Cosmology 2024

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

arXiv: 2308.00571
2024, ApJ, 960 132

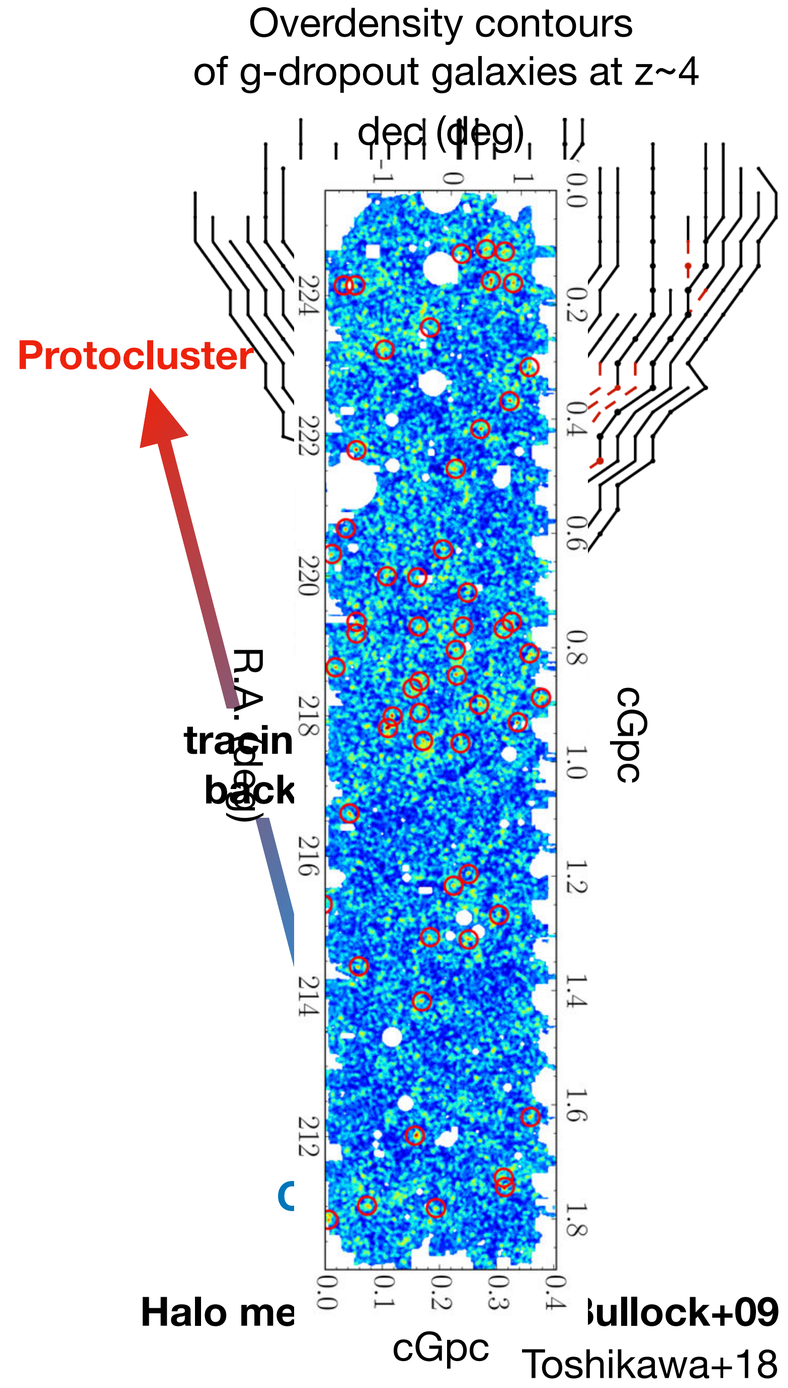
Jaehyun Lee, Changbom Park, Juhan Kim, Christophe Pichon, Brad K. Gibson,
Jihye Shin, Yonghwi Kim, Owain N. Snaith, Yohan Dubois, and C. Gareth Few

Formation of a cluster in HR5

- Galaxy protocluster
  - In theory- A group of structures that will eventually form a galaxy cluster
    - Can be traced using merger trees
    - Cluster progenitors are typically widespread

      ➡ ~20-50 cMpc at z>3 (Chiang+13, Muldrew+15)
  - In observation - Sufficiently overdense regions compared to surroundings (Overzier16)
    - Core identification is straightforward, but not the case in defining the boundary of galaxy protoclusters
  - Main aim of this study

    ➡ Finding a systematic approach to identify galaxy protoclusters

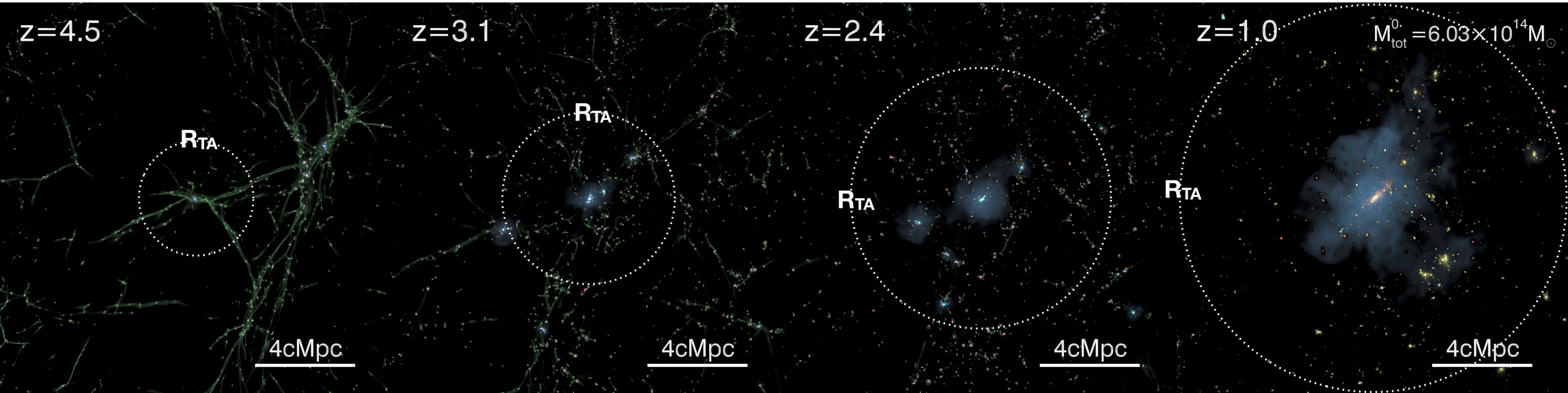


- Protocluster identification process proposed in this study

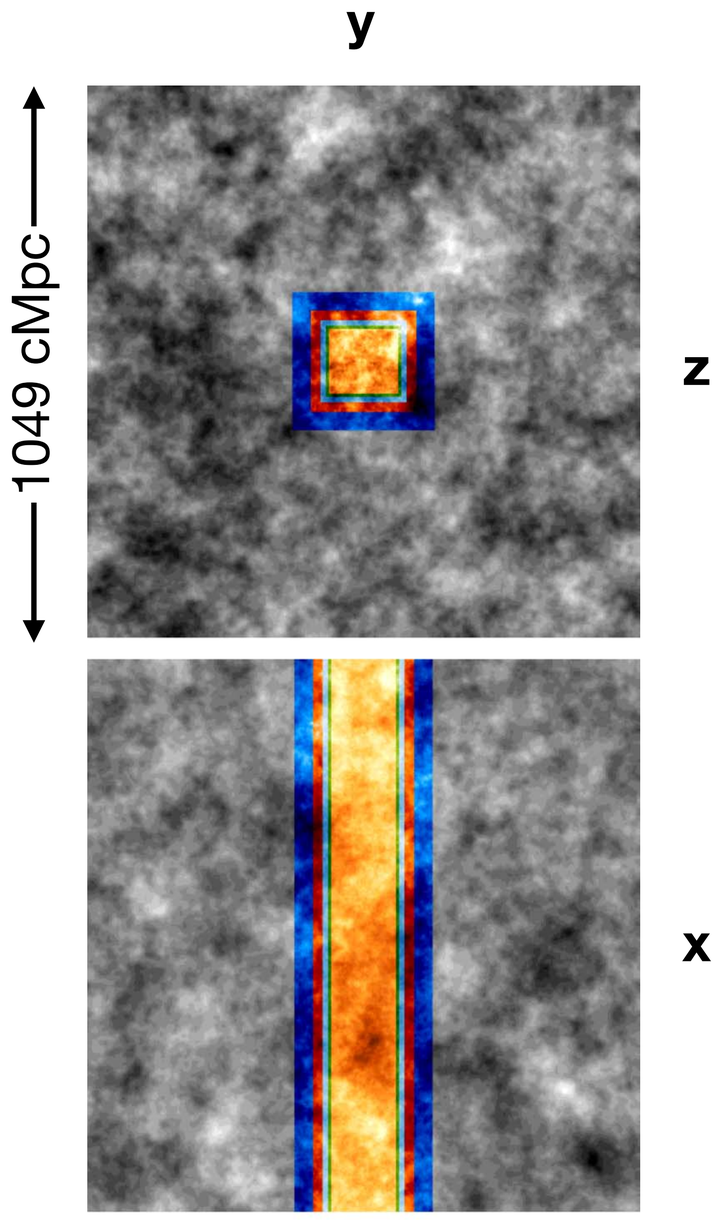
1. Finding protoclusters based on the spherical top-hat collapse theory from galaxies
    - For systematic search for galaxy protoclusters
2. Defining the turnaround radius (Gunn&Gott 72) as the characteristic boundary of a protocluster
    - Turnaround radius (R_{TA}) - surface on which gravitational infall counterbalances the Hubble flow

➡ Testing the scheme using a cosmological hydrodynamical simulation Horizon Run 5 (HR5)

Formation of a cluster in HR5



- Horizon Run 5 (HR5, Lee+21)
  - Adaptive Mesh Refinement code, **RAMSES** (Teyssier02, Dubois+14)
    - Optimized for MPI+OMP hybrid computing in the HR5 project
    - Cosmology - $h=0.684$, $\Omega_m=0.3$, $\Omega_\Lambda=0.7$
  - Resolution - $\Delta x \sim 1$kpc, $M_\star \sim 2\times10^6 M_\odot$ in the zoomed region,
  - Simulation box
    - **Volume - (1049 cMpc)^3~1cGpc^3**
    - **Zoomed region - 1049×119×127 cMpc^3** (~1/80 of the entire volume), effective volume ~ (250cMpc)^3

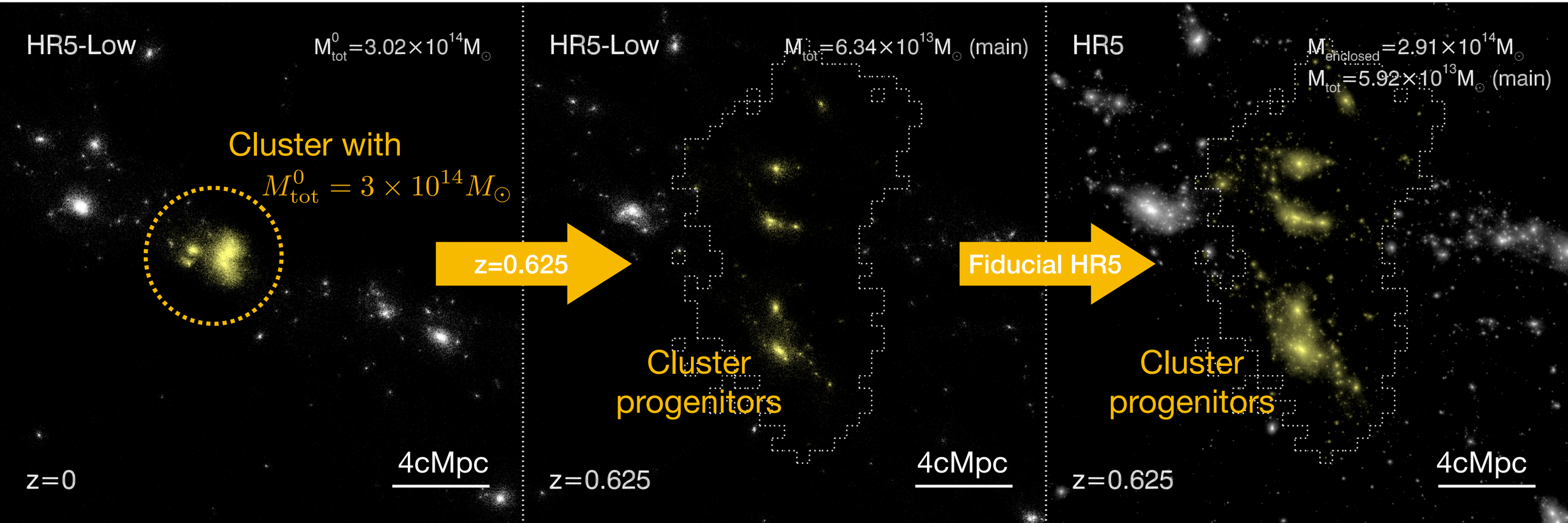


HR5 zoomed region in the initial condition (z=200)

- Identifying cluster candidates in HR5 using a low resolution simulation
  - Final epoch : **z=0.625, t_{age}=7.8 Gyr** - many clusters underdeveloped yet

    ➡ ~60 halos with $M_{tot}>10^{14}M_{\odot}$, while ~200 clusters expected at z=0
  - **HR5-Low :** Run using the IC of HR5, but with Δx_{min}=16 kpc

    ➡ 189 clusters identified at z=0



- Identification of protocluster regions based on the spherical collapse (SC) theory

1. Finding the sphere of radius R_{sc} that meets the top-hat overdensity $\delta_{\rm m}^{\rm sc}$ predicted by the SC theory
2. Assuming a sphere as a protocluster region if $M_{\rm tot}^{\rm sc} \geq 10^{14}\,{\rm M}_\odot$

✓Overdensity

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

- Einstein-de Sitter (EdS) universe ($\Omega_{m,0}$=1.0)

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

Simple analytic solution

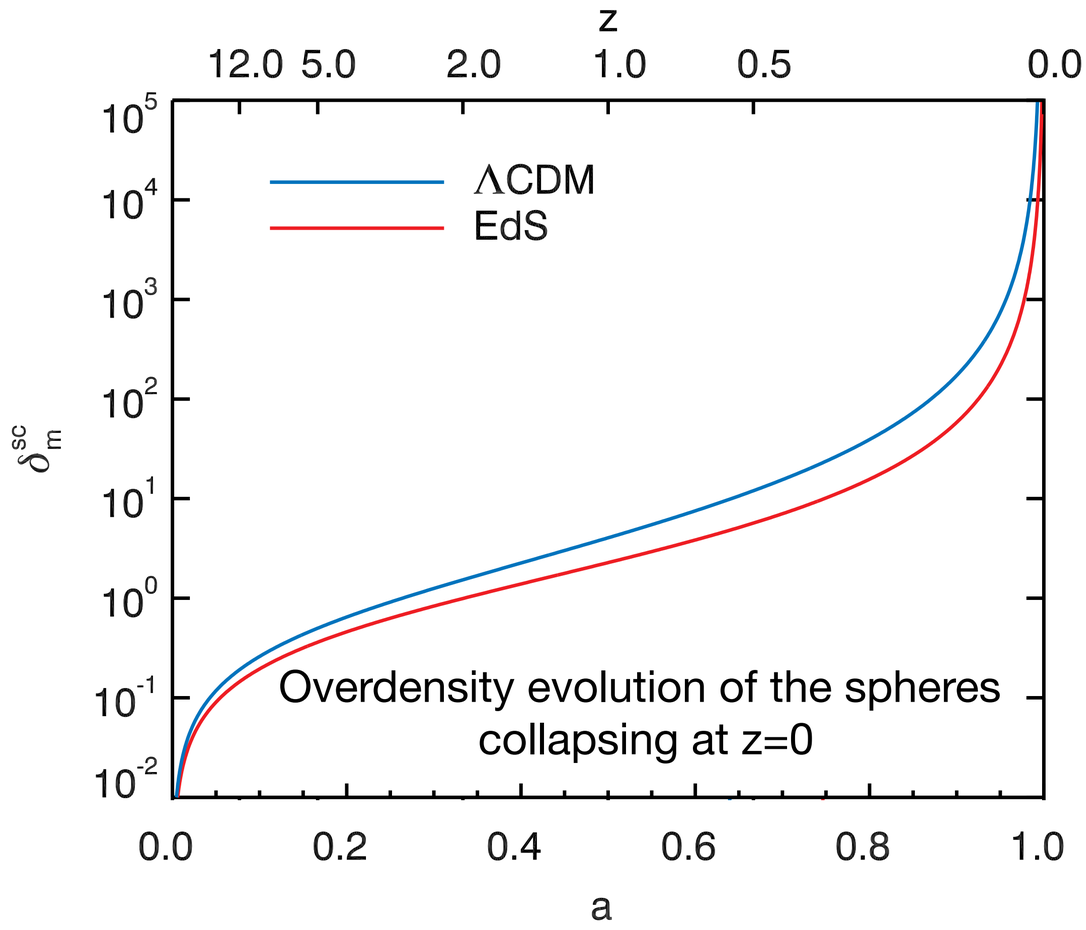
- The flat universe with non-zero Λ

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

(Pace+10)

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

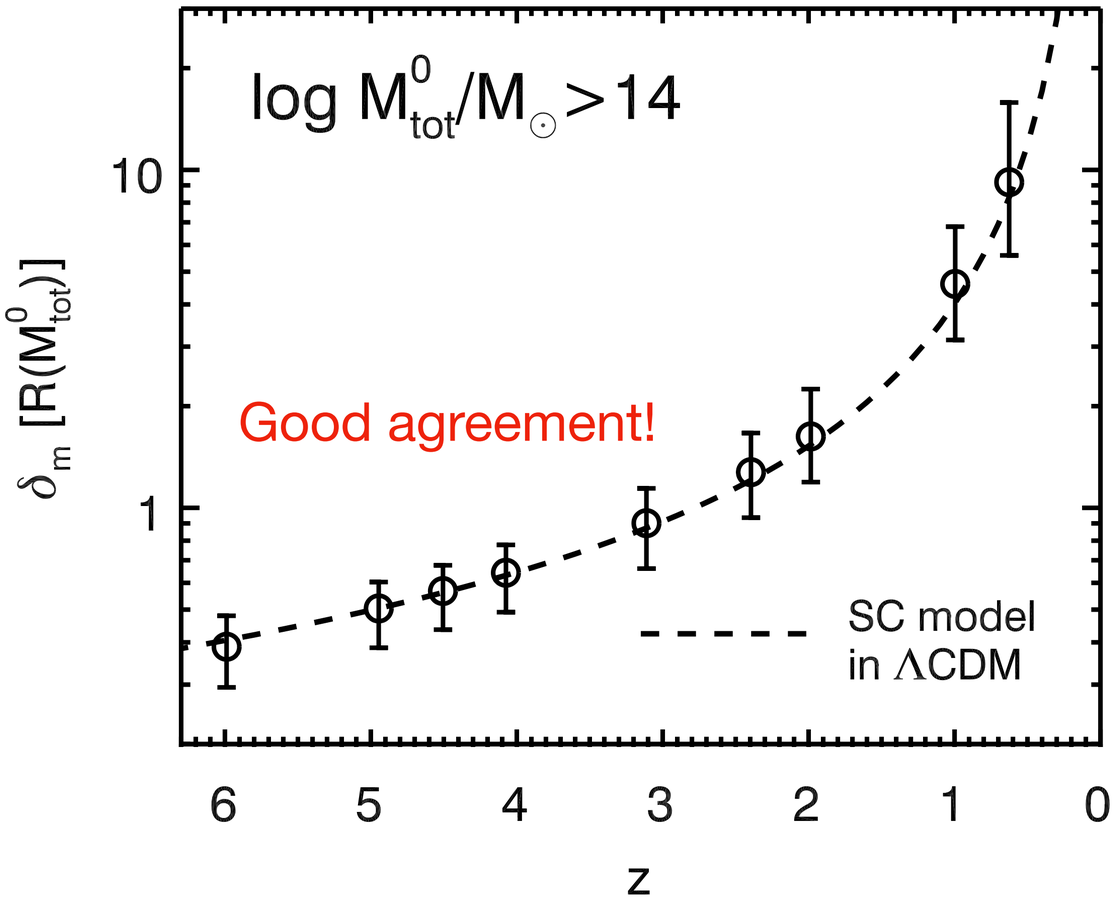
Numerically solved



- Does the SC theory work?
  - Overdensity within the radius enclosing z=0 cluster mass agrees well with $\delta_{\rm m}^{\rm sc}$

➡ The SC theory reasonably predicts cluster mass at z=0

Overdensity within the z=0 mass radius
of the HR5 protoclusters



- Protocluster identification process

1.Finding the spherical regions that meet $\bar{\delta} = \delta_{\rm m}^{\rm sc}$ relative to every galaxies

✓ $M_\star/M_{\rm tot}$ within $R_{\rm sc}$ necessary to derive $M_{\rm tot}$

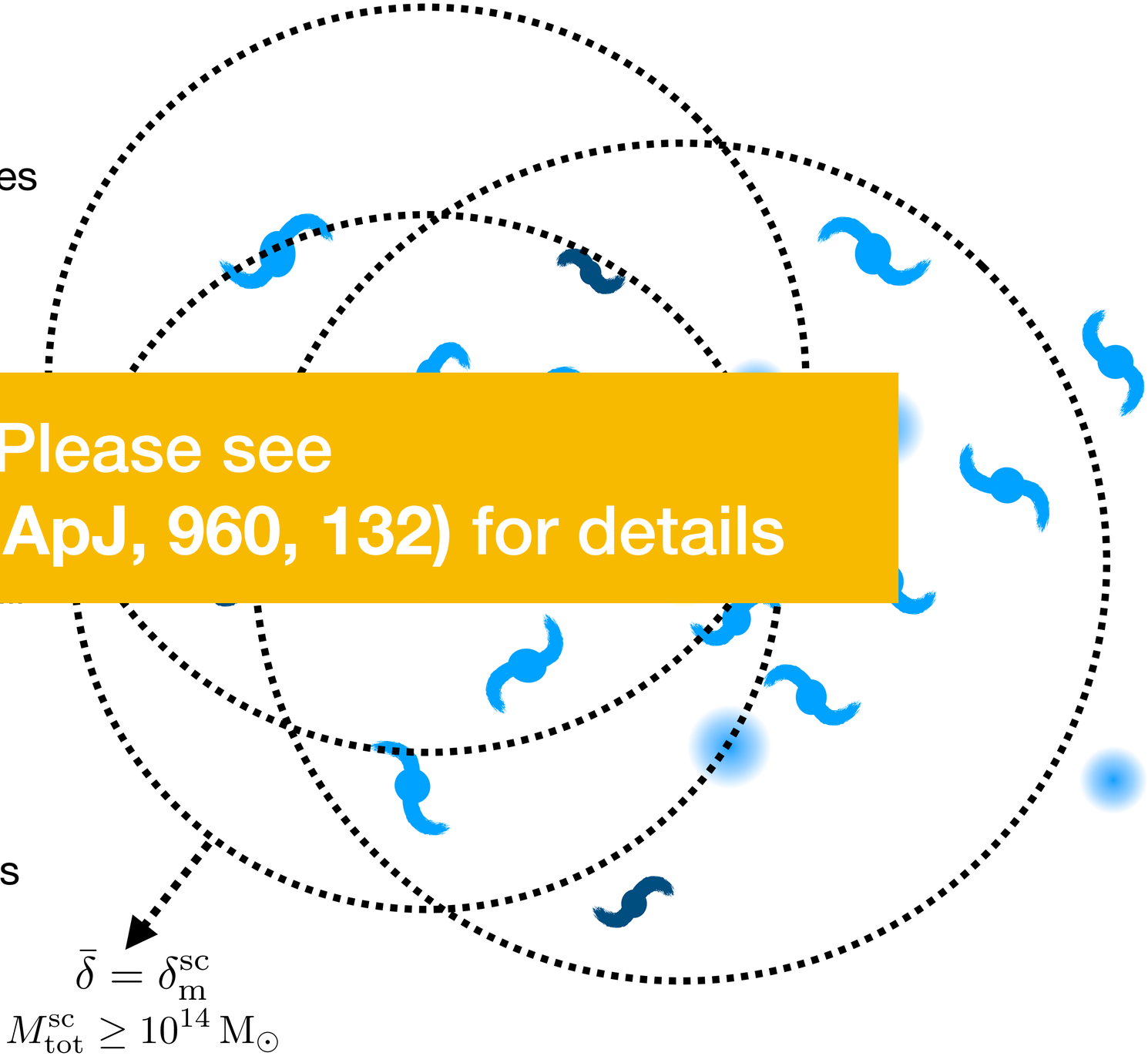
2. Selecting the spherical region of $M_{\rm tot}^{\rm sc}$

3. Find the sp… of $\bar{\delta} = \delta_{\rm m}^{\rm sc}$ again

✓ Iterating this step until the CM of galaxies converges

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

Please see
Lee+24 (2024, ApJ, 960, 132) for details



- Finding R_{sc} from galaxies using the stellar-to-total mass relation

✓ Fitting function for $\delta_{\rm m}^{\rm sc}$ collapsing at z=0

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

✓Fitting formula to estimate $M_{\rm tot}^{\rm sc}$ from $M_{\star}^{\rm sc}$

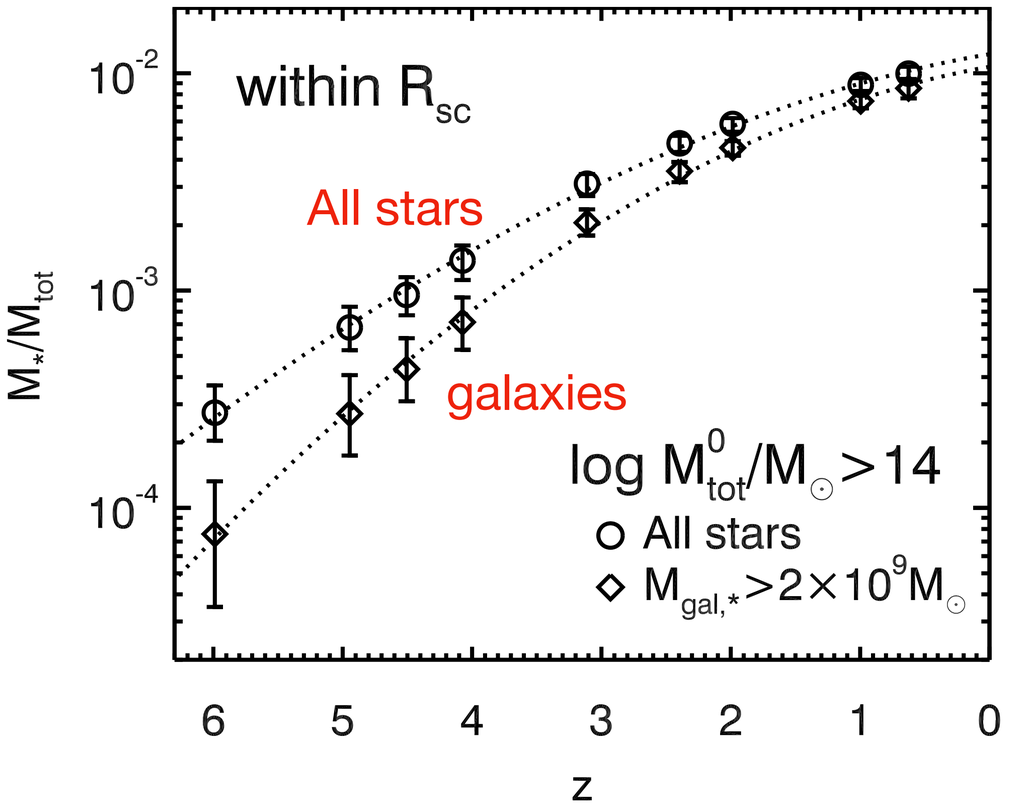
$$\log M_{\star}^{\rm sc}/M_{\rm tot}^{\rm sc} = \alpha(1+z)^{\beta}+\gamma$$

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

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

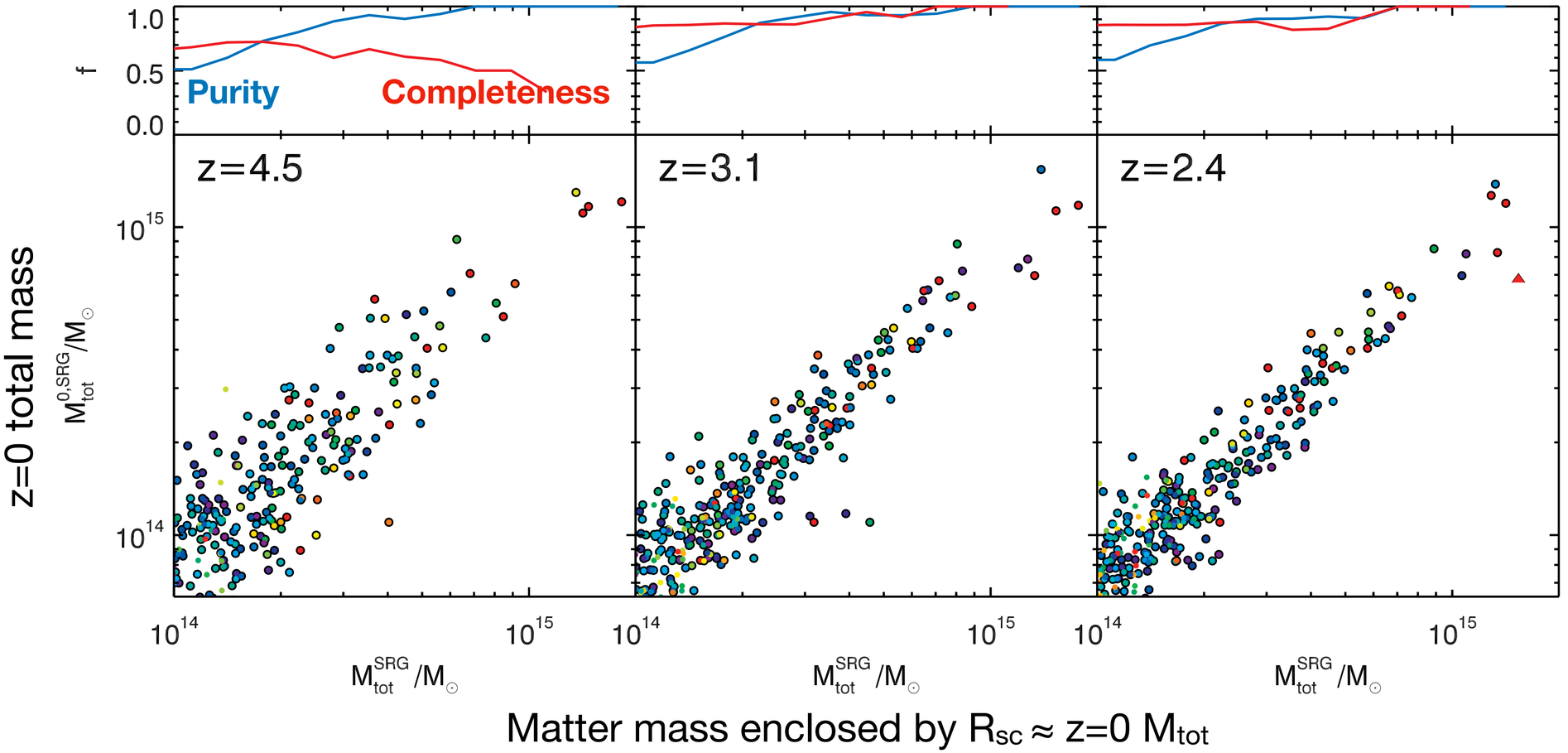
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Overdensity within final mass radius of the HR5 protoclusters

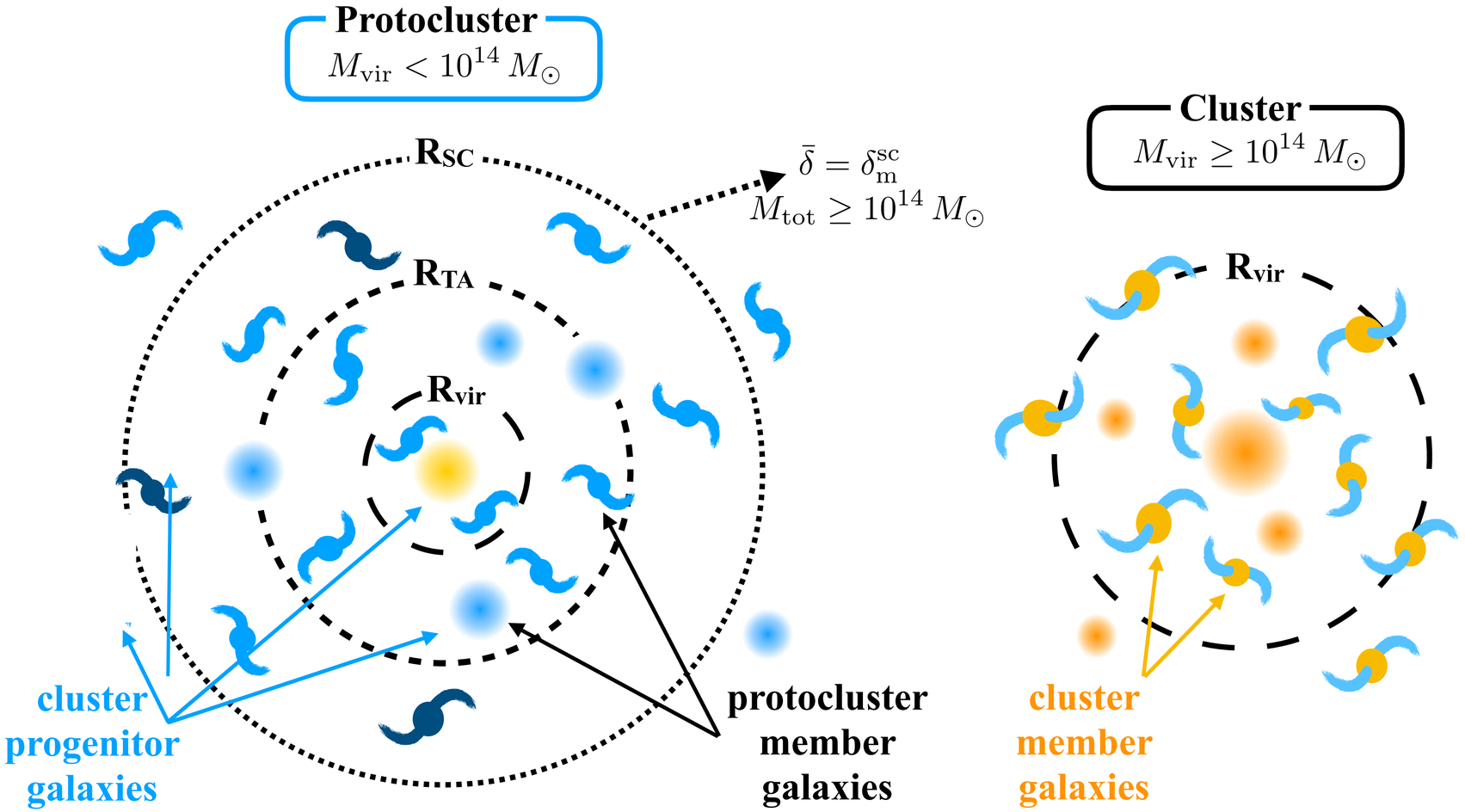


- Performance of the scheme
  - Purity - Fraction of the spherical regions enclosing bonafide protoclusters
  - Completeness - Fraction of the bonafide protoclusters recovered by the scheme

Redshifts from the ODIN survey



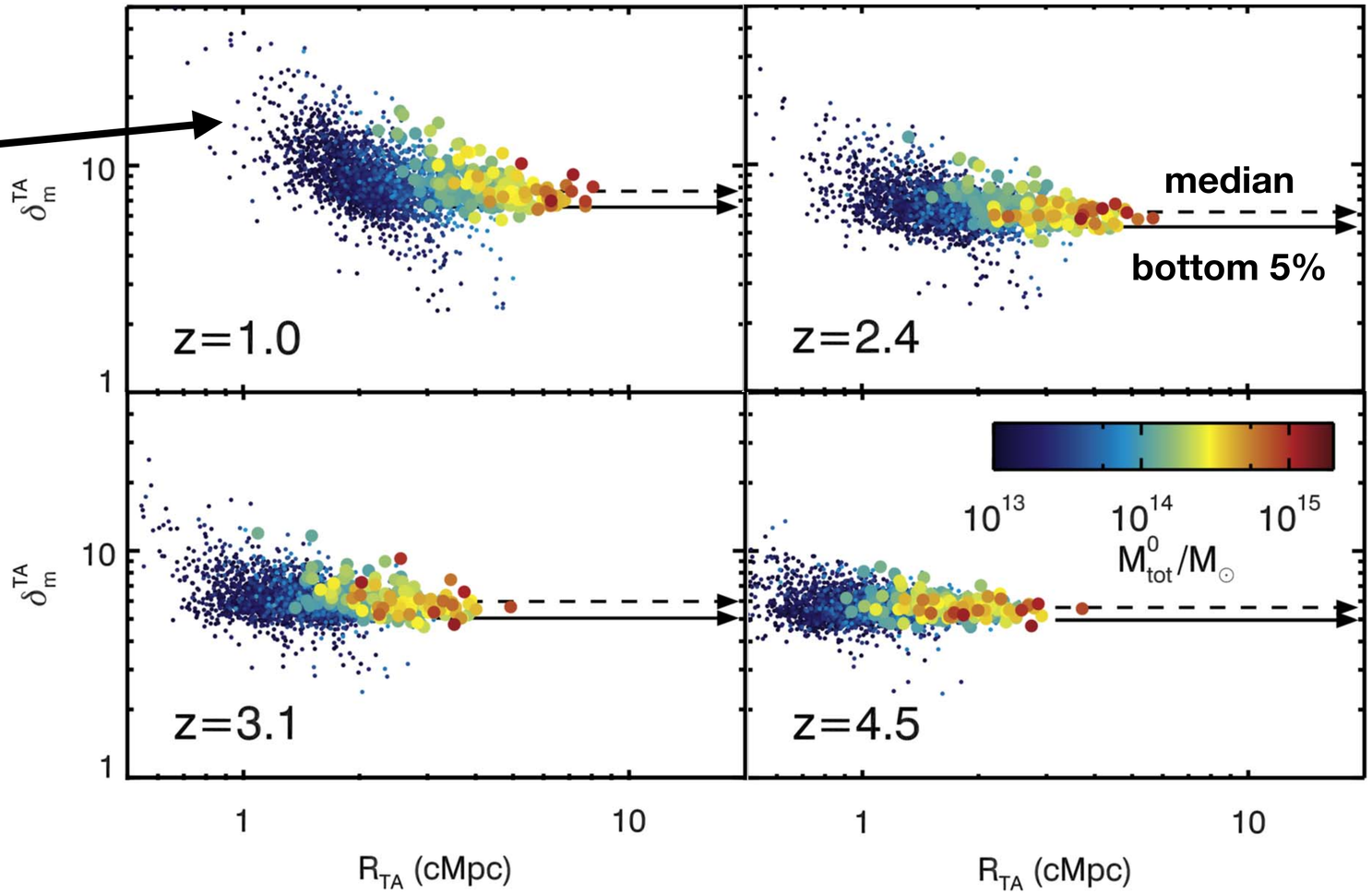
- Turnaround radius (R_{TA}) - Characteristic boundary of protoclusters
  - Surface on which gravitational infall counterbalances the Hubble flow
  - Galaxies within R_{TA} are falling into a common environment, having some degree of conformity



- Matter overdensity within R_{TA}
  - Matter overdensity hardly evolves within R_{TA} at z>2 ($\delta_{\rm m}^{\rm TA}$ ~5-6 at z>2) with small scatter

➡ Reasonable parameter to find R_{TA}

R_{TA} disturbed by neighbours



- Essential ingredients to finding R_{TA} from galaxy distribution

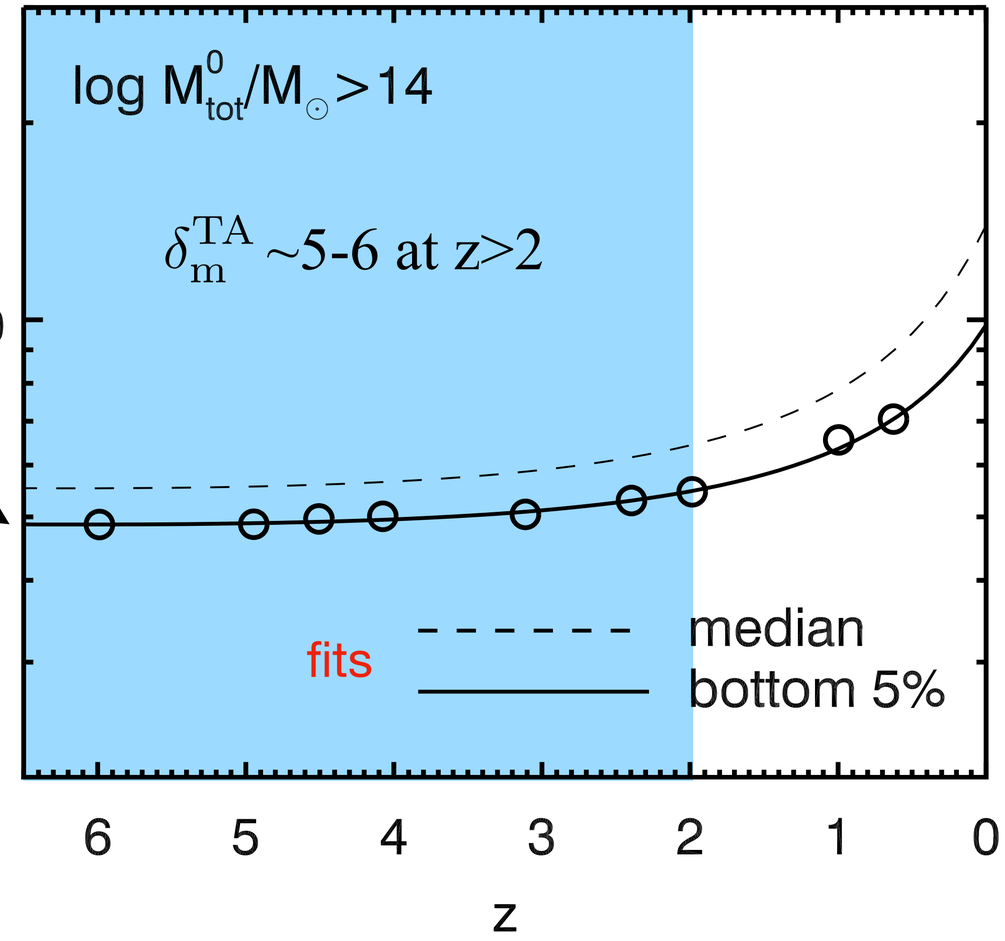
1. $\delta_{\rm m}^{\rm TA}$ at given redshift
2. $M_\star/M_{\rm tot}$ within R_{TA}

$$\delta_{\rm m}^{\rm TA}(z) = \frac{0.168\exp(4.068(1+z)^{-0.381})}{(1+z)^{-0.734}}$$

scatter <1% at z=0.5-6

Please see Lee+24 (2024, ApJ, 960, 132) for details

Redshift evolution of $\delta_{\rm m}^{\rm TA}$



- Essential ingredients to finding R_{TA} from galaxy distribution

1. $\delta_{\rm m}^{\rm TA}$ at given redshift
2. $M_\star/M_{\rm tot}$ within R_{TA}

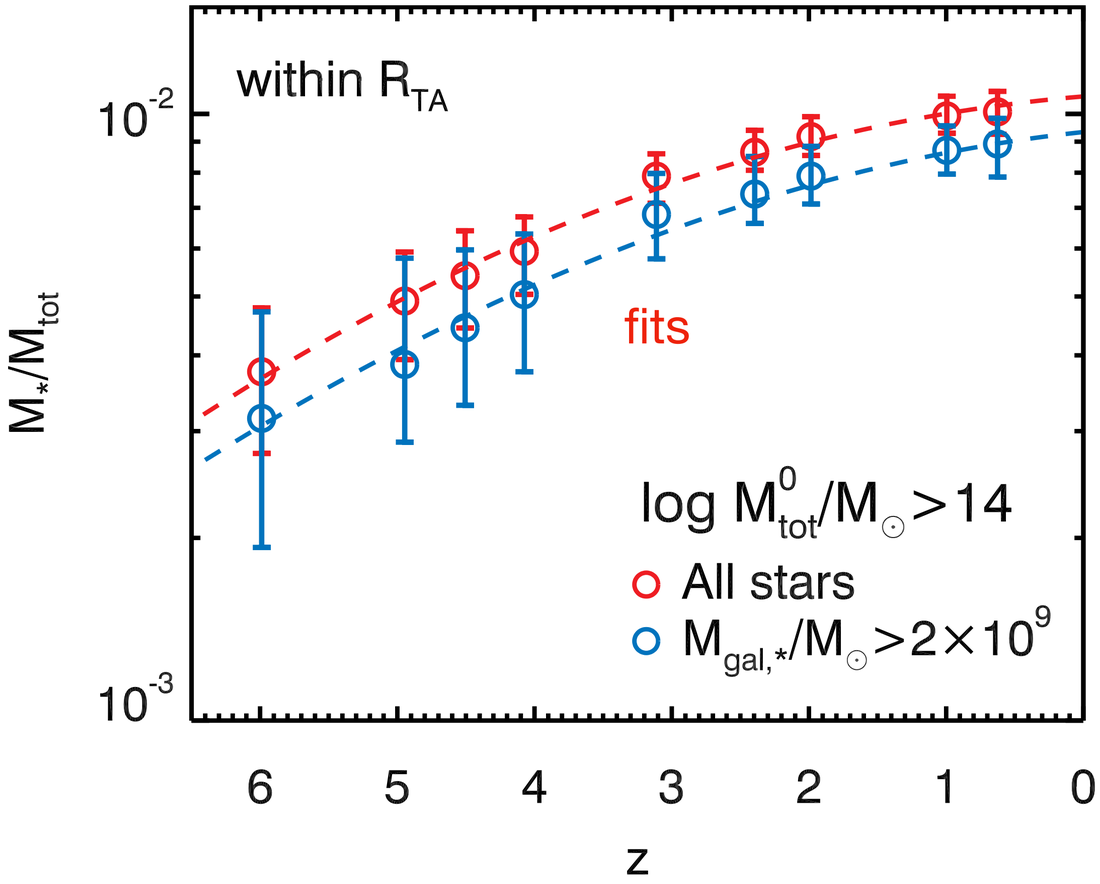
$$\log M_\star/M_{\rm tot} = \alpha(1+z)^\beta + \gamma$$

$(\alpha, \beta, \gamma) = (-0.0092, 2.027, -1.962)$ for total stellar mass

$(-0.0128, 1.882, -2.017)$ for galaxies with $M_\star > 2\times10^9 M_\odot$

Please see Lee+24 (2024, ApJ, 960, 132) for details

Redshift evolution of $M_\star/M_{\rm tot}$



- Summary

  - We propose an approach to identify protocluster regions based on the spherical collapse theory and the turnaround radius (R_{TA}) as the characteristic radius of a protocluster

    - This scheme is verified using a cosmological hydrodynamical simulation HR5

    - Protoclusters are successfully recovered from galaxy distribution using the scheme

    - R_{TA} can be estimated from galaxies by finding radius that meets $\delta_{\rm m}^{\rm TA}$

  - We are investigating the properties of protocluster galaxies as a function of R_{TA} - Please stay tuned!