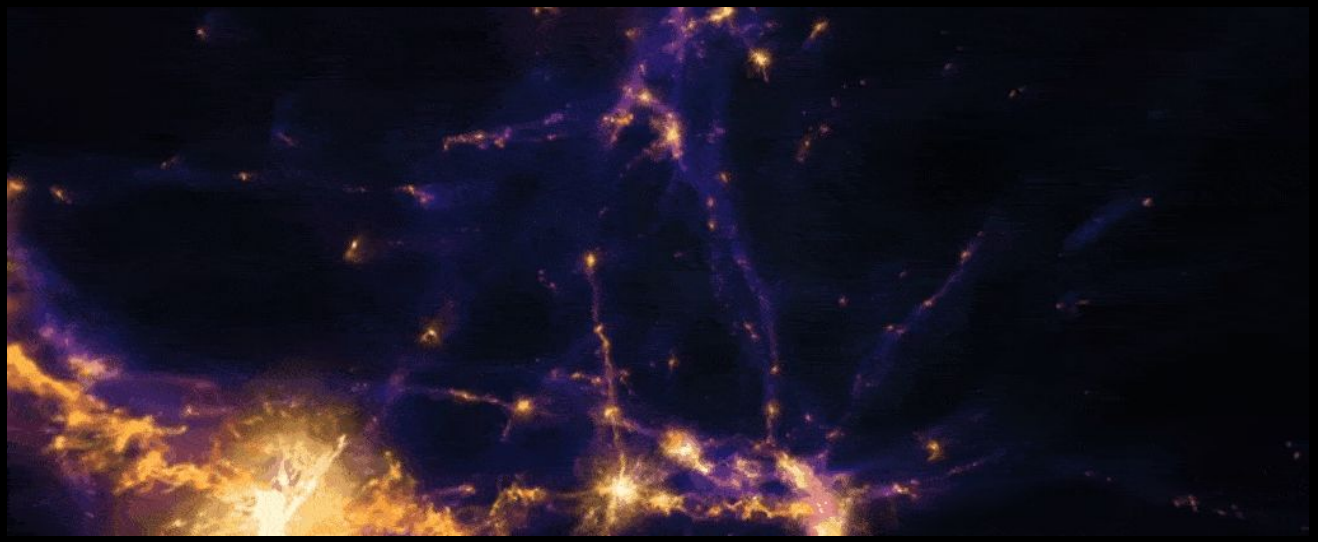
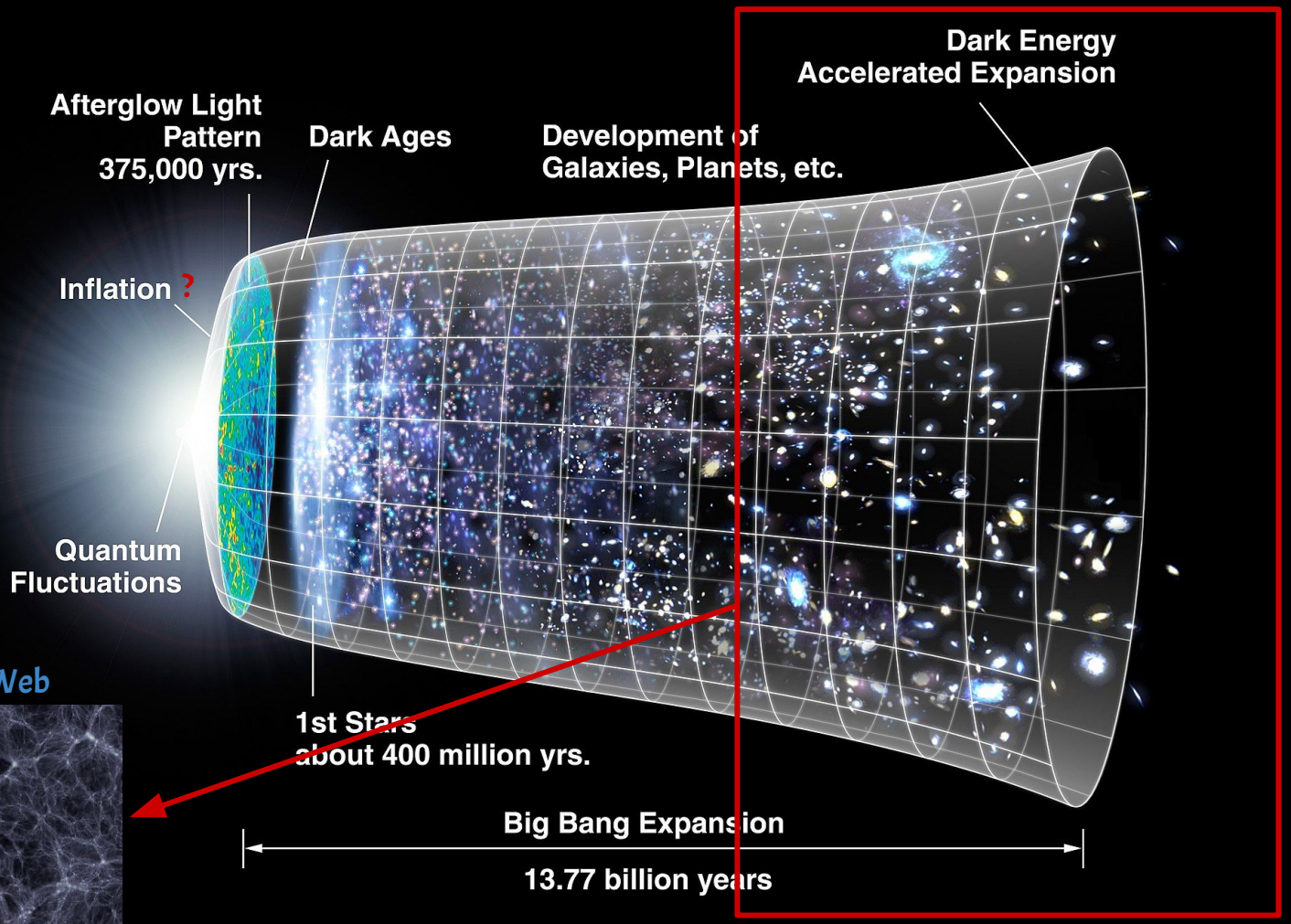
Limitations to the "basic" HOD model and beyond



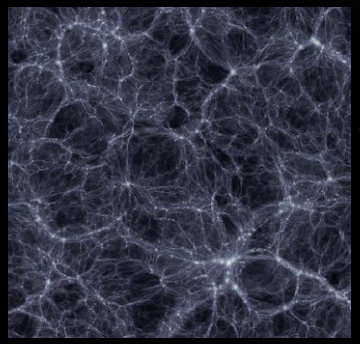
Boryana Hadzhiyska, S. Bose, D. Eisenstein, L. Hernquist and D. Spergel

HARVARD-SMITHSONIAN
CENTER FOR ASTROPHYSICS

Cosmology concordance model



Cosmic Web



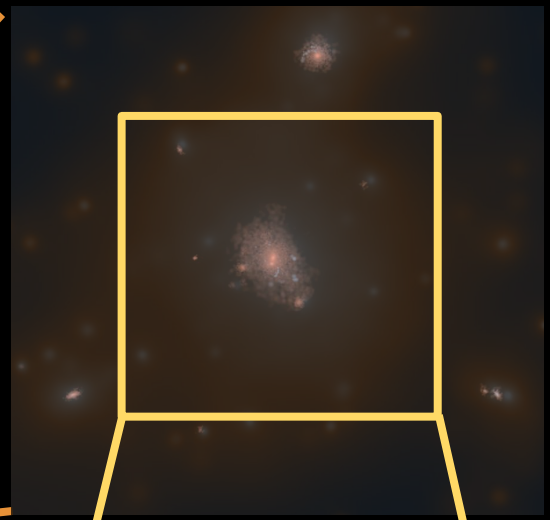
How are galaxies embedded in the cosmic web?

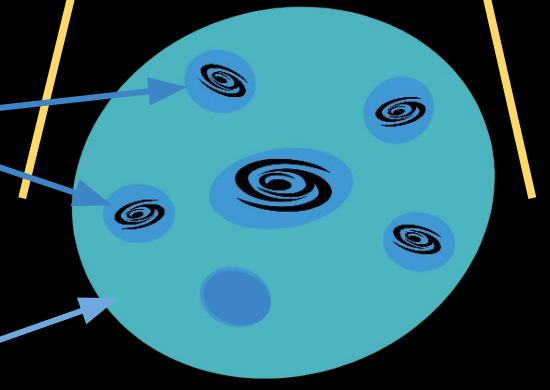
What is the nature of DM?

What are the cosmological parameters?

How do galaxy formation and evolution work?

=> How to diminishing 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

Ex: IllustrisTNG (2017)

Gravitational interactions

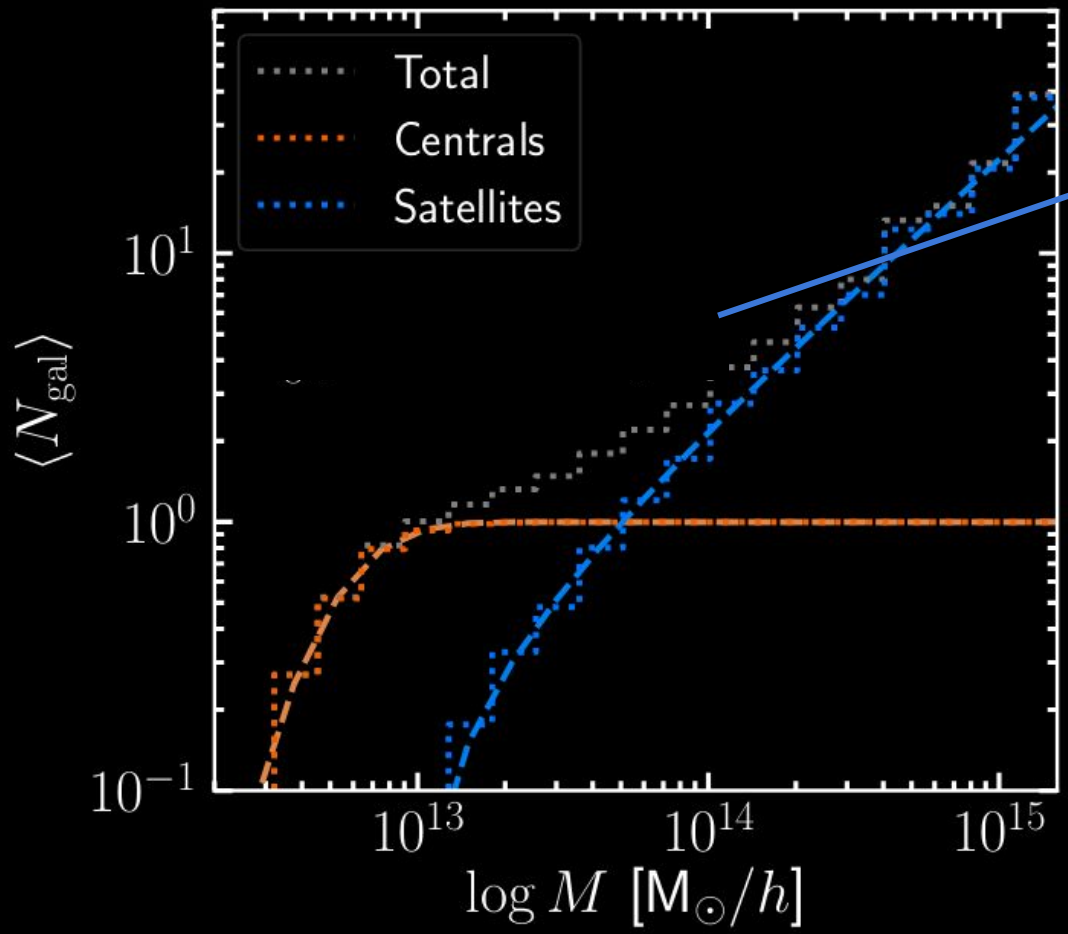
- Computationally efficient
- Can be employed at very large volumes ~ Gpc^3
- Need to adopt galaxy population models

Ex: ABACUS (Garrison et al. 2018)

How to populate halos with galaxies?

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

Basic HaloOccupationDistribution model



IllustrisTNG300
11665 galaxies
L = 205 Mpc/*h*

Zheng et al. (2005)

Basic HOD model

Assumptions:

- Mass predicts occupation $P(N_{gal}|M_{halo})$, 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

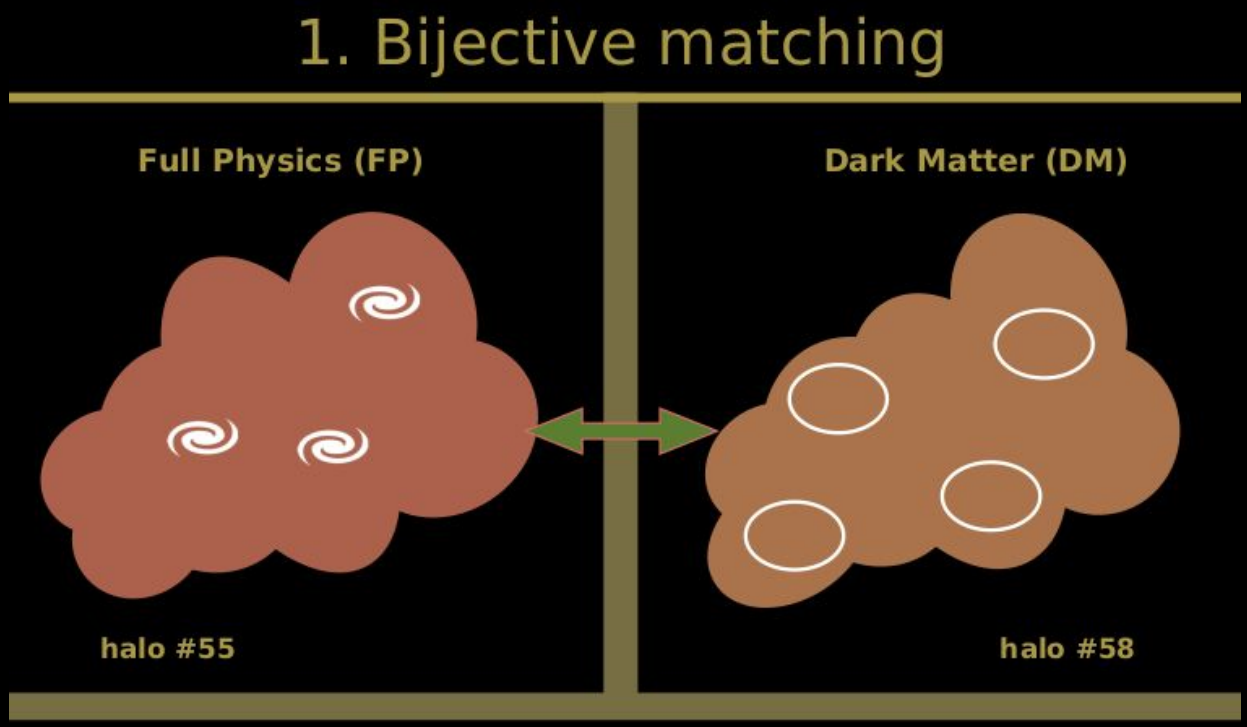
Reason for using IllustrisTNG:

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

Particular focus:

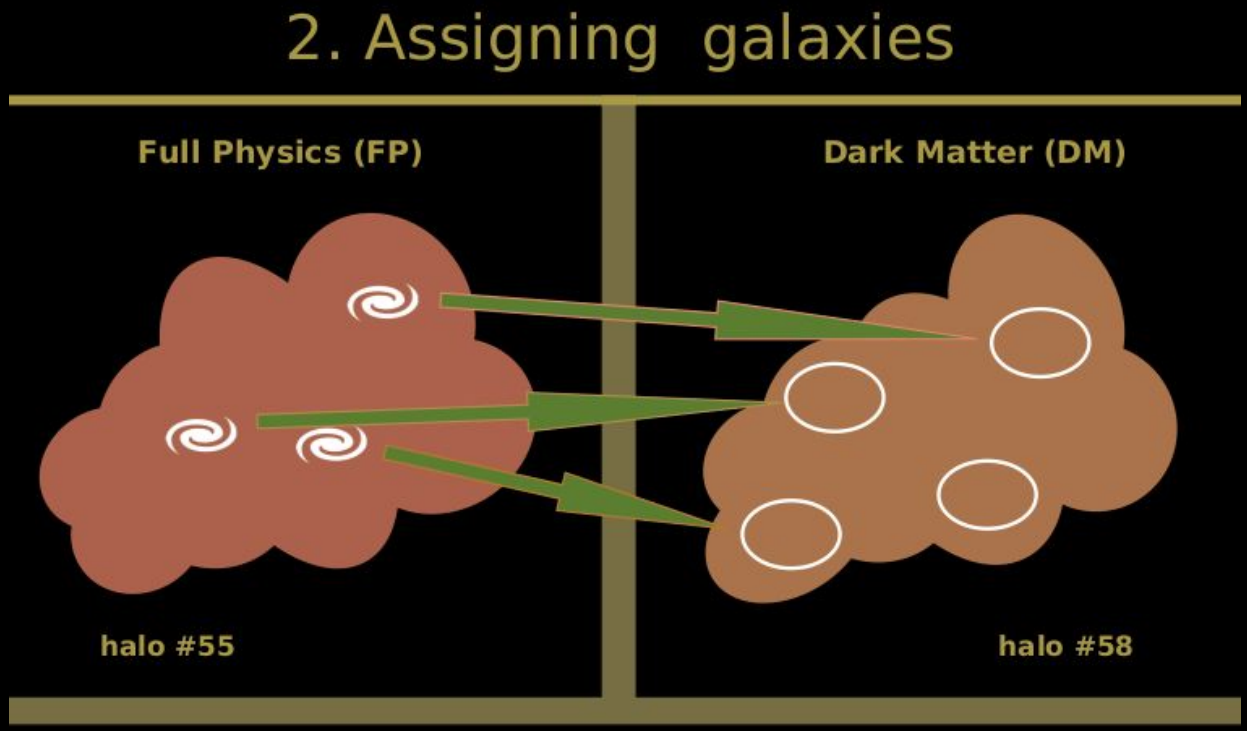
- Testing the fundamental assumptions of HOD modeling with hydrosims
- See also Zehavi et al. 2011, Zentner et al. 2014, Sinha et al. 2018, Beltz-Mohrmann et al. 2019

Assignment algorithm



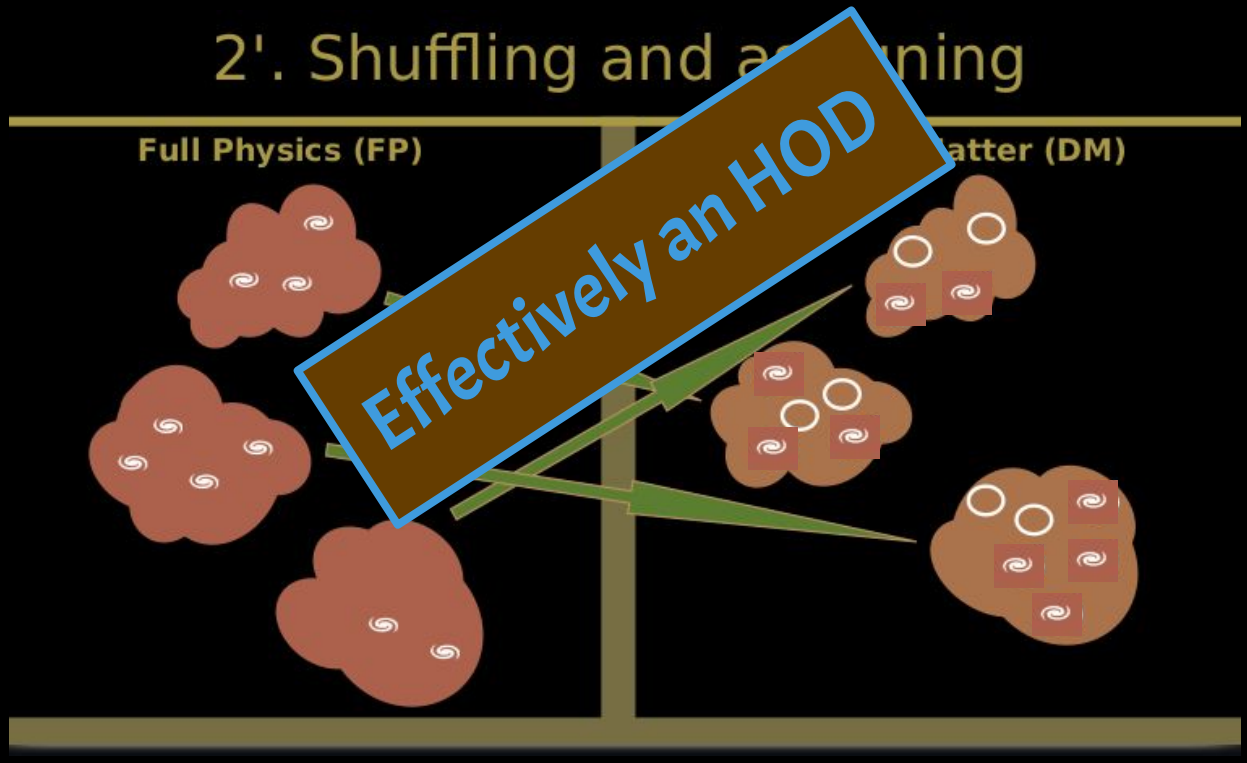
EITHER

Assignment algorithm



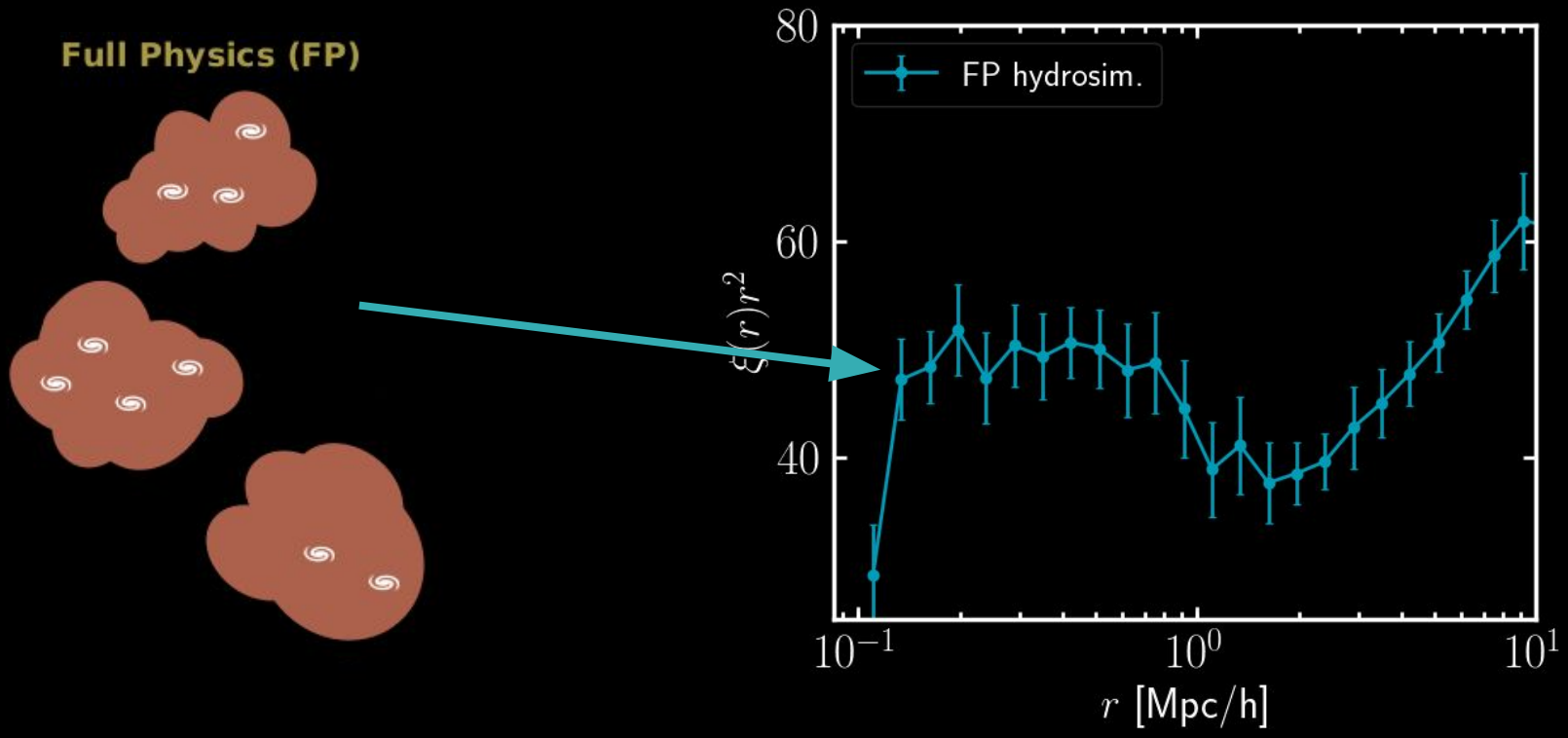
OR

Assignment algorithm



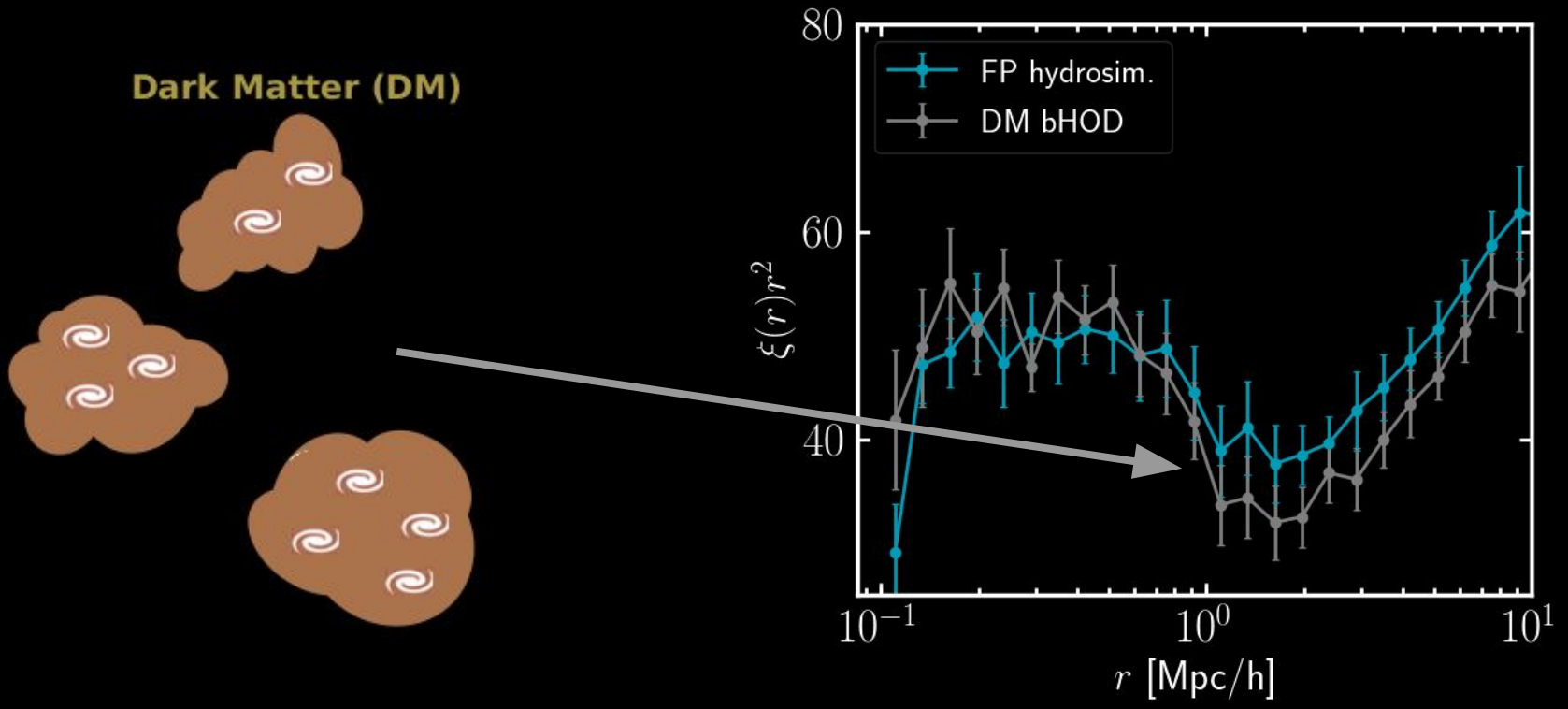
In 5% mass bins

Clustering of galaxies in FP



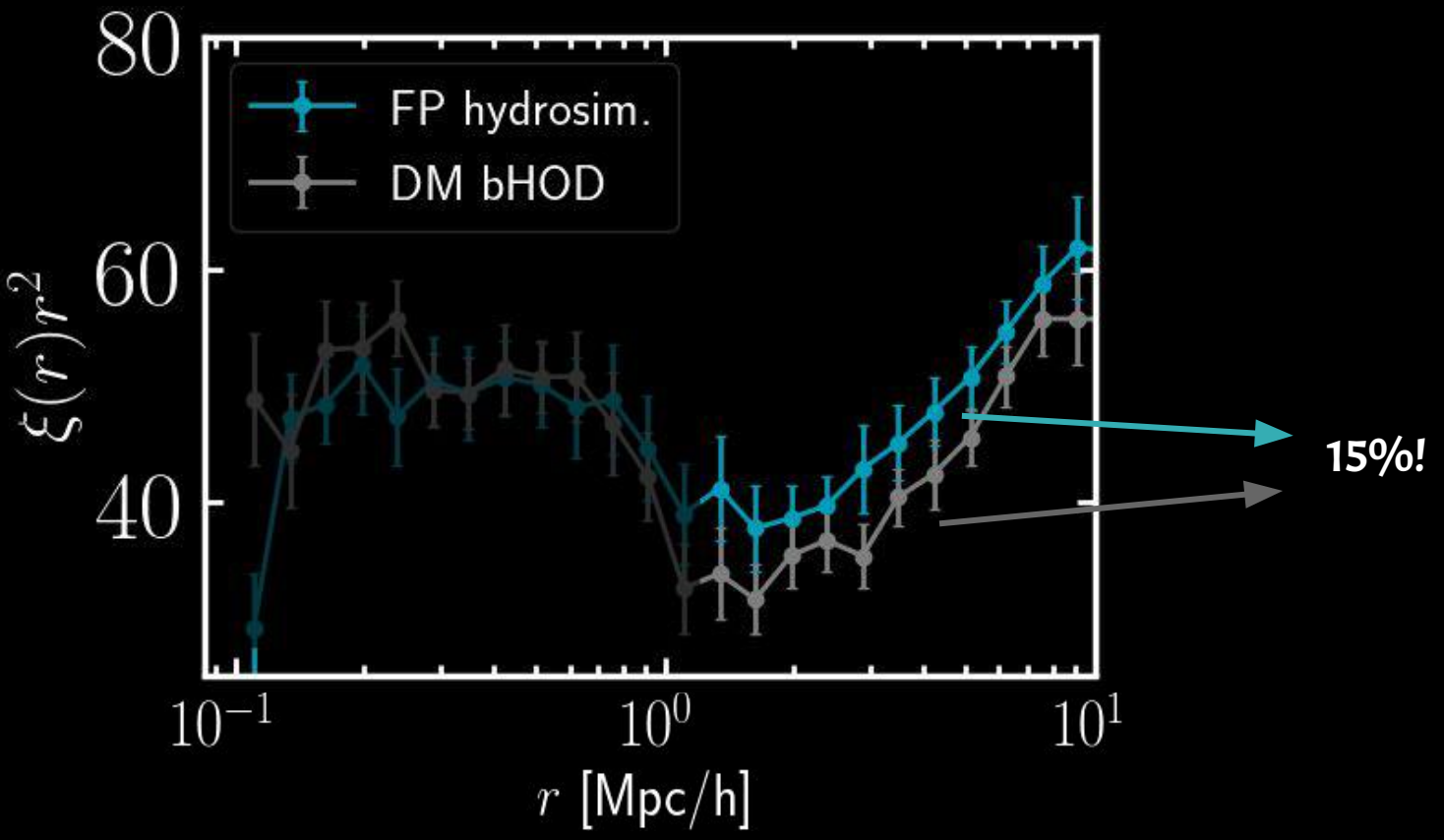
Galaxy correlation function for full-physics

Clustering of galaxies in DM

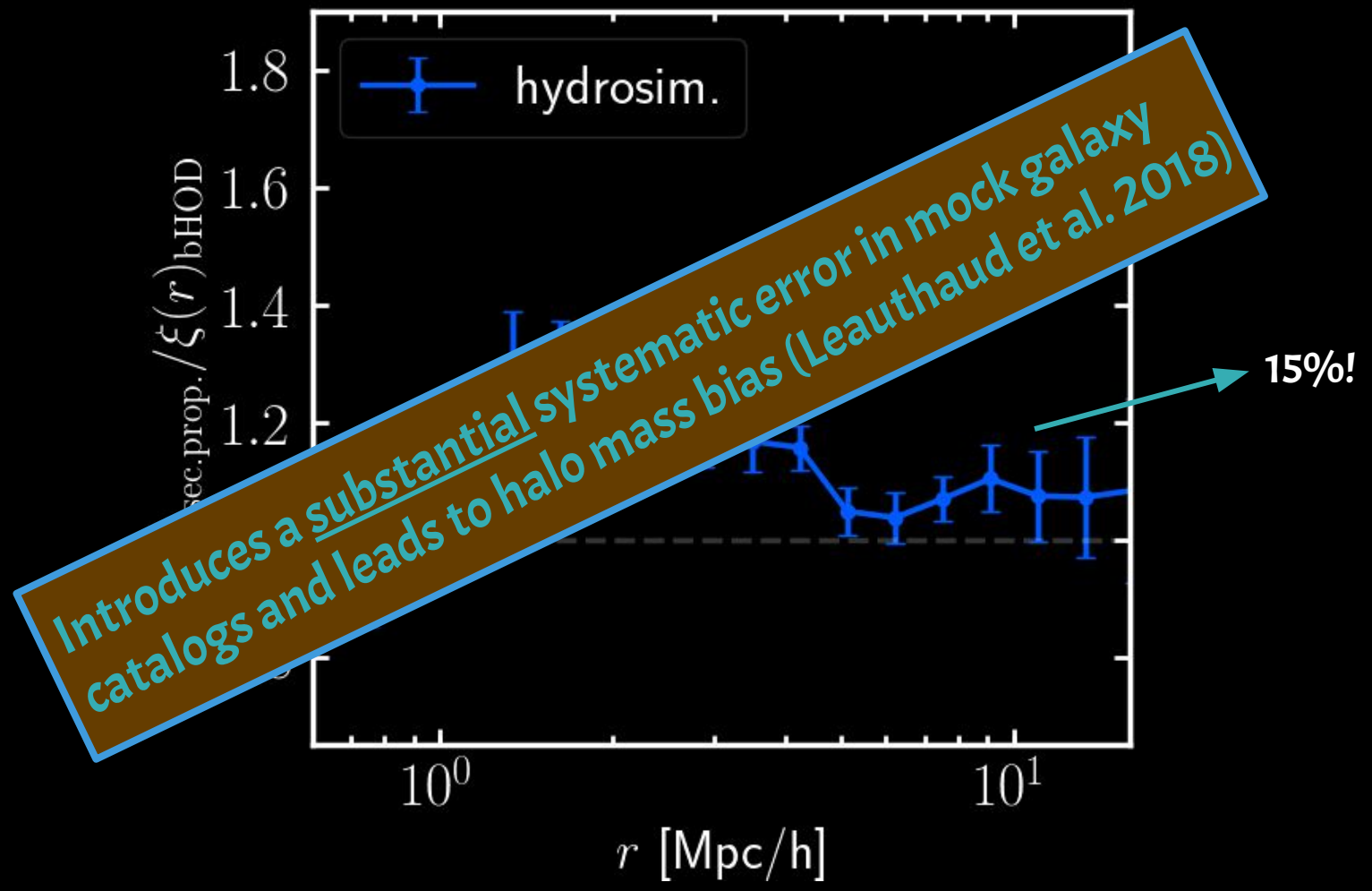


Galaxy correlation function for dark matter

15% discrepancy on large scales



Ratio of TNG to bHOD



What does this mean?

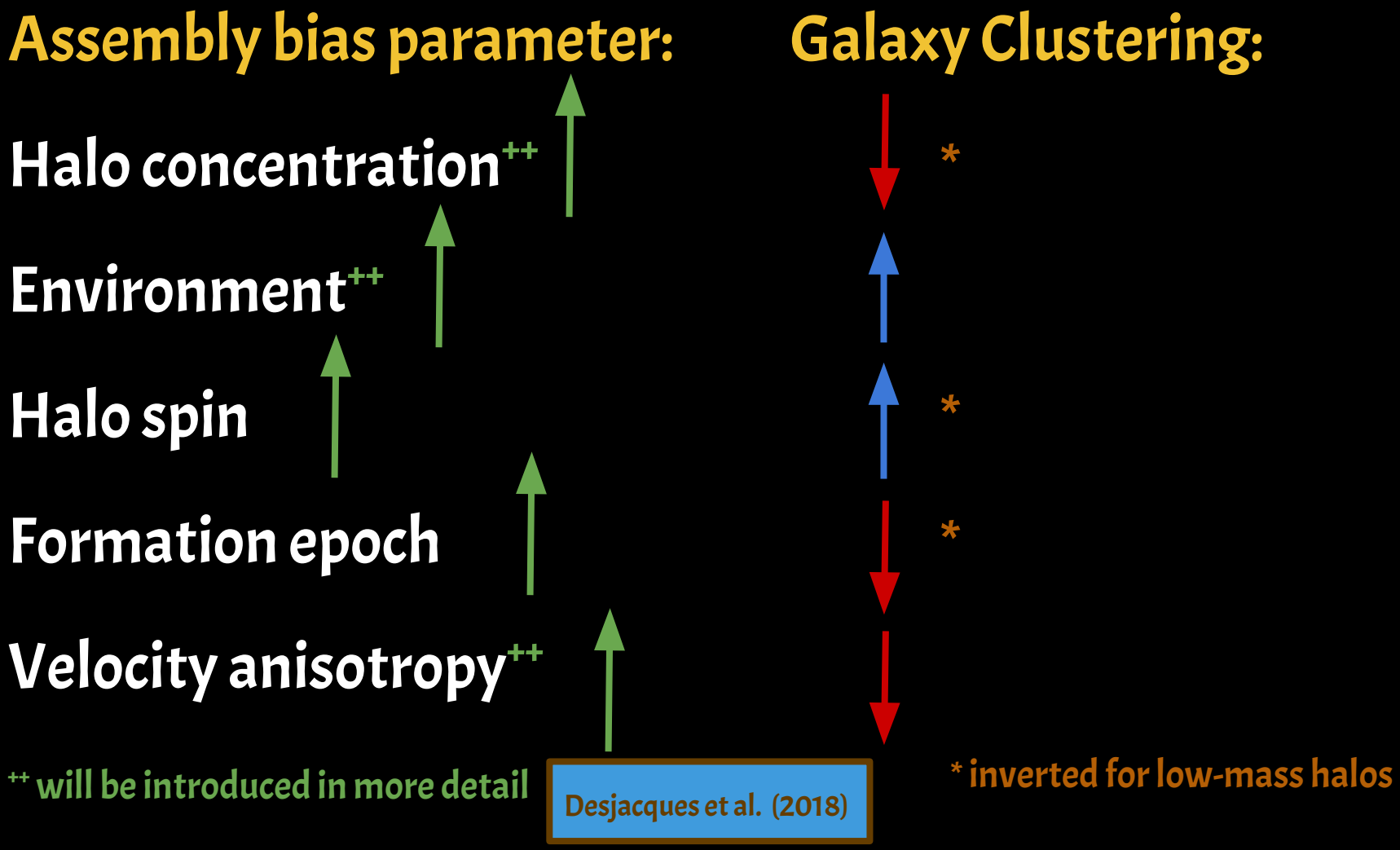
- Introduces a substantial systematic error in mock galaxy catalogs
- Leads to bias in determining halo mass (Leauthaud et al. 2018)
- Better models are needed for future surveys

How robust is this result?

- Choice of mass proxy (M_{200m}, M_{200c}, V_{max}, V_{peak})
- Box size and cosmic variance (ABACUS $L_{box} = 720$ Mpc/h)
- Choice of group finder (Friends-of-Friends vs. ROCKSTAR)

Augmenting the HOD with secondary halo properties

Halo properties at fixed mass



Halo Concentration

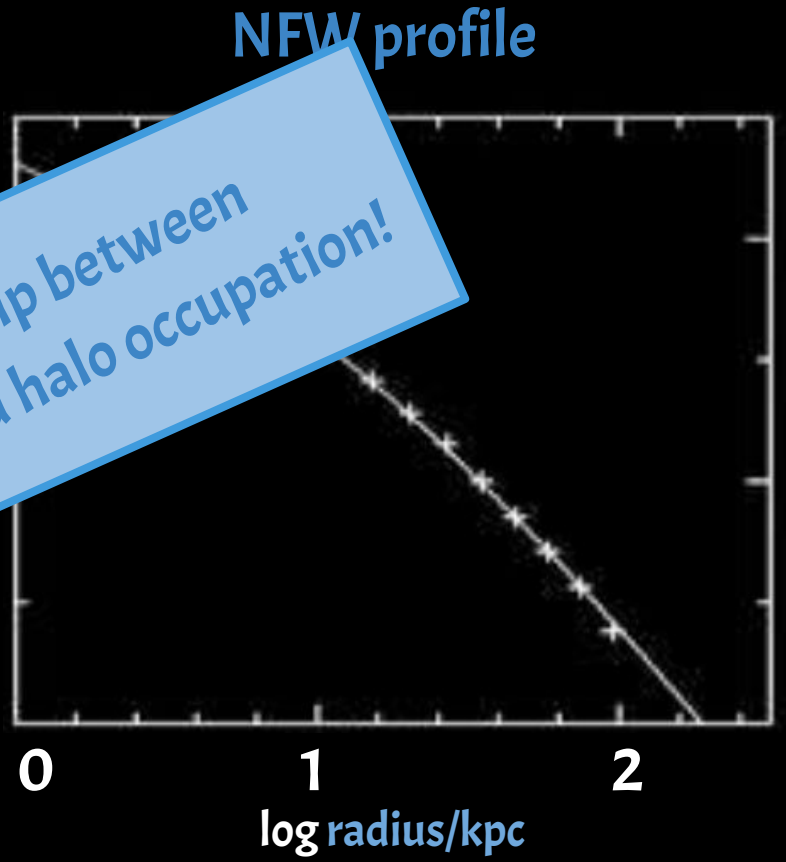
NFW formula:

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})[1 + \ldots}$$

Our concentrati… proxy:

$$c = R_{200c} / R_{\rm max}$$

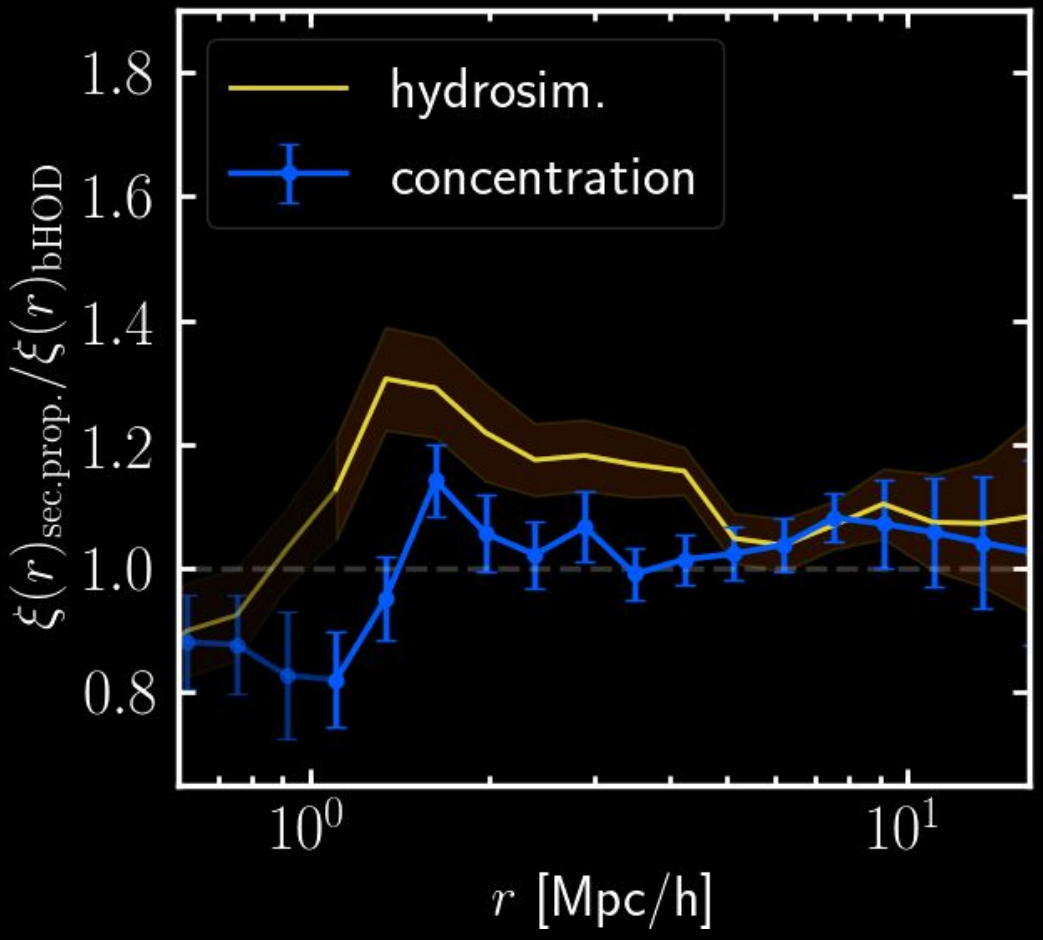
Inverted relationship between concentration and halo occupation!



Navarro, Frenk & White (1996)

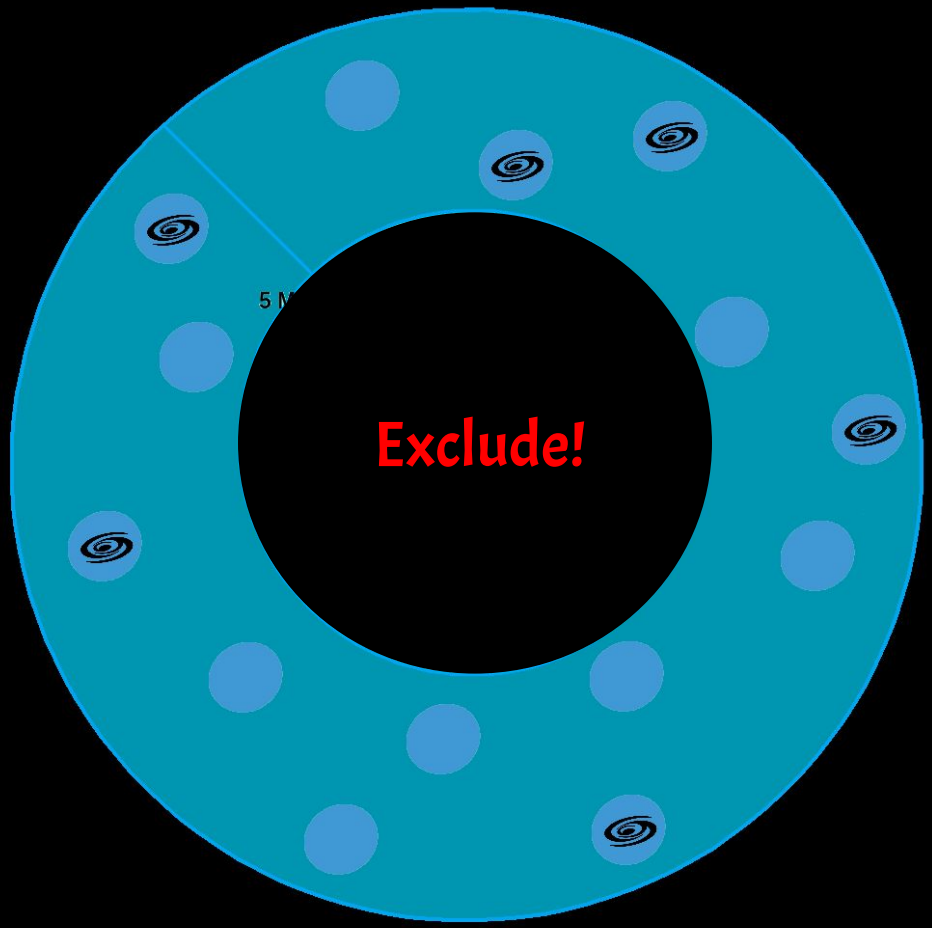
Rank-order *c* within each 5% mass bin in reverse

Halo Concentration



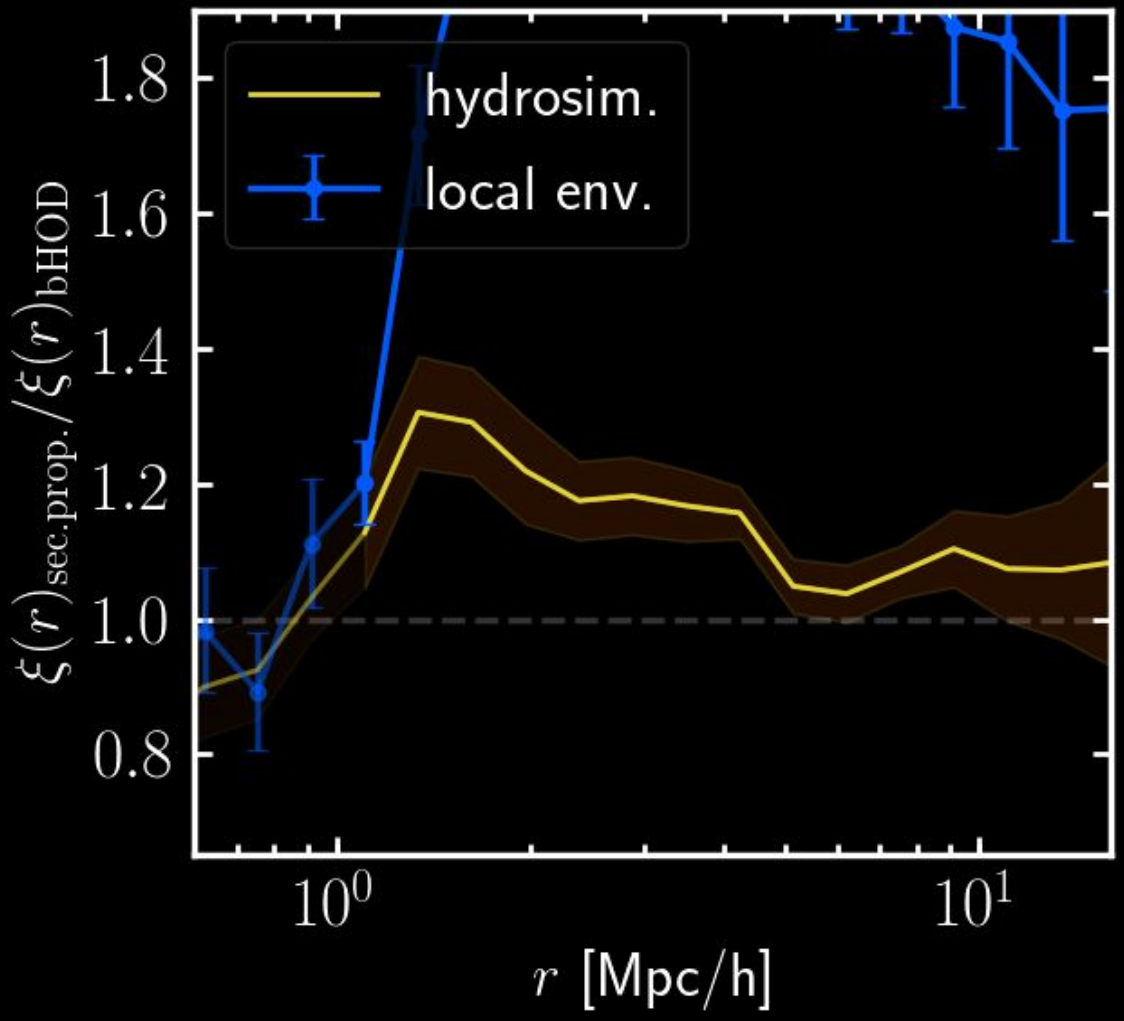
Environment (f_{env})

For each halo...



Rank-order f_{env} within each 5% mass bin

Environment ($f_{\rm env}$)



Velocity Anisotropy (β)

$$\beta = 1 - \frac{\sigma_{\tan}^2}{2\sigma_{\mathrm{rad}}^2}$$

$-\infty < \beta < 1$

$\beta = 0$, isotropic distribution

$\beta > 0$, radially dominated

$\beta < 0$, tangentially dominated

More clustered galaxies (mergers)

↓

large impact parameters

(deflections caused by gravity)

↓

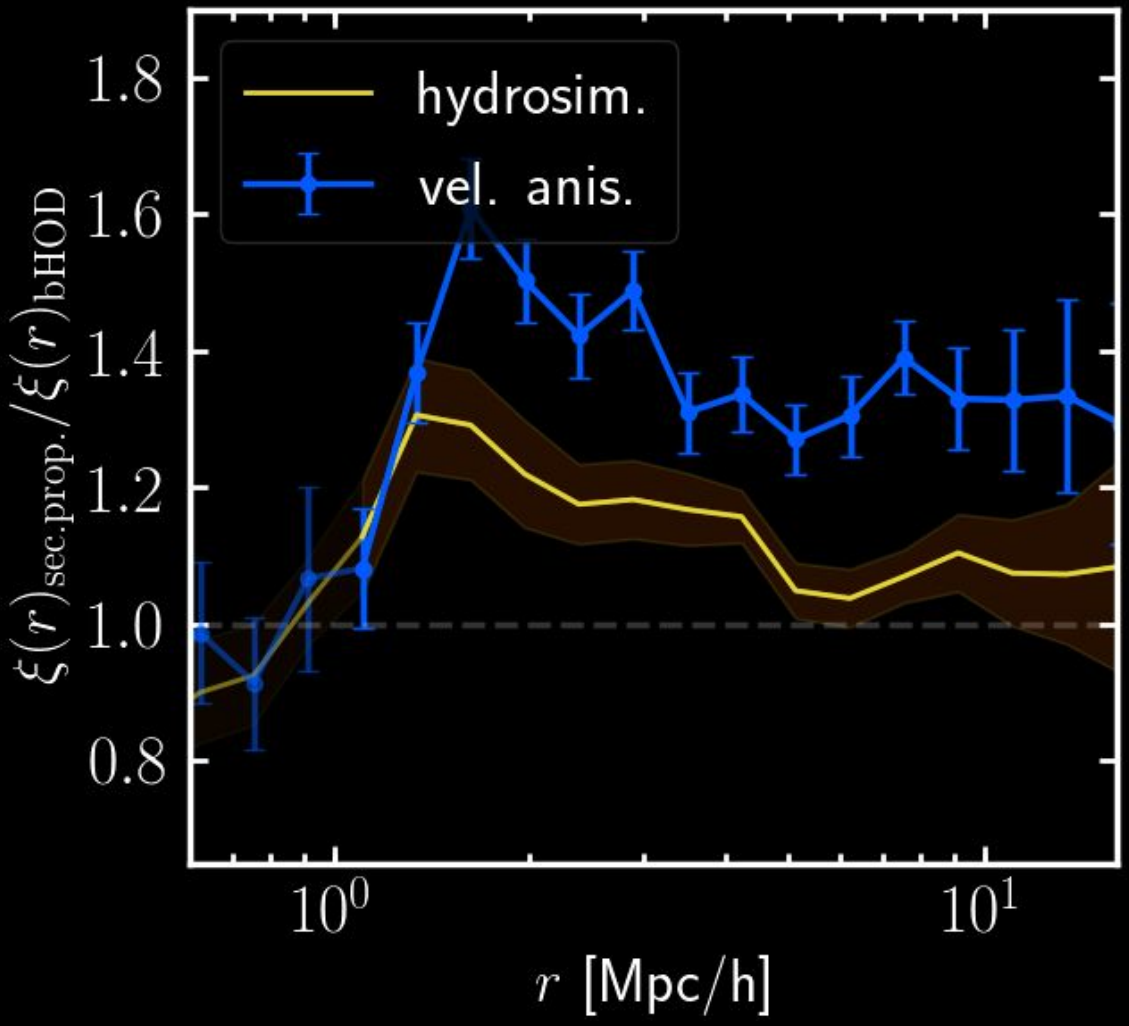
large $\sigma_{\tan}$

↓

smaller β

Rank-order β within each 5% mass bin in reverse

Velocity Anisotropy (β)



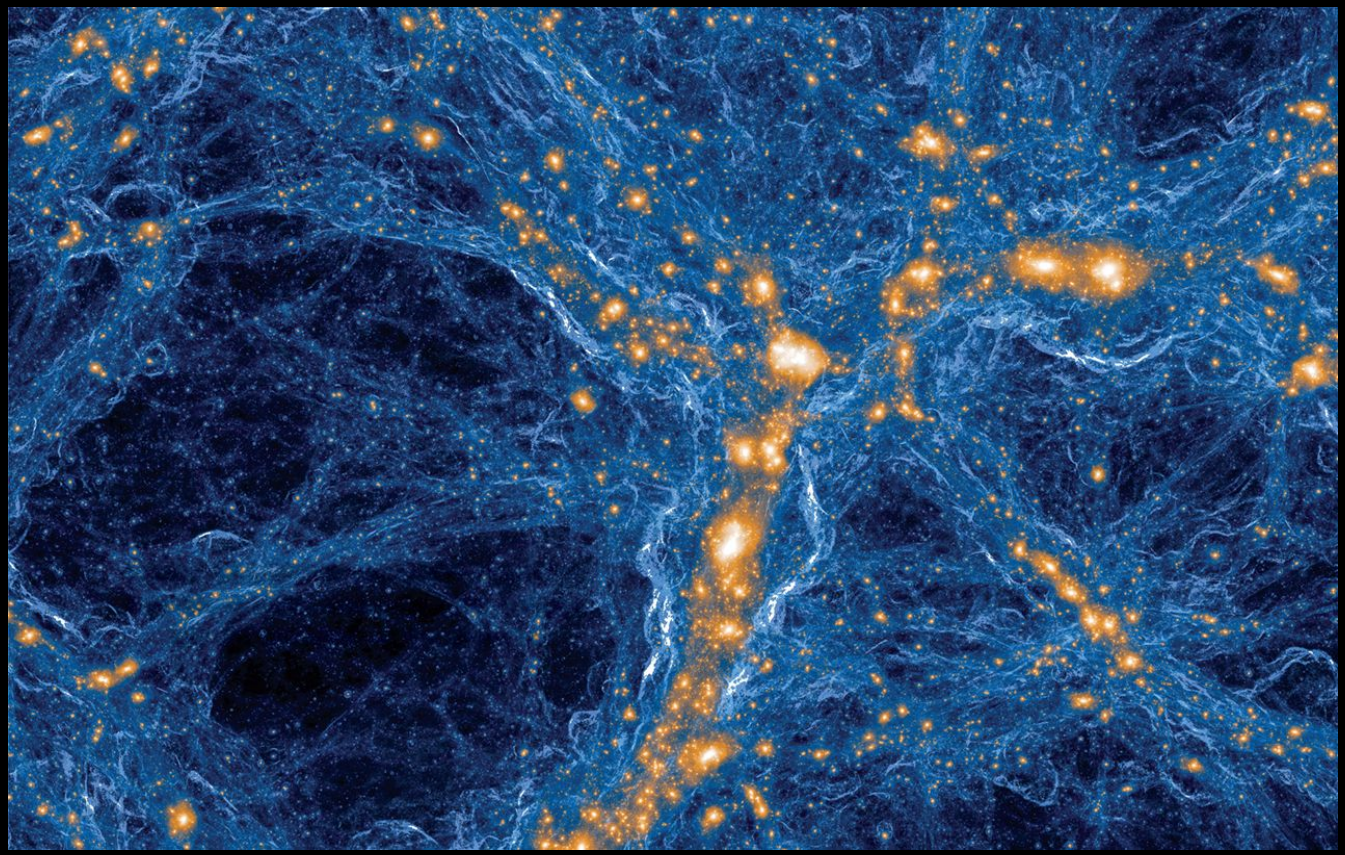
All secondary parameters

Secondary property	Difference from bHOD
hydrosimulation	15 ± 1%
local environment	98.6%
$\sigma^2 R_{\rm halfmass}$	35.4%
velocity anisotropy	35.8%
dispersion velocity	17.9%
$M_{\rm cent}/R_{\rm halfmass}$	6.1%
halo concentration	2.7%
halo spin	2.0%
formation epoch	0.6%

Focusing on Environment

Cosmic Web and Density Cuts

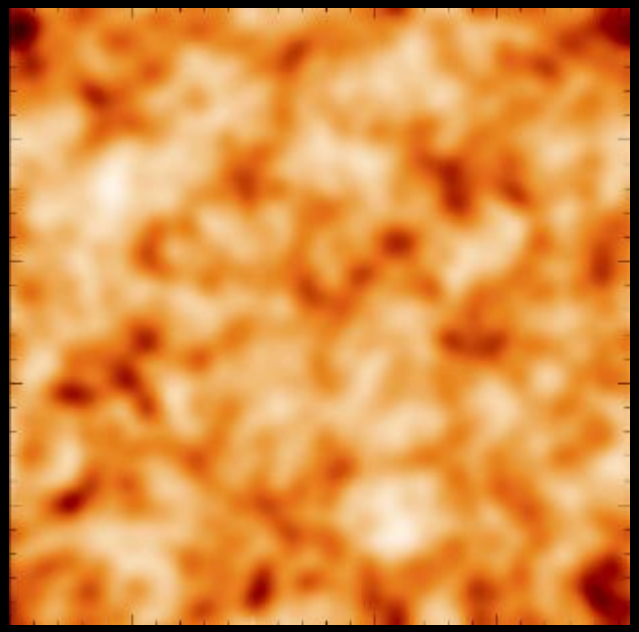
Cosmic Web



IllustrisTNG (2017)

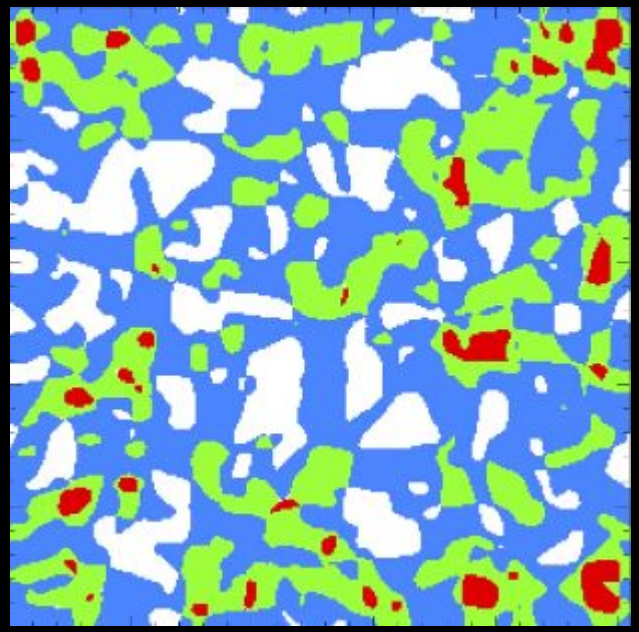
Cosmic Web

Dark Matter Density



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

DM Cosmic Web

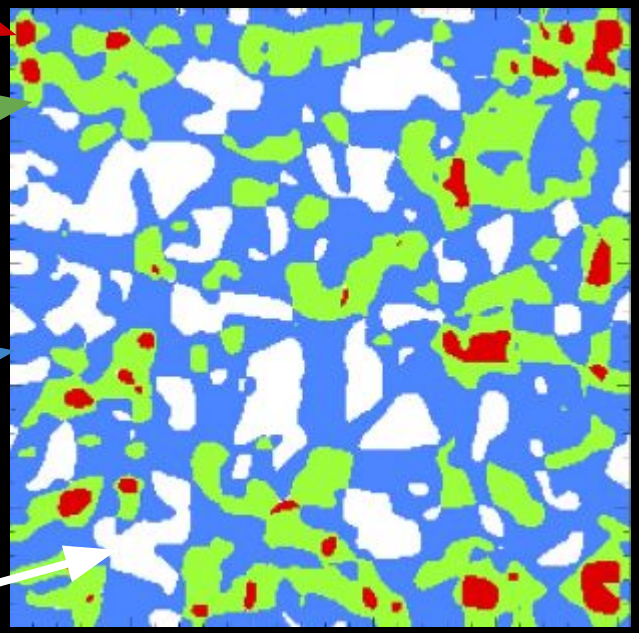


J. Bond & S. Myers (1996)

Cosmic Web

- Peaks
- Filaments
- Sheets
- Voids

DM Cosmic Web



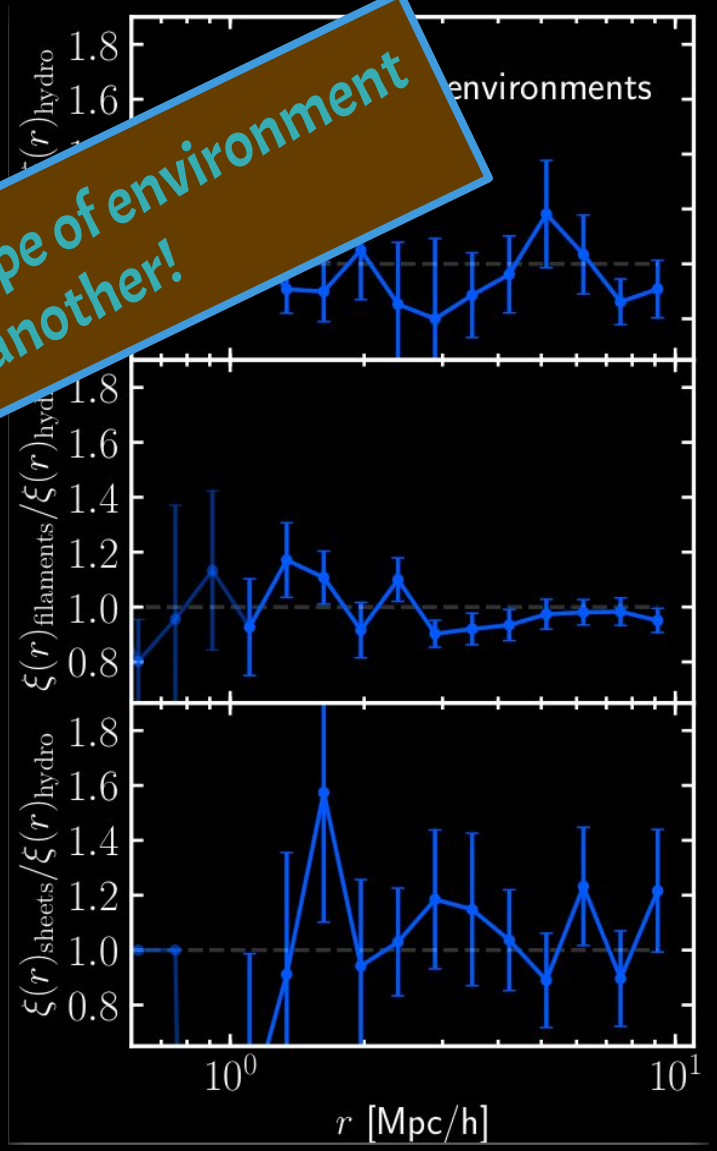
Cosmic Web

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!



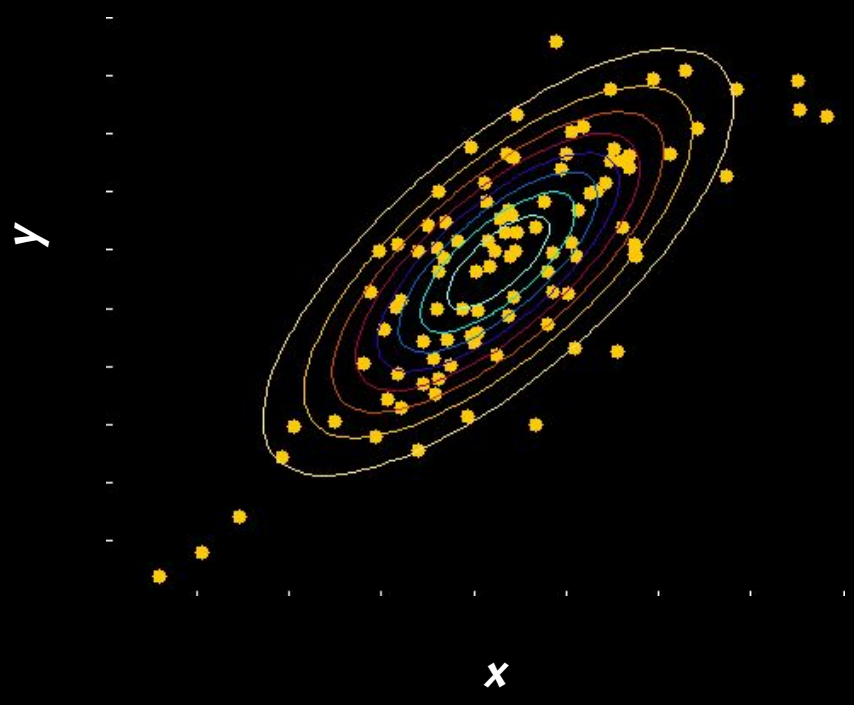
How do we construct new models?

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 $0 < r < 1$



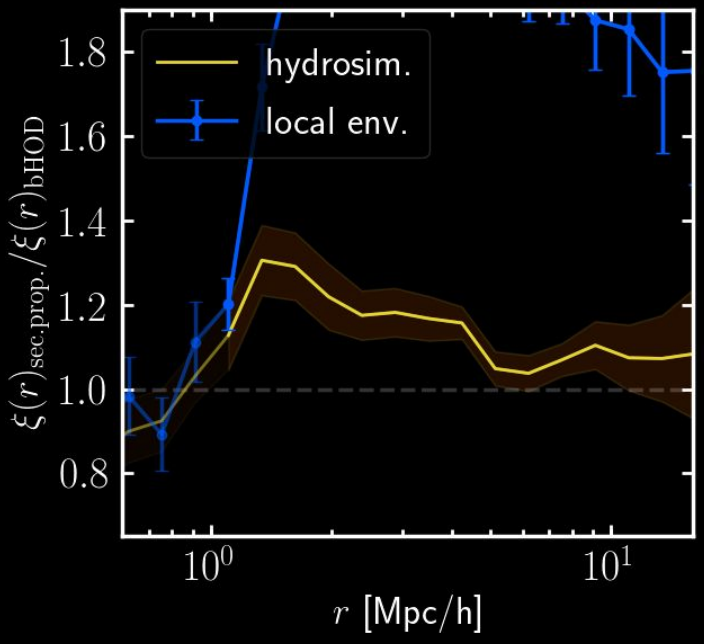
2. Convert (x, y) into integers (i,j)

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

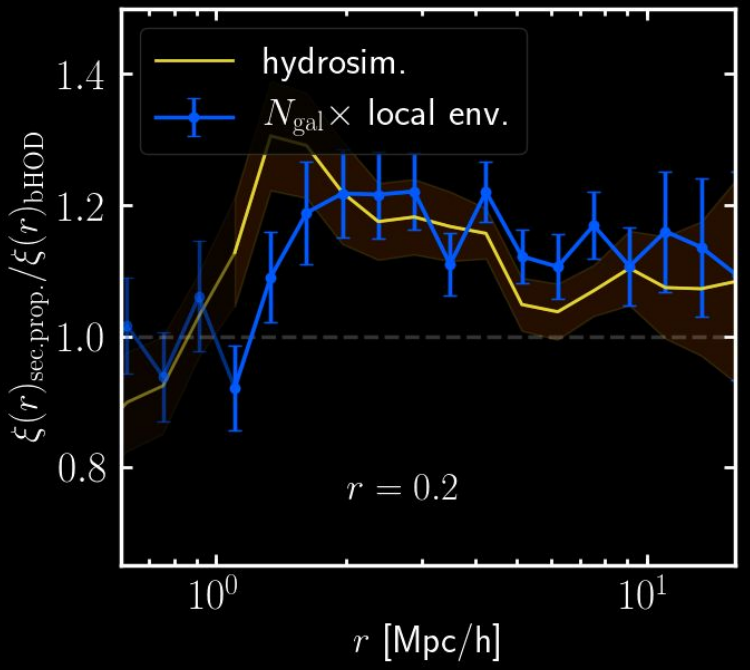
4. Apply (i,j) pairing to obtain corresponding (N_{gal}, f_{env})

An imperfect correlation for f_{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...

ARXIV:1911.02610

Episode I

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 [arXiv:1911.02610]

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

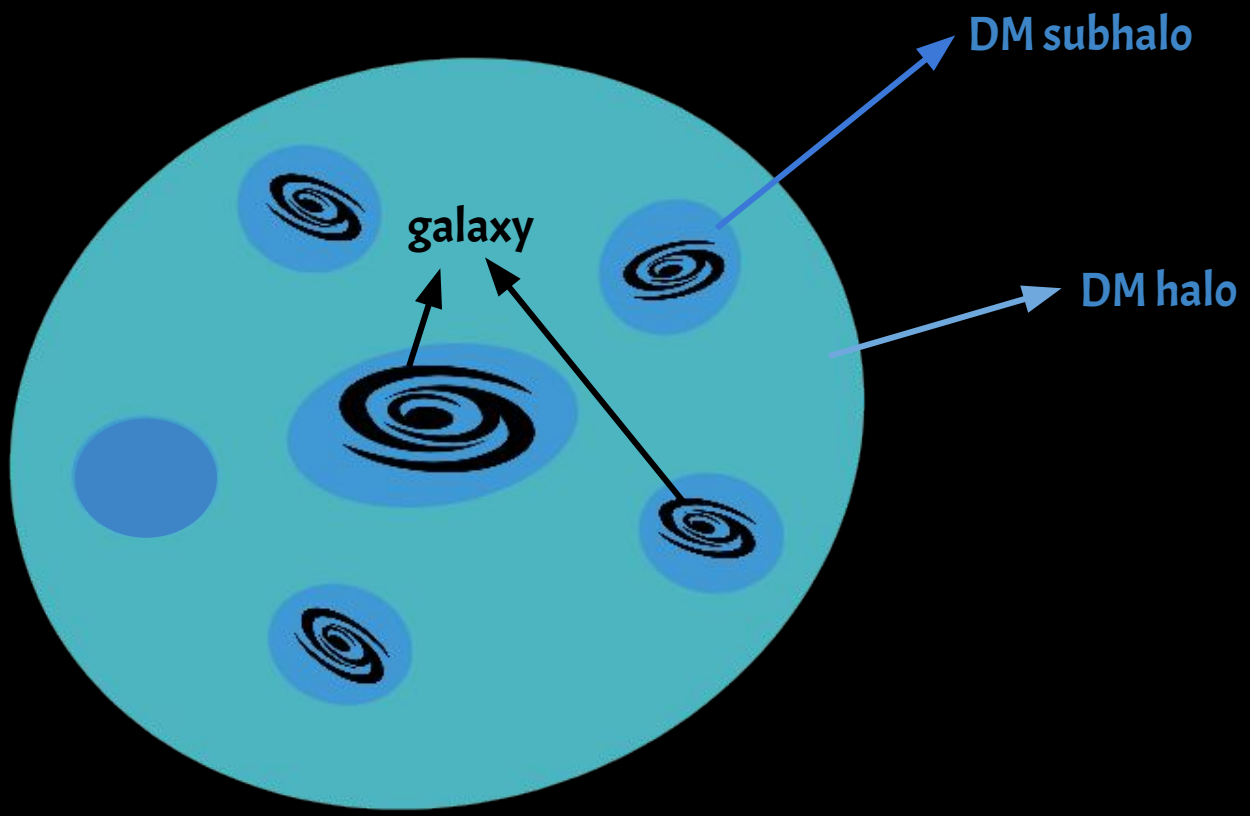
Episode I

The HOD Menace

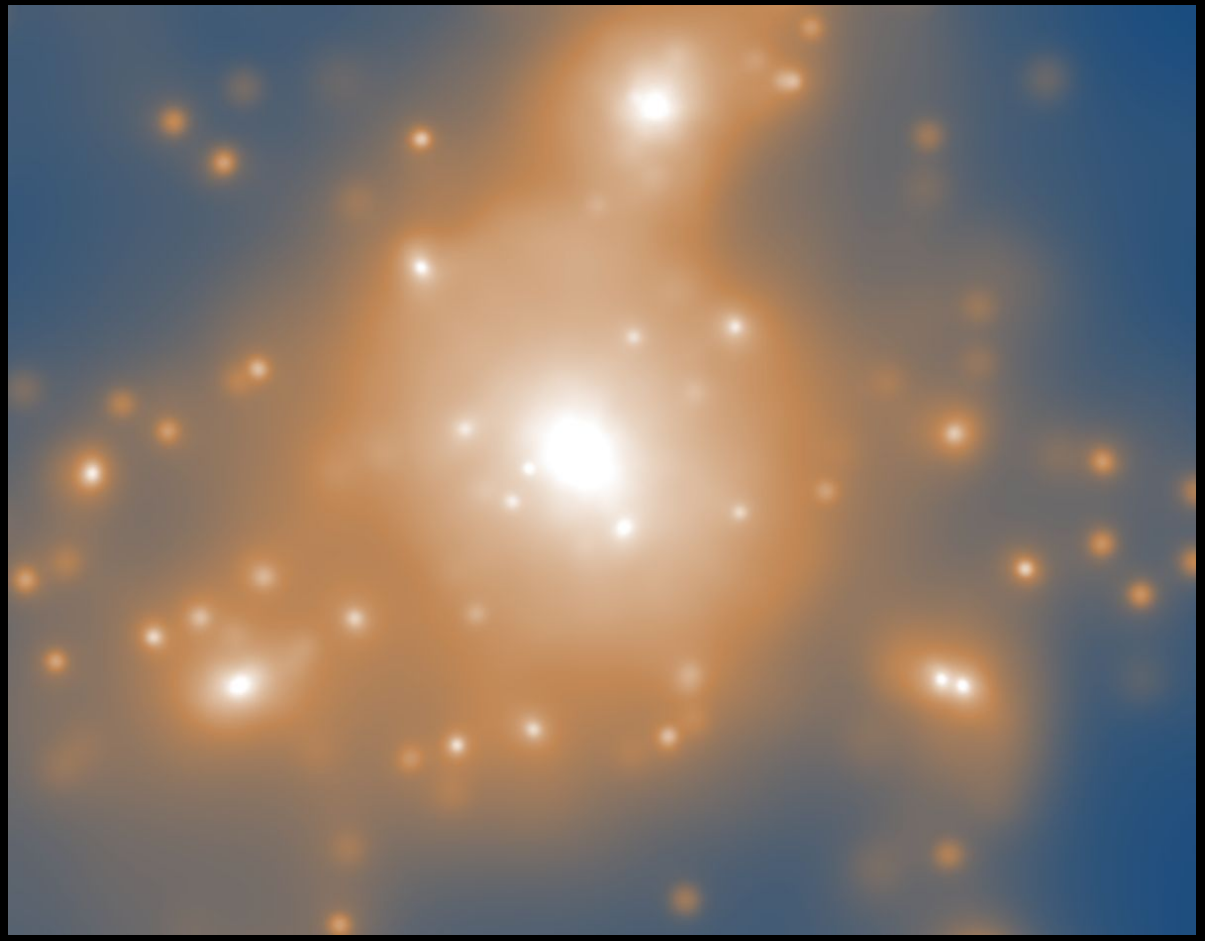
Thank you for the excellent guidance!

Looking forward to exploring more exciting ideas.

Relationship with Galaxies



Dark Matter vs. Stellar Light

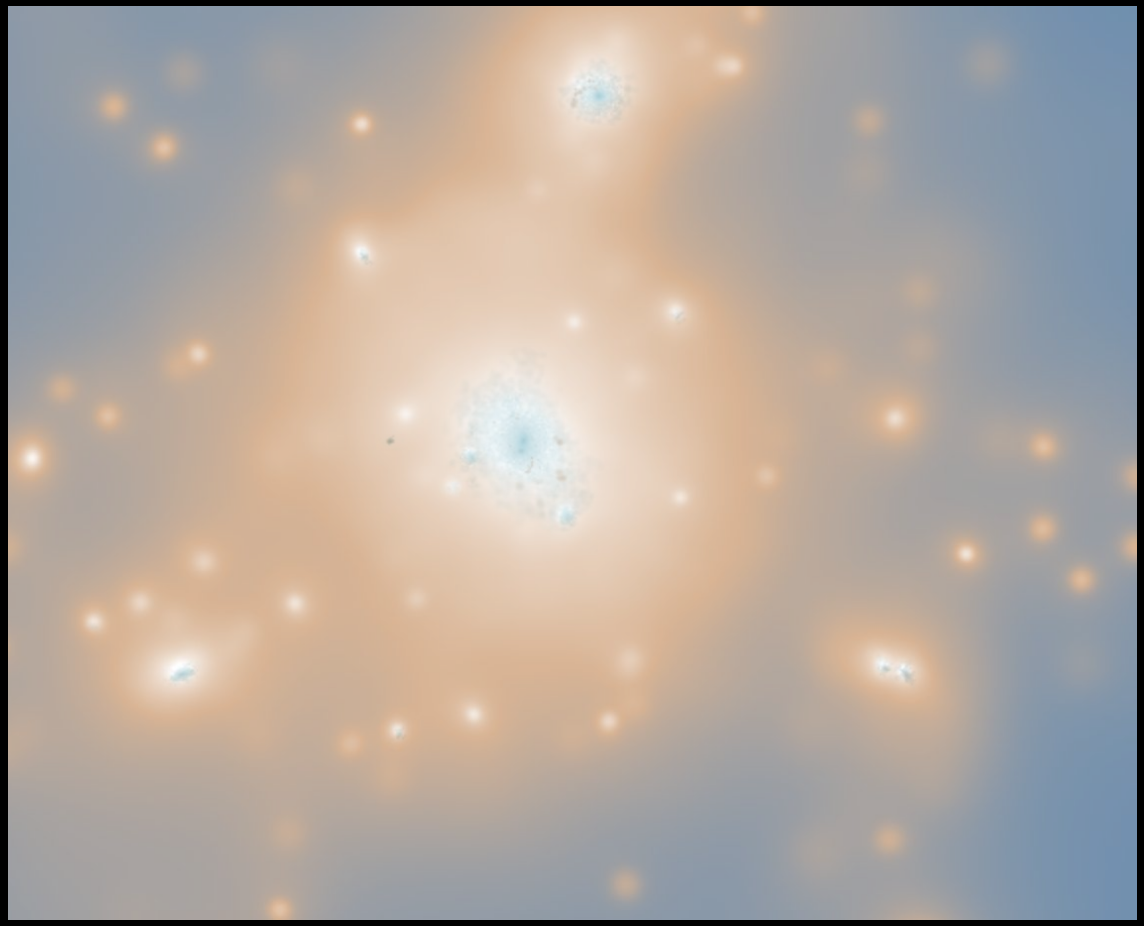


IllustrisTNG (2017)

Dark Matter vs. Stellar Light

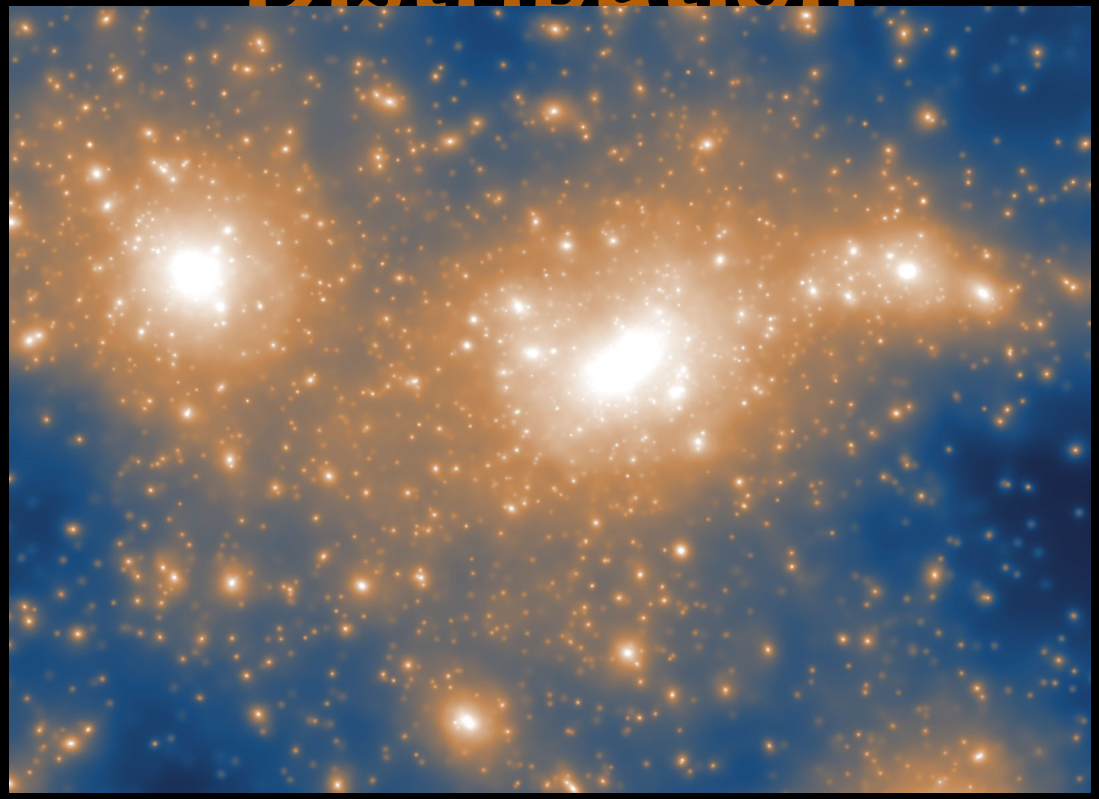
IllustrisTNG (2017)

Dark Matter vs. Stellar Light



IllustrisTNG (2017)

Darth Matter vs. Stellar Distribution

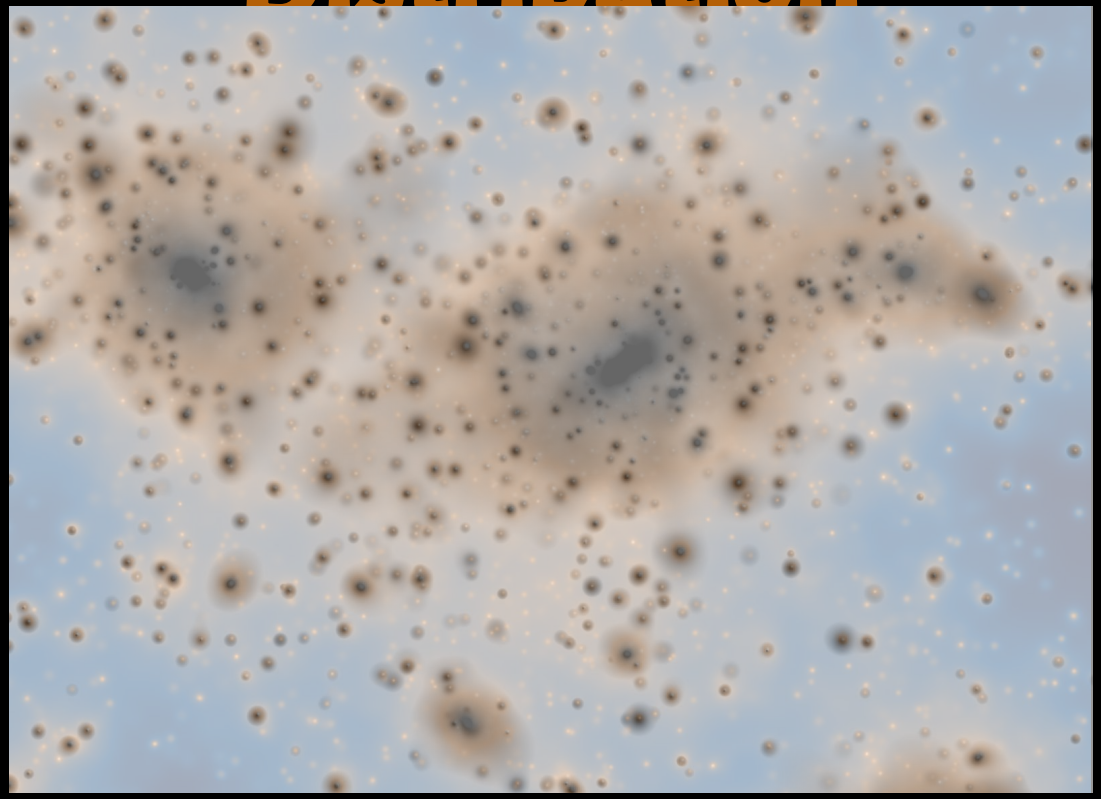


IllustrisTNG (2017)

Darth Matter vs. Stellar Distribution

IllustrisTNG (2017)

Darth Matter vs. Stellar Distribution



IllustrisTNG (2017)

How is the cosmic web related to galaxies?