Small but Mighty: The Formation of Globular Clusters in Cosmological Simulations

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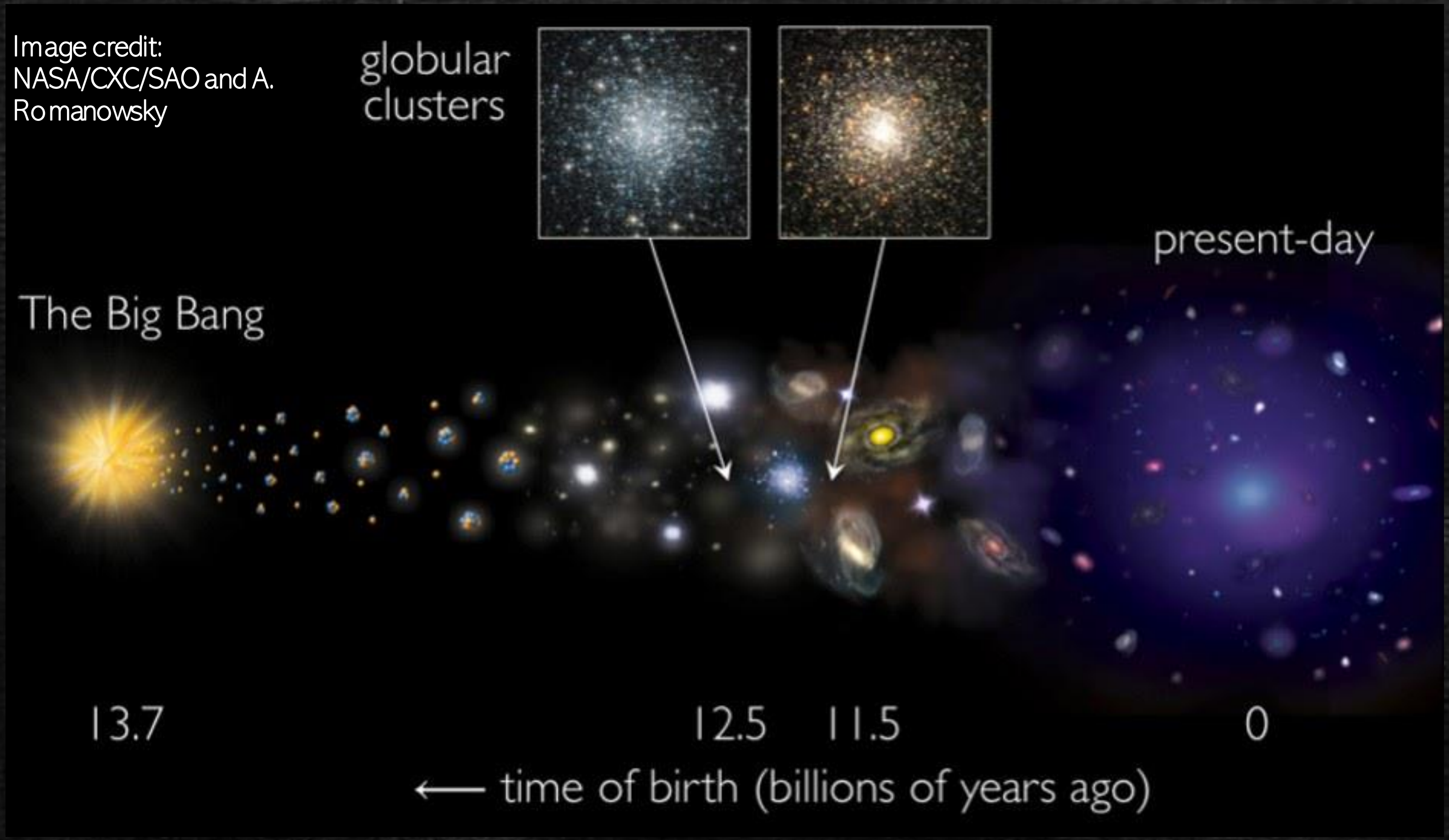
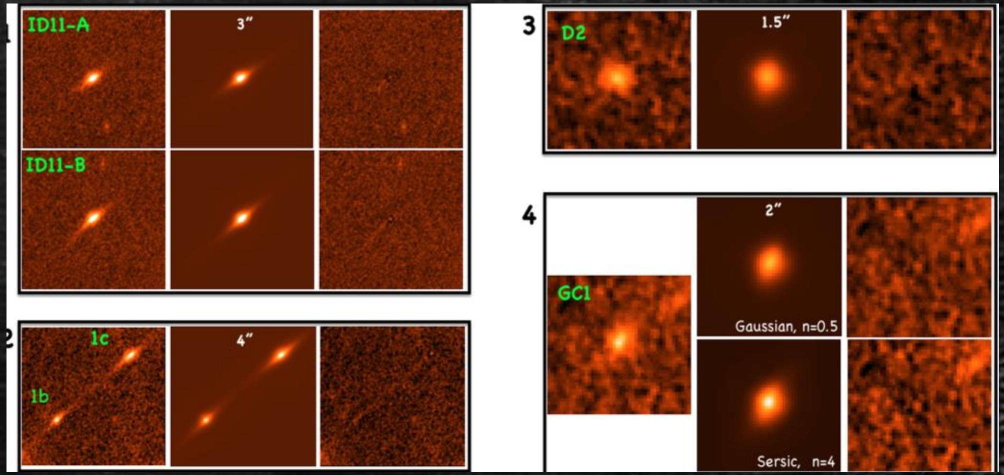
Motivation and The FiBY Simulations

OUTLINE:
We explore a suite of high-resolution cosmological simulations at high redshift to investigate theoretical scenarios concerning the formation of old, low-mass stellar systems with a focus on globular clusters (GCs).

FiBY SIMULATIONS:
The First Billion Years (FiBY) simulations are high-resolution cosmological SPH simulations. They track metal pollution and include SN feedback and formation of both Pop II / III stars

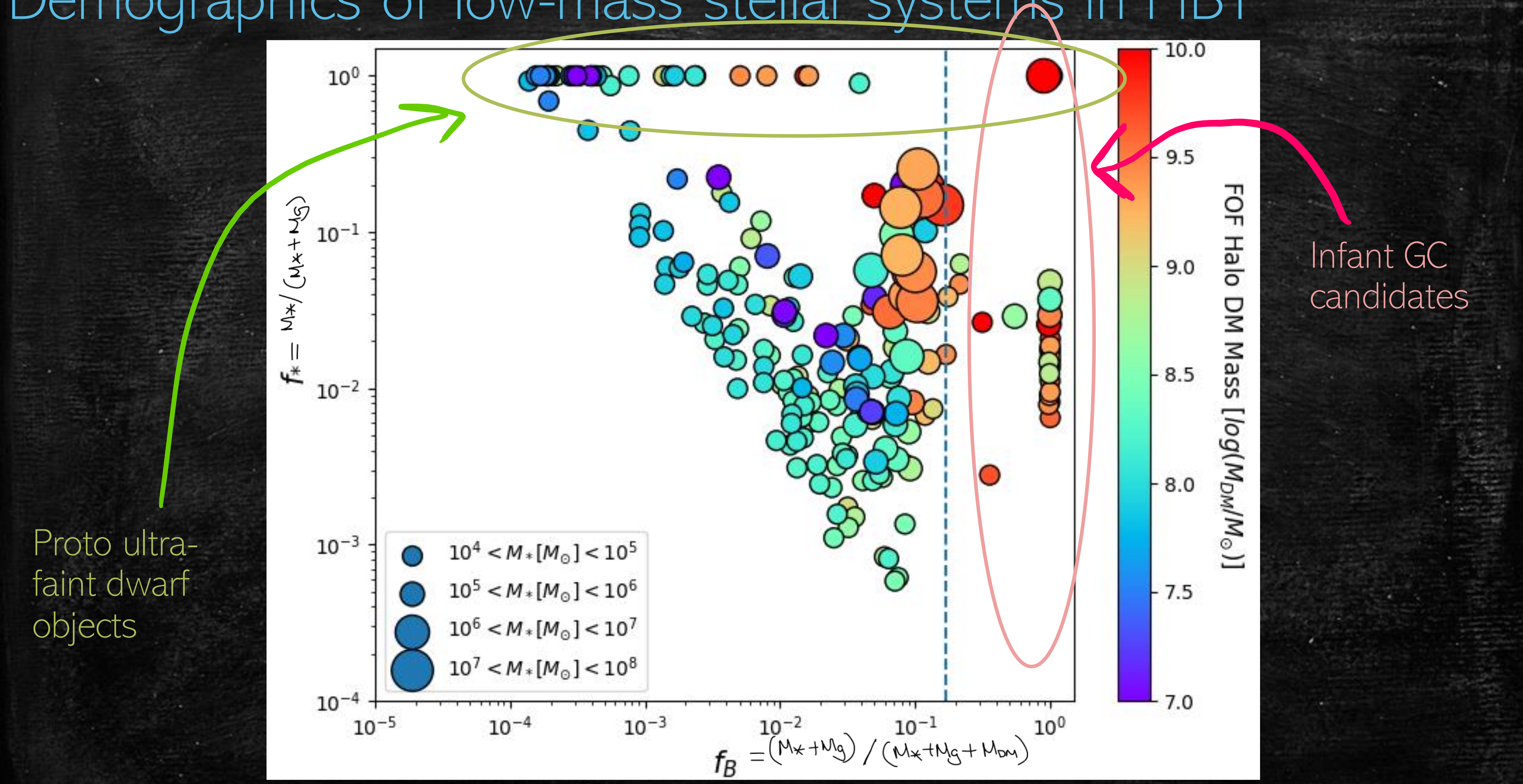




Vanzella+17

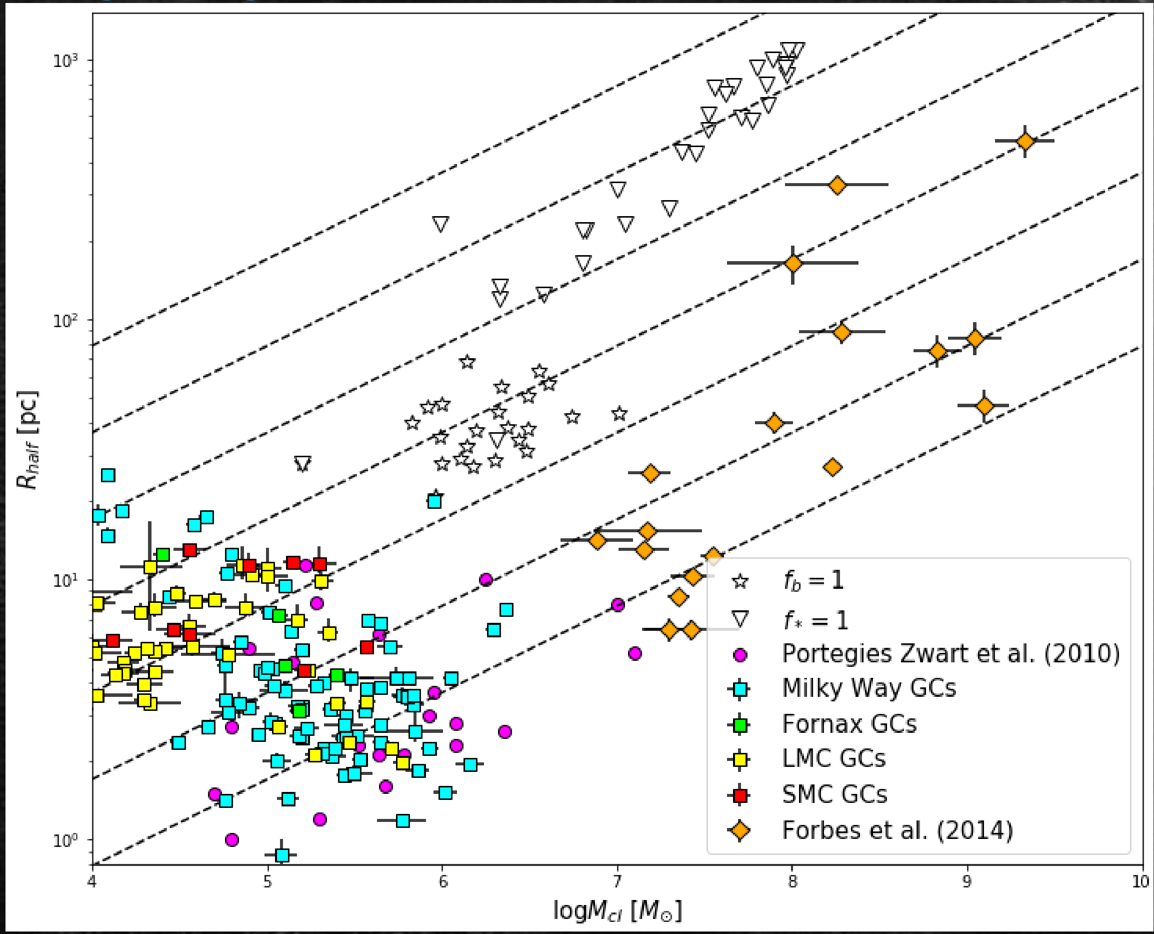
We use a simulated box of volume $(4\ \mathrm{cMpc})^3$ with 684^3 particles per type. The mass resolution is $1250 M_\odot$ and $6160 M_\odot$ for SPH and dark matter particles, respectively.

Demographics of low-mass stellar systems in FiBY



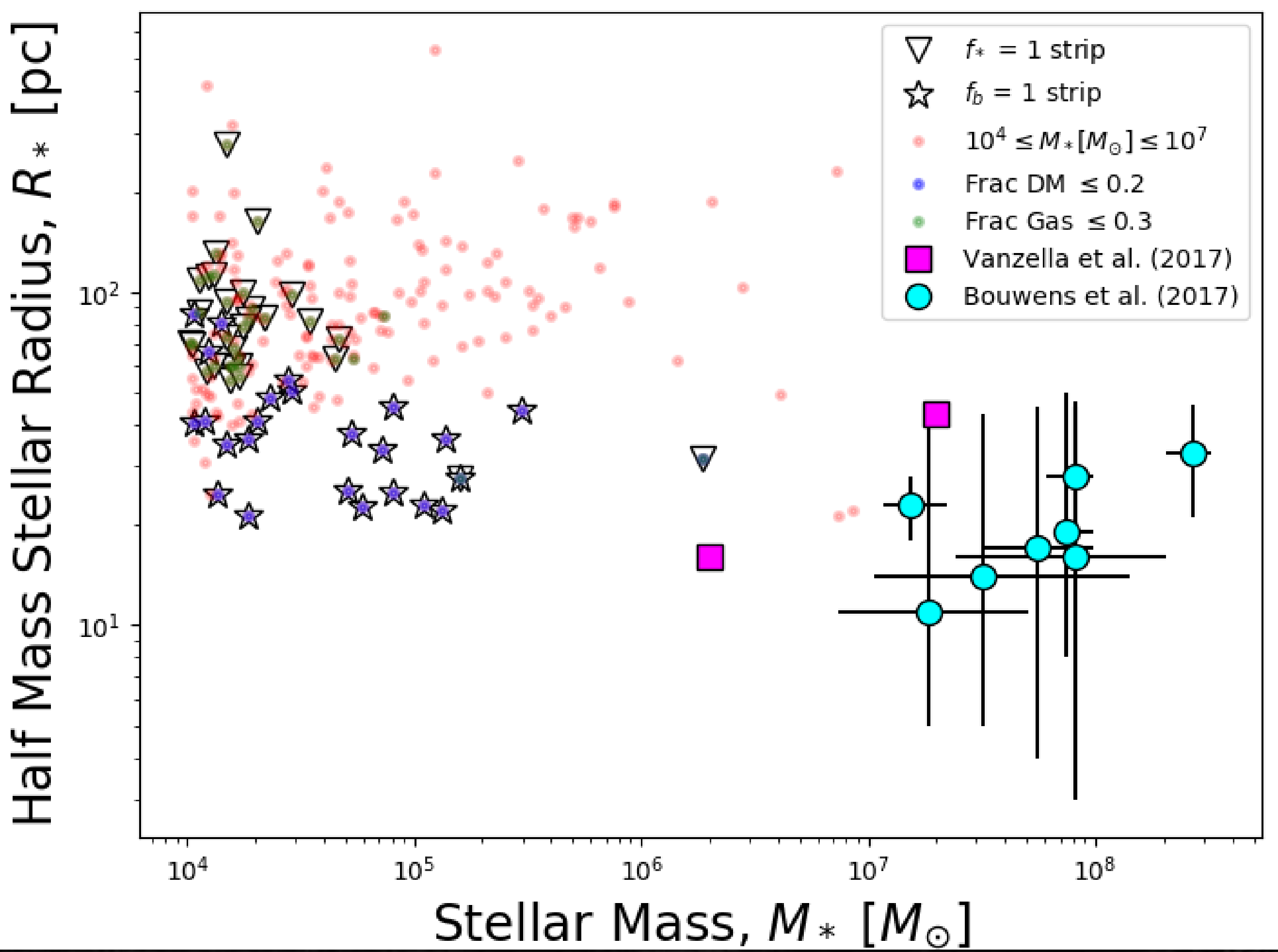
Phipps et al. (2020) | A&A, vol. 641, id. A132 | arXiv:1910.09924

Highlights from Paper I



Top: Size-mass plane for the simulation data and a selection of observational data for GCs, young massive clusters and ultra-compact dwarfs

Bottom: Comparison in the size-mass plane of the simulation data to preliminary high-redshift observations of proto-GCs



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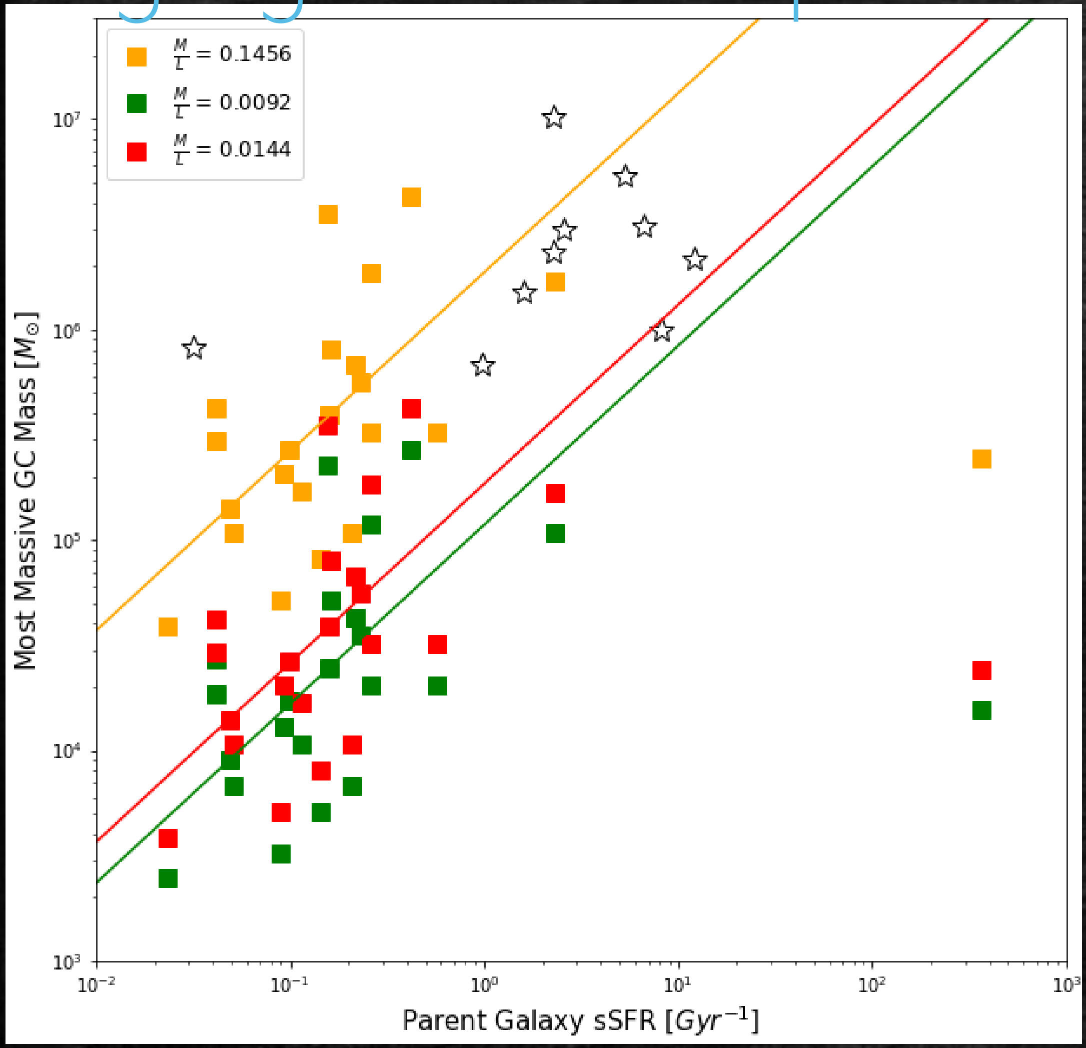
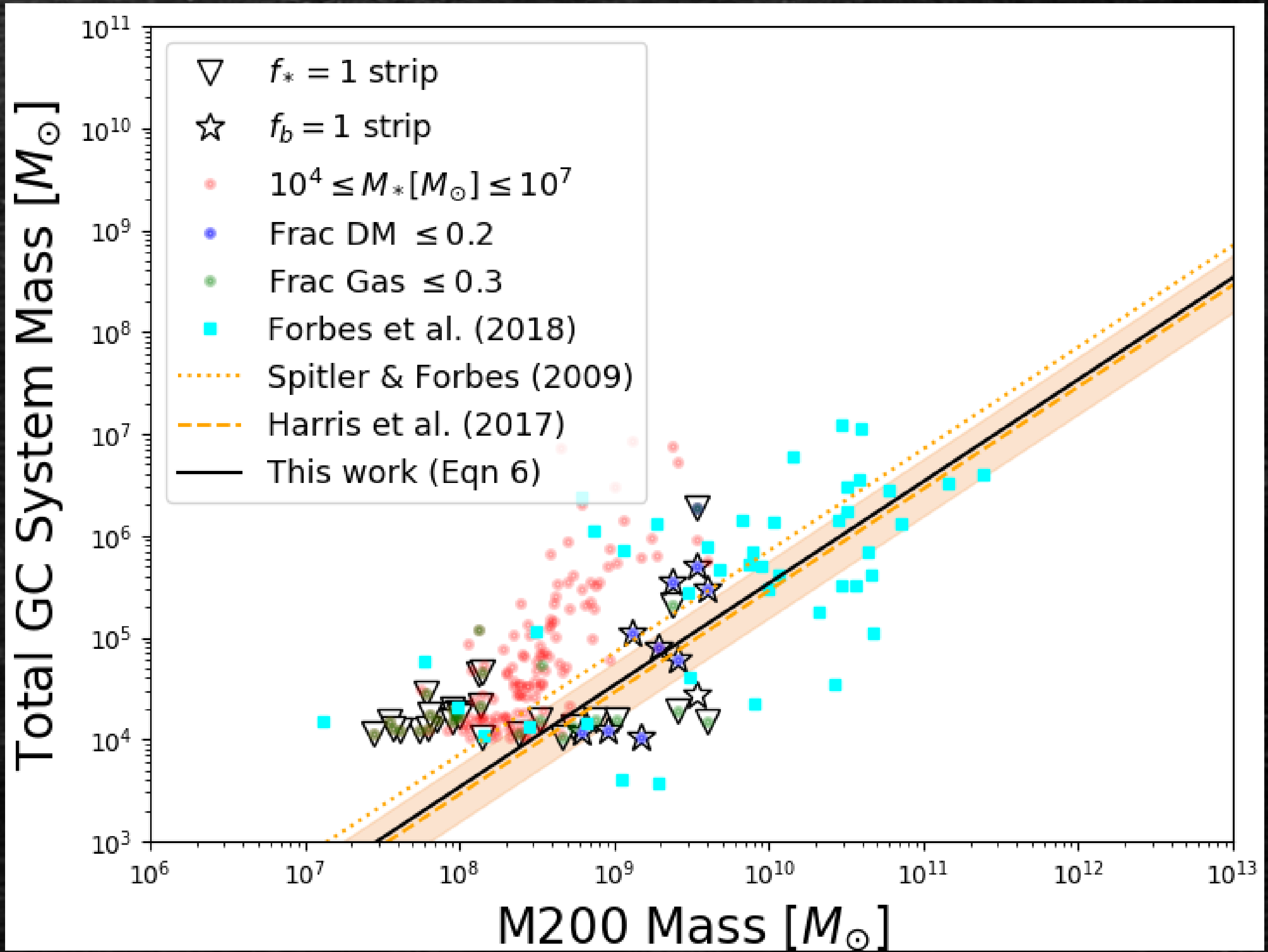


Bottom: GC system mass – halo mass relation at redshift six in the simulation compared to low-redshift observational data for dwarf galaxies



Top: The most massive GC in a system vs the sSFR of the host galaxy across low and high redshift

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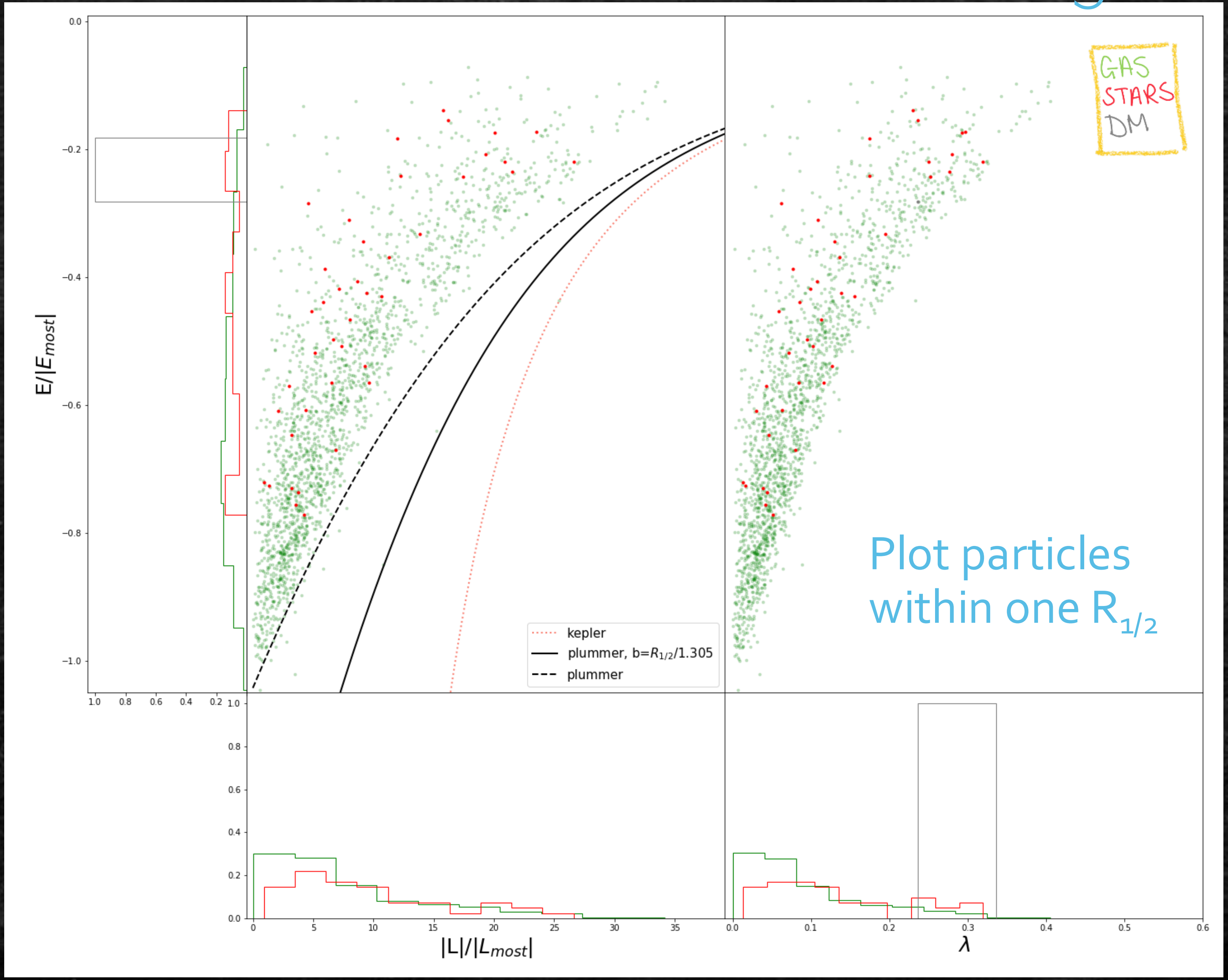
Structure Definition – Small Structures in Large Simulations

Left panel:
The `Lindblad' Diagram.

Energy and angular momentum normalised to the 10 most bound particles

Lines represent circular orbits in spherical potentials



Right panel:
Total energy against spin parameter for each particle

We use the Bullock+01 definition:

$$\lambda = \frac{L}{\sqrt{2}MRV}$$

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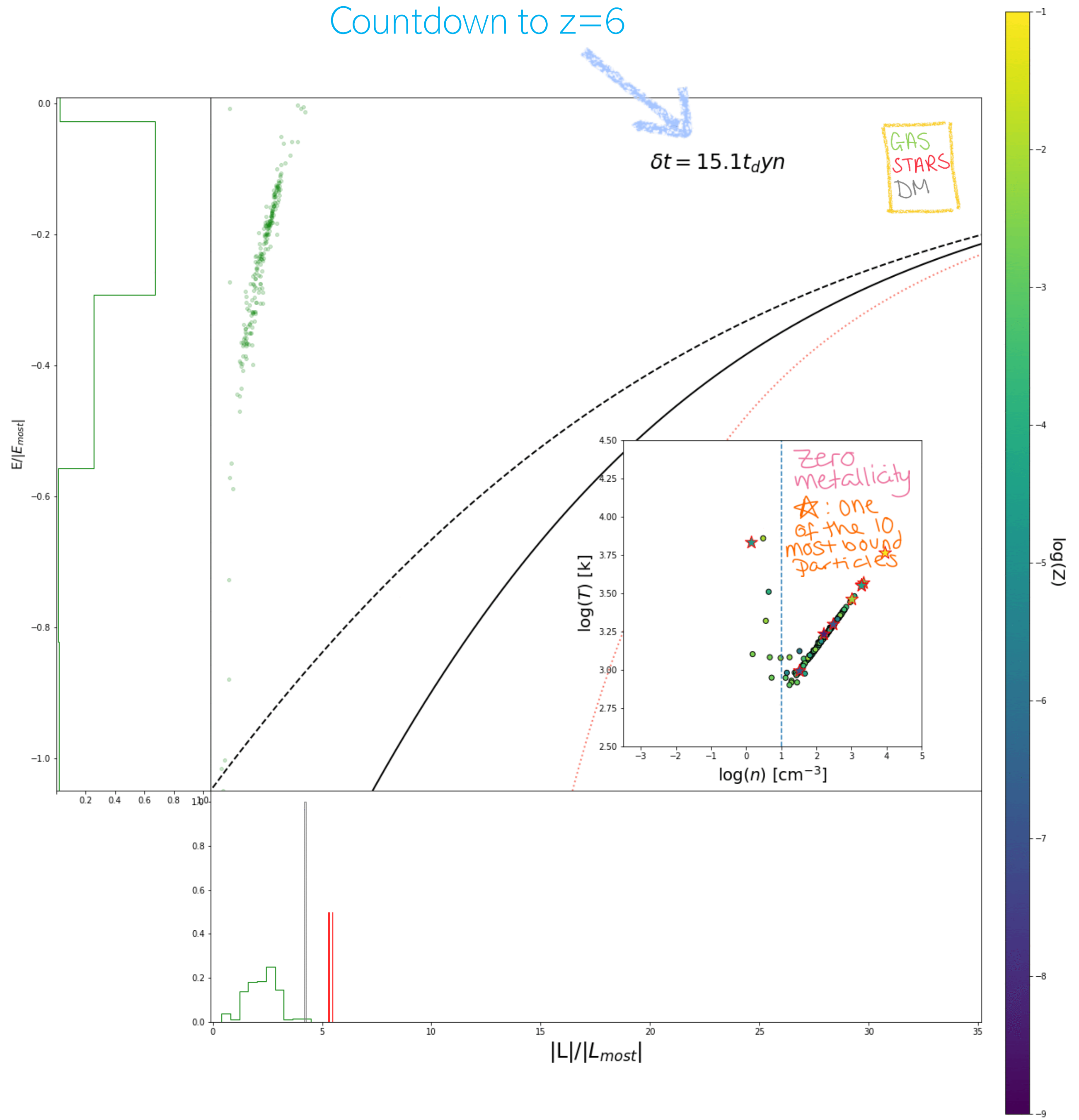
Phase-space Evolution Over Time

By evaluating the evolution of the `Lindblad' diagram over time, we can identify the moment in time where the infant GC candidate can be recognised as its own bound object. This was also confirmed with a quantitative analysis of the particle energies.



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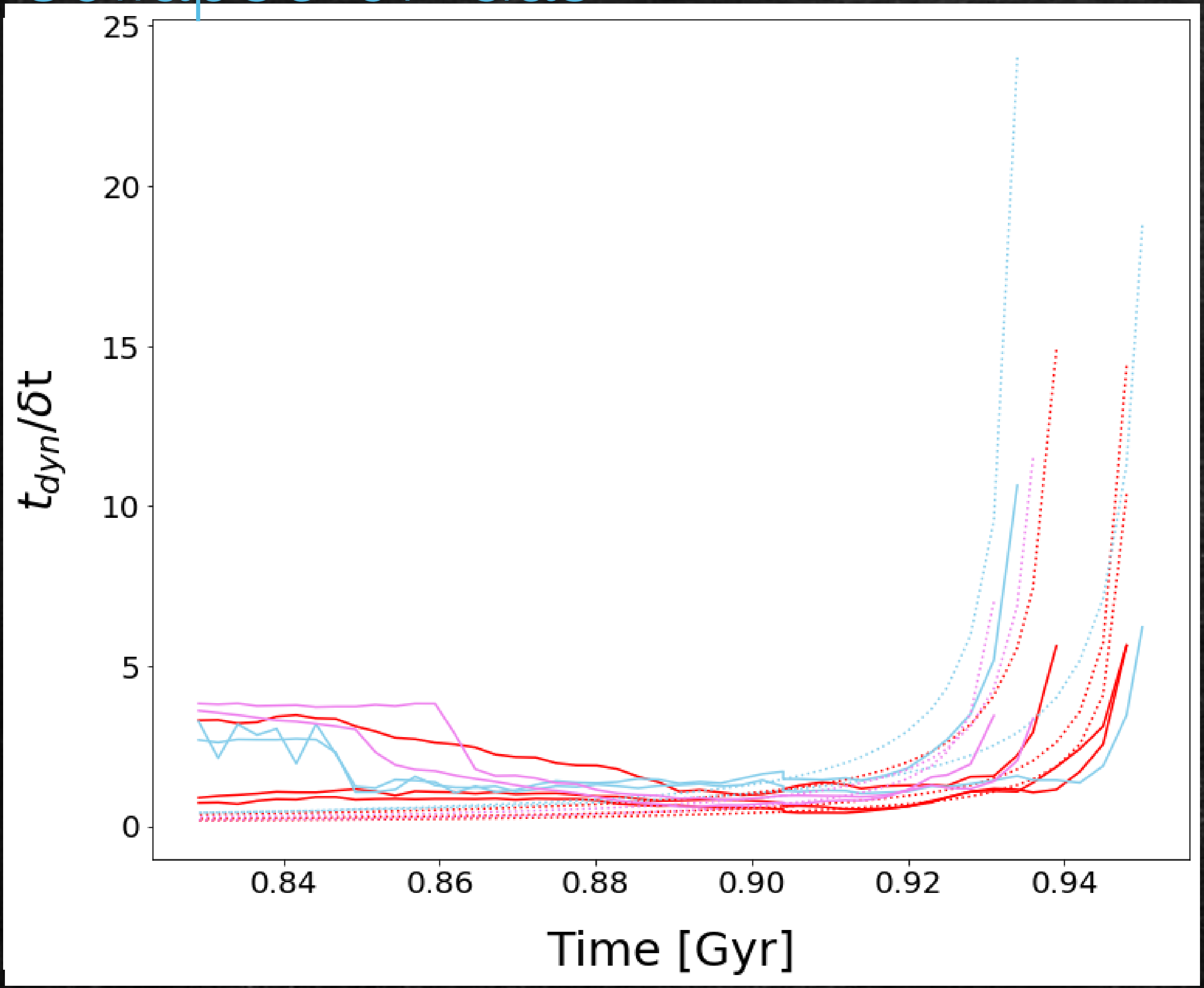
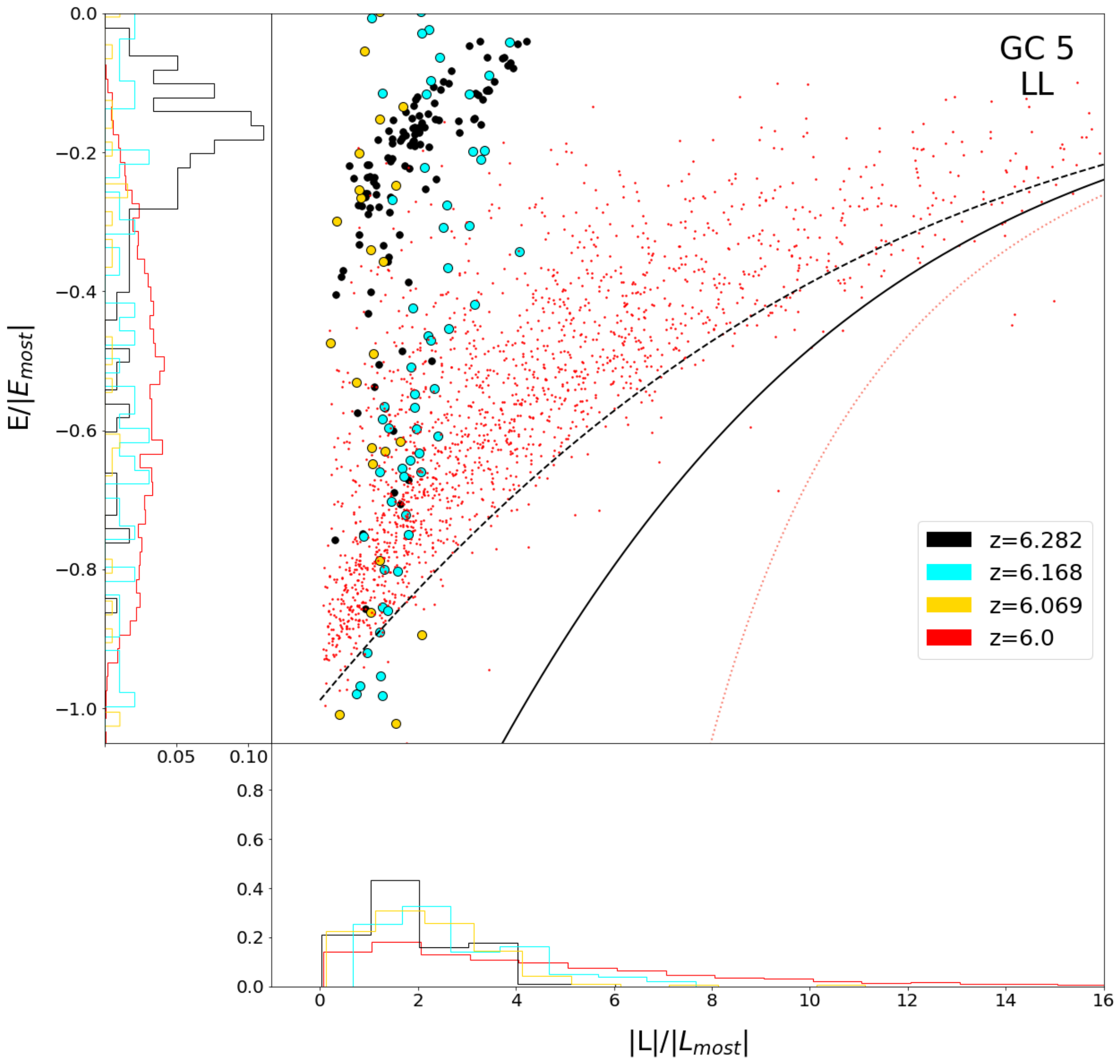
Collapse of Gas



Top: t_dyn : dynamical (crossing) timescale
δt: interval until 'formation time' of each candidate.

Bottom: Multiple snapshots of the phase space evolution overlaid. Darker colour represents an earlier snapshot.



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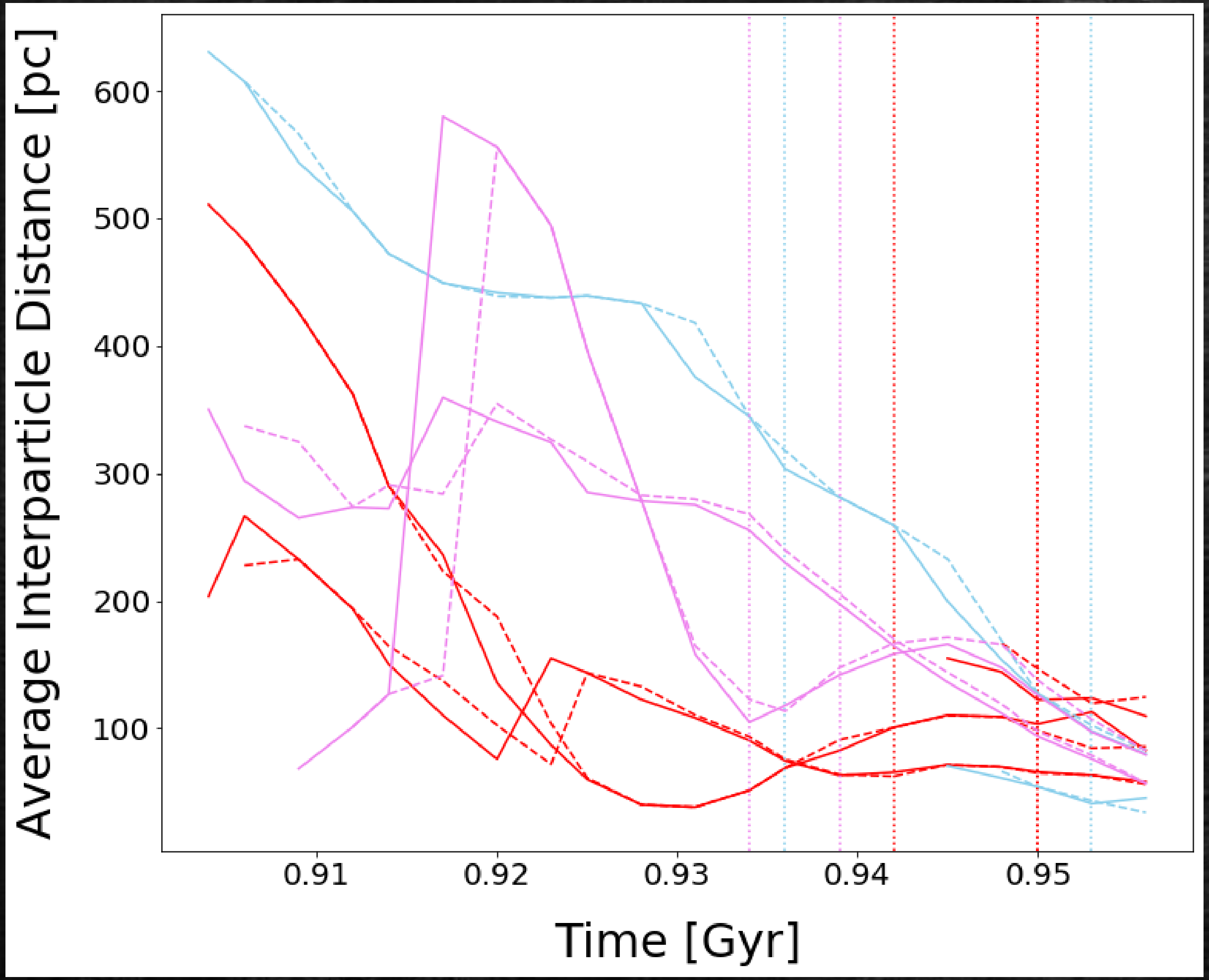
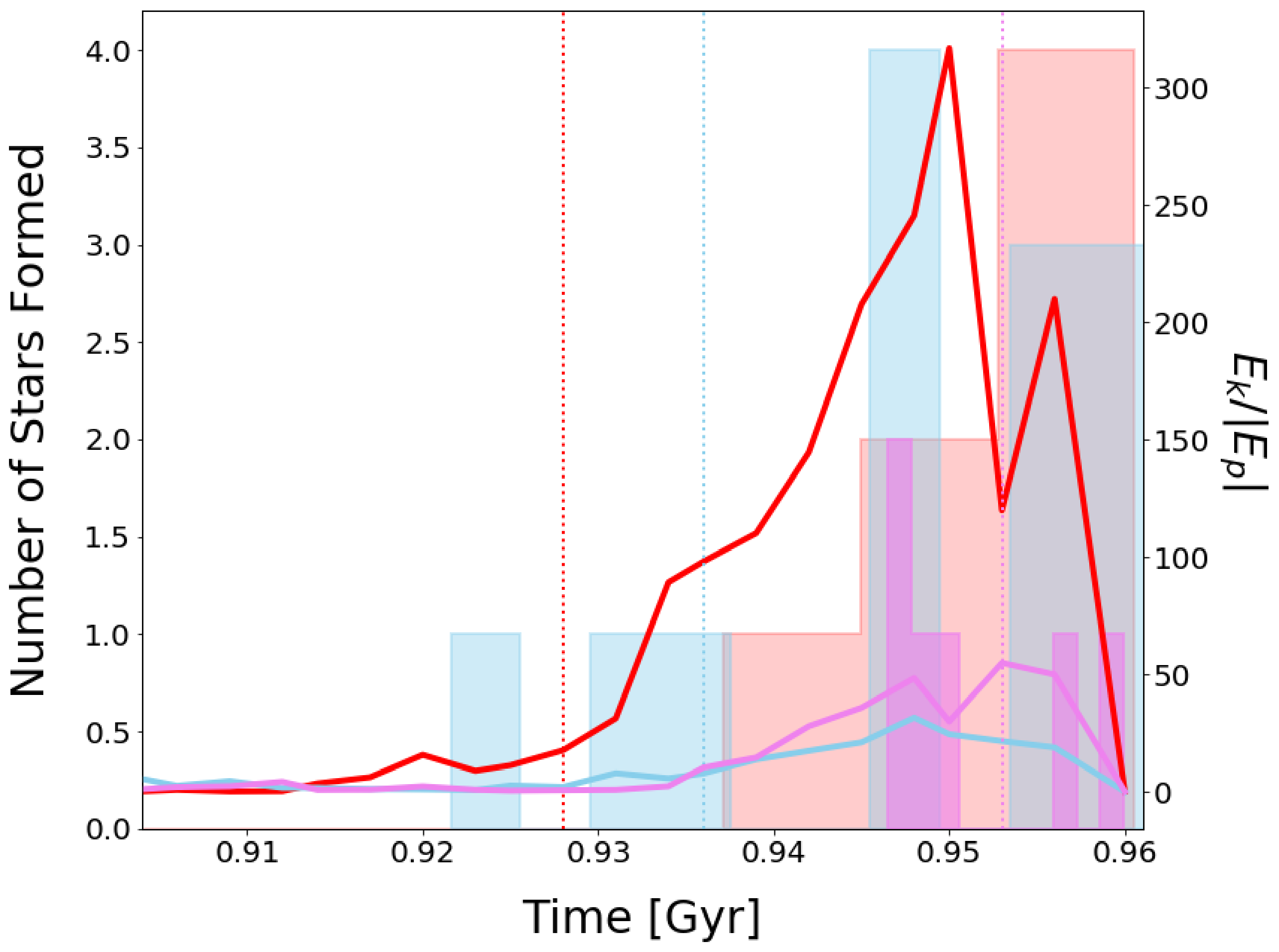
Infall of stars



Bottom: Solid lines – the evolution of the virial parameter for the star particles
Histograms – star formation histories of the candidates



Top: Solid/dashed lines – interparticle distance between the star particles over time

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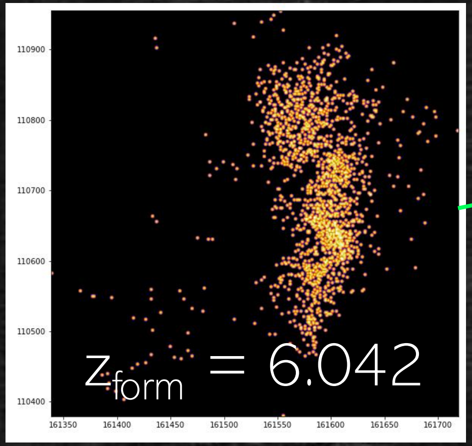
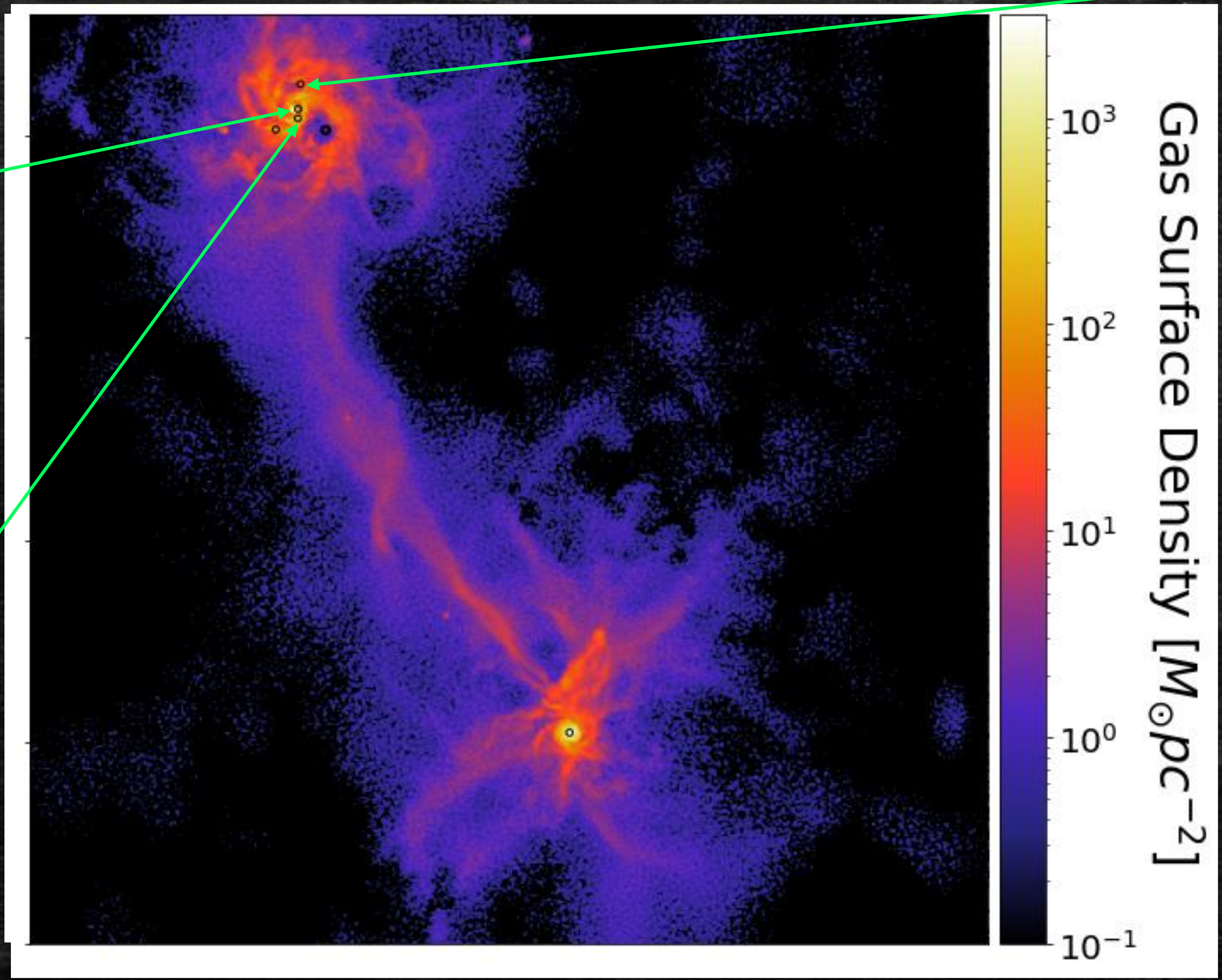
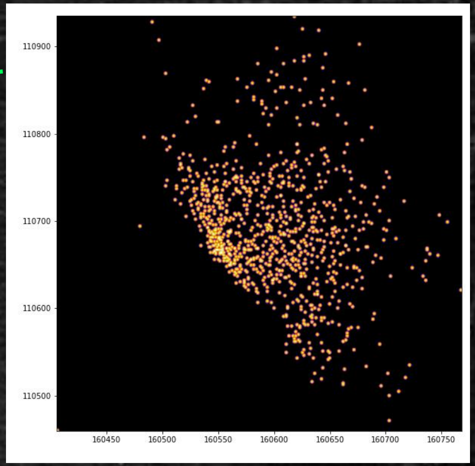
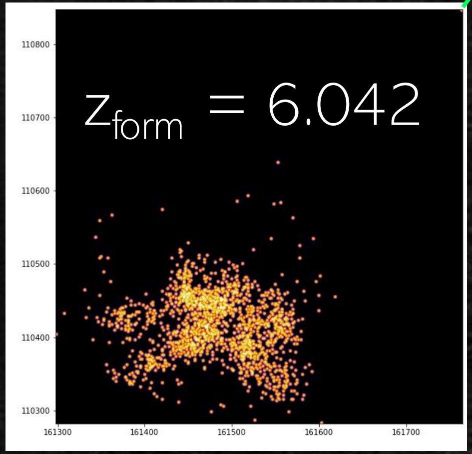
Impact of the Large-Scale Environment









The host of these candidates is undergoing a merger during the formation of these objects

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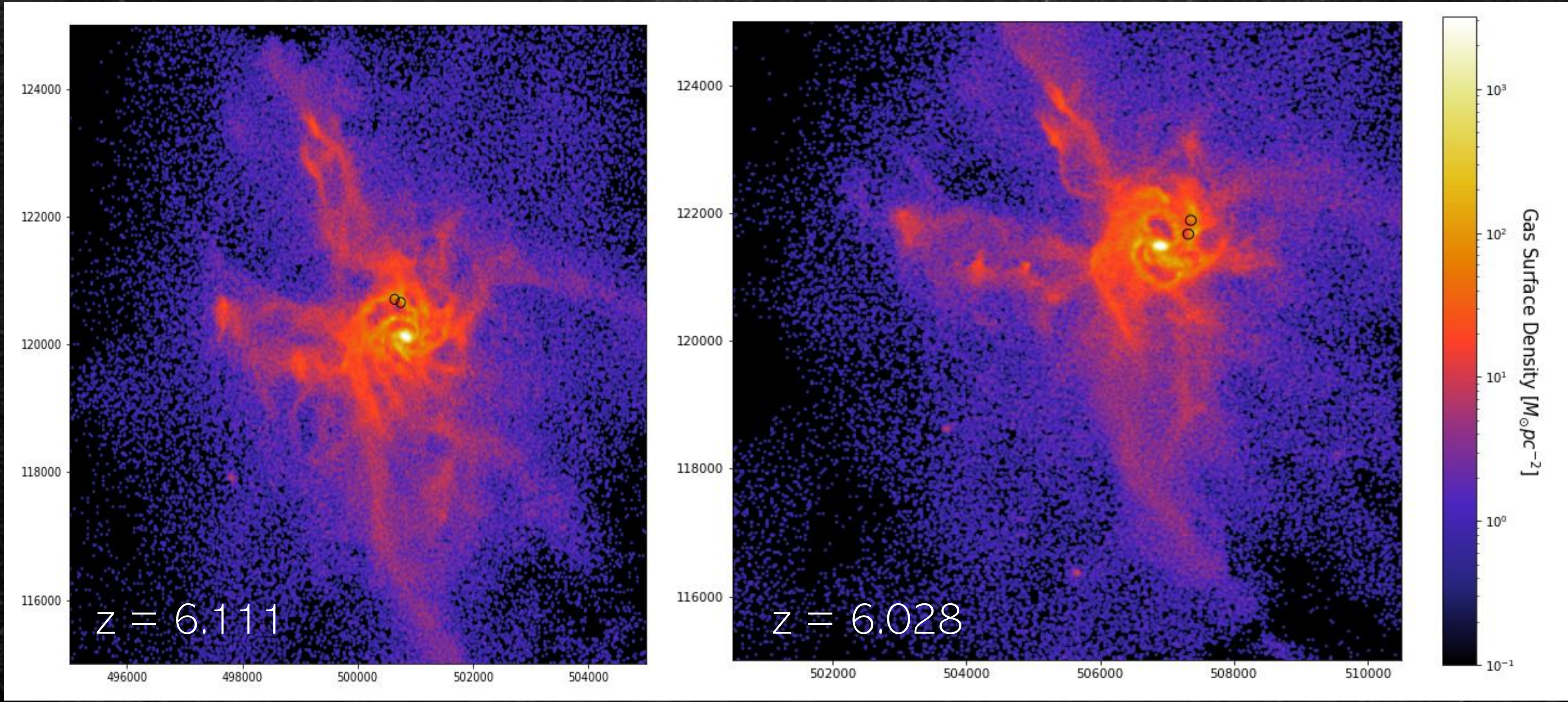
Impact of the Large-Scale Environment



Between the formation times of these two candidates, the host has rotated significantly, as visible from the spiral arms' orientation.

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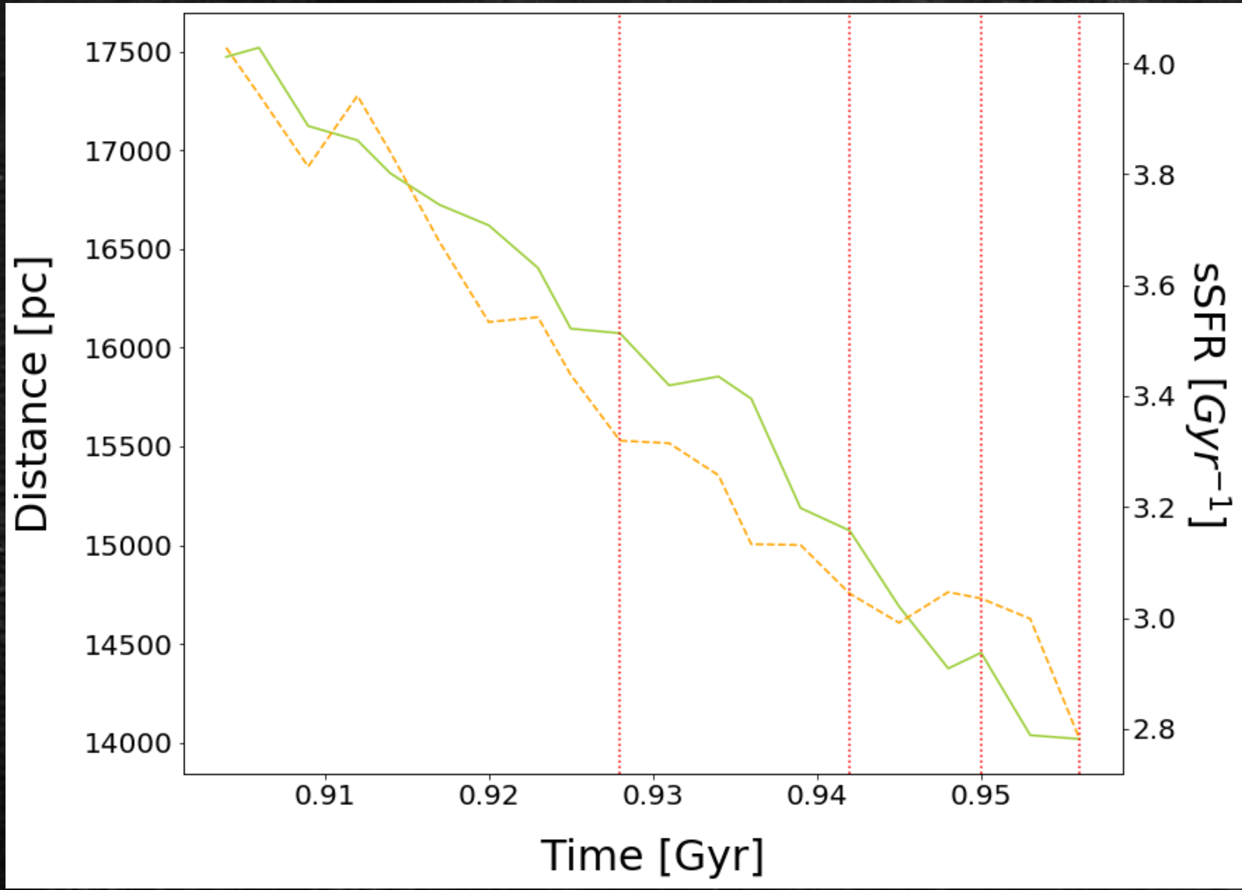
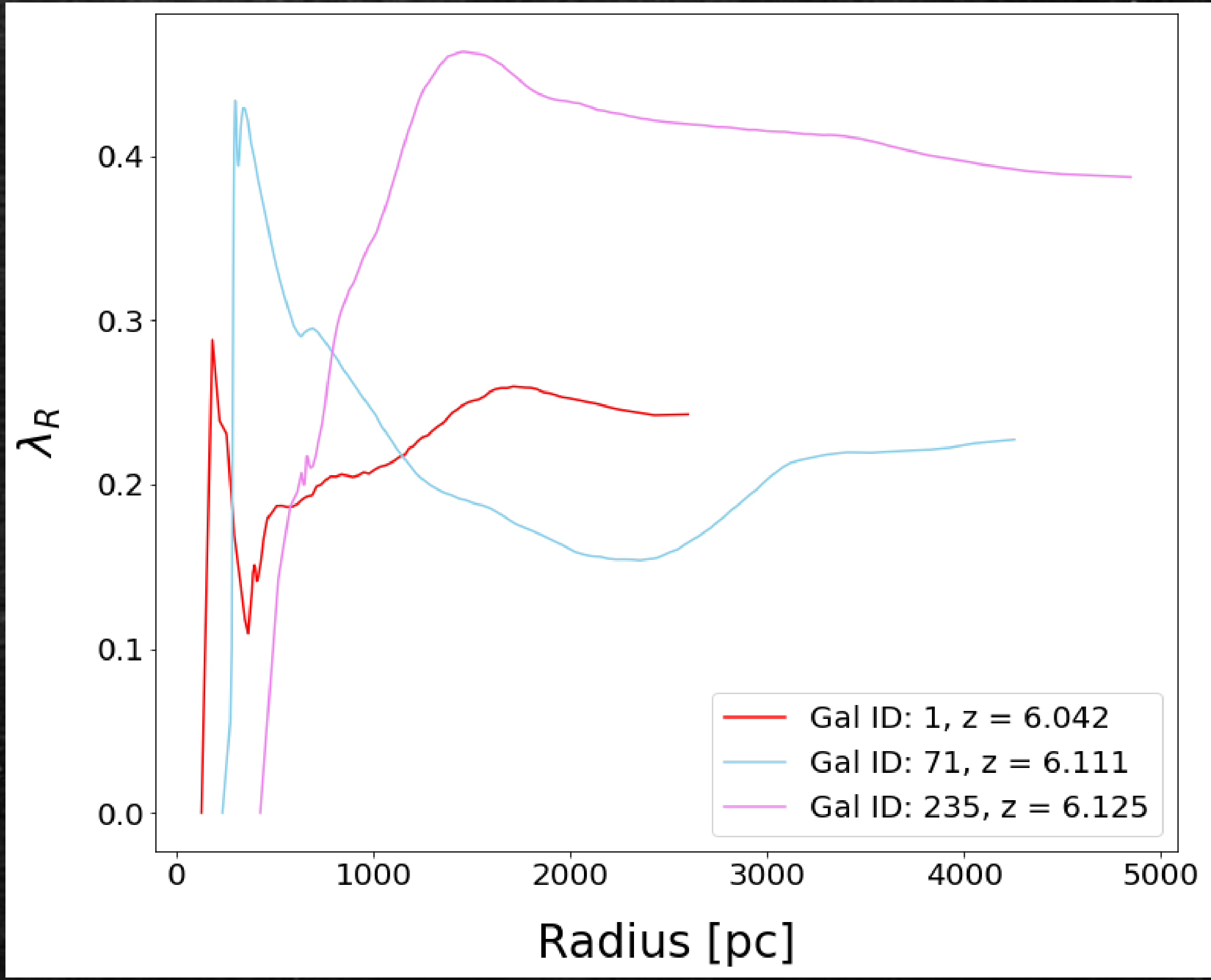
Impact of the Large-Scale Environment



Bottom: The radial profile of the spin parameter for the galaxies hosting candidates at different candidate 'formation times'



Top: Evolution of the distance between the centers of mass of the merging galaxy (solid green) and the sSFR of the galaxy hosting candidates (dashed orange)

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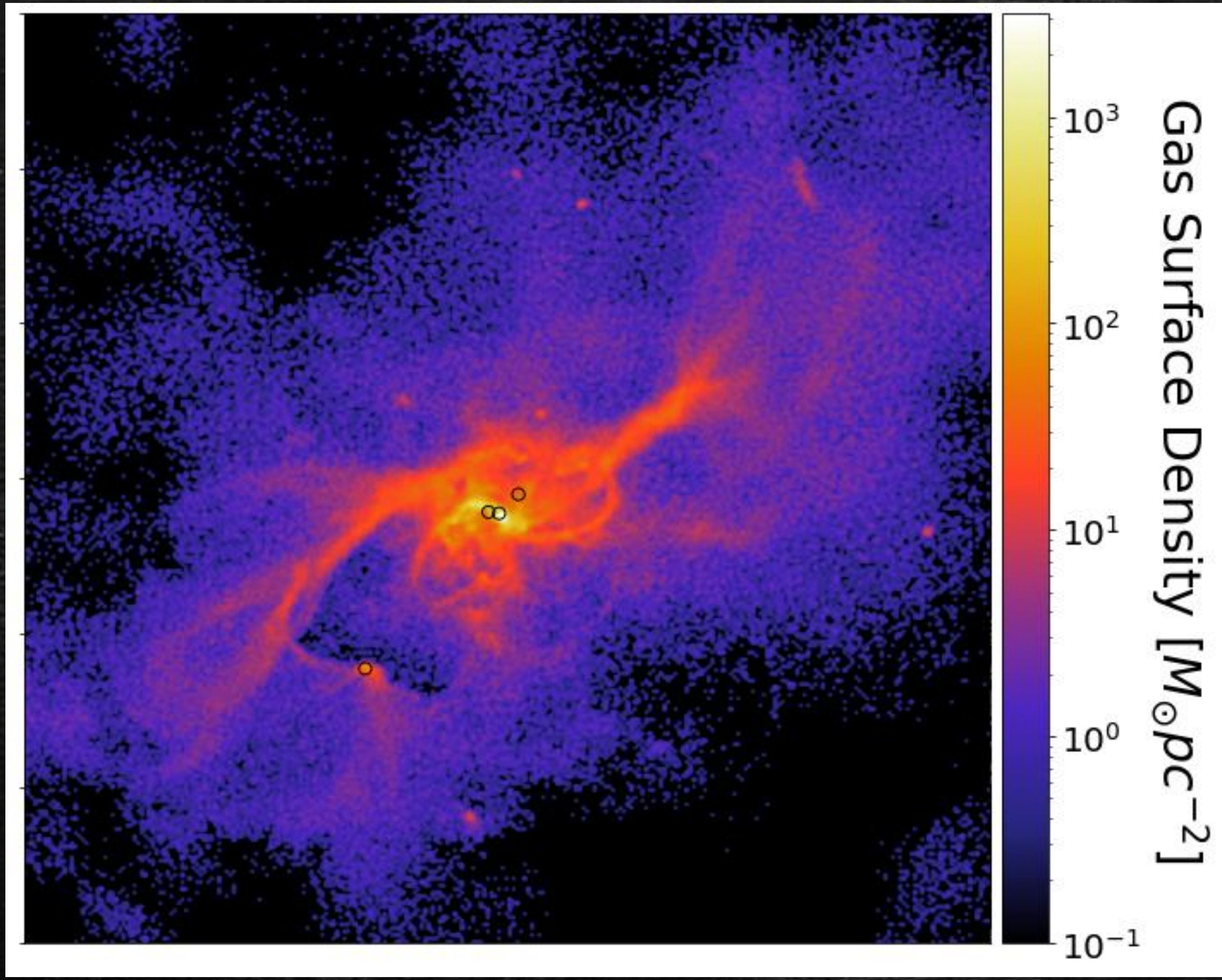
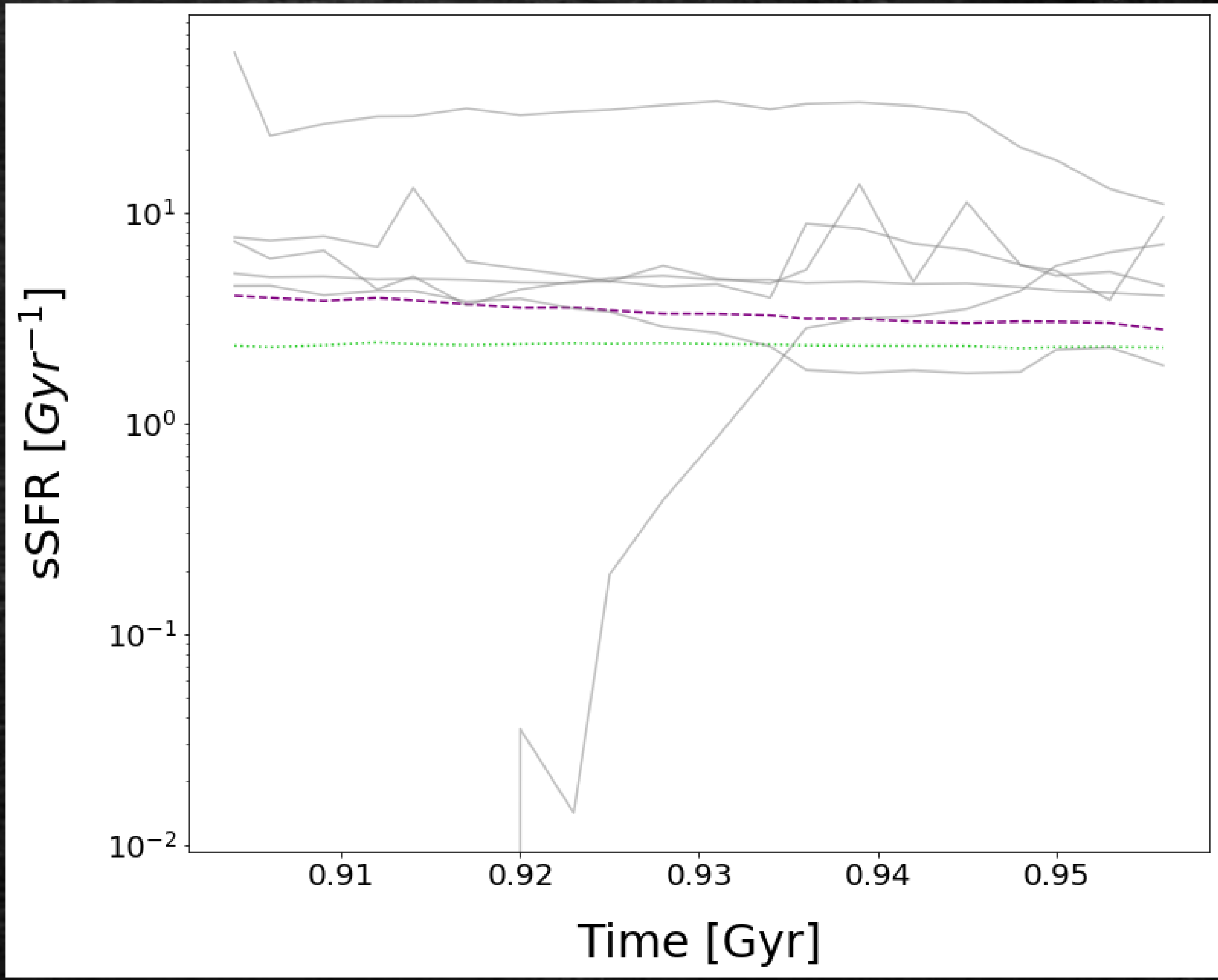
Impact of the Large-Scale Environment



Top: Morphology of the most common type of host galaxy for our candidates. A 'standard' high-redshift galaxy

Bottom: The sSFR evolution for all the hosts. Grey lines for the 'standard' host, green and purple are the rotating and merging hosts respectively



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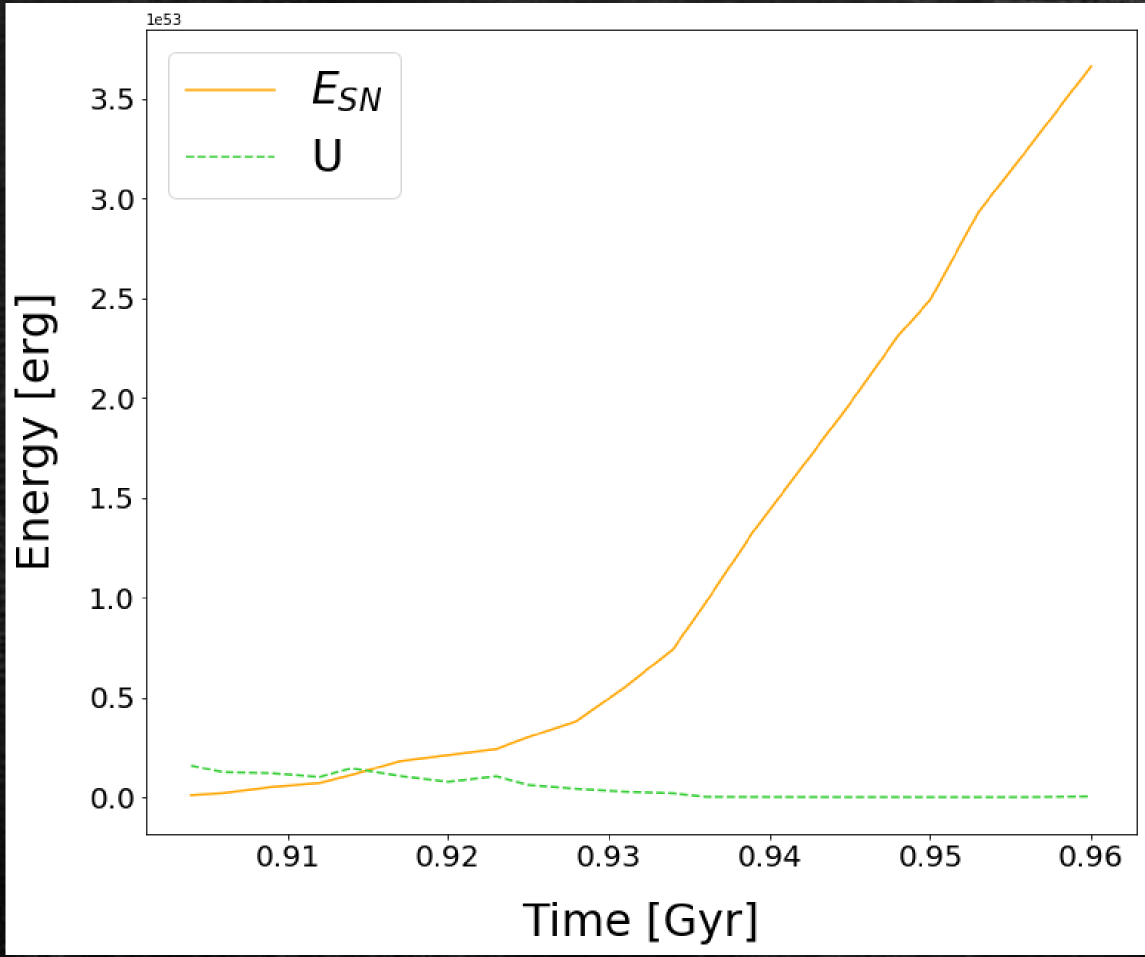
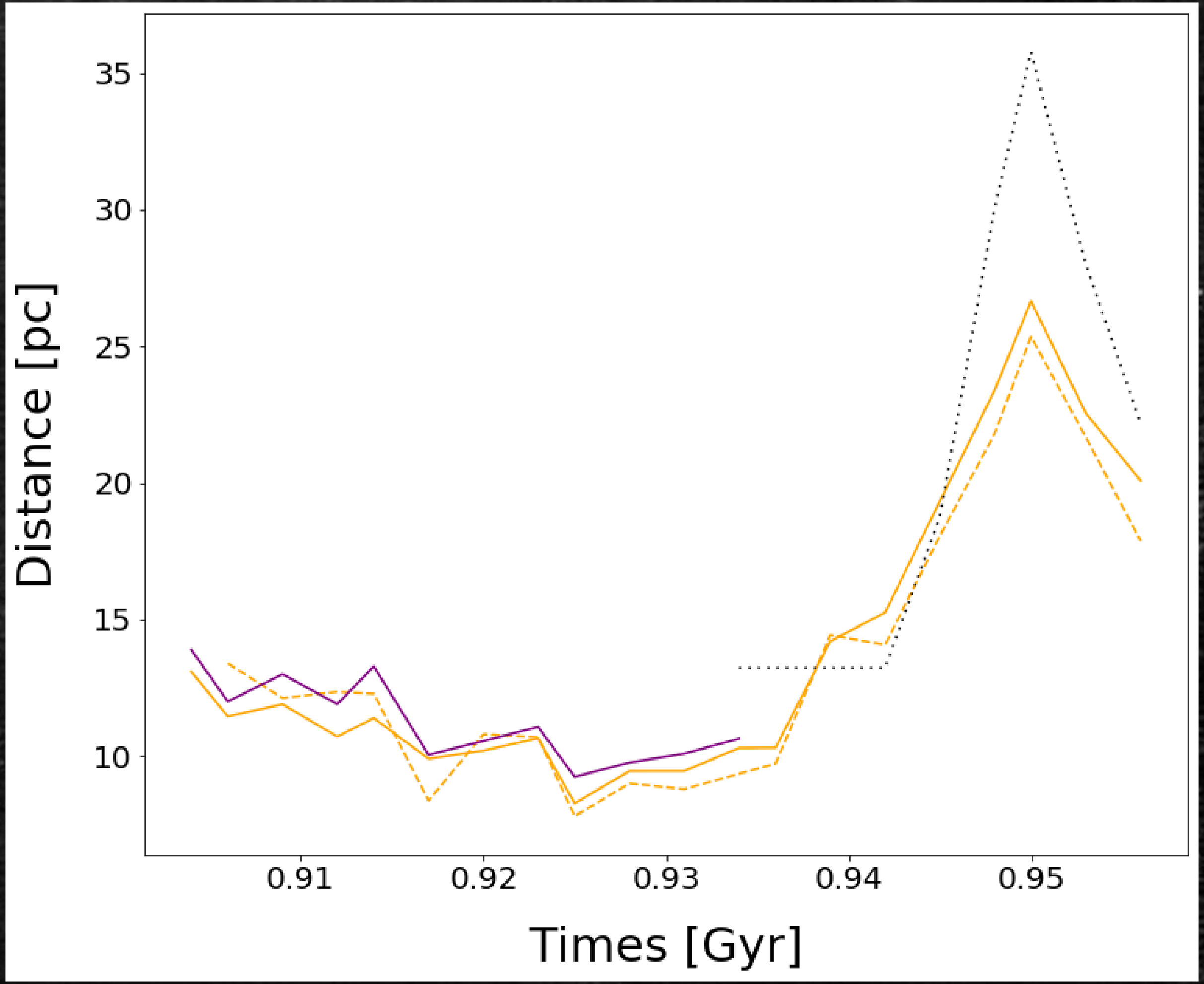
Potential future evolution



Top: Evolution of the potential energy (green dashed) and the cumulative supernova energy (orange solid)

Bottom: Gas (purple) and star (orange) interparticle distance over time. The grey dashed line is the theoretical prediction from adiabatic contraction



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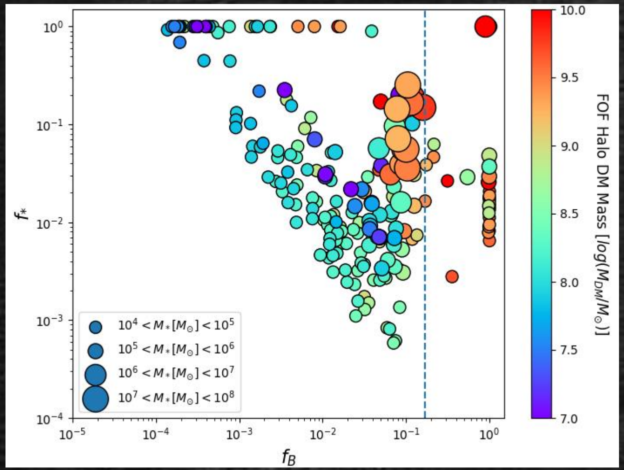
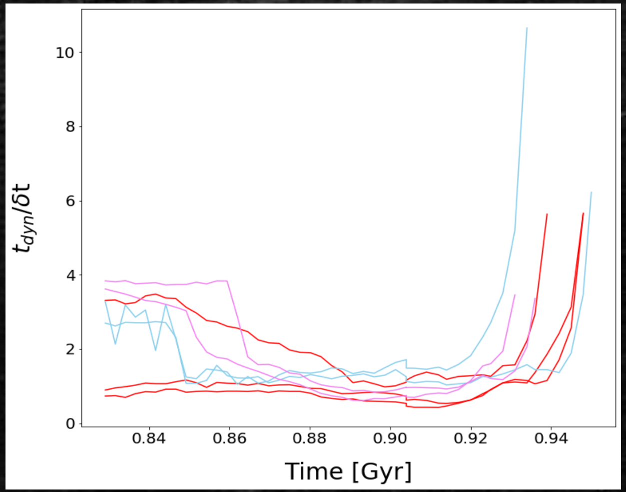
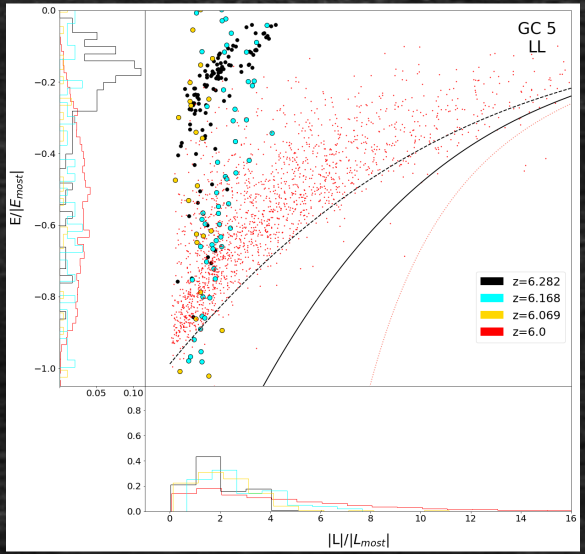
Conclusions



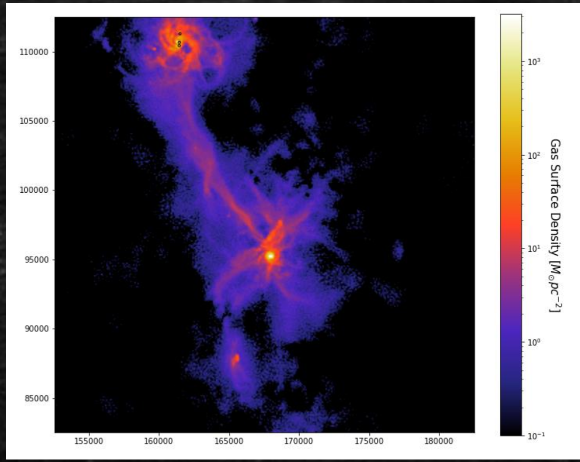
Our infant GC candidates are indeed distinct bound objects



The gas collapses dynamically 'pre-formation'.



The candidates can be grouped by their **phase-space** behaviour, indicating multiple GC formation channels.

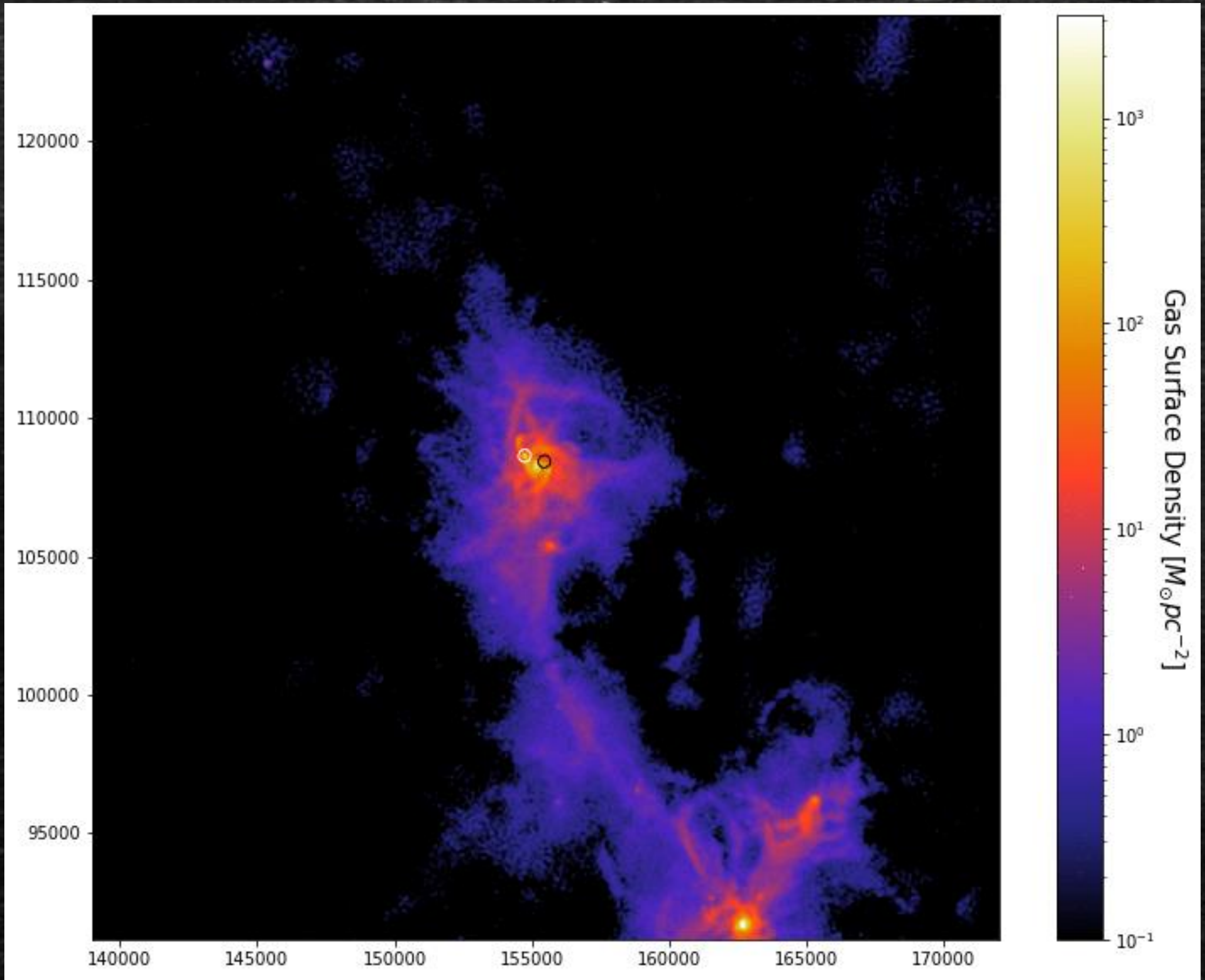


Such phase space grouping also maps into host galaxy grouping.

GC formation is shaped by the synergy of internal dynamical effects and the influence of the large-scale environment!

Potential future evolution

White circle shows the evolution path in the host galaxy of an infant GC candidate which only contains stars at z=6
Black circle shows the evolution path in the host galaxy of an infant GC candidate which is gas-rich at z=6



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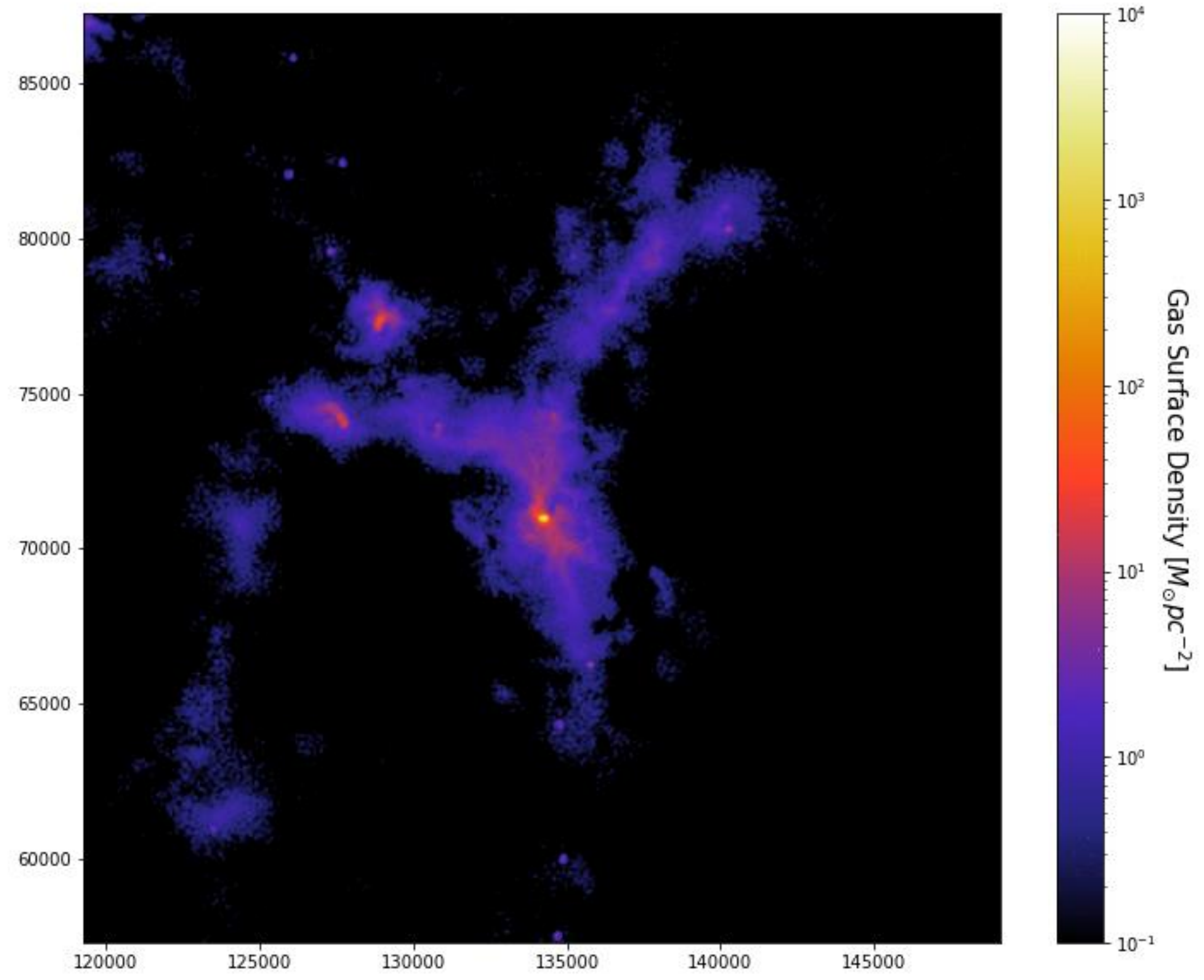
Impact of the Large-Scale Environment



The evolution of the gas density of one of the galaxies in the merger. Our largest infant GC candidate is at the center. Could potentially be witnessing the formation of a nuclear star cluster

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