THE GALAXY-DARK MATTER HALO CONNECTION: PREDICTIONS FROM HYDRODYNAMICAL SIMULATIONS

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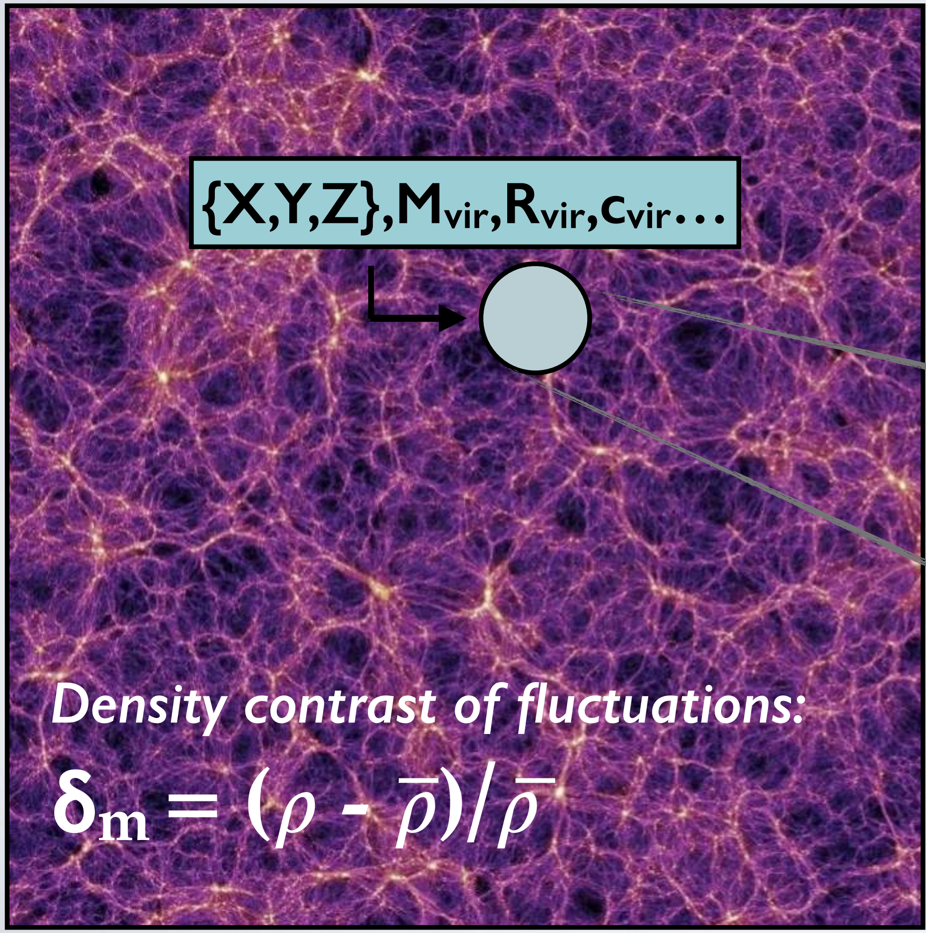
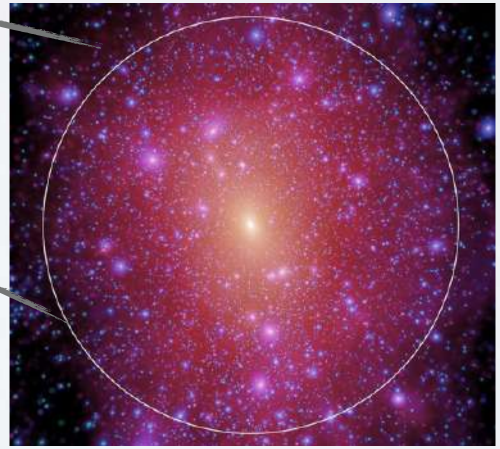
OUTLINE

1. Introduction: the Galaxy-Halo Connection
2. The Methodology: Hydrodynamical Cosmological Simulations
3. The Manifestation of Secondary Halo Bias on the Galaxy Population
4. Halo Assembly Bias and Occupancy Variations
5. Probing Secondary Halo Properties with observations: Kinetic Sunyaev Zel'dovich effect & Spin Bias
6. Summary

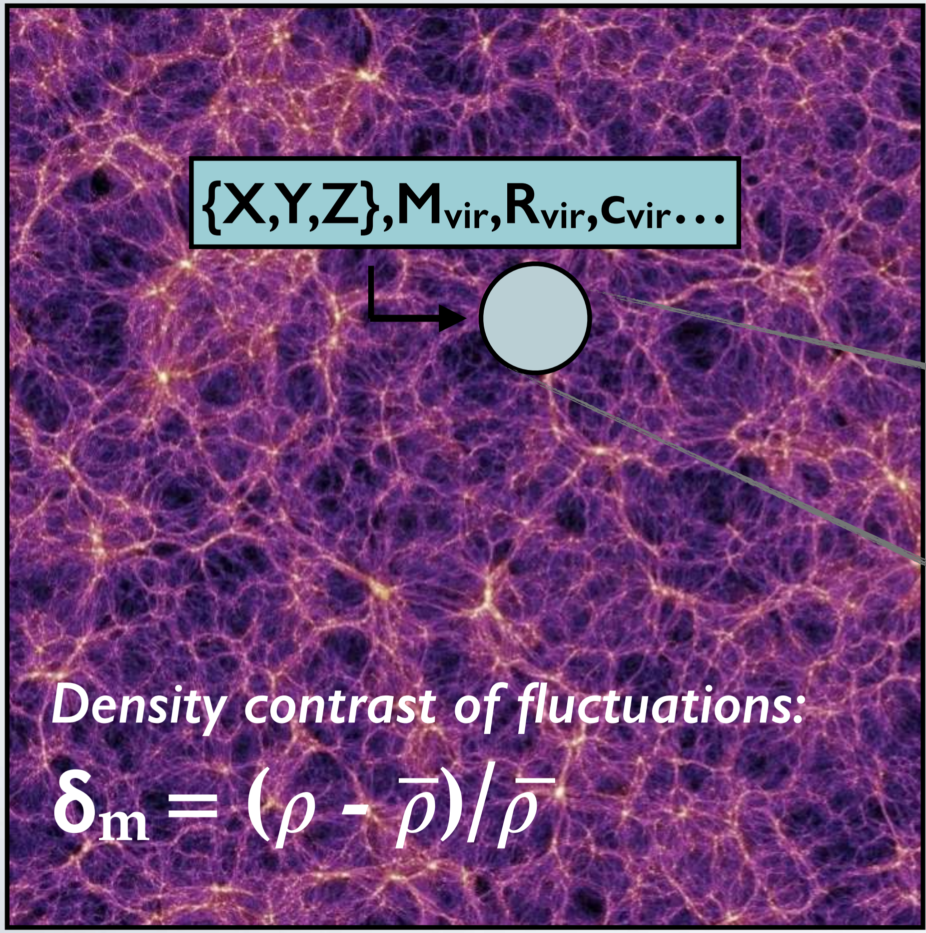
THE GALAXY-HALO CONNECTION



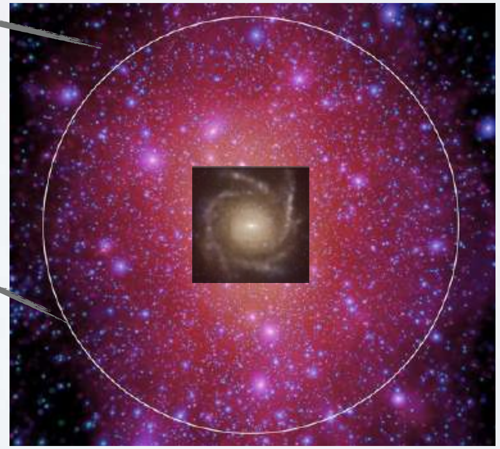
- In a Λ-CDM cosmological scenario (cold dark matter, baryons and dark energy)
- Fluctuations in the matter distribution were produced in the Inflation period
- Gravitational instability grew these fluctuations over time, producing virialized objects that separates from the expansion of the Universe and continue collapsing



THE GALAXY-HALO CONNECTION



- Dark matter is the skeleton in which galaxies form, evolve, and merge
- In this context, it is expected that the internal properties, and spatial distribution of galaxies are likely to be closely connected to the growth, internal properties, and spatial distribution of dark matter halos.



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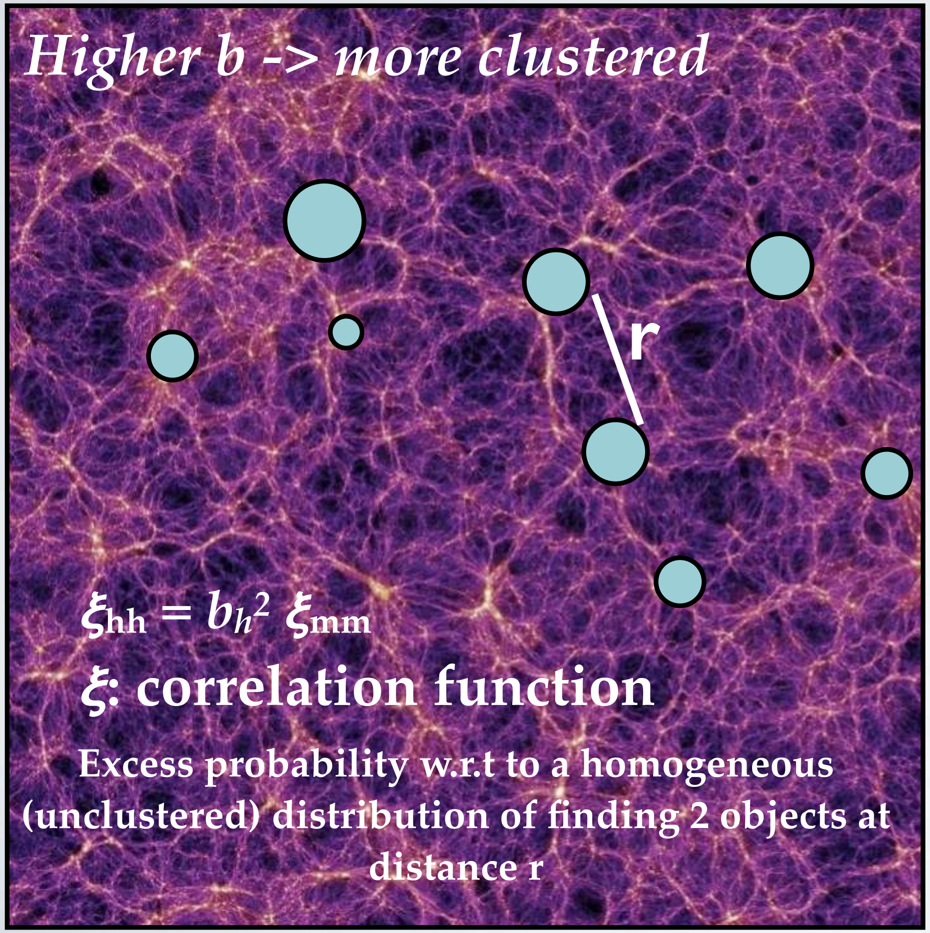
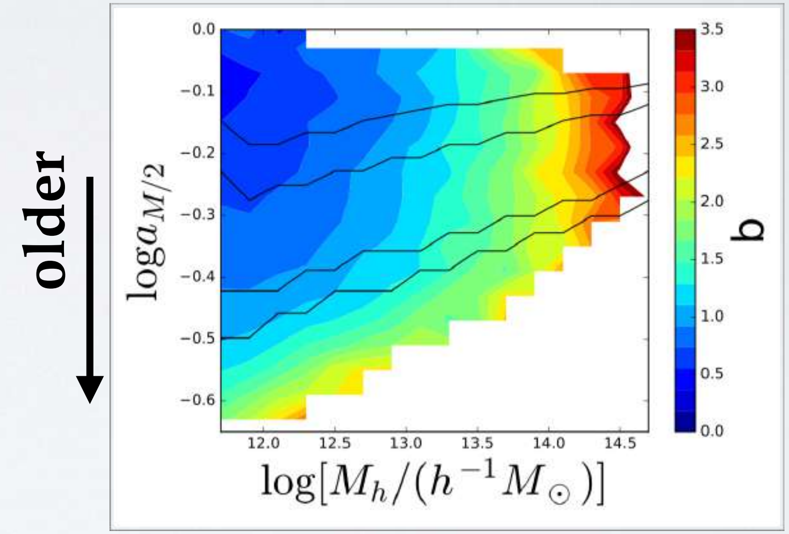


Halo Clustering depends primarily on halo mass

However, secondary halo properties (at fixed halo mass) also affect the spatial distribution of the dark matter haloes: **Secondary Halo Bias**



[Xu & Zheng (2018)]

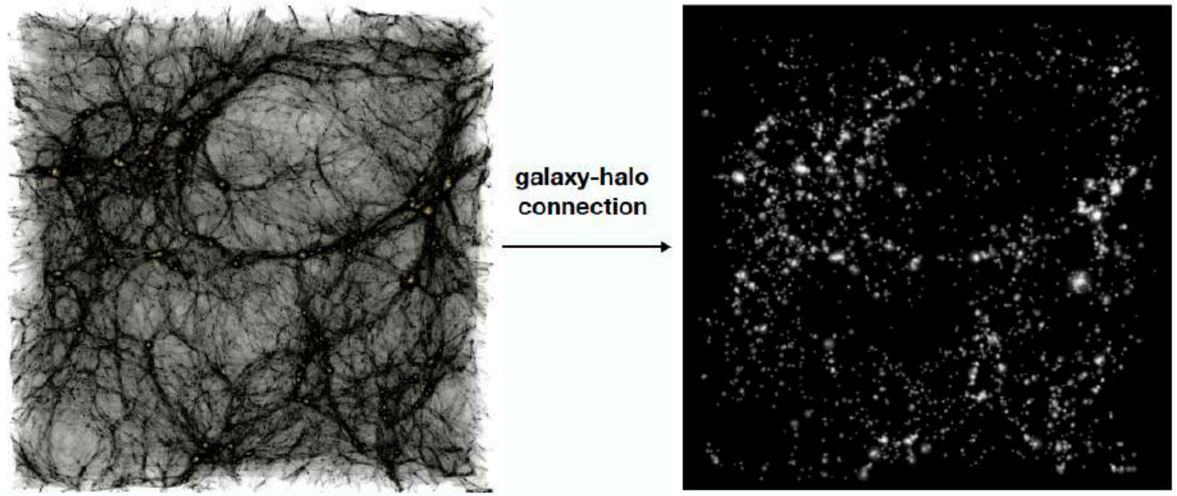
Halo Assembly Bias: Haloes that assemble earlier are more clustered than haloes that form at later times, at fixed halo mass

THE GALAXY-HALO CONNECTION

The Galaxy-Halo connection is important for:

- The physics behind galaxy formation
- Cosmology: cosmological parameters
- Properties and distribution of dark matter

- What halo property best matches with galaxies?
- What galaxy property best matches with halos?



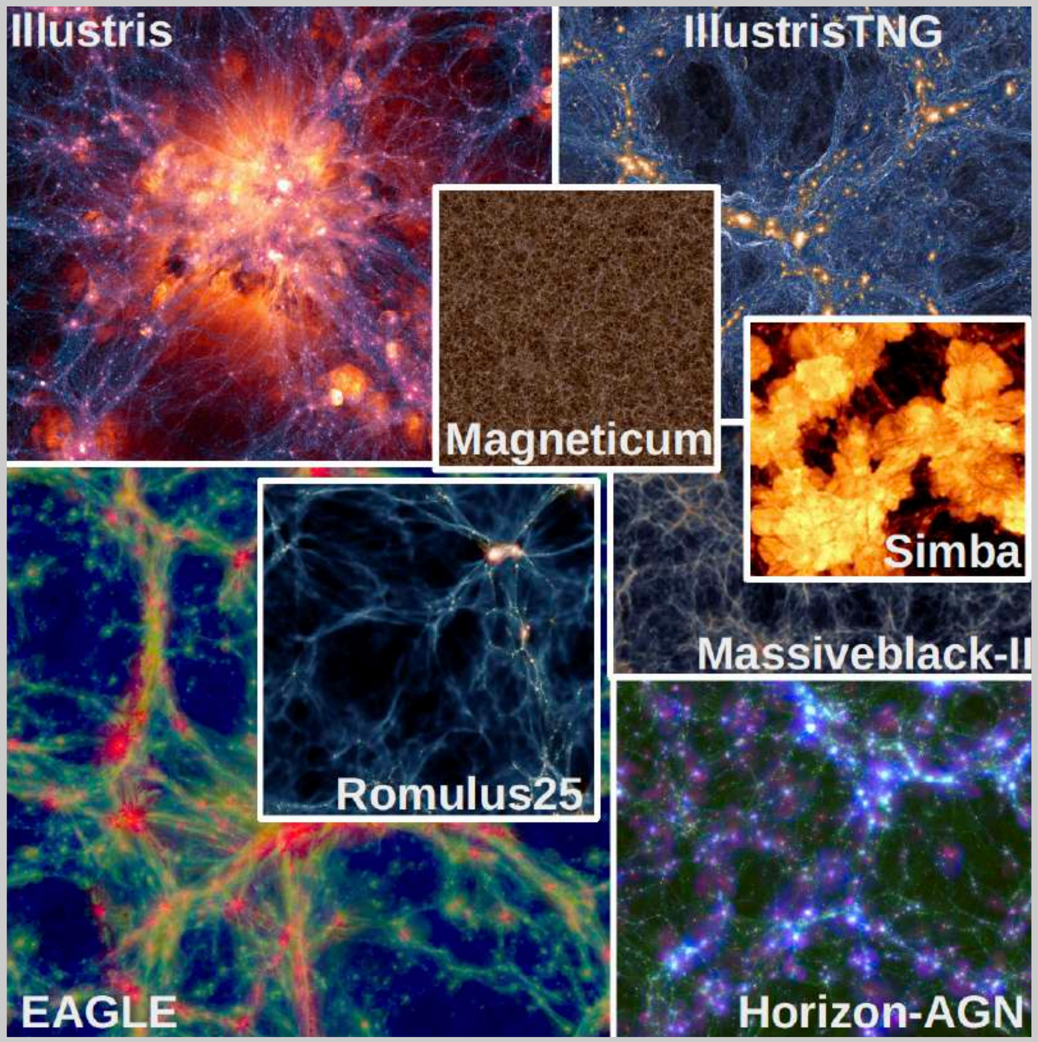
Approaches to modeling the galaxy-halo connection

← physical models | empirical models →

Hydrodynamical Simulations	Semi-analytic Models	Empirical Forward Modeling	Subhalo Abundance Modeling	Halo Occupation Models
Simulate halos & gas; Star formation & feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos & subhalos) plus assumptions about galaxy—(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

[Wechsler & Tinker (2018), Review]

HYDRODYNAMICAL COSMOLOGICAL SIMULATIONS



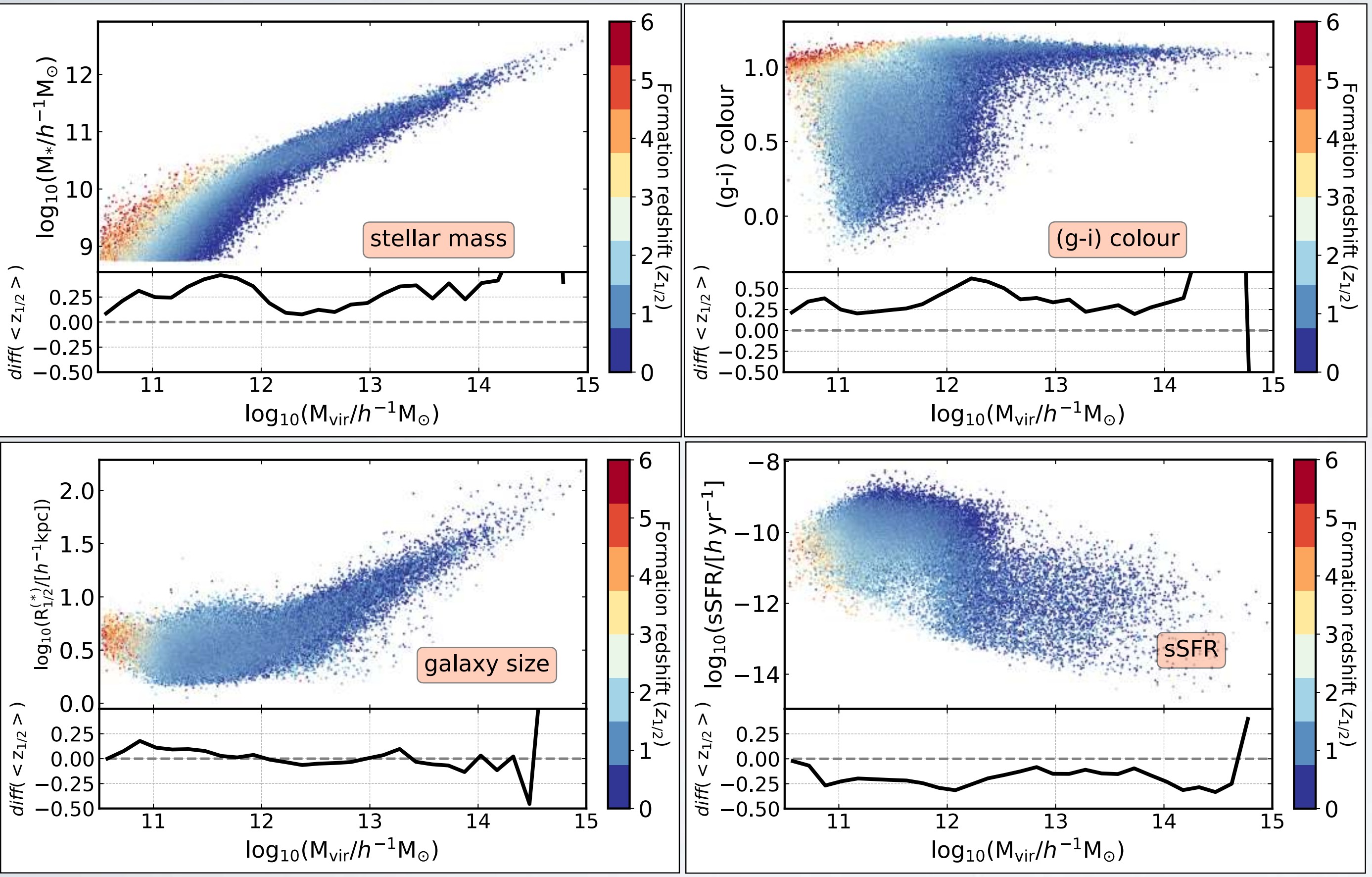
[Vogelsberger et al. (2020), Review]

Pros	Cons
They can track dark matter together with baryons self-consistently	Computationally expensive in comparison with dark matter only N-body simulations
Large volume suited to investigate the global properties of the galaxy population	Simulated boxes are small compared with those from SAM
Unlike SAM, hydrodynamical cosmological simulations allow studying the internal properties of galaxies together with large-scale properties in a self-consistent way	Different sub-grid parameters are calibrated to reproduce observational trends such as the SMF, galaxy sizes, etc

ILLUSTRIS-TNG

- Magneto-hydrodynamical simulation that builds on previous Illustris projects (Springel et al., 2018, Pillepich et al. 2018)
- Includes sub-grid models for star formation, stellar and AGN feedback, radiative metal-line gas cooling, and chemical enrichment from SNII, SNIa, and AGB stars.
- $M_{DM} \sim 4 \times 10^7\ h^{-1}M_\odot$; $M_{gas} \sim 7.6 \times 10^6\ h^{-1}M_\odot$
- **TNG300: 205 h^{-1}Mpc side length**
- **(One of the) first to allow for statistically solid secondary-bias measurements** (see e.g., Montero-Dorta et al. 2020B,C; Bose et al. 2019,2020, Hadzhiyska et al. 2020)
- **https://www.tng-project.org**

THE MANIFESTATION OF SECONDARY HALO BIAS ON THE GALAXY POPULATION



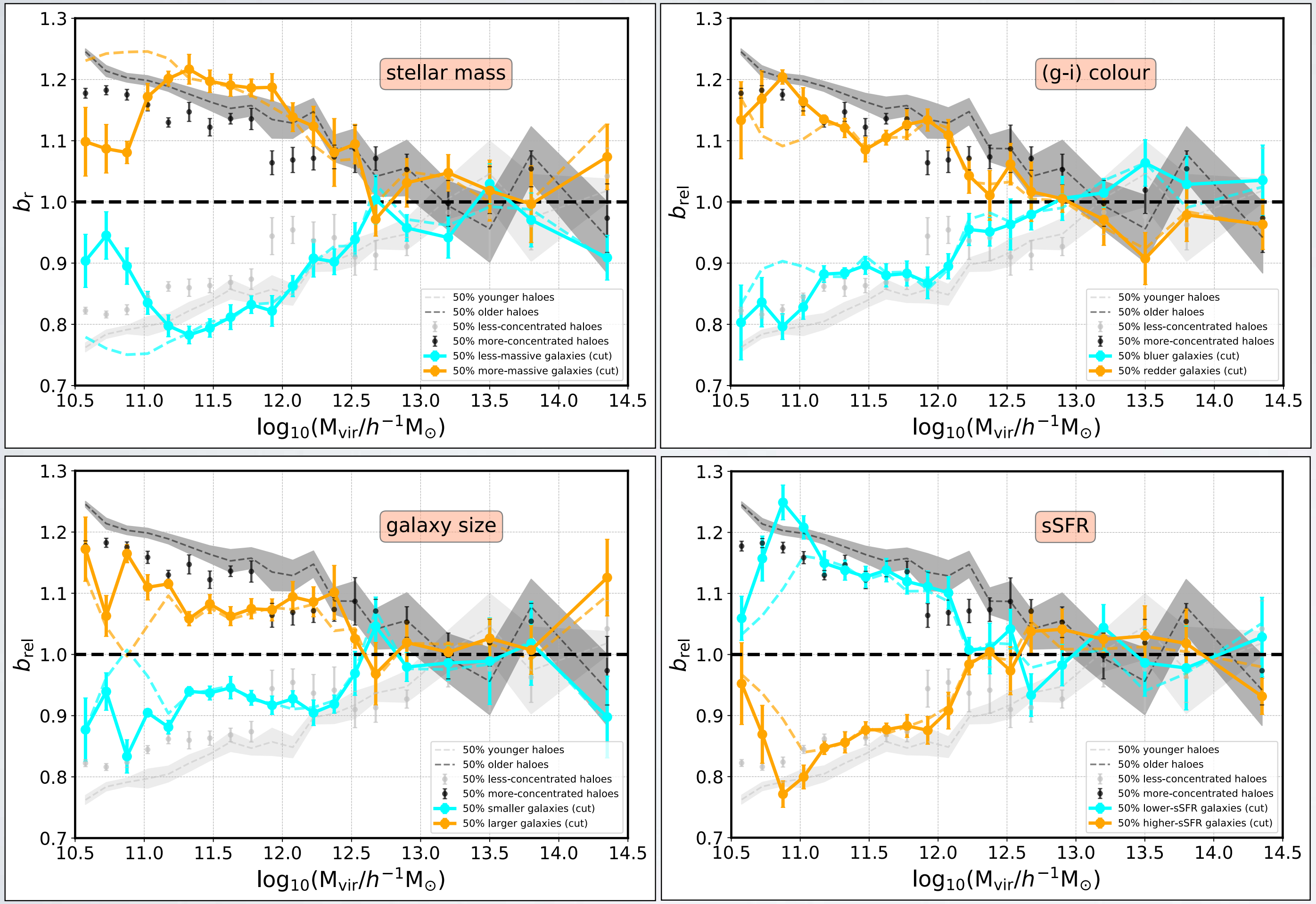
Antonio Montero-Dorta,
USP, Brazil & USM, Chile

At fixed halo mass:

- Older haloes harbour more massive central galaxies than younger haloes. More clear for $M_{vir} < 10^{12.5}\ h^{-1}M_{\odot}$
- Older haloes tend to host redder galaxies than younger haloes.
- Slight dependence of the sSFR of the galaxies with halo age
- Tight correlation of the galaxy size with halo mass

Montero-Dorta, Artale, Abramo, Tucci, Padilla, Sato-Polito, Lacerna, Rodriguez, & Angulo (2020B)

THE MANIFESTATION OF SECONDARY HALO BIAS ON THE GALAXY POPULATION



- At fixed halo mass, the clustering of central galaxies depend on galaxy properties that are correlated with secondary halo properties
- Galaxy size is an interesting case (no clear explanation for signal)

5 < r[Mpc/h] < 15

$$b_{\rm rel}(r, \mathrm{S|B}) = \frac{\xi_{[\mathrm{S,all}]}(r, \mathrm{S})}{\xi_{[\mathrm{B,all}]}(r, \mathrm{B})}$$

Montero-Dorta, Artale, Abramo, Tucci, Padilla, Sato-Polito, Lacerna, Rodriguez, & Angulo (2020B)

HALO ASSEMBLY BIAS AND OCCUPANCY VARIATIONS

Galaxy Assembly Bias

=

Halo Assembly Bias + Occupancy Variations?

Occupancy variations in hydrodynamical cosmological simulations (EAGLE and Illustris)

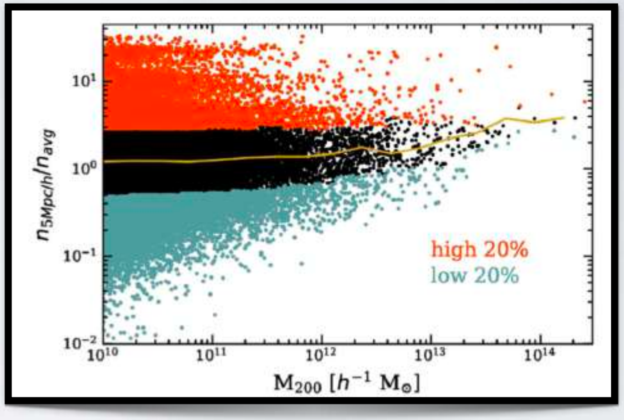
Large-scale environment of the haloes

High/Low dense regions

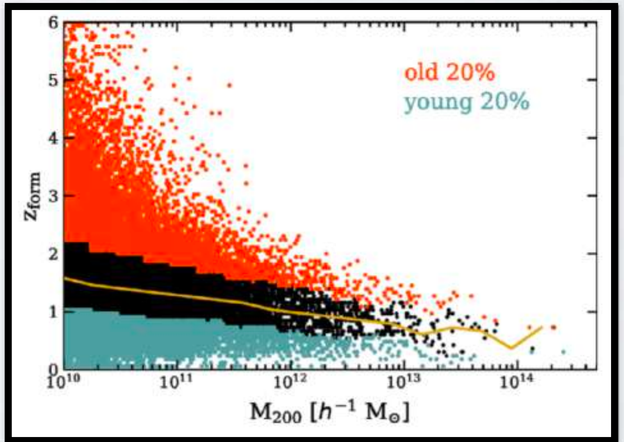
vs.

Formation time of the haloes

Old/Young haloes



Environment: count the number of subhaloes within a sphere of 5 h^{-1}Mpc



Formation time: the redshift at which the halo gained half of its present-day mass

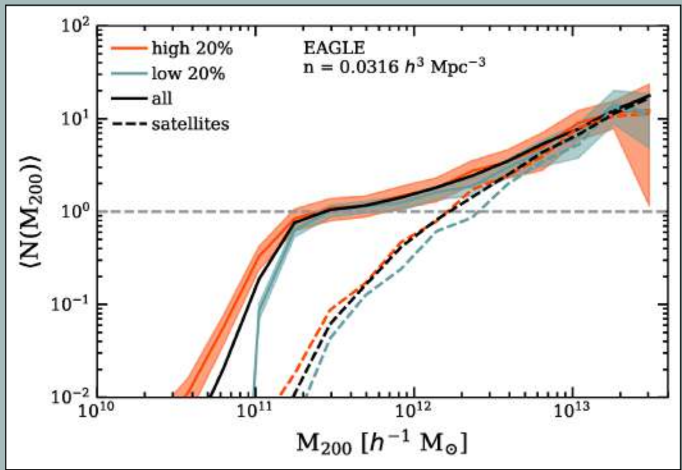
Artale, Zehavi, Contreras, & Norberg (2018), arXiv:1805.06938

HALO ASSEMBLY BIAS AND OCCUPANCY VARIATIONS

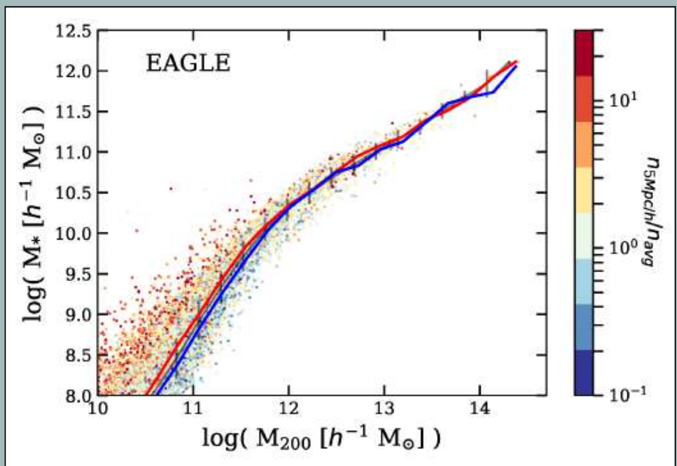
Artale et al. (2018)

Environment

Below to 2x $10^{11} h^{-1} M_{\odot}$ ($10^{12} h^{-1} M_{\odot}$): haloes in densest regions are more likely to host a central galaxy on average than those in low dense environments

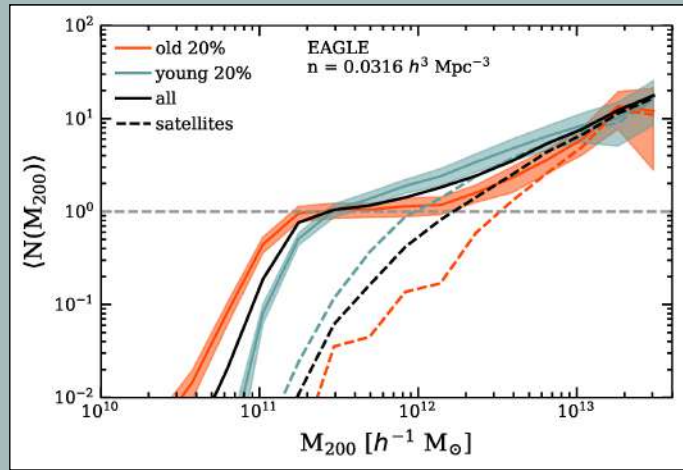


Below to $10^{12} h^{-1} M_{\odot}$: more massive centrals in denser environments

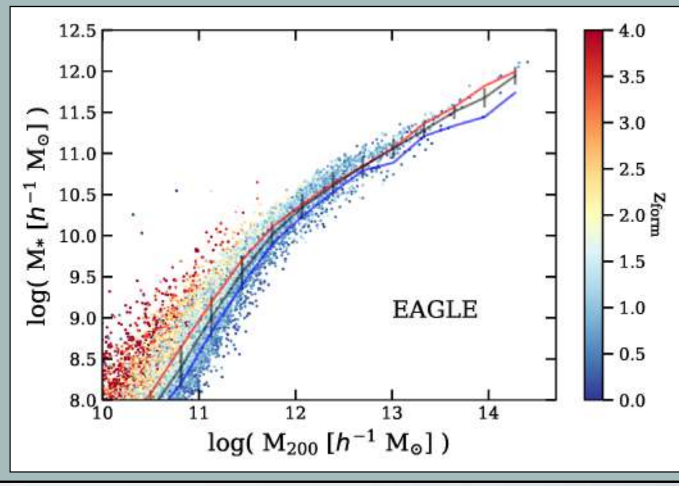


Formation Time

Low mass haloes: early-formed haloes (old) are more likely to have a central galaxy than late-formed haloes (young). This trend reverses at high mass haloes

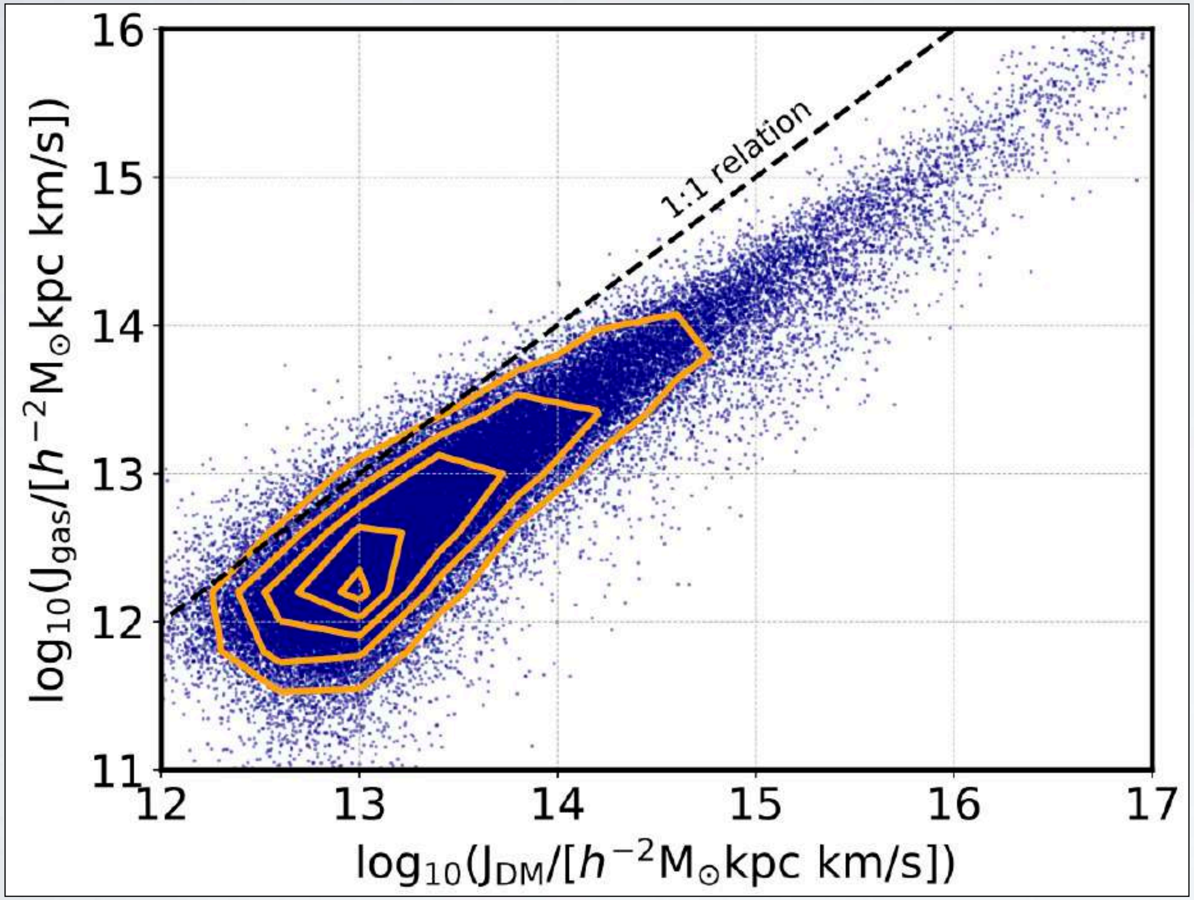


Central galaxies in early-formed haloes are more massive than in late-formed haloes



CAN WE DETECT THE SECONDARY HALO BIAS?

In particular: Halo Spin Bias



Angular momentum of the gas as a function of the angular momentum of the DM haloes in IllustrisTNG300

Spin defined as in Bullock et al. (2001)

$$\lambda = \frac{|\mathrm{J}|}{\sqrt{2}\,\mathrm{M_{vir}}\mathrm{V_{vir}}\mathrm{R_{vir}}}$$

Despite the turbulent movement of gas inside halos, a good level of correlation between gas angular momentum and total angular momentum is preserved

SUNYAEV-ZEL'DOVICH EFFECT

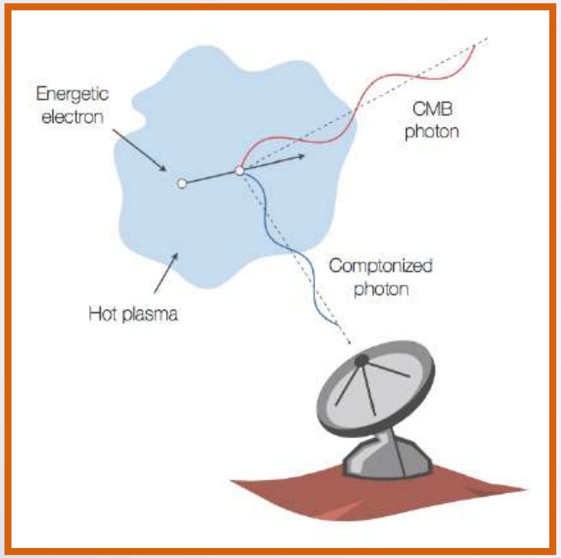
Sunyaev & Zel'dovich (1970-1980)

Thermal SZ effect (tSZ):

random motion of e^-

$$y(\vec{n}) \equiv \frac{\sigma_T k_b}{m_e c^2} \int_{los} dl\, T_e\, n_e$$

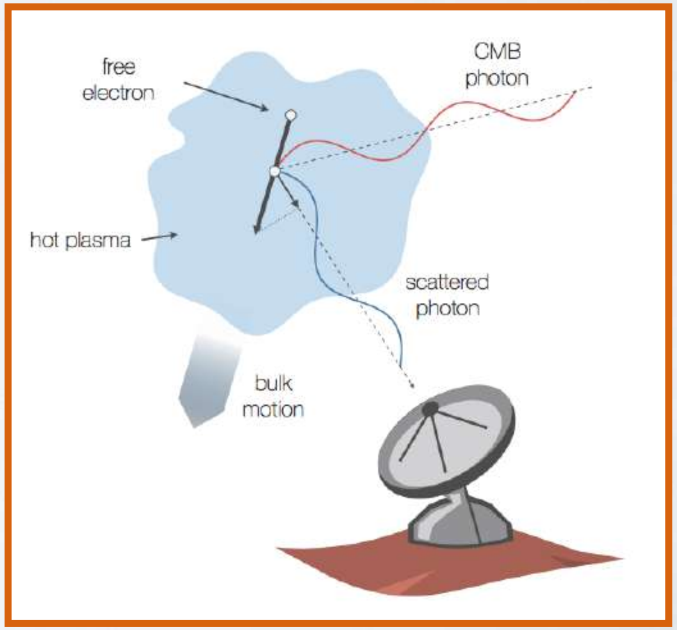
$$\left[\frac{\Delta T}{T_{\rm CMB}}\right]_{\rm tSZ} (\vec{n}) = g(x) y(\vec{n})$$



Kinetic SZ effect (kSZ):

bulk motion of e^-

$$\left[\frac{\Delta T}{T_{\rm CMB}}\right]_{\rm kSZ} (\vec{n}) = \frac{\sigma_T}{c} \int_{los} dl\; n_e\, \vec{v} \cdot \vec{n},$$

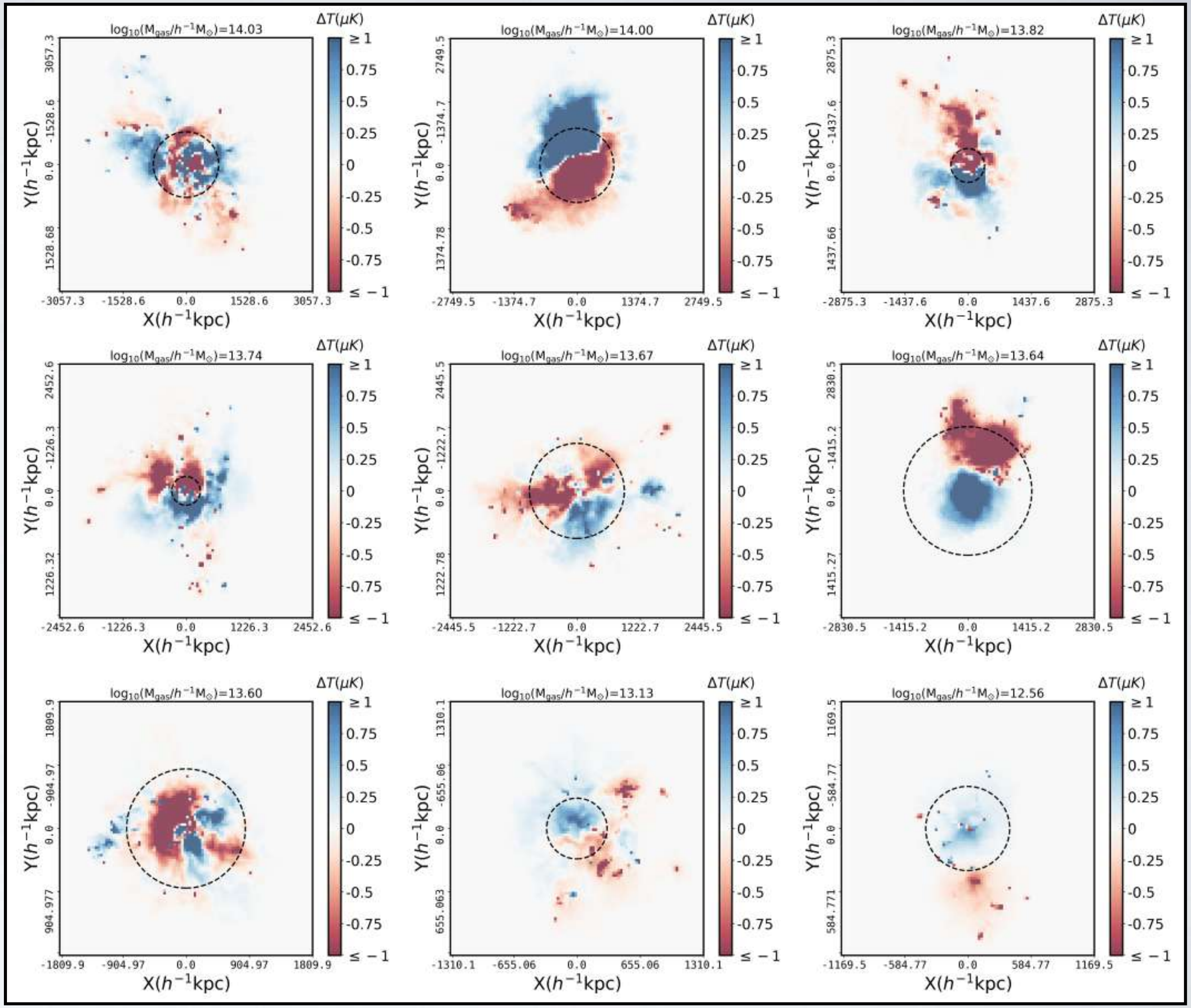


MEASUREMENT IN ILLUSTRISTNG300

Kinetic SZ effect (kSZ):

$$\left[\frac{\Delta T}{T_{\rm CMB}}\right]_{\rm kSZ}(\vec{n}) = \frac{\sigma_T}{c}\int_{los} dl\; n_e\; \vec{v}\;\cdot\;\vec{n},$$

- Subtract "group" velocity
- Assume that *los* lies perpendicular to the computed rotation axis of the halo
- Varying resolution: 20x20 — 60X60 h^{-2}kpc^2 — at z=0.05 ~ 20 arcsec



Montero-Dorta, Artale, Abramo, Tucci (2020, arXiv:2008.08607)

KINETIC SUNYAEV ZEL'DOVICH EFFECT & SPIN BIAS

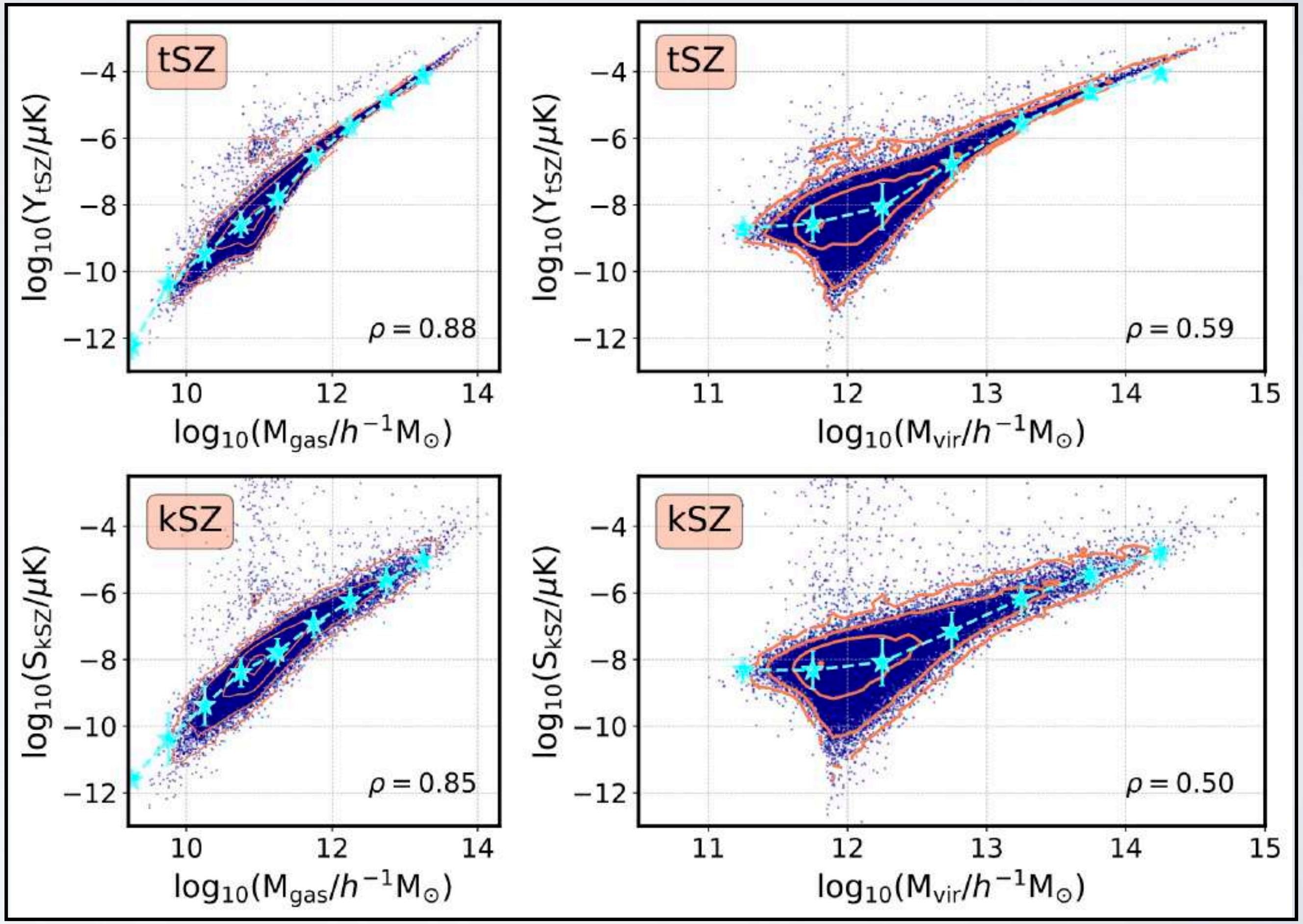
tSZ integrated signal:

$$\mathrm{Y_{tSZ}} = D\ \mathrm{T_{CMB}} \sum_{\mathrm{map}} y(x', y'),$$

kSZ integrated signal:

$$\mathrm{S}^{\theta}_{\mathrm{kSZ}} = D \sum_{+} [\Delta T]_{\mathrm{kSZ}} - D \sum_{-} [\Delta T]_{\mathrm{kSZ}}\,,$$

(dipole)



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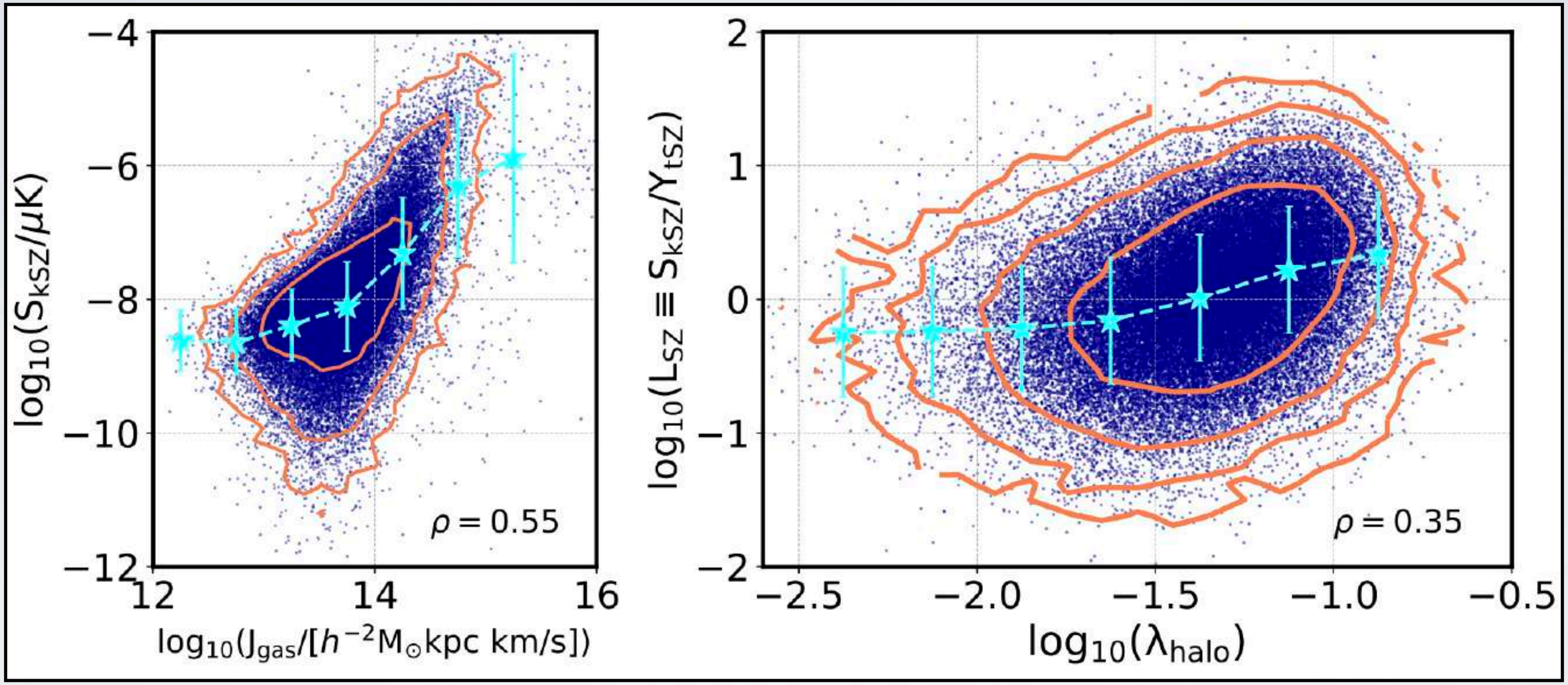
KINETIC SUNYAEV ZEL'DOVICH EFFECT & SPIN BIAS

TRACING HALO SPIN



$$\lambda = \frac{|\mathrm{J}|}{\sqrt{2}\,\mathrm{M_{vir}}\mathrm{V_{vir}}\mathrm{R_{vir}}}$$

Bullock et al. (2001)

↔

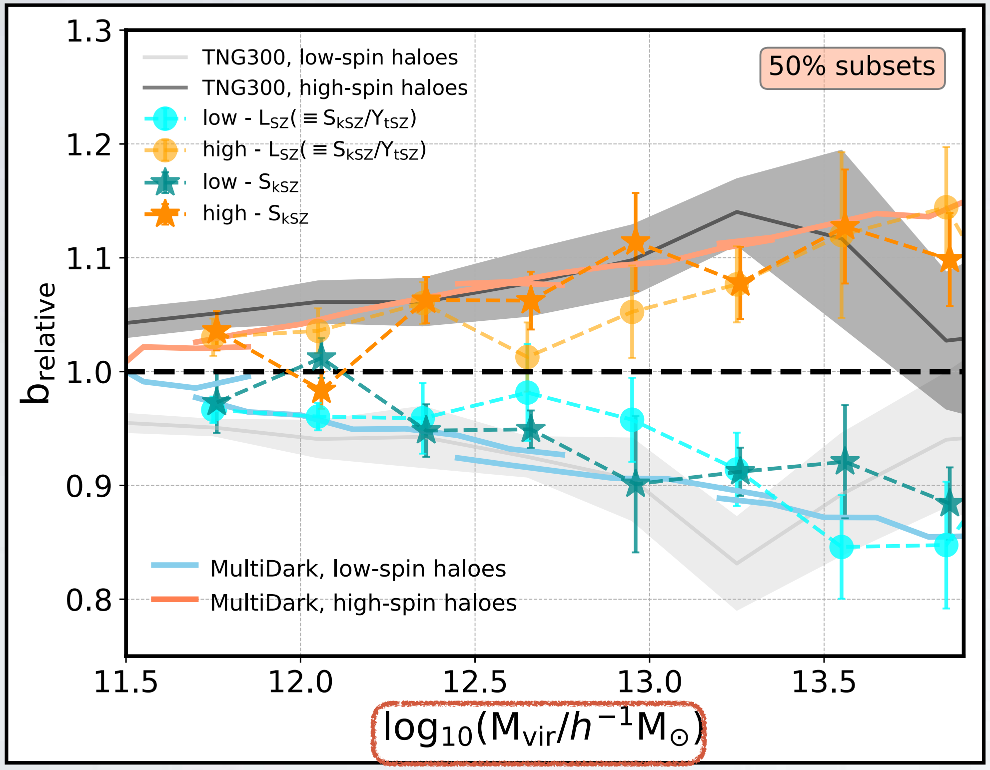
$$\mathrm{L_{SZ}} = \frac{\mathrm{S_{kSZ}}}{\mathrm{Y_{tSZ}}}.$$

$\mathrm{S_{kSZ}}$ ↔ **|J|**

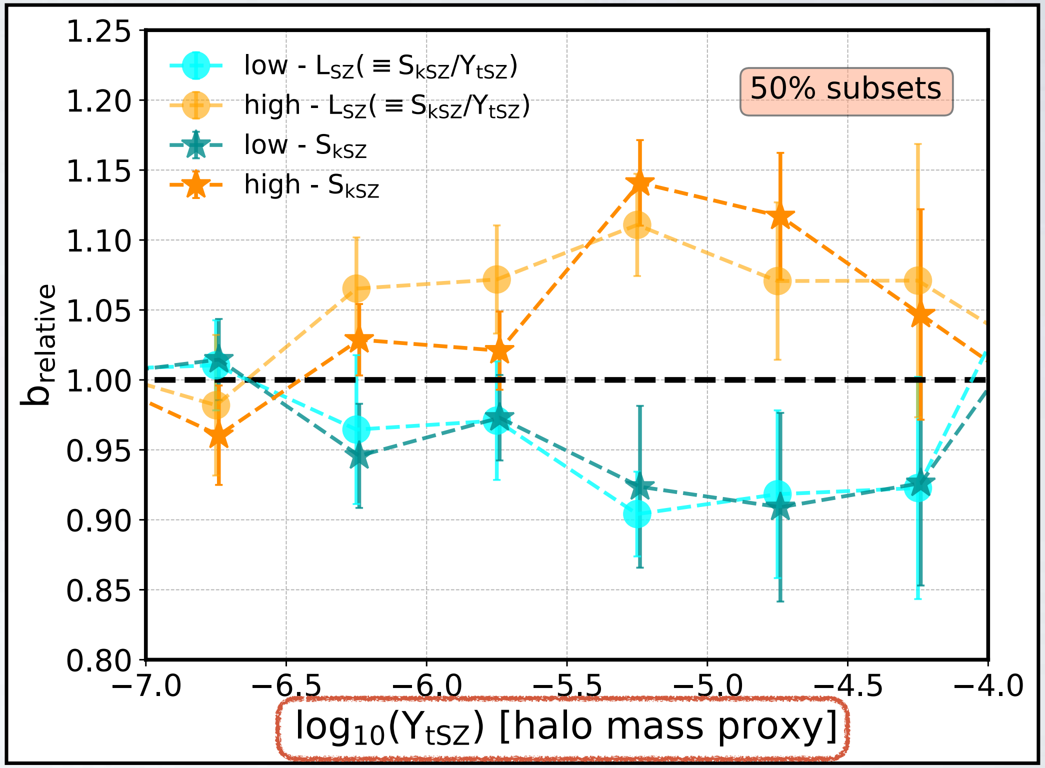
$\mathrm{Y_{tSZ}}$ ↔ $\mathbf{M_{vir}}$

KINETIC SUNYAEV ZEL'DOVICH EFFECT & SPIN BIAS

TRACING SPIN BIAS WITH TSZ/KSZ OBSERVATIONS



Splitting by kSZ



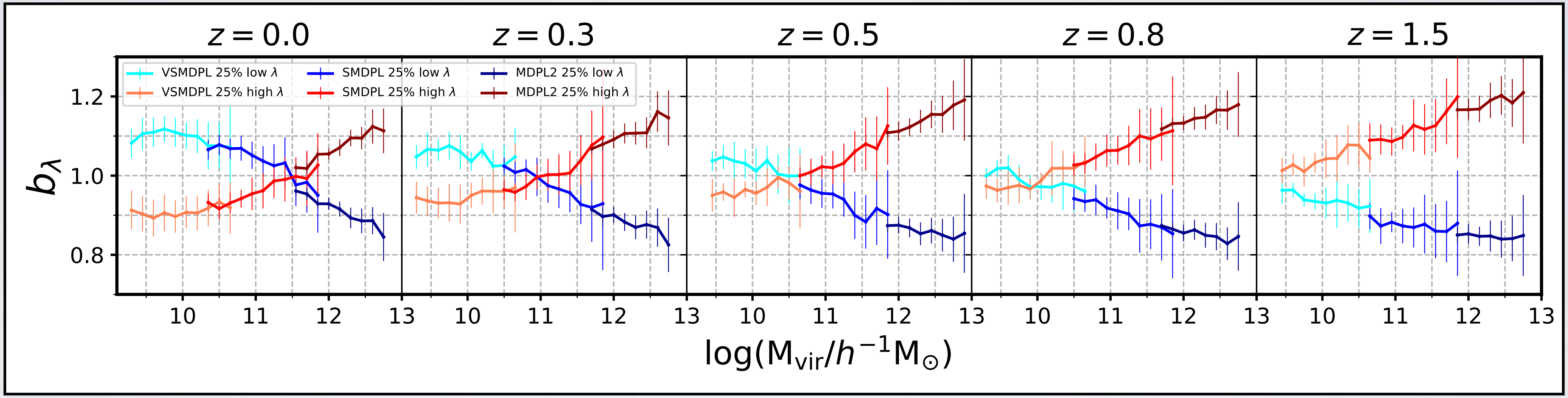
Splitting by kSZ & Binning by tSZ

Montero-Dorta, Artale, Abramo, Tucci (2020, arXiv:2008.08607)

Beatriz Tucci, MSc
USP, Brazil

THE ORIGIN OF SPIN BIAS

Poster presentation this Friday!



Tucci, Montero-Dorta, Abramo, Artale (2020)

- Secondary dependence of halo bias at fixed halo mass: **$b(\lambda|M_{vir})$**
- **Inversion at the low-mass end (Sato-Polito, Montero-Dorta, et al. 2019)**
- Unclear physical origin for the intrinsic signal (e.g., Lacerna & Padilla 2012, Johnson et al. 2019, Ramakrishnan et al. 2020)

SUMMARY

- Understanding the galaxy-halo connection is important: i) to comprehend the physics behind galaxy formation; ii) to constrain cosmological parameters; iii) to analyse the properties and distribution of dark matter
- State-of-the-art hydrodynamical cosmological simulations has shown to be a great tool to investigate the galaxy-halo connection and its properties at large-scale
- Almost all halo properties at fixed halo mass display some level of secondary halo bias
- Our results show that secondary halo bias manifests on the galaxy properties at fixed halo mass
- The formation time of the halos is a fundamental property to describe the occupancy variations
- The kinetic Sunyaev Zel'dovich effect can serve as an observational probe for spin bias in the near future