PRECISE summer school
Warsaw

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# hands-on cosmological simulations

## session 3: identifying structures & basic predictions of simulations

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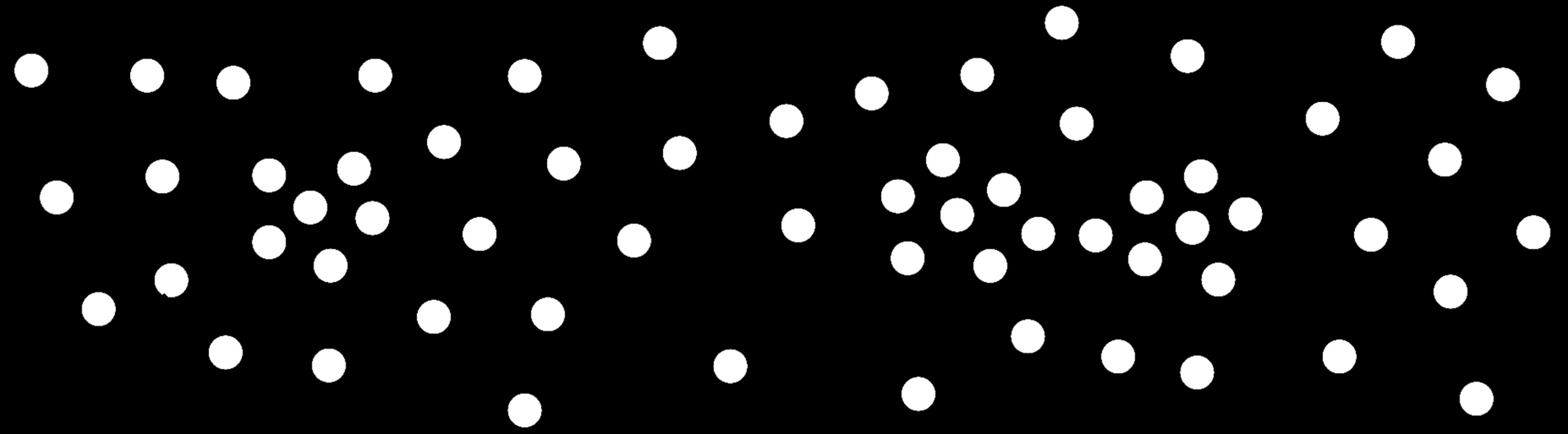
# identifying haloes & bound structures

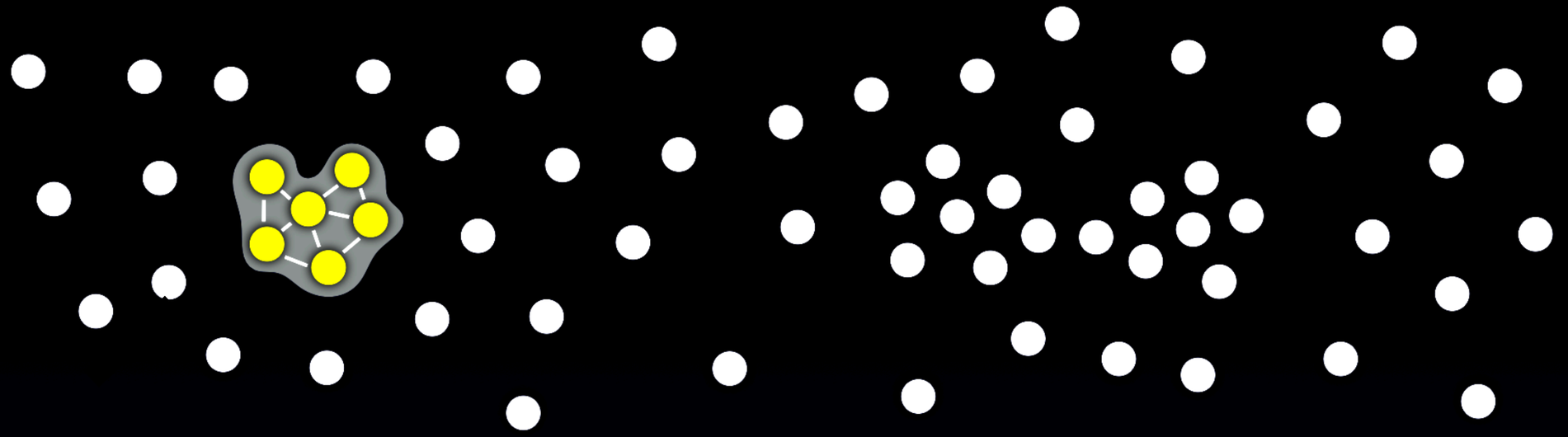
# the friends-of-friends algorithm



process: connect particles that are within some fraction, $b$, of the mean-interparticle separation, $\Delta x$, of one another. typical choice $b = 0.2$

visuals from Moster & Puchwein

# the friends-of-friends algorithm



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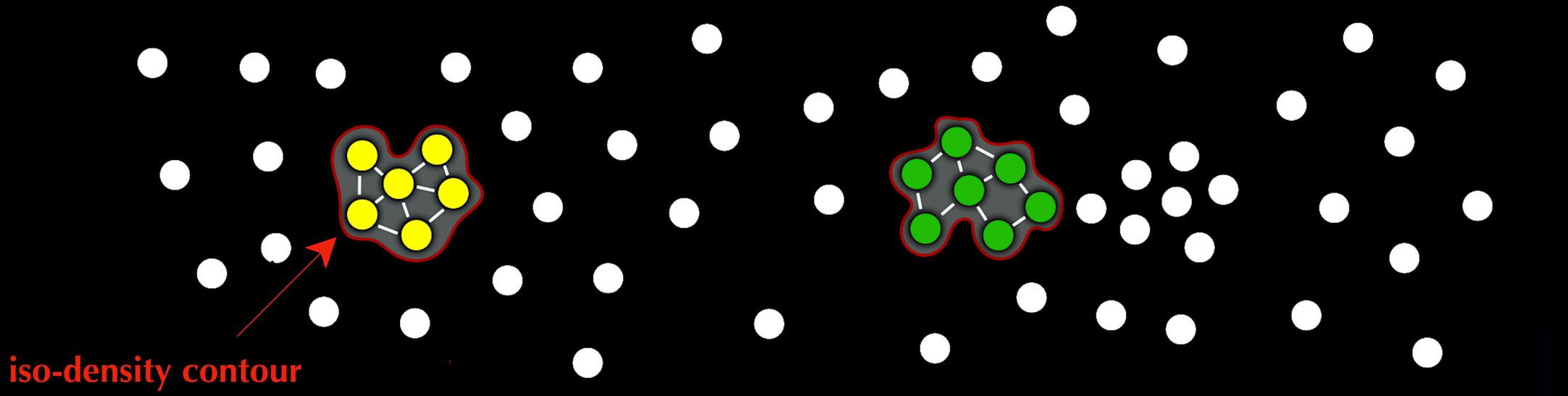


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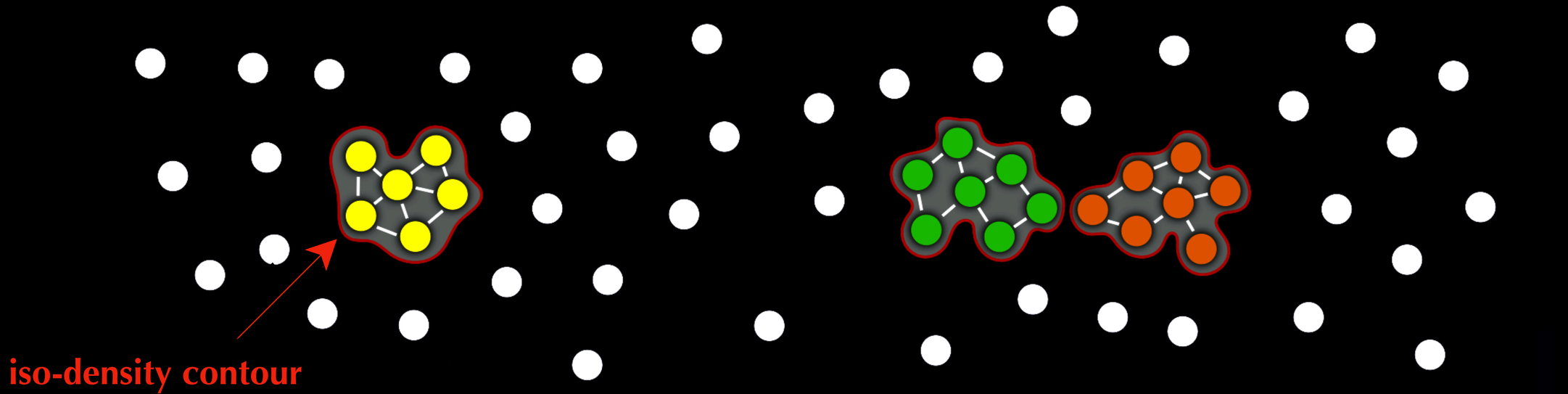


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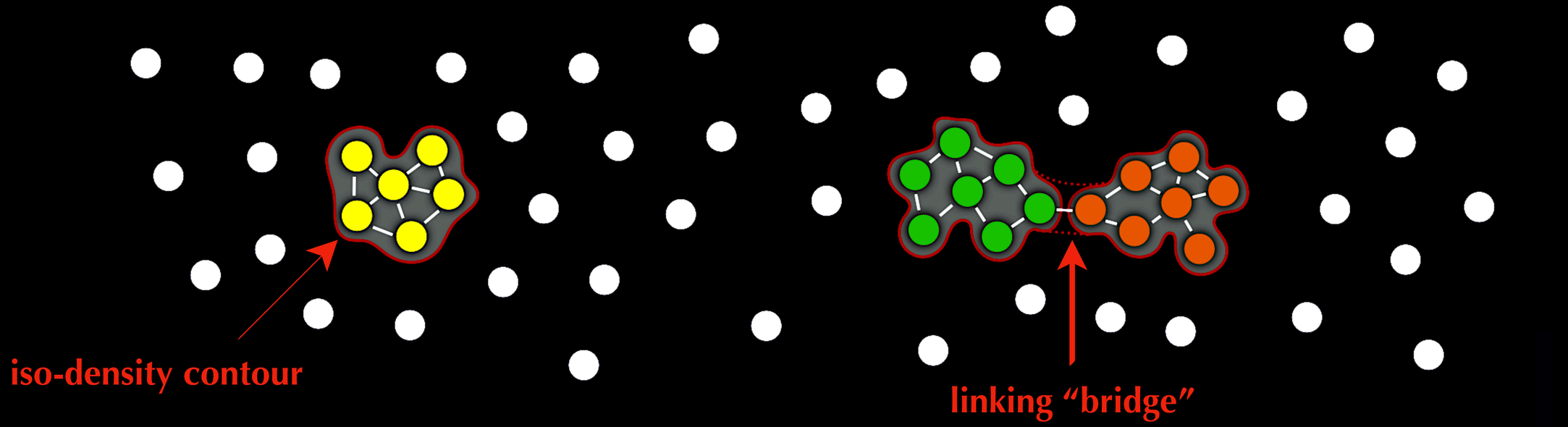
# the friends-of-friends algorithm

the FOF method is very simple & general, but exhibits unphysical pathologies

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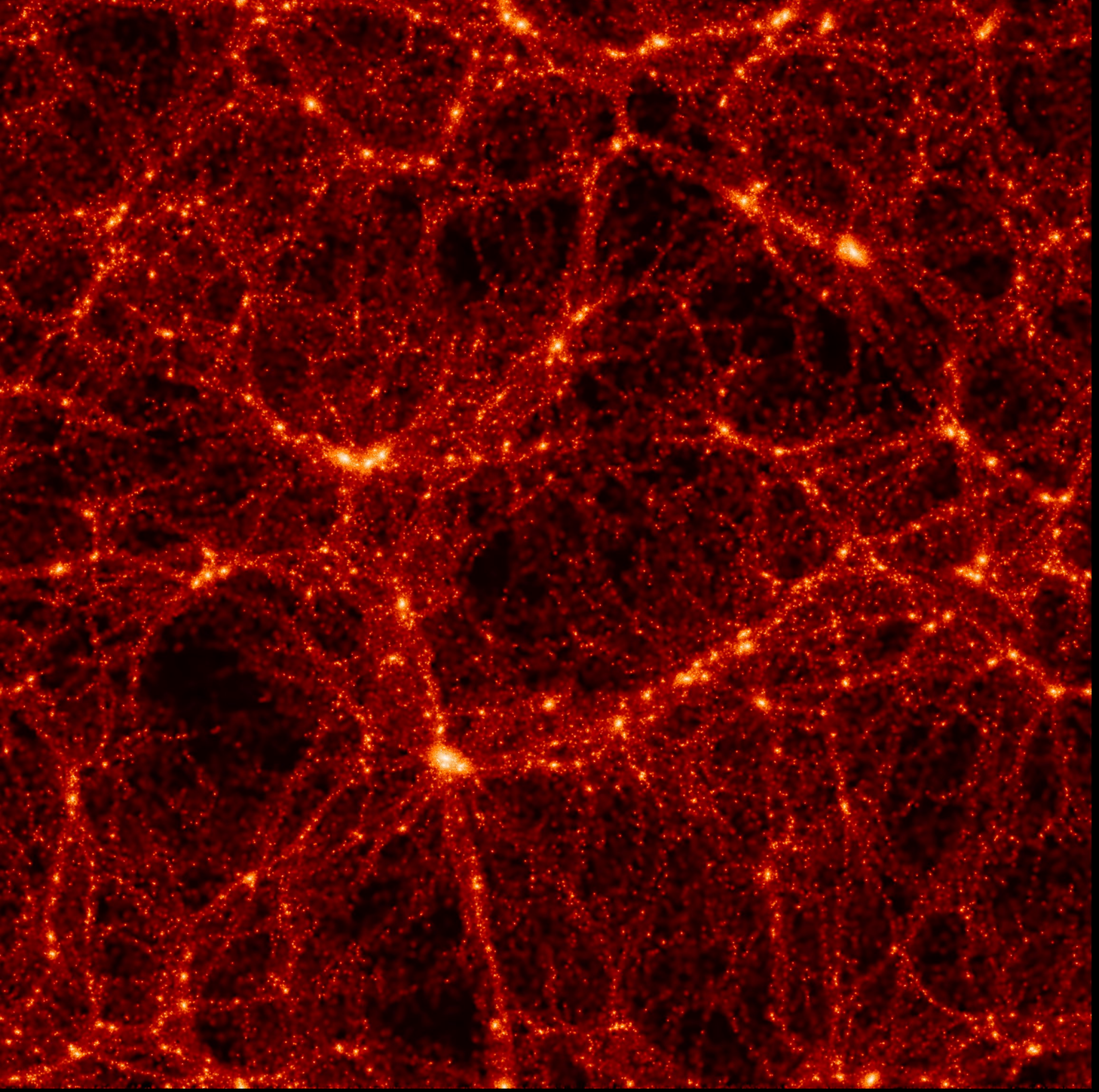
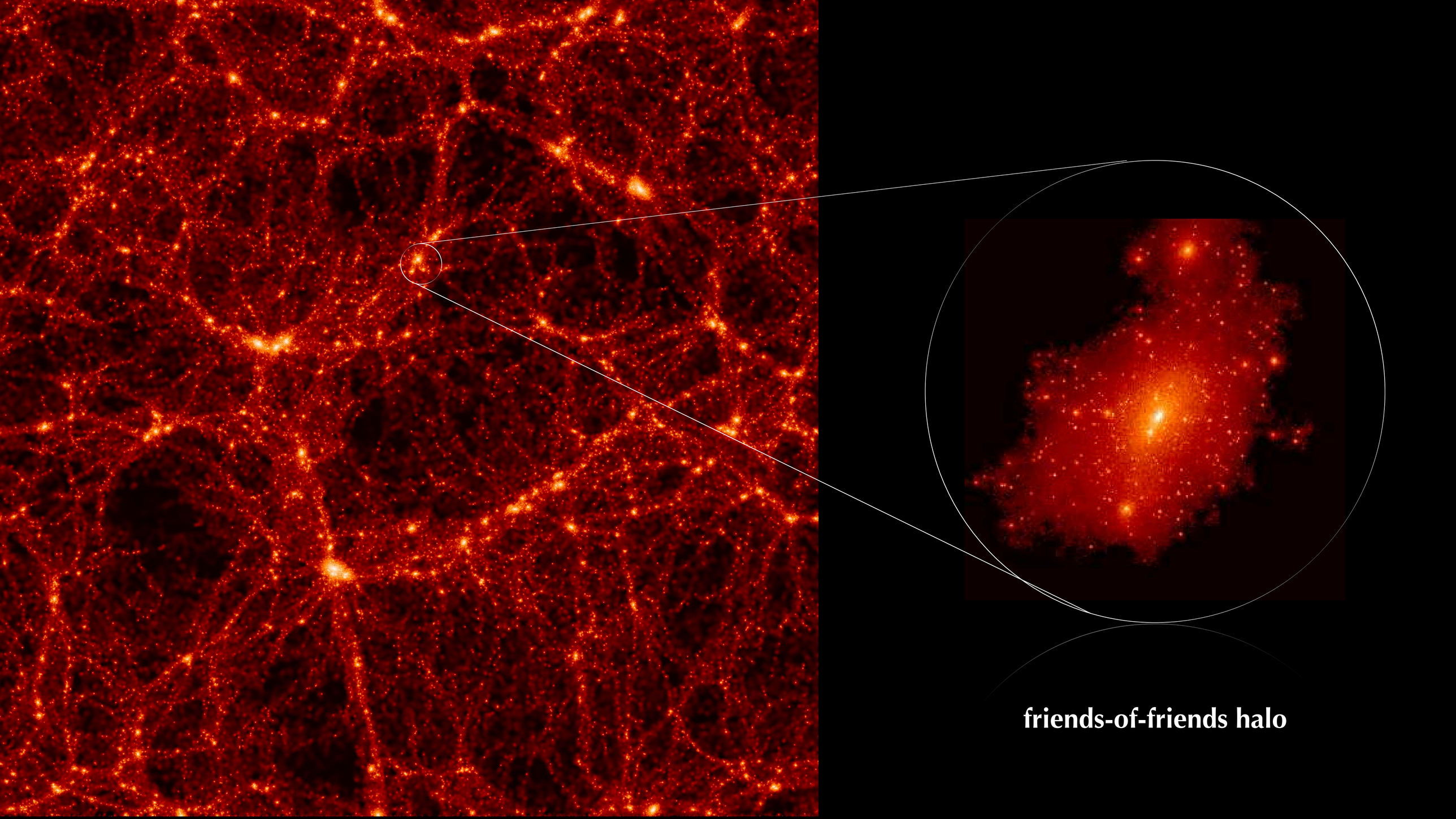
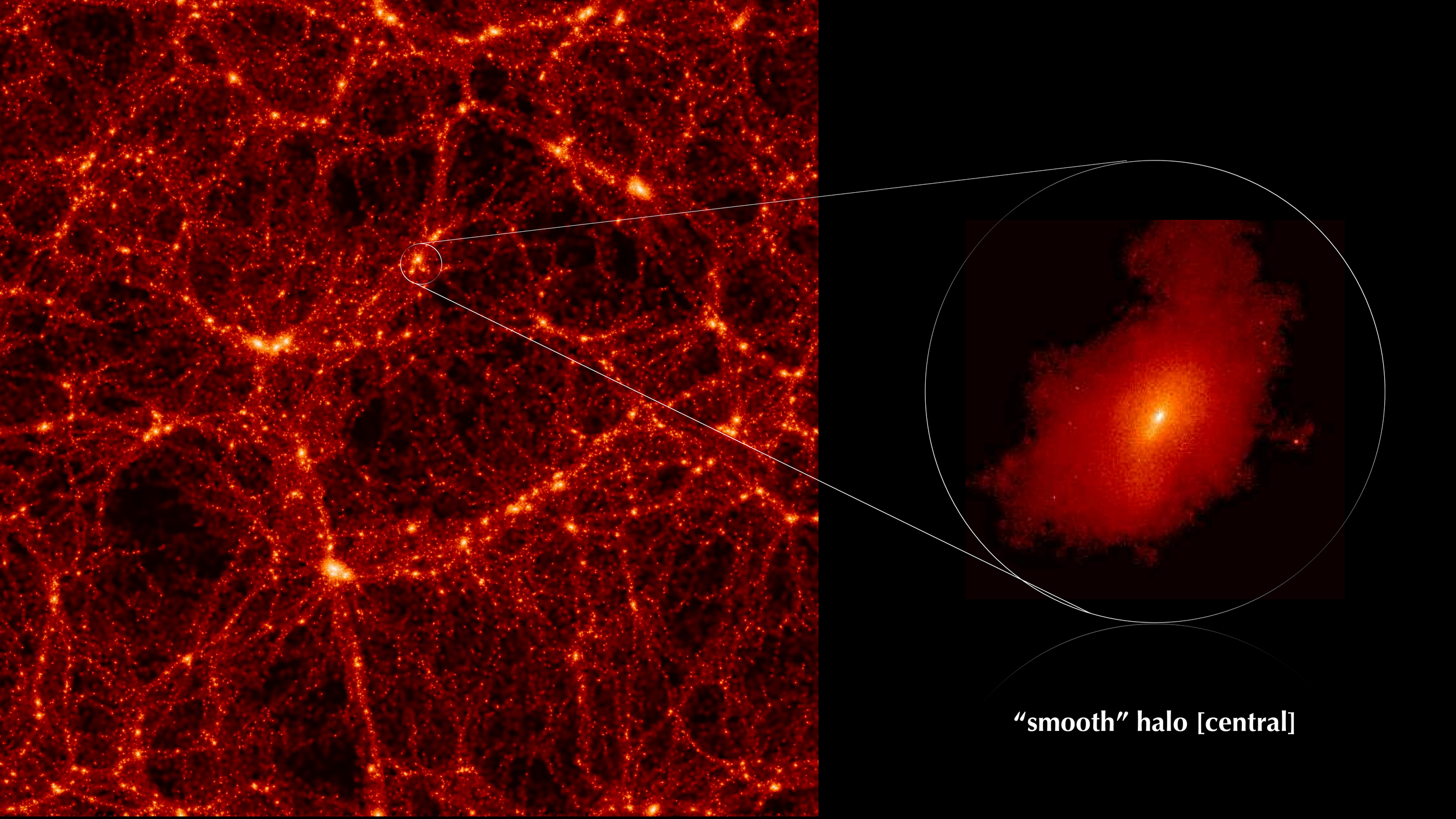
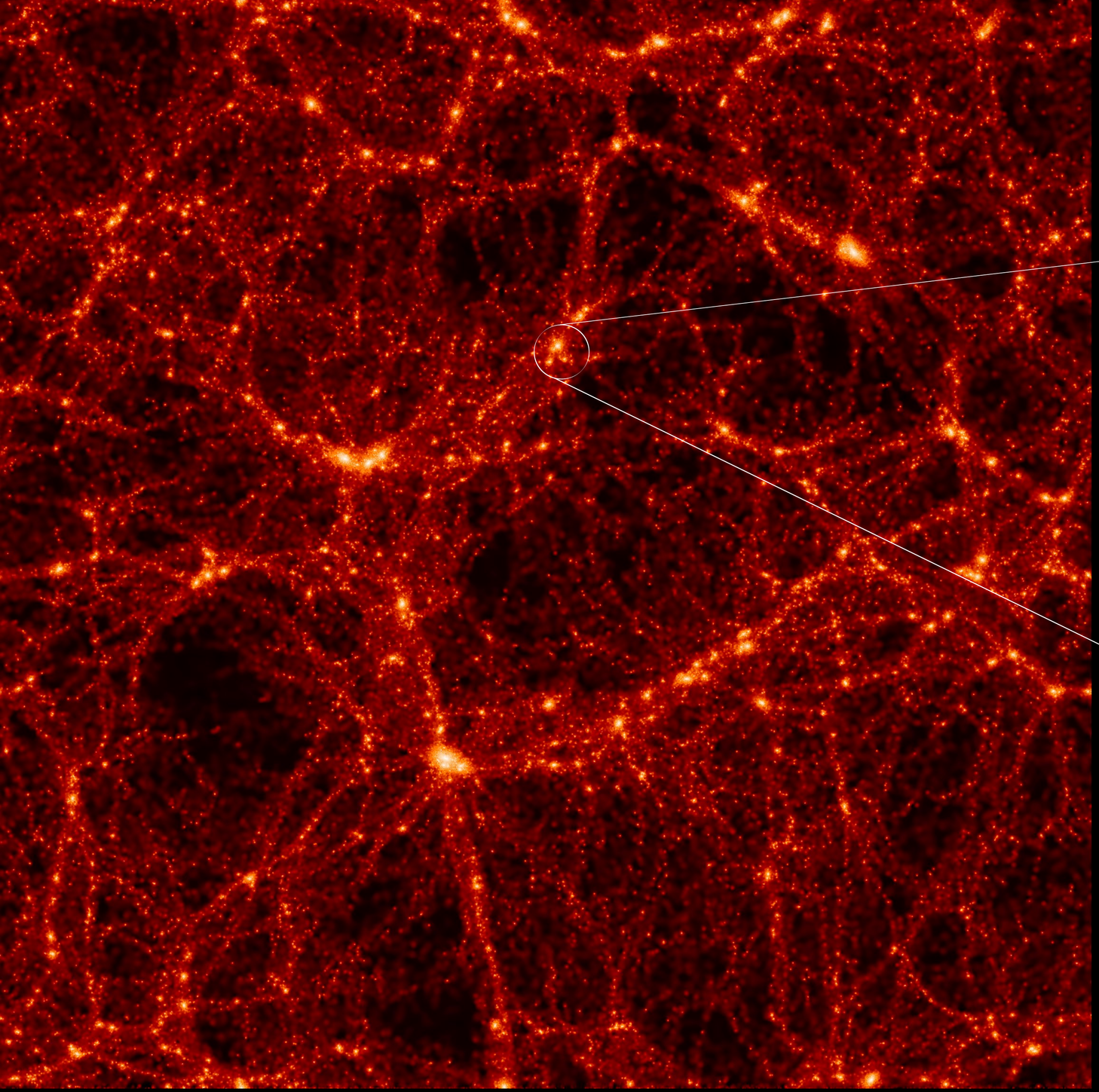
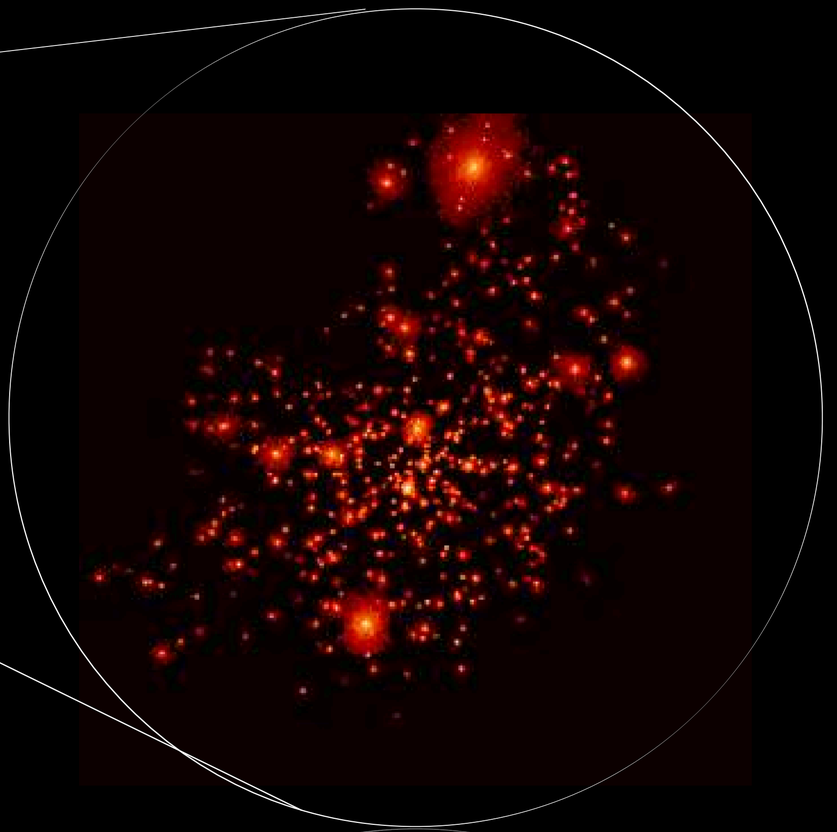



friends-of-friends halo

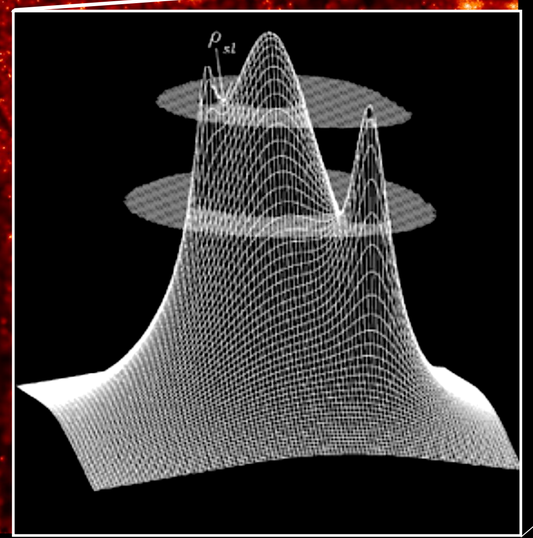

“smooth” halo [central]





substructures [satellites]

define substructures as local density maxima enclosed by iso-density contours that traverse saddle points in the density field

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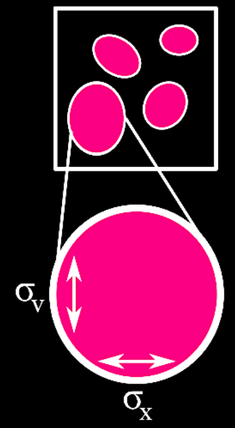



**1.** The simulation volume is divided into 3D Friends-of-Friends groups for easy parallelization.

**2.** For each group, particle positions and velocities are divided (normalized) by the group position and velocity dispersions, giving a natural phase-space metric.

**3.** A phase-space linking length is adaptively chosen such that 70% of the group's particles are linked together in subgroups.

**4.** The process repeats for each subgroup: renormalization, a new linking-length, and a new level of substructure calculated.

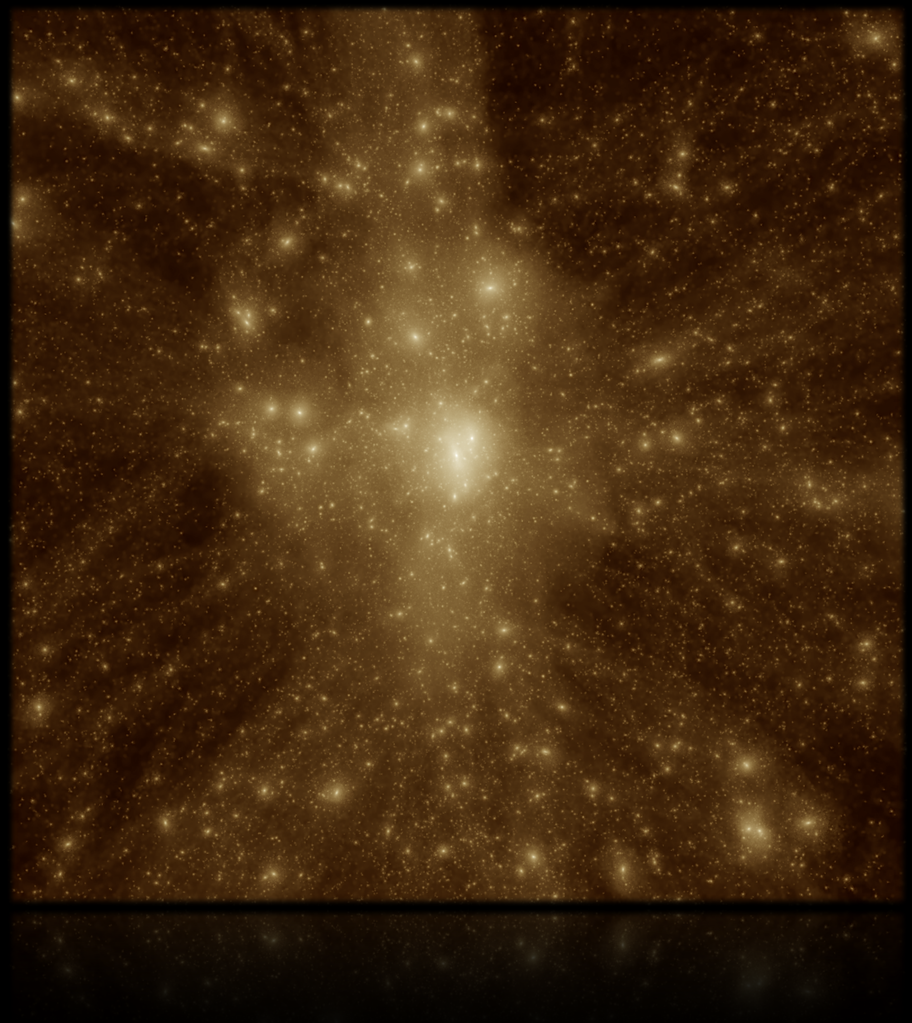
**5.** Once all levels of substructure are found, seed halos are placed at the lowest substructure levels and particles are assigned hierarchically to the closest seed halo in phase space.

**6.** Once particles have been assigned to halos, unbound particles are removed and halo properties (positions, velocities, etc.) are calculated.

**6D phase-space structure finding not always used**

**Behroozi+ (2013)**

# definitions of halo mass



DM haloes identified in N-body simulations are highly irregular objects. how do we define their mass / extent?

⇒ do what astronomers do best and assume everything is spherical

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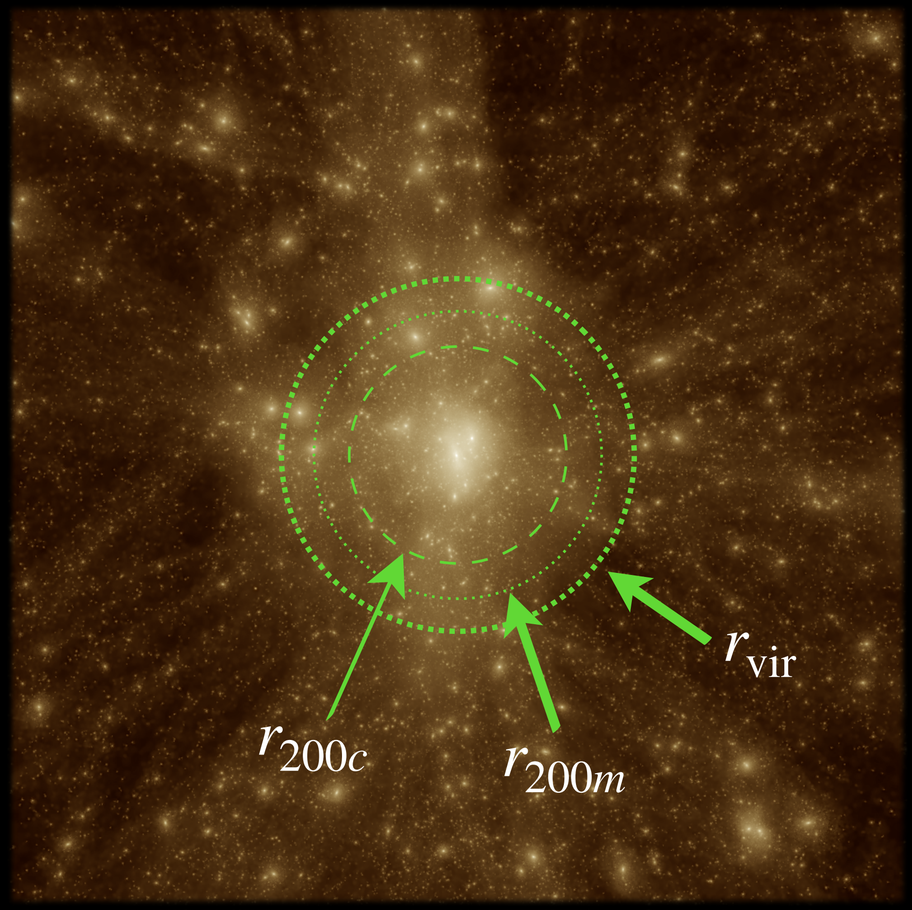


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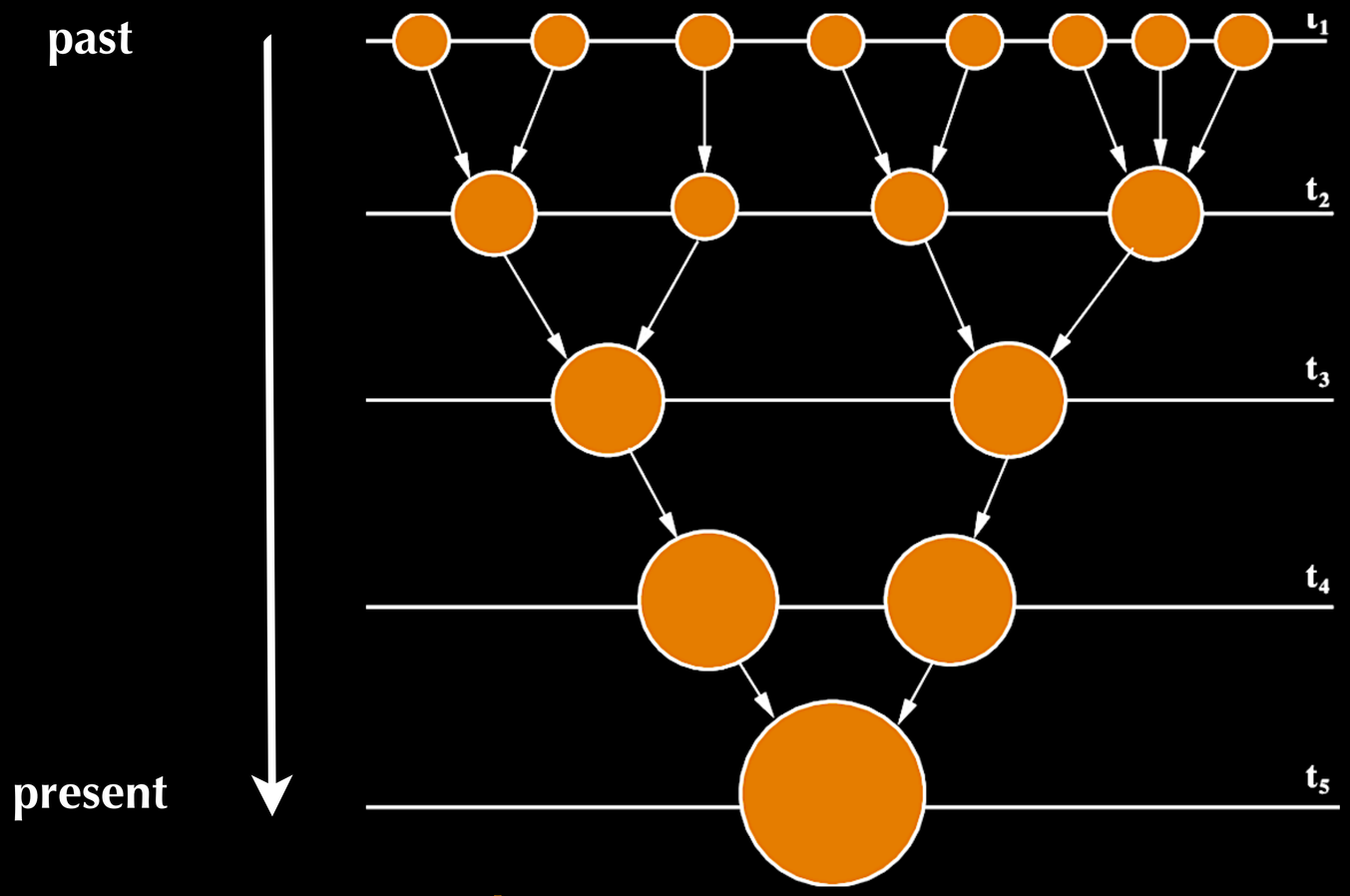
$$M_\Delta = \frac{4}{3}\pi\Delta\rho_{\rm ref}r_\Delta^3 \text{ where } \bar{\rho}(<r_\Delta) = \Delta\cdot\rho_{\rm ref}$$

virial mass/radius

# commonly used definitions

| label | $\Delta$ | $\rho_{\rm ref}$ | spherical | cosmology dependent? | binding information? |
|---|---|---|---|---|---|
| $M_{\rm FOF}$ | – | – | ✗ | ✓ | ✗ |
| $M_{\rm sub}$ | – | $\rho_{\rm host}$ | ✗ | ✗ | ✓ |
| $M_{200c}$ | **200** | $\rho_{\rm crit}$ | ✓ | ✓ | ✗ |
| $M_{200m}$ | **200** | $\rho_{\rm mean}$ | ✓ | ✓ | ✗ |
| $M_{\rm vir}$ | $18\pi^2 + 82x - 39x^2$<br>$x \equiv \Omega(z) - 1$ | $\rho_{\rm mean}$ | ✓ | ✓ | ✗ |

# growth histories of haloes




Baugh (2006)

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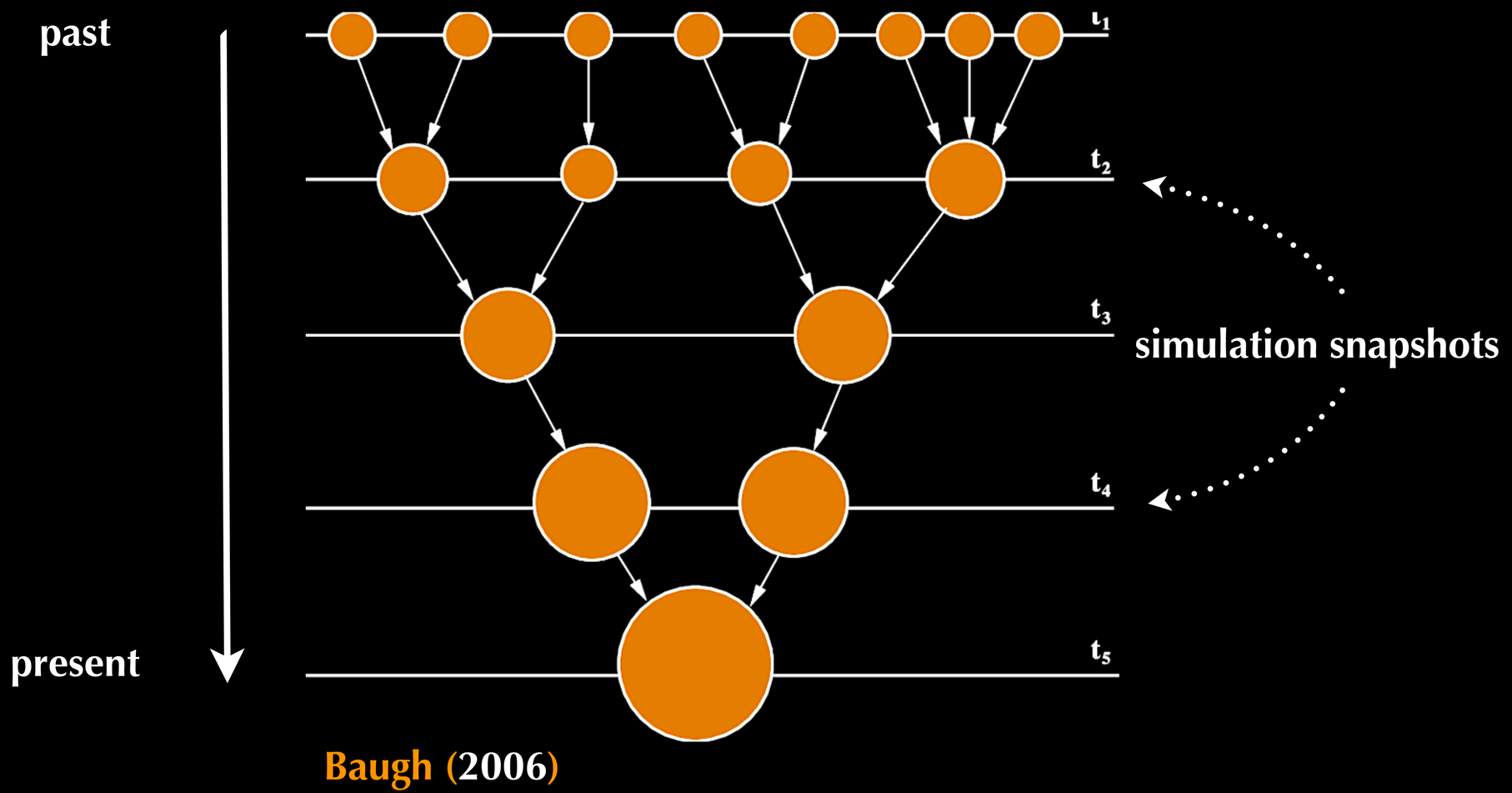


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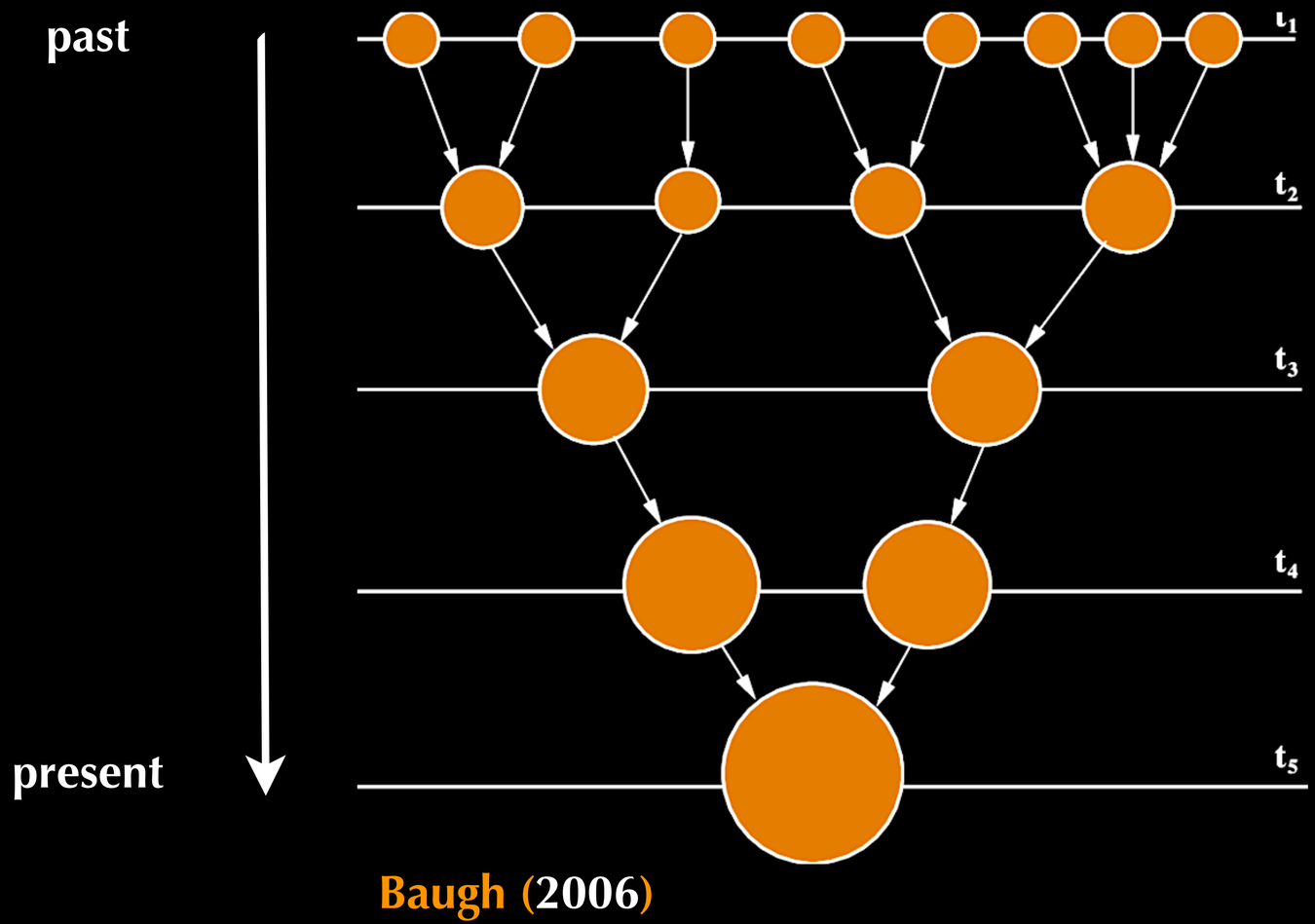


Baugh (2006)

by tracking unique sets of particle IDs between snapshots, we can identify the progenitors and descendants of a (sub)halo from one timestep to the next

simulation snapshots

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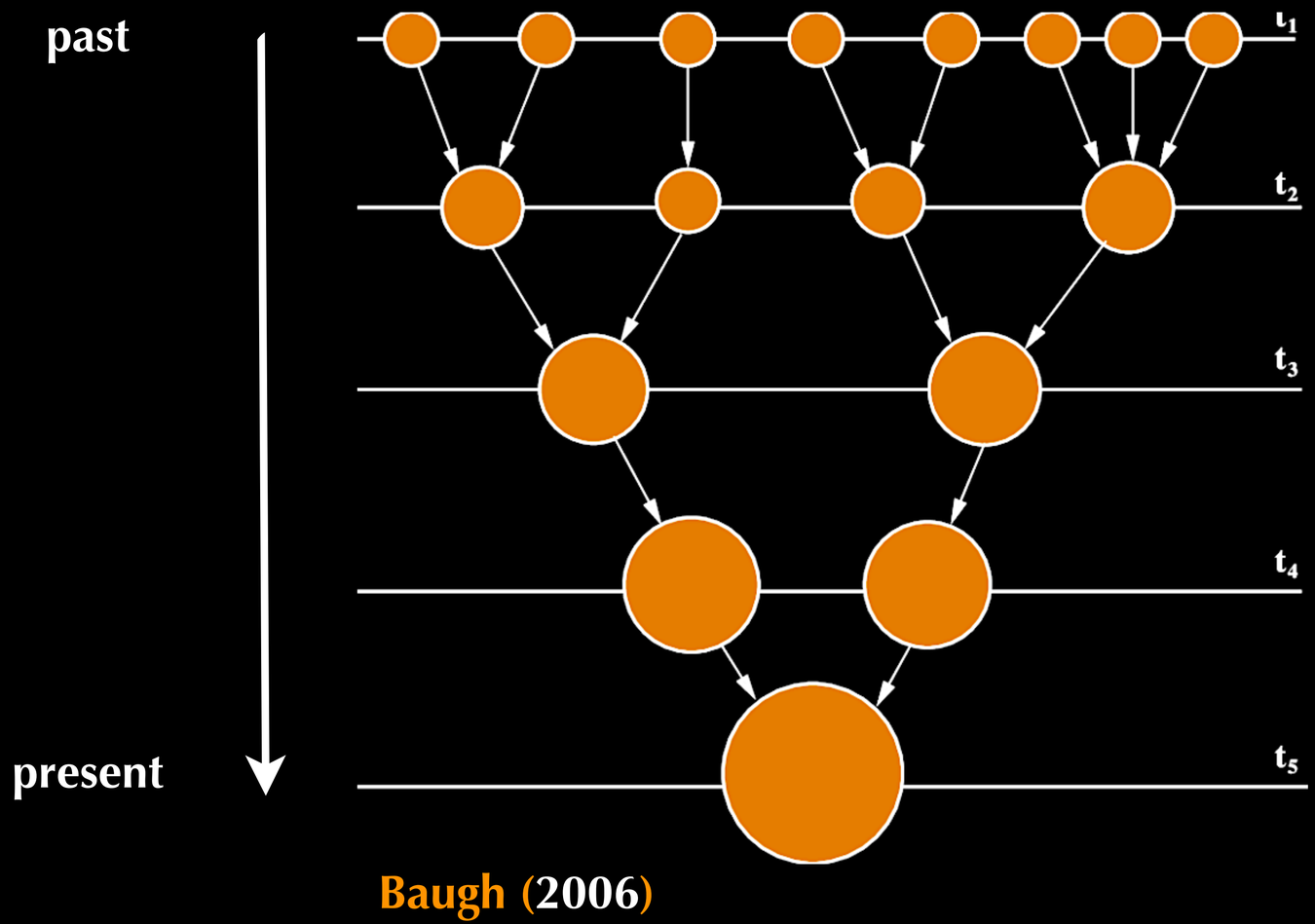


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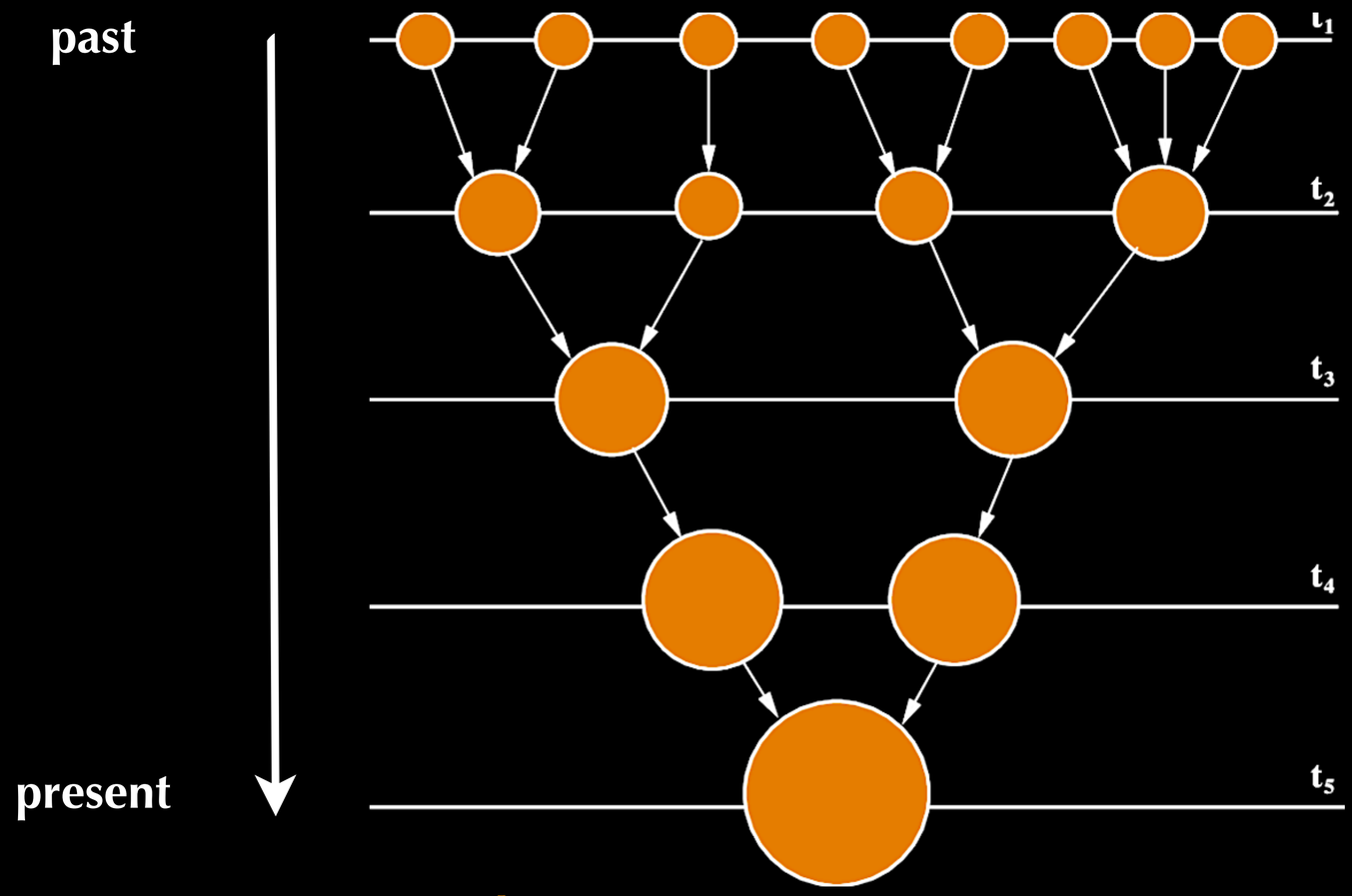


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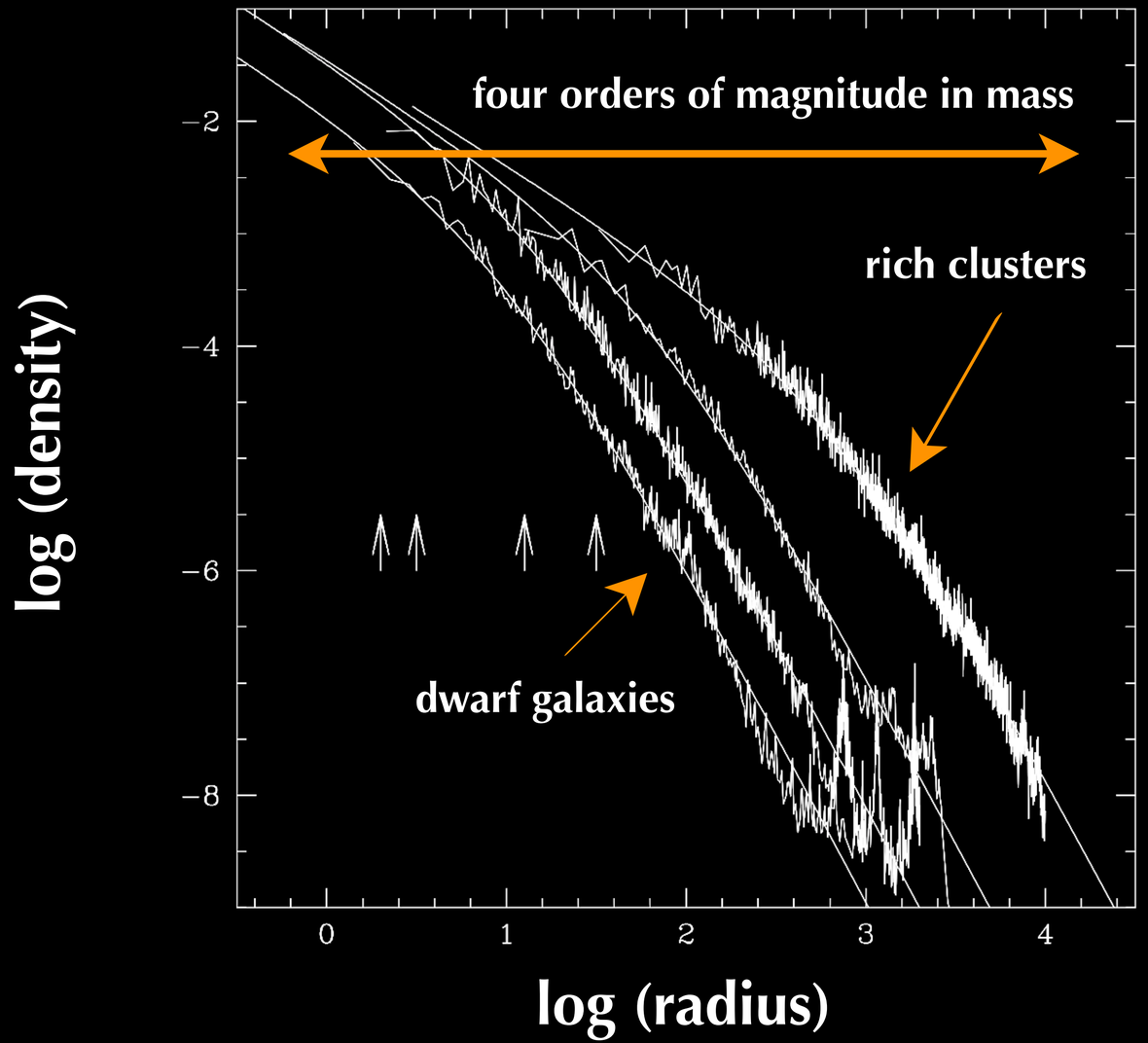
⇒ merger trees act as the skeleton on which many galaxy formation models (semi-analytic, empirical models etc.) are built

# some universal predictions

# self-similar structure



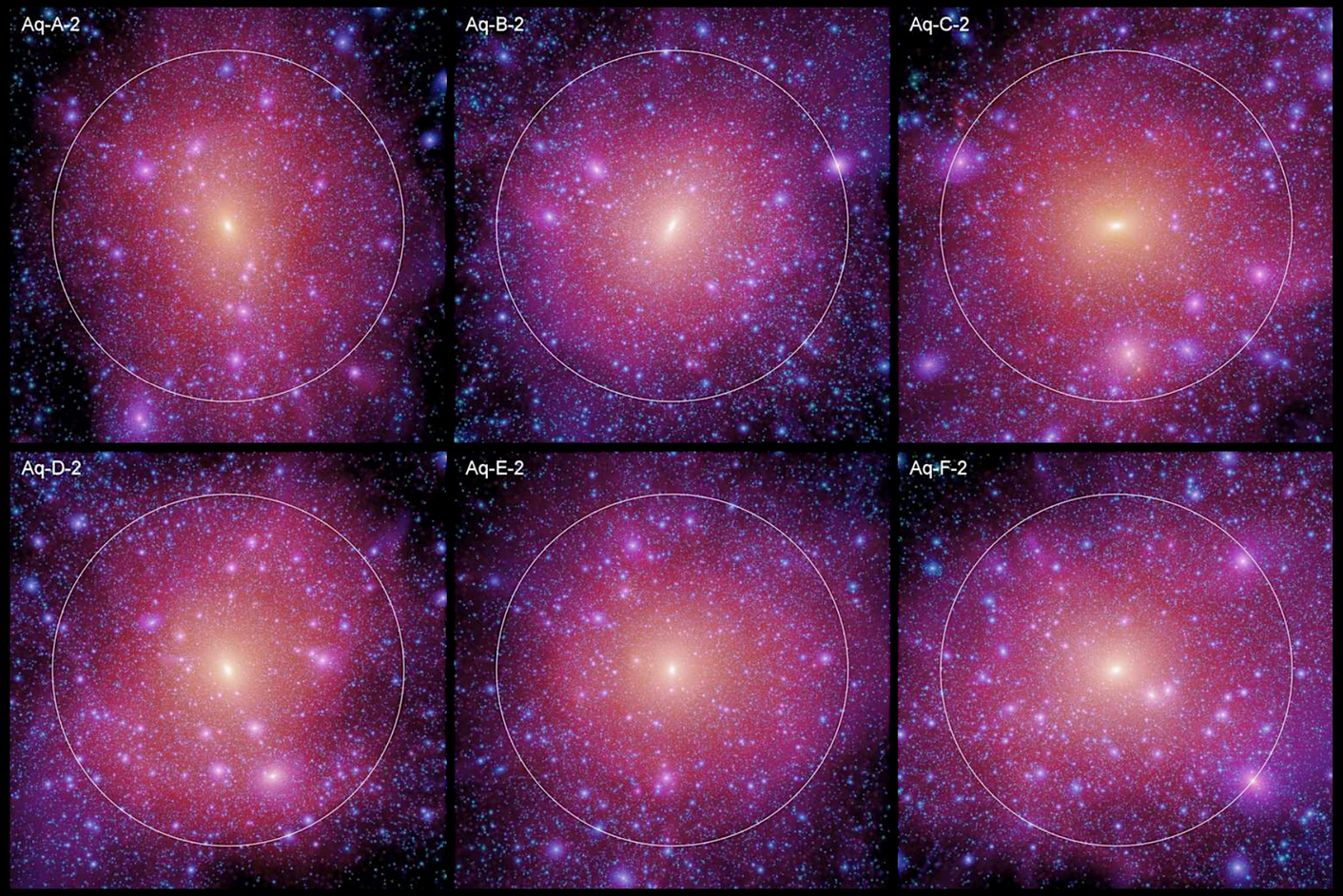

**centre:** $\rho \propto r^{-1}$

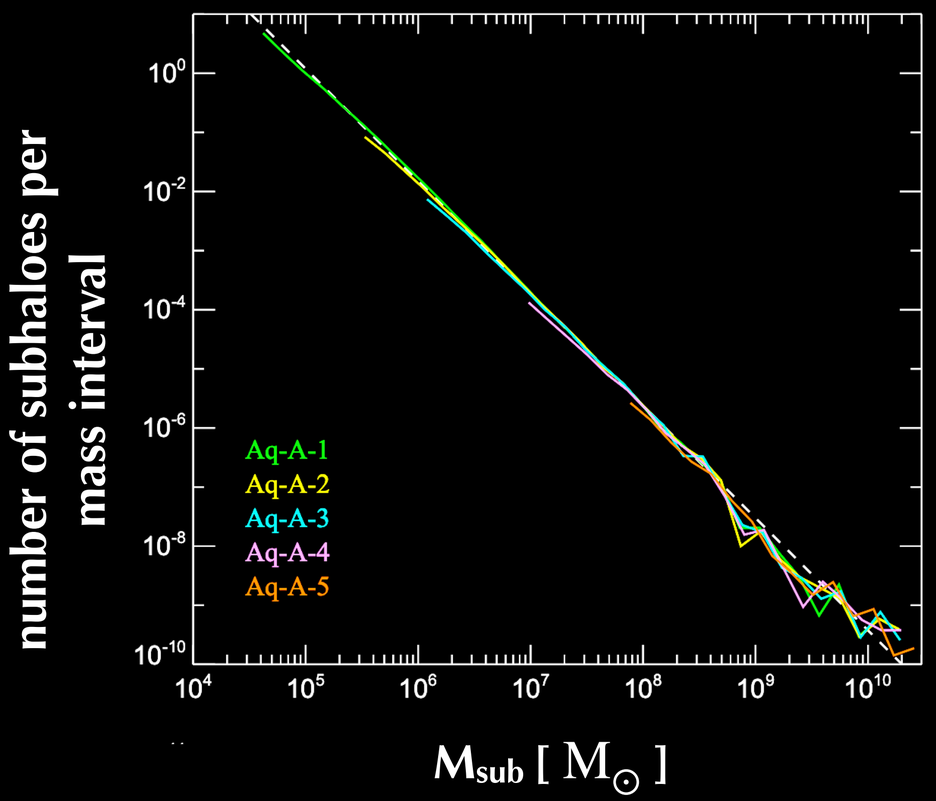
**middle:** $\rho \propto r^{-2}$

**outskirts:** $\rho \propto r^{-3}$

Navarro, Frenk & White (1996)

# self-similar abundance




Springel+ (2008)

# limits of N-body simulations