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Relating Galaxies across Cosmic Time

to study galaxy evolution

arXiv:2104.12223, 2211.00485

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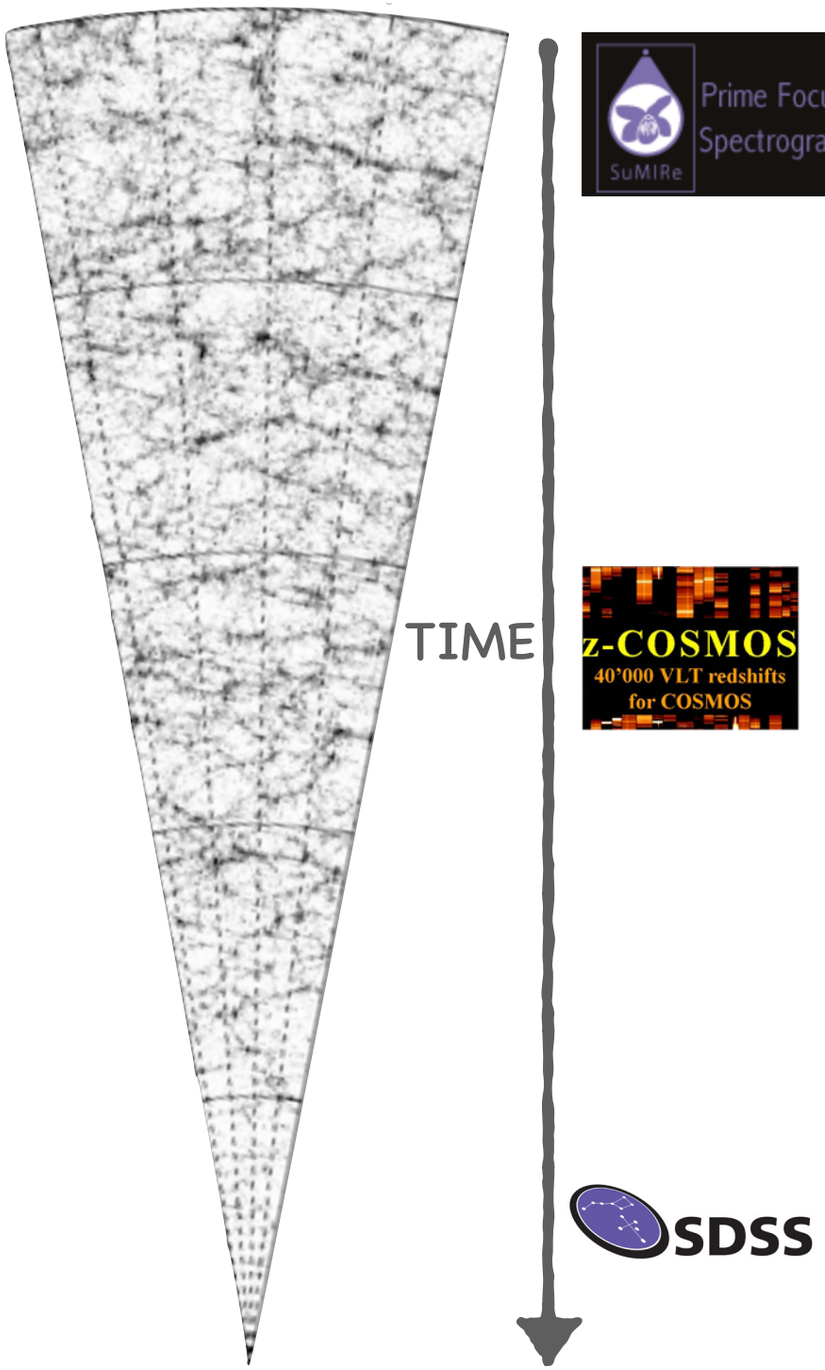
1. Connect Galaxies across Cosmic Time ⟶ The Problem



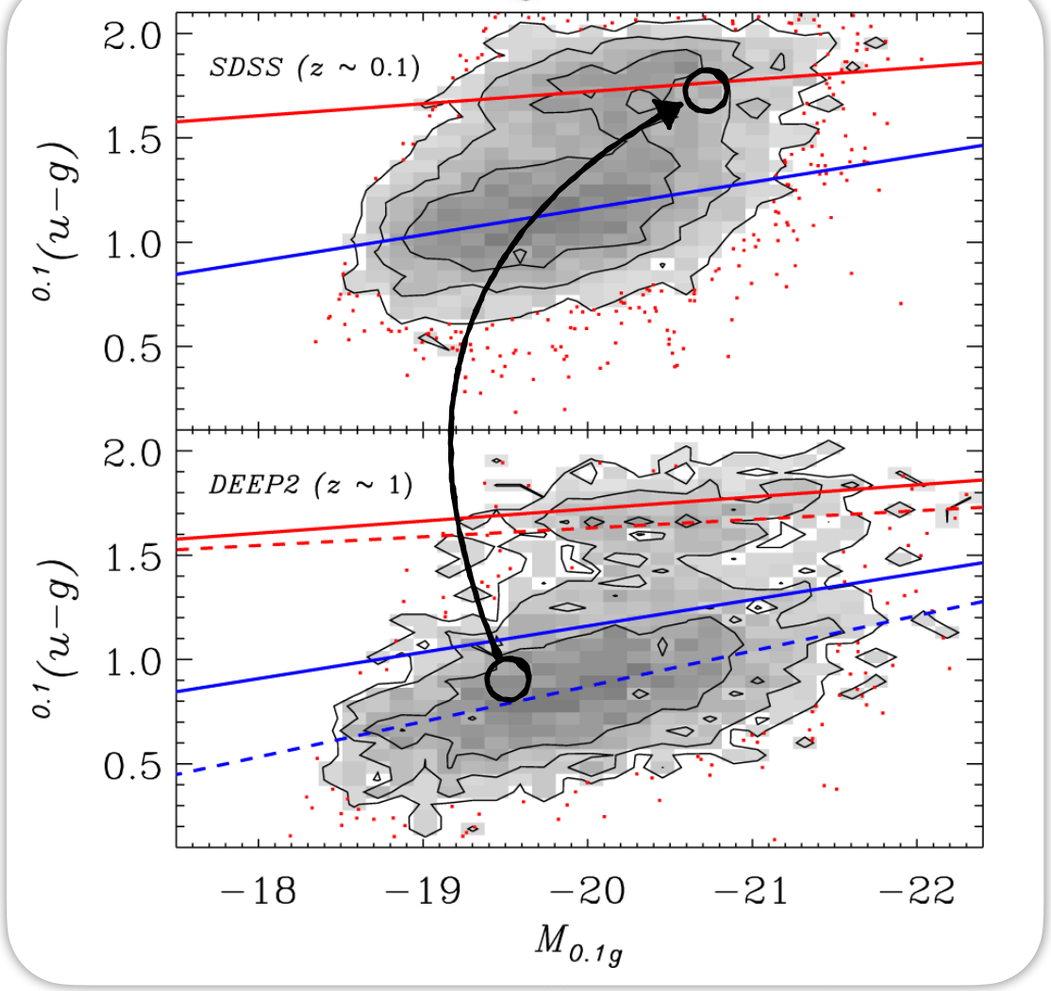
- Causally irrelevant
- Statistically connected

- What can we have?
  Time-dependent distribution function

$$P\left(\text{Mass, Luminosity, SFR, Color, Morphology, } \ldots \mid t\right)$$

- What do we want?
  Equation of motion in the phase space

$$f_1\left(\text{Mass, Luminosity, SFR, Color, Morphology, } \ldots \mid t\right) = 0$$
$$\cdots$$
$$f_n\left(\text{Mass, Luminosity, SFR, Color, Morphology, } \ldots \mid t\right) = 0$$



https://cosmo.nyu.edu/blanton/deep2sdss/

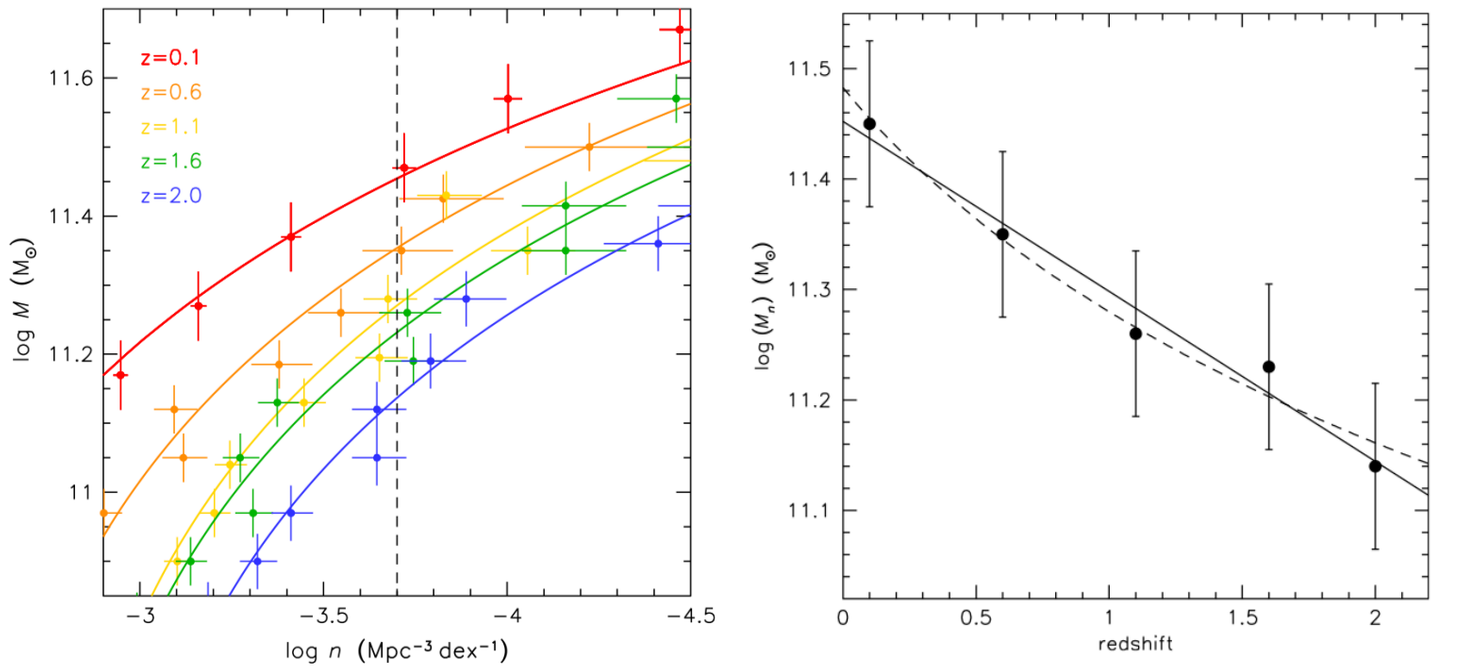
CONSTANT CUMULATIVE NUMBER DENSITY METHOD

$$n(>M_{*,1} \mid z_1) = n(>M_{*,2} \mid z_2)$$

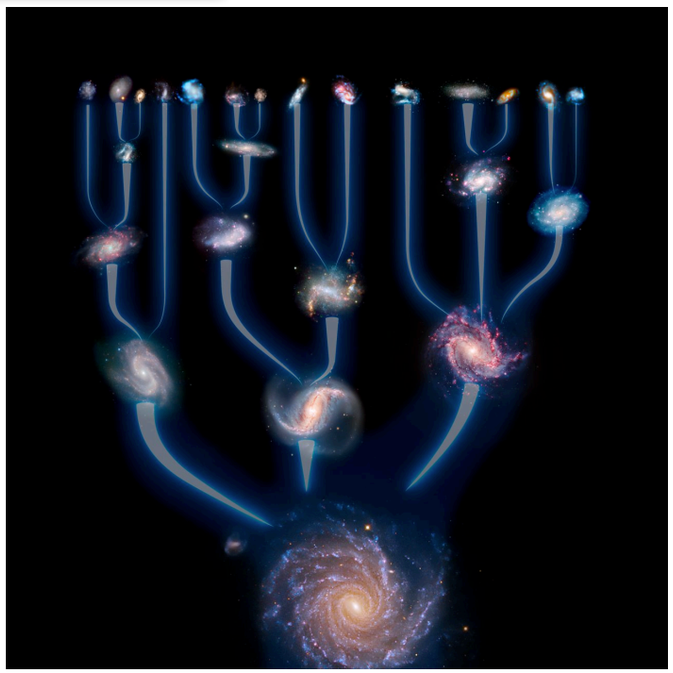
Galaxies $> M_{*,2}$ at z_2: Progenitor
Galaxies $> M_{*,1}$ at z_1: Descendant

ASSUMPTION:
Stellar mass rank preserves!

van Dokkum et al. 2010

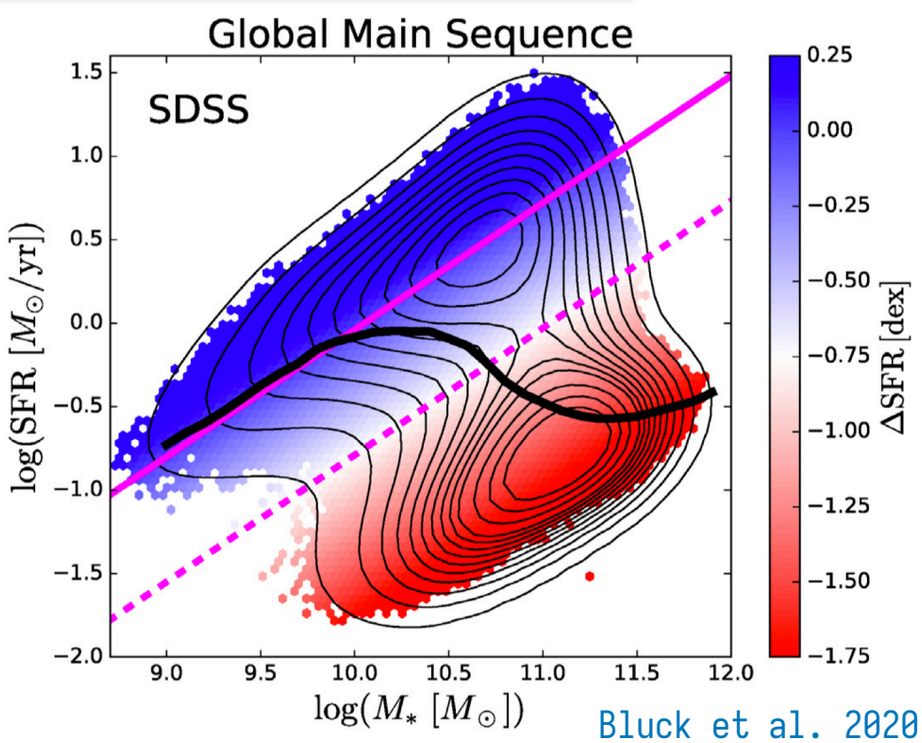


1. Galaxy mergers



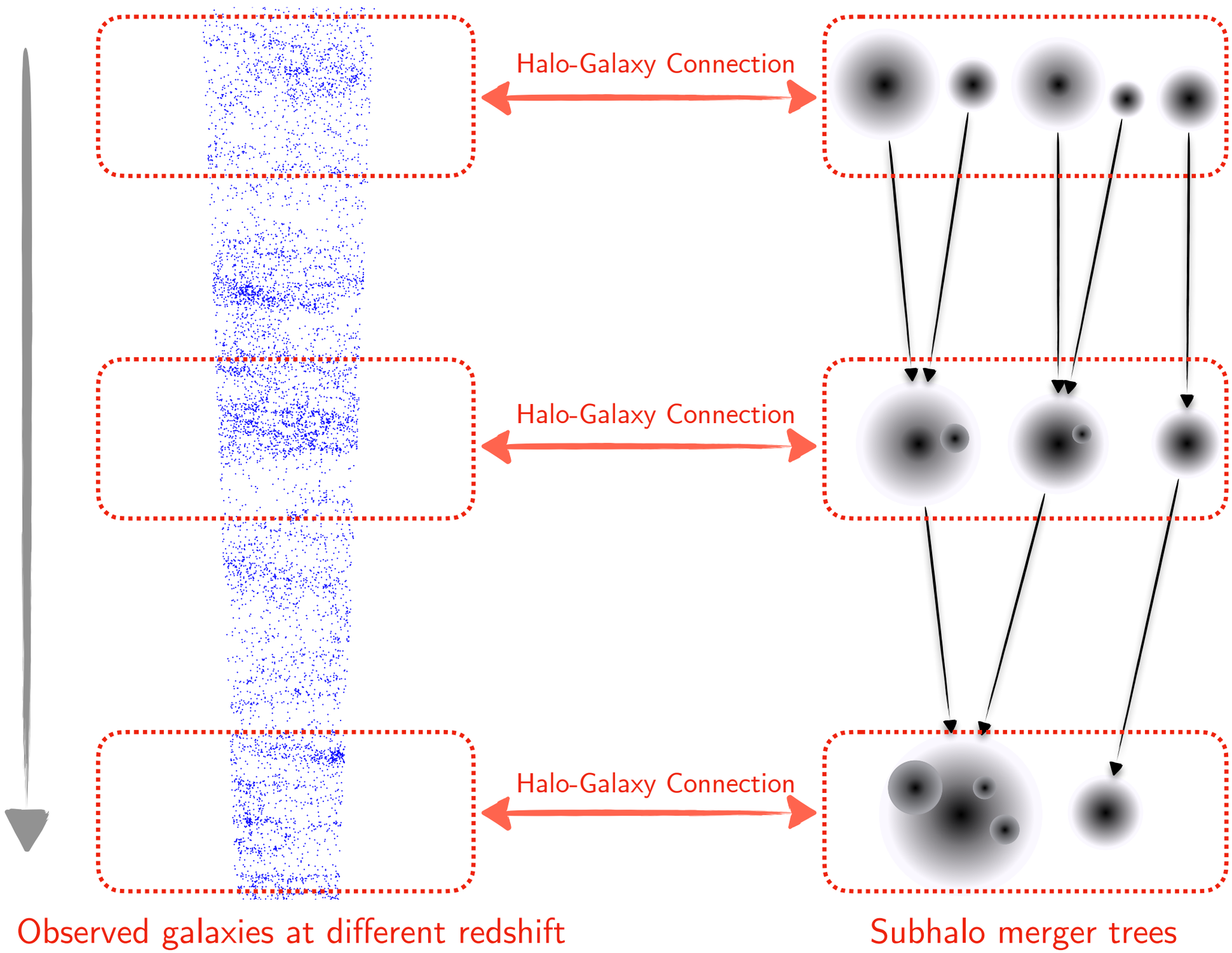
Credit: ESO/L. Calçada

2. Diversity in star formation rates



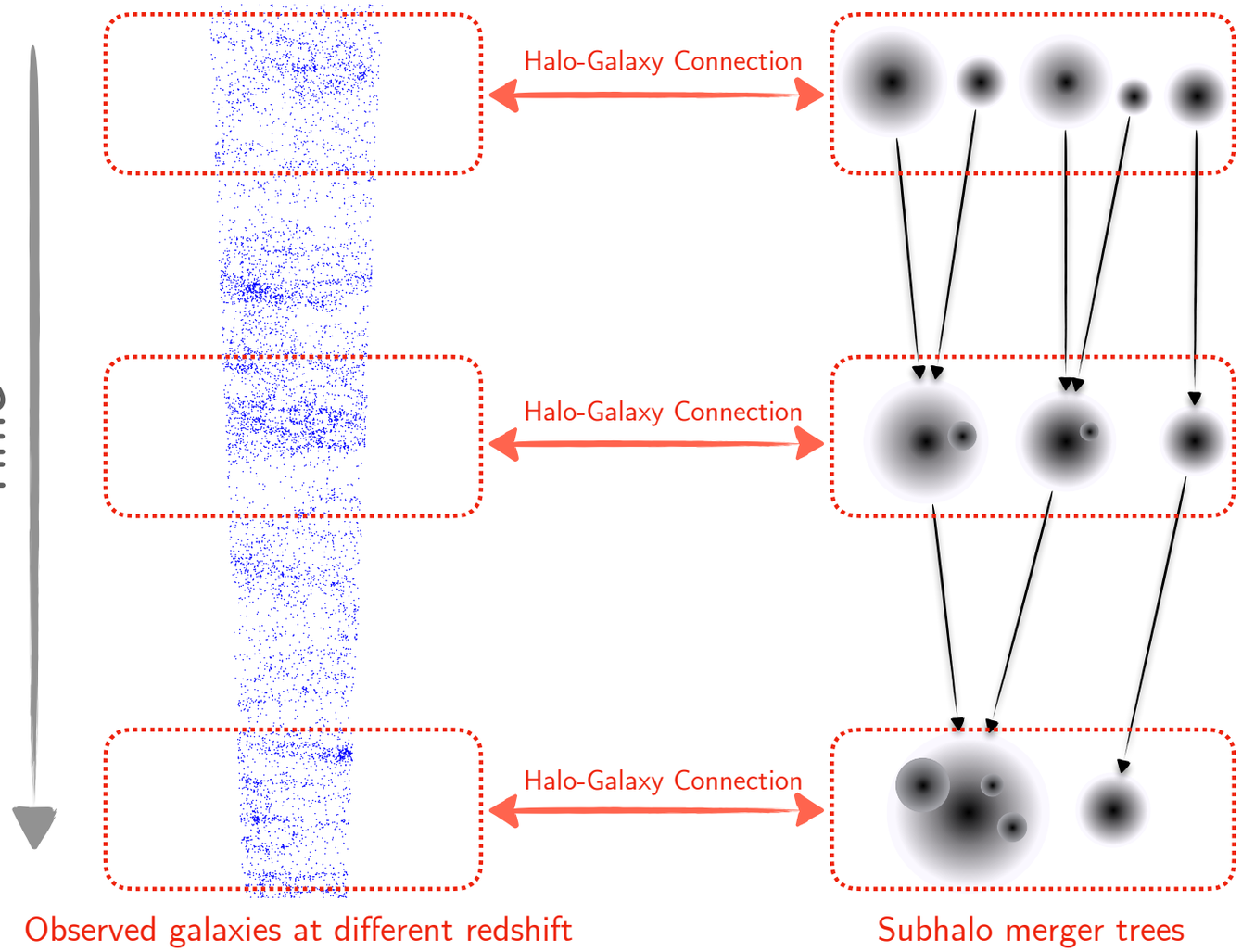
Bluck et al. 2020

1. Connect Galaxies across Cosmic Time ⟶ Framework



Wang et al. 2023a

1. Connect Galaxies across Cosmic Time ⟶ Method & Test

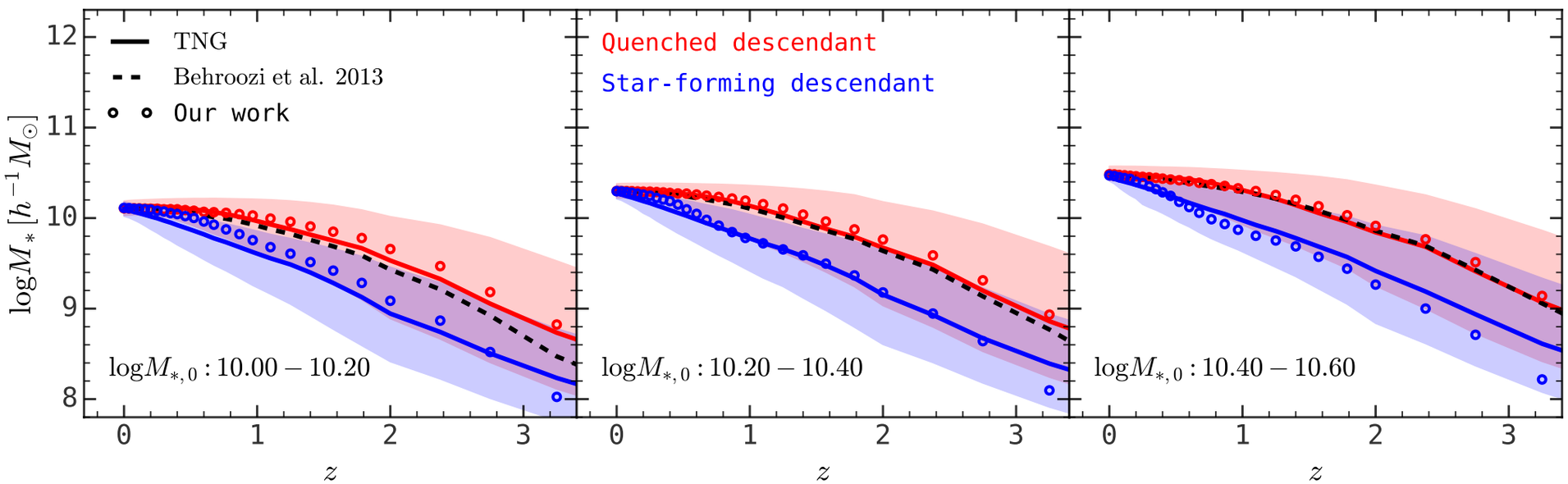


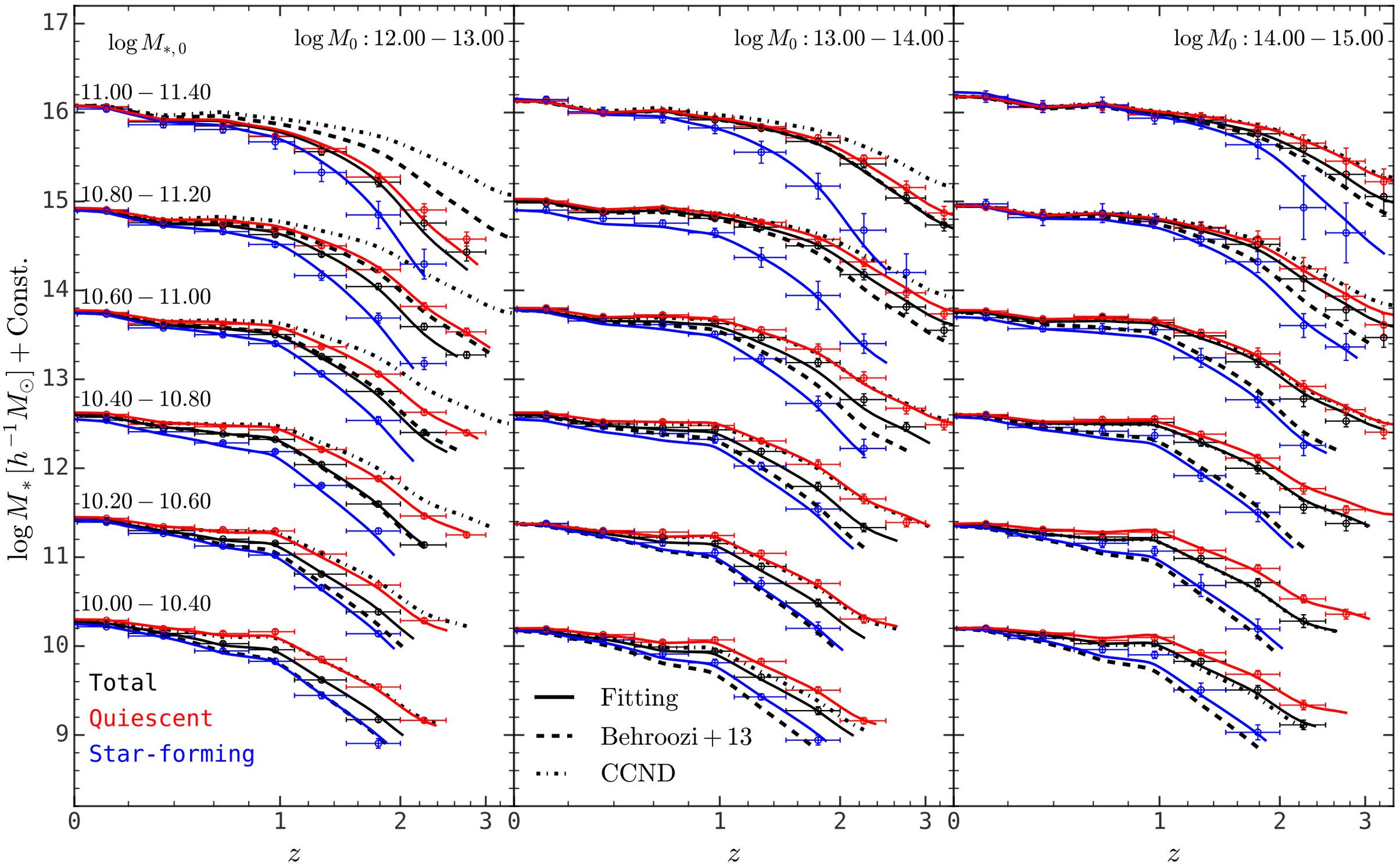
- **Sub-Halo Abundance Matching (SHAM):**
  Massive galaxy resides in massive subhalo.
  $n(>M_*) = n(>M_{\rm subhalo})$
- **Age Distribution Matching (ADM):**
  Galaxy formed/accreted early quenches early.
  $n(<\mathrm{sSFR}\,|\,M_*, M_h) = n(>z_{\rm starve}\,|\,M_*, M_h)$

Assign each subhalo

- **stellar mass (M_*)**
- **specific star formation rate (sSFR)**

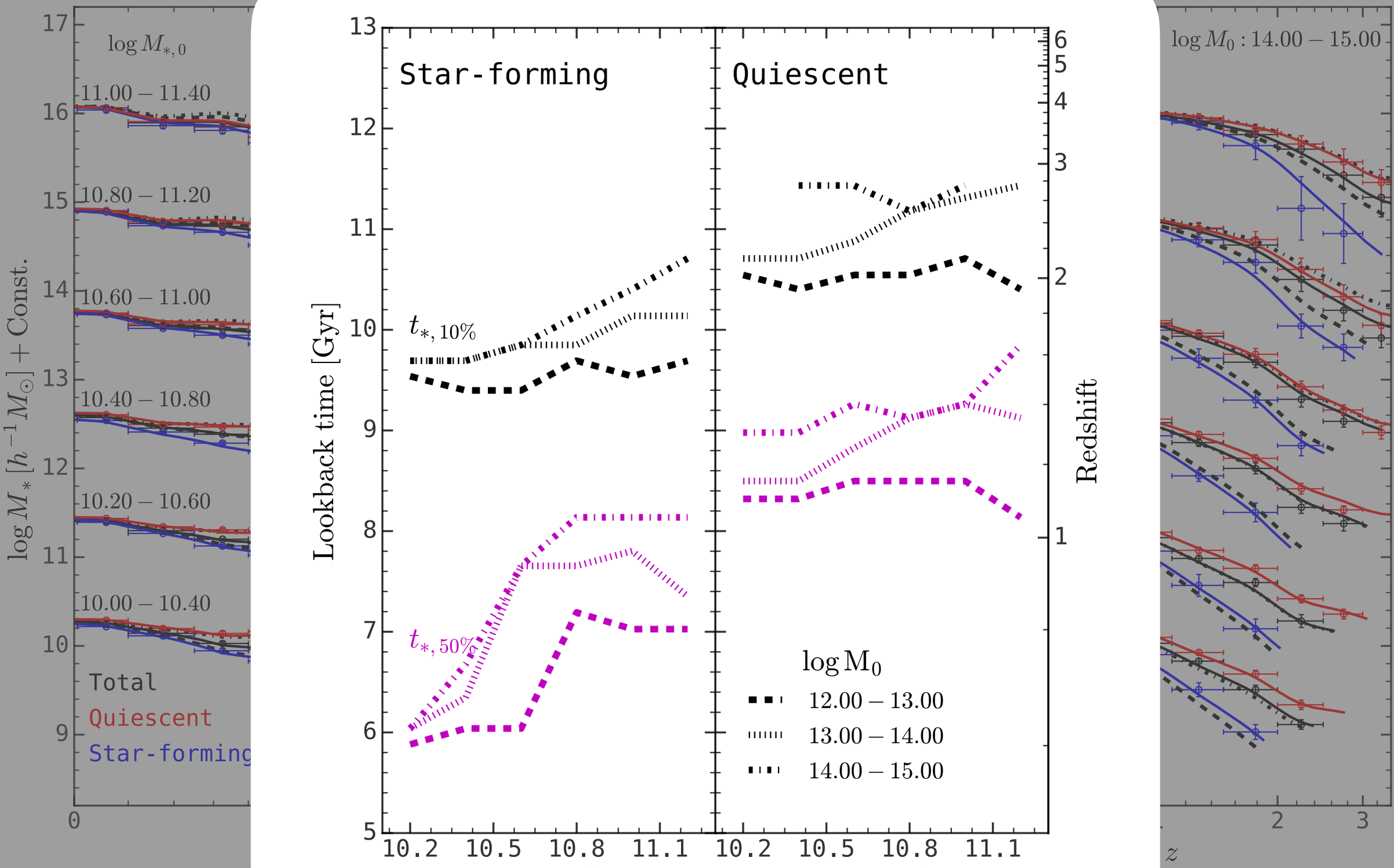
Trace the **assembly histories of galaxies** though **subhalo merger trees**





Wang et al. 2023a

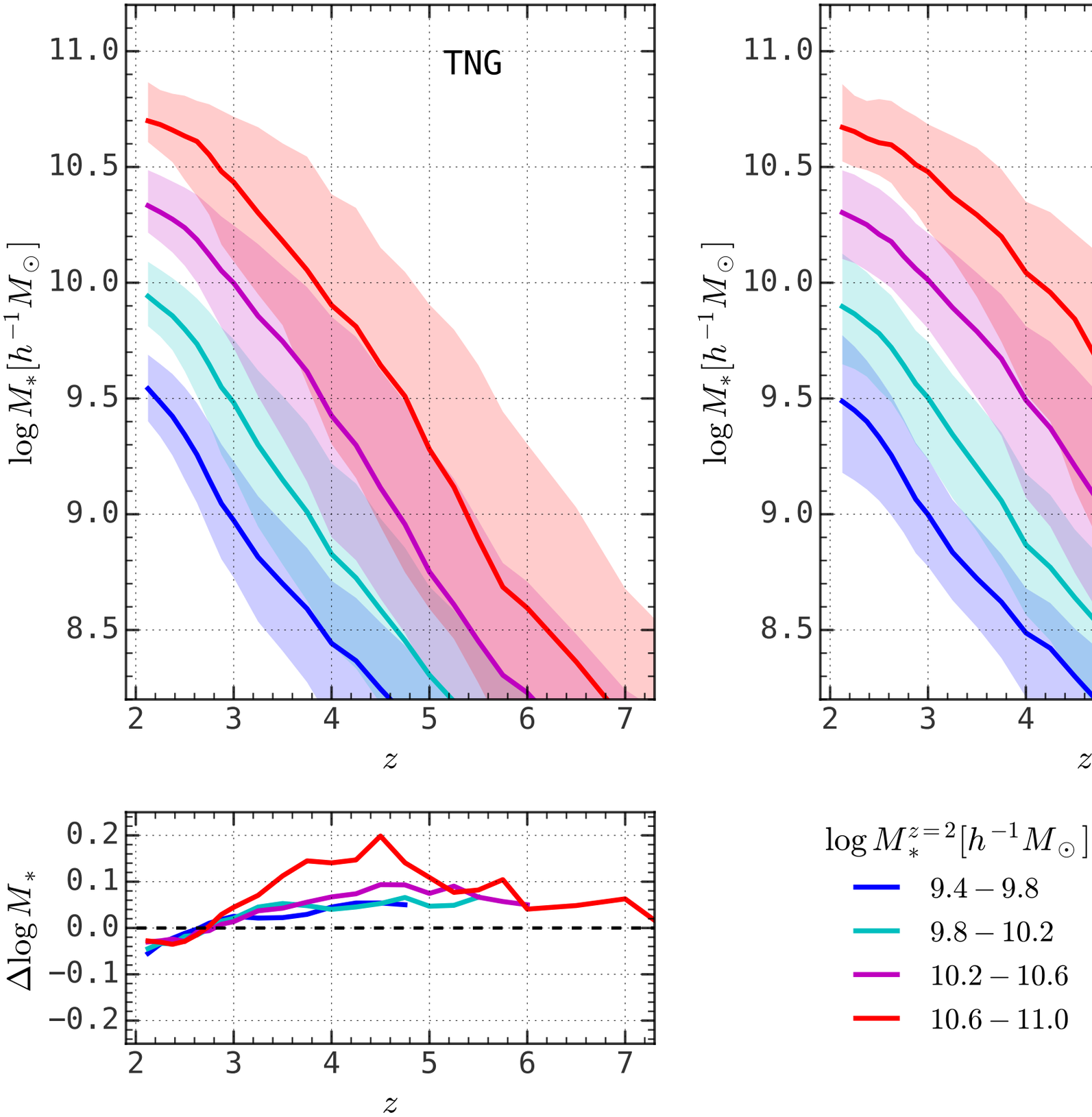
1. Connect Galaxies across Cosmic Time ⟶ Applied to observation



Wang et al. 2023a

2. Connect Galaxies across Cosmic Time ⟶ Connect $z \sim 2$ and $z \sim 6$

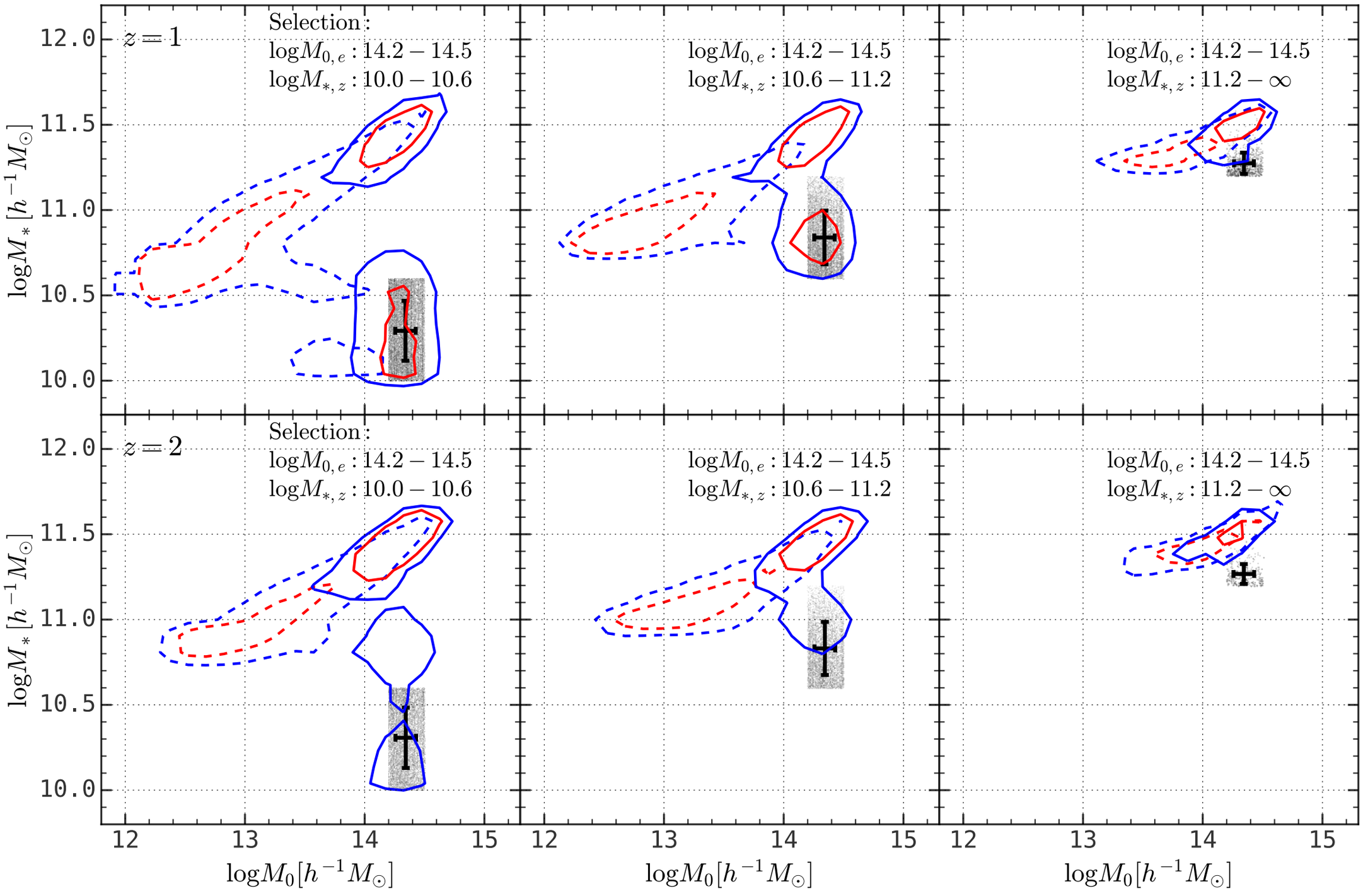
In progress...



$10^{10} - 10^{10.6} M_\odot$ $10^{10.6} - 10^{11.2} M_\odot$ $10^{11.2} - \infty M_\odot$

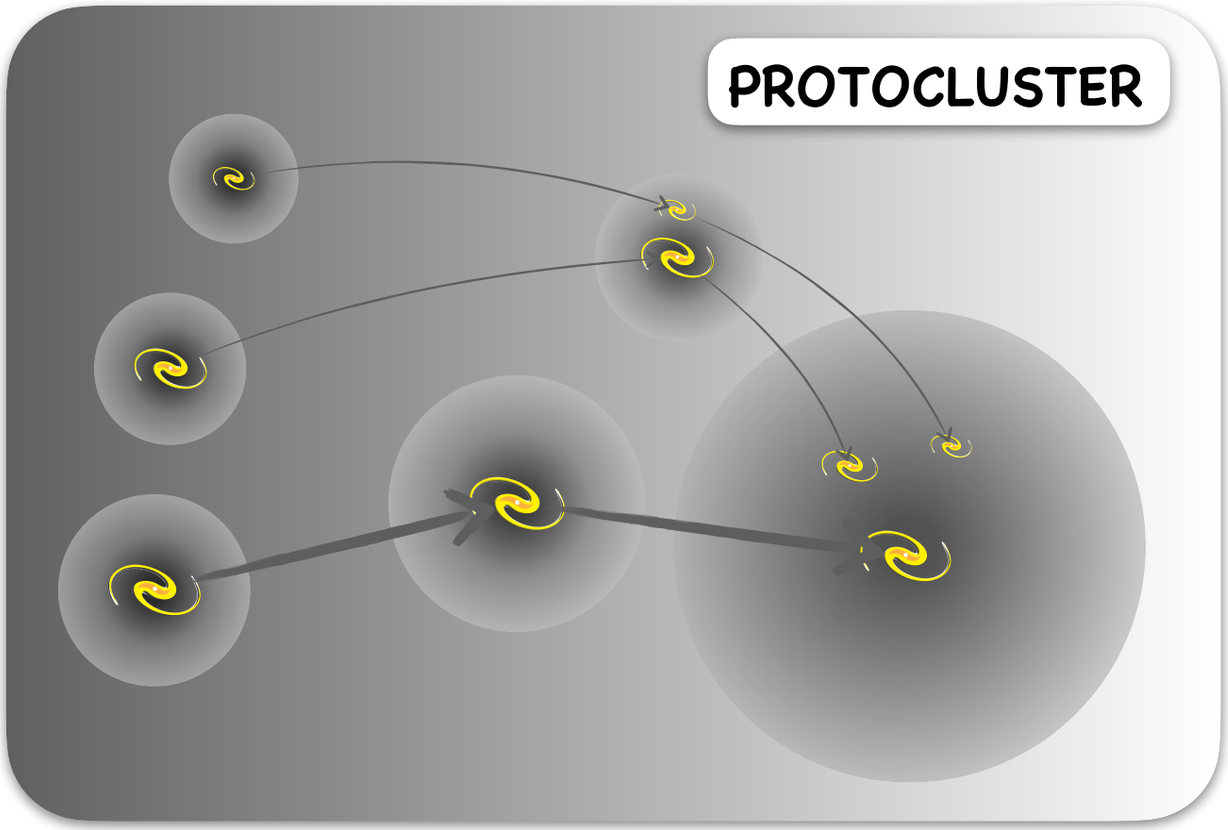
z=1

z=2



Wang et al. 2021

2. Connect Halos across Cosmic Time ⟶ Protocluster finder



① USE HALO AS TRACERS

Compared with previously used tracers:
Galaxies, Ly-α Absorption etc.

- Reliable catalog at $z \sim 1-2$
- Independent of baryonic physics
- Free of small-scale redshift space distortion effect ('Finger-of-God' effect)

② FRIENDS-OF-FRIENDS

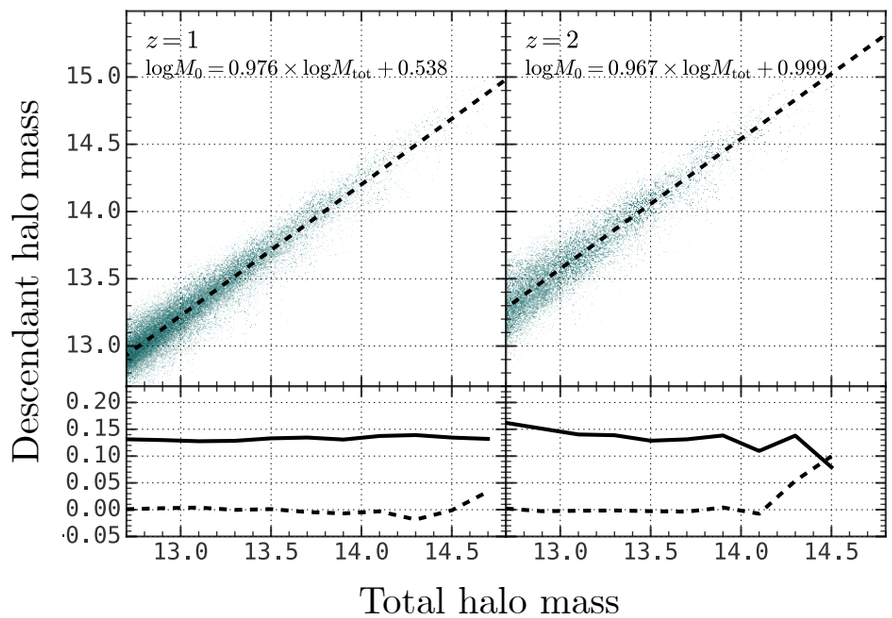
$$l_{\parallel} \cdot R_{\rm vir} \geqslant \left| X_i - X_j \right|$$

$$l_{\perp} \cdot R_{\rm vir} \geqslant \sqrt{\left(Y_j - Y_k\right)^2 + \left(Z_j - Z_k\right)^2}$$

X: line-of-sight direction
$R_{\rm vir}$: virial radius

i-th halo: $(X_i,\ Y_i,\ Z_i)$
j-th halo: $(X_j,\ Y_j,\ Z_j)$
$R_{\rm vir} = {\rm Max}(R_{i,{\rm vir}},\ R_{j,{\rm vir}})$
Two free parameters: $l_{\parallel}$ and $l_{\perp}$

③ DESCENDANT HALO MASS



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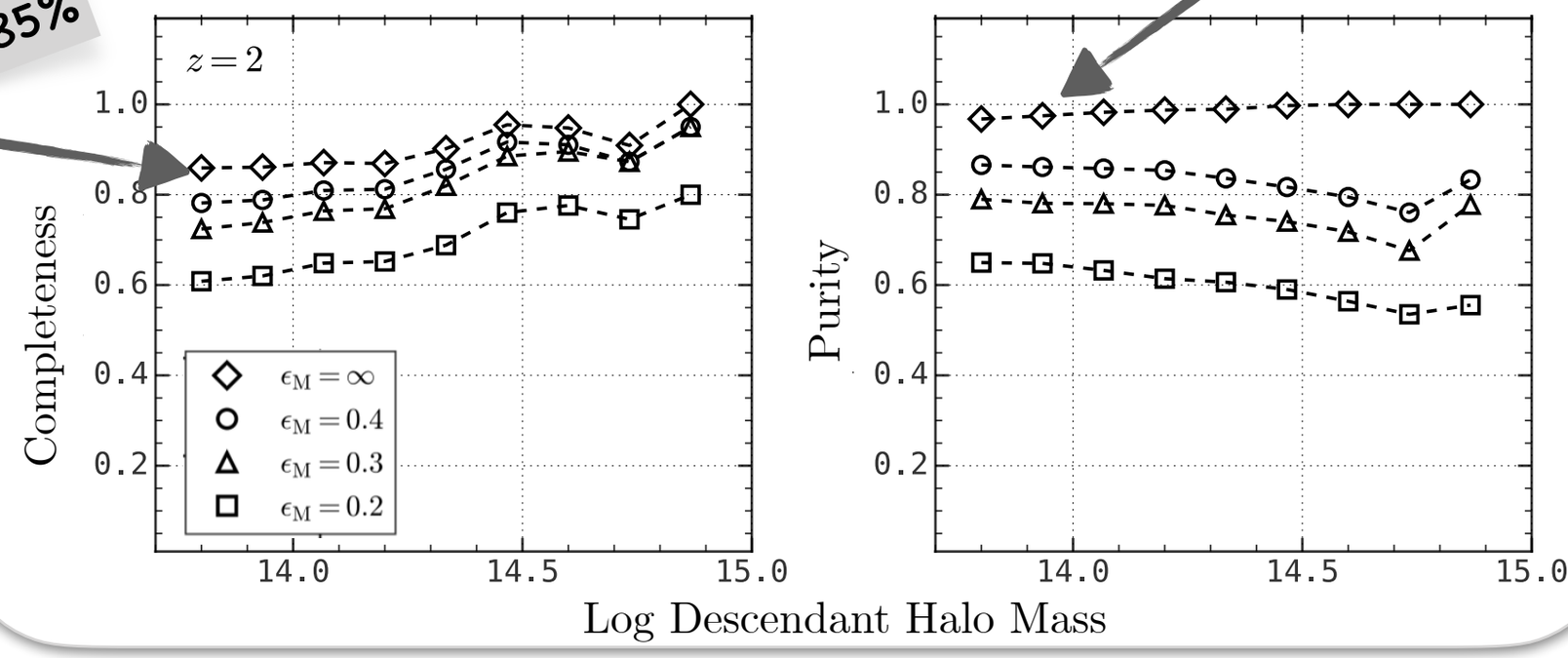
PROTOCLUSTER COMPLETENESS & PURITY

COMPLETENESS > 85%

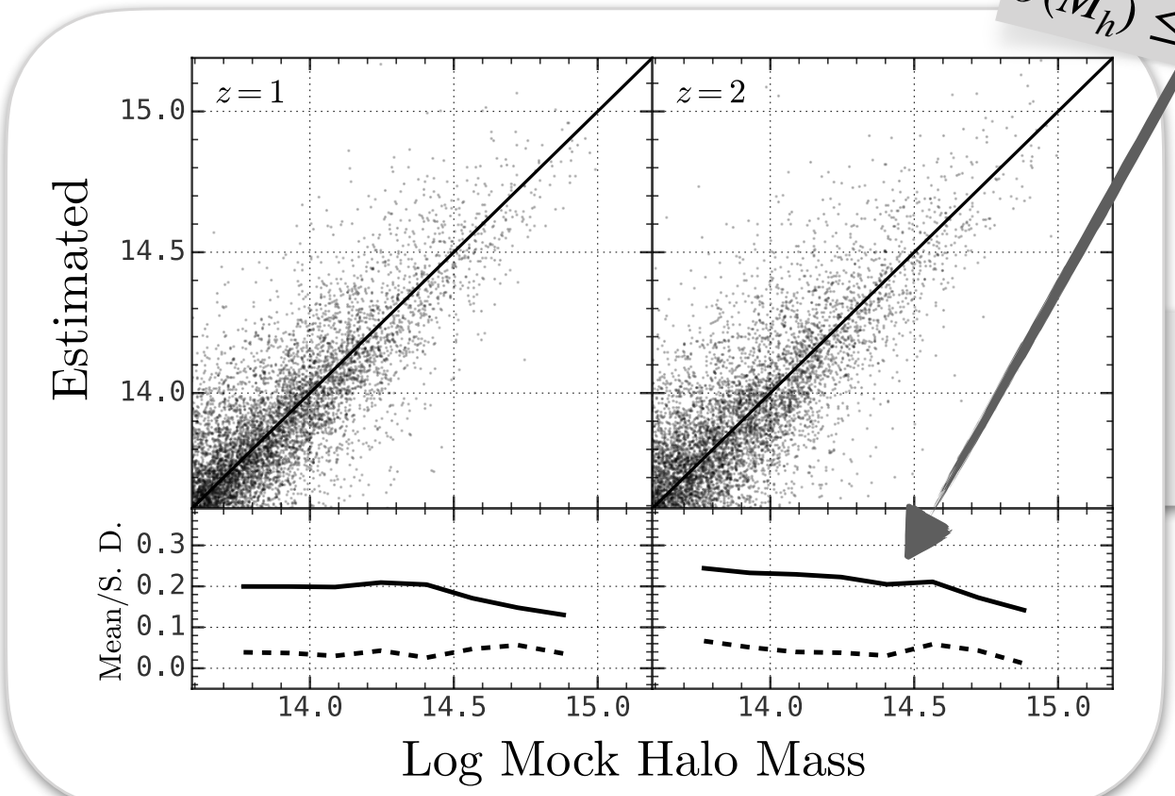
PURITY > 95%

$$\epsilon_{\rm M} = \left| \log\left(\frac{M_{h,\rm mock}}{M_{h,\rm esti}} \right) \right|$$

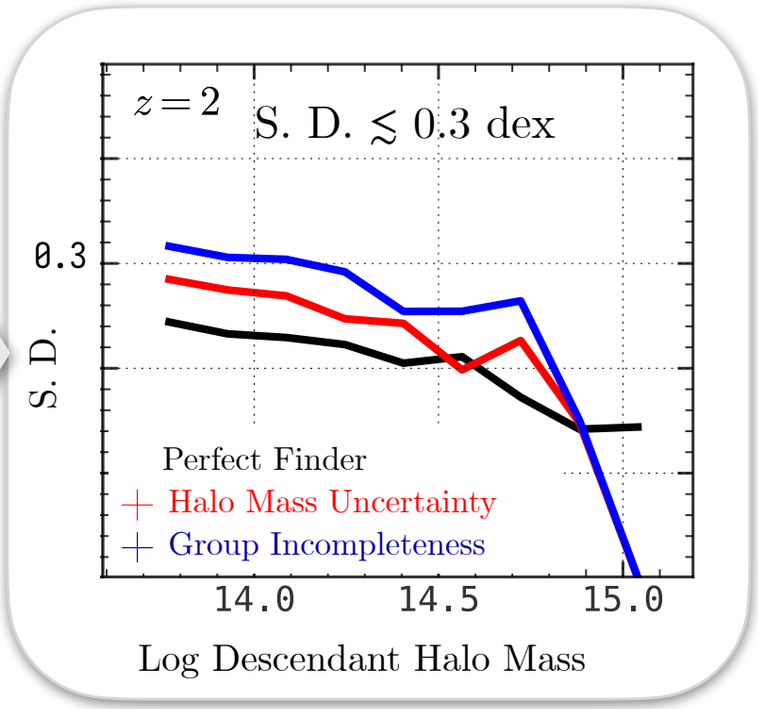


DESCENDANT HALO MASS ESTIMATION

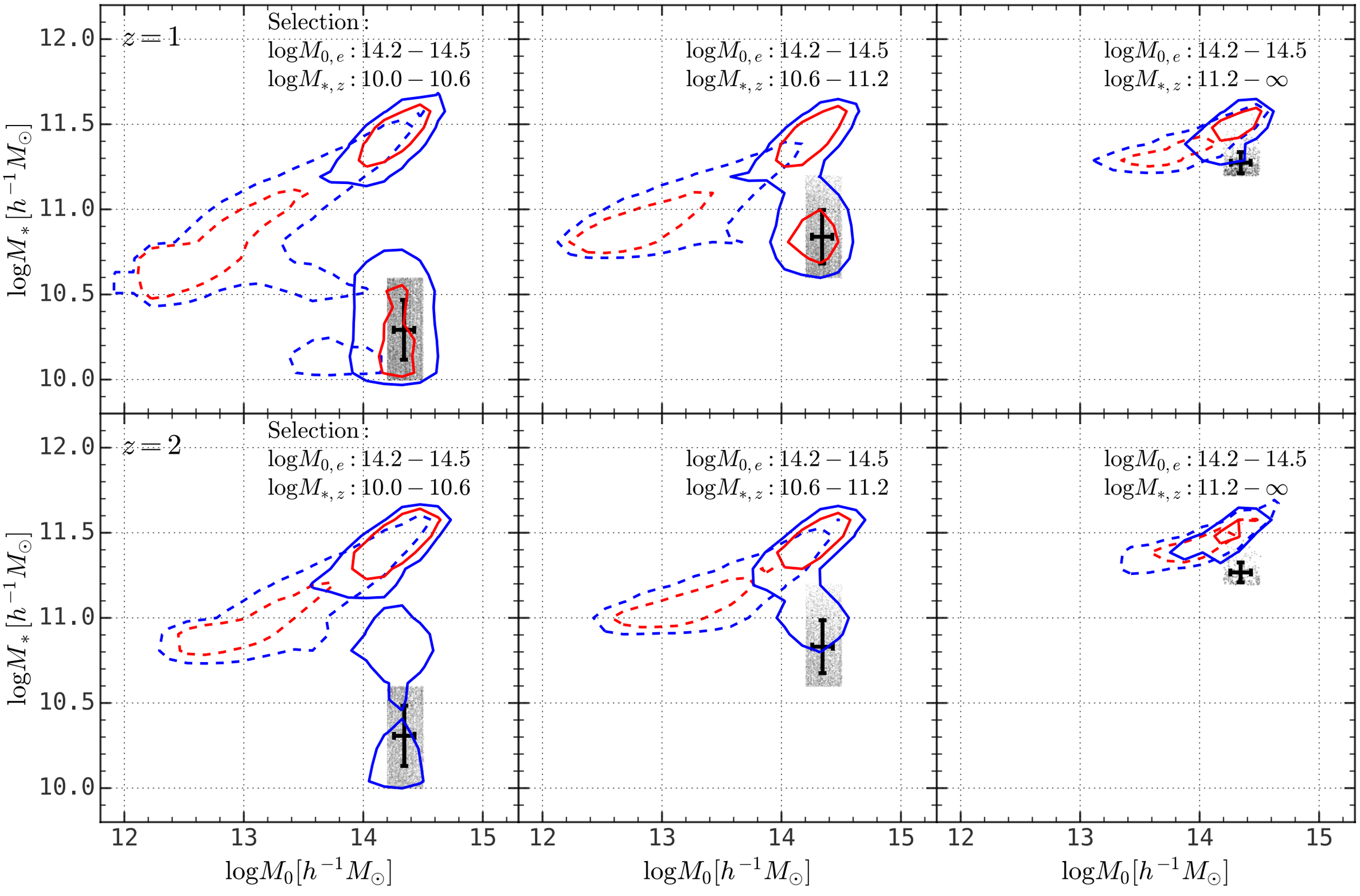
$\sigma(M_h) \leq 0.25$ DEX



Group Finding Imperfection



2. Connect Halos across Cosmic Time ⟶ Protoclusters finder performance



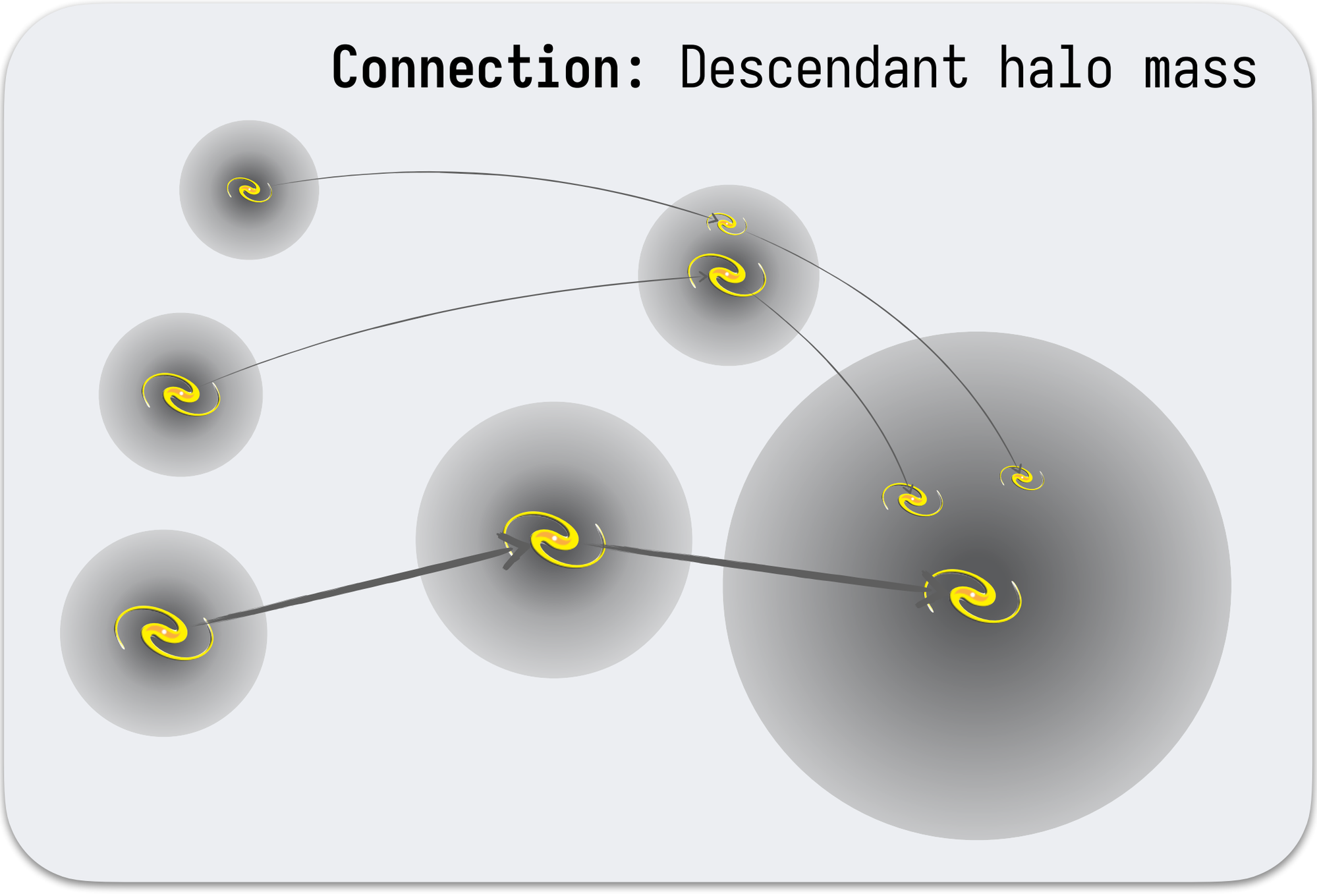
Protoclusters ⟺ Progenitor of clusters

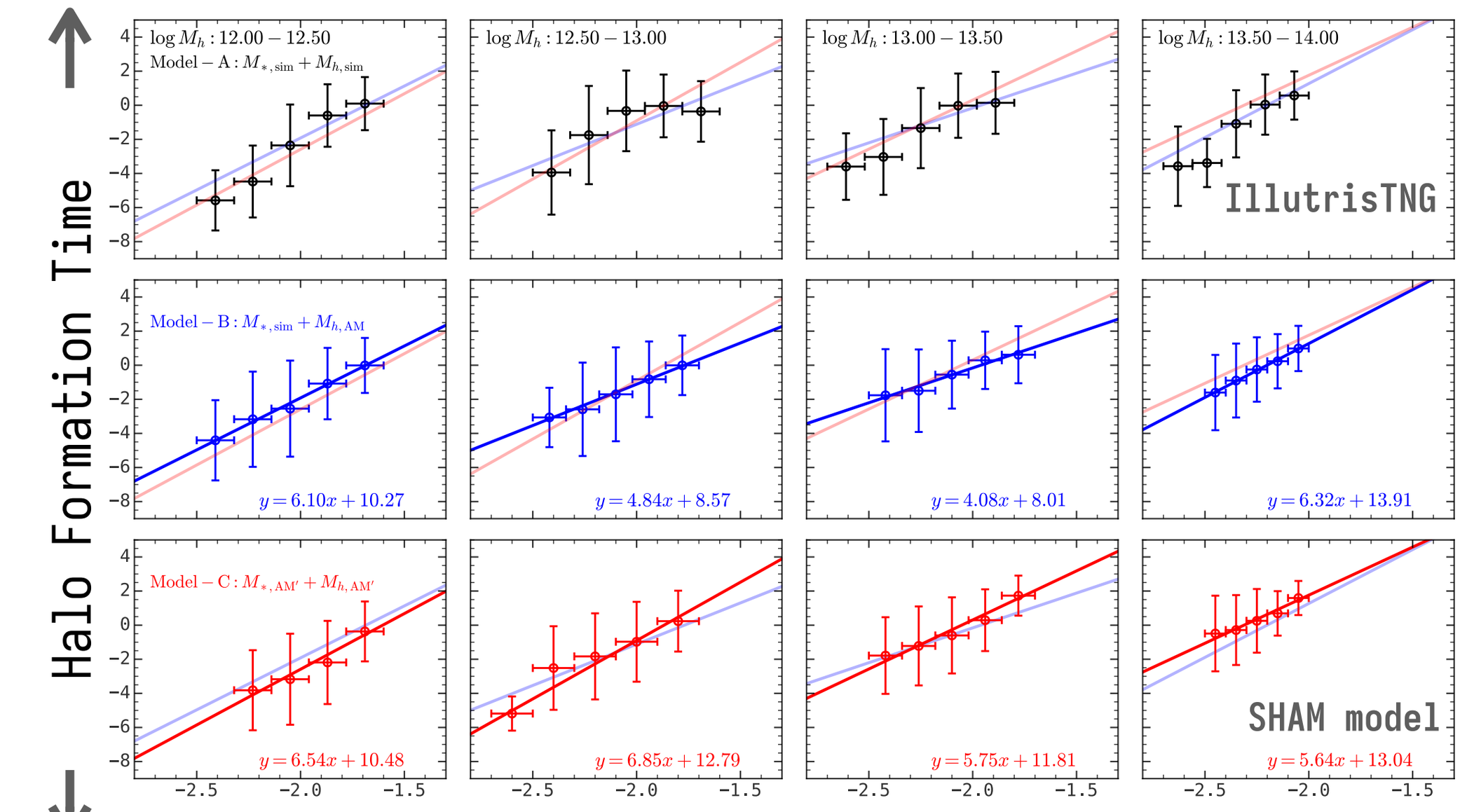
Protoclusters ⟺ ~~Progenitor of clusters~~

High-z Overdense Regions

Protoclusters ⟺ ~~Progenitor of clusters~~ High-z Overdense Regions

Connection: Descendant halo mass





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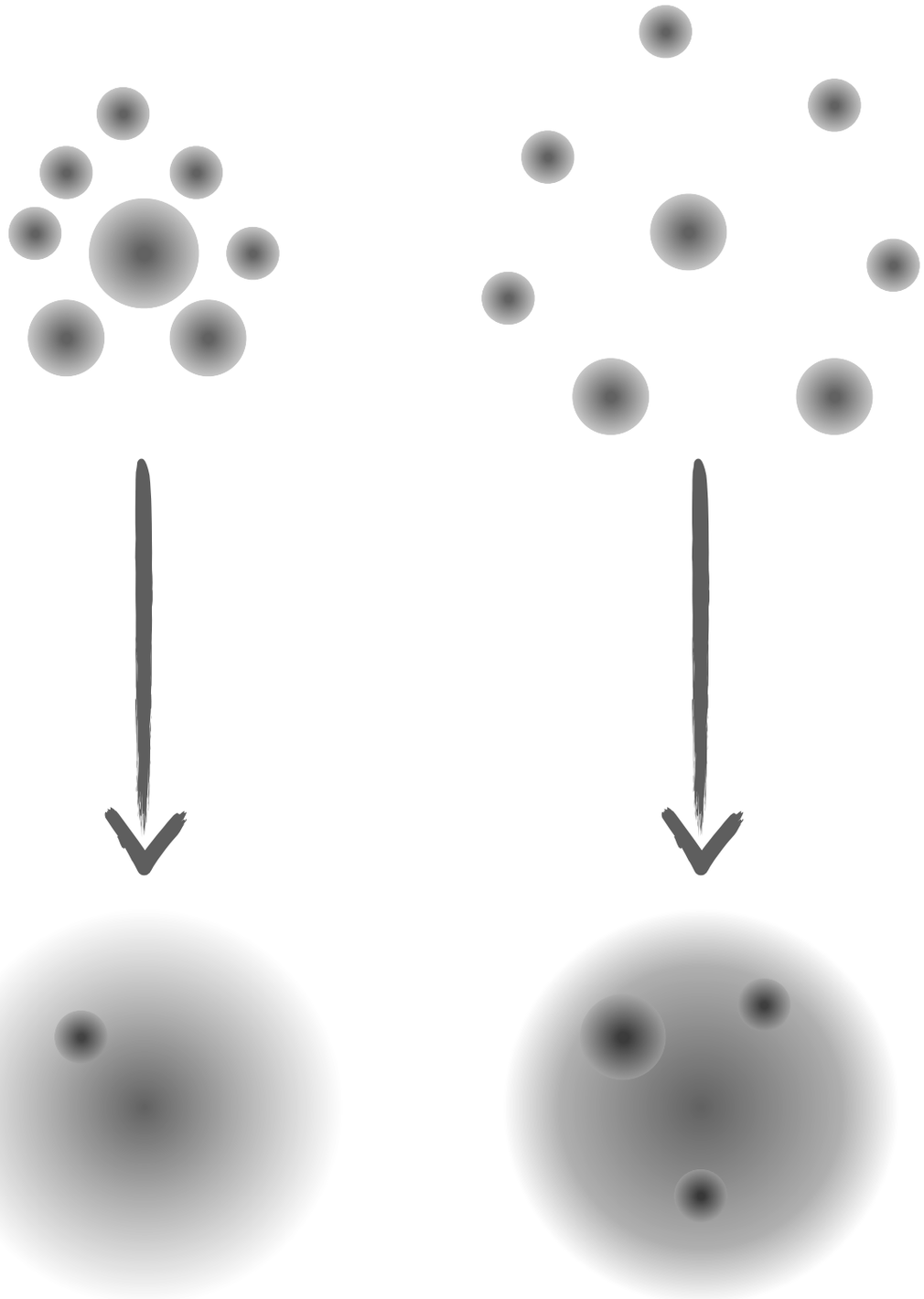
- More concentrated
- A dominant halo

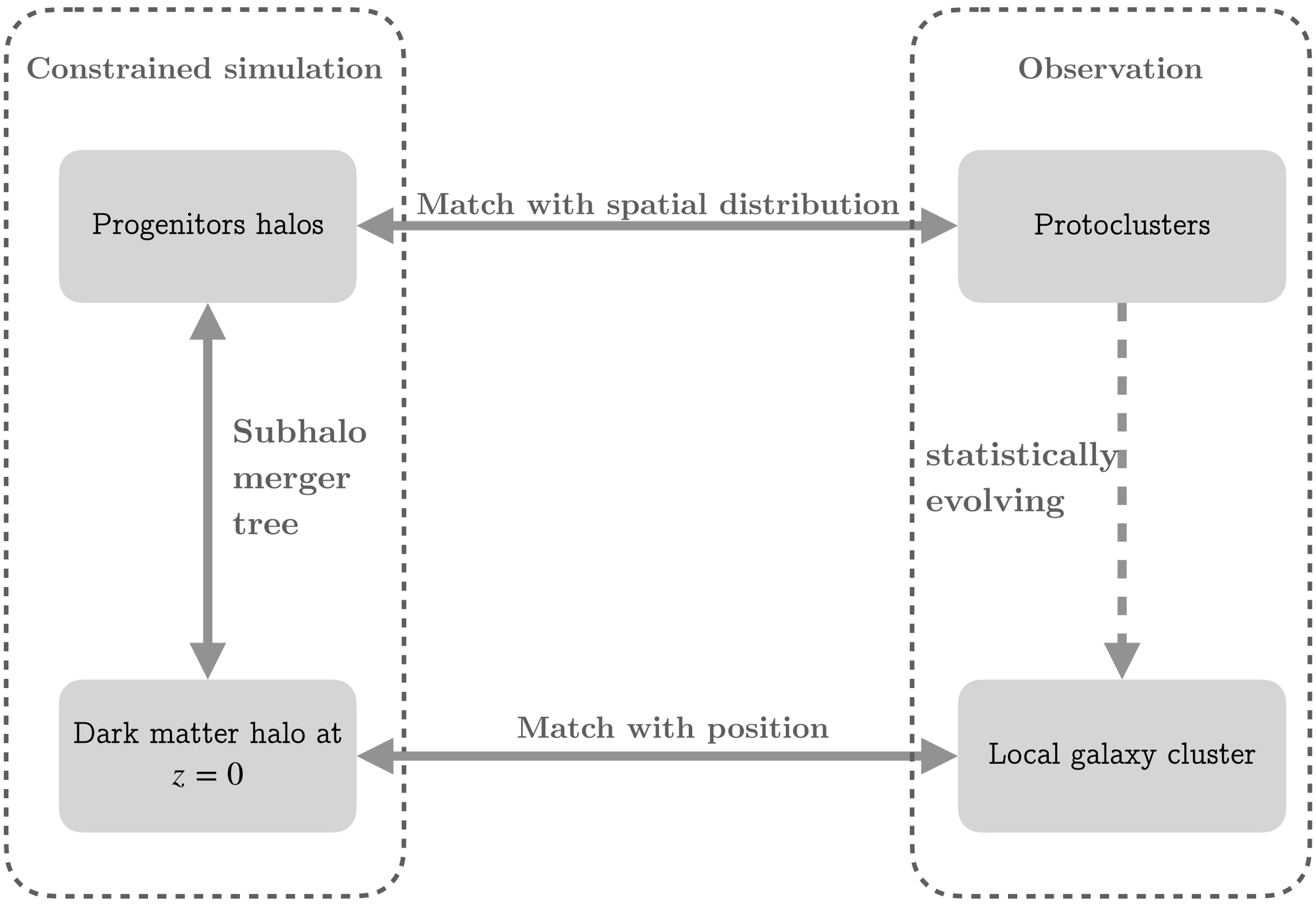


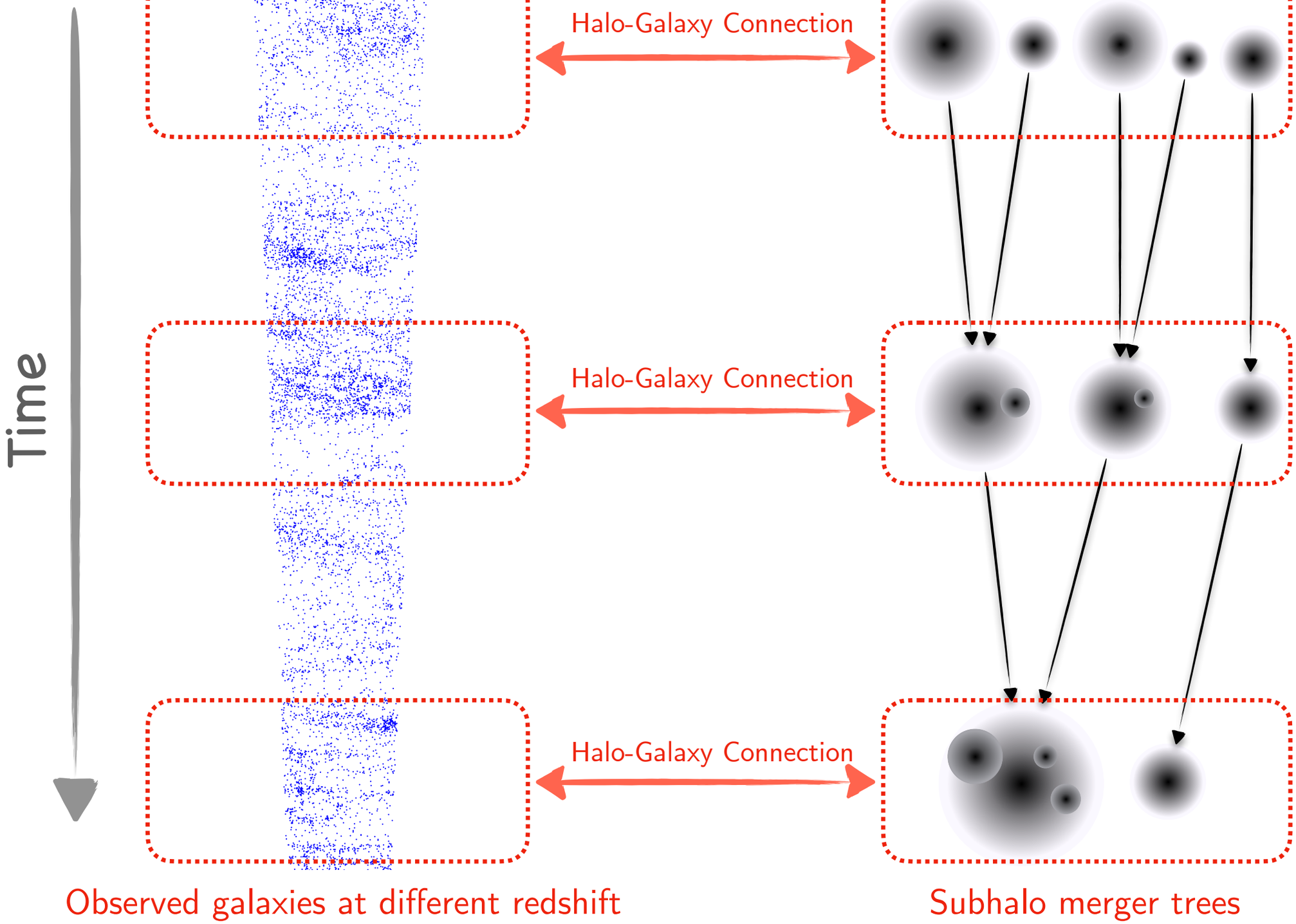
- Less concentrated
- No dominant halo

Early-formed halo
- More concentrated
- High SMHMR
- Larger gap

Late-formed halo
- Less concentrated
- Low SMHMR
- Smaller gap

Connection: Descendant halo mass & Formation time


Constrained simulation
Observation
Progenitors halos
Match with spatial distribution
Protoclusters
Subhalo merger tree
statistically evolving
Dark matter halo at $z = 0$
Match with position
Local galaxy cluster


Halo-Galaxy Connection
Halo-Galaxy Connection
Halo-Galaxy Connection
Time
Observed galaxies at different redshift
Subhalo merger trees