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Can matter enter voids? Inflows in underdense regions.

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Abstract

In this contribution, we report results from the analysis of a cosmological simulation specially designed to accurately resolve low-density regions, such as cosmic voids. Contrary to the common expectation, we find that some voids experience significant mass inflows over cosmic history. On average, 10% of the mass of voids in the sample at $z \sim 0$ is inflown from overdense regions, reaching values beyond 35% for a significant fraction of voids. More than half of the mass entering the voids lingers on periods of time up to 10 Gyr well inside them, reaching inner regions. This would imply that part of the gas lying inside voids at a given time proceeds from overdense regions (e.g., clusters or filaments), where it could have been preprocessed. These results could potentially challenge the scenario of galaxy formation in voids, since they dissent from the idea of them being pristine environments.

1 Introduction

Cosmic voids are underdense regions which fill up most of the volume in the Universe. They emerge in regions comprising negative primordial density fluctuations, and subsequently expand as the matter (dark matter [DM], gas and galaxies) around them collapses and forms walls, filaments, and clusters. Therefore, their dynamics are governed by outflows, which have been found both in simulations [11, 6], observations [4] and analytical models of isolated voids [1]. However, in a complex, non-linear, cosmological environment, it is in principle possible to expect that some matter that unbinds from dense structures (e.g., in galaxy cluster mergers [3]) ends up penetrating in and circulating through underdense regions.

Whether there are relevant inflows to voids or there are not is an important question to address, since voids are assumed to be pristine regions (i.e., uncontaminated by material coming from the outside). This implies important consequences for the galaxy formation scenario in these environments [10]. Within this context, the aim of the work reported in this contribution is to check whether there are any relevant inflows through the boundaries of cosmic voids. For this aim, we make use of a Λ cold dark matter (ΛCDM) cosmological simulation of a moderately large volume, which is specially designed to describe matter in and around cosmic voids.

This contribution is organised as follows. In Sec. 2, we cover the numerical aspects of this work, including the simulation details, the void identification scheme and the method used to estimate gas mass fluxes. In Section 3 we present our results, and in Section 4 we summarise and discuss our conclusions. While this is a short contribution, we refer the interested reader to [13], where we presented a complete description of this work.

2 Numerical details

Here, we provide the basic details about the numerical aspects concerning this work, while a more complete description can be found in [13].

2.1 The simulation

We have analysed the results of a cosmological, DM+hydrodynamics simulation of a periodic, cubic domain of comoving side length $L = 100\,h^{-1}$Mpc, carried on with `MASCLET` [8]. The simulation is well suited to describe the gaseous component in low-density regions such as cosmic voids, thanks to the Eulerian hydrodynamics and the Adaptive Mesh Refinement (AMR) scheme in `MASCLET`.

The initial conditions are set up at $z_{\rm ini} = 100$, with a procedure aimed to sample the regions which will evolve into voids at low redshift with enhanced resolution (see [9]). The simulation is then evolved with AMR, dynamically refining underdense regions and the structures emerging within them. Several gas cooling processes, a phenomenological treatment of star formation, supernova feedback and metal enrichment are also accounted for in the simulation, although this is not the main focus of this work.

2.2 The void finding strategy

To identify our sample of cosmic voids in the simulated domain, we have defined voids as the largest possible ellipsoids around underdense, peculiarly expanding regions, possibly limited by steep density gradients. In practical terms, our void finding algorithm is based on the one of [9], but imposing a smooth, ellipsoidal shape, in contrast to the complex, arbitrarily-shaped voids (i.e., non-convex, non-simply connected) of the original finder. In this sense, our ellipsoidal voids are more conservatively defined than the arbirarily-shaped ones, since by definition our algorithm looks for the largest possible ellipsoids inside the complex-shaped voids. Having a smooth shape is crucial for the reliability of the pseudo-Lagrangian estimation of gas mass fluxes (see Section 2.3).

Once the sample of cosmic voids is identified at each snapshot of the simulation (at each fix redshift), the evolutionary history of each void is traced by connecting, between each pair of snapshots, the voids which maximise their *volume retention*, defined as $VR = V_{A\cap B}/\sqrt{V_A V_B}$, where A (B) refers to the void in the first (second) iteration of the pair.

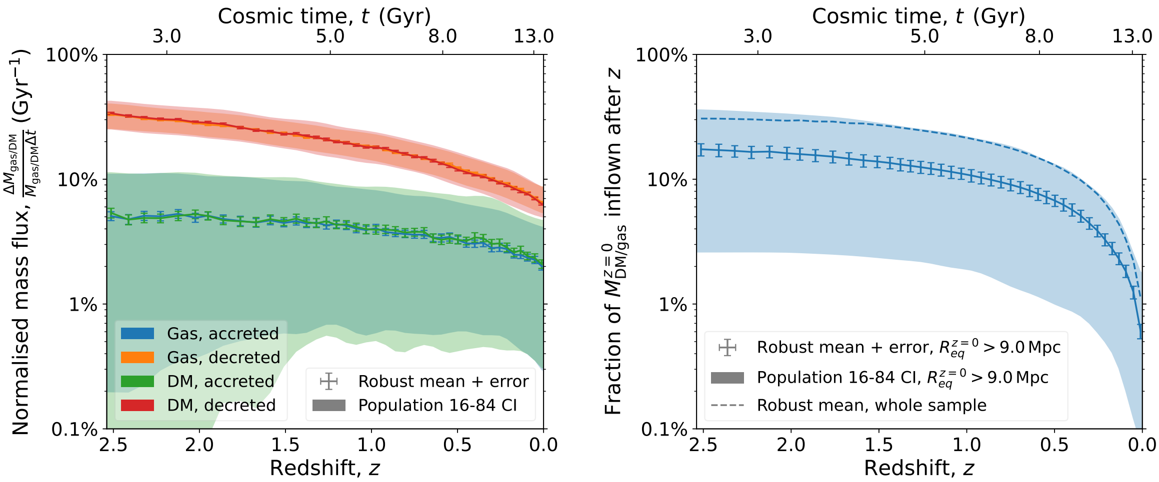

Figure 1: Evolution of the inflow and outflow rates in the void sample. *Left panel:* evolution of the normalised mass fluxes (of gas and DM; inflown and outflown; according to the legend in the bottom left corner) as a function of redshift (lower axis) or cosmic time (upper axis). Lines refer to the robust mean, and shaded regions correspond to $(16-84)$ confidence intervals (CIs) over the population. *Right panel:* Fraction of the gas mass having been inflown after a given redshift z. The solid line corresponds to the robust mean of this quantity over the subsample of voids with $R_{\rm eq}^{z=0} > 9\,{\rm Mpc}$, while the dashed line corresponds to the whole sample. The shaded region correspond to the $(16-84)$ CI for the former case. Figure from [13], ©AAS. Reproduced with permission.

2.3 The pseudo-Lagrangian estimation of gas mass fluxes

In order to estimate the fluxes of gas through the boundary of a void, given that Eulerian gas is not directly traceable, we use a simple pseudo-Lagrangian approach, which was also previously applied in the context of accretion flows onto galaxy clusters [12]. At each fix-time snapshot, we consider all volume elements (i.e., gas cells) of the simulation as pseudo-Lagrangian fluid elements, and we advect them using an explicit, first-order step. We use that information for assessing the flux of gas mass towards/from the (instantaneously fix) ellipsoidal boundary of the void at a given time[1]. We thoroughly discuss the validity of this approach in [13].

3 Results

Figure 1 presents a summary of our results over the void sample. In the left-hand side panel, we present the evolution of the integrated gas and DM mass fluxes, both for inflows and for outflows, normalised to the mass of the corresponding component (gas or DM) within the

[1]It is worth emphasizing that: (i) we are not properly integrating the motion of the pseudo-Lagrangian fluid elements, but only estimating the fluxes at a given, fix time; and (ii) our measured fluxes are not produced by the change of the volume of the void between a pair of snapshots, but to matter actively approaching/moving away from the void.

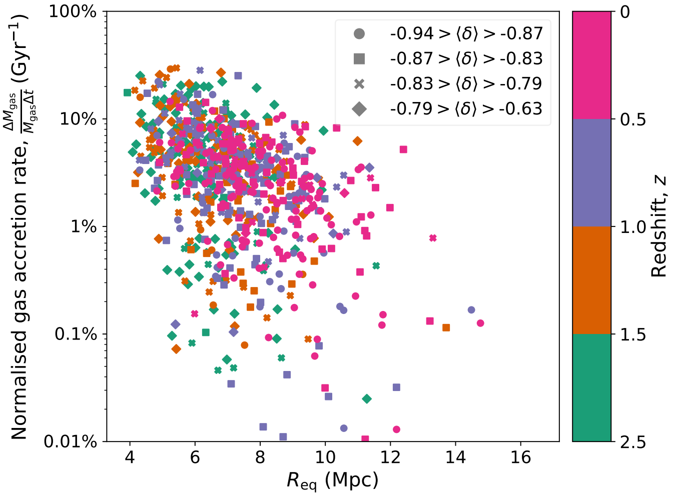

Figure 2: Normalized gas inflow rate (gas inflow per gigayear in units of the void's gas mass; vertical axis) versus the size of the void (equivalent radius; horizontal axis). The gas inflow rates are computed on four redshift intervals, shown in the colour scale. Different markers split the sample in different mean overdensity within the void according to the legend. Figure from [13], ©AAS. Reproduced with permission.

void at the given moment. This quantity is to be read as the fraction of the mass of the given component being inflown/outflown per unit time. Naturally, the flow of gas through void boundaries is dominated by outflows. However, inflows are also present in our sample in a statistical sense, with mean values $1/6 - 1/3$ those of the outflows. The average magnitude of the inflows evolves from $\sim 5\%\,\mathrm{Gyr}^{-1}$ at $z \simeq 2.5$ to $\sim 2\%\,\mathrm{Gyr}^{-1}$, with remarkably large scatter. This implies that, while many of the voids do not undergo significant inflows, some others suffer inflows considerably stronger than the mean.

The right-hand side panel of Fig. 1 presents the anticummulative inflown gas mass fraction, that is to say, the fraction of the gas mass of a void at redshift $z = 0$ that has been inflown since a given redshift z. The solid line (robust mean [2]) and the shaded region ($16 - 84$ percentiles) correspond to the subsample of large voids (equivalent radius at $z = 0$ $R_{\mathrm{eq}}^{z=0} > 9\,\mathrm{Mpc}$). This shows that around 10% of the current gas mass of the typical large void at $z = 0$ has been dynamically inflown since $z = 1$ (reaching beyond 20% since $z = 2.5$).

Looking at the whole population of voids, Fig. 2 displays the gas inflow rates (normalised to the gas mass within the void; vertical axis) in relation to size of the void (horizontal axis). Here, we have considered four broad redshift bins to compute the inflow rates, which are encoded in the figure by the colour. The plot shows that, at any cosmic epoch, there are voids having relevant inflow rates (higher than a few percents per Gyr). While small voids show the highest inflow rates (since they are more susceptible to external influences), large voids with large inflow rates do also exist.

4 Summary and conclusions

The results that we present in the contribution challenge the usual picture of voids as pristine environments due to their purely outflowing velocity field and, therefore, could potentially impact the scenario of galaxy formation and evolution in these environments. We find that, if voids are to be defined as the largest possible ellipsoidal regions around peculiarly expanding density minima, possibly limited by steep density gradients, then it is not possible to guarantee the absence of inflows. Material circulating within the void, coming from the outside, may be able to bring chemically and thermodynamically preprocessed gas, which could be subsequently accreted by void galaxies. A more complete presentation of our results can be found in [13].

While in this work we show the presence of inflows onto our sample of cosmic voids, it is worth emphasizing a few caveats and future directions. First, there are many different strategies to define a void, with remarkable differences in the resulting objects (see, for example, [5]). Therefore, future work should be directed to compare with other void definitions and identification strategies. Secondly, future cosmological simulations, capable of forming realistic galaxies both inside and outside voids, could be used to assess the impact of this effect on galaxies residing within voids, if any.

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