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A Conditional Abundance Matching Method of Extending Simulated Halo Merger Trees to Resolve Low-Mass Progenitors and Sub-halos

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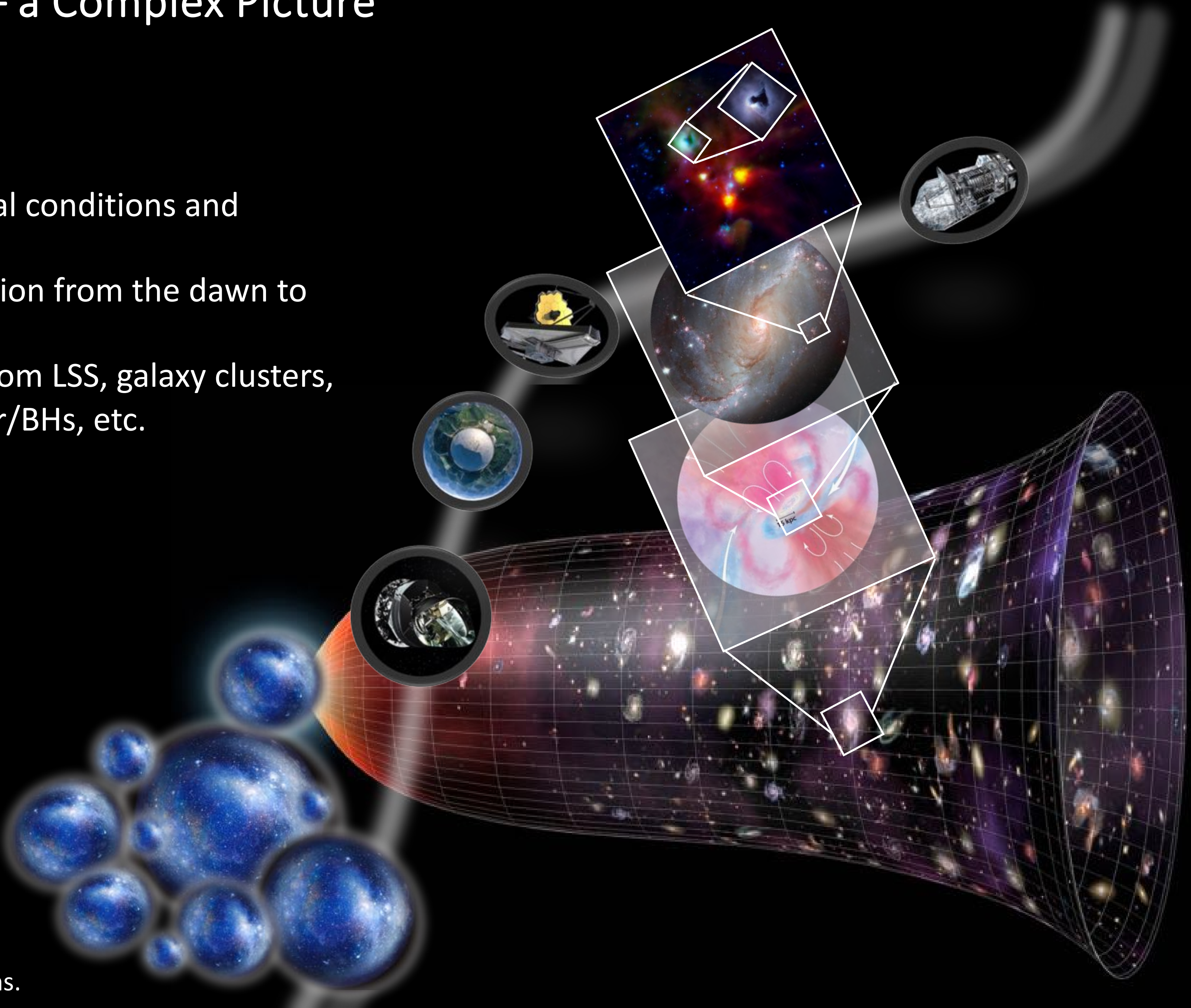
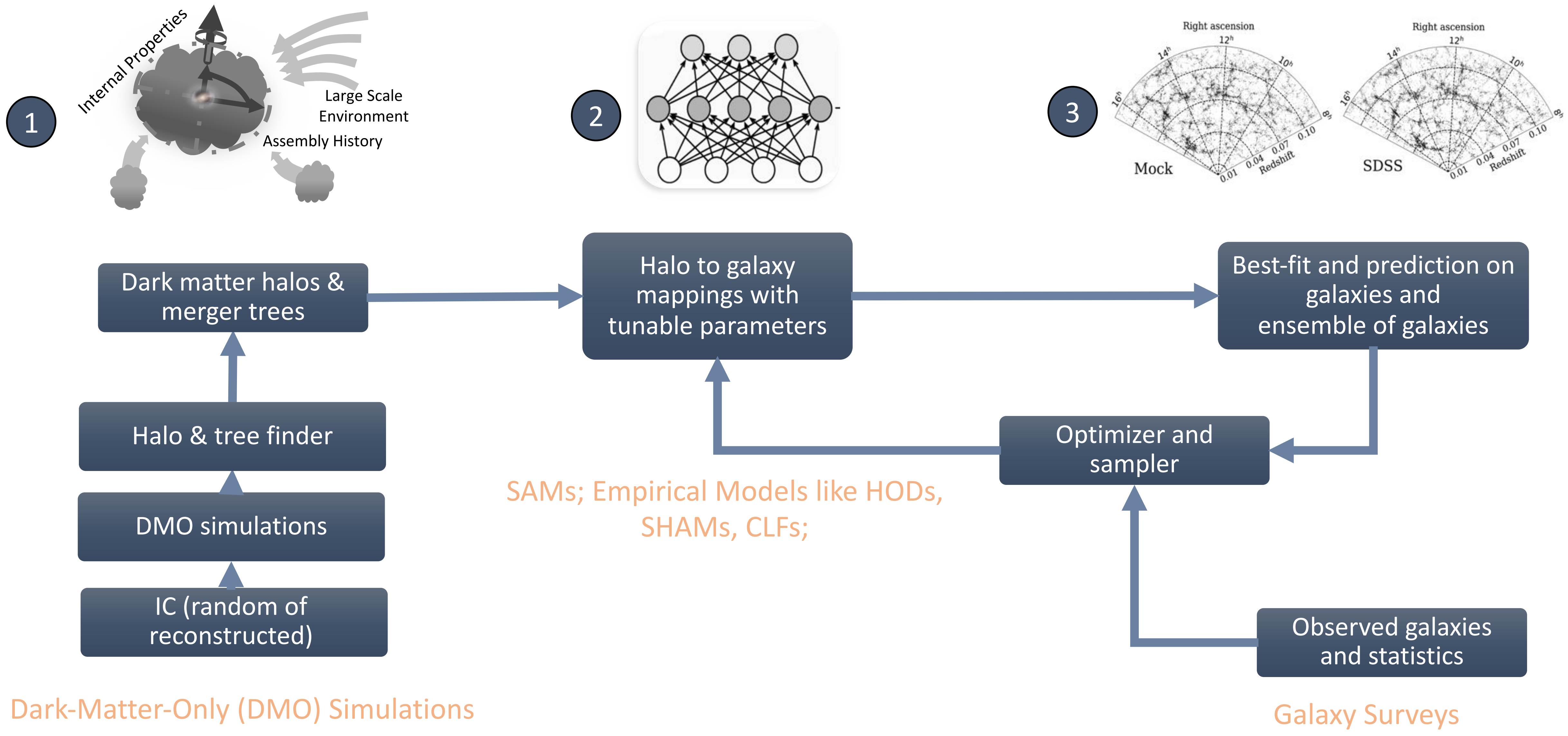
Galaxy Formation – a Complex Picture

- Cosmology as the initial conditions and background.
- Long time-scale evolution from the dawn to present.
- Multi-scale coupling from LSS, galaxy clusters, galaxies, gas cloud/star/BHs, etc.

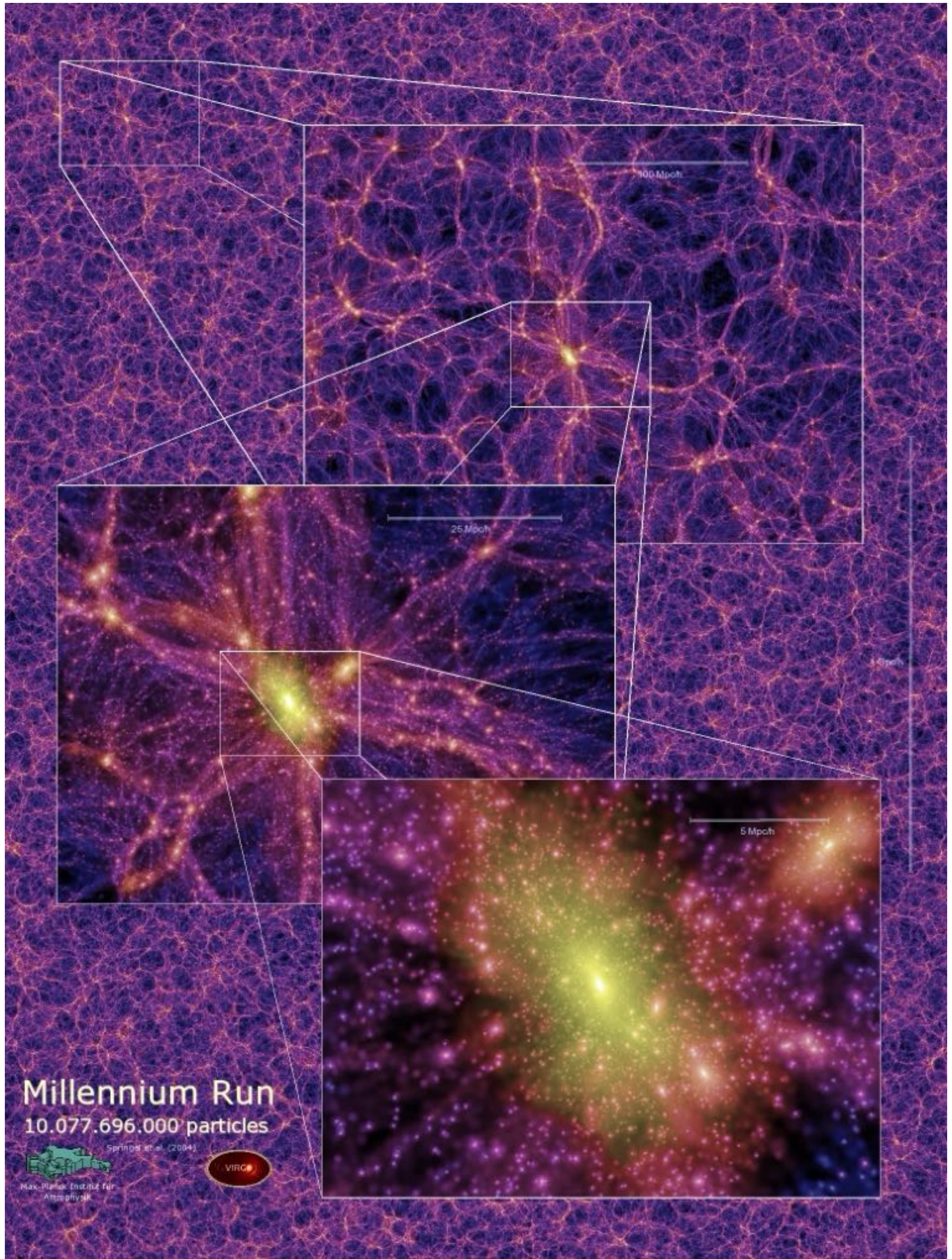


Credit: Planck, FAST, JWST, Herschel, TNG teams.

Thrive in the Difficulties of Galaxy Modeling – Abstraction and Hierarchy



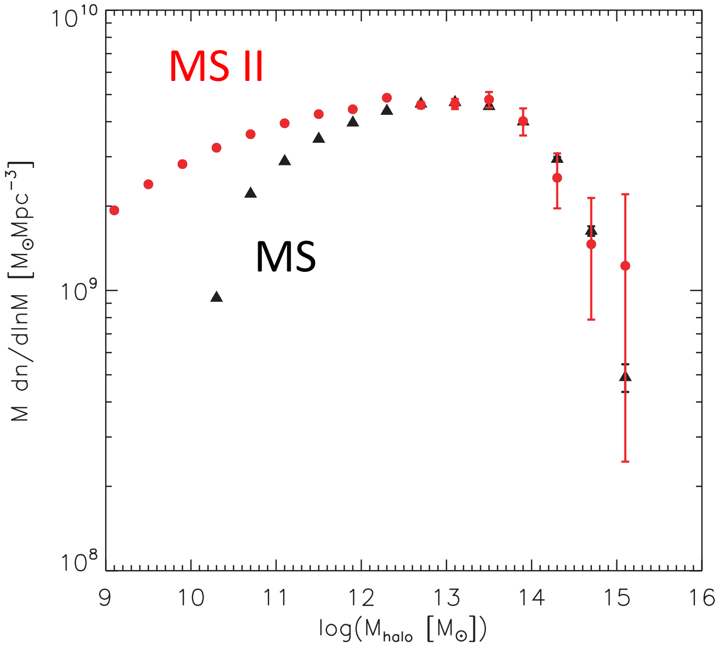
The Trade-off: Resolution Power and Simulation Volume

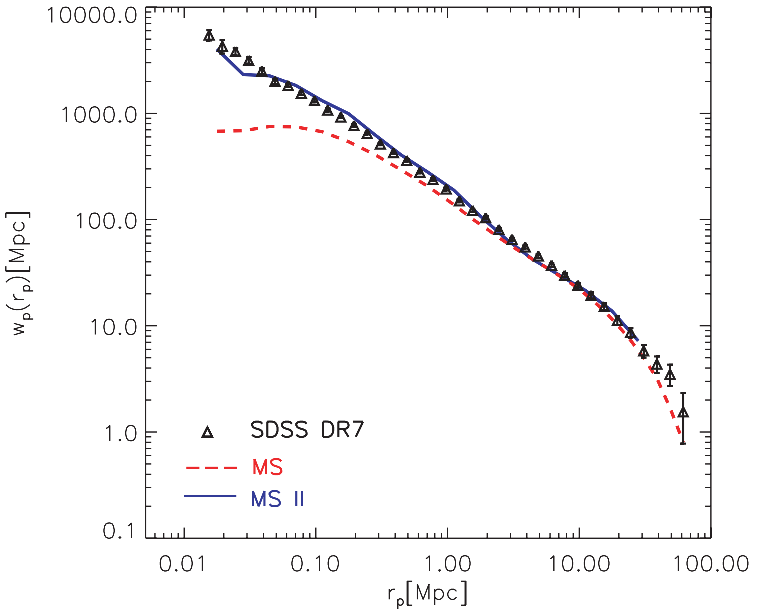


DMO simulations are always performed in finite volumes with finite resolutions

- Good statistics require large simulation volume.
- Precise modeling of small/faint objects requires fine resolution.

MS and MS-II runs – halo abundances and galaxy correlations





Guo+ 2010, SHAM

Credit: Virgo consortium

Missing-Subhalo Problem for Halo-based Models

In a real application of galaxy modeling

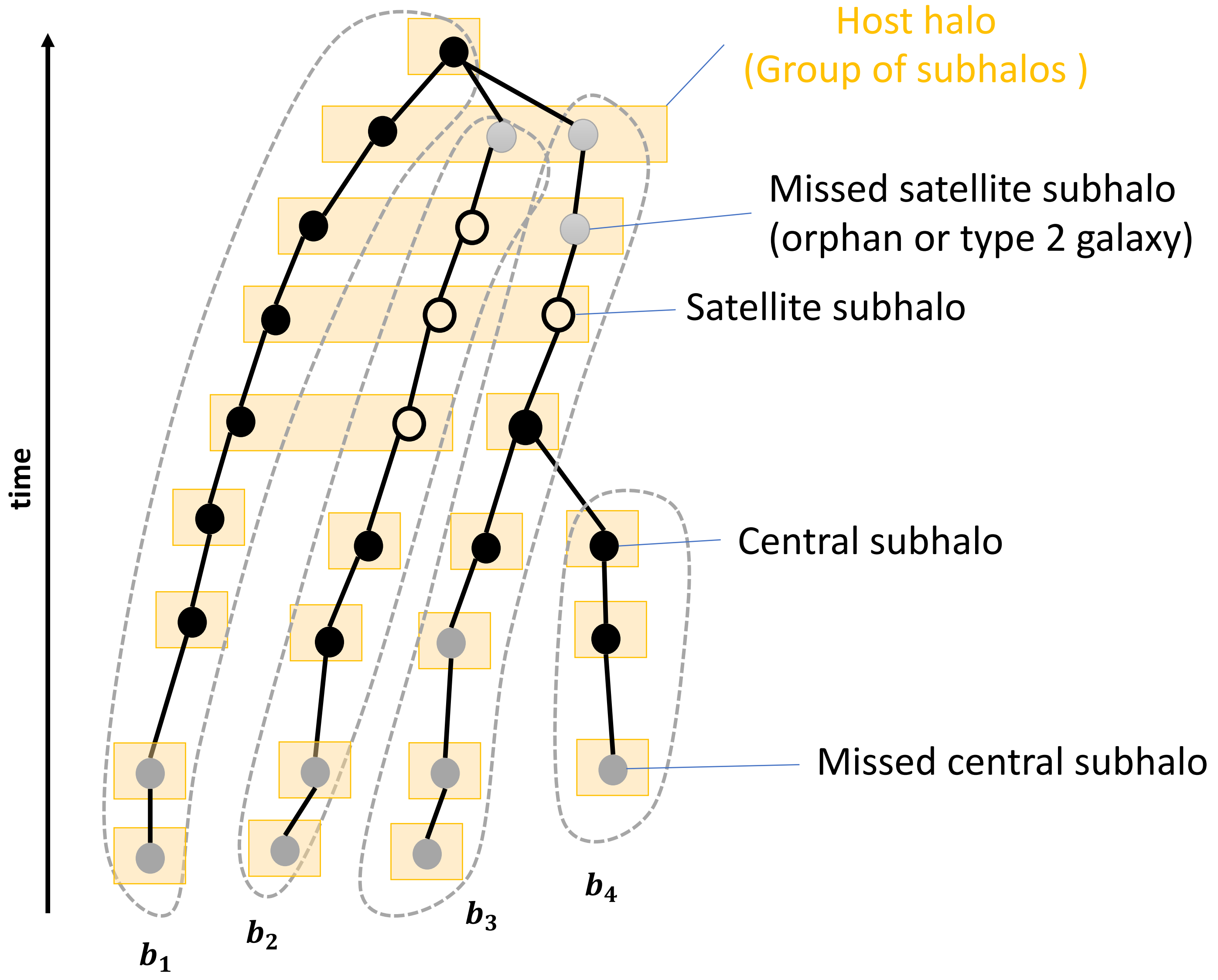
- The lower limit of sample size (simulation volume) is determined by the statistical target.
- The upper limit of CPU hours are detemined by the fundings at hand.
- Resolution upper limit = max CPU hours / min sample size.

Something that is missed with limited resolution power

- The assembly history of a central subhalo at high-z is missed, when its halo mass is below the resolution limit.
- The dynamic evolution of a satellite subhalo is missed, after it is disrupted numerically.

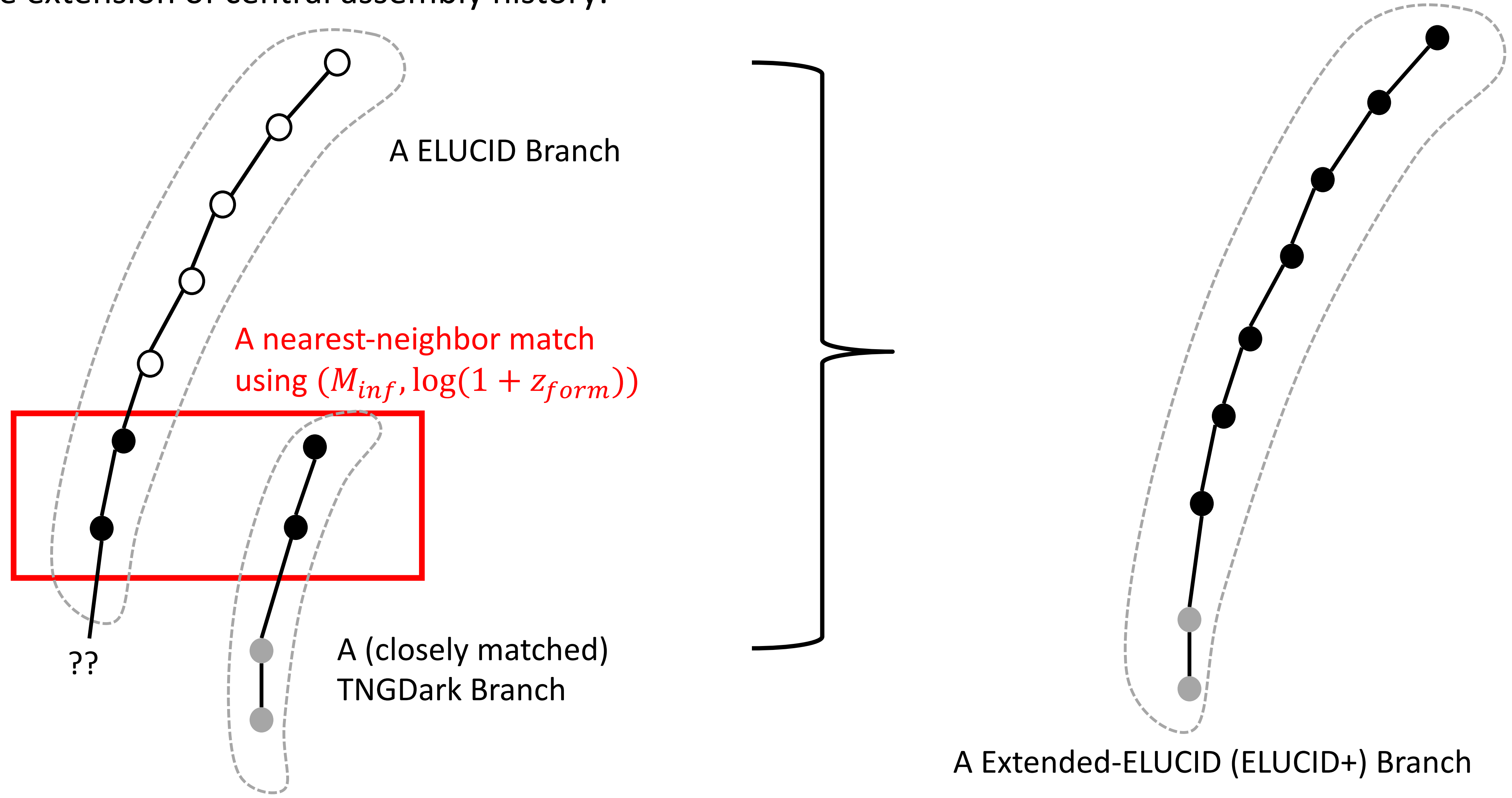
For ELUCID, $\mathrm{M_{halo,min}} = 10^{10} h^{-1} M_{\odot}$
For TNG100-1-Dark, $\mathrm{M_{halo,min}} = 2{\times}10^{8} h^{-1} M_{\odot}$

A example subhalo merger tree

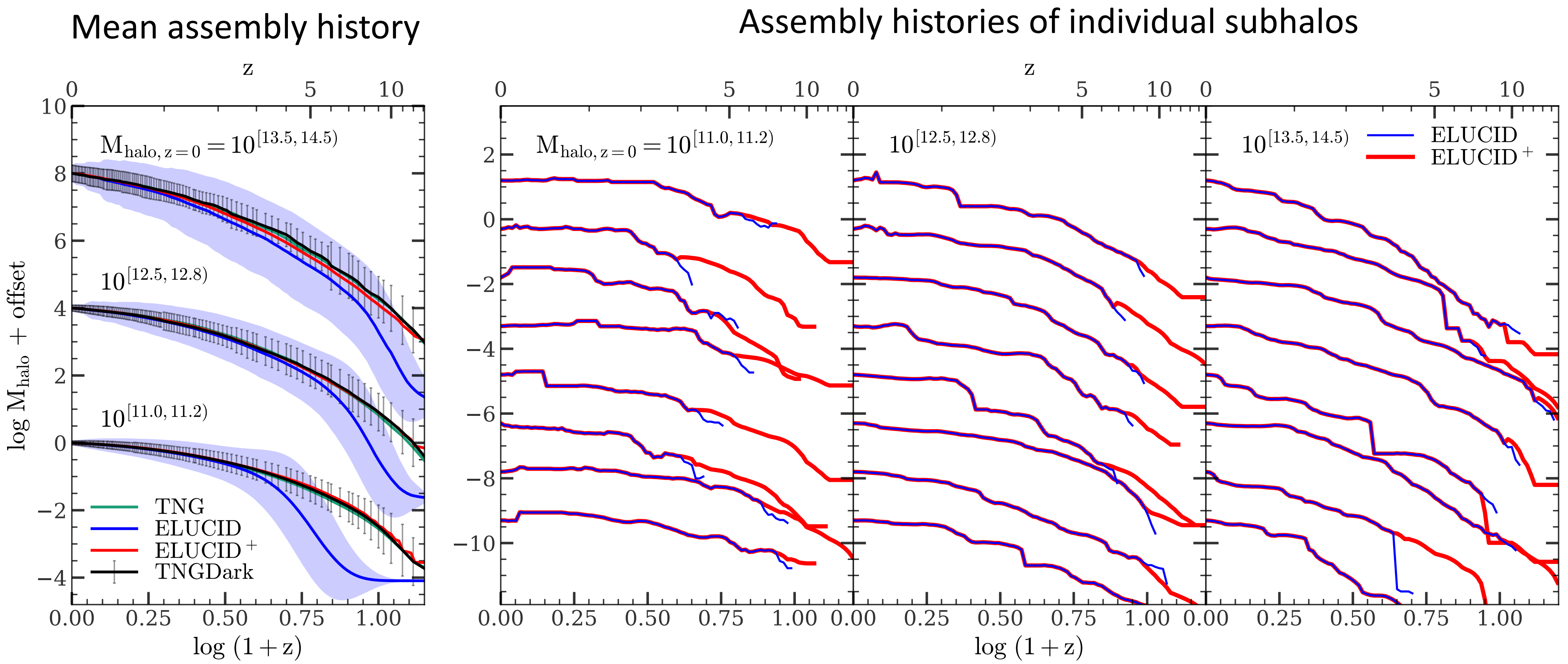


The Method: Learn From a High-resolution Simulation to Extend a Low-resolution Simulatio

The extension of central assembly history:

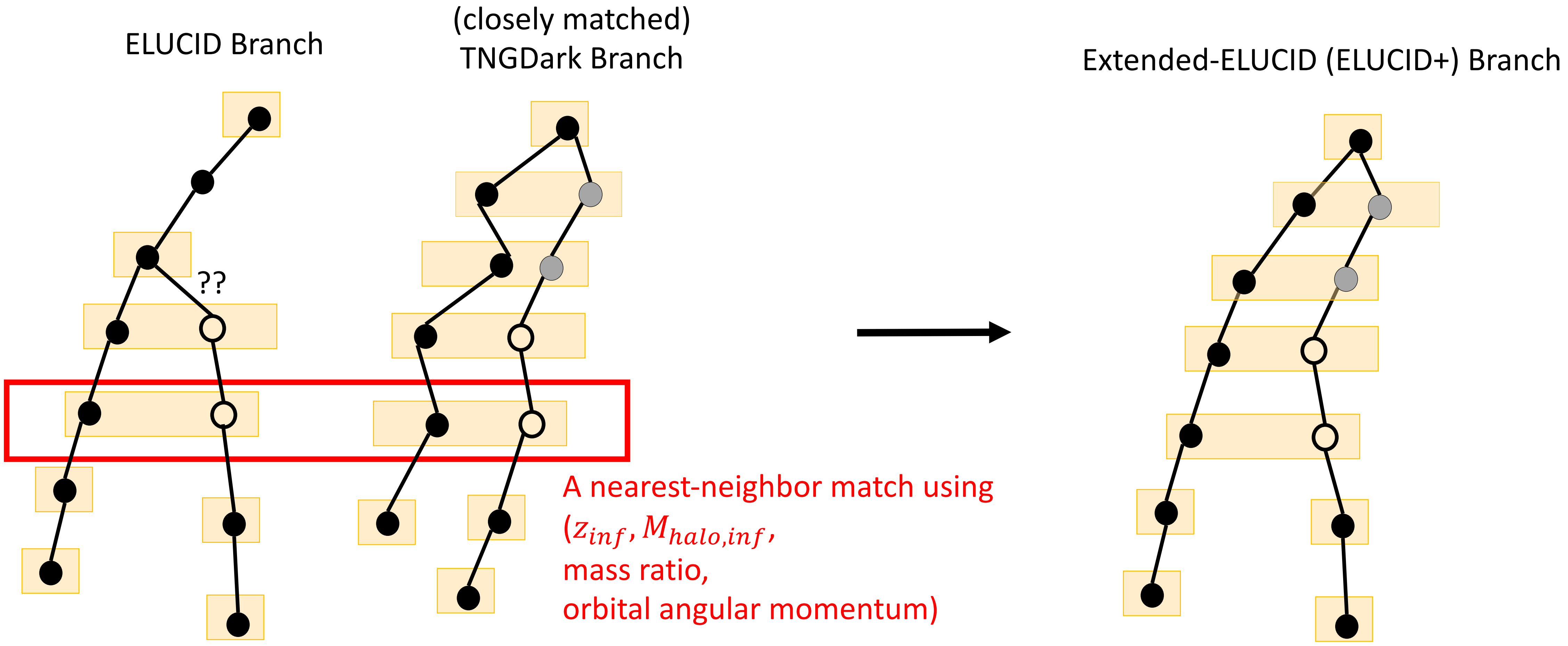


Extended subhalo mass functions for satellites

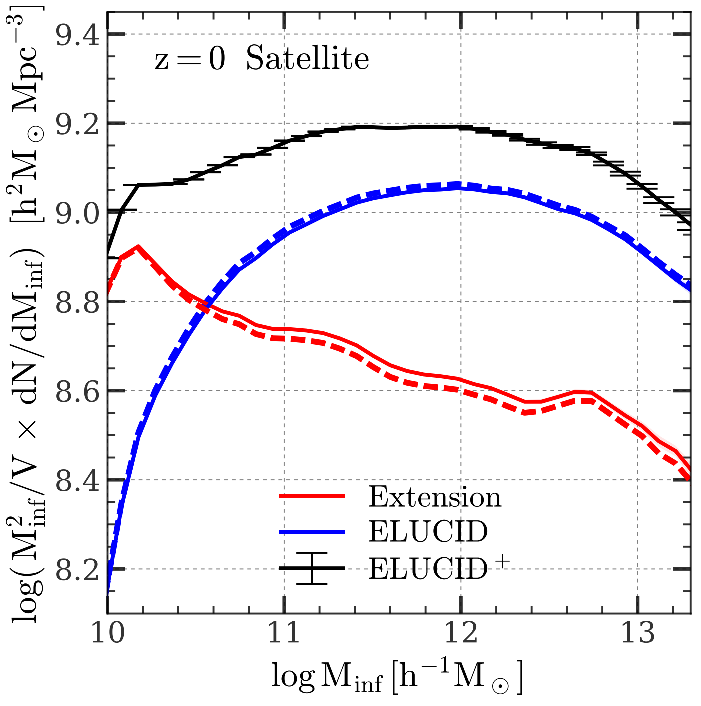


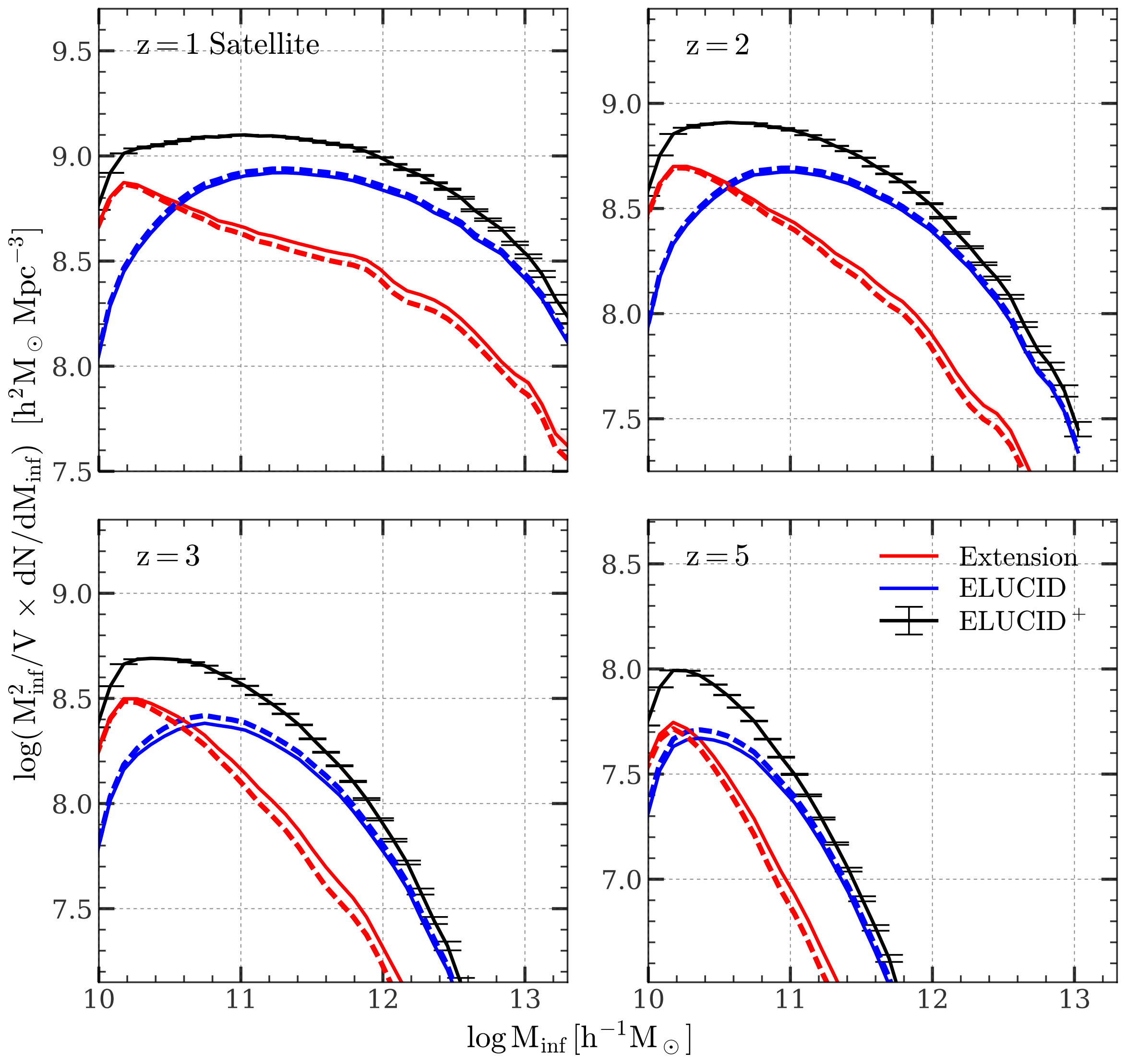
The Method: Learn From a High-resolution Simulation to Extend a Low-resolution Simulatio

The extension of satellite dynamic evolution

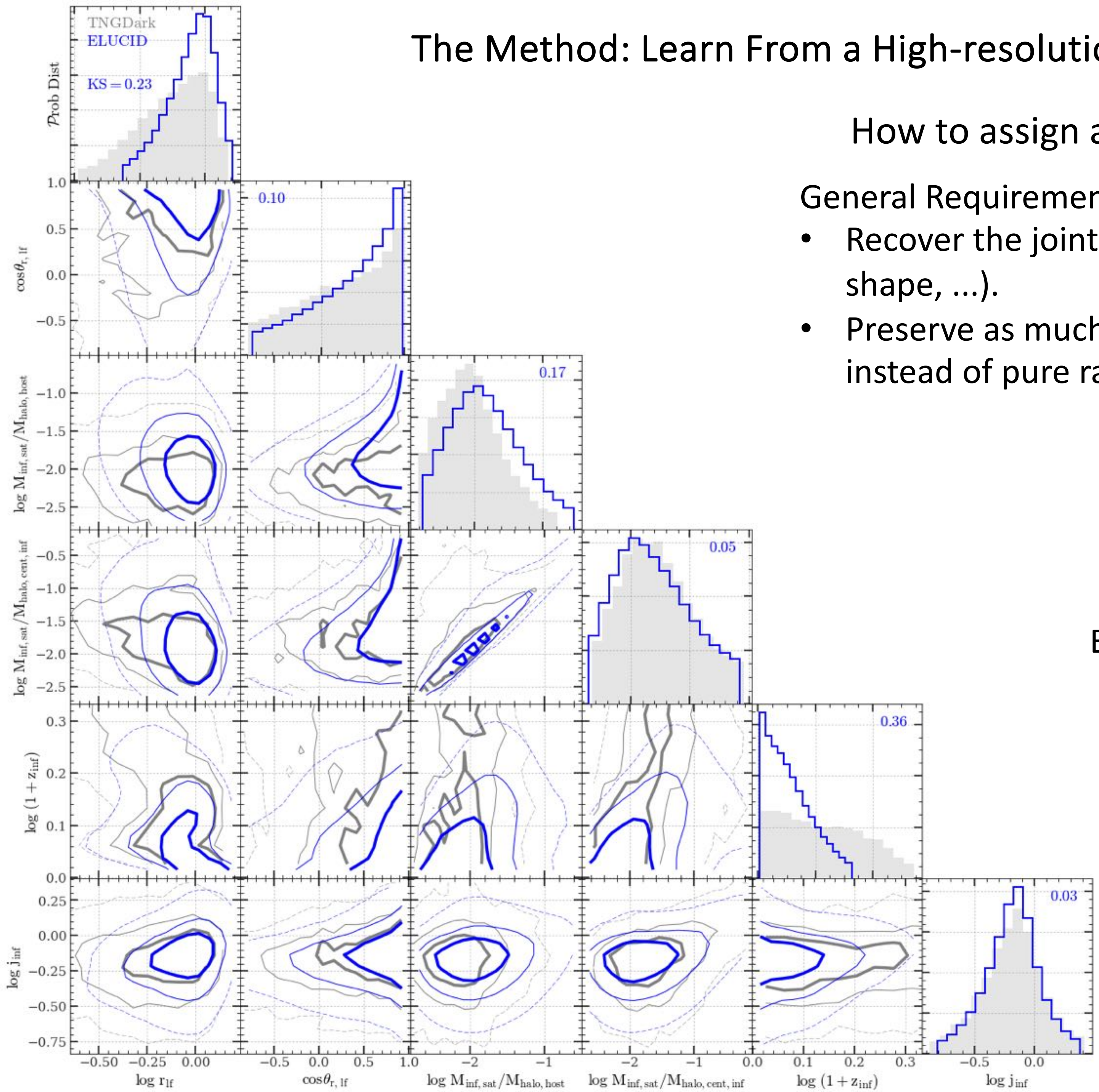


Abundance of the Extended Satellite Population





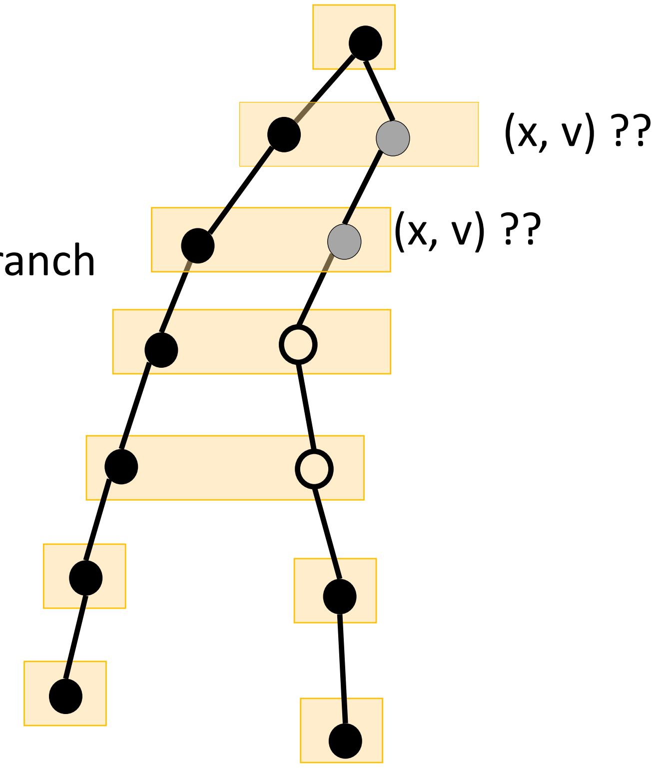
The Method: Learn From a High-resolution Simulation to Extend a Low-resolution Simulatio



How to assign a phase-space coordinate to satellite?

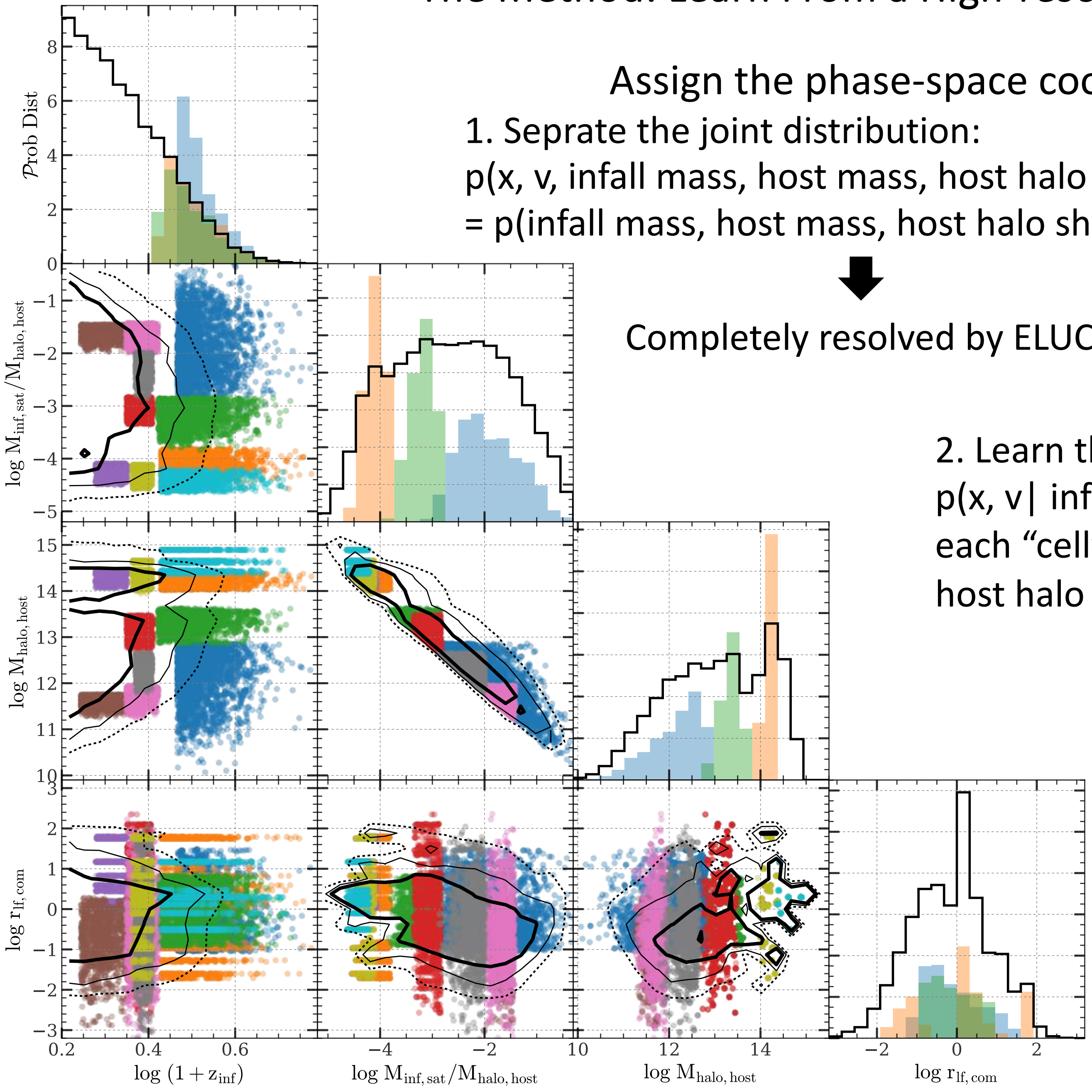
General Requirements:

- Recover the joint distribution p(x, v, infall mass, host mass, host halo shape, ...).
- Preserve as much information as possible from original simulation, instead of pure random sampling from the joint distribution.



ELUCID+ Branch

The Method: Learn From a High-resolution Simulation to Extend a Low-resolution Simulati



ELUCID satellites in cells

Assign the phase-space coordinates with conditional abundance matching

1. Seprate the joint distribution:
p(x, v, infall mass, host mass, host halo shape, ...)
= p(infall mass, host mass, host halo shape, ...) p(x, v | infall mass, host mass, host halo shape, ...)

Completely resolved by ELUCID

Partly missed by ELUCID

2. Learn the missed part from TNGDark:
p(x, v| infall mass, host mass, host halo shape, ...) is estimated in each “cell” of the conditioning variable (infall mass, host mass, host halo shape, ...).

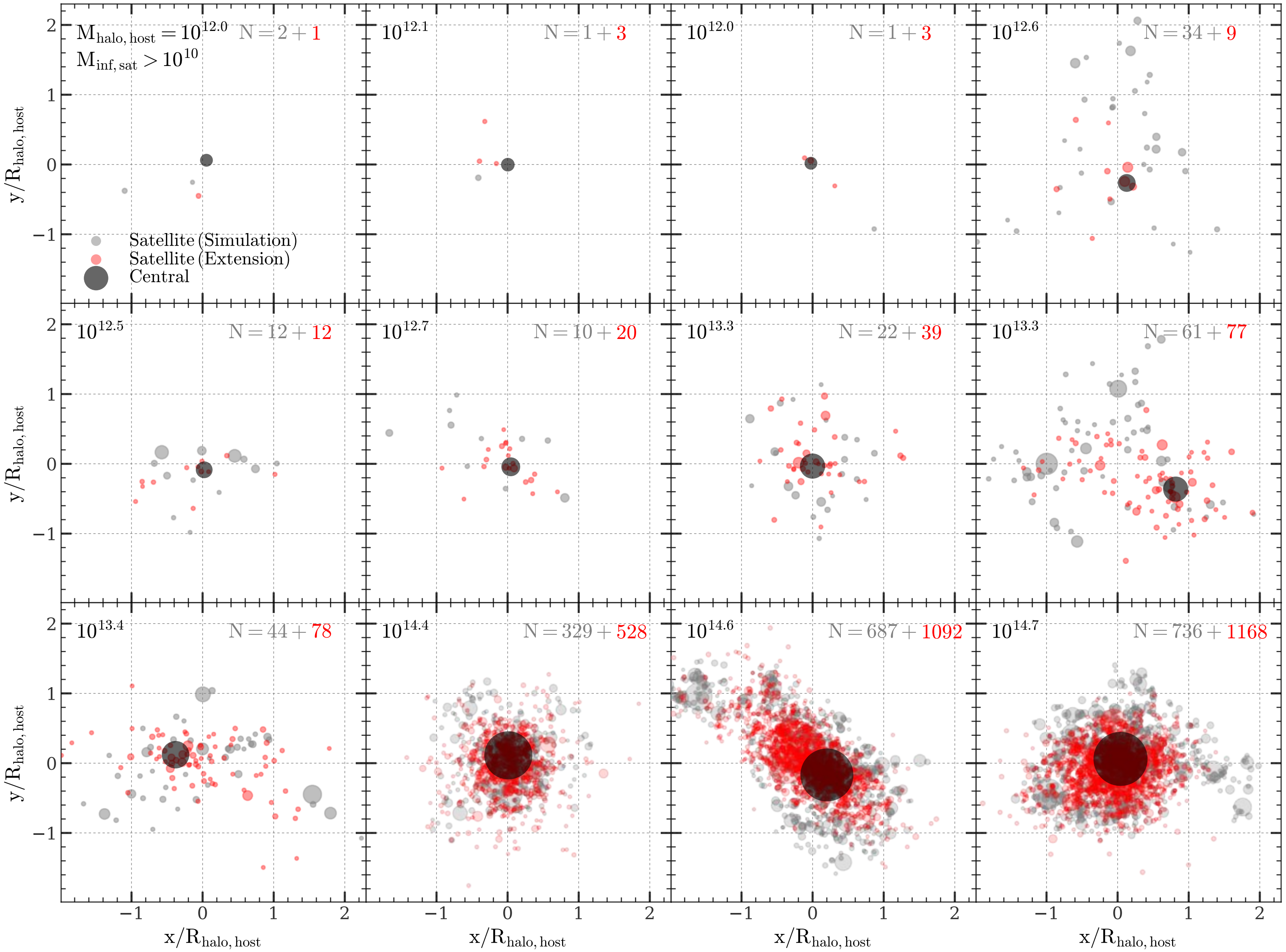
3. In each cell, match each ELUCID-resolved satellite to a TNGDark one (in some predefined order), and remove them from the cell.

4. Randomly match ELUCID-extended satellites to the remaining ones of TNGDark.

A Visual Inspection on the Extended Satellite Population

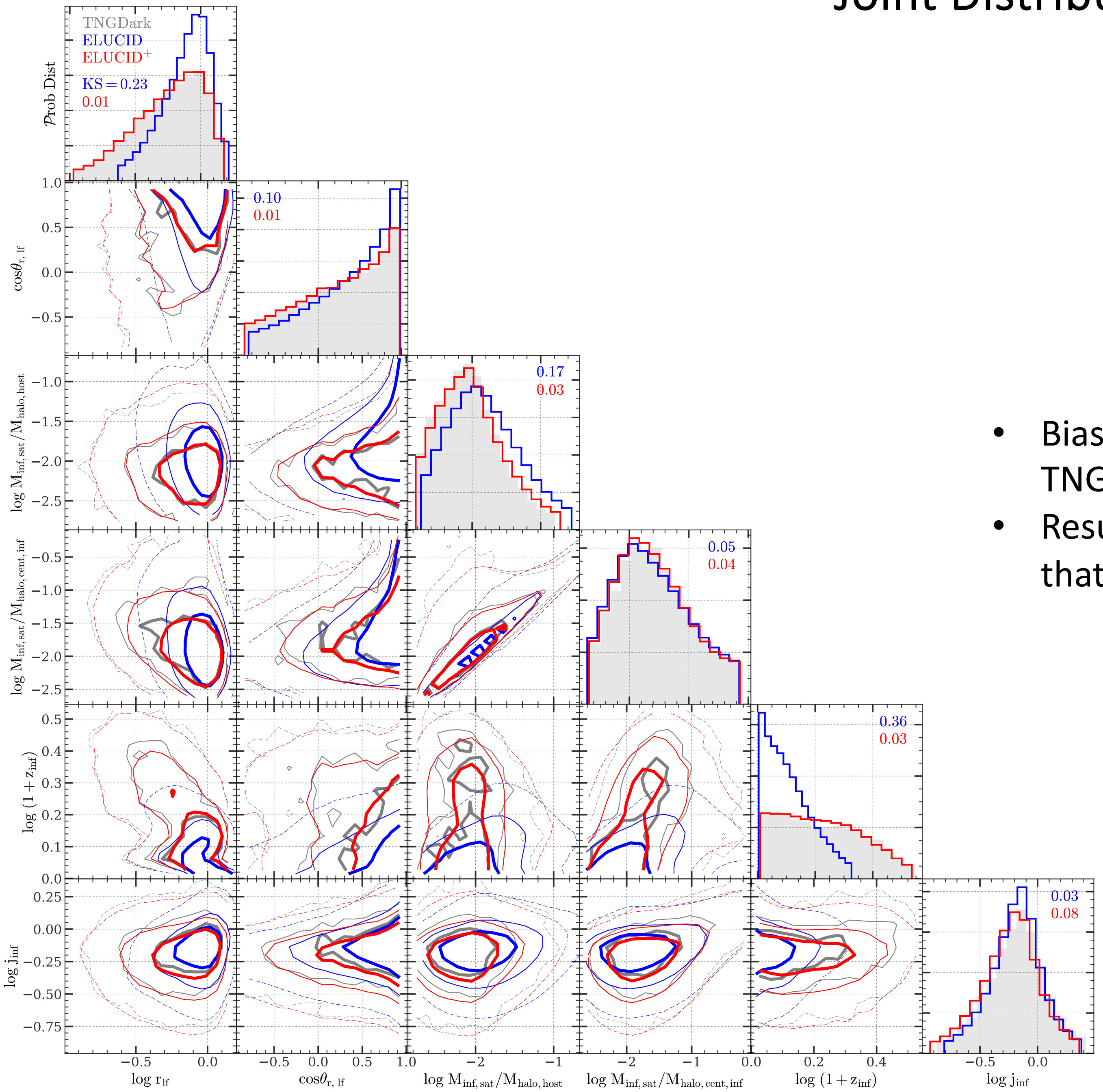
Two features of the extension as a result of the "information preservation" from the original simulation

1. Shape preserving (of the host halo).
2. Self-consistency (to the original simulation).



ELUCID example halos

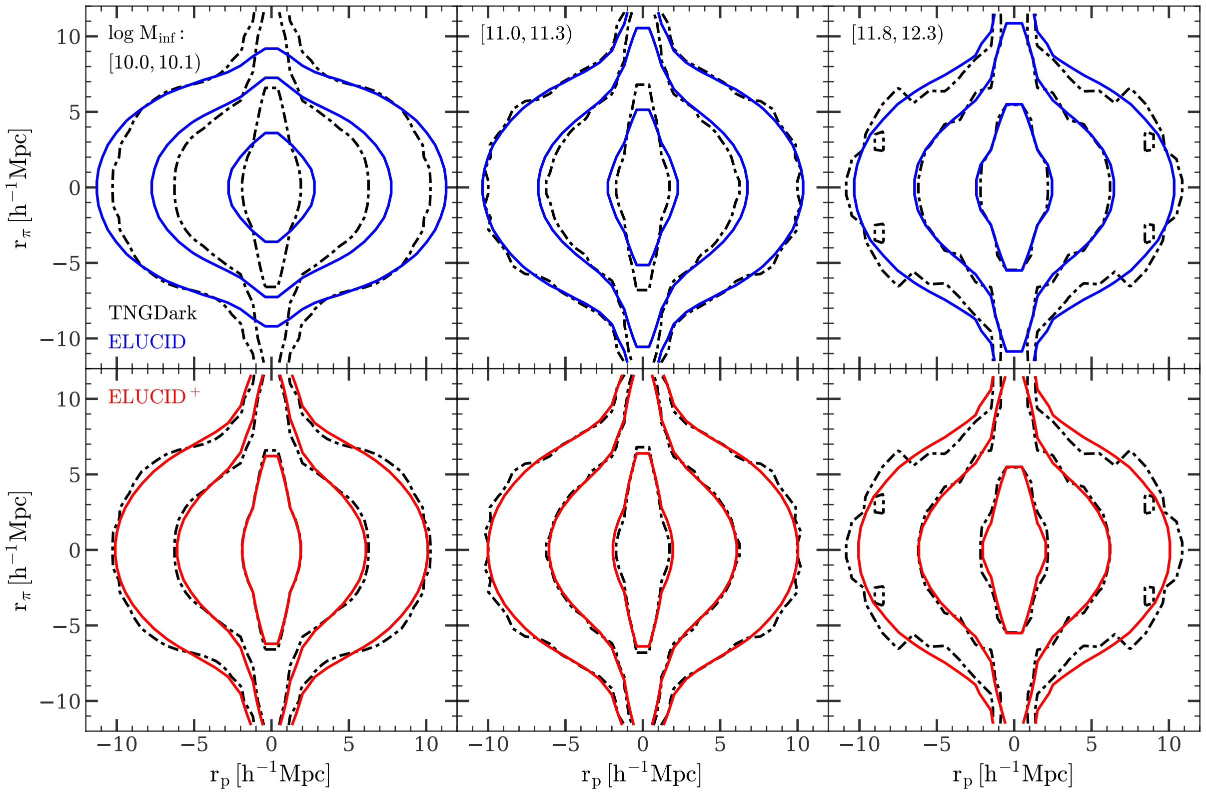
Joint Distribution of Satellite Properties



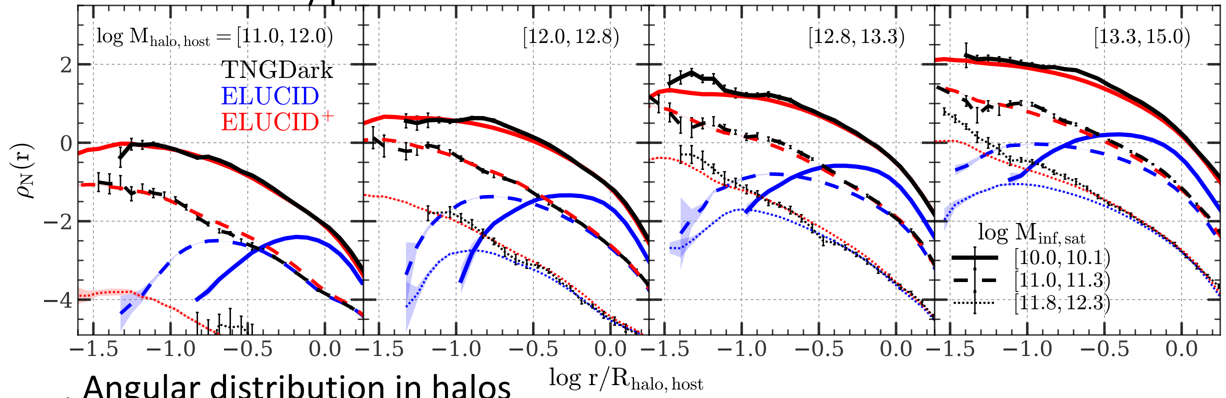
- Bias has been totally removed from ELUCID w.r.t. TNGDark.
- Resulted ELUCID+ joint distribution perfectly matches that of TNGDark.

Summary Statistics of Satellite Properties

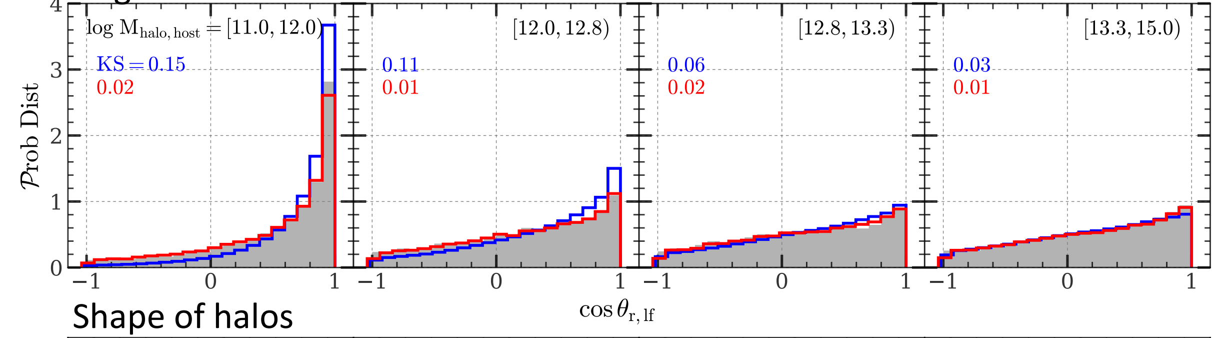
Redshift-space distortion pattern



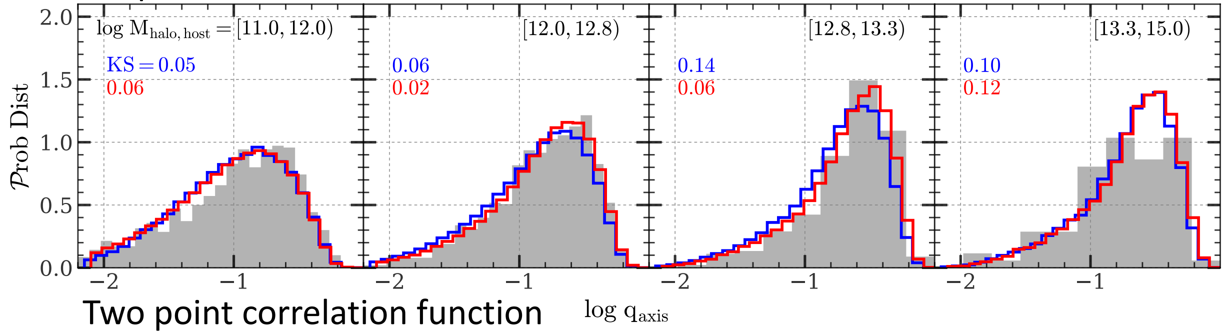
Number density profile



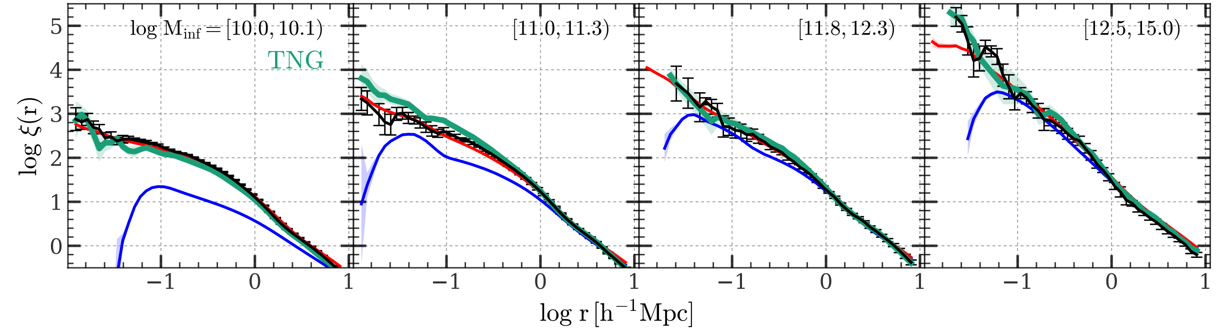
Angular distribution in halos



Shape of halos

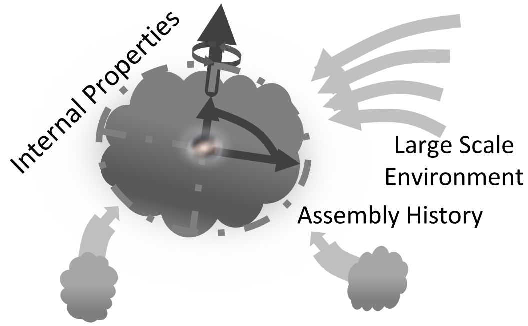


Two point correlation function



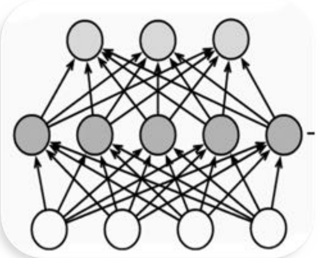
Implication on Halo-based Galaxy Models

1



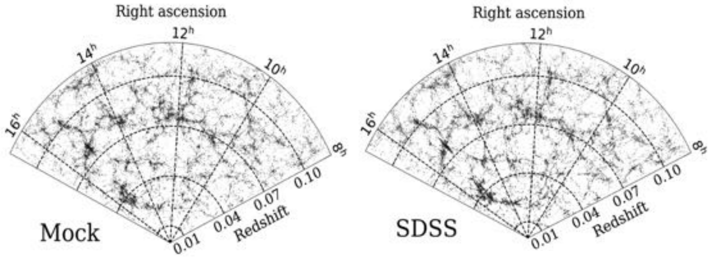
Dark matter halos & merger trees

2

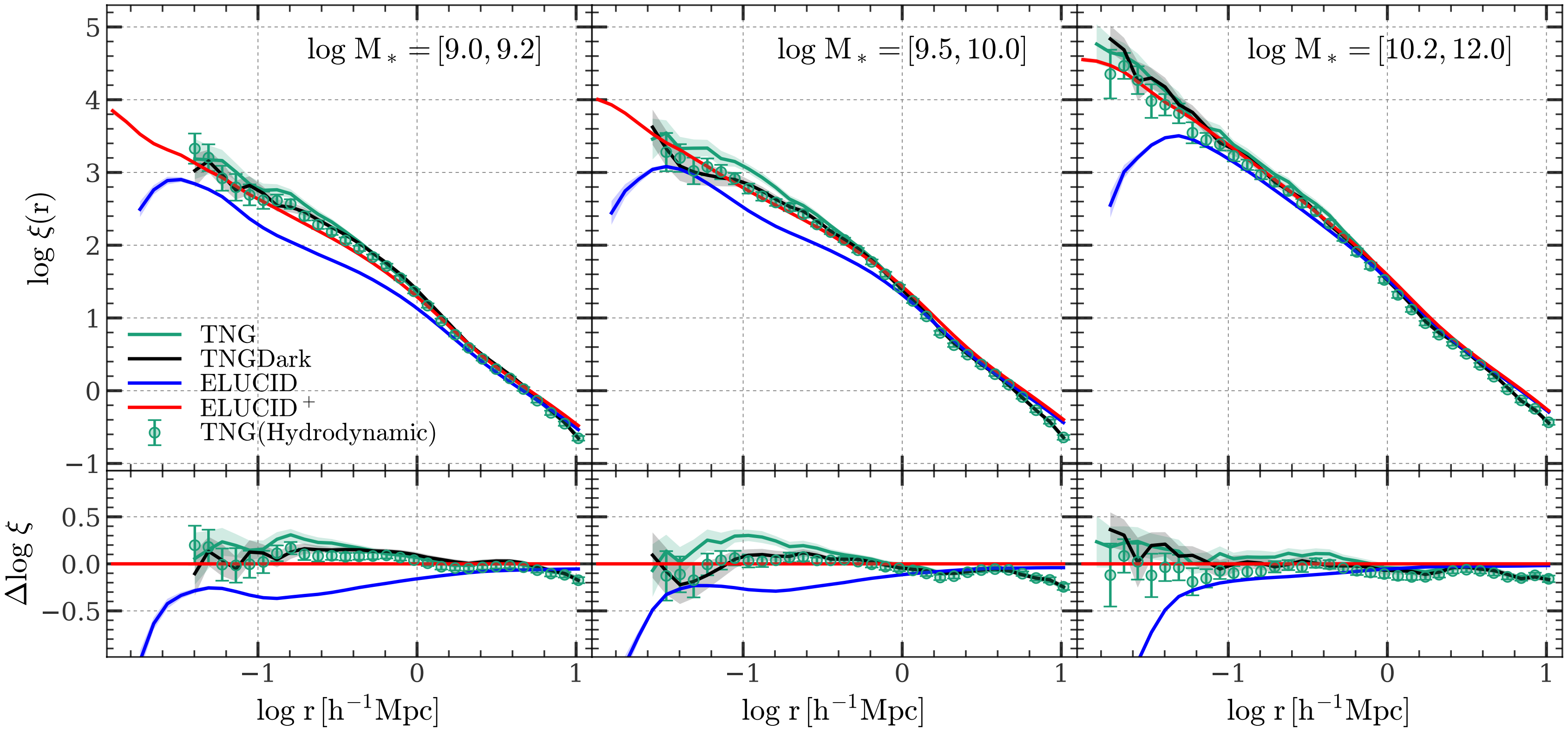


Halo to galaxy mappings with tunable parameters

3



Best-fit and prediction on galaxies and ensemble of galaxies



Summary

- An algorithm to extend subhalo merger trees is developed.
- The algorithm
  - Learn from a high-resolution simulation.
  - Complete the central and satellite assembly histories in any low-resolution DMO simulation.
  - Generate central histories that are unbias and smooth.
  - Recover the joint distribution of satellite properties with shape-preservation and self-consistency features.
  - Provide a more robust basis for the halo-based galaxy models.