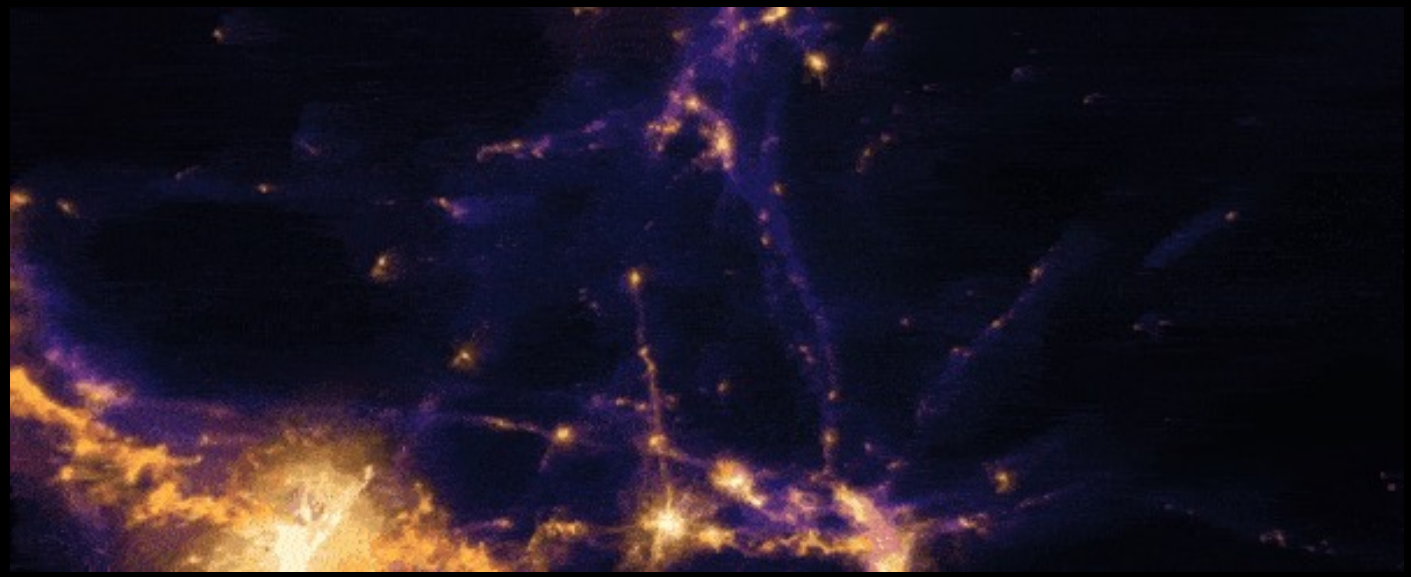
Forward modeling in the era of cosmological surveys



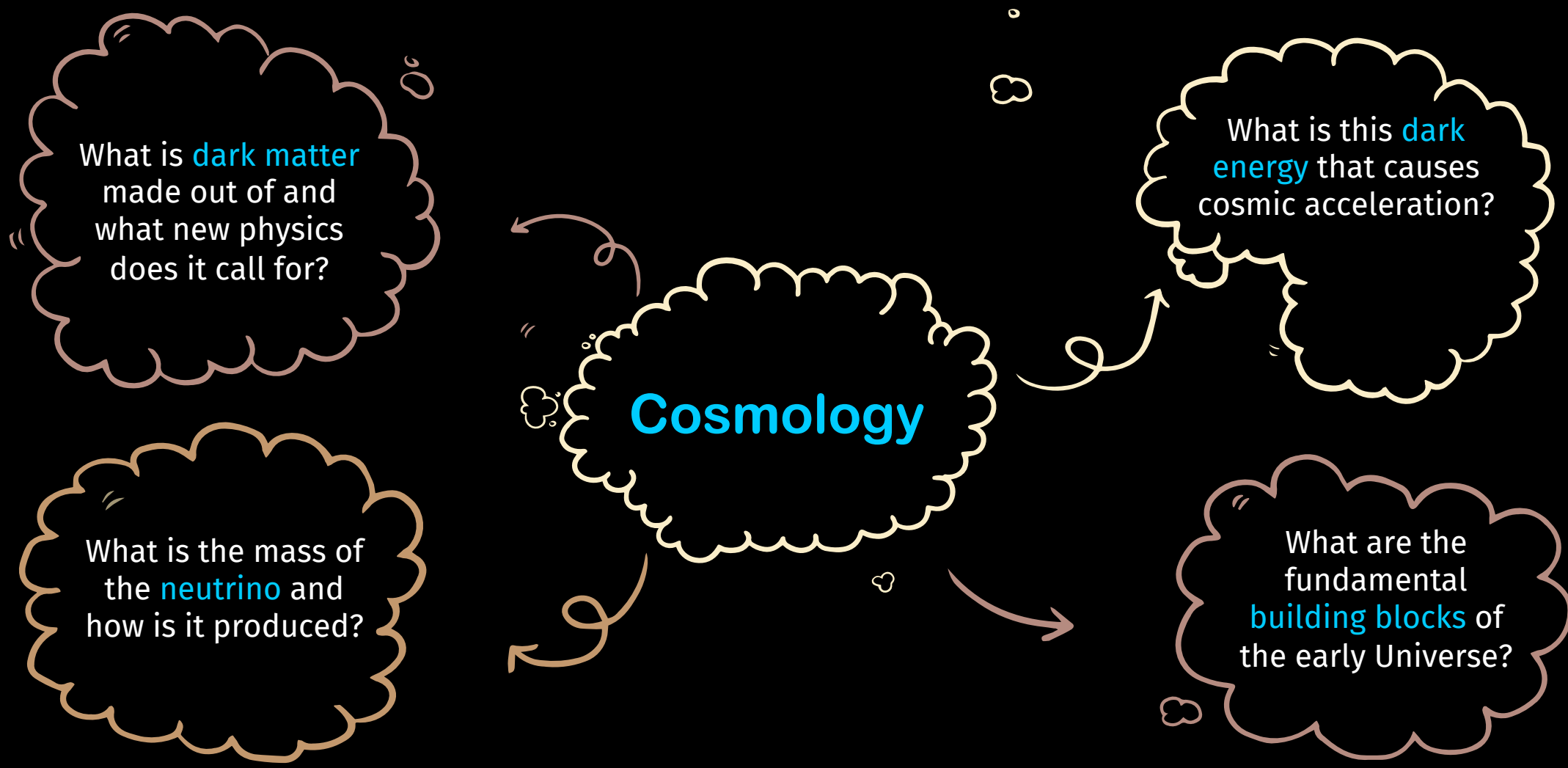
Boryana Hadzhiyska, PhD Candidate

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

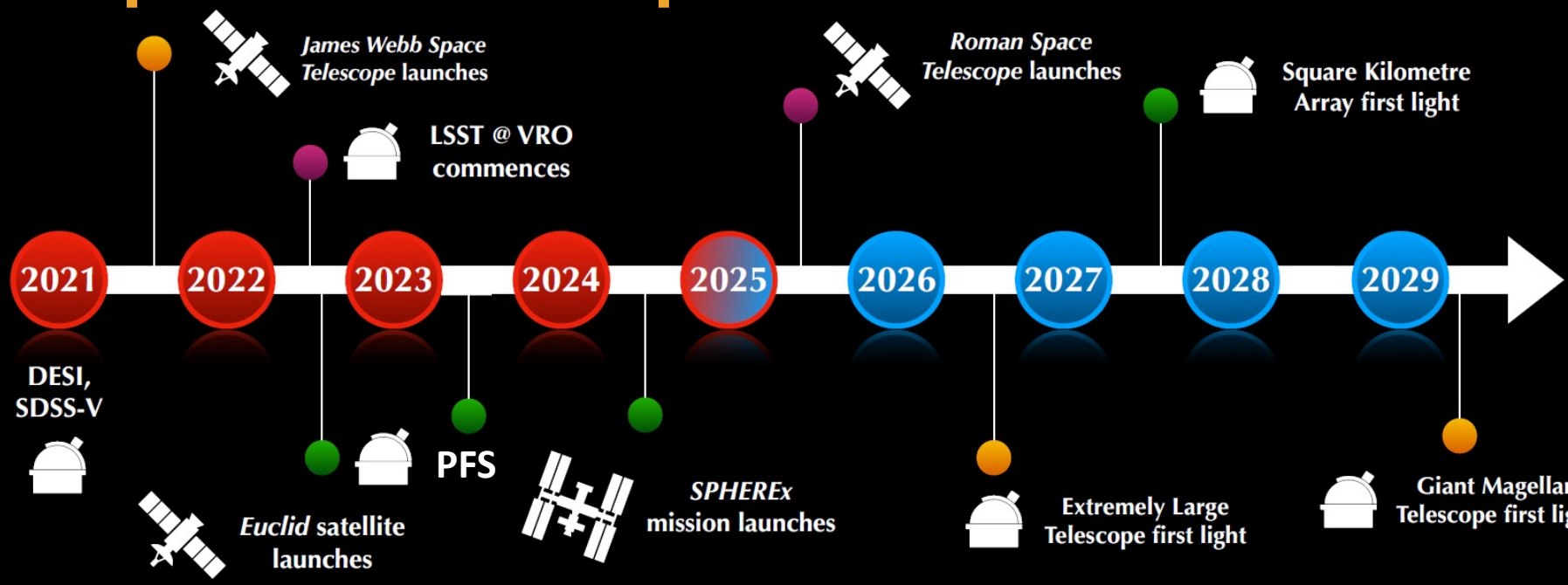
Kavli IPMU, Tokyo

11/15/2021

Large-scale structure holds the key to some of nature's greatest enigmas

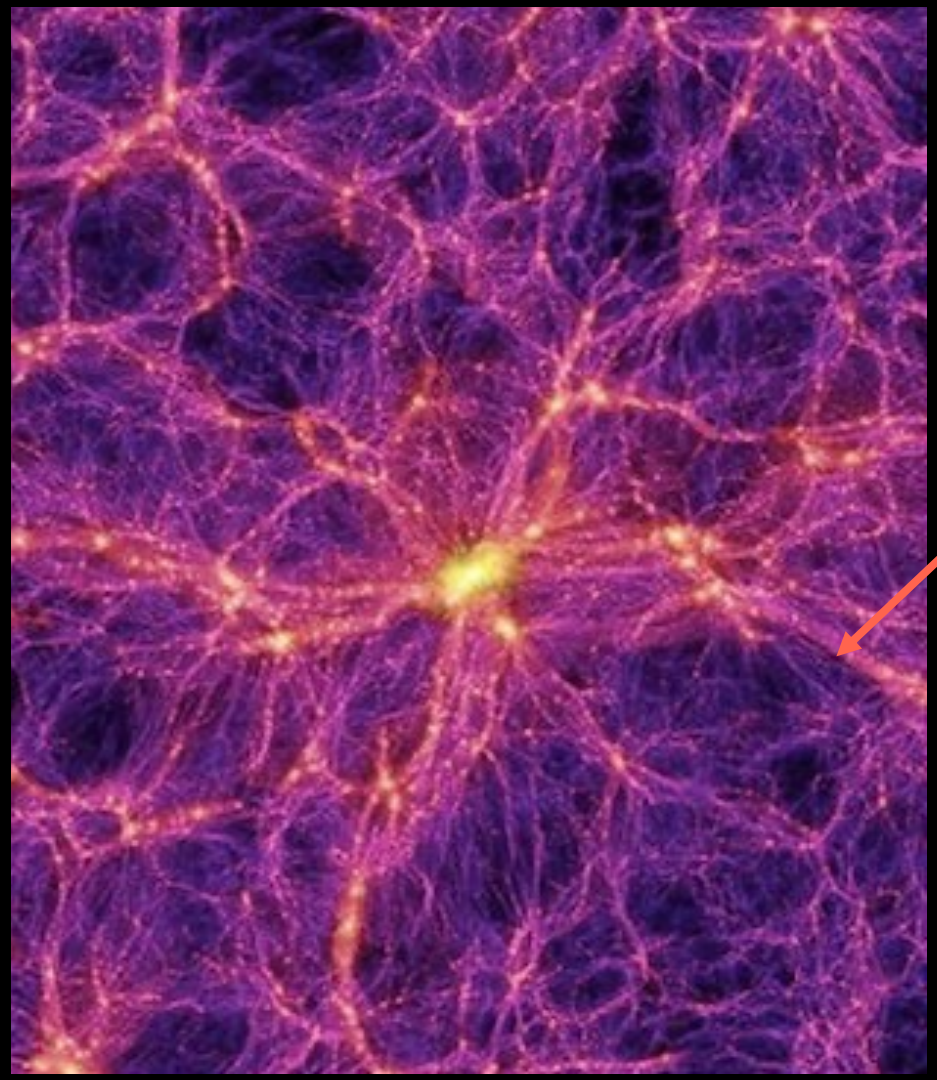


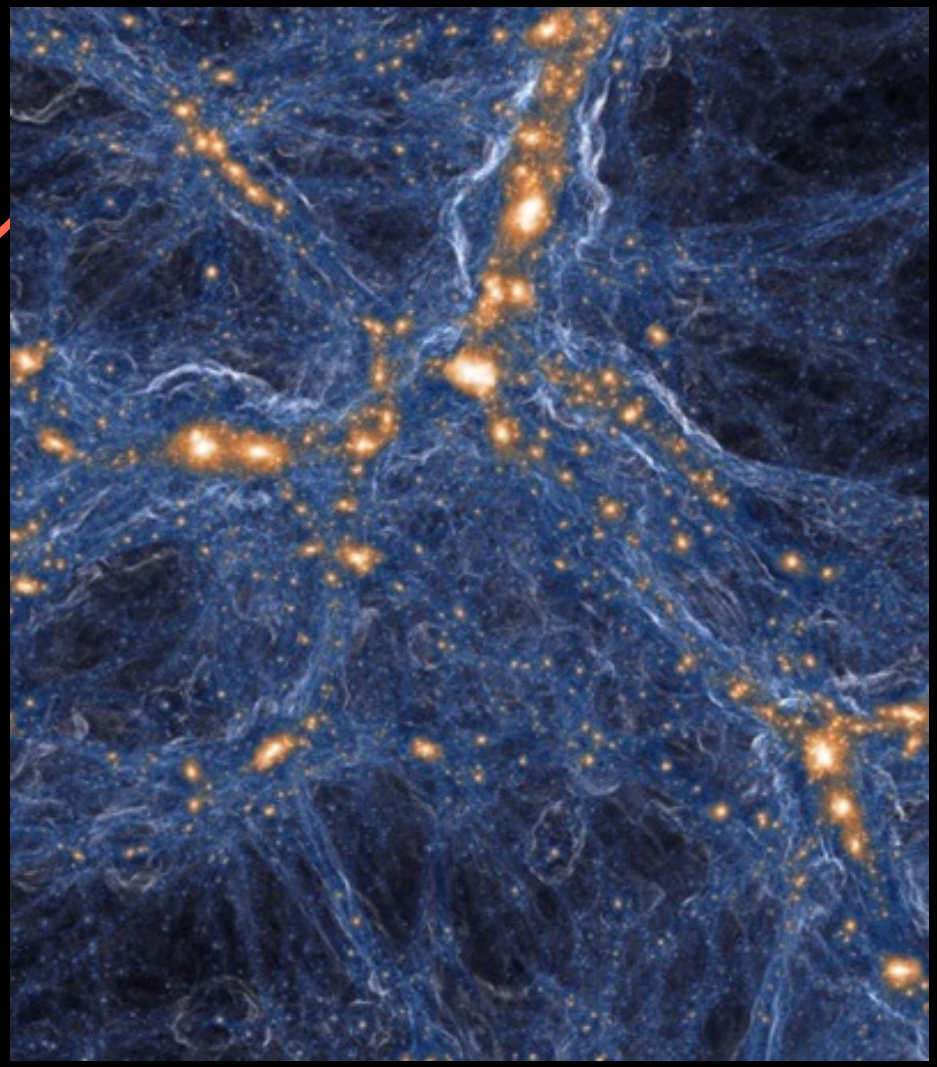
The duration of my postdoc



Timeline of major cosmological surveys in the next decade.

Types of cosmological simulations





My collaborators

Galaxy-halo connection:

- Lars Hernquist (CfA)
- Sownak Bose (CfA, Durham)
- Sihan Yuan (CfA, Stanford)
- Rachel Somerville (CCA)
- Jay Wadekar (IAS)

Hadzhiyska+ (2019b), MNRAS.493.5506H
Hadzhiyska+ (2020b), MNRAS.501.1603H
Yuan, Hadzhiyska+ (2020), MNRAS.502.3582Y
Hadzhiyska+ (2020c), MNRAS.502.3599H
Hadzhiyska+ (2021b), MNRAS.508..698H

Abacus *N*-body simulation:

- Daniel Eisenstein (CfA)
- Lehman Garrison (CfA, CCA)
- Nina Maksimova (CfA)

Hadzhiyska+ (2021a, MNRAS.tmp.2718H)
Hadzhiyska+ (2021b, MNRAS.tmp)
Maksimova+ (2021), MNRAS.tmp.2270M
Bose+ (2021, MNRAS.tmp)
Yuan+ (2021, MNRAS.tmp)

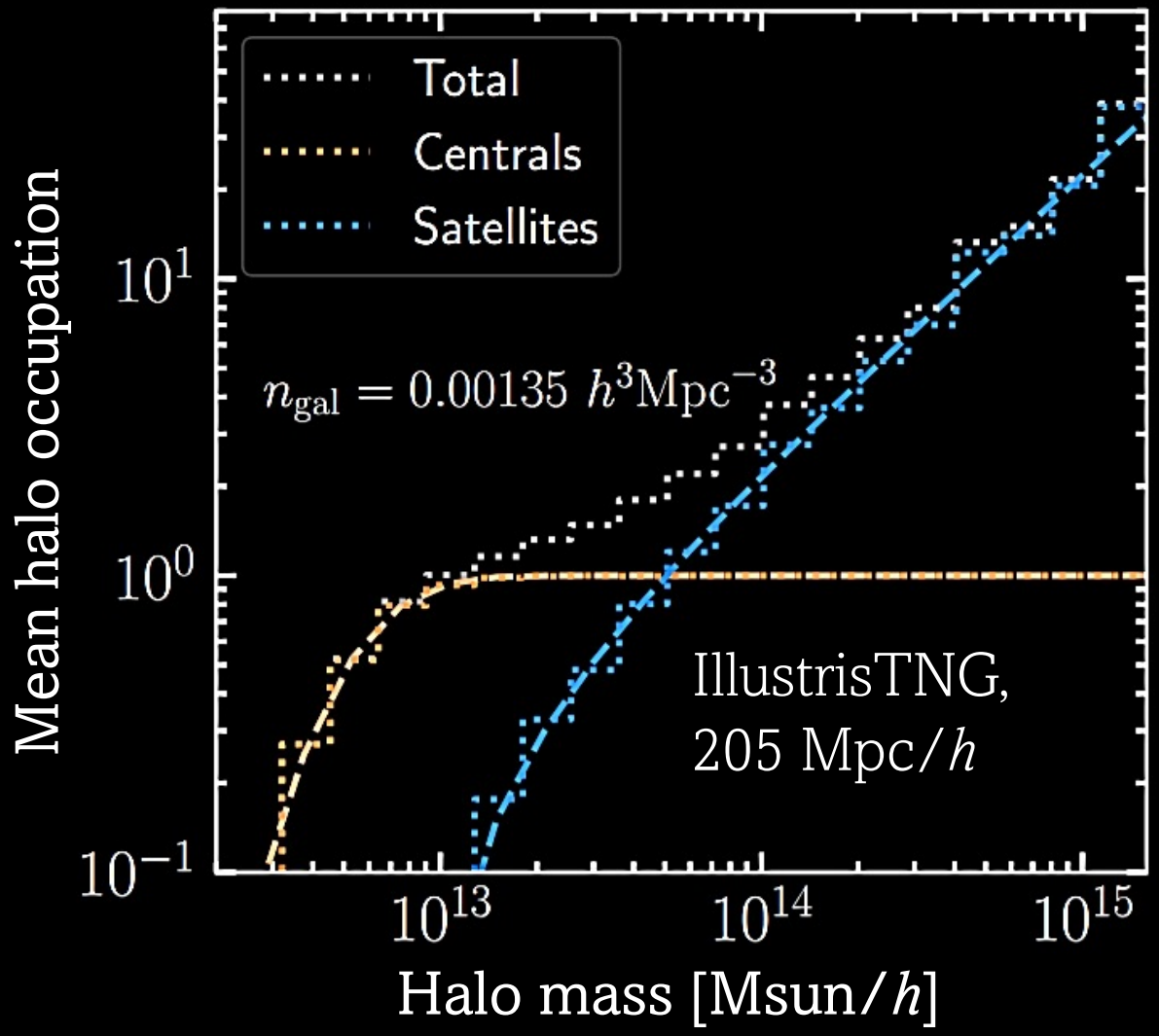
Analytic approaches (e.g., bias expansion, CMB):

- David Alonso (Oxford)
- Carlos García-García (Oxford)
- Andrina Nicola (Princeton, Washington University)
- Anže Slosar (Brookhaven National Lab)
- Blake Sherwin (Cambridge)

Hadzhiyska+ (2020a), JCAP...10..056H
Hadzhiyska+ (2021a), JCAP...09..020H
Hadzhiyska+ (2019a), PhRvD.100b3547H
Karim+ (2021, in prep.)

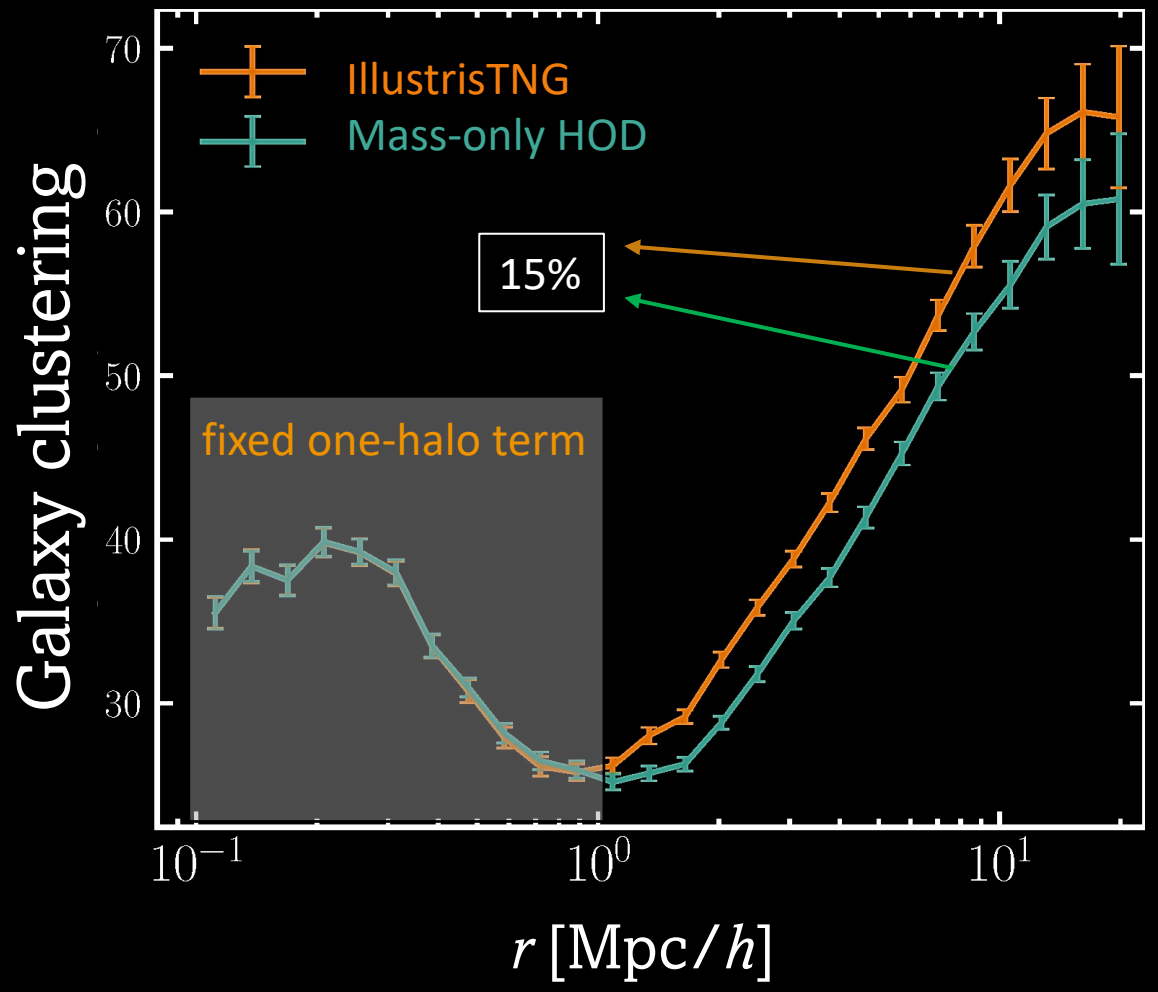
Why care about the galaxy-halo connection?

Halo occupation distribution (HOD)



- **HOD theory:** The properties of galaxies are dictated by the properties of the dark-matter halo they reside in.
- **Mass-only HOD:** simplest and most widely used; assumes halo mass alone predicts galaxy occupancy
- **Luminous red galaxies** (LRGs)

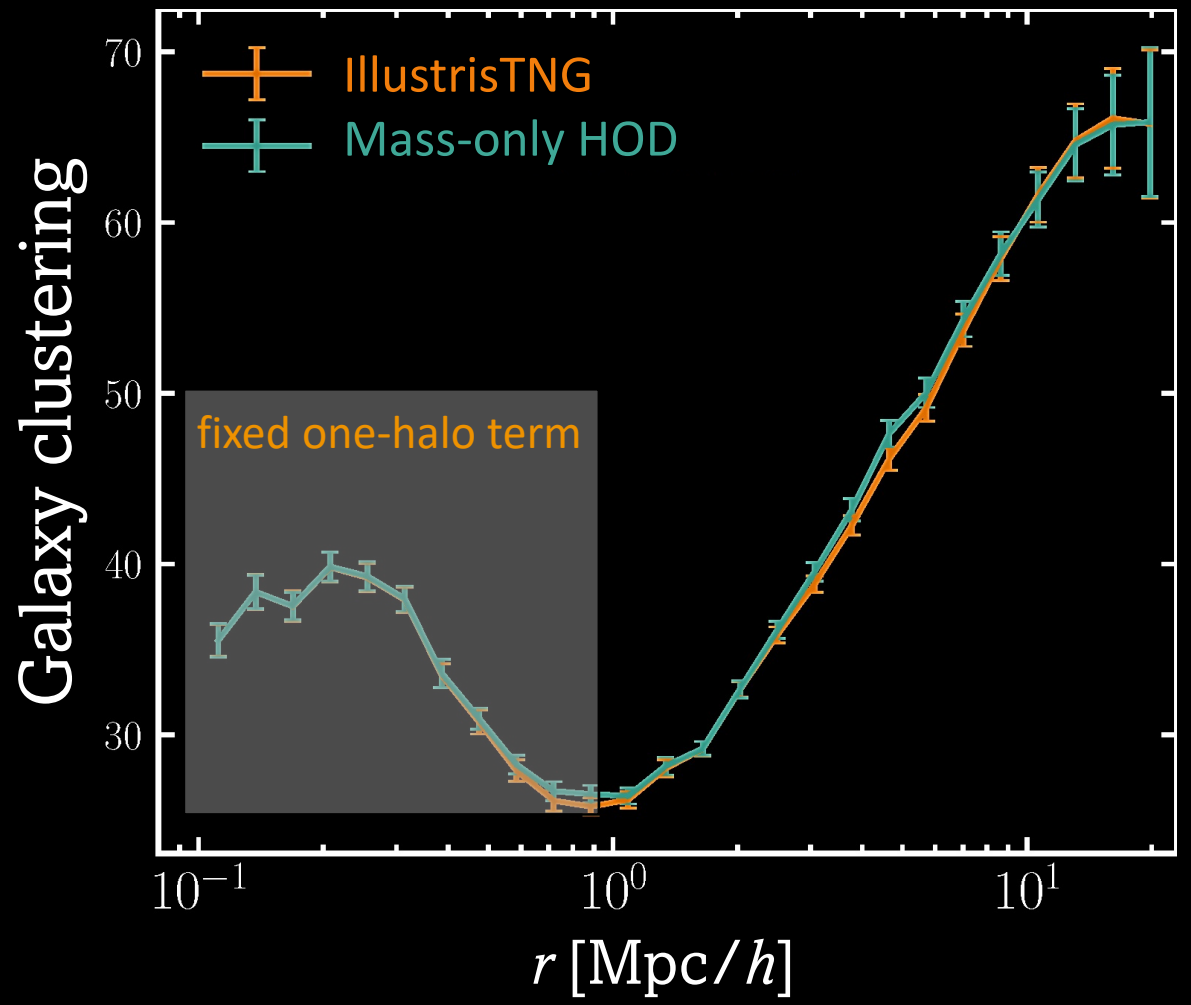
The mass-only HOD does not work well



- Mass-only HOD **cannot** recover the LRG clustering at the **10-15% level!** (see also Beltz-Mohrmann+ (2020), Xu+ (2020))
- Well above the **subpercent level** requirement set by experiments
- Evidence of **"assembly bias"** in TNG: dependence of halo occupancy on halo parameters other than mass

Hadzhiyska+ (2019), MNRAS.493.5506H

A new kind of “assembly bias” is to blame

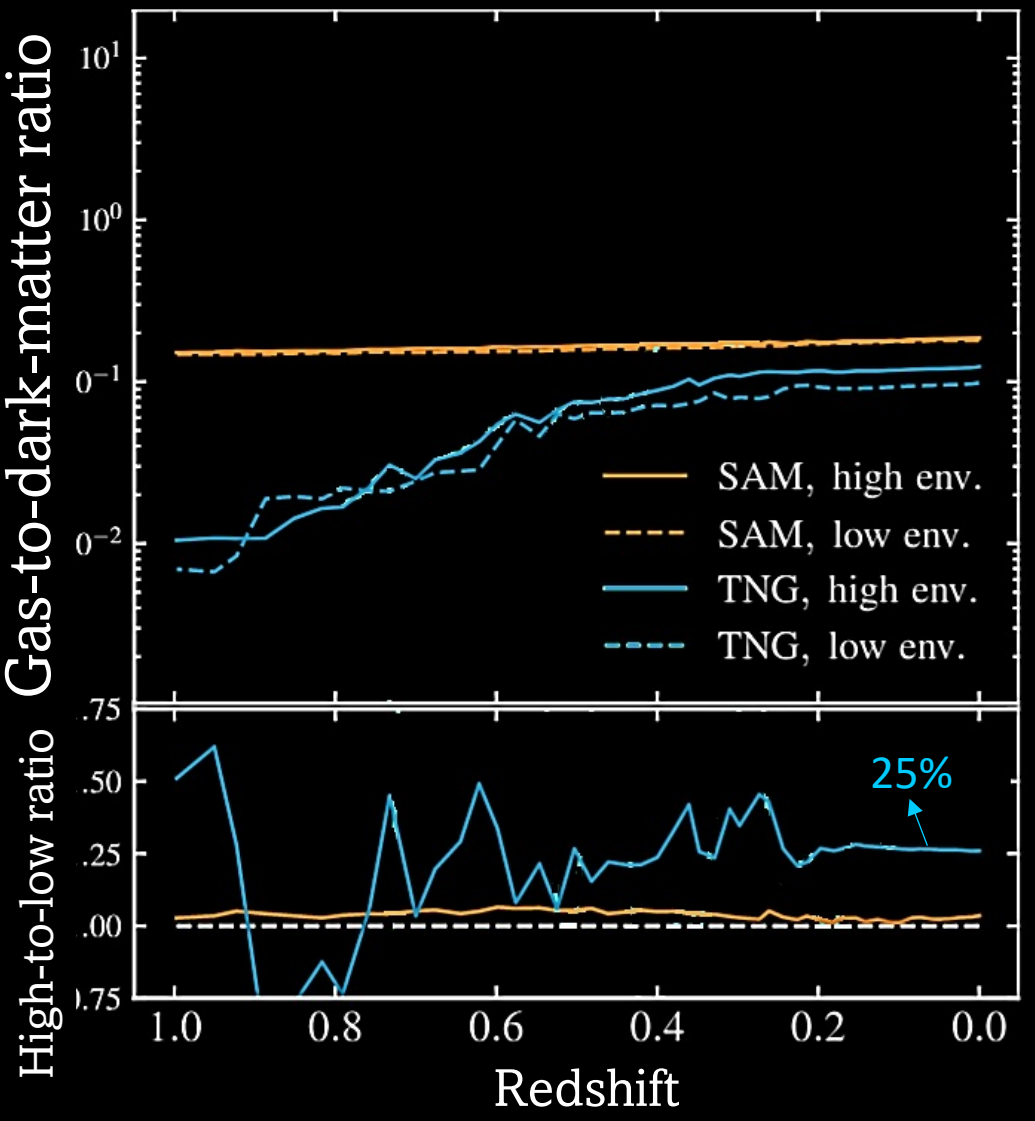


Hadzhiyska+ (2019), MNRAS.493.5506H

- Historically studied “assembly bias” parameters: concentration, formation time, spin, velocity dispersion, etc. cannot explain away the difference
- Halo environment can successfully reconcile the difference
- Needed are external halo properties

Hadzhiyska+ (2021b), MNRAS.508..698H

High-density regions supply more gas to the central

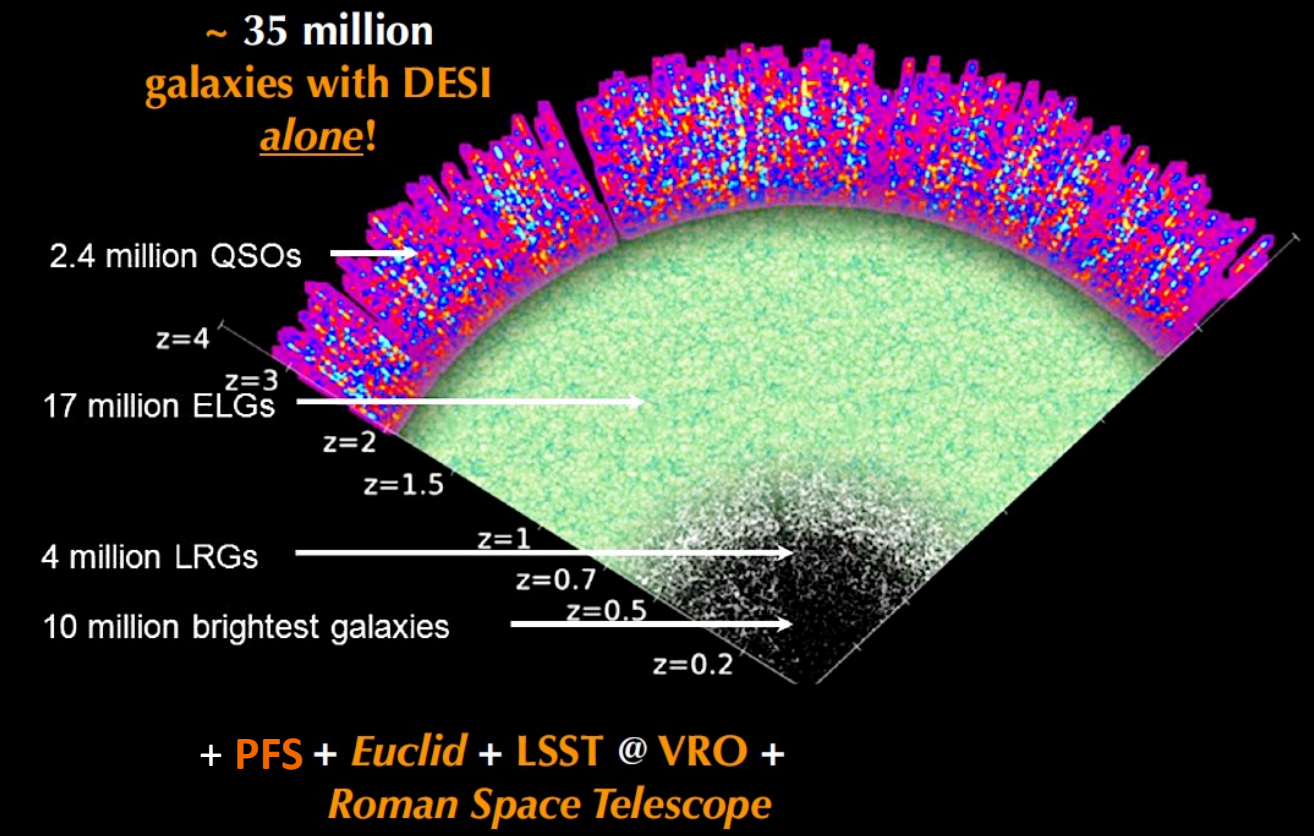


- At fixed halo mass, 25% more star-building material available inside high-density TNG halos (backsplash halos, quenching)
- Not the case in most HODs and semi-analytic models (SAMs), which use internal halo properties
- Incorporating environment in HODs and SAMs may be crucial to recovering the galaxy distribution

Why? Splashback, quenching, halo finding…
Hadzhiyska+ (2021b), MNRAS.508..698H

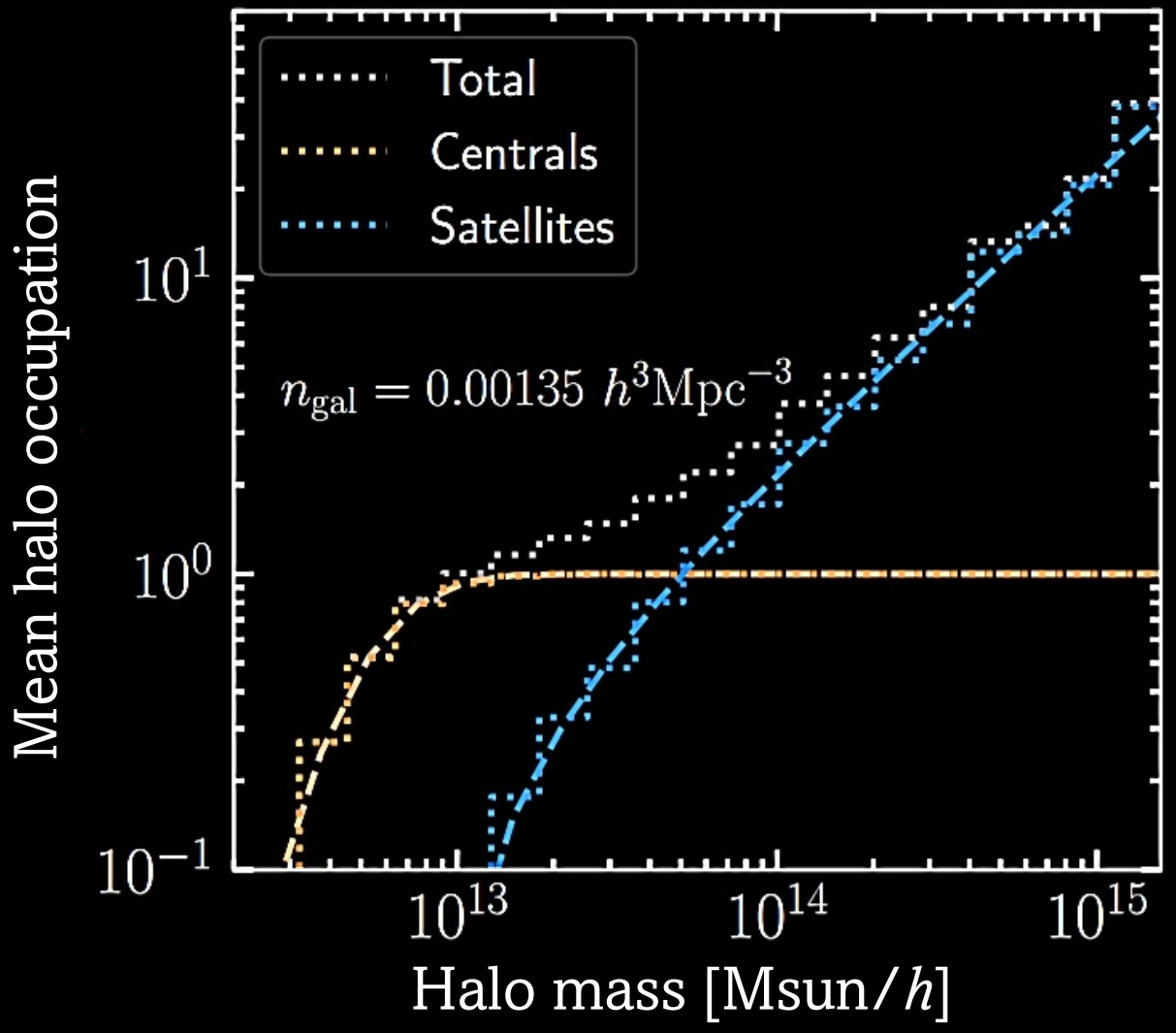
Emission-line galaxies (ELGs) are understudied

- ELGs: targets of many current and future galaxy surveys (DESI, PFS, *Euclid*)
- Not as well studied as LRGs
- Careful modeling needed to ensure no systematic bias is introduced in the cosmological inference



Emission-line galaxies (ELGs) behave differently from LRGs

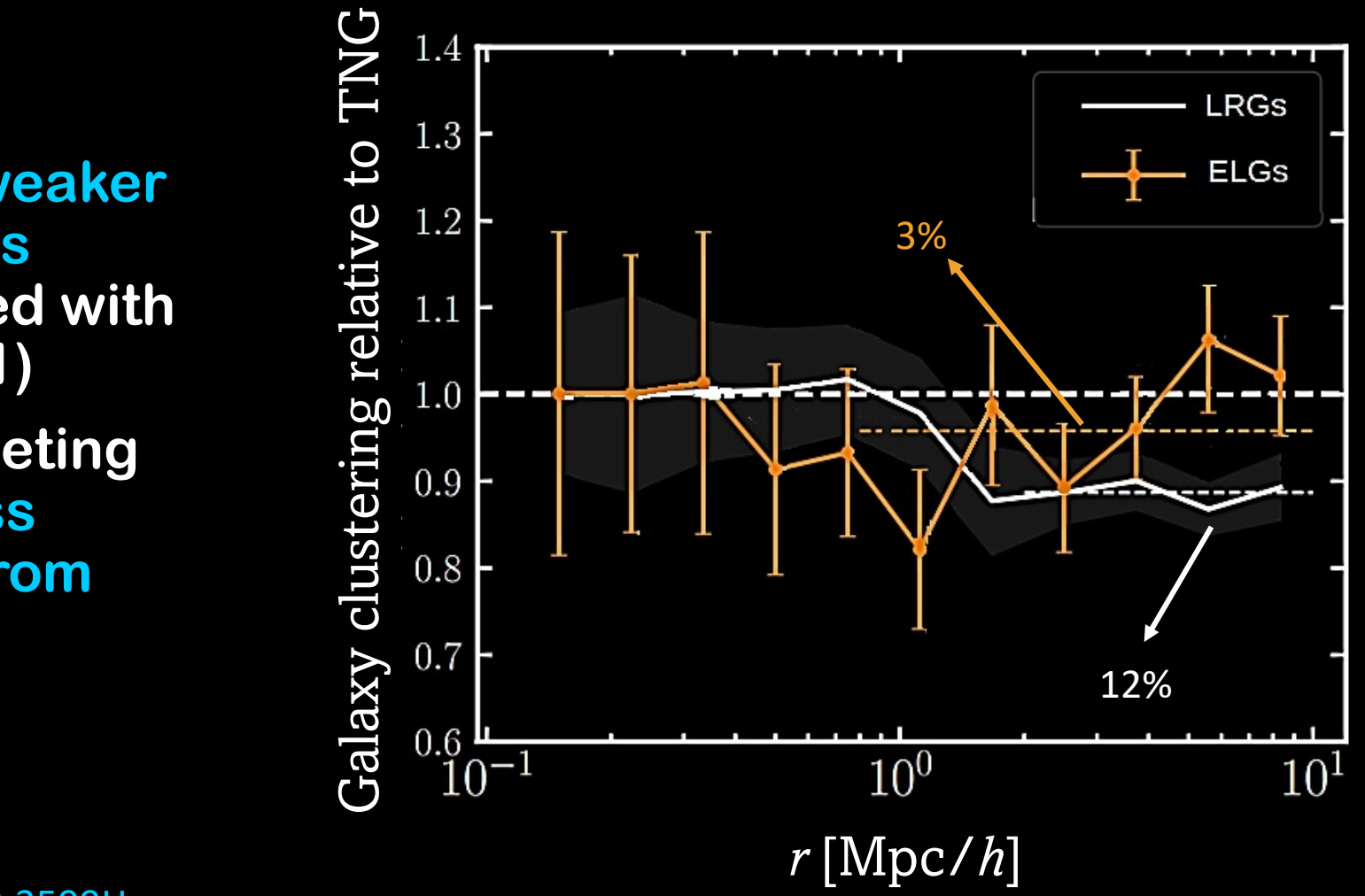
- Created synthetic colors for TNG galaxies at $z \sim 1$
- Extracted ELGs by applying the DESI/eBOSS color cuts
- Halo occupation drastically different from LRGs!
- Need specialized HOD function
- Require higher-resolution N-body simulations



Hadzhiyska+ (2020c), MNRAS.502.3599H

Emission-line galaxies (ELGs) behave differently from LRGs

- ELGs have a much weaker galaxy assembly bias signal (3%) compared with ~10% for LRGs ($z \sim 1$)
- Implies surveys targeting ELGs suffer from less systematic effects from assembly bias

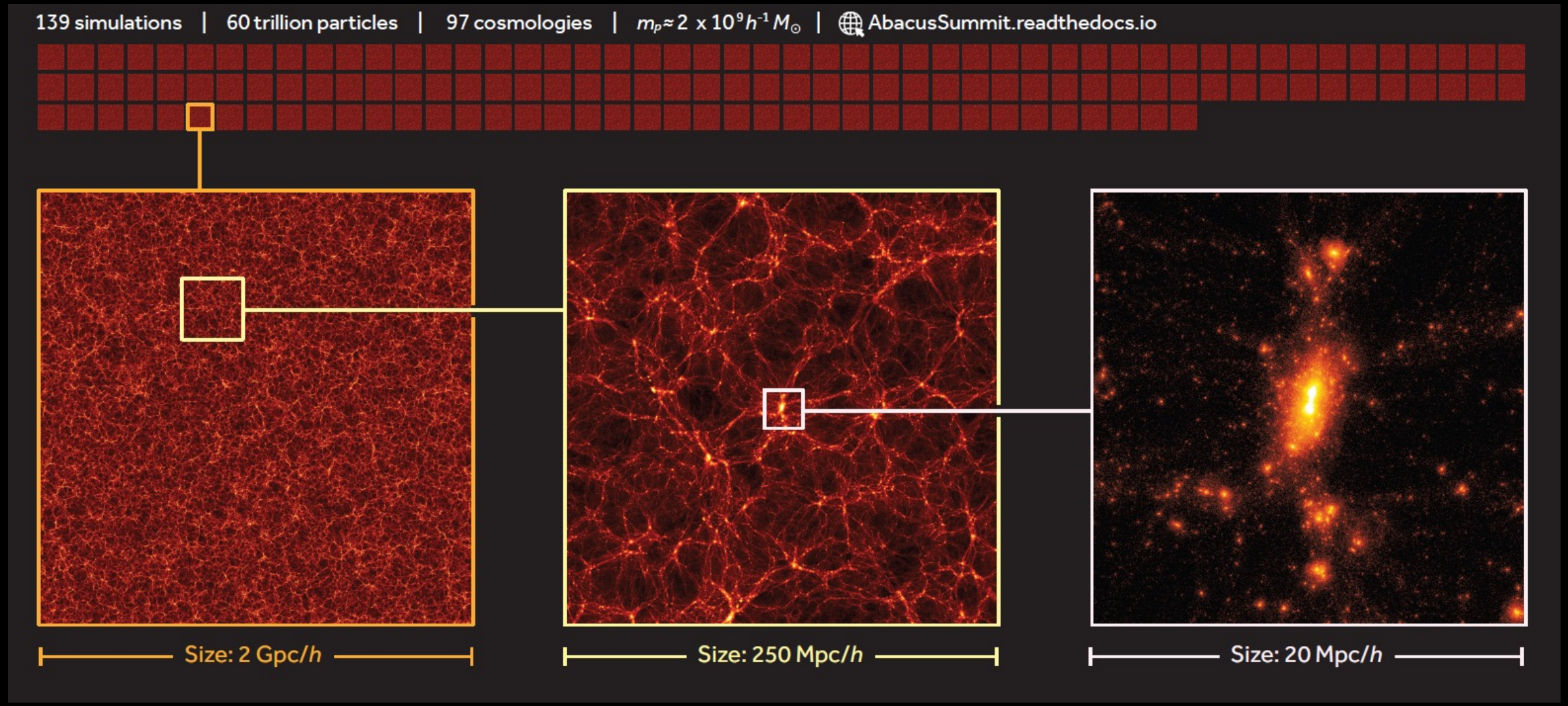


Hadzhiyska+ (2020c), MNRAS.502.3599H

How do we apply that knowledge to the analysis of surveys?

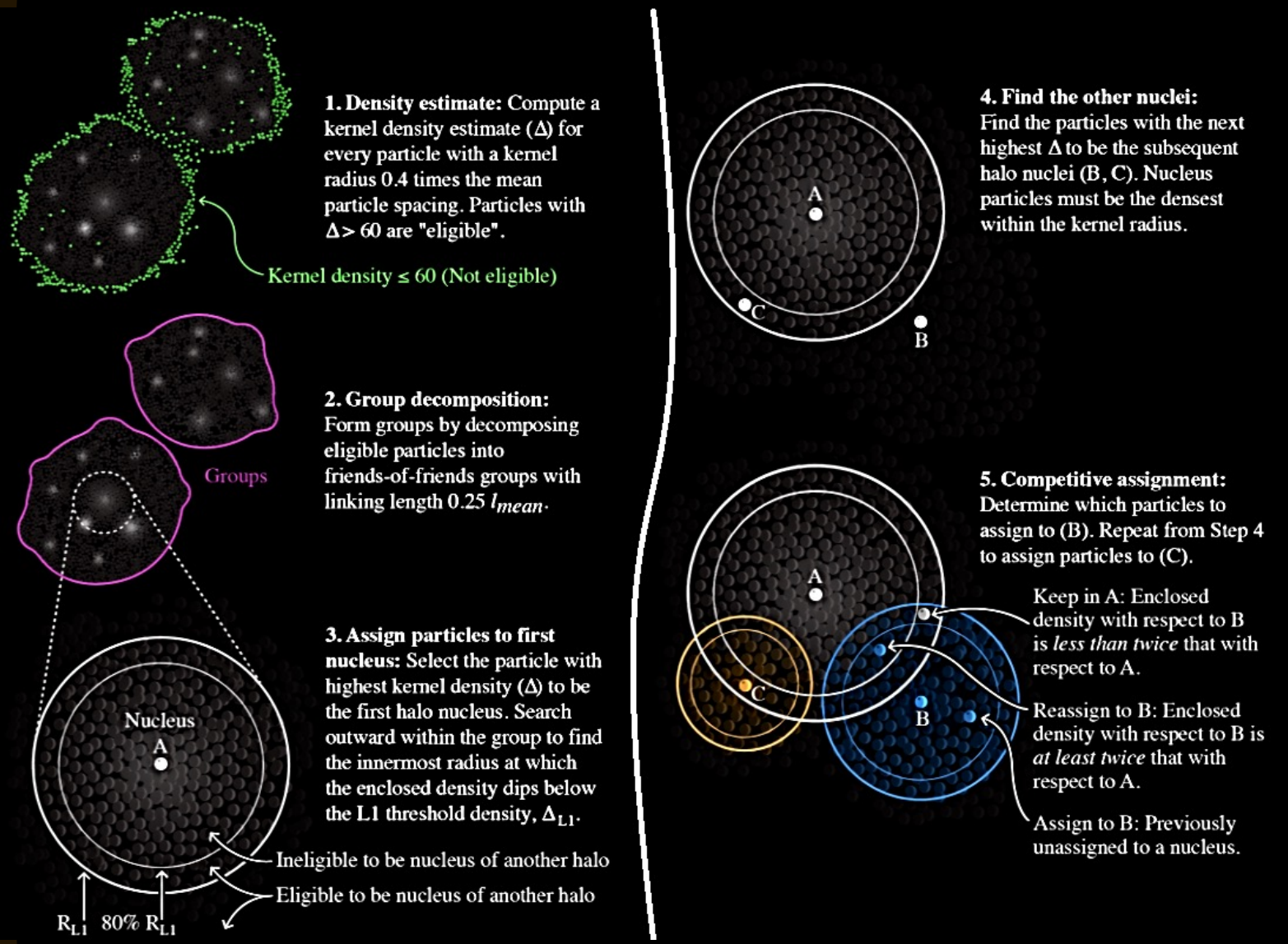
AbacusSummit: largest-yet *N*-body suite

N. Maksimova, L. Garrison, D. Eisenstein, B. Hadzhiyska+, 2021



CompaSO: A new halo finder

- Stands for “competitive assignment to spherical overdensities”
- Highly optimized and efficient for on-the-fly halo finding
- Comparable to more sophisticated, computationally expensive finders such as ROCKSTAR
- Generate galaxy mocks with assembly bias and one-halo modeling and computes stats in ~0.5 s

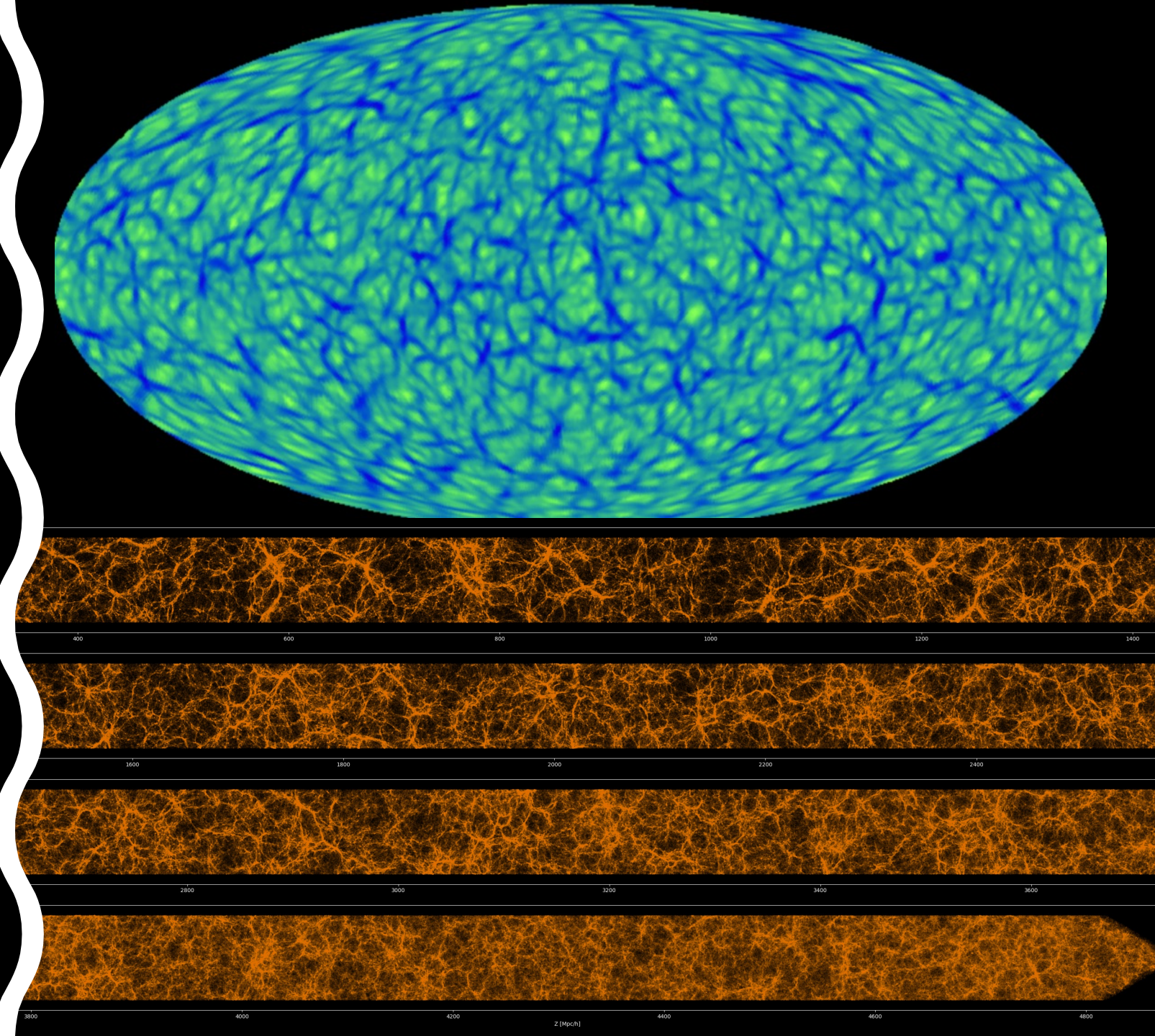


Hadzhiyska+ (2021a, MNRAS.tmp), Yuan+ (2021)

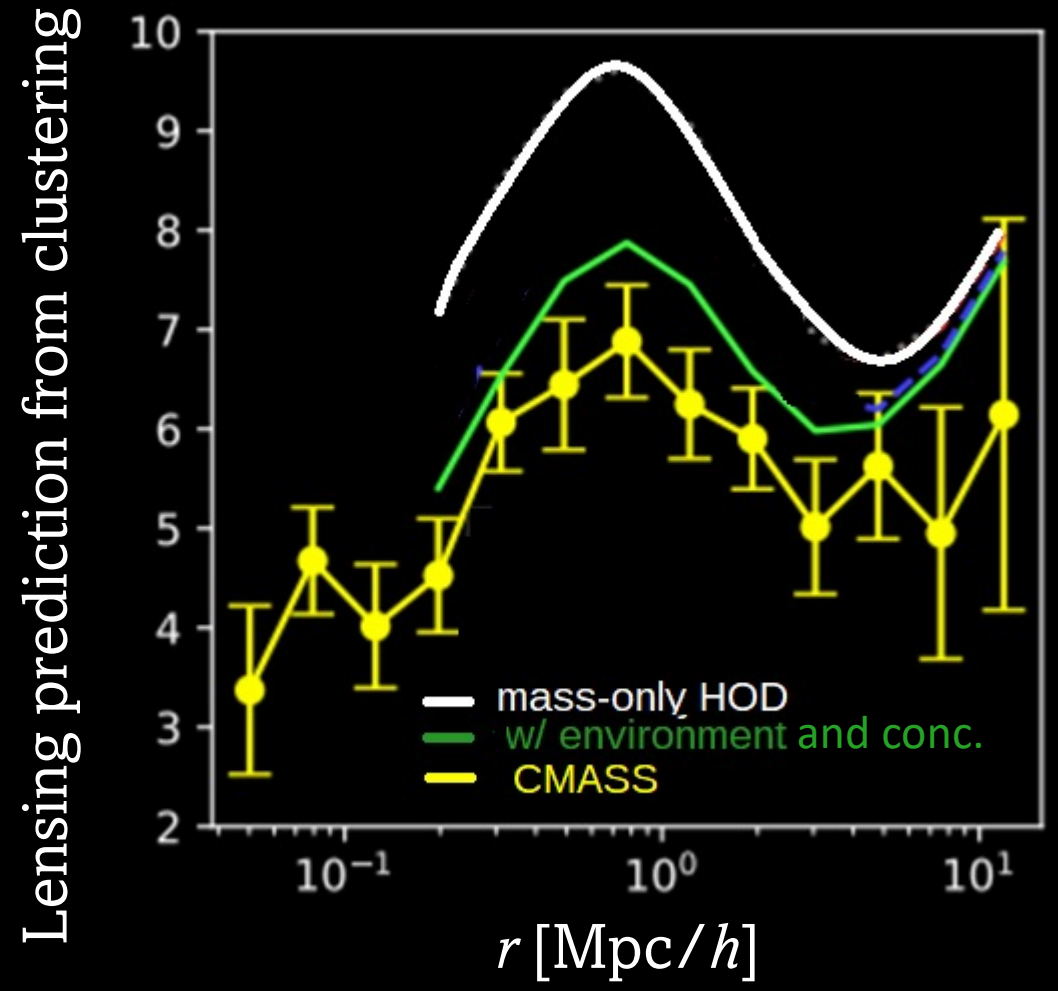
The AbacusSummit halo light cone catalogs

- Publicly available at DOI:10.13139/OLCF/1825069
- Currently available for fiducial cosmology only
- 25 simulations cover 2000 sq. deg. until $z \sim 2.4$
- 2 simulations cover the full sky until $z \sim 2.18$
- Easy to produce highly realistic and accurate on-sky mock catalogs

Hadzhiyska+ (2021b, MNRAS.tmp)



Detecting environment assembly bias in CMASS BOSS data



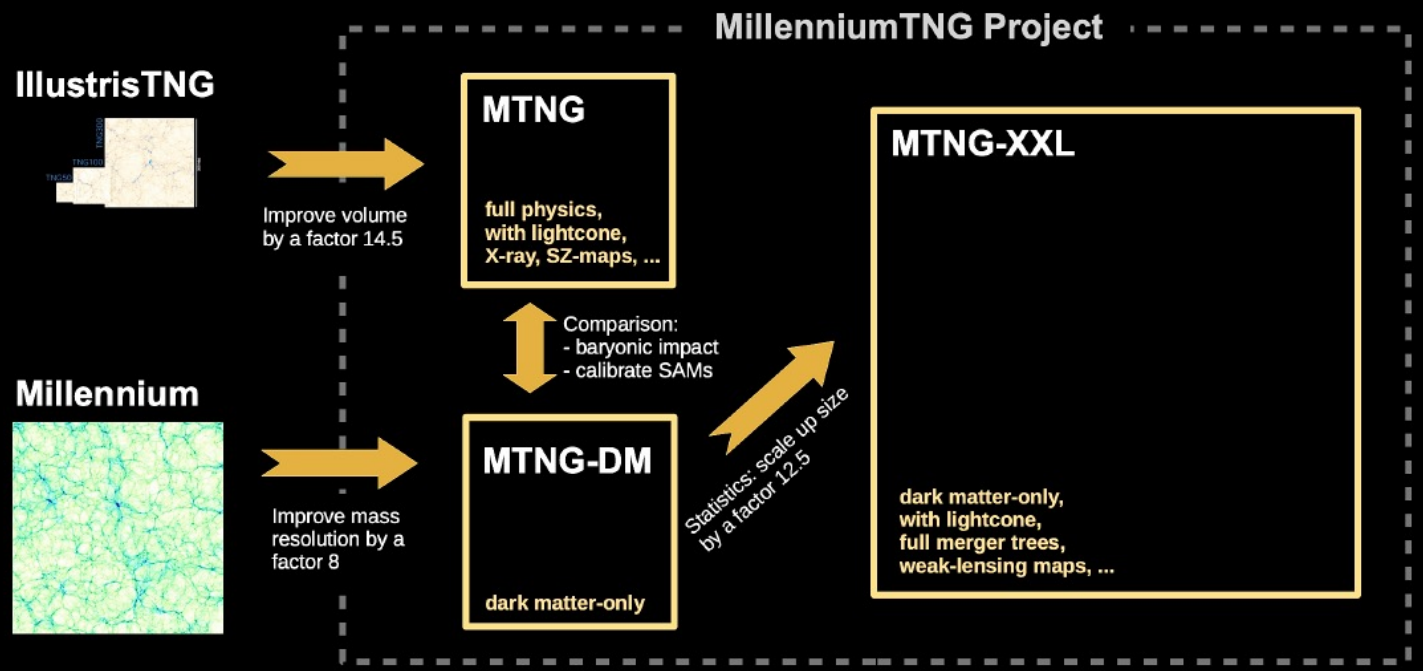
- Simple augmentation of the HOD model with environment and concentration
- Detected positive environment effect with high significance
- Including environment in the analysis reduces the tension by half in the "Lensing is low" tension
- Baryon effects + assembly bias explain it all?

Yuan, Hadzhiyska+ (2020), MNRAS.502.3582Y
Amodeo & ACT Collab. (2020)

Looking forward

MTNG: largest-yet hydro simulation

An effort led by:
Volker Springel, Lars Hernquist, Carlos Frenk, Simon White,
Ruediger Pakmor, Boryana Hadzhiyska, Sownak Bose,



- 15 x volume of TNG
- Better large-scale statistics
- Can study 3-point correlations, void statistics, counts-in-cell
- Various tracers (LRGs, ELGs, X-ray, SZ, CMB lensing)

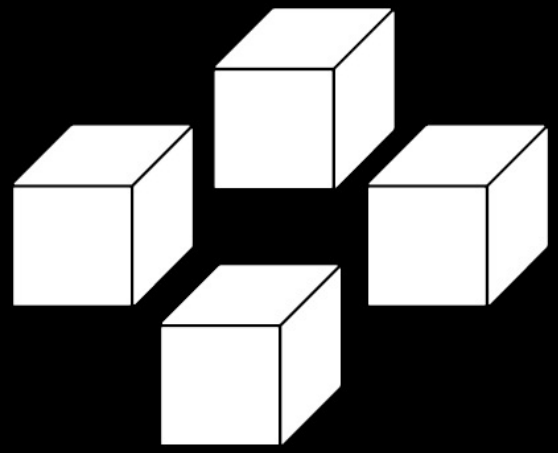
Hadzhiyska+ (2020b), MNRAS.501.1603H

MTNG: Ongoing and future projects

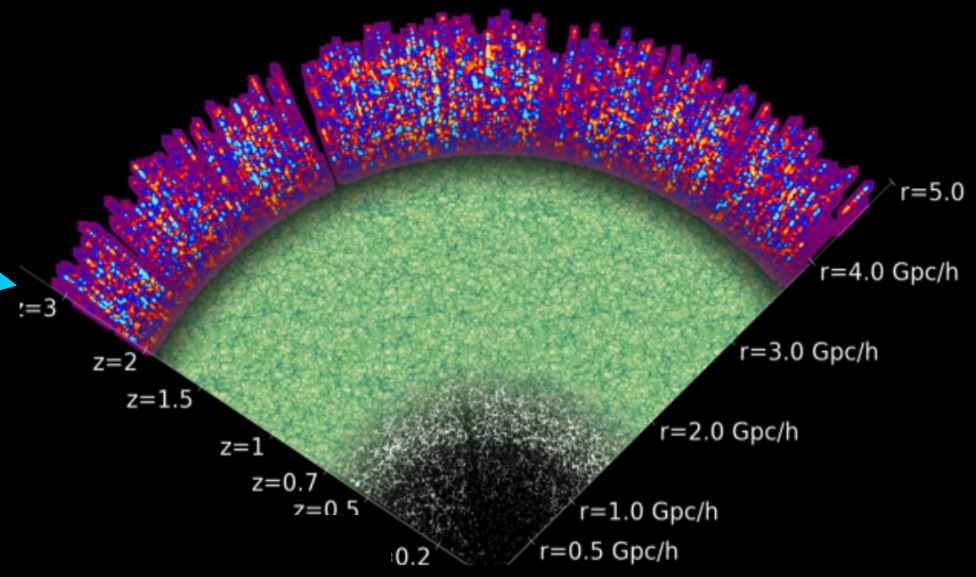
1. (Ongoing) Is tertiary assembly bias necessary for predicting the large-scale galaxy distribution?
2. (Ongoing) How sensitive are void statistics to baryonic and assembly bias effects?
3. (Ongoing) How do source overlap and assembly bias affect Sunyaev-Zel'dovich (SZ) analyses
4. (Long term) How do we construct a realistic galaxy population model, generalizable beyond the particulars of TNG physics?

Implementing an accurate galaxy-halo model into the analysis pipeline

AbacusSummit → MTNG-informed galaxy model → Constraining clustering amplitude and galaxy formation



Galaxy observations from PFS/DESI/*Euclid*/*Roman*



Captures full galaxy distribution, beyond 2PCF (Hadzhiyska+ 2020b)

Candidates: augmented HOD, machine-learning galaxy-halo, field-level (Osato et al. 2021)

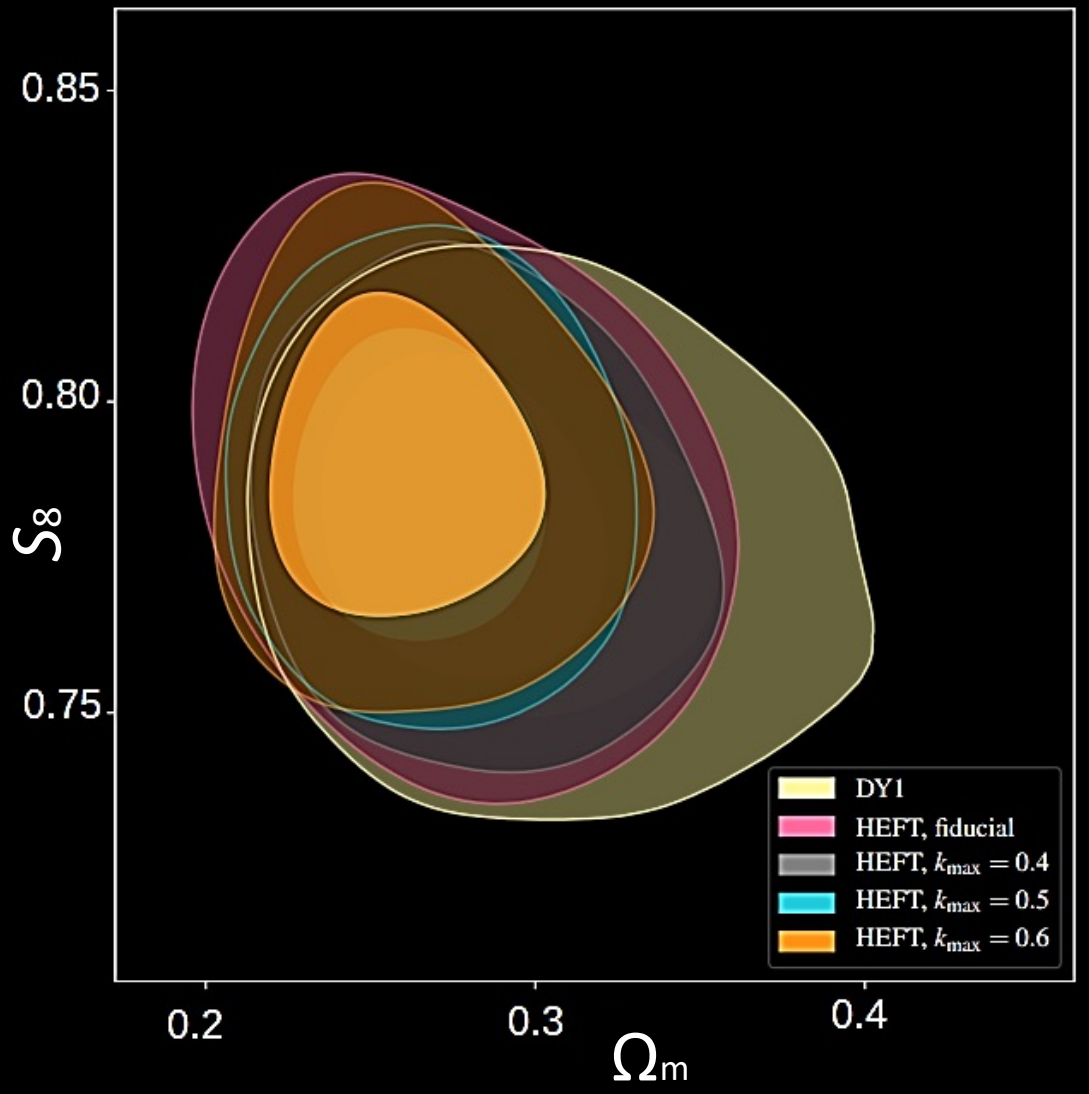
Open bracket: Hybrid Effective Field Theory

- Expansion to second order in Lagrangian Perturbation Theory
- Advection from Lagrangian to Eulerian space done numerically through sims
- Computing 15 basis spectra from Abacus to fit galaxy power spectrum

$$1 + \Delta_{g,L} = 1 + b_1\delta_L + b_2(\delta_L^2 - \langle\delta_L^2\rangle) + b_s(s_L^2 - \langle s_L^2\rangle) + b_\nabla\nabla^2\delta_L$$

$$1 + \Delta_g(\mathbf{x}) = \int d^3\mathbf{q}\,[1 + \Delta_{g,L}(\mathbf{q})]\,\delta^D(\mathbf{x} - \mathbf{q} - \Psi(\mathbf{q}))$$

$$P_{gm}(k) = \sum_{\alpha\in\mathcal{O}} b_\alpha P_{1\alpha}(k), \quad P_{gg}(k) = \sum_{\alpha\in\mathcal{O}}\sum_{\beta\in\mathcal{O}} b_\alpha b_\beta P_{\alpha\beta}(k)$$



Modi+ (2020), Hadzhiyska+ (2021a), JCAP...09..020H

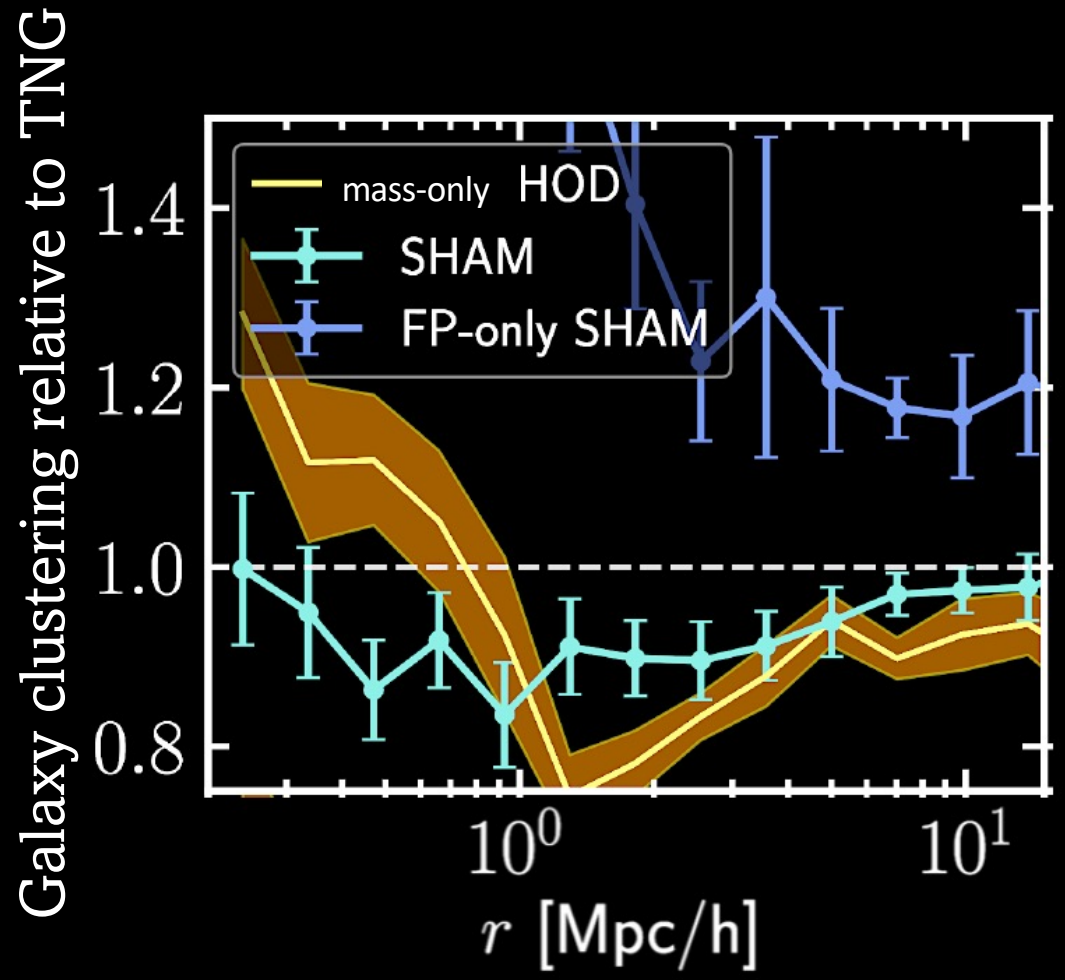
Surveys: Ongoing and future projects

1. (Ongoing) Cross-correlation between DESI ELGs and CMB lensing (*Planck*)
2. (Ongoing) Constraining cosmology from photometric surveys, BAO, CMB, with Hybrid Effective Field Theory (HEFT)
3. (Ongoing) ACTxDESI: Joint studies of SZ maps and DESI galaxies
4. (Long term) Joint studies of galaxies & CMB DESI/*Euclid*/*Roman*/Rubin and CMB+SZ
5. (Long term) Evolution of assembly bias effects over time → galaxy physics

Thank you!

Backup slides

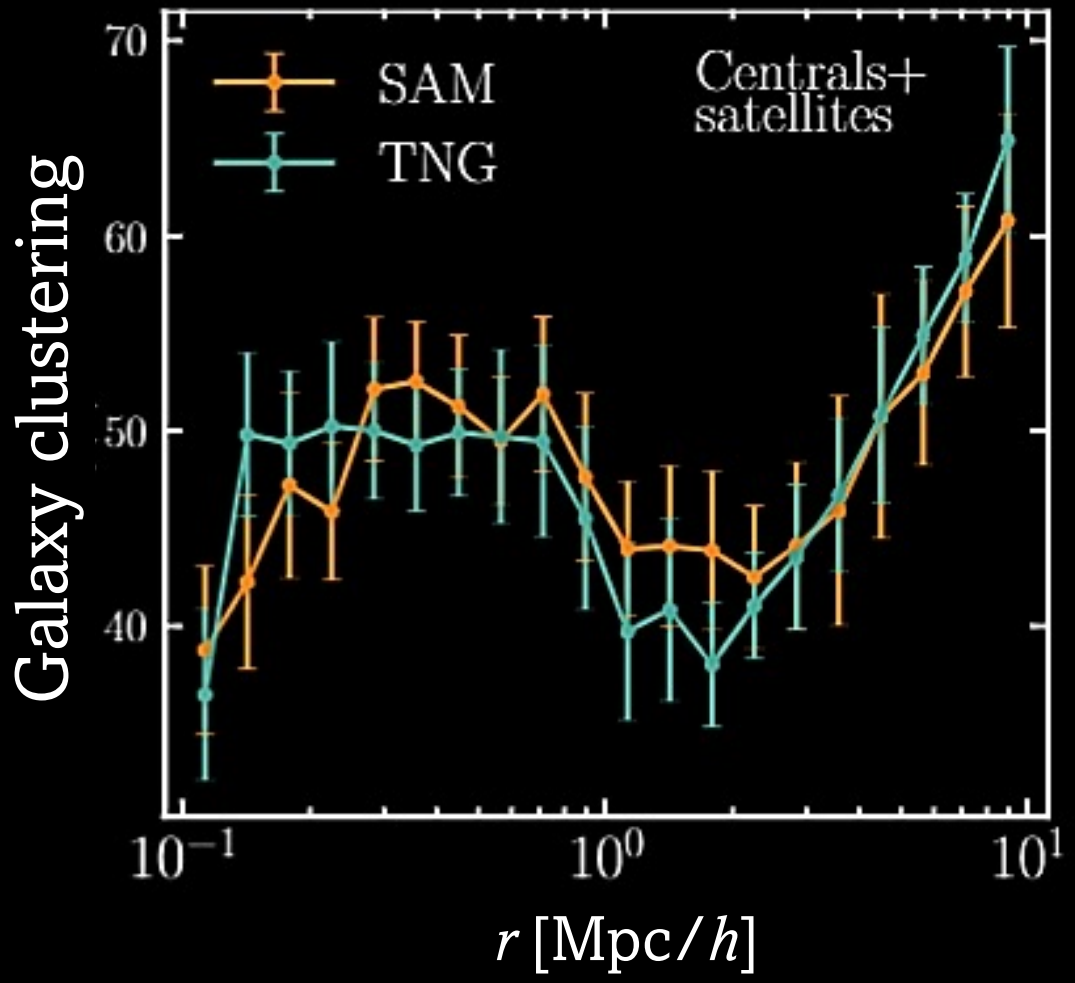
Other empirical methods fail, too!



Hadzhiyska+ (2020b), MNRAS.501.1603H

- **Subhalo abundance matching (SHAM):** "paints" galaxies onto subhalos after rank-ordering them by a dark-matter property
- **Fails** as well at > 5% level, requires subhalos, unclear how to treat different galaxy tracers
- More complex models can reproduce the TNG clustering such as **HOD models with assembly bias**, **semi-analytic models** (see Hadzhiyska,… Somerville+ 2021)

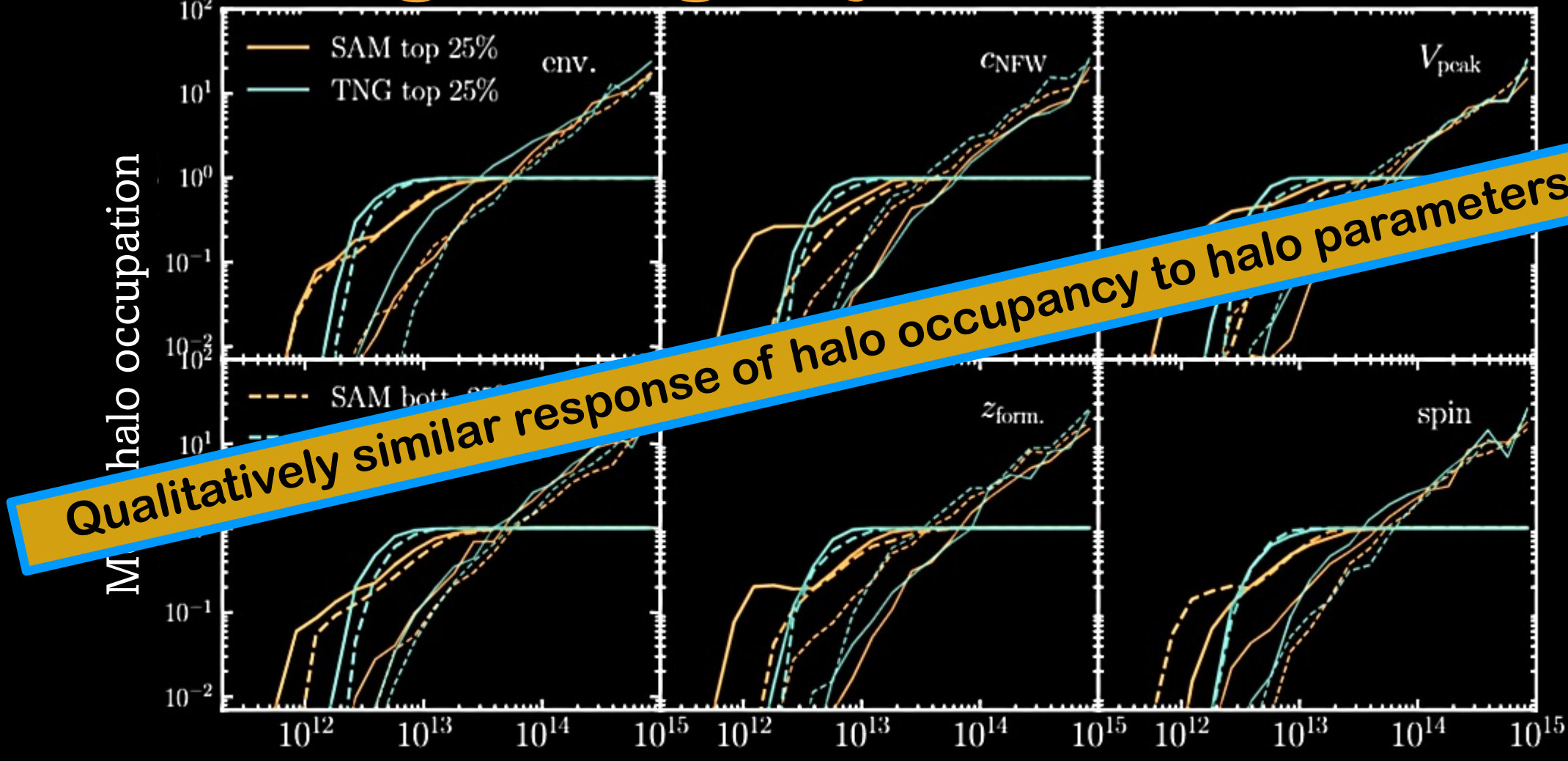
Physically intuitive but inexpensive methods go a long way



- Comparison between R. Somerville's SAM and TNG
- Despite not matched to each other, two-point clustering is well-matched b/n the two
- Suggests clustering can be recovered in cheaper ways
- Analysis needs to be repeated for other tracers and higher redshifts

Hadzhiyska+ (2021b), MNRAS.tmp.2334H

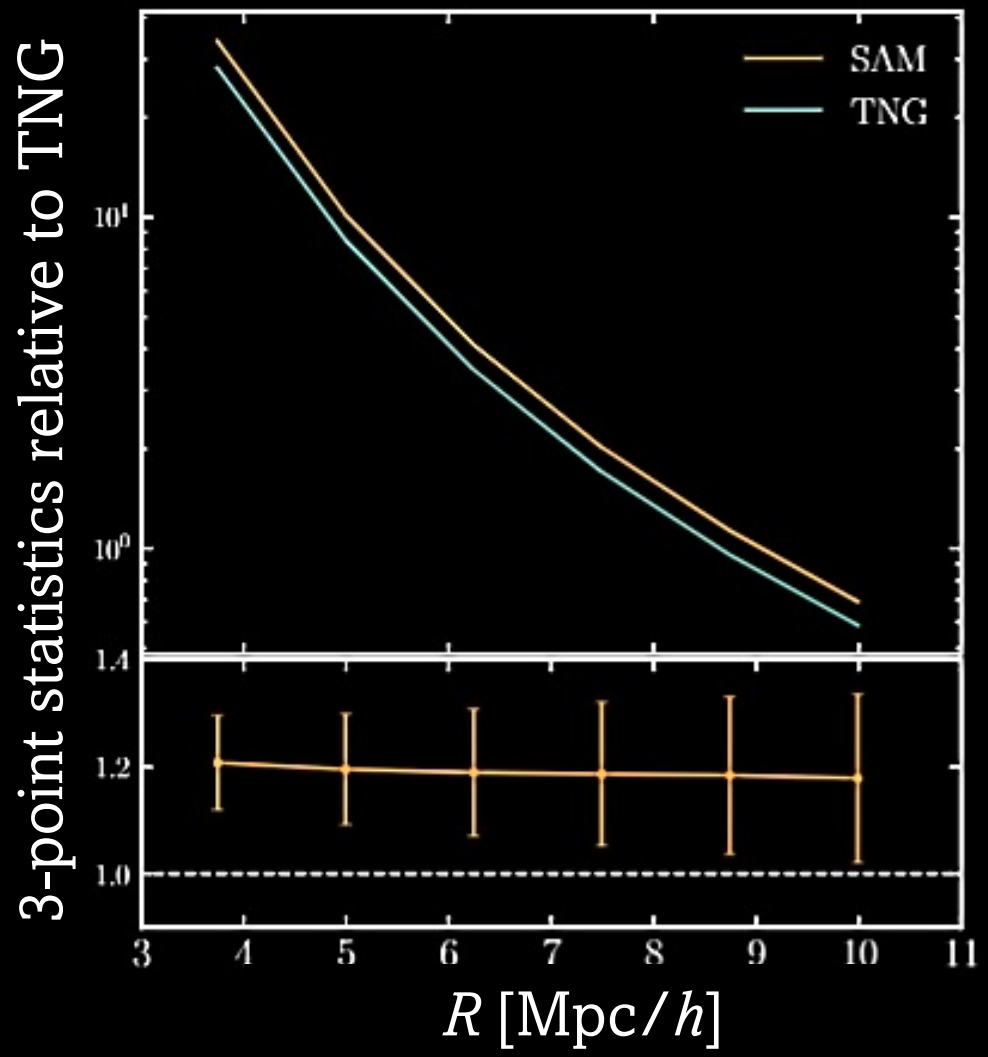
Physically intuitive but inexpensive methods go a long way



Qualitatively similar response of halo occupancy to halo parameters!

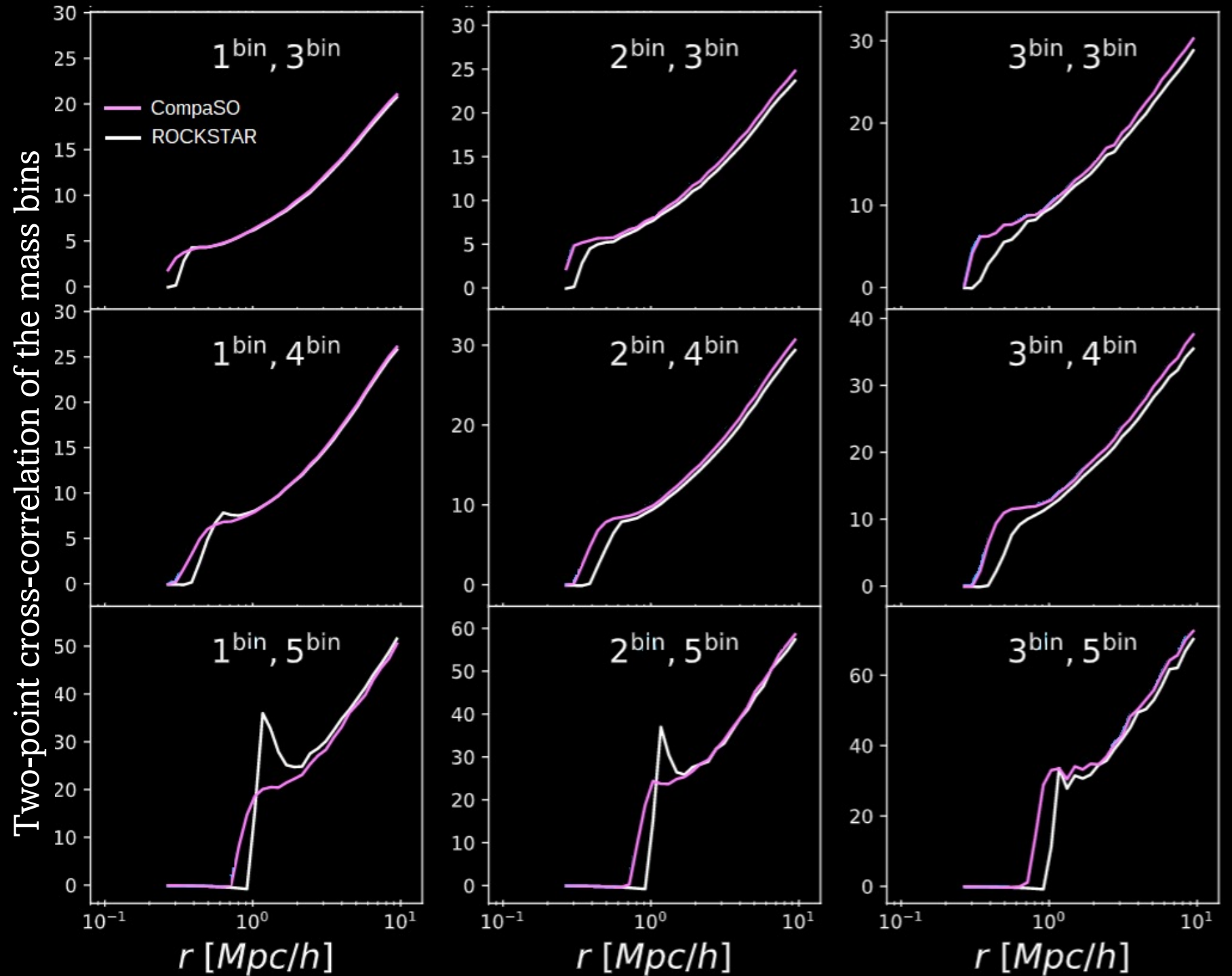
Hadzhiyska+ (2021b), MNRAS.tmp.2334H

Physically intuitive but inexpensive methods go a long way



- Despite having well-matched two-point clustering, SAM and TNG display **different** higher-order statistics
- Suggests including **higher-order statistics** in the calibration of SAMs
- Including more **observables for calibration** (e.g., cross-correlations with early Universe probes, alternative stats, wide range of redshifts)

Hadzhiyska+ (2021b), MNRAS.tmp.2334H



CompaSO: A new halo finder

- Performs substantially better than other configuration-space finders (is faster and more accurate)
- Comparable to more sophisticated, computationally expensive finders such as ROCKSTAR

Hadzhiyska+ (2021a, submitted)