Spatially-resolved properties of early-type group-dominant galaxies with MUSE: gas content, ionisation mechanisms and metallicity gradients

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ABSTRACT

With the goal of a thorough investigation of the ionised gas and its origin in early-type group-dominant galaxies, we present archival MUSE data for 18 galaxies from the Complete Local-Volume Groups Sample (CLoGS). This data allowed us to study the spatially-resolved warm gas properties, including the morphology of the ionised gas, EW(Hα) and kinematics as well as the gas-phase metallicity (12 + log(O/H)) of these systems. In order to distinguish between different ionisation mechanisms, we used the emission-line ratios [O iii]/Hβ and [N ii]/Hα in the BPT diagrams and EW(Hα). We find that the ionisation sources in our sample have variable impacts at different radii, central regions are more influenced by low-luminosity AGN, while extended regions of LINER-like emission are ionised by other mechanisms with pAGBs photoionisation likely contributing significantly. We classified our sample into three Hα+[N ii] emission morphology types. We calculate the gas-phase metallicity assuming several methods and ionisation sources. In general, 12 + log(O/H) decreases with radius from the centre for all galaxies, independently of nebular morphology type, indicating a metallicity gradient in the abundance profiles. Interestingly, the more extended filamentary structures and all extranuclear star-forming regions present shallow metallicity gradients. Within the uncertainties these extended structures can be considered chemically homogeneous. We suggest that group-dominant galaxies in our sample likely acquired their cold gas in the past as a consequence of one or more mechanisms, e.g. gas-clouds or satellite mergers/accretion and/or cooling flows that contribute to the growth of the ionised gas structures.

Key words: galaxies: abundances – galaxies: groups: general – galaxies: ISM – galaxies: elliptical and lenticular, cD, S0 – galaxies: nuclei

1 INTRODUCTION

Most galaxies are found in groups and clusters. The distinction between them is made by the number of their members, clusters have \( \approx 50 \) member galaxies and are more massive than groups. Bright galaxies at the centres of galaxy groups (hereafter BGGs) or group-dominant galaxies typically have stellar masses of \( M_* \approx 10^{10} - 10^{11} M_\odot \) (e.g., Gozaliasl et al. 2016; O’Sullivan et al. 2018; Kolokythas et al. 2022), with some BGGs also displaying X-ray emission (e.g., O’Sullivan et al. 2017) and containing cold H I and/or molecular gas in the range \( \sim 10^8 - 10^9 M_\odot \) (e.g., O’Sullivan et al. 2015, 2018). A significant fraction (~25%; Gozaliasl et al. 2016) of BGGs lie on the main sequence of the star-forming (late-type) galaxies at \( z \lesssim 0.4 \), and this fraction increases with redshift. However, most BGGs are early-type galaxies (ETGs), i.e., elliptical and/or lenticular (S0) galaxies. Early-type BGGs (e.g., Kolokythas et al. 2022), and many other ETGs in the literature (e.g., Shapiro et al. 2010; Fang et al. 2012; Gomes et al. 2016), contain warm ionised gas...
and ongoing low-level star-formation (SFR\(_{UV}\) ~0.01–0.4 M\(_{\odot}\) yr\(^{-1}\); Kolokythas et al. 2022), while in late-type BGGs the SF can reach ~10 M\(_{\odot}\) yr\(^{-1}\) (Oliva-Altamirano et al. 2014; Gozaliasl et al. 2016). This same activity is also found in a significant fraction of Brightest Cluster Galaxies (BCGs; e.g., Bildfell et al. 2008; Pipino et al. 2009; McDonald et al. 2010; Donahue et al. 2011; McDonald, Veilleux & Mushotzky 2011; Werner et al. 2014; Loubser et al. 2016). The ETGs (e.g., Phillips et al. 1986; Trinchieri & di Serego Alighieri 1991; Annibali et al. 2010), including some early-type BGGs\(^1\) also display low-ionisation nuclear emission-line regions (LINERs, Heckman 1980). The spectra of LINERs exhibit strong low-ionisation optical emission lines such as \([\text{O}\,\text{iii}]\lambda5007, [\text{O}\,\text{ii}]\lambda3726/29, [\text{N}\,\text{ii}]\lambda6584, [\text{S}\,\text{ii}]\lambda6717,6731\) and hydrogen Balmer lines (H\(_\alpha\), H\(_\beta\), etc.), commonly with \([\text{N}\,\text{ii}]\lambda6584 > \text{H}\,\alpha\) emission. Several explanations for LINER emission, in galaxies, have been proposed including shock-ionisation (e.g., Heckman 1980; Dopita & Sutherland 1995, 1996; Allen et al. 2008), photoionisation by ongoing low-level SF (e.g., Schawinski et al. 2007; Fogarty et al. 2015; Shapiro et al. 2010), hot evolved post-asymptotic giant branch (pAGB) stars (e.g., Binette et al. 1994; Stasinska et al. 2008; Annibali et al. 2010; Sarzi et al. 2010; Cid Fernandes et al. 2010, 2011), photoionisation by the "cooling" X-ray-emitting gas (Voit & Donahue 1990; Donahue & Voit 1991; Ferland, Fabian & Johnstone 1994; Voit, Donahue & Slavin 1994; Polles et al. 2021), thermal conduction from the hot gas (Sparks, Macchetto & Golombek 1989) and ionisation by low-luminosity active galactic nuclei (AGN) (e.g., Ferland & Netzer 1983; Barth et al. 1998; Ho 1999). Observational evidence suggests that more than one mechanism are likely to be at work in LINERs (e.g. Edwards et al. 2007; Fogarty et al. 2010). In fact, for the contribution of AGN to the photoionisation of LINERs may be restricted to the nuclear region (e.g., Sarzi et al. 2010), while pAGB stars are likely responsible for the extended gas emission (e.g., Binette et al. 1994; Sarzi et al. 2010; Gomes et al. 2016). Extended low-ionisation emission line regions (LIERs; Belfiore et al. 2016) or LINER-like extranuclear diffuse ionised gas (DIG) emission in ETGs has been detected and studied (e.g., Sarzi et al. 2006; Gomes et al. 2016) as part of the SAURON (Bacon et al. 2001) and Calar Alto Legacy Integral Field Area (CALIFA, Sánchez et al. 2012) surveys. These studies suggest low-luminosity AGN are likely contributing to LINER emission in a less than dominant way (Yan & Blanton 2014). Extended and DIG filaments are observed in BGGs/BCGs (e.g., Heckman et al. 1989; Crawford et al. 1999; O’Sullivan et al. 2012; Tremblay et al. 2018; Olivares et al. 2019). These ionised gas filaments seem to be co-spatial with large quantities of H\(_2\) and molecular gas, traced by CO, and soft X-ray emission features (Werner et al. 2014). McDonald et al. (2010) found that the extended warm gas in cluster galaxies, in general, is spatially coincident with cooling intracluster medium (ICM) flows. McDonald, Veilleux & Mushotzky (2011); McDonald, Veilleux & Rupke (2012) rule out collisional ionisation by cosmic rays, thermal conduction, photoionisation by ICM X-rays and AGN as strong contributors to the ionisation of the warm gas, in both the nuclei and filaments of cool core clusters. They argue that the data are adequately described by a composite model of slow shocks and SF. According to McDonald, Veilleux & Mushotzky (2011), the H\(_\alpha\) filaments in BGGs/BCGs are more strongly coupled with the cooling properties of the ICM than with the radio properties of the BCGs. The molecular gas in the filaments is located along old radio jets, lobes and/or below X-ray cavities, suggesting that AGN activity supplies a regular input of energy in those systems (Russell et al. 2016; O’Sullivan et al. 2021). Generally, the dominant ionisation mechanism, as well as their locations (i.e., nuclear and/or extended regions), is not clear and different processes may be at work during the evolution of each type of system.

Hot (10\(^5\) K) gas-phase metallicity is another key property for studying the effect of galactic environments and AGN/SF feedback in groups and clusters (see Davis et al. 2011). The X-ray emitting intra-group medium (IGrM) shows several emission lines typical of elements synthesised by stars/supernovae (SNe) and deposited in the IGrM/ICM via galactic winds from the group/cluster members (e.g., Liang et al. 2016), ram-pressure stripping/tidal interactions (Taylor & Babul 2001; McCarthy et al. 2008) and others (for a review see Schindler & Diaferio 2008). Several studies (e.g., Mernier et al. 2017; Gastaldello et al. 2021, and references therein) show that the average abundance profiles of Fe and other elements (e.g., O, Si, Ar) in the ICM/IGM increase towards the core of cool-core clusters/groups up to values of ~1.0 Z\(_{\odot}\), and decrease at large radii. This peaked distribution is associated with the release of metals from the galaxy members via mechanical feedback from AGN/SF activity, gas turbulence (Rennehan et al. 2019) or infalling galaxies through ram-pressure stripping across the evolution of the systems. Whereas some studies (e.g., Werner et al. 2006) report a rather flat O and Mg profiles, non-cool-core clusters and groups do not exhibit clear Fe abundance gradient in their cores. Mechanisms such as merger–induced sloshing motions (O’Sullivan, David & Vrtilek 2014, and references therein) can also transport the released metals from the galaxies into the IGM/ICM. On the other hand, the spatial distribution of abundances of the warm (10\(^4\) K) gas-phase in the interstellar medium (ISM) of the galaxies is also important for understanding the formation history of these systems. Studies of local star-forming galaxies have shown a negative metallicity gradient (the metallicity decreases radially) with increasing galactocentric radius (e.g., Martin & Roy 1992; van Zee et al. 1998, among many others). However, this radial distribution can present deviations from this simple negative gradient, namely a steep decrease of oxygen abundance (12 + \log(O/H)) in the nuclear regions and a flattening of the gradient in the outer parts (see Sánchez-Menguiano et al. 2018; Sánchez 2020, and references therein). Several mechanisms have been proposed to explain these features such as radial migration, infall of gas or satellite accretion. In early-type group-dominant galaxies, the presence of these features and the origin of their gas are poorly understood (e.g., Annibali et al. 2010). The cold gas in group and cluster ETGs potentially originates from two main sources: internal production (a large fraction of stellar mass is believed to be released in the form of cold gas, Davis et al. 2011) and external accretion, i.e., mergers, stripping gas from satellites, gas from the IGrM/ICM (e.g., Jung et al. 2022). A kinematical decoupling between gas and stars as evidence for external gas origin was found in many ETGs in the SAURON (Sarzi et al. 2006, 2010) and CALIFA (Gomes et al. 2016) surveys.

CLoGS (O’Sullivan et al. 2017) is an optically-selected sample of 53 groups at distances of less than 80 Mpc and is the first statistically complete sample of nearby galaxy groups studied with an extensive multi-wavelength dataset, including X-ray (Chandra and XMM-Newton; O’Sullivan et al. 2017), radio (GMRT and VLA; Kolokythas et al. 2018, 2019) and sub-mm (IRAM-30m and APEX; O’Sullivan et al. 2018) observations. In addition, we have anal-

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\(^1\) See the list of galaxies in this paper.
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2 THE DATA AND EMISSION LINE MEASUREMENTS

2.1 Observations and data reduction

Our sample consists of 18 group-dominant galaxies selected from the CLoGS nearby groups sample (O'Sullivan et al. 2017). Each galaxy has archival ESO VLT/MUSE (Bacon et al. 2010) data. Four of our targets were previously observed in the CALIFA IFU survey (NGC 677, NGC 924, NGC 1060 and NGC 7619). The observations (program ID 097.A-0366(A)) were made with the MUSE spectrograph, which used the Nasmyth B focus on Yepun the 8.2m VLT UT4. The observations were made in the wide field mode over a 1′×1′ Field of View (FoV) sampled by a system of 24 spectrographs with an spectral coverage between ~4800 and 9300 Å, a spectral resolution of ~2.6 Å, spectral sampling of 1.25 Å and spatial sampling of 0.2′′ per spaxel, leading to a total of 90,000 spectra per exposure. For each galaxy three exposures were taken. These observations were dithered with a few arcsecond dither pattern in order to cover a large portion of each galaxy’s ISM. Offset sky observations were used for sky subtraction. In Table 1 we show the general parameters for the sample members and the observation log.

The data were reduced using the MUSE pipeline (v2.6.2, Weilbacher et al. 2020), with steps including: bias correction, wavelength calibration, construction of datacubes from the individual spectra from the detectors, correction of the spectra to the heliocentric frame, sky subtraction, and merging of the individual exposures to form a combined datacube with a total of ~200,000 spectra per each galaxy. Finally, the data cubes were corrected for redshift and galactic extinction using the reddening function given by Cardelli, Clayton & Mathis (1989). In Figure 1 we show the nuclear spectra of each member of our sample. More details in Section 2.2.

2.2 Spectral fitting and emission-line measurement

We fitted and removed the stellar component within each spectrum (bin or spaxel), in order to obtain pure emission line spectra using the spectral synthesis code Fitting Analysis using Differential evolution Optimization (FADO, Gomes & Papaderos 2017) version V1.3B. Simple stellar population (SSP) templates from the Bruzual & Charlot (2003) libraries were used with metallicities between Z=0.004 and Z=0.05 and stellar ages between 1 Myr and 15 Gyr, for a Chabrier initial mass function (IMF, Chabrier 2003). FADO self-consistently reproduces the nebular characteristics of a galaxy, including the hydrogen Balmer-line luminosities, equivalent widths and nebular continuum. An important advantage of FADO is that its convergence scheme employs genetic differential evolution optimization. This results in improvements with respect to the uniqueness of spectral fits and the overall efficiency of the convergence schemes. Artificial intelligence is used to eliminate redundancies in the SSP base libraries which increases the computational efficiency. The fit was performed in the 4800-7000 Å spectral range assuming the Cardelli, Clayton & Mathis (1989) extinction law. The data cubes were tessellated using the Voronoi binning method (Cappellari & Copin 2003) to achieve an adequate signal to noise (S/N; we choose a S/N=30-50) per bin for the continuum between 6000 to 6200 Å. The Voronoi binning method lead to the dilution of the emission lines within the bins, so the shape of extended and diffuse emission lines was lost (see Erroz-Ferrer et al. 2019, for a similar approach). Then, the best fit stellar continuum or synthetic Spectral Energy Distribution (SED) was subtracted from the observed spaxels, with S/N > 3 in the continuum, to obtain pure emission-line data cubes. FADO provides as results, among others, mass contributions of individual stellar populations, mass- and luminosity-weighted stellar ages and metallicities, emission-line fluxes, equivalent widths (EWs), FWHMs and estimates of their uncertainties. In Figure 2 we show an example to illustrate the spectral modelling results with FADO from a nuclear 3′ aperture for the galaxy ESO0507-G025. In order to test the accuracy of these results, we carried out a single-Gaussian fit to each emission line. Our fit results were in good agreement with those from FADO, consequently for the analysis in this study we create the following emission line maps using FADO: Hα, Hβ, [O III]5007, [N II]6584 and [S II]λ6717, 6731. We note that, when deriving the maps we only use spaxels with emission fluxes >3σ above the background. We did not detect significant broad asymmetric emission-line profiles, so multiple-component decomposition of the emission lines was not necessary, because each emission line is well described by a single Gaussian profile. More details about the morphologies of these maps is given in Section 3.1.

Following a similar procedure to Parkash et al. (2019) we extracted for each galaxy a spectrum from a circular region at the galaxy continuum centre with a diameter of 3′ in order to mimic the SDSS spectral fibre aperture. From here on we refer to this circular region as the nuclear region and the spectra from this region as the nuclear spectrum (see Figure 1). The nuclear spectra of the galaxies are characterized by the presence of strong [N II]6584 emission with [N II]6584/Hα > 1, which is consistent with low-ionisation nuclear emission-line regions. Additionally, we extracted an integrated spectrum for each galaxy within an aperture which encompasses the extended emission in Figure 3 (see Section 3.1.1) with [N II]6584 emission > 3σ per pixel. In summary, we find 15/18 objects with intensive nuclear ionised-gas (LINERs) with [N II]6584 > Hα. Pagotto et al. (2021) found the strongest and most spatially extended emission, in their sample of massive ETGs in densest clusters of galaxies, came from the [N II]6584 lines. We find the same result for our sample. In Table 2 we present for each galaxy the 3′ nuclear and integrated observed F(Hα) flux, F(Hα)/F(Hβ) multiplied by a factor of 100, F([N II]6584) flux and EW(Hα), respectively. We note that using the spectral synthesis...
Table 1. General parameters of our sample and observing log. Col. (1) gives the galaxy name, Col. (2) the morphology, Cols. (3) and (4) give their coordinates, Col. (5) presents the galaxy extinction $A_V$ (mag) (Schiapparelli & Finkbeiner 2011) and Cols. (6)-(7) gives the distance and redshift, respectively. D (Local Group) and z from NED assuming $H_0 = 73.0$ km/sec/Mpc. In Col. (8) we give X-ray morphology (extent of the gas halo) and core type as cool-core/non-cool-core (CC/NCC) based on their temperature profiles (O’Sullivan et al. 2017) for systems where thermal emission was detected: group-like (GRP, extent >65 kpc), galaxy-like (gal, extent >10-65 kpc) and point-like (pnt, unresolved, extent smaller than the XMM-Newton PSF). Radio morphology (Kolokityas et al. 2018): point-like (pnt, radio source with sizes $\leq 11$ kpc), diffuse emission (diffuse, with no clear jet or lobe structure), small-scale jets (jet, $< 20$ kpc jets confined within the stellar body of the host galaxy) and large-scale jets (JET, $> 20$ kpc jets extending beyond the host galaxy and into the IGRM. Finally, Col. (9)-(11) shows the observation date, exposure time and mean airmass during the observations.

| Name       | Morph. | RA (J2000) | DEC (J2000) | $A_V$ (mag) | D (Mpc) | z   | X-ray/Radio morphology | Date of observation | Exp. time | Mean airmass |
|------------|--------|------------|-------------|-------------|---------|-----|------------------------|---------------------|-----------|-------------|
| NGC 193    | E      | 00h39m18.6s | +03d19m52s  | 0.062       | 62.7    | 0.014723 | GRP (CC) / JET          | 2016-06-08          | 3x900     | 1.524       |
| NGC 410    | E      | 01h01m58.9s | +33d09m07s  | 0.161       | 75.8    | 0.017659 | GRP (CC) / pnt           | 2016-08-16          | 3x900     | 1.937       |
| NGC 584    | E      | 01h31m20.7s | -06d52m05s  | 0.116       | 25.9    | 0.006011 | ... / pnt               | 2016-07-01          | 3x900     | 1.243       |
| NGC 677    | E      | 01h49m14.0s | +13d03m19s  | 0.243       | 71.9    | 0.017012 | GRP (CC) / diffuse       | 2016-07-20          | 3x900     | 1.344       |
| NGC 777    | E      | 02h00m14.9s | +31d25m46s  | 0.128       | 71.4    | 0.016728 | GRP (NCC) / pnt          | 2016-08-16          | 3x900     | 1.823       |
| NGC 924    | S0     | 02h26m46.8s | +20d29m51s  | 0.467       | 63.1    | 0.014880 | ... / pnt               | 2016-08-14          | 3x900     | 1.651       |
| NGC 940    | S0     | 02h29m27.5s | +31d38m27s  | 0.246       | 72.6    | 0.017075 | pnt / pnt               | 2016-08-21          | 3x900     | 1.814       |
| NGC 978    | E/S0   | 02h34m47.6s | +32d50m37s  | 0.253       | 67.3    | 0.015794 | gal (NCC) / pnt          | 2016-08-16          | 3x900     | 1.866       |
| NGC 1060   | E/S0   | 02h43m15.0s | +32d53m30s  | 0.532       | 73.4    | 0.017312 | GRP (CC) / jet           | 2016-08-22          | 3x900     | 1.845       |
| NGC 1453   | E      | 03h46m27.2s | -03d58m08s  | 0.289       | 52.9    | 0.012962 | GRP (NCC) / pnt          | 2016-07-22          | 3x900     | 1.358       |
| NGC 1587   | E      | 04h30m39.9s | +00d39m42s  | 0.197       | 50.0    | 0.012322 | GRP (NCC) / diffuse      | 2016-08-18          | 3x900     | 1.360       |
| NGC 4008   | E      | 11h58m17.0s | +28d11m33s  | 0.064       | 49.0    | 0.012075 | gal (NCC) / pnt          | 2016-05-13          | 3x900     | 1.668       |
| NGC 4169   | S0     | 12h12m18.8s | +29d10m46s  | 0.058       | 51.4    | 0.012622 | pnt / pnt               | 2016-05-19          | 3x900     | 1.728       |
| NGC 4261   | E      | 12h19m23.2s | +05d49m31s  | 0.049       | 28.4    | 0.007378 | GRP (CC) / JET           | 2016-04-17          | 3x880     | 1.311       |
| ESO0507-G025 | E/S0   | 12h51m31.8s | -26d27m07s  | 0.245       | 41.1    | 0.010788 | ... / diffuse            | 2016-04-12          | 3x900     | 1.107       |
| NGC 5846   | E      | 15h00m29.3s | +01d36m20s  | 0.153       | 23.1    | 0.005711 | GRP (CC) / jet           | 2016-05-16          | 3x880     | 1.579       |
| NGC 6658   | S0     | 18h33m55.6s | +22d53m18s  | 0.339       | 61.6    | 0.014243 | pnt / ...               | 2016-04-23          | 3x870     | 1.557       |
| NGC 7619   | E      | 23h20m14.5s | +08d12m22s  | 0.224       | 54.6    | 0.012549 | GRP (CC) / pnt           | 2016-05-23          | 3x870     | 1.444       |
Early-type group-dominant galaxies: ionised gas

Figure 1. Observed MUSE spectra for our sample of group-dominant galaxies extracted from a nuclear 3" aperture and covering the entire MUSE wavelength range.

case B recombination (Osterbrock & Ferland 2006, $n_e=100$ cm$^{-3}$ and $T_e=10^4$ K). The $E(B-V)_{gas}$ is calculated as follows

$$E(B-V)_{gas} = \frac{I_{\lambda} \kappa(H\alpha)}{I_{\lambda} \kappa(H\beta)} \log \left( \frac{(H\alpha/H\beta)_o}{2.86} \right),$$

(1)

where $\kappa(H\alpha)$ and $\kappa(H\beta)$ are the extinction values from the Cardelli, Clayton & Mathis (1989) curve with $R_V=3.1$. $(H\alpha/H\beta)_o$ is the observed ratio between $H\alpha$ and $H\beta$. Therefore, we corrected the emission lines for extinction using $I_{\lambda} = F_{\lambda} 10^{0.4E(B-V)_{gas} \kappa(\lambda)}$. The reddening parameters were set to 0.0 for unrealistic values of $(H\alpha/H\beta)_o < 2.86$ and when $H\beta$ was not detected. The assumption of $(H\alpha/H\beta)_o = 2.86$ instead of 3.1 in spectra with AGN(-like) features does not significantly affect the results. Galaxies with $(H\alpha/H\beta)_o > 2.86$ have low-reddening $E(B-V)_{gas}$ values from 0.13 to 0.46 mag. This result is not surprising as low-balmer decrements are also found in other ETGs (e.g., Annibali et al. 2010) and in the nuclei and nebular filaments of cool-core clusters (McDonald, Veilleux & Rupke 2012). On the other hand, $\sim 72\%$ (13/18) and $\sim 83\%$ (15/18) of our galaxies have unrealistic nuclear and integrated $(H\alpha/H\beta)_o$ values, respectively. This indicates that the derived $H\beta$ fluxes are larger for their corresponding $H\alpha$ fluxes. For galaxies with $(H\alpha/H\beta)_o > 2.86$ the $E(B-V)_{nuclear}$ are similar or slightly lower than the $E(B-$
we show an example (2015) diagrams. To do this, we used (Herpich et al. 2018) emission lines used in our analysis. The red upper lines correspond to the observed and modeled stellar spectrum, while for galaxies with (Hα) < 2.86 the E(B-V) is weak in pure H II regions. Therefore, the emission line ratios ([N II]/Hα and [O III]/Hβ can effectively discriminate between photoionisation under physical conditions that are typical for H II regions and other excitation mechanisms (e.g., AGN or shocks) which is likely present in our sample. In Figure 4 we show an example of the emission line ratio maps log([N II]/Hα) and log([O III]/Hβ), the log([N II]/Hα) vs log([O III]/Hβ) BPT diagram and the 2D BPT map for the galaxy ESO0507-G025. In this figure, we separate star-forming and AGN-ionised regions (i.e., Seyferts and LINERs) with blue demarcation lines from models by Kauffmann et al. (2003) (dotted line), Kewley et al. (2001) (solid line) and Schawinski et al. (2007) (dashed line). We colour coded the data points located in the different areas of the BPT diagram, i.e., AGN/LINERs in red, composite in orange and the star-forming H II dominated area in green. In Appendix C we show the emission line ratio maps and the BPT diagrams/maps for our entire sample. The BPT maps show that most of our data points/spaxels in the nuclear regions (see Figure 4) are dominated by AGN/LINERs while the SF becomes more important in the extended regions. We note that, in most cases, we obtain a very small or nonexistent number of data points (∼17% of the spaxels in ESO0507-G025) in the Hα area of the BPT diagrams (see figures in Appendix C). Most spaxels lie in the AGN/LINERs region of the diagrams (∼71% of the spaxels on average), while only in two cases (NGC 978 and ESO0507-G025) are most spaxels in the composite region with 62% and 55% of the spaxels, respectively.

Table 3 we present for each galaxy the emission line ratios log([O III]/Hβ), log([N II]/Hα) and log([S II]/Hα) from the 3" and integrated apertures. Figure 5 shows the BPT diagram ([O III]/Hβ versus [N II]/Hα of the nuclear regions (small squares) for galaxies where [O III]/Hβ and Hα are detected. In the figure, we compare these with values obtained from the integrated apertures (circles).
Figure 3. Example of Hα+[N II]λ6548,6584 emission line maps from our sample. We smoothed the emission line maps using a 3x3 box filter. MUSE continuum-subtracted spectra from a nuclear 3″ aperture covering the wavelength range from 6400 Å to 6800 Å are shown in the inset panels. The vertical lines in the inset panels indicate the wavelengths of the [N II]λ6548, Hα, [N II]λ6584, [S II]λ6717 and [S II]λ6731 emission lines. Fluxes in units of $\times 10^{-15}$ (erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$). In appendix B we show the emission line maps of all galaxies in our sample. The companion galaxy of NGC 978 is indicated in the figure. North is to the top and East to the left.
We use the same colour code to identify the galaxies in this diagram throughout the paper. In most cases, the nuclear values lie in the LINER region of the BPT diagram, while the integrated ones are in the composite region. The log([O III]/Hβ) for most galaxies decreases significantly when we consider the larger integrated aperture, which changes their positions in the BPT diagram. In the case of ESO0507-G025, NGC 924 and NGC 5846 the log([O III]/Hβ) increases and the log([N II]/Hα) ratio decreases. Figure 5 clearly shows that the ionisation structure of our sample galaxies can not be correctly assessed from small fixed apertures (e.g., SDSS aperture) and the ionisation sources and structure of the warm gas may be different in different parts of the galaxies (see Appendix C). In Section 4.1 and 4.2 we explore the effect of using different apertures on the observed properties of the ISM and the ionisation mechanisms likely present in our sample galaxies.

In summary, we find that all galaxies in our sample, with [O III] λ5007 and Hβ detections, have a dominant AGN/LINER nuclear region. Extended LINER-like regions are observed in most galaxies with filamentary structures (type i galaxies) and ring-like structures and/or extranuclear H II regions (type ii galaxies). Most spaxels in these regions fall in the BPT area of mixed contribution (composite) from SF and/or AGN.

### 3.3 Velocity field maps

We obtained the radial velocity $V([\text{N} \text{ II}])$ and velocity dispersion $\sigma([\text{N} \text{ II}])$ maps by fitting a single Gaussian to the $[\text{N} \text{ II}]/\text{H}α$ emission line profiles. The velocity dispersion $\sigma$ (or FWHM=2.35$\sigma$) was obtained as $\sigma^2 = \sigma^2_{\text{inst}} + \sigma^2_{\text{inst}}$, where $\sigma_{\text{inst}}$ is the instrumental dispersion, see Section 2.1. The detailed kinematical analysis of the emitting gas is beyond the scope of this paper, however in Figure 6 and Appendix D we show the velocity field maps for the type ii galaxies ESO0507-G025 and NGC 924, NGC 940 and NGC 4169, respectively. Radial velocity and velocity dispersion maps for our full sample are shown in Olivares et al. (2022). In order to include the kinematical information from the extended and filamentary structures we considered spaxels with $S/N \gtrsim 2$. In Figure 6 we see an example of these velocity fields for the galaxy ESO0507-G025. Clearly, this galaxy has two independent velocity structures or rotating discs, while the velocity dispersion in the nuclear region shows a bicone-shaped structure which increases in velocity dispersion with distance from the centre. The gas in these bicone structures is located in the AGN/LINERs region of the BPT diagram (see Figures 4 and 5) suggesting an outflow perpendicular to the observer.

Our velocity fields $(V$ and $\sigma$) are in agreement with those obtained independently by Olivares et al. (2022). In general, the radial velocity fields in our sample galaxies (see Appendix D and Appendix E) show a significant outflow in most galaxies.

**Figure 4.** Example of our emission line ratio maps log([N II]/Hα) and log([O III]/Hβ) (top row), and BPT diagrams (bottom row) for the galaxy ESO0507-G025. In the BPT diagrams we include the Kewley et al. (2001; solid line), Kauffmann et al. (2003; dotted line) and Schawinski et al. (2007; dashed line) model boundary lines which divide regions dominated by star-forming H II (green), composite (orange data points) and AGN/LINERs (red data points). The filled black data point corresponds to value in the 3” aperture. In Appendix C we show the emission line ratio maps and the BPT diagrams/maps for our entire sample. North is to the top and East to the left.
Table 3. Main properties of our sample galaxies from the simulated SDSS spectral fibre diameter (3") and integrated (int) apertures. SFR(Hα) calculated from the L(Hα) in the largest aperture int/3".

| Galaxy       | log ([O III]/Hβ) | log ([N II]/Hα) | log ([S II]/Hα) | L(Hα) (x10^5 erg cm⁻¹) | SFR(Hα) (M_☉ yr⁻¹) |
|--------------|------------------|-----------------|-----------------|-------------------------|---------------------|
| NGC 193      | -0.27 ± 0.22     | 0.14 ± 0.16     | -0.02 ± 0.15    | 2.01 ± 0.12             | 7.70 ± 0.52         |
| NGC 410      | ...              | ...             | -0.33 ± 0.15    | 3.55 ± 0.08             | 5.72 ± 0.13         |
| NGC 584      | -0.04 ± 0.40     | 0.13 ± 0.19     | -0.16 ± 0.34    | 0.53 ± 0.06             | 4.68 ± 0.54         |
| NGC 677      | -0.06 ± 0.22     | 0.01 ± 0.16     | -0.03 ± 0.08    | 5.22 ± 0.24             | 34.7 ± 3.50         |
| NGC 777      | ...              | ...             | 0.30 ± 0.28     | 0.61 ± 0.09             | 0.0028 ± 0.0004     |
| NGC 924      | 0.05 ± 0.37      | 0.14 ± 0.60     | 0.06 ± 0.14     | 0.10 ± 0.20             | 3.97 ± 0.28         |
| NGC 940      | 0.19 ± 0.43      | 0.34 ± 0.17     | 0.02 ± 0.25     | 8.84 ± 0.75             | 63.67 ± 1.50        |
| NGC 978      | -0.09 ± 0.17     | -0.15 ± 0.22    | -0.08 ± 0.14    | 1.81 ± 0.21             | 4.40 ± 0.49         |
| NGC 1060     | ...              | ...             | 0.10 ± 0.23     | 2.38 ± 0.33             | 8.80 ± 1.51         |
| NGC 1453     | -0.27 ± 0.26     | -0.52 ± 0.37    | 0.19 ± 0.08     | 4.52 ± 0.19             | 27.23 ± 2.64        |
| NGC 1587     | 0.27 ± 0.16      | 0.07 ± 0.11     | 0.03 ± 0.16     | 1.88 ± 0.11             | 15.37 ± 0.52        |
| NGC 4008     | ...              | ...             | 0.09 ± 0.41     | 0.47 ± 0.06             | 0.0022 ± 0.0003     |
| NGC 4169     | -0.05 ± 0.32     | -0.16 ± 0.51    | 0.24 ± 0.08     | 10.10 ± 0.16             | 14.75 ± 0.90        |
| NGC 4261     | 0.25 ± 0.48      | 0.34 ± 0.20     | -0.07 ± 0.29    | 12.08 ± 1.62             | 0.0556 ± 0.0074     |
| ESO0507-G025 | -0.08 ± 0.35     | 0.02 ± 0.34     | 0.05 ± 0.12     | 9.17 ± 0.52             | 42.56 ± 2.96        |
| NGC 5846     | -0.40 ± 0.19     | -0.24 ± 0.41    | 0.12 ± 0.18     | 0.47 ± 0.04             | 7.23 ± 0.81         |
| NGC 6658     | 0.54 ± 0.79      | 0.19 ± 0.19     | ...            | 0.65 ± 0.08             | 0.0030 ± 0.0004     |
| NGC 7619     | ...              | 0.40 ± 0.36     | ...            | 0.66 ± 0.17             | 0.0030 ± 0.0008     |

Figure 5. ([O III]/Hβ vs [N II]/Hα) diagnostic diagram for the nuclear spectra using equivalent 3" apertures to SDSS spectra (squares) and integrated emission (circles). The Kewley et al. (2001; solid line), Kauffmann et al. (2003; dotted line) and Schawinski et al. (2007; dashed line) model boundary lines in blue discriminate between areas of the diagram dominated by SF (H ii) and AGN/LINERs emission. The mean errors are shown in the lower of the figure.

Olivares et al. (2022) show rotation or gradients but with relatively small velocity ranges of around ±200-300 km s⁻¹. These variations are similar in both, the compact and extended gas emission regions. We see the highest σ([N II]) values, in most cases, at positions close to the continuum flux maximum with values of 150 to 300 km s⁻¹, while extended regions or filaments show lower values. In general, σ([N II]) values in the filaments vary little across the galaxies. This trend was also reported by McDonald, Veilleux & Rupke (2012) for a sample of galaxies in galaxy clusters. They found that the most extended optical filaments in their sample, likely originated from ICM cooling and were experiencing only minor turbulence.

3.4 [S II] / [O III] ratio

The [S II] / [O III] i6716 / [S II] i6731 intensity ratio was used to determine the electron density n_e([S II]). We computed the values of n_e([S II]) using the IRAF STSDAS package assuming λ([O III])=10000 K. We set unrealistic (saturated) values of [S II] i6716 / [S II] i6731 > 1.43 to n_e([S II]) ~ 1 cm⁻³ and for [S II] i6716 / [S II] i6731 < 0.46 to ~25425 cm⁻³. In Table 4 we show the electron density for the nuclear (3" aperture) regions for our sample. We note that the [S II] i6716 / [S II] i6731 ratio is greater than 1 for 12/18 galaxies, which indicates a predominantly low density regime (~100 cm⁻³). Only 6/18 galaxies show values ~1000 cm⁻³ in the nuclear regions. In Figure E1 (appendix E) we show the [S II] i6716 / [S II] i6731 ratio maps for our sample galaxies.

Interestingly, the ionisation cones observed in ESO0507-G025 (see the emission line ratio maps [O III]/Hβ and [N II]/Hα in Figure 4 and velocity fields in Figure 6) together with the high electron density and the shape of the spatially resolved [S II] i6716 / [S II] i6731 ratio map indicate that the central region of this galaxy is almost certainly ionised by an AGN (e.g., Kakkad et al. 2018). This clear pattern is not observed in our other galaxies. In general, the presence of high electron density in the nuclear regions and extended enhanced regions with densities ≥1000 cm⁻³ could indicate outflowing ISM likely driven by expanding hot gas heated by SNe, SF stellar winds, AGN activity and/or the collision/interaction of galaxies (Westmoquette et al. 2012). We will discuss in detail in Section 4 the results obtained in this section and their implications for the evolutionary stages of the gas in our sample galaxies.
we show the effects of using different apertures, and references therein. In our case, we where we show the unrealistic (saturated) values of $[\text{S}^{\text{ii}}]/\text{i.pc}/\text{i.pc}$

$$
\text{NGC 193} \quad 0.92 \pm 0.16 \quad \checkmark \\
\text{NGC 410} \quad 1.85 \pm 0.23 \\
\text{NGC 584} \quad 1.46 \pm 0.70 \\
\text{NGC 677} \quad 1.29 \pm 0.09 \\
\text{NGC 777} \quad 1.11 \pm 0.30 \\
\text{NGC 924} \quad 1.38 \pm 0.36 \\
\text{NGC 940} \quad 1.06 \pm 0.34 \\
\text{NGC 978} \quad 1.23 \pm 0.37 \\
\text{NGC 1060} \quad 0.66 \pm 0.37 \\
\text{NGC 1453} \quad 1.29 \pm 0.10 \\
\text{NGC 1587} \quad 1.21 \pm 0.24 \\
\text{NGC 4008} \quad 0.60 \pm 0.02 \\
\text{NGC 4169} \quad 1.07 \pm 0.25 \\
\text{NGC 4261} \quad 1.12 \pm 0.36 \\
\text{ESO0507-G025} \quad 0.46 \pm 0.09 \\
\text{NGC 5846} \quad 1.08 \pm 0.24 \\
\text{NGC 6658} \quad 0.29 \pm 0.12 \\
\text{NGC 7619} \quad 0.76 \pm 0.11 
$$

We note that, our average SFRs is ~16% lower than that found by Kolokythas et al. (2022) using GALEX FUV fluxes as SF indicator, while FIR SFRs (O’Sullivan et al. 2015) for some of our galaxies (NGC 777, NGC 940, NGC 1060 and NGC 5846) are one or two orders of magnitude higher than our SFR($H_\alpha$). Contamination of the FIR luminosity as a SF tracer can not be discarded. Most galaxies in both samples are AGN-dominated at FIR wavelengths and their derived FIR SFRs are greater than that expected from SF. However, in the case of NGC 940, they do not confirm the presence of a radio AGN (O’Sullivan et al. 2015). In summary, we find that in this and the aforementioned studies, the SFR in type i and type ii group-dominant galaxies, on average, are higher than in type i0 galaxies.

### 3.5 Star-formation rate

Following a common practice, the current star-formation rates (SFRs) were estimated from the integrated $H_\alpha$ luminosity L($H_\alpha$), assuming the Kennicutt (1998) formula, for a solar metallicity, after correction for a Chabrier (2003) initial mass function, i.e., SFR($H_\alpha$) (M$_{\odot}$ yr$^{-1}$) = 4.6 × 10$^{-42}$ × L($H_\alpha$) (erg s$^{-1}$) (Parkash et al. 2019). However, it is unlikely in our case that all $H_\alpha$ emission results from SF, since the BPT diagnostics indicate a LINER or composite nature for most spaxels in our emission line maps. Therefore, the derived SFRs are likely to be overestimates and are included here for comparison with other studies. Table 3 shows the resultant SFRs, obtained from the integrated apertures of the galaxies.

![Figure 6. Radial velocity V([N i]) (left panel) and velocity dispersion $\sigma$([N i]) (right panel) maps for the galaxy ESO0507-G025. The position of the continuum maximum is indicated by a X symbol. A zoom-in of the central region of the velocity dispersion map is shown in the inset panel. North is up and east is to the left.](MNRAS.000.1-36.2015)

Table 4. Electron density for the nuclear (3" aperture) regions of our sample of group-dominant galaxies. We show the unrealistic (saturated) values of $[\text{S}^{\text{ii}}]/\text{i.pc}/\text{i.pc}$

| Name         | $[\text{S}^{\text{ii}}]/\text{i.pc}/\text{i.pc}$ | Saturated values | $n_i([\text{S}^{\text{ii}}])$ (cm$^{-3}$) |
|--------------|-----------------------------------------------|------------------|-------------------------------------------|
| NGC 193      | 0.92 ± 0.16                                   | 839.3 ± 397.4    |                                            |
| NGC 410      | 1.85 ± 0.23                                   |                 |                                            |
| NGC 584      | 1.46 ± 0.70                                   |                 |                                            |
| NGC 677      | 1.29 ± 0.09                                   |                 |                                            |
| NGC 777      | 1.11 ± 0.30                                   |                 |                                            |
| NGC 924      | 1.38 ± 0.36                                   |                 |                                            |
| NGC 940      | 1.06 ± 0.34                                   |                 |                                            |
| NGC 978      | 1.23 ± 0.37                                   |                 |                                            |
| NGC 1060     | 0.60 ± 0.37                                   |                 |                                            |
| NGC 1453     | 1.29 ± 0.10                                   |                 |                                            |
| NGC 1587     | 1.21 ± 0.24                                   |                 |                                            |
| NGC 4008     | 0.69 ± 0.39                                   |                 |                                            |
| NGC 4169     | 1.07 ± 0.25                                   |                 |                                            |
| NGC 4261     | 1.12 ± 0.36                                   |                 |                                            |
| ESO0507-G025 | 0.46 ± 0.09                                   | 488.9 ± 21200.4 |                                            |
| NGC 5846     | 1.06 ± 0.24                                   | 471.4 ± 574.6   |                                            |
| NGC 6658     | 0.29 ± 0.12                                   | ≥ 24520.0       |                                            |
| NGC 7619     | 0.74 ± 0.11                                   | 1823.7 ± 1122.5 |                                            |

4 DISCUSSION

#### 4.1 Aperture effects

As shown in Section 3.2, aperture selection and 2D mapping can impact conclusions about the dominant mechanism ionising the gas in our sample. This was demonstrated in Figure 5 where we show the [O iii]/Hβ vs. [N i]/Hα diagnostic diagram for the nuclear and integrated apertures. The displacement of the data points in this diagram when the aperture is increased, indicates how our interpretation about the ionising sources can change depending on aperture size. The limitations of using SDSS spectra for nearby galaxies has also been highlighted recently using IFU spectroscopy (see Gomes et al. 2016, and references therein). In our case, we can see that in the inner most part of the galaxies, the gas is likely dominated by shocks and/or AGN activity given that the nuclear gas emission line ratios lie in the LINER region of the BPT diagram, however, at large apertures photoionisation by OB stars likely becomes increasingly more important.

In Figure 7 we show the effects of using different apertures on the observed properties of our sample. In panel a) we show the L($H_\alpha$) surface density $\Sigma(H_\alpha)$ calculated as L($H_\alpha$)/area, in b) the EW($H_\alpha$) and panel c) shows the log([N i]/Hα) emission line ratio.
In this figure, the apertures were selected to increase in steps of 1.5\textdegree of radius. The $\Sigma$, in panel a) of Figure 7, in all cases decreases with radius and shows the presence of extended H\textalpha emission beyond the SDSS aperture. Cid Fernandes et al. (2011) used the EW(H\textalpha) as an alternative method (explained below in Section 4.2) to the BPT diagrams (emission-line classification). Using this method, Gomes et al. (2016) argue that evolved pAGB stellar background is sufficient to photoionise the diffuse gas in ETGs and explain the observed EW(H\textalpha) in the range 0.5 - 2.4 \AA. Most EW(H\textalpha) values in panel b) irrespective of aperture lie within the area (grey region in the panel) which is consistent with pure pAGB photoionisation (Cid Fernandes et al. 2011; Gomes et al. 2016). We find that one type i galaxy (ESO0057-G025) and three type i galaxies (NGC 193, NGC 677 and NGC 1453) show EW(H\textalpha) > 2.4 \AA at their centres. These results indicate that PAGBs alone do not explain the observed values in these regions. The EW(H\textalpha) values of remaining galaxies are consistent with pure pAGB emission. The (N/H)/H\alpha found in the nuclear regions (SDSS aperture: see panel c) and at large radii, in most cases, is consistent with LINER emission since log(N/H)/H\alpha $\geq$ 0.0. We observe that the log(N/H)/H\alpha declines with increasing apertures in almost all cases, although the radial profiles differ significantly.

4.2 Ionisation mechanisms

In this section we examine the mechanisms responsible for the ionisation which produces the optical emission lines in our sample. For this, we use photoionisation models from the literature, which incorporate the expected physical conditions in our sample galaxies.

In Figure 8 we show the BPT diagram for the nuclear emission for our sample galaxies. The fill colour of the data points indicates the EW(H\textalpha) from the colour scale and the edge colour of the circles identifies the galaxies from the legend. Superimposed on the plot are shock models from Allen et al. (2008) calculated with the MAPPINGS III shock and photoionisation code. These shock models have solar metallicity, densities from $n = 0.01$ cm$^{-3}$ to 1000 cm$^{-3}$, velocities from $v = 100$ kms$^{-1}$ to 1000 kms$^{-1}$, and magnetic field $B = 1 \mu G$. The models for $v = 100$ kms$^{-1}$ (purple), 200 kms$^{-1}$ (red), 300 kms$^{-1}$ (green), 500 kms$^{-1}$ (orange) and 1000 kms$^{-1}$ (blue) are shown as coloured lines. The nuclear regions in our sample lie in the velocity range of $> 200$ kms$^{-1}$ to $> 1000$ kms$^{-1}$ and density between $-0.1$ cm$^{-3}$ to $< 100$ cm$^{-3}$. As in our case (see Table 4), a significant fraction of galaxies have saturated [S II] densities obtained for a sample of ETGs/LINERs with ionised gas with the Allen et al. (2008) models. The majority of their galaxies had $n_e \geq 100$ cm$^{-3}$ for an assumed T = 10,000 K. But as in our case (see Table 4), a significant fraction of galaxies have saturated [S II] ratios around 1.45 which are consistent with pre-shock densities ($n_e = 0.01$ to $\leq 100$ cm$^{-3}$). These pre-shock regions are observed in some regions of Figure E1. This could indicate with the increasing [S II]/[S III] which is strong AGN: log(N/H)/H\alpha > 0.4 and EW(H\textalpha) > 6 \AA, 3) weak AGN: log(N/H)/H\alpha > -0.4 and EW(H\textalpha) between 3 and 6 \AA, 4) retired galaxies: EW(H\textalpha) < 3 \AA and 5) passive galaxies: EW(H\textalpha) and EW([N II]) < 0.5 \AA. According to this classification scheme most of our sample (see Figure 10) can be classified as retired galaxies likely ionised by pAGB stars, independent of their position on the BPT diagram (see the EW(H\textalpha) colour scale values in Figures 8 and 9) and their optical emission morphology. In only ESO0057-G025 and NGC 677 do we see clear indications of AGN activity in the nuclear region from the WHAN diagram, with the EW(H\textalpha) ~3–6 \AA indicating a weak AGN).

In Figure 9 (upper panels) we show the BPT diagrams, as in Figure 8, but including two different photoionisation model grids from Krabbe et al. (2021). Their models consider the main (LINER) properties observed in our sample of group-dominant galaxies for two distinct SEDs. One model assumes pAGB stars (upper left panel) with different $T_{eff}$ as the ionising source and the other considers AGN SED with a multicomponent continuum (upper right panel). The models were created using the CLOUDY code version 17.0 (Ferland 2017) for metallicities Z/Z\odot = 0.2, 0.5, 0.75, 1.0, 2.0 and 3.0 and ionisation parameters U in the range of -4.0 $\leq$ log(U) $\leq$ -0.5 in steps of 0.5 dex. Their assumed density of $n_e$ 500 cm$^{-3}$ is typical for BCGs (e.g., Ciocan et al. 2021) and it is compatible with our values from Section 3.4. In both cases, most galaxies in our sample lie in the region between Z/Z\odot = 0.75 (12 + log(O/H)= 8.56) and Z/Z\odot = 1 (12 + log(O/H)= 8.69). However, NGC 4261 and NGC 940 have values compatible with models at 2-3 Z\odot (12 + log(O/H)= 8.99 - 9.17), assuming AGN activity. While for pAGB models, the values for NGG 4261, NGC 940, NGC 4169 and NGC 6658 are compatible with models at > 1.0 Z\odot metallicities. These results indicate that the nuclear regions in our sample are consistent, within the uncertainties, with metallicities slightly (above) solar, independent of the ionising sources. In Section 4.3 we estimate the gas phase metallicity for each nuclear region in our sample.

In Figure 9 (Bottom panel) we show the BPT diagram overlaid with the predicted emission line ratios from CLOUDY models obtained by Polles et al. (2021), which include photoionisation by X-ray emission. We show, in this figure, models for three values of metallicity Z/Z\odot = 0.3, 0.65 and 1 and several values of X-ray emission log(G$_i$) from 2.8 to 1.4 in steps of 0.2 dex with the turbulent velocity (produced by e.g., AGN jets, turbulent mixing between the hot and cold phases and the collisions between filaments) fixed to 10 km s$^{-1}$ (dotted colored lines and dotted black lines). In the same panel, we added three models for the aforementioned metallicities and turbulence velocities $v_{true}$ = 30, 10, 2 and 0 km s$^{-1}$ (solid colored lines and small dotted black lines). The X-ray radiation field G$_i$ is fixed to 100. In general, these grid of models can reproduce the observed values without an excess in X-ray luminosity, even if the optical depth A$_V$ increases (see figures E1 and E2 in Polles et al. 2021). In the case of NGC 5846, the observed emission line ratios (maroon open circle) are reproduced by models at very low (or no) turbulence velocities. Also, we find no sign of a clear rotational pattern (disturbed velocity field) in the FoV of the galaxy (see the $v_r$ map in Olivares et al. 2022) together with extended filaments of low velocity dispersion. This is in agreement with a cooling flows scenario, where the cool gas may have cooled in (or close to) the centre of the group (Temini et al. 2018; Jung et al. 2022). In addition, in this galaxy there is a good correlation between the CO cloud positions, detected by Temini et al. (2018), and the warm gas emission.

Cid Fernandes et al. (2011) introduced the WHAN diagram which uses the EW(H\textalpha) (or W\textbeta) in order to discriminate low ionisation AGN from galaxies that are ionised by evolved pAGB stars. This diagram identifies 5 classes of galaxies: 1) pure star-forming galaxies: log([N II]/H\alpha) $< 0.4$ and EW(H\textalpha) > 3 \AA, 2) strong AGN emission: log([N II]/H\alpha) $> 0.4$ and EW(H\textalpha) > 6 \AA, 3) weak AGN: log([N II]/H\alpha) $> -0.4$ and EW(H\textalpha) between 3 and 6 \AA, 4) retired galaxies: EW(H\textalpha) < 3 \AA and 5) passive galaxies: EW(H\textalpha) and EW([N II]) < 0.5 \AA. According to this classification scheme most of our sample (see Figure 10) can be classified as retired galaxies likely ionised by pAGB stars, independent of their position on the BPT diagram (see the EW(H\textalpha) colour scale values in Figures 8 and 9) and their optical emission. Although some galaxies in our sample have clear signatures of AGN activity as reported in studies at other wavelengths. For example, NGC 4261 is the

\footnote{The ratio of the ionizing photon density to the particle density.}
The brightest galaxy in the NGC 4261 group, Hubble Space Telescope (HST) WFPC2 observations (Jaffe et al. 1993) and our MUSE data reveals a bright nuclear optical source surrounded by a disc of gas and dust, while radio observations identified two jets perpendicular to the disc (Birkinshaw & Davies 1985; Scheneider 2006; Kolokythas et al. 2015). Recent kinematical studies using ALMA CO (Boizelle et al. 2021) find a dynamical mass for the central supermassive black hole (BH) in NGC 4261 of $1.67 \times 10^9 M_\odot$. So, the observed LINER properties in this galaxy may be explained by an obscured low-luminosity AGN (Zezas et al. 2005). In addition, 17/18 galaxies in our sample show detected radio continuum emission (Kolokythas et al. 2018); 4/18 show small ($\lesssim 20$ kpc; NGC 1060 and NGC 5846) and large-scale ($> 20$ kpc; NGC 193 and NGC 4261) jets, 3/10 diffuse (NGC 677, NGC 1587 and ESO0507-G025) and 10/18 a point-like or unresolved point source radio continuum morphology ($\lesssim 11$ kpc; NGC 410, NGC 584, NGC 777, NGC 924, NGC 940, NGC 978, NGC 1453, NGC 4008, NGC 4169 and NGC 7619).

The results in this section indicate that \( \text{EW}(H\alpha) \), \( \log \left( \frac{[N \, \text{II}]}{[S \, \text{II}]} \right) \) and the BPT diagrams, alone, cannot distinguish between dominant ionising sources producing the central and extended LINER-like emission in our sample. However, the overall $\log ([N \, \text{II}]/H\alpha)$ (Figure 5) shows that this emission line ratio decreases as the extent of the emission line region increases, indicating that the ionisation sources are having different impacts at different radii. The same decreasing value with the distance pattern is observed for \( \sigma([N \, \text{II}]) \), the 12 + log(O/H) abundances and in most cases the \( \text{EW}(H\alpha) \). Central regions are almost certainly influenced by low-luminosity AGN, while the extended regions are ionised by other mechanisms (SF and/or cooling flows shocks and pAGBs). The \( \text{EW}(H\alpha) \) in the outer parts is in the range of 0.5-2.4 Å (see Figure 7), thus indicating that pAGBs are likely contributing significantly to the ionization of these regions. Finally, our interpretations are based on the comparison with models. Factors like \( L_\gamma \) photon escape and dilution of nuclear EWs (Papaderos et al. 2013) have not been considered. Consequently, the addition of these processes may constitute an important element in understanding of ETGs with extended optical LINER-like emission.
likely ionised by pAGB stars, star-forming clusters and weak AGN. Therefore, the abundances in these regions can be estimated by:

$$12 + \log \left( \frac{\sigma}{n} \right) = 7.673 + 0.22 \times \sqrt{25.25 - 9.072 \times O3N2 + 0.127 \times O3,}$$

with $O3N2 = \log([O \text{III}]/H\beta \times H\alpha/[N \text{II}]).6584$ and $O3 = \log([O \text{III}].5007/H\beta$.

Finally, iii) we compare those values with the ones inferred from the N2 diagnostic, calibrated by Marino et al. (2013) (star-forming H II calibration) obtained using empirically calibrated direct abundance data ($T_e$-based measurements) from H II regions in the Califa survey. The Marino et al. (2013) calibration is defined as:

$$12 + \log \left( \frac{\sigma}{n} \right) = 8.743 + 0.462 \times N2,$$

We note that the emission line ratios used in any of these relations are not highly affected by reddening.

In Table 5 we show the oxygen abundance for the nuclear 3" region of each galaxy using the aforementioned methods and their distributions are shown in Figure 11. In the figure and table we see that the $12 + \log(O/H)$ derived from the AGN model and the AGN N2 calibrator are in agreement within the uncertainties (of $\pm 0.1$ dex) with those inferred from the H II calibration in $\sim 62\%$ ($8/13$) and $\sim 89\%$ ($16/18$) of the galaxies, respectively. These values drop to $\sim 38\%$ ($5/13$) and $\sim 0\%$ ($0/13$) when compared to pAGB and X-ray emission models, respectively. However, $100\%$ ($13/13$) of the nuclear DIG/LI(N)ERs abundances are in agreement, at $1\sigma$ level, with the H II values. We note that nuclear metallicities obtained from pAGB and X-ray emission models are, in most cases, lower compared to those obtained from the H II-based method. Two of our galaxies are included within the Annibali et al. (2010) sample of ETGs with ionised gas: NGC 1453 and NGC 5846. Those authors found $12 + \log(O/H) = 8.55 \pm 0.19$ and $8.84 \pm 0.17$ using the calibration in Kobulnicky, Kennicutt & Pizagno (1999) for NGC 1453 and NGC 5846, respectively. Our measurements are in reasonable agreement within the errors with those derived by Annibali et al. (2010) considering apertures and the intrinsic differences between the calibrations.

It is important to bear in mind that the N2 metallicity diagnostics are known to have a dependency on the ionisation parameter and the nitrogen-to-oxygen ratio of the gas, given that metallicities increase with N-enrichment. Unfortunately, we are unable to explore the extended metallicity distribution using methods that do not have a dependence on the aforementioned parameters, given that only the [N II].6584 and Hz emission lines were detected in most of our sample galaxies. On the other hand, the O3N2 method gives nuclear abundances that are in agreement, within the uncertainties, with the ones found using the N2-based abundances. Therefore, we used the N2 and O3N2 indicators, in galaxies with extended [N II].6584 emission, as a way of obtaining the spatially resolved morphologies of the ionised gas which can be translated into metallicities in a relative rather than absolute way. In Section 3.2 we showed that most spaxels in our spatially resolved BPT maps lie in the AGN and composite areas of the diagrams. Therefore, we calculated the pixel-by-pixel $12 + \log(O/H)$ abundance in those regions by adopting the Carvalho et al. (2020) (AGN N2; green dots) and Kumari et al. (2019) (DIG/LI(N)ERs O3N2; blue dots) calibrators. While values from the N2 calibration by Marino et al. (2013) (H II; black dots) are included for comparison. In Figure 12 we show for each galaxy in our sample the $12 + \log(O/H)$ abundances as function
of the radius from the galaxy’s centre. The dots are the median values within circular bins of 1.5” radii, except for the first bin which has a radius of 0.5”. The error bars, in this figure, denote the 1σ distribution of the Hα 12 + log(O/H) per bin.

In Figure 12 we see that the calibrators predict comparable metallicities but with a small offset (≤0.1 dex in most cases) in the innermost regions, while for the extended regions this difference can reach values of ~0.3 dex in the case of ESO0507-G025. From this figure it is clear that there is a break in the metallicity gradient slope with a very steep gradient in the central region which, as indicated in Section 4.2, is more influenced by low-luminosity AGN. We calculated the metallicity gradient (V_{O/H}) as the slope of the linear fit to the median 12 + log(O/H) values separately for the innermost and extended regions for all the calibrations considered. In Table F1 we present for each galaxy the results of our linear fitting and statistics of all pixels/spaxels used to create the 12 + log(O/H) profiles. From this table we see that the central metallicity gradients are in all cases negative, while the extended regions show a flat gradient.

4.4 Properties of the gas and its origin

4.4.1 Properties of the gas and metallicity gradients

From the previous section we see that the mean gas-phase metallicity in the nuclear and extended regions are ⟨(O/H)_{nuclear}⟩ > ⟨(O/H)_{extended}⟩ with the 12 + log(O/H) abundance generally decreasing with radius, independently of the ionisation source or method considered, with a flattening of metallicity gradients for the outermost regions. In Figure 13 we show the relationship between metallicity gradients V_{O/H} for the central and extended regions and Hα+[N ii] morphology of our sample. While in Table 6 we summarise the average metallicity gradients for each region and calibrator considered. A weak positive Spearman’s correlation ~0.6 between metallicity gradients and morphological Hα+[N ii] types of the galaxies is found in Figure 13. Despite the low number statistics in our study, these results suggest that the nuclear V_{O/H} of type i group-dominant galaxies, on average, is slightly higher than type i0 and type ii galaxies. However, the intrinsic uncertainties associated with these values lead us to consider the metallicity...
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gradients may not be statistically significant. Therefore, we argue that the similarity in the shape of the nuclear metallicity gradients in all galaxy types and the flattening of the outer regions in our sample of group-dominant galaxies with type i (strong nuclear emission plus extend filamentary structures) and type ii (strong or diffuse nuclear emission plus extranuclear Hα regions) morphologies are a common property in this group of galaxies. Several groups (e.g., Sánchez et al. 2014; Belfiore et al. 2017, and references therein) have studied the metallicity gradients in local galaxy samples. In Sánchez et al. (2014) and Sánchez (2020) they show that a significant fraction of galaxies in the CALIFA sample exhibit shallow metallicity slopes in their innermost and/or outermost regions. In particular, they argue that the flattening in the outer regions is a universal property of disc galaxies, which is independent of the inclination, mass, luminosity, morphology and the presence of bars. In this and other similar works, several mechanisms like radial motion, inside-out growth, metal-poor/rich gas accretion, turbulent transport and outflow of gas (e.g., Kewley et al. 2010; Sánchez-Menguiano et al. 2018; Sánchez 2020, see refer-

Table 5. Oxygen abundance determinations for the nuclear region (3" aperture) assuming pure H II regions (Marino et al. 2013; Hα), AGN models (Krabbe et al. 2021) and the AGN N2-based calibrator (Carvalho et al. 2020), the DIG/LI(N)ERs O3N2 calibrator (Kumari et al. 2019; DL), and pAGB (Krabbe et al. 2021) and X-ray (Polles et al. 2021) emission models, respectively.

|            | 12 + log(O/H)_{HII} | 12 + log(O/H)_{AGN} | 12 + log(O/H)_{DIG} | 12 + log(O/H)_{pAGB} | 12 + log(O/H)_{X-ray} |
|------------|---------------------|---------------------|---------------------|---------------------|---------------------|
|            | N2                  | model               | O3N2                | model               | model               |
| NGC 193    | 8.81±0.09           | 8.76±0.16           | 8.75±0.10           | 8.82±0.10           | 8.63±0.16           | 8.68±0.10           |
| NGC 410    | 8.75±0.05           | ...                 | ...                 | ...                 | ...                 |
| NGC 584    | 8.80±0.10           | 8.71±0.16           | 8.74±0.11           | 8.81±0.16           | 8.60±0.17           | 8.67±0.15           |
| NGC 677    | 8.74±0.08           | 8.56±0.08           | 8.65±0.10           | 8.78±0.10           | 8.55±0.05           | 8.48±0.27           |
| NGC 777    | 8.87±0.13           | ...                 | ...                 | ...                 | ...                 |
| NGC 924    | 8.77±0.07           | 8.57±0.11           | 8.70±0.08           | 8.79±0.15           | 8.55±0.12           | 8.60±0.18           |
| NGC 940    | 8.90±0.11           | 8.90±0.10           | 8.88±0.10           | 8.83±0.17           | 8.92±0.17           | >8.69               |
| NGC 978    | 8.71±0.07           | 8.56±0.01           | 8.64±0.08           | 8.77±0.08           | 8.55±0.03           | 8.33±0.25           |
| NGC 1060   | 8.79±0.12           | ...                 | ...                 | ...                 | ...                 |
| NGC 1453   | 8.83±0.06           | 8.83±0.06           | 8.78±0.05           | 8.83±0.10           | 8.74±0.14           | >8.69               |
| NGC 1587   | 8.78±0.06           | 8.59±0.11           | 8.70±0.07           | 8.77±0.08           | 8.54±0.10           | 8.60±0.13           |
| NGC 4008   | 8.71±0.12           | ...                 | ...                 | ...                 | ...                 |
| NGC 4169   | 8.85±0.06           | 8.85±0.04           | 8.81±0.05           | 8.83±0.12           | 8.81±0.10           | >8.69               |
| NGC 4261   | 8.90±0.13           | 8.90±0.13           | 8.88±0.12           | 8.83±0.19           | 8.91±0.26           | >8.69               |
| ESO0507-G025 | 8.76±0.06   | 8.57±0.08           | 8.69±0.07           | 8.79±0.14           | 8.55±0.07           | 8.59±0.16           |
| NGC 5846   | 8.80±0.10           | 8.75±0.18           | 8.74±0.11           | 8.83±0.09           | 8.59±0.16           | 8.67±0.14           |
| NGC 6658   | 8.83±0.11           | 8.81±0.28           | 8.78±0.11           | 8.78±0.31           | 8.81±0.32           | >8.69               |
| NGC 7619   | 8.93±0.20           | ...                 | ...                 | ...                 | ...                 |
The properties of the extended warm ISM in our sample of type i and type ii galaxies suggest, within the uncertainties, nearly solar (±0.2 dex) homogeneous chemical abundances (see Figure 12 and Table F1). This likely requires mechanisms (e.g., radial motions, gas-clouds or satellite accretion/interactions, AGN/SF-driven outflows) for the efficient gas transport, mixing and radial flattening of metallicity into the outer regions of the galaxies in a relative short time scale (e.g., Werk et al. 2011; Bresolin, Kennicutt & Ryan-Weber 2012; Rennehan et al. 2019; Rennehan 2021), likely similar to other low redshift galaxy classes.

### 4.4.2 Cold gas content

H\textsubscript{i} is a sensitive tracer of external environmental mechanisms in galaxies. A study of H\textsubscript{i} in ETGs by Serra et al. (2012) found that H\textsubscript{i} detections were relatively uncommon near Virgo cluster centre (10%) but were common (40%) in field with the detected H\textsubscript{i} mass inversely related to environment density. H\textsubscript{i} morphology was also found to vary in a continuous way from regular, settled H\textsubscript{i} discs and rings in the field to unsettled gas distributions (including tidal or accretion tails) at the Virgo cluster centre, with the H\textsubscript{i} and CO-richest galaxies found in the poorest environments where the SF detection rate was also higher. This implies that galaxy group processing is involved in evolving pre-existing ETG gas properties.

In our sample, 8/18 galaxies have the H\textsubscript{i} properties available from the literature and 18/18 have been observed in CO (see our Table G1 for a summary; O’Sullivan et al. 2015, 2018). In Figure G1 we show single dish H\textsubscript{i} spectra from the literature for 7 of these galaxies. Excluding the two galaxies in Table G1 which have a caveat about their H\textsubscript{i} properties (see Table G1 note) the mean H\textsubscript{i} in type ii galaxies is $17.2 \times 10^9$ M\textsubscript{\odot} compared to the mean H\textsubscript{i} in type i galaxies of $1.4 \times 10^9$ M\textsubscript{\odot}, i.e., the type ii have an order of magnitude more H\textsubscript{i}. NGC 940 was excluded from the above calculation because of the high uncertainty about it’s H\textsubscript{i} detection, however it has a large M(H\textsubscript{2}) mass ($6.1 \times 10^9$ M\textsubscript{\odot}). The H\textsubscript{2} mass of NGC 940 together with the H\textsubscript{i} masses of the other type ii galaxies confirms that the type ii galaxies are cold gas rich. To varying degrees, all the H\textsubscript{i} in our galaxies display double horned H\textsubscript{i} profiles which are indicative of rotating discs, with the clearest examples being NGC 924 and NGC...
3.1 which indicates that the cold gas
3.3 Holwerda et al. 2011 and Olivares et al. 2022. Starkenburg et al. 2019; Loubser et al. 2022
bet
more than 1000 solar masses, estimates, among others) indicate possible origins of this
and Appendix B). In sys-
mergers. They find that ordered discs take
840 which also have the lowest H
gas structures characteristic of ICM cooling. The presence of mis-
3/4 galaxies (NGC 193, NGC 1060 and NGG 940) with radio jet-like morphology present filamentary ionised
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gas is difficult, since different mechanisms could be acting at different evolutionary stages. Kolokythas et al.
2022 examined the relationships between radio power, SFR(FUV) and stellar mass for CLoGS, which includes our analysed galaxies, and find no correlations between these quantities. This suggests a mix of origins for the cool gas in these systems, including stellar mass loss, cooling from the IGrM/galaxy halo, settling gas due to mergers and tidal or ram pressure stripping (see also Loubser et al. 2022). In systems like NGC 978 and NGC 1587 the observed ionised gas could be associated with an interaction with the companion galaxy. Although, no cold gas has been reported in NGC 978 (see Figure B1), but the interaction debris gas may eventually enter the galaxy’s (hot) halo to trigger the SF and feed the AGN activity. On the other hand, the SF in extranuclear regions (type ii galaxies) is likely a later stage after streams gas settling from orbiting satellites (Jung et al. 2022). Kolokythas et al. (2022) argued that S0 group-dominant galaxies (type ii galaxies) occupy X-ray faint systems and have point-like radio sources (Kolokythas et al. 2018), which indicates that the cold gas is more likely to be the result of gas-rich mergers or tidal interactions instead of cooling from a hot IGrM. While in some type i galaxies (as in the case of NGC 5846 where the ionised gas morphology supports a cooling flow) the cooled gas from the IGrM may be an effective mechanism forming filaments and rotating discs in the galaxy nuclei (O’Sullivan et al. 2015; Olivares et al. 2022, and references therein). 3/4 galaxies (NGC 193, NGC 1060 and NGG 5846) with radio jet-like morphology present filamentary ionised gas structures characteristic of ICM cooling. The presence of misaligned or counter-rotating ionised gas discs with respect to the stellar body is a strong indication of external accretion of gas. We find direct evidence of this, Olivares et al. (2022) found that most of the galaxies in our sample have ionised gas kinematically decoupled from the stellar component, which suggests an external origin of the gas. Observational evidence (e.g., Sarzi et al. 2006; Gomes et al. 2016) and simulations (Starkenburg et al. 2019; Khim et al. 2021; Jung et al. 2022, among others) indicate possible origins of this misalignment in galaxies regardless of the morphology and environment, with early-type having higher misaligned fractions. We

Table 6. Average and standard deviation (sd) metallicity gradients (⟨O/H⟩), in units of dex/arcsec, for the central and extended regions (left and right values in each column) using the calibrators H i N2 regions (Marino et al. 2013), AGN N2 (Carvalho et al. 2020) and O3N2 DIG/LI(N)ERs (Kumari et al. 2019).

|          | H i N2 | AGN N2 | DIG/LI(N)ERs O3N3 |
|----------|--------|--------|-------------------|
|          | central (⟨V_O/H⟩)/sd | extended (⟨V_O/H⟩)/sd | central (⟨V_O/H⟩)/sd | extended (⟨V_O/H⟩)/sd | central (⟨V_O/H⟩)/sd | extended (⟨V_O/H⟩)/sd |
| type i0  | -0.032/0.022 | ... | -0.040/0.037 | ... | -0.010/0.012 | ... |
| type i   | -0.026/0.019 | 0.0011/0.0043 | -0.031/0.028 | -0.0013/0.0053 | -0.010/0.005 | -0.0012/0.0027 |
| type ii  | -0.029/0.020 | -0.0039/0.019 | -0.038/0.027 | -0.0025/0.017 | -0.008/0.005 | -0.0000/0.0003 |

4.4.3 Summary of properties, chemical abundances and possible scenarios for the origin of the gas in group-dominant galaxies

The interpretation of internal (stellar mass loss) and external mechanisms (cooling from the IGrM or mergers/interactions) for the origin of the gas in our sample is difficult, since different mechanisms could be acting at different evolutionary stages. Kolokythas et al. (2022) examined the relationships between radio power, SFR(FUV) and stellar mass for CLoGS, which includes our analysed galaxies, and find no correlations between these quantities. This suggests a mix of origins for the cool gas in these systems, including stellar mass loss, cooling from the IGrM/galaxy halo, settling gas due to mergers and tidal or ram pressure stripping (see also Loubser et al. 2022). In systems like NGC 978 and NGC 1587 the observed ionised gas could be associated with an interaction with the companion galaxy. Although, no cold gas has been reported in NGC 978 (see Figure B1), but the interaction debris gas may eventually enter the galaxy’s (hot) halo to trigger the SF and feed the AGN activity. On the other hand, the SF in extranuclear regions (type ii galaxies) is likely a later stage after streams gas settling from orbiting satellites (Jung et al. 2022). Kolokythas et al. (2022) argued that S0 group-dominant galaxies (type ii galaxies) occupy X-ray faint systems and have point-like radio sources (Kolokythas et al. 2018), which indicates that the cold gas is more likely to be the result of gas-rich mergers or tidal interactions instead of cooling from a hot IGrM. While in some type i galaxies (as in the case of NGC 5846 where the ionised gas morphology supports a cooling flow) the cooled gas from the IGrM may be an effective mechanism forming filaments and rotating discs in the galaxy nuclei (O’Sullivan et al. 2015; Olivares et al. 2022, and references therein). 3/4 galaxies (NGC 193, NGC 1060 and NGG 5846) with radio jet-like morphology present filamentary ionised gas structures characteristic of ICM cooling. The presence of misaligned or counter-rotating ionised gas discs with respect to the stellar body is a strong indication of external accretion of gas. We find direct evidence of this, Olivares et al. (2022) found that most of the galaxies in our sample have ionised gas kinematically decoupled from the stellar component, which suggests an external origin of the gas. Observational evidence (e.g., Sarzi et al. 2006; Gomes et al. 2016) and simulations (Starkenburg et al. 2019; Khim et al. 2021; Jung et al. 2022, among others) indicate possible origins of this misalignment in galaxies regardless of the morphology and environment, with early-type having higher misaligned fractions. We

Figure 13. Relationship between metallicity gradients (V_O/H) and Hα+[N ii] morphology of the galaxies. More details about the classes of emission line morphology are given in Section 3.1. Horizontal lines indicate the average of the metallicity gradients (⟨V_O/H⟩) for central (stars) and extended (crossed) fits considering three different calibrators for H i regions (black; Marino et al. 2013), AGN (green; Carvalho et al. 2020) and DIG/LI(N)ERs (blue; Kumari et al. 2019). The standard deviation for each quantity is indicated by the filled regions.

940 which also have the lowest H i profile asymmetries as measured by the Å_FWHM Parameter (Espada et al. 2011).

It seems likely the cold and warm discs in the type ii galaxies are part of the same kinematical gas structures, with support for this coming from the H i profiles and the [N ii] velocity fields in Figure 6 and Appendix D. In the [N ii] velocity fields we see that all of the type ii galaxies show clear rotating disc patterns, with NGC 940 presenting a highly symmetric case. The high levels of symmetry in the velocity fields, especially in NGC 940, together with the flattened metallicity gradients argue against the gas having been recently acquired. In particular, using Romulus hydrodynamic cosmological simulations Jung et al. (2022) examined the re-emergence of gaseous and stellar discs in BGGs following their destruction by mergers. They find that ordered discs take ~1 Gyr to be established. We suggest that our gas-rich systems obtained their cold gas at least ~1 Gyr ago (Holwerda et al. 2011; Jung et al. 2022), i.e., the H i virialization time scale after gas-clouds or satellite mergers/accretion. However, we observe that σ_gas,central ≥ σ_gas,extended so the warm gas in the central regions is unlikely to be dynamically relaxed (Olivares et al. 2022) in the gravitational potential of the galaxy, indicating an AGN outburst contribution. Those results are in agreement with the morphology of the warm gas distribution and velocity fields observed in our sample (Section 3.3).
argue that stellar mass loss is unlikely to be the dominant source of cold gas in our sample (see Olivares et al. 2022).

If we assume that the metallicity of the warm gas, in our sample, is represented by a single calibrator (AGN N2 or DIG/LI(N)ERs O3N2), on average, the nuclear regions are more metal rich than their extended structures, i.e., \((\langle O/H \rangle_{\text{nuclear}}) \geq \langle O/H \rangle_{\text{extended}}\). However, in Section 4.2 we find that the ionisation sources are having different impacts at different radii. Therefore, the abundance in the nuclear regions is well represented by the 3" apertures and they can be obtained as the average between the AGN N2 and the interpolated AGN abundances from the models (Figure 9). While for the extended regions the average abundances are from the data points in Section 4.3 (see Table 1) assuming the DIG/LI(N)ERs O3N2 calibrator. This is a reasonable assumption given that most of the spaxels in these regions are in the composite area of the BPT diagrams. In Table 7 we summarize and compare the gas-phase metallicities (\(Z = \log(O/H) - \log(O/H)_{\odot}\)) found in this work with those in the IGrM by O’Sullivan et al. (2017). In the nuclear regions the metallicities range from \(-0.9\) to \(1.7\, Z_\odot\). The metallicity in the extended structures often rise to values approaching the solar \(\sim 1.0\, Z_\odot\) or higher (\(\lesssim 0.3\) dex), while the IGrM has metallicities down to \(-0.1\) to \(0.7\, Z_\odot\). In the case of NGC 940, NGC 4261 and NGC 7619 the nuclear metallicities are \(\gtrsim 0.6\) dex higher than the solar value. Interestingly, in four cases (NGC 584, NGC 1587, ESO00507-G025 and NGC 5846) we found a drop in the nuclear metallicity with respect to the extended regions of \(\lesssim 0.2\) dex in NGC 584 and NGC 5846 and \(-0.1\) dex for NGC 1587 and ESO00507-G025. This suggest the acretion of metal-poor gas to the central AGN (e.g., do Nascimento et al. 2022). Since metallicity in the nuclear regions represent the average metallicity within the 3" apertures and the uncertainties on the abundances are of the order of \(-0.1\) dex, we find in our sample of group-dominant galaxies that

\[
Z_{\text{nuclear}} \geq Z_{\text{extended}} > Z_{\text{IGrM}}.
\]

Table 7. Comparison between Z (this work) and IGrM metallicities in units of \(Z/Z_\odot\). Column (1) average value between the AGN N2 and interpolated abundances from the AGN models. Column (2) abundances in the extended regions from DIG/LI(N)ERs O3N2 calibrator. Column (3) corresponds to IGrM metallicity from O’Sullivan et al. (2017).

| Galaxy   | Nuclear (1) | Extended (2) | IGrM (3) |
|----------|-------------|--------------|----------|
| NGC 193  | 1.15        | ...          | 0.68     |
| NGC 410  | 0.94        | ...          | 0.42     |
| NGC 584  | 1.08        | ...          | 1.35     |
| NGC 677  | 0.84        | ...          | 0.38     |
| NGC 777  | 1.41        | ...          | 0.63     |
| NGC 924  | 0.89        | 0.85         | ...      |
| NGC 940  | 1.57        | 1.07         | 0.06     |
| NGC 978  | 0.82        | ...          | >0.29    |
| NGC 1060 | 1.08        | ...          | 0.28     |
| NGC 1453 | 1.30        | 1.29         | 0.42     |
| NGC 1587 | 0.91        | 1.05         | 0.03     |
| NGC 4008 | 0.84        | ...          | 0.32     |
| NGC 4169 | 1.38        | 1.35         | 0.11     |
| NGC 4261 | 1.58        | ...          | 0.23     |
| ESO00507-G025 | 0.88 | 0.98       | ...     |
| NGC 5846 | 1.12        | 1.32         | 0.27     |
| NGC 6658 | 1.27        | ...          | <0.18    |
| NGC 7619 | 1.67        | ...          | 0.54     |

The mixing and dispersion of heavy elements in the ISM of galaxies, in general, should follow the "evolutionary" stages of disc growth at different spatial scales. It might be suggested, in our case, by a correlation between gas-phase metallicity gradients \(V_{\text{O/H}}\) and \(H_2+[N\,\alpha]\) morphology (see Figure 13), since the effect of gas flows over the lifetime of the galaxies seems to produce the flattening of abundances out to large radii (e.g., Kewley et al. 2010; López-Sánchez et al. 2015; Sánchez et al. 2014), following the formation of the extended structures. However, we find no correlation between the metallicity gradients and morphology (Section 4.4.1) in our sample of BGGs. This is in agreement with the idea of relatively short time scales for the radial dispersion and mixing of metals to large spatial scales likely produced by the AGN/SF-driven outflows, gas accretion and mergers/interactions. Furthermore, some of these metals will be transport by these mechanisms from the galaxies into the IGrM/ICM. In particular, group-dominant galaxies often host radio AGN that are interacting with the surrounding gas by forming cavities and shock fronts (see Olivares et al. 2022, for a description of these structures in our sample). As seen in Section 3.3 we observe large gas velocity dispersion in the central regions of the galaxies, likely associated with the presence of AGN activity. Therefore, group-dominant galaxies likely acquired their cold gas as a consequence of several possible mechanisms, i.e., gas-clouds or satellite mergers/accretion and cooling flows which together with the AGN/SF activity are likely contributing to the growth of the ionized gas structures and flattening the metallicity gradients.

5 CONCLUSIONS

In this paper, we present archival MUSE observations for a sample of 18 group-dominant galaxies from the CLOGS sample (O’Sullivan et al. 2017). We derive and removed the stellar continuum for all galaxies by fitting the stellar SEDs using the spectral synthesis code FADO (Gomes & Papaderos 2017). We studied the properties (i.e., emission line ratios, chemical abundances, etc) and structure of the warm gas, in each galaxy, in order to constrain the ionisation processes, the origin of their gas and its chemical abundance distribution. We summarise our main results as follows:

- We used the continuum-subtracted \(H_2+[N\,\alpha]\) images (see Figure 3) to classify the galaxies into three morphological groups or types: type i0 - strong or diffuse nuclear emission with (or without) unextended filamentary (\(\lesssim 1\) kpc) structures connected to the nuclear region, type i - strong or diffuse nuclear emission with extended (several kpc) filamentary structures beyond the nuclear region and type ii - i0 or i plus extranuclear \(H\,\alpha\) regions (well-defined or in distorted ring-like structures). We find that 5/18 (NGC 410, NGC 978, NGC 584, NGC 677, NGC 777, NGC 4169, NGC 1587, NGC 5846 and NGC 7619) and 4/18 galaxies are type ii (NGC 924, NGC 940, NGC 4169 and ESO00507-G025).

- In order to distinguish between different ionisation mechanisms, in Section 3.2 we used the following emission line ratios [O iii]/Hβ and [N ii]/Hα and the equivalent width EW(Hα). The spatially resolved log [N ii]/Hα ratios decreases as the extent of the emission line region increases, indicating that the sources of the ionisation are acting at different spatial scales. The same decreasing pattern with the distance is observed for the velocity dispersion \(\sigma\). Using emission-line diagnostic diagrams (or BPT diagrams) we find that all galaxies in our sample have a dominant LINER/AGN...
nuclear region. Extended LINER-like regions are observed in most galaxies with filamentary structures. In the same section, we studied the mechanisms (pAGBs, AGN and X-ray emission) responsible for the ionisation which produce the optical emission lines in our sample. Although, AGN, pAGBs and X-ray emission models are able to reproduce the observational data, we suggest that central regions are more influenced by a low-luminosity AGN, while extended regions are ionised by other mechanisms with pAGBs photoionisation likely contributing significantly as suggested by their EW(Hα) values.

- We calculated the gas-phase metallicity ([2.12 + log(O/H)]) using linear interpolations between the AGN, pAGBs and X-ray emission models (Krabbe et al. 2021) and their measured emission line ratios ([2.12 + log(O/H)]([2.12 + log(N/H)]/[2.12 + log(O/H)]). We also used the AGN N2 (Carvalho et al. 2020) and DIG/LIN(ER) O3N2-based (Kumari et al. 2019) calibrators. Using a single calibrator (AGN N2 or DIG/LIN(ER) O3N2), the 12 + log(O/H) in the nuclear and extended regions (see Figure 12) are (12 + log(O/H))nuclear > (12 + log(O/H))extended. We found that the metallicity gradients for the pixel-by-pixel data points are, in most cases, negative in the innermost regions with a flat gradient for the extended areas beyond the centre, which includes extended structures and some star-forming regions. In this sense, the morphological Hα+[N ii] types defined in this study indicate that group-dominant galaxies with extended filamentary structures (type i) and S0 galaxies with extranuclear SF regions (type ii), on average, have shallow metallicity gradients. Therefore, extended regions and ring-like structures of ionised gas can be considered chemically homogeneous (nearly solar) within the uncertainties. If the ionisation sources have different impacts at different radii (as seen in Section 3.2) we use the AGN N2 calibrator and AGN models to estimate the nuclear (3′ aperture) abundances and the DIG/LIN(ER) O3N2 calibrator. We found that the metallicity gradients for the pixel-by-pixel data points are, in most cases, negative in the innermost regions with a flat gradient for the extended areas beyond the centre, which includes extended structures and some star-forming regions. In this sense, the morphological Hα+[N ii] types defined in this study indicate that group-dominant galaxies with extended filamentary structures (type i) and S0 galaxies with extranuclear SF regions (type ii), on average, have shallow metallicity gradients. Therefore, extended regions and ring-like structures of ionised gas can be considered chemically homogeneous (nearly solar) within the uncertainties. If the ionisation sources have different impacts at different radii (as seen in Section 3.2) we use the AGN N2 calibrator and AGN models to estimate the nuclear (3′ aperture) abundances and the DIG/LIN(ER) O3N2 calibrator. We found that the metallicity gradients for the pixel-by-pixel data points are, in most cases, negative in the innermost regions with a flat gradient for the extended areas beyond the centre, which includes extended structures and some star-forming regions. In this sense, the morphological Hα+[N ii] types defined in this study indicate that group-dominant galaxies with extended filamentary structures (type i) and S0 galaxies with extranuclear SF regions (type ii), on average, have shallow metallicity gradients. Therefore, extended regions and ring-like structures of ionised gas can be considered chemically homogeneous (nearly solar) within the uncertainties. If the ionisation sources have different impacts at different radii (as seen in Section 3.2) we use the AGN N2 calibrator and AGN models to estimate the nuclear (3′ aperture) abundances and the DIG/LIN(ER) O3N2 calibrator. We found that the metallicity gradients for the pixel-by-pixel data points are, in most cases, negative in the innermost regions with a flat gradient for the extended areas beyond the centre, which includes extended structures and some star-forming regions.

ACKNOWLEDGEMENTS

We thank the reviewer for his/her careful reading of the manuscript and helpful comments which substantially improved the paper. PL (contract DL57/2016/CP1364/CT0010) and TS (contract DL57/2016/CP1364/CT0009) are supported by national funds through Fundação para a Ciência e Tecnologia (FCT) and the Centro de Astrofísica da Universidade do Porto (CAUP). SIL and KK are supported in part by the National Research Foundation of South Africa (NRF Grant Numbers: 120850). Opinions, findings and conclusions or recommendations expressed in this publication is that of the author(s), and that the NRF accepts no liability whatsoever in this regard. EOS acknowledges support for this work from the National Aeronautics and Space Administration through XMM-Newton award 80NSSC19K0106. AB acknowledges support from NSERC through its Discovery Grant Program. PL thanks Polychronis Papaderos for his very useful comments. We thank Angela Krabbe for providing us with the CLOUDY models used in this work.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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APPENDIX A: OTHER EMISSION LINE GALAXIES IN OUR MUSE DATACUBES

Other emission line galaxies in our MUSE FoVs. We found two objects in the FoV of NGC 677 and one in the FoV of NGC 777, NGC 924 and NGC 1453. In Figure A1 we show the position of these objects in the FoV. Using the Hα and [N ii]λ6584 emission lines we calculated: the redshifts, Hα SFRs and 12 + log(O/H) abundances using the H II calibrator. In Table A1 we summarize their main properties.
Table A1. Properties of the emission line galaxies detected in the field of our sample galaxies. a $z$ calculated using H/$\beta$.

| FoV     | z        | SFR(H/$\alpha$) (M$_\odot$ yr$^{-1}$) | 12 + log(O/H) N2 |
|---------|----------|----------------------------------------|-------------------|
| NGC 677 |          |                                        |                   |
| R1      | 0.283658 | 0.0154±0.0001                          | 8.50±0.09         |
| R2      | 0.282776 | 0.0030±0.0010                          | 8.53±0.17         |
| NGC 777 |          |                                        |                   |
| R1      | 0.232878 | 0.0046±0.0001                          | 8.48±0.15         |
| NGC 924 |          |                                        |                   |
| R1      | 0.491319 | ...                                    | ...               |
| NGC 1453|          |                                        |                   |
| R1      | 0.118373 | 0.0003±0.0001                          | 8.56±0.15         |
Figure A1. Emission line galaxies found in the FoV of the galaxies NGC 677, NGC 777 NGC 924 and NGC 1453.
APPENDIX B: Hα+[N II]λλ6548,6584 EMISSION LINE MAPS
Figure B1. $\text{H}\alpha + [\text{N} \text{II}]\lambda 6548, 6584$ emission line maps from our sample. We smoothed the emission line maps using a 3×3 box filter. MUSE continuum-subtracted spectra from a nuclear 3″ aperture covering the wavelength range from $6400$ Å to $6800$ Å are shown in the inset panels. The vertical lines in the inset panels indicate the wavelengths of the [N II]λ6548, Hα, [N II]λ6584, [S II]λ6717 and [S II]λ6731 emission lines. Fluxes in units of $10^{-15}$ (erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$). North is to the top and East to the left.
Figure B1 – continued
APPENDIX C: EMISSION LINE RATIO MAPS AND BPT DIAGRAMS OF THE GALAXIES
Figure C1. Emission line ratio maps log([N ii]/Hα), log([O iii]/Hβ) and log([O iii]/Hβ) vs log([N ii]/Hα) BPT diagram for emission lines with S/N > 3. In the BPT diagram we include the Kewley et al. (2001; solid line) and Kauffmann et al. (2003; dashed line) lines to divide between regions dominated by H ii and AGN/LINERs. Filled black data points correspond to our measured values in the 3" aperture enclosing the nuclear region.

Figure C2. Similar to Figure C1.

Figure C3. Similar to Figure C1.

Figure C4. Similar to Figure C1.

Figure C5. Similar to Figure C1.

Figure C6. Similar to Figure C1.

Figure C7. Similar to Figure C1.

Figure C8. Similar to Figure C1.

Figure C9. Similar to Figure C1.

Figure C10. Similar to Figure C1.

Figure C11. Similar to Figure C1.

Figure C12. Similar to Figure C1.

Figure C13. Emission line ratio maps log([N ii]/Hα) for galaxies with no Hβ and/or [O iii].λ5007 emission detection. North is to the top and East to the left.
APPENDIX D: [N II] λ6584 VELOCITY FIELDS
Figure D1. Radial velocity $v(\text{[N}\,\text{II}])$ (left panel) and velocity dispersion $\sigma(\text{[N}\,\text{II}])$ (right panel) maps for our type ii galaxies NGC 924, NGC 940 and NGC 4169. See also Figure 6 for ESO0507-G025. The position of continuum maximum is indicated by an X symbol. North is to the top and East to the left.
APPENDIX E: [S II]λ6716 / [S II]λ6731 RATIO MAPS
Figure E1. $\frac{[S \ II] \lambda 6716}{[S \ II] \lambda 6731}$ ratio maps. Using the temden IRAF STS package assuming $T_{e}(O \ III)=10000$ K, for reference, we find for $\frac{[S \ II] \lambda 6716}{[S \ II] \lambda 6731} = 1.43, 1.32, 1.00, 0.51$ and 0.46 an electron density $n_e(S \ II) = \sim 2, 100, 606, 10910$ and 48893 cm$^{-3}$, respectively. North is up and east is to the left.

Figure E1 – continued
APPENDIX F: RESULTS OF THE LINEAR FITTING
Table F1. Results of the linear fitting of Figure 12 and statistics for all data points or spaxels using the H\textsc{ii} N2 (Marino et al. 2013), AGN N2 (Carvalho et al. 2020) and AGN/Li(N)ERs O3N2 (Kumari et al. 2019) methods, respectively. The slope (metallicity gradient) from the linear fitting is indicated by $\nabla$ [O/H].

| Name          | intercept       | slope $\nabla$ [O/H] (dex/arcsec) | mean   | sd   | intercept       | slope $\nabla$ [O/H] (dex/arcsec) | mean   | sd   |
|---------------|-----------------|----------------------------------|--------|------|-----------------|----------------------------------|--------|------|
| NGC 193       | 8.878/8.83/8.83 | -0.022/-0.026/-0.009             | 8.808/8.74/8.81 | 0.09/0.11/0.04 | .         | .                  | .      | .    |
| NGC 410       | 8.87/8.87/8.82  | -0.034/-0.027/-0.009             | 8.808/8.76/8.82 | 0.10/0.12/0.04 | .         | .                  | .      | .    |
| NGC 584       | 8.84/8.78/8.81  | -0.036/-0.042/-0.009             | 8.778/8.69/8.83 | 0.13/0.18/0.05 | 8.69/8.63/8.78 | 0.030/0.0016/0.0002 | 8.778/8.69/8.82 | 0.12/0.17/0.08 |
| NGC 677       | 8.768/8.68/8.80 | -0.006/-0.008/-0.008             | 8.738/8.65/8.78 | 0.10/0.12/0.02 | .         | .                  | .      | .    |
| NGC 777       | 8.85/8.81/8.80  | -0.10/0.027/0.002                | 8.838/8.78/8.80 | 0.12/0.15/0.04 | .         | .                  | .      | .    |
| NGC 924       | 8.808/7.47/8.79 | -0.009/-0.009/0.002              | 8.728/7.65/8.60 | 0.17/0.24/0.04 | 8.79/8.68/8.75 | -0.006/0.0025/0.0001 | 8.768/7.28/8.62 | 0.16/0.12/0.03 |
| NGC 940       | 8.978/9.68/8.85 | -0.055/-0.072/0.017              | 8.608/8.51/8.70 | 0.04/0.06/0.02 | 8.63/8.53/8.82 | -0.005/0.0052/0.0005 | 8.688/5.68/8.72 | 0.14/0.20/0.05 |
| NGC 978       | 8.758/6.86/8.79 | -0.005/-0.005/-0.009             | 8.748/6.68/8.78 | 0.08/0.11/0.03 | .         | .                  | .      | .    |
| NGC 1060      | 8.758/6.7/8.7   | -0.014/-0.006/0.002             | 8.798/7.65/8.68 | 0.05/0.06/0.01 | 8.73/8.70/8.75 | 0.008/0.001/0.0001 | 8.738/6.66/8.68 | 0.04/0.06/0.01 |
| NGC 1453      | 8.868/8.38/8.83 | -0.021/-0.026/-0.008             | 8.838/7.8/8.80 | 0.10/0.19/0.04 | 8.778/6.98/8.78 | -0.001/0.001/0.0013 | 8.808/7.48/8.80 | 0.13/0.18/0.04 |
| NGC 1587      | 8.798/7.12/7.8   | -0.014/-0.013/-0.004           | 8.758/6.78/8.75 | 0.08/0.11/0.04 | 8.748/7.38/8.80 | -0.004/0.0019/0.0058 | 8.718/6.98/8.71 | 0.13/0.07/0.05 |
| NGC 4008      | 8.798/7.61/8.7  | -0.017/-0.015/-0.002           | 8.768/6.91/8.71 | 0.13/0.17/0.04 | .         | .                  | .      | .    |
| NGC 4169      | 8.888/8.58/8.33 | -0.042/-0.039/-0.006           | 8.718/6.18/8.78 | 0.05/0.07/0.03 | 8.818/7.48/8.81 | -0.0036/0.004/0.0004 | 8.748/6.98/8.82 | 0.20/0.25/0.06 |
| NGC 4261      | 8.908/8.88/8.82 | -0.010/-0.015/0.005            | 8.898/7.88/8.83 | 0.08/0.10/0.04 | .         | .                  | .      | .    |
| ESO0507-G025  | 8.818/7.48/8.82 | -0.011/-0.014/-0.007           | 8.818/7.58/8.68 | 0.09/0.13/0.02 | 8.588/5.08/8.68 | -0.001/0.0019/0.0001 | 8.748/6.68/8.68 | 0.06/0.09/0.01 |
| NGC 5846      | 8.918/8.98/8.85 | -0.068/-0.094/-0.020           | 8.828/7.78/8.84 | 0.04/0.05/0.08 | 8.788/7.18/8.81 | 0.0002/0.0011/0.0002 | 8.798/7.28/8.81 | 0.08/0.11/0.05 |
| NGC 6658      | 8.888/8.98/8.83 | -0.064/-0.105/-0.025           | 8.788/7.48/7.97 | 0.16/0.20/0.08 | .         | .                  | .      | .    |
| NGC 7619      | 8.978/9.97/9.7   | -0.065/-0.089/-0.035           | 8.888/8.85/8.73 | 0.12/0.17/0.04 | .         | .                  | .      | .    |
APPENDIX G: COLD GAS CONTENT

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Figure G1. H\textsc{i} profiles from NED with standardised x and y-axis. In the standardised plots, the NGC 677 and the ESO spectra velocities have been binned ×2.

Table G1. H\textsc{i} and H\textsc{2} properties and M\(\ast\) available from the literature.

| Name        | H\textsc{i}+[N\textsc{i}] morphology | V(H\textsc{i}) (km s\(^{-1}\)) | \(W_{20}(H\textsc{i})\) (km s\(^{-1}\)) | A flux(H\textsc{i})\(\text{a}\) | M(H\textsc{i})\(\text{b}\) \(\times 10^9\) M\(\odot\) | M(H\textsc{2})\(\text{c}\) \(\times 10^9\) M\(\odot\) | M\(\ast\)\(\text{d}\) \(\times 10^{11}\) M\(\odot\) | H\textsc{i} spectrum source                  |
|-------------|--------------------------------------|-------------------------------|-----------------------------------|-------------------------------|-----------------|-----------------|-----------------|-----------------|
| NGC 584     | i                                    | ...                           | ...                              | 0.12                          | <0.01           | 2.13            | ...             | Haynes et al. (2018) |
| NGC 677     | i                                    | 5138±6                        | 272±12                           | 1.10±0.07                     | 1.70            | <0.23           | 3.52            | Haynes et al. (2018) |
| NGC 924     | ii                                   | 4428±5                        | 509±10                           | 1.07±0.08                     | 9.12            | 0.05            | 1.88            | Haynes et al. (2018) |
| NGC 940     | ii                                   | 5127±4                        | 218±8                            | 1.02±0.08                     | 9.14            | 6.10            | 2.94            | Paturel et al. (2003) |
| NGC 1587    | i                                    | 7163±1                        | 302±2                            | 1.29±0.04                     | 2.51            | 0.23            | 3.03            | Gallagher, Knapp & Faber (1981) |
| NGC 4169    | ii                                   | 3811±7                        | 470±13                           | 1.56±0.07                     | 10.71           | 0.14            | 1.27            | Haynes et al. (2018) |
| ESO0507-G025| ii                                   | 3248±8                        | 450±16                           | 1.26±0.51                     | 31.62           | 0.42            | 2.84            | Barnes et al. (2001) |
| NGC 5846    | i                                    | 1804±14                       | 502±27                           | 1.4±0.04                      | 0.28            | 0.01            | 3.39            | Bottinelli & Gouguenheim (1979) |

\(\text{a}\) Asymmetry in the H\textsc{i} profiles using the method from Espada et al. (2011).

\(\text{b}\) From H\textsc{i} compilation in O’Sullivan et al. (2018), although as noted by those authors H\textsc{i} was not detected in NGC 940 and NGC 5846 during the ALFALFA survey as expected.

\(\text{c}\) From O’Sullivan et al. (2015) and O’Sullivan et al. (2018)

\(\text{d}\) From Kolokythas et al. (2022)