# Reconstructing the formation of the observed universe to explore the cosmic web

Houjun Mo
(UMass/TDLI)

Texas@Shanghai 12/11/2023

# Why reconstructing?

To help define the best sets of targets to interpret observational data

Galaxies alone are not sufficient to trace the whole ecosystem of the cosmic web;

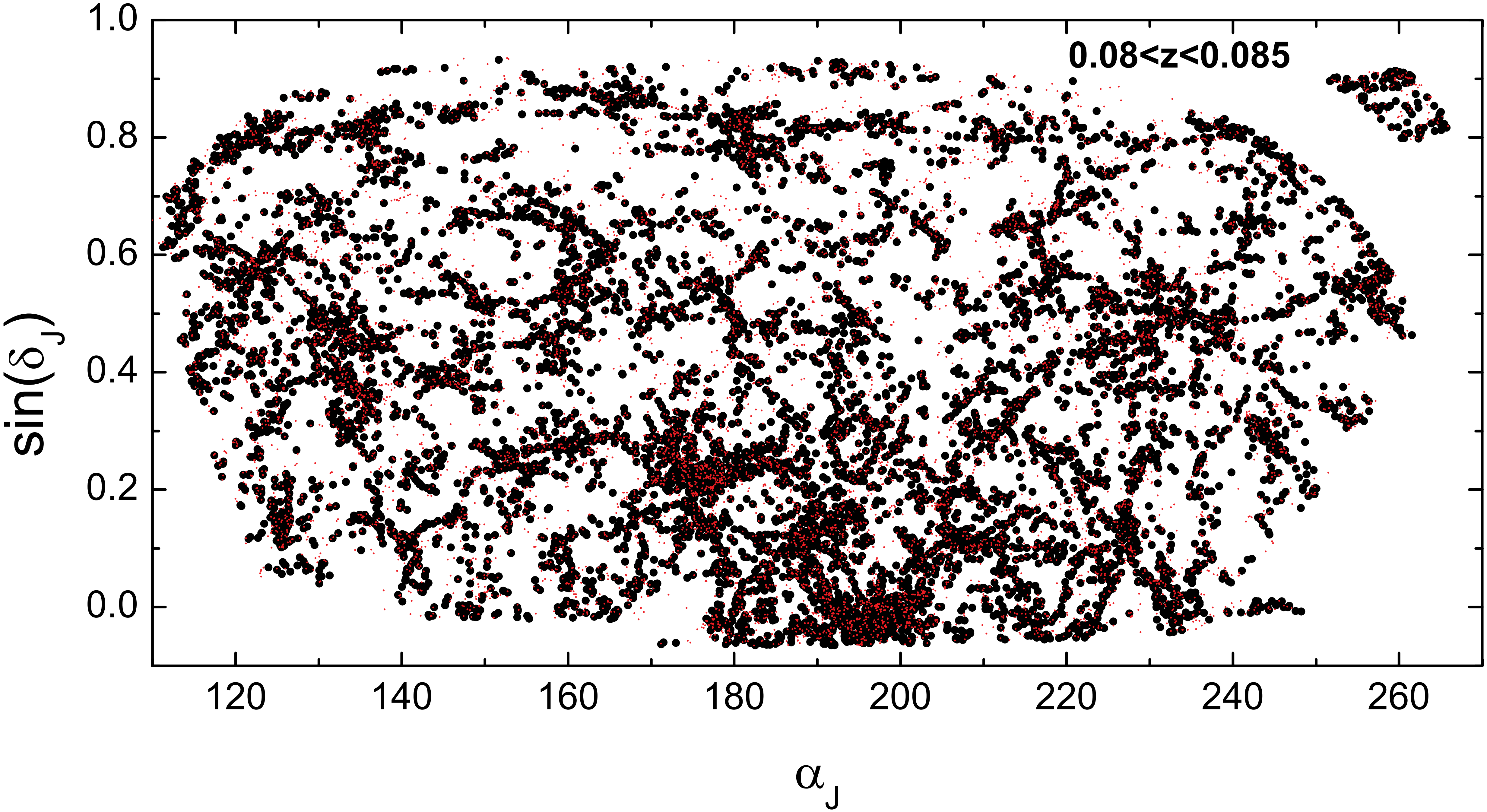
We need information about dark matter halos, and cosmic mass density field, environments

and formation histories of structures

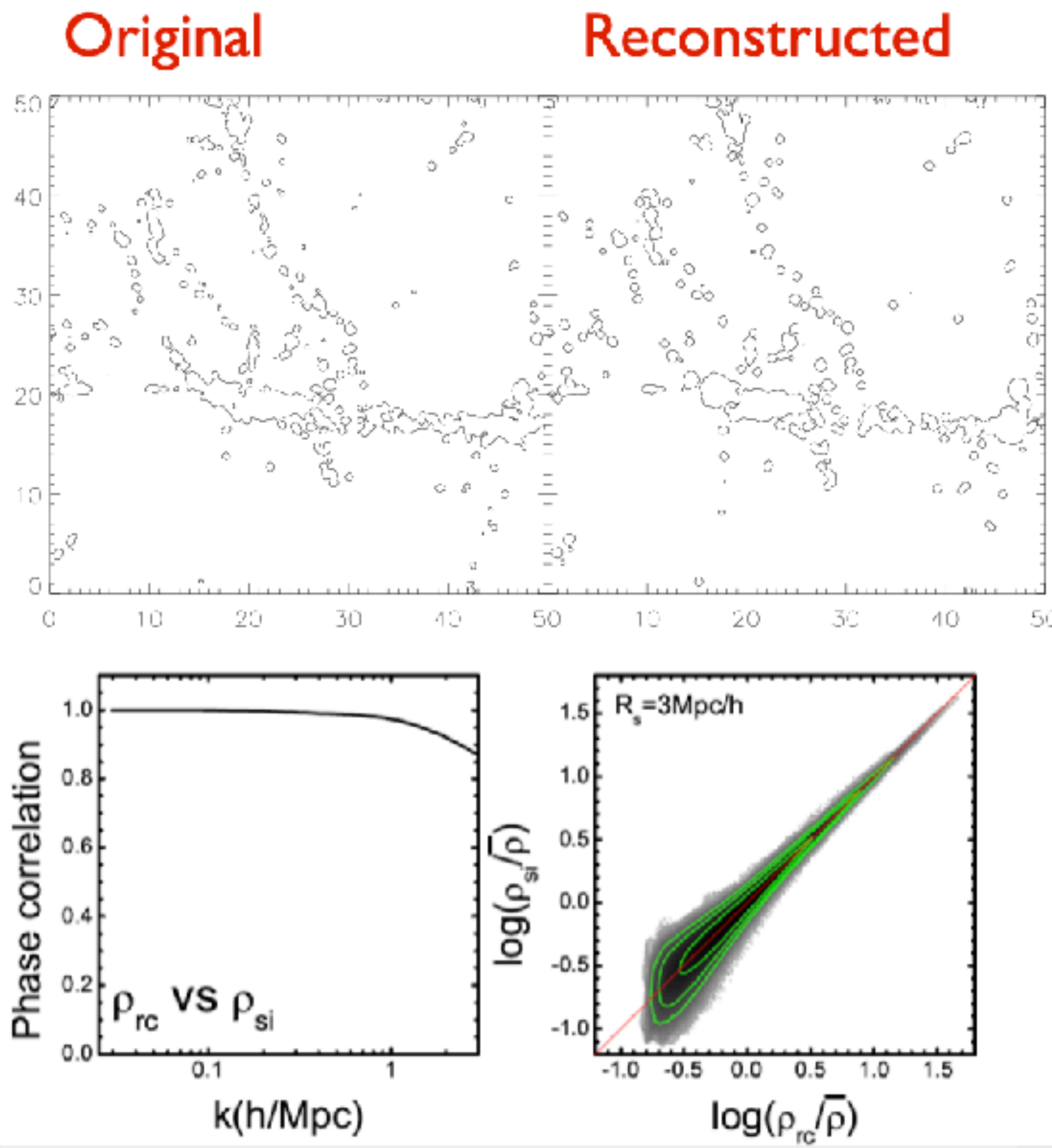
# Step 1: Dark matter halos reconstructed using galaxy groups

Yang et al. 2007

$M_{\rm th} = 10^{12} h^{-1} {\rm M}_\odot$ limited by SDSS redshift survey



# Step II: From dark matter halos to density field




Wang+ 2009

# Step 3. From current field to initial conditions

From $\rho_{\rm f}(\mathbf{x})$ to $\delta_j(\mathrm{k})$

to re-simulate the real cosmic web

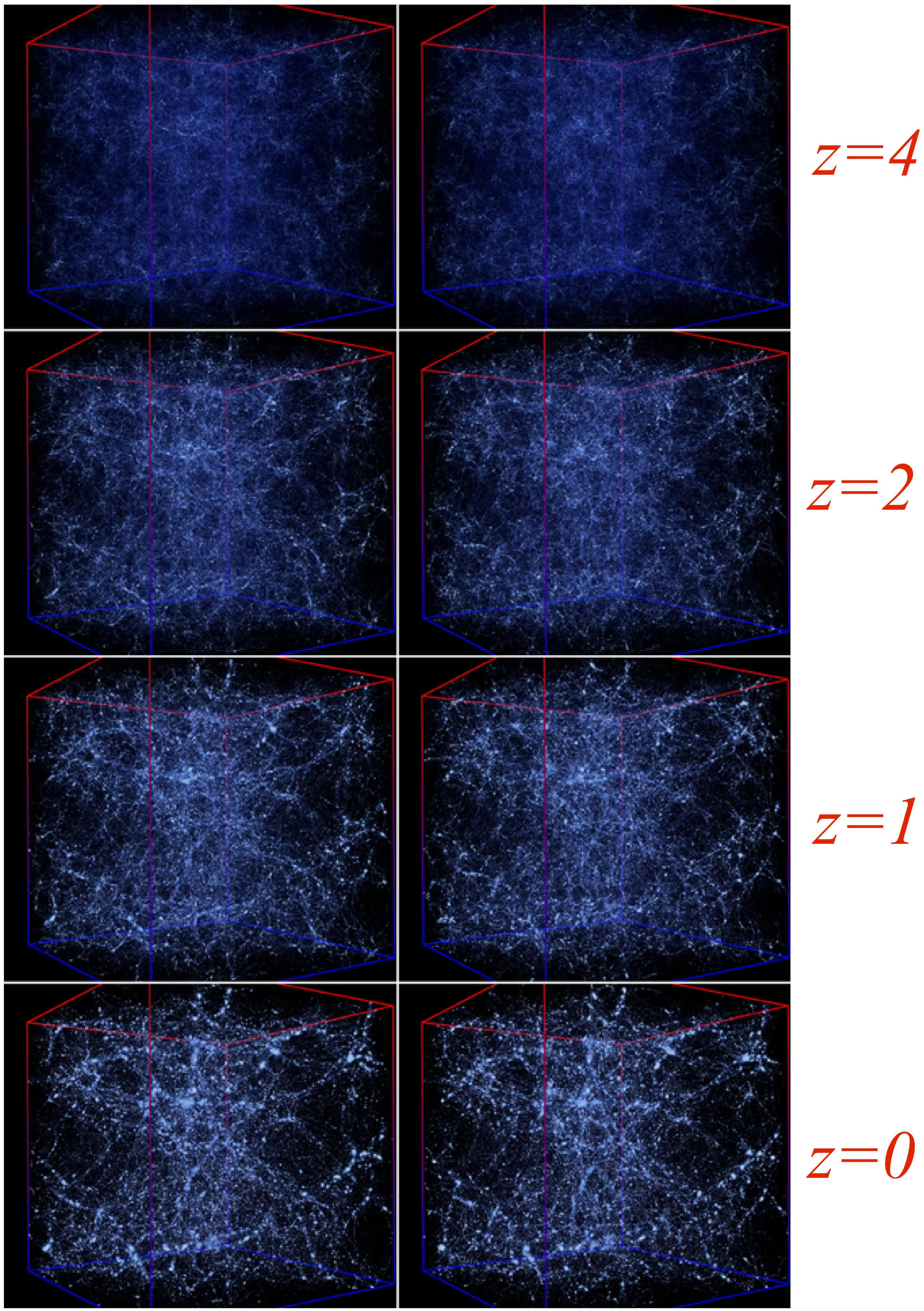
$$Q(\delta_j(\mathbf{k})|\rho_{\rm f}(\mathbf{x})) = \mathrm{e}^{-\sum_{\mathbf{x}}[\rho_{\rm mod}(\mathbf{x})-\rho_{\rm f}(\mathbf{x})]^2\omega(\mathbf{x})/2\sigma_{\rm f}^2(\mathbf{x})} \prod_{\mathbf{k}}^{\rm half}\prod_{j=0}^{1}\frac{1}{[\pi P_{\rm lin}(k)]^{1/2}}\mathrm{e}^{-[\delta_j(\mathbf{k})]^2/P_{\rm lin}(k)}$$

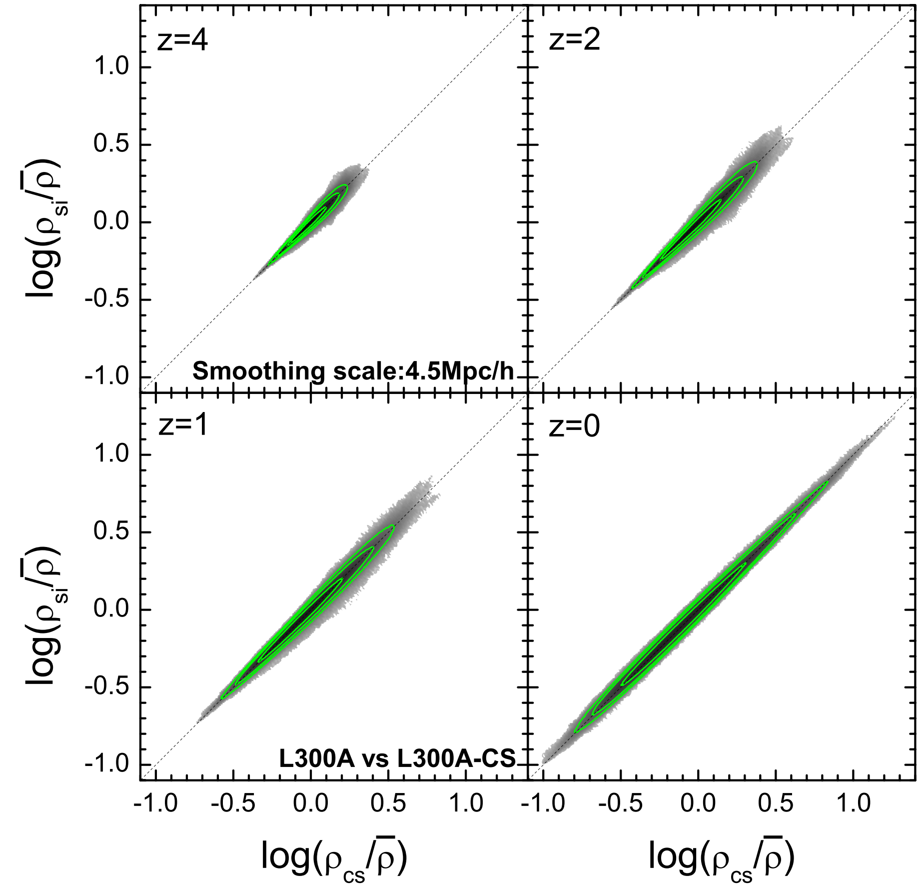
(likelihood) (prior)

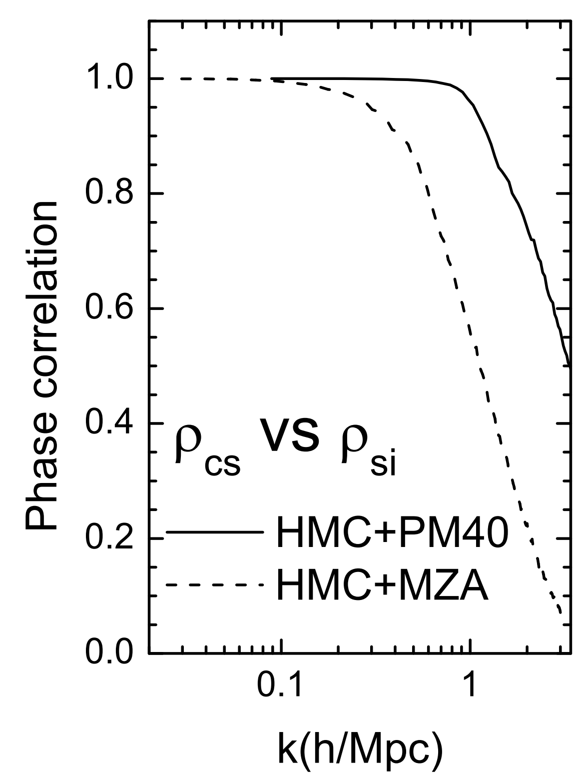
From $\delta_j(\mathrm{k})$ to $\rho_{\rm mod}(\mathbf{x})$ 2LPT; MZA; etc

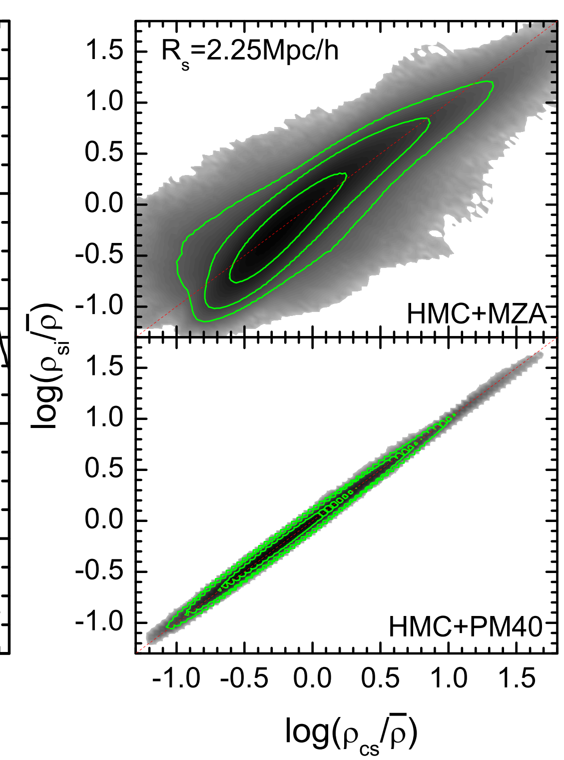
Hamiltonian Markov Chain with PM dynamics

Original From reconstructed IC



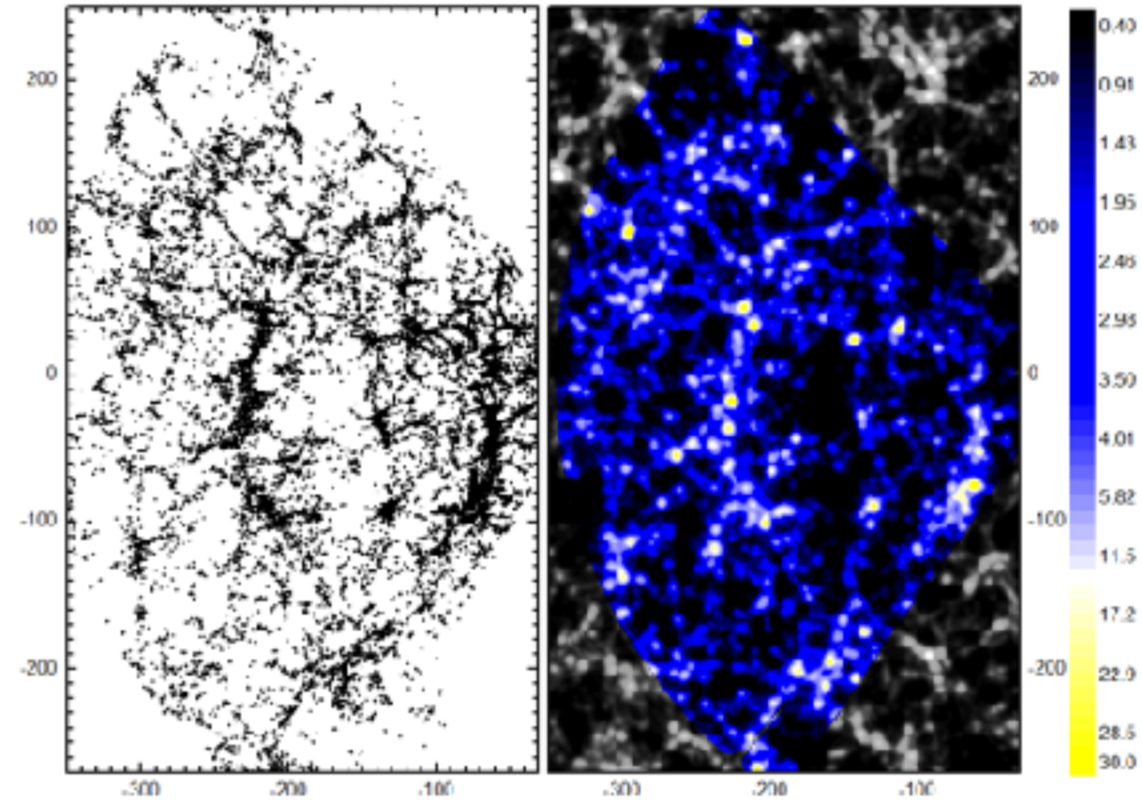



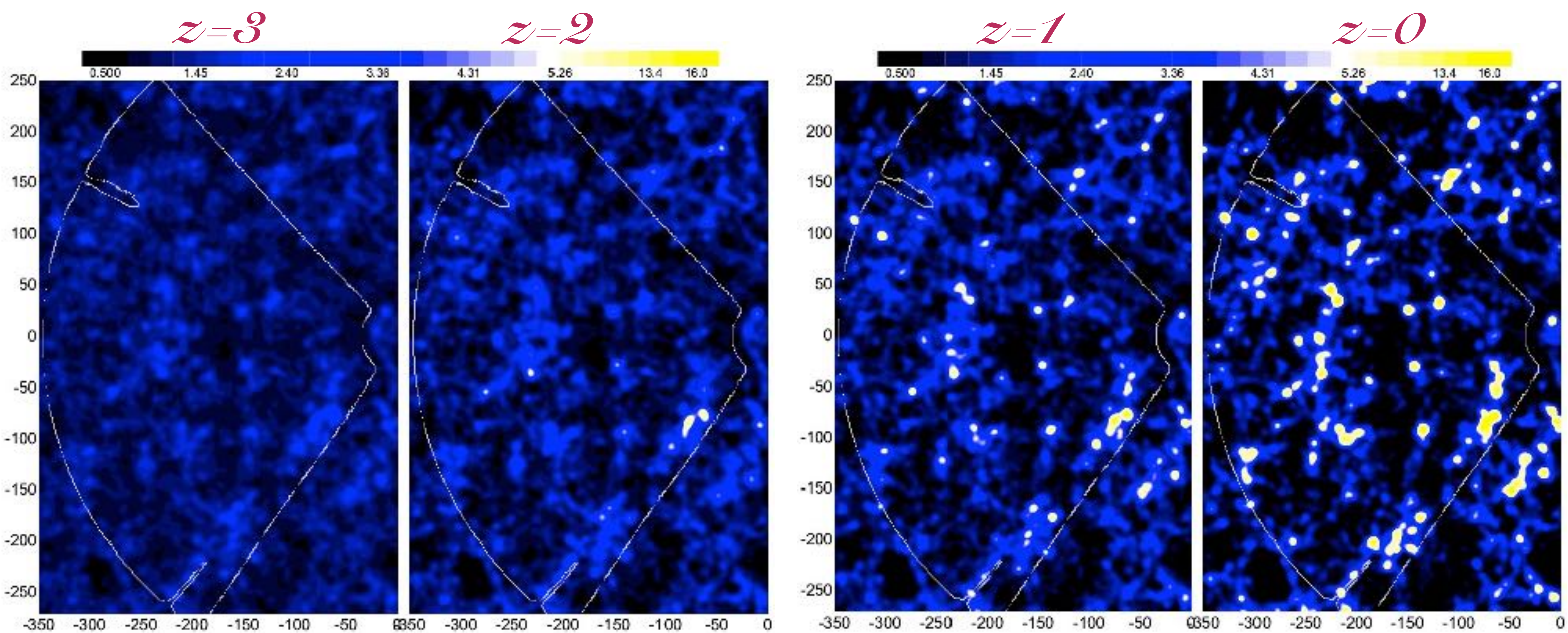



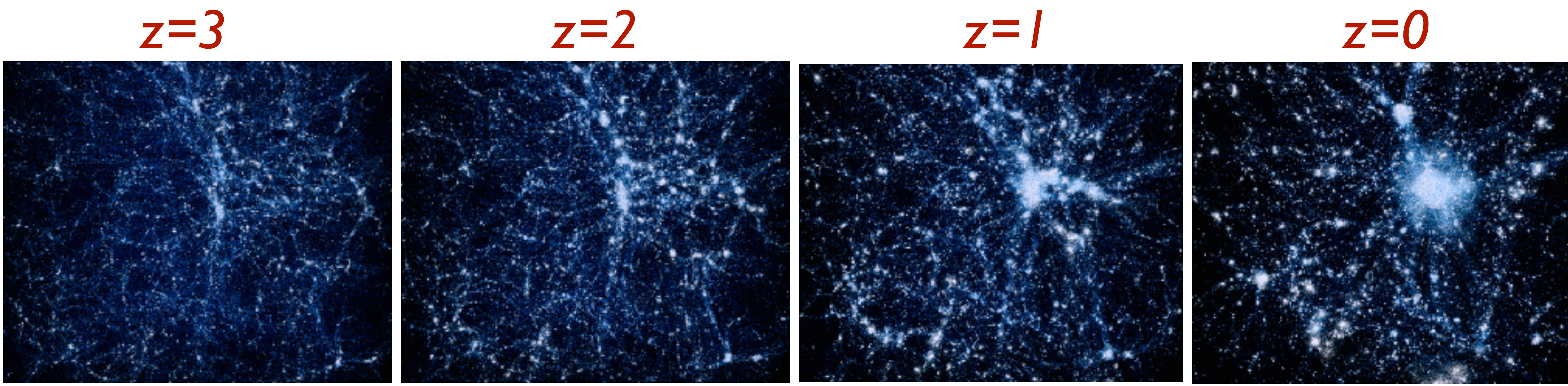
# Mass density field and evolution in SDSS from ELUCID

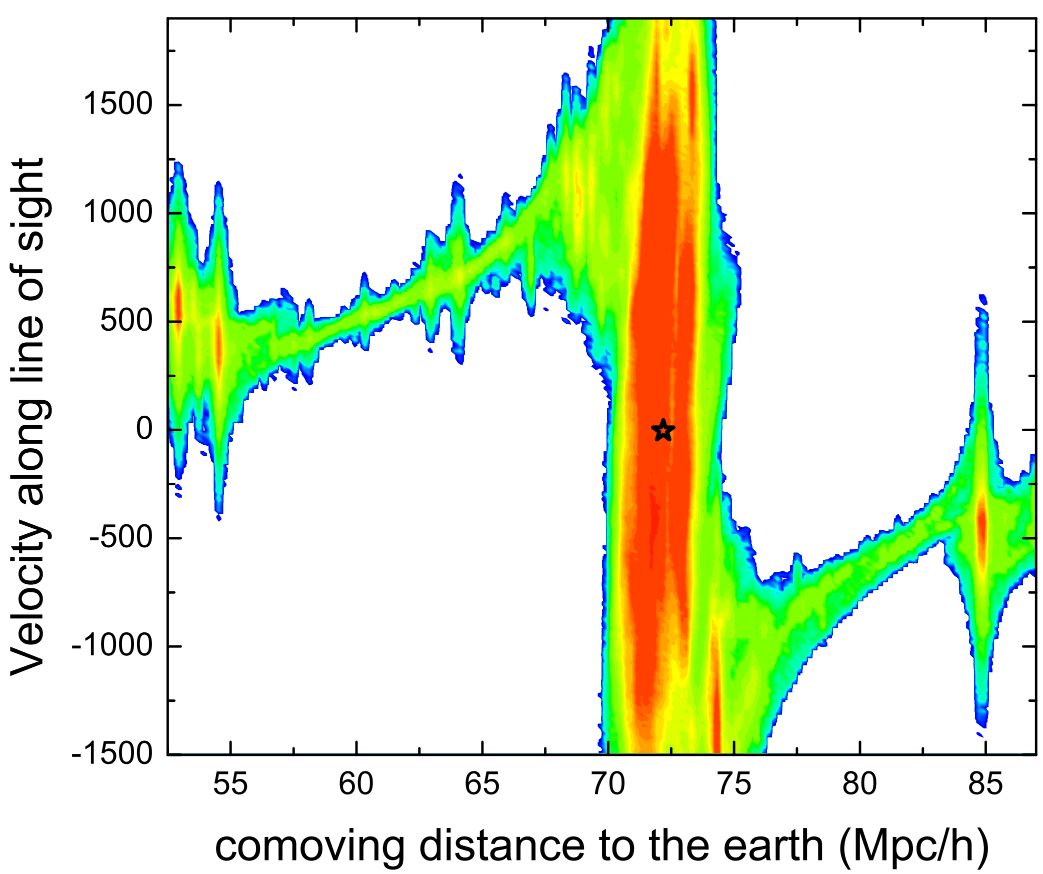
Wang et al. (2016)





# Formation of Coma Cluster



# Targets in cosmic web

Galaxies:

different masses, color, SFR, centrals vs satellites, in different environments.

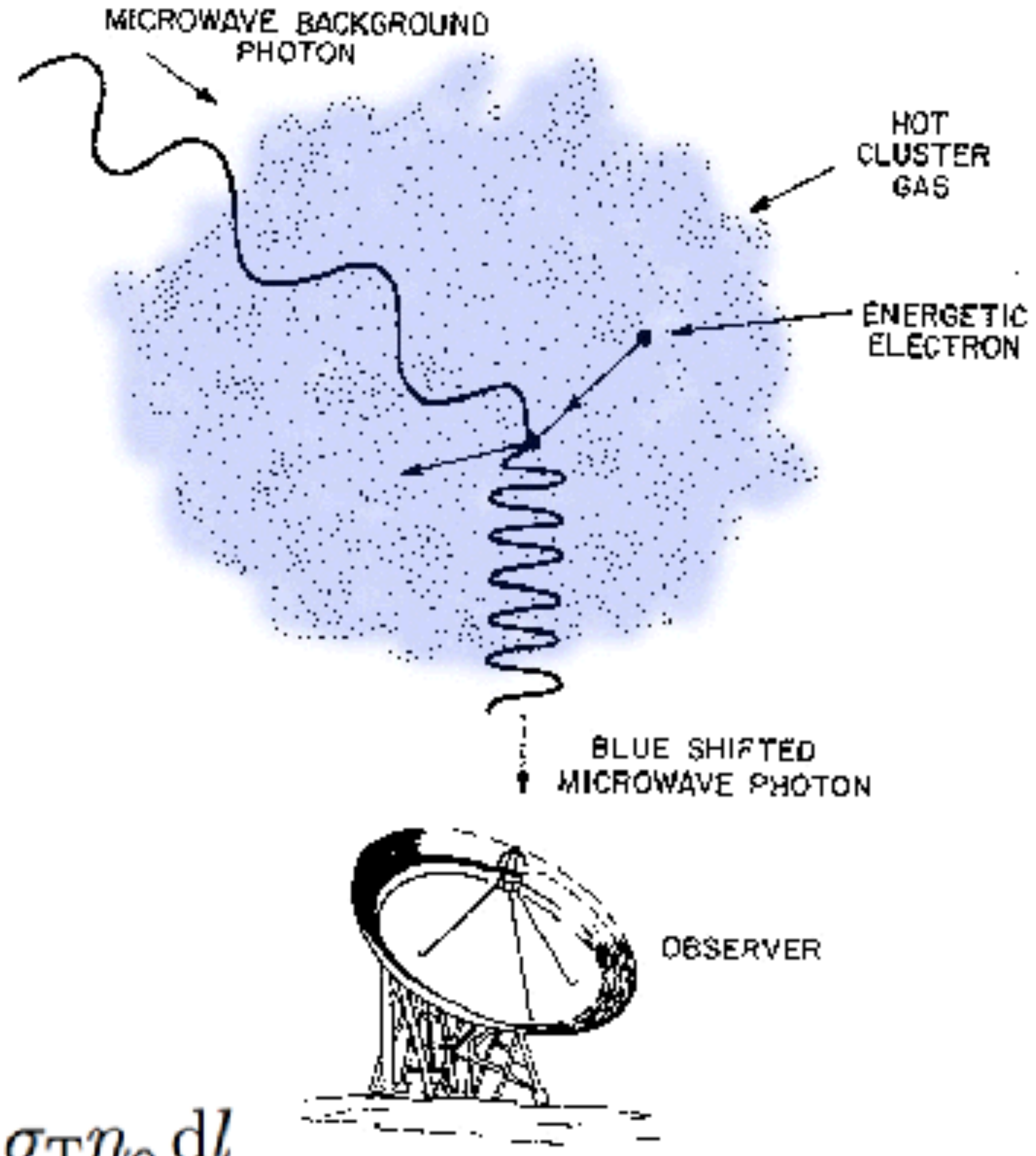
Galaxy groups/dark matter halos:

For each group, we have:
center position;
redshift $z$;
peculiar velocity $v_r$;
halo mass $M_{200}$ [$c$, $R_{200}$, $R_{500}$, $M_{500}$, $T_{\rm vir}$]

The dark matter density field:

$\rho_m(\mathbf{x})$: mass density as a function of location $\mathbf{x}$

# Sunyaev-Zel'dovich Effects




Thermal SZ Effect (tSZE):

$$\left(\frac{\Delta T}{T}\right)_{\rm tSZ} = g(x) y_{\rm tSZ}(\hat{\mathbf{r}}); \qquad y_{\rm tSZ} = \frac{\sigma_{\rm T}}{m_{\rm e}c^2}\int P_{\rm e}\,{\rm d}l\,;$$

$$Y_{500} = \int_{\Omega_{500}} y_{\rm tSZ}(\hat{\mathbf{r}})\,{\rm d}\Omega = \frac{\sigma_{\rm T}}{d_{\rm A}^2(z)}\frac{k_{\rm B}}{m_{\rm e}c^2}\int_{V_{500}} n_{\rm e}T_{\rm e}{\rm d}V$$

Kinetic SZ Effect (kSZE):

$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} = -\frac{\sigma_{\rm T}}{c}\int n_{\rm e}v_r\,{\rm d}l = -\frac{v_r}{c}\tau_{\rm e}\,; \quad \tau_{\rm e} = \int \sigma_{\rm T}n_{\rm e}\,{\rm d}l$$

$$K_{500} \equiv -\frac{c}{v_r}d_{\rm A}^2(z)\int_{\Omega_{500}}\left(\frac{\Delta T}{T}\right)_{\rm kSZ}(\hat{\mathbf{r}})\,{\rm d}\Omega = \sigma_{\rm T}\int_{V_{500}} n_{\rm e}{\rm d}V$$

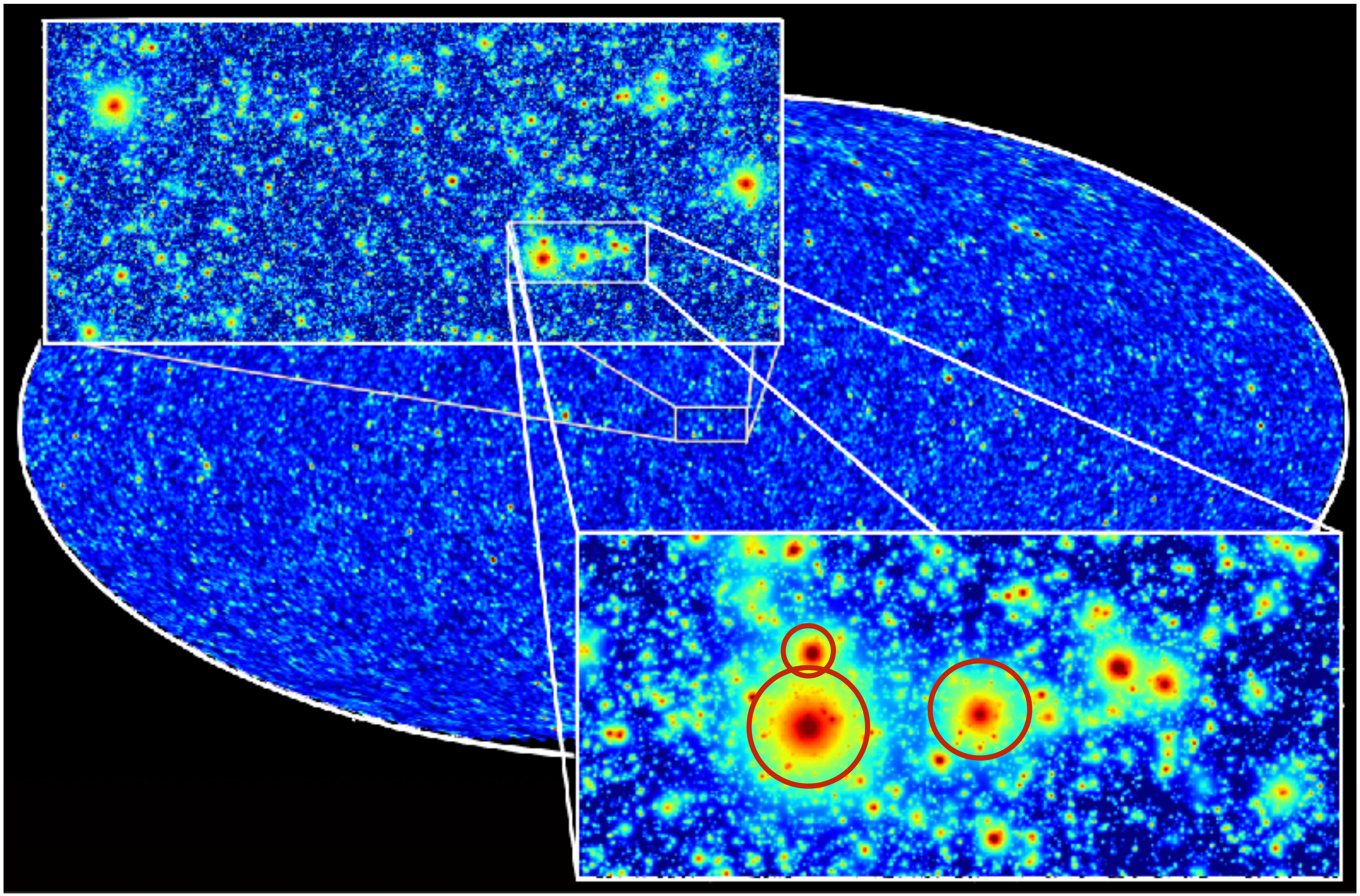
If we know $z$, $M$ ($V_{500}$) and $v_r$, we can in principle infer the total mass of ionized gas and its effective temperature.

# SZE from groups/halos

For each group, we have:
center position;
redshift $z$;
peculiar velocity $v_r$;
halo mass $M_{200}$ $[c, R_{200}, R_{500}, M_{500}, T_{\rm vir}]$

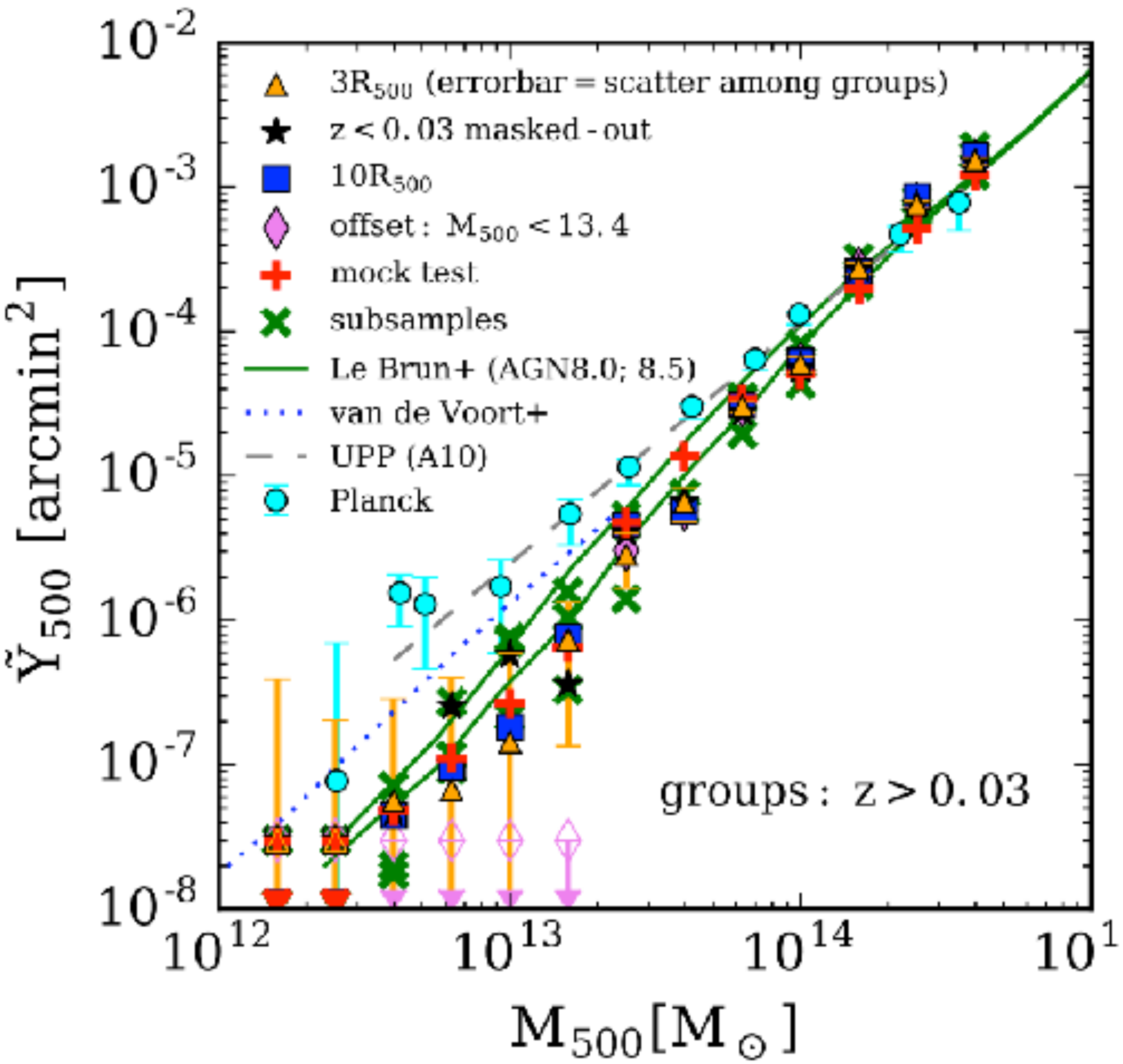
All this information is useful for extracting SZE from CMB maps, and for interpreting results

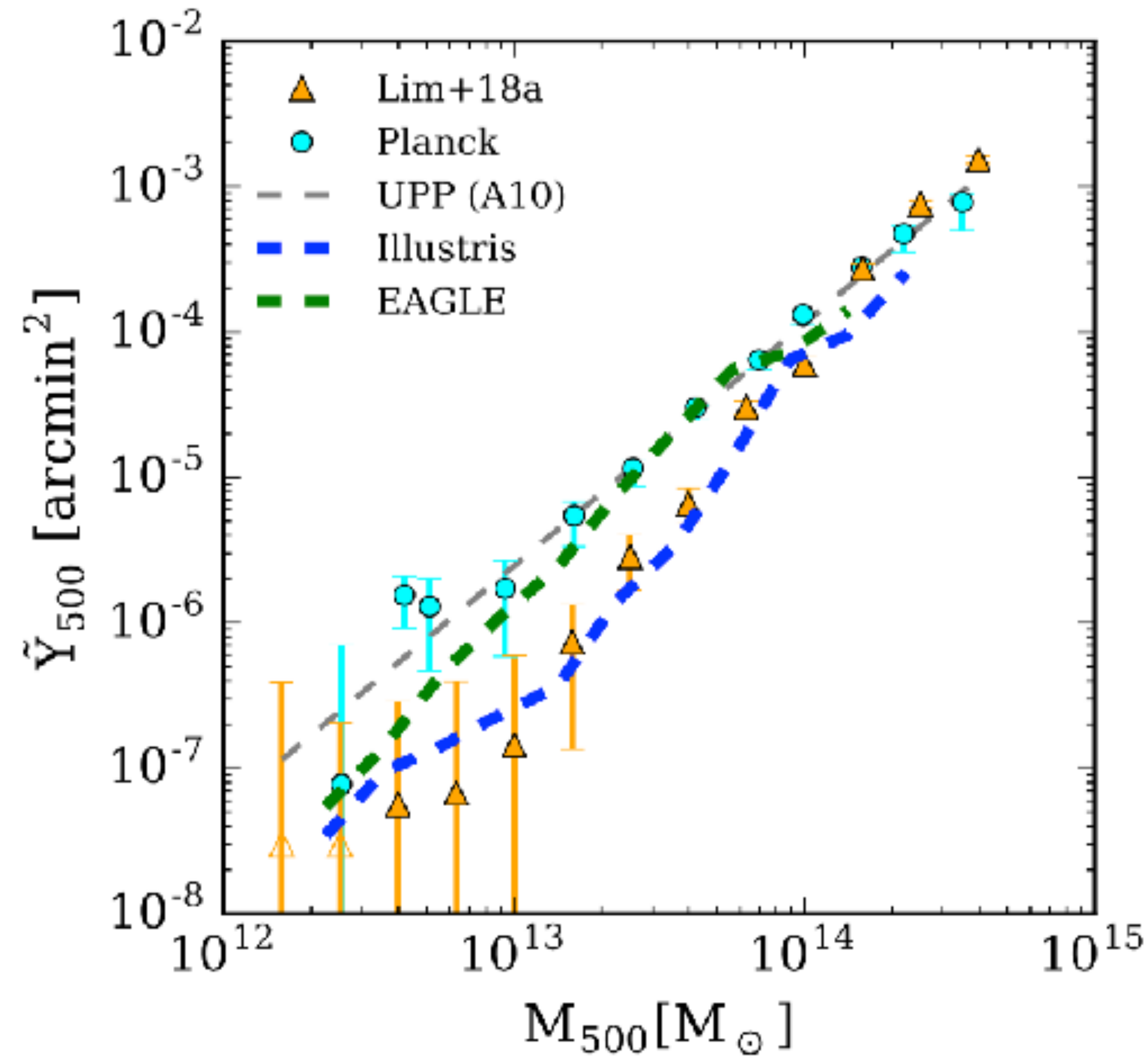
# Model maps to match observational maps



# Thermal SZE of galaxy groups

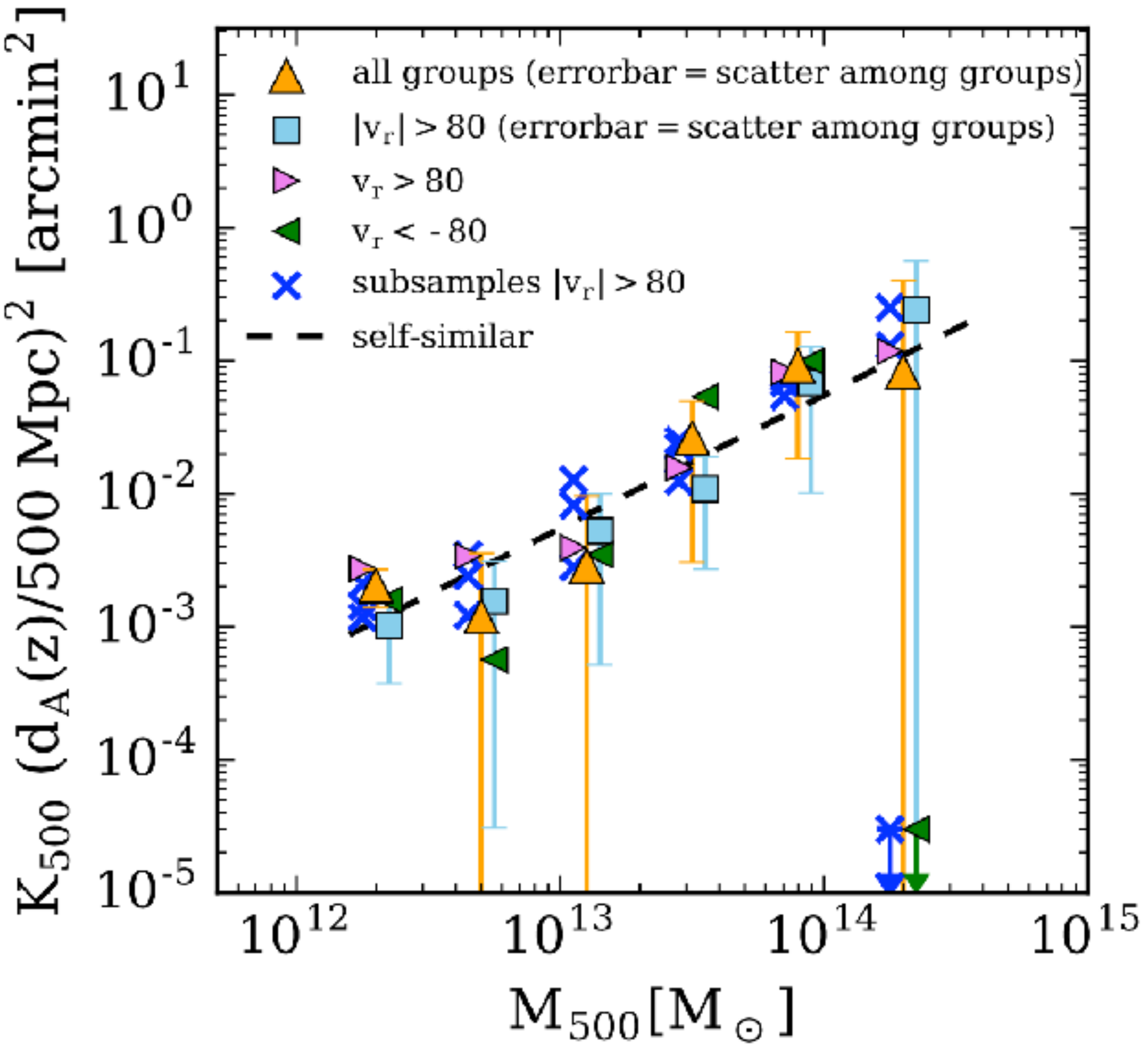
Lim et al. 2018a



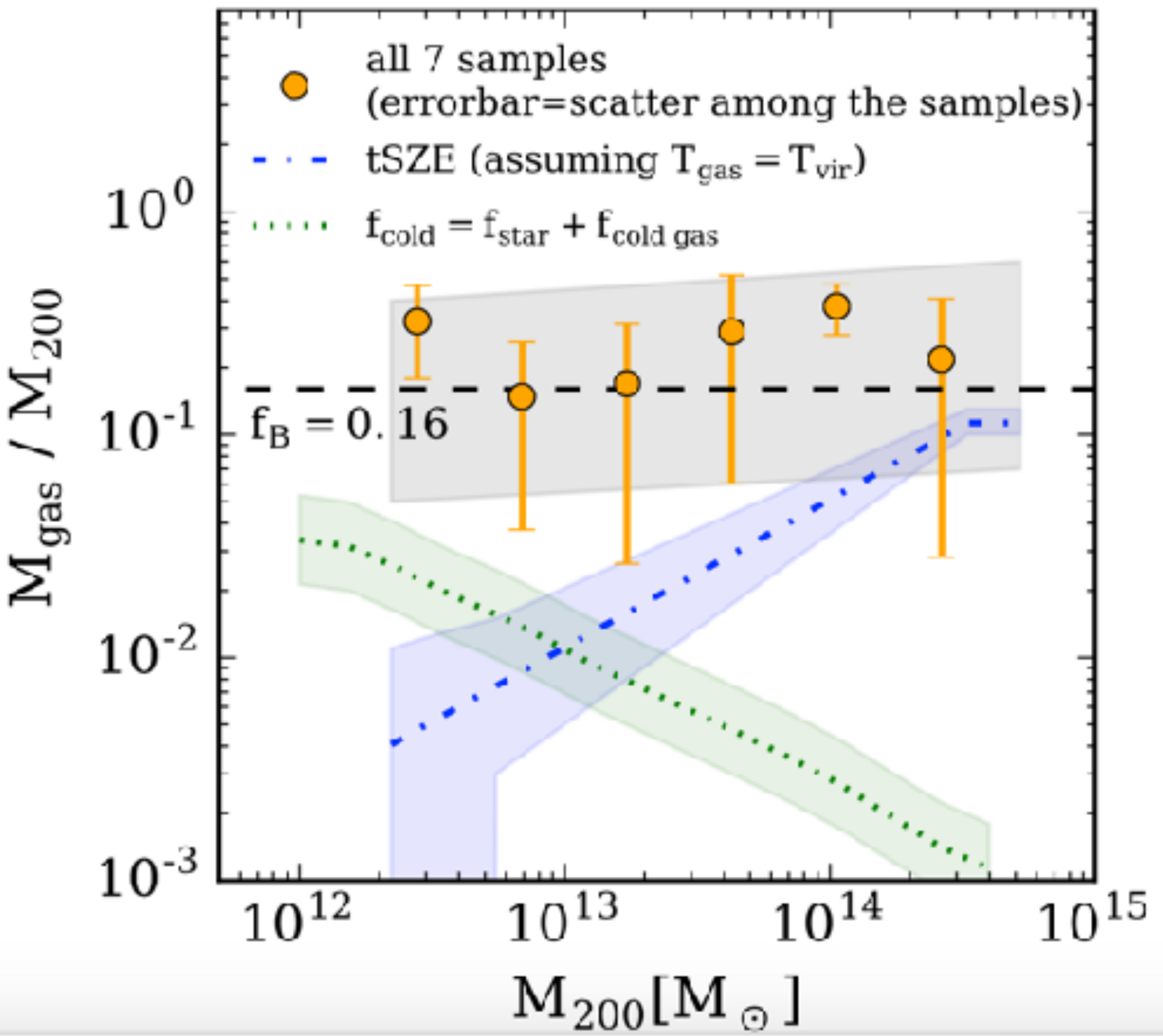



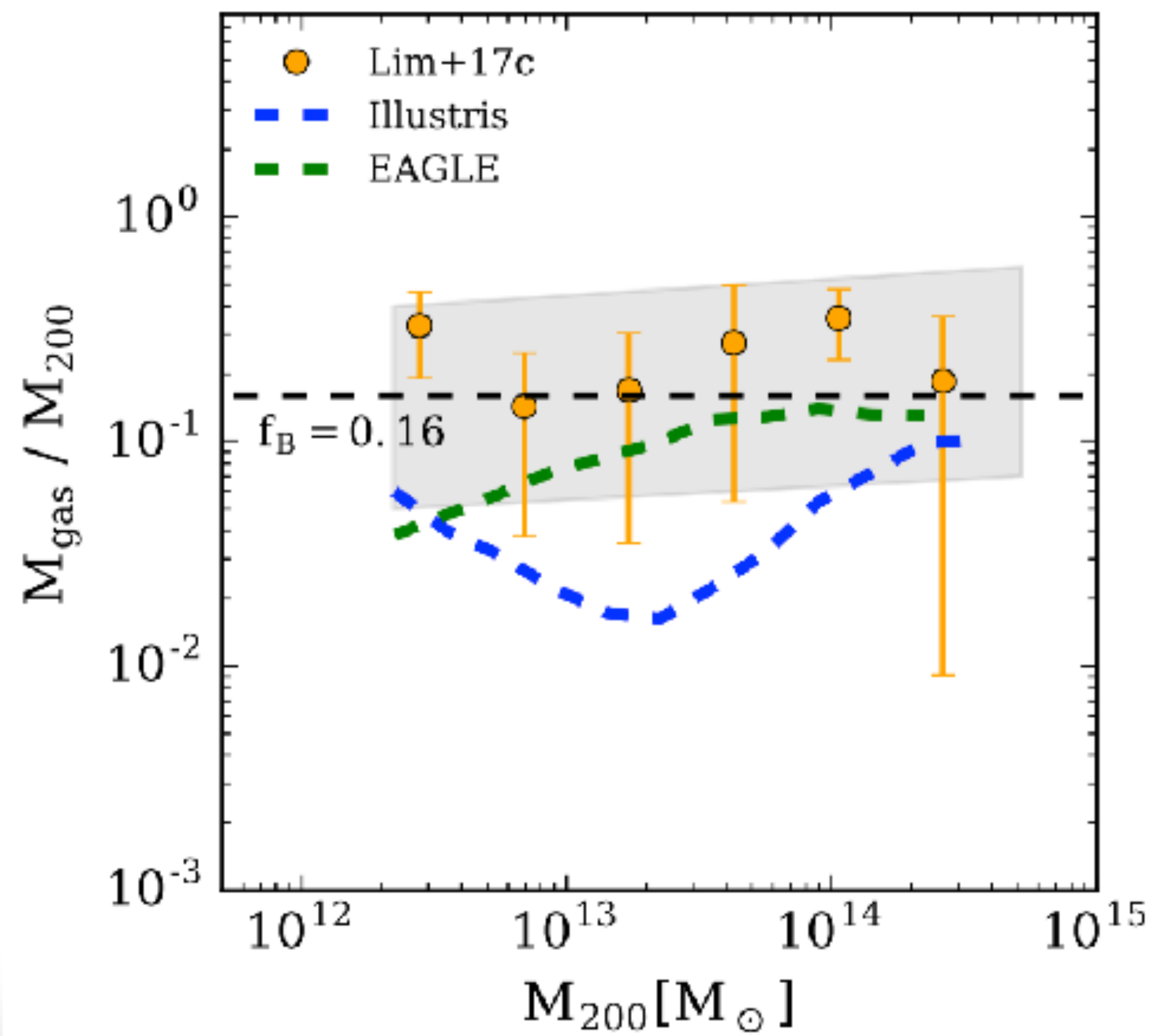
# Kinetic SZE of galaxy groups

Lim et al. 2020

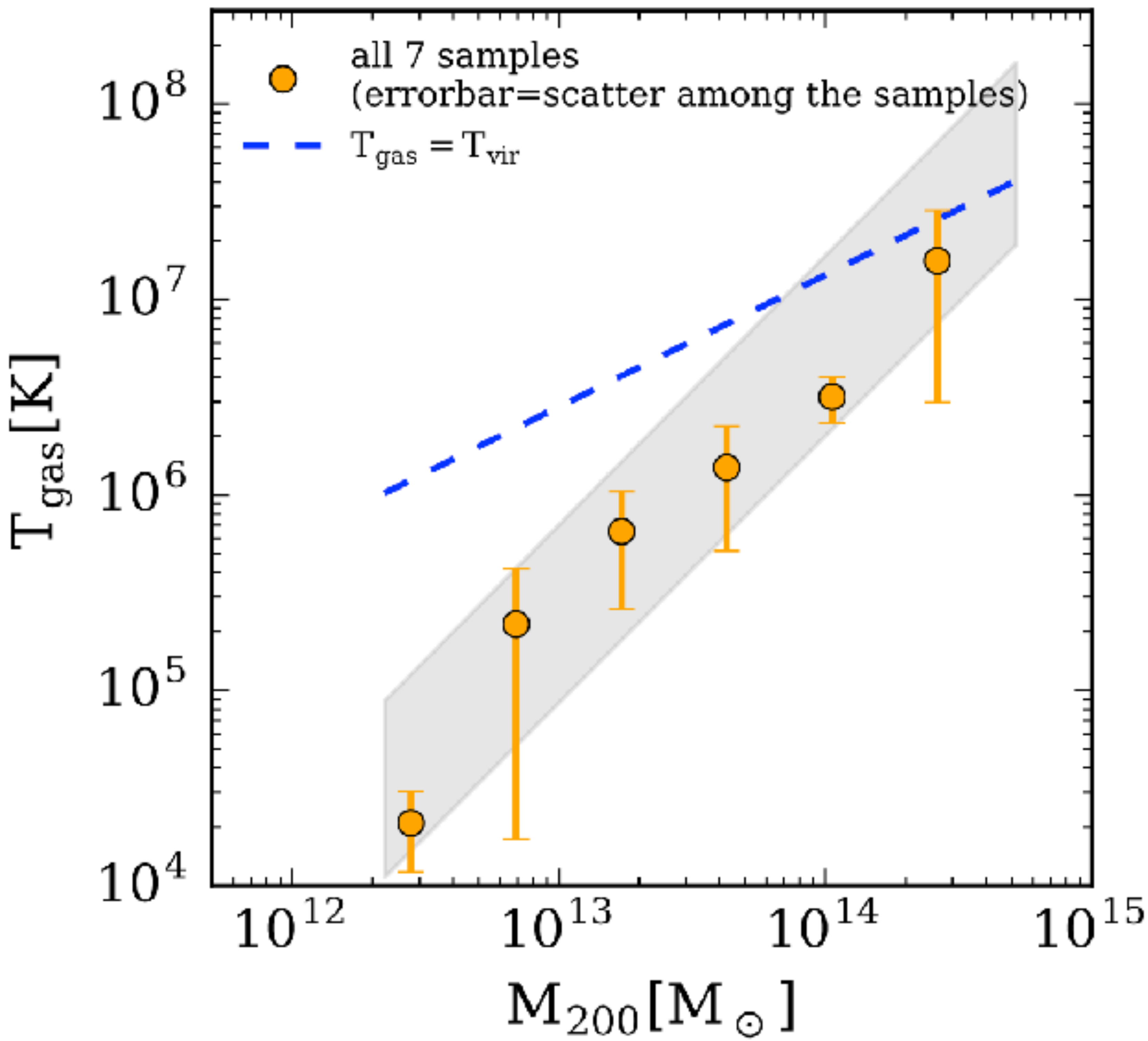


# Missing baryons found in ionized gas



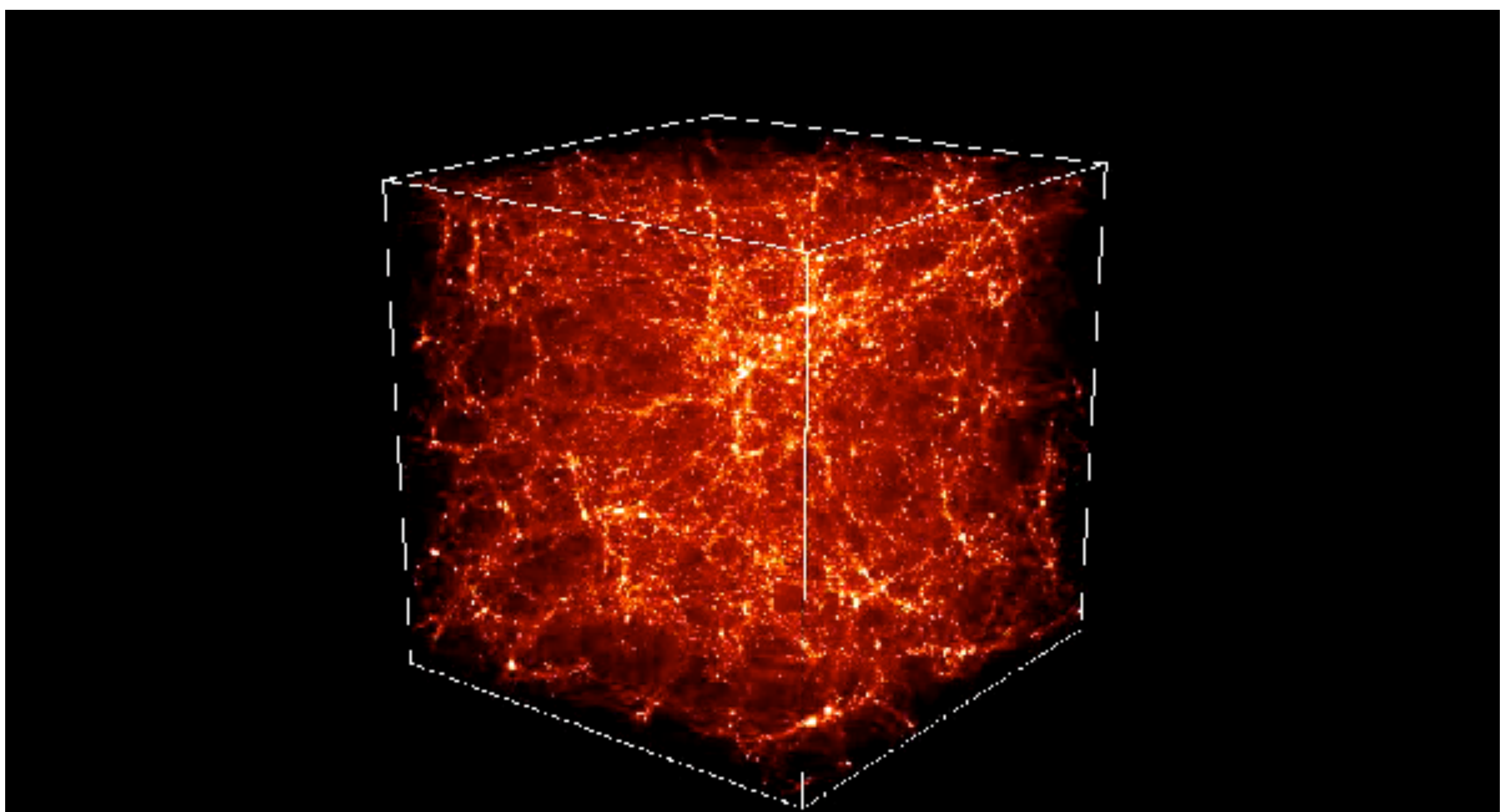
# Combining kSZE and tSZE: the missing baryons are in a warm-hot phase



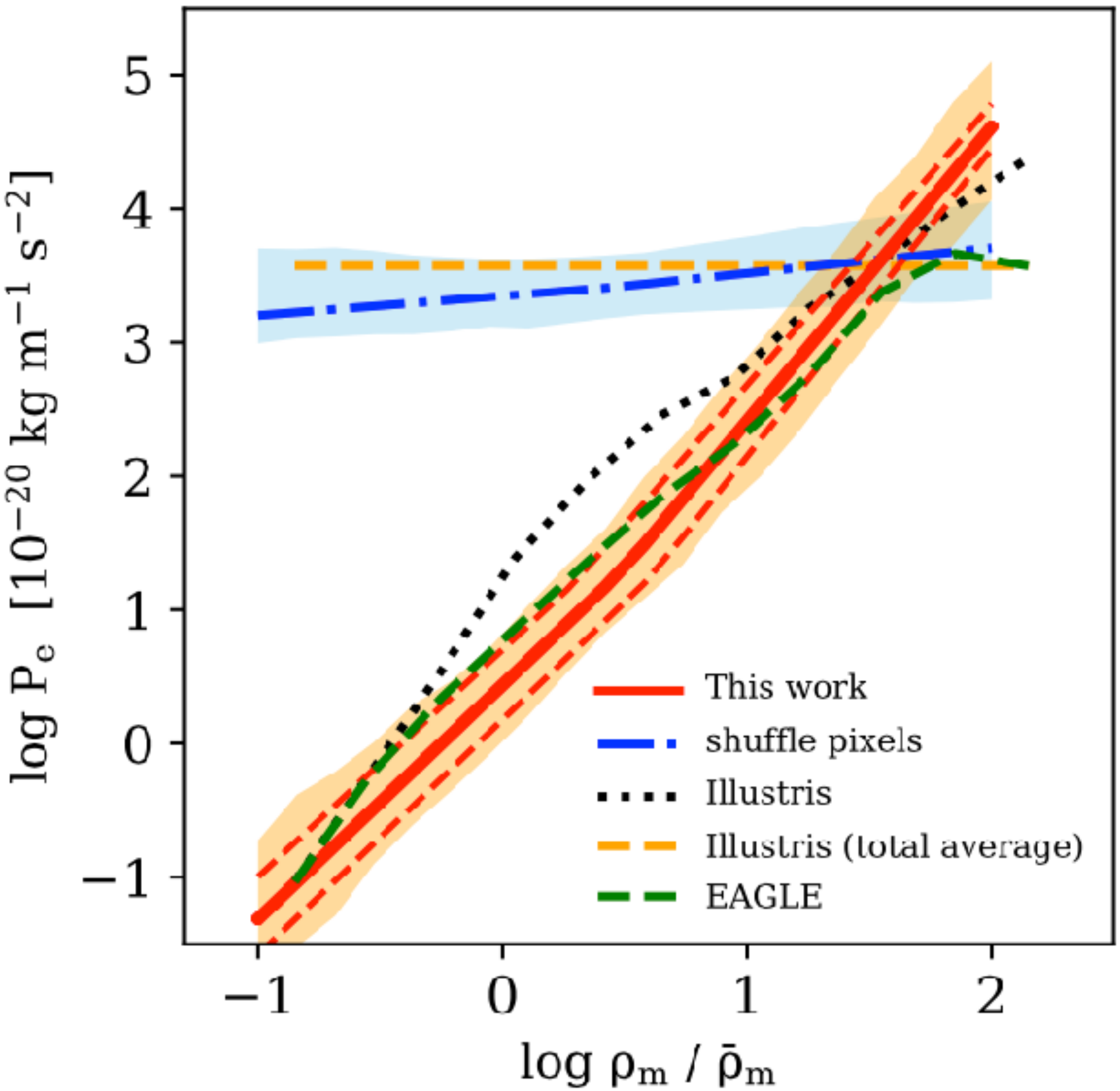
# Probe the energy content of IGM using thermal SZ effect

Based on reconstructed density field:

$$P_e = \begin{cases} A \times (\rho_m/\rho_{m,0})^{\alpha_1}, & \text{if } \rho_m \leqslant \rho_{m,0} \\ A \times (\rho_m/\rho_{m,0})^{\alpha_2}, & \text{if } \rho_m > \rho_{m,0}. \end{cases}$$

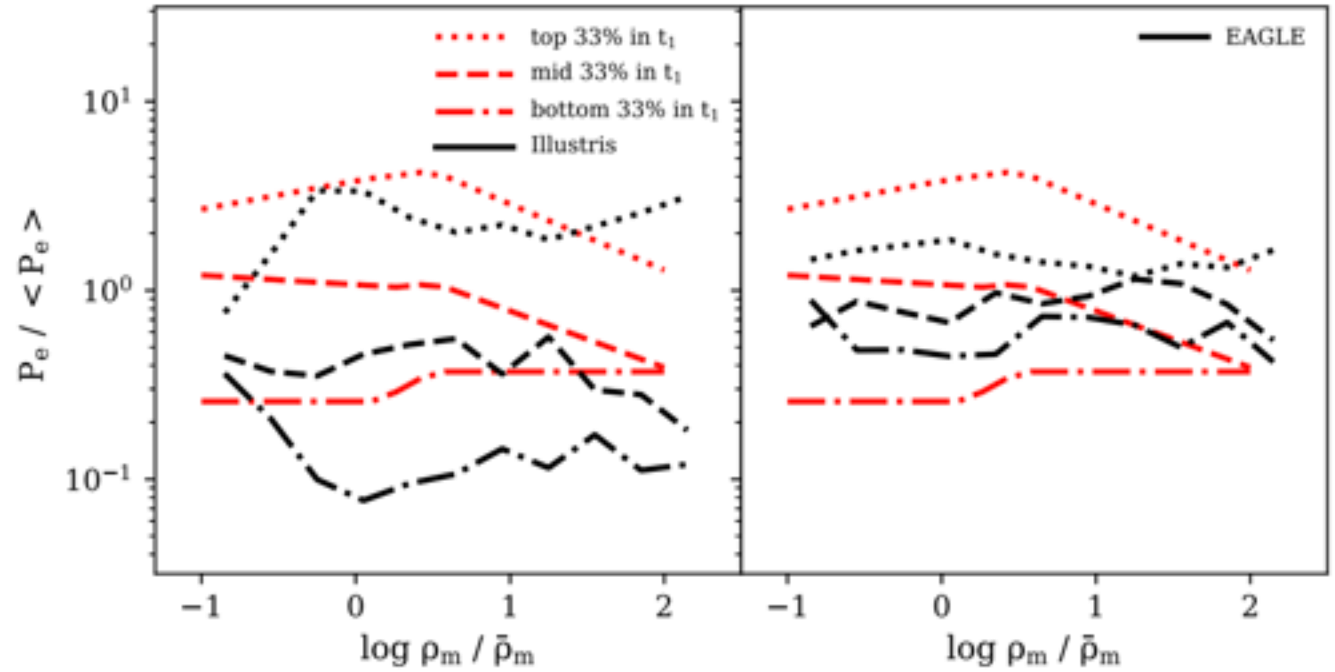


# Mass density field sampled on a grid of cubic cells of 1Mpc size




Lim et al. 2018b

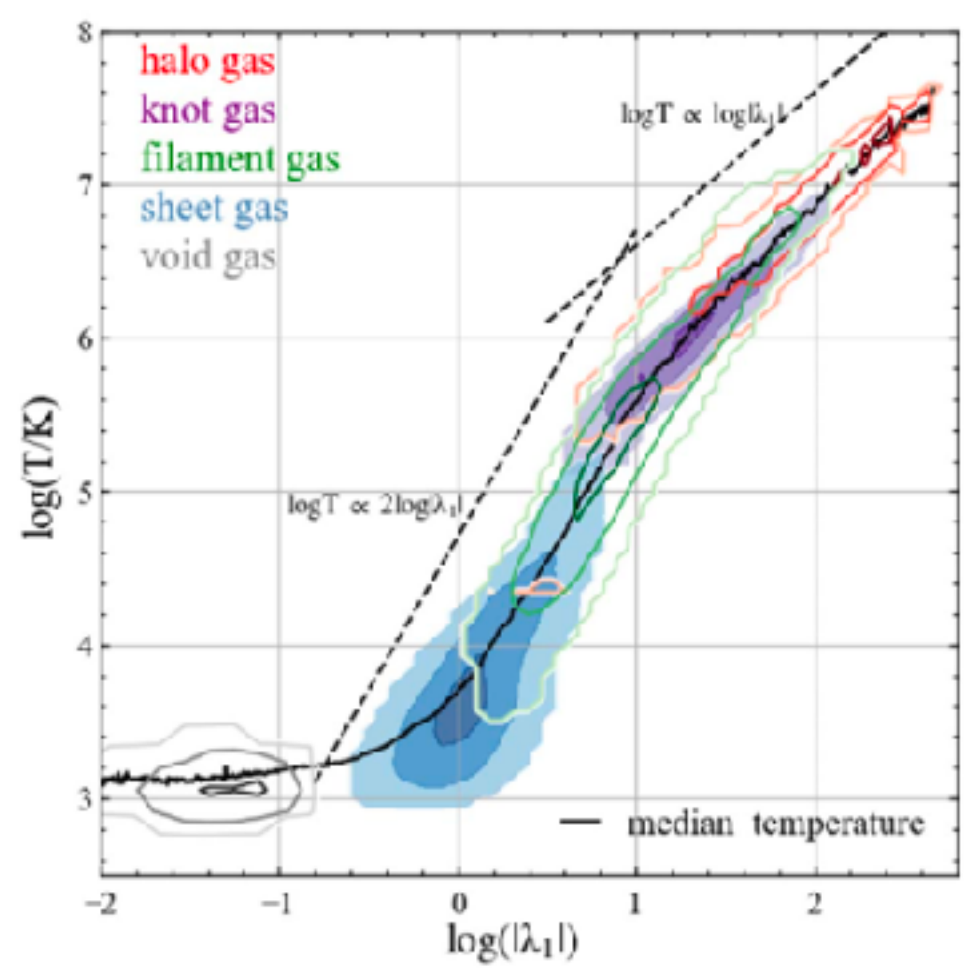
# Dependence on local tidal field



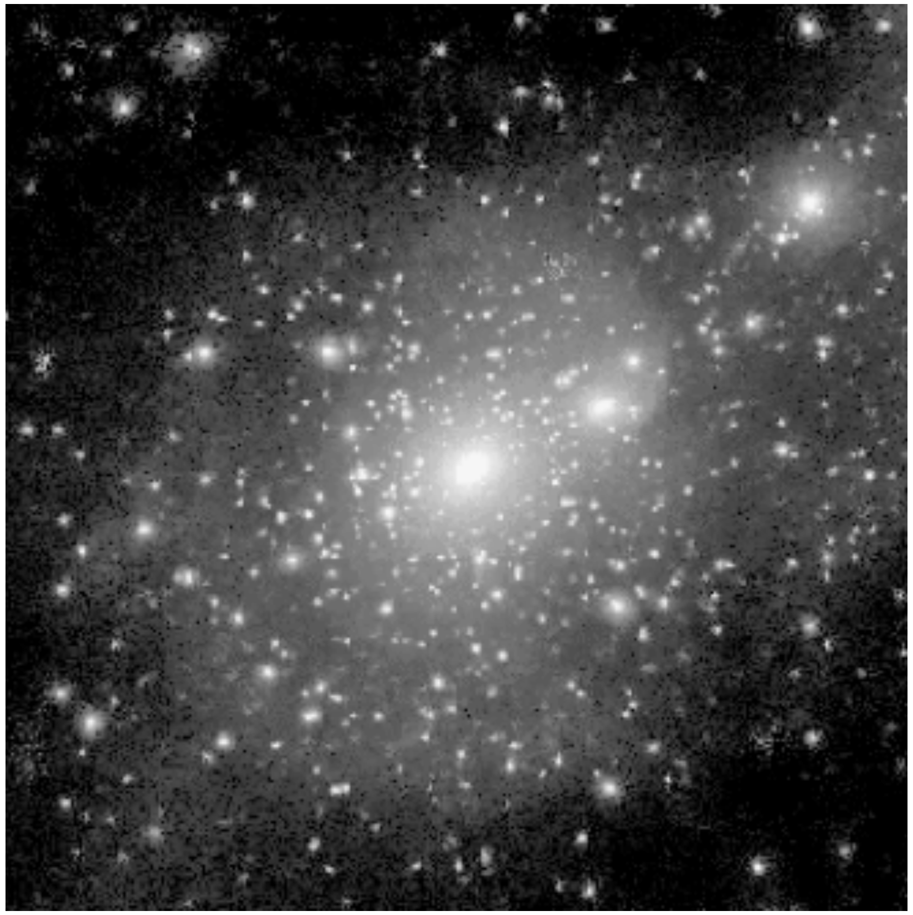

Lim et al. 2018b

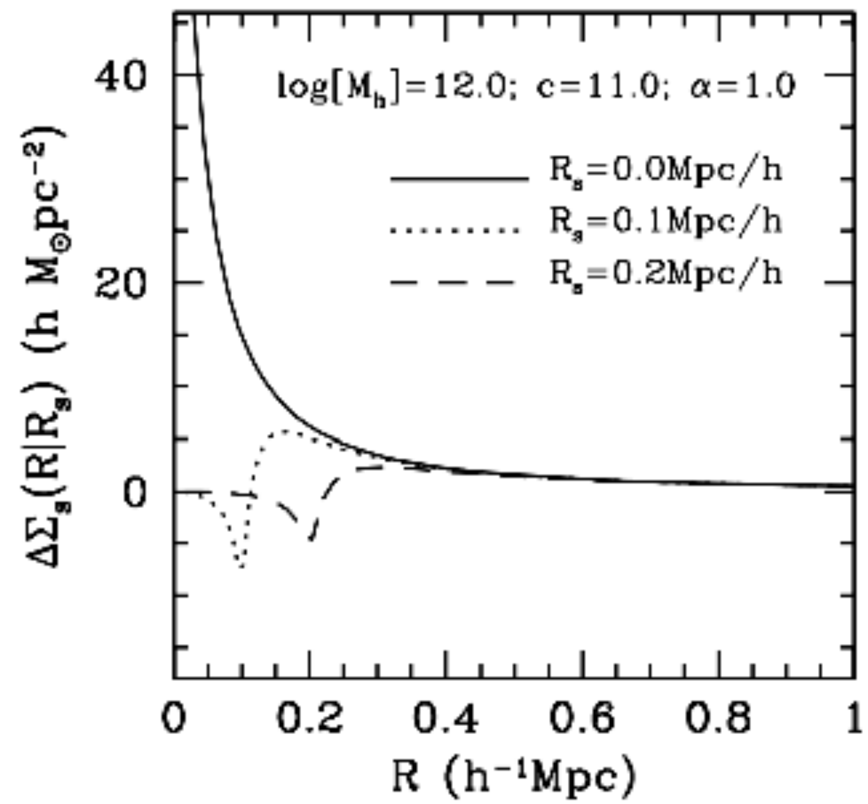
## As expected

Li et al. 2022

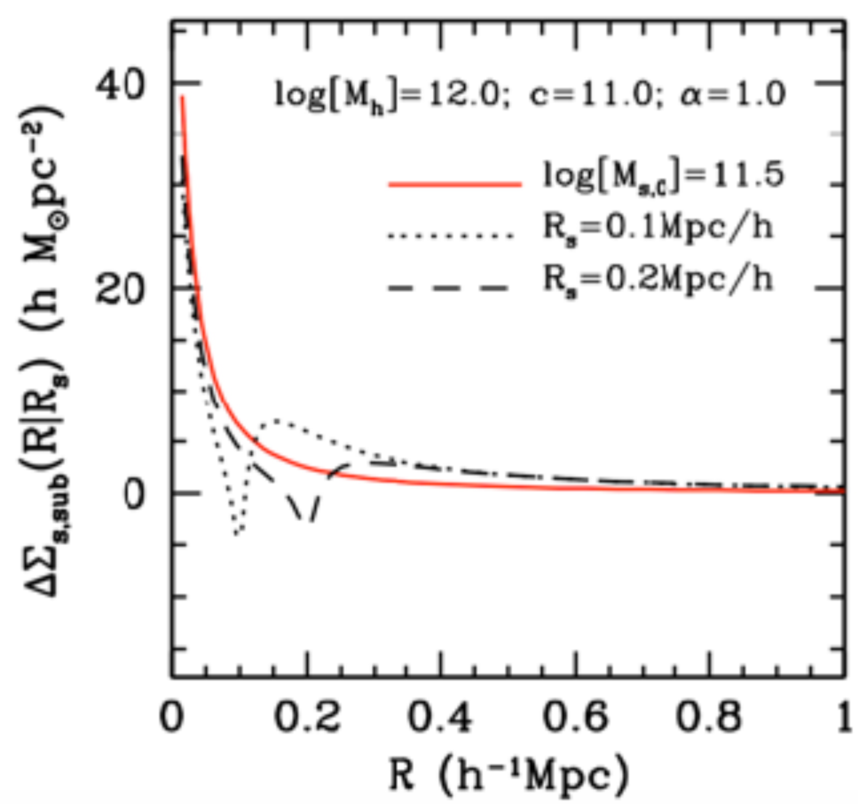


# Gravitational lensing by halos and subhalos






$M_{\rm sub} = 0$



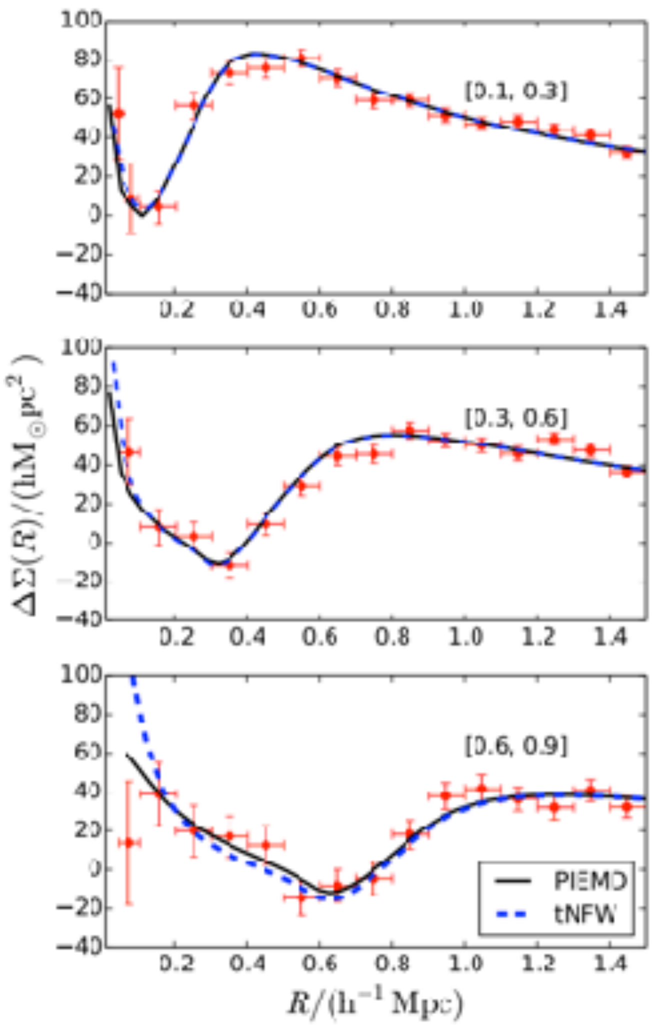

$M_{\rm sub} \neq 0$

Halo mass: mass around central galaxies;
Subhalo mass: mass around satellite galaxies

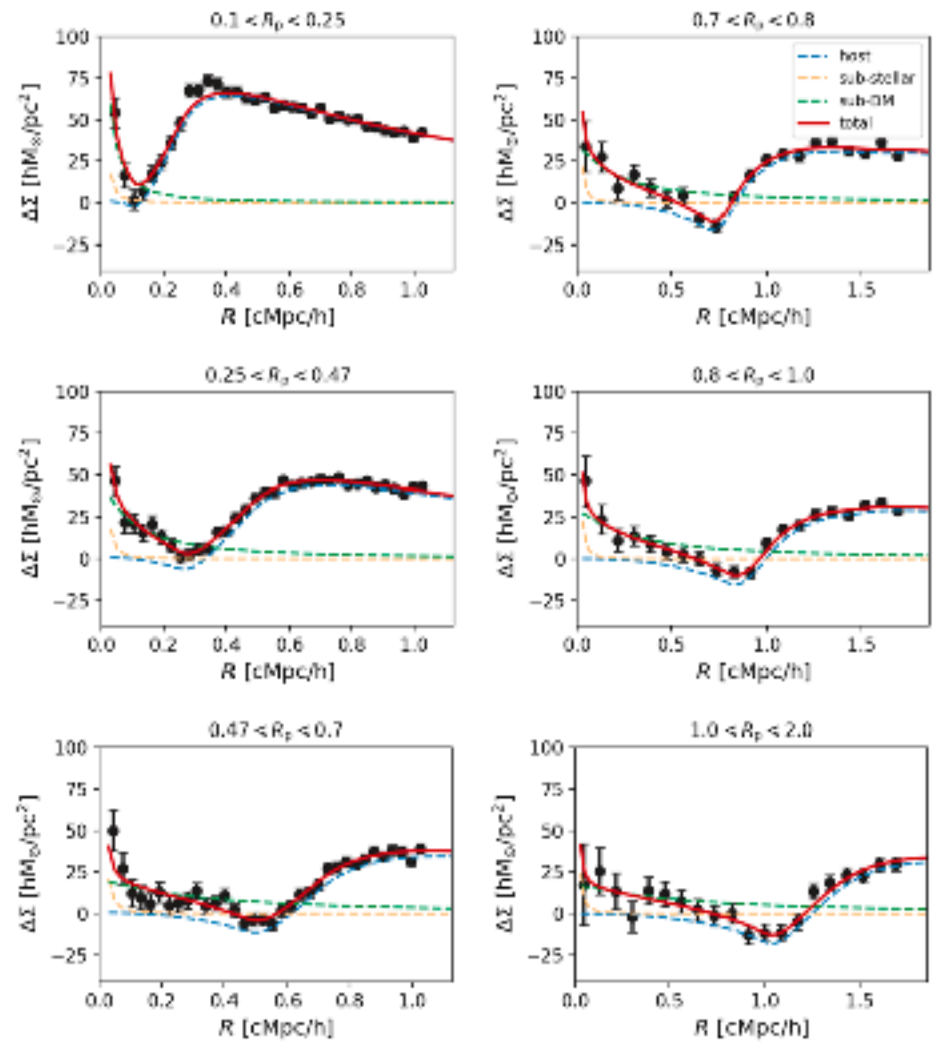
Yang+ 2006

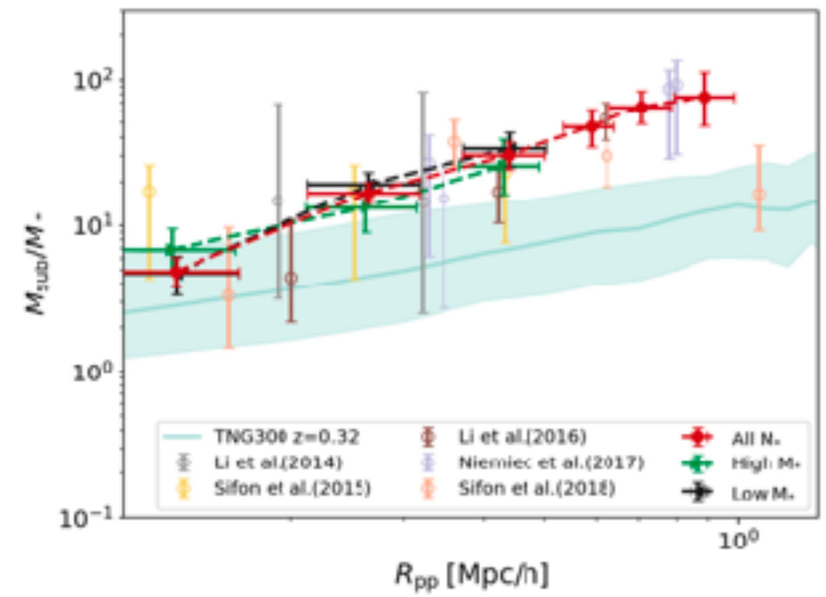
# Mass distribution around satellite galaxies

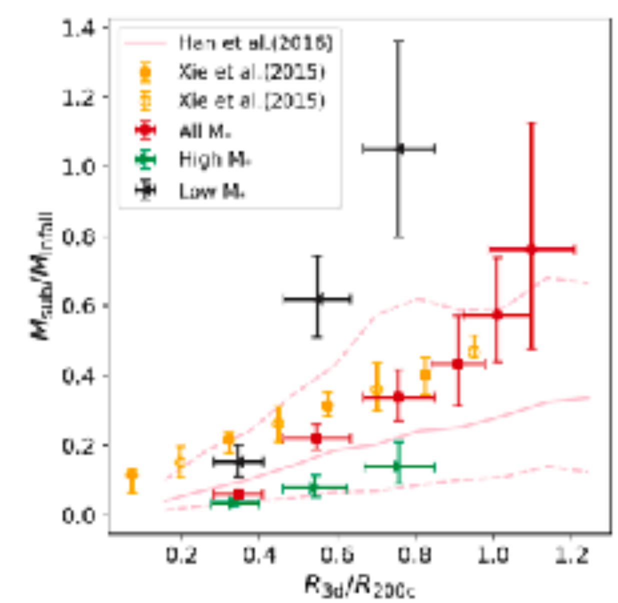
R. Li+ 2016

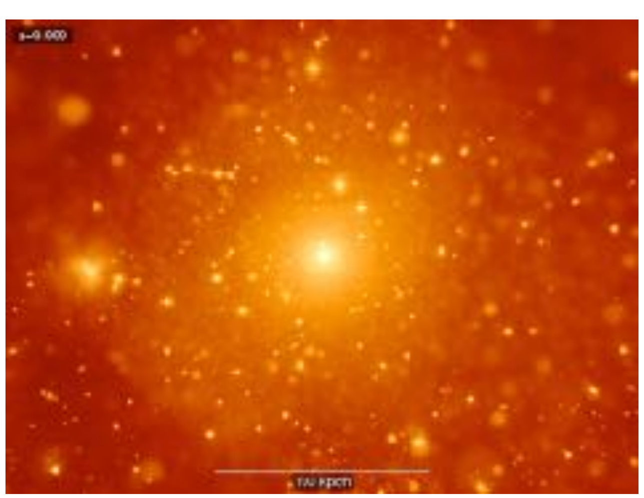



Wang, Li+ 2023

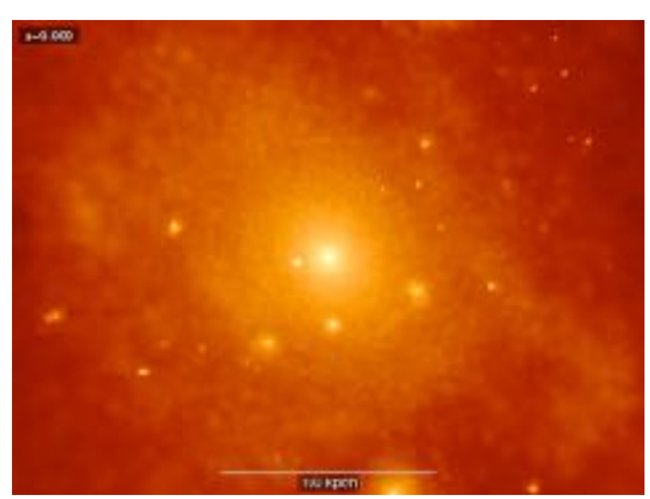


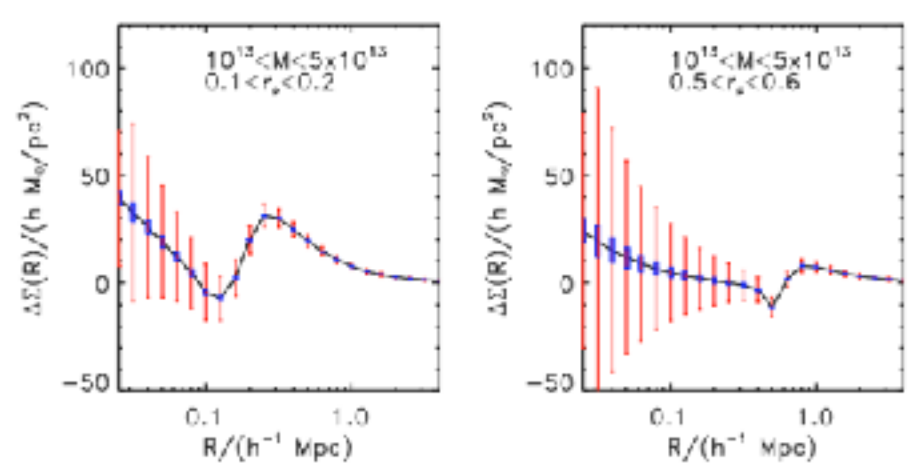



CDM

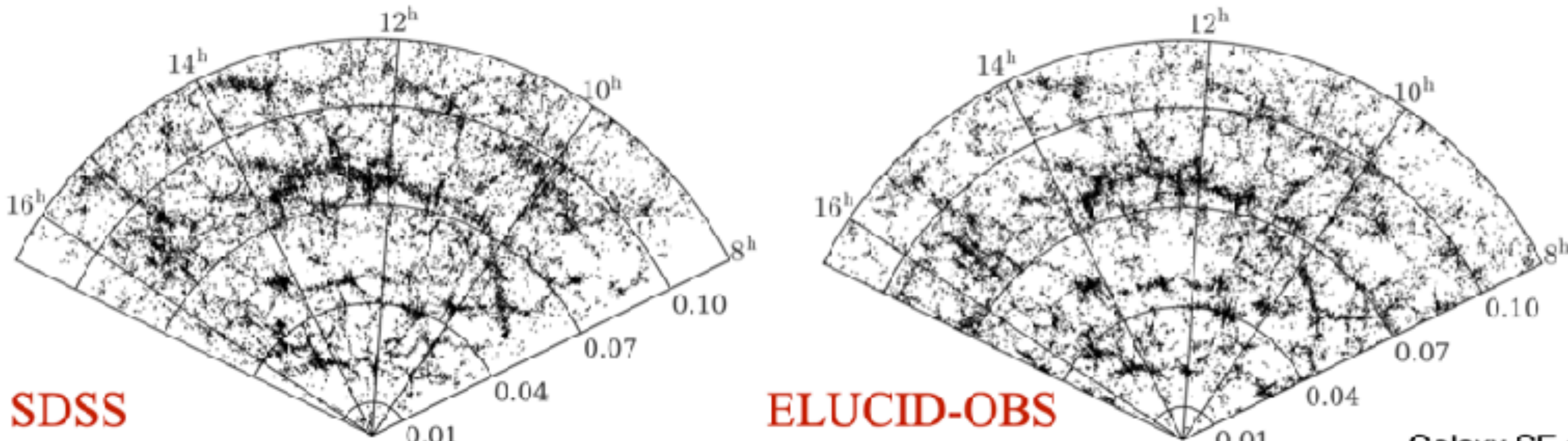


WDM

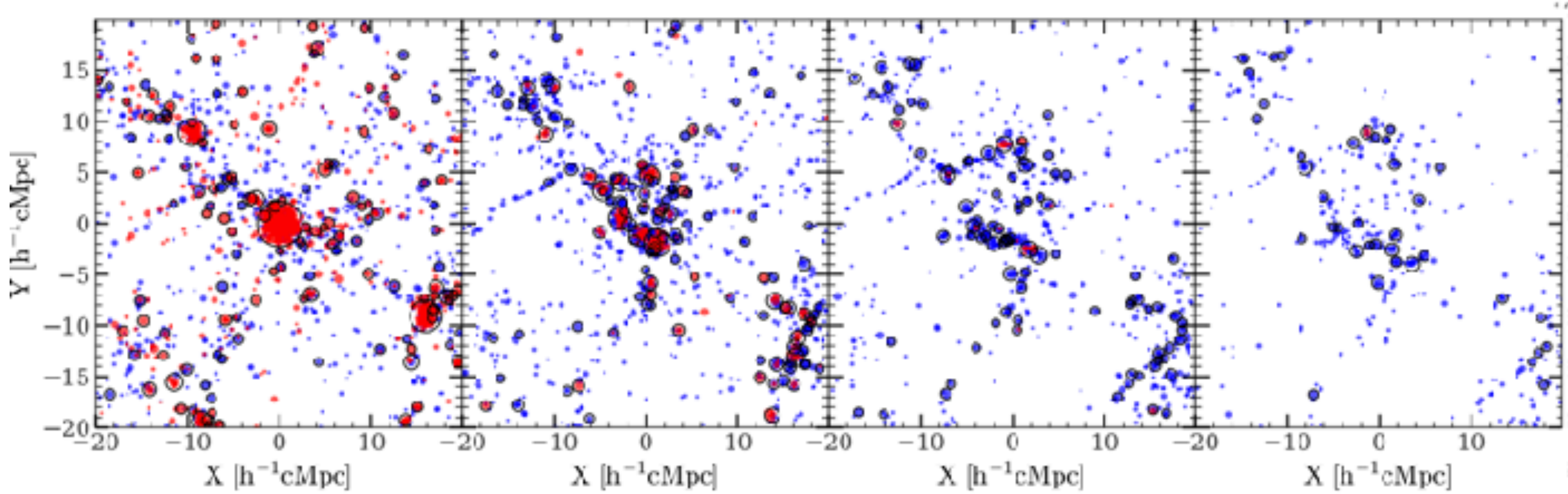



LSST

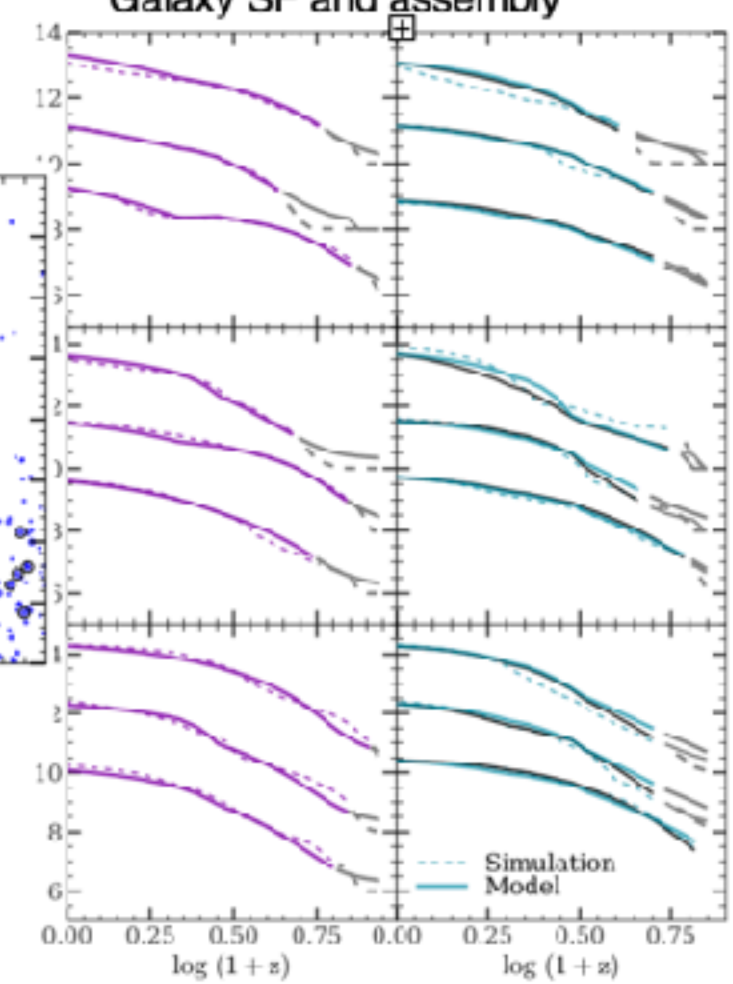
# Galaxies evolution from SDSS to JWST




Formation of Coma cluster



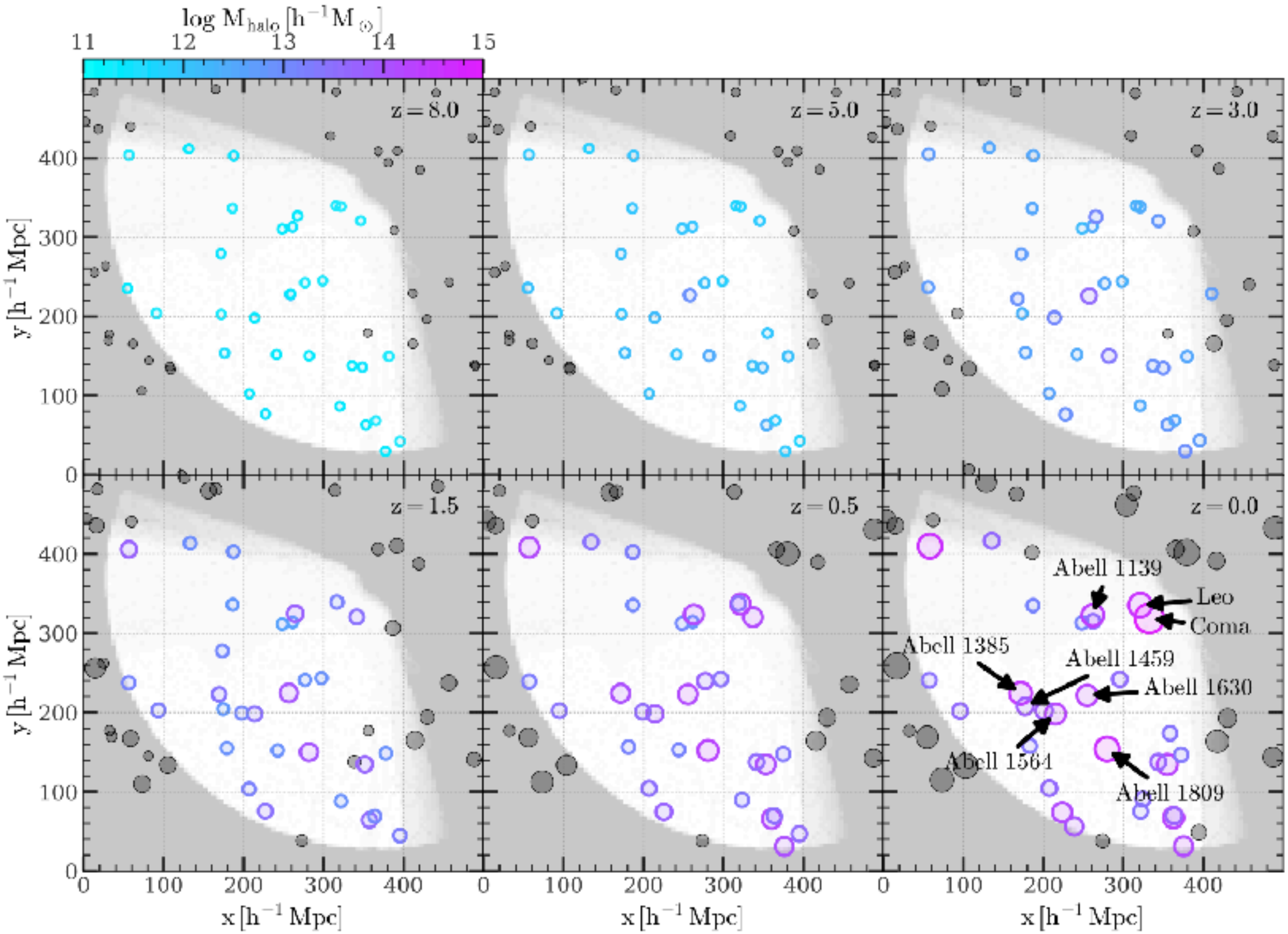

Galaxy SF and assembly



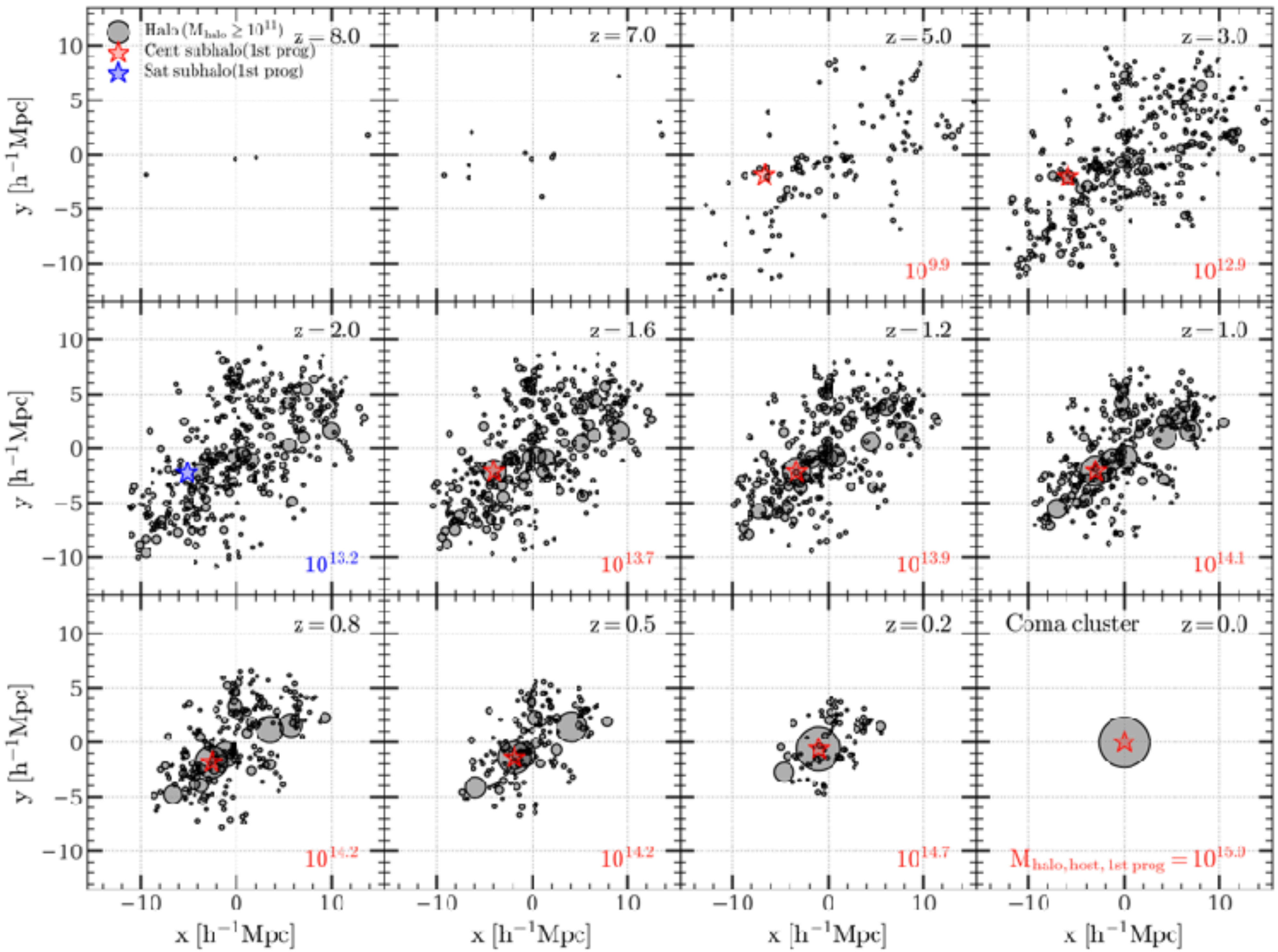

1. Descendants of high redshift galaxies
2. Progenitors of present galaxies

# Formation history of real low-z structure

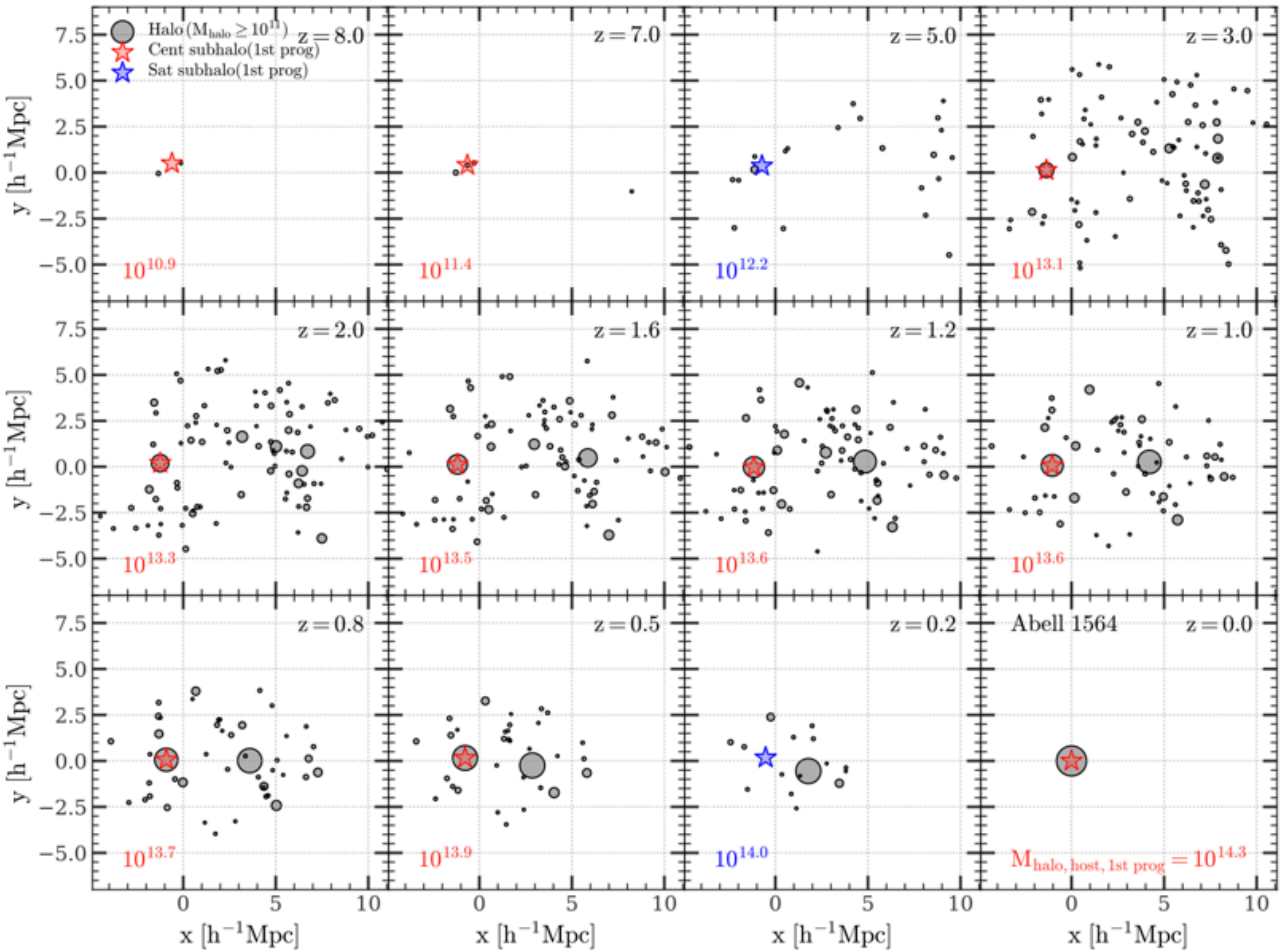
Chen et al 2023



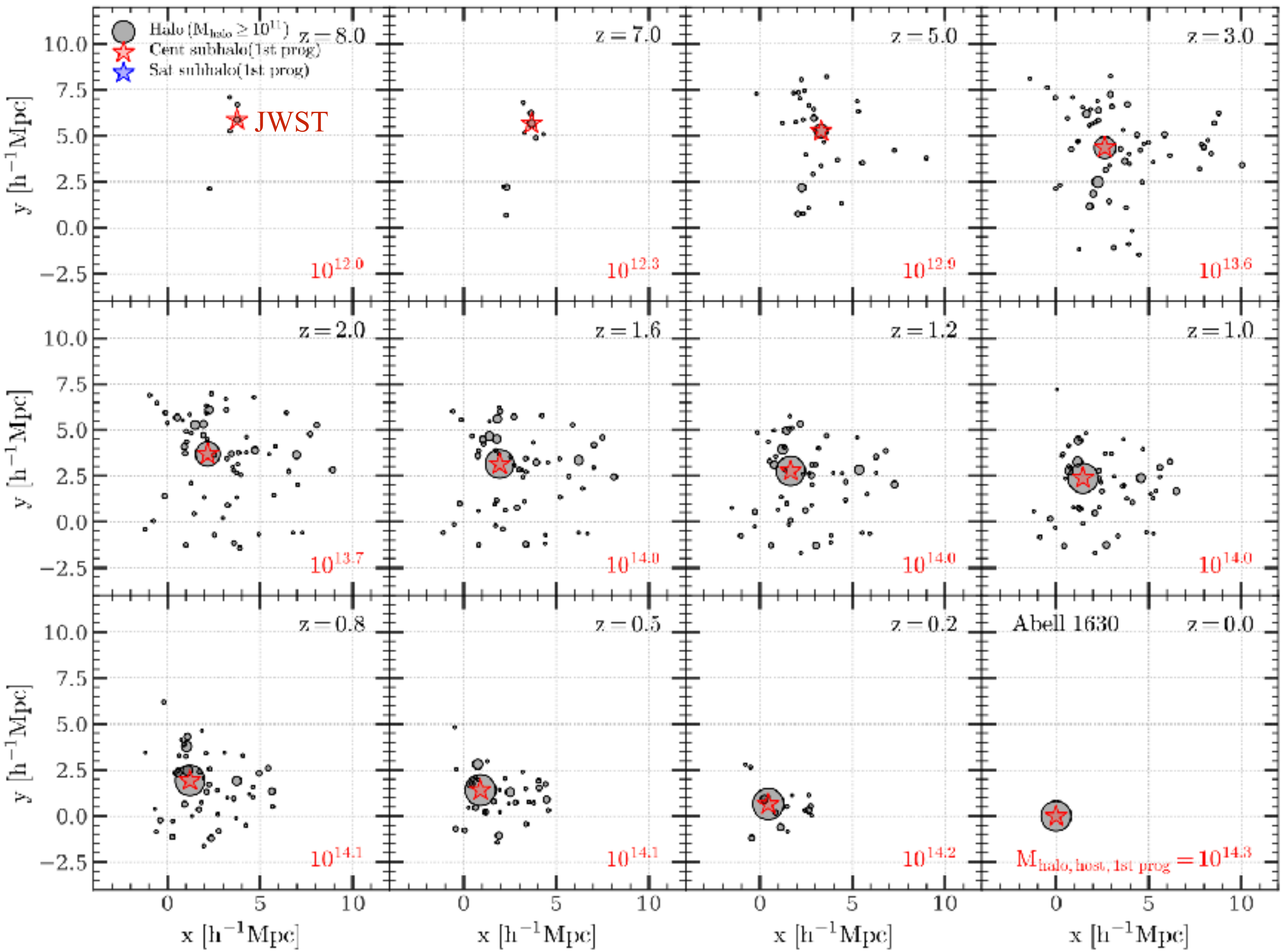
# Formation of the Coma cluster



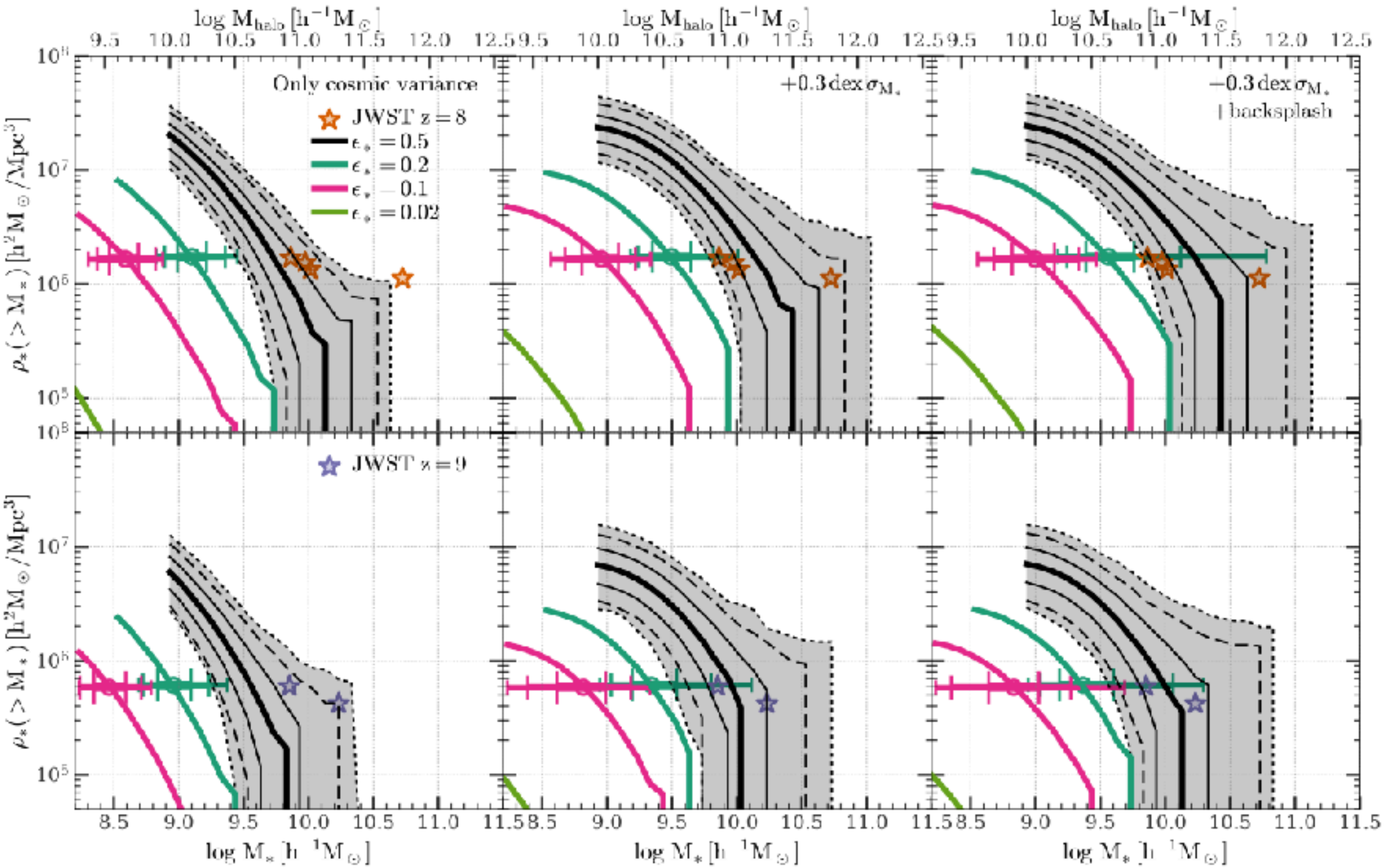
# Formation of Abell 1564



# Formation of Abell 1630

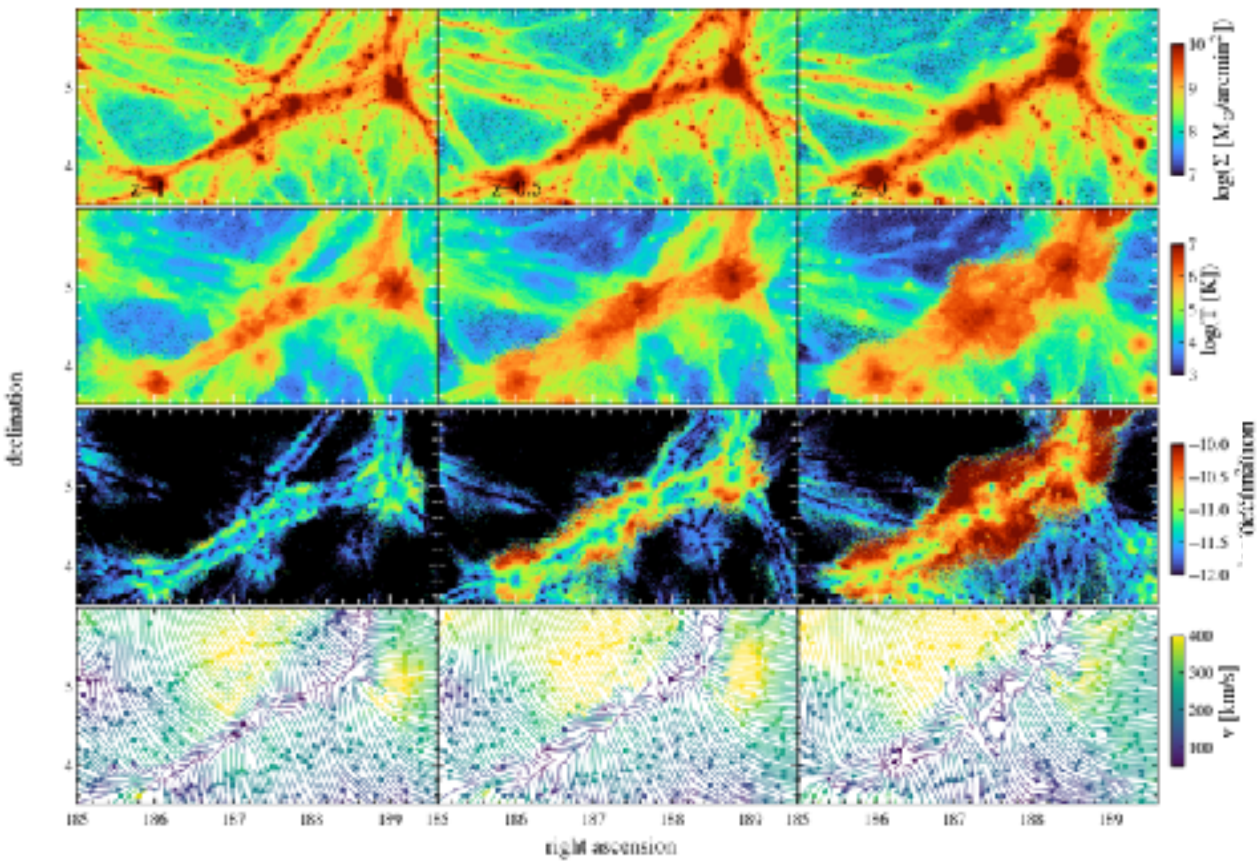


# Implications for JWST galaxies; cosmic variance large

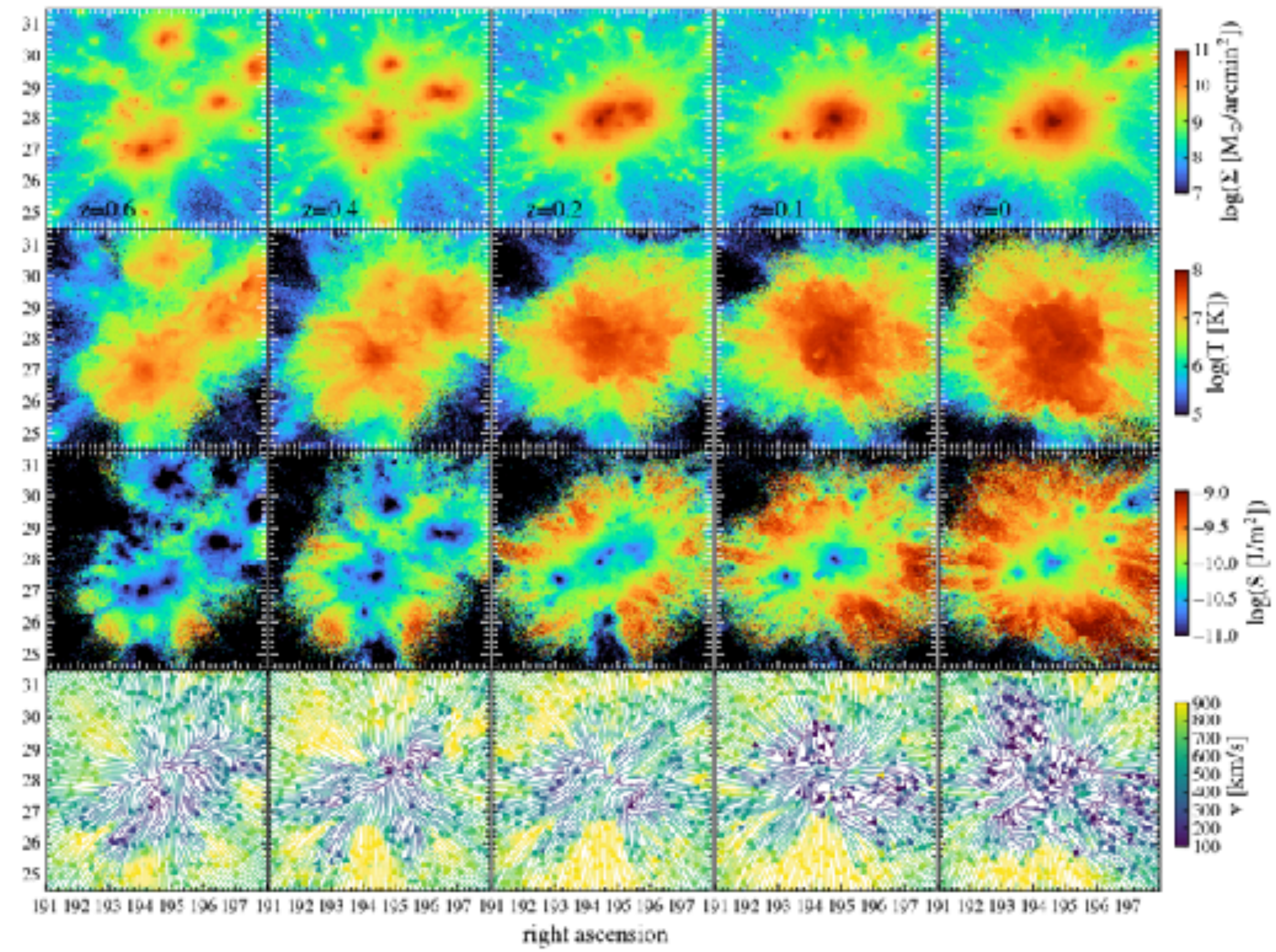


# Constrained gas simulations

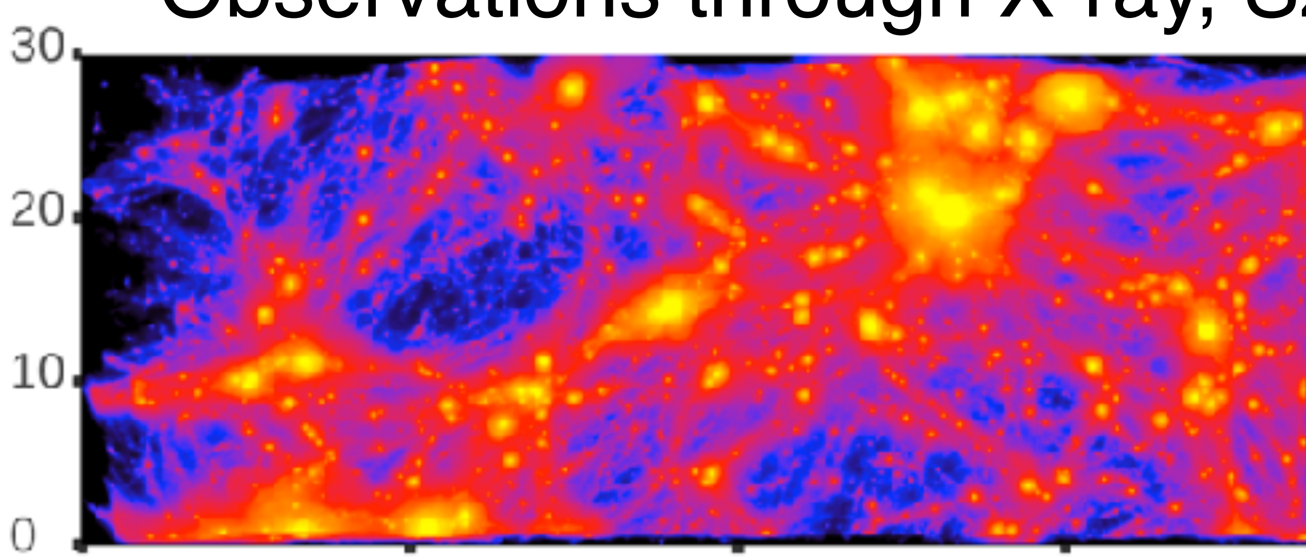
A filament in SDSS volume

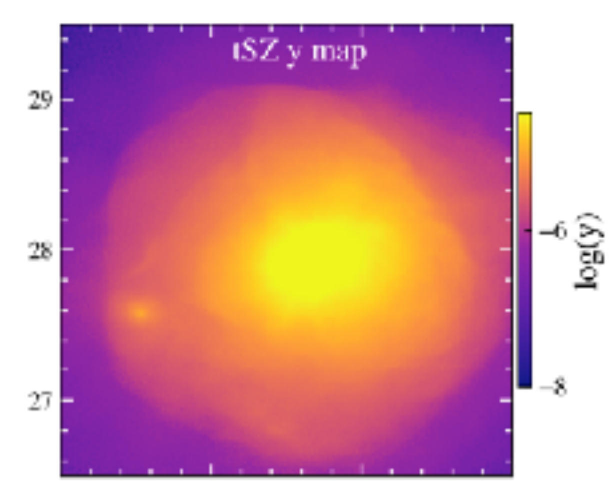



Coma cluster in the constrained simulation

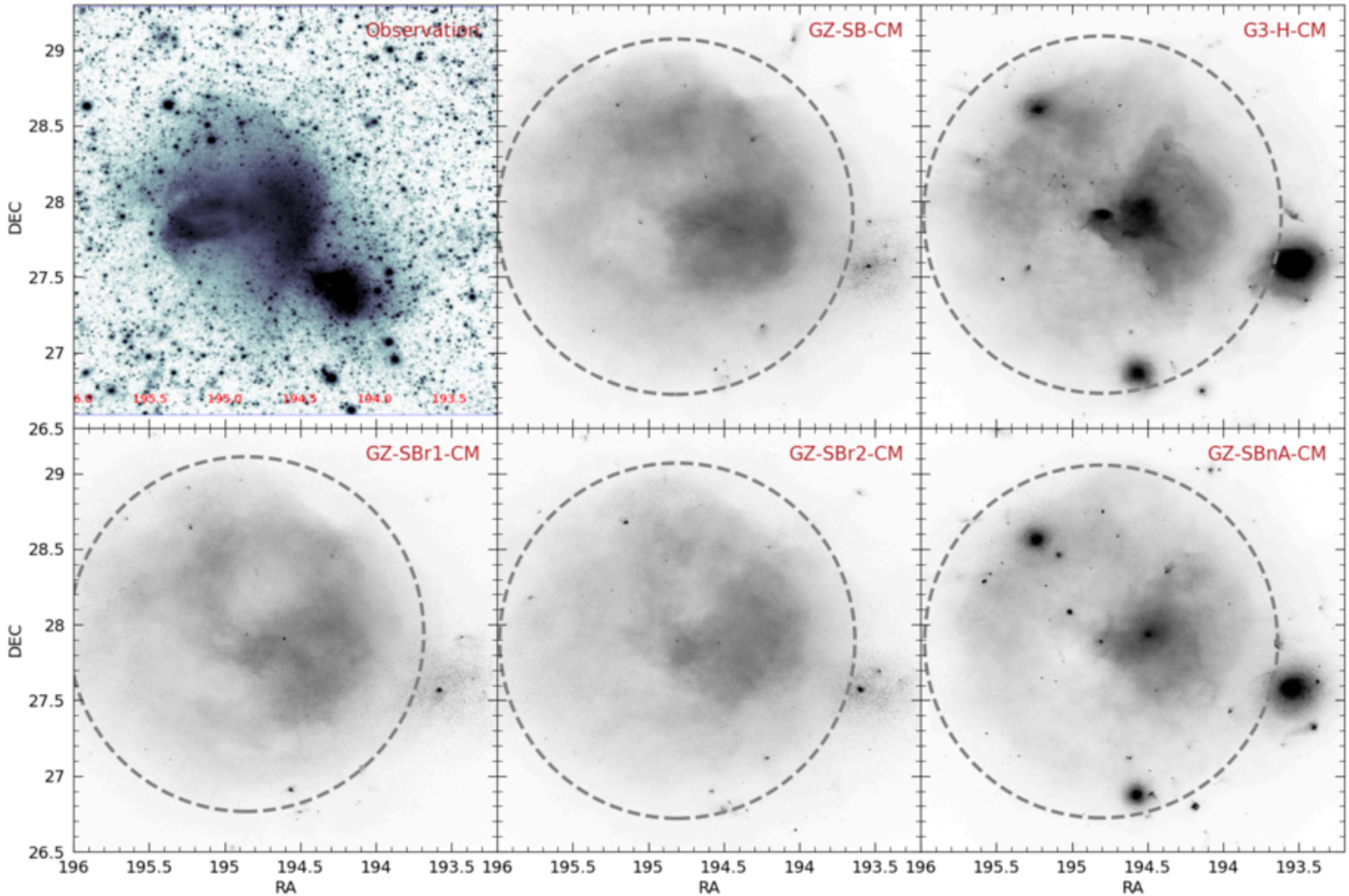



## Observations through X-ray, SZ, Absorptions

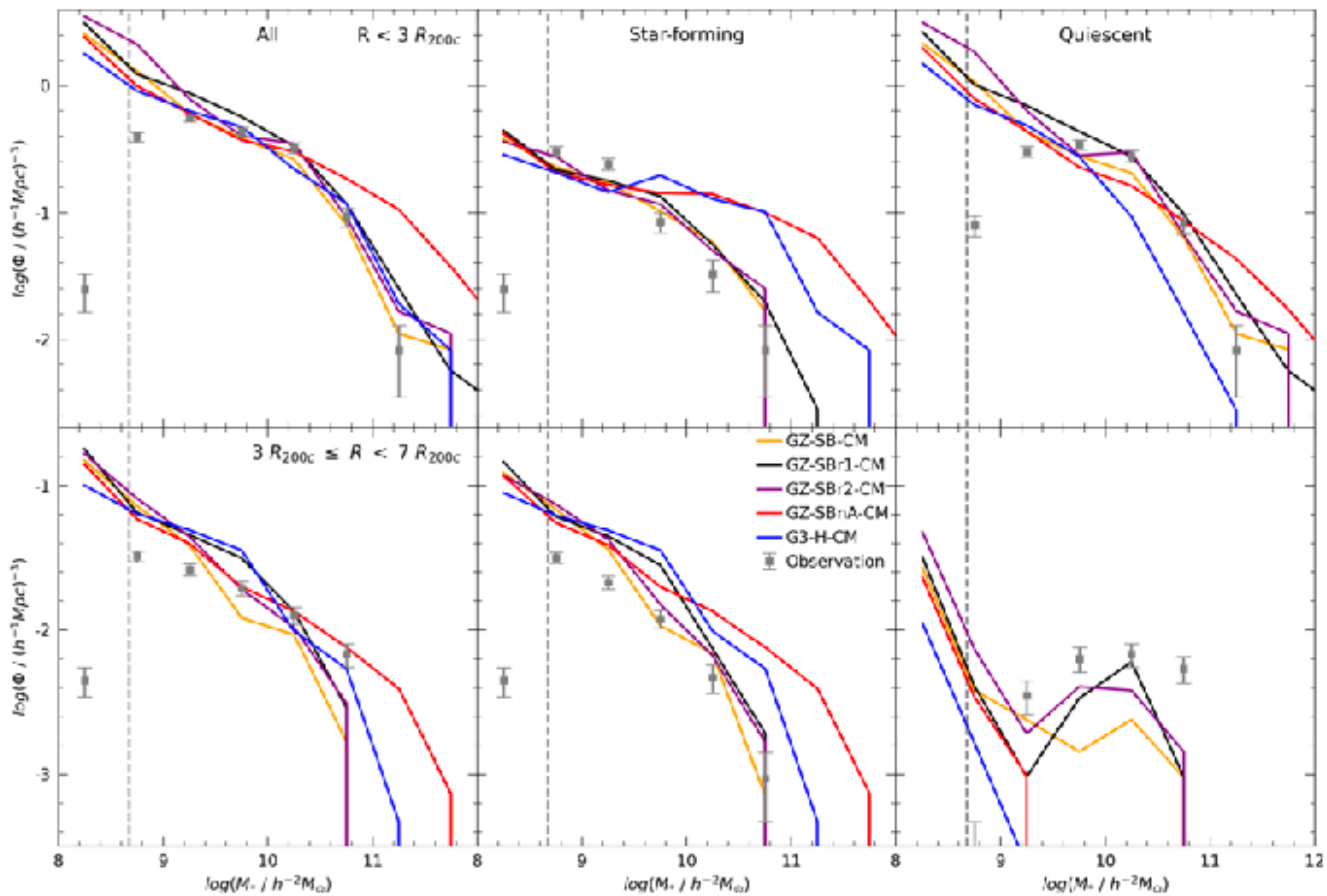


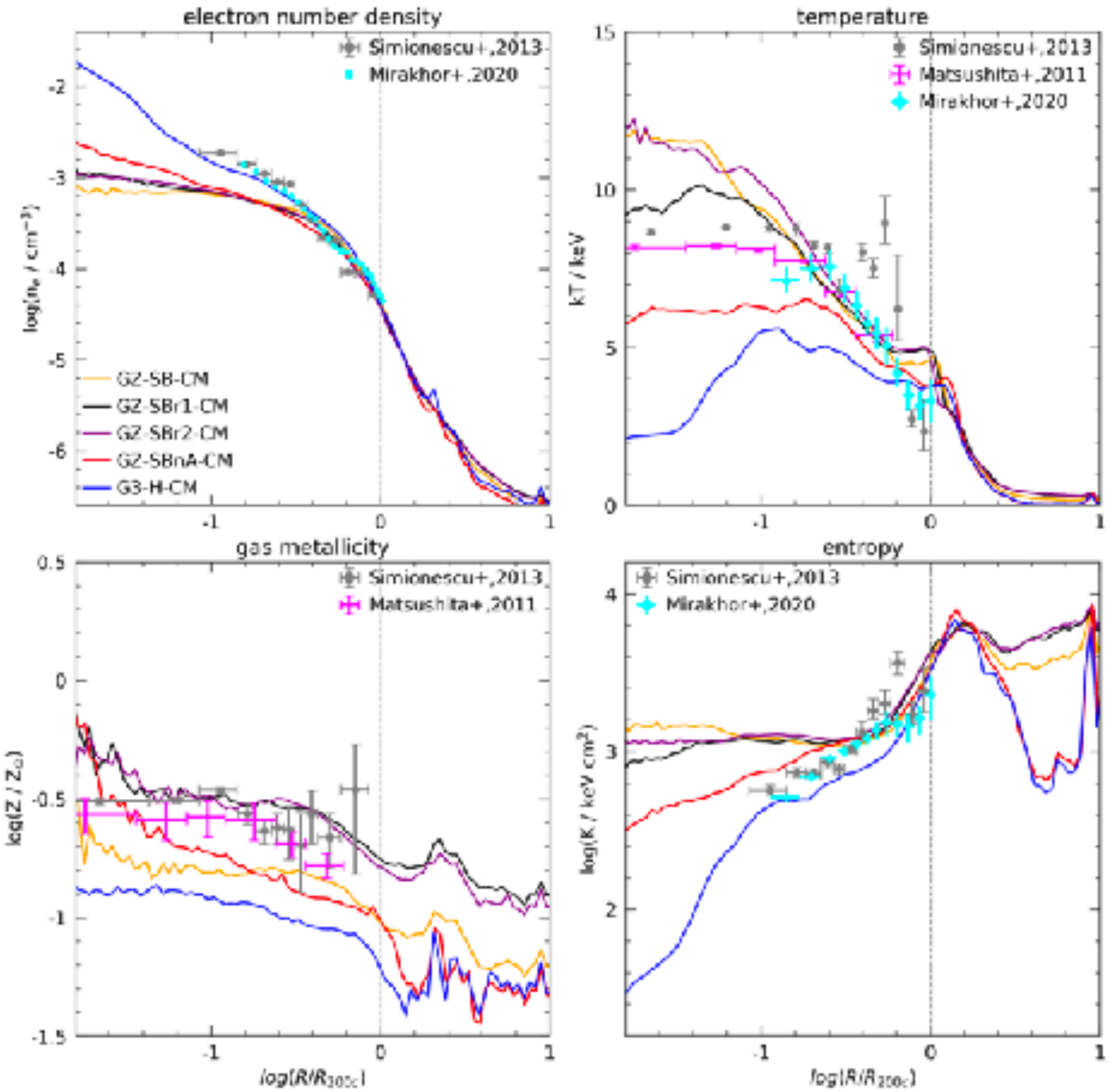
# Coma cluster as a testbed for galaxy formation; Predictions from different hydro simulations



# Strong feedback needed for stellar mass function of galaxies

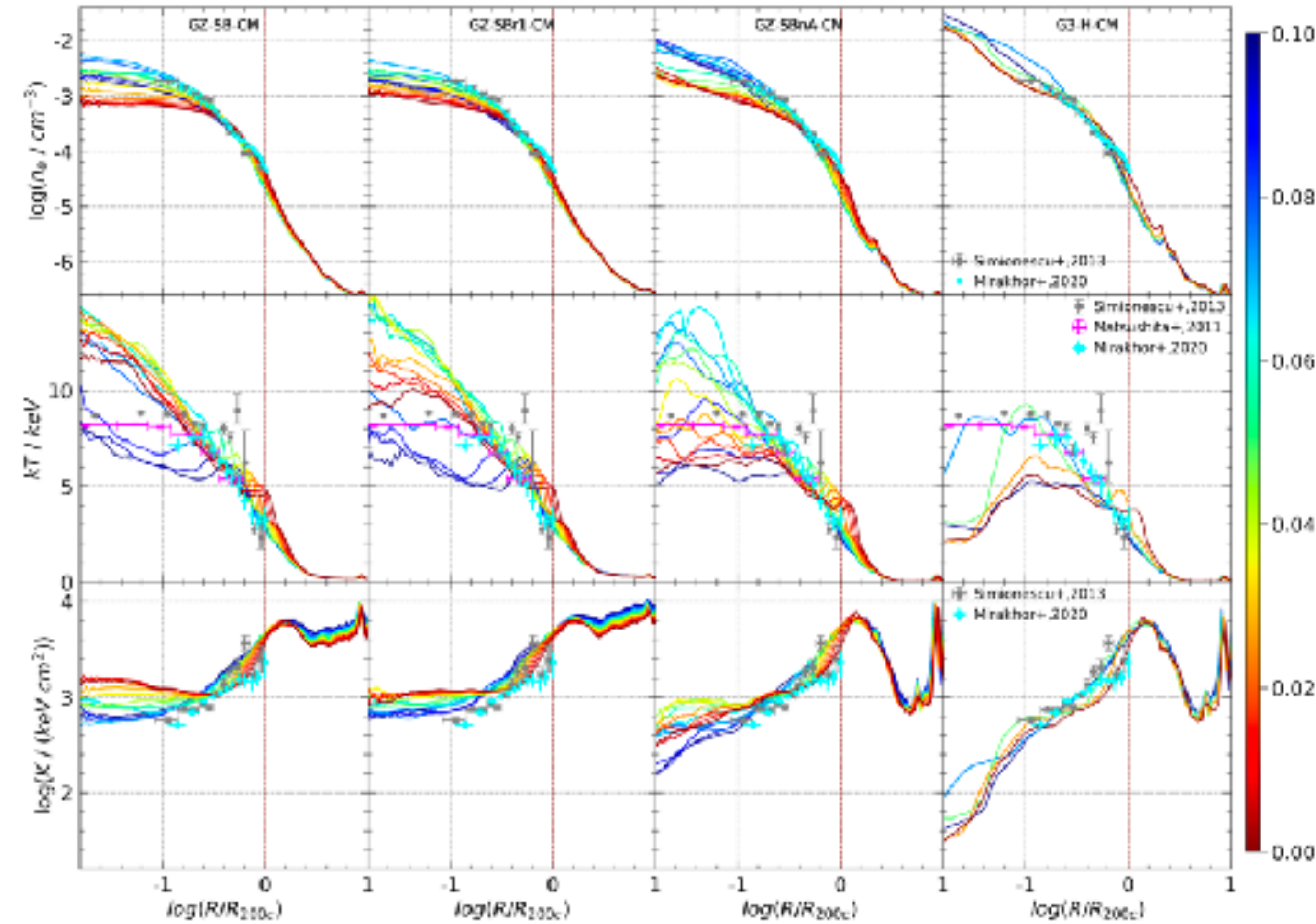


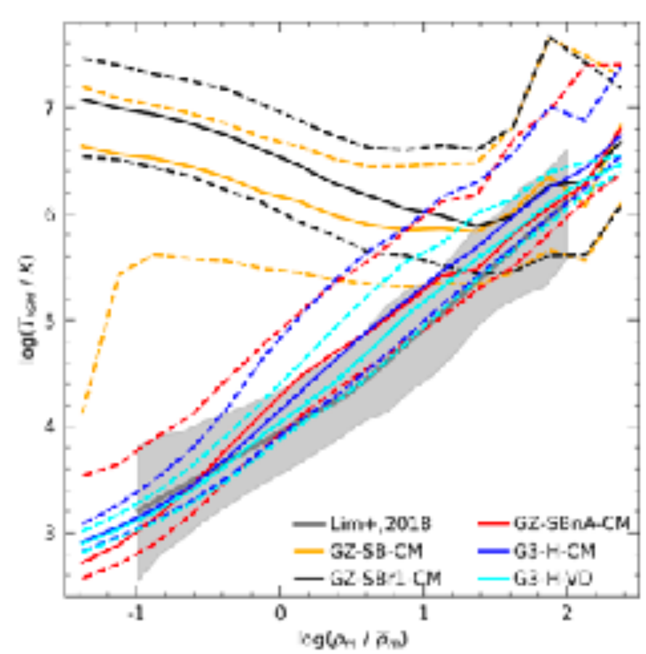
Strong feedback needed to match gas metallicity




Inner density and temperature profiles can change rapidly,

from a cool core to a hot core




IGM temperature near clusters depends sensitively on AGN feedback

None works perfectly

# Future

- Surveys of galaxies: BGS, HSC/PFS, 4MOST, WFIRST, CSS-OS; reconstruction and target selections.
- Future SZ surveys such as CMB-S4.
- Future X-ray surveys.
- High-z galaxies from JWST etc
- Reconstruction provides a powerful avenue to study the cosmic web and its evolution.