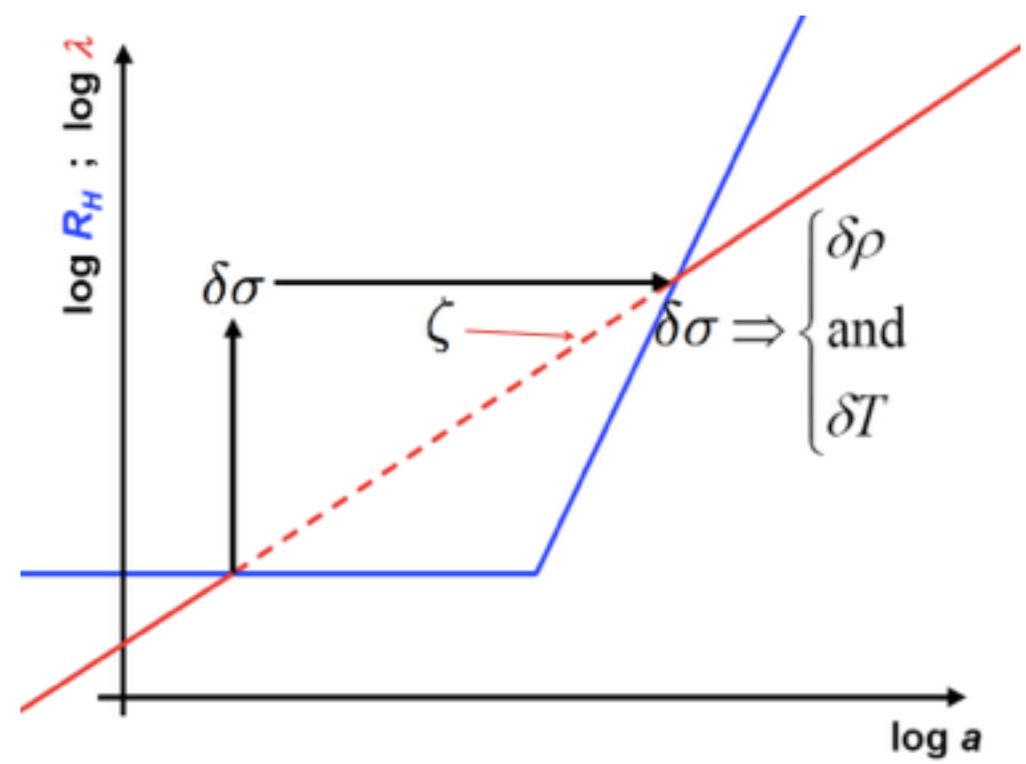
- Perturbations are of the adiabatic/curvature type
- Gaussian (or very close to it)

Single field



perturbations generated by inflaton itself at horizon crossing

Multi field



perturbations generated by other field(s) after inflation

What is the mechanism for primordial perturbations?

Primordial non-Gaussianity is the key ingredient

Local type quadratic non-Gaussianity

$$\zeta(x) = \zeta_{\rm G}(x) + f_{\rm NL}^{\rm loc}(\zeta_{\rm G}^2(x) - \langle\zeta_{\rm G}^2\rangle)$$

$\propto (n_s - 1) \ll 1$ Single field *Maldacena (2003)*

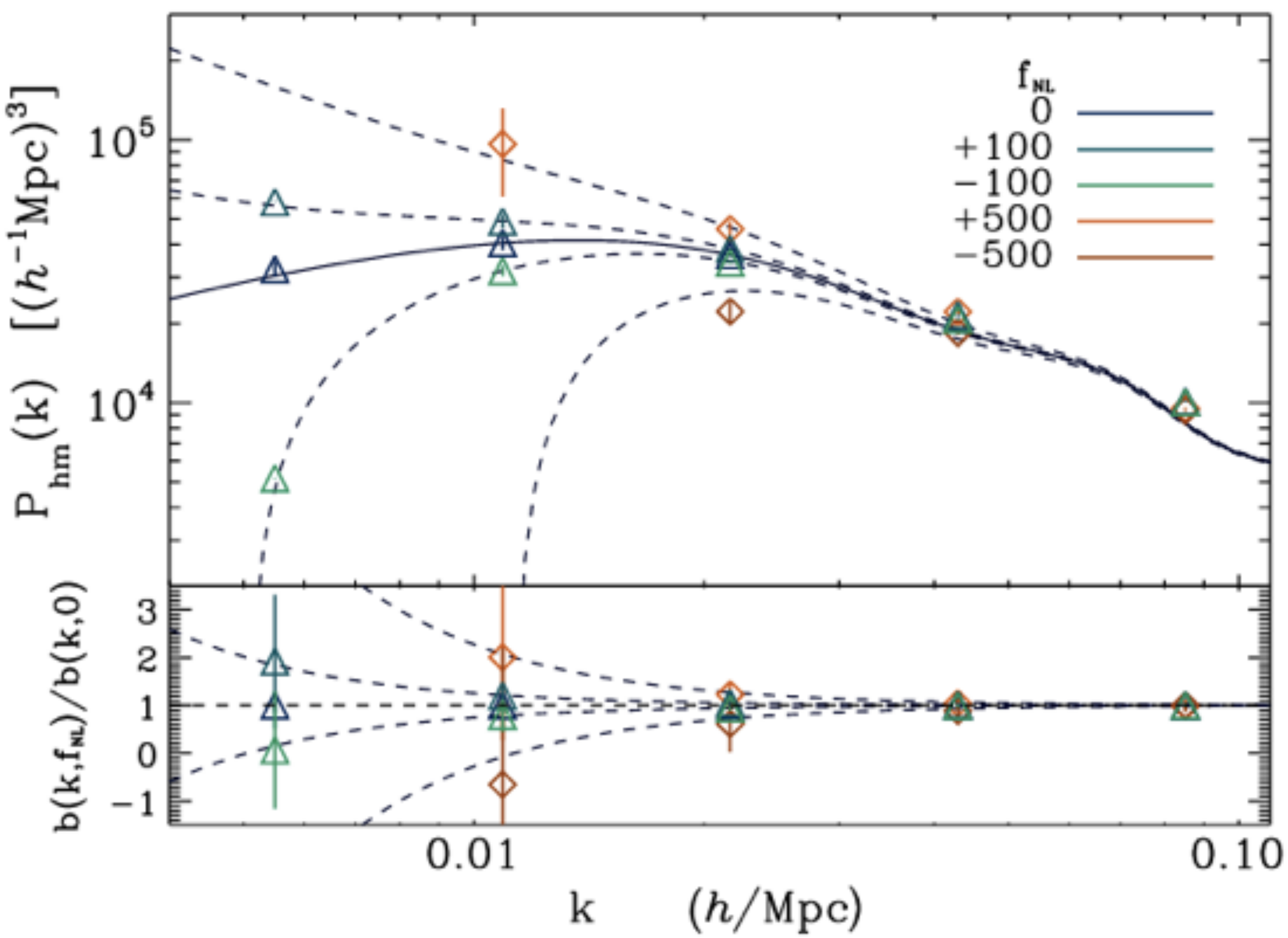
$f_{\rm NL}^{\rm loc}$ (squeezed limit) $f_{\rm NL}^{\rm loc} = 0.8 \pm 5.0$ *Planck (2015)*

$\gtrsim 1$ Multi field

What is the mechanism for primordial perturbations?

Primordial non-Gaussianity is the key ingredient

Signatures of primordial non-Gaussianity in Large Scale Structure



$$\frac{P_{\rm hm}(k)}{P_{\rm mm}(k)} = b_1 + \frac{2 f_{\rm NL}^{\rm loc}}{\mathcal{M}(k)} \delta_c b_1^{\rm L}$$

where $\mathcal{M}(k) \propto k^2$ at large scales

Dalal, Dore, Huterer, Shirokov (2007)

Matarrese & Verde (2008)

What is the mechanism for primordial perturbations?
Primordial non-Gaussianity is the key ingredient

Signatures of primordial non-Gaussianity in Large Scale Structure

$$\frac{P_{\rm hm}(k)}{P_{\rm mm}(k)} = b_1 + \frac{2f_{\rm NL}^{\rm loc}}{\mathcal{M}(k)}\delta_c b_1^{\rm L}$$

Future surveys seem to have very competitive forecasts…

Bispectrum shape	local	orthogonal	equilateral
Fiducial $f_{\rm NL}$	0	0	0
Galaxy clustering (spectr. z)	4.1 (4.0)	54 (11)	220 (35)
Galaxy clustering (photom. z)	5.8 (5.5)	38 (9.6)	140 (37)
Weak lensing	73 (27)	9.6 (3.5)	34 (13)
Combined	4.7 (4.5)	4.0 (2.2)	16 (7.5)

Euclid Collaboration (2012)

1σ errors	PS	Bispec	PS + Bispec	EUCLID	Current
$f_{\rm NL}^{\rm loc}$	0.87	0.23	0.20	5.59	5.8
Tilt n_s ($\times 10^{-3}$)	2.7	2.3	2.2	2.6	5.4
Running α_s ($\times 10^{-3}$)	1.3	1.2	0.65	1.1	17
Curvature Ω_K ($\times 10^{-4}$)	9.8	NC	6.6	7.0	66
Dark Energy FoM $= 1/\sqrt{\rm DetCov}$	202	NC	NC	309	25

SPHEREx collaboration (2014)

What is the mechanism for primordial perturbations?
Primordial non-Gaussianity is the key ingredient

Signatures of primordial non-Gaussianity in Large Scale Structure

$$\frac{P_{\rm hm}(k)}{P_{\rm mm}(k)} = b_1 + \frac{2 f_{\rm NL}^{\rm loc}}{\mathcal{M}(k)} \delta_c b_1^{\rm L}$$

...but is $\delta_c b_1^{\rm L}$ a accurate enough prediction for $\mathcal{O}(\sigma_{f_{\rm NL}}) \simeq 1$?

In this talk

- Model independent amplitude for non gaussian bias (Peak Background Split) *Slosar, Hirata, Seljak, Ho, Padmanabhan (2008)*
- Model dependent prediction from a first principles model of halo biasing (Excursion Set Peaks) *MB, Desjacques (2015)*
- Both these amplitudes are different than $\delta_c b_1^{\rm L}$

What is the mechanism for primordial perturbations?

Primordial non-Gaussianity is the key ingredient

Signatures of primordial non-Gaussianity in Large Scale Structure

$$\frac{P_{\mathrm{hm}}(k)}{P_{\mathrm{mm}}(k)} = b_1 + \frac{2 f_{\mathrm{NL}}^{\mathrm{loc}}}{\mathcal{M}(k)} \delta_c b_1^{\mathrm{L}}$$

…but is $\delta_c b_1^{\mathrm{L}}$ a accurate enough prediction for $\mathcal{O}(\sigma_{f_{\mathrm{NL}}}) \simeq 1$?

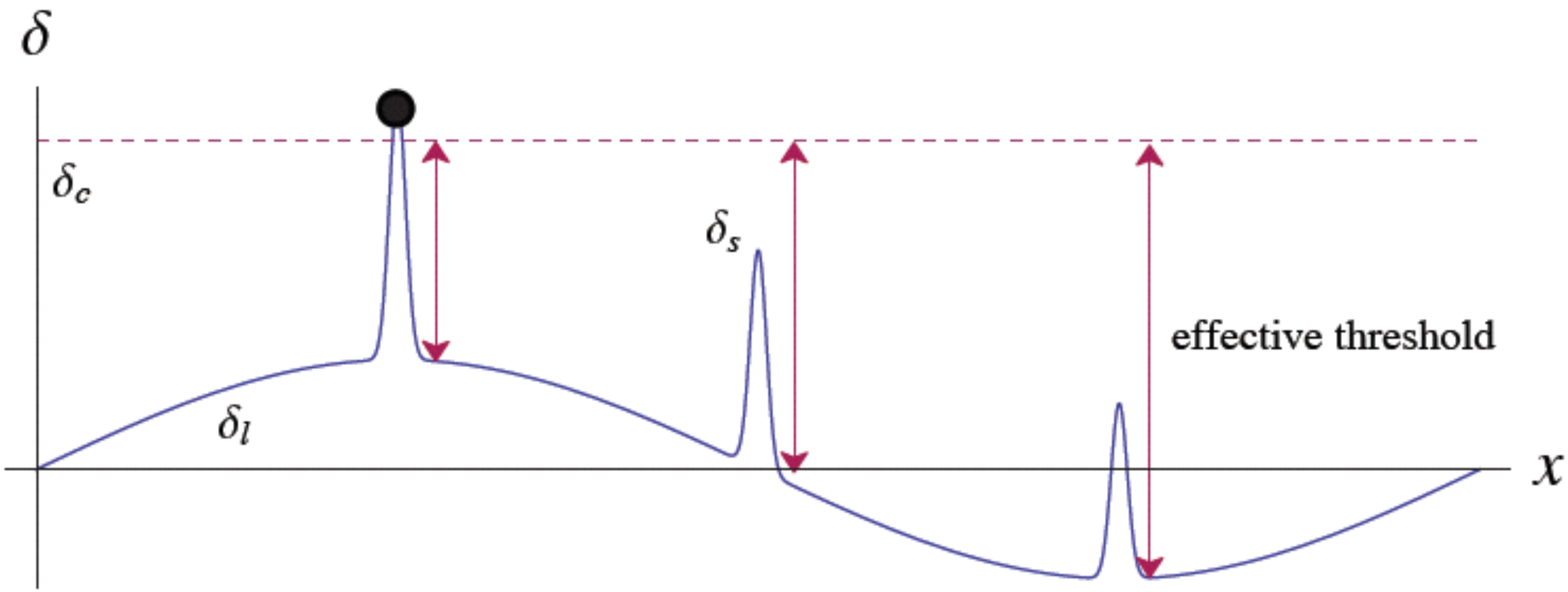
Not in this talk

- We observe redshifts and angles, not k
- Relativistic effects
- Astrophysical systematics
- Halo Occupation Distribution (how galaxies distribute in halos)
- …

Peak Background Split

Halo biasing
the Peak Background Split ansatz

$$\delta = \delta_{\rm L} + \delta_{\rm S}$$



long-wavelength field locally modulates threshold for collapse

Kaiser (1984)

Halo biasing
the Peak Background Split ansatz

$$\delta = \delta_{\rm L} + \delta_{\rm S}$$

$$\delta_h(\vec{x}, M, \delta_c) \equiv \frac{n_h(\vec{x}, M, \delta_c)}{\bar{n}_h(M, \delta_c)} - 1 \approx \frac{\bar{n}_h(M, \delta_c - \delta_{\rm L}(\vec{x}))}{\bar{n}_h(M, \delta_c)} - 1$$

$$\approx -\frac{1}{\bar{n}_h}\frac{d\bar{n}_h}{d\delta_c}\delta_{\rm L}(\vec{x}) + \dots$$

$$b_1$$

long-wavelength field locally modulates threshold for collapse

Halo biasing
the Peak Background Split ansatz

$$\Phi = \phi_{\mathrm{G}} + f_{\mathrm{NL}}\phi_{\mathrm{G}}^2$$

Local quadratic non-Gaussianity

Halo biasing
the Peak Background Split ansatz

$$\Phi = \phi_{\mathrm{G}} + f_{\mathrm{NL}}\phi_{\mathrm{G}}^2$$

Local quadratic non-Gaussianity

PBS ansatz

$$\Phi = \phi_{\mathrm{L}} + f_{\mathrm{NL}}\phi_{\mathrm{L}}^2 + (1 + 2 f_{\mathrm{NL}}\phi_{\mathrm{L}})\phi_{\mathrm{S}} + f_{\mathrm{NL}}\phi_{\mathrm{S}}^2$$

Non gaussian bias
the Peak Background Split ansatz

$$\Phi = \phi_{\rm G} + f_{\rm NL}\phi_{\rm G}^2$$

Local quadratic non-Gaussianity

PBS ansatz

$$\Phi = \phi_{\rm L} + f_{\rm NL}\phi_{\rm L}^2 + (1 + 2 f_{\rm NL}\phi_{\rm L})\phi_{\rm S} + f_{\rm NL}\phi_{\rm S}^2$$

$$\delta = \mathcal{M} \star \Phi$$

$$\delta_{\rm S} \approx \mathcal{M} \star (1 + 2 f_{\rm NL}\phi_{\rm L})\phi_{\rm S}$$

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

Non gaussian bias

the Peak Background Split ansatz

Long- and short-wavelength modes are now mixed, the effect is to modify the amplitude of the matter fluctuations

$$\sigma_8 \to (1 + 2 f_{\rm NL} \phi_{\rm L}) \sigma_8 = \hat{\sigma}_8$$

Non gaussian bias
the Peak Background Split ansatz

Long- and short-wavelength modes are now mixed, the effect is to modify the amplitude of the matter fluctuations

$$\sigma_8 \to (1 + 2 f_{\rm NL} \phi_{\rm L}) \sigma_8 = \hat{\sigma}_8$$

$$\equiv b_{\rm NG}^{\rm PBS}$$

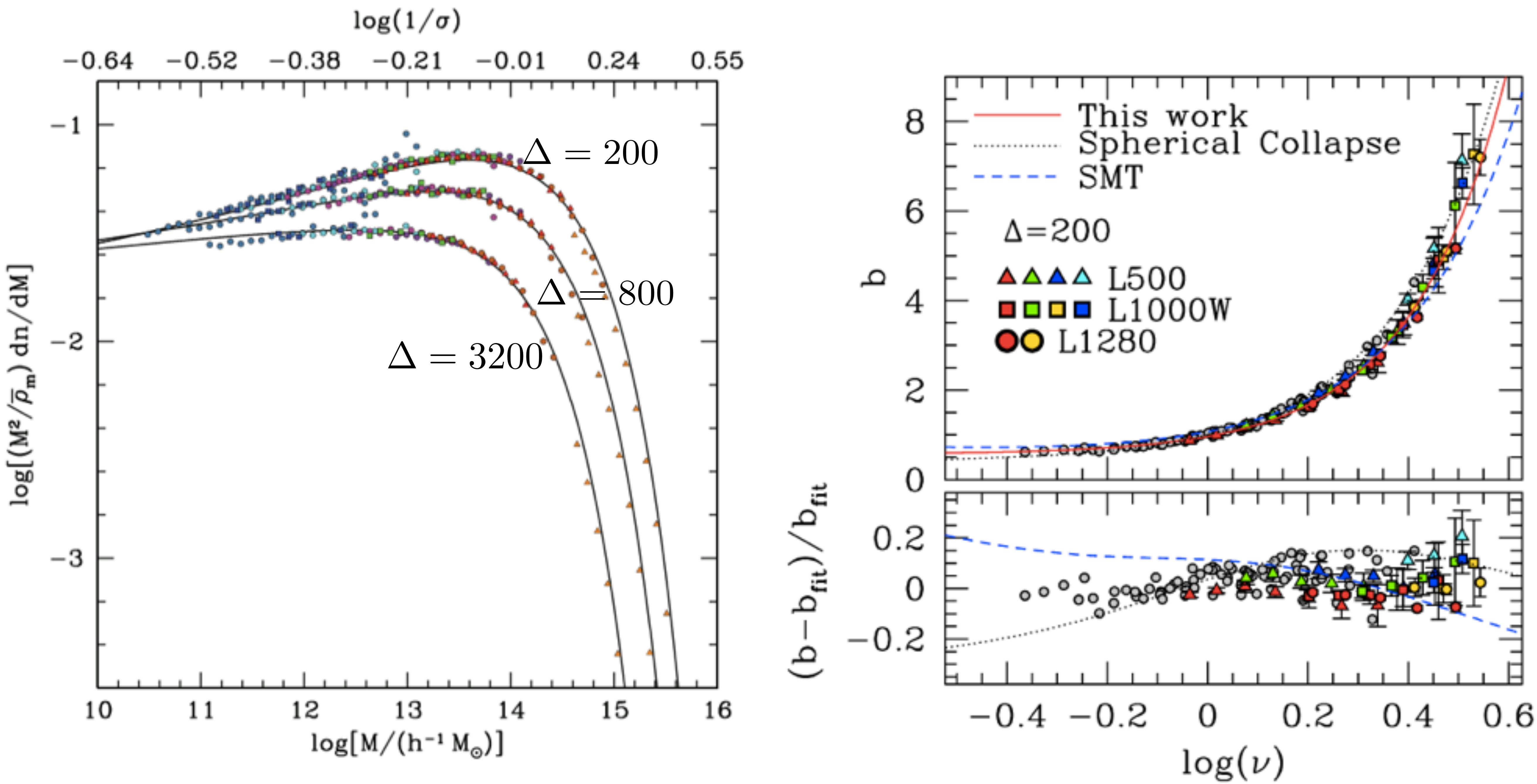
$$\delta_h(\vec{x}, M, \delta_c) \approx b_1\, \delta_{\rm L}(\vec{x}) + 2 f_{\rm NL} \frac{\partial \ln \bar{n}_h}{\partial \ln \hat{\sigma}_8} \phi_{\rm L}(\vec{x}) + \ldots$$

for universal mass function this is the well-known $\delta_c b_1^{\rm L}$
but in the case of non-universality things get more complicated

$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{k^2}$

Scoccimarro, Hui, Manera, Chan (2012)

On the universality of the mass function



Tinker et al. (2008)

Excursion Set Peaks

Halo biasing
the Excursion Set Peaks model

- **Peak model**: consider density peaks of the early distribution of matter and move them forward in time;
  Bardeen, Bond, Kaiser, Szalay (1986)

- (Most) **halos will form around initial peaks**;
  Ludlow & Porciani (2011)

- Impose that **peaks** on a given smoothing scale are **counted only if they satisfy a first crossing condition.**
  Paranjape, Lam, Sheth (2012)
  Paranjape, Sheth, Desjacques (2013)

Halo biasing
the Excursion Set Peaks model

Expand the density field and its gradient around maxima

$$n_{\rm pk}(\mathbf{x}) = \sum_p \delta^{(3)}(\mathbf{x} - \mathbf{x_p})$$
$$\approx |\mathrm{det}\zeta(\mathbf{x})|\, \delta^{(\mathbf{3})}[\eta(\mathbf{x})]$$

where ζ must be negative definite at the peak

A peak of the smoothed density field is defined by its height, slope and curvature

$$\nu(\mathbf{x}) \equiv \frac{1}{\sigma_0}\delta_s(\mathbf{x}) \quad \eta_i(\mathbf{x}) \equiv \frac{1}{\sigma_1}\partial_i\delta_s(\mathbf{x}) \quad \zeta_{ij}(\mathbf{x}) \equiv \frac{1}{\sigma_2}\partial_i\partial_j\delta_s(\mathbf{x})$$

Halo biasing
the Excursion Set Peaks model

N-point correlation function of discrete statistics involve 10N variables…

$$\langle n_{\rm pk}(\mathbf{x})\rangle = \langle|{\rm det}\zeta(\mathbf{x})|\,\delta^{(3)}[\eta(\mathbf{x})]\rangle$$
$$= \int {\rm d}\nu\,{\rm d}^6\zeta\,|{\rm det}\zeta|\,P_1(\nu,\eta=0,\zeta)$$

where ζ must be negative definite at the peak

…but effective local bias expansion of invariants

$$\delta_{\rm pk}(\mathbf{x}) = b_{10}\delta_s(\mathbf{x}) - b_{01}\nabla^2\delta_s(\mathbf{x}) + \frac{1}{2}b_{20}\delta_s^2(\mathbf{x}) - b_{11}\delta_s(\mathbf{x})\nabla^2\delta_s(\mathbf{x})$$
$$+\frac{1}{2}b_{02}[\nabla^2\delta_s(\mathbf{x})]^2 + \chi_{10}(\nabla\delta_s)^2(\mathbf{x}) + \frac{3}{2}\chi_{01}\left[\partial_i\partial_j\delta_s(\mathbf{x}) - \frac{1}{3}\delta_{ij}\nabla^2\delta_s(\mathbf{x})\right]^2$$

Desjacques (2013)

Galaxy biasing
the Excursion Set Peaks model

Effective local bias expansion in terms of rotational invariants

$$\delta_{\rm pk}(\mathbf{x}) = b_{10}\delta_s(\mathbf{x}) - b_{01}\nabla^2\delta_s(\mathbf{x}) + \frac{1}{2}b_{20}\delta_s^2(\mathbf{x}) - b_{11}\delta_s(\mathbf{x})\nabla^2\delta_s(\mathbf{x})$$
$$+ \frac{1}{2}b_{02}[\nabla^2\delta_s(\mathbf{x})]^2 + \chi_{10}(\nabla\delta_s)^2(\mathbf{x}) + \frac{3}{2}\chi_{01}\left[\partial_i\partial_j\delta_s(\mathbf{x}) - \frac{1}{3}\delta_{ij}\nabla^2\delta_s(\mathbf{x})\right]^2$$

and bias parameters are fully predicted by the model

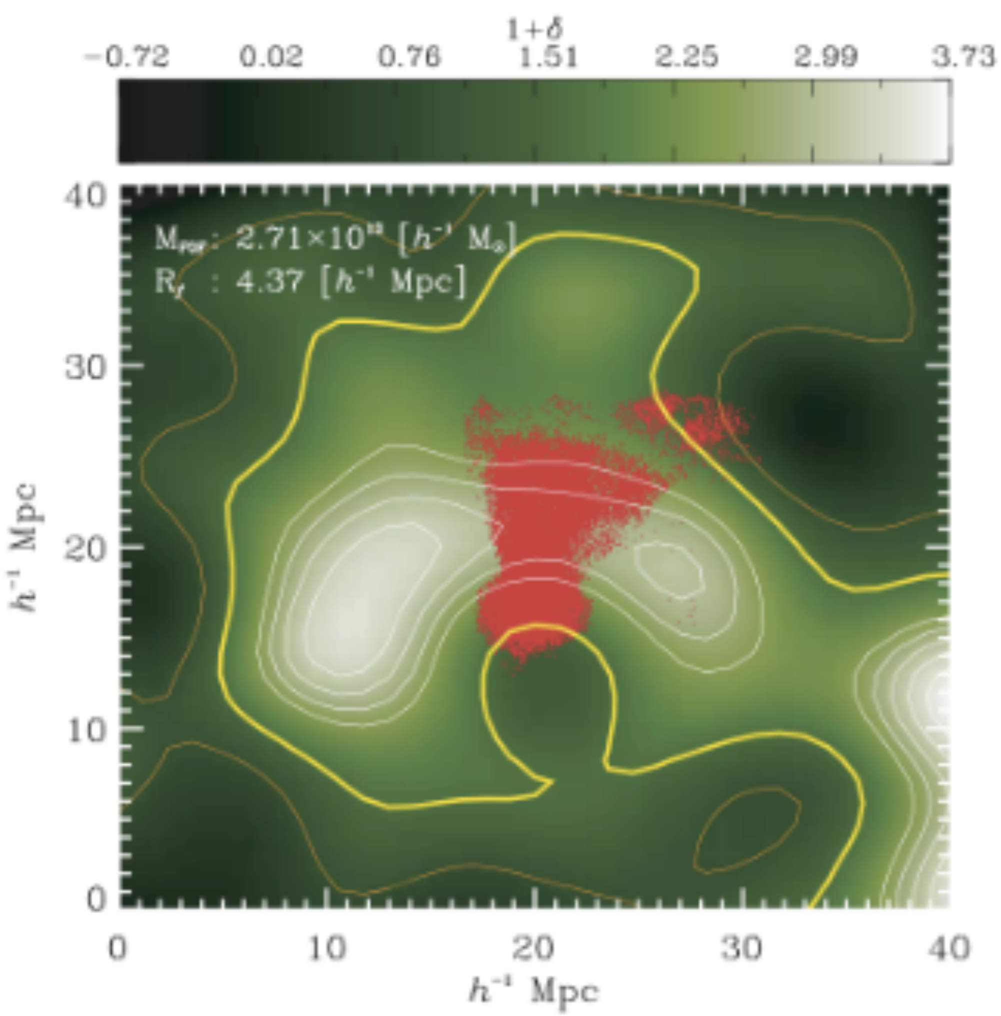
$$\sigma_0^i\sigma_2^j b_{ij} = \frac{1}{\bar{n}_{\rm pk}}\int d^{10}\mathbf{y}\, n_{\rm pk}(\mathbf{y})H_{ij}(\nu,u)P_1(\mathbf{y})$$

Desjacques (2013)

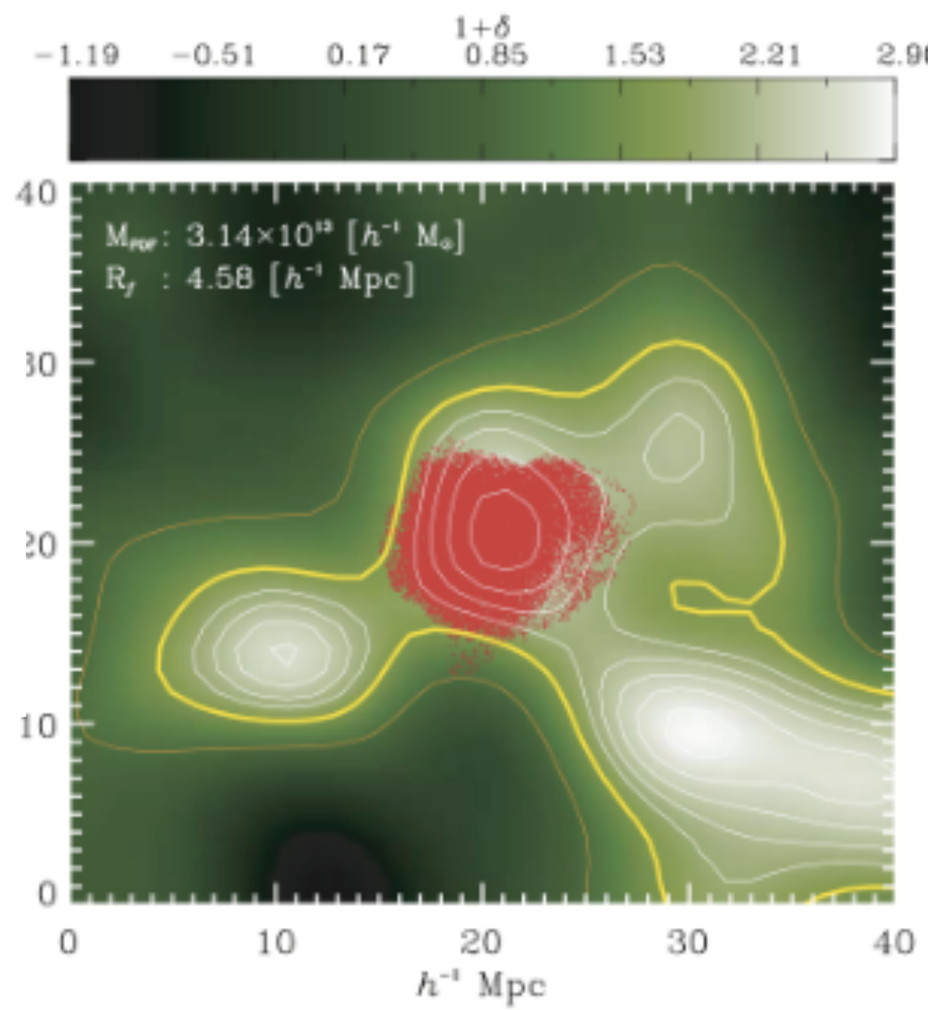
Galaxy biasing

the Excursion Set Peaks model

- (Most) halos will form around initial peaks;



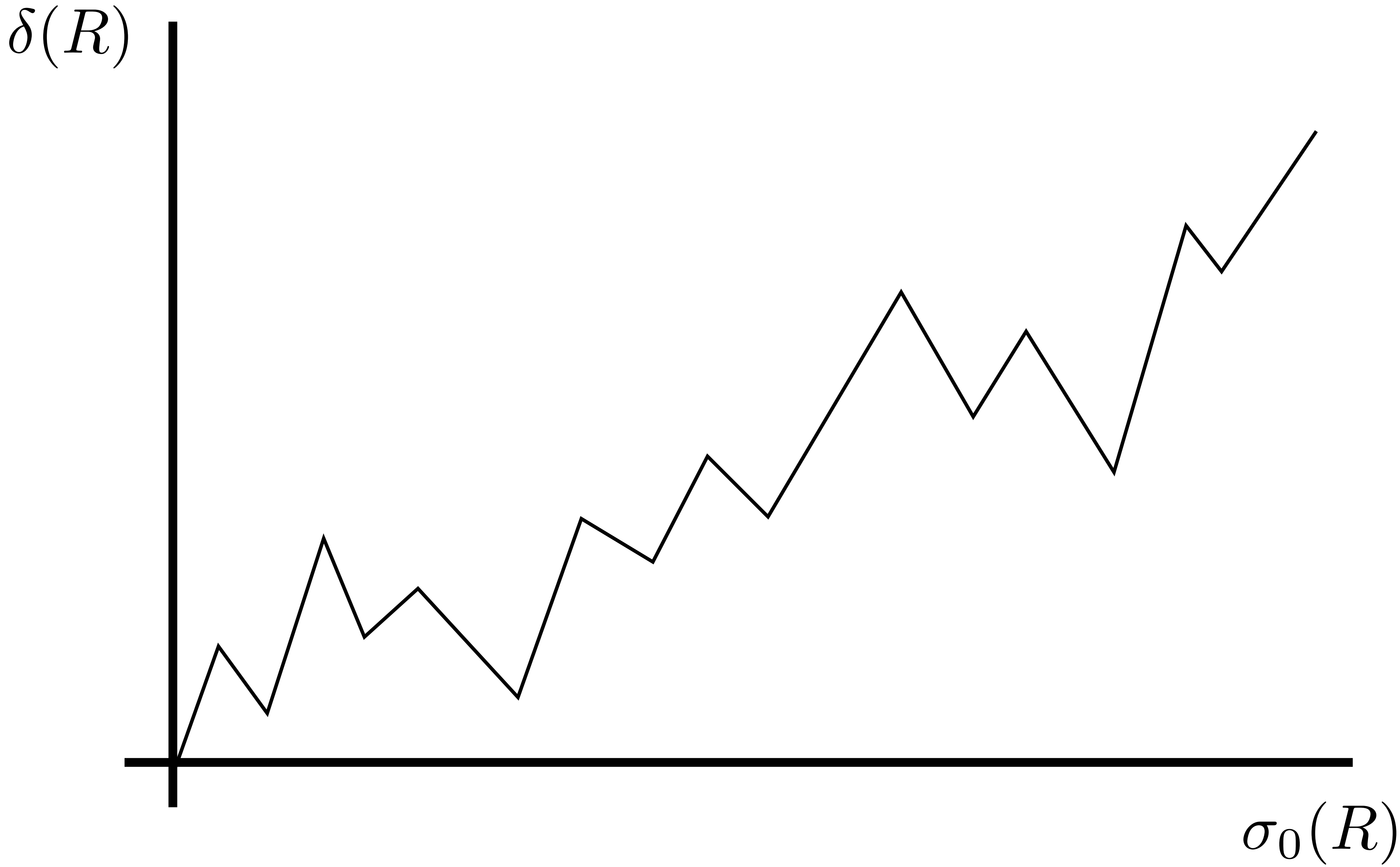
- Fraction of halos that can be associated with peaks on the mass scale of the halo:
  - 98% with $M>10^{15}$ h^{-1} $M_{\odot}$
  - 91% with $M>10^{14}$ h^{-1} $M_{\odot}$
  - 80% with $M>10^{12}$ h^{-1} $M_{\odot}$
  - 70% with $M>5\text{x}10^{11}$ h^{-1} $M_{\odot}$



Ludlow & Porciani (2011)
Ludlow, Borzyszkowski, Porciani (2014)

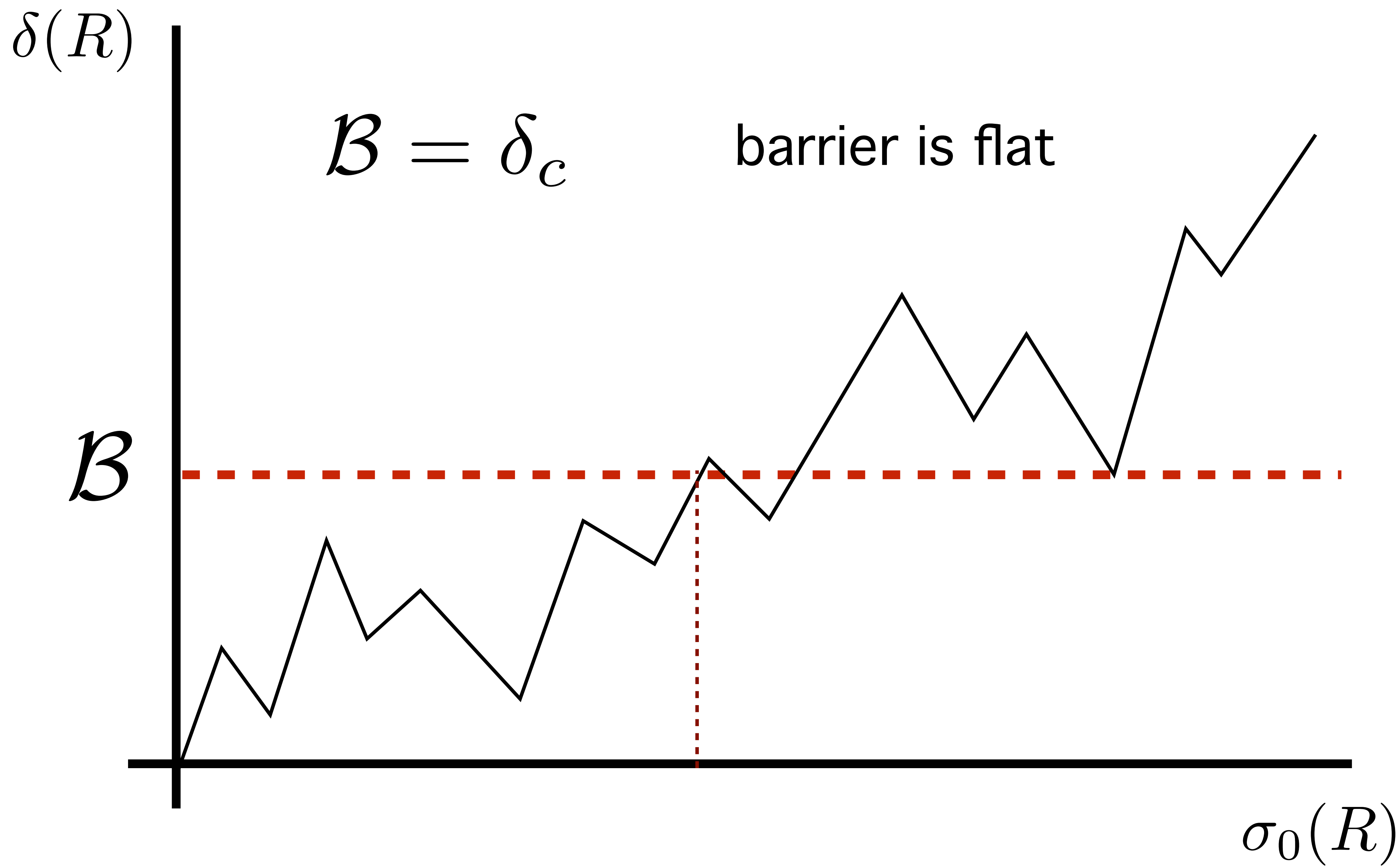
Galaxy biasing
the Excursion Set Peaks model

- Impose that **peaks** on a given smoothing scale are counted only if they satisfy a first crossing condition.



Halo biasing
the Excursion Set Peaks model

- Impose that **peaks** on a given smoothing scale are counted only if they satisfy a first crossing condition.

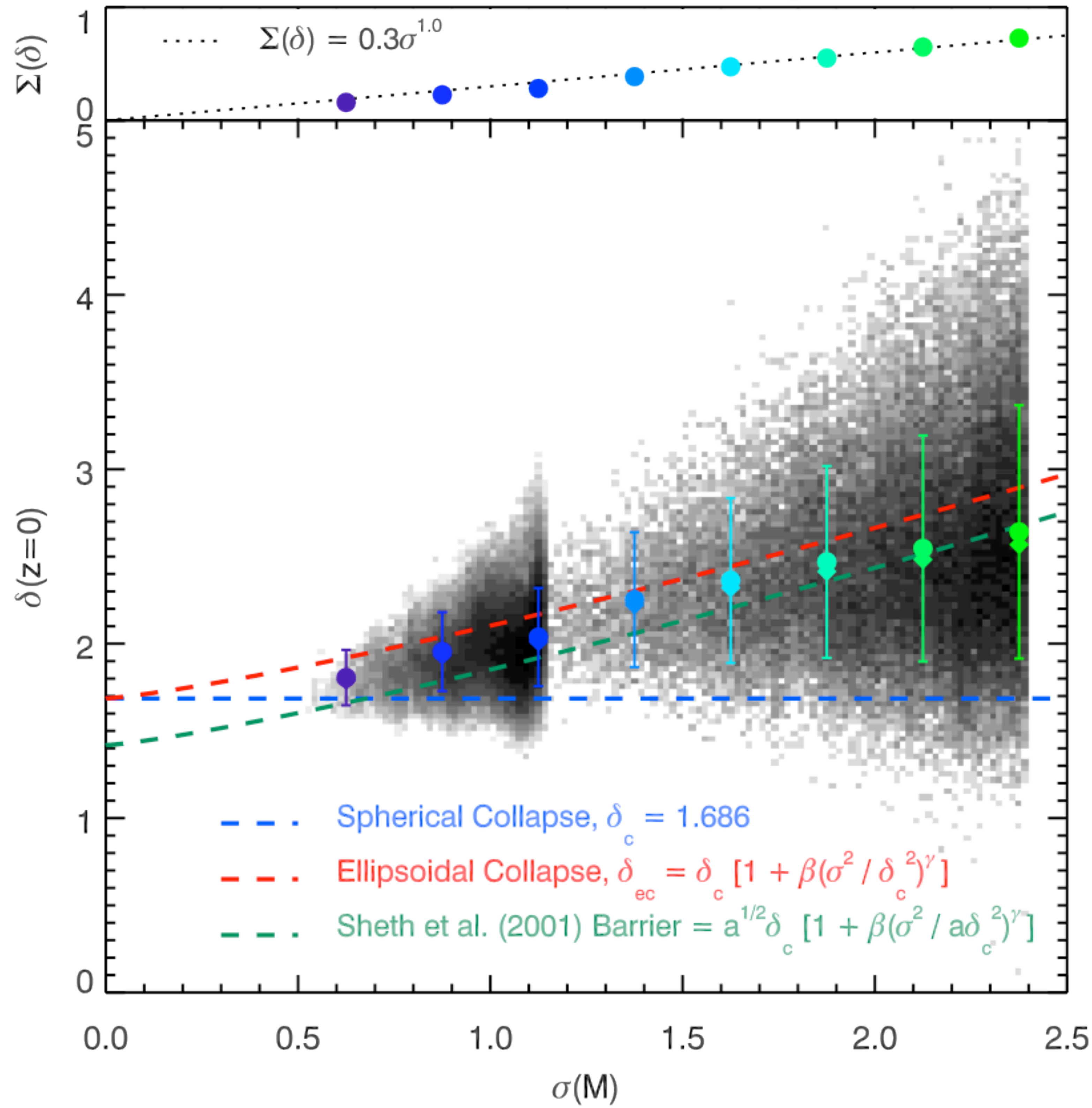


Halo biasing
the Excursion Set Peaks model

Collapse is not spherical
(at low masses)

Barrier is not flat
it decreases with mass and it scatters

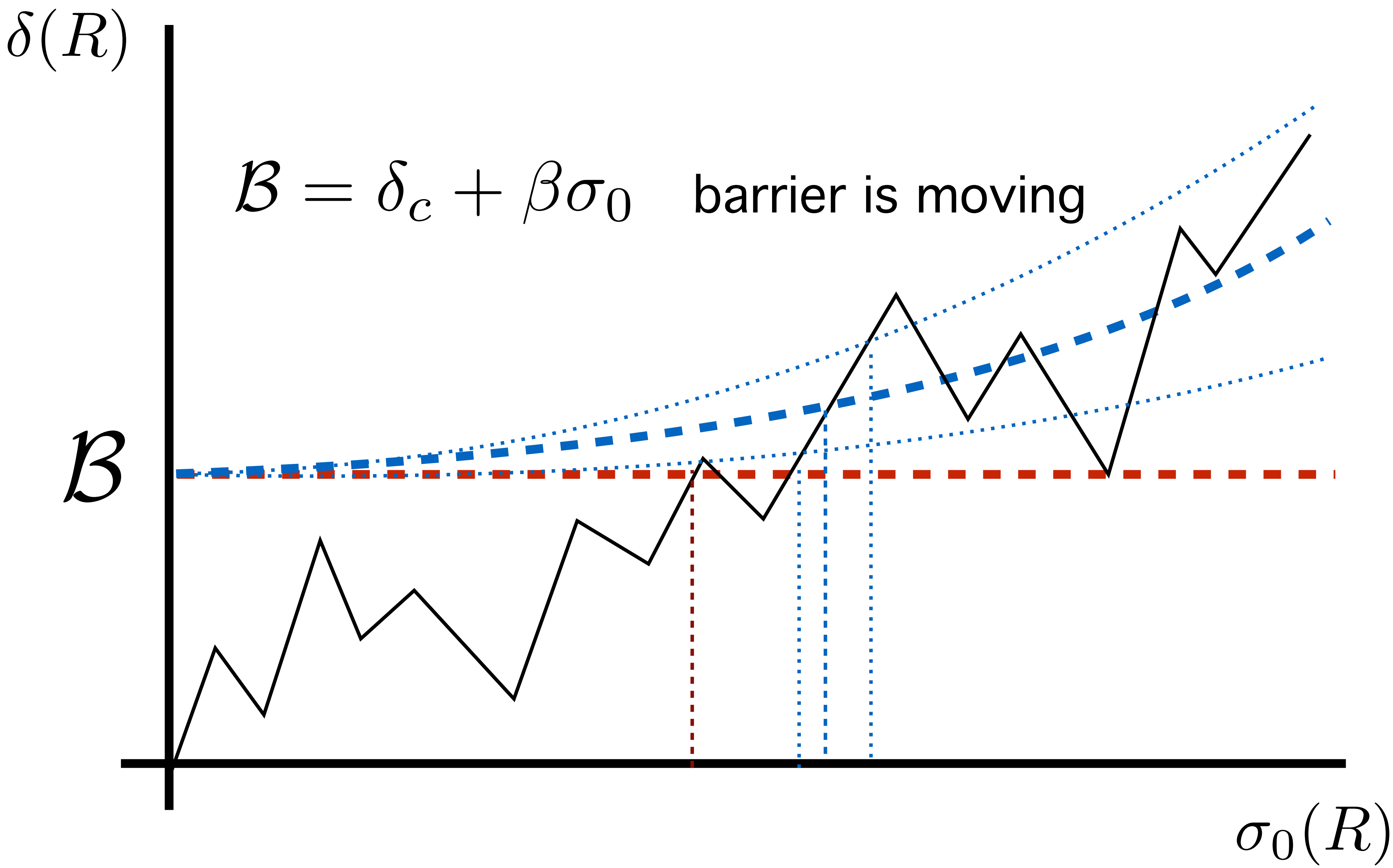
Scatter comes from
shear, tides, etc…



Robertson, Kravtsov, Tinker, Zentner(2009)

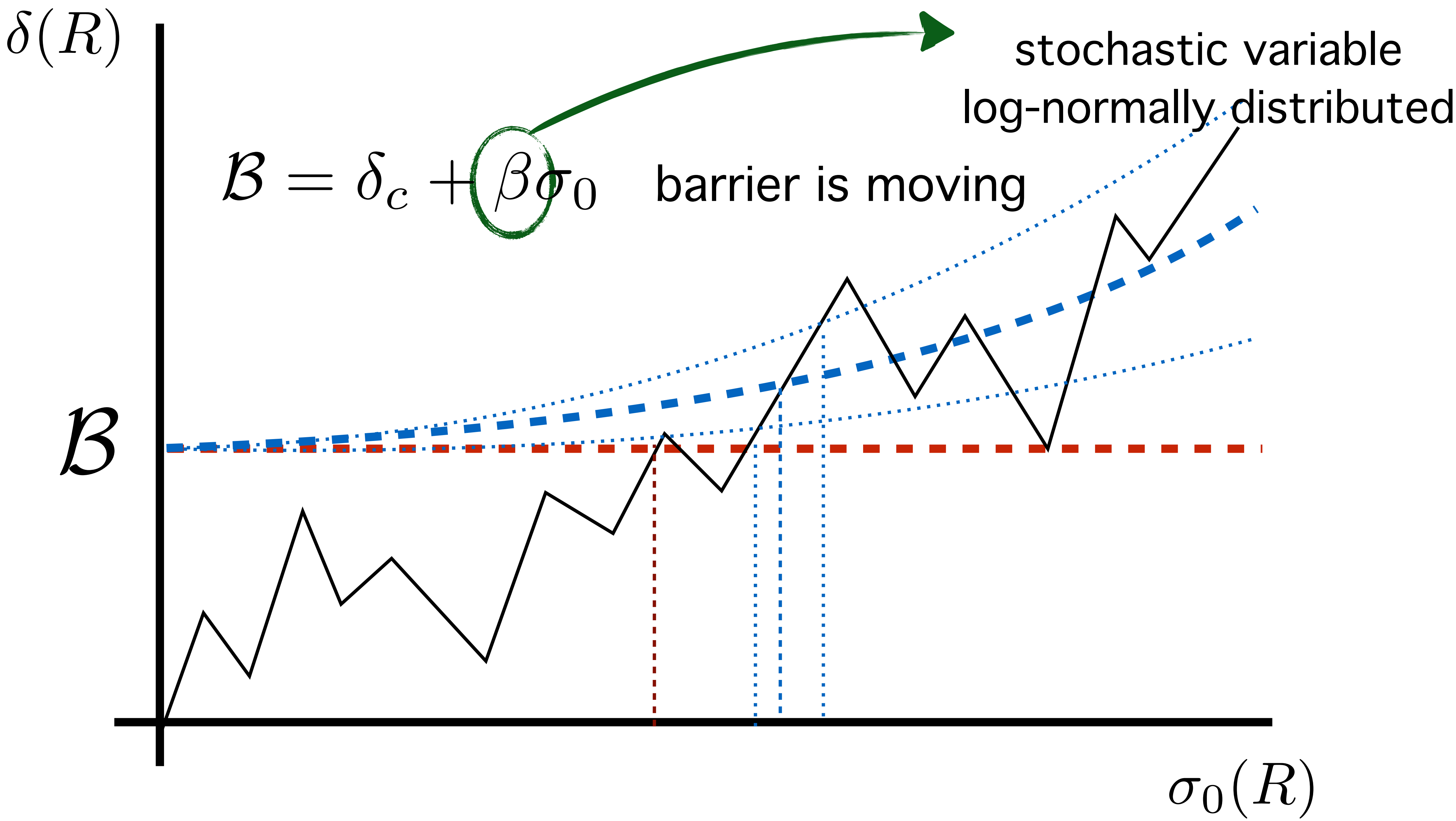
Halo biasing
the Excursion Set Peaks model

- Impose that **peaks** on a given smoothing scale are **counted only if they satisfy a first crossing condition.**



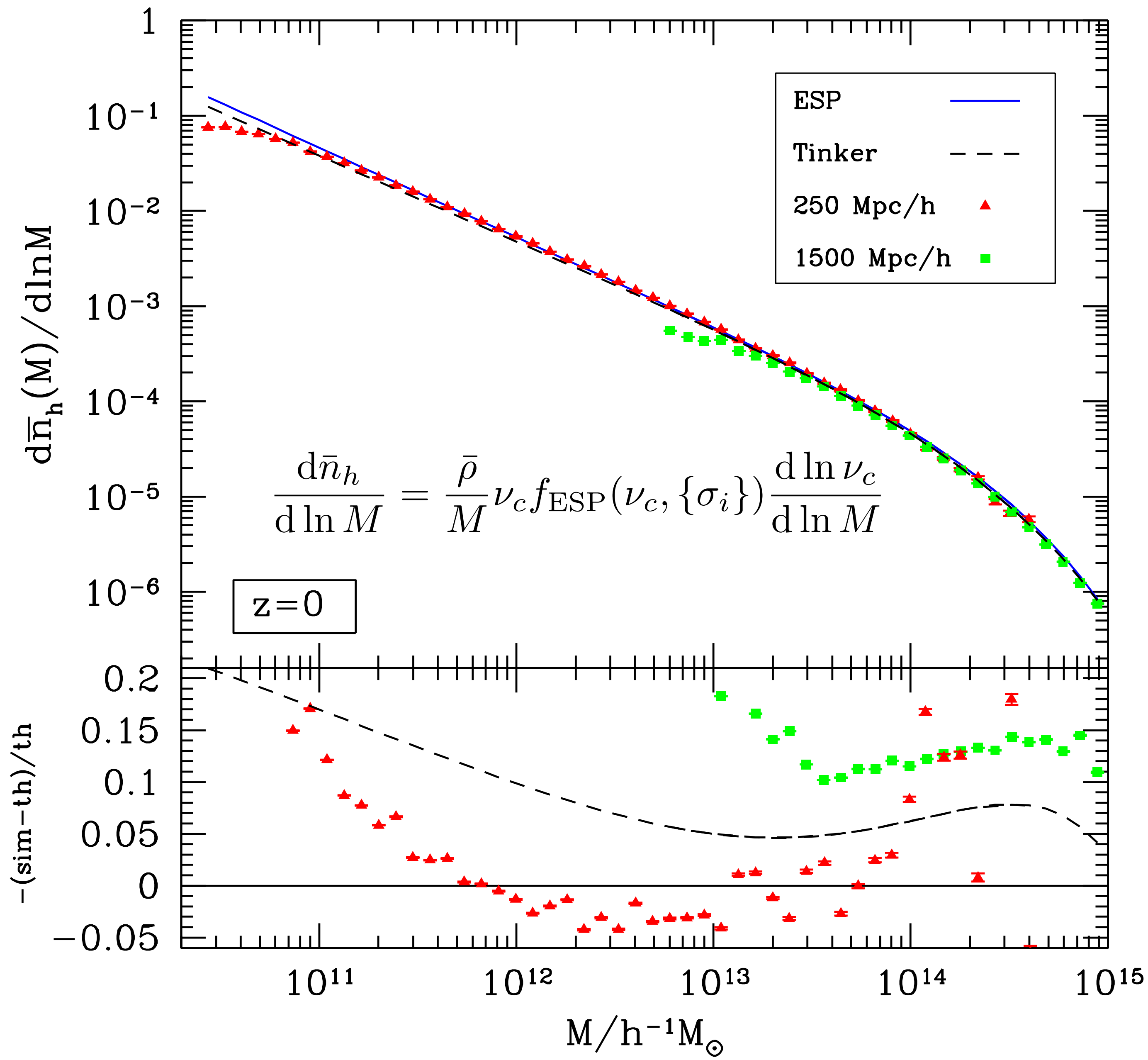
Halo biasing
the Excursion Set Peaks model

- Impose that **peaks** on a given smoothing scale are **counted only if they satisfy a first crossing condition.**



Halo biasing
the Excursion Set Peaks model

Putting all together we get a non universal halo mass function



MB, Chan, Desjacques, Paranjape (2013)

Non gaussian bias
the Excursion Set Peaks model

a remainder: we want to predict $$\frac{P_{\rm hm}(k)}{P_{\rm mm}(k)} = b_1 + 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{\mathcal{M}(k)}$$

using effective bias expansion (in Fourier space)

$$\delta_h(k) = c_1(k)\delta_m(k) + \int \frac{d^3\mathbf{q}}{(2\pi)^3} c_2(\mathbf{q}, \mathbf{k}-\mathbf{q})\delta_m(\mathbf{q})\delta_m(\mathbf{k}-\mathbf{q}) + ...$$

we can compute the halo - matter cross correlation $$\frac{\langle \delta_h \delta_m \rangle}{\langle \delta_m \delta_m \rangle}$$

$$c_1(k) \equiv \left(b_{10} + b_{01} k^2\right)$$

$$c_2(\mathbf{k_1}, \mathbf{k_2}) \equiv b_{20} + b_{11}\left(k_1^2 + k_2^2\right) + b_{02} k_1^2 k_2^2 - 2\chi_{10}\left(\mathbf{k_1} \cdot \mathbf{k_2}\right) + \chi_{01}\left[3\left(\mathbf{k_1} \cdot \mathbf{k_2}\right)^2 - k_1^2 k_2^2\right]$$

Non gaussian bias
the Excursion Set Peaks model

using effective bias expansion
we can compute the halo - matter cross correlation

$$P_{hm}(k) \overset{k\to 0}{\approx} \left[c_1(k) + \frac{2 f_{\rm NL}^{\rm loc}}{\mathcal{M}(k)} \int \frac{d^3\mathbf{q}}{(2\pi)^3} c_2(\mathbf{q}, -\mathbf{q}) P_{mm}(q) \right] P_{mm}(k)$$

$$c_1(k) \equiv \left(b_{10} + b_{01} k^2\right)$$

$$c_2(\mathbf{k_1}, \mathbf{k_2}) \equiv b_{20} + b_{11}\left(k_1^2 + k_2^2\right) + b_{02} k_1^2 k_2^2 - 2\chi_{10}\left(\mathbf{k_1}\cdot\mathbf{k_2}\right) + \chi_{01}\left[3\left(\mathbf{k_1}\cdot\mathbf{k_2}\right)^2 - k_1^2 k_2^2\right]$$

Non gaussian bias
the Excursion Set Peaks model

using effective bias expansion
we can compute the halo - matter cross correlation

$$P_{hm}(k) \overset{k\,\to\,0}{\approx} \left[c_1(k) + \frac{2 f_{\rm NL}^{\rm loc}}{\mathcal{M}(k)} \int \frac{d^3\mathbf{q}}{(2\pi)^3} c_2(\mathbf{q}, -\mathbf{q}) P_{mm}(q) \right] P_{mm}(k)$$

$$\equiv b_{\rm NG}^{\rm ESP}$$

$$c_1(k) \equiv \left(b_{10} + b_{01} k^2\right)$$

$$c_2(\mathbf{k_1}, \mathbf{k_2}) \equiv b_{20} + b_{11}\left(k_1^2 + k_2^2\right) + b_{02} k_1^2 k_2^2 - 2\chi_{10}\left(\mathbf{k_1} \cdot \mathbf{k_2}\right) + \chi_{01}\left[3\left(\mathbf{k_1} \cdot \mathbf{k_2}\right)^2 - k_1^2 k_2^2\right]$$

Non gaussian bias
the Excursion Set Peaks model

Is this result compatible with the PBS prediction?

$$b_{\rm NG}^{\rm ESP} = \int \frac{d^3\mathbf{q}}{(2\pi)^3}\, c_2(\mathbf{q},-\mathbf{q})P(q) = \sigma_0^2 b_{20} + 2\sigma_1^2 b_{11} + \sigma_2^2 b_{02} + 2\sigma_1^2\chi_{10} + 2\sigma_2^2\chi_{01}$$

$$? \quad \updownarrow \quad ?$$

$$b_{\rm NG}^{\rm PBS} = \frac{\partial \ln \bar{n}_h}{\partial \ln \sigma_8}$$

$$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{k^2}$$

Non gaussian bias
the Excursion Set Peaks model

Yes, almost…

$$b_{\rm NG}^{\rm ESP} = \int \frac{d^3\mathbf{q}}{(2\pi)^3}\, c_2(\mathbf{q},-\mathbf{q})P(q)$$
$$= \sigma_0^2 b_{20} + 2\sigma_1^2 b_{11} + \sigma_2^2 b_{02}$$
$$+ 2\sigma_1^2\chi_{10} + 2\sigma_2^2\chi_{01}$$

constant barrier

$B(\sigma) = \delta_c$

$$\equiv b_{NG}^{\rm PBS} = \frac{\partial \ln \bar{n}_h}{\partial \ln \sigma_8}$$

Desjacques, Gong, Riotto (2014)

moving barrier

$B(\sigma_0) = \delta_c + \beta\sigma_0$

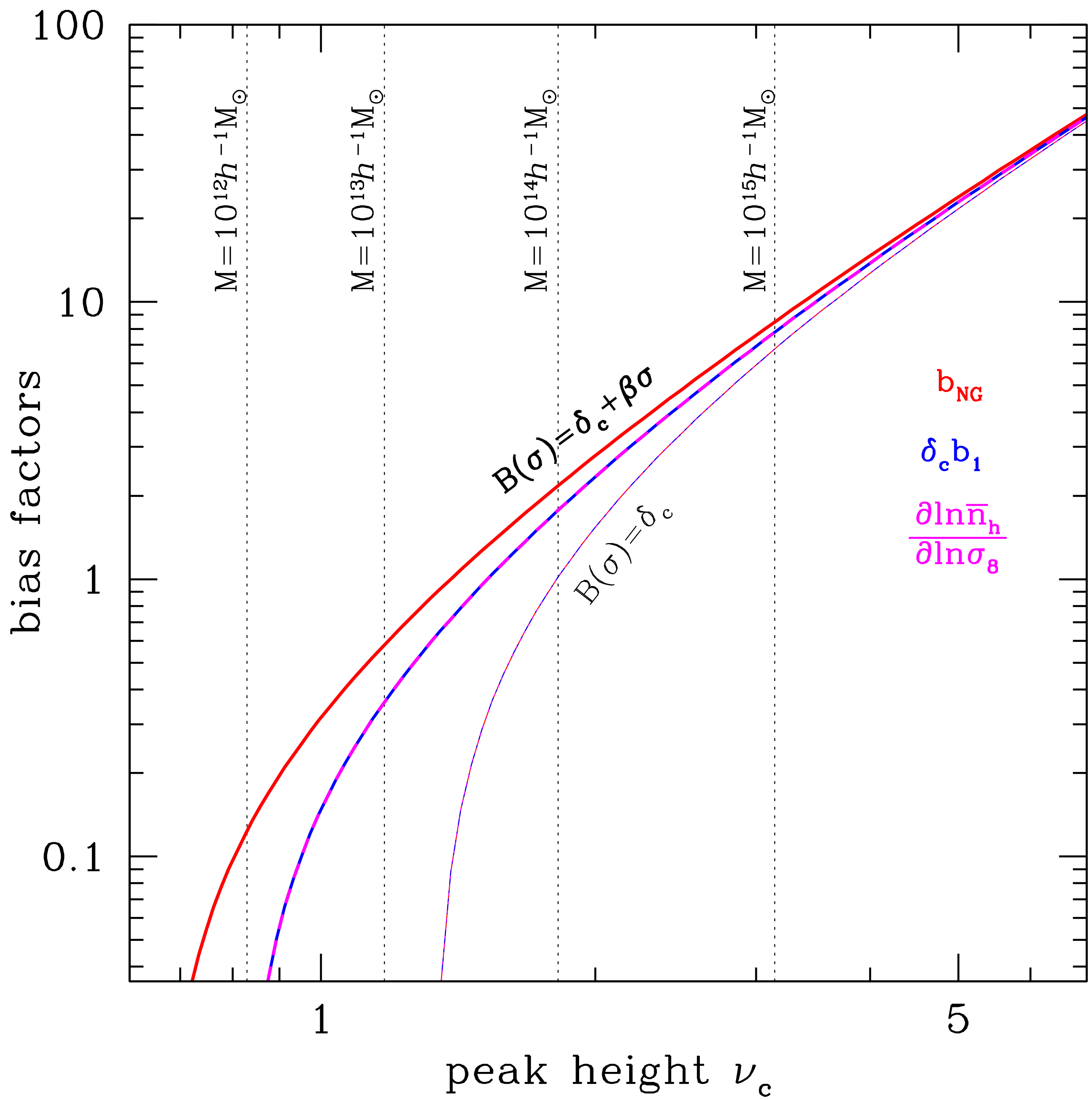
$$\neq b_{NG}^{\rm PBS} = \frac{\partial \ln \bar{n}_h}{\partial \ln \sigma_8}$$

MB, Desjacques (2015)

$$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc}\frac{b_{\rm NG}}{k^2}$$

Ferraro, Smith, Baumann, Green (2013)

Non gaussian bias
Summary of predictions (within ESP)



$$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{k^2}$$

MB, Desjacques (2015)

Non gaussian bias
Summary of predictions

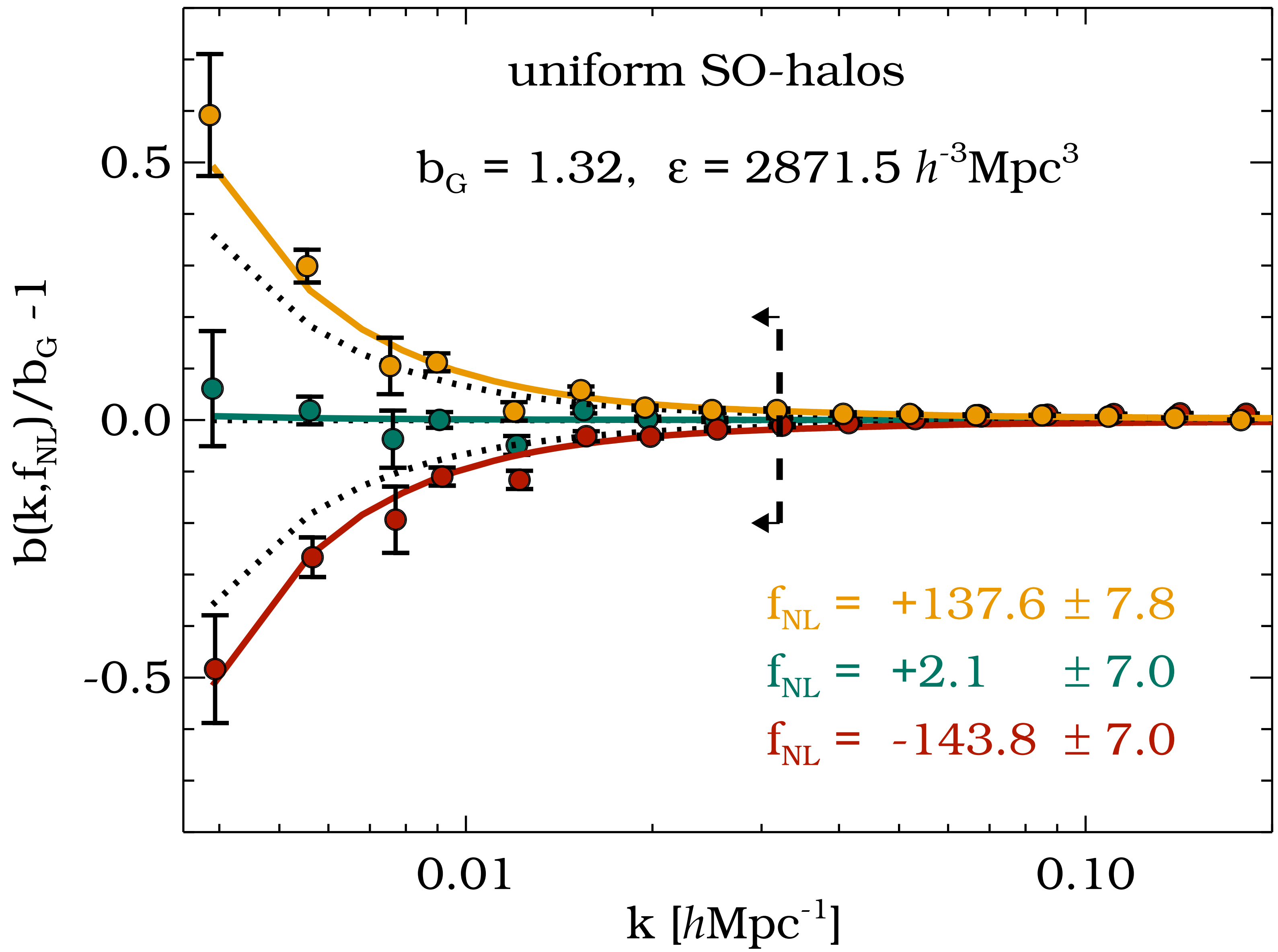
Non gaussian bias	Moving barrier	Non Universality
$\delta_c b_1^{\mathrm{L}}$	NO	NO
$\dfrac{\partial \ln \bar{n}_h}{\partial \ln \sigma_8}$	YES	YES
$b_{\mathrm{NG}}^{\mathrm{ESP}}$	YES	NO

$$\Delta b_{\mathrm{NG}}(k) \propto 2 f_{\mathrm{NL}}^{\mathrm{loc}} \frac{b_{\mathrm{NG}}}{k^2}$$

Non gaussian bias

What is the point of all this?

Input $\delta_c b_1^{\mathrm{L}}$ as the non gaussian bias amplitude



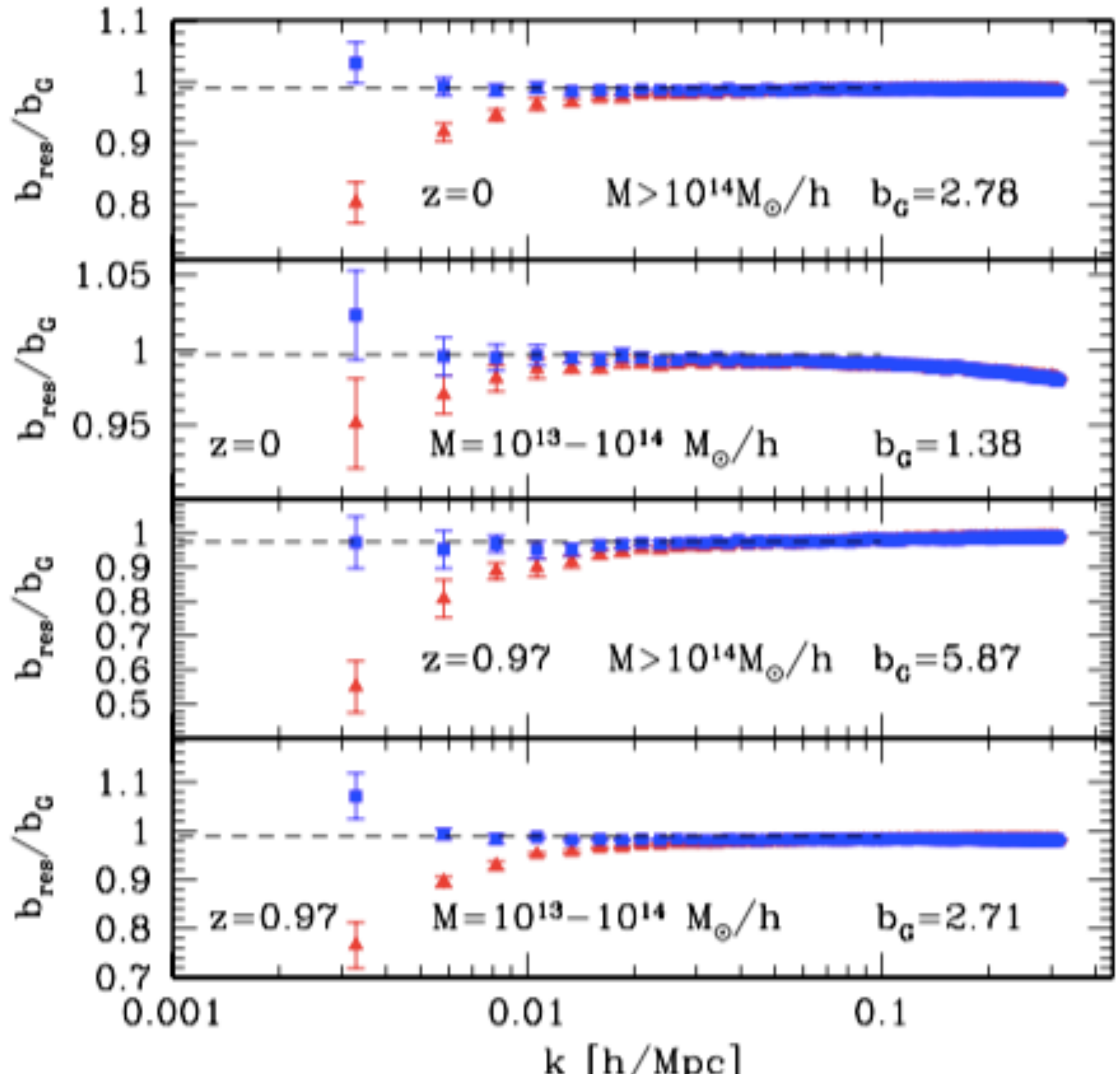
$$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{k^2}$$

Hamaus, Seljak & Desjacques (2011)

Non gaussian bias

What is the point of all this?

Compare $\delta_c b_1^{\mathrm{L}}$ with $\dfrac{\partial \ln \bar{n}_h}{\partial \ln \sigma_8}$

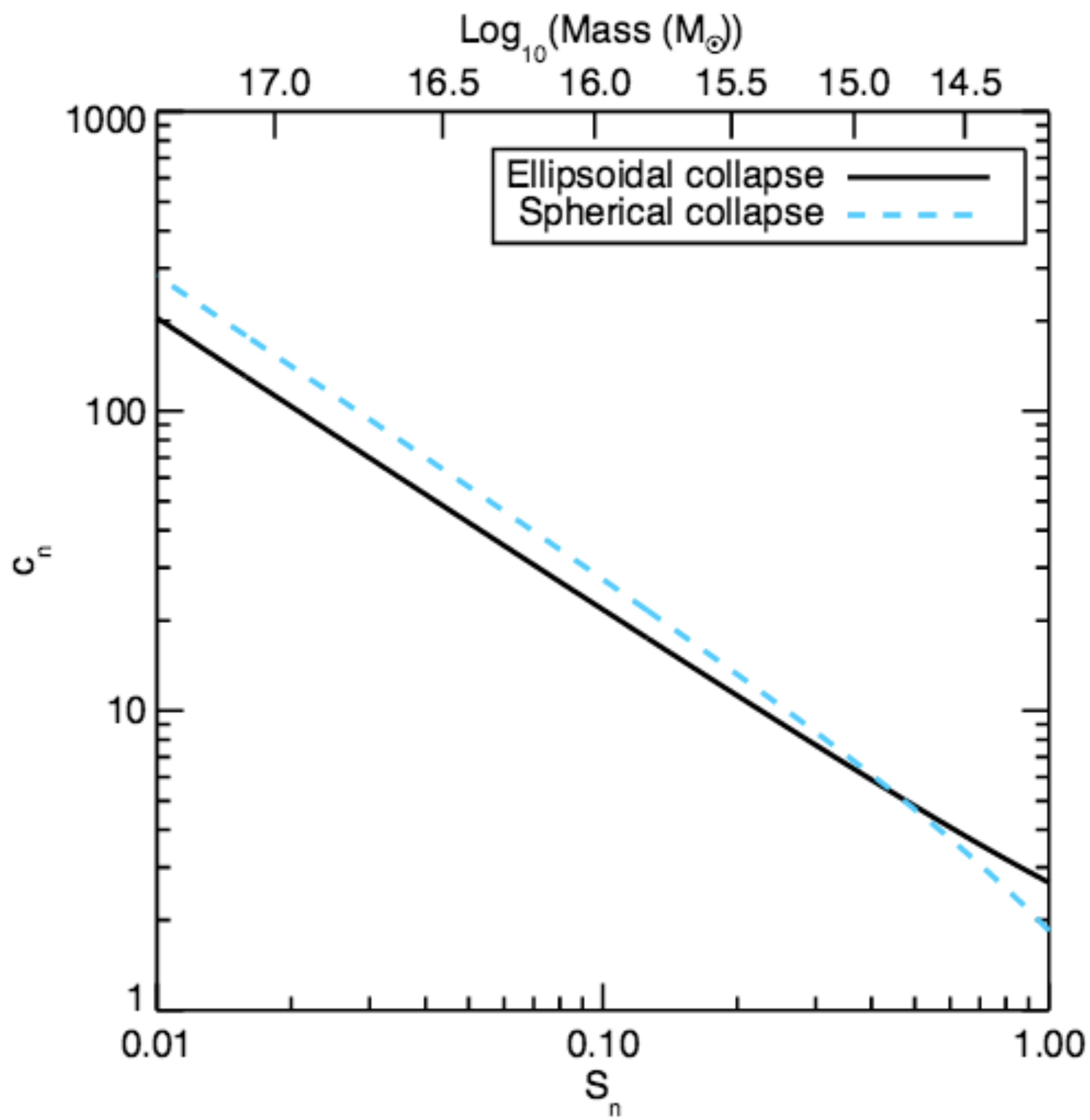


$$\Delta b_{\mathrm{NG}}(k) \propto 2 f_{\mathrm{NL}}^{\mathrm{loc}} \frac{b_{\mathrm{NG}}}{k^2}$$

Scoccimarro, Hui, Manera & Chan (2012)

Non gaussian bias
What is the point of all this?

Non gaussian bias with moving barrier



$$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{k^2}$$

Adshead, Baxter, Dodelson, Lidz (2012)

Non gaussian bias
What is the point of all this?

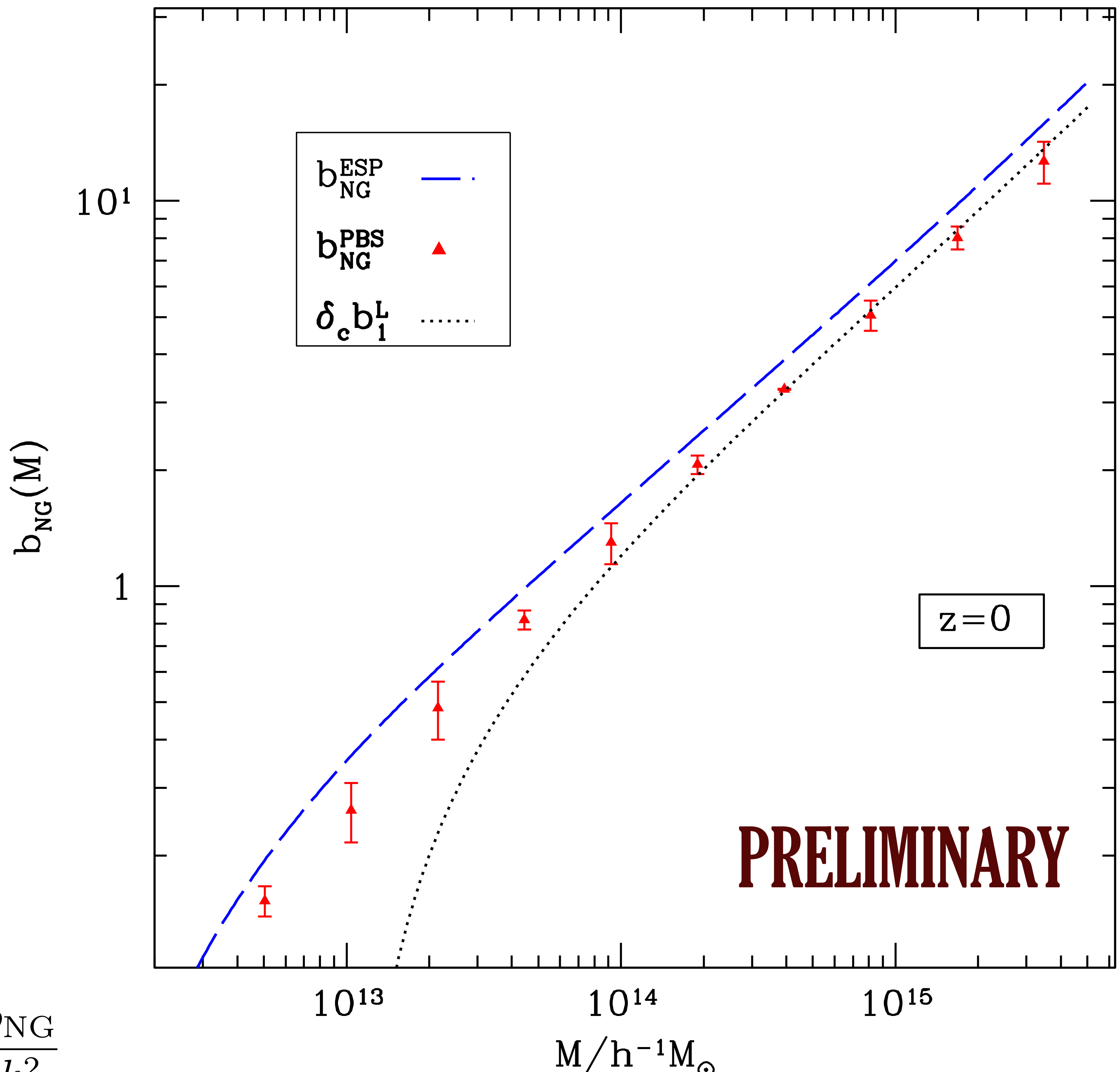
simple check: compute $$\frac{\partial \ln \bar{n}_h}{\partial \ln \sigma_8}$$ from simulations

- Run N body simulations with different σ_8 but same cosmology
- Find halos with Halo finder (Spherical Overdensity)
- Compute Halo Mass Function
- Compute numerical derivative of HMF wrt σ_8

$$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{k^2}$$

Non gaussian bias

Can we use $\delta_c b_1^L$?



$$\Delta b_{\rm NG}(k) \propto 2 f_{\rm NL}^{\rm loc} \frac{b_{\rm NG}}{k^2}$$

Concluding remarks

Take Home Message

1) Careful when making forecasts

Fisher forecasts use $b_{\rm NG} = \delta_c b_1^{\rm L}$

Bispectrum shape Fiducial $f_{\rm NL}$	local 0	orthogonal 0	equilateral 0
Galaxy clustering (spectr. z)	4.1 (4.0)	54 (11)	220 (35)
Galaxy clustering (photom. z)	5.8 (5.5)	38 (9.6)	140 (37)
Weak lensing	73 (27)	9.6 (3.5)	34 (13)
Combined	4.7 (4.5)	4.0 (2.2)	16 (7.5)

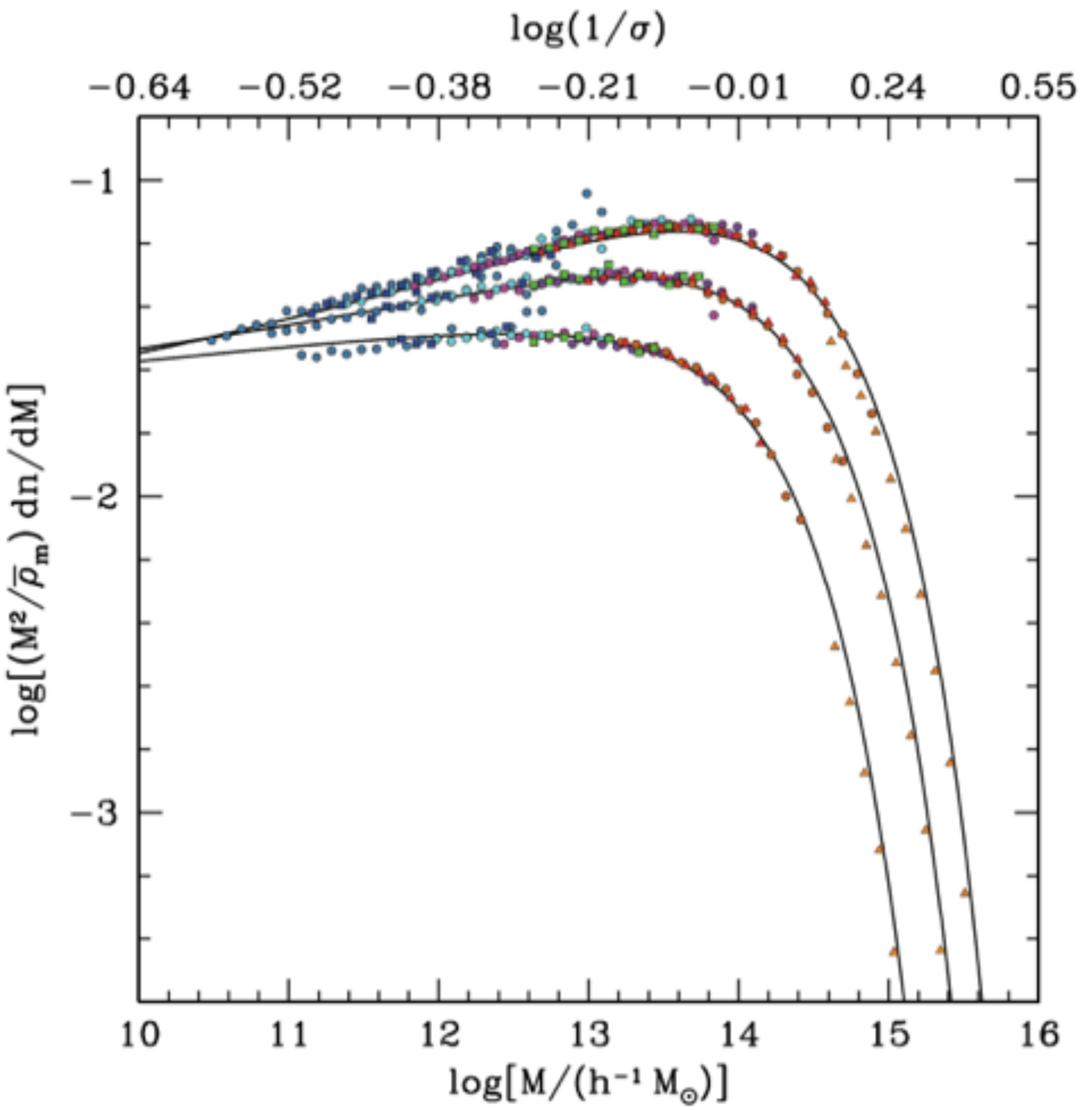
Euclid Collaboration (2012)

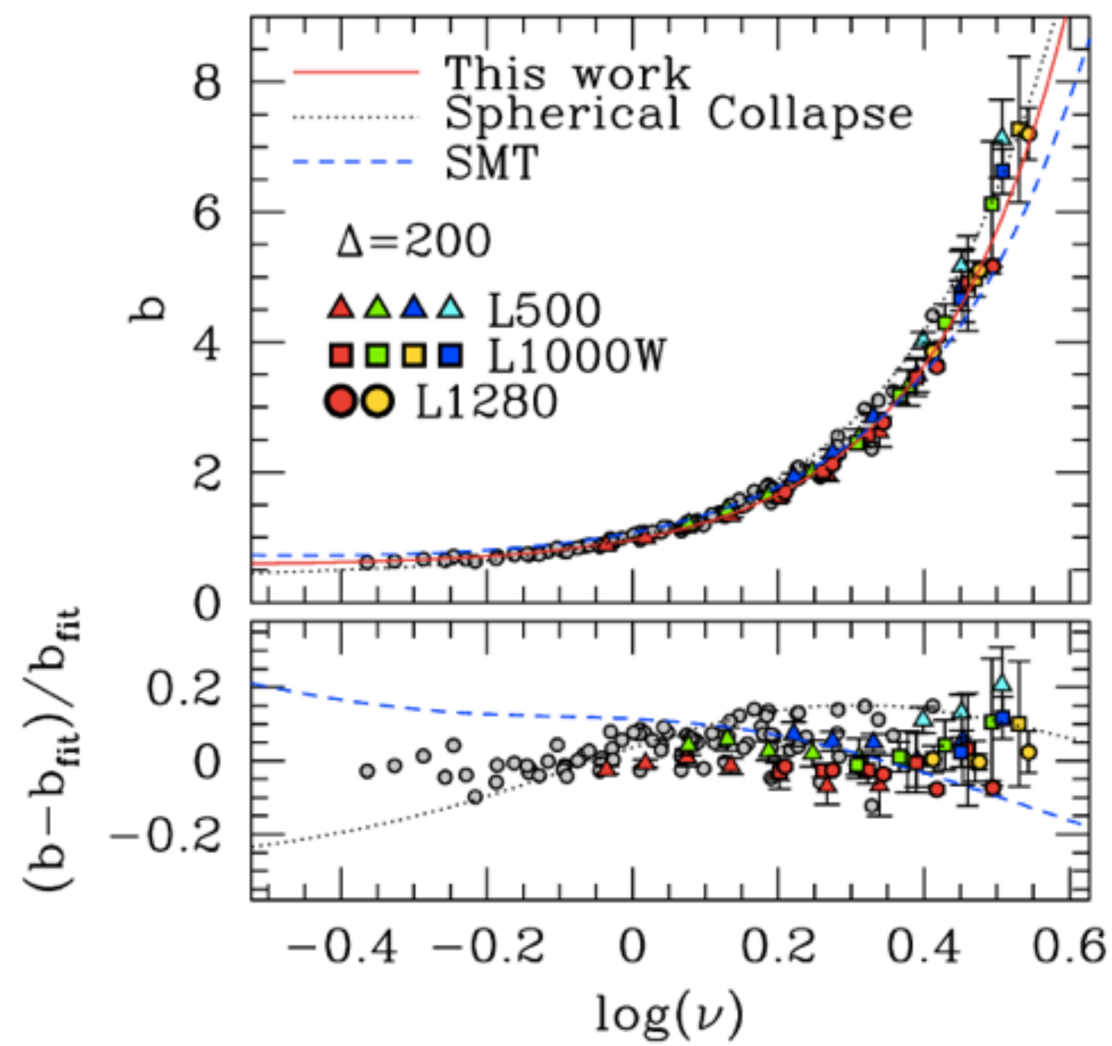
1σ errors	PS	Bispec	PS + Bispec	EUCLID	Current
$f_{\rm NL}^{\rm loc}$	0.87	0.23	0.20	5.59	5.8
Tilt n_s ($\times 10^{-3}$)	2.7	2.3	2.2	2.6	5.4
Running α_s ($\times 10^{-3}$)	1.3	1.2	0.65	1.1	17
Curvature Ω_K ($\times 10^{-4}$)	9.8	NC	6.6	7.0	66
Dark Energy FoM $= 1/\sqrt{\rm DetCov}$	202	NC	NC	309	25

SPHEREx collaboration (2014)

Take Home Message

2) If we do not want any modelling, fits maybe need to be changed

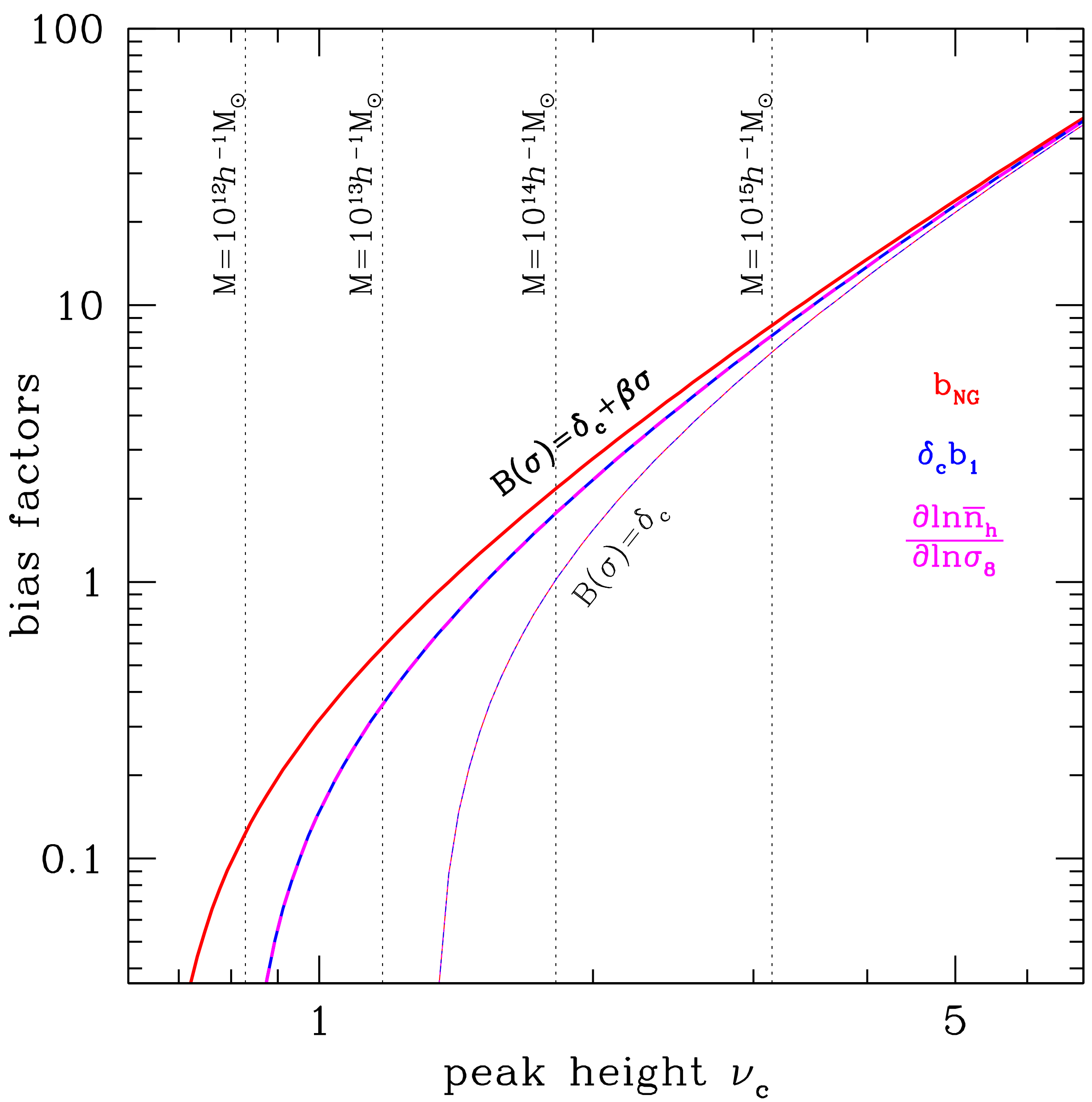


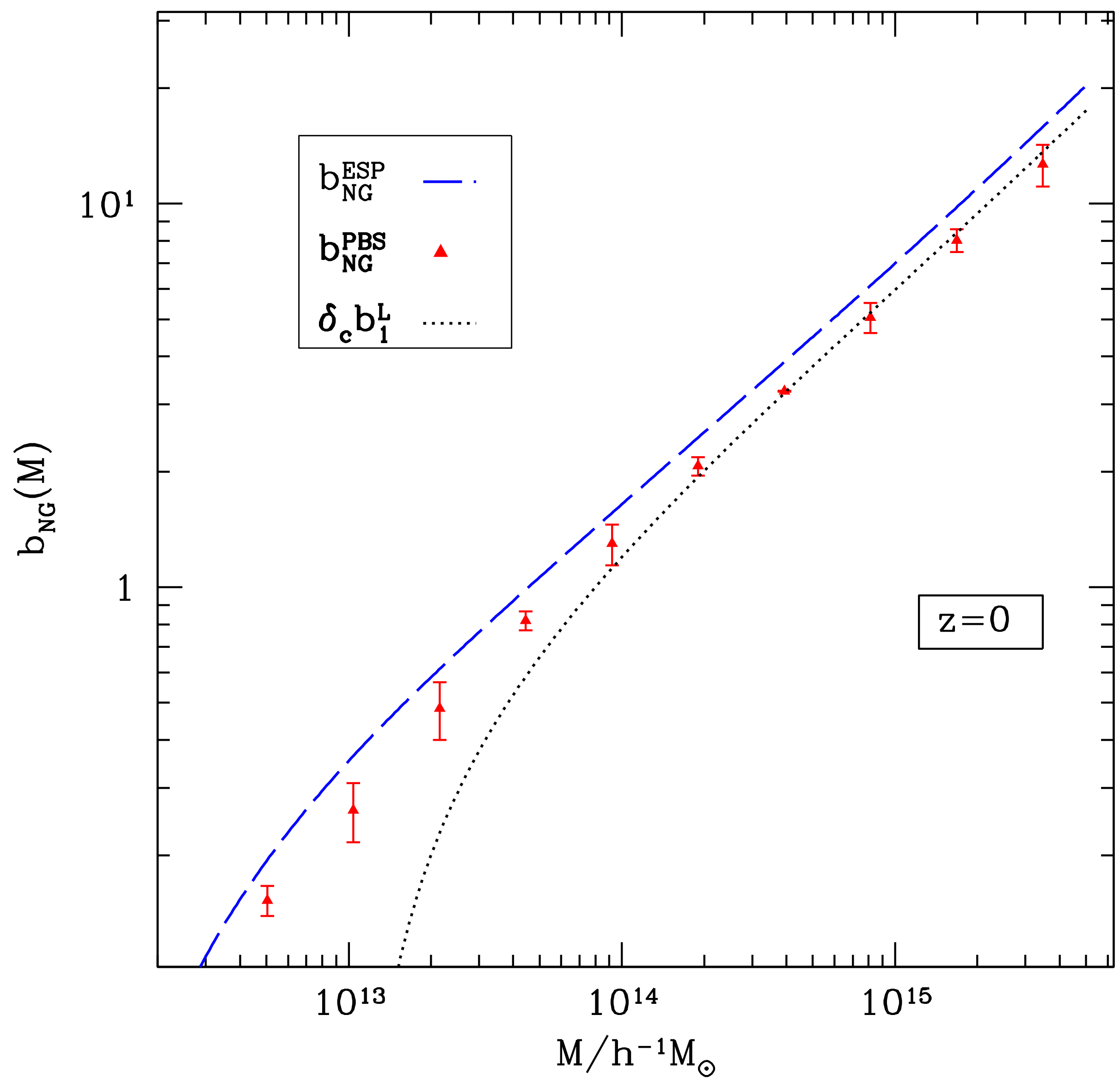


Even if halo mass function is universal to a certain degree, its derivative wrt matter amplitude may be very different than what expected

Take Home Message

3) Modelling needs a better understanding of collapse





work in preparation with Vincent Desjacques, Fabian Schmidt, Tobias Baldauf, Titouan Lazeyras