A robust measurement of the first higher-derivative bias parameter of dark matter halos

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Contents

Guidelines

Motivation

Why are we interested in the bias parameters of dark matter halos?

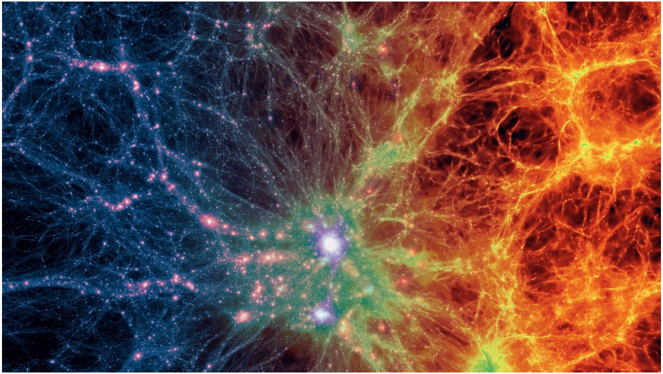


Image credit : Illustris collaboration

Bias formalism: link the distribution of LSS tracers to that of the underlying dark matter

Halo bias

▷ Perturbation theory: statistics of halos written in terms of bias parameters b_O multiplying operators O constructed out of the matter density field δ_m and the tidal field

$$\mathcal{K}_{ij} = \mathcal{D}_{ij}\delta_m = \left(\frac{\partial_i\partial_j}{\nabla^2} - \frac{1}{3}\delta^K_{ij}\right)\delta_m$$

▷ Bias expansion

$$\delta_h(\tau, \mathbf{x}, M) = \sum_O b_O(\tau, M) O(\tau, \mathbf{x})$$

e.g. Desjacques et al. (2018)

δ_h: fractional number density perturbation of halos

▷ Up to 2^{nd} order:

$$\delta_h = b_1\delta_m + b_2\delta_m^2 + b_{K^2}\mathcal{K}^2 + b_{\nabla^2\delta}\nabla^2\delta_m$$

$\mathcal{K}^2 = \mathcal{K}_{ij}\mathcal{K}^{ji}$

Guidelines

Amplified-mode simulations

▷ Superimpose a plane wave to the initial random density field

$$\delta^{(1)}(\mathbf{x}) = \delta_s^{(1)}(\mathbf{x}) + \Delta \cos(\mathbf{k}_0 \cdot \mathbf{x})$$

▷ Amplifies contribution of $b_{\nabla^2\delta}\nabla^2\delta_m$ in bias expansion

$$\delta_h = b_1\delta_m + b_{\nabla^2\delta}\nabla^2\delta_m$$

▷ Implementation in simulations straightforward since only need to modify initial distribution of particles before running the simulation in traditional way

▷ Fourier space density

$$\delta^{(1)}(\mathbf{k}) = \delta_s^{(1)}(\mathbf{n}k_F) + \frac{\Delta L^3}{2}(\delta^K_{\mathbf{n},\mathbf{m}} + \delta^K_{-\mathbf{n},\mathbf{m}})$$

Estimating $b_{\nabla^2\delta}$

- Halo density field

$$\delta_h(\mathbf{x}) = \frac{n_h(\mathbf{x})}{\bar{n}_h} - 1 = B_h \cos(k_0 x)\,, \quad B_h = [b_1 - b_{\nabla^2\delta} k_0^2] B_m$$

- Need to estimate $B_h \rightarrow$ use a χ^2 given by

$$\chi^2 = \sum_{x_i} \frac{1}{\mathcal{N}^2} \left[n_h(\mathbf{x}_i) - \bar{n}_h \left(1 + B_h \cos(k_0 x_i)\right)\right]^2$$

- Least-squares estimator

$$\frac{\partial}{\partial B_h} \chi^2(B_h) \stackrel{!}{=} 0 \Leftrightarrow \hat{B}_h = \frac{2 \sum_{\text{halos}} \cos(k_0 x_i)}{N_{\text{halos}}}$$

Estimating $b_{\nabla^2\delta}$

▷ In practice

$$\frac{\hat{B}_h^i(k_0, +\Delta) - \hat{B}_h^i(k_0, -\Delta)}{2\Delta} = b_1 - (b_{\nabla^2\delta} + b_1\, C^2_{\mathrm{s,eff}})k_0^2$$

▷ Run a suite of amplified-mode simulations for various k_0, and fit a second-order polynomial in k_0 to this ratio to get an estimate for $b_{\nabla^2\delta}(M)$

▷ Use the results of Lazeyras+ (2015) for b_1

▷ Effective matter sound speed $C^2_{\mathrm{s,eff}}$ measured from 1-loop matter power spectrum

$$\frac{P_{mm}(k) - P_{\mathrm{1-loop}}(k)}{P_L(k)} = -2C^2_{s,\mathrm{eff}}k^2$$

Other measurements and prediction

▷ $b_{\nabla^2\delta}$ has units [length]^2 $\rightarrow$ naive expectation

$$b_{\nabla^2\delta}(M) \sim -R_L^2(M)$$

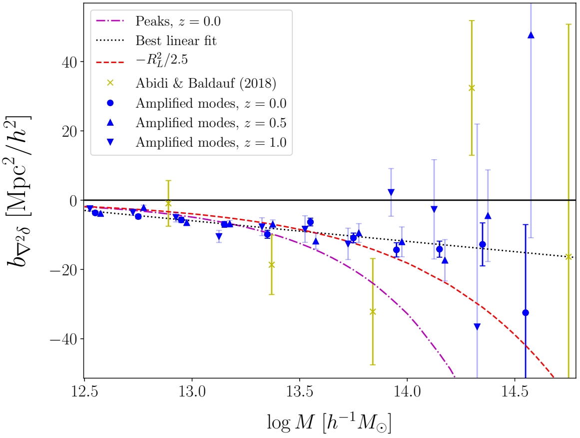
▷ Peak model together with velocity bias $\rightarrow$ scale-dependent bias for peaks

Bardeen+ (1986), Desjacques (2008), Desjacques & Sheth (2010)

▷ Abidi & Baldauf (2018): fit to 1-loop halo-matter power spectrum with 1 free parameter

$$P_{hm}^{1-loop}(k) \propto b_1, b_2, b_{K^2}, b_{\mathrm{td}}, b_{\nabla^2\delta}$$

$b_{\nabla^2\delta}$



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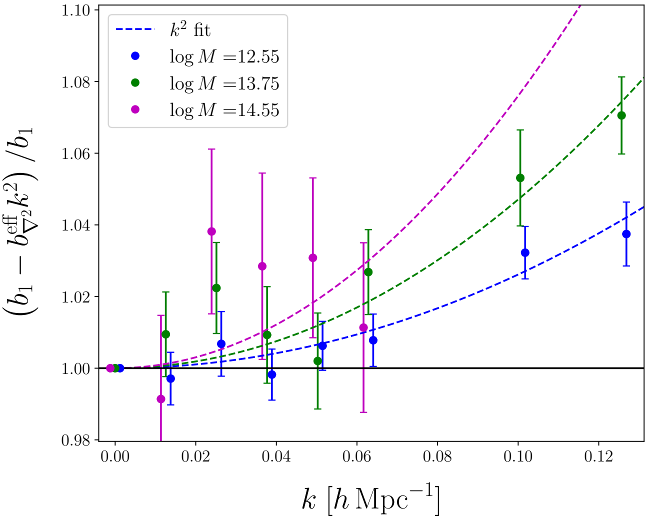
$$b_{\nabla^2\delta}(M) = -5.9\log M + 71.3\,(\mathrm{Mpc}/h)^2$$

Guidelines

Conclusions and Outlook

- First robust measurement of $b_{\nabla^2\delta}$ using amplified-mode simulations
- Results consistent with $-R_L^2$ as naively expected
- Good overall agreement of our results with Abidi & Baldauf (2018) as a cross-check of our results
- Important implications for future works such as determining the *reach of perturbation theory*, studying *stochasticity* of halo formation (coming from small scale perturbations) in more details, or accurately model *galaxy statistics* for surveys by including more bias parameters

Measuring $b(k)$



Comparison with 1-loop P_{hm} results