Non-Universality and Assembly bias in the hunt for Local Primordial non-Gaussianity

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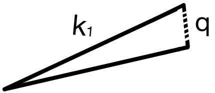
Local Primordial Non-Gaussianity (LPnG)

- Non-trivial soft limits of correlation functions characterise LPNG :

$$B_\zeta(q \to 0, k_1, k_2) \propto f_{NL} P_\zeta(k_1) P_\zeta(q)$$



$\sim$ f_{NL}

- $f_{NL} \sim 1$ is an important theoretical target for observations.

- Distinguishing feature of at least one additional light (m≪H) field during inflation. (Meerburg et al. 2019; Achúcarro et al. 2022)

Measuring LPnG

- CMB constraints from Planck (Aghanim et al. 2020) :

$$f_{NL} = -0.9 \pm 5.1$$

- Large Scale Structure (LSS) constraints are, as yet, systematics dominated.

  BOSS (Cabass et al. 2022) $\rightarrow$ $f_{NL} = -33 \pm 28$
  DESI LRG+QSO (Chaussidon et al. 2024) $\rightarrow$ $f_{NL} = -3.6^{+9.0}_{-9.1}$

- Significantly higher potential for improvement from LSS surveys (with improved control on systematics)

LPnG and Scale dependent bias

- Signature of LPnG on galaxy bias (Dalal et al. 2008) :

$$\Delta b_{NG} \propto b_\phi \frac{f_{NL}}{k^2}$$

- Constraints limited by a degenerate nuisance parameter : b_ϕ !

$$b_\phi = 2\frac{\partial \log n_g}{\partial \log A_s}$$

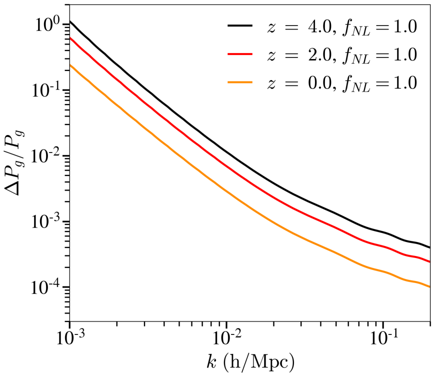


Figure: Fractional change in the galaxy power spectrum due to local $f_{NL} = 1$.

(Non-) universality and Assembly Bias

- Universality ansatz : $b_\phi = (b-1)\delta_c = b_L\delta_c$, $\delta_c \approx 1.68$

- Examples of universal tracers : dark-matter halos selected by mass or mass + spin/sphericity

- Non-universality : $b_\phi \neq (b-1)\delta_c$

- Examples of non-universal tracers : most (if not all) galaxies/quasars, dark-matter halos selected by mass and concentration.

  (Focus on the latter to understand the origin of non-universality)

Separate Universe framework

Effect of a long wavelength matter perturbation δ_L on small-scale clustering can be described in terms of modified, 'local' cosmological parameters. Eg.:

$$H_w = H\left(1 - \frac{1}{3}\frac{d\delta_L}{d\log a}\right) \text{ (local Hubble rate)}$$

$$a_W = a\left(1 - \frac{1}{3}\delta_L\right) \text{ (local scale factor)}$$

Growth factor response :

$$D_W(a) = D(a)\big(1 + R_{SU}\delta_L\big)$$

$$R_{SU} = \frac{13}{21} \text{ (EdS) ; } R_{SU} \approx \frac{13}{21} \text{ } (\Omega_\Lambda \sim 0.7)$$

(Non-) Universality in the Separate Universe

Separation of scales in halo formation:

$$b_L = \frac{d \log n_h}{d\delta_L} = \sum_i \frac{\partial \log n_h}{\partial \theta_i} \frac{d\theta_i}{d\delta_L}$$

$$b_\phi = 2\frac{d \log n_h}{d \log A_s} = \sum_i \frac{\partial \log n_h}{\partial \theta_i} \cdot 2\frac{d\theta_i}{d \log A_s}$$

Universality $\iff$

$$\frac{d\theta_i}{d\delta_L} \cdot \delta_c = 2 \cdot \frac{d\theta_i}{d \log A_s}, \quad \forall\ \theta_i$$

Need to know which small-scale statistics of the matter density field $\{\theta_i\}$ govern halo abundance $n_h(\{\theta_i\})$

Halos selected by Mass

Only relevant small-scale statistic : $\sigma(M, z) = \langle \delta_{L,R}^2 \rangle^{1/2} \propto A_s^{1/2}$

$$\left. \frac{d \log \sigma}{d \log \delta_L} \right|_{SU} = R_{SU} \approx 13/21 \sim \delta_c^{-1}$$

$$b_\phi = (b_h - 1) R_{SU}^{-1}$$

(universality of mass-selected dark matter halos)

Halos selected by Mass

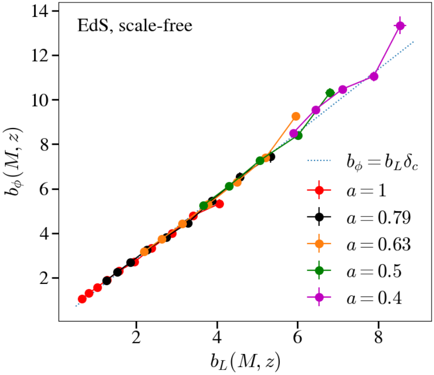


Figure: b_ϕ vs b_L for halos selected by mass in EdS (scale-free) cosmology

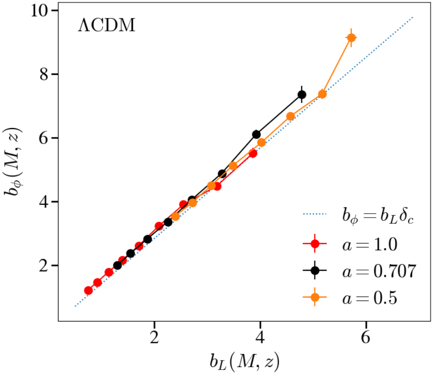


Figure: b_ϕ vs b_L for halos selected by mass in ΛCDM cosmology

High mass, concentration-selected halos

For high-mass halos, concentration $\longleftrightarrow$ peak curvature

Additional relevant statistics : $\theta_1 = \langle \delta_R \nabla^2 \delta_R \rangle$; $\theta_2 = \langle (\nabla^2 \delta_R)^2 \rangle$

Both $\theta_1,\ \theta_2$ obey :

$$\frac{d\theta_i}{d\delta_L} \cdot R_{SU}^{-1} = 2 \cdot \frac{d\theta_i}{d \log A_s}$$

$\implies$ High mass, concentration selected halos obey universality ! (i.e. $b_\phi = (b-1) R_{SU}^{-1} \approx (b-1)\delta_c$

Low mass, concentration-selected halos

For low-mass halos, concentration $\longleftrightarrow$ proximity to neighbouring massive peaks

$$n_{\rm high\ conc} = n_{pk}(\sigma(M)) \cdot \eta \cdot \chi \ \ ; \ \ n_{\rm low\ conc} = n_{pk}(\sigma(M)) \cdot (1-\eta)$$

η : probability of proximity to high-mass halos
χ : conditional escape probability

$$\frac{\partial \chi}{\partial \delta_L} < 0 \ \ ; \ \ \frac{\partial \chi}{\partial \log A_s} \approx 0 \ \ \Longrightarrow$$

$$b_{\phi,\text{high}} > (b_{\rm high} - 1)\delta_c \ \ ; \ \ b_{\phi,\text{low}} < (b_{\rm low} - 1)\delta_c$$

Concentration-selected halos

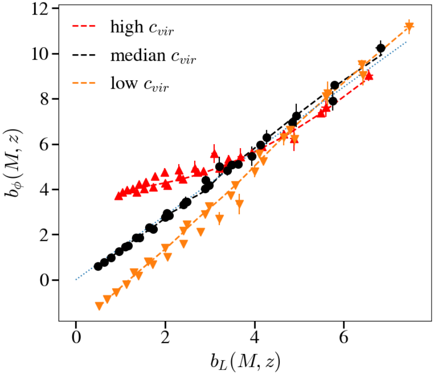


Figure: b_ϕ vs b_L for halos selected by mass and concentration in scale-free, EdS cosmology

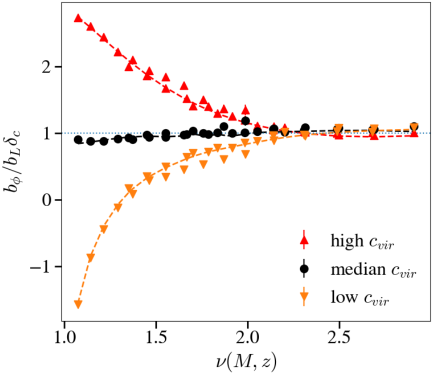


Figure: $b_\phi/b_L\delta_c$ vs $\nu \propto M^{1/6}$ for halos selected by mass in scale-free, EdS cosmology

Concentration-selected halos

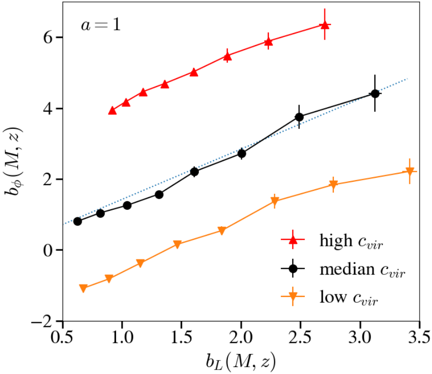


Figure: b_ϕ vs b_L for halos selected by mass and concentration in ΛCDM cosmology, z=0

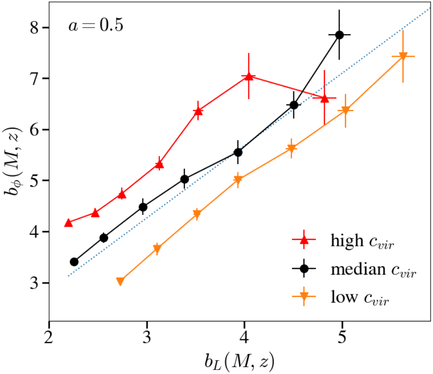


Figure: b_ϕ vs b_L for halos selected by mass and concentration in ΛCDM cosmology, z=1

Discussion/Implications

- The Separate Universe framework presents a useful way of understanding halo bias and/or non-universality in halo clustering.

- Universality restored for halos with high masses with $\nu \gtrsim 2 \leftrightarrow M \sim 10^{12} - 10^{13}\ M_\odot/h$ at $z = 3$ (high-redshift quasars/LBGs)

$\implies$ non-universality observed in quasars / tracers with high halo mass is an effect of the underlying tracer selection function. Eg. :

$$\frac{\partial \log\langle N\rangle_{\mathrm{HOD}}}{\partial \delta_L}\delta_c \neq 2 \cdot \frac{\partial \log\langle N\rangle_{\mathrm{HOD}}}{\partial \log A_s}$$