

Galaxy groups within voids

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ABSTRACT

Context. Despite cosmic voids being vast and almost empty, galaxy aggregations do exist within them, although they are much sparser than in denser regions like walls, filaments, and clusters. The internal matter distribution within voids might have an impact on the properties and evolution of void galaxies.

Aims. In this work, we aim to identify and characterise a sample of galaxy groups within voids in the local Universe ($z < 0.08$), taking into account the peculiarities of these vast and empty structures.

Methods. The void galaxies used in this study were selected from a well-defined void galaxy sample, from which the parent sample of the Calar Alto Void Integral-field Treasury survey (CAVITY) legacy project was drawn. To identify galaxy groups, we applied a friend-of-friend (FoF) –like group finder algorithm to the selected sample, ensuring a certain degree of gravitational binding among group members. The same algorithm was applied to identify a control sample of groups not in clusters nor voids, referred as NCNV groups.

Results. The catalogue of groups consists of 1367 physically bound groups, with a total of 3040 galaxies, plus 14 672 galaxy singlets. Most of the galaxies in voids are singlets (59%). In contrast, most of the NCNV galaxies in the control sample are in groups (60%). To consider the dynamical stage of the groups, we used the parameters harmonic radius (R_H), radial velocity dispersion (σ_{vir}^2), dimensionless crossing time ($H_0 t_c$), and group virial mass (M_{vir}). We also used the total optical (r band) luminosity, L_r , to estimate the mass-to-light ratio (M/L) of the groups. We studied the relations of void properties and these parameters with the group richness.

Conclusions. Galaxy groups can be found in any void in the local Universe, with no dependency of group richness on the density of voids. The densest groups in the studied sample of voids are composed of six galaxies; therefore, voids generally contain small groups, in comparison to denser structures such as filaments, walls, and galaxy clusters. Galaxy groups within voids are typically loose groups, in an early stage of their evolution.

Key words. galaxies: evolution – galaxies: fundamental parameters – galaxies: general – galaxies: groups: general – large-scale structure of Universe

1. Introduction

Cosmic voids are vast regions in the Universe defined by an unusually low density of galaxies. Surrounded by dense structure (filaments, walls, and clusters), voids represent about 70% of the volume of the present Universe, being an essential component of the cosmic web (van de Weygaert & Platen 2011; Mao et al. 2017; Jaber et al. 2024). The formation of voids began with tiny density variations in the early Universe after the Big Bang. Over time, gravity pulled matter from these under-dense regions into the denser areas, leading to the formation of the cosmic web and the expansion of the voids (Bond et al. 1996). For this reason, voids are crucial for understanding the overall structure

and expansion of the Universe (Hahn et al. 2007; Tikhonov & Klypin 2009; Ceccarelli et al. 2013; Lares et al. 2017; Li et al. 2024). The pristine low-density environment of voids provides an ideal place to examine the influence of environment on the formation and evolution of galaxies.

Despite cosmic voids being the least dense regions of the cosmic web, galaxies do exist within them, although they are much sparser than in denser regions such as filaments and clusters (Park & Lee 2009; Alpaslan et al. 2014b; Habouzit et al. 2020). Galaxies residing in voids, the so-called void galaxies, serve as pristine examples for studying galactic evolution, providing insights into how galaxies form and grow with minimal environmental influence (Grogin & Geller 1999; Pustilnik et al. 2002; Benson et al. 2003; Rojas et al. 2004). Void

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galaxies are often less massive and bluer, presenting late-type morphologies and actively forming stars, likely from pristine intergalactic gas due to the lack of surrounding galaxies that could potentially transform their morphology or halt their star formation, and presenting low gas-phase metallicities values (Grogin & Geller 2000; Rojas et al. 2004; Croton et al. 2005; Padilla et al. 2010; Hoyle et al. 2012; Liu et al. 2015; Florez et al. 2021; Porter et al. 2023; Domínguez-Gómez et al. 2023a; Rodríguez-Medrano et al. 2023; Argudo-Fernández et al. 2024). Although there is a small fraction of early-type galaxies in voids, these are systematically smaller (10–20%) than in denser environments (Pérez et al. 2025a). Void galaxies might also have had different star formation histories (SFHs), with more continuous and slower star formation rates than in denser environments (Domínguez-Gómez et al. 2023b). Recent integral field spectroscopy (IFS) observations from the Calar Alto Void Integral-field Treasury survey (CAVITY) project (Pérez et al. 2024) have revealed detailed spatially resolved stellar population properties of void galaxies (Conrado et al. 2024), showing a slightly higher half-light radius, lower stellar mass surface density, and younger ages (across all morphological types) than galaxies in filaments and walls. Moreover, both observations and simulations have found trends of galaxy properties as a function of the distance to the void centre, hereafter the void-centric distance. For instance, an increase in star formation activity and HI gas density has been reported in the inner region of the voids in comparison to larger void-centric distances, which points towards a large-scale modulation of star formation, and a higher stellar mass fraction with increasing void-centric distance (Ceccarelli et al. 2008; Ricciardelli et al. 2014; Rosas-Guevara et al. 2022). Void galaxies may also be connected by less massive void filaments or tendrils (Alpaslan et al. 2014b), and therefore galaxy properties might also be related to their local environment within voids (Grogin & Geller 2000; Lietzen et al. 2012; Galárraga-Espinosa et al. 2023, 2026).

Numerical simulations have shown that cosmic voids present an intricate internal network of substructures, making them a more complex environment than expected (Park & Lee 2009; Aragon-Calvo et al. 2010; Rieder et al. 2013; Cautun et al. 2014; Jaber et al. 2024). The internal matter distribution within the void (the void environment) might have an impact on the properties and evolution of void galaxies. However, not much work has been done on the observational identification and characterisation of void substructures to understand the impact of the void environment on galaxy evolution. Alpaslan et al. (2014b) quantified the filamentarity (i.e. linearity of structure) within a sample of voids identified in the Galaxy and Mass Assembly (GAMA) survey (Driver et al. 2009, 2011) through the GAMA Large Scale Structure Catalogue (Alpaslan et al. 2014a). They identified tendrils as coherent structures composed of up to five or six void galaxies, spanning about $10 h^{-1}$ Mpc, and found them to be rooted in filaments, either connected to other filaments or terminating in the voids. However, it is unknown if the galaxies are physically bound in groups within these tendrils. Ceccarelli et al. (2025) compared galaxy pairs in voids with those in denser structure, finding increased star formation activity in paired void galaxies, which are also bluer. In addition, Alfaro et al. (2022) characterised the halo occupation distribution of groups in cosmic voids, reporting that for the low-mass groups the youngest galaxies are only present inside voids, generally as central galaxies, where haloes populating voids have had a different formation history, inducing significant changes in the halo occupation distribution (Alfaro et al. 2020). Torres-Ríos et al. (2024) went one step further and classified galaxies as singlets and physically

bound group members in voids, using the Pan et al. (2012) catalogue of cosmic voids and void galaxies from the Sloan Digital Sky Survey Data Release 7 (SDSS-DR7; Abazajian et al. 2009), to investigate how the local environment influences the SFH of galaxies in comparison to galaxies in walls and filaments, and clusters. They found that the large-scale environment is related to a delay in mass assembly of up to ~ 2 Gyr, while the local environment is related to a shorter delay (< 1 Gyr). However, no identification of individual groups is provided to study their properties as a function of void peculiarities, or the properties of the void galaxies composing the groups. The degree to which the location of void galaxies within cosmic voids affects their evolution, considering the complexity of the local environment within the void, is an open question.

Finding galaxy groups in voids is not an easy task. Results from simulations have shown that, in contrast to denser environments, cosmic voids are more devoid of galaxies than they are of mass (Curtis et al. 2024). This means that the density profiles and tools generally used to identify galaxy groups and clusters in the large-scale structure (e.g. halo-based group finder algorithms; Yang et al. 2007) might not apply within voids or could provide biased results. Catalogues of groups and clusters based on friend-of-friend (FoF) algorithms, are usually limited to groups with a minimum richness ≥ 3 –4 galaxies, or even ≥ 8 –10 galaxies (Merchán & Zandivarez 2002; Deng et al. 2007; Tago et al. 2008; Wen et al. 2009), which under-represents the void environment. In other cases, the analysis of the groups is limited to denser groups, due to the uncertainties at lower densities (Tempel et al. 2017). A mixed methodology, i.e. finding physically bound galaxies within their local environment, would provide more accurate results. For instance, Taverna et al. (2023) applied a Hickson-like criteria to find compact groups (CGs) in different large-scale environments, finding almost no CGs residing in the inner regions of cosmic voids. In the present work, we aim to identify and characterise galaxy groups within voids in the Pan et al. (2012) catalogue of voids, taking into account the peculiarities of these vast and empty structures in the local Universe ($z < 0.08$). To do so, we applied a FoF-like group finder algorithm, ensuring a certain degree of gravitational bounding among group members. For this, we followed the criteria to select physically bound neighbours in isolated systems in Argudo-Fernández et al. (2015), instead of using a fixed aperture or a n th neighbour approach. To characterise these groups, assuming they are virialised, we estimated their dynamical properties and group mass-to-light ratios to investigate how light is traced by the underlying distribution of matter in voids.

This work is organised as follows. In Sect. 2 we describe the sample of voids and void galaxies used in this work. In Sect. 3, we describe the procedure to identify galaxy groups within voids and derive the properties to characterise these systems. In Sect. 4, we show the main results, and discuss them in Sect. 5. Finally, in Sect. 6, we present the main conclusions of this work. Throughout the paper, we used a cosmology with $\Omega_{\Lambda 0} = 0.7$, $\Omega_{m0} = 0.3$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Void galaxy sample

The sample of void galaxies that we used in this study is based on a well-defined sample of void galaxies, from which the parent sample of the CAVITY¹ project (Pérez et al. 2024) was built. CAVITY is a legacy project aimed at characterising the population of galaxies inhabiting voids using IFS data

¹ <https://cavity.caha.es/>

(García-Benito et al. 2024; Pérez et al. 2025b). The CAVITY parent sample is based on the catalogue of cosmic voids and void galaxies compiled by Pan et al. (2012) using photometric and spectroscopic data from the SDSS-DR7 (Abazajian et al. 2009). Pan et al. (2012) used a galaxy-based void-finding algorithm that uses redshift data to objectively find voids using a nearest-neighbour algorithm on a volume-limited galaxy catalogue. This VoidFinder algorithm is described by Hoyle & Vogeley (2002), based on the original method by El-Ad et al. (1997). The algorithm uses the three-dimensional distribution of galaxies in the SDSS-DR7 to initially classify galaxies as wall or void galaxies, understanding as void galaxies the galaxies that reside in a void region, whereas ‘wall’ galaxies reside in walls, filaments, and clusters. To do so, Pan et al. (2012) estimated the projected distance to the third nearest neighbour (d_{3rd}) of each galaxy. Galaxies are classified as wall galaxies if $d_{3rd} < 7$ Mpc. If distance is larger, they are left as potential void galaxies. In a first step, only the distribution of wall galaxies is used to identify the voids, using the VoidFinder algorithm to grow empty cells as spheres (merging the spheres when their overlap exceeds 50%). A void is defined when their growing sphere is bound by four wall galaxies, with their centre not confined to the initial cell, with a cut-off of $10 h^{-1}$ Mpc for the minimum radius of a void region. The sizes of the voids (R_{void}) are measured using their effective radius (r_{eff}), this is, the radius of voids (if spherical) or the radius of the sphere that has the same volume as the non-spherical void (if not spherical). The voids in the Pan et al. (2012) catalogue have a median effective radius of $17.83 h^{-1}$ Mpc, with values ranging from $10 h^{-1}$ Mpc (by definition) to $30 h^{-1}$ Mpc. In a second step, void galaxies are selected from the list of candidates as those falling within the limits of the identified voids. Pan et al. (2012) identified 1054 statistically significant voids covering 62% of the volume of the Universe up to $z < 0.107$. These voids are populated by 8046 galaxies brighter than an absolute magnitude limit of $M_r < -20.09$ mag (the volume-limited galaxy sample) and 79947 void galaxies with $m_r \leq 17.7$ mag and $z < 0.088$ (the magnitude-limited galaxy sample).

The design of the CAVITY sample secures a comprehensive investigation of void galaxies spanning various void sizes and dynamical stages. The target selection is based on the magnitude-limited sample in order to have a statistically robust sample size, while restricting to voids in the catalogue where the full volume (projected) of the void is included in the SDSS footprint. The CAVITY parent sample is limited to voids in the redshift range 0.005 and 0.050, to ensure an adequate spatial coverage across galaxy disks. For the purpose of the present study, we followed the same selection criteria but increasing the redshift range up to $z < 0.08$. This left us with 24931 void galaxies in 170 voids.

3. Galaxy groups and properties

3.1. Identification of physically bound groups

Each void was evaluated independently, considering only the galaxies that reside in it, in a two iteration process. First, we looked for neighbour galaxies with line-of-sight velocity difference $\Delta v \leq \pm 500 \text{ km s}^{-1}$ within 1 Mpc in projected distance (Argudo-Fernández et al. 2015). Galaxies with no neighbours within that volume were automatically classified as singlets (galaxies that are not physically bound to any other detected galaxy). A total of 14672 galaxies were classified as singlets. For the galaxies with neighbours in that volume, we followed a similar methodology as in Torres-Ríos et al. (2024) to find grouped

galaxies in voids, which used the criteria by Argudo-Fernández et al. (2015) to find physically bound neighbours in low density environments (i.e. isolated galaxies and isolated pairs). Physically bound neighbours are galaxies separated by a projected distance $d \leq 450$ kpc with $\Delta v \leq \pm 160 \text{ km s}^{-1}$. The first cut identifies candidate neighbours, while the second ensures physical bounding. In this first iteration, a sample of 2373 group candidates, with more than one neighbour, was identified. The central galaxy of each group candidate is identified as the most massive galaxy (see Sect. 3.3 for the details of the estimation of the stellar mass). We used this definition to identify unique groups in a second iteration as follows.

Using this methodology, there might be different groups, even with different number of members, with the same central galaxy. In this case we considered only the group with the largest number of galaxies. Also, some member galaxies in a group can be central galaxies of another nearby group. This means that the two groups are physically connected. When this happens, we merged the two groups and identify the central galaxy as the most massive of both groups. When a group member is found in two different groups but is not identified as the central galaxy in any of them, we considered the two groups separately, even if they share neighbours, since these galaxies would not physically connect the two groups. After this second iteration, a sample of 1367 physically bound groups, composed of 3040 galaxies, were identified in the sample of 170 voids considered in this work, where the groups with the largest number of members are composed of six galaxies. The typical number of members in the groups, hereafter the group richness (N_{gal}), is $N_{gal} = 2$.

Note that, even if singlet galaxies do not have any neighbour within $\Delta v \leq \pm 500 \text{ km s}^{-1}$ at 1 Mpc projected distance, this does not necessarily mean that singlet galaxies are isolated. Isolated galaxies have not been appreciably affected by their closest neighbours during a past crossing time $t_{cc} \approx 3$ Gyr (Verdes-Montenegro et al. 2005; Verley et al. 2007a,b). Considering that the redshift completeness of the SDSS main galaxy sample is flux limited to an apparent magnitude $m_r = 17.77$ mag, the faintest singlets at higher redshift might look as isolated as they do simply because possible physically bound neighbours are even fainter; therefore, these galaxies do not have an observed spectrum, and thus were not considered in our analysis. Following the criteria in Argudo-Fernández et al. (2015), we can identify a sample of potential isolated galaxies from the sample of singlets when $m_r \leq 15.7$ mag, which allows a homogeneous isolation definition without neighbours within at least 2 magnitudes fainter than the singlets. The subsample of potential isolated galaxies is composed of 1013 void galaxies, $\sim 7\%$ of the singlets. According to the criteria in Argudo-Fernández et al. (2015), these galaxies would have been ‘passively evolving’ over the last ~ 5 Gyr (since $z \sim 1$). Note that ultra-deep optical imaging of these galaxies may reveal faint external features that might indicate a probable history of interaction (Sánchez-Alarcón et al. 2023).

Following the same motivation, i.e. having groups with neighbours up to 2 magnitude fainter than central galaxies, and to take into account any potential bias or dependency with the redshift in the analysis of the results, we defined a subsample of groups where the central galaxy has $m_r \leq 15.7$ mag. Hereafter we refer to this subsample as the limited sample. Previous works by Yang et al. (2007) or Tempel et al. (2017), for instance, have also defined a volume-limited subsample within a redshift range to test any potential redshift bias. For reference, we have also compiled a subsample of groups with galaxies with absolute magnitude $M_r \leq -20.1$ mag, up to $z = 0.08$. However,

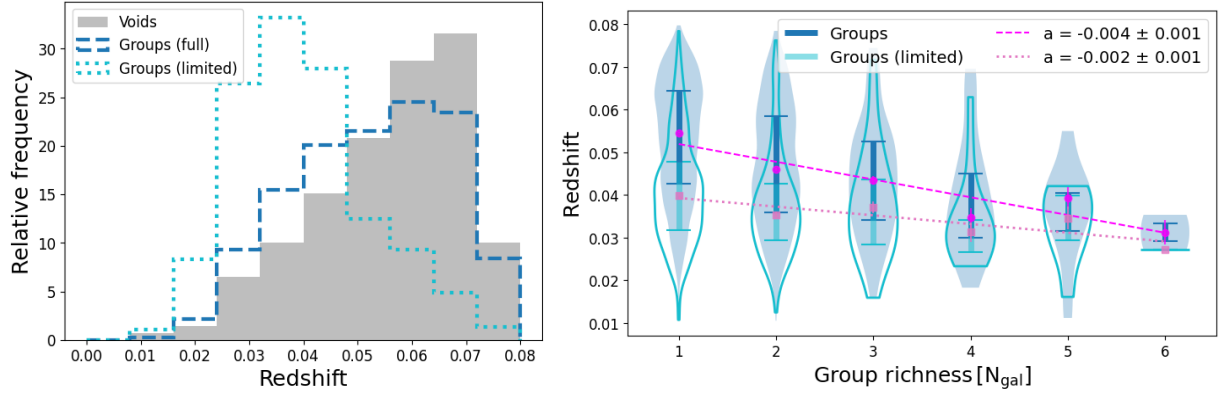


Fig. 1. Redshift distribution and dependence with the group richness. Left panel: Redshift distribution of the groups, as open dashed blue and dotted cyan open histograms, for the full (14 672 singlets and 1367 groups) and limited (1013 singlets and 395 groups) sample, respectively, in comparison to the distribution of the redshift of the voids (filled grey histogram). Right panel: Redshift of the group as a function of the group richness. The redshift distribution for groups with same group richness is represented by violin plots (filled blue distributions considering the full sample, and empty cyan distributions for the limited sample). The inner box in each violin plot represents the interquartile range of the median and its 95% of confidence intervals. Magenta circles and pink squares correspond to the median values in richness bins (considering the full sample or the limited sample, respectively) with their corresponding uncertainties, while the dashed magenta and dotted pink lines correspond to the linear least-square fit to the binned data, respectively. The slopes of the linear fits, with their corresponding uncertainties, are indicated in the legend.

throughout our analysis, we used the limited sample, instead of the absolute magnitude volume-limited sample for all group members, to consider any redshift dependence in comparison to the full sample, because of two main reasons. First, an absolute magnitude volume-limited sample under-represents low redshift galaxies ($z < 0.02$), and second, it also under-represents the characteristic population of galaxies in voids, which are often less massive and have a lower surface brightness than galaxies in denser environments (Galaz et al. 2011; Florez et al. 2021; Conrado et al. 2024); therefore, we would be missing the main galaxy populations in voids, including dwarf galaxies (Bidaran et al. 2025a,b). In fact, the maximum richness when using a volume-limited sample (with absolute magnitude $M_r \leq -20.1$ mag, up to $z=0.08$) is $N_{\text{gal}}=4$ for a total of five groups, reducing the study of the dynamical properties of the groups to three richness bins, limited to groups with $N_{\text{gal}}=2, 3$, and 4, which have low statistics. Table 1 shows the number of groups for each richness for the full, limited, and volume-limited samples. The left panel of Fig. 1 shows the redshift distribution for the full and limited samples in comparison to the redshift of the voids (filled grey histogram), measured as the median the redshift of the galaxies that reside in each void. The number of voids increases at higher redshift because the comoving volume spanned by the survey is larger. While the full sample follows the distribution of the voids, the distribution of the limited sample peaks at $z \sim 0.035$, following the redshift distributions for isolated galaxies, pairs, and triplets in Argudo-Fernández et al. (2015) (as shown in their Fig. 2). The right panel of Fig. 1 shows that group richness decreases with the redshift. This trend is steeper for the full sample than for the limited sample, showing that most of the singlets in the full sample are found at higher redshift, being affected by redshift bias. However, the differences are minimal (within the uncertainties) at higher group richness.

Figure 2 shows the distribution of the projected distance and line-of-sight velocity difference for group galaxies with respect to their central galaxy, for groups with more than one physically bound members. As shown in the figure, most of the group members are located within the limit values used to define physically bound neighbours. As an effect of the second iteration, a small fraction of group members can be found at projected distances up to 890 kpc, and with a Δv not

Table 1. Group richness and number of singlets and groups.

	N_{gal}	$N_{\text{groups}}^{\text{full}}$	$N_{\text{groups}}^{\text{lim}}$	$N_{\text{groups}}^{\text{vol}}$
Voids	1	14 672	1013 ^a	7674
	2	1137	292	128
	3	175	75	10
	4	36	18	5
	5	17	9	–
	6	2	1	–
NCNV	1	44 503	5082	27 795
	2	20 748	7062	18 048
	3	7737	4034	8042
	4	2992	1996	3491
	5	1459	1161	1395
	6	626	542	545

Notes. Number of groups in voids and in the control sample of NCNV groups when considering the full sample ($N_{\text{groups}}^{\text{full}}$) or the limited sample ($N_{\text{groups}}^{\text{lim}}$) as a function of the group richness (N_{gal}). For reference, the richness for groups in a volume-limited sample ($N_{\text{groups}}^{\text{vol}}$) with $M_r \leq -20.1$ mag, up to $z=0.08$, is also shown. ^(a) Among singlets in the full sample in voids, there are 1013 potentially isolated galaxies (singlets in the limited sample).

larger than $\pm 300 \text{ km s}^{-1}$. Note that these two conditions not necessarily occur simultaneously for the same member galaxy, and do not exclude these groups from the analysis. While the adopted linking criteria ($\Delta v \leq \pm 160 \text{ km s}^{-1}$, $d \leq 450 \text{ kpc}$) are conservative for low-density voids and follow established methods for physically bound pairs (Argudo-Fernández et al. 2015), we note that Hubble flow contributions ($\sim 35 \text{ km s}^{-1}$ at 500 kpc for $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and extended distances post-merging ($\sim 890 \text{ kpc}$ in rare cases) may introduce minor contamination by non-bound projections.

3.2. Control sample of groups

To compare with the properties of the population of galaxy groups in voids, we built a control sample of galaxy groups

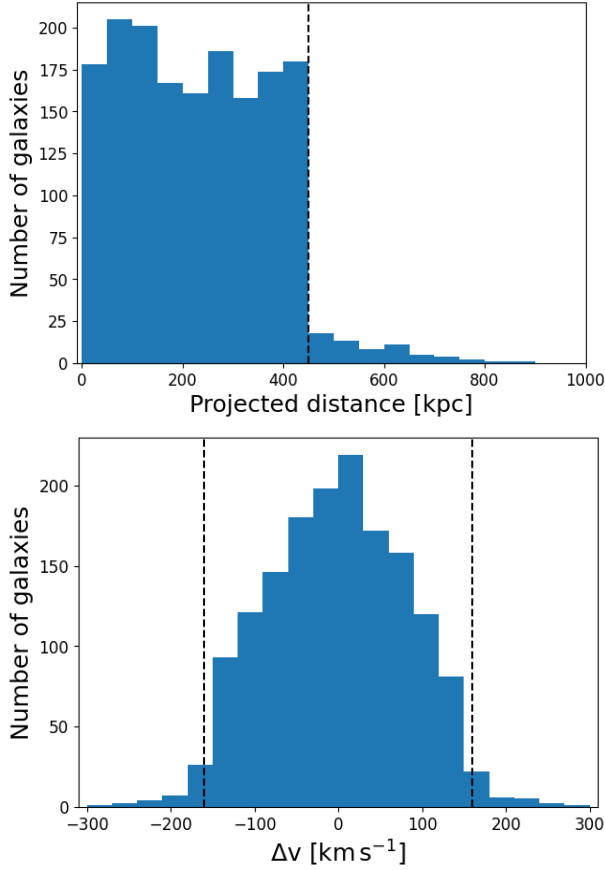


Fig. 2. Projected distance and line-of sight velocity difference. Distribution of the projected distance (upper panel), in kiloparsecs, and line-of sight velocity difference (lower panel), in kilometres per second, of group members with respect to the central galaxy of the group (full sample), for groups with $N_{\text{gal}} \geq 2$. The vertical dashed black lines indicate the limit values used to define the physically bound groups in the first iteration, following Argudo-Fernández et al. (2015).

outside voids. To do so, we applied the same algorithm to identify galaxy groups in voids, but to identify groups in a sample of galaxies not belonging to clusters or voids, hereafter NCNV (not in voids nor clusters), following Torres-Ríos et al. (2026). To select NCNV galaxies, we used the catalogue of group galaxies classified by Tempel et al. (2017), composed of 584449 galaxies up to a redshift $z=0.2$, based on data from the SDSS-DR12 (Eisenstein et al. 2011; Alam et al. 2015). First of all, we restricted the sample to galaxies in the same redshift range as the sample of 170 voids used in this study ($z < 0.08$, 220 614 galaxies). From this, we removed cluster galaxies (i.e. galaxies that are part of groups of 30 galaxies or more, Abell et al. 1989), and void galaxies (i.e. galaxies in common with the catalogue of void galaxies, Pan et al. 2012), leaving us with 156 700 NCNV galaxies.

After applying the group finder algorithm, we identified 44 503 singlets ($\sim 28\%$ of NCNV galaxies) and 11121 groups composed of 93 470 galaxies (60% of NCNV galaxies). To use this sample as a control sample, we only consider galaxy groups with similar richness (up to $N_{\text{gal}} = 6$), leaving us with 33 562 groups composed of 87 726 galaxies. Similarly as for groups in voids, we identified a limited sample and a volume-limited sample. The number of groups for each richness in each sample is also shown in Table 1.

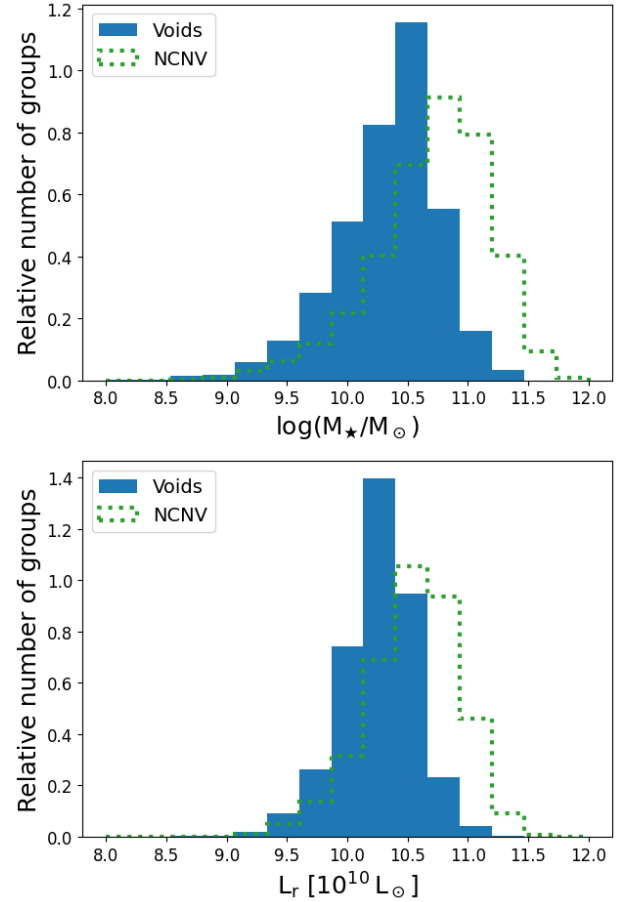


Fig. 3. Total stellar mass and optical luminosity. Distribution of the total stellar mass (upper panel), and total optical luminosity (lower panel) for the galaxy groups and singlets in the full sample, in solar units. The distributions for the control sample of NCNV groups are presented as open dotted green histograms.

3.3. Total stellar mass and optical luminosity

For each group, we estimated their total stellar mass and optical luminosity in the r band as the sum of the stellar mass and luminosity of their member galaxies (including singlets). Stellar masses were estimated by fitting the spectral energy distribution on the five SDSS bands using the k-correct code (Blanton & Roweis 2007). Luminosities were calculated using magnitudes corrected for extinction in the r band. Galactic reddening corrections in magnitudes at the position of each object are computed following Schlegel et al. (1998). To avoid selection effects due to the slightly different redshift of the group members, and to be consistent with the methodology to identify galaxy groups, we considered the redshift of the central galaxy as the redshift of the group.

The distributions of the computed total stellar mass and total luminosity of each group are presented in Fig. 3. The median value of the total stellar mass of the groups is $\log(M_{\star}/M_{\odot}) = 10.4^{10.6}_{10.1}$, while for the total optical luminosity is $\log(L_r/L_{\odot}) = 10.3^{10.5}_{10.1}$; where the upper and lower indices correspond to the 25th and 75th percentiles of the corresponding distribution, respectively. These values increase to $\log(M_{\star}/M_{\odot}) = 10.8^{11.0}_{10.5}$ and $\log(L_r/L_{\odot}) = 10.6^{10.8}_{10.3}$ in the control sample of NCNV groups.

Table 2. Catalogue of group galaxies.

(1) groupID	(2) voidID	(3) cavityID	(4) RA (deg)	(5) Dec (deg)	(6) z	(7) m _r (mag)	(8) M _r (mag)
1	44	1754	133.959488	0.831134	0.041743	15.44	−21.15
1	44	2884	133.859375	0.858172	0.041981	17.19	−19.42
2	649	2003	150.803421	1.148881	0.067632	16.46	−21.09
2	649	2004	150.816711	1.144060	0.067632	16.46	−21.09
3	649	2015	154.869186	1.062658	0.065402	16.68	−20.87
3	649	69 946	154.849915	1.052281	0.065557	17.66	−19.90
4	349	2859	143.087585	0.506555	0.071858	17.56	−20.22
4	349	69 991	143.024017	0.453879	0.072006	17.72	−20.07
5	38	3137	127.461372	48.374413	0.054634	16.15	−20.96
5	38	70 026	127.411751	48.389259	0.054823	17.69	−19.43
...	...	...	...	...	...	...	...

Notes. The full table is available at the CDS. The columns correspond to: (1) group identification; (2) void identification; (3) CAVITY galaxy identification; (4) J2000.0 right ascension in degrees; (5) J2000.0 declination in degrees; (6) redshift; (7) apparent magnitude in the *r* band; and (8) absolute magnitude in the *r* band.

3.4. Dynamical parameters

To characterise the dynamical stage of the galaxy groups, we calculated their projected harmonic radius, R_H , radial velocity dispersion, $\sigma_{v_r}^2$, dimensionless crossing time, $H_0 t_c$, and group virial mass, M_{vir} , defined as follows:

$$R_H = \left(\frac{1}{N_{\text{gal}}} \sum R_{ij}^{-1} \right)^{-1}, \quad (1)$$

$$\sigma_{v_r}^2 = \frac{1}{N_{\text{gal}} - 1} \sum (v_r - \langle v_r \rangle)^2, \quad (2)$$

$$H_0 t_c = \frac{H_0 \pi R_H}{\sqrt{3} \sigma_{v_r}}, \quad (3)$$

and

$$M_{\text{vir}} = \frac{3\pi N_{\text{gal}} R_H \sigma_{v_r}^2}{(N_{\text{gal}} - 1) G}, \quad (4)$$

where R_{ij} are the projected galaxy-galaxy separations (in megaparsecs), N_{gal} is the group richness, $v_r \propto cz$, and $\langle v_r \rangle$ the mean value of the radial velocity considering all member galaxies of the group. These parameters, as defined in [Hickson \(1982\)](#) and [Hickson et al. \(1992\)](#), quantify the dynamic configuration of groups and clusters. They provide a robust estimation of the evolution stage on systems, even in groups with a low number of members ([Feng et al. 2016](#); [Vázquez-Bustos et al. 2023](#)). The R_H parameter represents a measurement of the effective radius of the galaxy group. The $\sigma_{v_r}^2$ parameter corresponds to the dispersion of the radial velocities of the galaxies in the groups. We used $H_0 t_c$ as a measure of the time that takes a single galaxy to go across the system. The M_{vir} parameter is the mass estimation of a gravitationally bound system. It is derived from the effective radius of the group and its velocity dispersion, with a factor to account for the group richness. This parameter represents an approximation of the dark matter halo and baryonic mass.

Note that, by definition, these parameters (except R_H) can only be computed for groups (i.e. singlets are excluded). The de-projection factor $\sqrt{3}$ in Equations (3) and (4) is introduced as

an estimator of the ‘true’ three-dimensional velocity dispersion of a group. This factor comes from the assumption that groups have isotropic velocity distributions. This assumption may introduce statistical uncertainties considering that the small number of galaxies might dominate the estimate of the velocity dispersion ([Diaferio et al. 1993](#)). We took into account this fact in the analysis of the dynamical parameters.

The group virial mass was also used to compute the total mass-to-light ratio of the groups (M/L), as described in Sect. 4.3. The M/L is a key parameter for inferring the amount of dark matter in groups. However, given the uncertainties, it is impossible to provide a precise value for the M/L of small groups. Therefore, the aim of this work is limited to the study of the dependency of the estimated M/L values with the group richness, in comparison with the observed trends in groups located in denser environments in the literature.

4. Results

4.1. Galaxy groups in voids

Following the procedure described in Sect. 3.1, we identified a sample of group galaxies within cosmic voids in the local Universe ($z < 0.08$). The list of galaxies in groups (in the full sample) is provided in Table 2, while the catalogue of groups is provided in Table 3. The catalogue of groups is composed of 1367 physically bound groups (for a total of 3040 galaxies), plus 14672 galaxy singlets (galaxies that are not physically bound to any other detected galaxy). These groups are distributed in 170 voids from the catalogue of voids in [Pan et al. \(2012\)](#), from which the CAVITY parent sample was built. In contrast to void galaxies, where most of the galaxies are singlets (59%), most of the galaxies in the NVNC control sample are in groups (60%). As shown in Table 1, the densest groups in voids are composed of six galaxies. The typical richness of voids is $N_{\text{gal}} = 2$ (83% of the groups in the full sample and 74% in the limited sample). Therefore, voids generally contain small groups, in comparison to denser structures such as filaments and walls, with approximately ~64% of pair galaxies ([Kuutma et al. 2020](#)), and galaxy clusters ([Tempel et al. 2017](#)). In particular, 62% of the groups in the control sample of NVNC groups are composed

Table 3. Catalogue of groups in voids.

(1) groupID	(2) N_{gal}	(3) $\log(M_{\star})$ ($\log(M_{\odot})$)	(4) L_r ($10^{10} L_{\odot}$)	(5) σ_{v_r} (km s^{-1})	(6) R_H (kpc)	(7) H_{0t_c}	(8) $\log(M_{\text{vir}})$ ($\log(M_{\odot})$)
1	2	10.58	2.74	50.45	233.15	0.59	12.41
2	2	10.57	4.30	0.17 ^(a)	63.52	46.60	6.92
3	2	10.67	2.47	32.86	99.35	0.38	11.67
4	2	10.26	1.80	31.37	393.49	1.59	12.23
5	2	10.49	2.38	40.07	137.53	0.44	11.98
6	2	10.39	1.80	0.17 ^(a)	22.89	16.79	6.48
7	2	10.56	2.49	16.53	337.93	2.59	11.60
8	4	10.70	3.03	88.65	159.71	0.23	12.56
9	2	10.47	2.43	9.12	252.53	3.52	10.96
10	2	10.61	2.92	32.65	169.29	0.66	11.90
...	...	...	...	...	...	...	...

Notes. The full table is available at the CDS. The columns correspond to: (1) group identification; (2) group richness; (3) total stellar mass of the group in $\log(M_{\odot})$; (4) total r band luminosity of the group in $10^{10} L_{\odot}$; (5) σ_{v_r} , velocity dispersion in kilometres per second; (6) R_H , harmonic radius in kiloparsecs; (7) H_{0t_c} , crossing time; and (8) M_{vir} , virial mass in $\log(M_{\odot})$. ^(a)Note that groups with $\sigma_{v_r}^2 < 10 \text{ km s}^{-1}$ have unreliable virial mass estimations.

of two physically bound galaxies, in agreement with the literature. To investigate how our algorithm performs in comparison to other group finder algorithms, we did a crossmatch with the galaxies in the catalogue of groups in Tempel et al. (2017) (FoF algorithm) and in the catalogue of Yang et al. (2007) (halo-based algorithm) that are also found in the catalogue of void galaxies (Pan et al. 2012). In general, there is a good agreement: 83% of singlets in our catalogue are also singlets with a FoF algorithm (81% when considering the limited sample), while 94% of the group galaxies are still group galaxies (91% when considering the limited sample). When comparing with a halo-based algorithm, 73% and 67% are still singlets and group galaxies, respectively (91% and 78%, respectively, when considering the limited sample). Note that Yang et al. (2007) applied a strict magnitude limit cut-off for group members, and therefore there is a better agreement with the limited sample than for the full sample.

In Fig. 4, we present the void-centric distance, r/R_{void} , as a function of the group richness. The values of r/R_{void} were computed after normalising the position of the central galaxy in each group by the void size, R_{void} . A value of $r/R_{\text{void}}=1$ represents the maximum size of the voids if they were spherical. As can be appreciated from the figure, galaxy groups are evenly distributed within voids; however, the densest groups in voids avoid the innermost regions ($r/R_{\text{void}} < 0.6$). We note that the environment within voids might be an intricate region. Voids are not completely spherical, they are composed of the superposition of various cavities, and therefore, even considering the restricted selection criteria of void galaxies in Pan et al. (2012), there might be contamination by wall galaxies inside the void at larger void-centric distances. Also, as noted by Yang et al. (2007) and Tempel et al. (2017), galaxy groups can merge with other groups. Hence, dense galaxy groups within voids, and therefore more massive (both in stellar and virial mass), at larger void-centric distances, might be attracted by groups which belong to the walls surrounding voids. To quantify these effects, we used the classification of the environment in Torres-Ríos et al. (2024), who used the catalogue of void galaxies in Pan et al. (2012) to find grouped galaxies in voids, and the catalogue of groups and clusters compiled by Tempel et al. (2017) to reduce the contamination by galaxies in walls and filaments (hereafter wall). We

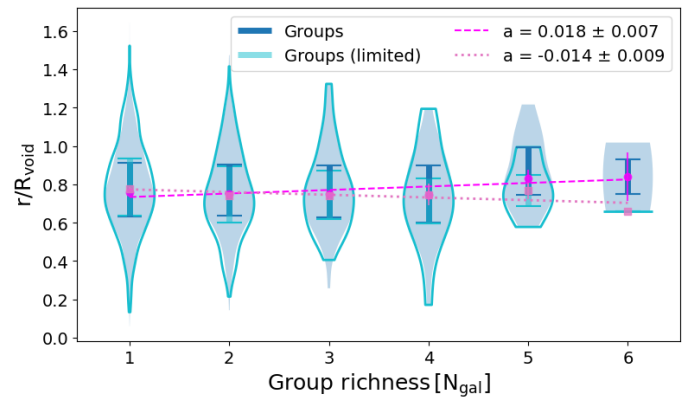


Fig. 4. Void-centric distance as a function of group richness. A void-centric distance value of the unit represents the maximum size of the voids if they were spherical. The distribution of void-centric distance for groups with the same group richness is represented by violin plots (filled blue distributions considering the full sample, and empty cyan distributions for the limited sample). The inner box in each violin plot represents the interquartile range of the median and its 95% of confidence intervals. Magenta circles and pink squares correspond to the median values in richness bins (considering the full sample or the limited sample, respectively) with their corresponding uncertainties, while dashed magenta and dotted pink lines correspond to the linear least-square fit to the binned data, respectively. The slopes of the linear fits, with their corresponding uncertainties, are indicated in the legend.

found that 37 singlets (0.3% of the sample) and 39 groups (fewer than 3% of the groups) might be associated with wall galaxies, with typical void-centric distance $r/R_{\text{void}} = 0.9$ and similar mass (both stellar and virial) than the rest of the groups. This might be related with the observed result that dense groups avoid the inner region of the voids. While voids expand, galaxy groups are pulled towards their surrounding walls. In addition, Alfaro et al. (2026), based on simulations, has recently reported that the radial gradient of individual bias (i.e. how individual galaxies trace the underlying dark matter field) within voids, generally increasing from negative values at the void centre to higher values at the edges, is robust across most void definitions, including the VoidFinder algorithm used in Pan et al. (2012). In contrast,

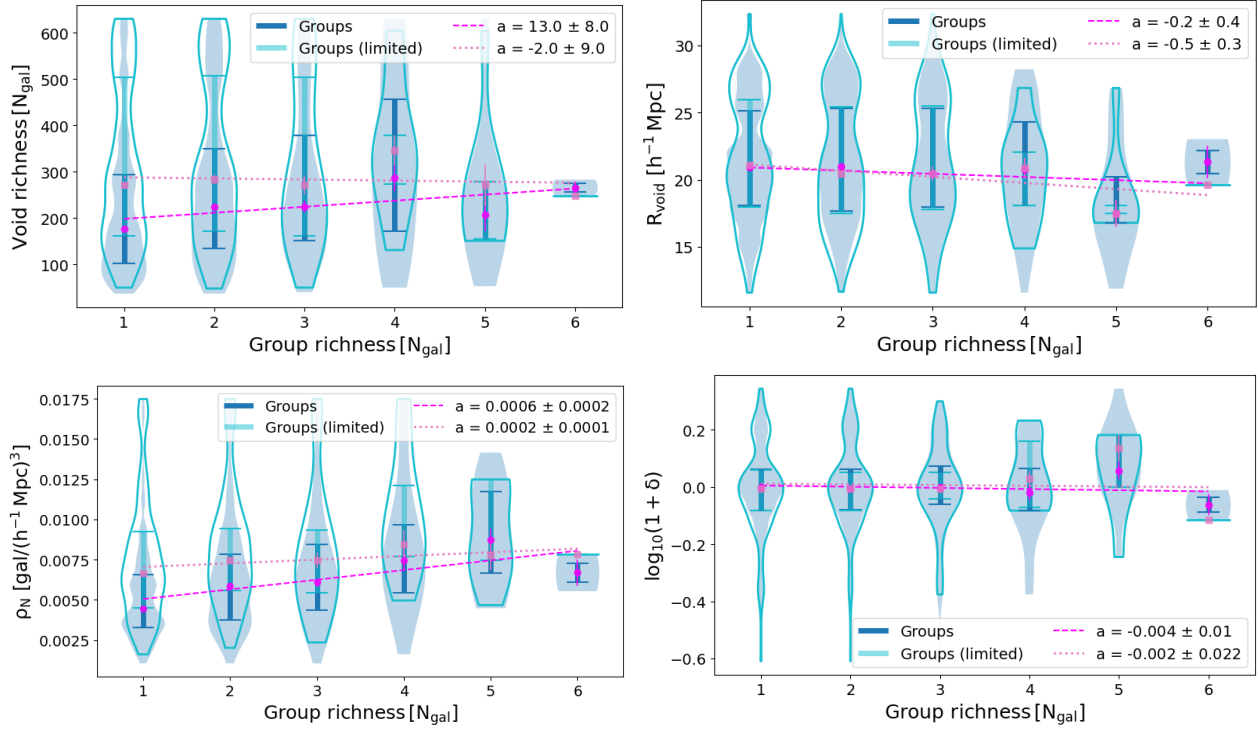


Fig. 5. Properties of the voids as a function of the group richness. From top left to bottom right: number of galaxies in the voids (void richness); size of the voids (R_{void}); the number density of galaxies in each void (ρ_N); and the over-density-corrected number density ($\log_{10}(1 + \delta)$). The distribution of void properties for groups with same group richness is represented by violin plots (filled blue distributions considering the full sample, and empty cyan distributions for the limited sample). The inner box in each violin plot represents the interquartile range of the median and its 95% of confidence intervals. Magenta circles and pink squares correspond to the median values in richness bins (considering the full sample or the limited sample, respectively) with their corresponding uncertainties, while dashed magenta and dotted pink lines correspond to the linear least-square fit to the binned data, respectively. The slopes of the linear fits, with their corresponding uncertainties, are indicated in the legend.

Zhang et al. (2026), based on both observations and simulations, report that void size distributions and radial density profiles depend strongly on the identification algorithm. The radial number density profiles differences are noticeable at larger void-centric distances ($r/R_{\text{void}} \gtrsim 1.0$). Therefore, our findings should be consistent, independently of the chosen void catalogue, at least in the inner regions of the voids.

The panels in Fig. 5 show the number of galaxies in the voids (void richness), void size, and void galaxy number density (including over-density-corrected number density), as a function of the group richness. We observe that group richness is independent of void size (upper right panel), where the median of the distribution of void size at each group richness is similar to the median value for the sample of 170 voids used in this work ($R_{\text{void}} \sim 20 h^{-1} \text{ Mpc}$). Note that void size does not vary with redshift in the considered redshift range ($0.005 \leq z \leq 0.080$). The group richness shows a tendency to increase with void richness (upper left panel), and consequently with galaxy number density of the void (lower left panel), which disappears when considering the limited sample of groups. This is because the void richness is affected by the Malmquist bias that is implicit in the SDSS galaxy sample, which leads to the preferential detection of intrinsically bright galaxies at higher redshift. For this reason we also consider the over-density-corrected galaxy number density of voids ($\log_{10}(1 + \delta)$), shown in the lower right panel), as defined in Argudo-Fernández et al. (2024), in which the over-density for the void-galaxy number density is estimated in each void using the methodology of Etherington & Thomas (2015). As a result, we found that the group richness is independent of the density of

the voids. This implies that there are no voids composed only of singlets or with no groups.

4.2. Dynamical stage of galaxy groups

Figure 6 shows the distribution of the dynamical parameters for the full sample of groups in voids. The median value of the dynamical parameters for the groups are $R_H = 204_{99}^{230} \text{ kpc}$, $\sigma_{v_r} = 43_{21}^{72} \text{ km s}^{-1}$, $H_0 t_c = 0.66_{0.34}^{1.81}$, and $\log(M_{\text{vir}}/M_\odot) = 12.2_{11.5}^{12.6}$; where the upper and lower indices correspond to the 25th and 75th percentiles of the distribution, respectively. In comparison, the median values of these parameters in the control sample of NCNV groups are $R_H = 240_{163}^{326} \text{ kpc}$, $\sigma_{v_r} = 73_{48}^{94} \text{ km s}^{-1}$, $H_0 t_c = 0.44_{0.26}^{0.73}$, and $\log(M_{\text{vir}}/M_\odot) = 12.5_{12.2}^{12.8}$. This indicates that, in general, galaxy groups in voids are less massive, less compact, and less evolved than in denser large-scale environments.

Similar to Fig. 5, in Fig. 7 we explored the dependence of the dynamical parameters for the groups in voids with respect to the group richness. The dispersion of the distributions of the dynamical parameters decreases with group richness, with galaxy pairs presenting the largest dispersion. The distributions for the limited sample are almost identical, indicating that these parameters are free of a redshift bias. In general, the median harmonic radius of groups does not vary with group richness, while the median radial velocity dispersion increases with group richness as is expected by definition (not shown). Consequently, the crossing time decreases with group richness while the virial mass increases. This trend suggests that groups become more compact and massive as the number of neighbours increases, as expected.

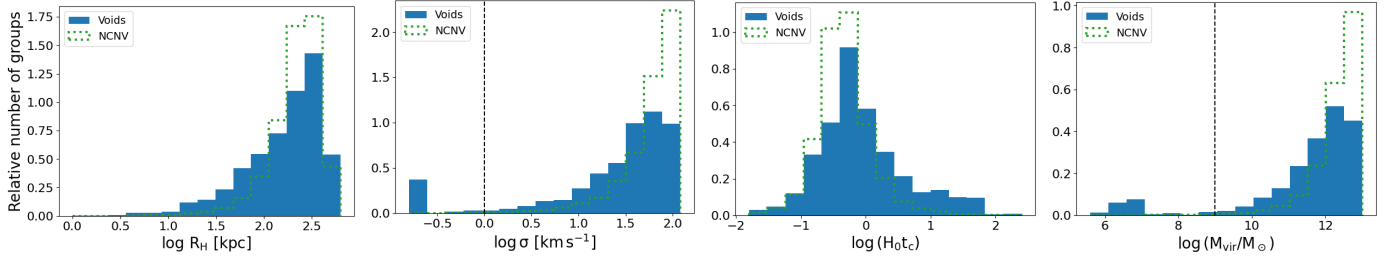


Fig. 6. Distribution of the dynamical parameters for the 1397 galaxy groups in the full sample. From left to right: effective radius of the groups, as $\log R_H$; observed velocity dispersion, as $\log \sigma$; dimensionless crossing time, as $\log (H_0 t_c)$; and group virial mass, as $\log M_{\text{vir}}$ in solar units. The dashed black line in the distribution of the observed velocity dispersion delimits the groups with $\sigma^2 < 10 \text{ km s}^{-1}$, and by consequence with $\log (M_{\text{vir}}/M_\odot) < 9$, which are excluded of the analysis of the groups using the group virial mass. The distributions of the parameters for the control sample of NCNV groups are presented as open dotted green histograms.

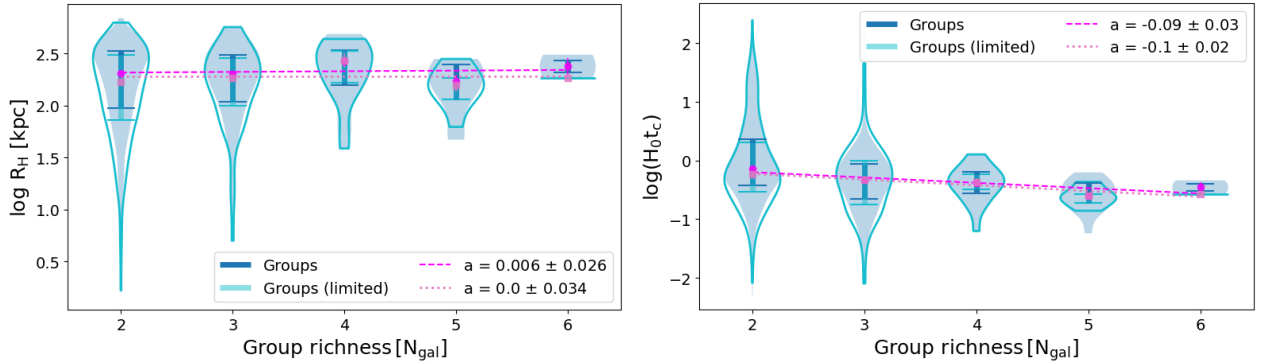


Fig. 7. Dynamical parameters of the galaxy groups with more than one member as a function of the group richness. The effective radius of the groups, as $\log R_H$ is shown in the left panel, while the dimensionless crossing time, as $\log (H_0 t_c)$ is shown in the right panel. The observed velocity dispersion and group virial mass are not shown since their correlation with richness is expected, by definition (presented in Equations (2) and (4)). The distribution of the dynamical parameters for groups with same group richness is represented by violin plots (filled blue distributions considering the full sample, and empty cyan distributions for the limited sample). The inner box in each violin plot represents the interquartile range of the median and its 95% of confidence intervals. Magenta circles and pink squares correspond to the median values in richness bins (considering the full sample or the limited sample, respectively) with their corresponding uncertainties, while dashed magenta and dotted pink lines correspond to the linear least-square fit to the binned data, respectively. The slopes of the linear fits, with their corresponding uncertainties, are indicated in the legend.

When considering the control sample of NCNV groups, the median harmonic radius slightly decreases with group richness (slope $a = -0.023 \pm 0.002$), indicating that the groups are more compact with an increasing number of galaxies. The correlation of $H_0 t_c$ with group richness is similar (slope $a = -0.06 \pm 0.01$). This indicates that galaxy groups in voids are less compact than in NCNV.

4.3. Mass-to-light ratio of galaxy groups

We used the total r band luminosity, L_r , as calculated in Sect. 3.3, and the virial mass from Sect. 3.4 to estimate the mass-to-light ratio (M_{vir}/L_r) for the galaxy groups in voids. Note that groups with $\sigma_{\text{vir}}^2 < 10 \text{ km s}^{-1}$ (which occurs in groups composed of two galaxies), which have unreliable virial mass estimations, are excluded from the analysis. The distribution of the $\log(M_{\text{vir}}/L_r)$, in units of $\log(M_\odot/L_\odot)$, is shown in Fig. 8. As expected, there is a wide range of values in the groups, with a median value of $\log(M_{\text{vir}}/L_r) = 1.9^{2.3}_{1.2}$, which corresponds to $M_{\text{vir}}/L_r \sim 105 h$; where the upper and lower indices correspond to the 25th and 75th percentiles of the distribution, respectively. The results for the control sample of NCNV groups are similar, with slightly less dispersion at lower mass-to-light ratio ($\log(M_{\text{vir}}/L_r) = 1.9^{2.3}_{1.5}$).

In the top panel of Fig. 9, we show how the M_{vir}/L_r varies with group richness, presenting a mild tendency to increase with

the number of physically bound members, with a slope $a = 18 \pm 8$ ($a = 7 \pm 9$ for the limited sample). Additionally, we present the mass-richness ratio ($M_{\text{vir}}/N_{\text{gal}}$) and luminosity-richness ratio (L_r/N_{gal}) as functions of the group richness in the same figure. The $M_{\text{vir}}/N_{\text{gal}}$ and L_r/N_{gal} show a very slight tendency to increase with richness (with large uncertainties), or is almost constant over the full richness range, respectively. The relation of the $M_{\text{vir}}/N_{\text{gal}}$ with the group richness has a slope 4 ± 3 (1 ± 4 for the limited sample); while the L_r/N_{gal} with the group richness has a slope -0.08 ± 0.04 , compatible with the slope for the limited sample (-0.05 ± 0.04), showing no trend with the group richness.

5. Discussion

Voids are extremely underdense regions, with average density contrast of about -0.9 with diameters generally from 20 to 100 Mpc (Pan et al. 2012). This means that void galaxies are very sparse, which very commonly leads to the misconception of void galaxies as isolated galaxies. However, as introduced in Sect. 1, many works have shown that there are substructures within voids. In this work, we identified a sample of physically bound groups within voids. Considering the group richness of the full sample, 59% of void galaxies are singlets, from which

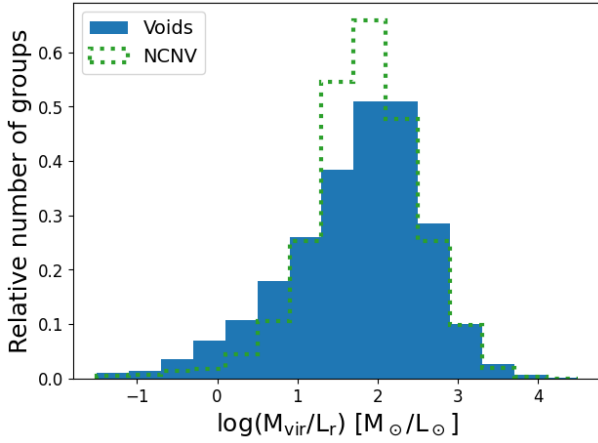


Fig. 8. Distribution of the mass-to-light ratio of the groups in the full sample with $N_{\text{gal}} \geq 2$. Only groups with $\log(M_{\text{vir}}/M_{\odot}) > 9$ are considered in the analysis. The distribution for the control sample of NCNV groups is presented as the open dotted green histogram.

only 7% are potential isolated galaxies considering the observational constraints (as discussed in Sect. 3.1), while 12% of the void galaxies belong to physically bound groups (3040 galaxies). The remaining void galaxies (29%) are connected to the large-scale structure within the voids (i.e. they have at least one neighbour with $\Delta v \leq \pm 500 \text{ km s}^{-1}$ at 1 Mpc projected distance), but are not physically bound with it.

We explored if group richness has any dependency with the properties of the voids, as void richness (number of galaxies in each void), void size, and the galaxy number-density of galaxies in a void (defined as the number of galaxies inhabiting a void divided by the total volume of the void). It is reasonable to assume that the densest groups are preferentially found in denser voids, as galaxies are more likely to become gravitationally bound to nearby neighbours and form groups in deeper potential wells. However, as shown in Fig. 5, after correcting by redshift bias, we found that group richness is independent of the density of the voids. This means that we can find galaxy groups, and therefore substructures, in any void in the local Universe, with densities from 0.001 to 0.017 $\text{gal}/(h^{-1} \text{ Mpc})^3$. For reference, in Fig. 10 we show the three-dimensional visualisation of two voids of a similar size ($R_{\text{void}} \sim 13 h^{-1} \text{ Mpc}$), but different numbers of galaxies: Void 941 ($\rho_N = 0.005 \text{ gal}/(h^{-1} \text{ Mpc})^3$ at $z = 0.01$) in the left panel, with 53 void galaxies, and Void 622 ($\rho_N = 0.014 \text{ gal}/(h^{-1} \text{ Mpc})^3$ at $z = 0.04$) in the right panel, with 154 void galaxies, thus about 3 times denser than Void 941. These two voids are included in the CAVITY parent sample. As expected, the more galaxies there are in a void, the greater the number of groups; however, the richness of the groups does not depend on how dense the void is.

The analysis of the values of the median harmonic radius, radial velocity dispersion, and crossing time found in this work indicates that galaxy groups within voids can be considered as loose groups (Mamon 1987). Even the densest groups in voids are more loose than similar richness groups outside voids. Loose groups are characterised by presenting low velocity dispersions (less than 200 km s^{-1} , Stierwalt et al. 2009) and galaxy separations by distances many times their own size (a few hundred kiloparsecs), forming sparse structures, independently of the group richness. These systems are low-density, typically containing spiral-rich members, and represent the most common environment for galaxies (examples include the Leo Triplet or

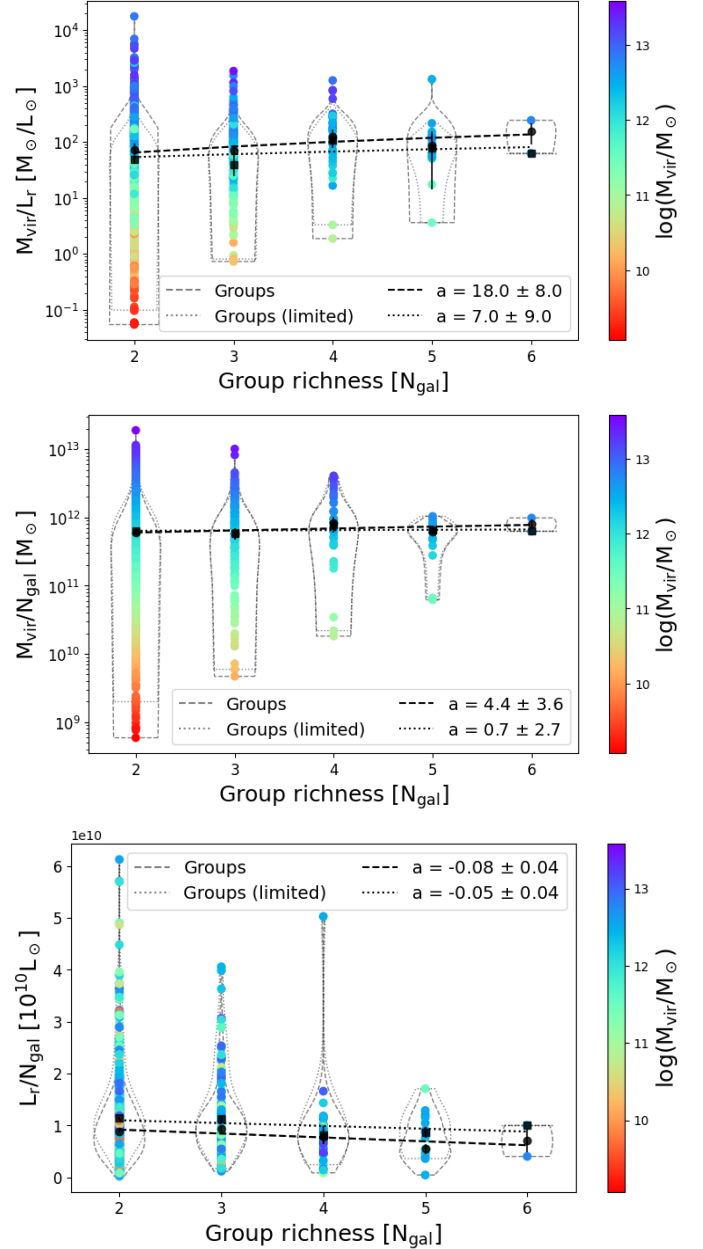


Fig. 9. Group mass-to-light ratio (top panel), mass-richness ratio (middle panel), and luminosity-richness ratio (bottom panel) as functions of group richness. The distribution of these parameters for groups with same group richness is represented by violin plots (dashed-grey-line distributions considering the full sample, and dotted-grey-line distributions for the limited sample). Different virial group masses are indicated according to the colour bar at the right of each panel. Black circles correspond to the median values in richness bins with their corresponding uncertainties, while dashed black lines correspond to the linear least-square fits to the binned data. The slopes of the linear fits, with their corresponding uncertainties, are indicated in the legend. Only groups with $\log(M_{\text{vir}}/M_{\odot}) > 9$ are considered in the analysis.

the Local Group), which can be also found in the vicinity of galaxy clusters (Einasto et al. 2003). The low dispersion of the velocity of the void galaxies might favour galaxy interactions and mergers within the groups; however, unlike in compact groups (median $H_0 t_c = 0.016$), crossing times values in the void groups are much larger (median $H_0 t_c = 0.66$ for the full sample), even larger than in the control sample of NCNV groups

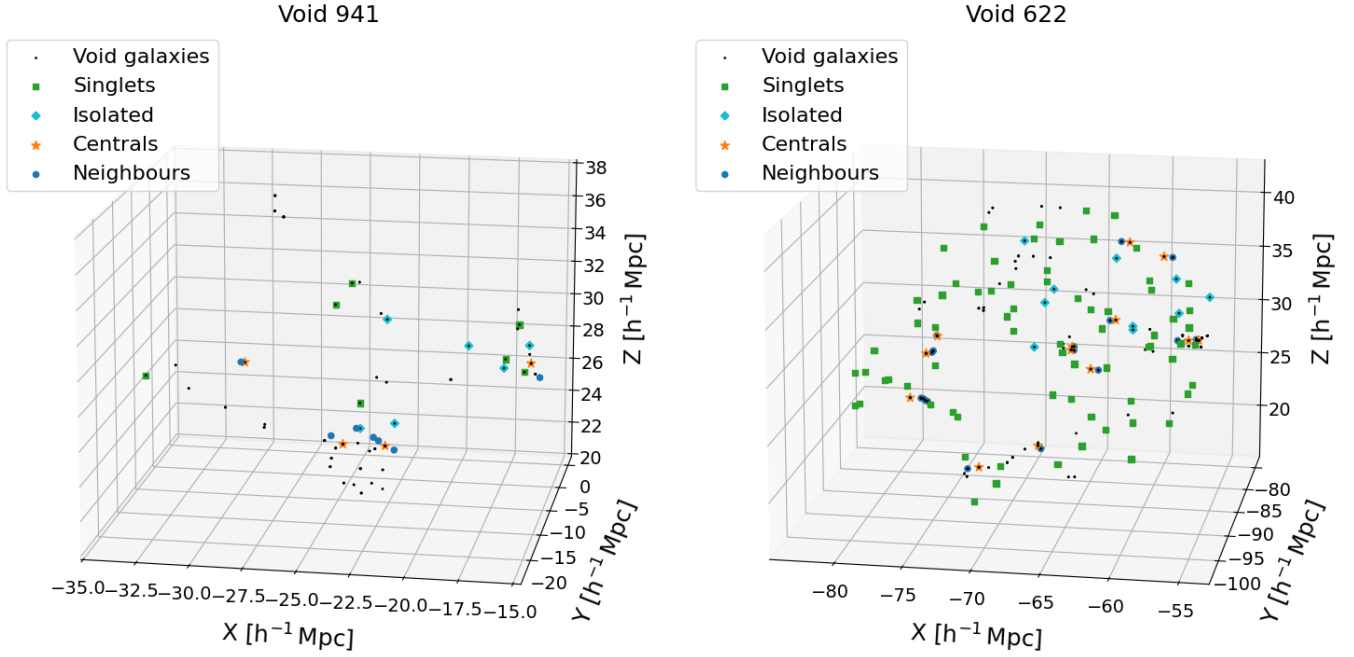


Fig. 10. Three-dimensional visualisation of voids. Spatial distribution of galaxies within two voids in the CAVITY sample (Void 941 and Void 622, in the left and right panels, respectively) as an example of the distribution of groups within voids of similar size ($R_{\text{void}} \sim 13 h^{-1} \text{ Mpc}$) but different number of galaxies (53 and 154 void galaxies, respectively). Void galaxies (black dots) act as tracers of the substructure of the voids. Of them, singlets (void galaxies with no neighbours $\Delta v \leq \pm 500 \text{ km s}^{-1}$ at 1 Mpc projected distance) are marked in green, from which potential isolated galaxies (singlets with $m_r \leq 15.7 \text{ mag}$) are marked in cyan, while central galaxies of groups with two or more members are marked in orange, with their corresponding physically bound members in blue, as indicated in the legend.

(median $H_{0c} = 0.44$) and in isolated triplets (median $H_{0c} = 0.38$, Vázquez-Bustos et al. 2023) for the groups with higher richness, which indicates the early stage of evolution of group galaxies in voids. On the other hand, since group in voids are inherently loose and of low density, long crossing times and a lack of virialisation² could be expected even without an early stage. In this scenario, galaxy groups in voids could be stable structures or in prolonged pseudo-equilibrium, due to the absence of frequent mergers. In other words, non-virialisation in void groups could be a permanent state due to global gravitational suppression, not a transitory one. However, the rate of mergers in voids at present Universe is comparable to the rate in filaments and walls ($\sim 3\%$, Vázquez-Bustos et al., in prep). Therefore, interactions are expected to occur within the groups, even if the void galaxies tend to experience mergers at later times than in denser environments (as found from simulations, Rodríguez-Medrano et al. 2024), which supports the first scenario where groups in voids are in an early evolutionary stage. This is also in agreement with recent observations which found that, more evolved groups are found in dense structures (clusters and superclusters), while poor groups reside everywhere in the cosmic web, where the less luminous groups at same richness (therefore less evolved) are found in low-density environments, as voids (Einasto et al. 2024).

The median mass-to-light ratio for galaxy groups in voids ($M_{\text{vir}}/L_r \sim 105 h$) is almost the double than the value reported for compact groups ($M_{\text{vir}}/L_r = 50 h$, Hickson et al. 1992). This might suggest a larger dark matter fraction in void groups, in agreement with recent simulations (Habouzit et al. 2020; Martizzi et al. 2020; Rosas-Guevara et al. 2022; Rodríguez-Medrano et al. 2024). Unfortunately, our derived

virial mass estimates for the groups (based on the group velocity dispersion, see Eq. (4)), have large uncertainties owing to the small number of galaxies per group. In fact, the median mass-to-light ratio for the control sample of NCNV groups with same richness is similar to the groups in voids. Therefore, no strong conclusions can be drawn in this regard. A dedicated study focused on identifying faint satellites in these groups would help to obtain more robust results. In this work, we limited the study to the analysis of the mass-to-light ratio as function of group richness, to compare with the observed trends of groups in denser environments.

Figure 9 shows the M_{vir}/L_r , $M_{\text{vir}}/N_{\text{gal}}$, and L_r/N_{gal} as a function of group richness. The trends found for the mass-to-light ratio and the L_r/N_{gal} (after correcting for redshift bias) are in agreement with the trends reported in Tempel et al. (2017), which only consider groups with richness greater than $N_{\text{gal}} = 6$. When extending to low richness groups, the mass-to-light ratio increases slightly with group richness while the L_r/N_{gal} relation is almost flat. This flat luminosity-richness relation has been also found in previous works based on galaxy clusters in the SDSS (Popesso et al. 2007; Wen et al. 2009). As also pointed out by Tempel et al. (2017), the mass-to-light ratio decreases with group richness when considering groups with similar mass, even with the wide range of M_{vir}/L_r values that we found for low richness groups. However, we found that the $M_{\text{vir}}/N_{\text{gal}}$ relation increases much slightly with group richness than reported in observational studies on denser groups and galaxy clusters (Tempel et al. 2017; Marinoni & Hudson 2002; Pisani et al. 2003; Wen et al. 2009). From simulations, the $M_{\text{vir}}/N_{\text{gal}}$ relation (so-called halo occupation distribution) can be described by a power law $N_{\text{gal}} \propto M_{\text{vir}}^{\beta}$, with β presenting expected values of less than 1 (White et al. 2001). With our data, we find $\beta = 0.71 \pm 0.13$ ($\beta = 0.98 \pm 0.37$ for the limited sample). Although with large

² Groups are supposed to be virialised if their crossing times are much smaller than the Hubble time, typically $0.1\text{--}0.5 H_0^{-1}$ (Paul et al. 2017).

uncertainties in the M_{vir} values, the $M_{\text{vir}}/N_{\text{gal}}$ relation shows the expected behaviour. The very slight increase with group richness may be due to the early stage of evolution of galaxy groups in voids and the sparse distance between the galaxies. Therefore the groups, although physically bound, they may still not be virialised. According to Wang et al. (2026), who studied observed red luminous galaxies in contrast to simulations, the clustering of these type of groups is directly connected to the underlying matter density field, which provides key information about non-linear structure formation and the galaxy–halo connection.

6. Summary and conclusions

In this work we identified a sample of galaxy groups in 170 cosmic voids in the local Universe ($z < 0.08$), taking into account the peculiarities of these vast and empty structures. For this, each void was analysed separately, considering only the galaxies that reside in it, and we applied a FoF-like group finder algorithm, ensuring a certain degree of gravitational bounding among group members. The sample of void galaxies that we used in this study is based on the well-defined sample of void galaxies from Pan et al. (2012) (also used in the CAVITY legacy project). The catalogue of groups is composed of 1367 physically bound groups (with a total of 3040 galaxies), and 14 672 galaxy singlets. We used the same group finder algorithm to identify a control sample of groups considering galaxies not part of either clusters nor voids (NCNV).

To consider the dynamical stage of the groups we used the following parameters: harmonic radius (R_H), radial velocity dispersion (σ_v), dimensionless crossing time ($H_0 t_c$), and group virial mass (M_{vir}), as explained in Sect. 3.4. We also used the total optical (r band) luminosity, L_r , to estimate the mass-to-light ratio (M_{vir}/L_r) for the galaxy groups in voids and in NCNV. We studied the relations of the group richness with void properties, the dynamical parameters, and the mass-to-light ratio. Our main findings are as follows:

- Galaxy groups can be found in any void in the local Universe. These are evenly distributed within voids. The more galaxies there are in a void, the greater the number of groups; however, the group richness is independent of the density of the voids;
- Most of the galaxies in voids are singlet galaxies (59%), from which only a few percent (7%) are potentially isolated galaxies, considering the observational constraints. In contrast, most of the galaxies in a control sample in NCNV are in groups (60%). The densest groups in voids are composed of six galaxies; therefore, voids generally contain small groups, in comparison to denser structures such as filaments, walls, and galaxy clusters;
- Considering their dynamical properties, galaxy groups within voids are typically loose groups, in an early stage of their evolution. The groups are more compact and massive with increasing number of galaxies, favouring galaxy interactions between their members;
- The work presented here has allowed us to extend the mass-to-light ratio, mass-richness ratio, and luminosity-richness ratio as functions of richness relations to lower ambient density values, confirming the trends observed in denser groups and clusters. However, the mass-richness relation is much flatter, which might be due to the early stage of evolution of galaxy groups in voids and the sparse distance between their galaxies. This result suggests that galaxy groups in voids, although physically bound, may still not be virialised.

The catalogue of group galaxies, with galaxy positions, redshifts, and optical magnitudes, as well as the catalogue of groups with group richness, total stellar mass, total optical luminosity, and dynamical parameters are publicly available to the scientific community. The data structure and first lines in our catalogues are described in Tables 2 and 3.

Data availability

Full Tables 2 and 3 are available at the CDS via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/712/A55>.

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References

- Abazajian, K. N., Adelman-McCarthy, J. K., & Agüeros. 2009, *ApJS*, **182**, 543
- Abell, G. O., Corwin, Jr., H. G., & Olowin, R. P. 1989, *ApJS*, **70**, 1
- Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, *ApJS*, **219**, 12
- Alfaro, I. G., Rodríguez, F., Ruiz, A. N., & Lambas, D. G. 2020, *A&A*, **638**, A60

- Alfaro, I. G., Rodríguez, F., Ruiz, A. N., Luparello, H. E., & Lambas, D. G. 2022, *A&A*, **665**, A44
- Alfaro, I. G., Montero-Dorta, A. D., Bustillos, J. F., et al. 2026, *A&A*, **711**, A267
- Alpaslan, M., Robotham, A. S. G., Driver, S., et al. 2014a, *MNRAS*, **438**, 177
- Alpaslan, M., Robotham, A. S. G., Obreschkow, D., et al. 2014b, *MNRAS*, **440**, L106
- Aragon-Calvo, M. A., van de Weygaert, R., Araya-Melo, P. A., Platen, E., & Szalay, A. S. 2010, *MNRAS*, **404**, L89
- Argudo-Fernández, M., Gómez Hernández, C., Verley, S., et al. 2024, *A&A*, **692**, A258
- Argudo-Fernández, M., Verley, S., Bergond, G., et al. 2015, *A&A*, **578**, A110
- Astropy Collaboration (Robitaille, T. P., et al.) 2013, *A&A*, **558**, A33
- Astropy Collaboration (Price-Whelan, A. M., et al.) 2018, *AJ*, **156**, 123
- Astropy Collaboration (Price-Whelan, A. M., et al.) 2022, *ApJ*, **935**, 167
- Benson, A. J., Hoyle, F., Torres, F., & Vogeley, M. S. 2003, *MNRAS*, **340**, 160
- Bidaran, B., de Daniloff, S., Pérez, I., et al. 2025a, *A&A*, **698**, A260
- Bidaran, B., Pérez, I., Sánchez-Menguiano, L., et al. 2025b, *A&A*, **693**, L16
- Blanton, M. R., & Roweis, S. 2007, *AJ*, **133**, 734
- Bond, J. R., Kofman, L., & Pogosyan, D. 1996, *Nature*, **380**, 603
- Cautun, M., van de Weygaert, R., Jones, B. J. T., & Frenk, C. S. 2014, *MNRAS*, **441**, 2923
- Ceccarelli, L., Padilla, N., & Lambas, D. G. 2008, *MNRAS*, **390**, L9
- Ceccarelli, L., Paz, D., Lares, M., Padilla, N., & Lambas, D. G. 2013, *MNRAS*, **434**, 1435
- Ceccarelli, M. L., Alonso, S., & Garcia Lambas, D. 2025, *A&A*, **700**, A196
- Conrado, A. M., González Delgado, R. M., García-Benito, R., et al. 2024, *A&A*, **687**, A98
- Croton, D. J., Farrar, G. R., Norberg, P., et al. 2005, *MNRAS*, **356**, 1155
- Curtis, O., McDonough, B., & Brainerd, T. G. 2024, *ApJ*, **962**, 58
- Deng, X.-F., He, J.-Z., Jiang, P., Luo, C.-H., & Wu, P. 2007, *A&A*, **474**, 783
- Diaferio, A., Ramella, M., Geller, M. J., & Ferrari, A. 1993, *AJ*, **105**, 2035
- Domínguez-Gómez, J., Pérez, I., Ruiz-Lara, T., et al. 2023a, *A&A*, **680**, A111
- Domínguez-Gómez, J., Pérez, I., Ruiz-Lara, T., et al. 2023b, *Nature*, **619**, 269
- Driver, S. P., Norberg, P., Baldry, I. K., et al. 2009, *Astron. Geophys.*, **50**, 5.12
- Driver, S. P., Hill, D. T., Kelvin, L. S., et al. 2011, *MNRAS*, **413**, 971
- Einasto, M., Einasto, J., Müller, V., Heinämäki, P., & Tucker, D. L. 2003, *A&A*, **401**, 851
- Einasto, M., Einasto, J., Tenjes, P., et al. 2024, *A&A*, **681**, A91
- Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, *AJ*, **142**, 72
- El-Ad, H., Piran, T., & Dacosta, L. N. 1997, *MNRAS*, **287**, 790
- Etherington, J., & Thomas, D. 2015, *MNRAS*, **451**, 660
- Feng, S., Shao, Z.-Y., Shen, S.-Y., et al. 2016, *Res. Astron. Astrophys.*, **16**, 72
- Florez, J., Berlind, A. A., Kannappan, S. J., et al. 2021, *ApJ*, **906**, 97
- Galárraga-Espinosa, D., Garaldi, E., & Kauffmann, G. 2023, *A&A*, **671**, A160
- Galárraga-Espinosa, D., Kauffmann, G., Bonoli, S., et al. 2026, *A&A*, **706**, A21
- Galaz, G., Herrera-Camus, R., Garcia-Lambas, D., & Padilla, N. 2011, *ApJ*, **728**, 74
- García-Benito, R., Jiménez, A., Sánchez-Menguiano, L., et al. 2024, *A&A*, **691**, A161
- Grogin, N. A., & Geller, M. J. 1999, *AJ*, **118**, 2561
- Grogin, N. A., & Geller, M. J. 2000, *AJ*, **119**, 32
- Habouzit, M., Pisani, A., Goulding, A., et al. 2020, *MNRAS*, **493**, 899
- Hahn, O., Carollo, C. M., Porciani, C., & Dekel, A. 2007, *MNRAS*, **381**, 41
- Hickson, P. 1982, *ApJ*, **255**, 382
- Hickson, P., Mendes de Oliveira, C., Huchra, J. P., & Palumbo, G. G. 1992, *ApJ*, **399**, 353
- Hoyle, F., & Vogeley, M. S. 2002, *ApJ*, **566**, 641
- Hoyle, F., Vogeley, M. S., & Pan, D. 2012, *MNRAS*, **426**, 3041
- Hunter, J. D. 2007, *Comput. Sci. Eng.*, **9**, 90
- Jaber, M., Peper, M., Hellwing, W. A., Aragón-Calvo, M. A., & Valenzuela, O. 2024, *MNRAS*, **527**, 4087
- Kuutma, T., Poudel, A., Einasto, M., et al. 2020, *A&A*, **639**, A71
- Lares, M., Luparello, H. E., Maldonado, V., et al. 2017, *MNRAS*, **470**, 85
- Li, G., Ma, Y.-Z., Tramonte, D., & Li, G.-L. 2024, *MNRAS*, **527**, 2663
- Lietzen, H., Tempel, E., Heinämäki, P., et al. 2012, *A&A*, **545**, A104
- Liu, C.-X., Pan, D. C., Hao, L., et al. 2015, *ApJ*, **810**, 165
- Mamon, G. A. 1987, *ApJ*, **321**, 622
- Mao, Q., Berlind, A. A., Scherrer, R. J., et al. 2017, *ApJ*, **835**, 161
- Marinoni, C., & Hudson, M. J. 2002, *ApJ*, **569**, 101
- Martizzi, D., Vogelsberger, M., Torrey, P., et al. 2020, *MNRAS*, **491**, 5747
- Merchán, M., & Zandivarez, A. 2002, *MNRAS*, **335**, 216
- Padilla, N., Lambas, D. G., & González, R. 2010, *MNRAS*, **409**, 936
- Pan, D. C., Vogeley, M. S., Hoyle, F., Choi, Y.-Y., & Park, C. 2012, *MNRAS*, **421**, 926
- pandas development team 2020, <https://doi.org/10.5281/zenodo.3509134>
- Park, D., & Lee, J. 2009, *MNRAS*, **400**, 1105
- Paul, S., John, R. S., Gupta, P., & Kumar, H. 2017, *MNRAS*, **471**, 2
- Pérez, F., & Granger, B. E. 2007, *Comput. Sci. Eng.*, **9**, 21
- Pérez, I., Gil, L., Ferré-Mateu, A., et al. 2025a, *A&A*, **695**, A84
- Pérez, I., Verley, S., Sánchez-Menguiano, L., et al. 2025b, in *Highlights of Spanish Astrophysics XII*, eds. M. Manteiga, F. González-Galindo, A. Labiano-Ortega, M. J. Martínez-González, N. Rea, M. Romero-Gómez, A. Ulla-Miguel, G. Yepes, C. Rodríguez-López, A. Gómez-García, & C. Dafonte, 93
- Pérez, I., Verley, S., Sánchez-Menguiano, L., et al. 2024, *A&A*, **689**, A213
- Pisani, A., Ramella, M., & Geller, M. J. 2003, *AJ*, **126**, 1677
- Popesso, P., Biviano, A., Böhringer, H., & Romaniello, M. 2007, *A&A*, **464**, 451
- Porter, L. E., Holwerda, B. W., Kruk, S., et al. 2023, *MNRAS*, **524**, 5768
- Pustilnik, S. A., Martin, J. M., Huchtmeier, W. K., et al. 2002, *A&A*, **389**, 405
- Ricciardelli, E., Cava, A., Varela, J., & Quilis, V. 2014, *MNRAS*, **445**, 4045
- Rieder, S., van de Weygaert, R., Cautun, M., Beygu, B., & Portegies Zwart, S. 2013, *MNRAS*, **435**, 222
- Rodríguez-Medrano, A. M., Paz, D. J., Stasyszyn, F. A., et al. 2023, *MNRAS*, **521**, 916
- Rodríguez-Medrano, A. M., Springel, V., Stasyszyn, F. A., & Paz, D. J. 2024, *MNRAS*, **528**, 2822
- Rojas, R. R., Vogeley, M. S., Hoyle, F., & Brinkmann, J. 2004, *ApJ*, **617**, 50
- Rosas-Guevara, Y., Tissera, P., Lagos, C. d. P., Paillas, E., & Padilla, N. 2022, *MNRAS*, **517**, 712
- Sánchez-Alarcón, P. M., Román, J., Knapen, J. H., et al. 2023, *A&A*, **677**, A117
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, **500**, 525
- Stierwalt, S., Haynes, M. P., Giovanelli, R., et al. 2009, *AJ*, **138**, 338
- Tago, E., Einasto, J., Saar, E., et al. 2008, *A&A*, **479**, 927
- Taverna, A., Salerno, J. M., Daza-Perilla, I. V., et al. 2023, *MNRAS*, **520**, 6367
- Tempel, E., Tuvikene, T., Kipper, R., & Libeskind, N. I. 2017, *A&A*, **602**, A100
- Tikhonov, A. V., & Klypin, A. 2009, *MNRAS*, **395**, 1915
- Torres-Ríos, G., Pérez, I., Verley, S., et al. 2024, *A&A*, **691**, A341
- Torres-Ríos, G., Verley, S., Pérez, I., et al. 2026, *A&A*, **710**, A337
- van de Weygaert, R. & Platen, E. 2011, in *International Journal of Modern Physics Conference Series*, **1**, 41
- van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, *Comput. Sci. Eng.*, **13**, 22
- Vásquez-Bustos, P., Argudo-Fernandez, M., Grajales-Medina, D., Duarte Puertas, S., & Verley, S. 2023, *A&A*, **670**, A63
- Verdes-Montenegro, L., Sulentic, J., Lisenfeld, U., et al. 2005, *A&A*, **436**, 443
- Verley, S., Leon, S., Verdes-Montenegro, L., et al. 2007a, *A&A*, **472**, 121
- Verley, S., Odewahn, S. C., Verdes-Montenegro, L., et al. 2007b, *A&A*, **470**, 505
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *Nat. Methods*, **17**, 261
- Wang, H., Eisenstein, D. J., Aguilar, J. N., et al. 2026, *MNRAS*, **545**, staf2069
- Wen, Z. L., Han, J. L., & Liu, F. S. 2009, *ApJS*, **183**, 197
- Wes McKinney 2010, in *Proceedings of the 9th Python in Science Conference*, eds. S. van der Walt, & J. Millman, 56
- White, M., Hernquist, L., & Springel, V. 2001, *ApJ*, **550**, L129
- Yang, X., Mo, H. J., van den Bosch, F. C., et al. 2007, *ApJ*, **671**, 153
- Zhang, Y., Yang, X., Guo, H., et al. 2026, *MNRAS*, **550**, stag1160