The effects of assembly bias on galaxy clustering predictions

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Galaxies vs matter?

- Dark matter
- Haloes + HOD
- Semi Analytical Model (SAM)

SDSS
HOD model

\[ N(M) = N_c(M) + N_s(M) \]
\[ N_c(M) = \frac{1}{2} \left[ 1 + erf \left( \frac{\log M - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right] \]
\[ N_s(M) = N_c(M) \times \left( \frac{M - M_0}{M_1} \right)^\alpha \]

Zheng et al. 2005

- HOD is based on the halo model
- Galaxy populations described according to halo properties (commonly mass)
- We can model clustering to measure HOD
- HOD can be used for measuring dark matter haloes
- We need to know (or model) bias

Coupon et al. 2012
HOD model

Assumptions

\[ \xi_{gal} = \xi_{gal}^{1halo}(r) + b_{gal}^2 \xi_{Lin}(r) \]

\[ \xi(r) = \frac{1}{2\pi^2} \int k^3 P(k) \frac{\sin(kr)}{kr} dk \]

\[ P_{1h}(k) = \int dM n(M) \frac{N^2(M)}{n_{gal}^2} |u_h(k|M)|^2 \]

\[ P_{2h}(k) = P_{Lin}^{m}(k) \times \left[ \int dM n(M) \frac{N(M)}{n_{gal}} b_h(M, r) |u_h(k|M)| \right]^2 \]
HOD model

Assumptions

• The galaxy occupation is only dependent on halo mass

\[ \xi_{gal} = \xi_{gal}^{1halo}(r) + b_{gal}^2 \xi_{m}^{Lin}(r) \]

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The galaxy occupation is only dependent on halo mass.
- Galaxies follow an NFW profile.
HOD model

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Pujol et al. 2014
HOD model

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Assumptions

- The galaxy occupation is only dependent on halo mass
- Galaxies follow an NFW profile
- Correct model for halo bias
- No assembly bias
Reconstruction method

\[ b_g(L) = \int dM b_h(M)n(M) \frac{N_g(L, M)}{n_g(L)} \]

**Advantages**

- Linear and constant bias, no scale dependence
- Only 2-halo term dominates
- No density profile assumptions needed
- No bias model needed if we measure halo bias

**Millennium Simulation**

\[ \Lambda CDM \]
\[ \Omega_m = 0.25 \quad \sigma_8 = 0.9 \]
\[ \Omega_\Lambda = 0.75 \quad h = 0.73 \]
\[ V = (500h^{-1} \text{Mpc})^3 \]
\[ m_p = 8.6 \times 10^8 M_\odot \]

**Assumptions**

- No assembly bias
- Galaxy occupation only mass dependent
Halo and galaxy bias

- Halo bias consistent with theoretical predictions
- Tinker et al. 2010 is the most consistent model

\[ b_{g,h}(r) = \sqrt{\frac{\xi_{g,h}(r)}{\xi_m(r)}} \]

fitted as constant at
\[ r = [20 - 30]h^{-1} \text{Mpc} \]
HOD measurements

Number of galaxies per halo of mass $M_h$ at different luminosity thresholds (solid) vs SDSS DR-7 (dashed) from Zehavi et al. 2011

$$b_g(L) = \int dM b_h(M) n(M) \frac{N_g(L,M)}{n_g(L)}$$

Guo et al. 2011 HOD

Bower 2006 HOD

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HOD measurements

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bias reconstructions

Results

• Underprediction of galaxy bias of 5-10%
• FOF mass obtain better reconstructions than gravitationally bound masses

Consequences

• Assembly bias
• Galaxy population correlated with assembly bias

\[ b_g(L) = \int dM b_h(M) n(M) \frac{N_g(L, M)}{n_g(L)} \]

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Assembly bias effects

- Galaxy bias > halo bias for low mass haloes
- HOD not compatible with galaxy clustering for halo masses < $10^{12}$Msun
- Indication of low mass haloes with high clustering

Strong subhalo abundance dependence of halo bias for fixed mass. Indication of assembly bias

For a fixed mass bin, haloes (or main haloes) with more subhaloes (and more galaxies) have more clustering.

Correlation between halo occupation and halo bias for fixed mass, independent of the SAM.
Assembly bias vs galaxy properties

- Assembly bias can be related to galaxy properties, in this case the colour of the central galaxy.

- As a consequence the bias reconstruction does not make a good prediction of bias.

- We are not able to predict the occupation of these galaxies from the HOD assumptions, we can get large errors because of the misinterpretation of clustering.

- Care must be taken when measuring the properties of haloes or galaxy occupations if we assume the HOD model.

Halo bias vs mass for different central colours

Reconstructed vs real bias for red central galaxies
Conclusions

• We used the Millennium Simulation to measure the linear bias at large scales and test the HOD model, where no assumptions for the profile of the galaxies in haloes are needed.
• We find underprediction of galaxy bias of 5-10%, an indication of assembly bias.
• FOF mass obtain better reconstructions than gravitationally bound masses.
• For fixed host halo mass $< 10^{12}$Msun, galaxy bias $> $ halo bias, inconsistent with the HOD assumptions.
• Strong subhalo abundance dependence of halo bias for fixed mass. This is independent of the galaxy formation model.
• Care must be taken when using HOD to estimate the mass of haloes or galaxy occupations.