Realistic initial conditions for N-Body simulations of young stellar clusters

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Young stellar clusters

$$M = 10^2 - 10^5 \mathrm{M}_\odot$$
$$\mathrm{Age} = 10 - 100 \mathrm{Myr}$$
$$\rho > 10^3 \ \mathrm{stars\ pc}^{-3}$$

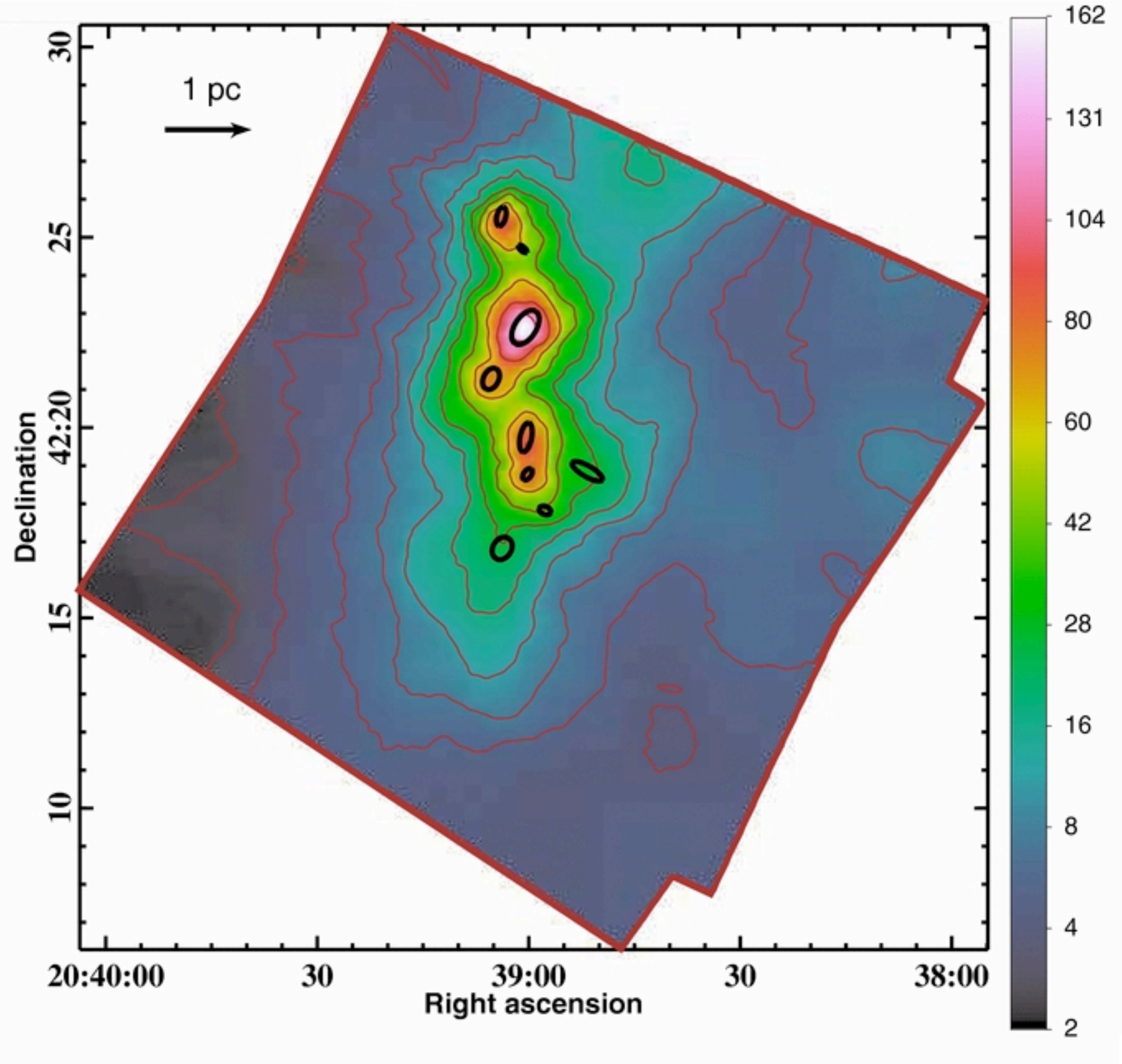
- Nurseries of massive stars (Lada & Lada 03)
- Fundamental for shaping binary populations
- Short dynamical friction timescale
  ⟶ mass segregation
- Important for the formation of stellar exotica like black holes, blue stragglers..
- Gaia BH3: the first BH belonging to a stellar cluster
  $M \sim 2 \times 10^3 - 4 \times 10^4 \mathrm{M}_\odot$ (Balbinot+24)

NASA, ESA, and P. Crowther (University of Sheffield)

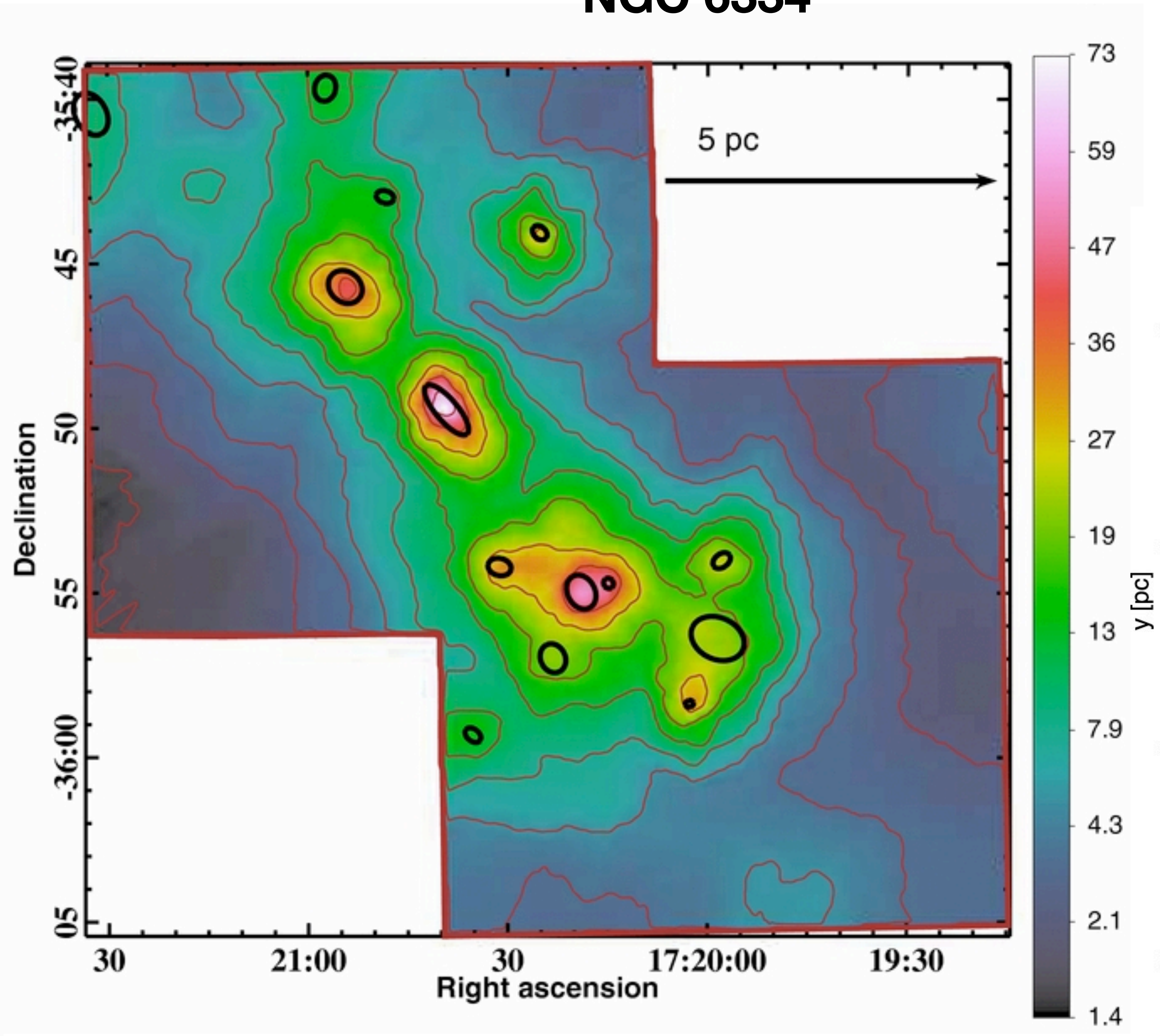
Observed star-forming regions

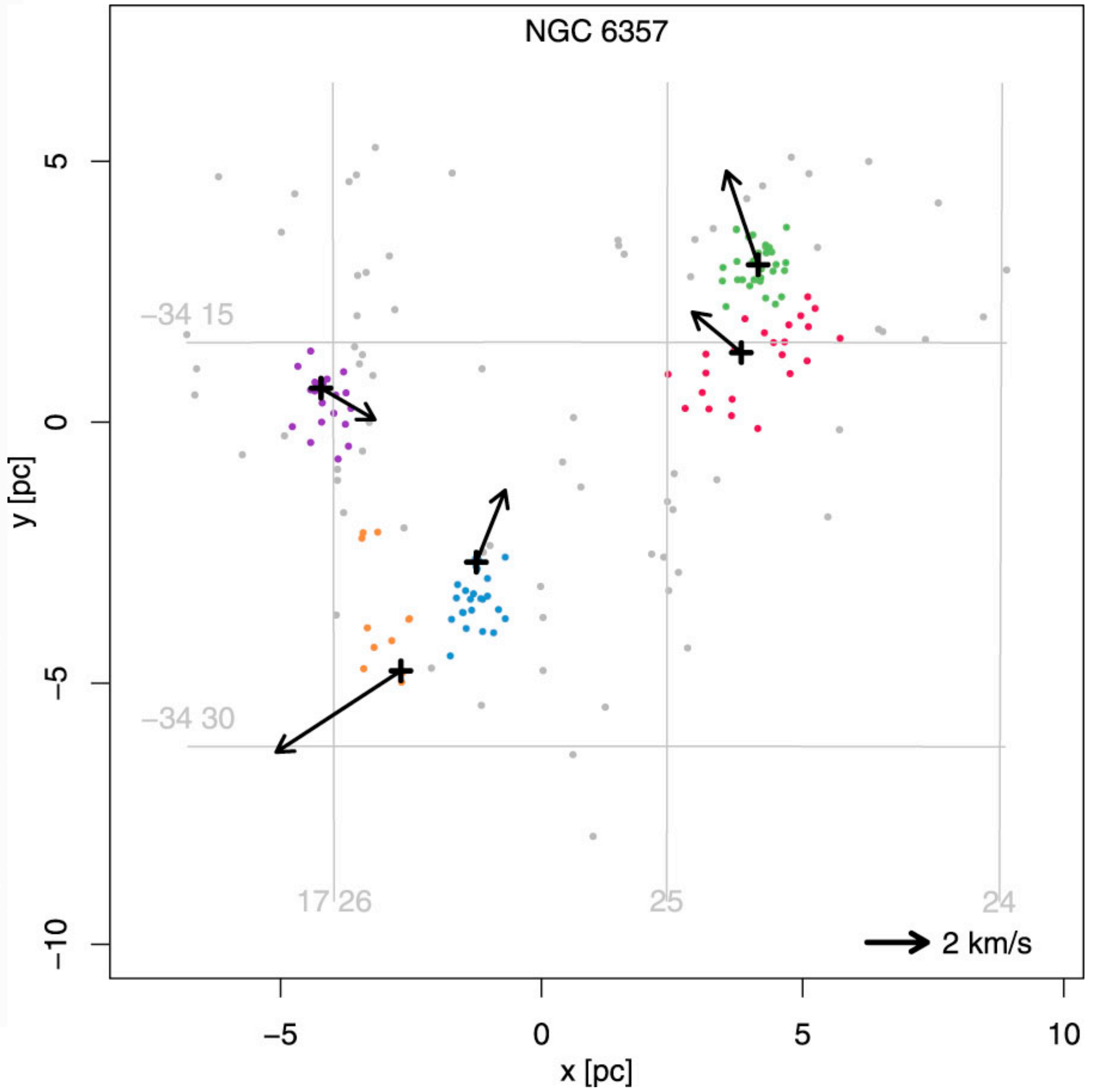
- Sub-structured
- Sub-clump motions
- Rotation
- No virial equilibrium

DR21



NGC 6334



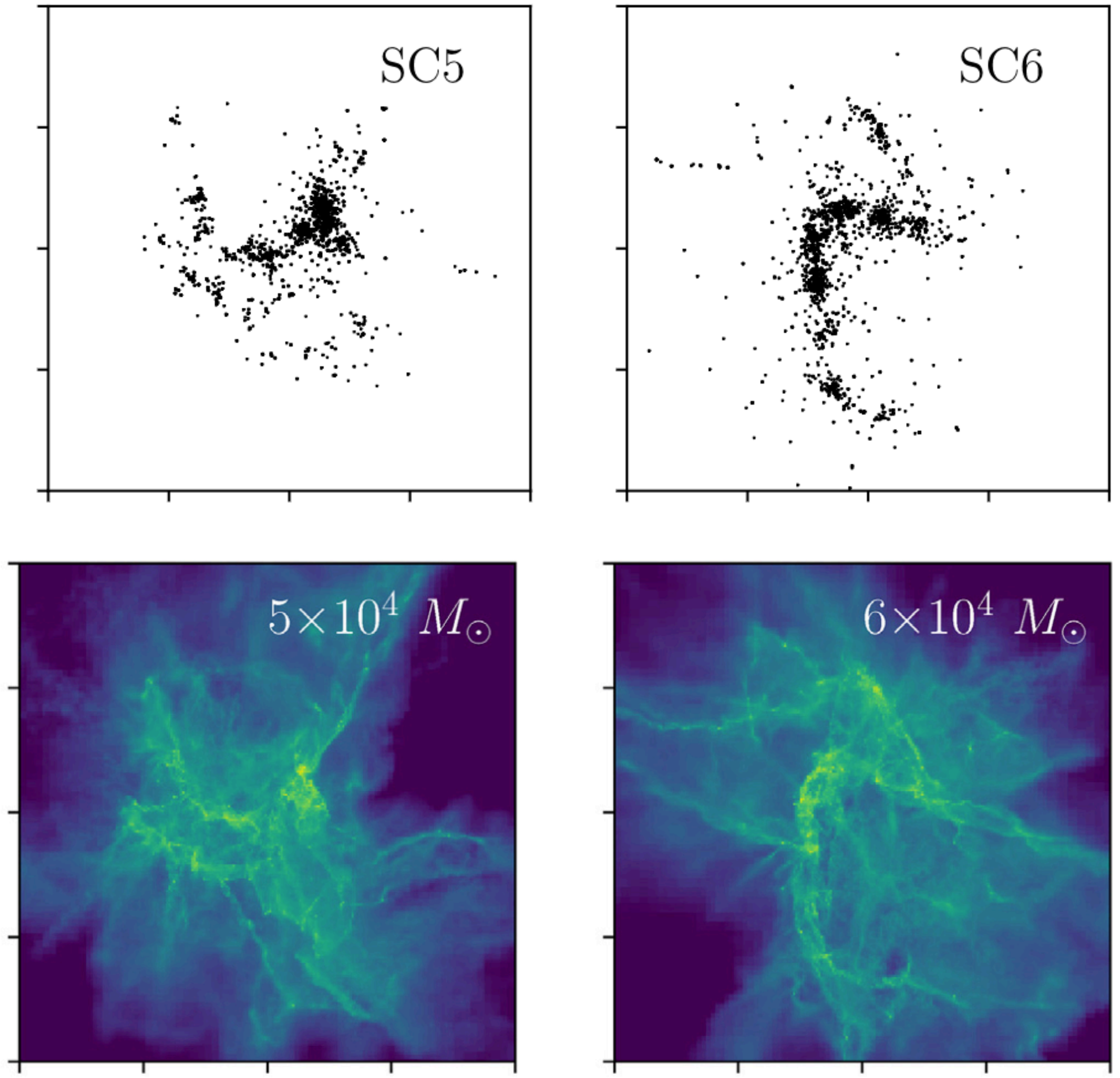


Kuhn+14

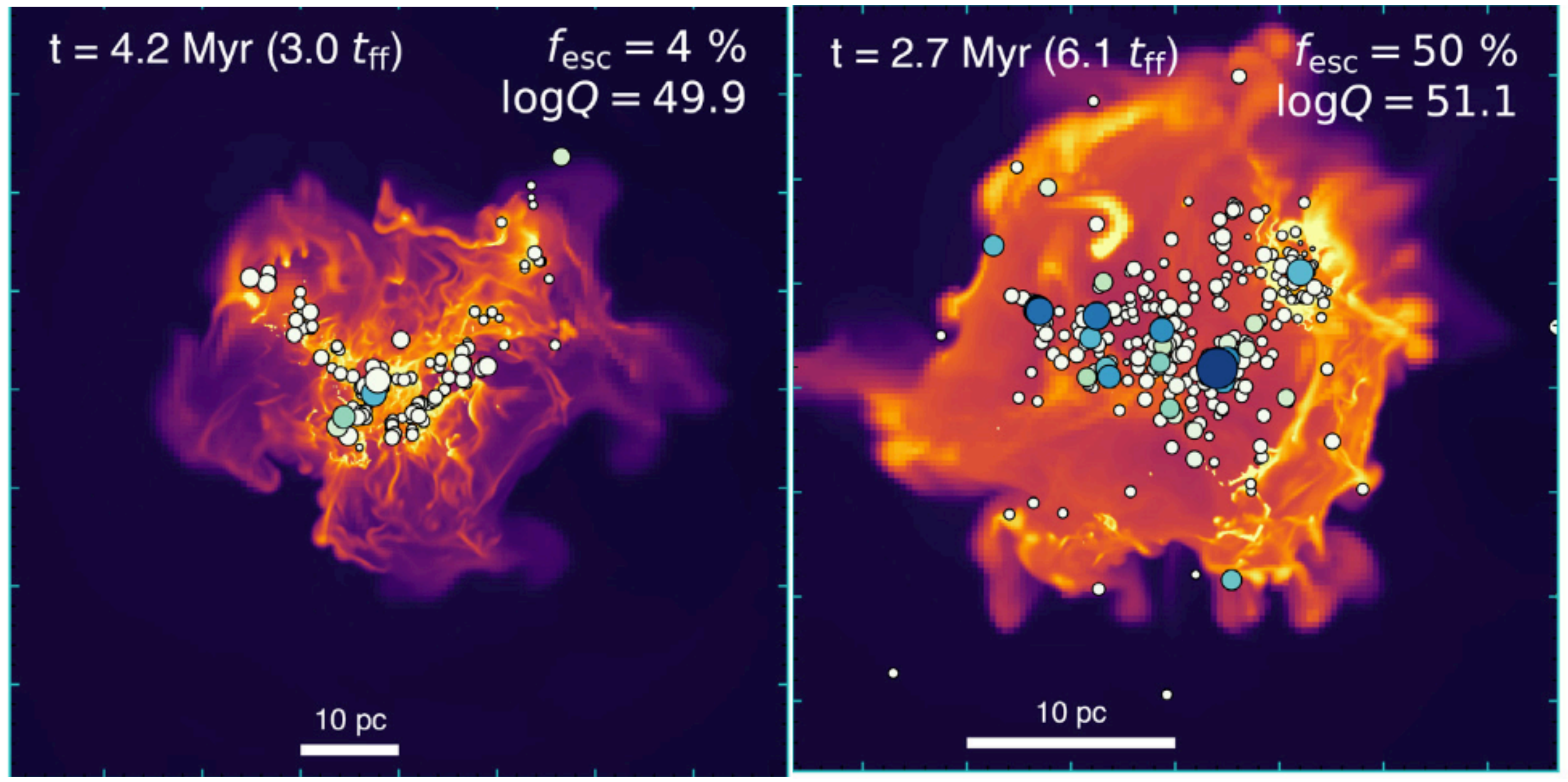
Kuhn+19

Wide range of sizes, morphologies, and numbers of stars

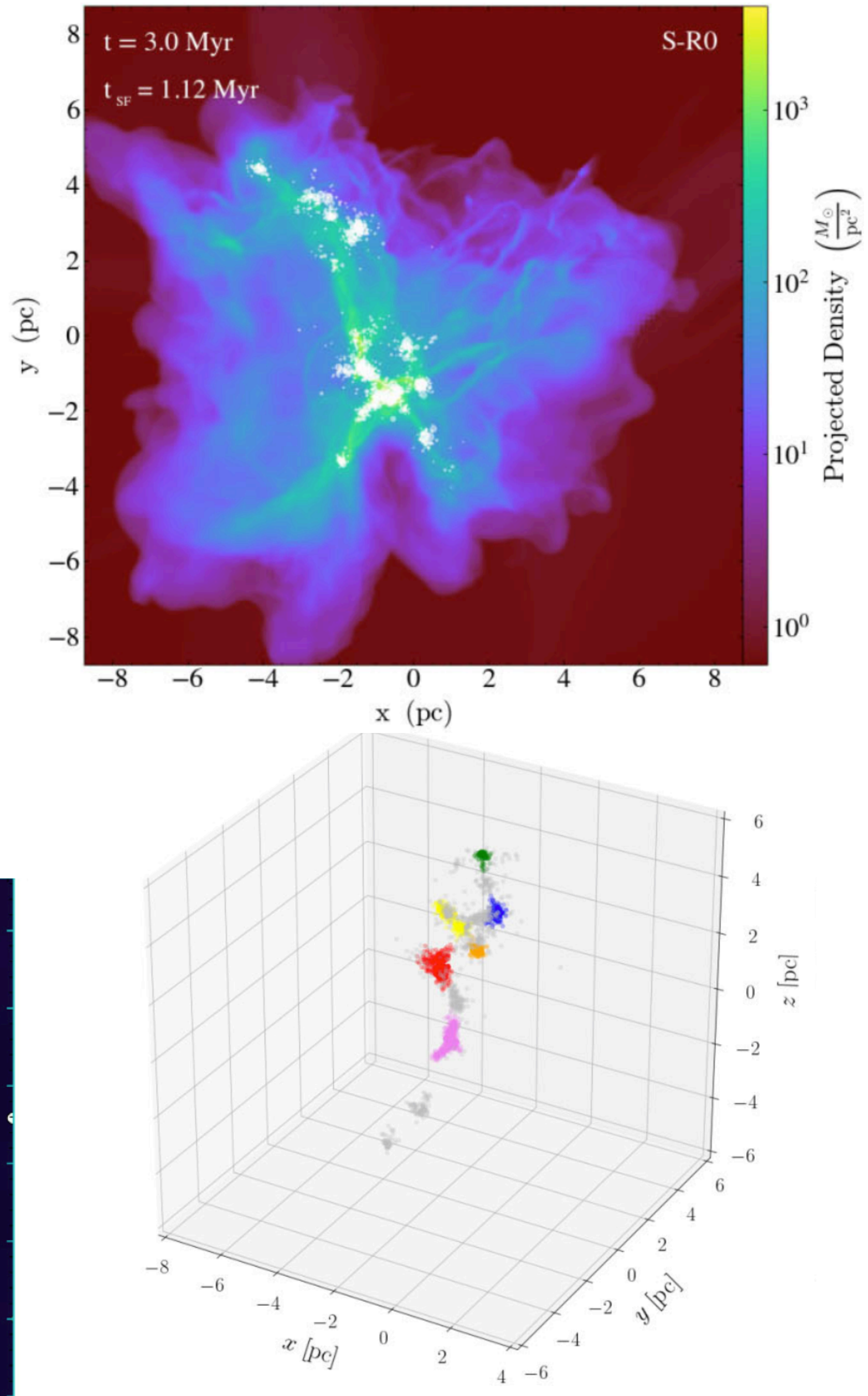
Simulated molecular clouds



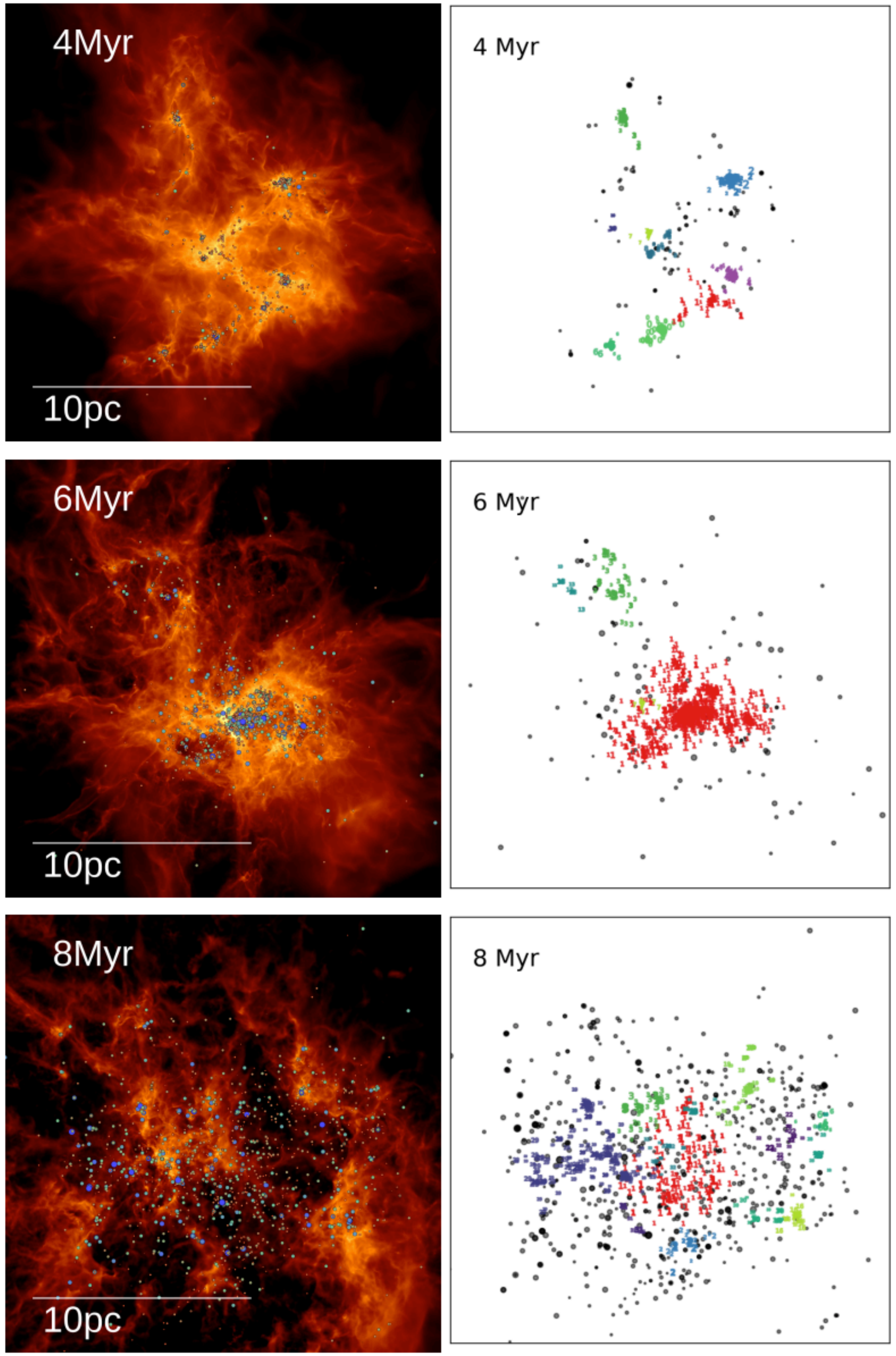
Ballone+20



He+19



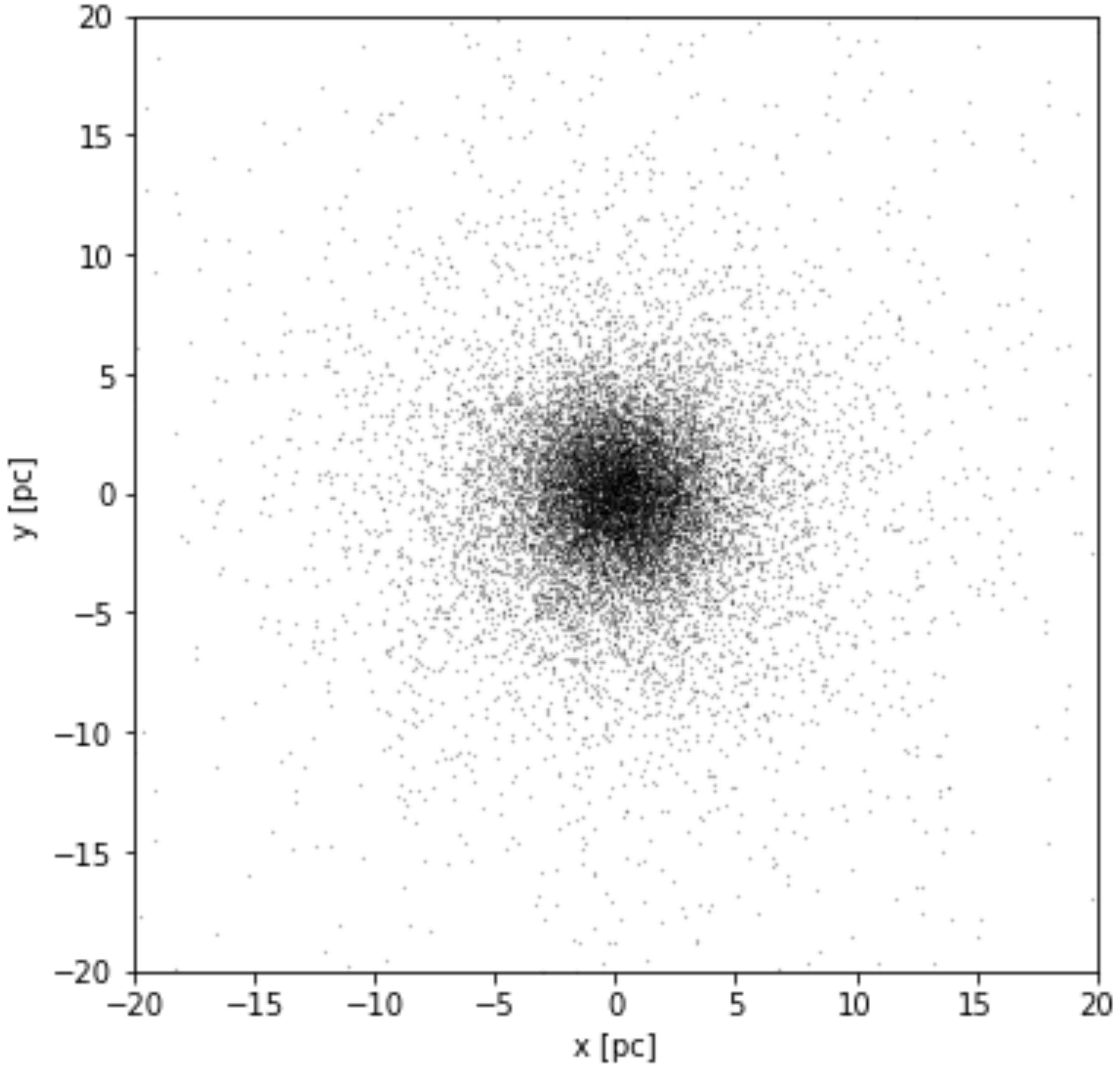
Cournoyer-Cloutier+23



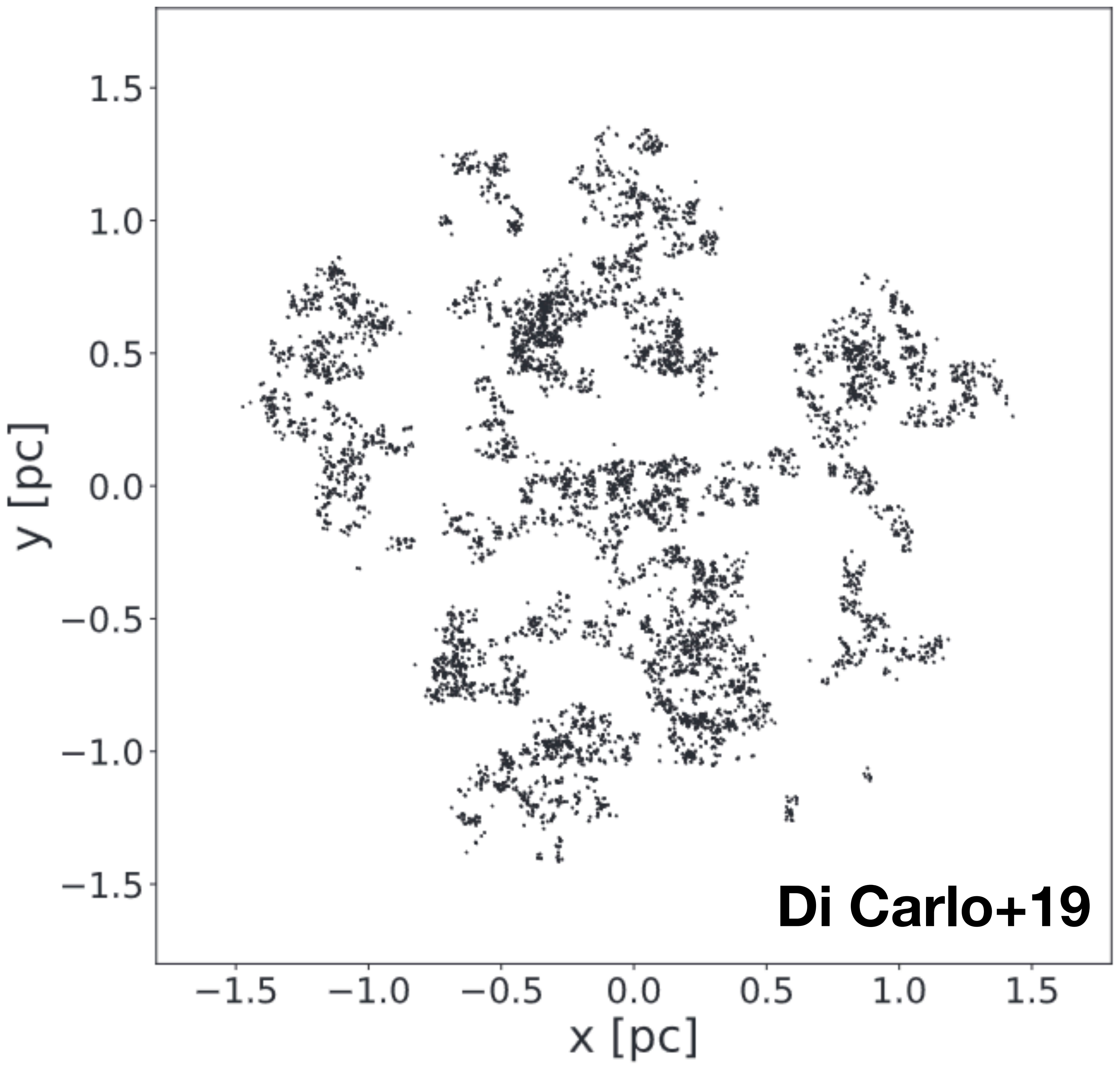
Guszejnov+22

Initial conditions for N-Body simulations

Plummer or King models

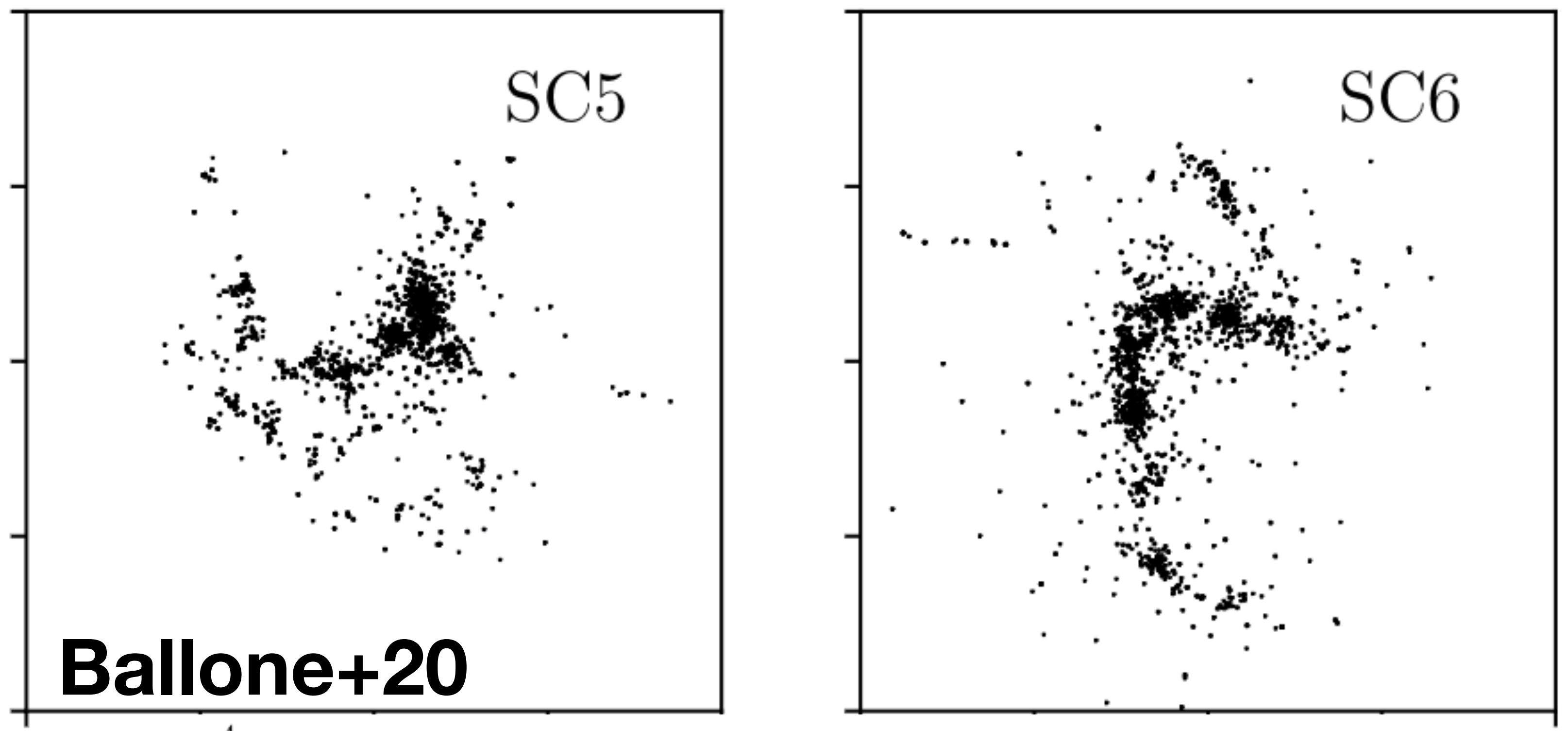


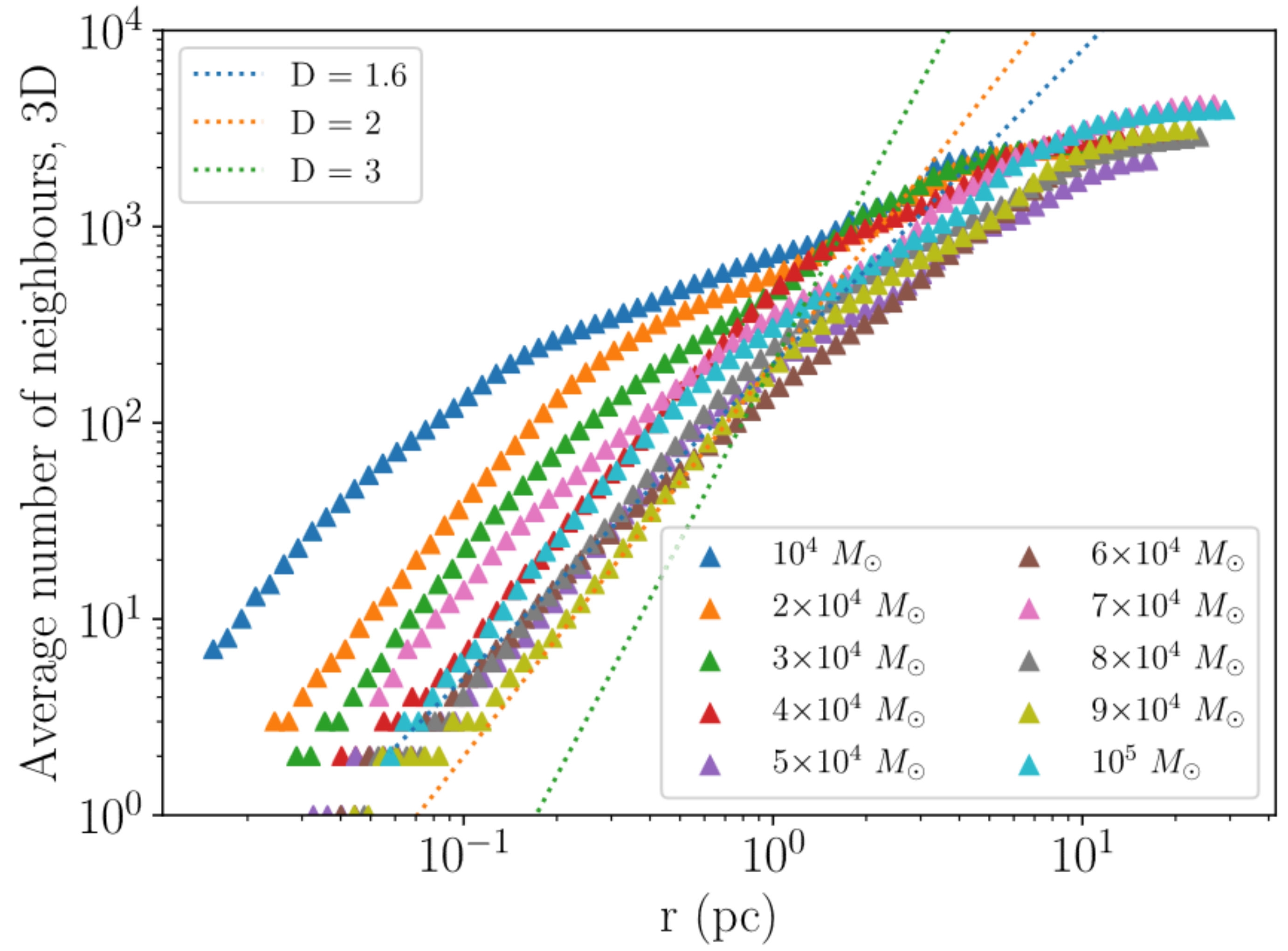
Fractal



Goodwin & Whitworth04; Schmeja & Klessen06, Allison+10; Küpper+11; Parker+14, Di Carlo+19, Rastello+19 Daffern- Powell & Parker20, Livernois+21

Hydrodynamic simulations

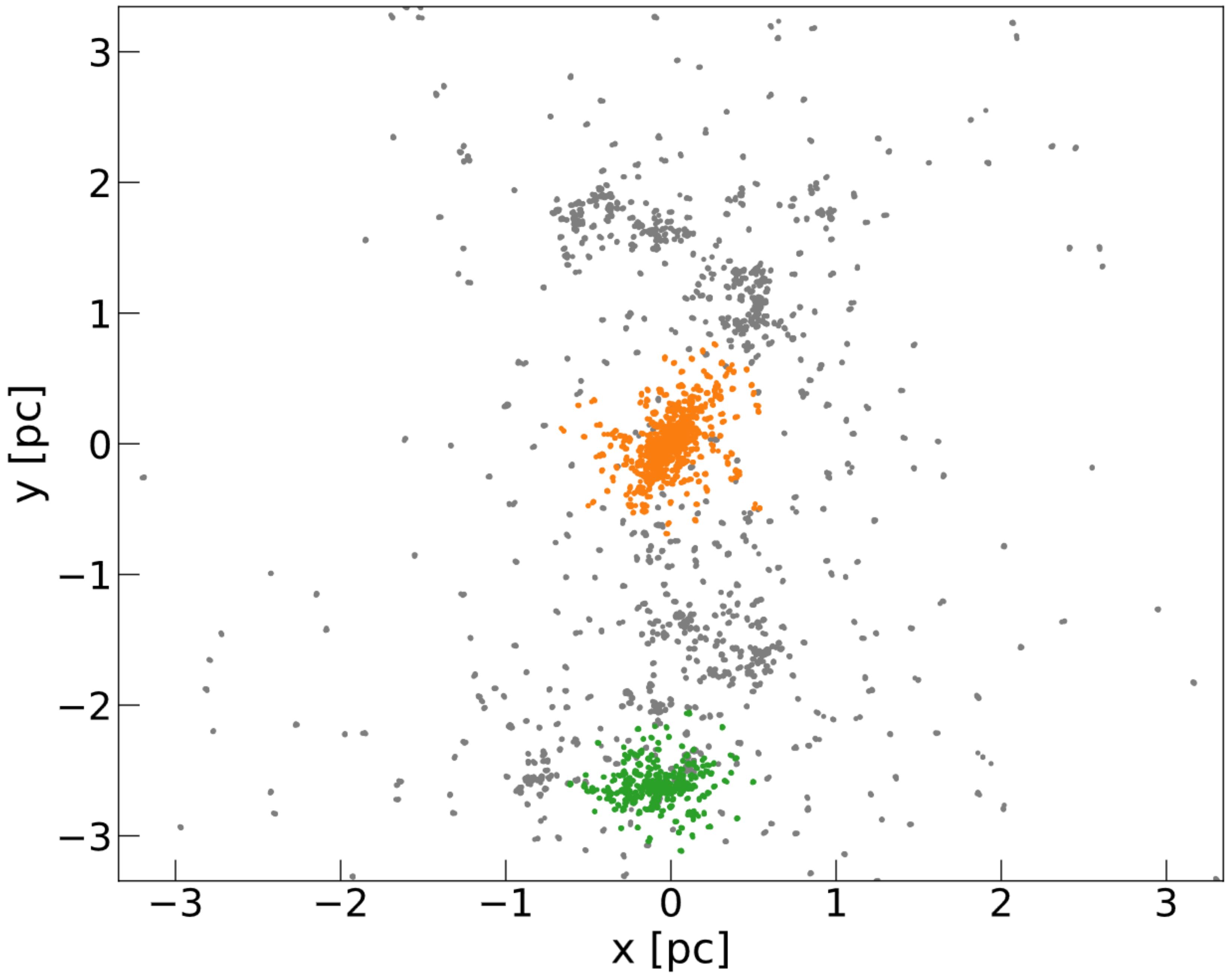


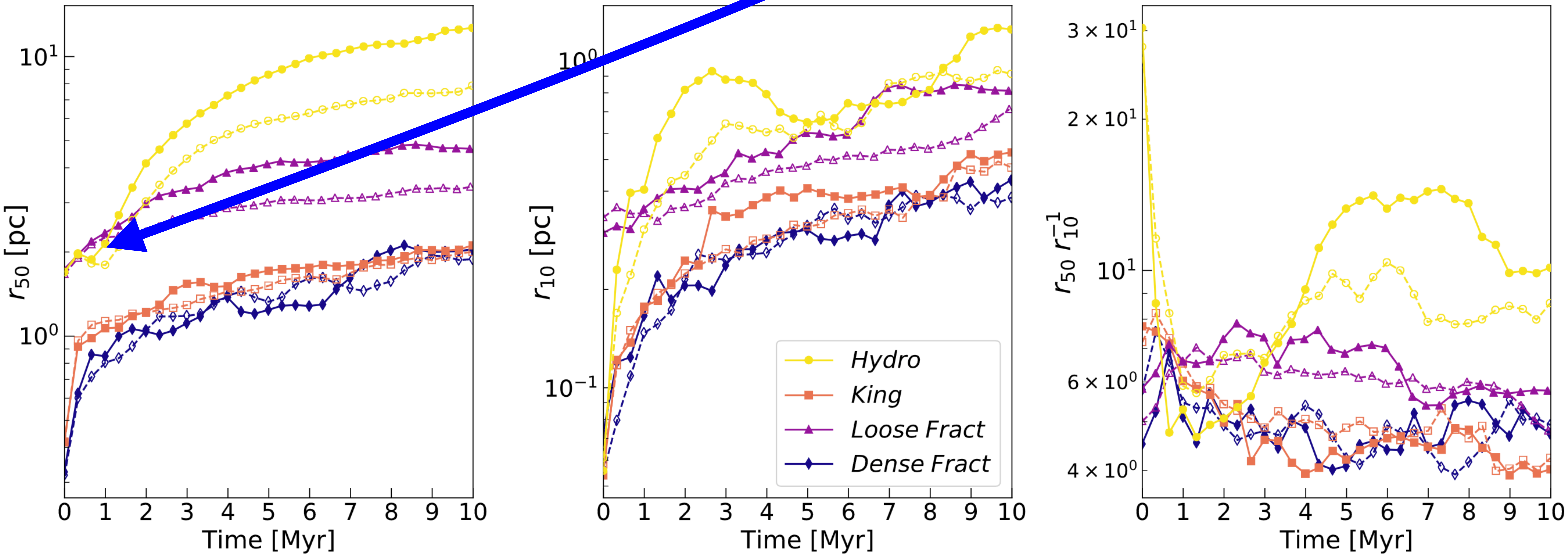


Moeckel & Bate10, Moeckel12; Parker & Dale13; Fujii & Portegies Zwart15, Ballone+21, Farias+22, Rantala+24

King vs fractal vs hydro

- Mergers between clumps delay the expansion
- Different evolution at different scales



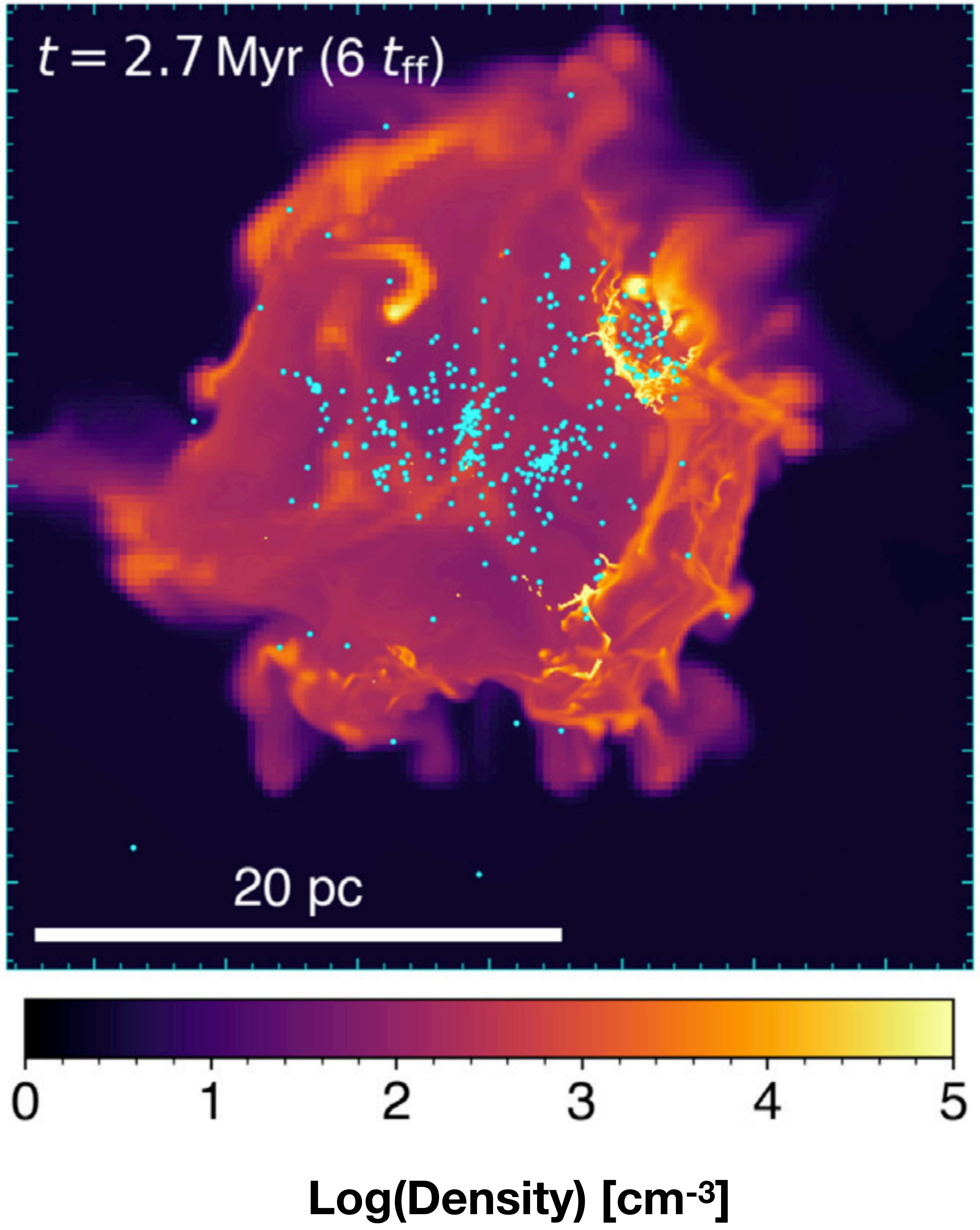


Torniamenti+21

Molecular cloud simulations

He+19

Radiation magnetohydrodynamic simulations with RAMSES (He+19)



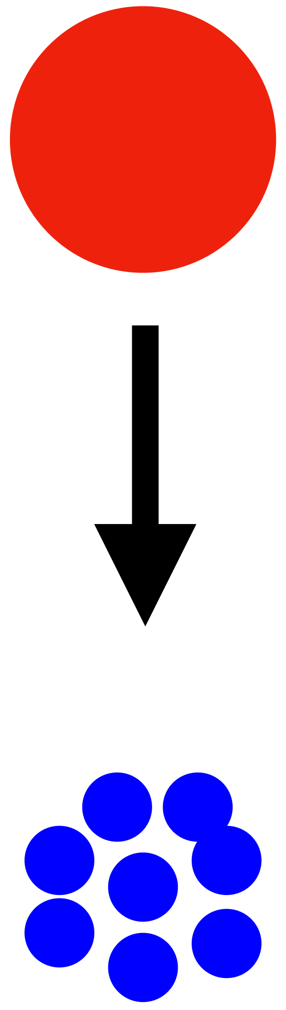
- Star formation through sink particles
- Feedback from ionizing UV radiation
- $\overline{n}_{gas} = 1.8 \times 10^4 cm^{-3}$
- $M_\star = 10^{3-4} M_\odot$

Simulations evolved for ~ 10 t_{ff}, IC taken at 2-3Myr after the onset of SF

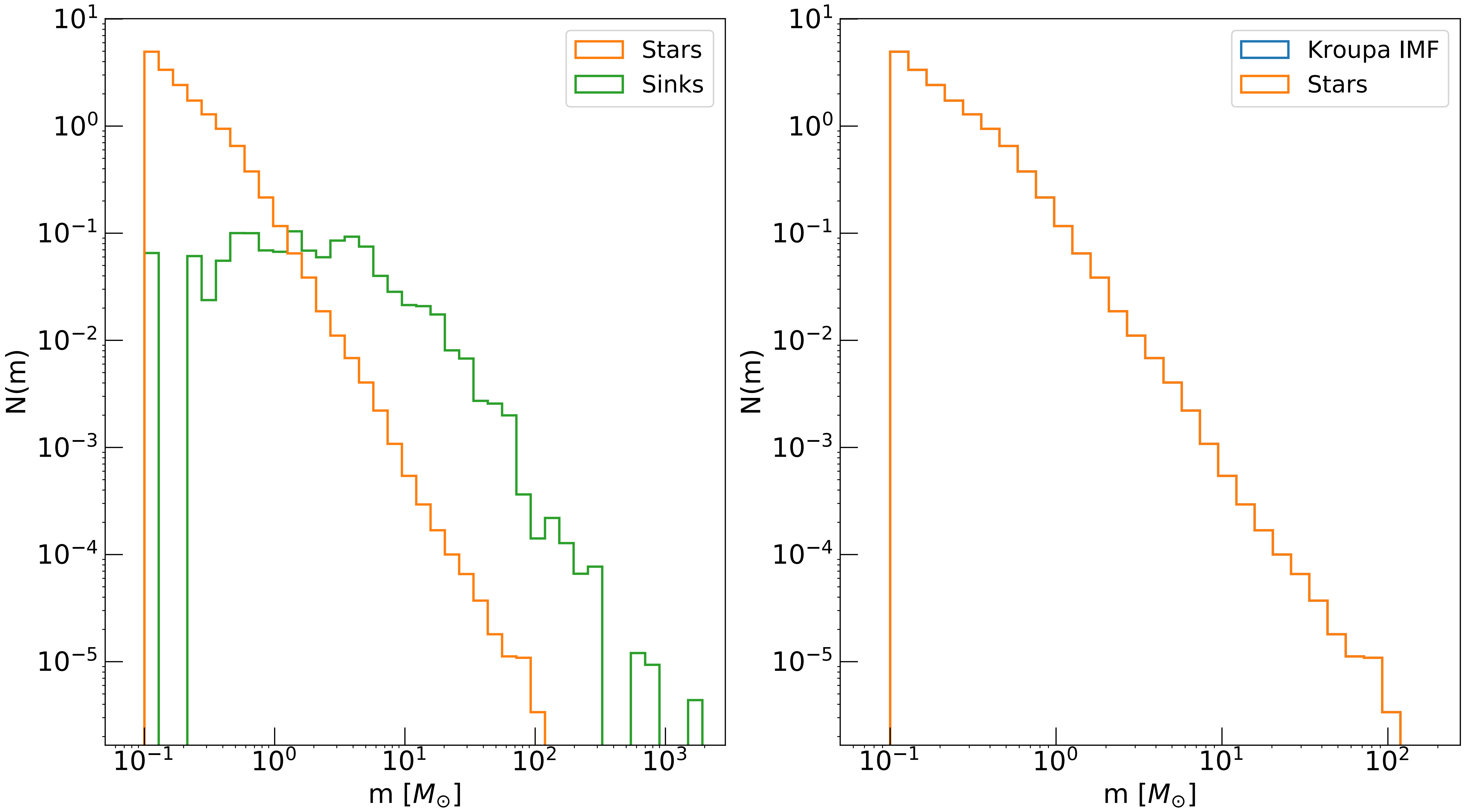
From sink MF to realistic IMF

Joining-splitting algorithm (Ballone+20)

- Stars distributed following an IMF with Mstars=Msinks
- Sinks are joined or split to produce stars inheriting the position and velocity of their parent sinks.



Plummer distribution in virial eq. around the position of the sink



Wang+20 PETAR

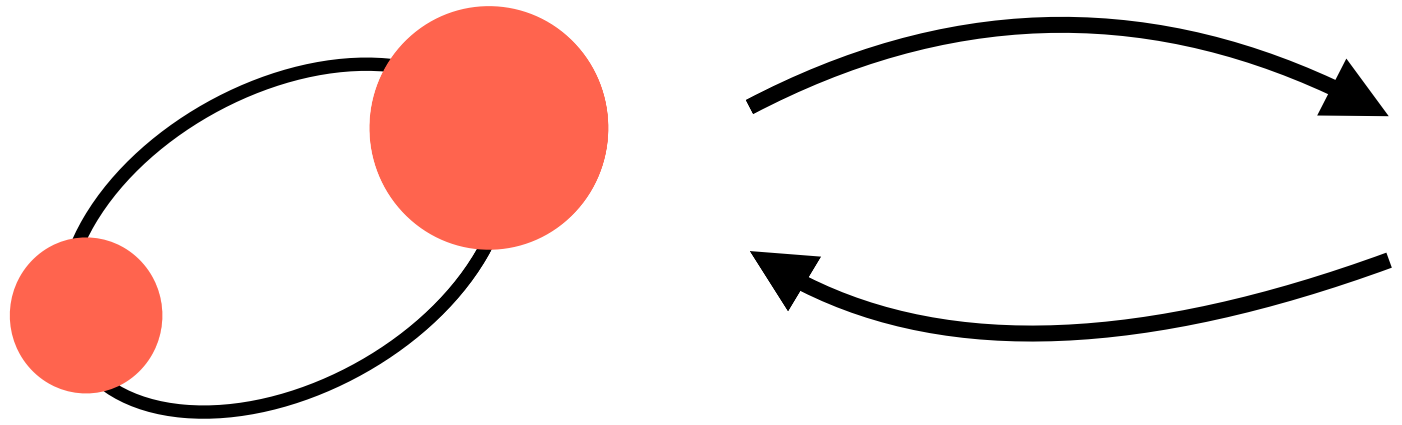
SEvN Iorio+23

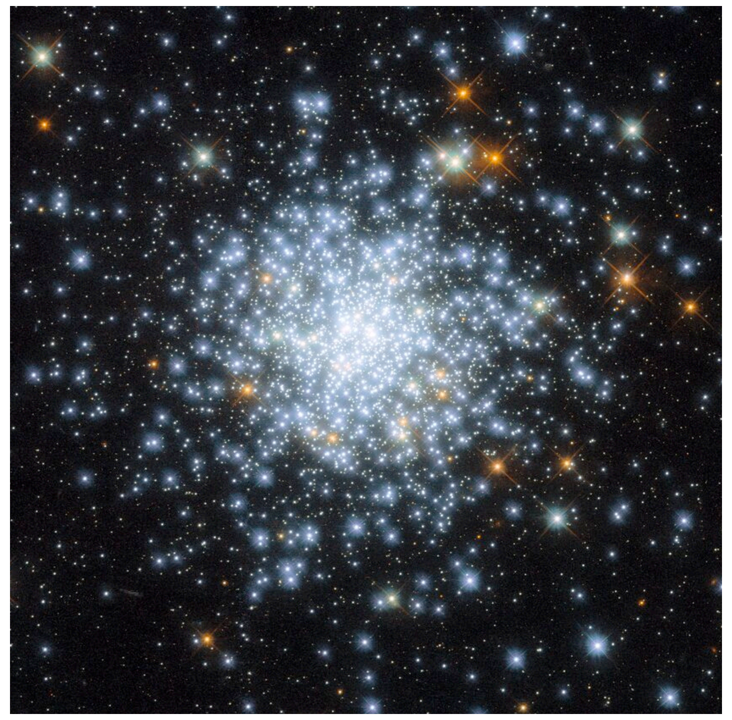
N-Body designed for modelling multiples and close encounters

- Long-range forces : Barnes–Hut particle tree
- Short range forces :
  - Fourth-order Hermite for stars and the centers-of-mass of multiple systems
  - Slow down algorithmic regularization for close-distance multiple systems

Rapid binary population synthesis code

- On-the fly interpolation of pre-evolved stellar tracks (available PARSEC (Bressan+12) and MIST (Choi+16))
- Binary evolution prescriptions are based on analytic and semi-analytic formulas
- Easy to change stellar evolution prescriptions by substituting the stellar tracks





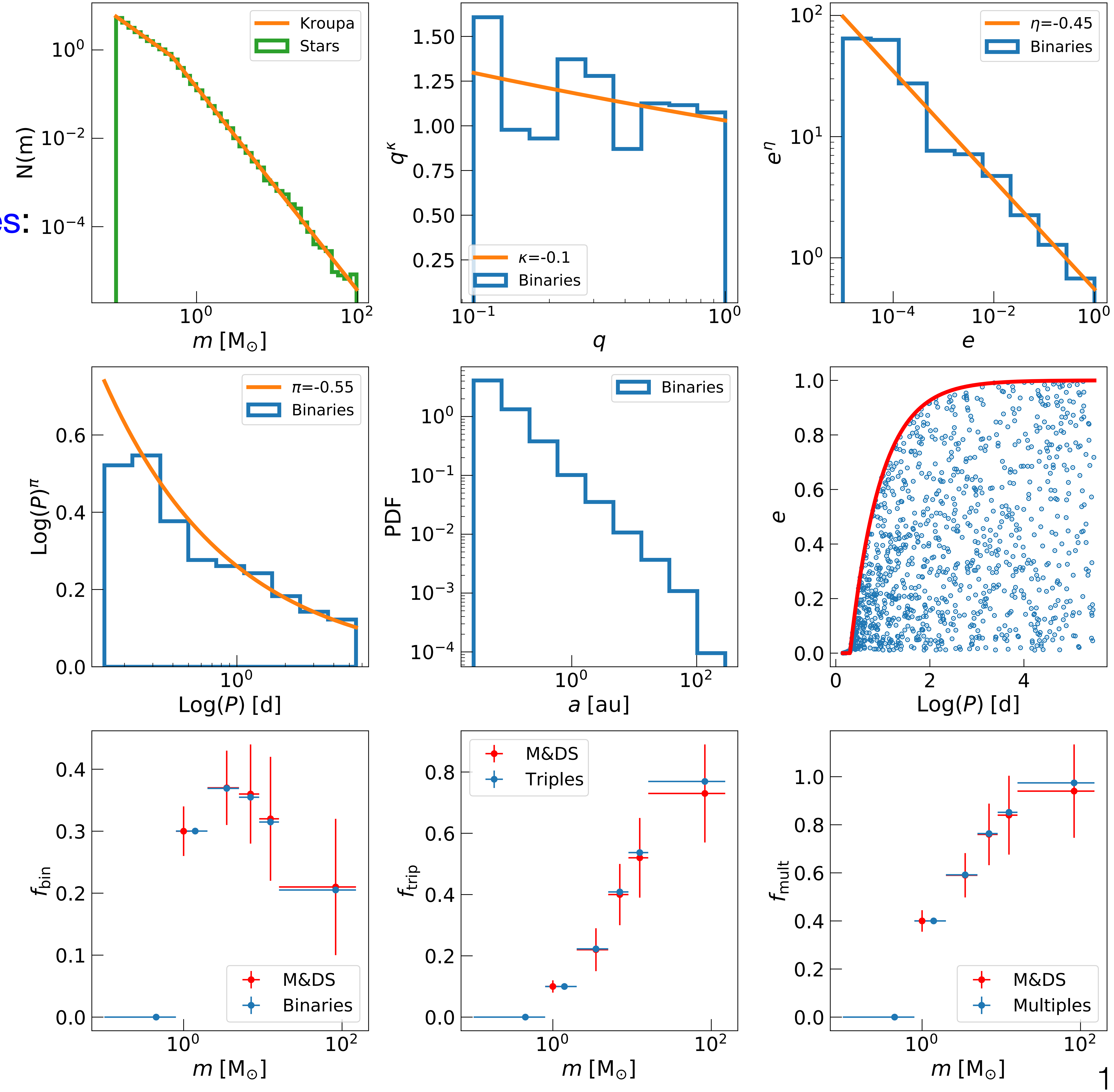
Important to explain the properties of the binary compact objects

Setup

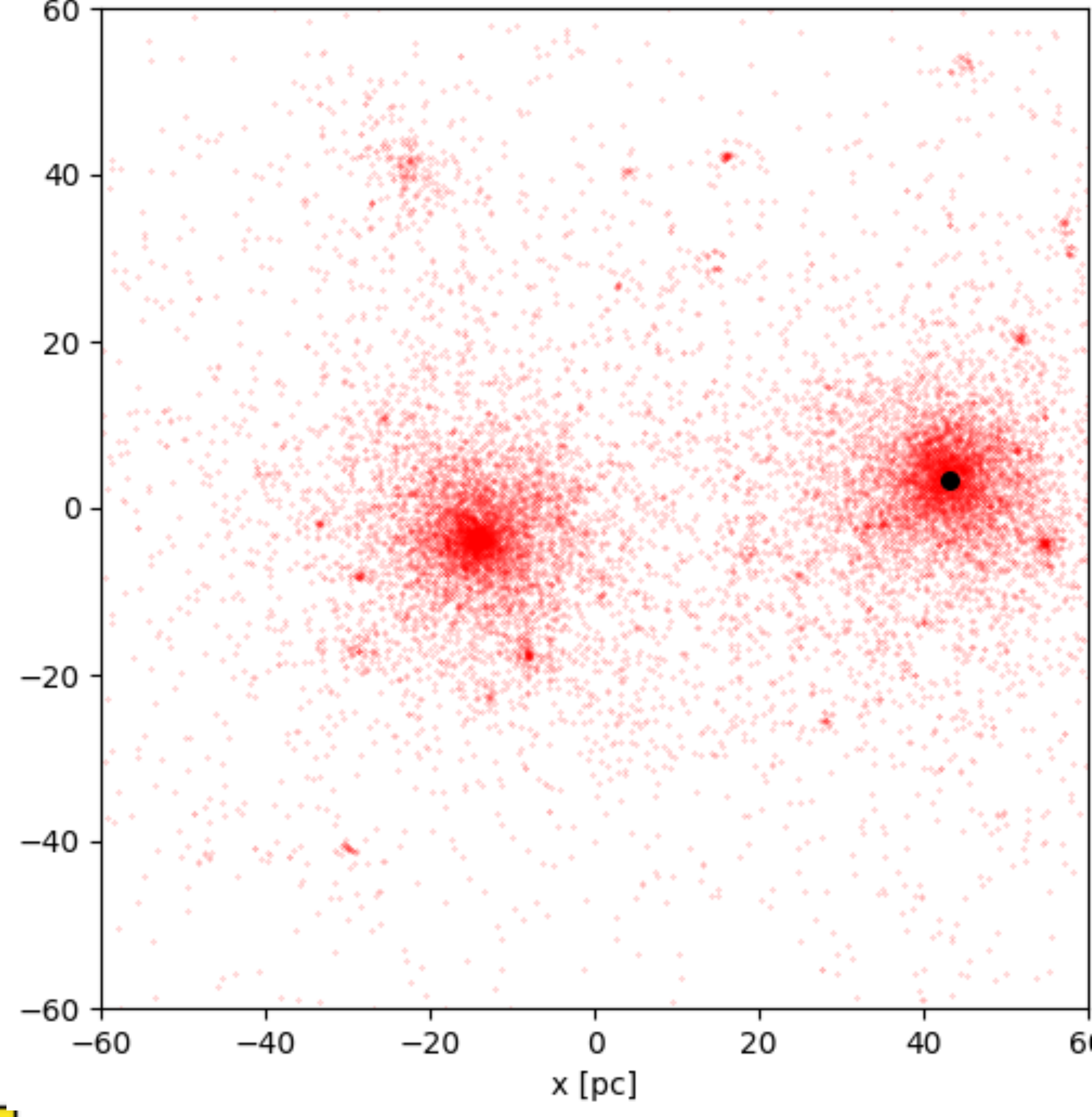
- Observational based binary population properties:
    - q, e and P distributed following Sana+12
    - $e_{max}(P), f_{bin}, f_{trip}$ from Moe & di Stefano 17

- External potentials with GALPY (Bovy15):
    - Galactic potential
    - Exponentially decaying gas potential

- Stellar and binary evolution with MOBSE and SEVN (Mapelli17, Iorio+23)



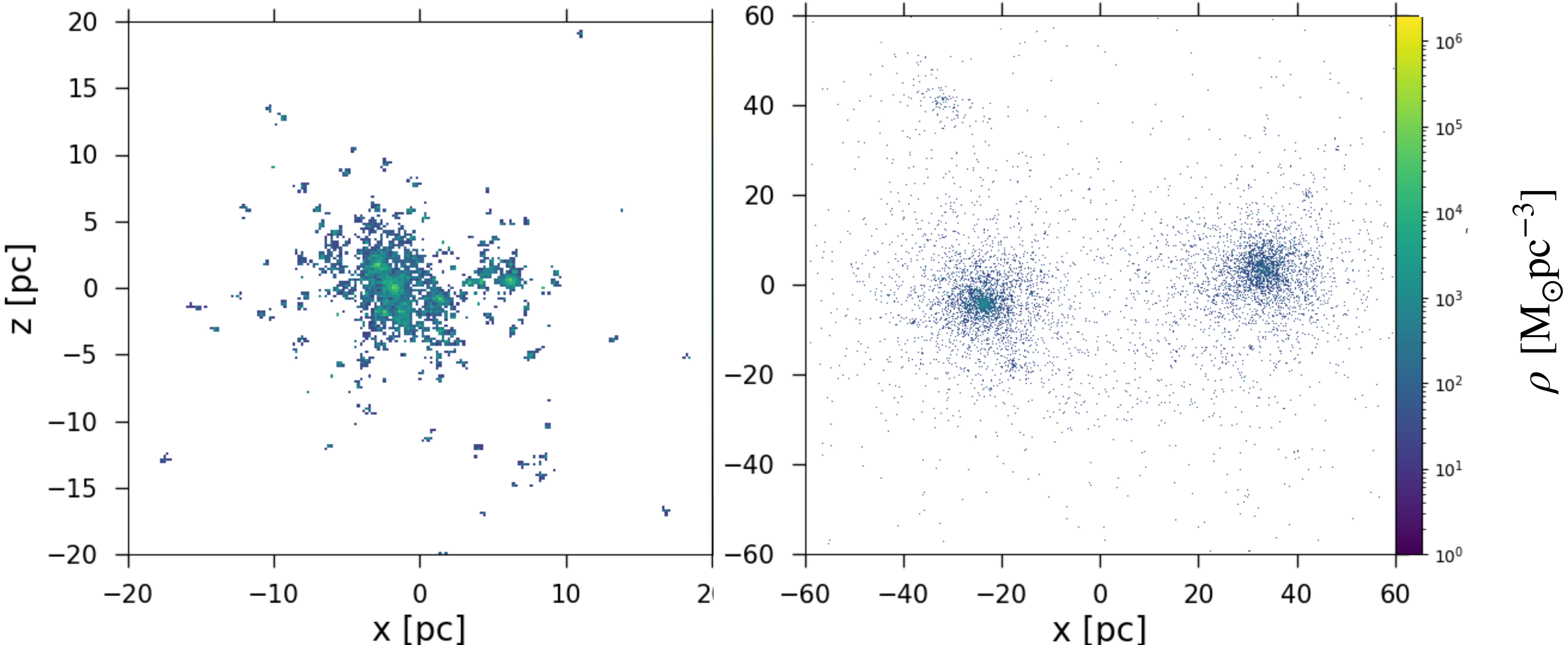
Density distribution



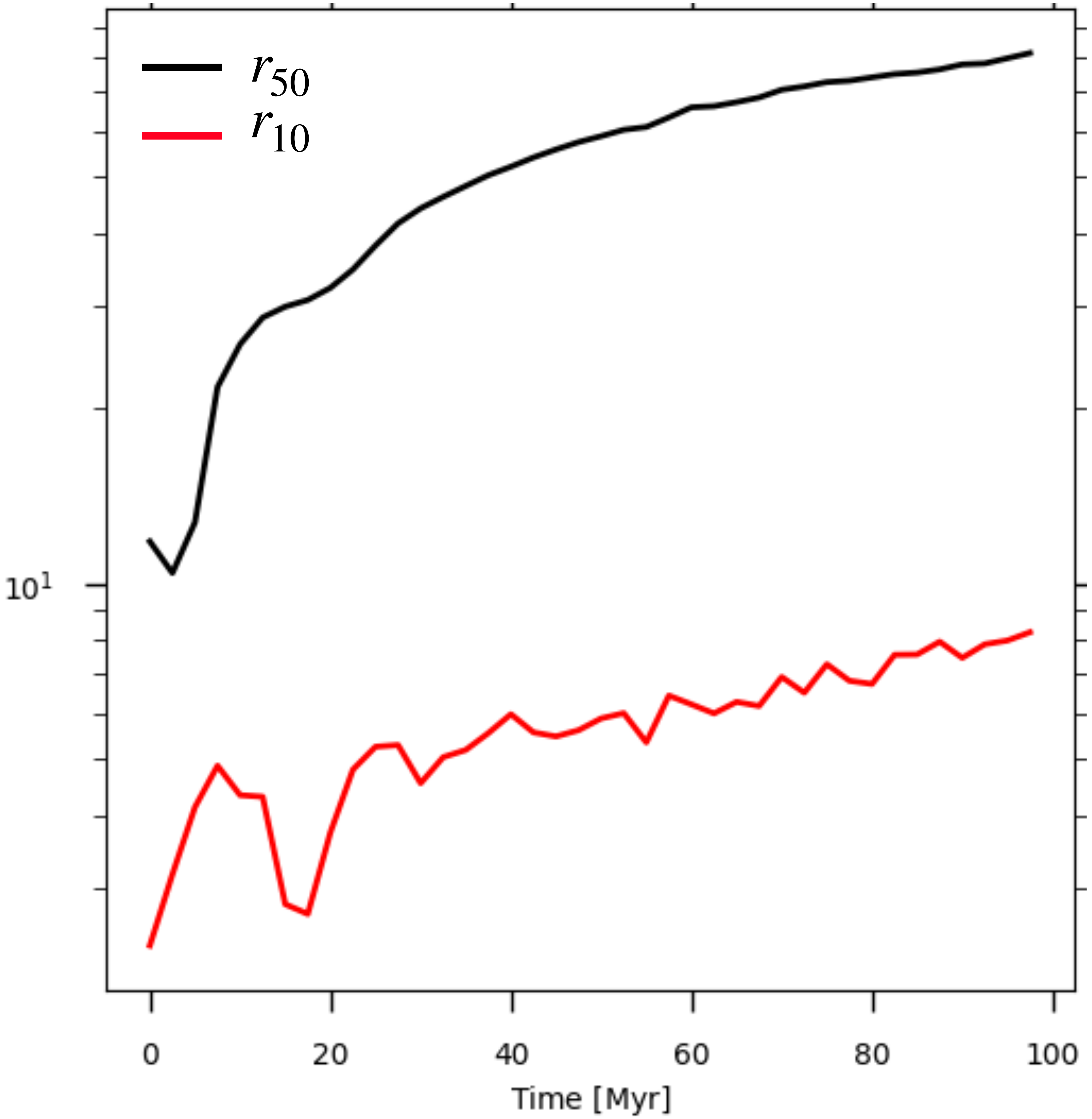
Initially several dense clumps that then merge and survive for 100Myr

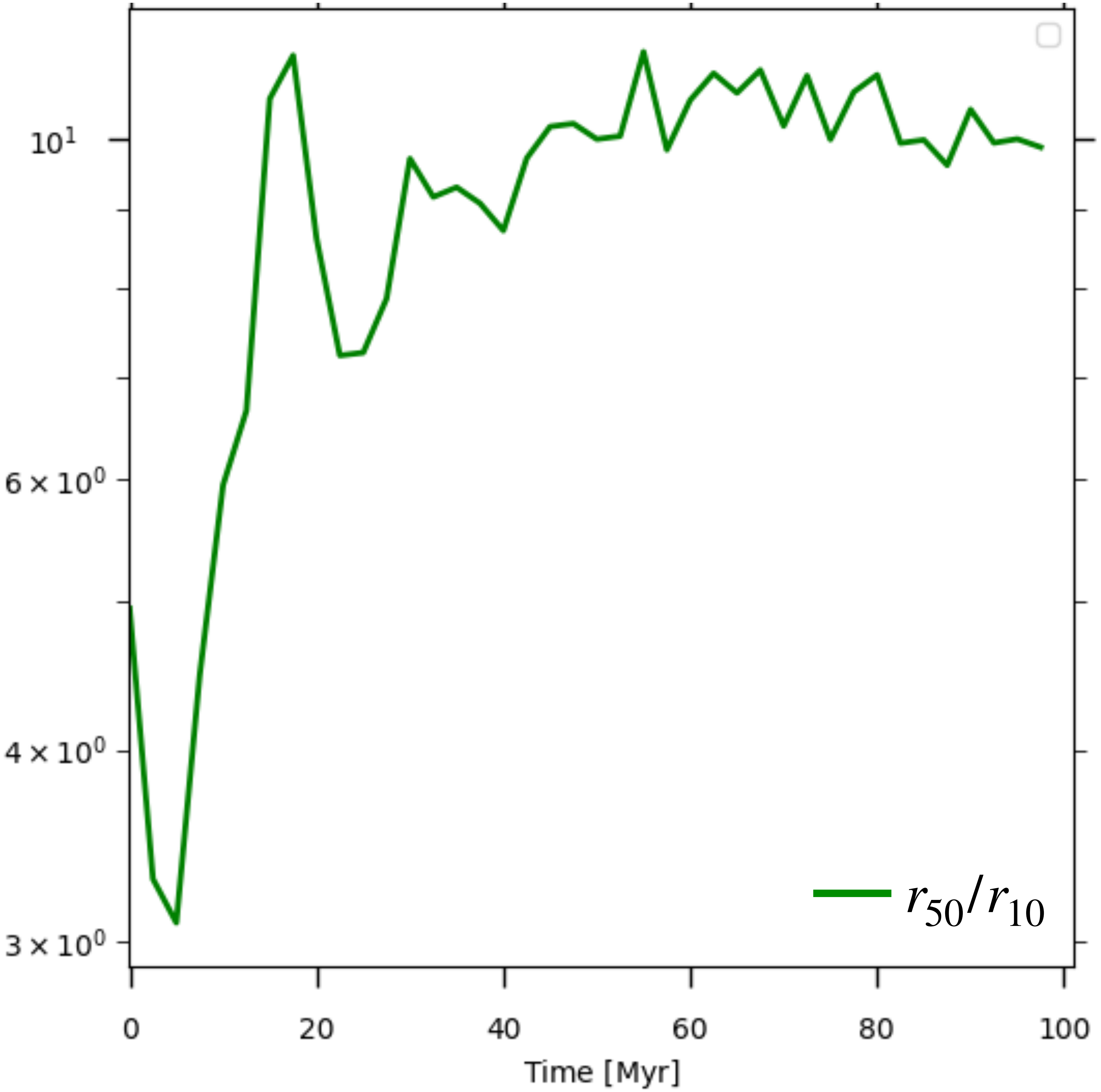
Time 0 Myr

Time 100Myr



Evolution of the cluster





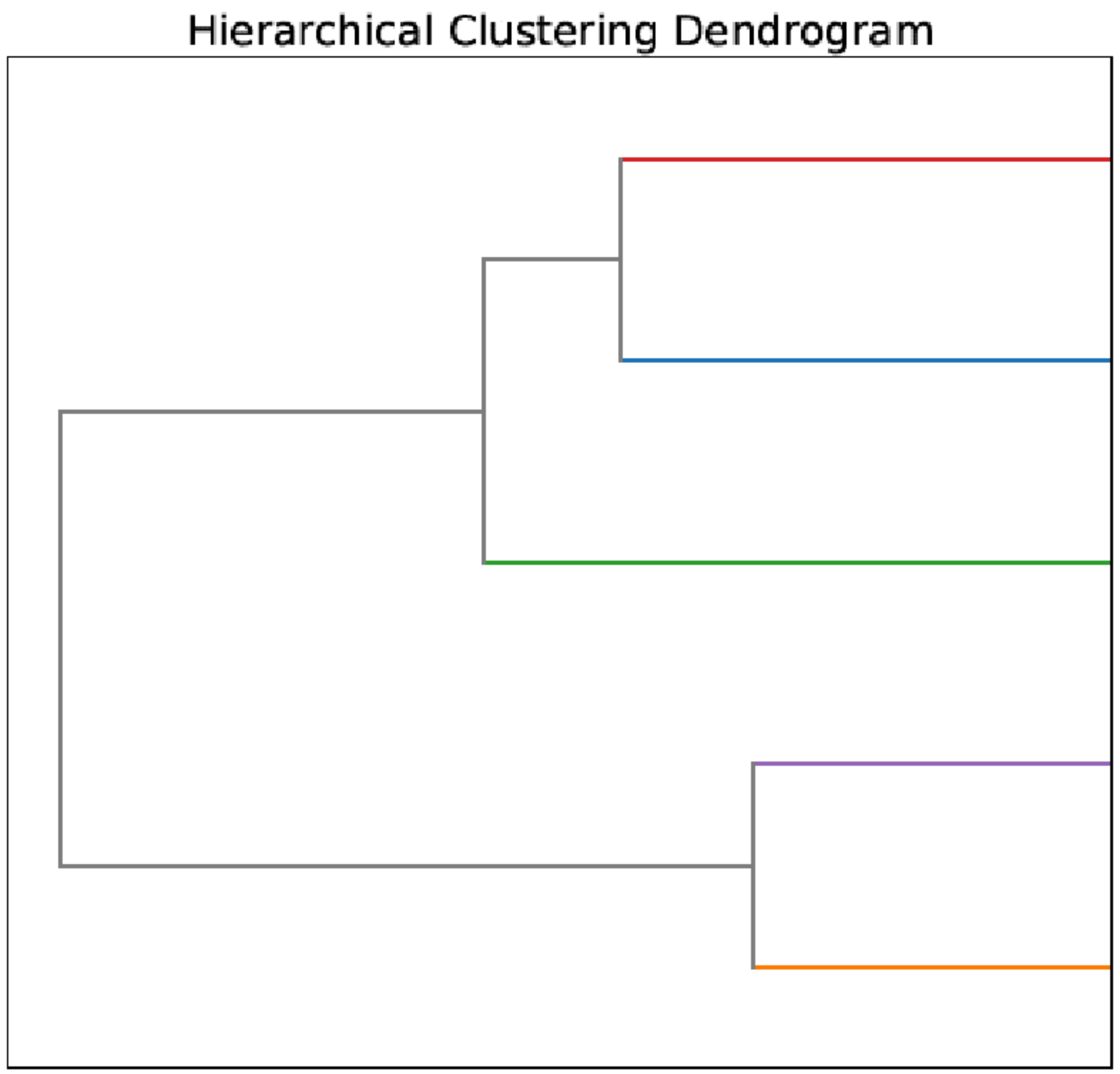
Hierarchical generative algorithm

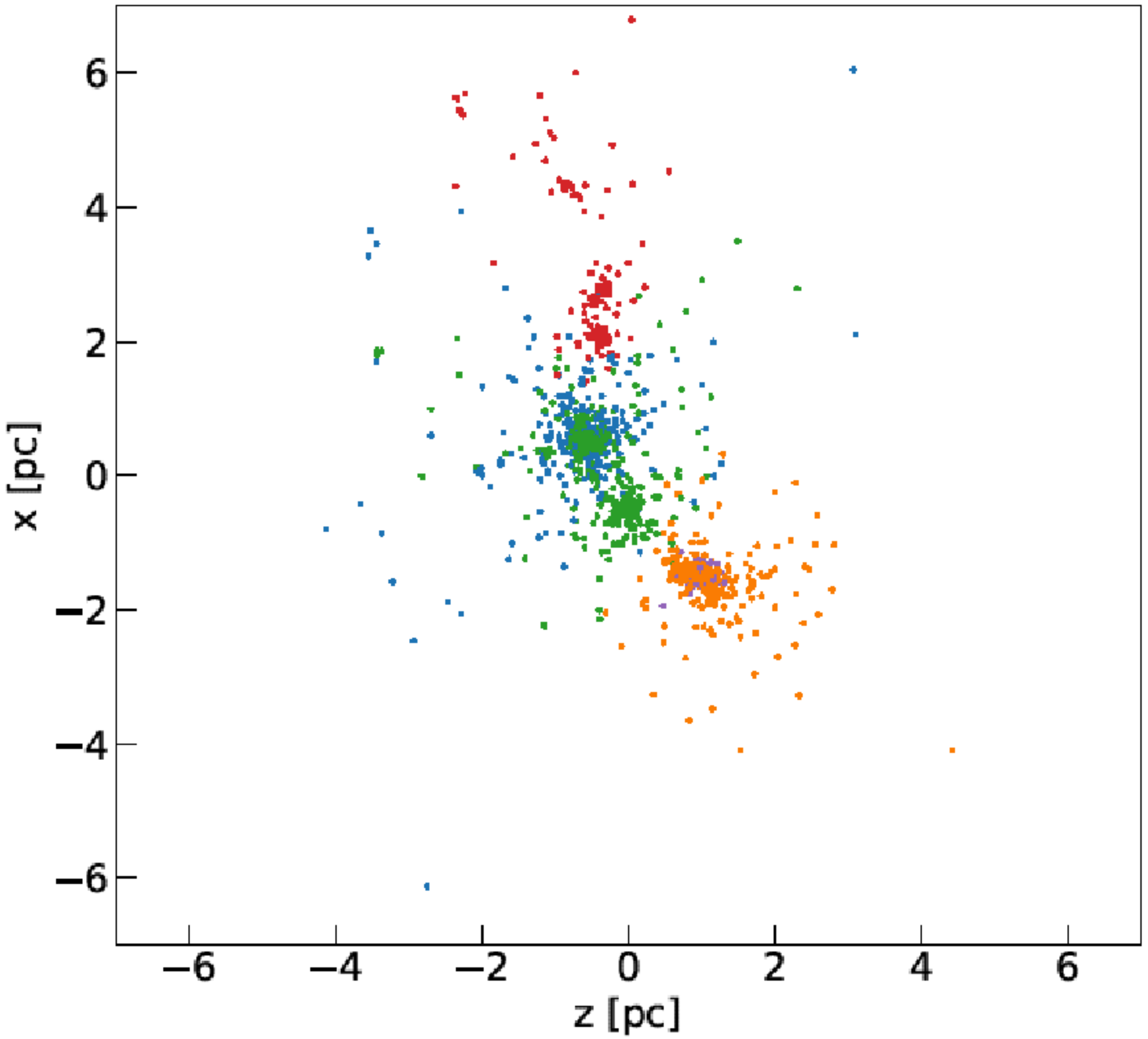
Create multiple realizations maintaing the small scale structure

Torniamenti+22

At every node is associated:

- Distance l
- Relative velocity u
- Mass ratio q





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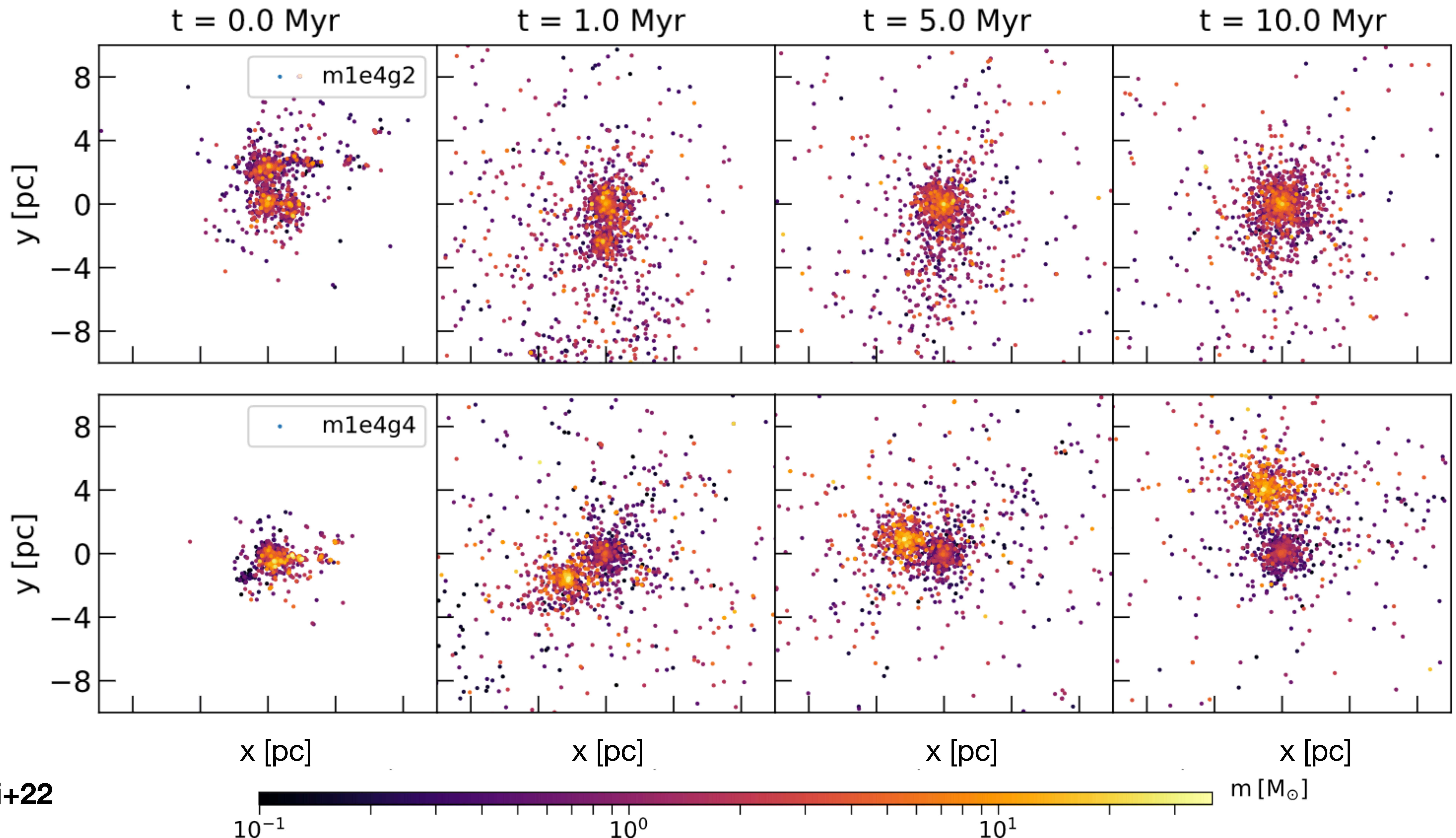

Torniamenti+22

Summary

- **Hydrodynamic simulations offer realistic initial conditions for N-Body simulations**

- **When star formation is modelled through sinks a splitting-joining algorithm can be used to generate the initial conditions**

- **Hierarchical generative algorithm allows to create new realizations maintaing the small scales while changing the large scales**

- **These tools are used to study the formation and evolution of BH in young stellar clusters**

Credits: ESO/WFI/2.2-m MP
Northwestern Visualization/Carl Rodriguez