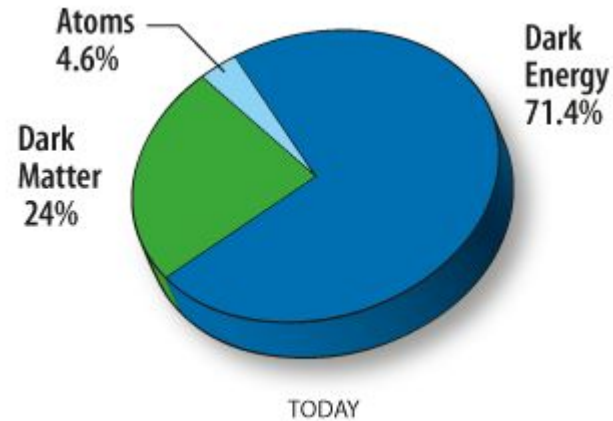

Can we link galaxy assembly times to the assembly times of their host halos? A perspective from Mutual Information II

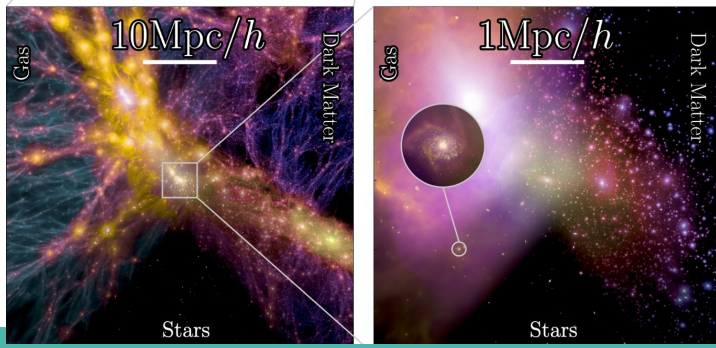
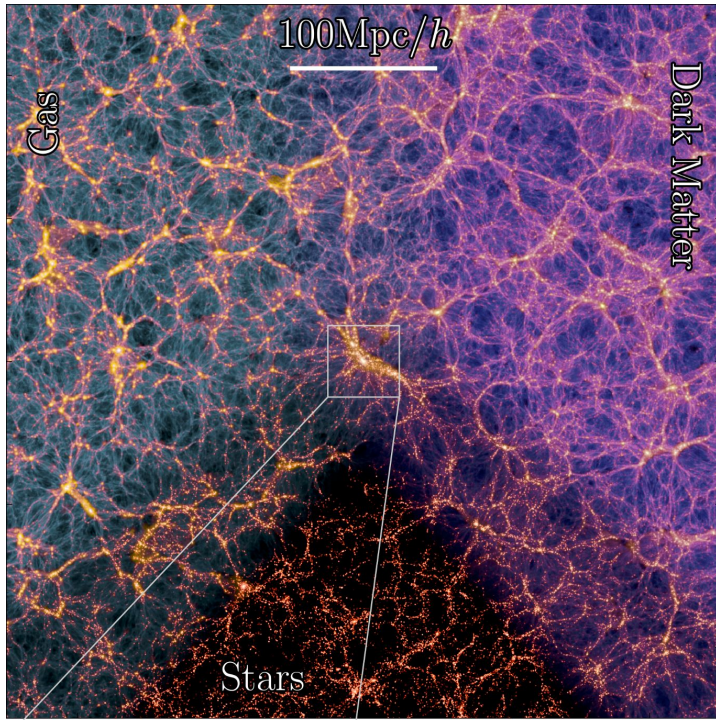


Yeimy D. Camargo C.- Universidad Nacional de Colombia.
Rigoberto A. Casas-M. - Universidad Nacional de Colombia.

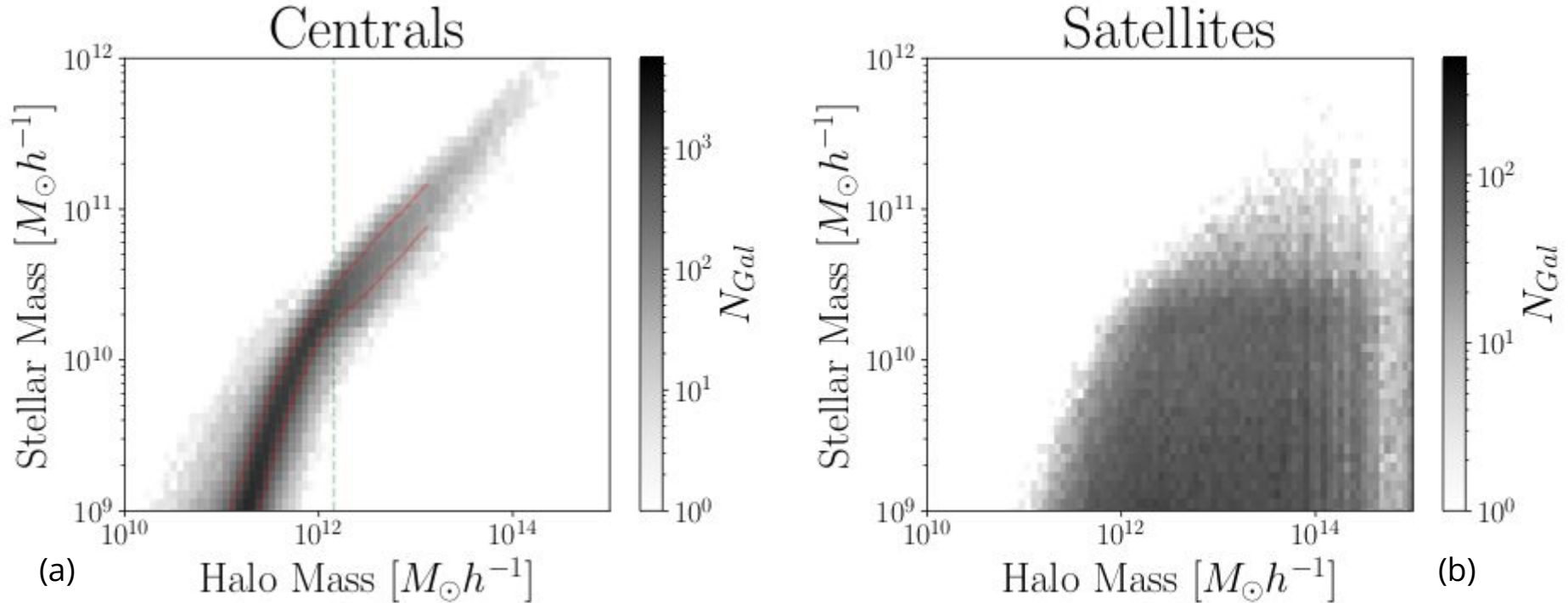
According to the (Λ CDM) model...



The galaxies form and evolve inside Dark Matter (DM) haloes as a result of the non-linear evolution of density perturbations in matter, **establishing a close relationship between the galaxies and their host DM haloes.**



Stellar to Halo Mass relation (SMHM)



Stellar-to-halo mass relation (SMHM) for central galaxies (a) and satellite galaxies (b). The red lines represent the region within 1σ of the mean stellar mass at fixed halo mass. Central galaxies show a pronounced relationship between the stellar mass of the galaxies and the mass of their host halo, particularly for halos with $M_H = 1.43 \times 10^{12} M_{\odot} h^{-1}$ (shown by dashed green line).

Galaxy- Halo Connection

Halo Occupation Distribution (HOD)

(Peacock & Smith 2000; Kravtsov et al. 2004; Wechsler & Tinker 2018; Cooray & Sheth 2002)

$$P(N_G | M_H)$$

Conditional Luminosity Function (CLF)

(Yang et al. 2003; Vale & Ostriker 2004a; Vale & Ostriker 2004b)

$$P(L_G | M_H)$$

Describe the positions of galaxies inside of Halos.

- ★ The Probability Distribution that a halo of virial mass M contains N galaxies.
- ★ The relation between the galaxies and DM distributions within halos.

Abundance Matching (AM)

Halo Abundance Matching (HAM)

SubHalo Abundance Matching (SHAM)

(Mo et al. 1999; Vale & Ostriker 2004, 2006; Kravtsov 2013; Lim et al. 2016; Kravtsov et al. 2004, Guo et al. 2010)



Galaxy- Halo Connection

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Abundance Matching (AM)

Halo Abundance Matching (HAM)

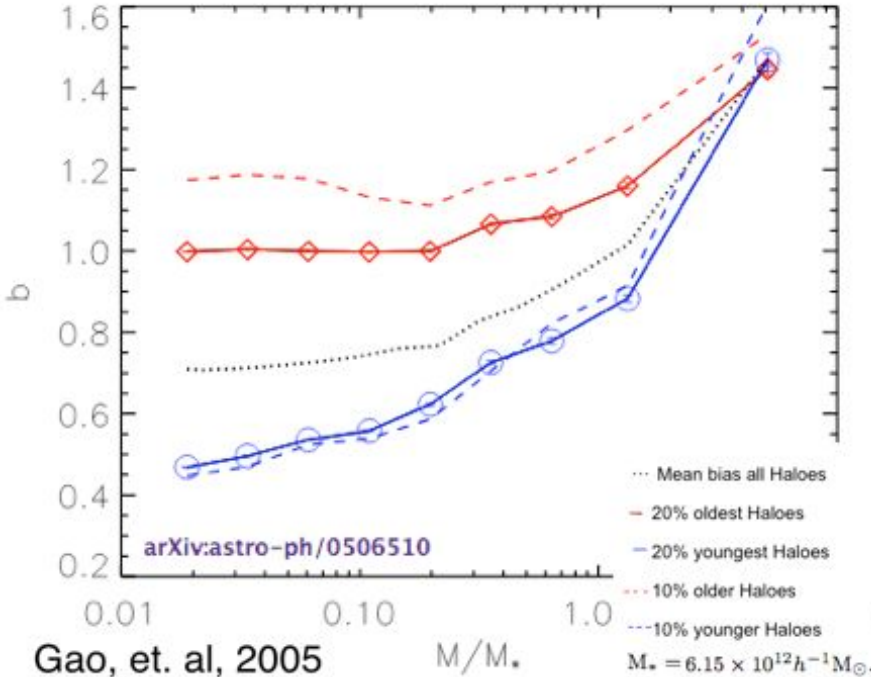
SubHalo Abundance Matching (SHAM)

(Mo et al. 1999; Vale & Ostriker 2004, 2006; Kravtsov 2013; Lim et al. 2016; Kravtsov et al. 2004, Guo et al. 2010)

Populate galaxies into halos and subhalos, assuming a roughly monotonic correspondence between the ranking orders of galaxy luminosities (or stellar masses) and those of the masses of dark matter halos. (Lim et al 2016)



Halo Assembly Bias



Halo Assembly Bias: At fixed halo mass, large-scale bias depends on a secondary halo property (e.g. formation redshift or concentration).

Halos that assemble a significant fraction of their mass earlier on are more tightly clustered than those that take more time to acquire the same mass (Gao, Springel & White 2005; Wechsler et al. 2006; Li, Mo & Gao 2008; Salcedo et al. 2018; Antonio D. Montero-Dorta et. al 2025).

Galaxy Assembly Bias: The dependence of galaxy clustering/number of galaxies on halo secondary halo property (Croton, Gao & White 2007; Jung, Lee & Yi 2014; Artale et al. 2018; Zehavi et al. 2018; Contreras et al. 2019; Montero-Dorta et al. 2020, 2021; Xu & Zheng 2020)

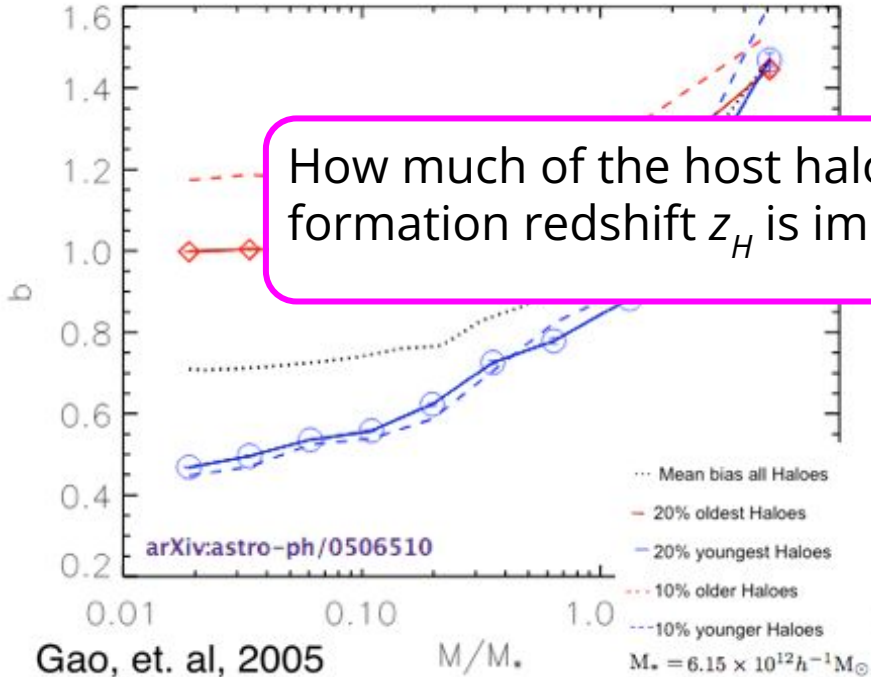
Halo Assembly Bias



Halo Assembly Bias: At fixed halo mass, large-scale bias depends on a secondary halo property (e.g. formation redshift or concentration).

Halos that assemble a significant fraction of their mass earlier in time (Croton et al. 2006;

How much of the host halo's assembly history, quantified by the formation redshift z_H is imprinted in the galaxies?



Galaxy Assembly Bias: The dependence of galaxy clustering/number of galaxies on halo secondary halo property (Croton, Gao & White 2007; Jung, Lee & Yi 2014; Artale et al. 2018; Zehavi et al. 2018; Contreras et al. 2019; Montero-Dorta et al. 2020, 2021; Xu & Zheng 2020)

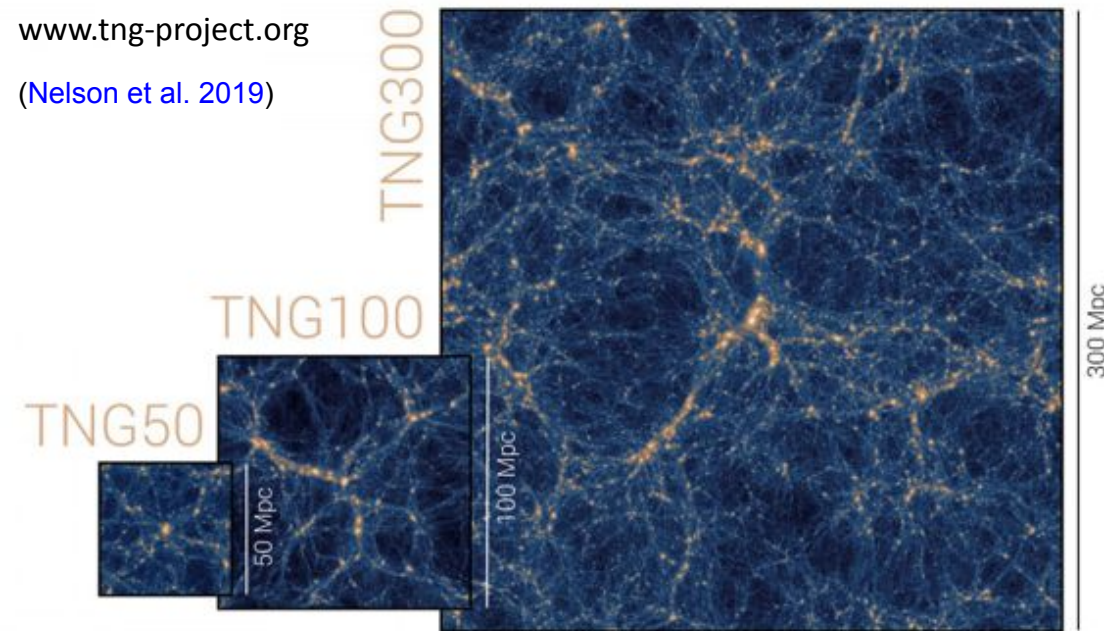


The Age Distribution Matching Model

The most massive galaxies are assigned to the most massive halos, the galaxies in a star mass bin are ordered by time of formation of their host halos, and then assigned a color or star formation rate (SFR) based on their position in the ordered list. As a result, the oldest halos (early assembly halos) contain the reddest galaxies, while younger halos (late assembly halos) contain the bluest galaxies. This concept is commonly used to establish a connection between galaxy color as a proxy for the age of their dark-matter halos and is widely employed in investigations that study galaxy catalogs, aiming to establish correlations between the properties of galaxies and simulated DM halos, providing insights into the age of the halos.

Using this model [Hearin et al. \(2014\)](#) found that the Age Distribution Matching model correctly predicts the color ($g - r$) of central and satellite galaxies, the clustering measure from the projected galaxy two-point correlation function (2PCF) as a function of stellar mass, as well as the scale of these colors with the mass of their host halo from the Sloan Sky Digital Survey (SDSS) DR7.

[Behroozi et al. \(2019\)](#) proposed a model that links galaxy star formation rates (SFRs) to the assembly history and redshift of their host haloes. They found a stronger correlation between SFR and assembly history in smaller haloes compared to larger ones.



name	volume [(Mpc) ³]
TNG300-1	302.6 ³
TNG300-2	302.6 ³
TNG300-3	302.6 ³

Λ CDM cosmology:

$$\Omega_m = 0.2726, \Omega_b = 0.0456,$$

$$\Omega_\Lambda = 0.7274, \sigma_8 = 0.809$$

$$h = 0.704. \text{ (Vogelsberger, et al. 2014)}$$

Illustris TNG:

$$\Omega_m = 0.38089, \Omega_b = 0.0486,$$

$$\Omega_\Lambda = 0.6911, h = 0.6774$$

(Planck Collaboration, et al. 2016)

- ★ The Illustris project is a suite of state-of-the-art cosmological galaxy formation simulations. Each simulation in IllustrisTNG evolves a large swath of a mock Universe from soon after the Big-Bang until the present day while taking into account a wide range of physical processes that drive galaxy formation.
- ★ TNG300, hydrodynamical simulations have reached a sufficient volume and resolution to study clustering of all matter components in The Universe on the relevant scales.
- ★ **Free Data access.**

Mutual Information (MI)

Joint probability density function

$$MI(x, y) = \int_x \int_y P(x, y) \ln \left(\frac{P(x, y)}{P(x)P(y)} \right) dx dy,$$

Marginal probability density functions

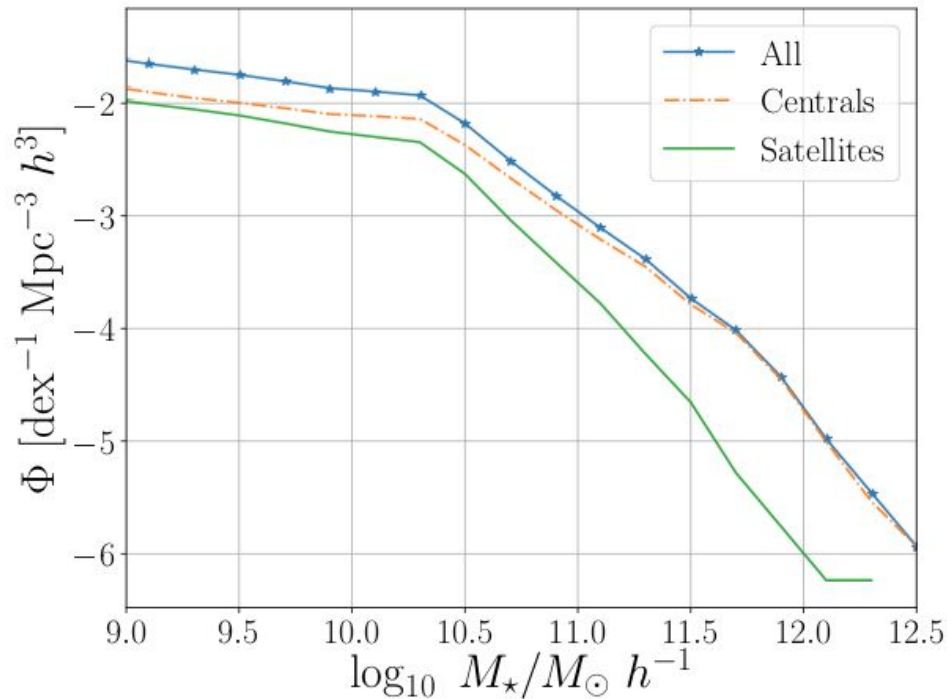
The MI quantifies the reduction in uncertainty of variable y based on the knowledge of variable x . If x and y are independent, $MI(x, y) = 0$

The MI captures non-linear dependencies.





Data Samples



Stellar mass functions for all galaxies and their partition into Centrals and satellites. Although the mass resolution in TNG300-1 resolves individual galaxies below $10^9 M_{\odot} h^{-1}$ we use this value as a threshold because galaxies above this mass have an appropriate resolution in the formation history to estimate their assembly time.

Galaxy Mass (M_{\star}): Sum of masses of all particles/ The stellar mass within twice the stellar half-mass radius of each subhalo $z=0$.

$$10^9 \leq M_{\star}[M_{\odot}h^{-1}] \leq 10^{11.5}$$

We impose a minimum of 10^3 galaxies in a mass bin of 0.25 dex.

DM Halo Mass (M_H): Is estimated using the total mass enclosed within a sphere whose mean density is 200 times the critical density of the universe at $z=0$.



Previously:

Using the Mutual Information

Our goal is to study the relationship between:

Assembly time of galaxies (z_G): Redshift at which the galaxy in the branch reaches exactly half of its stellar mass at $z=0$.

specific Star Formation Rate (sSFR): The Star Formation Rate (SFR) of all gas cells in each subhalo, normalized by its stellar mass.

$$sSFR = \frac{SFR}{M_\star}$$

Galaxy Color (g-i): Are computed by summing up the luminosities of stellar particles of each subhalo.

and their

Assembly time their host DM halos (z_H): Redshift at which the DM Halo in the branch reaches exactly half of halo mass at $z=0$.

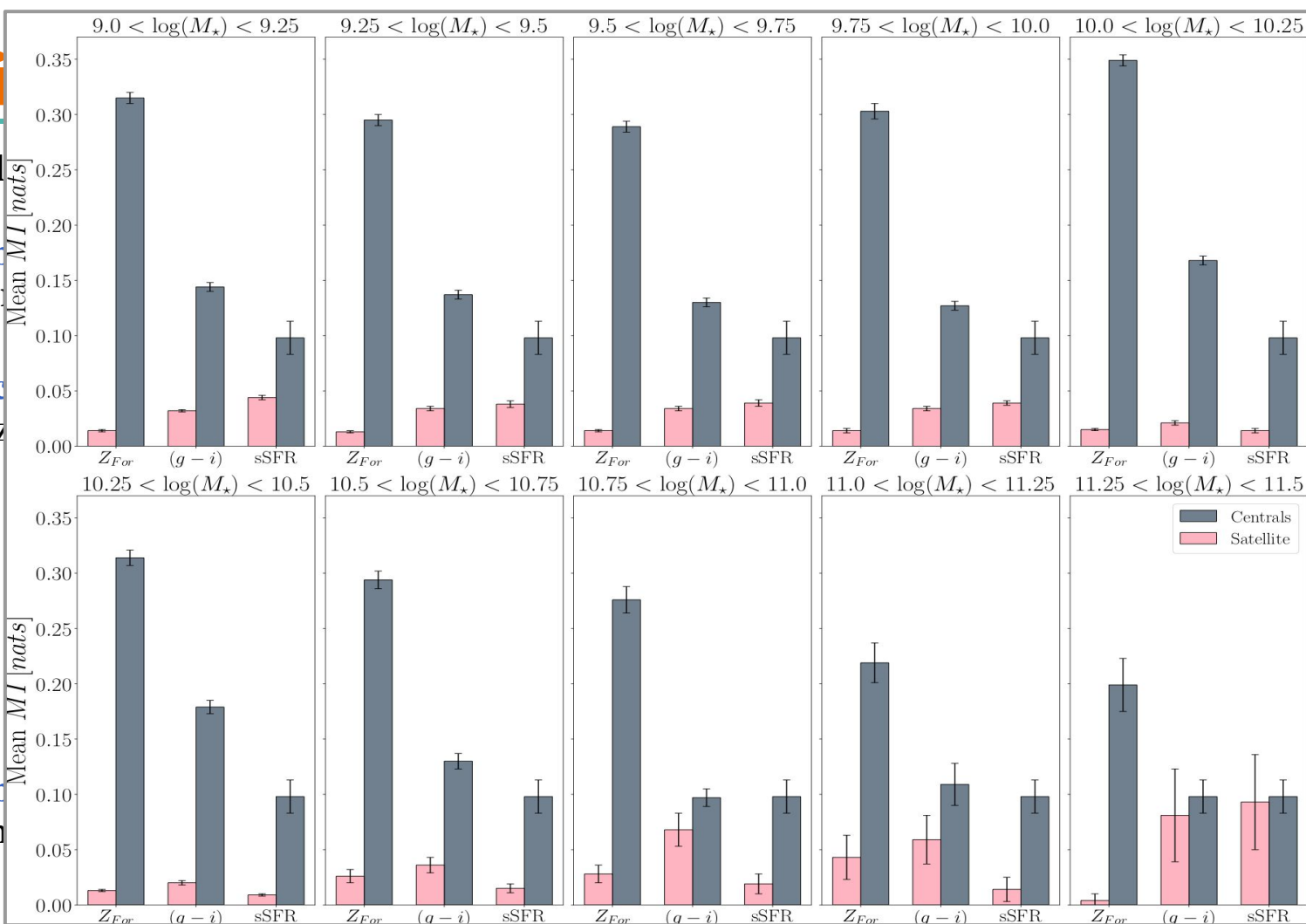


Information

exactly half of
each subhalo,

in subhalo.

which reaches



Previous

Our goal

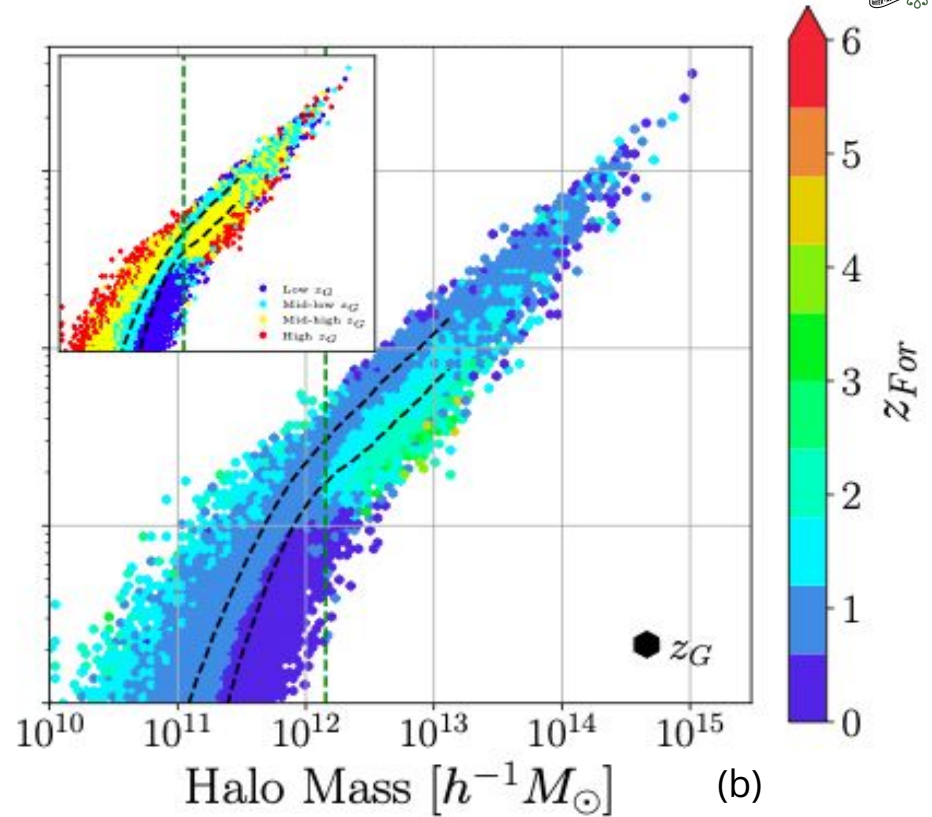
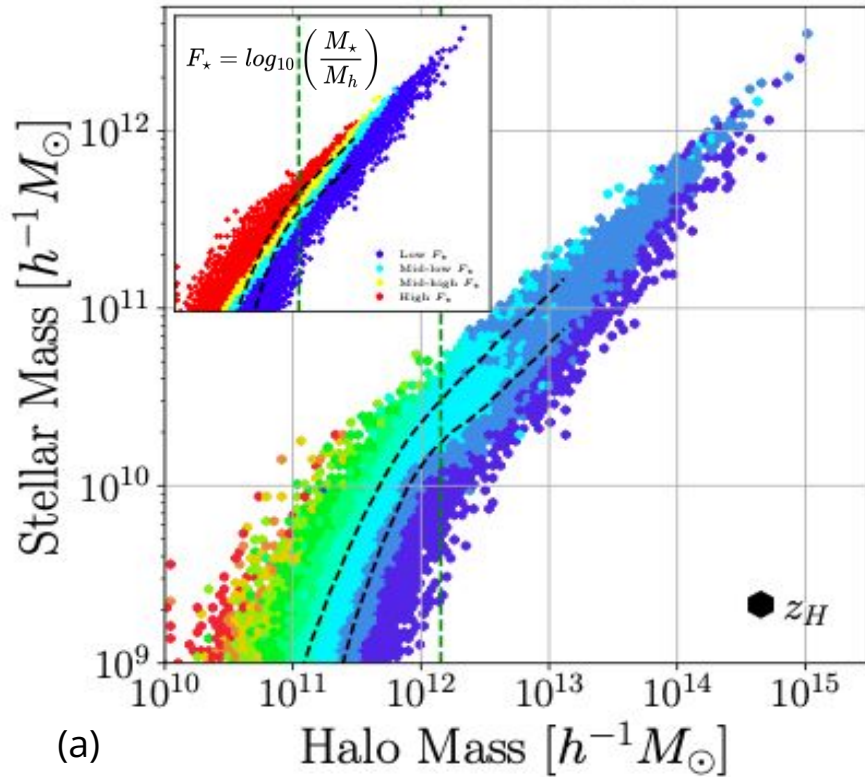
Assemble
its stellar

specific
normaliz

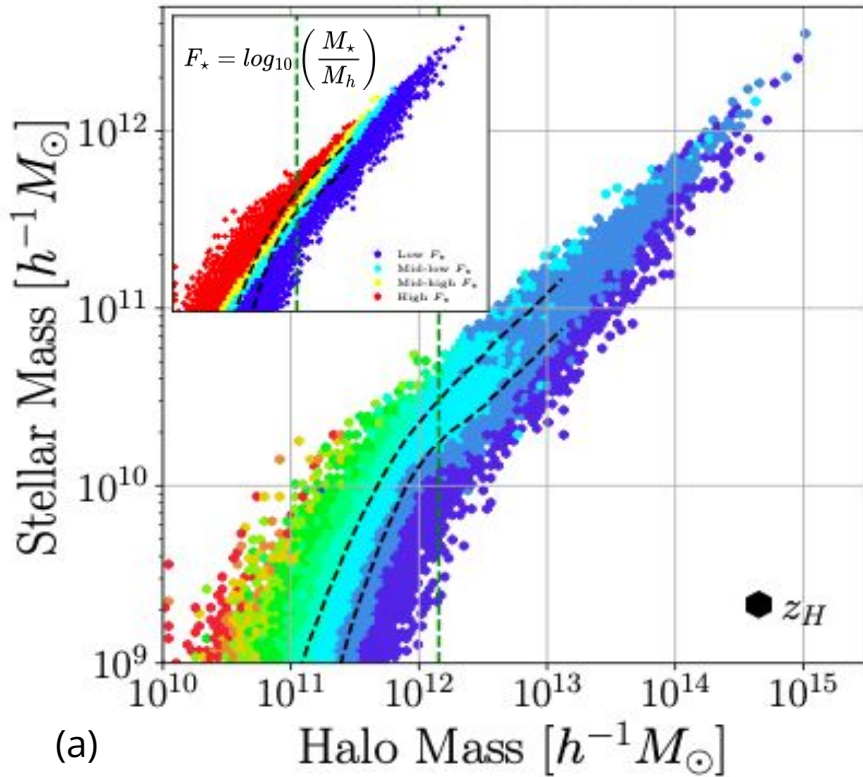
Galaxy

Assemble
exactly h

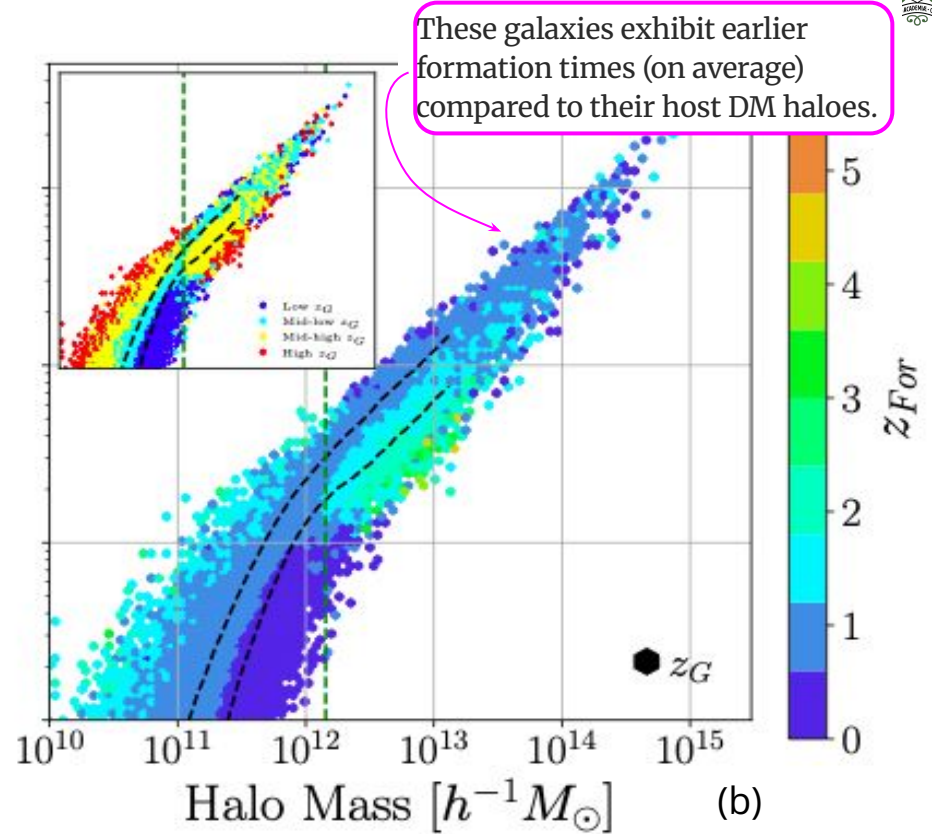
Stellar to Halo Mass relation (SHMR)



Stellar to Halo Mass relation (SHMR)



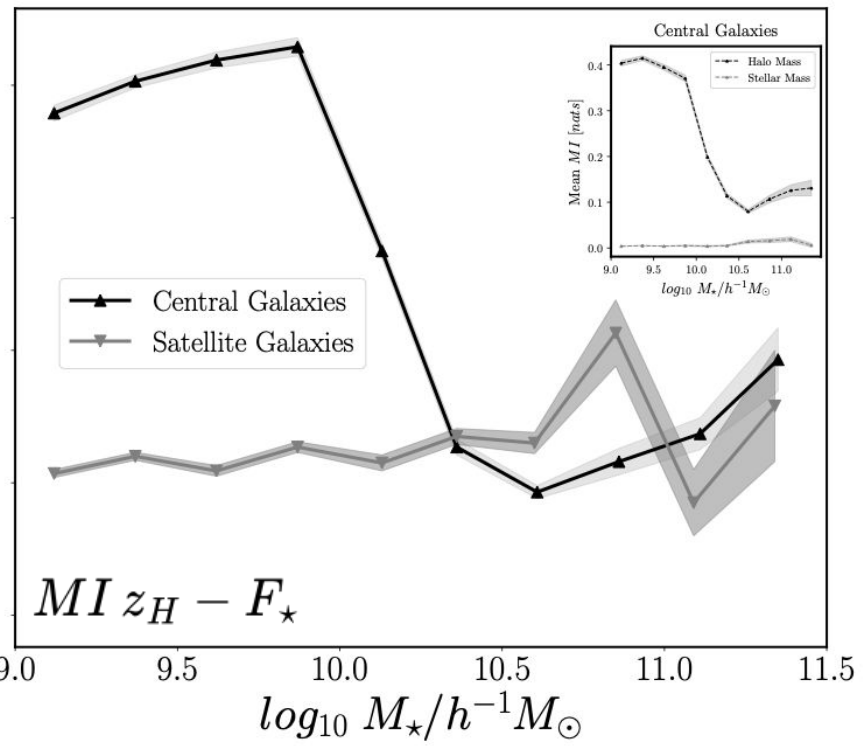
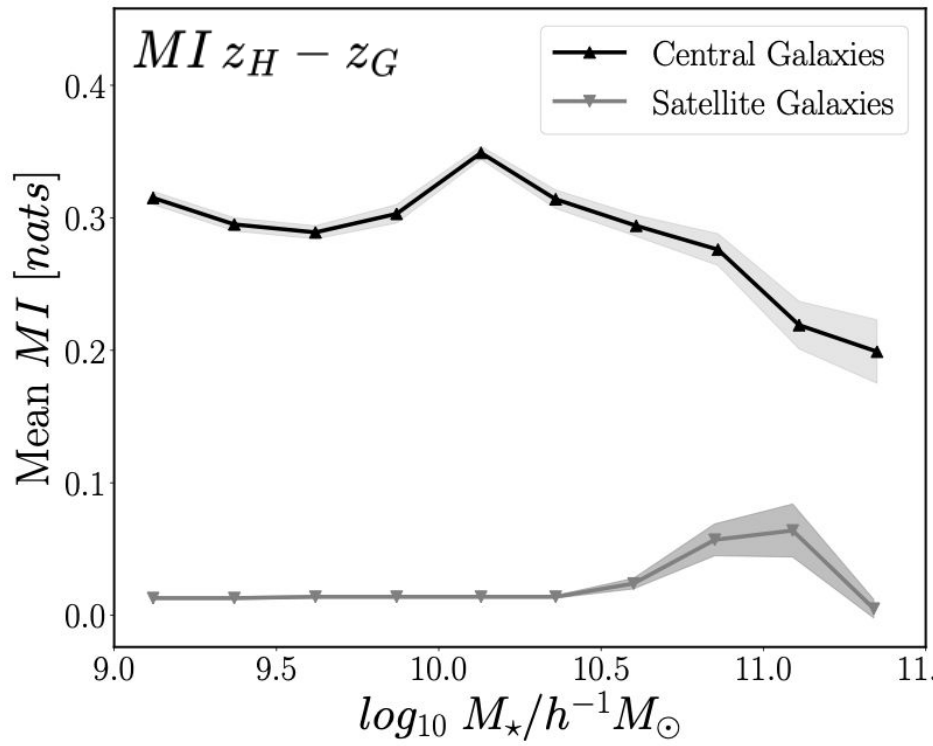
(a)



(b)

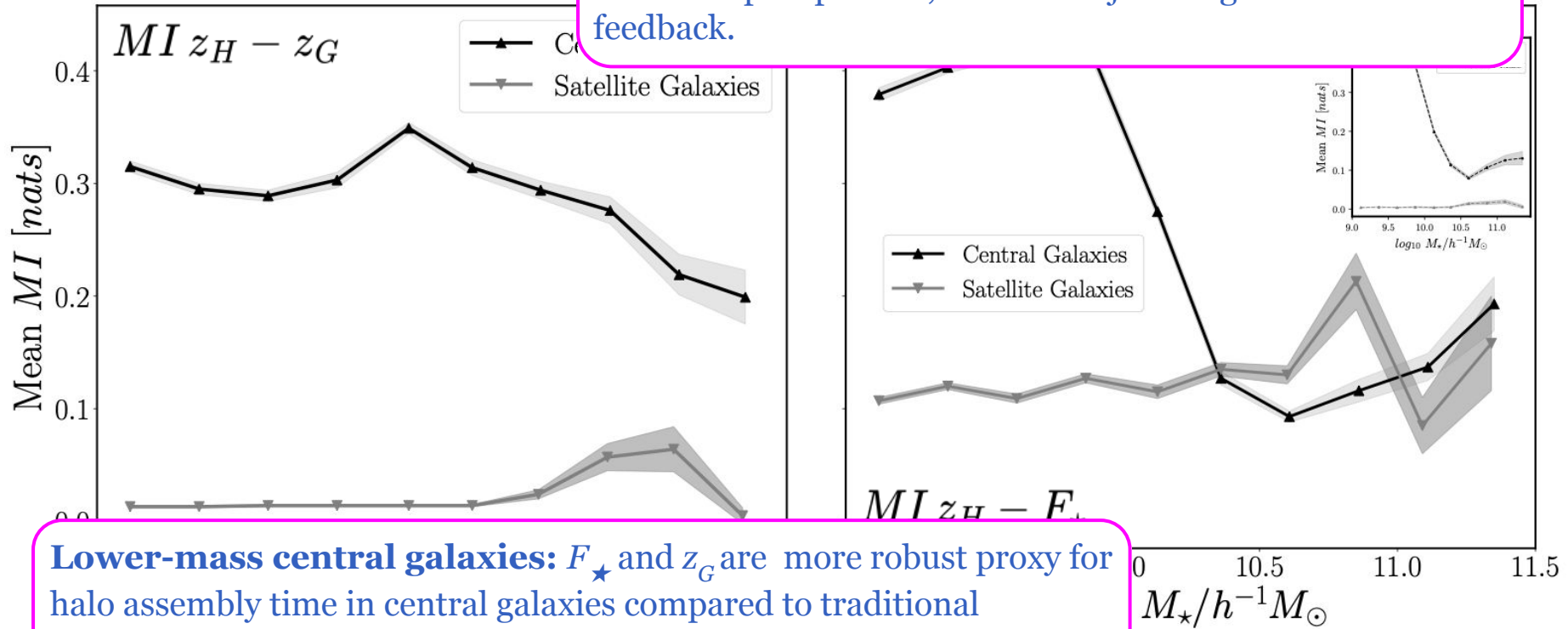


Results

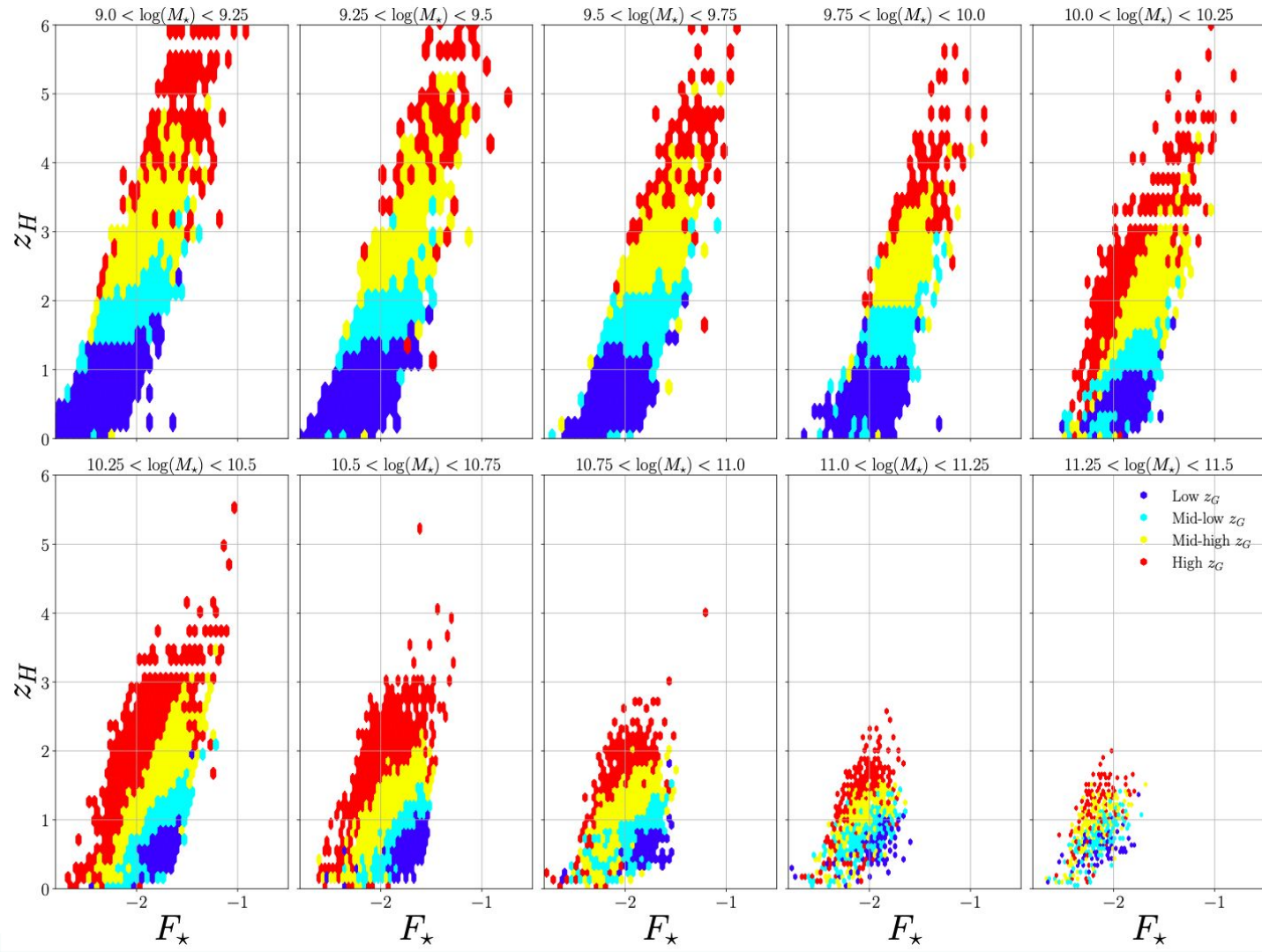


Results

Higher-mass central galaxies exhibit a weaker correlation, indicating that their formation history involve more complex process, such as major mergers and AGN feedback.



Lower-mass central galaxies: F_\star and z_G are more robust proxy for halo assembly time in central galaxies compared to traditional measures like colour (g-i) and sSFR.





Objective:

Using the Mutual Information

Cluster Observables: Halos that host a central galaxy (in our stellar mass range), together with their satellite population selected by r-band absolute magnitude $M_r < -19$.

Magnitude Gap: Difference in r-band absolute magnitude $M_r < -19$ between the central galaxy and the k-th brightest satellite (k=1 and k=4)

At fixed halo mass, early-assembling halos are more likely to have the central accrete or tidally disrupt nearby massive satellites, leaving fainter survivors and thus increasing the r-band magnitude gap.

and their

Assembly time their host DM halos (z_H): Redshift at which the DM Halo in the branch reaches exactly half of halo mass at $z=0$.



Objective:

Using the Mutual Information

Cluster Observables: Halos that host a central galaxy (in our stellar mass range), together with their satellite population selected by r-band absolute magnitude $M_r < -19$.

Nearest-satellite distance : Distance from the central galaxy to the nearest and to the fourth-nearest satellite

At fixed halo mass, early-assembling halos have already merged with their innermost luminous satellites via dynamical friction; thus the nearest surviving (bright) satellite lies at larger radii.

and their

Assembly time their host DM halos (z_H): Redshift at which the DM Halo in the branch reaches exactly half of halo mass at $z=0$.



Using the Mutual Information

Objective:

Cluster Observables: Halos that host a central galaxy (in our stellar mass range), together with their satellite population selected by r-band absolute magnitude $M_r < -19$.

Distance to brightness: Distance from the central galaxy to the second fourth brightest satellite.

At fixed halo mass, early-assembling halos are more likely to have had their brightest satellites merge with the central galaxy via dynamical friction; the surviving brightest satellites therefore reside at larger radii, increasing the distance to the brightest satellite (on average). Conversely, in younger halos, the brightest satellite is typically found at smaller radii.

and their

Assembly time their host DM halos (z_H): Redshift at which the DM Halo in the branch reaches exactly half of halo mass at $z=0$.



Using the Mutual Information

Objective:

Cluster Observables: Halos that host a central galaxy (in our stellar mass range), together with their satellite population selected by r-band absolute magnitude $M_r < -19$.

Richness: Number of satellites per halo with $M_r < -19$

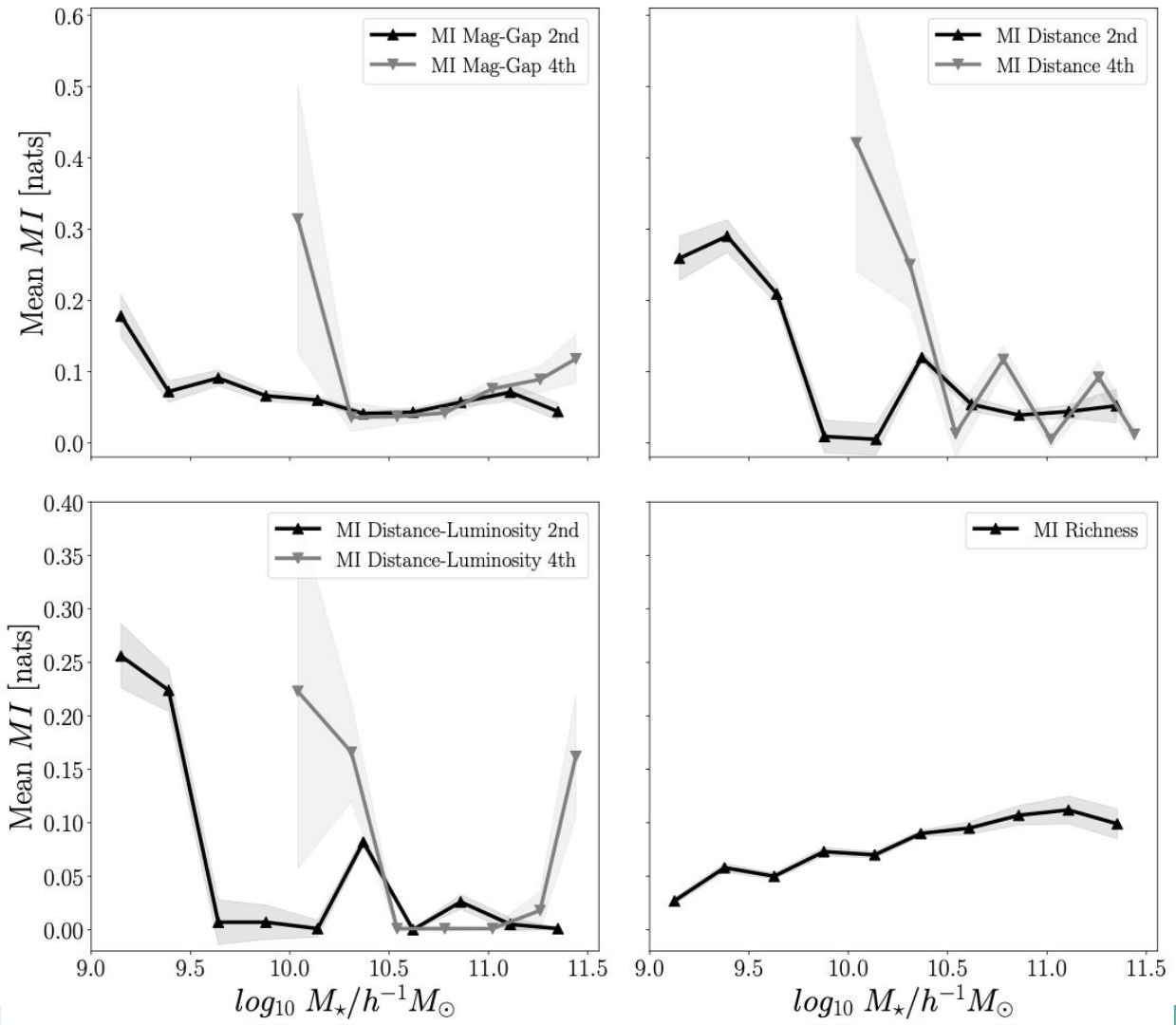
At fixed halo mass, early-assembling halos host fewer satellites; mergers with the central and tidal stripping reduce richness on average.

and their

Assembly time their host DM halos (z_H): Redshift at which the DM Halo in the branch reaches exactly half of halo mass at $z=0$.

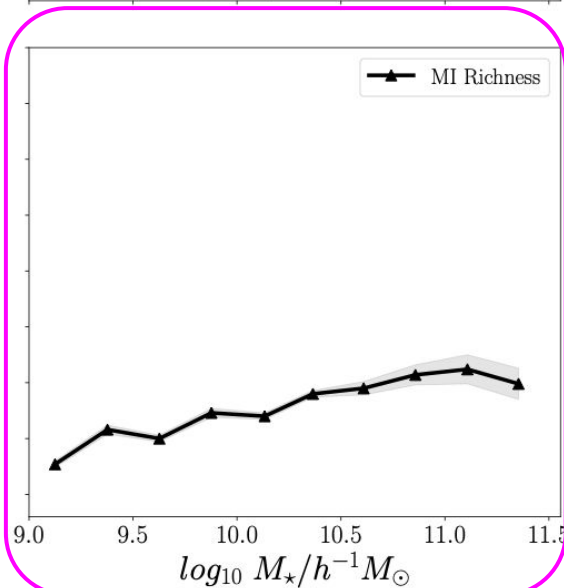
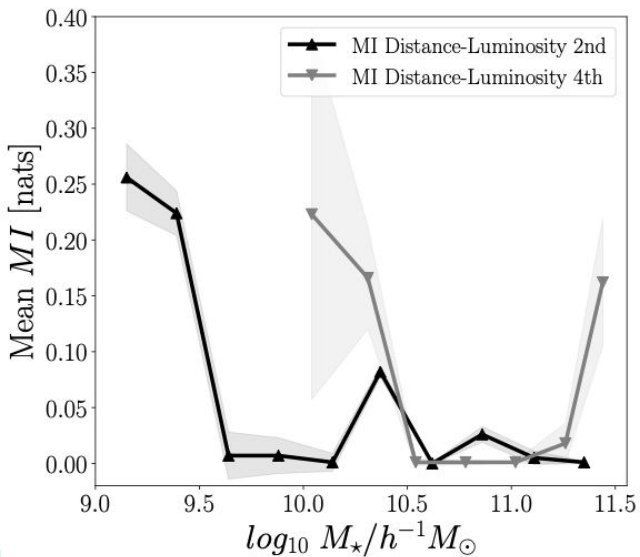
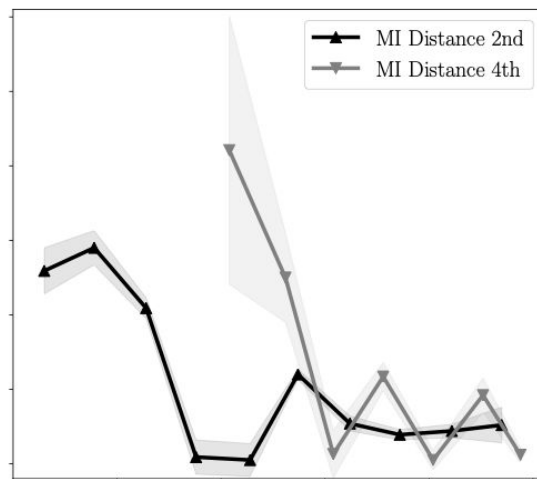
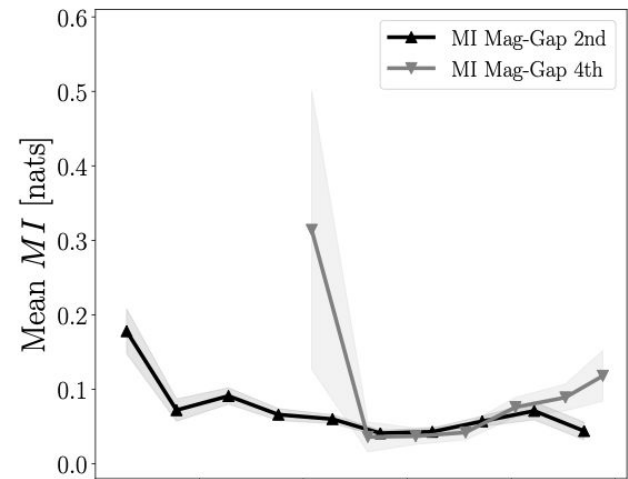


Mutual Information

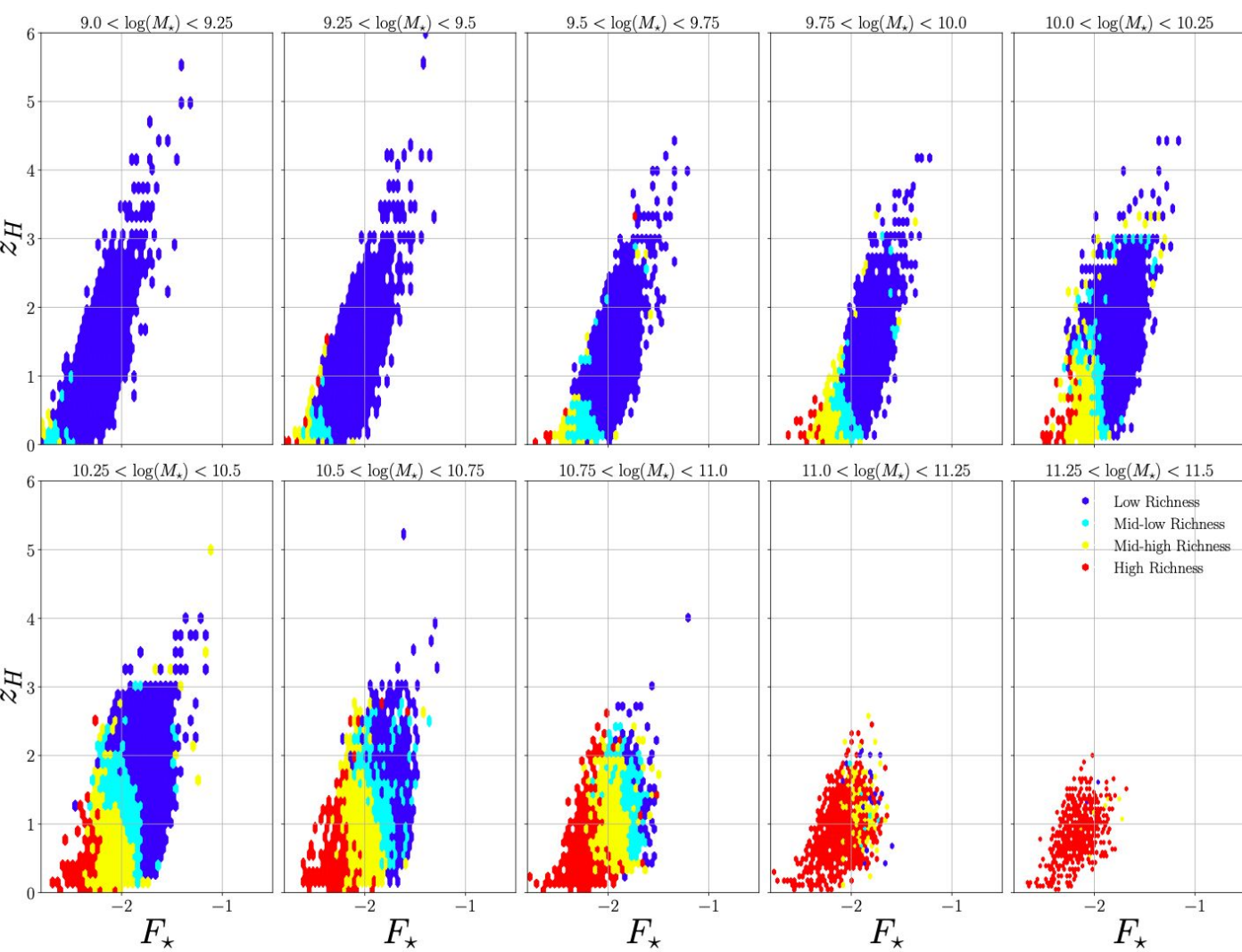




Mutual Information



The richness of satellite populations emerges as a slightly stronger proxy. The MI Satellite richness **increases with stellar mass**; hence it becomes a **more effective tracer** of formation history in **massive haloes**. This trend suggest that in massive haloes, richness correlates more closely with halo assembly history than other metrics, such as the magnitude gap, the distance to the closest satellite, or the distance to the brightest satellite. **This reflects prolonged hierarchical growth and satellite accretion in such systems.**



For low-mass haloes, high F_* and early assembly times are associated with lower richness, while low F_* and late assembly times correspond to an increase in the number of satellites.

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