

LETTER TO THE EDITOR

Impediments to the cosmic growth of galaxies: The outflow budget from Star Formation and Active Galactic Nuclei

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ABSTRACT

The gas reservoir of galaxies can be altered by outflows that are driven by star formation and luminous active galactic nuclei. Jets heating the surroundings of host galaxies can also prevent the gas from cooling and prevent inflows. Spectacular examples for these three mass-displacement channels have been observed, but their importance in transforming the galaxy population depends on the occurrence rates of the outflow triggers. We investigate the absolute and relative importance of these three channels. In an observation-driven approach, we combined distribution functions and scaling relations to empirically compare average outflow rates across the total stellar mass spectrum of the galaxy and across cosmic time. This hinges on local outflow studies, which should be extended to systematic, large, and diverse samples, and we did not consider a halo-heating effect by radiation-driven outflows so far. Independent of simulations, our results show the dominance of star formation-driven outflows in low-mass galaxies. Massive galaxies today are predominately prevented from growing further by jet heating, while at $z = 1-3$, all three processes are approximately similarly important. Over the full mass spectrum and cosmic history, outflows driven by the radiation from active galactic nuclei are never the dominant process.

Key words. galaxies: formation – galaxies: jets – galaxies: nuclei – quasars: general – galaxies: statistics

1. Introduction

Star formation (SF) and the growth of supermassive black holes (SMBHs) are processes that are thought to shape the evolution of galaxies. Evidence for this comes from cosmological simulations, in which these feedback mechanisms are effective in reproducing the luminosity function and color distribution of galaxies, for example [Croton et al. \(2006\)](#). However, the observational evidence on the role and importance of the various feedback mechanisms is more complex.

Observations are most clear in the rare extremes: very massive systems where jets that are produced near the SMBH heat the intergalactic matter (e.g., see reviews of [Fabian 2012](#); [Heckman & Best 2014](#)), and bulk outflows of gas associated with rapid SMBH growth as an active galactic nucleus (AGN; e.g., [Cicone et al. 2014](#)). It is observationally difficult to distinguish the proposed feedback mechanisms and establishing causality for most systems. This is in part due to the different timescales on which AGN and SF act in comparison to the impact of their activity (e.g., [Hickox et al. 2014](#)). Nevertheless, multivariate analyses of local galaxies suggest that the outflow rates are a function of AGN luminosity, star formation rate (SFR) and stellar mass (M_* ; e.g., [Fluetsch et al. 2019](#)). To circumvent peculiarities of individual systems, large surveys of galaxies have been used to establish statistical differences, for example, in AGN and non-AGN host galaxies. Understanding the selection effects is crucial, however, as are the limitations in characterizing the host galaxy when it is contaminated with AGN light. Nevertheless, the AGN accretion rate distributions as a function

of basic host galaxy properties such as M_* and SFR over cosmic time were measured (e.g., [Aird et al. 2012](#); [Bongiorno et al. 2012](#); [Aird et al. 2018](#); [Georgakakis et al. 2017](#)). The feedback in galaxy clusters was even more reliably established by linking AGN luminosity and cluster heating (see below).

In this work, we combine existing measurements to quantify the mechanisms that are effective at carrying gas out of a galaxy. We focus on outflows associated with SF activity, AGN jets, and AGN luminosity, and we investigate their importance as a function of galaxy mass and cosmic time.

2. Method

The goal of this work is to compute the average outflow rates of different feedback mechanisms as a function of stellar mass and redshift.

For SF- and AGN-related outflows, we relied on the relation of (F19 hereafter [Fluetsch et al. 2019](#)). F19 found that the total (molecular, ionized, and neutral hydrogen) outflow mass rate can be accurately predicted given stellar mass, SFR, and AGN luminosity (see the middle left panel of Figure 1),

$$\dot{M}/M_\odot = (1.29 \times \text{SFR} + 0.81 \times L_{\text{AGN},43})^{1.13} / M_{*,11}^{0.37}, \quad (1)$$

where $L_{\text{AGN},43}$ is the bolometric AGN luminosity in units of 10^{43} erg/s, $M_{*,11}$ is the stellar mass in units of $10^{11} M_\odot$, and SFR is the star formation rate in units of $M_\odot/\text{yr}$.

2.1. Outflows from star formation

We obtained (specific) SFR distributions ([Whitaker et al. 2014](#); [Tomczak et al. 2016](#); [Smit et al. 2014](#); [Schreiber et al. 2015](#);

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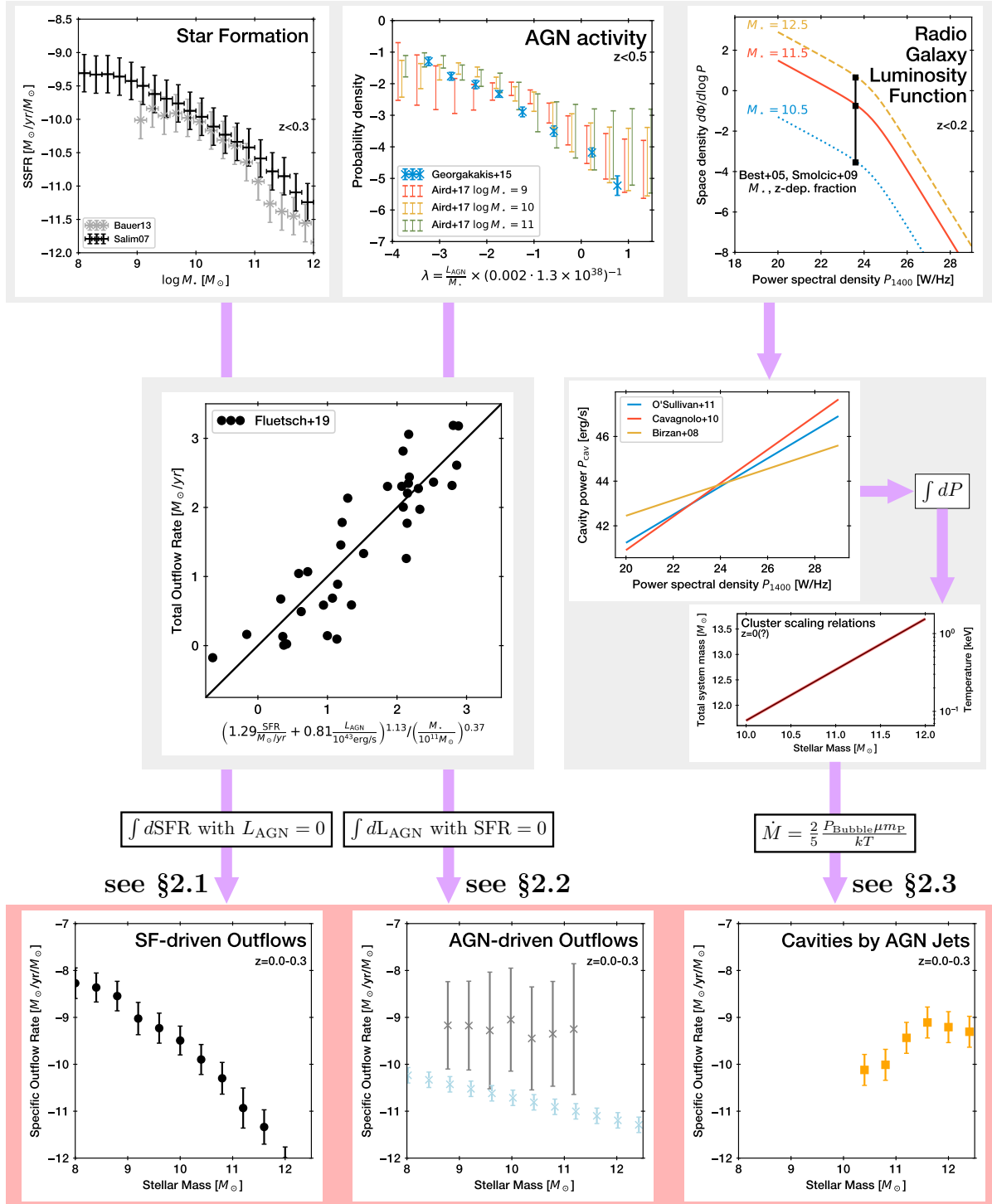


Fig. 1. Workflow starting from distribution functions (top row) that are convolved with scaling relations (middle row) into rates of mass displacement (bottom row) at a given galaxy stellar mass and redshift. We show the lowest-redshift bin.

Salmon et al. 2015; Salim et al. 2007; McLure et al. 2011; Labbé et al. 2013; Karim et al. 2011; Kajisawa et al. 2010; Bauer et al. 2013; Zwart et al. 2014) from the literature compilation of Behroozi et al. (2019). For each of these SFR distributions that was measured at a certain stellar mass and redshift (shown in the top left panel of Figure 1 for $z = 0$), we used the F19 relation with $L_{\text{AGN},43} = 0$ to compute the outflow rate due to SFR alone. Integration over the SFR probability distribution gives the average outflow rate at a given stellar mass (bottom

left panel of Figure 1). We used the variance across the measurements as approximate uncertainties.

2.2. Outflows that are radiatively pushed by active galactic nuclei

To compute the outflows associated with luminous AGN, we require the AGN luminosity as a function of stellar mass. Aird et al. (2018) found the specific accretion rate distribution

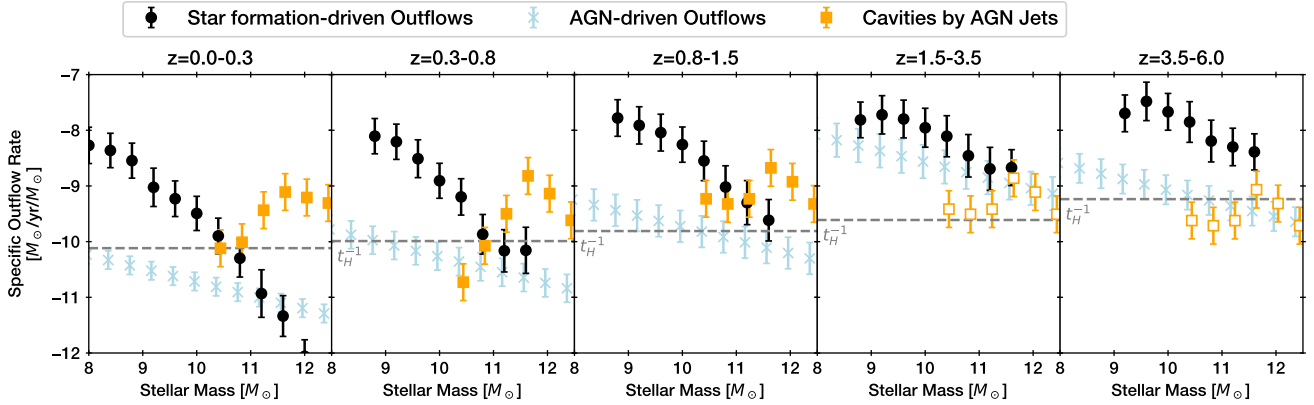


Fig. 2. Mass dependence of outflow channels. The panels indicate different redshift intervals. We compare SF-driven outflows (black error bars, Sect. 2.1), AGN-driven outflows (blue, Sect. 2.2), and AGN jet cavities preventing inflows (orange, Sect. 2.3). AGN outflows are only weakly dependent on stellar mass. The horizontal dashed line indicates the inverse Hubble time at that redshift. In the two right redshift panels, the AGN jet power is extrapolated (open orange points).

(SARD), $p(\lambda|M_\star) \propto L_{\text{AGN}}/M_\star$, to follow a power law over a range of stellar masses and redshifts. At low redshifts, these measurements are shown in the top middle panel of Figure 1. Aird et al. (2018) started from a galaxy sample and computed the AGN luminosity (from X-ray emission) and stellar mass (from broadband photometry) for each galaxy. However, because the survey area was limited, their sample was not able to constrain the bright end of the luminosity function (near $\lambda \geq 1$). The uncertainties are large at this end and follow a Gaussian extrapolation because the authors assumed a two-component Gaussian mixture model to empirically fit the distribution. Georgakakis et al. (2017) also used large-area surveys, but their method was different. Instead of starting with a galaxy sample, they detected an AGN sample in the X-rays and measured the SARD of the host galaxies by fitting the SED. They did not assume an SARD shape, but estimated the space density in redshift and SARD bins. They reported a universal SARD shape corresponding to a power law with index -1 , with an exponential cutoff at approximately twice the Eddington limit. This limit is also required to match the SARD with the X-ray luminosity function (Aird et al. 2013). We generally used the measurements of Aird et al. (2018) and fully propagated the space density uncertainties. When the uncertainties became large (>0.5 dex) at the bright end, we imposed an exponential cutoff of Georgakakis et al. (2017) to the upper error bars of Aird et al. (2018). We propagated the uncertainties in the relative normalizations. Our combination is very similar to the recent results of Laloux et al. (2024), and we show it as the dashed error bars in the top middle panel of Figure 1.

After converting the AGN luminosity into an outflow rate with Eq. (1) (setting SFR = 0), we integrated over the SARD to obtain the total outflow rate at a given stellar mass. The outflow rates are shown in the bottom middle panel of Figure 1.

2.3. Bubbles blown by active galactic nuclei

In the centers of galaxy clusters and massive galaxies, radio-emitting AGN are common (e.g., Sabater et al. 2019). Their radio jets are thought to inject heat into the cluster gas, which would otherwise cool quickly, and the created hot bubbles slowly rise by buoyancy and slowly disperse their energy (see e.g., Fabian 2012). Outside gas, which would otherwise fall into the cluster, would condense onto and thereby grow a galaxy, is stalled at large distances (see e.g., Croton et al. 2006). To com-

pute the mass accretion prevented by this mechanism, we combined several correlations.

We started with the shape of the AGN radio luminosity function determined by Sadler et al. (2002). A comparison of radio luminosity works finds that the shape shows little evolution and is consistent between works and radio wavelengths (e.g., Smolčić et al. 2009; Heckman & Best 2014; Sabater et al. 2019). The fraction of AGN that emit in the radio at more than 4×10^{23} W/Hz depends on the mass (their Figure 11 Smolčić et al. 2009). The combination is a mass-dependent radio luminosity function and is shown in the top right panel of Figure 1. Next, the radio luminosity of AGN correlates well with the power stored in bubbles (e.g., Bîrzan et al. 2008; Cavagnolo et al. 2010; O’Sullivan et al. 2011). This is shown in the second plot in the right column. By integrating over the power distribution, we estimated the total power injected into bubbles by AGN jets. The bubble power is eventually radiatively cooled away by cooling flows. The accretion rate is (Fabian 1994)

$$\dot{M} = \frac{2}{5} \frac{P_{\text{Bubble}} \times \mu m_p}{kT}. \quad (2)$$

We used the bubble power as the cluster luminosity that is to be emitted at a plasma temperature T . The remaining constants are the Boltzmann constant k , the proton mass m_p , and the mean molecular mass, $\mu \approx 0.6$ in ionized plasmas (Pratt et al. 2019). As the cluster temperature T , we used the relatively tight relation between the stellar and total mass of the system (Vikhlinin et al. 2009), combined with the relation of the total system mass to the temperature (Gonzalez et al. 2013; Kravtsov et al. 2018). These relations are shown in the left and right axes of the third panel in the right column of Figure 1.

The resulting total mass rate is shown in the bottom right panel of Figure 1. We propagated the systematic uncertainties of the cavity-radio power relations, which vary most between works, and the fit uncertainties in the mass-temperature and $M_{500}-M_\star$ relation. Unlike the outflows rates in the previous two sections, Eq. (2) computes the rate of an inflow that could have occurred, were it not prevented by the AGN energy injection.

3. Results

Our main result is presented in Figure 2. The importance of SF-driven outflows (black, Sect. 2.1), AGN-driven outflows (blue,

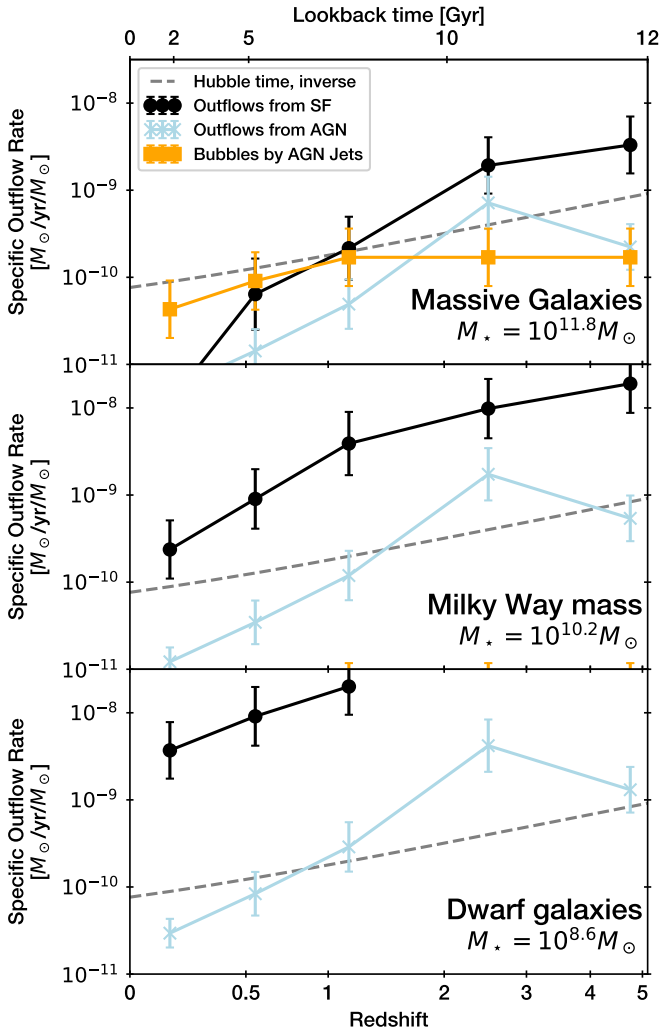


Fig. 3. Redshift evolution of the outflow rate in three mass bins. The lower-mass systems (lower panels) are dominated by SF outflows (black), while in high-mass systems (top panel), AGN jet bubbles (orange) dominate at low redshift.

Sect. 2.2), and AGN jet bubbles preventing inflows (orange, Sect. 2.3) is compared for different redshift intervals. The points above the dashed horizontal line indicate that the process is important because the outflow rate exceeds the current stellar mass divided by the Hubble time. The main findings are that (1) in massive systems, AGN jets dominate. (2) In low-mass systems, SF-driven outflows dominate. (3) At higher redshifts ($z \sim 2$), all three channels appear to be important.

Figure 3 presents the same information as a function of redshift. For massive galaxies (top panel), SF-driven outflows were most important at $z > 1$, but at the present time, AGN jets are the dominant channel. For smaller systems (middle and bottom panel), SF-driven outflows always dominate. This figure should be interpreted with care, as galaxies grow in mass over cosmic time and thus do not remain in a single panel.

4. Discussion and conclusion

We presented a framework to compare the key channels that influence the growth of galaxies. For this purpose, we combined the most recent distribution functions and scaling relations of

outflows driven by SF or AGN and cavities blown by AGN jets. Our approach is analogous to the semi-analytic treatment of modelers of gas reservoirs that are filled by gravitational collapse. The gas reservoir can be emptied by outflows and gas accretion that is prevented by the heating of the intergalactic medium of the galaxy (see e.g., Croton et al. 2006).

We did not rely upon simulations, however. Instead, we obtained our results by combining observed relations collated from a large body of research undertaken over the past decades. A prediction based on Figure 3 is that dominant AGN-driven outflows are widespread at $z \sim 1-2$, and they dominate SF-driven outflows at high galaxy stellar masses. This is indeed found in high-resolution integral-field observations (e.g., Genzel et al. 2014).

We acknowledge that several of the relations we used have considerable caveats. To name but a few, a more accurate determination of the AGN activity in the luminous regime is required to accurately determine the total luminosity density (see the large gray error bars in the middle bottom panel of Figure 1). We extrapolated a local outflow relation out to high redshift and across a wide mass range. The Fluetsch relation needs to be extended to larger well-selected samples. As discussed in Sect. 4.2 of the recent review by Harrison & Ramos Almeida (2024), the scatter in the relation may be very large because a large fraction of luminous AGN lack strong outflows (e.g., Ramos Almeida et al. 2022). However, because the population calculation in a given AGN luminosity and stellar mass bin requires the (arithmetic) mean outflow rate, the change is potentially small, and even if it were not, it would further reduce the low total population outflow rate we find, and would not alter our conclusions. While the relation was established at moderate- to high-mass galaxies, low-mass galaxies are more frequently satellite galaxies that may undergo additional environmental quenching (see e.g., Peng et al. 2010; Bluck et al. 2020). No such additional quenching mechanisms were considered here. More work is also needed to understand the validity of applying cluster scaling relations in the galaxy group regime and to understand the importance of projection effects in the relations of cavity energy (Eckert et al. 2021).

We focused on AGN-driven gas ejection because it is commonly invoked as a means for quenching SF. While we find ejection to be unimportant, radiation-driven feedback of AGN may nevertheless be effective in different ways. For example, the injected energy may induce a similar halo-heating effect as radio jets, as suggested in simulations (e.g., Gabor & Bournaud 2014; Bower et al. 2017; Nelson et al. 2019) and evidenced in hot halo-gas found through the Sunyaev–Zel’dovich effect in quasars (e.g., Ruan et al. 2015; Crichton et al. 2016; Jones et al. 2023). To address this, the framework we presented could be extended in the future with a mix of the radio jet-heating and AGN outflow calculations. A study similar to ours was indeed recently conducted by Heckman & Best (2023), who came to similar conclusions. While this work focused on the mass outflow rate, Heckman & Best (2023) focused on energy injection, which can address the entropy injected by AGN outflows as an alternative mechanism. Their approach to feedback from massive stars relied on models, while our approach relies on observed outflow rate relations. Both approaches have systematic uncertainties (see e.g., Hardcastle & Croston 2020). Their jet bubble calculations are similar to ours, but we calculated the prevented rate of gas inflow based on these calculations. For AGN radiation-driven outflows, we used the more recent tight relation by Fluetsch et al. (2019), which allowed us to distinguish star formation and AGN as causes. It is reassuring that

two works with different approaches reached the same conclusions. The reverse cross-over case, where equatorial radio jets drive molecular outflows (see discussion in Sect. 4.2 of [Harrison & Ramos Almeida 2024](#)), could also be considered in the future, but would require further observational studies that establish relations.

In summary, we find that the transportation of gas out of galaxies driven by luminous AGN is not an effective feedback mechanism. SF-driven outflows are effective in removing gas in the low-mass regime, while AGN jets are effective in the high-mass regime. Unless there are order-of-magnitude underestimates in our assumptions, outflows driven by AGN radiation that extract gas from galaxies that is thus unavailable for star formation is a subdominant galaxy evolution process. Nevertheless, in massive galaxies and especially at $z = 1-3$, the outflow rates of all three channels considered in this work are comparable and are almost equally important.

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References

- Aird, J., Coil, A. L., Moustakas, J., et al. 2012, *ApJ*, **746**, 90
Aird, J., Coil, A. L., Moustakas, J., et al. 2013, *ApJ*, **775**, 41
Aird, J., Coil, A. L., & Georgakakis, A. 2018, *MNRAS*, **474**, 1225
Bauer, A. E., Hopkins, A. M., Gunawardhana, M., et al. 2013, *MNRAS*, **434**, 209
Behroozi, P., Wechsler, R. H., Hearin, A. P., & Conroy, C. 2019, *MNRAS*, **488**, 3143
Bîrzan, L., McNamara, B. R., Nulsen, P. E. J., Carilli, C. L., & Wise, M. W. 2008, *ApJ*, **686**, 859
Bluck, A. F. L., Maiolino, R., Piotrowska, J. M., et al. 2020, *MNRAS*, **499**, 230
Bongiorno, A., Merloni, A., Brusa, M., et al. 2012, *MNRAS*, **427**, 3103
Bower, R. G., Schaye, J., Frenk, C. S., et al. 2017, *MNRAS*, **465**, 32
Cavagnolo, K. W., McNamara, B. R., Nulsen, P. E. J., et al. 2010, *ApJ*, **720**, 1066
Cicone, C., Maiolino, R., Sturm, E., et al. 2014, *A&A*, **562**, A21
Crichton, D., Gralla, M. B., Hall, K., et al. 2016, *MNRAS*, **458**, 1478
Croton, D. J., Springel, V., White, S. D. M., et al. 2006, *MNRAS*, **365**, 11
Eckert, D., Gaspari, M., Gastaldello, F., Le Brun, A. M. C., & O'Sullivan, E. 2021, *Universe*, **7**, 142
Fabian, A. C. 1994, *ARA&A*, **32**, 277
Fabian, A. C. 2012, *ARA&A*, **50**, 455
Fluetsch, A., Maiolino, R., Carniani, S., et al. 2019, *MNRAS*, **483**, 4586
Gabor, J. M., & Bournaud, F. 2014, *MNRAS*, **441**, 1615
Genzel, R., Förster Schreiber, N. M., Rosario, D., et al. 2014, *ApJ*, **796**, 7
Georgakakis, A., Aird, J., Schulze, A., et al. 2017, *MNRAS*, **471**, 1976
Gonzalez, A. H., Sivanandam, S., Zabludoff, A. I., & Zaritsky, D. 2013, *ApJ*, **778**, 14
Hardcastle, M. J., & Croston, J. H. 2020, *New Astron. Rev.*, **88**, 101539
Harrison, C. M., & Ramos Almeida, C. 2024, *Galaxies*, **12**, 17
Heckman, T. M., & Best, P. N. 2014, *ARA&A*, **52**, 589
Heckman, T. M., & Best, P. N. 2023, *Galaxies*, **11**, 21
Hickox, R. C., Mullaney, J. R., Alexander, D. M., et al. 2014, *ApJ*, **782**, 9
Jones, G. C., Maiolino, R., Carniani, S., et al. 2023, *MNRAS*, **522**, 275
Kajisawa, M., Ichikawa, T., Yamada, T., et al. 2010, *ApJ*, **723**, 129
Karim, A., Schinnerer, E., Martínez-Sansigre, A., et al. 2011, *ApJ*, **730**, 61
Krautsov, A. V., Vikhlinin, A. A., & Meshcheryakov, A. V. 2018, *Astron. Lett.*, **44**, 8
Labbé, I., Oesch, P. A., Bouwens, R. J., et al. 2013, *ApJ*, **777**, L19
Laloux, B., Georgakakis, A., Alexander, D. M., et al. 2024, *MNRAS*, **532**, 3459
McLure, R. J., Dunlop, J. S., de Ravel, L., et al. 2011, *MNRAS*, **418**, 2074
Nelson, D., Pillepich, A., Springel, V., et al. 2019, *MNRAS*, **490**, 3234
O'Sullivan, E., Giacintucci, S., David, L. P., Vrtilek, J. M., & Raychaudhury, S. 2011, *MNRAS*, **411**, 1833
Peng, Y.-J., Lilly, S. J., Kovač, K., et al. 2010, *ApJ*, **721**, 193
Pratt, G. W., Arnaud, M., Biviano, A., et al. 2019, *Space Sci. Rev.*, **215**, 25
Ramos Almeida, C., Bischetti, M., García-Burillo, S., et al. 2022, *A&A*, **658**, A155
Ruan, J. J., McQuinn, M., & Anderson, S. F. 2015, *ApJ*, **802**, 135
Sabater, J., Best, P. N., Hardcastle, M. J., et al. 2019, *A&A*, **622**, A17
Sadler, E. M., Jackson, C. A., Cannon, R. D., et al. 2002, *MNRAS*, **329**, 227
Salim, S., Rich, R. M., Charlot, S., et al. 2007, *ApJS*, **173**, 267
Salmon, B., Papovich, C., Finkelstein, S. L., et al. 2015, *ApJ*, **799**, 183
Schreiber, C., Pannella, M., Elbaz, D., et al. 2015, *A&A*, **575**, A74
Smit, R., Bouwens, R. J., Labbé, I., et al. 2014, *ApJ*, **784**, 58
Smolčić, V., Zamorani, G., Schinnerer, E., et al. 2009, *ApJ*, **696**, 24
Tomczak, A. R., Quadri, R. F., Tran, K.-V. H., et al. 2016, *ApJ*, **817**, 118
Vikhlinin, A., Burenin, R. A., Ebeling, H., et al. 2009, *ApJ*, **692**, 1033
Whitaker, K. E., Franx, M., Leja, J., et al. 2014, *ApJ*, **795**, 104
Zwart, J. T. L., Jarvis, M. J., Deane, R. P., et al. 2014, *MNRAS*, **439**, 1459