The better half - Asymmetric star-formation due to ram pressure in the EAGLE simulations

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ABSTRACT

We use the EAGLE simulations to study the effects of the intra-cluster medium (ICM) on the spatially resolved star-formation activity in galaxies. We study three cases of galaxy asymmetry dividing each galaxy in two halves using the plane (i) perpendicular to the velocity direction, differentiating the galaxy part approaching to the cluster center, hereafter dubbed as the “leading half”, and the opposite one “trailing half”, (ii) perpendicular to the radial position of the satellite to the centre of the cluster, (iii) that maximizes the star-formation rate (SFR) difference between the two halves. For (i), we find an enhancement of the SFR, star formation efficiency (SFE), and interstellar medium pressure in the leading half with respect to the trailing one and normal star-forming galaxies in the EAGLE simulation, and a clear overabundance of gas particles in their trailing. These results suggest that ram pressure (RP) is boosting the star formation by gas compression in the leading half, and transporting the gas to the trailing half. This effect is more pronounced in satellites of intermediate stellar masses $10^{9.5} - 10^{10.5} M_\odot$, with gas masses above $10^9 M_\odot$, and located within one virial radius or in the most massive clusters. In (iii) we find an alignment between the velocity and the vector perpendicular to the plane that maximizes the SFR difference between the two halves. It suggests that finding this plane in real galaxies can provide insights into the velocity direction.

Key words: galaxy evolution – cosmological simulations – IFS

1 INTRODUCTION

Galaxy clusters are important laboratories to study galaxy evolution because they allow us to explore the maximal effect of interactions and nurture on the evolution of galaxies. As galaxies plunge into the intra-cluster medium (ICM) of groups and clusters of galaxies, they experience different effects from their surrounding environment including ram pressure (RP) and tidal stripping. These are believed to produce changes in the galaxy properties ranging from gas loss to enhanced star formation (SF) activity due to the increase of pressure acting on the disc of the galaxy (Kapferer et al. 2009; Steinhauser et al. 2012; Safarzadeh & Loeb 2019). Since the seminal work of Gunn & Gott (1972), RP is a well known physical mechanism thought to be a major driver behind the observed absence of spiral galaxies in the central regions of dense cluster environments.

Gunn & Gott (1972) showed that RP is proportional to the density of the ICM times the relative velocity of the satellite galaxy and the brightest cluster galaxy. RP may accelerate the star-formation rate (SFR) of the galaxies residing in dense environments, thus prompting their transition from an active to a passive state (Gunn & Gott 1972; Moore et al. 1996; Jaffe et al. 2015).

In observations, the effect of RP has been studied in galaxies that are being gas-stripped in galaxy clusters, identified via their distorted morphologies (Smith et al. 2010; McPartland et al. 2016). Historically, this identification has been performed via visual inspection of images of cluster members (Poggianti et al. 2016; McPartland et al. 2016), and in mock images of hydrodynamical simulations (Yun et al. 2019). It allows to determine their abundance and dependence with redshift. Ideally, integral field spectroscopy (IFS) is used to map the spatially resolved emission of the stellar and gas
components, its kinematics and re-construct their evolution. The GASP (GAs Stripping Phenomena in galaxies with MUSE) survey performed an unprecedented IFS detailed study of local galaxies, in the redshift range 0.04–0.07 (Poggianti et al. 2017; Bellhouse et al. 2019). This ESO large program uses 120 hours to push the state-of-art, observing one hundred local galaxies in the field and clusters to a level of detail much greater than can be done in larger surveys with IFS such as SAMI (Sydney-Australian-Astronomical-Observatory Multi-object IFS; Croom et al. 2012) and MaNGA (Mapping Nearby Galaxies at APO, Bundy et al. 2013). Yet, the number of objects analyzed in the GASP and SAMI or MANGA survey differs by two orders of magnitude.

The advent of large scale surveys motivates to find other methods to study galaxy evolution and specifically RP in a statistical manner. Particularly in view of photometric surveys such as SDSS (Sloan Digital Sky Survey, Abazajian et al. 2009), VST-ATLAS (Shanks et al. 2015), J-PAS (Benitez et al. 2014), LSST (Ivezic et al. 2008) in the near future or spectroscopic ones like GAMA (Baldry et al. 2010), DESI (Aghamousa et al. 2016), BOSS (Dawson et al. 2013), DEVILS (Davies et al. 2018), and WAVES (Driver et al. 2018). They permit to measure galaxies under the effect of RP in thousands of clusters at different redshifts. Machine learning techniques have been used to classify galaxies according to their morphology (Banerji et al. 2010) and could be used to identify galaxies undergoing strong transformation processes or RP effects, for example.

In this work, we propose a statistical method using the EAGLE (Schaye et al. 2015) suite of hydrodynamical simulations immersed in a cosmological context to explore statistical ways to measure the RP effect on cluster galaxies and its consequences on other physical properties of galaxies. The rationale of this approach is twofold. We use hydrodynamical simulations because they allow to explore the spatially resolved properties and study galaxy evolution self-consistently. It permits to select large and statistically complete samples. We use the EAGLE galaxies because they follow the general scaling relations between stellar mass, SFR, metallicity, and gas content, as it is described in detail in Lagos et al. (2016). They reproduce the observed galaxy colours (Trayford et al. 2015), the fraction of passive galaxies as a function of stellar mass (Furlong et al. 2015), and the slope of the spatially resolved SFR–stellar-mass and mass–metallicity relations, down to kilo parsec scales (Trayford & Schaye 2019). We analyze all the galaxies forming stars, above certain SFR or mass limit, identified as members of clusters and groups, and use the simplest approach of dividing each galaxy satellite into halves. The one that faces the medium as it moves through the ICM, which we will refer to as the leading half, and the one facing the opposite way, the trailing half of the galaxy. If the timescale for the effect of RP stripping on the SF activity is shorter than the dynamical timescale of the disc, the enhancement of the SF should be more prominent in the leading half, which will be subject to the effect of RP. In this case we can expect to find different average SF properties or colors in the leading half with respect to the trailing one.

We apply this method to samples of simulated galaxies, in order to study the dependence of this effect with cluster and galaxy properties. We aim to measure the property differences between the leading and trailing halves of the galaxies and study whether these differences are detectable with current and future instruments and facilities.

This work is organized as follows: in section §2 we describe the simulation and methods. Three cases for halving the galaxies are presented. The first one is dubbed “the velocity cut” because it uses the three dimensional velocity vector of satellites to define the leading and trailing half. In typical observations of large galaxy samples, it will be difficult to obtain this vector. It motivates us to present two cases of possible observational application based on the three dimensional position vector, of the center of potential, of satellites (section §2.3). With the current accuracy achieved in photometric redshifts of large scale surveys (Ascaso et al. 2016), we expect it possible. The analysis of mock galaxies and projected images will be presented in a separate article. In the first observationally driven case, we choose the most simplistic approach of studying the differences between the half that faces the center of the group/cluster, and compare it to the opposite one (Troncoso-Iribarren et al. 2016). In section §3 we show the results for the first case. In section §4.1, we study our second observationally driven case, namely the maximum anisotropy cut, in which we divide the galaxy according to the plane that maximizes the SFR difference. In the same section we analyze the differences between the two observationally driven cases. In sections §4.2, §4.3, §4.4 we analyze the dependence of the first case with the cluster and galaxy properties, and compare it to main-sequence galaxies in the EAGLE simulation, respectively. Finally in section §5 we use the three cases to discuss our findings and study the strength of the anisotropy on cluster and galaxy properties. In section §6 our conclusions are presented.

2 SIMULATION AND METHODS

2.1 EAGLE simulation

The EAGLE project (Schaye et al. 2015) is a suite of hydrodynamical simulations immersed in a LCDM cosmology, adopting the Planck Collaboration XVI (2014) cosmological parameters. It uses up to seven billion baryon and dark matter particles per individual simulation to follow the physics of galaxy formation. These simulations were performed within the framework of the Virgo consortium and broadly reproduce the properties of the local Universe and galaxies as our Milky Way (Furlong et al. 2015; Trayford et al. 2015; Lagos et al. 2016). For further details please see Schaye et al. (2015) and Crain et al. (2015). The particle data and halo catalogues are publicly available in the EAGLE website.

In this work we use the ReILO100N1504 simulation, a periodic box of 100cMpc of length and 1504 gas and dark matter particles in its initial conditions. This simulation is the one with the largest volume in the EAGLE suite, and therefore provides the best statistical sample of galaxies in groups and clusters. We select groups/clusters in the range of \( \log_{10}(M/M_\odot) = 13.6 - 14.6 \), concentrating on large satellites to avoid resolution problems, with typically thousands (hundreds) of stellar (gas) particles per galaxy. The simulation suite was run with a modified version of the GADGET-3 Smoothed Particle Hydrodynamics (SPH) code (Springel 2005). These modifications are collectively dubbed ANARCHY (Schaller et al. 2015). It was run with a suite of subgrid models including radiative cooling and photoheating (Wiersma, Schaye & Britton 2009), stellar evolution and chemical enrichment (Wiersma et al. 2009) taking into account energy feedback from the stars (Dalla Vecchia & Schaye 2012), black hole growth and active galactic nuclei (Rosas-Guevara et al. 2015). Following the SF law of Schaye & Dalla Vecchia (2008), the SFR of each gas particle is calculated

1 http://icc.dur.ac.uk/Eagle/database.php
with the Kennicutt-Schmidt (KS) law \cite{Kennicutt1998} based on a pressure scheme

\[
\text{SFR}_i = \dot{m}_i A \left( \frac{M_\odot}{\text{pc}^2} \right)^{-n} \left( \frac{f_k \bar{P}_i}{G} \right)^{(n-1)/2},
\]

(1)

where \( m_i \) is the mass of the gas particle, \( \gamma = 5/3 \) is the ratio of specific heats, \( G \) is the gravitational constant, \( f_k \) is the mass fraction in gas (assumed to be unity), and \( \bar{P}_i \) is the entropy-weighted average pressure. \( A \) and \( n \) are fixed to the observational results of the KS law, \( A = 1.515 \times 10^{-4} M_\odot/\text{yr}/\text{pc}^2 \) and \( n = 1.4 \).

In this ANARCHY version of pressure-entropy SPH, each gas particle \( i \) carries its (pseudo) entropy \( S_i \), which is used to solve the hydrodynamics of each particle (see equation 4 in \cite{EAGLE_2017}), and calculate their entropy-weighted average pressure and entropy-weighted average density following,

\[
\bar{P}_i = S_i \left( \frac{1}{S_i \gamma} \sum_{j=1}^{N} m_j S_j^{1/\gamma} W_{ij}(h_\gamma) \right)^{\gamma} = S \varphi^\gamma,
\]

(2)

where \( W_{ij}(h_\gamma) \) is the value of the kernel at that location. EAGLE uses the C\(_2\) scheme of \cite{Wendland1995}. The total SFR of the galaxy is the sum of the SFRs of individual gas particles.

We normalize the pressure, \( P/k \), with the Boltzmann constant and use the conversion factor \( 1.38 \times 10^{-16} \text{[dyn/cm}^2\text{]} \) or \( 10^{-17} \text{[N/}\text{m}^2\text{]} \) to compare with observational measurements. We calculate the pressure of each particle, without weighting by the entropy, using the equation of state \( P_i = S \varphi_{\gamma} \), where \( \rho \) is the standard SPH density.

To properly model SF, EAGLE introduces density and metallicity thresholds for certain cases, below which SF is not feasible or simply to avoid modeling cases that are non-resolved by the limits of the simulation. This prevents unrealistic cases such as, hot/metal rich gas forming stars or the formation of spurious stars at high-redshift, when the mean density of the Universe is similar to the critical density of SF. Gas can be converted into stars only if it manages to cool down and reach high densities. Because the efficiency of gas is a strong function of the gas density and metallicity, Shaeve \cite{Shaeve2004} introduced a threshold density above which stars form that is metallicity-dependent,

\[
n_{\text{th}}(Z) = 0.1 \left( \frac{Z}{0.002} \right)^{-0.64},
\]

(3)

where \( Z \) is the metallicity of the gas.

\section{The galaxy sample}

\subsection{The satellite sample}

We consider all galaxies of the largest simulation box of the suite RefL0100N1504 that reside in clusters/groups of mass greater than \( 10^{13} M_\odot \), in snapshot 28, corresponding to \( z = 0 \). These groups are found using the multistage procedure, based on a friends of friends (FOF) algorithm, described in \cite{Schaye2015}.

For the mass scale of the clusters and groups, we use an overdensity of \( M_\text{200c} \), as in \cite{Craaij2015}. \( M_\text{200c} \) is the mass enclosed in a radius with a density of two hundred times the critical density. The mass limit \( M_\text{200c} > 10^{13} M_\odot \) selects the first 25 most massive haloes of the simulation, hosting 3062 galaxies altogether of any stellar mass.

We exclude of this analysis the halo with GroupNumber=17 because the position difference between the center of mass and the maximum of the potential, normalized to its virial radius, is one order of magnitude larger than all the other haloes. This kind of disparity is usually associated with merging galaxy clusters. This suggests that it is not in equilibrium. We discard 117 galaxies by excluding this cluster.

Galaxies are identified using the algorithm SUBFIND \cite{Springel2001,Dolag2009}. It is used to identify local over-dense self-bound substructures or sub-haloes, within the full particle distribution of FOF haloes. Here, we consider all the particles found by the algorithm and not constrain it to certain spherical aperture. It is in contrast with most of the EAGLE publications, which commonly used 30 pkpc \cite{Trayford2019}.

Since we are interested in the analysis of star-forming galaxies, we select the ones with a mass of star-forming gas,
Mass(SF gas) > 0, reducing our sample to 513 galaxies. Additionally, we only analyze galaxies that are well suited for statistics, i.e. with more than one hundred particles in their stellar and gas components (N_{gas} > 100 and N_{dust} > 100). This reduces the sample to 227 galaxies. By selecting the satellites that reside within one virial radius, 16% of the total satellite galaxies that form stars in the simulation at z=0 remain in our sample (80 galaxies). This condition might be too conservative; relaxing the threshold to 50 particles, enlarges the sample in 20% but does not change the final results and conclusions and hence we preserve the present choices for the definition of our sample. Within one virial radius, there is only one galaxy with stellar mass < 10^{8.5} M_{\odot}; we decided to exclude it and make this the stellar mass cut for our final sample selection, i.e 79 (211) satellites at r < 1(3) \times r_{vir}, respectively. Our final sample spans a wide range of stellar masses, 8.5 < \log_{10}M_*(M_{\odot}) < 11.5, star formation rates, –1.3 < \log_{10}\text{SFR}[M_*/yr] < 1.1, gas masses 8.5 < \log_{10}M_{\text{gas}}(M_{\odot}) < 10.5, and masses of star-forming gas 8.5 < \log_{10}M_{\text{SF gas}}(M_{\odot}) < 10.5, metallicities, and gas fractions (see fig. A1).

2.2.2 The control sample

In order to compare the properties of our satellites with the galaxies that are non affected by environmental process, we select a control sample of central and isolated galaxies. We ran a search for galaxies in the snapshot 28 that fulfill the conditions i) it is a central galaxy (SubGroupId=0) and ii) it is consider as a field galaxy, 3) it does not have neighbor galaxies within one virial radius, 4) it has a mass > 10^{11} M_*, and 5) it has star forming gas masses > 2 \times 10^{12} M_{\odot}. We found 3182 galaxies.

From those, we selected the ones with properties similar to our satellites sample, it is logM_* > 8.5, N_{gas} > 100, –1.3 < \log_{10}\text{SFR}[M_*/yr] < 1.1, log M_{\text{gas}} > 8.5, and log M_{\text{SF gas}} > 8.5, ending up into 2191 galaxies. We remark that all galaxies in this sample have sSFR > 0.01[Gyr^{-1}]. Hence they follow the main-sequence criterion defined in [Furlong et al. (2015)].

We define a second control sample, hereafter dubbed “main-sequence sample”, following [Furlong et al. (2015)], we select the galaxies with sSFR[Gyr^{-1}] > 0.01, log M_*(M_*) > 9, and imposing the condition of being a central galaxy SubGroupId = 0, . This sample contains 6340 galaxies. It will be used in sections §4.4 and §5 to connect our results with observational works.

2.3 Methods

The EAGLE consortium provides a wide variety of physical properties for each gas, dark matter, and stellar particle [Crain et al. (2015)]. For the positions, velocities, SFRs, entropies, densities, metallicities, and element abundances of gas particles, and the positions, velocities, metallicities, element abundances, and ages of stellar particles.

2.3.1 Halving the galaxies

In the following, three different cases are studied depending on the plane that divides the galaxy. For all cases the three-dimensional structure of the galaxy is analyzed. In a forthcoming study we will study projection effects and EAGLE mock images [Trayford et al. (2017)] available in the public database [McAlpine et al. (2016)].

Firstly, we define the velocity cut, which refers to the measurements that can be performed when the three-dimensional velocity of the satellite’s center of potential is known. In this case, the galaxy is halved according to the plane that contains its centre of potential, and that is normal to its velocity vector relative to the cluster center of mass.

It can be expected that this plane will maximize the SFR difference between the two halves as it is the direction in which RP should be maximal. Yet, the three-dimensional velocity vector is not an observable quantity.

The second case is dubbed radial cut because it refers to the most simplified version that could be performed in current observations of galaxies in clusters. The galaxy is divided with respect to the plane normal to its three-dimensional position vector with respect to the cluster center of mass. We remark that in this case the three-dimensional position vector of the cluster member is used. In current observational studies only the two dimensional information is used and this cut can be applied to upcoming data with precise photometric redshifts of each cluster member. These two cases are explained and discussed in [Troncoso Iribarren et al. (2016)].
difference; a 2-dimensionnal version of this cut would also be applicable to observational data. We search for the plane that maximizes the SFR difference between two galaxy sides and explore whether this maximum difference correlates with the velocity vector. This last case is dubbed maximum anisotropy cut and the results are presented in section 5.3.1. Fig. 1 shows the cartoon representation of the three cases.

We define the falling angle as the angle between the three-dimensional position and the velocity vector of the galaxy, both relative to the central galaxy of each cluster

\[
\cos(180 - \phi) = \frac{(\mathbf{v}_{CM} - \mathbf{v}_{CG}) \cdot (\mathbf{v}_{CM} - \mathbf{v}_{CG})}{\|\mathbf{v}_{CM} - \mathbf{v}_{CG}\| \cdot \|\mathbf{v}_{CM} - \mathbf{v}_{CG}\|}.
\]

(4)

This angle contains information about the ellipticity of the orbit.

2.3.2 Measuring characteristic properties of each galaxy half

Visually inspecting the EAGLE galaxy shown in Fig. 2, we realize that summing a property over all particles in each half may bias the difference between halves because one of them may be more massive or contain more particles than the other one (the adopted center is that of the gravitational potential). Hence, the intrinsic asymmetries between the two halves could bias the SFR, density, pressure, etc.

In section 5.3.1, we discuss the implications of directly integrating over each galaxy half, considering different numbers of particles. Hereafter, we define observables that are independent of the intrinsic mass asymmetries between the two halves.

The SFR enhancement or percentage excess of the leading half with respect to the trailing half is defined as

\[
\delta_{SFR} \equiv \frac{SFR^{wm}(LH) - SFR^{wm}(TH)}{SFR^{wm}_{total} (LH)},
\]

where \(SFR^{wm}(LH)\), \(SFR^{wm}(TH)\) are the mass-weighted average SFR of the gas particles in the leading and trailing halves, respectively. The normalization term \(SFR^{wm}_{total}(LH)\) corresponds to the gas mass-weighted average SFR of all gas particles in the galaxy.

Thus, this quantity is unaffected by the mass difference between the two halves. We also calculate the median enhancement, which is defined as the difference between the median values of each half, normalized to the median value of the complete galaxy. This quantity is insensitive to the difference in the number of particles between the two halves. For example, the median pressure enhancement of the gas particles is defined as follows,

\[
\delta_{P} \equiv \frac{P^{\text{median}}(LH) - P^{\text{median}}(TH)}{P^{\text{median}}_{total}},
\]

where \(P^{\text{median}}(LH)\), \(P^{\text{median}}(TH)\) are the medians of pressure of the gas particles in the leading and trailing halves, respectively. Analogously, volume weighted average quantities can be measured in order to take into account the volume represented by each particle. For a particular particle property, these three quantities can be constructed; i.e. for the metallicity, we calculate the mass-weighted average enhancement, \(\delta Z_{E}^{wm}\), the median enhancement \(\delta Z_{E}^{wm}\), and the volume-weighted average enhancement \(\delta Z_{E}^{vwm}\). These quantities might differ if extreme asymmetries between the two halves are present. If the number, mass, and volume of the particles in each half are similar, then the three quantities described above converge to similar values. In the particular case of the SF (see equation it is, intrinsically, an entropy-weighted quantity because it is based on the entropy-weighted pressure of each particle. The quantity \(\delta_{SFR}^{wm}\) is then weighted by the entropy and gas mass of the particles.

We define the enhancement of the star-formation efficiency (SFE) as,

\[
\delta_{SFE} \equiv \frac{SFE^{wm}(LH) - SFE^{wm}(TH)}{SFE^{wm}_{total}},
\]

where,

\[
SFE^{wm} = \frac{\sum \dot{m}_{\text{gas}} (SFR/m_{\text{gas}})}{\sum \dot{m}_{\text{gas}}}
\]

is the gas mass-weighted average of the SFE. The numerator of the SFE is the sum over the individual SFR, while the denominator is the sum of the gas mass of the particles. Both depend on the number of particles, but the ratio between them is independent of the resolution.

Another way to formulate the enhancement of a property is the logarithmic ratio or excess between the two halves, for example

\[
SFR_{E}^{wm} = \log_{10} \frac{SFR^{wm}(LH)}{SFR^{wm}(TH)},
\]

where \(SFR^{wm}(LH)\), \(SFR^{wm}(TH)\) are the median SFR of the leading and trailing halves, respectively. The analogous quantity for the gas mass-weighted average SFE

\[
SFE_{E}^{wm} = \log_{10} \frac{SFE^{wm}(LH)}{SFE^{wm}(TH)}
\]

Finally, the integrated quantities, representing the global SFR, pressure, age of each galaxy are calculated simply adding up all the individual values. With the exception of SFE, the aforementioned quantities can differ from studies of the EAGLE team because they typically use an aperture of 30pkpc (McAlpine et al. 2016), which corresponds to roughly an R_{\text{20}} Petrosian aperture that is a good approach for direct comparison with observations (Schaye et al. 2015). In the case of the SFR, more than 85% of the galaxies give similar results (below 10% of difference) for SFR estimators suggesting that few particles are further than 30 pkpc of the galaxy center of potential. Although those particles are not representative of the median, they record important information of the galaxy transformation processes occurring in situ and galaxy deformations. For this reason, we suggest for future observational works to use the full photometry, building a surface brightness light profile for every galaxy and to measure the photometry in a radius such that it reaches the sky brightness level.

Another representative global value is the average over all particles in the galaxy (independent of the number of particles describing each galaxy). For example, the average pressure of the galaxy is two orders of magnitude smaller than the pressure obtained from adding the individual pressure of each particle over all the galaxy. The former might be associated to the restoring force or self-gravity of the galaxy, referred to as anchoring force or \(\Pi_{\text{gal}}\) in the observational work of GASP (Jaffé et al. 2018; Bellhouse et al. 2019).

2.3.3 Cluster dynamical state

To determine the level of dynamical relaxation of each cluster, we measure the position shift between the center of mass and the minimum of the potential, normalized to its virial radius, which we refer to as relaxation index. We divide our group sample into two: those with relaxation index above and below the median index, which we referred to as relaxed and less relaxed clusters. We will study whether this index plays a role in the effect of the ICM on SF. The median cluster masses of the relaxed clusters are \(\log_{10} M[M_{\odot}] = 13.86 \pm 0.09\), while the less relaxed are more massive, \(\log_{10} M[M_{\odot}] = 14.07 \pm 0.14\).
Figure 3. Logarithmic ratio between leading and trailing halves of the median SFR, gas mass-weighted average SFE, and median pressure as a function of the falling angle, stellar mass and SFR-weighted pressure. Galaxies within the 25 most massive groups, within one virial radius and with more than one hundred gas particles are shown. The halves were defined dividing the galaxies by the plane perpendicular to the velocity vector at their center of mass, with respect to the central galaxy. The falling angle is defined in Eq. 4. In each panel, the solid green line shows the median value of the control sample. The left panel shows the logarithmic ratio between the median SFR of the leading and trailing half as a function of the falling. The middle panel shows the logarithmic ratio of the gas mass-weighted average SFE of the leading and trailing half as a function of the stellar mass. The right panel shows the analogous quantity for the mean pressure as a function of the SFR-weighted average pressure of the galaxy. The black dashed line shows the case with equal pressure or SFR in both galaxy sides. Red line shows the median of all galaxies. Filled red squares are the medians at each bin, while the errors are the 1-sigma errors. Diamonds show galaxies residing in relaxed clusters, while crosses in less relaxed clusters (see section 2.3.3). The galaxy ID 6082966 that is shown in Figure 2 has been marked in a blue square in every panel.

2.3.4 Jellyfish classification

To discern if certain galaxy correspond to the jellyfish classification, we visually inspected in three dimensions their gas and stellar particles, and mock images available in the EAGLE database. A galaxy is classified as jellyfish if the star-forming gas particles are located in a preferential direction with respect to its center of potential or stellar content, i.e. the gas component presents extended tails showing a clear overabundance of gas particles in a preferential side. Following the criteria described in section §3 of Yun et al. (2019), we search for asymmetric gas distributions or portions of asymmetric gas (Gas tails/wakes).

We also use the former defined quantities, Eq. 8 and Eq. 9 to rank our galaxy sample by the level of asymmetry.

3 RESULTS

In this section we study the differences in the properties associated to the gas and stellar particles between the leading and trailing halves. The SFR, density, and pressure are properties inherent to the gas particles. Metallicities and oxygen abundances can be measured in both the stellar and gas particles, the former refers to the fraction of mass in elements heavier than Helium associated to each particle, while the latter corresponds to the ratio between the Oxygen and Hydrogen abundance. Furthermore, the scale factor at which stellar particles were formed is stored, and we use this information to study the ages of the stellar populations.

We analyze galaxies that reside up to three virial radius of the cluster and have a minimum of one hundred stellar and gas particles describing the stellar and gas components, separately, as described in section 2.2. The latter condition ensures that each half is traced with reasonable statistics.

In the following subsections, the results for the gas and stellar particles are presented. Individual symbols in the plots shows the properties of individual satellites within one virial radius; the trends for satellites located within three virial radius are also analyzed.

We study the differences of properties in the leading and trailing halves, firstly as a function of the falling angle defined in section 2.2, secondly as a function of cluster properties (mass and radius), and finally as a function of the galaxy global properties (stellar mass, SFR, mass of gas). Hereafter, in all instances, except in sections 3.1 and 3.2, the results of the first case are reported. The reported values correspond to the median of the sample or at each bin. The asymmetric error bar indicates the error with respect to the median, i.e. the upper and lower one sigma percentile normalized by the square root of the number of galaxies, $+\sigma/\sqrt{N}$, $-\sigma/\sqrt{N}$, respectively. The only exception occurs in section 4.4 in which we report the one sigma percentile at each bin. The properties of the control sample are reported in table 1 and the median value is shown in each figure with a green solid line.

3.1 Gas particles

From this point on, we analyze only the gas particles which have SFR $> 0$; this way we select the star-forming gas that traces the galaxy disc.

For the galaxy sample described in section 2.2 the median of the number of gas particles describing each galaxy is $519_{-31}^{+81}$, while the hydrogen number density corresponds to $n_H \approx 1.00_{-0.03}^{+0.05}$[cm$^{-3}$]. Errors indicate the error on the median. The gas particles in the simulation follow an ideal-gas equation of state (EOS), only gas which is deemed to be star-forming is placed on an artificial EOS that accounts for the sub-grid physics which takes place at high-density regions. It ensures that the ISM pressure increases with density. Hence, the temperature is artificial and will not be used in the following analysis.

Figure 2 presents the spatially resolved properties of the individual EAGLE galaxy ID6082966. The left panel of Figure 2 shows a face-on image, composite in the u, g, and r filters of the SDSS. The image was taken from the public data release (McAlpine et al. 2016) and created with the radiative transfer code from Trayford et al. (2017). The middle panel of Fig. 2 shows the three-dimensional view of the gas particles divided in two parts according to the plane perpendicular to the velocity vector with respect to the central galaxy. Blue diamonds indicate particles of the leading half, while the red dots correspond to the trailing one. Each side of the cube is
in proper megaparsecs (pMpc). The right panel of Fig. 3 shows the logarithmic counts of the gas particles in logarithmic pressure bins for the leading (blue) and trailing (red) half. It shows an increase in pressure of the leading half (blue histogram) with respect to the trailing one (red histogram), by a factor of ~ 6. The pressure of the leading half might be increasing due to the compression against the ICM. The middle and right panels evidence that the trailing half of this galaxy contains more gas particles than the leading half. In section 3.1.1 we study whether this is a particular case or a typical behaviour of cluster galaxies.

In Figure 3 we show quantitative measurements of the difference in properties for all the galaxies in our sample defined in section 2.3.2. The left panel shows the logarithmic ratio enhancement of the median SFR as a function of the falling angle. The middle panel presents the logarithmic ratio enhancement of the gas mass-weighted average SFE as a function of the stellar mass. The right panel shows the logarithmic ratio enhancement of the median pressure as a function of the SFR-weighted pressure. In each panel, the red line indicates the median of the logarithmic ratio enhancement of the median pressure as a function of the SFR-weighted pressure. In each panel, the red line indicates the median of the logarithmic ratio enhancement of the median pressure as a function of the SFR-weighted pressure. In each panel, the red line indicates the median of the logarithmic ratio enhancement of the median pressure as a function of the SFR-weighted pressure. 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In this subsection, we present the comparison of the integrated properties considering the same number of particles on both sides. We select a fixed percentage of 20% of the total number of gas particles per side, choosing the most distant ones with respect to the center of mass, hereafter referred as quintiles.

On either side this selection reduces the effects of intrinsic asymmetries between the two halves, such as different number of particles, mass, etc., which could dominate the differences seen in Fig. 3. In the upper, middle, and lower panel of Fig. 4, each individual symbol shows the difference of the integrated SFR, of number of particles, and gas mass over all the particles located in the leading and trailing half, respectively. In each panel of Figure 4 the solid green line shows the median value of the control sample. The red line in the middle panel shows the median of the difference between the number of particles residing in each half. Most of the satellites (78%) show an overabundance of gas particles in the trailing half with respect to the leading half. Only 22% of them show the opposite enhancement.

The red line in the top panel shows the median SFR difference if all gas particles are considered in each half, while the blue line indicates the mean difference from the quintiles. The SFR difference increases from $-0.10^{+0.05}_{-0.02}$ (red line) to $+0.017^{+0.005}_{-0.003}$ (blue line) showing that the difference in mass or number of particles between halves can mask the SFR difference. The median value of the quintiles is positive and close to 2%, with an error three times higher for the positive than negative values.

These results suggest that positive SFR differences between leading and trailing halves would be measured in observables if the extreme galaxy sides, of equal area, are analyzed, since differences are stronger. A similar median of the SFR enhancement is measured if different percentages of the number of particles are considered. The median SFR of the leading half (20% of particles) is 2% higher than the SFR overall the galaxy. To measure this difference might be challenging in observational works as discussed in section 3.3.

In the bottom panel, the mass difference between the gas particles of the trailing and leading half is shown. Although each gas particle has a different mass, the trend of the mass difference is pretty similar to the one of the number of particle difference. Here, all the gas particles found by the SUBFIND algorithm with $SFR > 0$ are considered (see section 2.2.1). Following the previous results, in Figure 4 the galaxies located within one virial radius of the group or cluster center are shown. If all galaxies up to 2 (3) virial radius are taken into account, the number of selected galaxies triples and the fraction of galaxies with a more abundant leading half rises from 22% to 34 (38)%, while the median SFR difference of the quintiles is close to zero, $+0.005_{-0.002}^{+0.004}$ and negligible in observations (below 0.5% of the total galaxy SFR). This suggests that the RP effect, which is causing the overabundance in the trailing half, is less effective in the outer cluster regions (above one virial radius).

### 3.1 Integrated differences

#### 3.1.1 Gas phase metallicities

For the galaxy sample described in section 2.2 located within one virial radius, the median metallicity and oxygen abundance enhancement are $\langle \Delta Z_{Fe} \rangle = 3^{%-1}_{%+1}$, $\langle \Delta O/H_{\odot} \rangle = 3^{%-1}_{%+1}$, respectively. The median of the mass-weighted average metallicity enhancement $\langle \Delta Z_{Fe} \rangle = 4^{%-1}_{%+1}$, and Oxygen abundance enhancement are $\langle \Delta O/H_{\odot} \rangle = 4^{%-1}_{%+1}$, respectively. There is a marginal difference of the chemical enrichment, of $3 \sim 4\%$, between the leading and trailing halves with respect to the overall galaxy value. The gas of the leading half is richer $3 \sim 4\%$, in terms of metals and Oxygen abundance, than the trailing half. There are two cases with falling angles around 50 degrees, in which the median metallicity or oxygen abundance enhancement is higher than 50% of the median metallicity or oxygen abundance of the complete galaxy. The same satellites show the highest SFR differences and enhancements (see figure A3).

These differences in SFR, SFE and pressure do not translate into significant differences in the stellar populations properties (such as stellar ages and metal abundances) as the amount of new star formation is on average negligible compared to the existing stars.

### 4 CONNECTION WITH OBSERVABLE QUANTITIES

In this section we discuss the feasibility of confronting the results presented in section 3 with observations. The first subsection studies a case that might be applicable to observations. The second and...
third sections are dedicated to the dependency of the SFR enhancement with cluster and intrinsic properties of the satellites, while the fourth one compares our results with main-sequence galaxies of the EAGLE simulation.

4.1 Maximum anisotropy cut

Firstly, we need to find the appropriate plane to divide the halves that is feasible in observations. Hereafter, we use the three-dimensional positions and velocities, while projections effects and analysis of mock images will be presented in a separate article. Future photometric surveys of broad, medium and narrow bands will be able to trace the three-dimensional structure of thousands of groups and clusters. An example is the J-PAS survey reaching a precision of 0.003 × (1 + z) (Ascaso et al. 2016).

As analyzed in Troncoso Iribarren et al. (2016), the most simple case is choosing the plane perpendicular to the radial vector of the center of potential with respect to its central galaxy (see middle panel of Figure 1). Yet, when analyzing the SFR differences using this plane, we find no significant difference between the two halves or neither a correlation with the velocity case. In some cases, we even find an enhancement in the half pointing away from the central galaxy.

In order to look for another possible observationally applicable plane to divide a galaxy in two halves, we perform a search in all the possible orientations, homogeneously sampling the sphere, for the plane that maximizes the mass-weighted SFR difference or enhancement between the trailing and leading half, Eq. 5. Hereafter, this maximum difference is dubbed SFR$_{\text{max}}$

In Figure 5 we focus the attention on the galaxy sample described in section 2.2.1 and satellites located within one virial radius. The left upper panel of Figure 5 shows the histogram of the alignment angle $\alpha$, defined as the angle between the vector normal to the plane that maximizes the mass-weighted SFR difference and the velocity vector (see right panel of Figure 1). In the case of perfect alignment, alignment angle equal to zero, the vector normal to the plane that maximizes the difference corresponds exactly to the direction of the velocity with respect to the ICM. The blue distribution is broad and peak around an angle of zero degrees. It suggest that statistically the plane that maximizes the difference indicates the velocity with respect to the ICM, but it cannot used in a case-by-case form.

The right upper panel of Figure 5 shows the analogous angle for the radial vector. It shows that the distribution is nearly random suggesting that there is little or non alignment between the plane that maximizes the enhancement and the radial vector. This result suggests that even if we could measure the tri-dimensional structure of the cluster, the RP effects cannot be measured without knowing the velocity of each satellite mainly because there is no alignment between the position and velocity direction with respect to the central galaxy. The bottom panels of Figure 5 show the maximum SFR asymmetry as a function of the alignment angle in each case, with respect to the velocity or position vector. In the case of the position vector (right panel), no trend is observed, while a weak one exits between small velocity alignment angles and higher values of maximum SFR asymmetry left panel. It shows that higher asymmetry is likely to be caused by the galaxy velocity, i.e. RP.

By splitting our sample in four bins of falling angle in Figure 5 we found that the satellites with a falling angle below 45 degrees tend to show an alignment ($\cos \alpha > 0.75$), while the other bins show no preferential alignment. The black histogram shows this sub sample. The same group of galaxies show the highest SFR enhancements (see Figure 3 and A3). No dependency with the relaxation index is observed.

We visually inspected ten satellites of stellar masses above $10^{10}$[$M_{\odot}$] showing the highest asymmetry $\delta$SFR$_{\text{max}} > 0.6$, namely ID 11529078, 9440185, 16300531, 10751313, 6082966, 14895218, 11525815, 15691064, 4561773, 10687442. They are classified as jellyfish galaxies according to the criterion described in section 2.3. In the case of ID 16300531 and 14895218, the observed asymmetry is mild with respect to the other eight examples. We visually inspected the satellites of stellar masses above $10^{10}$[$M_{\odot}$] because the optical mock images are available in the EAGLE database and the number of gas particles is high enough to perform a visual inspection with high statistics.

We study the correlation between the mass-weighted SFR enhancement ($\delta$SFR$_{\text{max}}$) and the maximum mass-weighted SFR enhancement (SFR$_{\text{max}}$). We measure a moderate positive correlation between the SFR$_{\text{max}}$ and the positive values of $\delta$SFR$_{\text{max}}$ or $\delta$SFR$_{\text{max}}$, with a Pearson correlation coefficient, $R = 0.48$, $R = 0.46$, respectively.

No correlation is observed and measured for the logarithmic ratio excess of the same quantities (SFR$_{\text{max}}$ and SFR$_{\text{max}}$).

These results suggest that an observational analysis using the plane that maximizes the SFR difference between the two galaxy halves would provide an indication of the direction of the peculiar velocity of the galaxy, and would help to reconstruct the effect of RP. In forthcoming article by Rodriguez et al. subm. (2019), we have applied this method, projected on the sky plane, to the SDSS photometric data (Abazajian et al. 2009).

4.2 Dependence with cluster properties

We now consider the selected satellite sample of section 2.2 located within 3 virial radii (211 galaxies), i.e. satellites with more than one hundred particles in their stellar and gas components, stellar masses above $10^{9}$[$M_{\odot}$], residing in groups more massive than
It is worth to mention that 60% of our sample has stellar masses one virial radius, are not longer forming stars because their gas was also a limit of the simulation. In the sSFR case, it is remarkable that RP the lowest values of each quantity.

In the top panel, the purple line indicates the median SFR$_{\text{mw}}$ of the galaxies located within 3 virial radius. It appears to decrease with increasing radius up to $r = 1 \times r_{\text{vir}}$, above this radii the trend is consistent with zero. In the middle panel the satellites residing within one virial radius show an increase of the $\delta$SFR$_{\text{mw}}$ with cluster mass, while for ones located within 1 and 3 virial radii the trend vanishes. In the bottom panel, the $\delta$SFR$_{\text{mw}}$ tends to keep constant with falling angles, for both group of satellites, located within one or one and three virial radii. The first group presents a higher median around 0.1, while the second one around zero. The satellites located further out and with falling angles above 110 degrees show negative $\delta$SFR$_{\text{mw}}$, i.e. its trailing half is more star-forming than the leading half.

A similar trend for the logarithmic ratio excess of the mass-weighted SFR (SFR$_{\text{mw,rel}}$) as a function of the virial radii, cluster mass and falling angle is observed.

Regarding the alignment, the angle between the velocity vector and the normal vector to the plane that maximizes the SFR difference, we observe no dependency with cluster mass or relaxation index.

There is small signal of the SFR enhancement to correlate with the falling angle for galaxies at $r < 3 \times r_{\text{vir}}$, however a larger sample of simulated cluster galaxies is required to conclusively claim that.

### 4.3 Comparison with other intrinsic galaxy properties

We also study whether the asymmetry in SFR is also visible in other galaxy properties. In this section we mention the overall differences found, but relegate the figure to the Appendix (Fig A1). We studied the mass-weighted SFR enhancement or percentage excess as a function of the galaxy intrinsic properties, SFR, stellar mass, specific star formation rate (sSFR), star-forming gas mass, and total gas mass. A positive median excess, with respect to the control sample, is observed on all properties for satellites located within one virial radius, except by the negative enhancement observed in the lowest values of each quantity.

In the SFR case, it might be a result of reaching the resolution limit of the simulation. In the sSFR case, it is remarkable that RP also affects the gas of less active satellites. Another possible explanation is such small satellites ($M_* < 10^{9.5}M_\odot$) located within one virial radius, are not longer forming stars because their gas was fully consumed or lost by RP and other process related to galaxy assembly itself like mergers, starvation, etc.

It is worth to mention that 60% of our sample has stellar masses within $M_* < 10^{9.5-10.5}M_\odot$, which is dubbed the intermediate mass sample. Outside this range the statistics are poorer.

### 4.4 Comparison with EAGLE main sequence galaxies

As explained in section §2.2.2, we select the main sequence galaxies with sSFR > 0.01 Gyr$^{-1}$ (Furlong et al. 2015) and stellar masses above 10$^7 M_\odot$, and excluding satellites (SubGroupNumber = 0).

The top panel of Figure 7 shows the SFR-weighted average pressure as a function of stellar mass for main sequence (dotted line) and cluster galaxies in EAGLE located within one (black line) and three virial radii (red line), selected according the criteria defined in section §2.2. The shaded region shows the dispersion of the main sequence galaxies in EAGLE. The dispersion of the satellites, located within one and three virial radii, is similar to the one shown in the gray shaded region.

In the middle panel of Figure 7, the median pressure of the satellite galaxies (black crosses), and for the leading (blue diamonds), and trailing halves (red triangles) are plotted as a function of the stellar mass. The errorbars show the error on the median. The median of the leading halves is higher than the trailing halves and also higher than the galaxy as a whole for all the stellar mass bins. Only satellites located within one virial radius are considered. A similar trend, with smaller differences between the samples, is observed when all satellites are considered. Satellites in the mass range 10$^{9.5-10.5}M_\odot$ show the strongest differences. The lower limit 10$^{9.5}M_\odot$ might be indicating that we are reaching the limit of the simulation to trace the RP stripping, indeed these galaxies are the ones described with the lowest number of gas particles in the simulation 242+32 with respect to the median of the full satellite sample 519+81. The upper limit 10$^{10.5}M_\odot$ indicates that satellites with stellar masses above it, might constitute a different population of particular properties. [Wright et al.] (2019) show that the quenching timescale of satellites of masses within the range 10$^{9.5-10.5}M_\odot$ is larger than for satellites outside this range. It suggests that the quenching timescale of galaxies outside this stellar mass range is so short that we are not able to trace the RP stripping.

Other explanation is that these satellites are displaced of the main sequence, as it is discussed in the following. The bottom panel indicates the position of the main sequence galaxies in the logarithmic SFR, stellar mass plane. Red, black lines show the median of the cluster galaxies located within one and three virial radii, respectively. The dotted line shows the SFR of the main-sequence galaxies of the EAGLE simulation, while the gray shaded region marks the dispersion of the data. The dispersion of the satellites, located within one and three virial radii, is similar to the one shown in the shaded area. Except for the most massive galaxies (> 10$^{11}M_\odot$), where the dispersion is higher due to few statistics. Our satellites show higher SFR at low-masses, most likely due to the imposed limit on the number of particles ($N_{gas} > 100$), while higher masses lie below the median. This shows that the satellites with SFR lower than the main sequence galaxies also show pressure enhancement, confirming that RP is increasing the ISM pressure even though there is SFR suppression.

Another aspect to consider is that in the case of satellites of masses above/below > 10$^{10.5}/10^{9.5}M_\odot$ we might not be able to measure RP because we are reaching the limits of the simulation in two senses i) we sample few galaxies or ii) only the ones with low SFR, hence few gas particles are available to trace the RP.
Figure 6. Mass-weighted SFR enhancement as function of cluster properties, measured in the first case, namely velocity cut (see text). Top, middle, and lower panel shows the median SFR enhancement as a function of the radial distance to the central galaxy normalized to the virial radius, cluster mass, and falling angle, respectively. Diamonds show galaxies residing within one virial radius of relaxed clusters, while crosses in less relaxed clusters (see section 2.3.3). Red diamonds and blue crosses indicate the median of the SFR enhancement for satellites within one and three virial radii, respectively. Purple squares indicate the median of the SFR enhancement for satellites within three virial radii. The error bars show the one sigma error.

Figure 7. Comparison of the pressure and SFR between our sample of cluster galaxies described in section 2.2 and $z = 0$ main sequence galaxies in the EAGLE simulation, according to the definition of Furlong et al. (2015), sSFR $> 0.01$ Gyr$^{-1}$ and excluding satellites. Top panel: SFR-weighted average pressure as a function of stellar mass for main sequence (dotted line) and our cluster galaxies in EAGLE located within one (black line) and three virial radii (red line). The shaded region shows the dispersion of the data. Middle panel: the median pressure of the galaxy (black crosses), leading (blue diamonds), and trailing halves (red triangles) is plotted versus the galaxy stellar mass for our satellites located within one virial radius. Errors bars show the error on the median. Bottom panel: location of the cluster galaxies in the log$_{10}$SFR − log$_{10}$M$_*$(M$_\odot$) plane. Black and red lines show the median of the cluster galaxies located within one and three virial radius, respectively. The dotted line shows the SFR of the main-sequence galaxies of the EAGLE simulation, while the gray shaded regions marks the dispersion of the data.
5 Discussion

We have measured the differences of pressure, SFR, metallicity, oxygen abundance and age between the leading and trailing halves for the set of EAGLE satellites defined in section 4.2, considering different intervals of cluster mass, falling angles, and radial distance to the central galaxy.

The left, middle and right panels of Figure 3 show that the leading half presents an enhancement of the median SFR, gas mass-weighted SFE, and median pressure with respect to the trailing half. The middle panel of Figure 2 puts in evidence that most of the analyzed satellites present and overabundance of gas particles in the trailing half with respect to the leading half. This suggests a transport of gas from the leading to the trailing half due to the compression of the ICM. In absolute terms, the top panel of Figure 7 shows that, overall, the pressure of the analyzed satellites tend to lie above the median values of the main-sequence galaxies. Yet, the satellite and main sequence pressures are consistent with the same distribution. The middle panel of the same figure shows an excess of the median pressure of the leading (blue diamonds) with respect to the overall galaxy (black crosses) which in turn is higher than the trailing half (red triangles). This indicates that the pressure enhancement is driven by the leading half (blue crosses), most likely due to compression of the ISM by the interaction with the ICM.

Depending on the chosen way to measure the SFR excess or enhancement in the simulation, we find different dependence of the effect as a function of the falling angle. For example, the bottom panel of Figure 5 shows that vector normal to the plane that maximizes the SFR difference is 10° lower than for the overall galaxy (black crosses) which in turn is higher than the trailing half (red triangles). This indicates that the pressure enhancement is driven by the leading half (blue crosses), most likely due to compression of the ISM by the interaction with the ICM.

We have measured the SFR enhancements due to the effect of RP. Hence, the plane that maximizes the SFR difference is recommended for statistical and observational studies of RP effects.

The median or the mass-weighted SFR enhancements are preferentially positive, indicating that the leading half is more star-forming than the trailing half, for satellites that satisfy the following conditions: located within one virial radius, with overall mass-weighted SFR greater than 0.5 $M_\odot$/yr, a stellar mass greater than $10^{9.5} M_\odot$, and gas masses greater than $10^{9.5} M_\odot$. Galaxies within one virial radius show higher SFR enhancement than galaxies located outside this radius. The SFR enhancement is higher in galaxies residing in massive clusters and within one virial radius. This dependence vanishes when all satellites are considered. No trend is observed as a function of the falling angle. Hence, the galaxies with asymmetric star-formation are most likely to be found with properties within the limits mentioned above.

The moderate correlation between $SFR_{E}^{\text{max}}$ and $\delta SFR_{E}^{\text{max}}$, or $\delta SFR_{E}^{\text{max}}$, indicates that an observational analysis that searches for the maximum $SFR_{E}^{\text{max}}$ difference and selects the quintile with the highest $SFR_{E}^{\text{max}}$, would help to find the galaxies most affected by RP without visually inspecting all cluster members. Furthermore, we have visually inspected, according the criteria defined in section 3.3.4, the galaxies selected with the highest asymmetry ($SFR_{E}^{\text{max}} > 0.6$) and stellar mass above $10^{10} M_\odot$, classifying them as jellyfish galaxies.

Figure A2 shows the maximum mass-weighted SFR difference as a function of intrinsic galaxy properties and of cluster properties. Red and blue lines show the median of galaxies located within one and three virial radii, respectively. In every panel, the solid green line shows the median value of the control sample. In every panel, the median of the satellites located within one virial radius is higher than the control sample, except by log_{10}SFR(1 Gyr^{-1}) > -1. For satellites located within one virial radius, a positive correlation between the $SFR_{E}^{\text{max}}$ and the stellar mass is observed, while a negative one is seen for the sSFR, and radial distance to the central galaxy. Although we found a moderate correlation between $SFR_{E}^{\text{max}}$ and $\delta SFR_{E}^{\text{max}}$, no correlation is observed between the $SFR_{E}^{\text{max}}$ and the cluster mass or falling angle. If all satellites located up to three virial radii, these trends vanish. No dependence with other galaxy properties such as SFR, gas mass is observed.

Simultaneous SFR and gas maps of cluster galaxies, and particularly jellyfish galaxies would allow to study a correlation between the SFR and SFE enhancements. For example, combining MUSE with ALMA maps of jellyfish galaxies would allow such measurements and confirmation or refutation of our predictions (see Figure 3).

5.2 Properties in the Local Universe

The mass-weighted SFR enhancement is the percentage difference between the leading and trailing half with respect to the overall value, see Eq. 1. The $SFR_{E}^{\text{max}}$ values reported in Table 1 of around 10%, indicate that our mass-weighted SFR individual measurements of each half must be more precise than this, or otherwise the RP effects cannot be detected in observational studies.

Using photometry it could be possible to use blue band magnitudes to trace the SFR. IFU observations allow to find asymmetries in SFR in individual galaxies. However, this would be quite challenging because in order to achieve accurate SFR measurements it is necessary to detect the H$_\alpha$ line with a reasonable signal to noise, which is typically obtained by integrating three times longer for H$_\alpha$, depending on the extinction. Since in this work we are proposing to integrate the SFR in galaxy halves, not using the indi-
individual spaxels, the signal increases as $\sqrt{N_{\text{spx}}/2}$, where $N_{\text{spx}}$ is the number of total spaxels of the IFU.

One way to loosely mimic this type of observations is achieved by selecting only the particles above a certain SFR threshold. This makes the integrated SFR of the leading half 20% higher than the trailing one, which would be even easier to detect in IFU observations.

5.3 Misleading results using the most simplistic radial case.

Troncoso Iribarren et al. (2016) reported the results using a simplistic radial cut proposed in section 2.3.1 using the EAGLE satellites and the same selection reported in section 3.2.2. Figure 2 of their work shows that the behavior of the SFR differences as a function of the falling angle of the velocity and radial cut are clearly dissimilar. This suggests that observations could show the opposite results due to projection effects on the plane used to cut the galaxy in halves. In observations, the plane perpendicular to the radial position is the most simplistic one that can be used because the three-dimensional velocity vector with respect to its central galaxy is unknown. Hence, the results of the observations might be biased in this case. Yun et al. (2019) found a similar result, by analyzing the correlation between the gas tails of the TNG jellyfish galaxies (2600) and the satellite bulk velocity and position with respect to the host center (see Fig. 7). They also found no alignment in the case of the position, while for the velocity there is a clear indication to form angles around 180 degrees.

6 CONCLUSIONS

Using the biggest simulation of the EAGLE consortium, we measure differences in the physical properties of halves of galaxies that are falling into clusters (see Figure 2). We dissect the galaxies that are star-forming in two halves by using three planes that define our three cases of study: velocity cut, radial cut, and maximum anisotropy cut (see Figure 1). The first plane divides the satellites using the plane perpendicular to the three-dimensional velocity vector, the second one uses the plane perpendicular to the three-dimensional distance to its central galaxy, while the third one finds the plane that maximizes the SFR difference between both halves.

In the first case, using the velocity cut, we observe an enhancement of the SFRs, SFEs, and pressure of gas particles in the leading half with respect to the trailing one (see Figure 3), while the number of gas particles in the trailing half is systematically higher than in the leading one (see Figure 4).

We suggest that the measured differences are evidence of RP acting on the leading half, transporting the gas from the leading to the trailing half, enhancing the ISM pressure in the leading half, and consequently boosting its SFR. This effect depends on the cluster properties as well as galaxy intrinsic properties as follows.

- For satellites located within one virial radius, we observe a positive correlation between the SFR enhancement and the stellar mass, the cluster mass, the gas mass, and the SFR. We find a negative correlation for the specific star-formation rate and radial distance to the central galaxy. If all satellites, including those located farther than the virial radius, are considered then the trends vanish (see Figure 6 and Figure A1).

These differences are small, around 10% of the overall mass-weighted SFR value, hence it might be difficult to detect them using data from ground based large scale surveys (see Figure 5). In the case of photometric surveys, this effect could be measured using blue bands as a SFR tracer, while for IFUs the situation improves when halves of the galaxy and not individual spaxels are analyzed.

- When dividing the sample according to the dynamical state of the host cluster, we do not find a difference of the median or mass-weighted average SFR enhancement in relaxed compared to less-relaxed clusters. There are more infalling galaxies and of small falling angles in less-relaxed than in relaxed clusters (see Figure 7). Both types of clusters show similar numbers of galaxies receding away from the cluster centre.

- By comparing our sample of satellites with the main-sequence galaxies of the EAGLE simulation, we found that of all the satellites selected here have a higher pressure, which is even higher in the leading half compared to the trailing one. We suggest that it is the compression of the ISM due to the interaction with the ICM that drives the pressure enhancement. Our sample of satellites is overall more star-forming than main-sequence galaxies up to $10^{10.5} [M_\odot]$, above this limit our satellites are suppressed in SF but still show ISM compression in their leading half (see Figure 7). These RP affected satellites contribute to the scatter observed in the global scaling relations of local galaxies residing in groups and clusters (Lin et al. 2014; Koyama et al. 2013; Peng et al. 2010).

The radial cut proposed clearly fails to detect the real physics occurring behind the RP effects.

The maximum anisotropy cut, that uses the plane that maximizes the SFR difference between the two halves, allows us to find that the vector normal to this plane is aligned with the three-dimensional velocity of the galaxy (see Figure 5). This finding suggests this is the most suitable way in observations to detect and study RP effects on statistical samples of observed galaxies.

This alignment is also reflected in a moderate correlation between the maximum SFR difference and the SFR difference found using the velocity direction of the satellite to halve the galaxy.

Selecting the galaxies with the highest SFR difference, would allow to find the galaxies most affected by RP without visually inspecting all cluster members. This automatic method can be used to select asymmetric galaxies, without visually inspecting all satellites, in the era of large scale surveys (J-PAS, BOSS, LSST, etc.) and future ones.

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APPENDIX A: DEPENDENCY WITH CLUSTER AND GALAXY PROPERTIES

Here we analyze the dependency of the SFR and its maximum difference with cluster and galaxy properties. We report the mass-weighted SFR because it can be directly related to observable quantities. In Figure A1, the mass-weighted SFR enhancement, measured in the first case (see text), as function of galaxy intrinsic properties is shown. From up to right, SFR, star-forming gas, stellar mass, and total mass of gas. The red, blue lines show the median of galaxies located within one and three virial radii, respectively. The Figure A2 shows the maximum mass-weighted SFR difference, measured in the observational case (see text), as function of galaxy and cluster properties. In the left and middle panels, from up to right, SFR, star-forming gas, stellar mass, and total mass of gas. In the right panel the SFR$_{max}$ as a function of the distance to the central galaxy (top), cluster mass (middle), and falling angle (bottom). The red, blue lines show the median of galaxies located within one, and one and three virial radii, respectively. In each panel, the solid green line shows the median value of the control sample.
Figure A1. Mass-weighted SFR enhancement, measured in the first case (see text), as function of galaxy intrinsic properties. From top to right, sSFR, SFR, mass of the star-forming gas, stellar mass, and total mass of gas. In each panel, the solid green line shows the median value of the control sample. Red, blue lines show the median of galaxies located within one and three virial radii, respectively. The errors are the one sigma percentile. Diamonds, crosses show satellites located within one virial radius, residing in relaxed and less relaxed cluster, respectively (see section 2.3.3).
Figure A2. Maximum mass-weighted SFR enhancement (see text) as function of cluster and galaxy intrinsic properties. Left and middle panels show the maximum SFR enhancement as a function of the galaxy intrinsic properties. From top to right, sSFR, SFR, mass of the star-forming gas, stellar mass, and total mass of gas. The right panels show the same quantity as a function of the cluster properties. From top to bottom, radial distance to the central galaxy normalized to the virial radius, cluster mass, and falling angle. In each panel, the solid green line shows the median value of the control sample. Diamonds show galaxies residing within one virial radius of relaxed cluster, while crosses in less relaxed clusters (see section 2.3.3). Red and blue crosses indicate the median of the SFR$_{max}$ at each bin for satellites within one and three virial radii, respectively. The error bars show the one sigma percentile.
Figure A3. Visualization of the halo of GroupNumber=8 in the EAGLE simulation. *Left*: Composite image of the cluster, the transparent purple represents the dark matter distribution, while the column density of the HI gas is shown in a color code scale. The HI and H2 maps are coloured by column density, according to the colour bars at the bottom, with column densities in units of cm$^{-2}$. Particles are smoothed by 1 kpc in the NH2 and NHI maps. The separation between the gas components was performed according the recipes described in Lagos et al. (2015). The field of view is 3×3 Mpc and it is projected in the x-y plane of the simulation. *Right*: Example of Jellyfish galaxies in the same cluster. The bottom and top panels of HI and H2 maps have a size of 154 × 154 kpc$^2$, while the middle one is 77 × 154 kpc$^2$. 