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The Three Hundred: The existence of massive dark matter-deficient satellite galaxies in cosmological simulations

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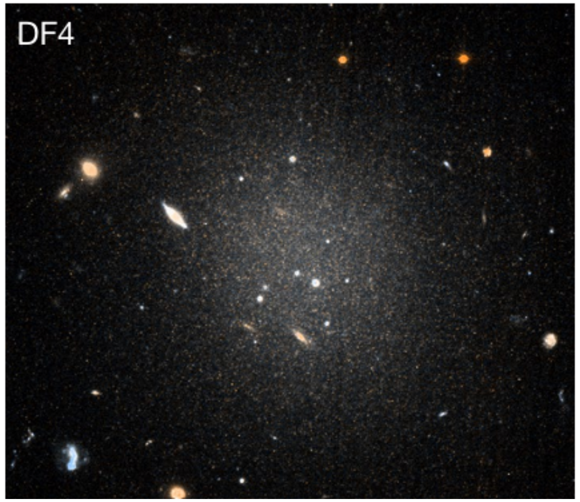
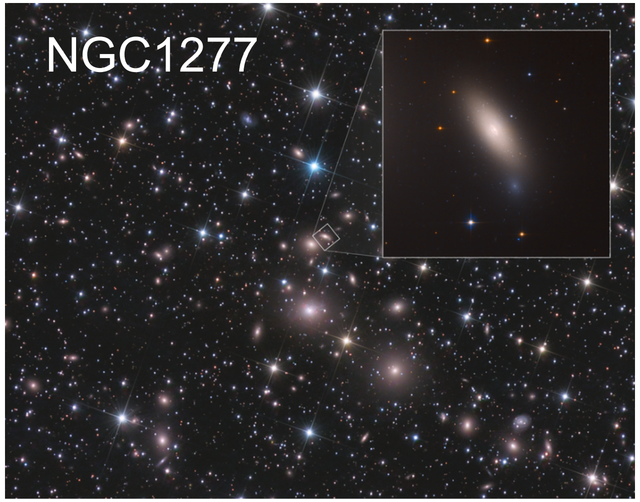
Introduction

- In ΛCDM paradigm of galaxy formation and evolution, galaxies are thought to be formed within dark matter halos (White & Rees 1978). This paradigm allows for the existence of dark matter-deficient galaxies.
- E.g., Tidal dwarf galaxies (TDGs, Duc et al. 2004, and references therein) are formed from tidal debris produced during interactions between galaxies, such as mergers or close encounters. TDGs generally have low masses and retain little dark matter from their parents' halos.
- However, there have been many claims over the recent years about galaxies without dark matter in principle not associated with TDGs. Two main scenarios:
  - a high-velocity collision of gas rich galaxies very early on ('mini Bullet cluster event'), where the dark matter components do not interact and separate from their baryonic counterpart, thus producing a dark matter-deficient remnant (Silk 2019, Shin et al. 2020, Lee et al. 2021).
  - these galaxies were formed as normal galaxies, but their dark matter halos were strongly stripped by tidal interactions

Introduction

- While these dark matter-deficient galaxies are all low-mass galaxies (for instance, NGC1502-DF2 has a stellar mass of $M_{*}\sim 2\times 10^{8}\ M_{\odot}$), NGC1277 (Comerón et al. 2023) a massive galaxy (stellar mass $M_{*}\sim 1.6\times 10^{11}\ M_{\odot}$) located in the Perseus galaxy cluster, is claimed to be compatible with lacking dark matter, too.
- This may be at odds with theoretical predictions based on ΛCDM (Santucci et al. 2022).
- Although similar mechanisms as the ones described before can be invoked for the formation of such a galaxy, the high stellar mass of NGC 1277 has included a new feature to check for and thus added a degree of complexity to this issue.





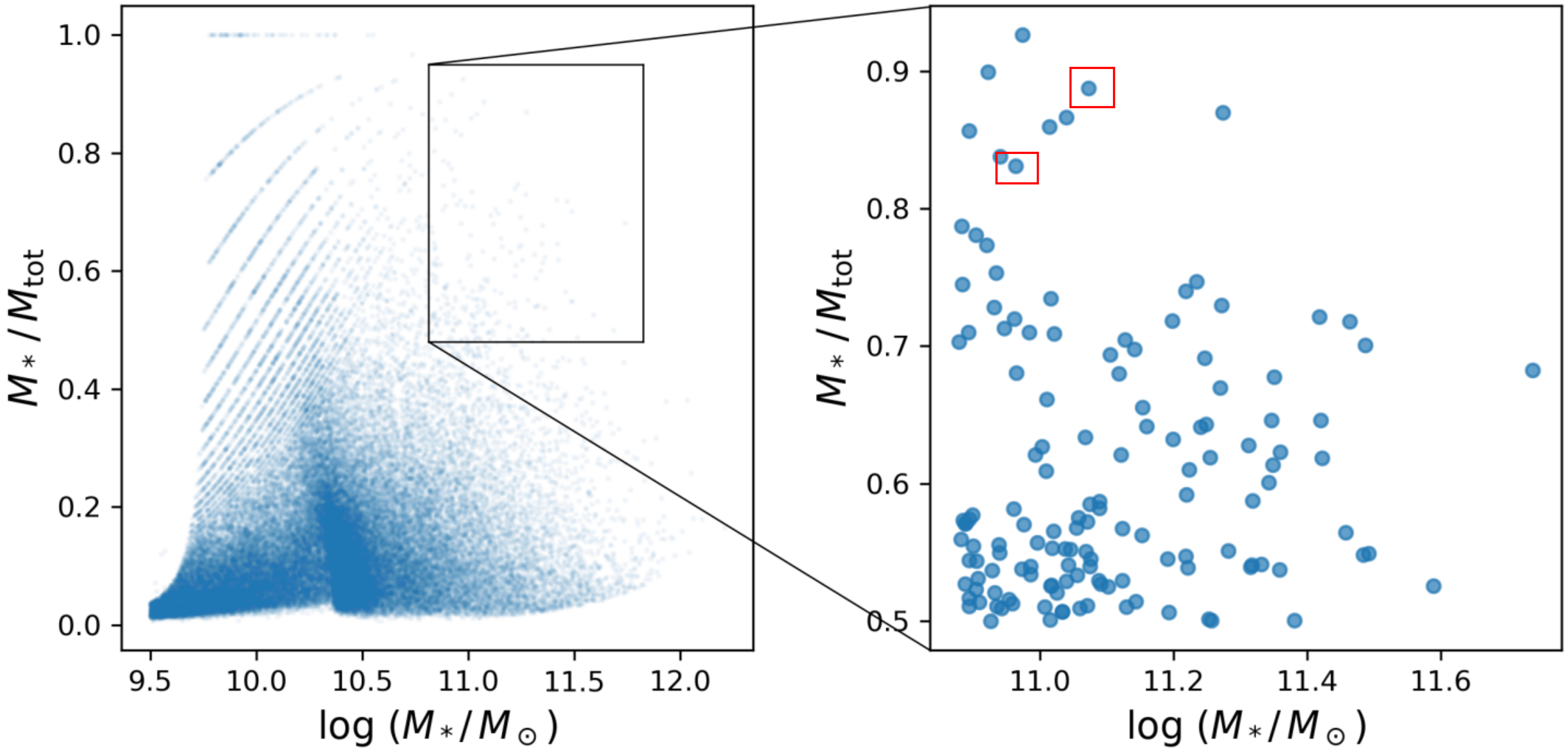
Motivated by this situation, in this work the authors explore the 324 theoretically modelled galaxy clusters of The Three Hundred project (Cui et al. 2018) in order to test whether there is any physical phenomenon able to occasionally produce massive dark matter-deficient galaxies within galaxy clusters.

Samples -- The Three Hundred sample

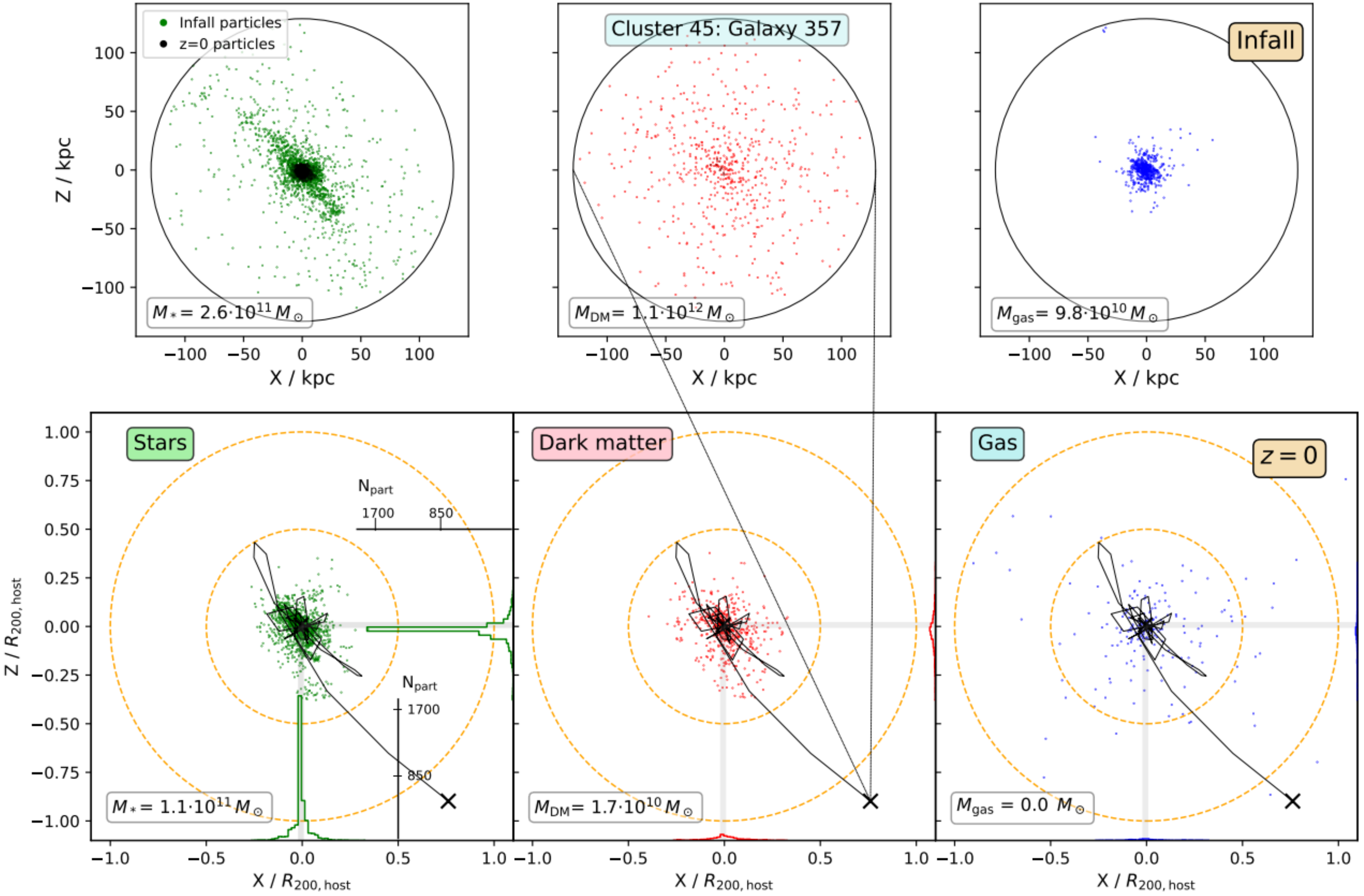
- The Three Hundred data set consists of a suite of 324 spherical regions of diameter $30h^{-1}$Mpc centred on the most massive objects found within a parent cosmological dark matter only simulation of side length $1h^{-1}$Gpc (MultiDark Planck 2, Klypin et al. 2016).
- After splitting the initial dark matter particles into dark matter and gas, those regions have been re-simulated from their initial conditions including now full hydrodynamics using the smoothed particle hydrodynamics (SPH) code Gadget-X.
- The dark matter (gas) mass resolution is $12.7 \cdot 10^8 h^{-1} M_\odot$ ($2.4 \cdot 10^8 h^{-1} M_\odot$). Stellar particles have an average mass of $0.4 \cdot 10^8 h^{-1} M_\odot$
- Halo and galaxy catalogues, respectively, have been generated by the open-source object finder for cosmological simulations AHF, and MergerTree code that comes with the halo finder, is utilised to track the evolution of identified structures across different simulation snapshots.

Finding dark matter-deficient galaxies

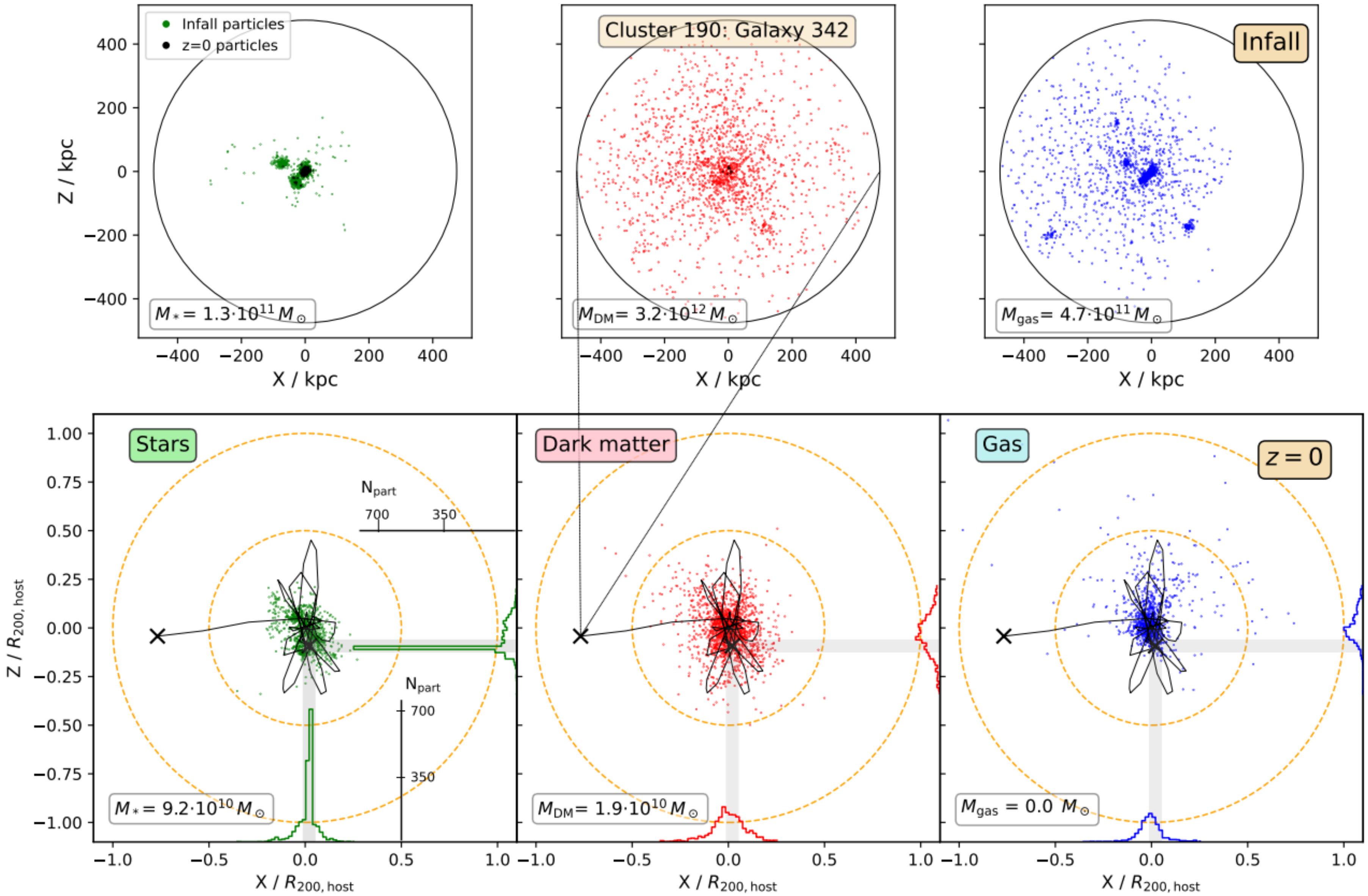
- Selection criteria at redshift $z = 0$: distance less than R_{200} to the host cluster centre, stellar mass $M_* \geq 10^{9.5}\,M_\odot$ and total mass $M_{tot} < 10^{13}\,M_\odot$



Example case studies -- M_*=1.1·10^{11}Msun, M_*/M_{tot}= 0.87.



Example case studies--M_*=9.2·10^{10}Msun, M_*/M_{tot}= 0.83



How the masses of the objects evolve in relation to orbital parameters

In both cases, we clearly see the gradual decrease in total mass after the galaxy enters the host's R_{200}. At the same time, the stellar-to-total mass ratio increases, while the stellar mass remains relatively constant during this time.

The gas has already been completely removed after the second pericentre passage.

This strippng scenario is produced by tidal forces, that act first on the outer DM halo, while the stellar component, which is much more centrally concentrated, is harder to strip. This commonly accepted framework of tidal stripping can lead to massive dark matter-deficient galaxies.

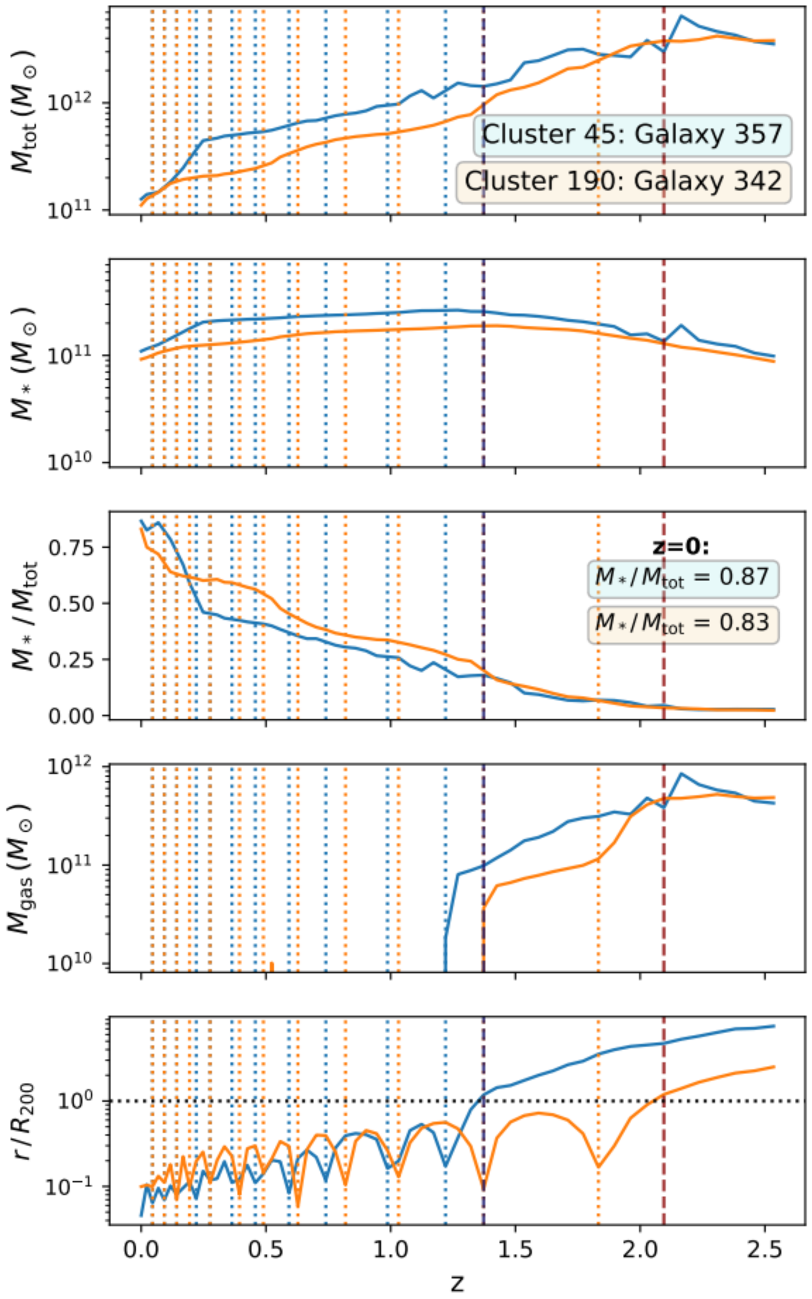
Mtot

M*

stellar-to-total mass ratio

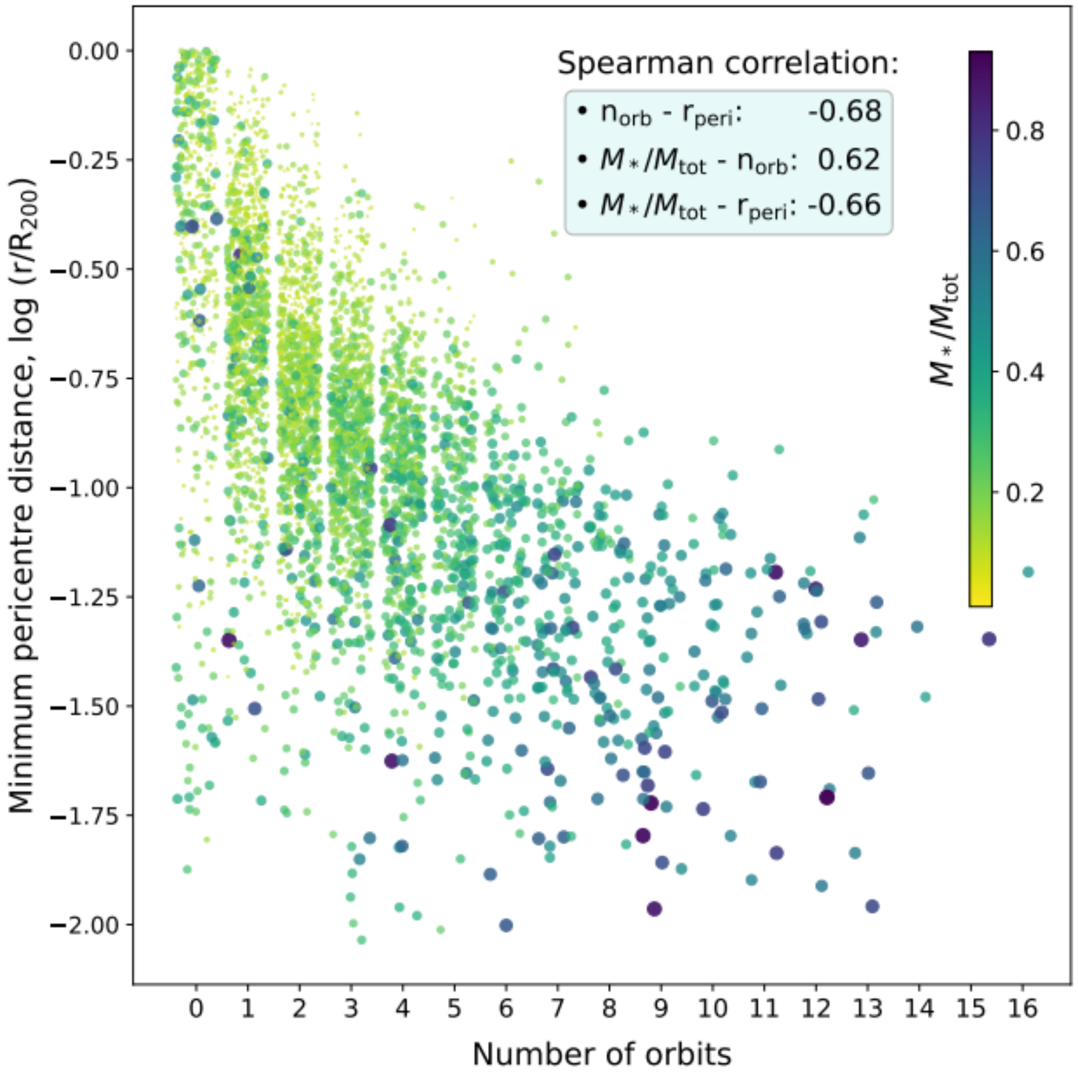
Mgas

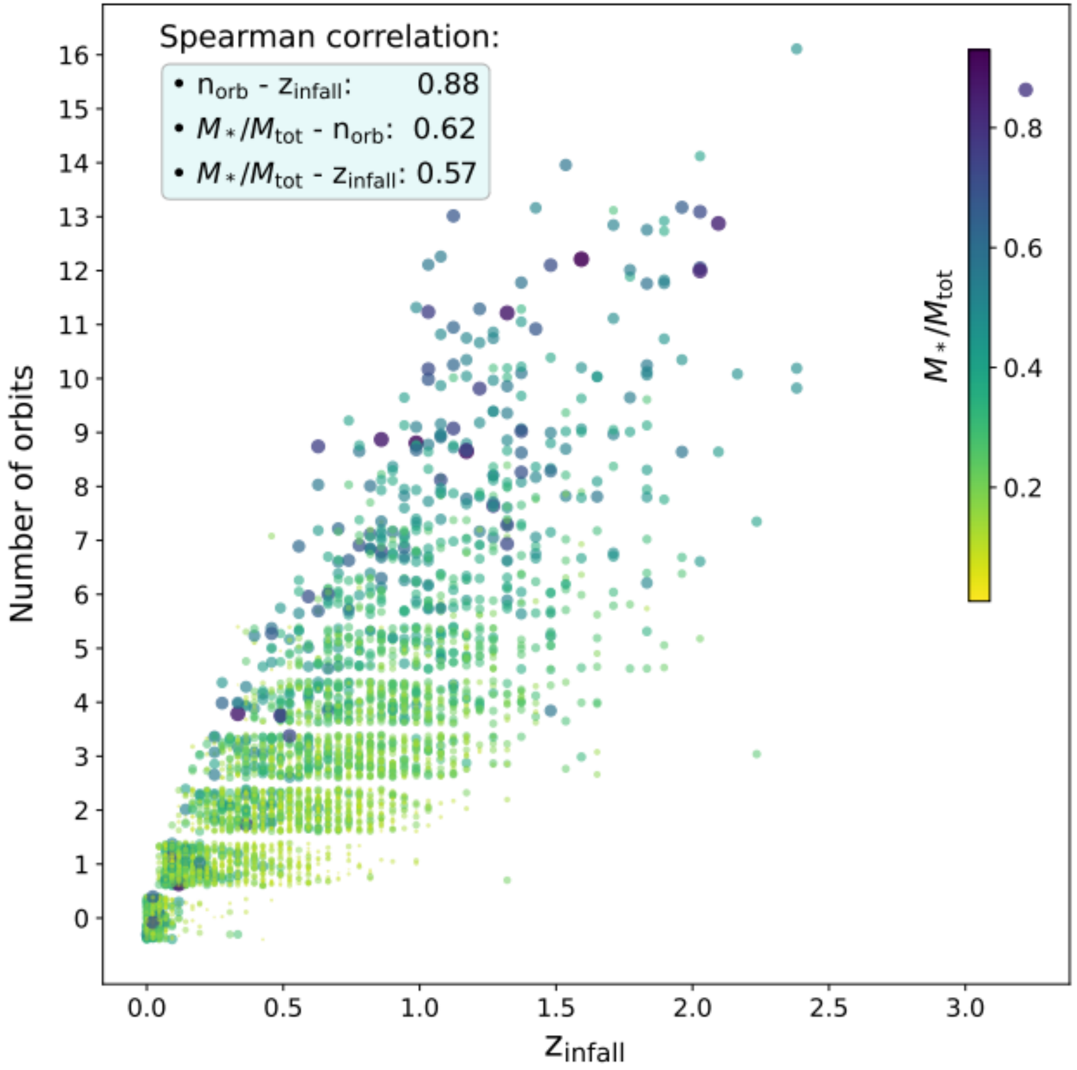
The distance to cluster centre



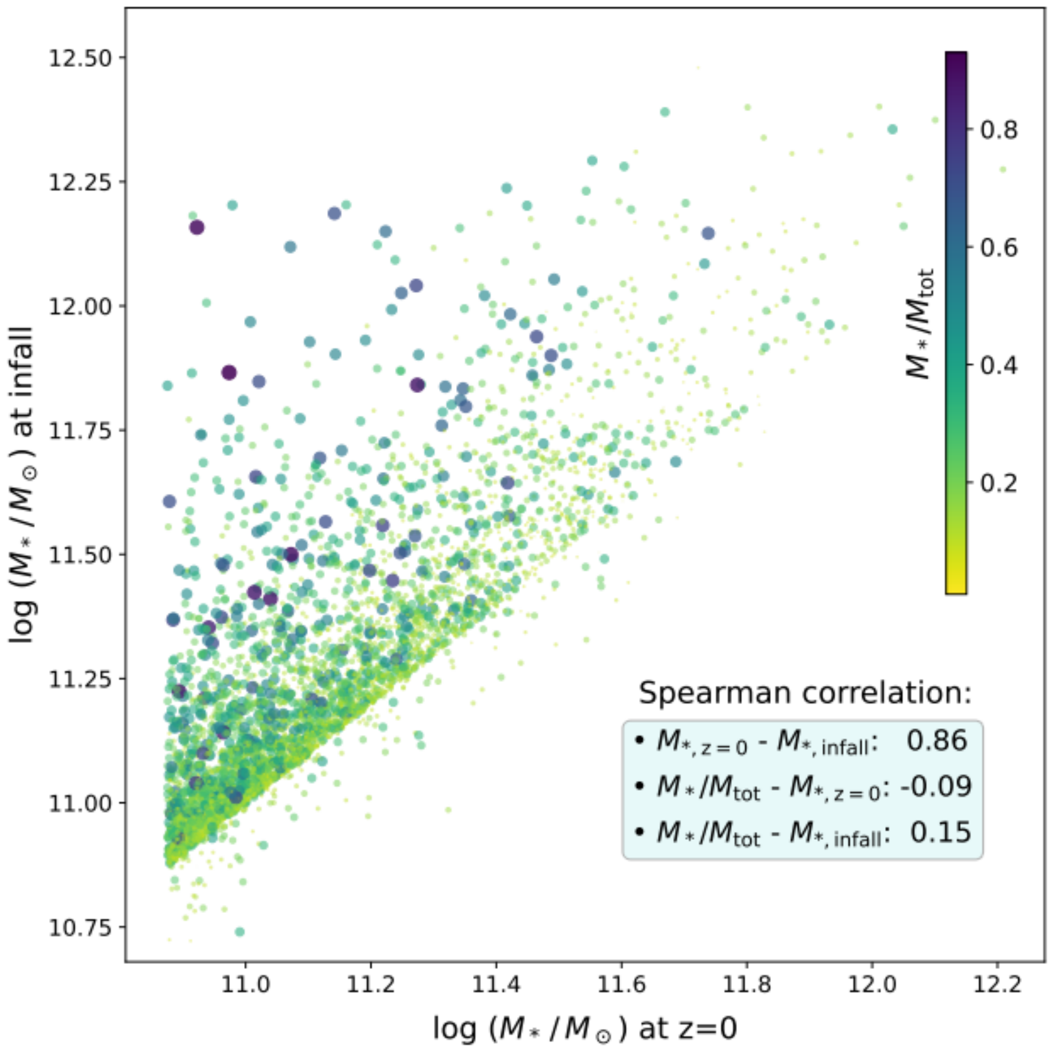
Statistics studies

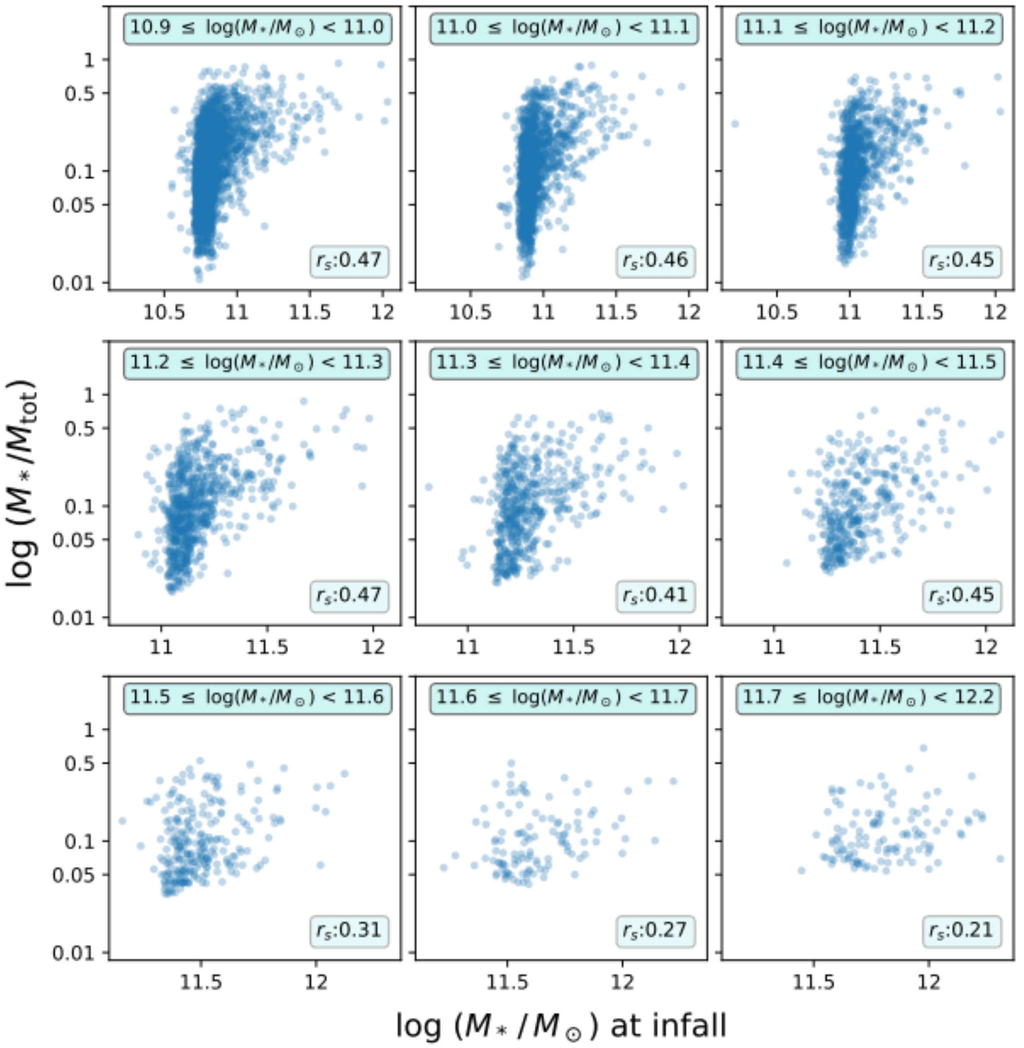
refine the selection to include only those with stellar masses $M_* \geq 7.5 \cdot 10^{10}$Msun





Statistics studies





Conclusions

- Motivated by the discovery of a massive, dark matter-deficient galaxy (i.e. NGC 1277, Comerón et al. 2023) in the Perseus galaxy cluster, the authors have used a set of 324 hydrodynamical re-simulations of galaxy clusters to search for galaxies that are similar in their stellar and dark matter contents.
- Massive dark matter-deficient galaxies do exist in the simulations, but they require some specific conditions to be formed.
- The lack of dark matter in these galaxies is a result of the prolonged interaction with their host after infall. As they orbit, tidal interactions strip away their dark matter, leaving behind predominantly stellar material, which was more concentrated towards the centre and hence harder to strip.
    - More dark matter-deficient galaxies have a high number of orbits and with pericentre distances on average closer to the cluster centre.
    - More dark matter-deficient also have on average higher infall redshifts than general galaxies.
    - The galaxies that end up being more dark matter-deficient today were amongst the most massive ones at their infall time, indicating that to obtain galaxies as extreme as the ones we obtain, an already very massive object at infall is required

- This is a generally accepted physical scenario for the mass loss of subhalos after infall into a particularly dense host environment and a natural outcome of hierarchical structure formation.
- Therefore, the existence of such objects is therefore not in contradiction with theoretical ΛCDM predictions.

Conclusions

- Motivated by the discovery of a massive, dark matter-deficient galaxy (i.e. NGC 1277, Comerón et al. 2023) in the Perseus galaxy cluster, the authors have used a set of 324 hydrodynamical re-simulations of galaxy clusters to search for galaxies that are similar in their stellar and dark matter contents.
- Massive dark matter-deficient galaxies do exist in the simulations, but they require some specific conditions to be formed.
- The lack of dark matter in these galaxies is a result of the prolonged interaction with their host after infall. They experienced a larger number of orbits and have on average smaller pericentre distances than average galaxies.
- At infall time, these objects are already very massive, with a concentrated stellar core, either being a single massive galaxy or the central galaxy of an infalling group.
- While the stars are more concentrated towards the centre, the dark matter halo is generally more extended, and so it is more easily stripped.
- When a galaxy undergoes many orbits, with pericentres very close to the host centre, this effect is intensified and can give rise to objects at $z = 0$ as extreme as the examples presented here.

- The existence of such objects is therefore not in contradiction with theoretical ΛCDM predictions.