The evolution of the radio luminosity function of group galaxies in COSMOS

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ABSTRACT

To understand the role of the galaxy group environment on galaxy evolution, we present a study of radio luminosity functions (RLF$s$) of group galaxies based on the Karl G. Jansky Very Large Array-COSMOS 3 GHz Large Project. The radio-selected sample of 7826 COSMOS galaxies with robust optical and near-infrared counterparts, excellent photometric coverage, and the COSMOS X-ray galaxy groups ($M_{200c} > 10^{13.5} M_\odot$) enables us to construct the RLF$s$ of group galaxies (GG$s$) and their contribution to the total RLF since $z \sim 2.3$. Using the Markov chain Monte Carlo algorithm, we fitted a redshift-dependent pure luminosity evolution model and a linear and power-law model to the luminosity functions. We compared it with past RLF studies from VLA-COSMOS on individual populations of radio-selected star-forming galaxies (SFGs) and galaxies hosting active galactic nuclei (AGN). These populations are classified based on the presence or absence of a radio excess concerning the star formation rates derived from the infrared emission.

We find that the density of radio galaxies in groups is low compared to the field at $z \sim 2$ down to $z \sim 1.25$, followed by a sharp increase at $z \sim 1$ by a factor of six, and then a smooth decline towards low redshifts. This trend is caused by both a decrease in the volume abundance of massive groups at high-$z$ and the changes in the halo occupation of radio AGN, which are found by other studies to reside at smaller halo mass groups. This indicates that the bulk of high-$z$ log$_{10}(M_{200c}/M_\odot) > 13.5$ groups must have formed recently, and so the cooling has not been established yet. The slope of the GG RLF is flatter compared to the field, with excess at high radio luminosities. The evolution in the GG RLF is driven mainly by satellite galaxies in groups. At $z \sim 1$, the peak in the RLF, coinciding with a known overdensity in COSMOS, is mainly driven by AGN, while at $z > 1$ SFGs dominate the RLF of group galaxies. A drop in the occurrence of AGN in groups at $z > 1$ by a factor of six results in an important detail for the processes governing galaxy evolution.

Key words. galaxies: active – galaxies: evolution – galaxies: groups: general – radio continuum: galaxies

1. Introduction

The properties and evolution of galaxies are known to be strongly linked to their external environment. Massive halos are found to play a key role in galaxy evolution. At low redshifts, it has been found that clusters of galaxies are mostly dominated by early-type galaxies composed of old stellar populations, while low-density environments typically host late-type galaxies with younger and bluer stars, producing the star formation (SF) density distance to cluster centre relations and affecting the morphology of galaxies (e.g. Oemler 1974; Dressler 1980). We expect that galaxies in dense regions experience various physical processes such as tidal forces, mergers, high-speed interactions, harassment, and gas stripping, which in turn contribute to dramatic morphological changes and the quenching of star formation (e.g. Larson 1980; Byrd & Valtonen 1990). However, these physical processes’ precise timing and relative importance are not yet well understood.

The environmental processes that affect galaxy evolution could directly or indirectly influence the accretion onto the central black hole in galaxies, notably those with a stellar bulge (Magorrian et al. 1998). Both local and large-scale processes, which may affect cluster galaxies, also have the potential to affect the gas distribution in the galaxies and hence may trigger or suppress active galactic nuclei (AGN) activity.

Apart from the role of the galaxy group and cluster environment on radio emission of the brightest galaxy of the group, Khosroshahi et al. (2017) suggested that the radio luminosity of the brightest group galaxy (BGG) also depends on the group dynamics, in a way that BGGs in groups with a relaxed, virialised morphology are less radio luminous than the BGG with the same stellar mass but in an evolving group. This was supported numerically by a semi-analytic approach (Raouf et al. 2018), where they predicted the radio power for the first time. However, the numerical models cannot be constrained without an observational constraint reaching high redshift.

Many radio studies (Best et al. 2002; Barr et al. 2003; Miller & Owen 2003; Reddy & Yun 2004) showed an increase in radio-loud AGN activity in galaxy clusters, at a range of redshifts, and in both relaxed and merging systems. The radio emission (<30 GHz) in galaxies is dominated by synchrotron radiation from accelerating relativistic electrons, with a fraction of free-free emission (e.g. Sutherland 1989; Condon 1992; Clemens et al. 2008; Tabatabaei et al. 2017). The feedback from...
supernovae explosions in star-forming galaxies (SFGs) and that from the growth of the central supermassive black hole (SMBH) in AGN are two main sources of acceleration of cosmic electrons.

To use radio emission as a proxy for measuring star formation rates (SFRs) or AGN feedback, it is important to estimate which process dominates the radio emission: star formation processes or SMBH accretion. We follow the method demonstrated in Delvecchio et al. (2017), who measured the radio excess compared to the total star formation-based infrared (IR) emission. Objects that exhibit radio excess above what is expected from star formation alone, as calculated from their infrared emission, are deemed AGN, and the rest are SFGs. These populations contribute different percentages to the energy budget. In the radio, this is quantified by calculating the radio luminosity function (RLF). Novak et al. (2018) studied the 3 GHz VLA-COSMOS RLF and calculated the relative contributions to the RLF from the AGN and SFG populations down to submicrojansky levels. AGN and SFGs contribute differently to the RLF: AGN are known to dominate the bright part of the RLF, and SFGs dominate the faint part. In particular, 90% of the population at the faint end (<0.1 mJy) is linked to SFGs. In clusters of galaxies, Yuan et al. (2016) who studied the RLF of the brightest cluster galaxies (BCGs) up to z = 0.45 found no evolution and a dominant population of AGN, as most of their BCGs are associated with AGN. Branchesi et al. (2006) compared clusters at 0.6 < z < 0.8 to the local Abell clusters and found very different RLFs. These studies target populations dominated by AGN and thus probe the high end of the radio luminosity function. The question arises as to how much smaller mass environments, those of groups of galaxies, and their members contribute to the observed radio source population.

In this work, we investigated the population of galaxies inside X-ray galaxy groups in the COSMOS field (Gozaliasl et al. 2019) to quantify their contribution to the RLF at 3 GHz VLA-COSMOS (Novak et al. 2018; Smolčić et al. 2017a). Section 2 describes the X-ray and radio data used throughout this work. Section 3 focuses on methods for deriving the RLF and its evolution through cosmic time. In Section 4, we present and discuss the results on the RLF of group galaxies and calculate their contribution to the total RLF at 3 GHz. We further separate the galaxies into BGGs and satellites (SGs). We also use the radio excess parameter and the presence of jets/lobes to disentangle AGN and SFGs in the radio and provide the relative contributions of these populations to the group galaxies (GG) RLF and the total RLF. This is presented in Section 5. Finally, in Section 6, we provide a summary. The tables with the analysis results can be found in the appendix tables (Table A.1 is available at the CDS and Tables A.2–A.9 are available on Zenodo).

We assumed flat cold concordance Lambda cold dark matter (ACDM) cosmology defined with a Hubble constant of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, dark energy density of $\Omega_{\Lambda} = 0.7$, and matter density of $\Omega_m = 0.3$. For the radio spectral energy distribution, we assumed a simple power law described as $S_{\nu} \propto \nu^{-\alpha}$, where $S_{\nu}$ is the flux density at frequency $\nu$, and $\alpha$ is the spectral index. If not explicitly stated otherwise, $\alpha = 0.7$ is assumed.

2. Data

The Cosmic Evolution Survey (COSMOS) is a deep multi-band survey covering a $2 \text{ deg}^2$ area, thus offering a comprehensive data set to study the evolution of galaxies and galaxy systems. The full definition and survey goals can be found in Scoville et al. (2007). The sample selection for this study is described below.

2.1. Radio selected galaxies

We used radio-selected samples of galaxies cross-matched with multiwavelength optical/near-infrared (NIR) and value-added catalogues in the COSMOS field. The radio data were selected from the VLA-COSMOS 3 GHz Large Project (Smolčić et al. 2017a), with a median sensitivity of 2.3 mJy beam$^{-1}$ and resolution of 0.75 arcsec. The cross-correlation of the radio and multi-wavelength sources can be found in Smolčić et al. (2017b). Only sources within the COSMOS2015 catalogue (Laigle et al. 2016) or with i-band counterparts were given the availability of reliable redshift measurements. The COSMOS2015 catalogue contains the high-quality multiwavelength photometry of $\sim$800 000 sources across more than 30 bands from near-ultraviolet (NUV) to near-infrared (NIR) through several surveys and legacy programmes (see Laigle et al. 2016, for a detailed description).

2.2. X-ray galaxy groups catalogue

Finoguenov et al. (2007) and George et al. (2011) presented primary catalogues of the X-ray galaxy groups in COSMOS. These catalogues combined the available Chandra and XMM-Newton data (with improvements in the photometric data sets) used to identify galaxy groups, with secure identification reaching out to $z \sim 1.0$. On completion of the visionary Chandra programme (Elvis et al. 2009; Civano et al. 2016), high-resolution imaging across the full COSMOS field became available. Furthermore, more reliable photometric data provided a robust identification of galaxy groups at a higher redshift, thus resulting in a revised catalogue of extended X-ray sources in COSMOS (Gozaliasl et al. 2019), which was obtained by combining both the Chandra and XMM-Newton data for the COSMOS field.

The COSMOS galaxy group catalogue that we used in this study relies on a combination of an updated version of the initial group catalogues with 183 groups and a new catalogue of 73 groups described in Gozaliasl et al. (2019, and in preparation), which combines data of all X-ray observations from Chandra and XMM-Newton in the 0.5–2 keV band with robust group identification up to $z \sim 2.0$. It reaches an X-ray limit of $3 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.5–2 keV range and contains groups with $M_{500} = 8 \times 10^{12} – 3 \times 10^{15} \text{ M}_\odot$.

Group halo mass is the total mass (commonly called $M_{200c}$) that was determined using the scaling relation $L_X \sim M_{200c}$ with weak-lensing mass calibration as presented by Leauthaud et al. (2010). The radius of the group $R_{200}$ is defined as the radius enclosing $M_{200c}$ with a mean overdensity of $\Delta \sim 200$ times the critical background density. Gozaliasl et al. (2019) discussed the mass completeness of the group sample given the surface brightness limitation of the X-ray data set. Over the $0.5 < z < 1.2$ redshift range, the evolution of the group mass limit is weak and lies within the observational uncertainties, which are around log$(M_{\text{group}}/M_\odot) \sim 13.38$ at $z \sim 0.5$ and log$(M_{\text{group}}/M_\odot) \sim 13.5$ at $z > 0.5$.

The redshift of the group is the redshift of the peak of the galaxy distribution within the group radius while slicing the light cone with a redshift step of 0.05. In most cases, this is the redshift of the peak of the galaxy distribution within the group radius. In this study, we followed the redshift of the group for every group that was selected.
BGGs have robust spectroscopic redshifts. The centre of groups from the X-ray emission is determined with an accuracy level of $\sim 5''$, using the smaller scale emission detected by Chandra data. The BGGs do not always locate at the peak of the X-ray centre emission. As described in Gozaliasl et al. (2019), the off-central BGG probably resides in groups more likely to have experienced a recent halo merger. The rest of the group galaxies (GGs) are called satellite galaxies (SGs).

A quality flag has been assigned to groups depending on the robustness of the extraction and the potential availability of spectroscopic redshift (Gozaliasl et al. 2019). In our study, we only kept the groups with flags 1, 2, and 3. We only considered groups with BGG galaxies more massive than $\log M_*/M_\odot = 10$. We refer the reader to Gozaliasl et al. (2019) for further information on identifying groups. Within the virial radius of these groups, the above selection criteria resulted in a total of 306 objects distributed in the galaxy groups. In Fig. 1, we present the data for the group galaxies used in our analysis. The spectroscopic redshifts are available for 35% of our sources, and the median accuracy of the photometric redshifts is $\Delta z/(1 + z_{\text{spec}}) = 0.007$ (Laigle et al. 2016).

### 2.3. Sample of group galaxies used in this analysis

To analyse the radio luminosity function of group galaxies in COSMOS, we cross-matched the galaxy group catalogue and the 3 GHz VLA-COSMOS data (Smolcic et al. 2017a) within a 0.8$''$ radius. We furthermore used the 3 GHz VLA-COSMOS data presented by Novak et al. (2018), who constructed RLFs up to $z \sim 5.5$, to compare to the total RLF in COSMOS up to $z \sim 2.3$. Additionally, Novak et al. (2018) separated objects in SFGs and AGN following the radio excess prescription of Delvecchio et al. (2017). This method is based on the excess radio emission expected from star formation alone. Delvecchio et al. (2017) fitted the infrared spectral energy distribution of radio sources at 3 GHz VLA-COSMOS and calculated the contribution of the 3 GHz VLA-COSMOS radio sources to the radio luminosity by applying a conservative cut. Galaxies that exhibit an excess in radio emission above $3\sigma$ from what is expected from SF alone were deemed AGN, with the rest being SFGs. This method was used to separate the Novak et al. (2018) sample, which we use here for comparison, in SFGs and AGN. Finally, Novak et al. (2018) described possible biases and uncertainties associated with the data sample selection, and thus we refer the reader to this reference.

### 3. Methods and analysis

We describe the process of calculating the RLF for galaxies in groups in COSMOS (Gozaliasl et al. 2019) using the VLA-COSMOS 3 GHz data. We applied a cut in group mass, $M_{200c} > 10^{13.5} M_\odot$, to account for a difference in the limiting mass of the group catalogue with redshift (Sect. 2.2). This cut is demonstrated in the bottom frame of Fig. 1. We further separated group galaxies into BGGs and SGs. We compared the RLF of the population of SFGs and AGN at 3 GHz VLA-COSMOS in the same redshift bins to the total RLF calculated from the 3 GHz data (Novak et al. 2017; Smolcic et al. 2017a). We fitted linear and power-law models to the RLFs of GGs and compare them to the total RLF to obtain the contribution of GGs to the total RLF at 3 GHz VLA-COSMOS, something that has not been shown before in COSMOS.

### 3.1. Measuring the radio luminosity function

To obtain the total RLFs for GGs, SFGs, and AGN, we followed the method adopted by Novak et al. (2017) (see their Sect. 3.1). They computed the maximum observable volume $V_{\text{max}}$, for each source (Schmidt 1968) and simultaneously applied completeness corrections that take into account the nonuniform rms noise and the resolution bias (see Sect. 3.1 in Novak et al. 2017). Then, the
RLF is
\[
\Phi(L, z) = \frac{1}{\Delta \log L} \sum_{i=1}^{N} \frac{1}{V_{\text{max},i}} (V(z + \Delta z) - V(z))C(z),
\]
where \( L \) is the rest-frame luminosity at 1.4 GHz, derived using the radio spectral index of a source calculated between 1.4 GHz (Schinnerer et al. 2010) and 3 GHz (Smolčič et al. 2017a), and \( \Delta \log L \) is the width of the luminosity bin. The radio spectral index should remain unchanged between frequencies and is only available for a quarter of the 3 GHz VLA-COSMOS sample. For the rest of the sources detected only at 3 GHz, we assumed \( \alpha = 0.7 \). The latter corresponds to the average spectral index of the entire 3 GHz population (see Sect. 4 in Smolčič et al. 2017a). \( V_{\text{max}} \) is the maximum observable volume given by
\[
V_{\text{max},i} = \sum_{z_{\text{min}}}^{z_{\text{max}}} \frac{(V(z + \Delta z) - V(z))C(z)}{\Delta z},
\]
where the sum starts at \( z_{\text{min}} \) and adds co-moving spherical shells of volume \( 4\pi V = V(z + \Delta z) - V(z) \) in small redshift steps \( \Delta z = 0.01 \) until \( z_{\text{max}} \). \( C(z) \) is the redshift-dependent geometric and statistical correction factor. This takes into account sample incompleteness. For a thorough description of the biases, see Section 6.4 in Novak et al. (2017). The correction factor is given by
\[
C(z) = \frac{A_{\text{obs}}}{41253 \text{ deg}^2} \times C_{\text{radio}}(S_{1.4\text{GHz}}(z)) \times C_{\text{opt}}(z),
\]
where \( A_{\text{obs}} = 1.77 \text{ deg}^2 \) is the effective unflagged area observed in the optical-to-NIR wavelengths, \( C_{\text{radio}} \) is the completeness of the radio catalogue as a function of the flux density \( S_{1.4\text{GHz}} \), and \( C_{\text{opt}} \) is the completeness owing to radio sources without an assigned optical-NIR counterpart. Completeness corrections are shown in Smolčič et al. (2017a) in their Fig. 16 and Table 2, and in Novak et al. (2017) in their Fig. 2.

The redshift bins are large enough not to be severely affected by photometric redshift uncertainty and follow the selection of Novak et al. (2017) to allow comparisons. Luminosity bins in each redshift bin span the data’s observed luminosity range. To eliminate possible issues due to poorer sampling, the lowest luminosity ranges from the faintest observed source to the 5\( \sigma \) detection threshold at the upper redshift limit (corresponding to \( 5 \times 2.3 \text{ mJy beam}^{-1} \) at 3 GHz). The reported luminosity for each RLF is the median luminosity of the sources within the bin. The RLFs for all group galaxies are shown in Figs. 2 and 3 (black points) and are also listed in Table A.2. The RLFs for the BGGs and SGs are also shown in Figs. 2 and 3 (red squares/yellow stars) and are listed in Tables A.3 and A.4, respectively. The \( z \) bins in Figs. 2 and 3 are split in two halo mass \( M_{200c} \), bins, above and below \( 10^{13.5} M_{\odot} \), and for our further analysis, we used the values above. We note that at \( 1.6 < z < 2.3 \) we do not have SGs above our halo-mass cut \( M_{200c} > 10^{13.5} M_{\odot} \). This is related to limits in the radio power that are probed at those redshifts, leading to low statistics and a scarcity of less massive groups. As discussed in Novak et al. (2018), there is only a 5–10% loss of completeness on the optical/NIR counterparts above \( z \approx 2 \).

### 3.2. The total RLF at 3 GHz VLA-COSMOS

We used the total RLF derived from the SFG and AGN populations at 3 GHz VLA-COSMOS (Novak et al. 2017, 2018; Smolčič et al. 2017c) to compare to the RLF values derived for the group galaxies in COSMOS. The RLFs of the SFG and AGN populations are calculated similarly for the same redshift bins as those described above and for the same area coverage as the galaxy groups in COSMOS. To fit the RLF, two models are used in the literature (e.g. Condon 1984; Sadler et al. 2002; Gruppioni et al. 2013): the pure luminosity evolution (PLE) and the pure density evolution (PDE). The RLF is fit, assuming its shape remains unchanged at all observed cosmic times. Only the position of the turnover and normalisation can change with redshift. This corresponds to the translation of the local LF in the log \( L \)–log \( \Phi \) plane (Condon 1984) and can be divided into pure luminosity evolution (horizontal shift) and pure density evolution (vertical shift).

To describe an RLF across cosmic time, the local RLF is evolved in luminosity or density, or both (e.g. Condon 1984). This is parametrised (Novak et al. 2018) using two free parameters for density evolution \( (\alpha_D, \beta_D) \), and for two luminosity evolution \( (\alpha_L, \beta_L) \) to obtain
\[
\Phi(L, z, \alpha_L, \beta_L, \alpha_D, \beta_D) = (1 + z)^{\alpha_L + \alpha_D} \times \Phi_0 \left( \frac{L}{1 + z} \right)^{\beta_L + \beta_D},
\]
where \( \Phi_0 \) is the local RLF. Since the shape and evolution of the RLF depend on the galaxy population type, Novak et al. (2017) used a power-law plus log-normal shape of the local RLF for SFGs. They used the combined data from Condon et al. (2002), Best et al. (2005), and Mauch & Sadler (2007) to obtain the best fit for the local value:
\[
\Phi_0^{\text{SF}}(L) = \Phi_* \left( \frac{L}{L_*} \right)^{1-\sigma} \exp \left[ -\frac{1}{2\sigma^2} \log^2 \left( 1 + \frac{L}{L_*} \right) \right],
\]
where \( \Phi_* = 3.55 \times 10^{-3} \text{ Mpc}^{-3} \text{ dex}^{-1}, L_* = 1.85 \times 10^{21} \text{ W Hz}^{-1}, \alpha = 1.22, \) and \( \sigma = 0.63 \).

It was noted by Novak et al. (2017) that the PDE of SF galaxies would push the densities to very high numbers, thus making them inconsistent with the observed cosmic star formation rate densities. This is a consequence of the fact that our data can only constrain the bright, log-normal part of the SF RLF. For AGN, it was shown by Smolčič et al. (2017c) that the PDE and PLE densities do not deviate strongly from a simple power law at the observed luminosities. Considering the above reasoning, while also trying to keep the parameter space degeneracy to a minimum, we decided to only use the PLE for our analysis. Thus, we adopted the approach of Novak et al. (2018), who fitted the total RLF for SFG and AGN populations by constructing a four–parameter redshift-dependent, pure-luminosity evolution model with two parameters for the SFG and AGN populations of the following form:
\[
\Phi(L, z, \alpha_L^{SF}, \beta_L^{SF}, \alpha_L^{AGN}, \beta_L^{AGN}) = \Phi_0^{SF} \left( \frac{L}{1 + z} \right)^{\alpha_L^{SF} + \alpha_L^{AGN}} \times \Phi_0^{AGN} \left( \frac{L}{1 + z} \right)^{\beta_L^{SF} + \beta_L^{AGN}},
\]
where \( \Phi_0^{SF} \) is the local RLF for SFGs as in Eq. (5); for the non-local Universe it is a function of the quantity in parentheses, namely \( L/(1 + z)^{\alpha_L^{SF} + \alpha_L^{AGN}} \times \Phi_0^{AGN} \) is the local RLF for AGN of the following form:
\[
\Phi_0^{AGN}(L) = \frac{\Phi_*}{(L_*/L)^{\alpha} + (L_*/L)^{\beta}}.
\]
where $\Phi_\star = \frac{1}{4} \cdot 10^{-5.5} \text{Mpc}^{-3} \text{dex}^{-1}$, $L_\star = 10^{24.59} \text{W Hz}^{-1}$, $\alpha = -1.27$, and $\beta = -0.49$ (Smolčić et al. 2017c; Mauch & Sadler 2007); for the nonlocal Universe it is a function of the quantity $L/(1+z)^{\gamma_{200c} < \beta_{\text{AGN}}}$.

Novak et al. (2018) used the Markov chain Monte Carlo (MCMC) algorithm, available in the Python package emcee (Foreman-Mackey et al. 2013), to perform a multivariate fit to the data. The redshift dependence of the total evolution parameter $\alpha + z \cdot \beta$ (see Eq. (6)) is necessary to describe the observations at all redshifts. The best-fit values for SFGs, based on the results of Novak et al. (2018), are $\alpha_{\text{SF}} = 3.16$ and $\beta_{\text{SF}} = -0.32$, and for AGN are $\alpha_{\text{AGN}} = 2.88$ and $\beta_{\text{AGN}} = -0.84$. The $\alpha_L$ and $\beta_L$ values for both SFGs and AGN are valid for $z < 5.5$ and within the redshift range of our sample of group galaxies. We used these values to plot the fit to the RLF for SFGs and AGN in Fig. 3, shown with blue and red lines, respectively. The total RLF (including all SFGs and AGN) is shown as a dashed black line in Fig. 3.

### 3.3. Fitting the RLF of Group Galaxies and Comparing to the Total 3 GHz RLF

Fitting the GG RLF is not a simple task. Performing an MCMC fit to the GG data with four free parameters ($\alpha_{\text{SF}}, \beta_{\text{SF}}, \alpha_{\text{AGN}}, \text{and } \beta_{\text{AGN}}$), similarly to what was done in Novak et al. (2018), is proven to be problematic, and the MCMC does not converge. Below, we investigate whether the functional form of the RLF, as presented above, can fit the GG RLF.

#### 3.3.1. Scaled fit

We scaled the total 3 GHz RLF to fit the GG RLF using a MCMC method. The resulting GG RLF is shown in Fig. 2. There is a large deviation in the RLF values of GGs compared to the scaled fit, especially above luminosities of $10^{26} \text{W Hz}^{-1}$. We performed a $\chi^2$ test for the goodness of the fit between the GG values and the predicted scaled fit. The results are shown in Table A.9 in...
the appendix. The \( \chi^2 \) is large for most redshift bins, suggesting the model is not a good fit to the data. Additionally, we plot the ratio between data and model (see Fig. 4). It is evident that for the redshift bins with \( \tilde{z}_{\text{med}} = 0.35 \) and 1.2 the model underfits the data in the high-luminosity bins by up to ~2 orders of magnitude, suggesting that the functional form of the RLF does not work well in the case of group galaxies. Hence, we explored an alternative method for fitting the GG RLF.

### 3.3.2. Power-law fit

We fitted a power law (linear regression fit in log-log) to the radio luminosity function of the group galaxies and, separately, of the BGGs and SGs, from redshifts 0.07 to 2.3 of the following form:

\[
y = \Phi_\bullet/(L_\bullet^\gamma) \cdot L^\gamma,
\]

where \( L_\bullet \) is arbitrarily chosen to be 10^{24} \, \text{W Hz}^{-1}, and \( \Phi_\bullet \) is the density at \( L_\bullet \).

Table A.5 shows the results for each fit. The best-fit model for the GGs is shown in Fig. 3, where we also compare the radio luminosity function of group galaxies to the total radio luminosity function of radio galaxies in the 3 GHz VLA-COSMOS survey and the radio luminosity function of AGN and the star-forming population. We also present the linear regression fit for BGGs, but exclude the one for SGs for clarity. The radio emission due to the star formation outweighs that from the AGN in lower redshifts, i.e., at \( z < 1 \), except at high-radio-luminosity bins where the AGN contribution dominates. This behaviour has been described in Novak et al. (2017) and Smolčič et al. (2017a), and agrees with other surveys. Adopting a fit similar to the total RLF used in Novak et al. (2018) provides a very poor fit to the GG data, particularly in the high-luminosity bins. Similarly, allowing both luminosity and \( \Phi_\bullet \) to be free parameters resulted in the slope fit being dominated by two points with the smallest error. These tell us the GGs do not necessarily follow the shape of the total 3 GHz RLF, particularly at high luminosities, where we see increased radio activity of GG member galaxies.
3.3.3. Methods comparison

To investigate which method fits the GG RLF best, we compared the predicted to the real values. As mentioned earlier, we performed a \( \chi^2 \) test for the goodness of the fit between the GG values and the predicted ones (Table A.9). The test yields similar results for both methods, where the linear regression fit gives slightly better results, but neither of the models is a good fit to the data.

Furthermore, we visually inspect the RLF grid plots in Figs. 2 and 3. Both methods provide fairly good fits to the data. Should we use these fit lines to predict a value, it would not necessarily agree with the observed values in some areas of the parameter space. In particular, as seen in Fig. 2 for the scaled RLF, it does not fit the GGs above a radio luminosity of \( 10^{25} \text{ W Hz}^{-1} \) well in all redshift bins, i.e. the part that can be dominated by AGN contribution (based on the 3 GHz RLF). In Fig. 3, for the power-law RLF, we also see the fit is not good for GGs above radio luminosity \( 10^{25} \text{ W Hz}^{-1} \), but this is mainly in the redshift bins \( z \sim 0.35 \) and \( z \sim 1.2 \). From the ratio between data and model in Fig. 4, we see that the linear regression fit deviates less, on average, than the scaled fit from the observational data at all luminosities and redshifts.

To sum up, the \( \chi^2 \) test suggests neither of the fitting methods fits the data well. By visual inspection and from the ratio between data and model (Fig. 4), we see that we under-fit the GG RLF when using either of the two fitting methods for radio luminosities above \( 10^{25} \text{ W Hz}^{-1} \) in the redshift bins \( z_{\text{med}} = 0.35 \) and 1.2. Below this value, there is a good rough agreement, with marginally better fits for the power-law RLF. The ratio between data and model in Fig. 4 aids us in selecting a method, i.e. the power-law, linear-regression fit. Thus, for the remainder of this analysis, we used the power-law fit method, but also present results of the scaled method for completeness (see Table A.6).

3.3.4. GG contribution to the total RLF

We calculate fractions obtained by the different methods we examined, the fraction of GG RLF to the total RLF if we apply the power-law, linear-regression fit (Sect. 3.3.2) and the fraction of GG RLF to the total RLF if we apply the scaled RLF (Sect. 3.3.1).

To quantify the contribution of the RLF of group galaxies to the total RLF of the 3 GHz population, we divide the power-law RLF of GGs, assuming a fixed slope of \( \gamma = -0.75 \), with the total RLF from the 3 GHz sample for each redshift bin. This gives the fractional contribution of group galaxies to the total RLF. In the top panel of Fig. 5, we plot the fraction with respect to the radio luminosity at 1.4 GHz up to \( 10^{25} \text{ W Hz}^{-1} \). The reason for that is the RLF of 3 GHz VLA-COSMOS observations is not well constrained above that luminosity (Novak et al. 2018). Furthermore, we should consider that our model might be a good representation of the universe at \( L > 10^{25} \text{ W Hz}^{-1} \), and the COSMOS is...
We also calculated the RLFs of all massive galaxies with $M_\odot > 10^{11.2} M_\odot$, which are 3 GHz sources, and compared them to the total RLF. This fraction is shown in the middle panel of Fig. 5. We see an increase in the contribution to the total RLF at $z_{med} = 0.3$, and at higher redshifts it is similar to that of GGs. The choice of this stellar-mass cut, as a comparison, was motivated by the study of Smolčić et al. (2017c) in order to select massive galaxies across all redshifts. We discuss this further in the next section.

The bottom panel of Fig. 5 presents fractions using the scaled fit method presented in Sect. 3.3.1. The fraction is the same across the adopted luminosity range, as expected for a scaled fit. In Fig. 6, we plot the radio luminosity function and the fraction, for the scaled and power-law fits, in relation to redshift for the GGs, BGG, and SGs, and discuss this in the following section.

4. Evolution of the RLF in galaxy groups

The top panel of Fig. 5 shows that the contribution of GGs to the total RLF increases from $z \sim 2$ to 0.07, in particular for objects above radio luminosities at $10^{23}$ W Hz$^{-1}$. This picture suggests an evolutionary scenario for the RLF of galaxy groups. We investigated this further by plotting the RLF of GGs, BGGs, and SGs (left panel) in Fig. 6, as well as their relative contribution to the total 3 GHz RLF as a function of redshift (right panel). The GG RLF has a low value at $z \sim 2$ down to $z \sim 1.25$, followed by a sharp increase in the GG RLF at $z \sim 1$ by a factor of six. After this, there is a smooth decline, mimicking a mild evolution by a factor of two. This is an interesting trend, which is not observed in the total RLF. As seen by the normalisation value of the total $\Phi_\gamma$ for a fixed radio luminosity at $10^{24}$ W Hz$^{-1}$ (shown in cyan), galaxies in the 3 GHz sample display a decrease in their RLF with redshift across all redshifts, while the RLF of GGs increases at $z \sim 1$ (left panel of Fig. 6); the peak at $z_{med} \sim 0.9$ coincides with known overdensities in the COSMOS field. Interestingly, Smolčić et al. (2017c) showed that a similar trend can be reproduced with galaxies. In their Fig. 1, they present a slight increase in the median values of $M_\bullet$ in their radio excess sample up to redshift $z = 1$, and the depletion of massive galaxies above $z > 1$, which we also see in the X-ray groups. We observed this at a median value of $\sim 10^{11.2} M_\odot$. In the middle panel of Fig. 5, we see that massive galaxies above $10^{11.2} M_\odot$ contribute a large fraction to the total 3 GHz RLF below $z < 1$. This suggests that not all massive galaxies are in groups, but those that are remain radioactive (Fig. 5). The GG contribution to the RLF shows a nearly flat, but slightly enhanced, behaviour below $z < 0.75$, while the GG’s RLF does not exhibit a large contribution of radio emission at the lowest redshift bin as the massive galaxies’ RLF does. This suggests those massive galaxies are either in the field or occupy halo masses below our adopted cut at $\log_{10}(M_{200c}/M_\odot) > 13.5$.

The RLF of SGs dominates the RLF of group galaxies up to a redshift of $z_{med} \sim 1.2$, with overdensities below $z = 1$ (Fig. 6–right). The fraction for the linear-regression fit method is a range of values that correspond to the adopted luminosity range (see also Fig. 5), plotted as violin plots. Both fractions follow the mild evolutionary trend we observe in the left panel. Scoville et al. (2013) studied the large-scale structure (LSS) in COSMOS and also report a statistically significant overdensity at $z = 0.93$. Additionally, the strongest density peaks, where we have massive clusters in COSMOS, are at redshifts 0.37, 0.73, and 0.83. Our $0.4 < z < 0.7$ bin misses LSS on both ends. Above $z > 2$ we do not currently have enough SGs to perform a robust analysis. This is likely to improve with future observations.

The relative contribution of the SGs to the RLF of group galaxies is higher by a factor of two than that of BGGs below $z \sim 1$. Additionally, BGGs contribute a small amount to the RLF of GGs, as seen in the left panel of Fig. 6, despite them being the most massive galaxies of the group. This is a very interesting result highlighting the importance of identifying the member group galaxies within a group and the need for high-sensitivity and high-resolution observations.

For reference, we split the redshift bins into low- and high-halo-mass objects. Objects with group masses below $10^{13.5} M_\odot$ contribute significantly to the lowest redshift bins and are linked to SGs, but this contribution was not taken into account in our analysis in order to ensure our sample is complete (see Sect. 2). The low-halo-mass points (Table A.5 and Fig. 3) show a faster
turnover as we do not expect to detect many low-mass, high-luminosity objects.

Yuan et al. (2016), who studied BCGs, found that RLFs of 7138 BCGs in the 0.05 < z < 0.45 range do not show significant evolution with redshift. This no-evolution pattern of BCGs agrees with our results for BGGs in COSMOS. In the left panel of Fig. 6, we see that the RLF of BGGs fluctuates slightly with redshift, but it is the RLF of satellites that drives the redshift evolution.

Novak et al. (2018) discussed possible biases that could affect the calculations. These include the assumed shape of the radio SED being a power law and the radio excess criterion being too conservative and thus excluding low-luminosity AGN from the sample. We refer the reader to their discussion (see their Section 3.4). Furthermore, Novak et al. (2018) discussed possible biases that affect the RLF of the high-luminosity bin, i.e., bright radio but faint in the near-infrared sources (K = 24.5 mag). We constrained our sample to halo masses above 10^{13.5} M_⊙ in order to perform an unbiased analysis. Incidentally, after the halo-mass cut, the remaining group galaxies in our sample are brighter than K = 24.5 mag.

In summary, we observe a nearly flat, but slightly enhanced, behaviour of the contribution of X-ray galaxy groups to the 3 GHz RLF up to z ~ 0.75, driven by SFGs and AGN (see Sect. 5) in GGs; this is followed by an increase and then a sharp drop. This agrees with past studies of the COSMOS field, and in particular with the study of Hale et al. (2018), who in their Fig. 10 showed that the AGN bias starts to deviate from values close to 5 × 10^{13} M_⊙ at z < 1 toward 1 × 10^{14} M_⊙ at z > 1. This explains the sharp drop we observe at z > 1, since we are probing halo masses > 10^{15} M_⊙ (see bottom panel of Fig. 1).

5. The AGN and SFG contribution to the GG RLF

The group galaxy population has a mixture of contributions from AGN and SFGs. To explore how much these populations contribute to the GG RLF, we cross-correlated the X-ray galaxy group catalogue with the sample of Vardoulaki et al. (2021), which is a value-added catalogue at 3 GHz VLA-COSMOS, and it includes 130 FR-type radio sources (FRI, FRII; Fanaroff & Riley 1974, and hybrids FRI/FRII), 1818 jet-less compact radio AGN (COM AGN), and 7232 SFGs (see Table 1). Radio AGN in the Smolčić et al. (2017b) sample were selected on the basis of their radio excess, as mentioned above. This criterion, due to the 3σ cut applied, excludes several FR-type radio AGN, which were identified in Vardoulaki et al. (2021) and classified as radio AGN because they exhibit jets/lobes. SFGs are objects that do not display radio excess.

To separately quantify the contribution of these populations to the group RLF and to the total RLF, we calculated their RLFs as described in Sect. 3, using the V_{max} method. All AGN and SFGs are in groups with halo masses of M_{200c} > 10^{13.5} M_⊙. The results for the AGN and SFG populations inside galaxy groups are shown in Fig. 7, where we also plot the RLF of AGN and SFGs from the sample of Novak et al. (2018), as in Fig. 3, and the total RLF at 3 GHz. In order to compare the RLF of AGN and SFGs that are GGs and the total RLF, we followed the analysis in Sect. 3.3.2. We fitted a linear regression and normalised it to 10^{25} W Hz^{-1} by applying Eq. (8) for γ = −0.75. The results are shown in Fig. 7.

For completeness and to enable comparisons between the methods, we also present the scaled AGN and SFG parts of the total RLF to the GG data and overplot it in Fig. 7. In Table 2, we give the scaling coefficients used in Fig. 2 at the five redshift bins (separately for the AGN and SFG scaled fits). Visually, we see that the scaled RLF is not a good fit to the SFG at z < 0.4 and to the AGN at z < 1.6, inside X-ray galaxy groups. We performed a χ^2 test for the AGN and SFGs, at all redshift bins, and present the results in Table A.9. The results show that neither of the fitting methods fits the data well.

We further calculated and plot the fractional contribution of AGN and SFGs that lie inside groups to the total RLF at 3 GHz (Fig. 8) by replicating Fig. 5. The fraction was calculated by dividing the RLF of AGN and of SFGs inside galaxy groups by the total 3 GHz RLF. The fractions per redshift bin are curved lines due to the total RLF being curved. We find that there is a significant contribution from group AGN and SFGs at redshifts z < 1.6, and very little contribution above that. We present the values for these fractions in Table 3. For completeness, we calculated the fractional contribution of the AGN and SFG RLF to the GG and total RLFs in the case where the scaled fit method is used. The fractions are also presented in Table 1. In Fig. 8, we overplot the fraction of AGN and SFG RLFs to the GG RLF, where both RLFs were calculated using the scaled fit method. The respective lines follow the scaled AGN and SFG distributions, where AGN contribute more to the total RLF at higher luminosities, while SFGs dominate at lower luminosities. We stress that the scaled method for AGN and SFGs inside galaxy groups in COSMOS, and given the current dataset, is an approximation. It assumes the total 3 GHz RLF fits the subpopulations of AGN and SFGs inside galaxy groups. The reason for using a scaled fit is the smaller numbers of objects in galaxy groups compared to the total 3 GHz sample. Ideally, with a larger sample of AGN and SFGs inside groups, an MCMC procedure can provide a good fit to the subpopulations. Our analysis suggests that the total 3 GHz RLF is not a good fit for individual populations inside galaxy groups and that the picture is more complicated than that.

For the linear-regression fit method, we obtain a constant value across all luminosities in Fig. 8 because the divided fits are both linear. The contribution of AGN RLF to the GG RLF is significant at the redshift bin z med = 0.6 of around 56% and at z med = 0.8 with fraction around 33%, and dominates the GG RLF.

| Redshift z_{med} | 0.3 | 0.6 | 0.9 | 1.2 | 2 |
|------------------|-----|-----|-----|-----|---|
| AGN              | 0.258 | 0.133 | 0.224 | 0.032 | 0.028 |
| SFG              | 0.041 | 0.044 | 0.094 | 0.012 | 0.016 |

Table 1. AGN and SFGs inside X-ray galaxy groups. Data from (Vardoulaki et al. 2021), cross-correlated with the X-ray galaxy group catalogue (Gozaliasl et al. 2019, and in prep.).

Table 2. Scaling coefficients for functional form of RLF (scaled fit) for AGN and SFG populations.
The fraction in SFGs is around 20\% for \(z_{\text{med}} = 0.6\) and \(z_{\text{med}} = 0.8\), while at \(z_{\text{med}} = 1.2\) the SFGs are dominating the GG RLF, with a fraction of 52\%. At \(z_{\text{med}} = 0.3\) we also see enhanced contribution in both AGN and SFGs compared to the GG RLF. This can be explained by the linear regression fit being normalised to \(10^{24} \, \text{W Hz}^{-1}\) and forced to have a slope of \(\gamma = -0.75\). For \(z > 1.6\), the contribution of SFGs to the GG RLF drops sharply and below 1\%, while we do not have AGN above \(z > 1.6\). These findings suggest that both AGN and SFGs contribute to the GG RLF, with the AGN contribution peaking around \(z \sim 1\).

There are 67 AGN associated with BGGs and 71 with SGs, as shown in Table 1. For SFGs, we obtain 47 BGGs and 193 SGs. Due to the small number of sources per bin, we cannot replicate Fig. 6 by splitting the AGN and SFGs’ RLF inside groups in BGGs and SGs and calculating their RLF. Fig. 6 suggests the evolution of the GG RLF is driven by satellites. Based on our results from Fig. 8, at the \(z_{\text{med}} = 0.3\) redshift bin, the SG AGN or SFGs are responsible for the peak of the GG RLF, while at \(z_{\text{med}} = 0.8\) the increase is mainly driven by AGN.

How much of the AGN contribution to the GG RLF comes from extended radio emission, given the capabilities of the 3 GHz VLA-COSMOS survey, is not easy to estimate due to sample size limitations. From Table 1, we see that \sim 82\% of AGN inside galaxy groups are jet-less AGN. However, in order to robustly answer this question we need to separate FRs and COM AGN inside groups and calculate their RLFs per redshift bin, as above, which we cannot do given the small number of FRs per redshift bin. To have an idea of how extended the FRs within the AGN sample are, we look at the linear projected sizes \(D\) of FRs in Vardoulaki et al. (2021). The sensitivity and resolution of the 3 GHz VLA-COSMOS survey are 2.3 \(\mu\text{Jy/beam}\) and 0\'\ Primerose, respectively. This means that we are able to resolve and disentangle structures of \sim 6 kpc at \(z \sim 2\). The
smallest FR reported in Vardoulaki et al. (2021) has \(D = 8.1\) kpc at \(z = 2.467\), just above the resolution limit, and the smallest edge-brightened FR has \(D = 24.3\) kpc at \(z = 1.128\), where the lobes are separated by 8 kpc. Inside X-ray galaxy groups, the smallest FR has \(D = 13.37\) kpc at \(z = 0.38\) with the most extended having \(D = 68.4\) kpc and \(z = 1.168\); this is also the most extended object in the Vardoulaki et al. (2021) FR sample. Future surveys with increased sensitivity and resolution will be able to resolve jets and lobes in AGN that appear compact at 3 GHz VLA-COSMOS. With future observations at larger sky areas and improved statistics, we will be in a better position to resolve this issue.

Nobels et al. (2022) showed, via hydrodynamical simulations of galaxy groups/clusters with masses above \(M_{200c} > 10^{13.5} M_\odot\) (as the ones studied here), a cyclical behaviour of AGN quenching and star formation activity: long periods where star formation is quenched by the AGN are followed by shorter periods of star formation and black hole accretion. This is because the reduction of AGN feedback makes the ICM unstable to precipitation and thus initiating a new episode of intense star formation. Furthermore, Pasini et al. (2020) reported that feedback mechanisms in groups and clusters of galaxies are similar. In our study, we find that the AGN contribution to the galaxy group’s RLF dominates at redshifts up to \(z = 0.8\). The hosts of these AGN at 3 GHz VLA-COSMOS are quenched, based on the study of Vardoulaki et al. (2021). AGN at \(z = 0.8\) show low star formation rates (SFRs \(\sim 8 M_\odot/yr\)) compared to SFGs at similar redshifts (SFRs \(\sim 24 M_\odot/yr\)). At lower redshifts (\(z = 0.3\)), both AGN and SFG populations show low median SFRs (\(\sim 1.2\) and \(\sim 3.4 M_\odot/yr\), respectively). The median SFR in the field shows similar median values compared to the one inside galaxy groups for \(z = 0.3\) & 0.8, for both AGN and SFGs.

To verify the cyclical behaviour presented in Nobels et al. (2022), a study of the duty cycle of individual objects is needed, which is beyond the scope of this analysis. A thorough analysis comparing AGN and SFGs in relation to a large-scale environment is presented in Vardoulaki et al. (2021), and we refer the reader to that study. A detailed investigation of AGN feedback since \(z = 5\) at 3 GHz COSMOS is presented in the studies of Smolčić et al. (2017c) and Ceraj et al. (2018).

Our analysis suggests that the bulk of high-\(z\) \(L_{1.4GHz}/M_\odot\) \(> 13.5\) groups must have formed recently, and so the cooling has not been established. This is linked to the drop in occurrence of AGN in groups at high \(z\) by a factor of six, suggesting that AGN feedback is lower by a factor of six at high redshifts. Hence, AGN feedback in the groups we are studying (\(L_{1.4GHz}/M_\odot\)) in the range 13.5–14.5) must be a recent phenomenon. There seems to be a change in the way groups operate above \(z > 1\), with a faster evolution. Mass changes quickly, and there is not enough time to virialise. Due to the lack of virialisation, the cooling does not start, and the AGN activity is suppressed. This change can be triggered by (1) high thermalisation of matter, which is not sufficient in this case; or (2) dynamically young groups where gas cooling does not happen. On the other hand, low-mass groups form at \(z = 6\). These are found to host radio AGN and have time to virialise, cool, and provide feedback. Additionally, cooling times for energetic electrons are much lower at high-\(z\).

### 6. Summary and conclusions

We present a study of radio luminosity functions, RLFs, of group galaxies in the COSMOS field based on data from the VLA-COSMOS 3 GHz Large Project (Smolčić et al. 2017a) and the X-ray galaxy groups catalogue (Gozaliasl et al. 2019, in prep.). The X-ray galaxy groups cover halo masses in the 10^{12.5}–3\times10^{14} M_\odot range and the 0.07 < z < 2.3 redshift range. To probe the same group population at all redshifts, we applied a halo-mass cut and only selected groups with halo masses of \(M_{200c} > 10^{13.5} M_\odot\). Furthermore, we applied completeness corrections to the calculation of the RLF (Novak et al. 2017), and all galaxy-group members are brighter than \(K = 24.5\) mag, which allows for an unbiased analysis.

We calculated the RLF of galaxy groups based on the \(V_{\text{max}}\) method and compared it to the 3 GHz RLF from Novak et al. (2018), who fit the total RLF with pure-luminosity evolution models that depend on redshift. The AGN and SFG populations, characterised by the radio-excess parameter, were fit with an MCMC algorithm. We fitted the group galaxies’ (GGs) RLFs using two methods: (a) scaling the total 3 GHz RLF and (b) using a linear (power-law) fit and estimating the contribution to the total RLF. We also studied how much satellites (SGs), brightest group galaxies (BGGs), AGN, and SFGs contribute to the RLF of galaxy groups and to the total 3 GHz RLF. The two fitting methods provide similar results, with the ratio between data and model (Fig. 4) suggesting the power-law fit was slightly better for the GG RLF. The linear regression fit is the adopted method for the interpretation of the results.

Our main results are summarised below:

1. The relative contribution of the group galaxies to the total 3 GHz radio luminosity function in galaxies in the COSMOS field generally decreases with increasing redshift, from 4% at low \(z\) to 1% at \(z > 1\), with an overdensity below \(z < 1\); this is in line with large-scale structure studies of the COSMOS field.
2. The GG RLF has a low value at \(z \approx 1.25\), followed by a sharp increase in the GG RLF at \(z \approx 1\) by a factor of six. This is followed by a smooth decline, which is driven mainly by satellite GGs. The latter suggests a mild evolution in the RLF of GGs from \(z \approx 1\) to 0.07 by a factor of three.
3. The RLF of SGs dominates the RLF of group galaxies up to a redshift of \(z \approx 1.2\), where we observe a drop in the RLF of both BGGs and SGs.
4. The AGN dominate the GG RLF at $z \sim 1$, while the SFGs dominate the GG RLF at $z_{med} = 1.2$.

In summary, we observed a nearly flat, but enhanced, behaviour of the contribution of galaxy groups to the total 3 GHz RLF up to $z \sim 0.75$, driven by SGs and AGN in GGs. This is followed by an increase and then a sharp drop, which agrees with the literature and is related to AGN occupying less massive halos above $z > 1$. The enhanced contribution and sharp drop are not driven by a possible sensitivity drop at high redshifts, but by the actual abundance of massive groups, which is enhanced in high-density peaks with regard to normal galaxies and creates an enhancement of the fractional contribution of radio galaxies. In a case where all the galaxies are groups of similar masses, but we detect only some with X-rays, the ratio would have stayed the same, independent of the density of the field.

Another important result of this analysis is the RLF itself for group galaxies, as well as the contribution of the satellites and BGGs in group environments, which is a major observational constraint for tuning the models. Our study provides an observational probe for the accuracy of the numerical predictions of the radio emission in galaxies in a group environment. Finally, our results show a drop in the occurrence of AGN in groups at high $z$ by a factor of six, suggesting that AGN feedback is lower by a factor of six at high redshifts. The bulk of high-$z$ AGN is enhanced in high-density peaks with regard to normal galaxies and creates an enhancement of the fractional contribution of radio galaxies. This is followed by an increase and then a sharp drop, which agrees with the literature and is related to AGN occupying less massive groups, as well as the contribution of the satellites and BGGs in group environments. The ratio would have stayed the same, independent of the density of the field.

**Data availability**

Table A.1 is available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/693/A61. Tables A.2–A.9 have been uploaded to Zenodo https://zenodo.org/records/14192888

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Appendix A: Numerical results from the calculation of the radio luminosity function in X-ray galaxy groups in COSMOS

Table A.1 is available via CDS and Tables A2-A9 are available in Zenodo.

### Table A.1: Radio properties of Group Galaxies in COSMOS

| ID  | radio 3 GHz X-ray ID (deg., J2000.0) | X-ray R.A. (deg.) | radio R.A. (deg.) | Redshift z | log$_{10}$($L_{1.4\text{GHz}}$/$W\text{ Hz}^{-1}$) | log$_{10}$($L_X$/$10^{42}\text{ erg s}^{-1}$) | log$_{10}$(M$_{200c}$/10$^{13}$M$_\odot$) | R$_{200c}$ (deg.) | Rank Class | BGG Radio Classification |
|-----|------------------------------------|-------------------|-------------------|------------|---------------------------------|-----------------------------------|---------------------------------|-----------------|---------------|-------------------------|
| (1) | (2)                                | (3)               | (4)               | (5)        | (6)                             | (7)                               | (8)                             | (9)             | (10)          | (11)        |

**Notes.** Basic radio properties of group galaxies in COSMOS. Columns 1 & 2: The 3 GHz radio ID (Smolčić et al. 2017a) and the X-ray galaxy group ID (Gozaliasl et al. 2019, and in prep.), respectively. Columns 3 & 4: Right Ascension (R.A.) and Declination (Dec) of the radio position in degrees, respectively. Columns 5 & 6: Right Ascension (R.A.) and Declination (Dec) of the X-ray galaxy group position in degrees, respectively. Columns 7 & 8: Redshift of the radio source and the X-ray galaxy group, respectively. The character ‘s’ denotes spectroscopic and ‘p’ denotes photometric redshift for the X-ray groups. Column 9: Radio luminosity at 1.4 GHz in W Hz$^{-1}$. Column 10: X-ray galaxy group luminosity and error in 10$^{42}$ erg s$^{-1}$. Column 11: Halo mass at M$_{200c}$ in 10$^{13}$ M$_\odot$ and error. Column 12: Virial radius of the group R$_{200c}$ in degrees. Column 13: BBG rank, where 0 denotes if the group galaxy is the brightest of the X-ray galaxy group and values > 0 are for satellite galaxies. Column 14: Radio classification based on a combination of the radio excess parameter (Smolčić et al. 2017b; Delvecchio et al. 2017) and objects having radio jets (Vardoulaki et al. 2021); ‘AGN’ exhibit radio excess or have radio jets, while ‘SFG’ do not.

### Table A.2: Radio-luminosity functions of GGs obtained with the $V_{\text{max}}$ method.

A halo mass cut, M$_{200c}$ > 10$^{13.5}$ M$_\odot$, was applied. We note that the error on Φ is in dex.

| z  | z$_{\text{med}}$ | log $L_{1.4\text{GHz}}$ | log$L_{1.4\text{GHz}}$(med) | log Φ | N |
|----|-----------------|-------------------------|------------------------------|-------|---|
|    |                 | [W Hz$^{-1}$]           | [W Hz$^{-1}$]                | [Mpc$^{-3}$ dex$^{-1}$] |

### Table A.3: Radio-luminosity functions of BGGs obtained with the $V_{\text{max}}$ method.

A halo mass cut, M$_{200c}$ > 10$^{13.5}$ M$_\odot$, was applied. We note that the error on Φ is in dex.

| z  | z$_{\text{med}}$ | log $L_{1.4\text{GHz}}$ | log$L_{1.4\text{GHz}}$(med) | log Φ | N |
|----|-----------------|-------------------------|------------------------------|-------|---|
|    |                 | [W Hz$^{-1}$]           | [W Hz$^{-1}$]                | [Mpc$^{-3}$ dex$^{-1}$] |

### Table A.4: Radio-luminosity functions of satellites obtained with the $V_{\text{max}}$ method.

A halo mass cut, M$_{200c}$ > 10$^{13.5}$ M$_\odot$, was applied. We note that the error on Φ is in dex.

| z  | z$_{\text{med}}$ | log $L_{1.4\text{GHz}}$ | log$L_{1.4\text{GHz}}$(med) | log Φ | N |
|----|-----------------|-------------------------|------------------------------|-------|---|
|    |                 | [W Hz$^{-1}$]           | [W Hz$^{-1}$]                | [Mpc$^{-3}$ dex$^{-1}$] |

### Table A.5: Best power-law fit parameters.

A halo mass cut, M$_{200c}$ > 10$^{13.5}$ M$_\odot$, was applied.

| Sample | z | log Φ* | γ | log Φ* (γ = −0.75) |
|--------|---|--------|---|-------------------|
|        |   | [Mpc$^{-3}$ dex$^{-1}$] |       | [Mpc$^{-3}$ dex$^{-1}$] |
Table A.6. $\Phi^*$ fits using the scaled method. A halo mass cut, $M_{200c} > 10^{13.5} M_\odot$, was applied.

| sample | $z$ | $\log \Phi^*$ (scaled) [Mpc$^{-3}$ dex$^{-1}$] |
|--------|-----|------------------------------------------|

Table A.7. Radio-luminosity functions of AGN inside X-ray GGs obtained with the $V_{\text{max}}$ method. A halo mass cut, $M_{200c} > 10^{13.5} M_\odot$, was applied. We note that the error on $\Phi$ is in dex.

| $z$ | $z_{\text{med}}$ | $\log L_{1.4\text{GHz}}$ [W Hz$^{-1}$] | $\log L_{1.4\text{GHz}}$(med) [W Hz$^{-1}$] | $\log \Phi$ [Mpc$^{-3}$ dex$^{-1}$] | N |
|-----|-----------------|---------------------------------|---------------------------------|-----------------|-----|

Table A.8. Radio-luminosity functions of SFGs inside X-ray galaxy groups obtained with the $V_{\text{max}}$ method. A halo mass cut, $M_{200c} > 10^{13.5} M_\odot$, was applied. We note that the error on $\Phi$ is in dex.

| $z$ | $z_{\text{med}}$ | $\log L_{1.4\text{GHz}}$ [W Hz$^{-1}$] | $\log L_{1.4\text{GHz}}$(med) [W Hz$^{-1}$] | $\log \Phi$ [Mpc$^{-3}$ dex$^{-1}$] | N |
|-----|-----------------|---------------------------------|---------------------------------|-----------------|-----|

Table A.9. $\chi^2$ test results for the GGs (Sect. 3.3.3) AGN, and SFGs (Sect. 5). PL is for the power-law, linear-regression fit, and SC is for the scaled fit. DoF denotes the degrees of freedom.

| $z_{\text{bin}}$ | model | $\chi^2$ | p-value | DoF | AGN | $\chi^2$ | p-value | DoF | SFGs | $\chi^2$ | p-value | DoF |
|-----------------|-------|--------|--------|------|-----|--------|--------|------|-----|--------|--------|------|