SSG 2024

Identification of Galaxy Protoclusters using the Spherical Top-hat Collapse Theory

(Lee et al 2024, ApJ, 960, 132)

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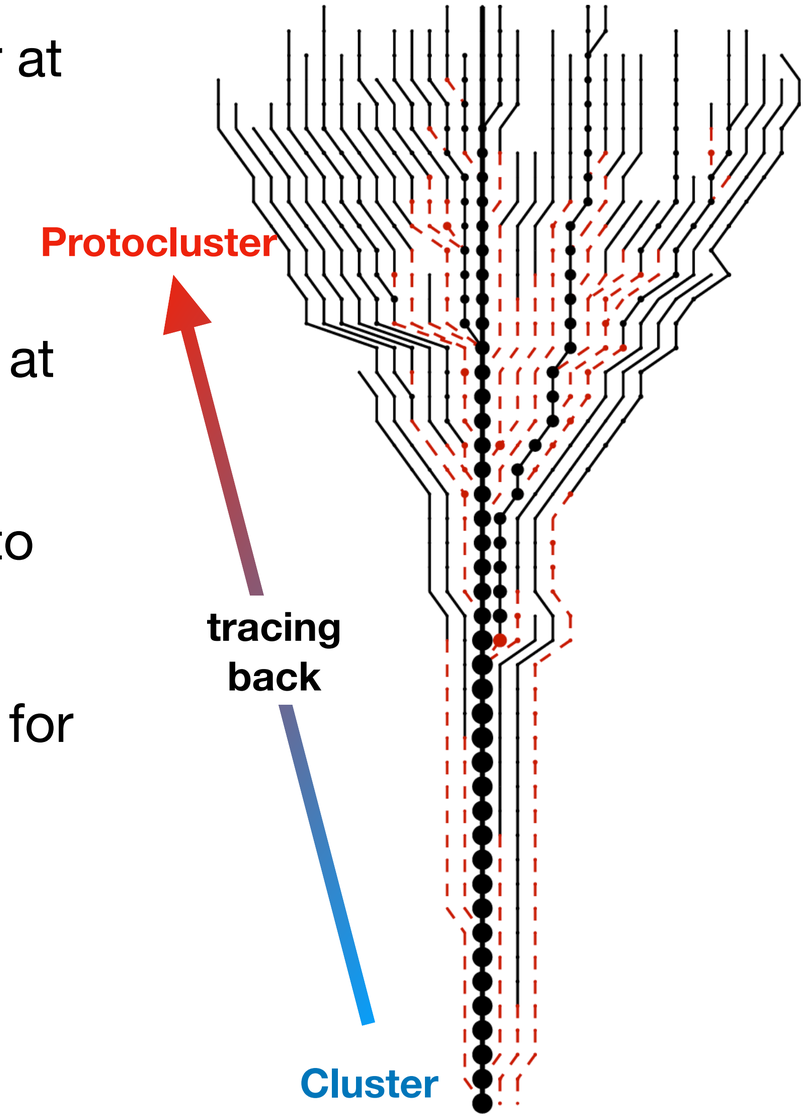
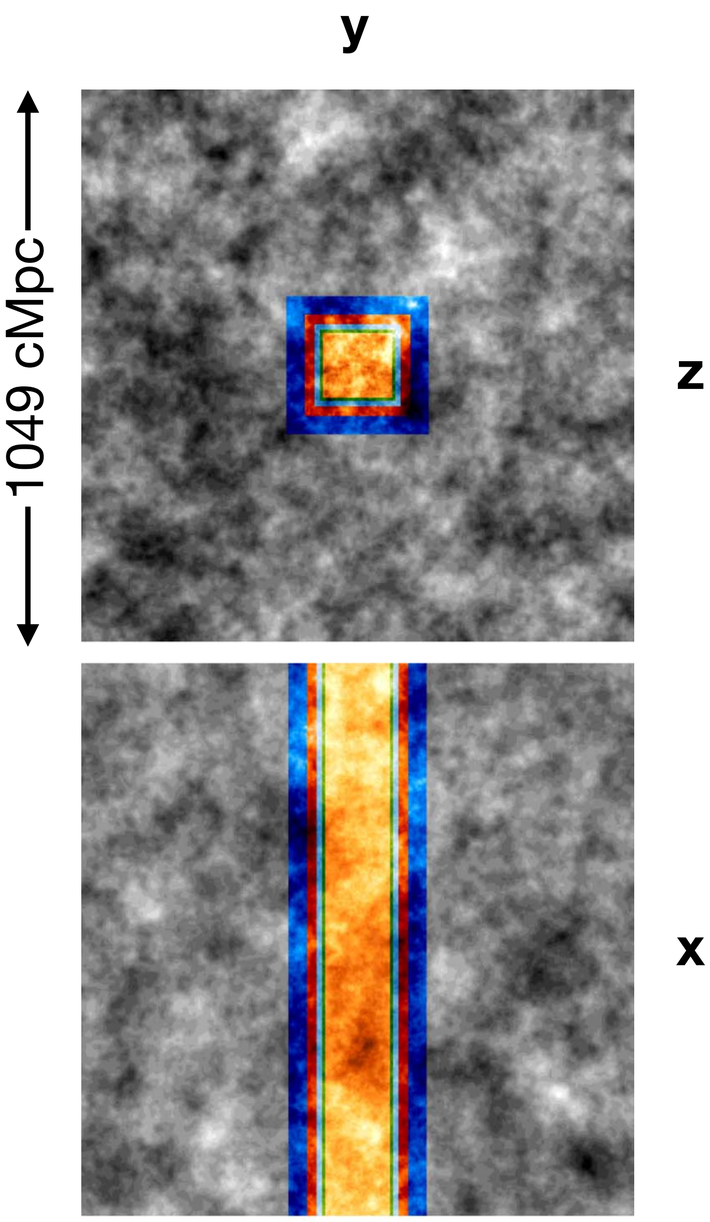
Formation of a cluster in HR5

- What is a protocluster?
  - In theory- A group of structures that will form a galaxy cluster at some stage
    - Able to be traced using merger trees
    - Cluster progenitors are typically widespread (~20-50 cMpc at z>3, e.g., Chiang+13, Muldrew+15)
  - In observations - the region sufficiently overdense compared to surroundings
    - Cores are identified, but no clear threshold has been made for the spatial boundary of protoclusters
- **Main aim of this study**
  - Finding a physically motivated definition of the protocluster boundary



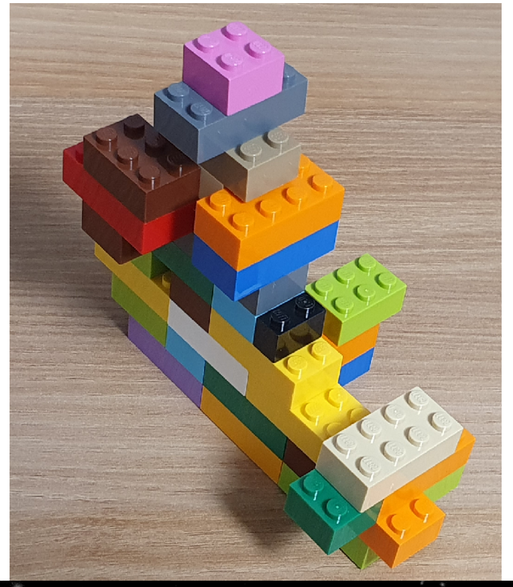
Halo merger trees **Bullock+09**

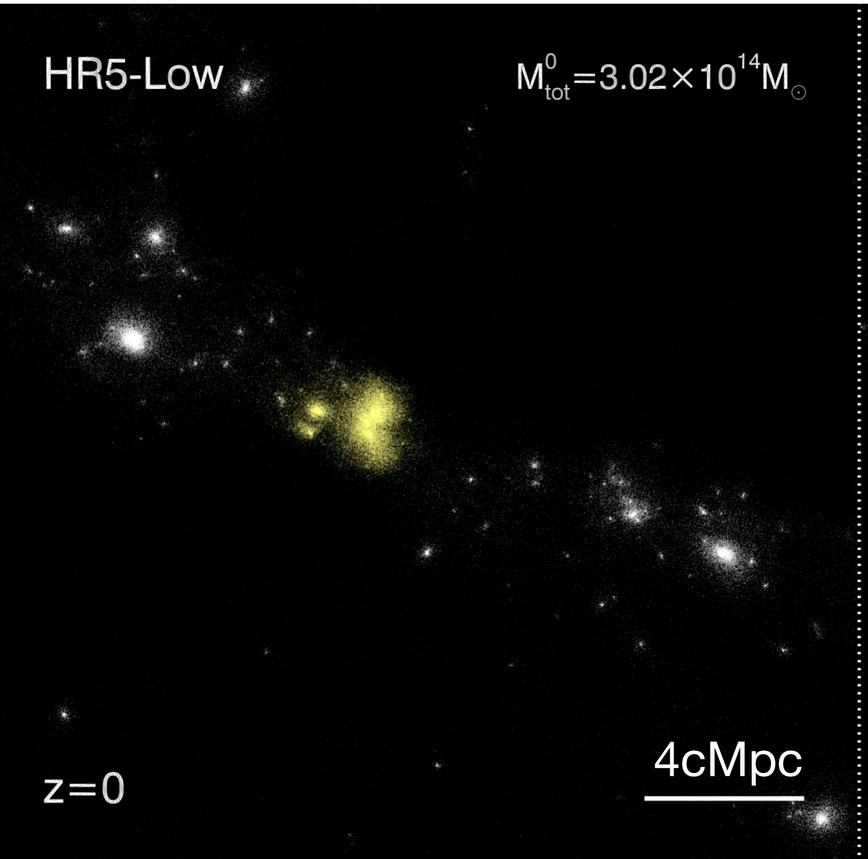
- Horizon Run 5 (HR5, Lee & Shin+21)
  - Adaptive Mesh Refinement code, **RAMSES** (Teyssier02, Dubois+14)
    - Optimized for MPI+OMP hybrid computing for **Nurion** at KISTI
  - Cosmology - h=0.684, Ω_m=0.3, Ω_Λ=0.7 (compatible with the Planck data)
  - Simulation box
    - **Volume - (1049 cMpc)^3**
    - **Zoomed region - 1049×119×127 cMpc^3** (~1/80 of the entire volume), effective volume ~ (250cMpc)^3
  - Spatial resolution - down to 1kpc in the zoomed region
  - **<u>Final snapshot - z=0.625</u>**

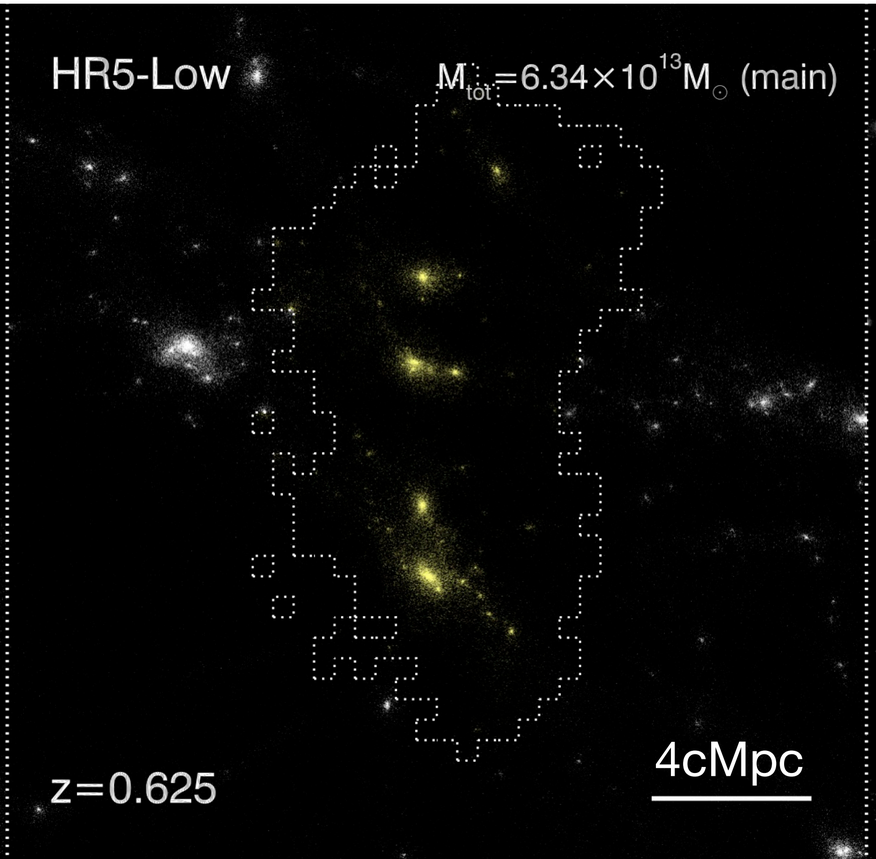


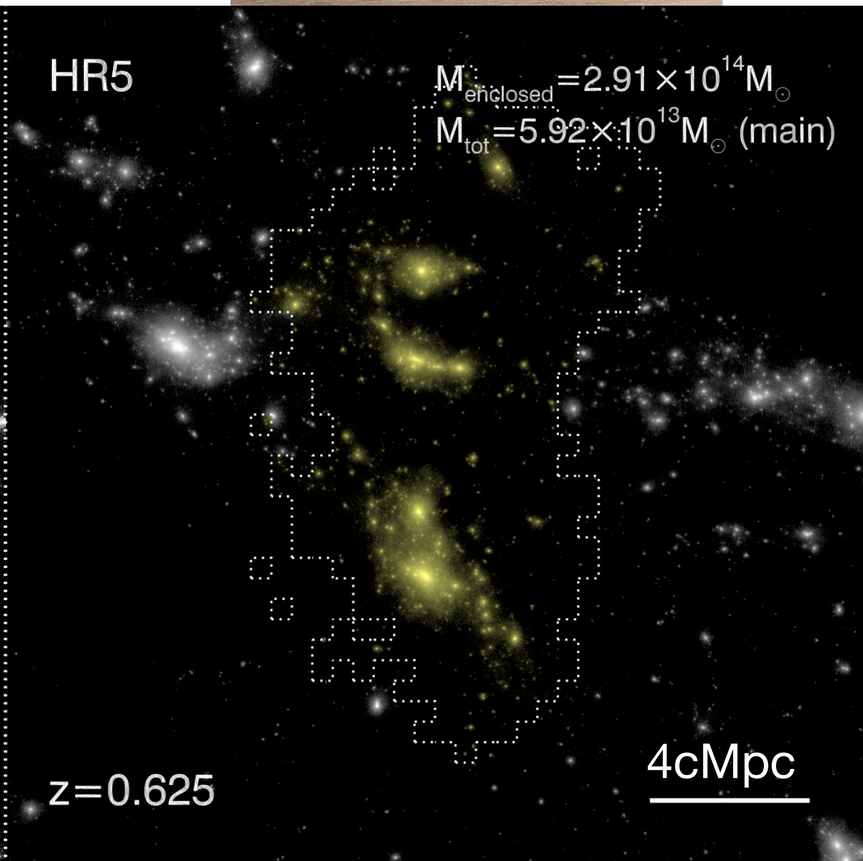
HR5 zoomed region in the initial condition (z=200)

- Identifying cluster candidates in HR5 using a low resolution simulation
  - Final epoch : **z=0.625, t_{age}=7.8 Gyr** - many clusters are underdeveloped yet (~60 halos reach $M_{tot}>10^{14}M_{\odot}$, while ~200 clusters expected at z=0)
  - **HR5-Low :** based on the initial condition of HR5 with Δx_{min}=16 kpc, down to z=0. ~190 clusters identified at z=0

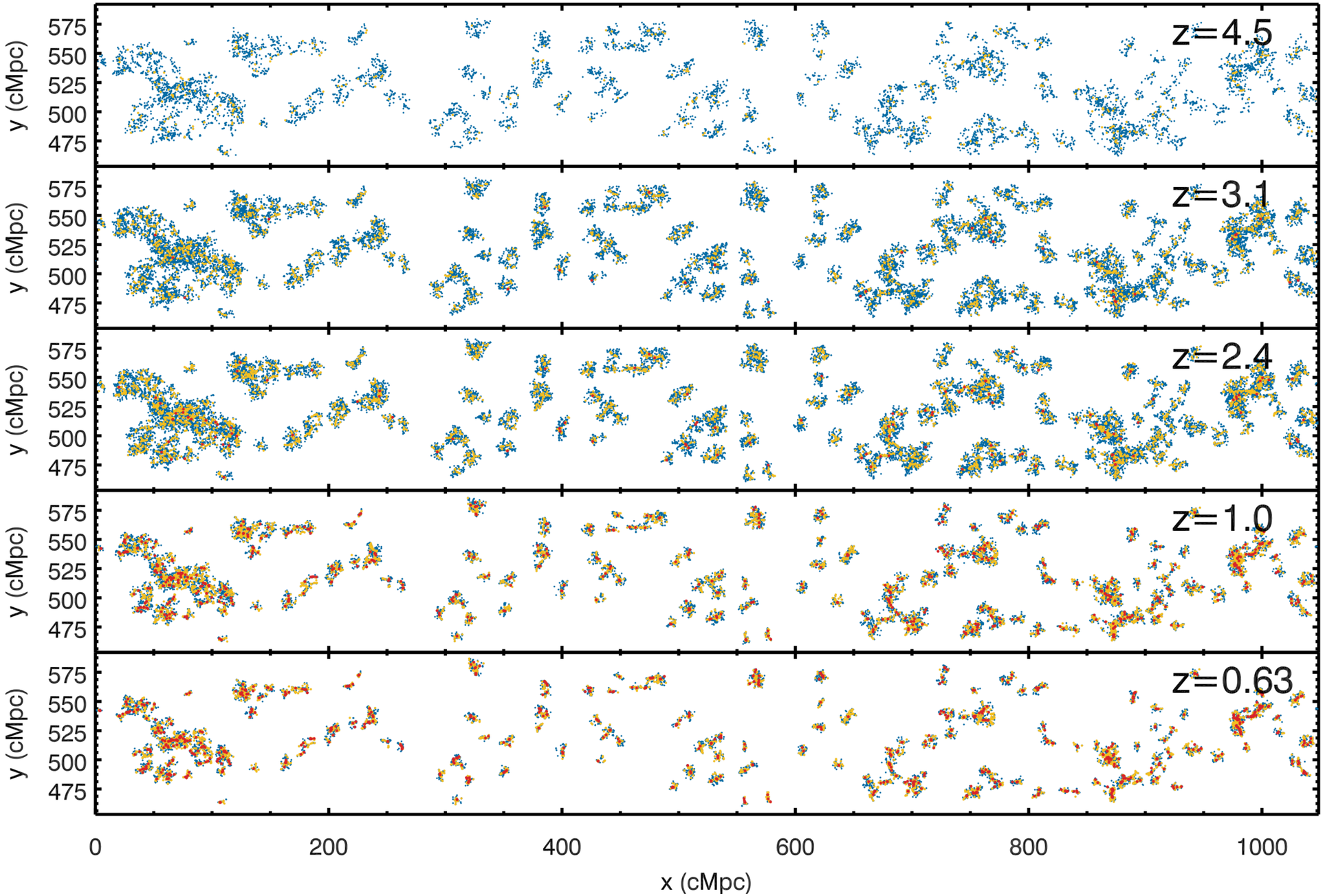






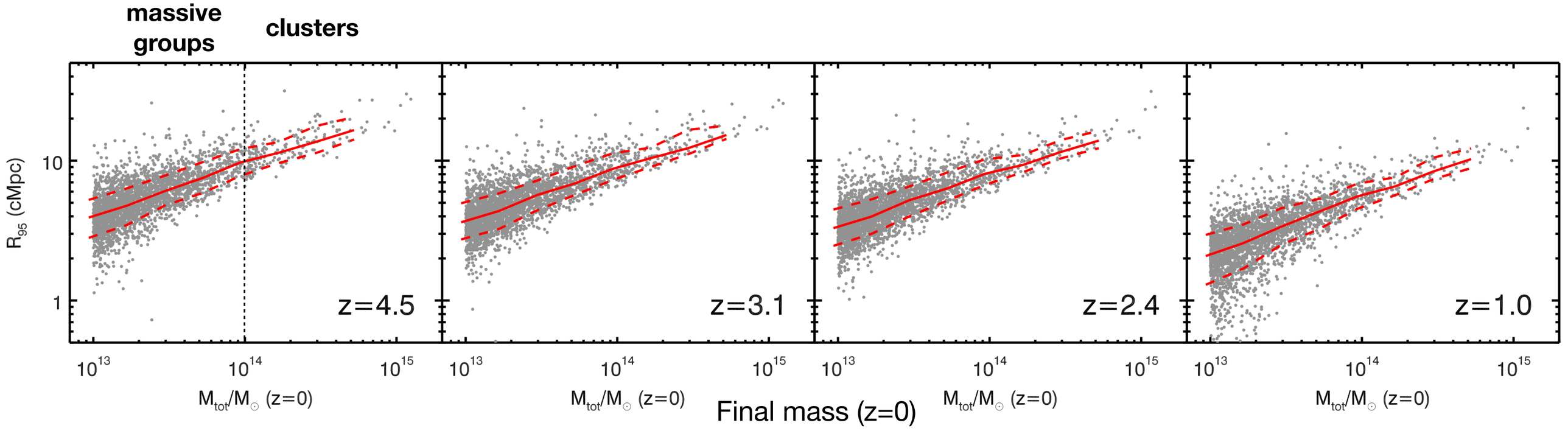


- Distribution of cluster progenitor galaxies in HR5



log M★/M⊙= 9-10
log M★/M⊙=10-11
log M★/M⊙=11-12

- Distribution of the cluster progenitor galaxies
  - Ranging from 10cMpc to 30cMpc
    - Too widespread for galaxies to be physically associated with each other
    - Virial radius only encloses very central region of protoclusters.
    - New definition is needed to characterize the boundary of protoclusters



- Turnaround radius (R_{TA}) - the characteristic radius of a protocluster

  - Distance to the surface on which gravitational infall counterbalances the Hubble flow (Gunn&Gott 72)

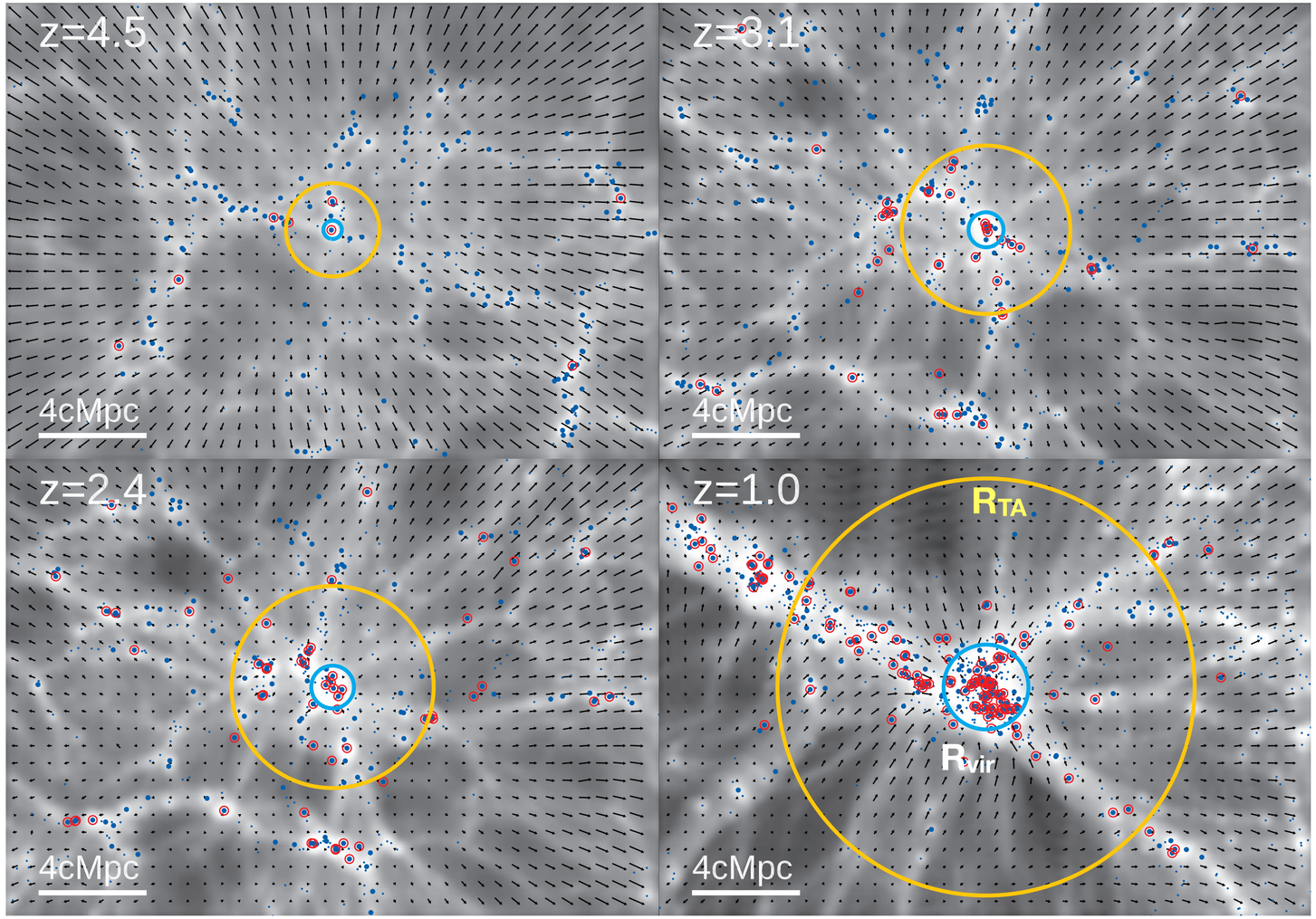
$$v_r = H(z)|\boldsymbol{r}| + \boldsymbol{e_r} \cdot \boldsymbol{v} = 0$$

  - Measured from the velocity and density fields of all matter (DM, gas, star, BH)

  - Protocluster center in this study: the most massive cluster progenitor galaxy

  - We suggest the turnaround radius as the characteristic boundary of protoclusters

Field of a protocluster of $M^0_{\rm tot} = 3 \times 10^{14}\, M_\odot$



- Identifying protocluster regions using the spherical collapse model
  - Finding the sphere of radius R_{sc} that meets the top-hat overdensity $\delta_{\rm m}^{\rm sc}$
  - A sphere is assumed as a candidate region enclosing protocluster(s) when $M_{\rm tot}^{\rm sc} \geq 10^{14}\,{\rm M}_\odot$
  - Einstein-de Sitter (EdS) universe ($\Omega_{m,0}$=1.0)

$$\ddot{R} = -\frac{GM}{R^2} \qquad \delta \equiv \frac{\rho}{\bar{\rho}} - 1 = \frac{9}{2}\frac{(\theta - \sin\theta)^2}{(1-\cos\theta)^3} - 1$$

  - The flat universe with non-zero Λ

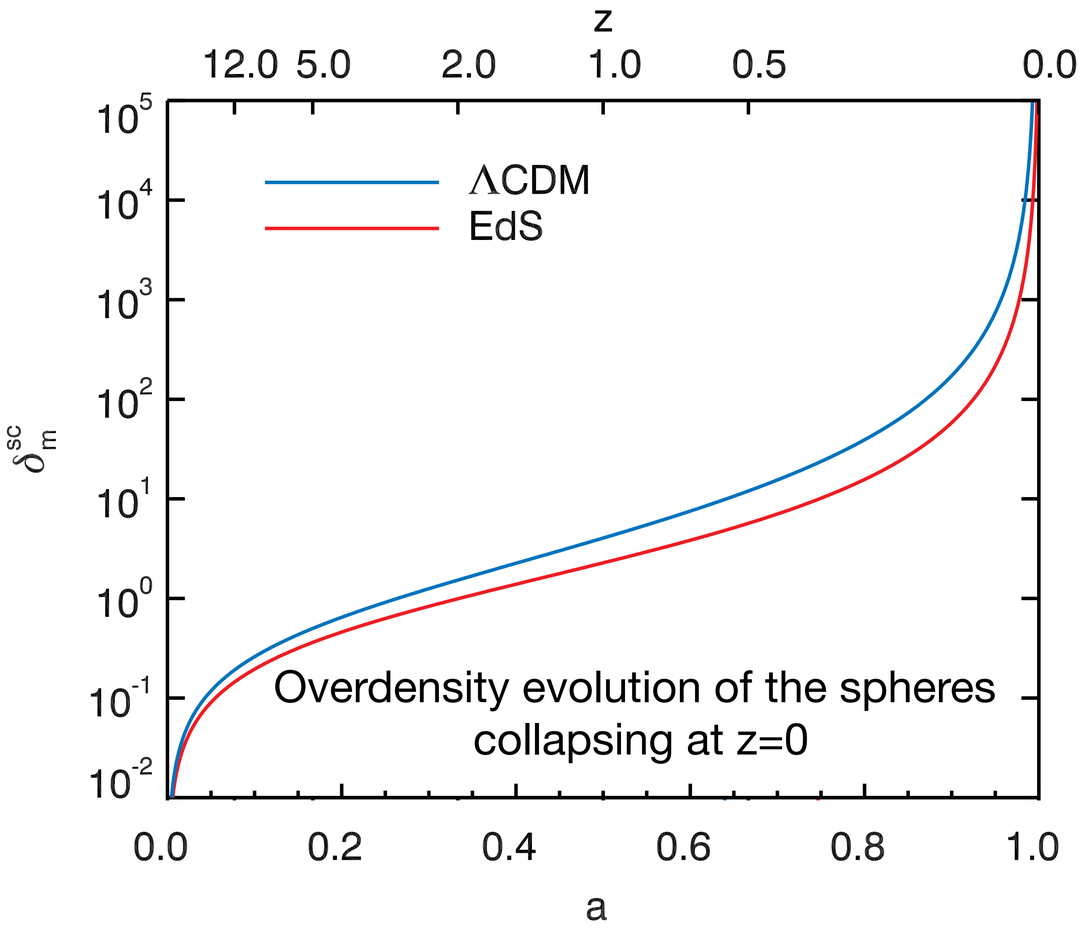
$$\ddot{\delta} + \left(\frac{3}{a} + \frac{\dot{E}(a)}{E(a)}\right)\dot{\delta} - \frac{4}{3}\frac{\dot{\delta}^2}{1+\delta} - \frac{3}{2}\frac{\Omega_{\rm m,0}}{a^5 E^2(a)}\delta(1+\delta) = 0$$

(Pace+10)

where $E(a) = H(a)/H_0 = \sqrt{\Omega_{\rm m,0}/a^3 + \Omega_{\Lambda,0}}$

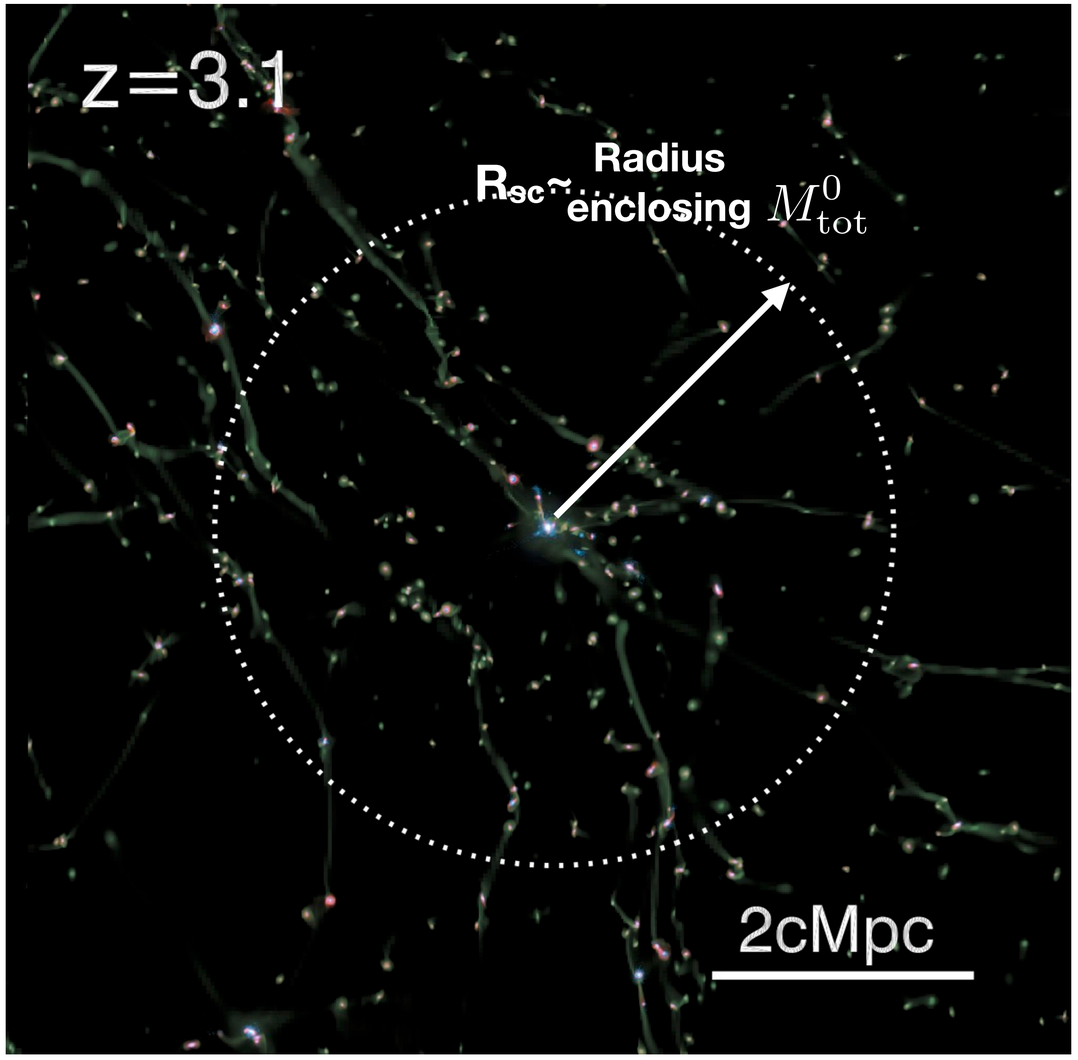
Overdensity

$$\delta_m \equiv \rho_m / \bar{\rho}_m - 1$$

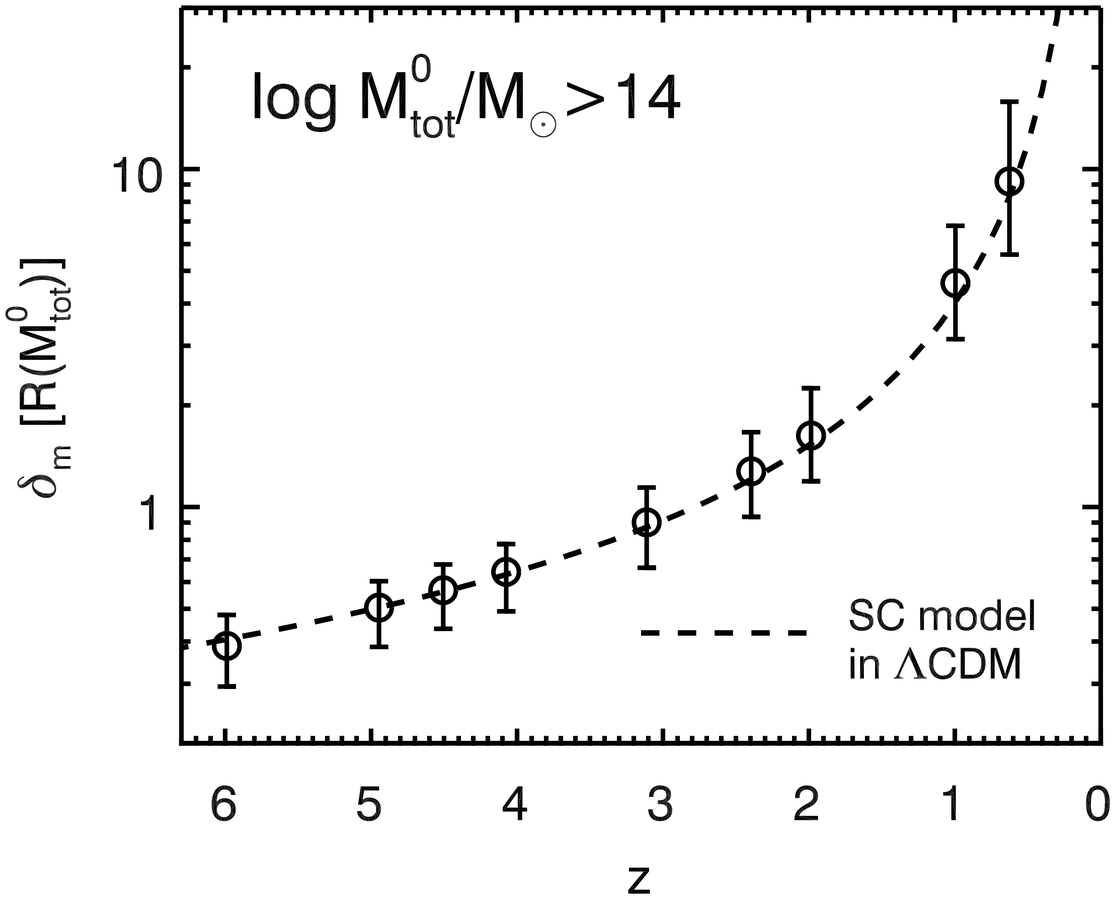


- Final mass radii of protoclusters nicely agree with R_{sc}

➡ Strong justification for adopting the SC model

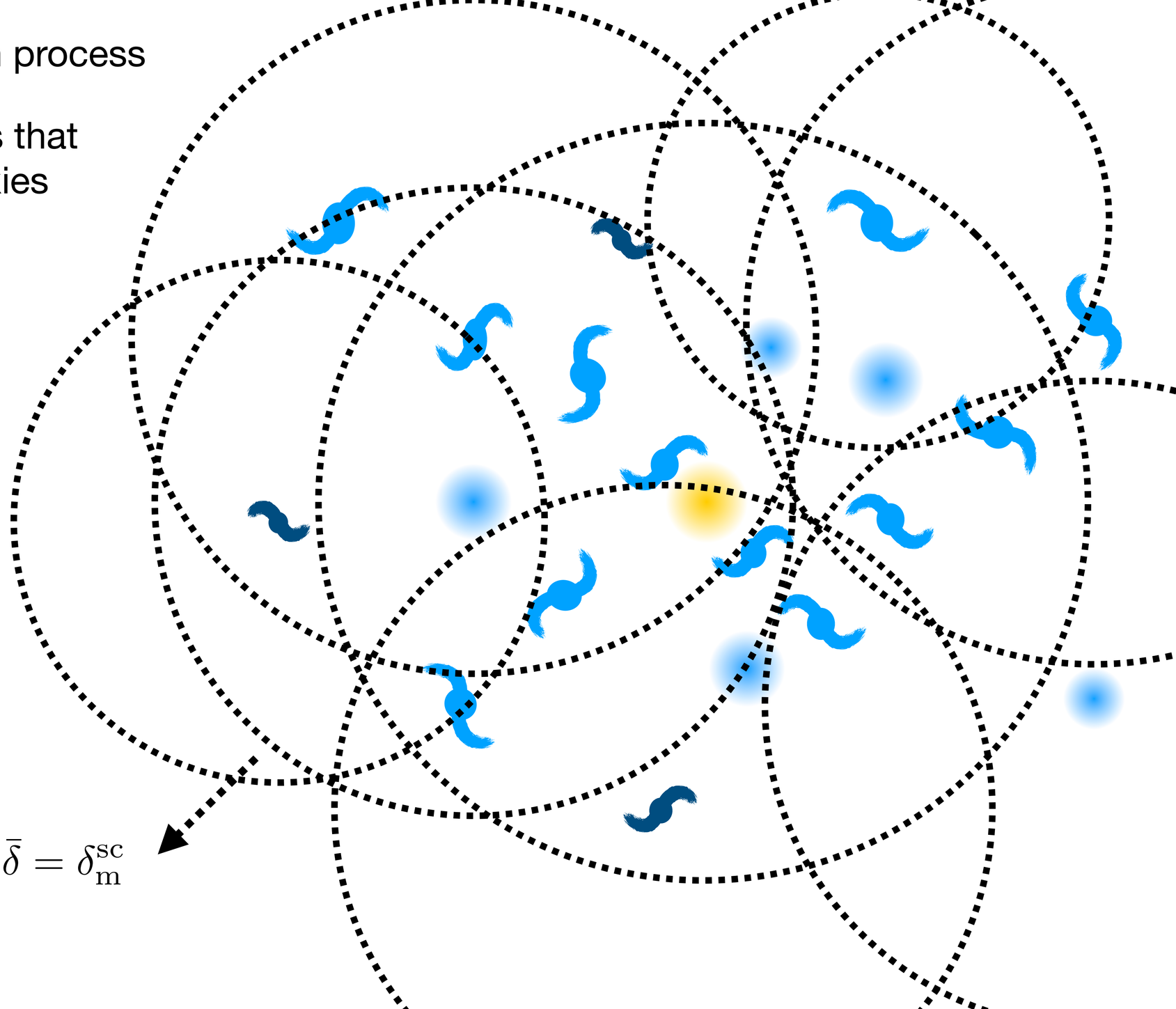


Overdensity within final mass radius of the HR5 protoclusters



- Protocluster region identification process

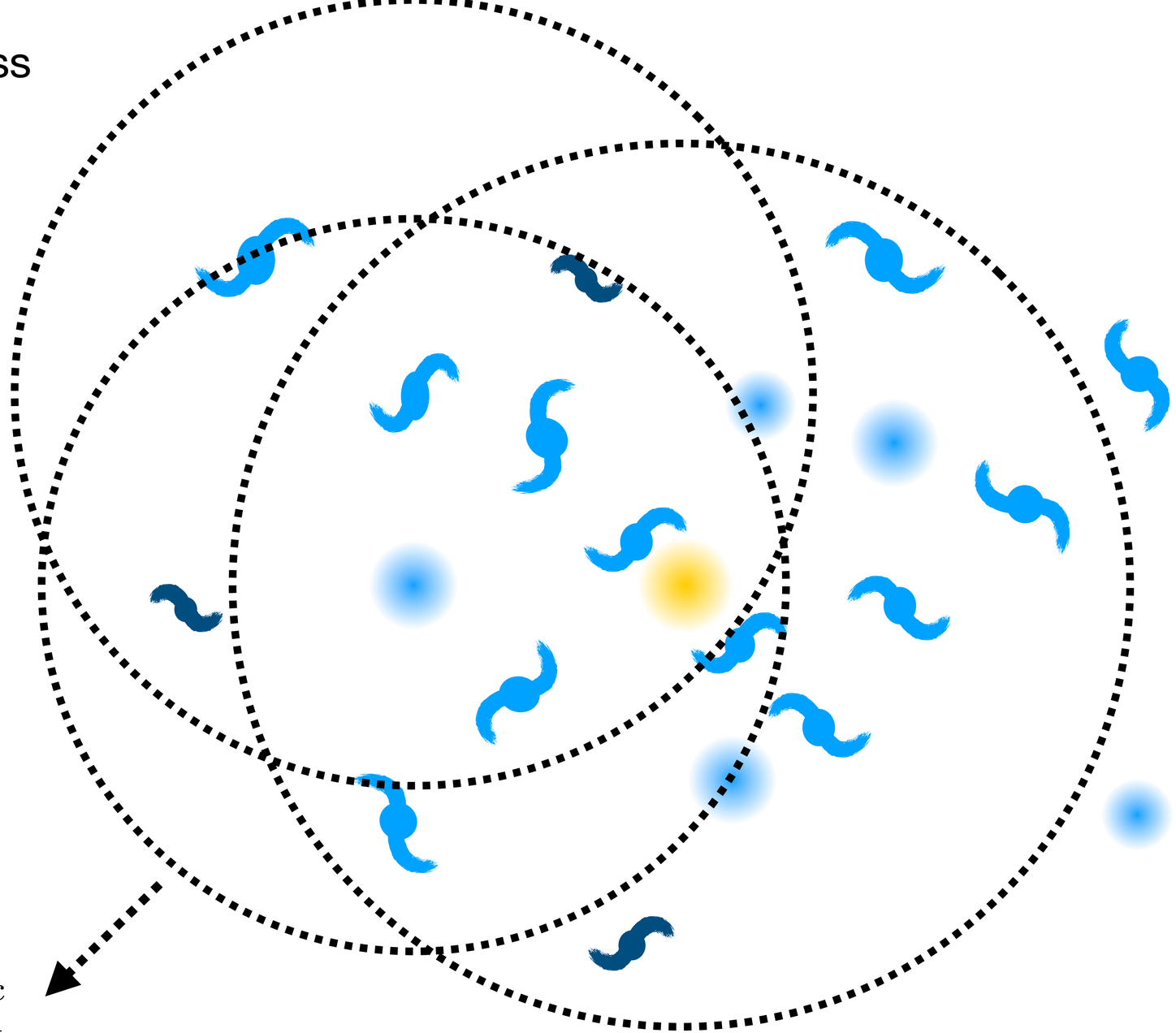
  1. Finding the collapsing radius that meet $\overline{\delta} = \delta_{\mathrm{m}}^{\mathrm{sc}}$ relative to galaxies



- Protocluster region identification process

  1. Finding the collapsing radius that meet $\bar{\delta} = \delta_{\mathrm{m}}^{\mathrm{sc}}$ relative to galaxies

  2. Selecting the spheres of $M_{\mathrm{tot}}^{\mathrm{sc}} \geq 10^{14}\,\mathrm{M}_{\odot}$



$$\bar{\delta} = \delta_{\mathrm{m}}^{\mathrm{sc}}$$
$$M_{\mathrm{tot}}^{\mathrm{sc}} \geq 10^{14}\,\mathrm{M}_{\odot}$$

- Protocluster region identification process

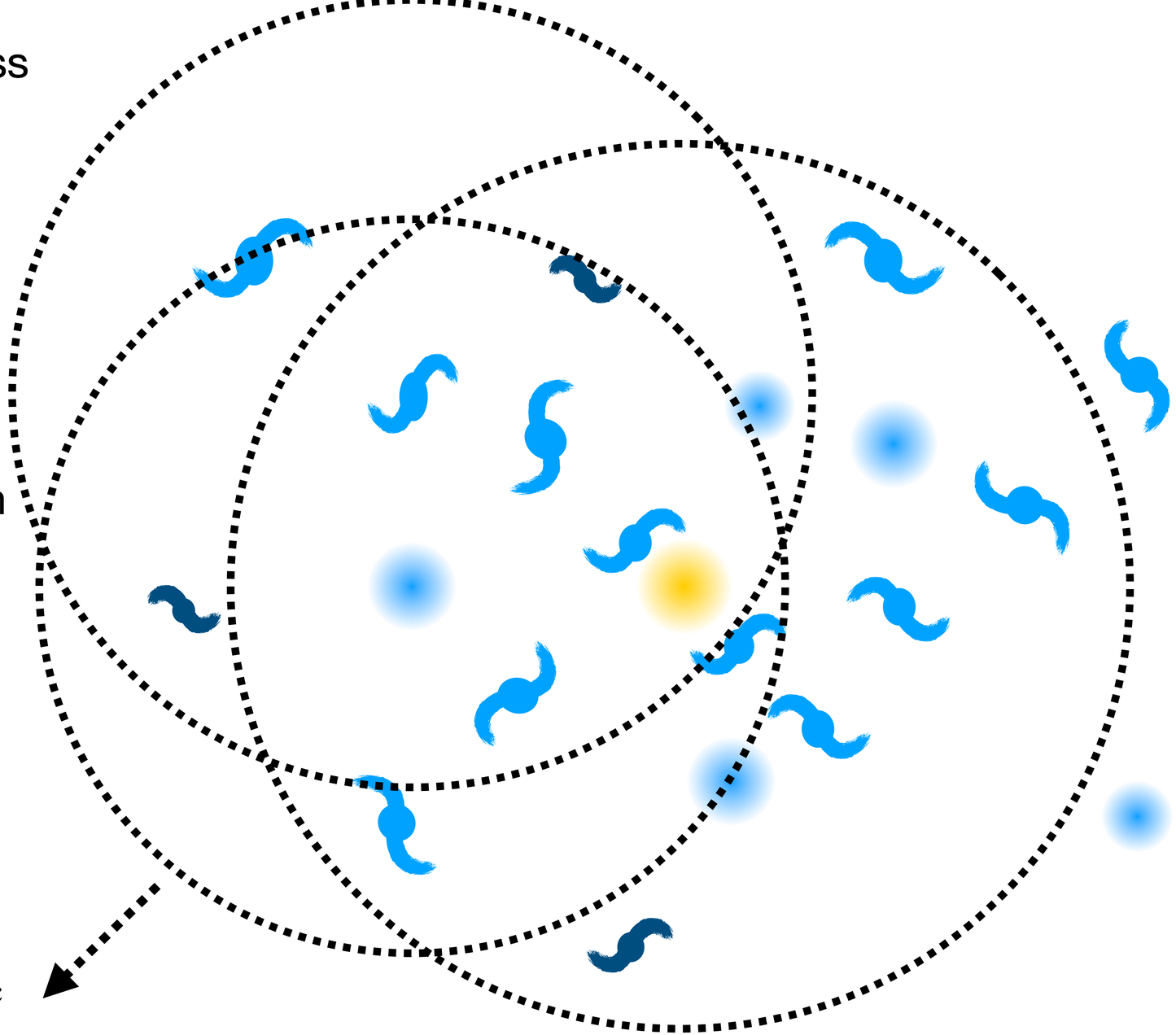
1. Finding the collapsing spheres that meet $\bar{\delta} = \delta_{\mathrm{m}}^{\mathrm{sc}}$ relative to galaxies

2. Selecting the spheres of $M_{\mathrm{tot}}^{\mathrm{sc}} \geq 10^{14}\,\mathrm{M}_{\odot}$

3. Finding the center of galaxy mass in the collapsing radius, re-measuring the radii of $\bar{\delta} = \delta_{\mathrm{m}}^{\mathrm{sc}}$

   ✓ Iterating this step until the CM converges

4. Removing the non-cluster scale spheres or those embedded in larger ones



$$\bar{\delta} = \delta_{\mathrm{m}}^{\mathrm{sc}}$$
$$M_{\mathrm{tot}}^{\mathrm{sc}} \geq 10^{14}\,\mathrm{M}_{\odot}$$

- Estimating total mass from stellar mass distribution within R_{sc}

  - Fitting function for the spherical top-hat overdensity collapsing at z=0 in the LCDM universe

$$\delta_{\rm m}^{\rm sc}(z) = \frac{0.0224\exp\left(5.39\,z^{-0.246}\right)}{(1+z)^{0.294}}$$

~0.3% accuracy at z=0.5-6

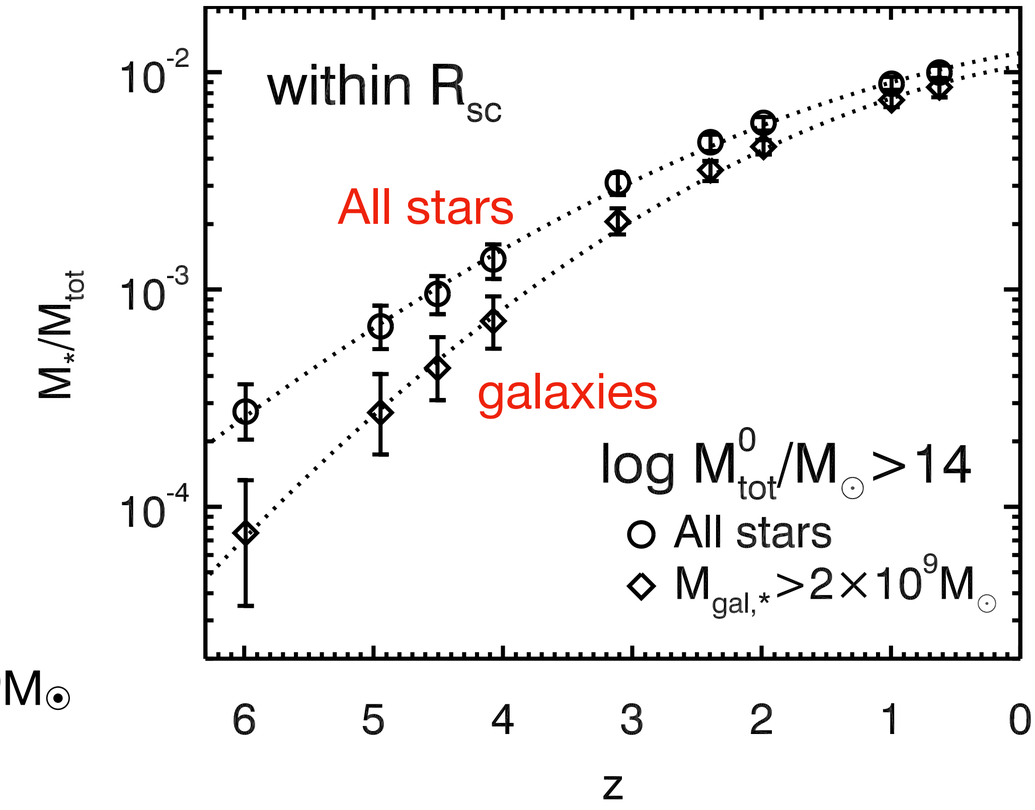
  - Fitting function for stellar-to-total mass relation within R_{sc}

$$\log M_\star/M_{\rm tot} = \alpha(1+z)^\beta + \gamma$$

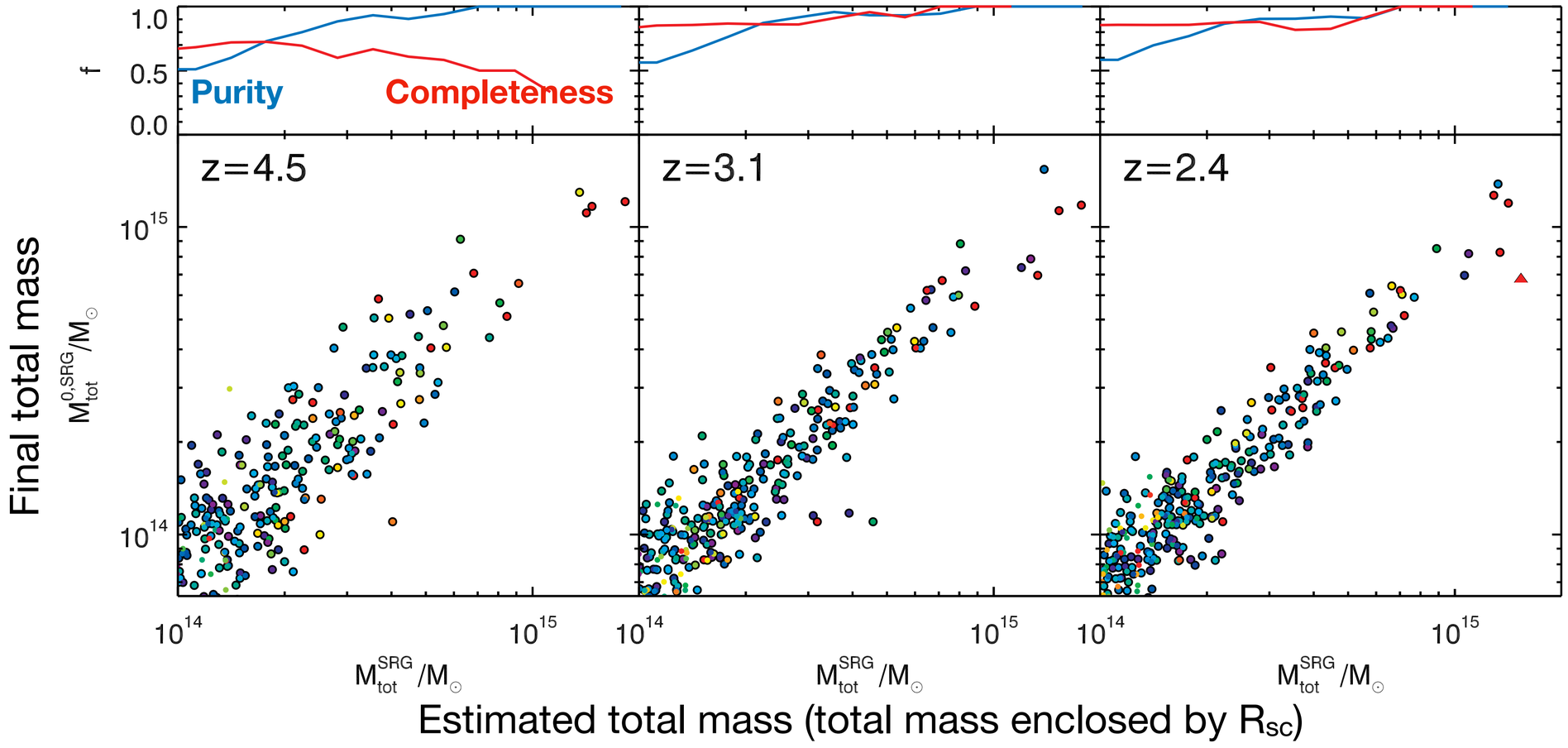
$(\alpha,\beta,\gamma) = (-0.057, 1.755, -1.855)$ for entire stellar mass

$(-0.055, 1.903, -1.915)$ for galaxies with $M_\star > 2\times10^9 M_\odot$

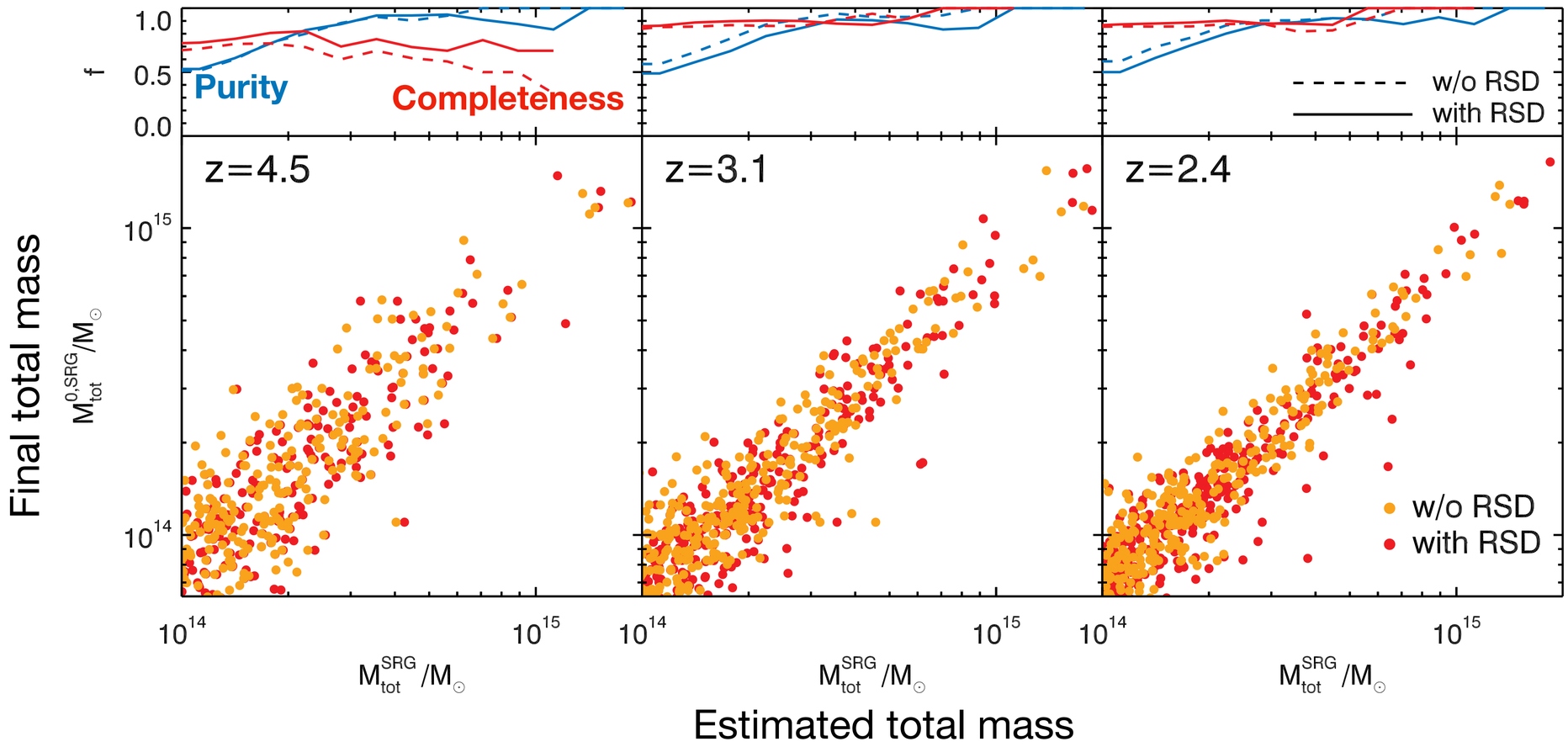
Overdensity within final mass radius of the HR5 protoclusters



- Performance of the scheme
  - Purity - the number fraction of the spherical regions enclosing the bonafide protoclusters to entire spheres more massive than given mass
  - Completeness - the number fraction of the bonafide protoclusters enclosed by the spheres to entire protoclusters above given mass



- Redshift space distortion (RSD) effect
  - Galaxy distribution is flattened in redshift space nearby dense environments (Kaiser effect)
    - 1σ of Δx~3cMpc
  - RSD rather slightly enhances the completeness at the cost of the purity



- Summary
  - ~190 clusters are identified at z=0.625 in HR5 using HR5-Low
  - We suggest the turnaround radius R_{TA} as the characteristic boundary of a protocluster
  - We propose an approach to identify protocluster regions based on the spherical collapse model
    - This scheme successfully recovers protoclusters from galaxy distribution
    - Redshift space distortion does not have significant impact on the protocluster identification scheme
  - We will investigate the properties of protocluster galaxies as a function of R_{TA} - Please stay tuned!