Precision measurements of the local bias of dark matter halos

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Motivation

Why are we interested in the large-scale local bias parameters of dark matter halos?

- essential to describe the statistics of halos on large scales, a key ingredient of the theoretical description of large-scale structure
- most observed tracers of LSS, such as galaxies, reside in halos
- essential for the halo model description of the non-linear matter density field

Halo bias

▷ Perturbation theory : statistics of halos written in terms of bias parameters multiplying operators constructed out of the matter density field (δ_m).

▷ Most important bias parameters on large scales are those multiplying powers of δ_m (*local bias parameters*) :

$$\delta_h(\mathbf{x},\tau) \supset b_1(\tau)\delta_m(\mathbf{x},\tau) + \frac{1}{2}b_2(\tau)\delta_m^2(\mathbf{x},\tau) + \frac{1}{6}b_3(\tau)\delta_m^3(\mathbf{x},\tau) + \cdots$$

δ_h : fractional number density perturbation of halos

▷ This talk : precision measurements of b_1, b_2, b_3 using a novel technique, *separate universe simulations*.

▷ Comparison to biases determined by fitting to halo 2- and 3-point statistics and theoretical predictions from the excursion set-peaks (ESP).

Separate universe simulations

- Separate universe approach : **long-wavelength density perturbation is included in an N-body simulation**

$$\tilde{\rho}_m(t) = \rho_m(t) \cdot [1 + \delta_m(t)]$$

Sirko (2005), Baldauf+ (2011), Sherwin+ (2012), Li+(2014), Wagner+ (2014)

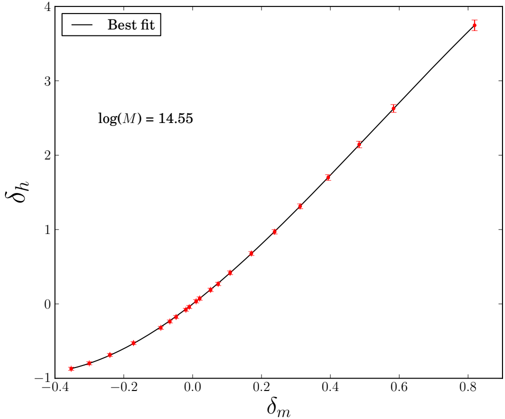
$\rightarrow \Omega_m, \Omega_\Lambda, \Omega_K$ and H_0 different from their fiducial values, and simulation ran to a different scale factor.

- Wagner+ (2014) : full non-linear computation $\Rightarrow \delta_m$ can be large!

Halo bias from separate universe simulations

Local bias parameters = response of the halo abundance to a long-wavelength density perturbation

$\rightarrow$ measure $\delta_h = [\tilde{N}(M) - N(M)]/N(M)$ in a suite of separate universe simulations and fit a polynomial in δ_m to find the b_i.



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Excursion set peaks (ESP)

ESP aims at unifying the *peak model* of Bardeen et al. (1986) and the *excursion set formalism* of Bond et al. (1991)

→ **on a given smoothing scale R, consider only the peaks that have a smaller height $\nu \equiv \delta_c/\sigma$ at the next larger smoothing scale**

Paranjape & Sheth (2012)

- Peak-background split (PBS) : effect of a long wavelength perturbation δ_L :

$$\delta_c \to \delta_c - \delta_L \Leftrightarrow \nu \to \nu(1 - \delta_L/\delta_c) \equiv \nu_1$$

Mo & White (1996)

Excursion set peaks (ESP)

- Mass function :

$$\frac{\mathrm{d}n_h}{\mathrm{d}\ln M} \equiv n_h^d = \frac{\bar{\rho}_m}{M} f(\nu) \left| \frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M} \right|$$

- Bias parameters :

$$b_n(\nu) \equiv \frac{1}{n_h^d(\nu)} \frac{\partial^n n_h^d(\nu_1)}{\partial \delta_L^n}\bigg|_{\delta_L=0} = \frac{1}{f(\nu)} \frac{\partial^n f(\nu_1)}{\partial \delta_L^n}\bigg|_{\delta_L=0}$$

$\rightarrow$ f from ESP + moving barrier + top-hat filter

Paranjape+ (2013)

- Barrier for collapse : $B(\sigma) = \delta_c + \beta\sigma$

  β lognormal distributed, $\langle\beta\rangle = 0.5, \mathrm{Var}(\beta) = 0.25$

Robertson+ (2009)

Bias from correlations and other predictions

▷ Check of the validity of the method : **comparison of separate universe results with measurements from correlations in the fiducial cosmology**

- $b_1 = P_{hm}/P_{mm}$
- b_2 estimated from B_{mmh}
- b_3 could be estimated from trispectrum but too complicated $\rightarrow$ we don't do it

▷ Other predictions :

- Tinker et al. (2010) best fit (b_1 only)
- PBS argument : $b_n(\nu) \equiv \frac{1}{n_h(\nu)} \frac{\partial^n n_h(\nu_1)}{\partial \delta_L^n}\Big|_{\delta_L=0}$ with n_h the Tinker et al. (2008) best fit mass function
- Sheth and Tormen (1999) prediction (PBS)

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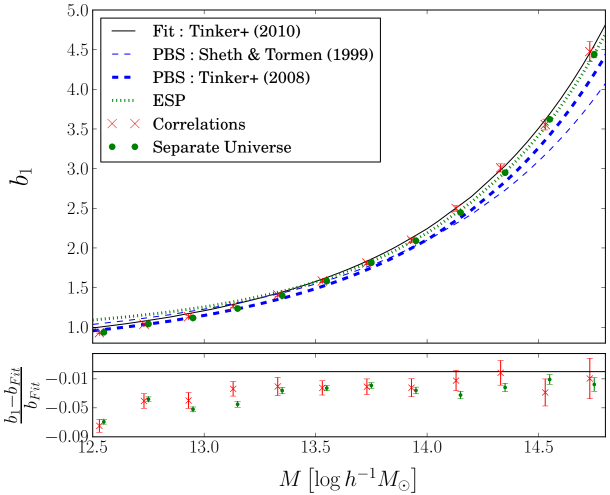
Simulations and halo catalogs

- Suite of separate universe simulations described in Wagner et al. (2014) ran with GADGET-2
- Fiducial cosmology : flat ΛCDM, $\Omega_m = 0.27$, $h = 0.7$, $\Omega_b h^2 = 0.023$, $n_s = 0.95$, $A_s = 2.2 \cdot 10^{-9}$
- δ_m corresponding to $\delta_L = \{\pm 0.5, \pm 0.4, \pm 0.3, \pm 0.2, \pm 0.1, \pm 0.07, \pm 0.05, \pm 0.02, \pm 0.01, 0.00, 0.15, 0.25, 0.35\}$
- Halos identified using AHF (SO halos) at $z_f = 0$

  Gill+ (2004), Knollmann+ (2009)
- Key point : density threshold $\rightarrow \rho_h = 200\rho_m$. Simulations with a different background density, the threshold must be rescaled

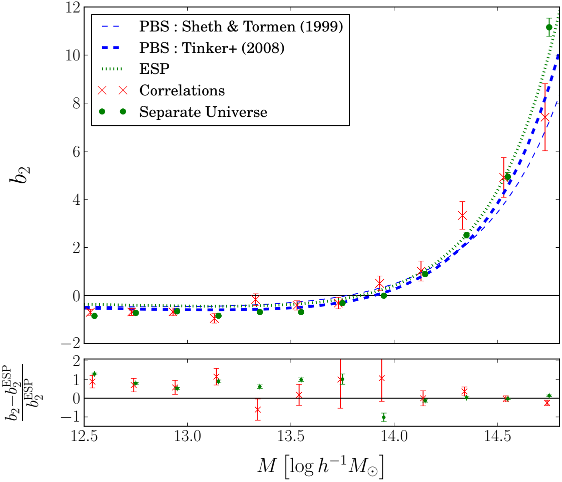
$$\Delta_{\mathrm{SO}} = \frac{200}{1 + \delta_m}$$

b_1


Fit : Tinker+ (2010)
PBS : Sheth & Tormen (1999)
PBS : Tinker+ (2008)
ESP
Correlations
Separate Universe
b_1
$\frac{b_1 - b_{Fit}}{b_{Fit}}$
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
−0.01
−0.05
−0.09
12.5
13.0
13.5
14.0
14.5
$M\ [\log h^{-1} M_\odot]$

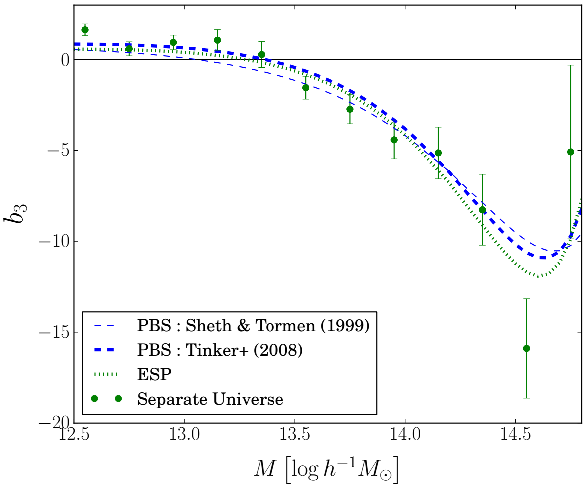
TL+ (2015)

b_2


PBS : Sheth & Tormen (1999)
PBS : Tinker+ (2008)
ESP
Correlations
Separate Universe
b_2
$\frac{b_2 - b_2^{\rm ESP}}{b_2^{\rm ESP}}$
$M\ [\log h^{-1} M_\odot]$
12
10
8
6
4
2
0
−2
1
−1
12.5
13.0
13.5
14.0
14.5

TL+ (2015)

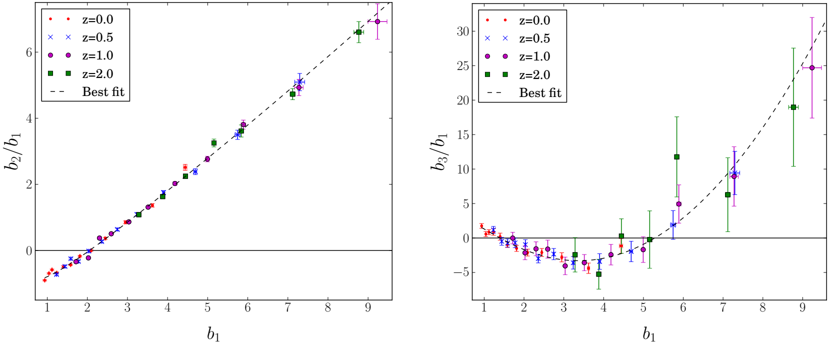
b_3



0
−5
−10
−15
−20
12.5
13.0
13.5
14.0
14.5
b_3
$M\ [\log h^{-1} M_\odot]$
PBS : Sheth & Tormen (1999)
PBS : Tinker+ (2008)
ESP
Separate Universe

TL+ (2015)

Fitting formulae



$$b_2(b_1) = 0.412 - 2.143\, b_1 + 0.929\, b_1^2 + 0.008\, b_1^3$$

$$b_3(b_1) = -1.028 + 7.646\, b_1 - 6.227\, b_1^2 + 0.912\, b_1^3$$

TL+ (2015)

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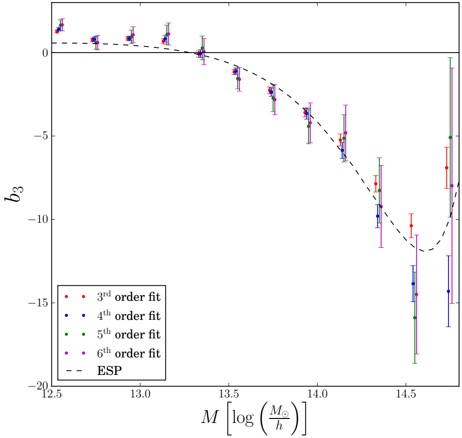
Conclusions

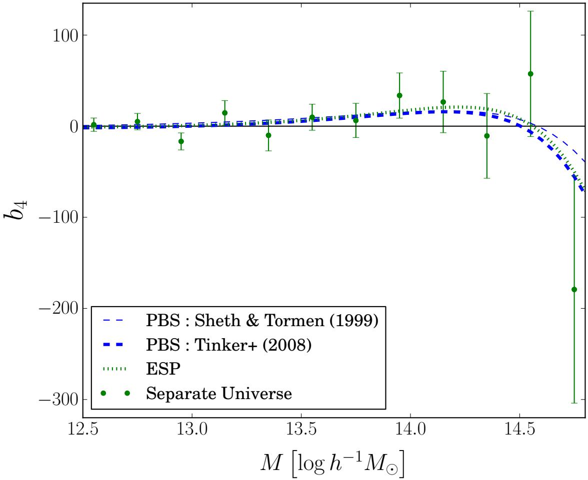
- Good agreement with correlation points, ESP prediction and other curves proves the validity of the method
- Easy to implement and physically motivated method
- Most precise measurements to date for b_2 and b_3 $\rightarrow$ efficient technique
- ESP performs very well at high mass but not at low mass $\rightarrow$ well known problem of the peak model that doesn't work for low peaks
- Tinker+ (2008) mass function very precise but the biases derived from it are not so good $\rightarrow$ fits to the halo mass function have limited range of application $\rightarrow$ have to go into the details of halo collapse to come up with something that agrees with $n_h(M)$ and b

Effect of the fitting polynomial degree



⇒ need a fit of degree $n + 2$ to get unbiased b_n TL+ (2015)

b_4



100
0
−100
−200
−300
12.5
13.0
13.5
14.0
14.5
b_4
$M\ [\log h^{-1} M_\odot]$
PBS : Sheth & Tormen (1999)
PBS : Tinker+ (2008)
ESP
Separate Universe

TL+ (2015)