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Using Simulations to better understand environmental effects on Satellite galaxies

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Abstract. Numerical simulations have proven crucial tools for understanding environmental effects that influence the HI content of galaxies. They have provided a variety of new tools and diagnostics that can be applied to observations to greatly deepen our understanding of the processes at play. Furthermore, recent results from cosmological simulations make it increasingly clear that we cannot ignore the close connection between dense environments and their surrounding large scale structure. However, while hydrodynamical cosmological simulations have been shown to be highly successful at matching global gas scaling relations of central galaxies, it remains challenging to accurately match the properties of satellite galaxies. Thus, the complex physics at play on satellite galaxies may potentially provide valuable constraints on the sub-grid physics employed in the next generation of simulations.

Keywords. numerical simulation, galaxy evolution, galaxy environment, large scale structure

1. Introduction

1.1. *Simulations as Tools to Understand Environmental Effects*

Over the last decades, numerical simulations have become essential tools to help us understand the effect that dense environments, such as galaxy clusters, have on their satellite galaxies.

The types of numerical simulations that are generally used for this goal can be broadly split into three main categories; Semi-Analytical Models (SAMS; where galaxy properties are painted onto the halos of a dark matter only simulation according to analytical recipes), large volume hydrodynamical cosmological simulations (where the gas and formation of the galaxies is treated self-consistently in a fully cosmological context), and wind-tunnel like simulations (where a fully-formed individual galaxy is constructed in a closed box, modelled at high resolution, and subjected to the dense environment by feeding in environmental mechanisms through the walls of the box). Each approach has different advantages and disadvantages. Wind-tunnel like simulations generally allow for the highest resolution simulations, and controlled experiments can be conducted, but they lack a fully cosmological context. Meanwhile, large volume hydrodynamical cosmological simulations have the cosmological context, but are often limited in spatial resolution, and with limited ability to conduct controlled experiments. Finally, SAMs allow huge volumes and massive statistical samples of galaxies to be considered and evolved across time, but the treatment of environmental effects acting on the gas disk of galaxies is challenging to include semi-analytically, although recently progress has been made (e.g., Cora et al. 2018; Xie et al. 2020a).

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1.2. *Some Limitations of Current Hydrodynamical Cosmological Simulations: the Over-Stripping and Over-Quenching Problem*

With the recent availability of large amounts of public data from cosmological hydrodynamical simulations, such as TNG, Horizon-AGN, and EAGLE, there has been an explosion in publications taking advantage of this data resource.

Nevertheless, we have also learnt that there appears to be a common issue shared between these simulations, which is directly relevant for the study of environmental effects in dense environments. Satellites of galaxy clusters have too little cold gas content (the over-stripping problem, e.g., Marasco et al. 2016; Brown et al. 2017; Stevens et al. 2019) and simultaneously too little star formation (the over-quenching problem, e.g., Xie et al. 2020b; Stevens et al. 2020; Donnari et al. 2021). This is especially an issue for lower mass satellites in more massive clusters. Given that the cold gas is the fuel for star-formation, it is perhaps unsurprising that over-stripped galaxies are often over-quenched.

It is not yet clear what is the primary cause of this issue. However, a number of factors could be at play. Limited spatial reason results in a limited ability to resolve dense gas which would be more difficult to strip. Furthermore, the effect could be a result of how sub-grid feedback recipes couple to the cold disk gas of satellites, perhaps explaining why the over-stripping/-quenching effect has differing satellite and host mass dependencies between the different simulations.

In any case, it is important to be aware of this limitation. It is tempting to download publically available data of hydrodynamical cosmological simulations, and extract a sample of galaxies that resembles your own observed sample. And, then investigate the origins of those modelled galaxies, assuming they have the same origins as the observed sample. However, this assumption may not be valid, given this known limitation. for example, the simulated galaxies may have got into their current day state through an accelerated process of gas loss and quenching when compared to the observed galaxies. Thus, any direct comparison between observations and simulated galaxies of clusters, especially involving the use of gas fractions, and star formation rates or star formation histories, should bear this in mind when interpreting their results.

2. Alternative uses of Simulations for Studying Environmental Effects in Dense Environments

The limitations noted in the previous section may be sensitive to the details of the hydrodynamical treatment, or the exact sub-grid physics treatment of star formation and feedback. However, there are alternative ways to use numerical simulations to better understand environmental effects acting on galaxies which are not so sensitive to the exact treatment of the baryonic physics involved, and provide valuable diagnostic tools for direct application to observations. An example of this is the projected phase space diagram, as described in the following.

2.1. *Projected Phase-Space (PPS) Diagrams: Adding a Time Dimension to Environmental Effects*

While it is possible to form a phase-diagram from any two parameters, here we specifically refer to a plot of projected velocity versus projected radius, where the velocity of satellite galaxies are in the frame of reference of their host cluster, and projected radius is measured with respect to the cluster centre. As each cluster has different mass and size, typically the projected velocity is normalised by the velocity dispersion of the cluster, while the projected radius is normalised by Virial radius of the cluster. This enables stacking of the PPS diagram of each cluster together into a master PPS diagram, where the total number of satellite galaxies included on the plot can be statistically much larger.

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The stacking of multiple clusters also helps to overcomes the effects of non-sphericity and irregularity in the shape of the clusters, which tend to be averaged out in the master stack.

The value of the PPS diagram for interpreting observations of satellite galaxies is galaxies which fell into the cluster a long time ago, compared to those that fell in recently, are preferentially found at different locations within the PPS diagram. In a 3D PS diagram, the separation of different infall times is quite clear Rhee et al. (2017). However in a 2D projected PS diagram, there is more mixing due to projection effects Oman and Hudson (2016). Nevertheless, there is still a tendency for recent infallers to be located differently than ancient infallers, even if there is a lot of overlap in their distributions in the 2D projected PS diagram.

This property can be of great value, as we know that environmental effects do not act instantly when a satellite galaxies first enters a cluster. By being able to put constraints on when galaxies fell into clusters using a PPS diagram, we are also able to constrain the rate at which environmental effects act to transform their galaxies. Therefore, rather than just comparing hosts of different masses (e.g. clusters versus groups), we can attempt to split satellite samples by their time of infall. In this way, we add the missing time-dimension to stuides of how dense environments transform infalling galaxies.

In this way, dark matter only cosmological simulations of galaxy clusters (that have very little dependency on hydrodynamical effects or sub-grid physics) can be used to build diagnostic diagrams that constrain observed satellite galaxy infall times into their hosts. One example is given in Rhee et al. (2017) where the PPS diagram is divided into 5 regions, and the break down of recent infallers, intermediate infallers, ancient infallers, and interlopers is provided in each region. An alternative example is given in Pasquali et al. (2019), where the PPS diagram is split into 7 numbered zones whose shape is chosen so that the median infall time of satellites systematically shifts from ancient to recent infallers as we move from zone 1 out to zone 7. Pasquali et al. (2019) show how the spectroscopic properties (luminosity weighted ages, metallicities, and alpha-abundances) of SDSS satellite galaxies change as their median infall time changes, for a broad range of host masses from giant galaxies up to massive clusters, and for a broad range of saellite masses. In Smith et al. (2019), the same approach is used but considering the stellar mass growth histories of galaxies derived from SED fitting. This study demonstrated that even low mass groups can significantly quench their satellites, once sufficient time since infall has occurred, and showed that some satellites were quenched even before infalling into their clusters (also see Section 3.1).

2.2. *PPS diagrams Combined with Star Formation Rates (SFRs)*

When combining PPS diagrams derived from simulations with the observed SFRs of satellite galaxies, it becomes possible to constrain the decline in a satellite galaxy's SFR after falling into dense environments. An example of this is given in Rhee et al. (2020). Here, the spectroscopically derived SFRs of SDSS satellite galaxies are placed in a pixelated PPS diagram. In each pixel, a distribution of the satellite infall time is extracted from a cosmological simulation. Then, using abundance matching, the infall time distribution is matched with the distribution of observed SFRs. The result is a trend of SFR versus infall time for all the galaxies in a pixel, and the pixels can be combined to produce a master SFR-infall time trend. Finally, using a sophisticated Markov Chain Markov Chain (MCMC) approach, a delayed quenching model is fit to the master SFR-infall trends, and the probability density functions of the main model parameters are produced. In Rhee et al. (2020), it was found that the delay time was typically of order the time for a satellite to first infall until it reaches first pericentre, suggesting that

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rapid quenching is triggered by pericentre passage. Secondly, the e-folding time during the rapid quenching phase was found to be sensitive to galaxy mass. A similar approach is also applied in Oman et al. (2020) to understand when atomic gas is stripped from satellite galaxies (see also Yoon et al. 2017).

2.3. *PPS diagrams Combined with the Tail Directions of Jelly Fish (JF) Galaxies*

Location in a PPS diagram is not the only way to constrain where a satellite galaxy is along its orbit. The direction of a JF galaxy's tail with respect to the cluster centre can also provide complementary information. This is because first infaller satellites into clusters typically follow quite radial and plunging orbits. Thus, when a gas rich galaxy first enters the cluster and suffers ram pressure, the gas tail it produces tends to point away from the cluster centre. However, once the satellite passes pericentre (if the tail is still visible) then its tail will now point towards the cluster centre. Thus, observed distributions of JF tail directions with respect to the cluster centres can provide information on two important timescales – when JF galaxies first form visible tails, and also how long the tails last after pericentre (if at all). In Smith et al. (2022b), location in a PPS diagram is combined with histograms of JF tail directions to attempt to constrain these timescales. Dark matter only cosmological simulations are used, thus the results are not sensitive to the hydrodynamic treatment or sub-grid physics. Instead, a simple semi-analytical recipe is used to paint tails onto in-falling satellite halos into groups and clusters. The recipe parameters include at which radius in the cluster the JF tail first becomes visible, and how long before or after pericentre the tail disappears. The model parameters are systematically varied, and a line-of-sight projected version of each model parameter set is then produced (in the form of satellite distribution in a PPS diagram and a projected tail direction histograms) to enable a fairer comparison with the observations. In Smith et al. (2022b), the observational data set are JF galaxies identified in LOFAR radio continuum observations (Roberts et al. 2021). While this initial study was primarily a test of concept, the results demonstrate that radio continuum tails typically appear at a distance of roughly three quarters of the cluster Virial radius on first infall, and typically remain visible for several hundred Megayears after pericentre (in stark contrast to the gas stripping measured in some cosmological hydrodynamical simulations, e.g. Lotz et al. 2019). Thus, here dark matter only cosmological simulations are essentially combined with observations to put useful constraints on how gas stripping should be occurring in hydrodynamical cosmological simulations. Furthermore, when considering the case of lower mass satellites located in higher mass hosts, the model suggests that the JF tails appear earlier and disappear more soon after pericentre, as would be expected if lower mass satellites are more affected by the ram pressure. Similar results have since been recovered for optically selected Jellyfish galaxies using the same methodology in Salinas et al. (2024).

3. Simulations to Understand Quenching Beyond the Cluster Virial Radius

While we have so far focused on how we can use simulations to better understand quenching inside the dense environments of clusters, it is known that suppression of star formation in galaxies can be observed out to as many as 4-5 Virial radii from their nearest cluster (e.g. Haines et al. 2015). In Bahé et al. (2013), various scenarios are tested for how quenching can arise beyond the cluster Virial radius. It is well known that some galaxies can fall into a cluster, and then follow an orbit that later takes them out beyond the cluster Virial radius. These galaxies are known as 'back-splash' galaxies, and if they should be sufficiently affected by their time spent in the cluster environment,

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this is one way that quenching might arise beyond the cluster Virial radius. However, the cosmological simulations if Bahé et al. (2013) demonstrate that it is rare for a back-splash galaxies to reach further than 2 Virial radii (or in more extreme cases, 3 Virial radii). As an alternative, environmental quenching of satellite galaxies could also arise in group mass hosts, which are found in the required range of radius surrounding cluster galaxies. If such groups are later accreted into clusters, they can contaminate the cluster population with galaxies that have already begun to be transformed (so called 'pre-processing' of the cluster population; Mihos 2004). Nevertheless, Bahé et al. (2013) showed that, even after removing all the confirmed back-splash galaxies and confirmed satellites of nearby hosts in their simulations, a signal for quenching persisted out to many Virial radii about clusters.

3.1. *Quenching in Filaments and Void Walls*

To explain this surprising result, Bahé et al. (2013) suggested that this remaining signal of quenching could be the result of galaxies directly interacting with the hot gas inside the cosmological filaments. The ambient filament gas is substantially lower density than the ambient gas found in clusters or groups, and also the relative velocities of galaxies passing through that gas might be expected to be generally lower. Therefore, ram pressures might be expected to be significantly weaker than those found in clusters. Nevertheless, the ram pressures that are measured to arise in cosmic filaments in the Bahé et al. (2013) simulations are found to be sufficient to affect the gas content, at least in lower mass galaxies (see also Benítez-Llambay et al. (2013) and Song et al. 2021).

More recently, ram pressures arising in the even lower density environment of void walls were considered in Thompson et al. (2023), in a set of hydrodynamical cosmological zoom simulations of voids. A population of central halos were identified that are actively experiencing fast flows of ambient gas past their halos, and these 'fast-flow' halos were found to be exclusively located close to void walls. When the direction of the flow was considered, it was found to have a strong preference to be directed towards the void walls, regardless of which side of the wall the halos are located on. A number of cases of clear JellyFish (JF) like gas morphologies were also identified, each with their JF tails pointing toward the void walls. The phenomena was eventually explained in the context of the complex flows of ambient gas that arise within the large scale structure of the Universe. Walls are often found at the location where two expanding voids collide. Void galaxies tend to move with the expansion of the void, and thus they approach the void wall, moving at a similar speed as the surrounding ambient gas of the void. However, things dramatically change once they reach the void wall. While the ambient gas shocks, stalls, and joins the void wall, the collision-less galaxies can cross the void wall and exit from the other side. At this moment, they find themselves moving head-on into a counter flowing ambient gas from expanding void on the other side of the wall. The result is a temporary fast flow of ambient gas past the halos, where the flow is always directed back towards the void wall. Typically, the ambient gas densities and galaxy relative velocities are even lower than those found in filaments, but the complex dynamics of the large scale structure can give rise to these short bursts of ram pressure. Thompson et al. (2023) finds they are still relatively weak compared to those found in dense environments, but are expected to be sufficient to strip the hot gas from the halos of low mass dwarf galaxies, potentially initialising a starvation like process, long before the dwarf galaxies reach a dense environment.

This type of direct environmental effect between a galaxy and ambient gas within the large scale structure could be, in part, responsible for the changes in galaxy properties, seen in observations, as a function of distance from filaments and void walls. For example, SDSS galaxies are found to have redder optical colours (Kraljic et al. 2020), and to

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have older spectroscopically-measured luminosity-weighted ages, higher metallicities and alpha-abundances as they approach filaments and walls (Winkel et al. 2021).

Most massive galaxy clusters are closely linked to the surrounding large scale structure through a network of cosmic filaments, that can act as highways, bringing galaxies into the cluster environment. In this way, any environmental effects arising in the filament environment are then brought into the cluster population via filament feeding, thus impacting on the cluster by contaminating its population with 'filament pre-processed' galaxies. Nevertheless, the change in galaxy properties inside cosmic filaments can generally be considered a second-order effect, in comparison with the dependency of a galaxy's properties on its own mass. As a result, it is first necessary to carefully normalise out the changes in galaxy properties due to galaxy mass (as more massive galaxies naturally tend to be found closer to filaments anyhow), in order to to detect the change in galaxy properties with distance from the filament. However, in the following sections, we will detail how the impact of the large scale structure on the cluster can be much more significant than the 'filament pre-processing' we have described so far.

3.2. *The Large Scale Velocity Field's Impact on the Orbits of Infalling Satellites*

When galaxies first infall into a cluster or group, how deep they plunge into the host is expected to play a key role on how strong the environmental effects acting upon it will be. Nearer the cluster centre, the tidal field is expected to be stronger. Furthermore, more plunging orbits tend will orbit through a denser intracluster medium and have higher orbital velocities, likely driving strong ram pressures as well.

In Smith et al. (2022a), we considered the key parameters dictating how plunging the orbit of a first infaller will be (as quantified through the size of the pericentre distance on first passage). After considering a variety of possibilities, we concluded that the most important factor dictating the pericentre distance was the tangential velocity of the infaller when it first passes the cluster Virial radius. In many ways, it is obvious that infallers with a small tangential velocity when entering the cluster will have a more radially infalling orbit, that might be expected to result in a smaller pericentre distance. However, what should be highlighted is that the tangential velocities of the first infallers are not something controlled by the cluster, and are entirely dictated by the dynamics they inherit from the large scale velocity field surrounding their cluster. Furthermore, those infallers with smaller pericentres due to this effect were confirmed to suffer stronger and more rapid tidal mass loss during their first passage in our simulations. As a consequence, two identical clusters may subject their satellites to environmental effects at their cores with very different strengths, as dictated by circumstances arising far outside the Virial radii of the clusters (a result that was confirmed with our simulation). The implication of this result is that it may no longer be sufficient to simply quantify the environment inside of the host of a satellite galaxy – we may need to additionally consider the large scale dynamics surrounding the cluster, if we are to truly understand the strength of environmental effects acting at the cores of clusters.

3.3. *Transformation of Cluster and BCG shape by Filament feeding*

As most massive clusters are connected to cosmic filaments, the growth of the cluster may occur preferentially along the directions of the filament, a process known as 'filament-feeding'. As we will discuss in this section, this preferential feeding from particular directions can have a dramatic impact on the entire shape of a cluster and transform the shape of its Brightest Cluster Galaxy (BCG).

In Smith et al. (2023), we considered a set of galaxy clusters from the Hectospec Cluster Survey (HeCS; Rines et al. 2013). For each cluster, the deep Hectospec spectroscopy

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enables us to identify numerous cluster members (typically hundreds) out to three Virial radii, and accurately determine the overall shape of the cluster on the sky, as trced out by its satellite members. Furthermore, many of the clusters are also located in the SDSS spectroscopic survey footprint, which provides (shallow) spectroscopy out to tens of Virial radii around the clusters. With the SDSS spectroscopy, we build filament maps, as traced out by the DISPERSE tool (Sousbie 2011). In this way, we were able to search for signal of alignment between the cluster shape and the positions of the surrounding filaments. The BCG of each cluster was also identified, and its shape and position angle recorded. Using this data set, we identified an extremely high significance signal (less than a one in a million chance of it arising by chance) for alignment between the BCG position angle, the cluster shape, and the surrounding filaments. The signal of alignment with the filaments is detectable as far as 10 Virial radii from clusters. The strength of the alignment signal was found to be significantly stronger for clusters with more extended and elliptical shaped BCGs, and signal strength was enhanced when we used a luminosity-weighted map of the filamentary structure.

A likely interpretation of these results is that the feeding of clusters from specific direction by filaments can dramatically transform the shape of the cluster, so as they are extended along the direction of the filament-feeding. Furthermore, as the BCG is the central galaxy of the cluster it likely also suffers mergers from the same preferential direction. This could transform its shape to be extended along the direction of the filament-feeding, much like the cluster as a whole. What is truly astonishing is the incredible range of scale involved. In figure with scale limits of 3 Virial radii of the cluster, the BCG appears so small that it is impossible to see its shape and position angle. And yet the BCG tends to align with the shape of the cluster on these scales. Indeed, it aligns with much larger structures all the way out to 10 Virial radii. This truly shows the consequences the large scale structure can have, not only in transforming clusters on Mpc scales but even physically transforming their galaxies on scales of $\sim$ hundreds of kiloparsecs.

3.4. *The Chilean Cluster Galaxy Evolution Survey (CHANCES)*

The CHANCES survey is a Chilean-led survey of ~ 100 nearby clusters (redshift<0.03), using deep spectroscopy from 4MOST (Haynes et al. 2014) to identify more than 300,000 galaxies in the vicinity of clusters out to 5-6 Virial radii. The aim is to study many of the research interests discussed in this proceedings and more, connecting clusters to their large scale surrounding structure. The spectroscopy is sufficiently deep that dwarf galaxies of stellar masses $\sim 10^8\,M_\odot$ will be detected, meaning that galaxies which are highly sensitive to environmental effects will be included. And given the large numbers of dwarfs, accurate tracing out of the surrounding large scale structure will be possible with huge numbers of tracer galaxies, including smaller and fainter filaments.

There is also an intermediate redshift sub-survey (the 'Evolution' sub-survey) of clusters at redshifts from 0.07 to 0.45, to study the evolution of galaxy clusters over that time period, and a sub-survey on the Circum-Galactic medium. Synergy with E-ROSITA Predehl et al. (2021) and MEERKAT Knowles et al. (2022) provides complementary data on the X-ray properties of many clusters, and HI gas content of their satellites.

4. New Tools for Filament Tracing: 1-DREAM

Given the importance of the Large Scale Structure for a better understanding of environmental transformation in dense environments that has been repeatedly expressed in this proceedings, it is important that we have multiple tools to identify, trace-out, quantify and parameterise the large-scale structure in the vicinity of clusters. As part of an

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international collaboration between computer scientists and astronomers in Chile, the Netherlands and the UK, we have developed a set of tools for exactly these purposes.

We have developed '1-DREAM' (One Dimensional Recovery Extraction and Analysis of Manifolds). This is actually a 5-tool package (LAAT, MBMS, DimIndex, Crawling, SGTM), that has been made available to the public (https://git.lwp.rug.nl/cs.projects/1DREAM). The first tool, LAAT stands for 'Locally Aligned Ant Technique'. It is essentially an ant colony pheromone algorithm in which virtual ants wander through a cosmological volume, leaving behind pheromone trails that eventually decay away. They prefer to walk in the direction of one dimensional structures, and their pheromone trails attract more ants to do the same, highlighting the presence of a filament structure, even in a noisy background. Thus, they are ideal at detecting and highlight cosmic filaments embedded in the noisy and complex large scale structure. The MBMS tool provides a means to identify the skeleton backbone of filaments that the LAAT tool highlights. The DimIndex tool can distinguish the 1D structures (filaments), 2D structures (walls) and 3D structures (nodes) of the large scale structure. The Crawling tool allows a series of vectors to be laid along the backbone of the filament. Finally the SGTM tool allows a means to identify members of the filaments, using Bayesian probabilistic modelling. For a full description of the various algorithms please see the method description paper (Canducci et al. 2022).

Installation is simple and quick, following a step-by-step guide on the GitHub webpage, with a minimal number of dependencies required. All tools have been conveniently wrapped in Python, in order to encourage the astronomical community to download and use the toolbox. Where required, codes are parallelised to run on multiple CPUs for decreased run-times. The package also comes with a set of guided examples. This includes a new cosmological volume example, in which hundreds of individual filaments are identified in the volume. In most cases, a user can be up-and-running with the guided examples in one afternoon.

1-DREAM has already been used for wide range of applications from tail tracing in Jellyfish galaxy tails (Canducci et al. 2022), filament finding in cosmological simulations (Awad et al. 2023) and observational filament finding around the the Fornax-Eridanus Complex (Raj et al. 2024), to stellar stream finding about Galactic globular clusters (Awad et al. 2024), with many more publications currently in preparation/submitted.

5. Conclusions

Numerical simulations have proven a crucial tool to improve our understanding of environmental effects operating on satellite galaxies in dense environments, allowing us to pick apart the impacts of the various mechanisms using controlled experiments. However, there are some well known limitations to the publically available data of large volume hydrodynamical cosmological simulations. In particular, low mass cluster satellites are typically too gas poor and have lower star formation rates (the 'over-stripping' and 'over-quenching' problem), compared to observations of similar mass satellite galaxies in equivalent environments. As a result, users of the data should try to be aware that an observational sample and simulated sample of cluster satellites, with similar gas fractions or star formation rates today, likely reached their current day properties on different timescales and following distinct evolutionary tracks.

However, numerical simulations can also be used to develop new diagnostical tools for a better interpretation of observational data, in ways that are far less sensitive to the detailed treatment of hydrodynamics or subgrid-physics. A clear example of this is the projected phase space diagram, which can be used to provide constraints on satellite infall times, adding a time dimension to our study of environmental effects. Coupled with

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complementary observational data sets such as star formation rates or the observed distributions of Jellyfish tail directions, projected phase space diagrams can provide valuable new insights into the gas stripping and star formation quenching process that galaxies undergo when they enter dense environments.

Finally, we emphasise that recent literature highlights that we should not consider dense environments in isolation. A true understanding of environmental effects acting on the cluster satellites requires insight into the role of the large scale structure surrounding clusters, both for pre-processing infallers, and altering the orbits of infalling galaxies, resulting in stronger environmental effects at cluster cores. Furthermore, filament-feeding of clusters seems capable to transform the entire shape of clusters and their Brightest Cluster Galaxies. The consequences span a huge range of physical scale from the 10-20 Mpc scales of the large scale structure itself, to the Megaparsec scales of clusters, down to the 100 kpc scales of the Brightest Cluster Galaxies.

For a comprehensive recent review of how dense environments impact on their satellite populations, from both an observational and theoretical perspective, it is recommended to read the Dawes Review 9: The role of cold gas stripping on the star formation quenching of satellite galaxies (Cortese et al. 2021).

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