Limitations to the “basic” HOD model and beyond

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Cosmology concordance model

- Afterglow Light Pattern 375,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy
  Accelerated Expansion
- Inflation?
- Quantum Fluctuations

Cosmic Web

- 1st Stars about 400 million yrs.
- Big Bang Expansion
  13.77 billion years
How are galaxies embedded in the cosmic web?

What is the nature of DM?
What are the cosmological parameters?
How do galaxy formation and evolution work?

⇒ How to diminish systematic bias in future observations (DESI, LSST, WFIRST, etc.)?
Why study the Cosmic Web?

- Creating a model which explains DM nature
- Inferring cosmological parameters
- Understanding galaxy formation and evolution
- Diminishing systematic bias in future observations (DESI, LSST, WFIRST, etc.)
Hydrodynamical vs. N-body simulations

Baked-in physics models
- Computationally expensive
- Have limited volumes for studying large scales
- Provide galaxy populations as outputs

Gravitational interactions
- Computationally efficient
- Can be employed at very large volumes ~ Gpc³
- Need to adopt galaxy population models

Ex: IllustrisTNG (2017) Ex: ABACUS (Garrison et al. 2018)
How to populate halos with galaxies?

- SAMs, Empirical Forward modeling, Abundance matching
- Halo Occupation Distribution (HOD)
Basic Halo Occupation Distribution model

IllustrisTNG300
11665 galaxies
$L = 205 \text{ Mpc}/h$

Zheng et al. (2005)
Basic HOD model

Assumptions:

- Mass predicts occupation $P(N_{\text{gal}} | M_{\text{halo}})$, no assembly bias
- Poisson process, gravitation only

Contestations:

- Zehavi et al. (2011), Zentner et al. (2014), Sinha et al. (2018)

Alternatives:

- SHAM (Kravtsov et al. 2014), GRAND-HOD (Yuan et al. 2018), decorated HOD (Hearin et al. 2016)
Testing the fundamentals of HOD with TNG hydrosims

(See also Beltz-Mohrmann et al. 2019)
Motivation for project

Reason for using IllustrisTNG:

- Phase-matched realizations of hydro- and N-body sims
- Sophistication in galaxy formation

Particular focus:

- Testing the fundamental assumptions of HOD modeling with hydrosims
- See also Zehavi et al. 2011, Zentner et al. 2014, Sinha et al. 2018, Beltz-Mohrmann et al. 2019
Assignment algorithm

1. Bijective matching

- Full Physics (FP)
  - halo #55
- Dark Matter (DM)
  - halo #58
EITHER
Assignment algorithm

2. Assigning galaxies

Full Physics (FP)  Dark Matter (DM)

halo #55  halo #58
OR
Assignment algorithm

2'. Shuffling and assigning

Full Physics (FP) vs. Dark Matter (DM)

Effectively an HOD

In 5% mass bins
Clustering of galaxies in FP

Full Physics (FP)

Galaxy correlation function for full-physics
Clustering of galaxies in DM

Galaxy correlation function for dark matter
15% discrepancy on large scales
Introduces a substantial systematic error in mock galaxy catalogs and leads to halo mass bias (Leauthaud et al. 2018)
What does this mean?

- Introduces a **substantial** systematic error in mock galaxy catalogs
- Leads to **bias** in determining halo mass (Leauthaud et al. 2018)
- Better models are needed for future surveys
How robust is this result?

- Choice of mass proxy ($M_{200m}$, $M_{200c}$, $V_{\text{max}}$, $V_{\text{peak}}$)
- Box size and cosmic variance (ABACUS $L_{\text{box}} = 720$ Mpc/$h$)
- Choice of group finder (Friends-of-Friends vs. ROCKSTAR)
Augmenting the HOD with secondary halo properties
Halo properties at fixed mass

Assembly bias parameter:

- Halo concentration
- Environment
- Halo spin
- Formation epoch
- Velocity anisotropy

Galaxy Clustering:

* inverted for low-mass halos

** will be introduced in more detail

Desjacques et al. (2018)
Halo Concentration

Our concentration proxy:

\[ c = \frac{R_{200c}}{R_{\text{max}}} \]

NFW formula:

\[ \rho(r) = \frac{\rho_s}{(r/r_s)[1 + (r/r_s)]} \]

Inverted relationship between concentration and halo occupation!

Navarro, Frenk & White (1996)
Rank-order $c$ within each 5% mass bin in reverse
Halo Concentration

\[ \xi(r)_{\text{sec. prop.}} / \xi(r)_{\text{bHOD}} \]

- **hydrosim.**
- **concentration**

\[ r \ [\text{Mpc/h}] \]

Graph showing the ratio of satellite property correlation function to the bias-related HOD (Hydrostatic Initial Conditions, Halo Occupation Distribution) correlation function. The graph includes data points for both hydrodynamic simulations and concentration models, illustrating the concentration parameter at different radial distances (\( r \)).
For each halo...

*Environment (f_{env})*

Exclude!
Rank-order $f_{\text{env}}$ within each 5% mass bin
Environment ($f_{\text{env}}$)

![Graph showing the relationship between $\xi(r)$ and $r$ with a comparison between hydrosim and local env]
Velocity Anisotropy ($\beta$)

$\beta = 1 - \frac{\sigma^2_{\text{tan}}}{2\sigma^2_{\text{rad}}}$

$-\infty < \beta < 1$

$\beta = 0$, isotropic distribution

$\beta > 0$, radially dominated

$\beta < 0$, tangentially dominated

More clustered galaxies (mergers)

large impact parameters
(deflections caused by gravity)

large $\sigma_{\text{tan}}$

smaller $\beta$
Rank-order $\beta$ within each 5% mass bin in reverse
Velocity Anisotropy ($\beta$)

\[ \frac{\xi(r)_{\text{sec. prop.}}}{\xi(r)_{\text{bHOD}}} \]
| Secondary property            | Difference from bHOD |
|-----------------------------|----------------------|
| hydrosimulation             | 15 ± 1%              |
| local environment           | 98.6%                |
| $\sigma^2 R_{\text{halfmass}}$ | 35.4%                |
| velocity anisotropy         | 35.8%                |
| dispersion velocity         | 17.9%                |
| $M_{\text{cent}}/R_{\text{halfmass}}$ | 6.1%                |
| halo concentration          | 2.7%                 |
| halo spin                   | 2.0%                 |
| formation epoch             | 0.6%                 |
Focusing on Environment

Cosmic Web and Density Cuts
Cosmic Web

IllustrisTNG (2017)
Cosmic Web

Dark Matter Density

$t_{ab} \equiv \frac{k_a k_b}{k^2} \delta(k)$

DM Cosmic Web

J. Bond & S. Myers (1996)
Cosmic Web

- Peaks
- Filaments
- Sheets
- Voids
Cosmic Web

1. Assign each halo an environment type
   - Peaks
   - Filaments
   - Sheets
   - Voids

2. Shuffle the halo occupation numbers of each type in 5% mass bins
Cosmic Web

● Peaks

● Sheets

At fixed halo mass, galaxies in one type of environment cluster differently from galaxies in another!
How do we construct new models?

Implement correlations with a second parameter
An imperfect correlation for $f_{env}$

For each 5% mass bin with $N_h$ halos:

1. Draw $N_h$ pairs $(x, y)$ from Gaussian with $0 < r < 1$

2. Convert $(x, y)$ into integers $(i, j)$

3. Convert $N_{gal}$ into $\{i_{par}\}$ and $f_{env}$ into $\{j_{par}\}$

4. Apply $(i,j)$ pairing to obtain corresponding $(N_{gal}, f_{env})$
An imperfect correlation for $f_{\text{env}}$

**Perfect Correlation**

**Imperfect correlation**
Next episode...

- Testing **secondary** halo properties in merger trees
- Understanding the effect of **environment**
- Studying **tertiary** halo properties
- Including **new** statistics (counts-in-cell, etc.)
- Applying to **data**
- Modeling **baryonic effects** in N-body sims
- Verifying result in **larger** box
Conclusions...

Episode 1

THE HOD MENACE

We found a 15% discrepancy on large scales with HOD. Secondary candidates are environment and velocity anisotropy. Our hope is to reduce the systematic errors for future galaxy surveys and deduce correct DM and galaxy evolution properties.
Conclusions

Findings:

- 15% discrepancy on large scales with basic HOD
- Secondary candidates: halo environment and velocity dispersion anisotropy

Future:

- reduce systematic errors for future galaxy surveys
- deduce correct DM and galaxy evolution properties
Episode I
The HOD Menace

Thank you for the excellent guidance!

Looking forward to exploring more exciting ideas.
Relationship with Galaxies
Dark Matter vs. Stellar Light

IllustrisTNG (2017)
Dark Matter vs. Stellar Light

IllustrisTNG (2017)
Dark Matter vs. Stellar Light
Darth Matter vs. Stellar Distribution

IllustrisTNG (2017)
Darth Matter vs. Stellar Distribution

IllustrisTNG (2017)
Darth Matter vs. Stellar Distribution

IllustrisTNG (2017)
How is the cosmic web related to galaxies?