Large-scale assembly bias from separate universe simulations

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Quantifying and understanding the galaxy-halo connection

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Halo (assembly) bias

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

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

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

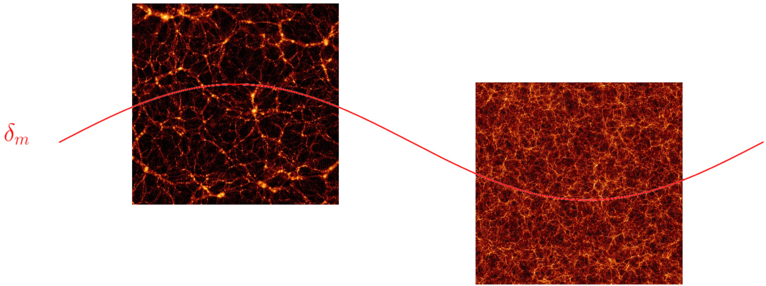
δ_h : fractional number density perturbation of halos

$\triangleright$ Assembly bias : additional dependence of δ_h, b_i on any other property than M

$\triangleright$ This talk : measurements of assembly bias in b_1 and b_2 wrt concentration, spin, mass accretion and shape using a novel technique, *separate universe simulations*.

Separate universe simulations

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



Separate universe simulations

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

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

- Ω_m, Ω_Λ, Ω_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!
- Choices in quantities to match : $\Omega_m h^2 = \tilde{\Omega}_m \tilde{h}^2$
  Comoving box size matched $\rightarrow \tilde{m}_p = m_p$
- Allows to really measure (assembly) bias on large scales

Simulations and halo finding

- Suite of separate universe simulations described in Wagner+ (2014) ran with GADGET-2, initialized at $z = 49$
- Fiducial cosmology : flat ΛCDM, $\Omega_m = 0.27$, $h = 0.7$, $\Omega_b h^2 = 0.023$, $n_s = 0.95$, $A_s = 2.2 \cdot 10^{-9}$
- Three sets of simulations :
  - $L = 500\, h^{-1}\mathrm{Mpc}$, $N_p = 256^3$; $N_p = 512^3$
  - $L = 250\, h^{-1}\mathrm{Mpc}$, $N_p = 512^3$
  - 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) with $\rho_h = 200\rho_m$

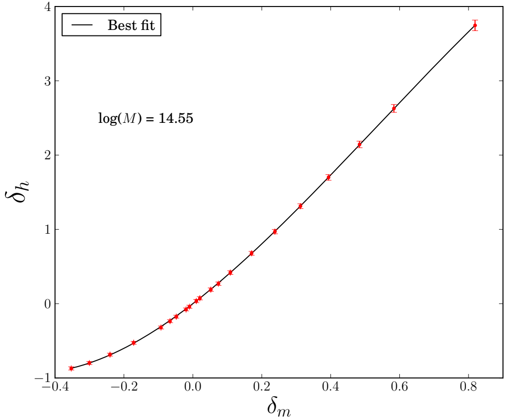
  Gill+ (2004), Knollmann+ (2009)
- Key point : in simulations with a different background density, the threshold must be rescaled

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

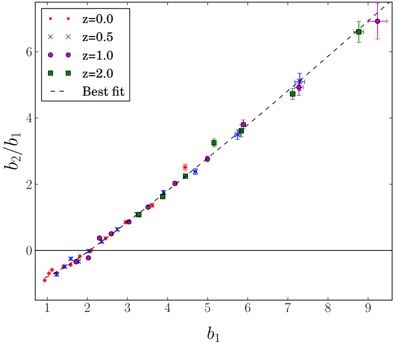
Halo bias from separate universe simulations

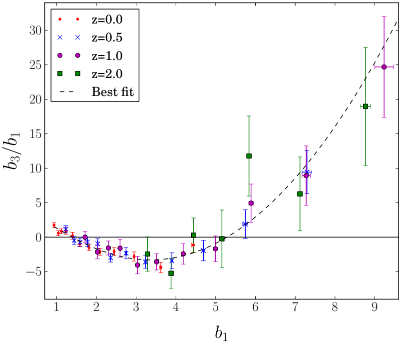
Local bias parameters = response of the halo abundance to a long-wavelength density perturbation

$\rightarrow$ 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.



Local bias





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

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

TL+ (2015, 1511.01096) (see also Hoffmann+ (2016))

Guidelines

1. Separate universe simulations and halo bias

2. Assembly bias

Assembly bias

▷ Additional dependence on property p

$$\rightarrow [\tilde{N}(M,p) - N(M,p)]/N(M,p) \text{ vs } \delta_m$$

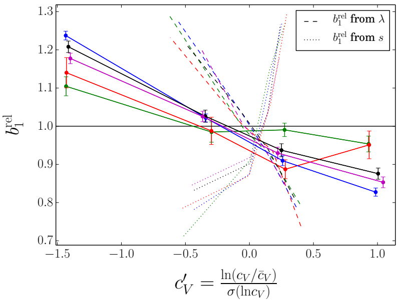
▷ Assembly bias w.r.t.

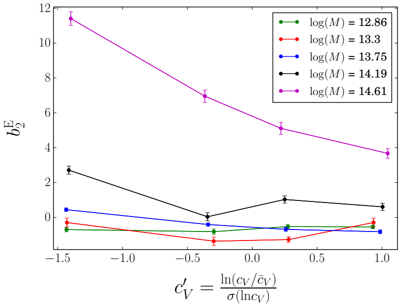
- NFW concentration (c_V) (Prada+ (2012) estimator)
- shape $s = c/a$ ($a > c$)
- spin parameter $\lambda = |\mathbf{J}|/(\sqrt{2}MVr_{200})$ (Bullock+ (2001))
- mass accretion rate
  $M^{-1}dM/dz = [M(0.5) - M(0)]/[0.5\, M(0)]$

▷ Comparison with previous results (Gao+ (2005,2007), Faltenbacher+ (2010), Wechsler+ (2006), ...)

▷ Finally also look at reconstructing assembly bias wrt property p_1 using result wrt another property p_2 and the mean relation $p_1(p_2)$, and at assembly bias wrt two quantities

Bias as a function of concentration

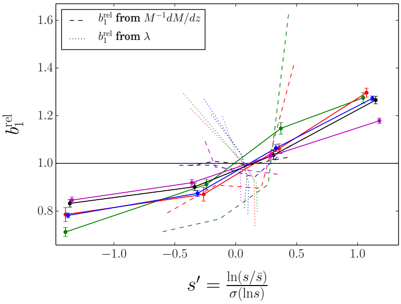


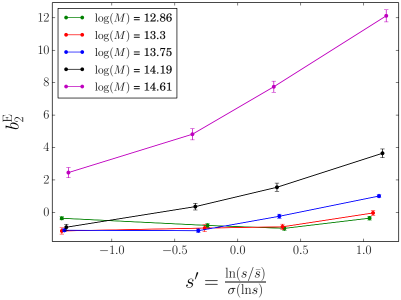


TL+ (2016, arXiv:1612.04360)

▷ Less concentrated halos more clustered → agrees with eg. Gao+ (2005, 2007) and Wechsler+ (2006). Effect decreasing with mass. Also agrees with Paranjape+ (2016), Mao+ (2017)

Bias as a function of shape

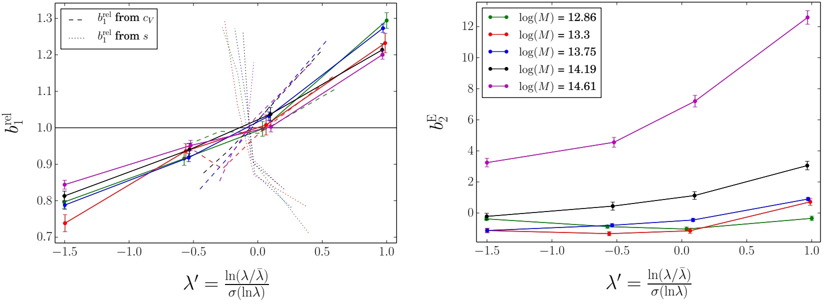




TL+ (2016, arXiv:1612.04360)

▷ More spherical halos more clustered. Effect more important at low mass → agrees with Faltenbacher & White (2010)

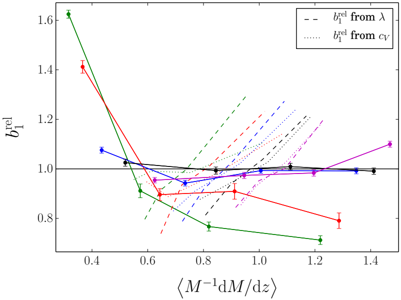
Bias as a function of spin

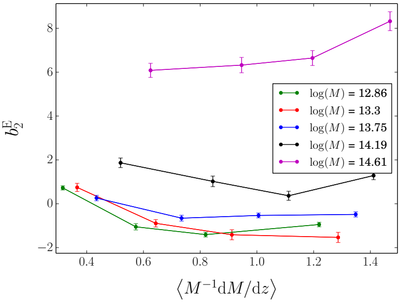


TL+ (2016, arXiv:1612.04360)

▷ Halos with more spin are more clustered. Effect almost mass independent → agrees with Gao & White (2007), Mao+ (2017)

Bias as a function of mass accretion rate

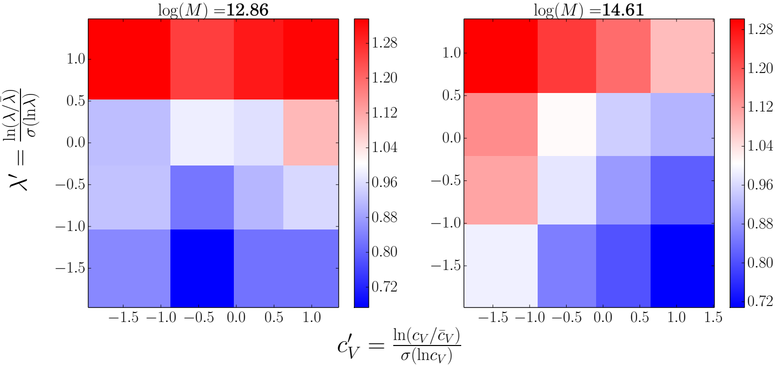




TL+ (2016, arXiv:1612.04360)

▷ Almost no assembly bias → in agreement with Mao+ (2017)

Binning in more than one property : λ and c_V

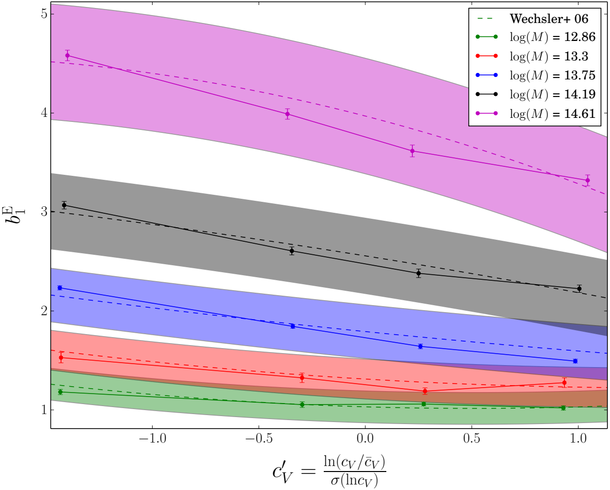


TL+ (2016)

Conclusions

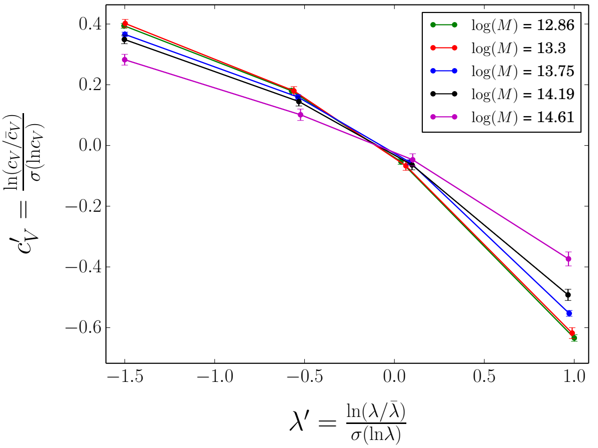
- Separate universe simulations allow to really measure assembly bias on large scales
- Qualitative agreement with previous results
- One of the first precise measurement of the effect in b_2 (see also Angulo+ (2008), Paranjape & Padmanabhan (2016))
- Reconstruction of assembly bias in one property using assembly bias in another one and mean relation between the two does not work
- Binning in two properties to explore variation of assembly bias when several halo properties are specified : specifying an additional property (almost) doesn't change assembly bias wrt another one

Comparison of $b_1(c)$ with Wechsler+ (2006)



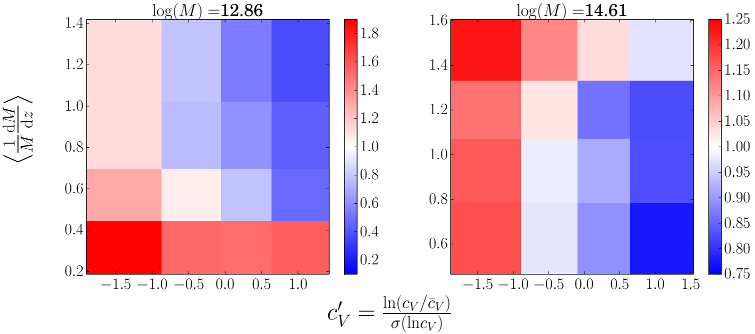
TL+ (2016)

Mean relation $c_V(\lambda)$



TL+ (2016)

Binning in more than one property : $M^{-1}dM/dz$ and c_V



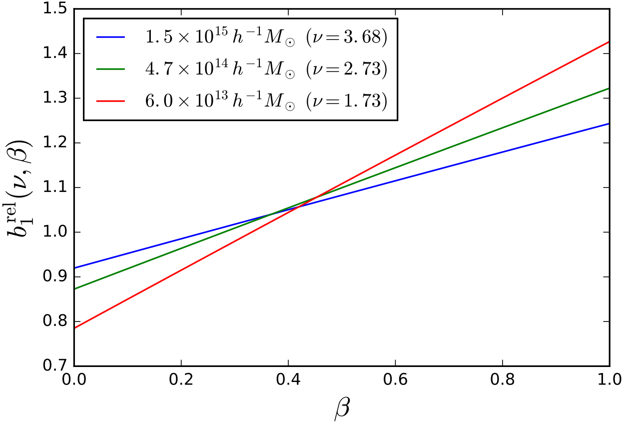
TL+ (2016)

Assembly bias from stochastic barrier

Reminder : height of the peak needs to match the critical overdensity $B(\sigma) = \delta_c + \beta\sigma$

- stochastic parameter β describes the scatter of protohalo densities around δ_c measured in simulations
- bias parameters at fixed β obtained by differentiating $(d\nu/dM)f(\nu,\beta) \propto \nu f(\nu,\beta)$ wrt ν
- can be interpreted as effect of initial shear on peaks (more shear $\rightarrow$ slower collapse).
- however no model that relates β (nor the initial amount of shear) to properties of final halos

Assembly bias from stochastic barrier



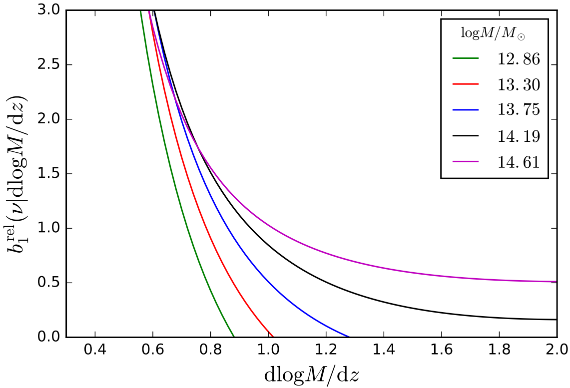
Assembly bias as a function of mass accretion rate

Another ESP variable : slope x of the trajectory $\delta(\sigma)$ (traditionally associated to concentration)

For mass accretion :

- recast the barrier as $\frac{\delta_c}{D(z)} = \delta[\sigma(M)] - \beta\sigma(M)$
- so $\frac{dM}{dz} = -\delta_c \left[\left(\frac{d\delta}{d\sigma} - \beta\right)\frac{d\sigma}{dM}\right]^{-1}\frac{dD}{dz}$
- define $\alpha = \frac{\gamma\nu}{x-\beta\gamma} \propto \frac{dM}{dz}$
- bias parameters at fixed α obtained by differentiating $(d\nu/dM)f(\nu,\alpha) \propto \nu f(\nu,\alpha)$ wrt ν

Assembly bias as a function of mass accretion rate



Interpretation : low $dM/dz \leftrightarrow x - \gamma\beta \gg \gamma\nu$ $\rightarrow$ unlikely to have such steep slope $\rightarrow$ large bias.