PRECISE summer school
Warsaw

July 06, 2023

hands-on cosmological simulations

session 3: identifying structures & basic predictions of simulations

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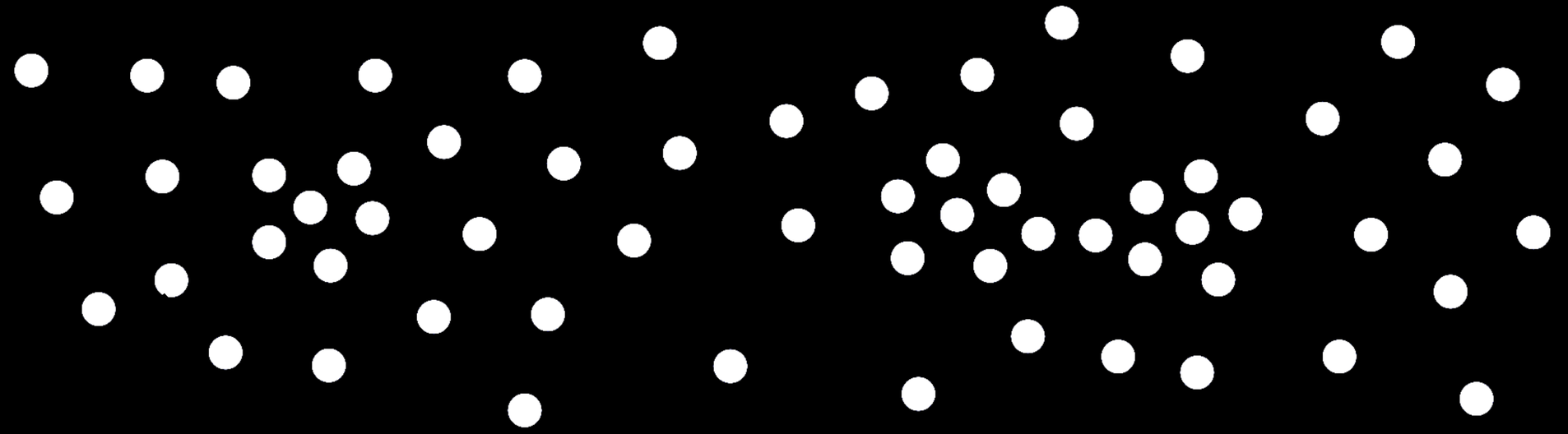
identifying haloes & bound structures

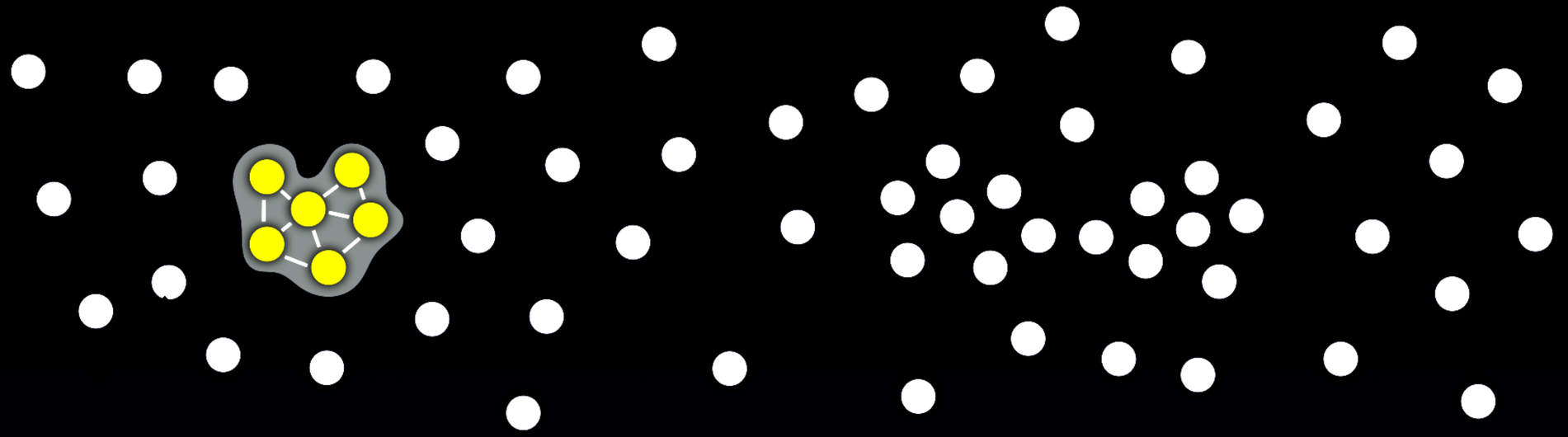
the friends-of-friends algorithm



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

visuals from Moster & Puchwein

the friends-of-friends algorithm



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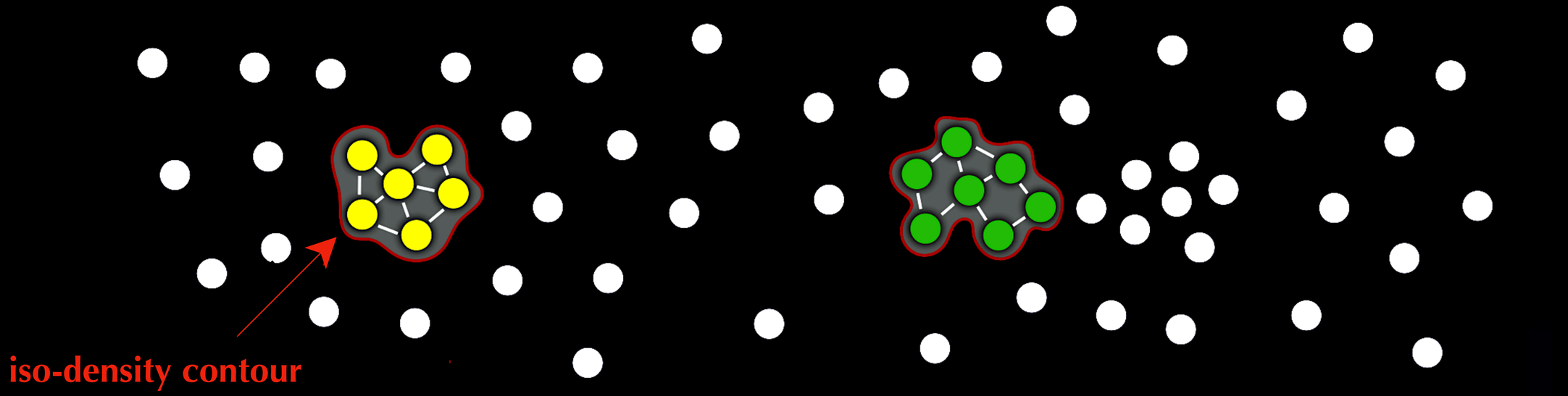

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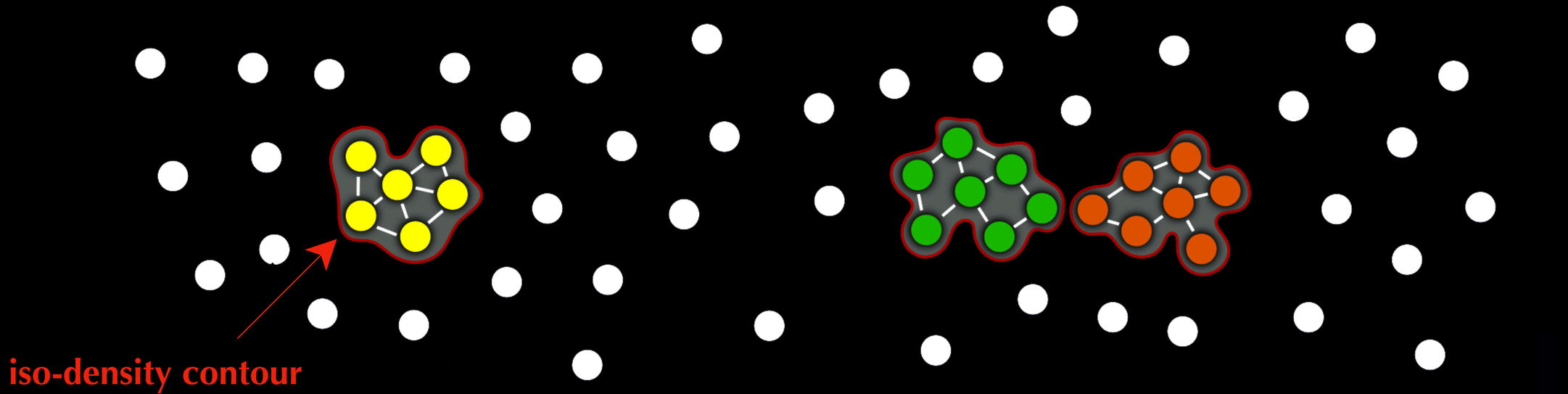

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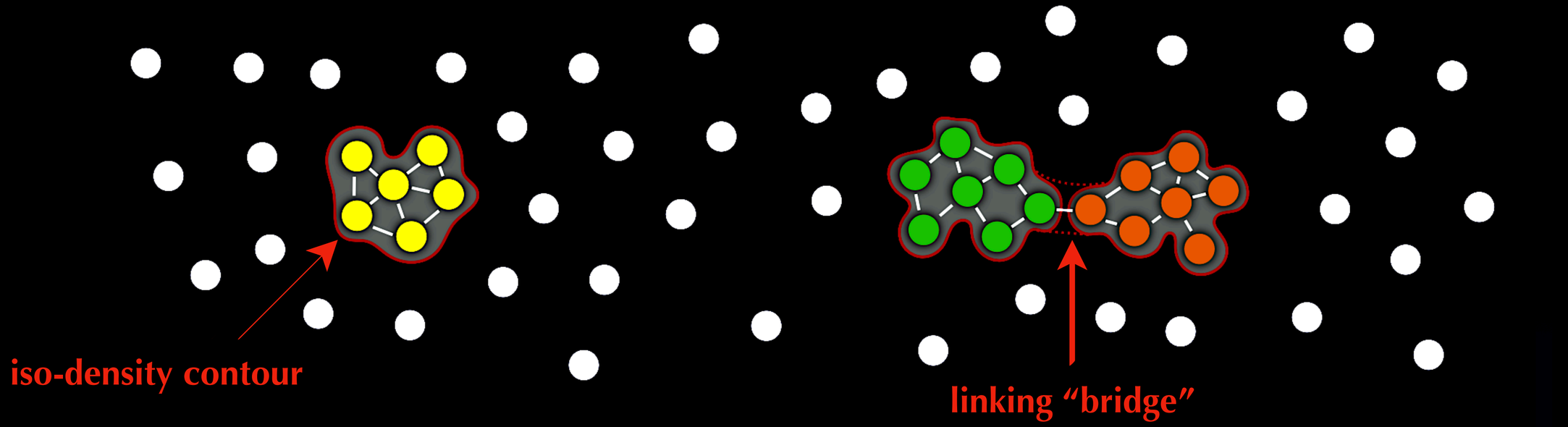
the friends-of-friends algorithm

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



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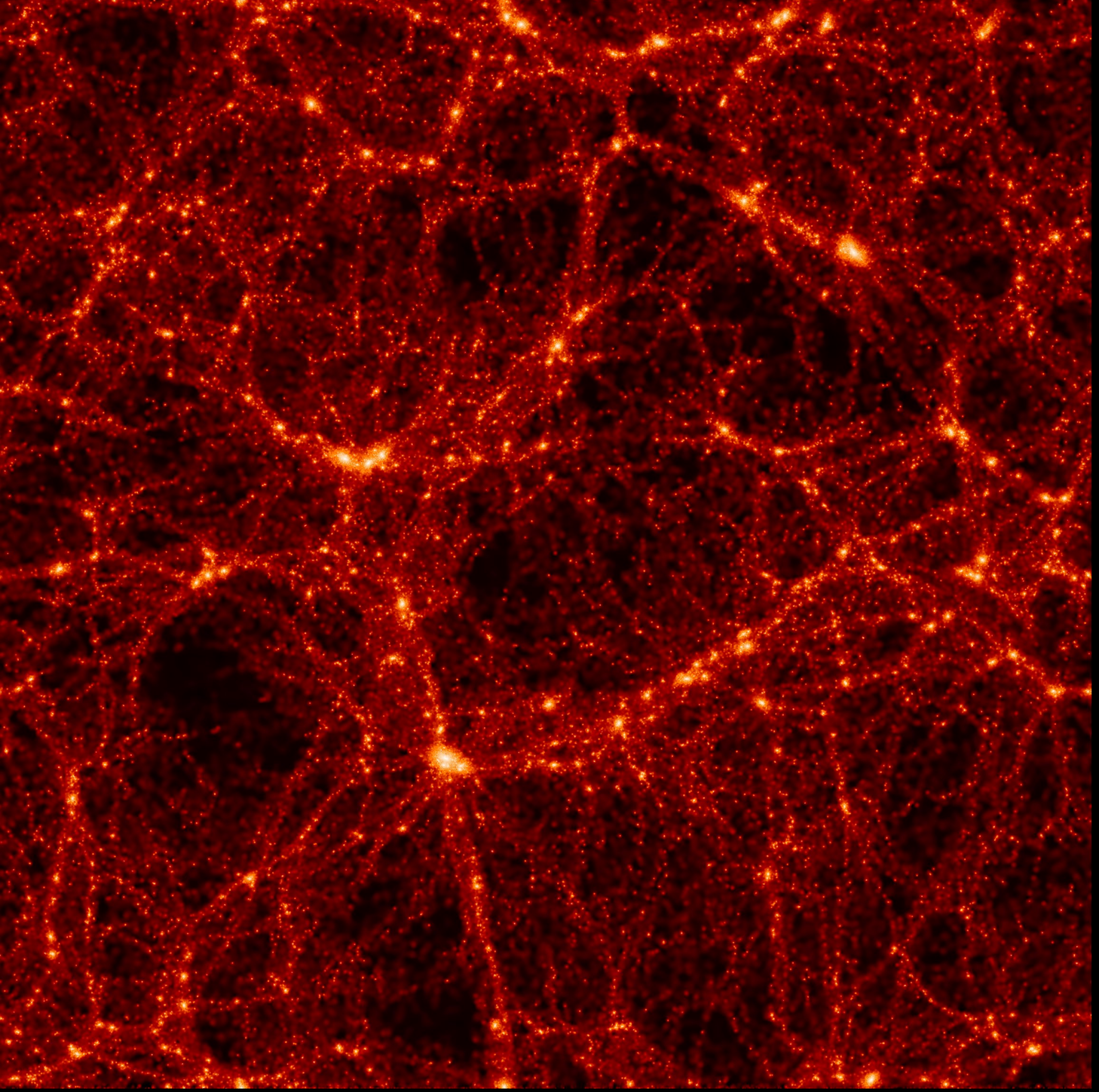
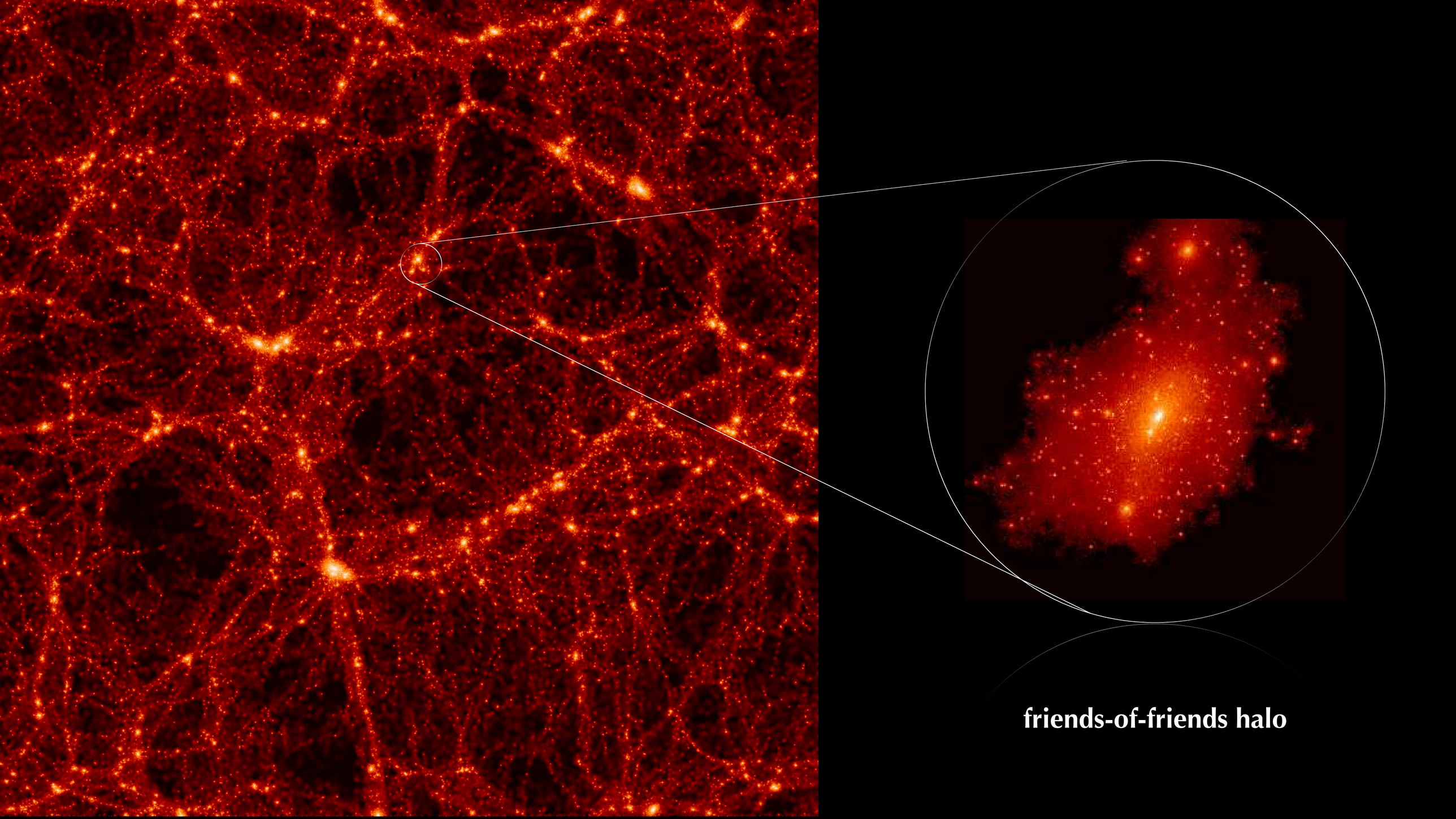
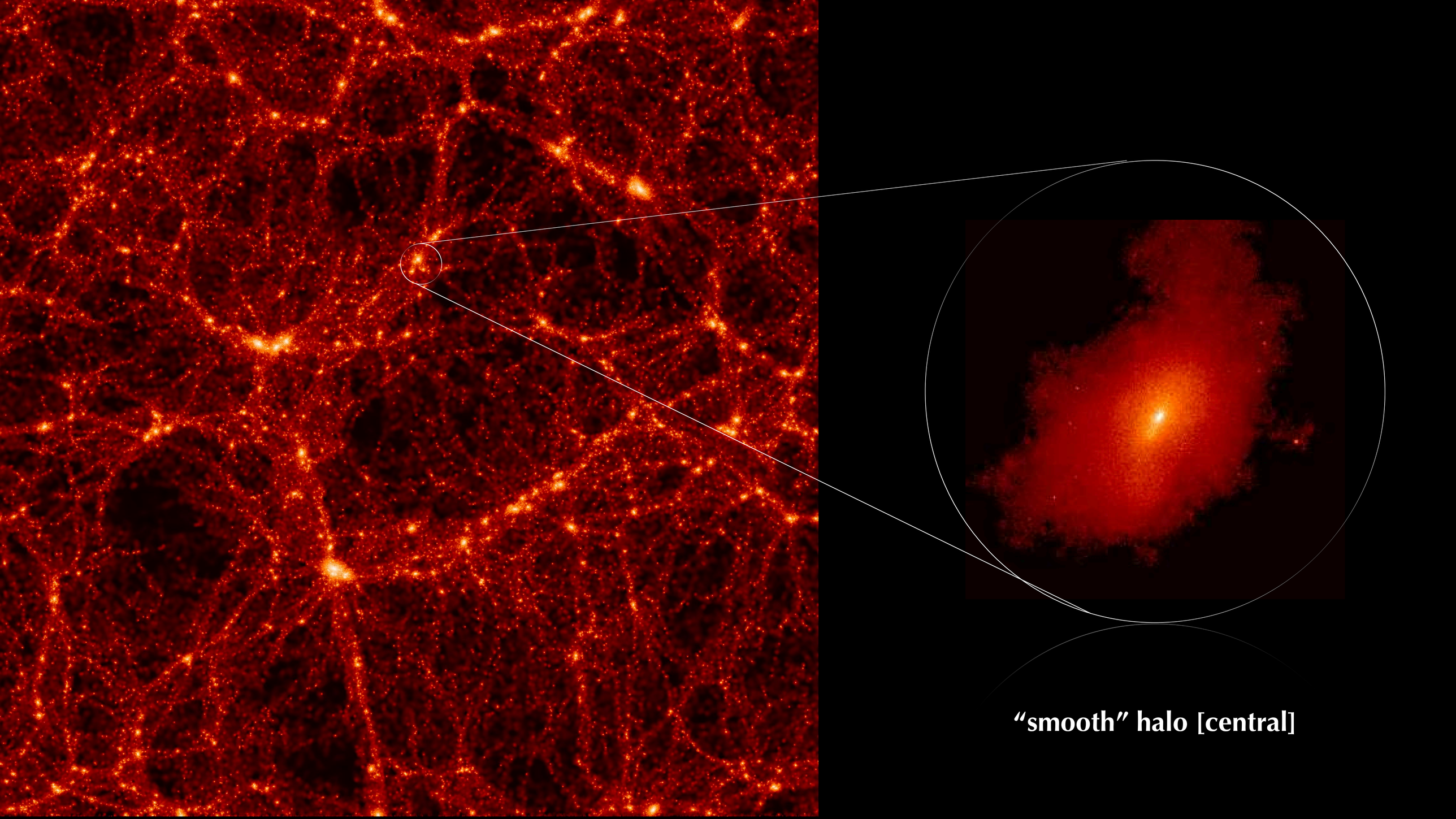
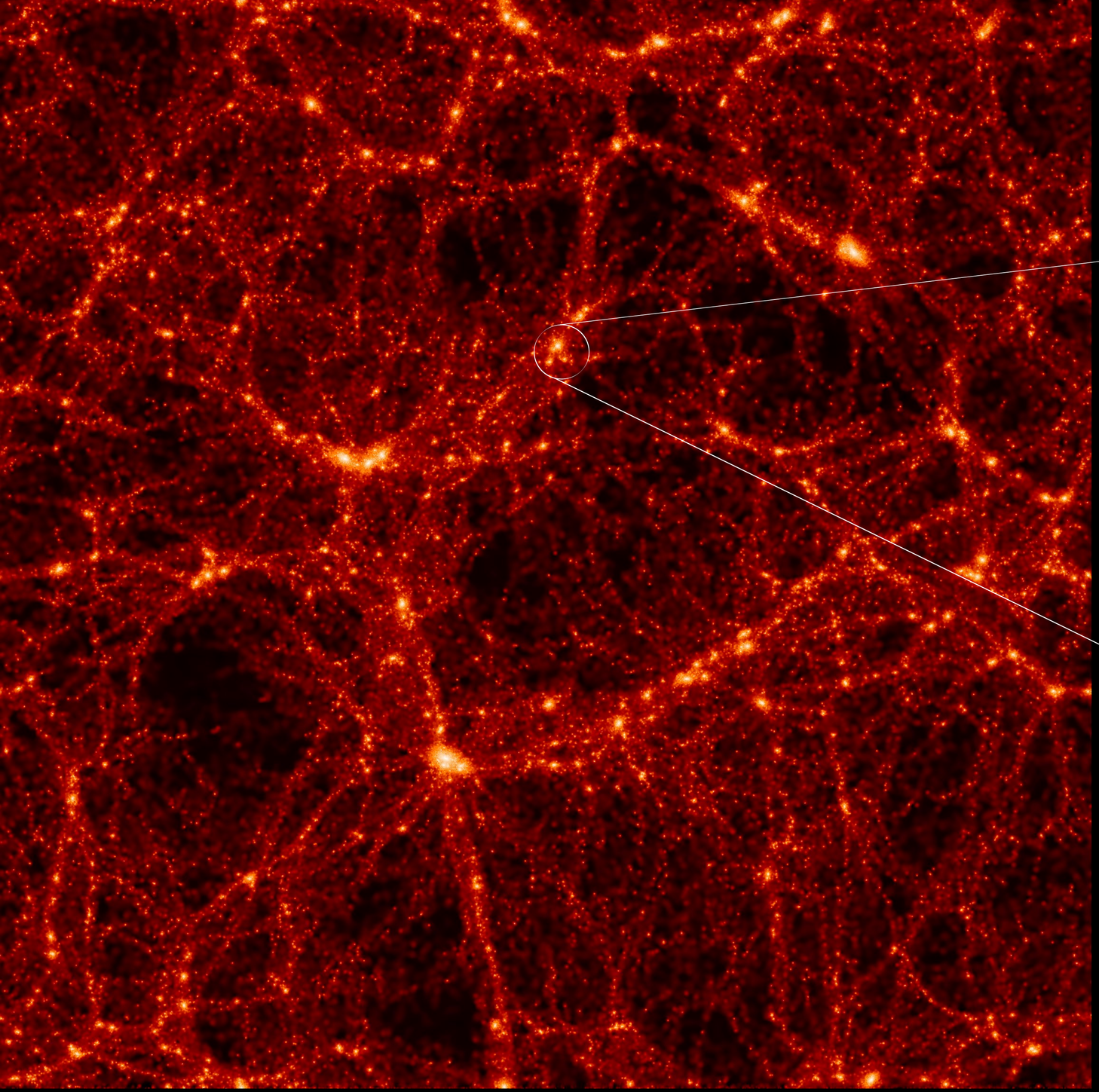
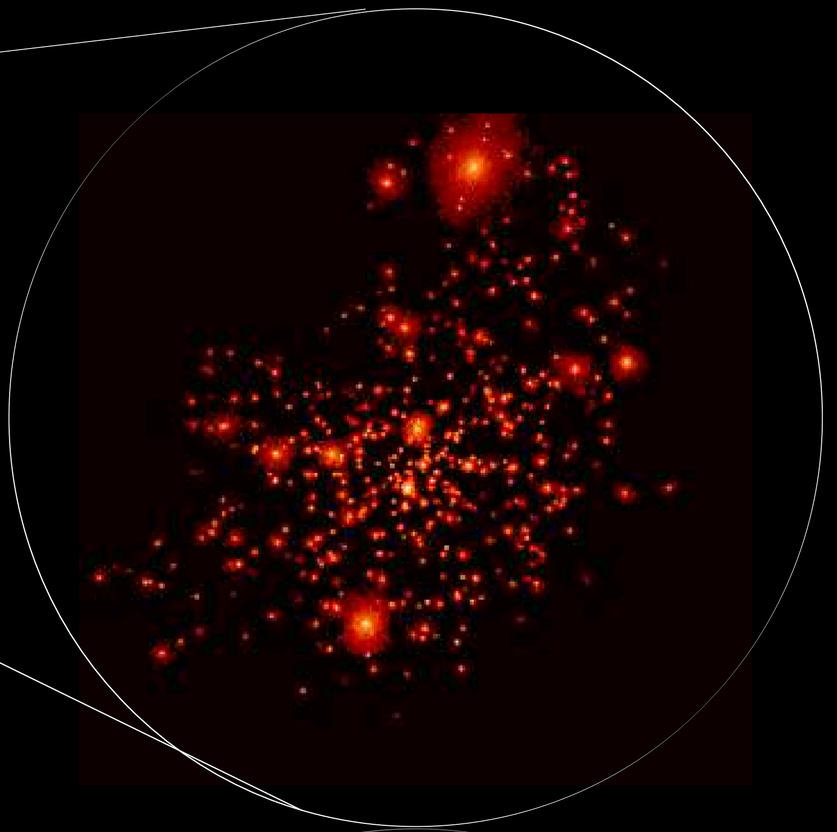



friends-of-friends halo

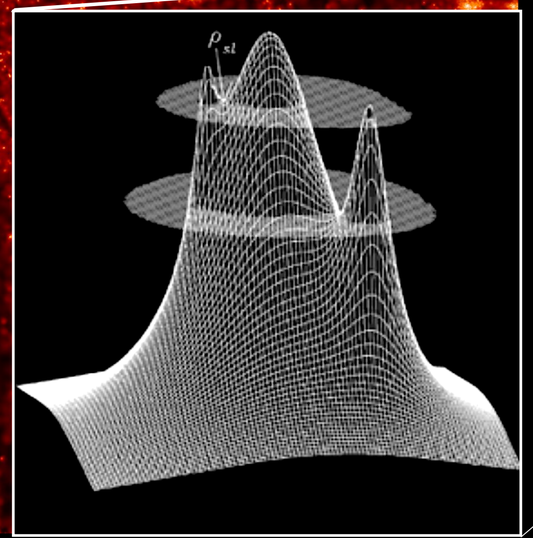

“smooth” halo [central]



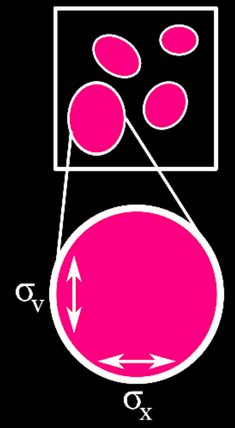


substructures [satellites]

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



substructures [satellites]



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.

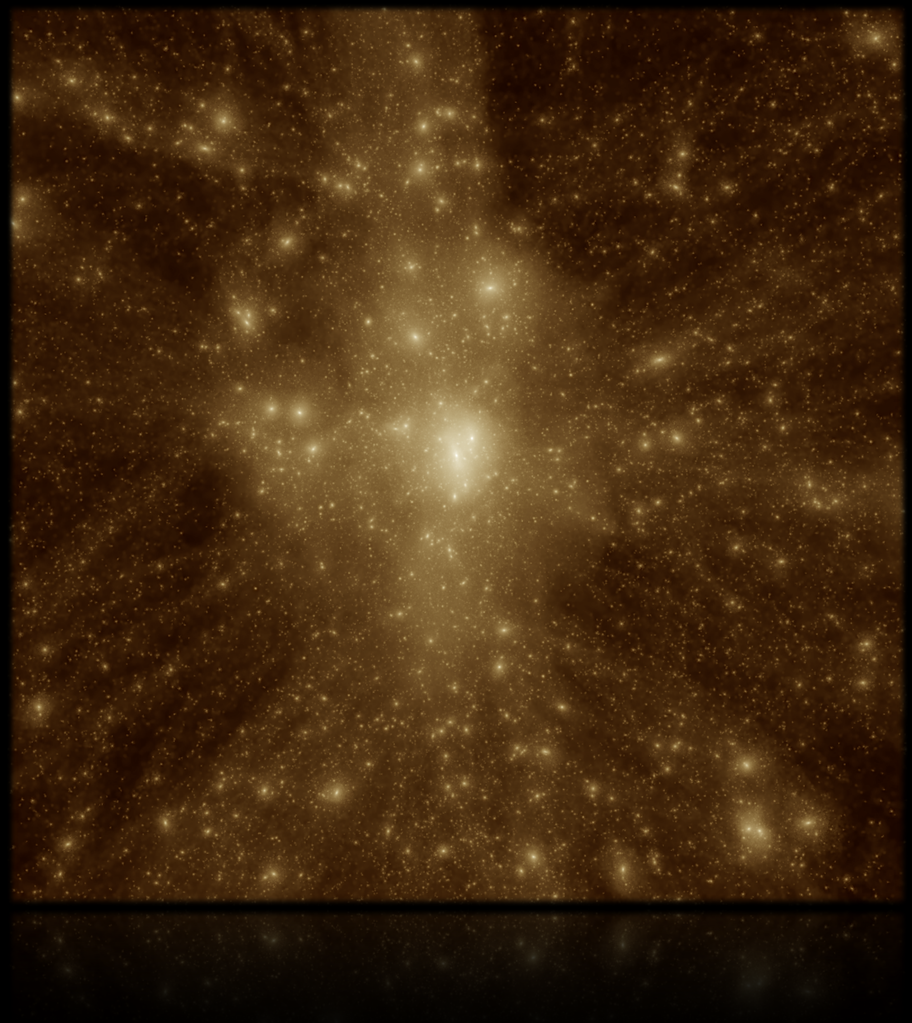
5. Once all levels of substructure are found, seed halos are placed at the lowest substructure levels and particles are assigned hierarchically to the closest seed halo in phase space.

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)

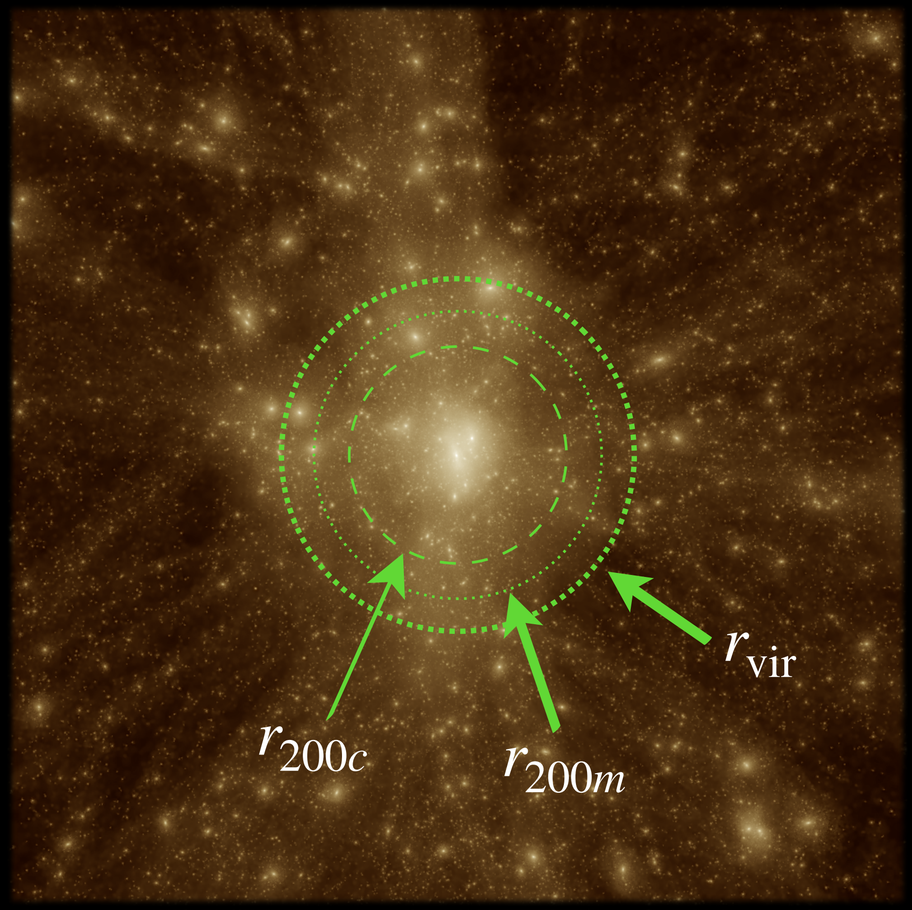
definitions of halo mass



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

definitions of halo mass



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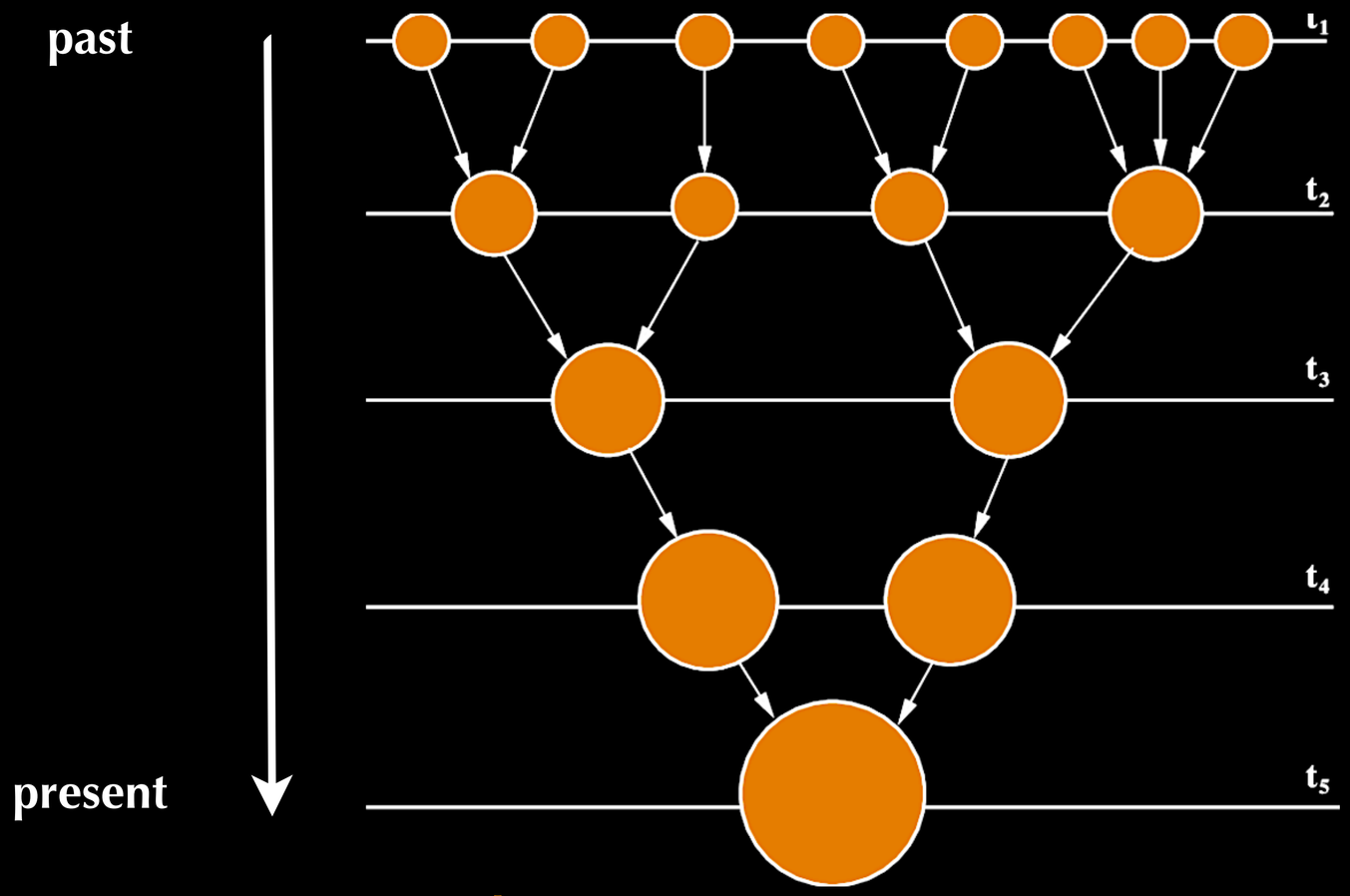
$$M_\Delta = \frac{4}{3}\pi\Delta\rho_{\rm ref}r_\Delta^3 \text{ where } \bar{\rho}(<r_\Delta) = \Delta\cdot\rho_{\rm ref}$$

virial mass/radius

commonly used definitions

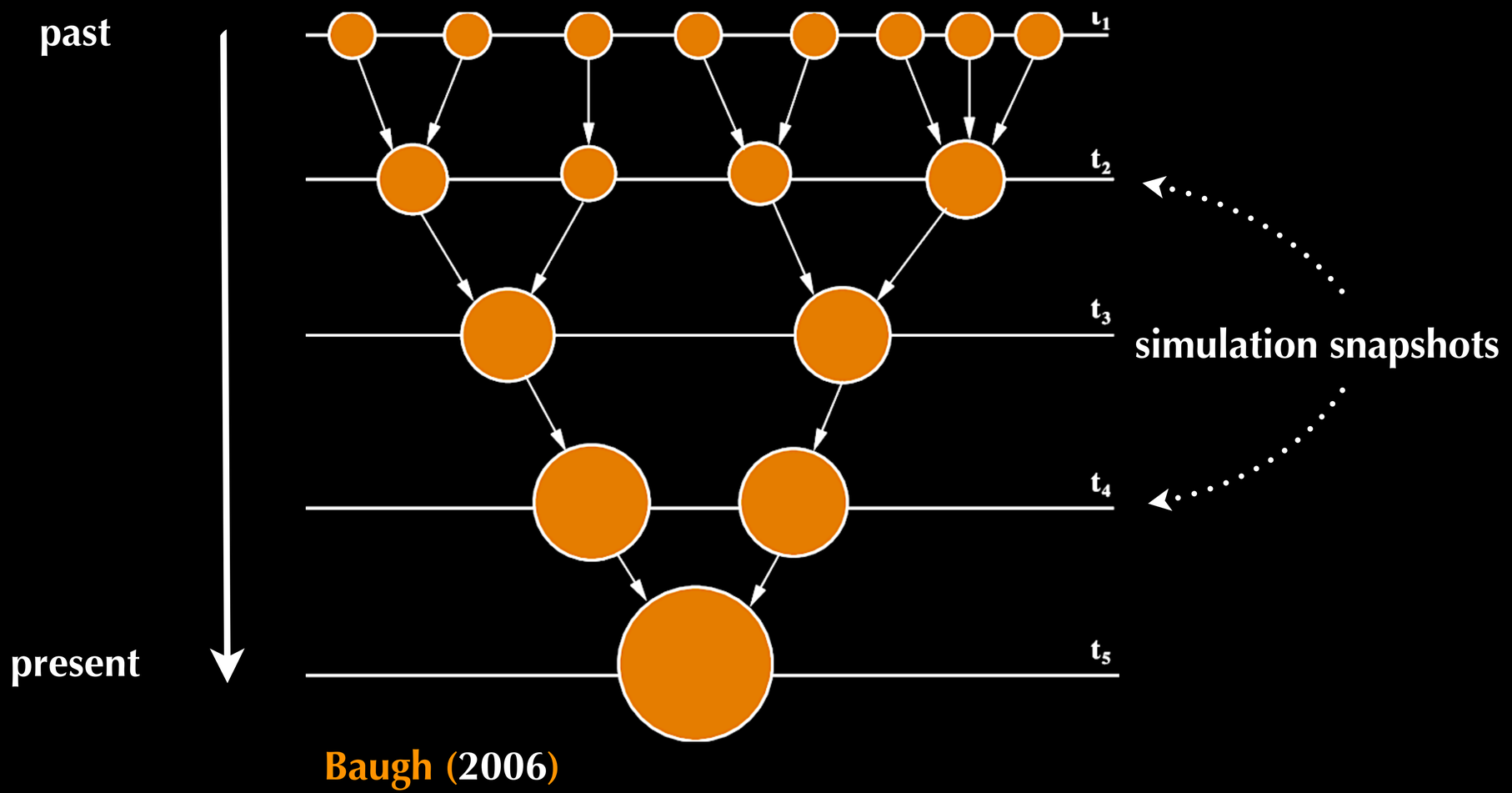
label	Δ	$\rho_{\rm ref}$	spherical	cosmology dependent?	binding information?
$M_{\rm FOF}$	–	–	✗	✓	✗
$M_{\rm sub}$	–	$\rho_{\rm host}$	✗	✗	✓
M_{200c}	**200**	$\rho_{\rm crit}$	✓	✓	✗
M_{200m}	**200**	$\rho_{\rm mean}$	✓	✓	✗
$M_{\rm vir}$	$18\pi^2 + 82x - 39x^2$ $x \equiv \Omega(z) - 1$	$\rho_{\rm mean}$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

growth histories of haloes



Baugh (2006)

growth histories of haloes



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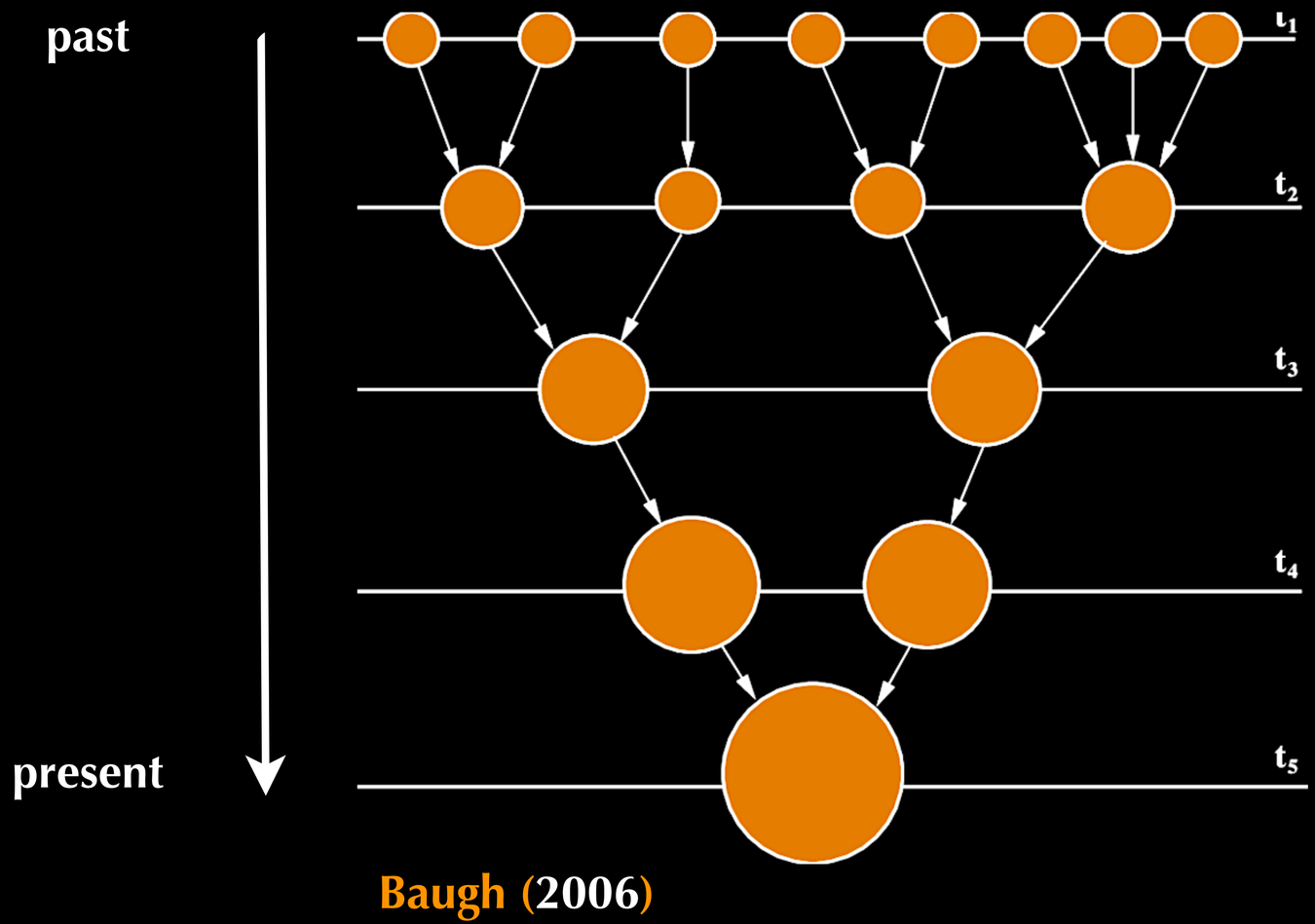
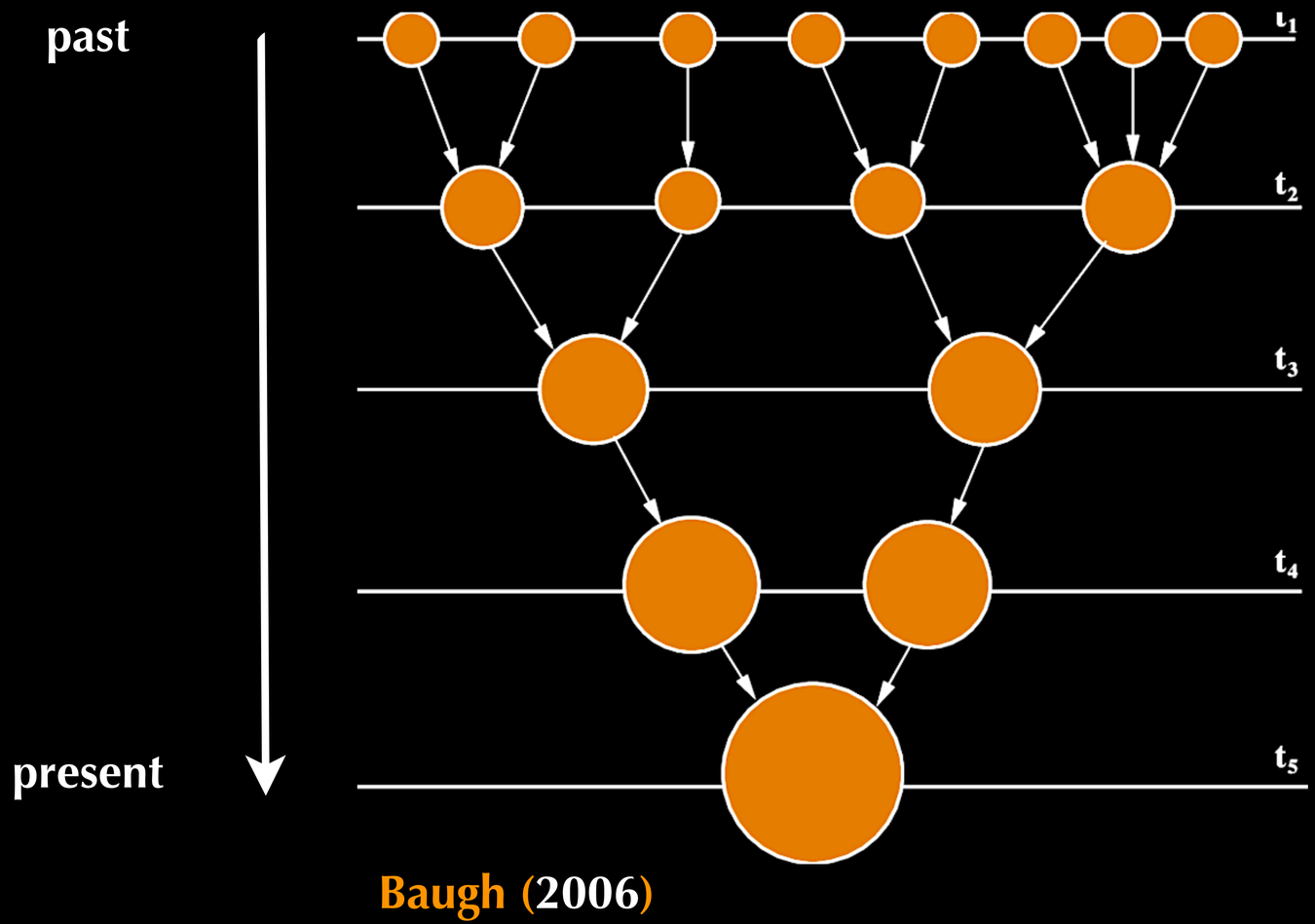


Baugh (2006)

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

growth histories of haloes



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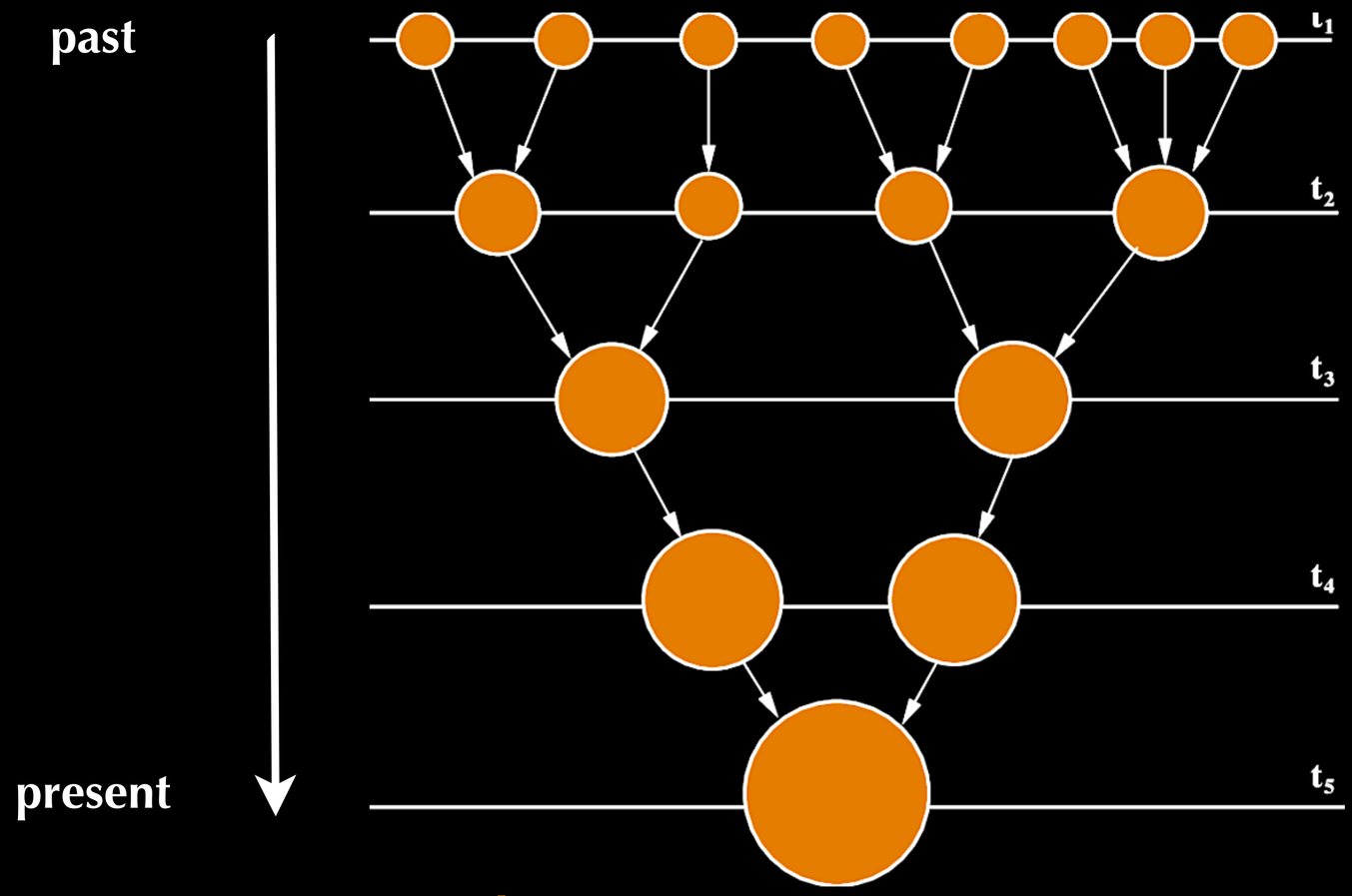

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simulation snapshots

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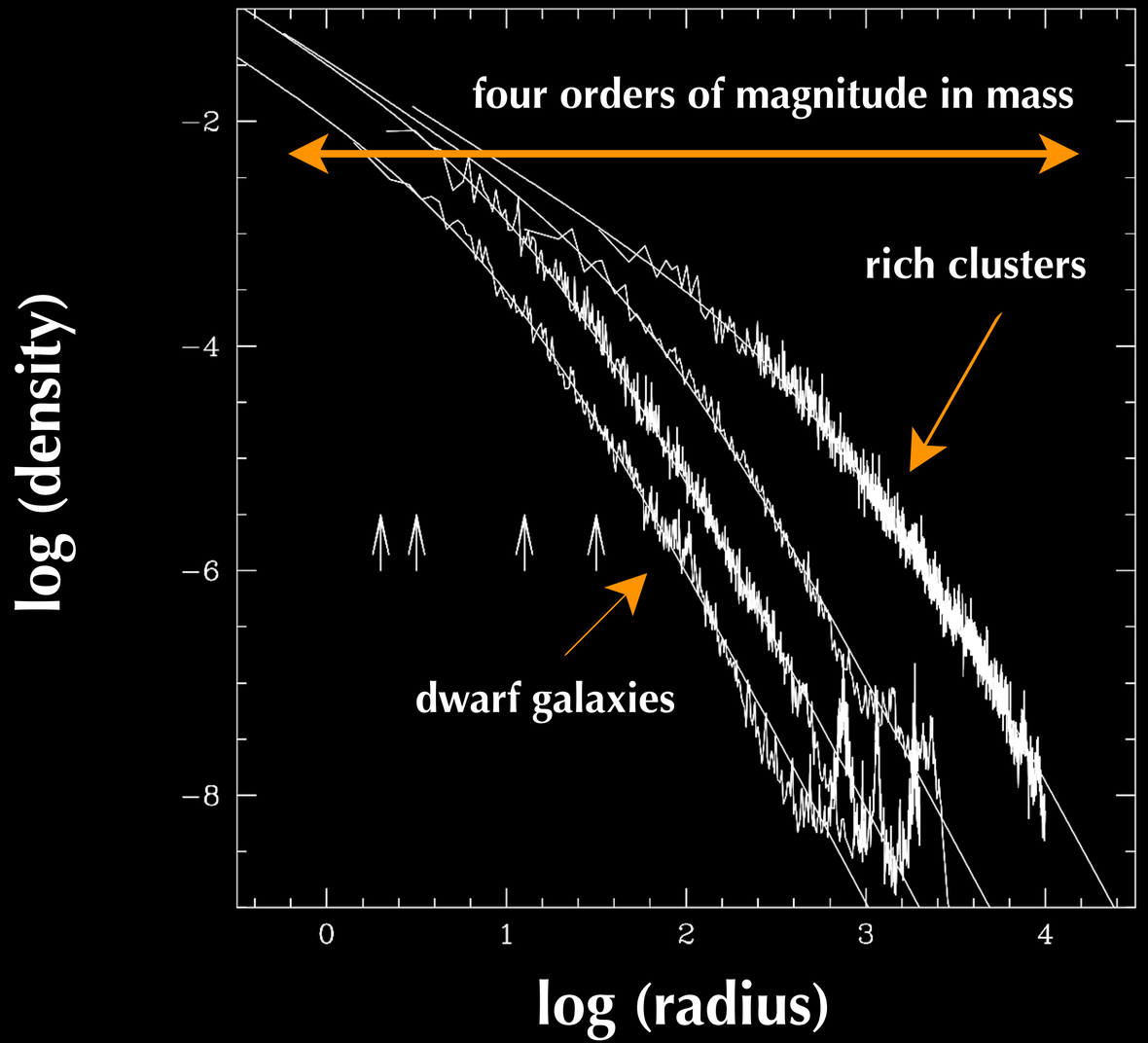
⇒ merger trees act as the skeleton on which many galaxy formation models (semi-analytic, empirical models etc.) are built

some universal predictions

self-similar structure



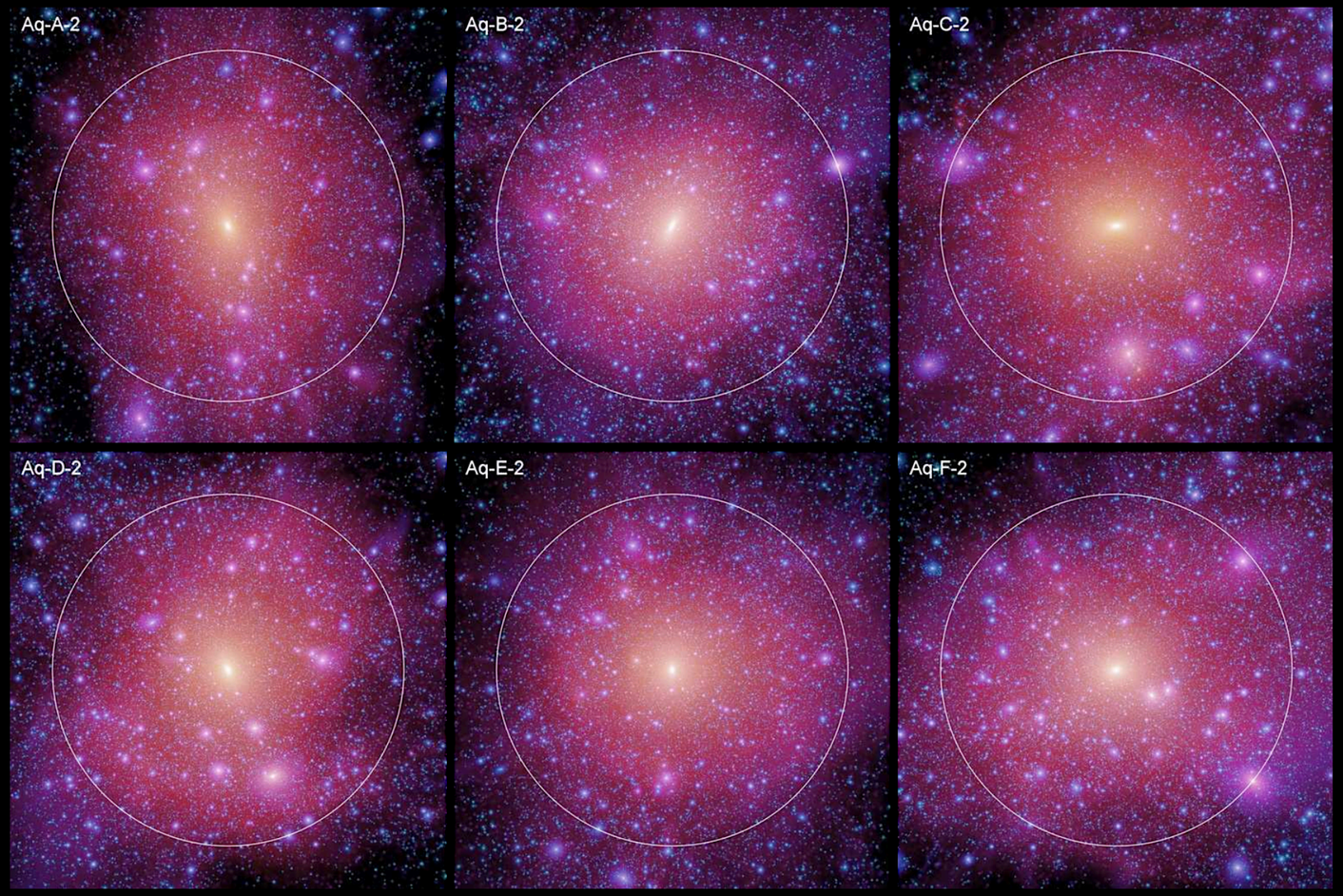
centre: $\rho \propto r^{-1}$

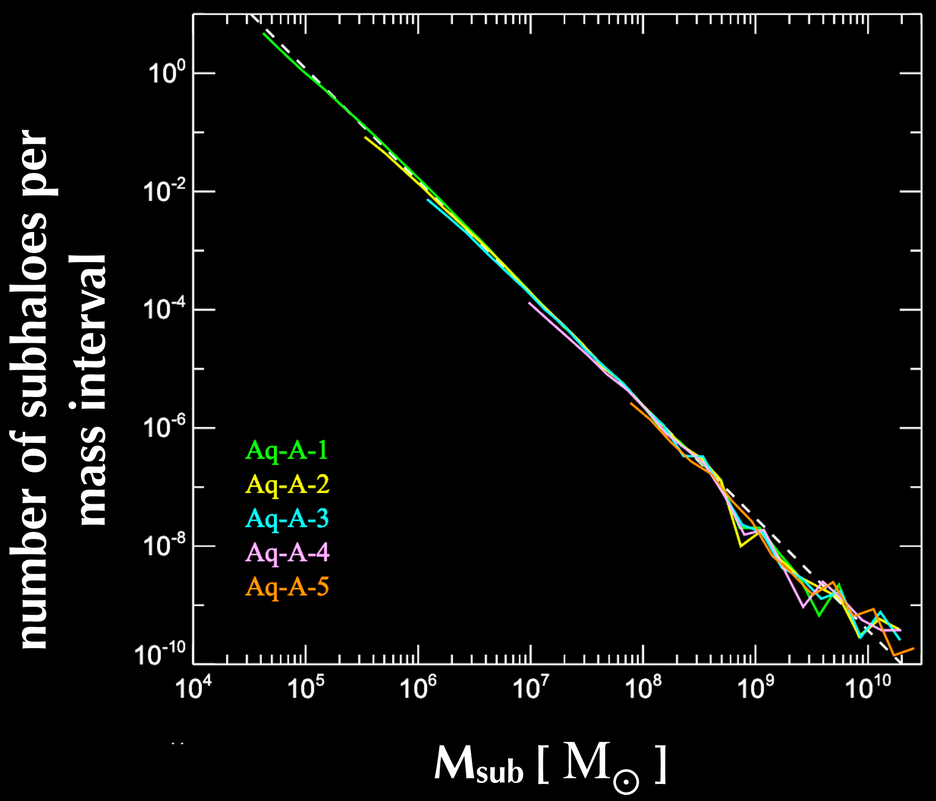
middle: $\rho \propto r^{-2}$

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

Navarro, Frenk & White (1996)

self-similar abundance

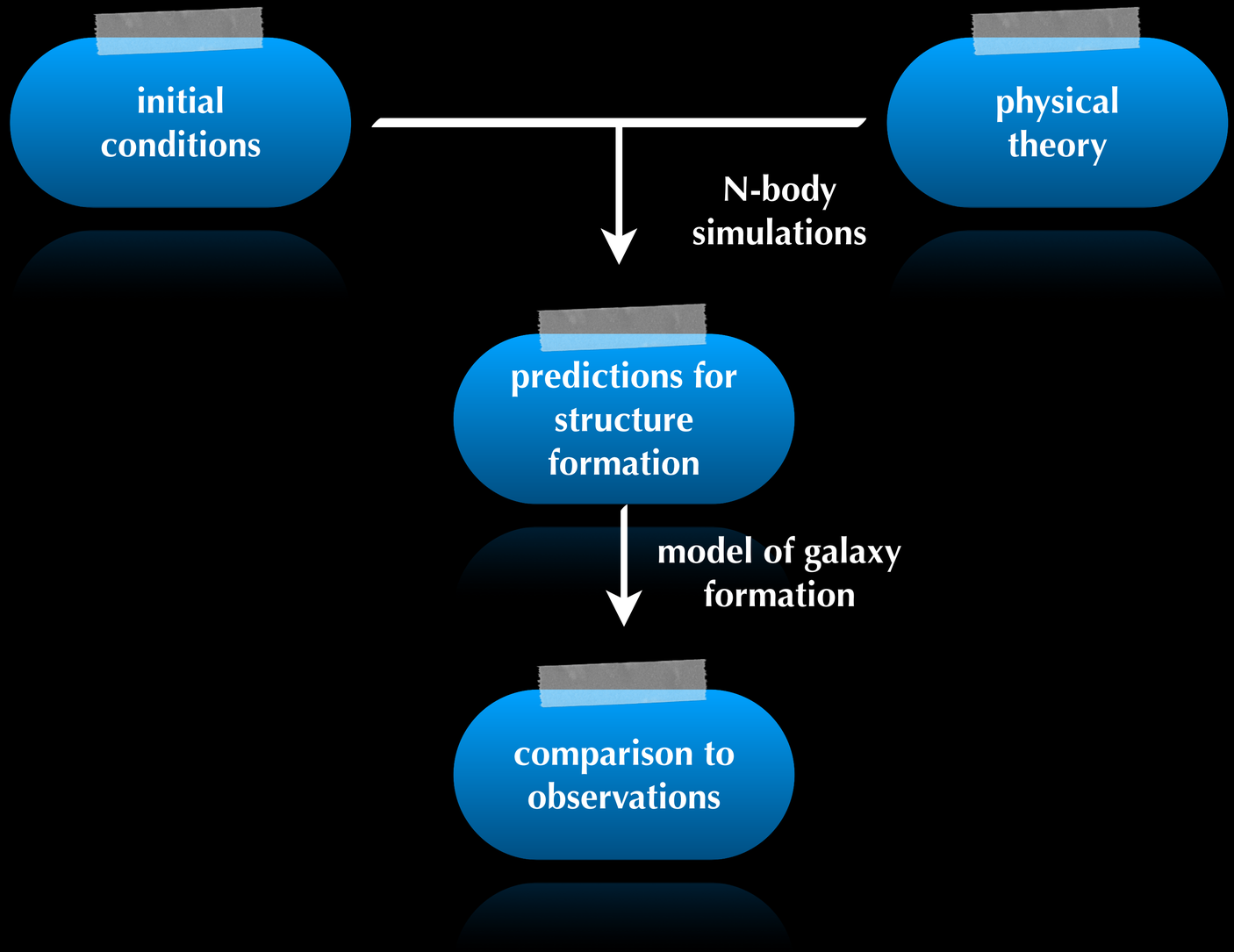


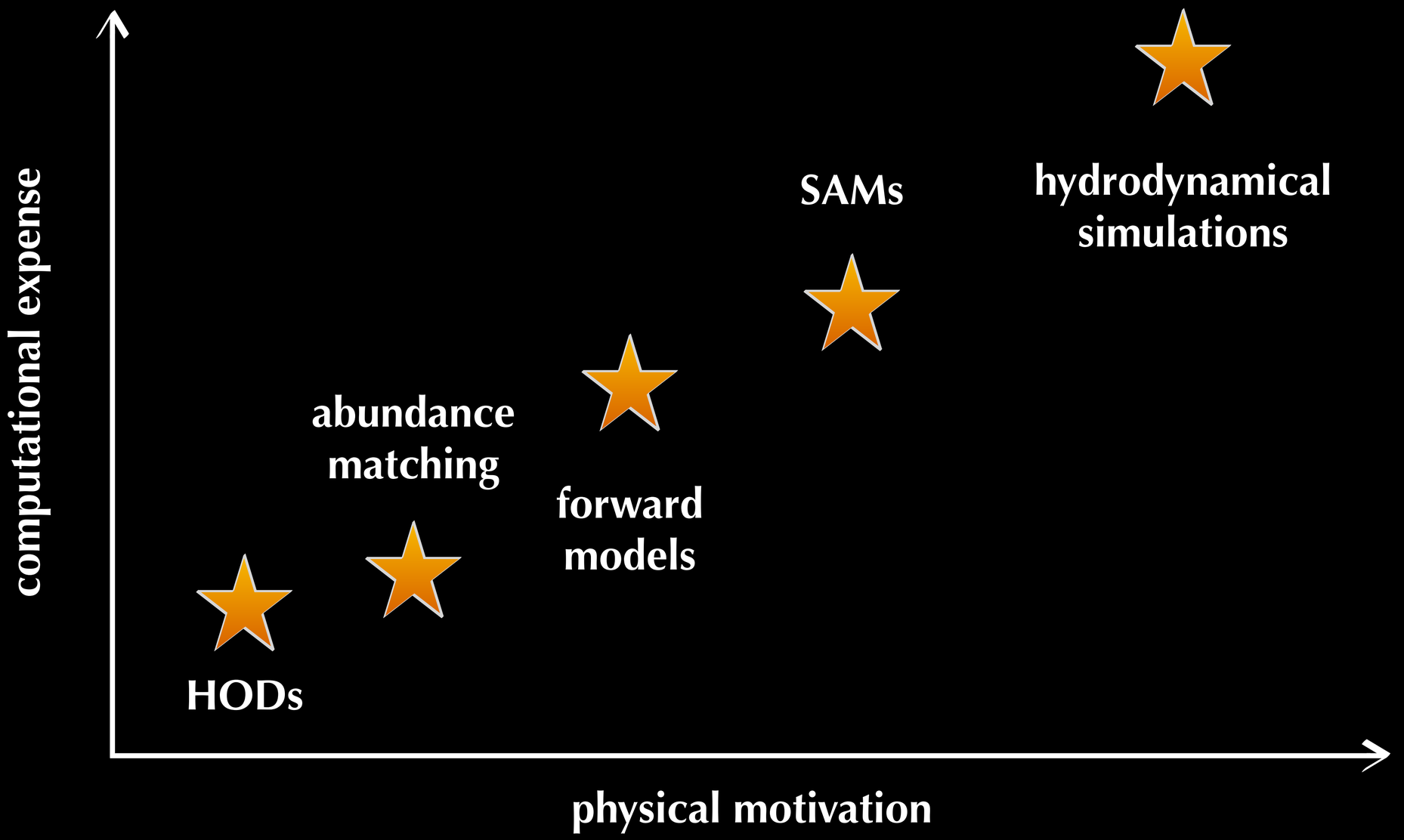


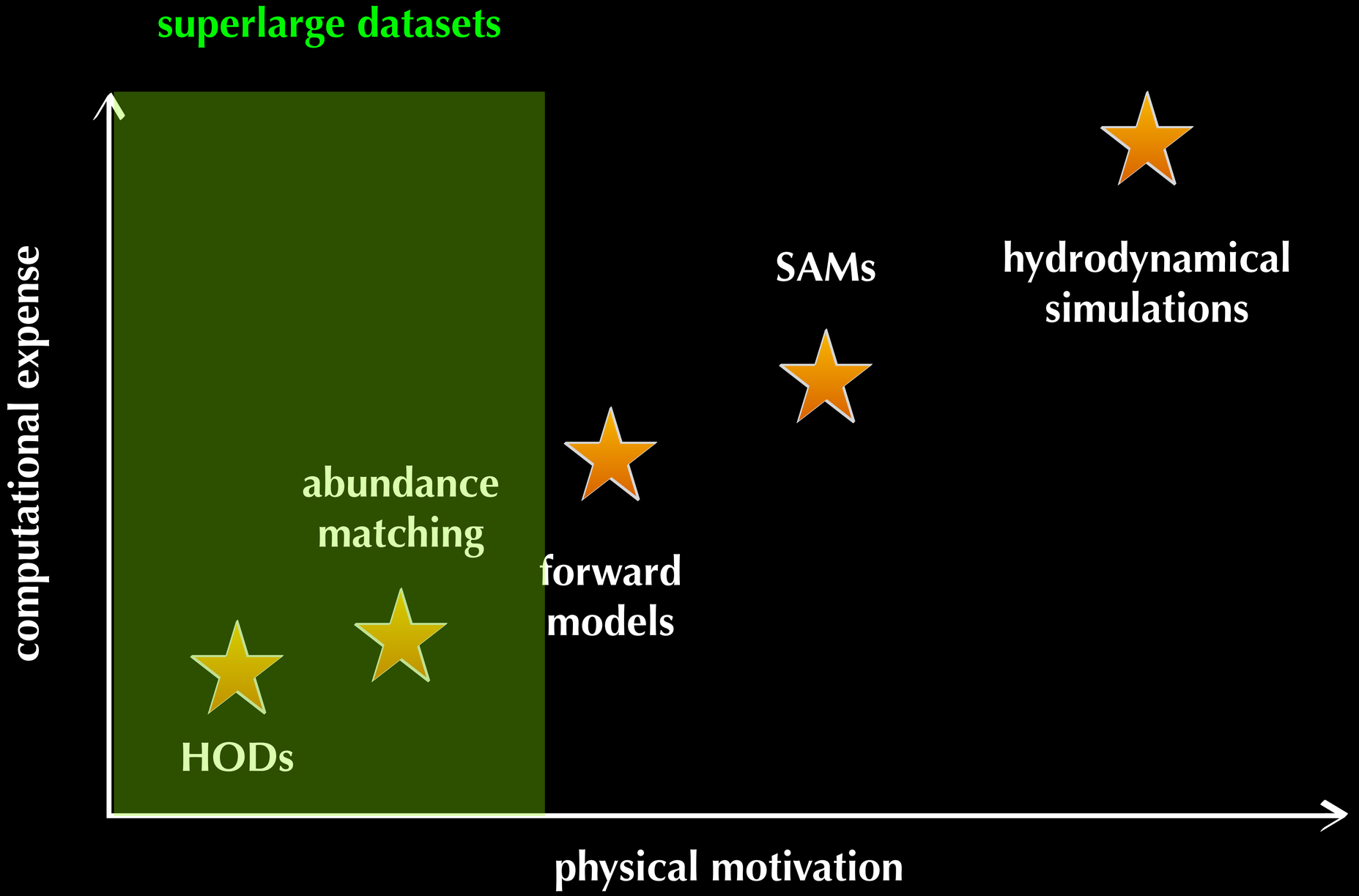
Springel+ (2008)

adding galaxies

the pathway to simulating the cosmos




computational expense
physical motivation
HODs
abundance matching
forward models
SAMs
hydrodynamical simulations


superlarge datasets
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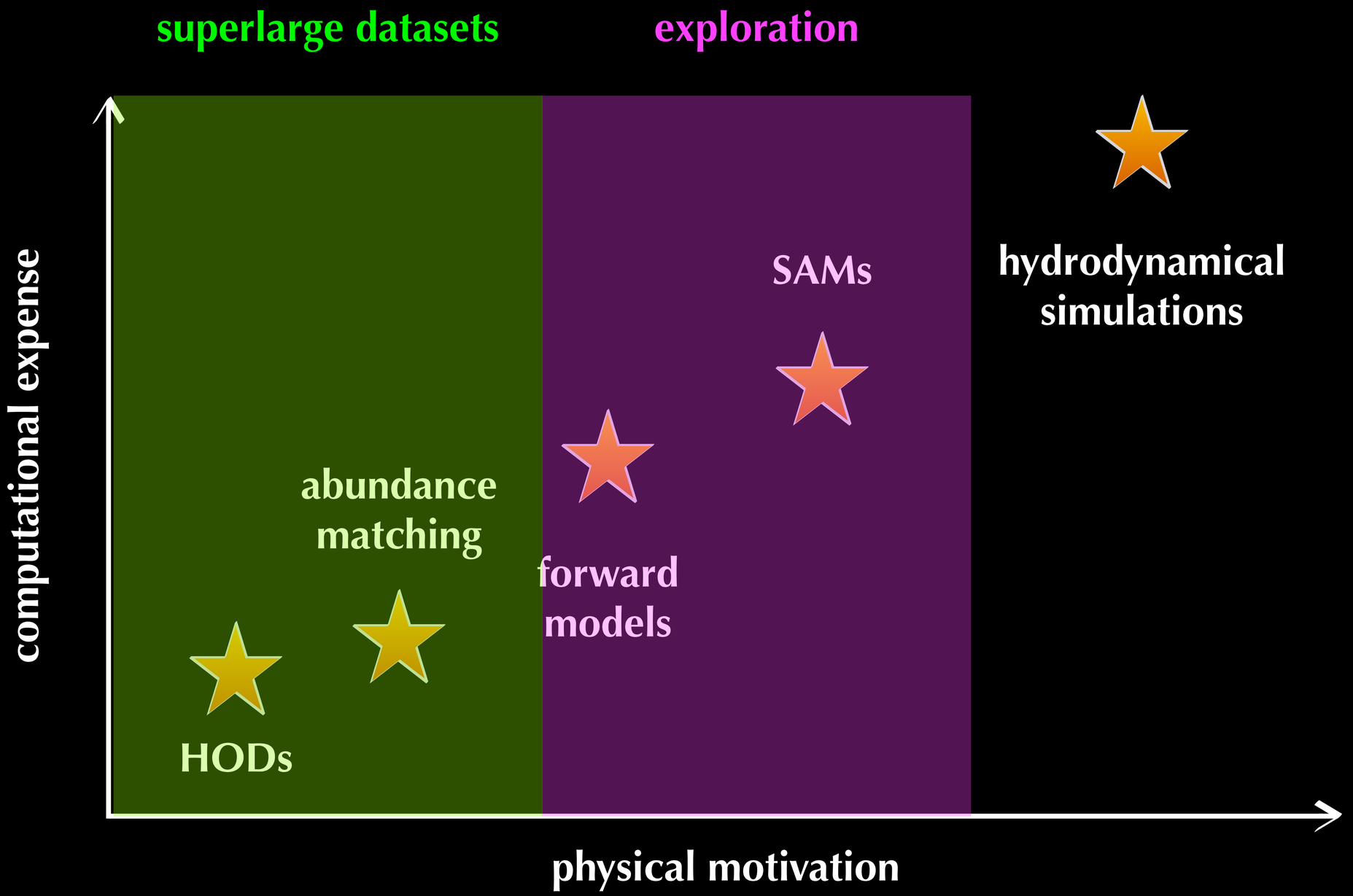
superlarge datasets
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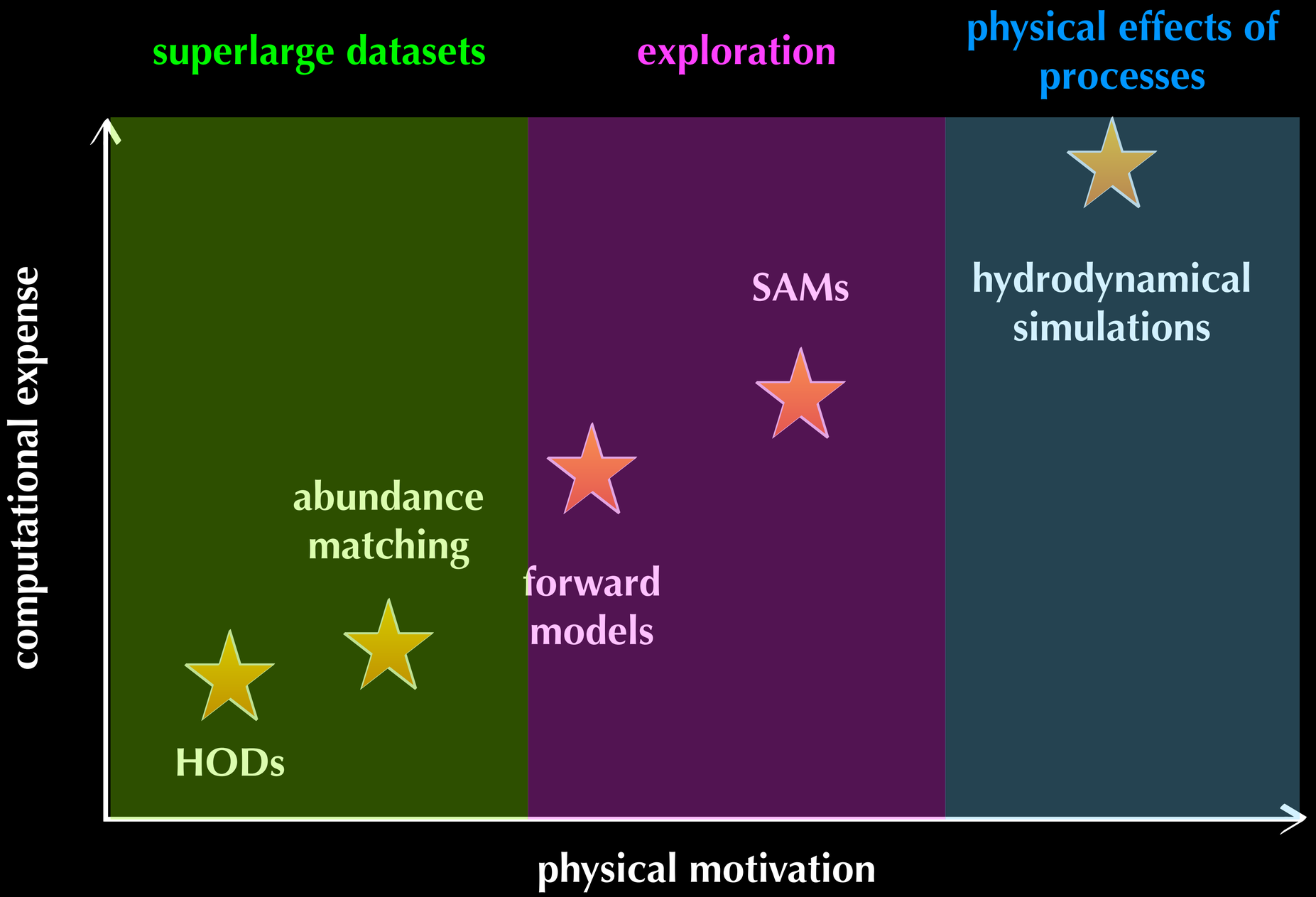
superlarge datasets
exploration
physical effects of processes
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forward models
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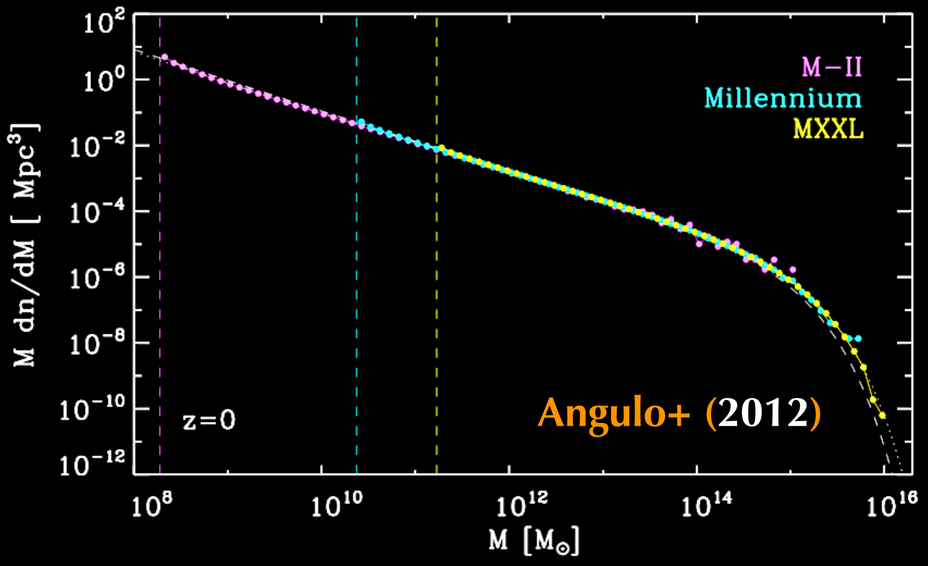
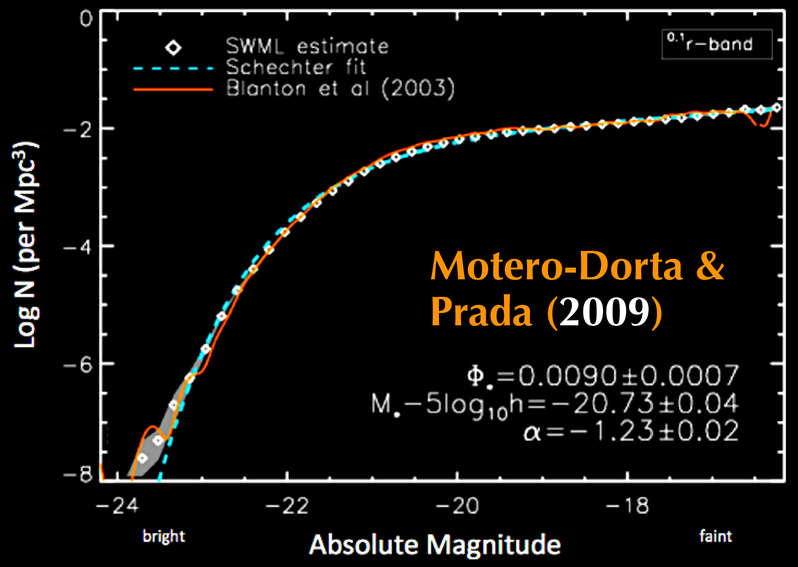
hydrodynamical simulations

… but their objectives are similar

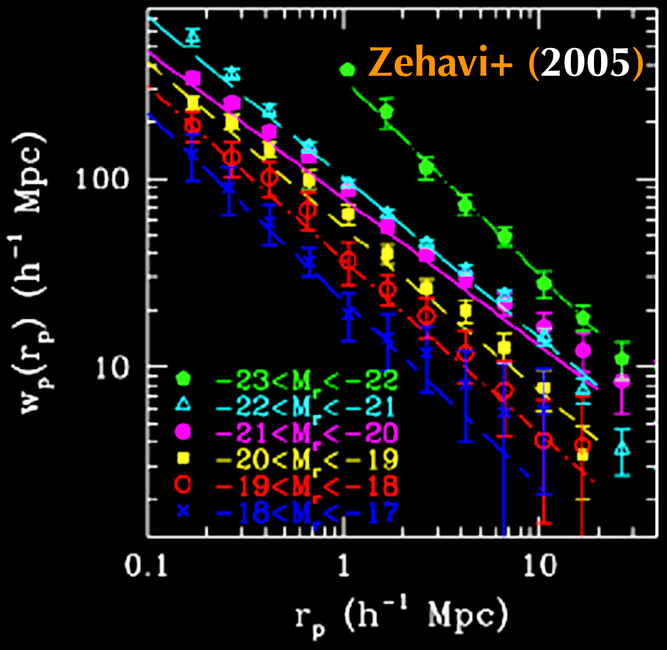
DM halo mass function



galaxy luminosity function



galaxy clustering



$$P\left(N_{\mathrm{gal}} \mid M_{\mathrm{halo}}\right)$$

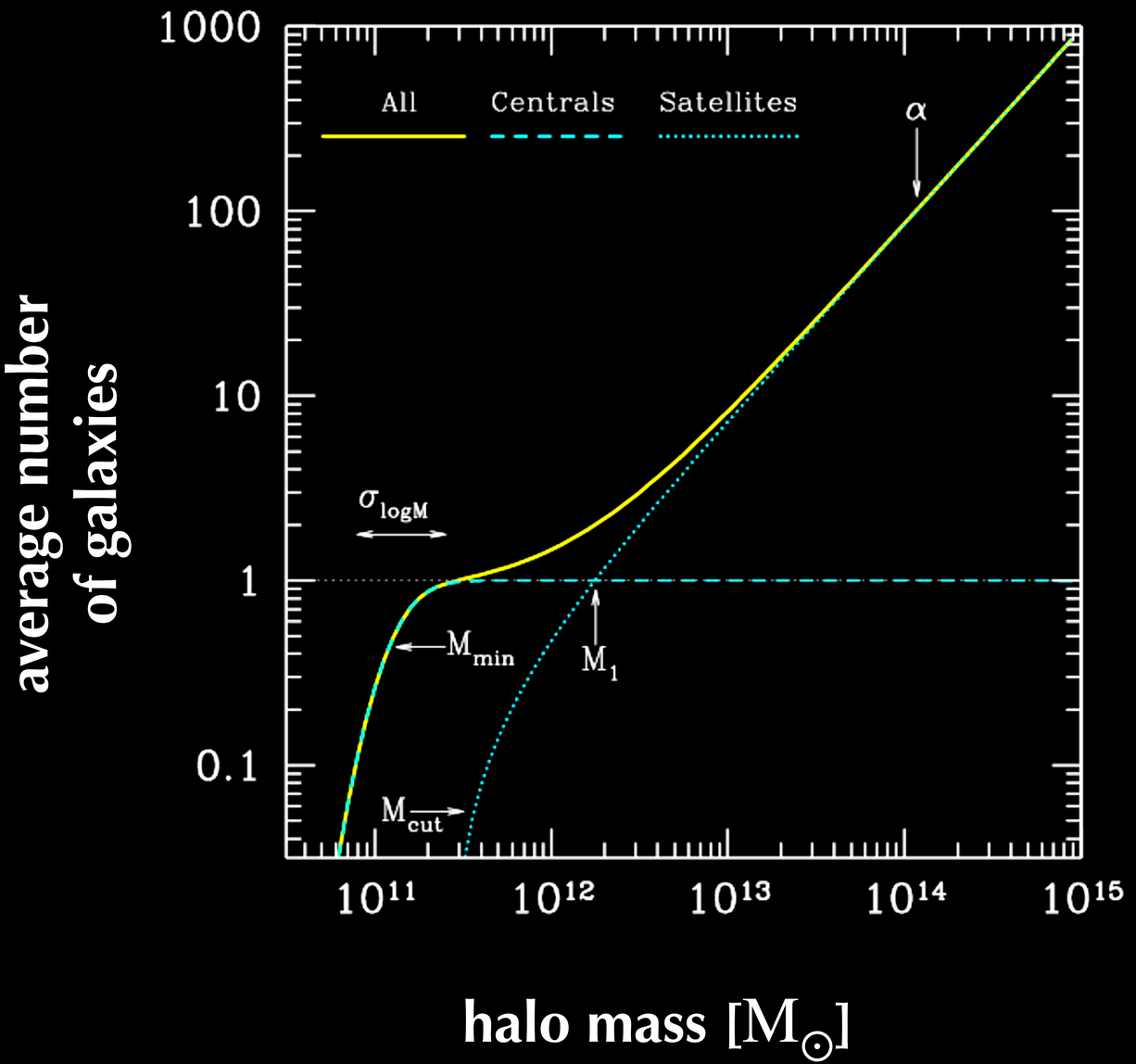
“halo occupation distribution”

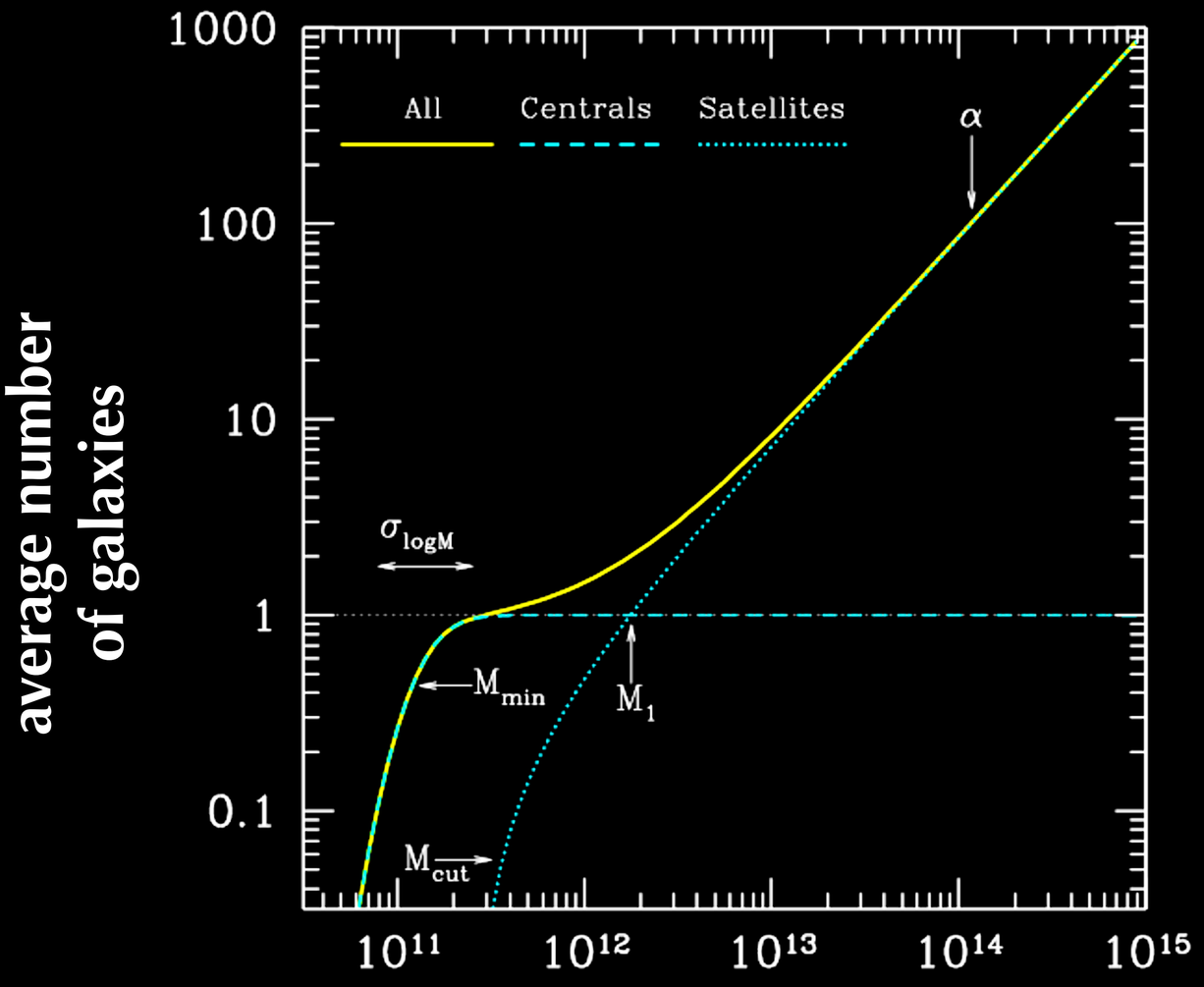
$$P\left(N_{\rm gal} \,|\, M_{\rm halo}, z_{\rm form}, \cdots\right)$$

“halo occupation distribution”

+

“assembly bias”

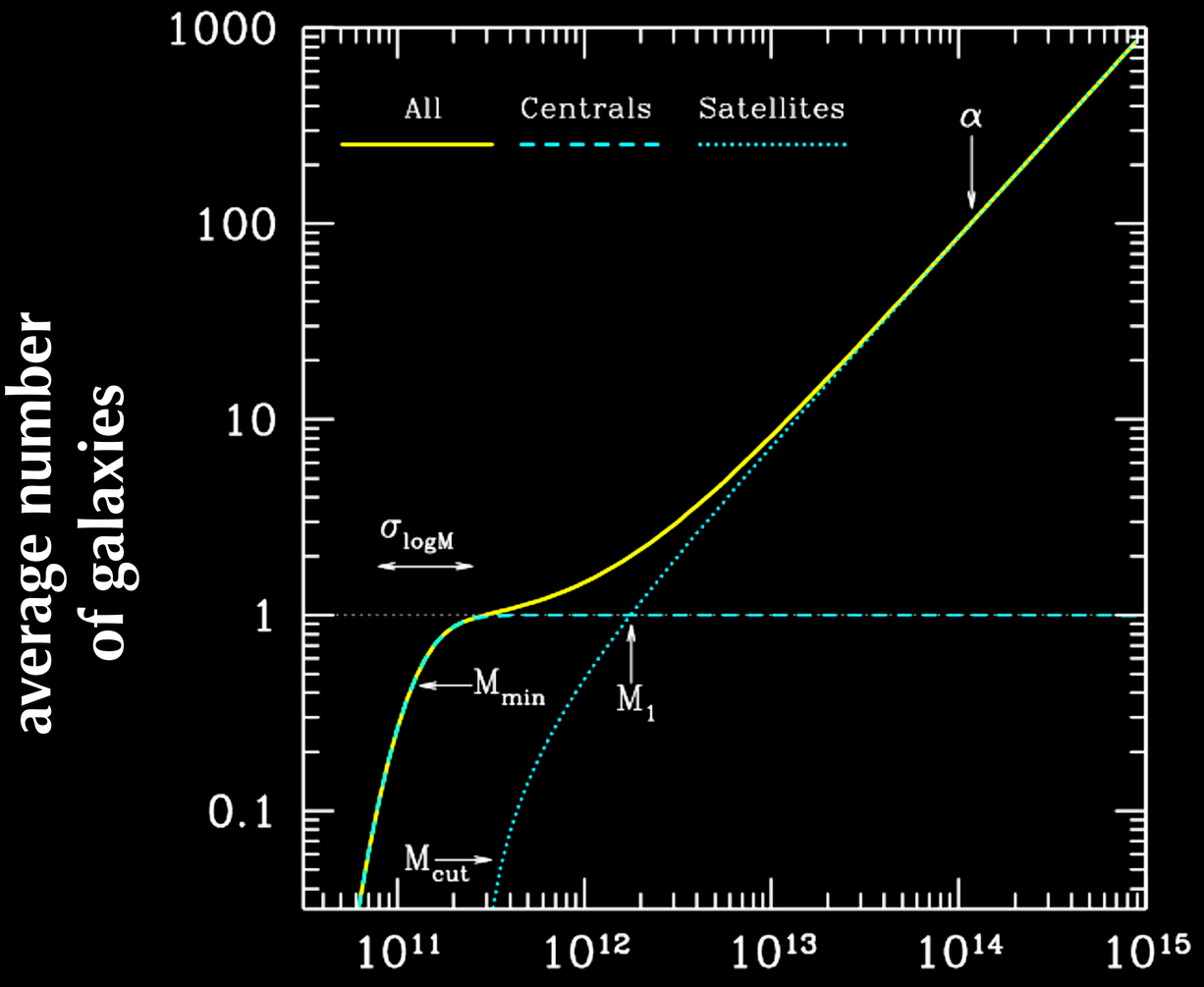

1000
100
10
1
0.1
All
Centrals
Satellites
α
σ logM
M min
M 1
M cut
10^11
10^12
10^13
10^14
10^15
average number of galaxies
halo mass [M⊙]



Zheng+ (2005)

$$N_{\rm cen}\left(M_{\rm halo}\right) = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M_{\rm halo} - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

$$N_{\rm sat}\left(M_{\rm halo}\right) = \left(\frac{M_{\rm halo} - M_{\rm cut}}{M_1}\right)^{\alpha}$$



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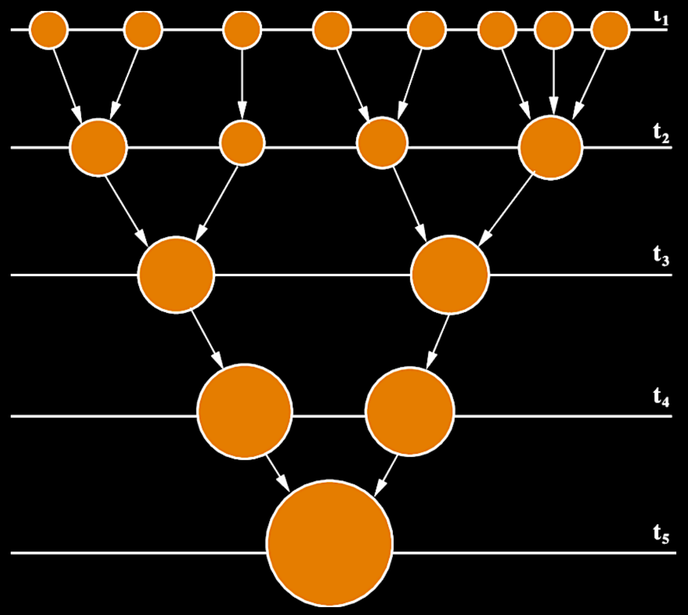
the 5 free parameters of this model are tuned so as to reproduced observed data

empirical forward models

halo assembly histories



N-body simulation

Baugh (2006)

$$\mathrm{SFR}\left(M_{\mathrm{halo}}, z\right) = \varepsilon\left(M_{\mathrm{halo}}\right) \times f_B \times \frac{\mathrm{d}M_{\mathrm{halo}}}{\mathrm{d}t}$$

empirical forward models

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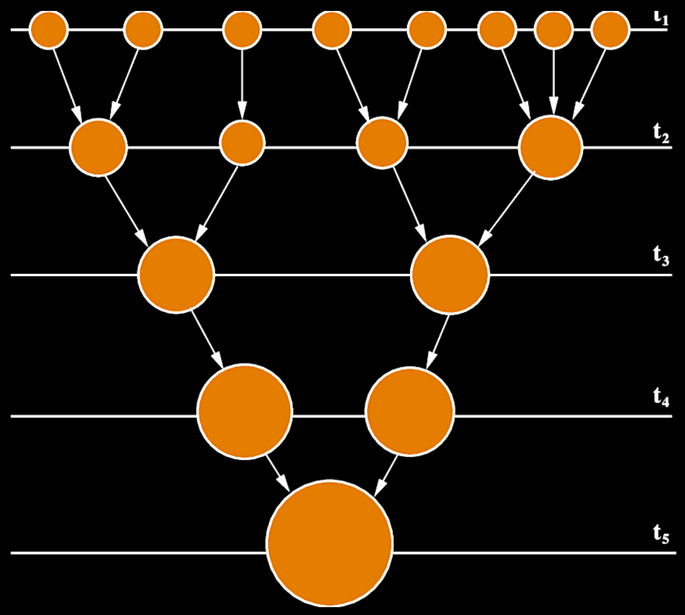

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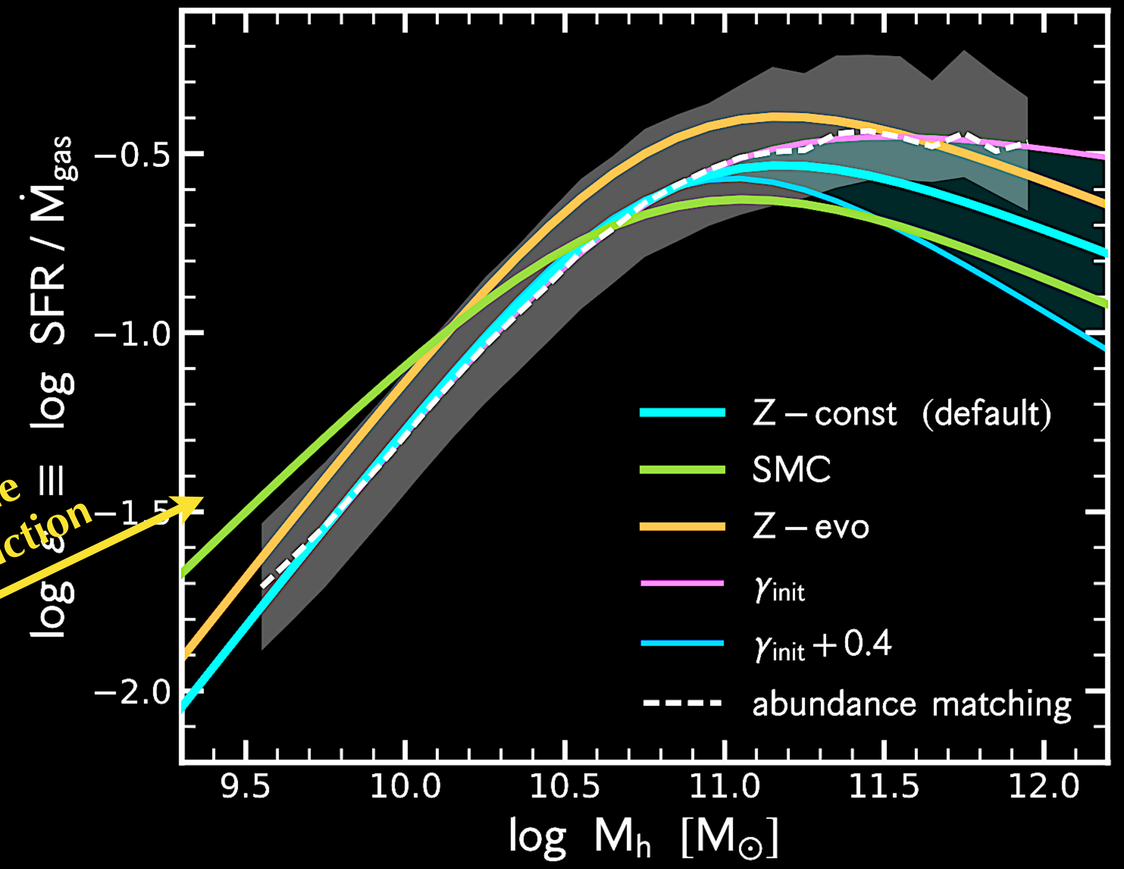
calibrated to match the observed luminosity function



modelling cosmic baryons

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi$$

Euler equation
[conservation of momentum]

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\cdot\mathbf{v} = 0$$

continuity equation
[conservation of mass]

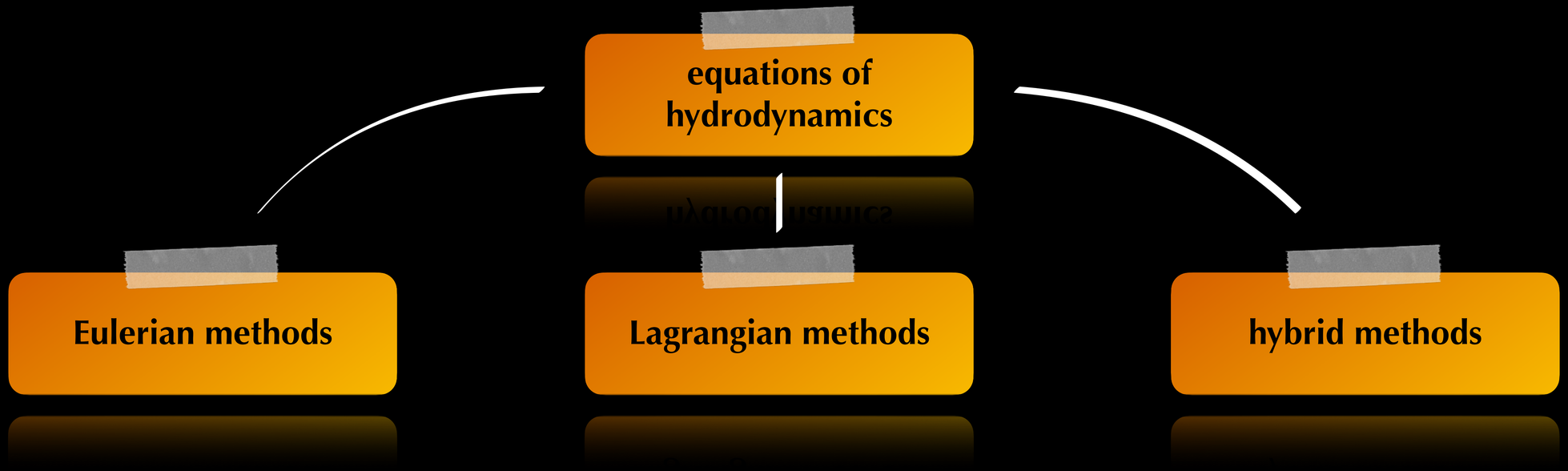
$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\cdot\mathbf{v} - \frac{\Lambda\left(u,\rho\right)}{\rho}$$

1st law of thermodynamics
[conservation of energy]

$$P = \left(\gamma - 1\right)\rho u, \quad \gamma = 5/3$$

equation of state of an ideal monoatomic gas

equations of hydrodynamics


equations of hydrodynamics
Eulerian methods
Lagrangian methods
hybrid methods

equations of hydrodynamics

Eulerian methods

Lagrangian methods

hybrid methods

RAMSES, Enzo

equations of hydrodynamics

Eulerian methods

Lagrangian methods

hybrid methods

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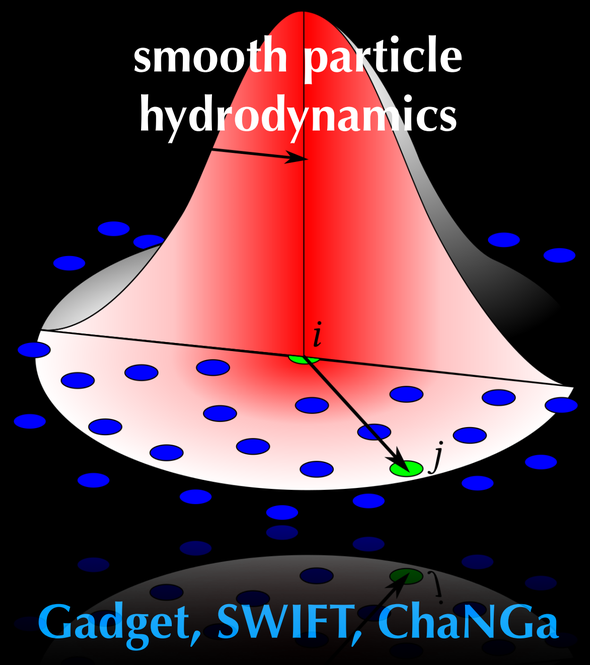


Gadget, SWIFT, ChaNGa

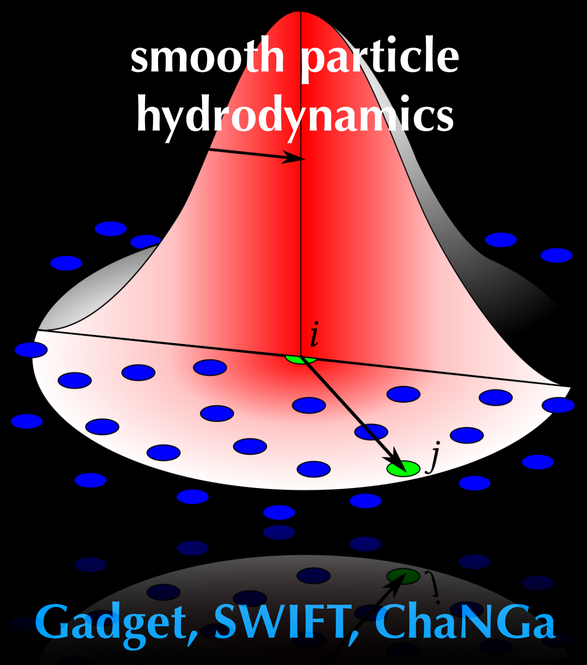
equations of hydrodynamics

Eulerian methods

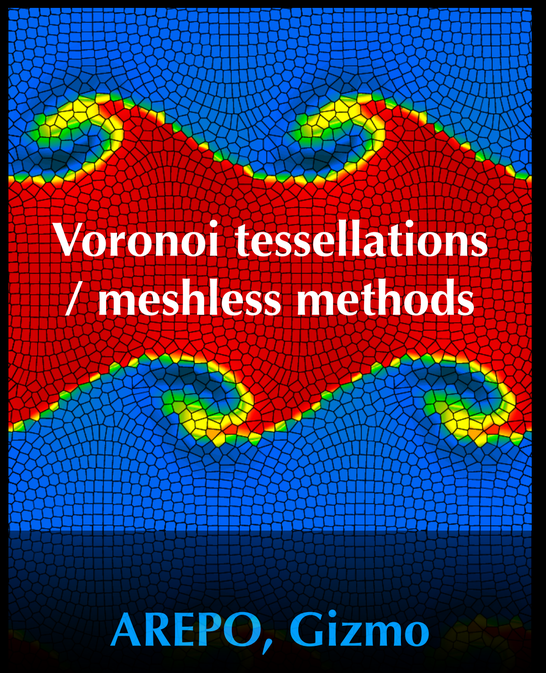
Lagrangian methods

hybrid methods

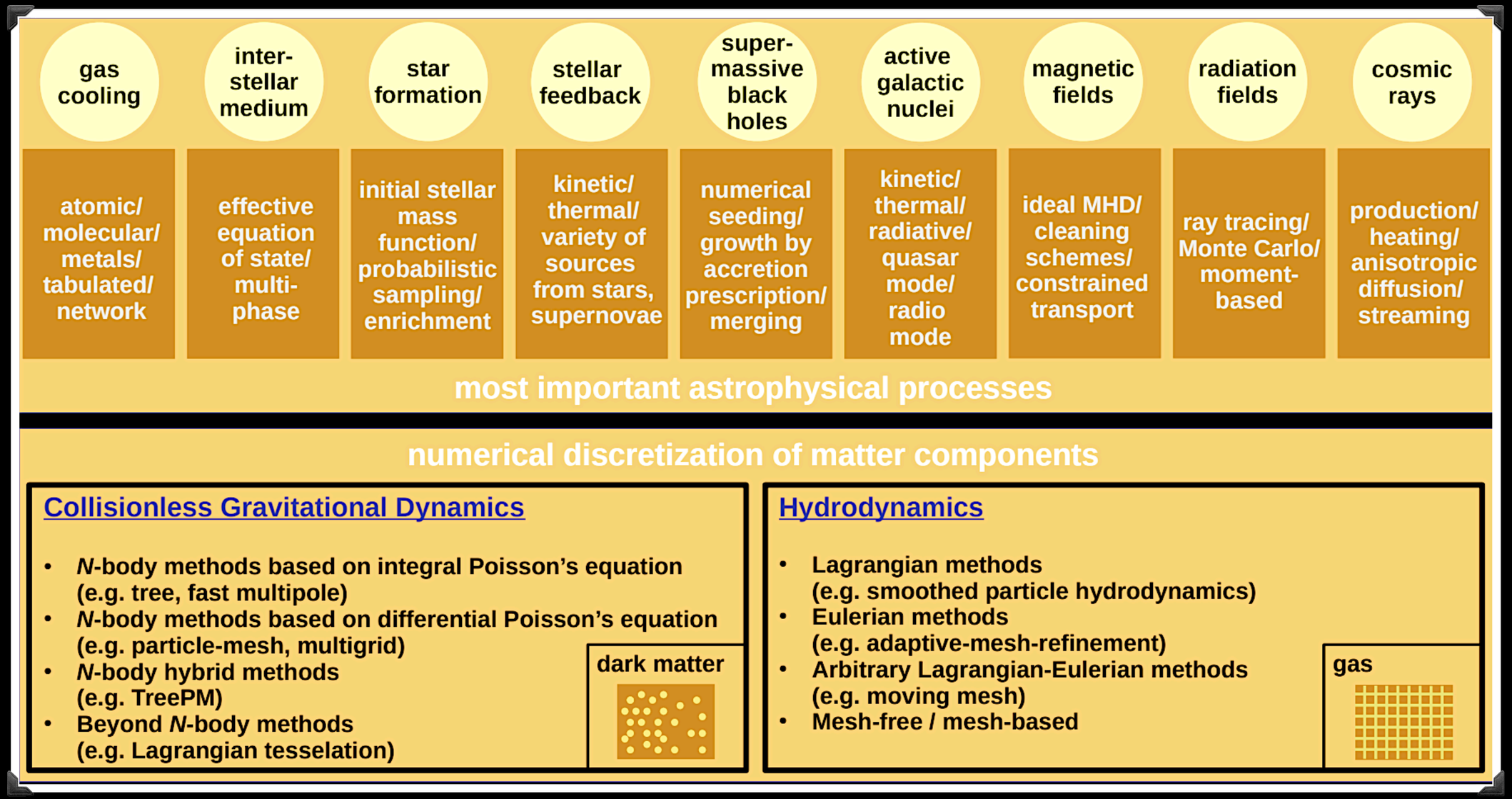
RAMSES, Enzo



Gadget, SWIFT, ChaNGa



AREPO, Gizmo



Vogelsberger+ (2020)

ultimately, what method / approach to modelling galaxies is used depends on the i) objectives and ii) the size of the problem being addressed!

limits of N-body simulations [a rough guide]

item	set by	limitation

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mass resolution	number of particles	smallest structures [haloes/galaxies] resolved

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cosmic variance	box size / number of IC realisations	most massive haloes / largest modes in correlation function + power spectrum

limits of N-body simulations [a rough guide]

item	set by	limitation
mass resolution	number of particles	smallest structures [haloes/galaxies] resolved
spatial resolution	softening / cell size	accuracy of gravitational force on small scales
temporal resolution	softening	size of timesteps / internal halo structure / galaxy formation model
cosmic variance	box size / number of IC realisations	most massive haloes / largest modes in correlation function + power spectrum
subgrid model	mass + spatial resolution	“realism” of galaxy formation physics