

Investigating central star formation in local AGN host galaxies: Is there tension between coeval growth and AGN feedback?

Q. Ni^{1,*}, K. Nandra¹, A. Merloni¹, J. Comparat^{1,2}, D. Tubín-Arenas³, and Y. Zhang^{1,4}

¹ Max-Planck-Institut für extraterrestrische Physik (MPE), Gießenbachstraße 1, D-85748 Garching bei München, Germany

² Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 53, Avenue des Martyrs, 38000 Grenoble, France

³ Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

⁴ Max-Planck-Institut für Astrophysik (MPA), Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany

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ABSTRACT

It has been argued that supermassive black holes (BHs) coevolve with the central parts of galaxies as a result of the common fuel for both the BH and star formation in the galaxy central region, as supported by the particularly significant relation between BH growth and the central mass density within 1 kpc (Σ_1) found among star-forming galaxies. In the context of this scenario, one would naturally expect a close observational link between active galactic nucleus (AGN) activity and star formation activity in the central regions, e.g., the surface star formation rate density in the central 1 kpc region ($\Sigma_{\text{SFR}, 1 \text{ kpc}}$), as a manifestation of coeval growth. With ≈ 3000 galaxies in the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) survey that have X-ray coverage from SRG/eROSITA, *XMM-Newton*, or *Chandra*, we studied how the X-ray AGN fraction varies with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$. We found that the fraction of X-ray AGNs with relatively higher specific BH accretion rates increases with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, consistent with the expectation. A comparison of the mean star formation rate surface density (Σ_{SFR}) profiles of the host galaxies of these AGNs and normal galaxies sharing similar properties reveals elevated Σ_{SFR} in AGN hosts across the entire central region. As for optically selected AGNs, their hosts also tend to show high Σ_{SFR} in the central regions on average compared to normal galaxies, but they differ from X-ray AGNs in terms of the trend of AGN fraction versus $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, which can be explained by selection effects. While these general trends all support the coeval growth scenario, they do not contradict observational evidence for AGN feedback suppressing star formation, as the average effects of such feedback might be modest in the local Universe.

Key words. galaxies: active – galaxies: evolution – galaxies: nuclei – galaxies: star formation

1. Introduction

Supermassive black holes (BHs) are thought to coevolve with their host galaxies, as motivated by the well-established correlation between BH mass and bulge properties in the local Universe (e.g. Kormendy & Ho 2013). Two processes are generally invoked in this scenario. First, because BHs and galaxies share the same gas reservoir, some level of coeval growth is naturally expected. Second, active galactic nucleus (AGN) feedback is considered to play an important role in the regulation of galaxy evolution (e.g. Croton et al. 2006) by directly interacting with the gas reservoir via different modes and channels (e.g. Fabian 2012; Alexander & Hickox 2012; Harrison 2017).

It has been found that BH growth is closely related to various host-galaxy properties, and compactness in the galaxy central regions is particularly effective in tracking the long-term average BH growth level among star-forming (SF) galaxies (Ni et al. 2019, 2021), which supports the picture of gas in the central kiloparsec of galaxies as a common fuel for both AGNs and galaxies. In this scenario, one would expect a higher AGN fraction and/or BH growth level among galaxies with high central star formation rate (SFR), similar to what is observed for the global SFR (e.g. Chen et al. 2013; Andonie et al. 2024). At the same time, there have been some studies showing AGNs with suppressed gas fraction or star formation in the centers (e.g. Bing et al. 2019; Ellison et al. 2021; Lammers et al. 2023), which have been uti-

lized as evidence for AGN feedback, but are potentially in tension with the picture of coeval growth.

Integral field unit (IFU) surveys are widely utilized in studies of this kind to spatially resolve the properties of AGN hosts and compare them with those of normal galaxies (that are selected to constitute a control sample). Currently, because of the limited number of *James Webb* Space Telescope (JWST) IFU observations and our limited understanding of how to recover a complete and unbiased sample from these available observations, this type of study has been restricted to the low-redshift Universe with IFU data from the Calar Alto Legacy Integral Field Area (CALIFA) survey (Sánchez et al. 2012), the Sydney Australian Astronomical Observatory Multi-object Integral-field Spectrograph (SAMI) Galaxy Survey (Bryant et al. 2015), and the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) survey from Sloan Digital Sky Survey IV (SDSS-IV; Bundy et al. 2015), which has the largest sample size, ideal for population studies. In different studies, AGNs are selected at different wavelengths via diverse selection criteria, and normal galaxies in the control sample are also selected differently, which might explain the wide range of (and sometimes contradictory) results arising. When comparing optically selected AGNs with normal galaxies, both suppressed central SFRs (e.g. Bing et al. 2019; Lammers et al. 2023) and elevated central SFRs (e.g. Sánchez et al. 2018; Gatto et al. 2025) are reported. Mulcahey et al. (2022) studied radio-detected AGNs (which are selected combining radio, optical, and mid-infrared diagnostics), and found that the average stellar population age (which can track specific SFR) profile of AGN hosts is similar to that of con-

* Corresponding author: qni@mpe.mpg.de

troil galaxies. In addition to IFU-based studies, there have also been attempts established based on multi-band pixel-by-pixel spectral energy distribution (SED) fitting. Utilizing narrowband photometric surveys, Acharya et al. (2024) reported a suppression of specific SFR in the central regions of X-ray-selected AGN hosts compared with matched SF galaxies. While AGN selection methods vary in their respective merits and drawbacks, X-ray selection is considered to be rather clean and unbiased (e.g. Hickox & Alexander 2018). However, due to the lack of X-ray coverage with IFU surveys, previous studies based on IFU data do not fully make use of X-ray-selected AGNs in the sample.

In this work, we combined X-ray AGN selection with optical AGN selection of MaNGA galaxies to further study how AGN activity links with the star formation properties in the central regions of galaxies. We particularly aimed to resolve the potential tension between coeval growth expected from a common fuel for both the BH and the galaxy—where AGN activity is linked with elevated central star formation—and the so-called AGN negative feedback—where AGN activity is linked to suppressed central star formation. We also discuss how the AGN selection method might affect the observed results.

The paper is structured as follows. In Sect. 2 we describe the sample construction process. In Sect. 3 we detail the analysis results, and we discuss what they imply in Sect. 4. The conclusions are presented in Sect. 5. Throughout this paper, stellar masses (M_*) are given in units of $M_\odot$; SFRs are given in units of $M_\odot \text{ yr}^{-1}$. The surface mass density (Σ_*) and that in the central 1 kpc region (Σ_1) are given in units of $M_\odot \text{ kpc}^{-2}$; the surface density of SFR (Σ_{SFR}) and that in the central 1 kpc region ($\Sigma_{\text{SFR}, 1 \text{ kpc}}$) are given in units of $M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$. L_X represents the rest-frame 2–10 keV X-ray luminosity in units of erg s^{-1} . $L_{[\text{O III}]}$ represents the (extinction-corrected) luminosity of the [O III] $\lambda 5007$ emission line in units of erg s^{-1} . L_X/M_* and $L_{[\text{O III}]} / M_*$ correspond to the X-ray and [O III] luminosity per unit stellar mass, respectively, in units of $\text{erg s}^{-1} M_\odot^{-1}$. Reported uncertainties are at the 1σ (68%) confidence level. A cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ is assumed.

2. Sample selection and construction

2.1. The galaxy sample obtained from MaNGA

The IFU observations from MaNGA map $\geq 10\,000$ nearby galaxies at $z = 0.01\text{--}0.15$ with $0.5 \text{ arcsec} \times 0.5 \text{ arcsec}$ spaxels (Bundy et al. 2015). It covers galaxies with a relatively flat distribution in terms of i -band absolute magnitude and provides spectroscopic coverage out to 1.5 and 2.5 effective radii (r_e) for the primary and secondary samples, respectively. There is also a color-enhanced sample to have more objects in the low-density regions of the color-magnitude space. We started from the Sánchez et al. (2022) MaNGA pyPipe3D value-added catalog, which is built upon reduced data with version 3.1.1 of the MaNGA Data Reduction Pipeline (DRP; Law et al. 2016). All the galaxies in the main sample can be identified with the MANGA_TARGET1 flag, and there are weights provided by the DRP catalog to correct the combination of these samples to a volume-limited sample. We marked broad-line AGNs from the Oh et al. (2015) and Fu et al. (2023) catalogs, which were removed from the sample utilized in this study¹. We also

required objects to have $z < 0.1$, so that each spaxel spans over $\lesssim 1 \text{ kpc}$, which is the minimum scale we are trying to resolve in this study.

2.2. MaNGA galaxies with X-ray coverage and the selection of X-ray AGNs

2.2.1. eROSITA

We checked the MaNGA objects observed by the extended ROentgen survey with an Imaging Telescope Array (eROSITA) on board the Spektrum-Roentgen-Gamma (SRG) orbital observatory (Predehl et al. 2021), and there are 1870 objects within the coverage. As MaNGA galaxies are bright foreground galaxies with a field of view of the MaNGA fiber array ranging from 12 to 32'' in diameter, we adopted a 30'' matching radius (comparable to the point spread function size of eROSITA), directly matched these galaxies with the eROSITA all-sky survey data catalog from the cumulative four scans (eRASS:4), and retained matches within 3σ position errors. Then we adopted the 0.2–2.3 keV flux ML_FLUX reported in the source catalog, and converted it to L_X assuming galactic absorption with $\Gamma = 1.7$. For undetected sources, we obtained the background level from the background maps and derived the minimum number of counts required for a source to be detected in the 0.2–2.3 keV band. We then derived the corresponding flux sensitivity with the corresponding energy conversion factor (ECF) = 1.074×10^{-12} (e.g. Tubín-Arenas et al. 2024). We then converted this flux sensitivity at the galaxy position to $L_{X,\text{limit}}$ of the galaxy.

2.2.2. XMM-Newton

With the RapidXMM database (Ruiz et al. 2022), we found 890 MaNGA galaxies within XMM-Newton coverage. We also directly matched those MaNGA galaxies with the 4XMM-DR14 catalog (Webb et al. 2020) with a 30'' matching radius, and adopted sources within the 3σ position error. We converted the X-ray fluxes to L_X assuming a power-law model with Galactic absorption and $\Gamma = 1.7$ following the preference order of 4.5–12 keV band, and 0.2–12 keV band, thus minimizing the effects of X-ray obscuration. We also estimated $L_{X,\text{limit}}$ for the X-ray source to be detected at each MaNGA galaxy position, utilizing the 0.2–12 keV band flux reported in RapidXMM. A power-law model with Galactic absorption and $\Gamma = 1.7$ was again assumed through the conversion process.

2.2.3. Chandra

We made use of the Chandra Source Catalog (CSC) version 2.0 limiting sensitivity properties (Evans et al. 2024), and found 514 galaxies within Chandra coverage. The CSC provides 0.5–7 keV band flux sensitivity for a point source to be detected at a given position, and we converted this limiting flux to $L_{X,\text{limit}}$ via the approach reported in 2.2.2. For sources detected within the 3σ Chandra position error, we adopted the order of 2–7 keV band, 0.5–7 keV band, and 0.5–2 keV band to estimate L_X , with assumptions similar to those above.

2.2.4. X-ray AGN selection

There are 2770 MaNGA galaxies with X-ray coverage from eROSITA, XMM-Newton, or Chandra. For each galaxy, we estimated the contribution in L_X from the X-ray binary (XRB), L_{XRB} , through a redshift-dependent function of M_* and SFR

¹ Oh et al. (2015) selected broad-line AGNs based on the full width at half maximum (FWHM) of the H α emission line of SDSS DR7 spectra. Fu et al. (2023) selected broad-line AGNs based on the FWHM of all the Balmer lines utilizing MaNGA spectra directly.

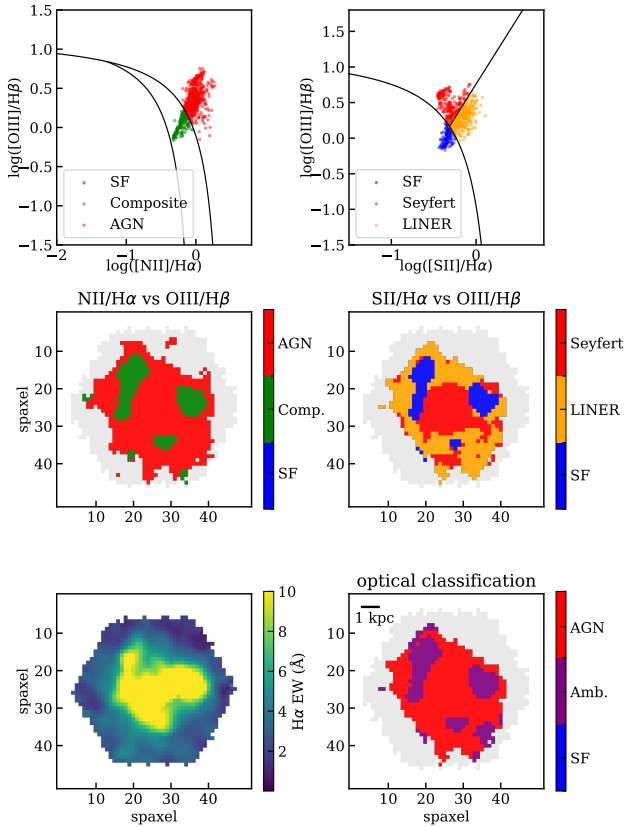


Fig. 1. Example of an optically selected AGN. In the top two panels, all the valid spaxels are plotted on the [N II]-based and [S II]-based BPT diagrams. In the middle panels, we show the 2D maps of how these spaxels are classified according to the BPT diagrams. In the lower-left panel, we show the $H\alpha$ EW map. In the lower-right panel, we show the final spaxel-level classification, which combines all the information.

(model 269, [Fragos et al. 2013](#)), which was derived utilizing observations in [Lehmer et al. \(2016\)](#). We also estimated the contribution from X-ray hot gas ([Mineo et al. 2012](#)), L_{gas} . If $L_X > 3 \times (L_{\text{XRB}} + L_{\text{gas}})$ (which is an empirical selection method for identifying sufficiently excessive X-ray emission from AGNs; see e.g., [Birchall et al. 2022](#) for details), we classified the object as an X-ray AGN. We further classified sources with $\log L_X < 41$ as non-AGNs even if they meet this criterion, in order to remove any potential contamination from ultraluminous X-ray sources. We note that, among $10 < \log M_\star < 10.5$ galaxies, the detected X-ray sources have luminosities comparable to the expectation from XRB contributions. Thus, we did not select X-ray AGNs with $\log M_\star < 10.5$. For $\log M_\star > 10.5$ galaxies, we can safely probe X-ray AGNs with $\log L_X/M_\star \gtrsim 30.5$. For $\log M_\star > 11$ galaxies, X-ray AGNs can be probed down to $\log L_X/M_\star \sim 30$.

We also removed extended X-ray sources in the catalog to avoid any contamination from halo gas. For sources detected in eROSITA, we adopted the cut of the EXT_LIKE > 3 ; for *XMM-Newton*-detected sources, we adopted the cut of SC_EXT_ML > 6 ; for *Chandra*-detected sources, we used extent_flag reported in CSC. Around 20% of the X-ray sources are marked as extended.

2.3. Optical AGN selection

Among all the MaNGA galaxies with X-ray coverage, we selected optical AGNs based on the Baldwin-Phillips-Terlevich (BPT) classification diagrams in [Kewley et al. \(2006\)](#), where

different emission line strengths are used to identify the dominant ionization mechanism, as well as the WHAN diagram ([Cid Fernandes et al. 2011](#)), where the equivalent width (EW) of $H\alpha$ is utilized to remove fake AGNs (post-asymptotic giant branch stars can produce ionized gas with line ratios similar to those of low-ionization nuclear emission-line regions).

To perform the classification, we computed the flux ratios of [O III]/ $H\beta$, [N II]/ $H\alpha$, and [S II]/ $H\alpha$, for valid spaxels—which are spaxels that have all these emission lines detected at $S/N > 3$. We then classified these valid spaxels into classes: AGN, SF, and ambiguous (Amb.). We classified a spaxel as an AGN spaxel if it was identified as an AGN in both [N II]-based and [S II]-based BPT diagrams, and has $EW(H\alpha) > 3 \text{ \AA}$. We classified a spaxel as SF if it was classified as SF in both BPT diagrams. Spaxels that could not be strictly classified into one of these categories were classified as ambiguous. In Fig. 1, an example of this spaxel-by-spaxel classification is presented. A general classification was then obtained by analyzing spaxels within apertures of 1, 2, and 3 kpc in radius, which cover the typical narrow-line region (NLR) size among most AGNs in the MaNGA sample. If the number of valid spaxels is > 5 within a given aperture, and the fraction of AGN spaxels is greater than 20% of the total and exceeds the SF and ambiguous spaxel fraction, we classified this object as an AGN. Following the approach in [Albán & Wylezalek \(2023\)](#), we also computed the average flux ratios of [O III]/ $H\beta$, [N II]/ $H\alpha$, and [S II]/ $H\alpha$, as well as the average $H\alpha$ EW in the galaxy’s central 1, 2, and 3 kpc apertures, utilizing spaxels where the relevant emission lines have $S/N > 3$. We classified an object as an AGN if it was identified as an AGN in both BPT diagrams within any of the given apertures, and average $EW(H\alpha) > 3 \text{ \AA}$ within the aperture was also required. We then combined the classification results from all the methods: if an object was classified as an AGN by any of the methods, it was recognized as an optically selected AGN.

For these optically selected AGNs, we derived $L_{[\text{O III}]}$ based on the [O III] luminosity map and the spaxel-by-spaxel AGN classification map. To create the [O III] luminosity map, we first derived the uncorrected [O III] luminosity map from the pyPipe3D [O III] flux map. Dust attenuation was then corrected using the Balmer decrement measurements from $H\alpha$ and $H\beta$ flux maps, assuming the [Calzetti \(2001\)](#) dust extinction law with $R_V = 3.1$, and an intrinsic $H\alpha/H\beta$ ratio of 3.1 ([Kewley et al. 2006](#)). We then integrated [O III] luminosity over spaxels that were classified as AGN spaxels as the total $L_{[\text{O III}]}$.

2.4. Spatially resolved measurements of star formation

To investigate star formation in the central regions, for all the MaNGA galaxies in our sample, we obtained the SFR surface density in the central 1 kpc region, $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, in order to represent the absolute level of star formation. We also fully leveraged the MaNGA IFU data and obtained the radial profile of SFR density (see Sect. 2.4.1). We also combined the Σ_{SFR} map and the $\Sigma_\star$ map to calculate the spaxel-by-spaxel deviation from the spatially resolved star formation main sequence (MS) and derive the radial profile of this deviation (see Sect. 2.4.2). In addition, we produced the map of D_n4000 and obtained the spatial profiles, which are closely related to age and can be utilized as another independent tracer of star formation properties (see Sect. 2.4.3).

2.4.1. Σ_{SFR} measurements

We derived Σ_{SFR} using the spatially resolved decomposition of the stellar populations provided by the pyPipe3D analysis

(Sánchez et al. 2016a, 2022), which gives the fractions of luminosity from 273 templates spanning 39 stellar ages (1 Myr – 14.1 Gyr) and 7 metallicities. We converted the luminosity fractions to stellar mass fractions using the mass-to-light ratios provided for each simple stellar population (SSP) model. We then summed up the mass fractions at a certain age (but with different metallicities), which gave us the integrated $M_\star$ at a certain age for each spaxel. This allowed us to derive the SFR for each spaxel. The SFR_{ssp} adopted throughout this work is the average SFR within ~ 100 Myr, which was calculated by adding all the masses with ages $\lesssim 100$ Myr and then dividing by the time:

$$\text{SFR}_{\text{ssp},t} = \frac{\sum_{\text{age}=0}^t M_{\star,\text{age}}}{t} \quad (1)$$

As stated in Sánchez et al. (2016b), stellar population parameters obtained from SSP decomposition (e.g., age and metallicity) for MaNGA galaxies typically have uncertainties of 0.1–0.2 dex estimated from Monte Carlo simulations. The Monte Carlo uncertainty in $M_\star$ derived from SSP decomposition is typically comparable to that of these parameters (e.g. Cid Fernandes et al. 2014). These small uncertainties provide a reasonable basis for SSP-based SFR measurements, although the precision of such measurements naturally degrades in the regime of very old stellar populations. We also note that these Monte Carlo uncertainties reflect the statistical errors propagated from the flux measurement uncertainties through the fitting procedure, and do not include systematic effects. For SFR measurements, a significant portion of the uncertainty arises from the adopted SSP templates, along with other systematic uncertainties related to dust attenuation and star formation history parameterization. By comparing with SFR values estimated from $\text{H}\alpha$ emission, the scatter of SSP-based SFR values is found to be around 0.3 dex (Sánchez et al. 2022), which demonstrates the general reliability of this type of measurement, considering that SFR averaged over the recent 100 Myr can be very sensitive to star formation history priors and difficult to constrain precisely (e.g. Leja et al. 2019). We further divided SFR_{ssp} per spaxel by the area per spaxel to get Σ_{SFR} measurements.

To obtain $\Sigma_{\text{SFR},1\text{ kpc}}$, we adopted the Sérsic profiles measured in the NASA-Sloan Atlas (NSA) catalog (Blanton et al. 2011) and created elliptical apertures with a major axis of 1 kpc and calculated the mean Σ_{SFR} within the aperture². When measuring the radial profile of Σ_{SFR} , we also took elliptical apertures with different major axis sizes and used the mean Σ_{SFR} of all the spaxels within different elliptical annuli. For all the Σ_{SFR} measurements, including $\Sigma_{\text{SFR},1\text{ kpc}}$ measurements, we adopted the inclination correction suggested in Hsieh et al. (2017).

² We also performed Monte Carlo simulations incorporating spectral noise for a set of randomly selected objects to assess the typical uncertainty scale of individual $\Sigma_{\text{SFR},1\text{ kpc}}$ measurements with pyPipe3D. The resulting scatter ranges from $\lesssim 0.05$ dex to $\lesssim 0.5$ dex. This scatter can be very small when there is considerable star formation activity, but it increases when the central stellar population is older and exhibits little recent star formation, and it can be even larger for galaxies with very quiescent centers. Σ_1 , as measured in Sect. 2.4.2, typically shows a scatter of < 0.1 dex. These uncertainties also suggest that systematic uncertainties from, for example, dust attenuation, star formation history parameterization, and initial mass function constitute a considerable fraction of (or even dominate) the uncertainty in $\Sigma_{\text{SFR},1\text{ kpc}}$ and Σ_1 . The estimated typical uncertainty scales in $\Sigma_{\text{SFR},1\text{ kpc}}$ and Σ_1 , presented in the right panel of Fig. 2, combine the representative Monte Carlo scatters (we take the median of the scatter range) in quadrature with empirical systematic uncertainty floors inferred from the scatter between integrated pyPipe3D estimates and other independent measurements (e.g. Sánchez et al. 2022).

2.4.2. Deviation from the spatially resolved star formation MS

We obtained $\Sigma_\star$ maps utilizing the stellar mass maps provided by the pyPipe3D data products, which are also estimated from SSP decomposition. By comparing with $M_\star$ values estimated from multi-band photometry, the uncertainty of SSP-based $M_\star$ measurements is found to be around 0.2 dex (Sánchez et al. 2022), suggesting the general reliability of this type of measurement. We then measured the $\Sigma_\star$ radial profiles and Σ_1 by taking the mean value of spaxels within the elliptical apertures or annuli with different major axis sizes, with inclination correction performed following Hsieh et al. (2017). Following the spatially resolved star formation MS obtained in Hsieh et al. (2017), $\log \Sigma_{\text{SFR}} = 0.715 \times \log \Sigma_\star - 8.065$, we derived the deviation from this MS (ΔMS) for each spaxel, which enabled us to calculate the radial profile of ΔMS .

2.4.3. D_n4000 measurements

The strength of the 4000 Å break, D_n4000 , is defined as the ratio of the average flux density in the narrow continuum bands 4000–4100 Å and 3850–3950 Å. D_n4000 closely tracks the stellar population age, and can also serve as an indicator for specific SFR (sSFR) at $D_n4000 \lesssim 1.8$ (e.g. Brinchmann et al. 2004; Spindler et al. 2018). To measure spatially resolved D_n4000 profiles, we utilized the Data Analysis Pipeline (DAP; Westfall et al. 2019) spectral fitting results, which include the best-fitting stellar continuum models without emission-line components for all the spaxels.

2.5. Sample properties

In Fig. 2, we plot all the galaxies in the sample on the SFR versus $M_\star$ plane and the $\Sigma_{\text{SFR},1\text{ kpc}}$ versus Σ_1 plane. X-ray and optical AGNs are marked as labeled. While there is a considerable fraction of AGNs among SF galaxies, we can see that in terms of the spatially resolved star formation MS, the central 1 kpc regions of most AGNs and normal galaxies lie below it (see Sect. 4.3 for discussions).

In Fig. 3, we plot the X-ray/[O III] luminosities for X-ray/optical AGNs to approximate the accretion rate of these objects assuming a bolometric correction (e.g. Hopkins et al. 2007; Lamastra et al. 2009; Duras et al. 2020) and a radiative efficiency; in Fig. 4, we plot the $L_X/M_\star$ and $L_{[\text{OIII}]} / M_\star$ distributions, which can be used to approximate the specific black hole accretion rate (sBHAR), assuming $M_\star$ as a proxy for the BH mass. Most AGNs in our sample have $\log L_X/M_\star \lesssim 31$ and $\log L_{[\text{OIII}]} / M_\star \lesssim 30$. Following the conversion factor between $L_X/M_\star$ and Eddington ratio reported in Eq. 2 of Aird et al. (2018) (which assumes a constant ratio between $M_\star$ and BH mass as well as a constant bolometric correction factor; see Aird et al. 2018 for details) and the average ratio of L_X and $L_{[\text{OIII}]}$ reported in Lamastra et al. (2009), these values correspond to very weak accretion activity with Eddington ratios $\lesssim 0.1\%$.

As can be seen in Fig. 5, $\log L_X$ and $\log L_{[\text{OIII}]}$ as well as $\log L_X/M_\star$ and $\log L_{[\text{OIII}]} / M_\star$, are loosely correlated among objects that are identified as AGNs in both X-ray and optical bands. This indicates that the L_X – $L_{[\text{OIII}]}$ relation is not merely driven by the tendency for more massive galaxies to exhibit higher L_X and $L_{[\text{OIII}]}$ values, and we can compare the sBHAR of X-ray-selected AGNs and optically selected AGNs through a conversion—though with caution, as the scatter is significant (the measurement uncertainties of luminosities in this work may contribute substantially to the observed scatter, see Sect. 4.2 for

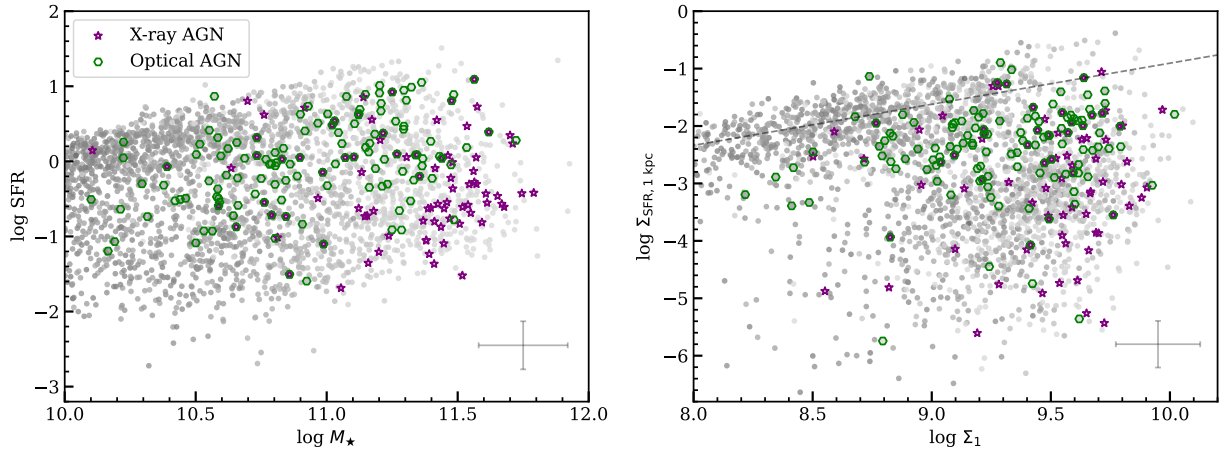


Fig. 2. Left: X-ray-selected AGNs and optically selected AGNs on the $M_\star$ versus SFR plane, as labeled. All galaxies in the sample are displayed as background points, with grayscale intensity encoding their weights. The error bar in the corner indicates uncertainties in $M_\star$ and SFR derived from pyPipe3D SSP decomposition, estimated by comparison with independent measurements (Sánchez et al. 2022). Right: Similar to the left panel, but for the Σ_1 versus $\Sigma_{\text{SFR},1 \text{ kpc}}$ plane. The dashed line depicts the spatially resolved star formation MS from Hsieh et al. (2017). The error bar in the corner indicates approximate uncertainty scales for Σ_1 and $\Sigma_{\text{SFR},1 \text{ kpc}}$ (see Footnote 2).

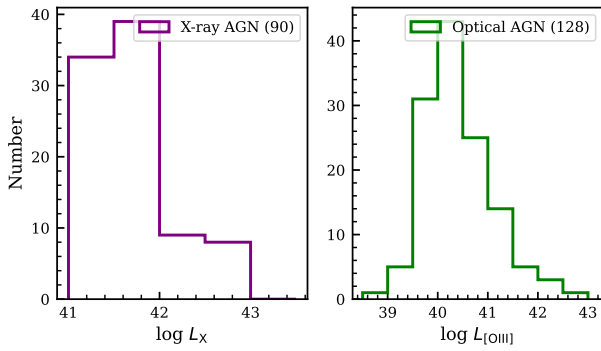


Fig. 3. Left: $\log L_X$ distribution of X-ray AGNs. L_X represents the rest-frame 2–10 keV X-ray luminosity in units of erg s^{-1} . Right: $\log L_{[\text{O III}]}$ distribution of optical AGNs. $L_{[\text{O III}]}$ represents the (extinction-corrected) luminosity of the $[\text{O III}] \lambda 5007$ emission line in units of erg s^{-1} .

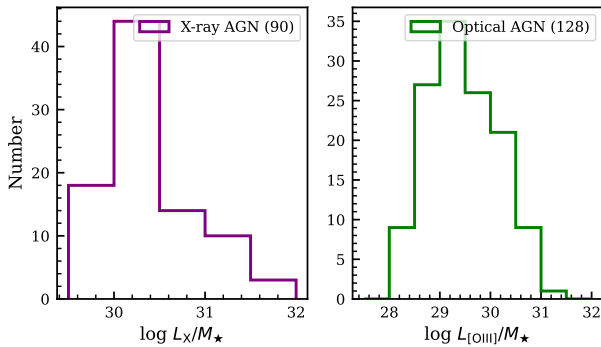


Fig. 4. Left: $\log L_X/M_\star$ distribution of X-ray AGNs. Right: $\log L_{[\text{O III}]} / M_\star$ distribution of optical AGNs. $L_X/M_\star$ and $L_{[\text{O III}]} / M_\star$ correspond to the X-ray and $[\text{O III}]$ luminosity per unit stellar mass, respectively, in units of $\text{erg s}^{-1} M_\odot^{-1}$.

discussions). Throughout the paper, we perform the analyses for X-ray AGNs and optical AGNs separately. Since we grouped X-ray AGNs into two categories with a cut at $\log L_X/M_\star = 30.5$, we adopted a $\log L_{[\text{O III}]} / M_\star$ cut of 29.5 for optical AGNs (which roughly corresponds to $\log L_X/M_\star = 30.5$ given the

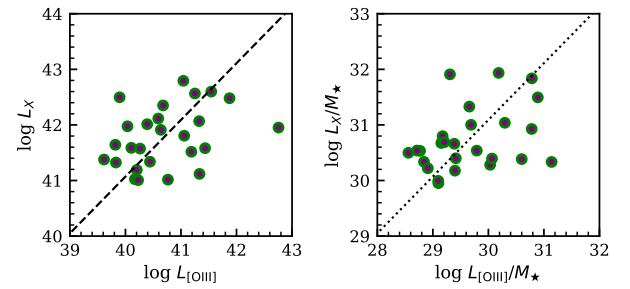


Fig. 5. Left: L_X versus $L_{[\text{O III}]}$ for objects that are identified as both X-ray and optical AGNs. The dashed line shows the best-fit $\log L_X - L_{[\text{O III}]}$ relation reported in Lamastra et al. (2009). Right: $L_X/M_\star$ versus $L_{[\text{O III}]} / M_\star$ for objects that are identified as both X-ray and optical AGNs, with the best-fit relation converted from the $\log L_X - L_{[\text{O III}]}$ relation.

Lamastra et al. (2009) relation represented in Fig. 5). We refer to X-ray AGNs with $\log L_X/M_\star > 30.5$ as higher- $L_X/M_\star$ AGNs, and those with $\log L_X/M_\star < 30.5$ as lower- $L_X/M_\star$ AGNs. Similarly, we refer to optical AGNs with $\log L_{[\text{O III}]} / M_\star > 29.5$ as higher- $L_{[\text{O III}]} / M_\star$ AGNs, and those with $\log L_{[\text{O III}]} / M_\star < 29.5$ as lower- $L_{[\text{O III}]} / M_\star$ AGNs. We do not directly refer to these subsamples as higher- or lower-sBHAR X-ray or optical AGNs because of the considerable scatter observed between $\log L_X/M_\star$ and $\log L_{[\text{O III}]} / M_\star$, which comes from both the measurement uncertainty of these luminosities and the intrinsic uncertainty involved in using $L_X/M_\star$ or $L_{[\text{O III}]} / M_\star$ as a proxy for the specific accretion rate (e.g. Aird et al. 2018; Duras et al. 2020; Suh et al. 2020). We also caution that most AGNs in the higher- $L_X/M_\star$ or $L_{[\text{O III}]} / M_\star$ subsamples are still likely to have low Eddington ratios, as discussed in the paragraph above.

3. Analyses and results

3.1. AGN fraction as a function of central SFR density

3.1.1. X-ray-selected AGN fraction

In Fig. 6, we show how the X-ray AGN fraction varies as a function of $\Sigma_{\text{SFR},1 \text{ kpc}}$. To ensure that the contamination from other X-ray sources does not affect the results (see Sect. 2.2.4 for details),

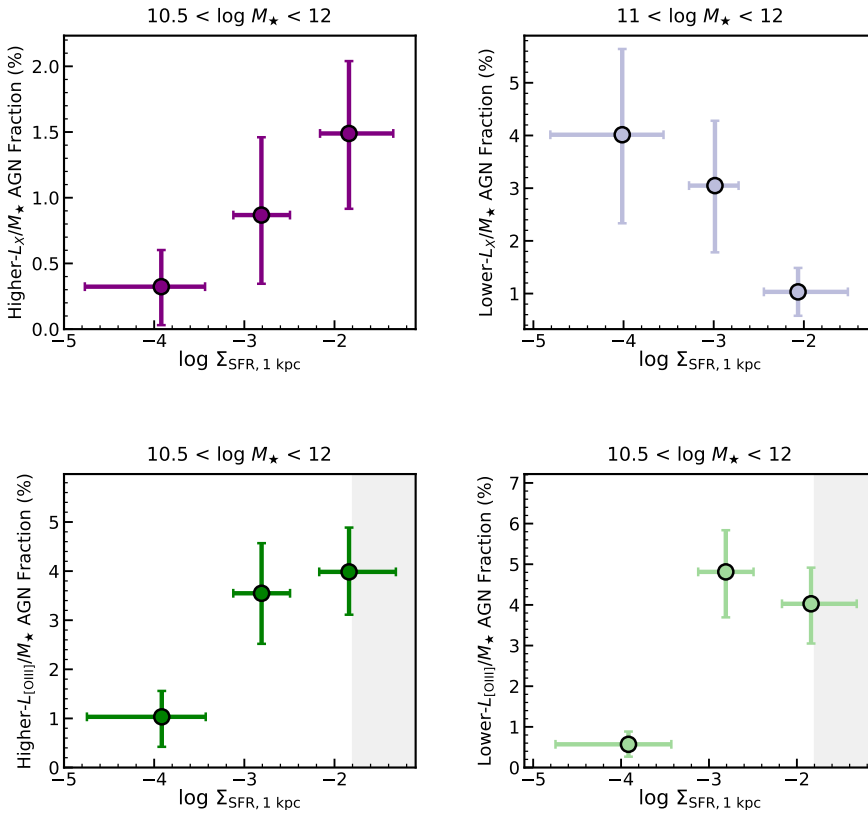


Fig. 6. Left: Fraction of X-ray AGNs with higher L_X/M_* ($\log L_X/M_* > 30.5$) as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, among objects with $10.5 < \log M_* < 12$. The y-axis error bars represent the 1σ confidence interval of AGN fraction from bootstrapping (i.e. randomly drawing the same number of objects from the sample 1000 times). The x-axis error bars represent the 16th and 84th percentiles of the $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ values. Right: Similar to the left panel, but for the fraction of lower- L_X/M_* ($\log L_X/M_* < 30.5$) X-ray AGNs as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, among objects with $11 < \log M_* < 12$.

Fig. 7. Left: Fraction of higher- $L_{[\text{OIII}]} / M_*$ ($\log L_{[\text{OIII}]} / M_* > 29.5$) optical AGNs as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, among objects with $10.5 < \log M_* < 12$. The y-axis error bars represent the 1σ confidence interval of AGN fraction from bootstrapping. The x-axis error bars represent the 16th and 84th percentiles of the $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ values. The gray shaded region represents the $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ range where optical AGN selection is considerably affected by contamination from star formation (see Sect. 4.1 for details). Right: Similar to the left panel, but for the fraction of lower- $L_{[\text{OIII}]} / M_*$ ($\log L_{[\text{OIII}]} / M_* < 29.5$) optical AGNs as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ among $10.5 < \log M_* < 12$ galaxies.

we studied $\log L_X/M_* > 30.5$ AGNs (i.e., higher- L_X/M_* AGNs) only among objects with $\log M_* > 10.5$ (that have X-ray coverage with $L_{X,\text{limit}}/M_* \leq 30.5$ as well), and $\log L_X/M_* = 30$ – 30.5 AGNs (i.e., lower- L_X/M_* AGNs) only among galaxies with $\log M_* > 11$ (also with $L_{X,\text{limit}}/M_* \leq 30$). We divided galaxies satisfying the above criterion into $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ bins with an equal number of objects per bin and then calculated the X-ray AGN fraction. When calculating the fraction, we adopted the weight reported in the MaNGA DAP catalog for each object to recover the results for a volume-limited sample³.

We can see that the higher- L_X/M_* AGN fraction (with a median $\log L_X/M_* \approx 31$) increases with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ in the M_* range we probed. Due to the limited number of X-ray AGNs with relatively high L_X/M_* , we are only able to probe them in this large mass range. At the same time, among the most massive galaxies, the fraction of lower- L_X/M_* AGNs (with even lower specific accretion rate, $\log L_X/M_* = 30$ – 30.5) decreases with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, in contrast to what has been observed for the fraction of higher- L_X/M_* X-ray AGNs among galaxies with relatively smaller M_* .

3.1.2. Optically selected AGN fraction

We further plot the fraction of optically selected AGNs as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ among galaxies in our sample. We studied two groups of optically selected AGNs: those with higher-

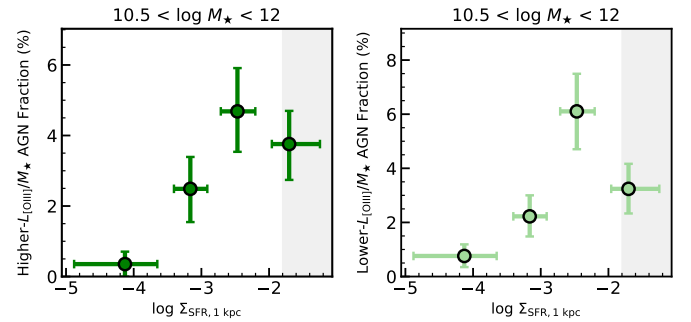


Fig. 8. Similar to Fig. 7, but presented in four $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ bins.

$L_{[\text{OIII}]} / M_*$ values ($\log L_{[\text{OIII}]} / M_* > 29.5$) and those with relatively lower- $L_{[\text{OIII}]} / M_*$ values ($\log L_{[\text{OIII}]} / M_* < 29.5$), to roughly match the L_X/M_* scales in Sect. 3.1.1 (see Sect. 2.5 for details). Although it is possible to estimate the [O III] flux upper limit for non-detections in individual spaxels, deriving $L_{[\text{OIII}]}$ requires integration over AGN spaxels. This is not possible when the classification itself is unavailable. Furthermore, even when an upper limit of $L_{[\text{OIII}]}$ can be estimated, proper decomposition is needed to truly estimate the AGN $L_{[\text{OIII}]}$ upper limit for weak AGNs among SF hosts (see Sect. 4.2). Giving an upper limit of $L_{[\text{OIII}]}$ for an optically selected AGN to be properly detected for each MaNGA galaxy is beyond the scope of this work, and we leave it for future work. We instead utilized all the galaxies as the parent sample, similar to previous MaNGA studies of optical AGNs. For optical AGNs in different $L_{[\text{OIII}]} / M_*$ groups, we studied them first in the large $\log M_* = 10.5$ – 12 range following the approach in Sect. 3.1.1 (see Fig. 7), and then in smaller M_* bins to enable better comparison with the X-ray AGN sample (see Figs. 9 and 10).

³ We verified that the general trend does not vary qualitatively if no weight is adopted. We also note that since we only use objects with X-ray coverage, the weights to recover a volume-limited sample may not be exactly the same as those provided in the catalog. However, we have verified that the objects with X-ray coverage (as well as those selected using different $L_{X,\text{limit}}/M_*$ thresholds) roughly span the same property space as the full sample.

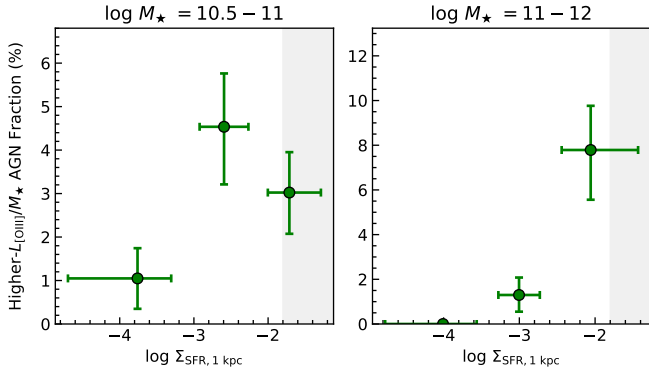


Fig. 9. Similar to Fig. 7, but for the fraction of higher- L_{OIII}/M_* optical AGNs as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ among objects with $10.5 < \log M_* < 11$ (left) and objects with $11 < \log M_* < 12$ (right).

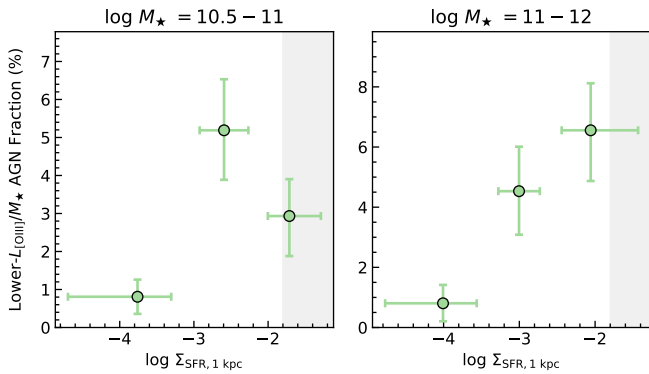


Fig. 10. Fraction of lower- L_{OIII}/M_* optical AGNs as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, among objects with $10.5 < \log M_* < 11$ (left) and objects with $11 < \log M_* < 12$ (right).

We see that both the higher- L_{OIII}/M_* and lower- L_{OIII}/M_* optical AGN fractions increase with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ when the $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ is small, but this increasing trend is not significantly present at the high- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ end, especially for the lower- L_{OIII}/M_* AGNs. When we group galaxies into more $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ bins (see Fig. 8), we can clearly observe a decreasing trend at the high- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ end. If we study it in smaller M_* ranges (see Figs. 9 and 10), we can see that this decreasing trend is mostly associated with the $\log M_* = 10.5\text{--}11$ objects. Among $\log M_* = 11\text{--}12$ galaxies, the optical AGN fraction consistently increases with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$. While it would be natural to conclude AGN negative feedback at a smaller mass range, we argue that it is actually more complicated, and discuss how selection effects come into play in Sect. 4.1. In all M_* and L_{OIII}/M_* ranges, we do not observe an elevated optical AGN fraction among low- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ galaxies as we observed for the lower- L_X/M_* X-ray AGN fraction among massive galaxies (see the right panel of Fig. 6), and we discuss this in Sect. 4.1 as well.

3.2. Comparing the star-formation profiles of AGNs and normal galaxies with similar global properties

We also compare the full Σ_{SFR} radial profiles of X-ray/optical AGNs with normal galaxies that share similar global properties. We have presented how AGN fraction is related to $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, and we note that AGN fraction is related to global SFR as well. The full radial profile comparison will help to address whether

the link between AGN activity and SFR in the galaxy's central region is more than the manifestation of more AGNs among SF galaxies, and why this would be the case.

3.2.1. Profiles of X-ray-selected AGN hosts

Similar to the approach described in Sect. 3.1.1, we divided the X-ray AGNs into two categories: higher- L_X/M_* ($\log L_X/M_* > 30.5$) AGNs among galaxies with $\log M_* = 10.5\text{--}12$, and lower- L_X/M_* ($\log L_X/M_* = 30\text{--}30.5$) AGNs only among galaxies with $\log M_* > 11$.

When selecting normal galaxies to constitute the control sample, we limited our selection to galaxies with $L_{X, \text{limit}}/M_*$ smaller than the L_X/M_* lower limit of the AGN sample. Furthermore, we excluded optical AGNs to make sure that the contamination in the control sample is as small as possible (we verified that our results did not change if we included optical AGNs in the control sample). For each X-ray AGN, we selected two normal galaxies with the closest M_* , SFR, and z values utilizing the NearestNeighbors algorithm in the scikit-learn Python package. Then, for both the X-ray AGN sample and the control galaxy sample, we derived the mean radial profile of Σ_{SFR} using elliptical annuli with a width of 1 kpc, extending out to 10 and 15 kpc for AGNs in the higher- and lower- L_X/M_* samples, respectively, corresponding to ~ 2 median R_e for each sample. As can be seen in Fig. 11, higher- L_X/M_* AGNs with $\log L_X/M_* > 30.5$ at $\log M_* = 10.5\text{--}12$ show a steeper and more concentrated Σ_{SFR} profile compared to normal galaxies when the total global SFR is roughly the same. In the central regions, higher- L_X/M_* X-ray AGNs have higher Σ_{SFR} , and the difference in Σ_{SFR} is more prominent when the radius is small. In addition to the mean profile of Σ_{SFR} , we also present the comparison of the mean Σ_* , ΔMS , and D_n4000 profiles. We note that X-ray AGNs also have slightly higher Σ_* in the center – nevertheless, the differences in Σ_* profiles are not as significant as those in the Σ_{SFR} profiles, as a lot of quiescent hosts are included in this study where Σ_* cannot trace the gas density very well. While both X-ray AGNs and normal galaxies show suppressed star formation relative to the spatially resolved star formation MS, as indicated by their mean ΔMS profiles, X-ray AGNs still show a mean ΔMS that is apparently high compared to normal galaxies in the central regions. In terms of D_n4000 , we can see that X-ray AGNs are generally younger, and the difference is more prominent in the central regions (also indicating high sSFR when $D_n4000 \lesssim 1.8$). As for the lower- L_X/M_* AGNs ($\log L_X/M_* = 30\text{--}30.5$) among $\log M_* = 11\text{--}12$ galaxies, their mean Σ_{SFR} profile, ΔMS profile, and Σ_* profile do not show noticeable differences when compared with normal galaxies. At the same time, we can see that they have slightly younger cores and older outer regions.

3.2.2. Profiles of optically selected AGN hosts

We grouped the optical AGNs into two L_{OIII}/M_* groups as we did in Sect. 3.1.2, and we compared the profiles of higher- and lower- L_{OIII}/M_* optical AGNs with those of normal galaxies following the approach described in Sect. 3.1.1. When constructing the control sample of normal galaxies, we also excluded all the defined X-ray AGNs to make sure that the contamination in the control sample is as small as possible (we verified that our results did not change qualitatively but became less prominent when we included X-ray AGNs in the control sample). The control sample was again constructed by selecting two normal galaxies with the closest M_* , SFR, and z values. As can be seen in Fig. 12, both higher- and lower- L_{OIII}/M_* AGNs show higher central Σ_{SFR}

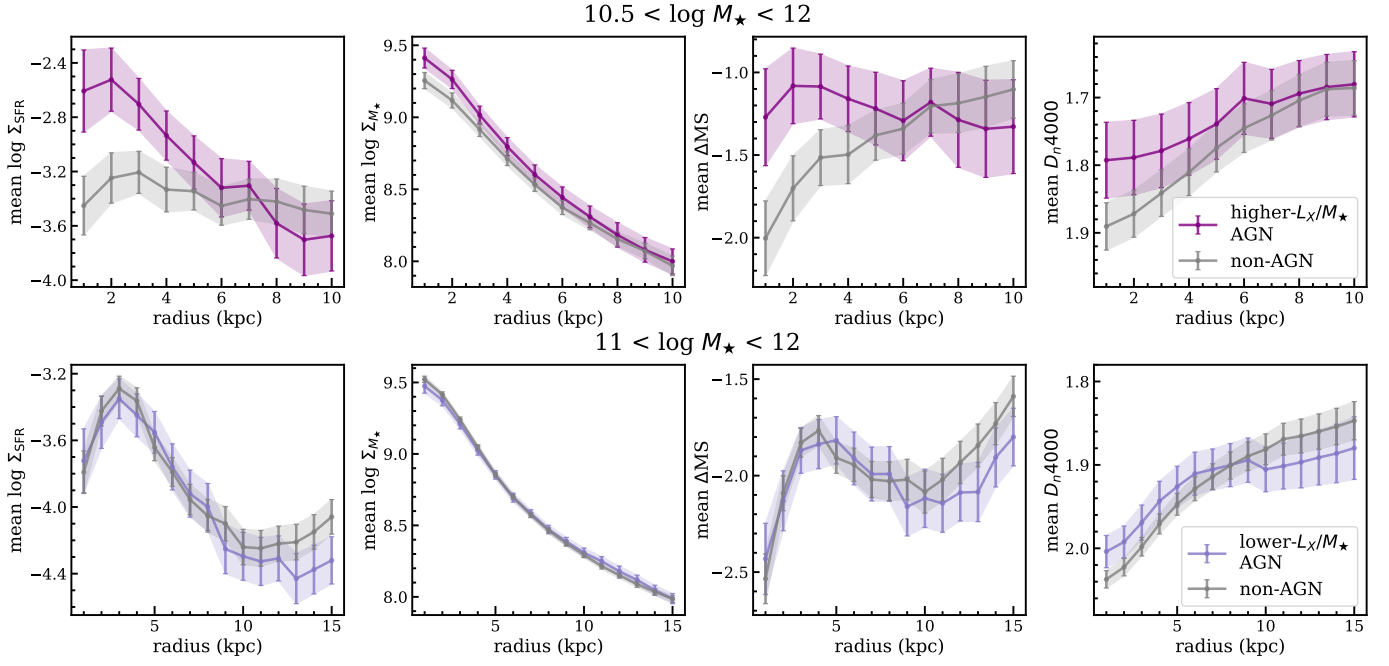


Fig. 11. Top: Mean Σ_{SFR} , Σ_{M_*} , ΔMS , D_n4000 profiles of higher- L_X/M_* X-ray AGNs compared with normal galaxies in the control sample matched according to M_* , SFR, and z individually, sampled with a 1 kpc interval in major-axis radius. Error bars represent the standard error of the mean. Bottom: Similar to the top panel, but for lower- L_X/M_* X-ray AGNs.

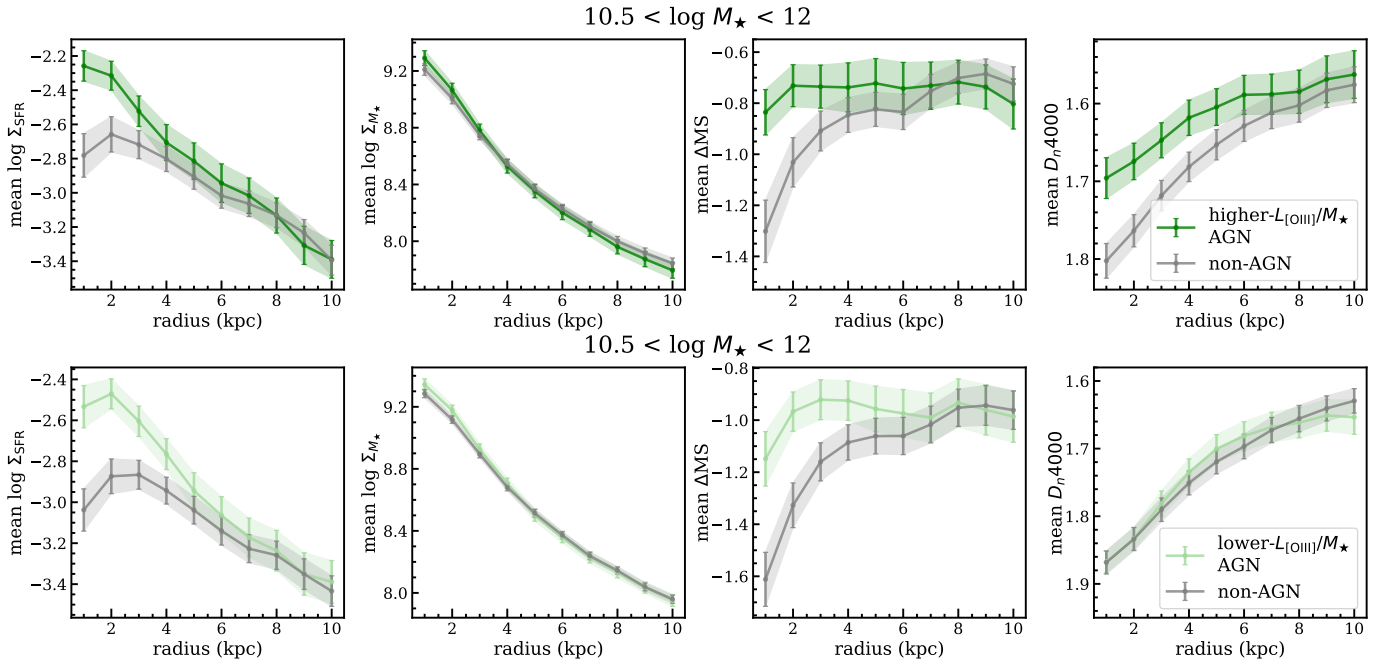


Fig. 12. Similar to Fig. 11, but for higher- $L_{[\text{OIII}]} / M_*$ optical AGNs (top) and lower- $L_{[\text{OIII}]} / M_*$ optical AGNs (bottom).

compared to normal galaxies. They also exhibit higher central ΔMS compared to normal galaxies. Similar to X-ray AGN hosts, the differences in Σ_* profiles of optical AGN hosts compared with those of normal galaxies are not significant.

4. Discussion

4.1. Missing optical AGNs among high- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ galaxies and low- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ galaxies

As can be seen in Figs. 7 and 8, the increasing trend of the optical AGN fraction with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ is not present when the $\Sigma_{\text{SFR}, 1 \text{ kpc}}$

is high. It is natural to link this with negative feedback, where AGNs are thought to be responsible for suppressing star formation in galaxy centers. However, before we know whether negative feedback is observed or not, we need to account for the bias associated with the BPT-based optical AGN selection method. Among SF areas, H II regions can produce emission lines that mimic AGN features, and when the AGN is relatively weak or is obscured, the AGN signal may be buried beneath the SF activity. For example, in the BPT diagram we utilized to identify the dominant source of ionization, SF spaxels with weak and/or obscured AGN signal may fall into the “ambiguous” and “SF” spaxels.

As suggested by the correlation between SFR and $L_{[\text{OIII}]}$ reported in [Villa-Vélez et al. \(2021\)](#),

$$\log \text{SFR} = \log L_{[\text{OIII}]} - 41.2, \quad (2)$$

higher SFRs require a higher threshold for reliable AGN detection. This also works for the surface density of these values. We note that $\geq 90\%$ of the optical AGNs in our sample have $[\text{O III}]$ surface luminosity densities ($\Sigma_{L_{[\text{OIII}]}}$) in the central 1 kpc region of $\geq 10^{39.7} \text{ erg s}^{-1} \text{ kpc}^{-2}$. When $\Sigma_{L_{[\text{OIII}]}}$ generated by the central star formation is comparable to that generated by the AGN, we consider it difficult to identify the AGN from the BPT diagram. This corresponds to $\log \Sigma_{\text{SFR}, 1 \text{ kpc}} \sim -1.8$. In reality, we note that AGNs identified via BPT diagrams typically contribute more to the total $[\text{O III}]$ flux when they pass the classification line (e.g. [Davies et al. 2014](#)). There are also uncertainties associated with the $\log \text{SFR} - \log L_{[\text{OIII}]}$ relation: [Villa-Vélez et al. \(2021\)](#) noted that variations in metallicity and ionization parameters can theoretically lead to a spread of up to 1.1 dex; the empirical scatter of this relation reported ranges from ≈ 0.3 to 0.6 dex (e.g. [Moustakas et al. 2006](#); [Villa-Vélez et al. 2021](#)). These indicate that the $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ threshold for an optical AGN to be very safely detected could be even lower. Given the contamination threshold, a fraction of optical AGNs may be missed in the highest $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ bin, so we cannot conclude negative feedback from this. For galaxies with $\log M_{\star} = 10.5 - 11$, most objects grouped into the highest $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ bin in Fig. 9 have $\log \Sigma_{\text{SFR}, 1 \text{ kpc}}$ values from -2.1 to -1.3 . Thus, a significant fraction of AGNs in this bin are likely to suffer strongly from selection effects, contributing to the clear drop in the AGN fraction at the high- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ end. For galaxies with $\log M_{\star} = 11 - 12$, most objects grouped into the highest $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ bin have $\log \Sigma_{\text{SFR}, 1 \text{ kpc}}$ values from -2.5 to -1.5 . A large fraction of these objects are likely less affected by selection bias; thus, the increasing trend can be clearly observed. While AGNs with higher $L_{[\text{OIII}]}$ do not naturally translate into higher $[\text{O III}]$ surface luminosity density, higher- $L_{[\text{OIII}]} / M_{\star}$ AGNs are more likely to have higher $\Sigma_{L_{[\text{OIII}]}}$. Thus, we can see that the drop at the high- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ end is more pronounced among optical AGNs with lower $L_{[\text{OIII}]} / M_{\star}$.

Also, when we selected optical AGNs, we required the emission lines utilized in the study to have $S/N > 3$ and $H\alpha \text{ EW} > 3 \text{ \AA}$. This naturally makes it difficult to classify weak and/or obscured AGNs, especially among quiescent galaxies with low $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ values. Thus, for optically selected AGNs in this study, we are not able to observe the elevated low- $L_{[\text{OIII}]} / M_{\star}$ AGN fraction among low- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ galaxies as we observed for X-ray-selected AGNs, leading to the observed discrepancy.

4.2. Is coeval growth in tension with AGN feedback?

Unlike optically selected AGNs, the fraction of higher- $L_X / M_{\star}$ X-ray AGNs with $\log L_X / M_{\star} > 30.5$ shows a steadily increasing trend with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ (see the left panel of Fig. 6), consistent with the expectation from the coeval growth picture arising from the common origin of gas in the vicinity of the BH and in the central region of galaxies. We note that X-ray selection is not completely safe from missing obscured AGNs, especially since a fraction of sources were selected in the eROSITA sky coverage, which is mainly sensitive in the soft band rather than the hard band (the obscuration effect is minimized in the hard band). If we consider that the obscuration level of AGN structure itself (e.g., torus) does not vary significantly with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, the obscuration level from the host-galaxy component (which also leads to considerable obscuration; e.g., [Goulding et al. 2018](#); [Gilli et al. 2022](#))

could increase with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$. As the increasing trend is present even with potential obscuration bias, we consider the picture of common fuel and coeval growth to be stable. If we look at the $D_n 4000$ profiles (see the top panel of Fig. 11), we can see that these higher- $L_X / M_{\star}$ X-ray AGNs, as well as all the optical AGNs with higher $L_{[\text{OIII}]} / M_{\star}$ (see Fig. 12), generally have younger stellar populations compared to galaxies with similar $M_{\star}$ and SFR, suggesting different star formation histories; that is, galaxies that host these AGNs are more likely to have more recent star formation episodes so that the average age appears lower, and the cold gas replenishment also triggers AGN activity.

Due to the limited sample size, we cannot statistically prove how significant $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ is as an indicator of AGN activity or BH growth compared to total SFR. However, analysis results in Figs. 11 and 12 already demonstrate that the link between AGN activity and $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ is more than simply manifesting the link between AGN activity and global SFR, as these AGNs and control galaxies have similar global SFRs. In [Ni et al. \(2021\)](#), we found that the projected central surface mass density within 1 kpc, Σ_1 , is more effective in predicting the BH growth level compared to other compactness parameters among SF galaxies. This can be understood at a phenomenological level from the slope of the Σ_{SFR} radial profiles: the differences between AGNs and normal galaxies in Σ_{SFR} , and thus in the available gas fuel, are more prominent in the central regions.

However, there is well-established observational evidence that AGNs can evacuate gas in the central regions of galaxies (e.g., [García-Burillo et al. 2014](#); [Fluetsch et al. 2019](#); [Parlanti et al. 2025](#)), so one would naturally expect reduced $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ in these cases. This raises the question of how these results can be consistent with a higher AGN fraction among galaxies with higher levels of central star formation.

In Fig. 13, instead of comparing the mean Σ_{SFR} profiles of X-ray AGNs and matched normal galaxies as a function of major-axis radius, we show the distribution of the difference in $\log \Sigma_{\text{SFR}}$ ($\Delta \log \Sigma_{\text{SFR}}$; $\log \Sigma_{\text{SFR}} (\text{AGN}) - \log \Sigma_{\text{SFR}} (\text{control galaxy})$) at the individual level) at different radii. Similar to the obvious difference in mean $\log \Sigma_{\text{SFR}}$ as shown in Fig. 11, the median $\log \Sigma_{\text{SFR}}$ of X-ray AGNs is also higher in the central regions. At the same time, the wide distribution of $\Delta \log \Sigma_{\text{SFR}}$ suggests the unreliability of deriving a universal conclusion for the AGN feedback scenario via a limited number of objects, particularly a single observation (which has been a widely adopted approach), as it will easily lead to a conclusion of positive or negative feedback—which could be at play for this particular object but not all the others. When considering the overall trend, while we attribute the link between AGN incidence and higher central Σ_{SFR} (on average) to coeval growth from a common fuel supply, the wide distribution of $\Delta \log \Sigma_{\text{SFR}}$ can be attributed to various factors.

We first need to account for AGN variability. The X-ray luminosity of AGNs can vary by orders of magnitude over a Myr timescale (e.g. [Hickox et al. 2014](#)), and the SFR we adopted in this study is measured over even longer timescales. The observed X-ray AGNs with a certain $L_X / M_{\star}$ criterion might not fulfill this criterion over most of the time during which the SFR is estimated; similarly, the normal galaxy used for comparison might be an X-ray AGN in recent history. While $L_{[\text{OIII}]}$ also exhibits variability and is subject to the same timescale effect mentioned above, compared with the X-ray emission, $[\text{O III}]$ emission is much closer to a long-term average measurement, as it comes from the NLR that is further away from the central supermassive BH (on a $\sim 10^4 - 10^5$ light-year scale) and has an extended spatial distribution. In this case, one would expect smaller scatters of the $\Delta \log \Sigma_{\text{SFR}}$ compared to normal galaxies, if variability plays

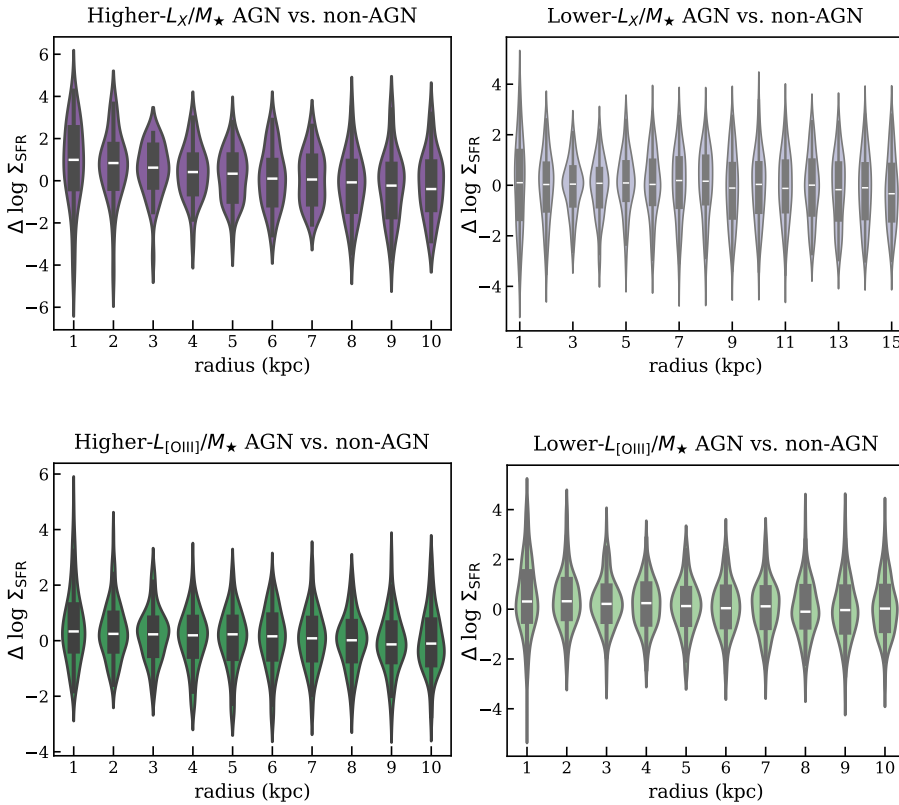


Fig. 13. Left: Violin plot showing the distribution of differences in Σ_{SFR} between higher- L_X/M_* AGNs and matched control galaxies at each radius. Similar to the mean Σ_{SFR} profiles presented in Fig. 11, clear differences in the medians are also observed, especially in the central regions. However, the distributions of $\Delta \log \Sigma_{\text{SFR}}$ for individual matched pairs remain broad, spanning both positive and negative values. Right: Similar to the left panel, but for lower- L_X/M_* AGNs. The $\Delta \log \Sigma_{\text{SFR}}$ distributions are also broad, while no clear differences in the medians are observed in galaxy central regions (aligning with the lack of significant differences in the mean Σ_{SFR} profiles).

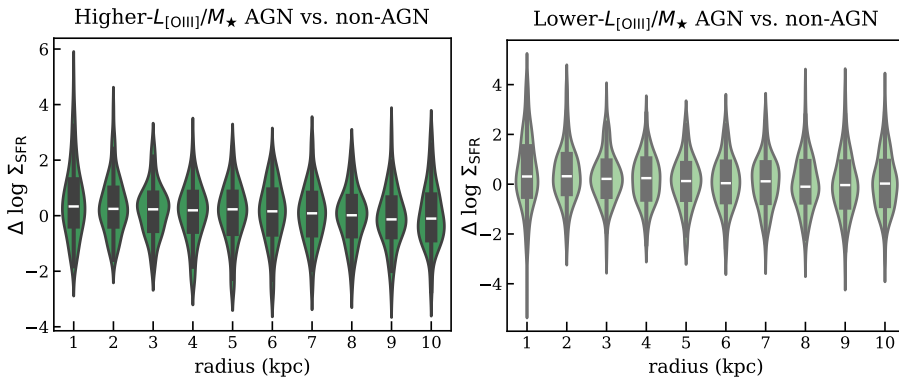


Fig. 14. Similar to Fig. 13, but for higher- $L_{[\text{OIII}]} / M_*$ optical AGNs (left) and lower- $L_{[\text{OIII}]} / M_*$ optical AGNs (right). Consistent with the clear differences in the mean Σ_{SFR} profiles presented in Fig. 12, offsets in the median values of the distributions (indicated by short horizontal lines) are observed for both groups in the central regions of galaxies. The overall distributions of $\Delta \log \Sigma_{\text{SFR}}$ for individual matched pairs are broad, extending significantly into both positive and negative values.

a smaller role here. We do observe that the scatter is slightly smaller, particularly at the central radii. However, the scatter is still considerable, which might be related to the optical AGN selection bias in this study (see Sect. 4.1), so some unclassified AGNs may remain in the matched control galaxy sample.

In addition, there might be real hints of feedback in action. It has been argued that negative feedback on star formation is most efficient in powerful AGNs (e.g. [Cicone et al. 2014](#)), as the powerful AGN winds could blow out gas in the central regions and stop the gas from fragmentation (e.g. [Zubovas & Bourne 2017](#)). For AGNs that are not especially luminous, such as objects in our sample, small-scale outflows can inject turbulence into the ISM, and/or heat the gas, thus also weakening the star formation, especially in the central region (e.g. [Parlanti et al. 2025](#)). At the same time, positive AGN feedback is also predicted and observed, whereby the ISM is compressed and the SFR is enhanced (e.g. [Maiolino et al. 2017](#); [Shin et al. 2019](#)). We cannot confidently argue that we have observed strong evidence for positive AGN feedback, as the overall elevated Σ_{SFR} spans areas larger than what AGNs at this low level of luminosity can impact. However, we might have observed evidence for negative AGN feedback, though very slight, as the Σ_{SFR} profiles in Figs. 11 and 12 show either a small decline in the central few kiloparsecs (though this decline is small compared to the absolute value of Σ_{SFR}), or a flattening of the inwardly increasing trend within the central few kiloparsecs. Under the negative AGN feedback scenario, one might expect more extended tails toward negative $\Delta \log \Sigma_{\text{SFR}}$ and a smaller median $\Delta \log \Sigma_{\text{SFR}}$ value in the central region among higher- $L_{[\text{OIII}]} / M_*$ optical AGNs compared to lower- $L_{[\text{OIII}]} / M_*$ optical AGNs in Fig. 14, if more powerful AGNs launch more powerful outflows. We observe slightly more extended negative $\Delta \log \Sigma_{\text{SFR}}$ tails over the central region among lower- $L_{[\text{OIII}]} / M_*$ optical AGNs. However, we note that the selection effect also plays a role in optical AGN identification as dis-

cussed earlier, and the differences are not significant; therefore, from these plots, we cannot reliably test whether central star formation suppression is more pronounced among AGN hosts with higher AGN luminosities. Also, we note that $L_{[\text{OIII}]}$ obtained from summing over the [O III] flux reported in pyPipe3D data products in AGN-dominated spaxels may not be a robust indicator of the true AGN luminosity. As we have discussed, weak or obscured AGN emission is hard to distinguish from the emission lines associated with SF activity; also, AGN outflows can broaden the [O III] emission line, and the shifted wings may contribute significantly, but they are not accounted for correctly given the current pyPipe3D line-measurement method (a single Gaussian fitting; [Sánchez et al. 2016a](#)). Thus, our subsamples divided according to $L_{[\text{OIII}]} / M_*$ might not distinguish true specific accretion power very clearly, which is also shown in Fig. 4 – a better measurement of the $L_{[\text{OIII}]}$ from the AGN will help to further investigate the negative AGN feedback scenario, if objects with higher- and lower-sBHAR are better separated.

Among massive galaxies with $\log M_* > 11$, we observe a decreasing trend of notably low sBHAR ($\log L_X / M_* < 30.5$) AGNs with increasing $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ (see the right panel of Fig. 6). We interpret this as being associated with both large M_* and the low sBHAR, where stochastic fueling from condensed hot halo gas serves as the major fuel. Hot halo gas fueling has long been proposed as a source for powering low-sBHAR AGNs, and both the trend of increasing low-sBHAR radio AGN fraction and X-ray AGN fraction with M_* has been observed among massive galaxies (e.g. [Best & Heckman 2012](#); [Ni et al. 2023](#)). Among massive galaxies with $\log M_* > 11$, lower $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ is indeed associated with galaxies with higher M_* and older stellar populations. These galaxies tend to reside in larger halos (e.g. [Wechsler & Tinker 2018](#)), which also contain more fuel to power AGNs with low levels of accretion activity through the stochastic condensation of halo gas, so that an elevated

lower- $L_X/M_\star$ AGN fraction is observed at the low- $\Sigma_{\text{SFR},1 \text{ kpc}}$ end. For galaxies with similar $M_\star$, older galaxies tend to form earlier in more massive halos (e.g. Rodríguez-Puebla et al. 2015; Wechsler & Tinker 2018) that have more fuel for the central BH. This explains why $\log L_X/M_\star < 30.5$ AGN hosts on average have older stellar populations in the outskirts compared to matched normal galaxies (see the bottom panel of Fig. 11), which is consistent with their formation history. They also have younger cores as a result of a slightly enhanced level of central star formation fueled by a larger reservoir of condensed halo gas. We also do not observe an obvious difference in the mean Σ_{SFR} profiles of these X-ray AGNs and normal galaxies (see Fig. 11). We note that the SFR in this study was derived based on decomposing the stellar continuum (see Sect. 2.4.1), which is not very sensitive to a small level of very recent star formation (at the ~ 10 Myr scale) when the overall stellar population is old. Σ_{SFR} derived from SSP decomposition is more stable for the average SFR over a longer period, such as the 100 Myr scale used in this study. Higher levels of H α emission can indeed be observed among these massive AGN hosts that cannot fully be attributed to AGN emission, indicating very weak star formation activity (which supports that what fuels the AGN must fuel the galaxy at the same time, to some extent) that becomes hard to detect when averaged out to longer timescales (see Fig. 15)⁴. In general, we observe more low- $L_X/M_\star$ AGNs among galaxies with low $\Sigma_{\text{SFR},1 \text{ kpc}}$, which depleted their cold gas earlier but have more hot halo gas fuel available. Also, compared to the mean Σ_{SFR} profiles of higher- $L_X/M_\star$ AGNs among less massive galaxies, the mean Σ_{SFR} profile of massive $\log L_X/M_\star < 30.5$ AGN hosts shows a larger decline in the central $\lesssim 3$ kpc region. For low-accretion-rate AGNs among massive galaxies, jet activity is considered to be very prevalent (e.g. Best et al. 2005). AGN jets are known to be a key mechanism for maintenance-mode AGN feedback, during which the surrounding gas is heated and disturbed, and cannot cool and form stars efficiently. Simulation results (e.g. Gaibler et al. 2012) predict that jets can create a small cavity in the galaxy center ($\lesssim 3$ kpc) and increase the SFR in the outer regions; these effects might explain the central Σ_{SFR} decline we observed among massive $\log L_X/M_\star < 30.5$ AGN hosts that is more noticeable (in both scale and amplitude) compared to that among other AGN hosts. While a single AGN active episode is short, the cavities left behind can persist on timescales comparable to those over which the SSP-based SFR is estimated (~ 100 Myr). In the bottom panel of Fig. 11, we see the central Σ_{SFR} decline almost equally in terms of AGNs and non-AGNs, which would be consistent with the effects of AGN jet-mode feedback on the relevant timescales.

4.3. Comparison with previous studies

In Fig. 16, we plot the mean ΔMS profiles as well as the specific SFR surface density (Σ_{sSFR}) profiles of all the galaxies in the sample grouped into different $M_\star$ and SFR bins. We can see that galaxies in the MaNGA sample have suppressed central star formation properties on average, while most of them do

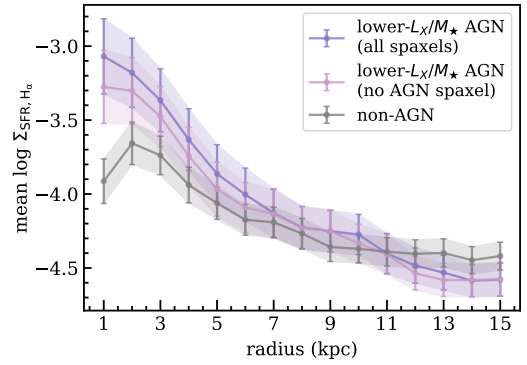


Fig. 15. SFR surface density profiles estimated from H α , of X-ray AGNs with lower $L_X/M_\star$ ($\log L_X/M_\star < 30.5$) and normal galaxies utilized in Fig. 11. We can see that even the mean Σ_{SFR} estimated from H α emission from spaxels that are not AGN-dominated is elevated compared to that of non-AGNs in the control galaxy sample, suggesting that a minute level of SF enhancement is likely among the hosts of these very weak AGNs, when we select an SF indicator that is sensitive to very recent SF activity.

not host detectable AGNs⁵. Thus, it is not surprising to observe suppressed SFRs among AGN hosts (e.g. Acharya et al. 2024) or low gas fractions among AGN regions (e.g. Ellison et al. 2021); galaxies at low redshift have suppressed centers on average, and AGN regions are just located in the centers. A causal relation between AGN feedback and the suppression of central SFR concluded this way needs further caution.

Even when the control galaxies are selected, if one does not take into account the limitation of optical AGN selection bias, suppressed central SFRs can be observed among some subsamples (e.g. Bing et al. 2019; Lammers et al. 2023; Gatto et al. 2025). Also, the effects of high global SFR and high central SFR in predicting the high level of AGN activity are hard to disentangle when control galaxies are selected only based on $M_\star$. In Fig. 17, we plot the mean Σ_{SFR} profiles for all the galaxies in the sample, grouped according to $M_\star$ and SFR values. We can see that for a given $M_\star$, when the global SFR is high, the profiles are more centrally concentrated. This effect is more prominent among $\log M_\star < 11$ galaxies, where the Σ_{SFR} profiles become flatter when the global SFR decreases, and Σ_{SFR} values in the central regions go through much larger variations compared to Σ_{SFR} in the outer regions. This is consistent with the expectation of cold gas supply distributed according to the host-galaxy potential well. Among the most massive galaxies, we can see signs of elevated Σ_{SFR} in the central regions that do not relate to fueling at the global scale. Together, these factors point to the need to select control galaxies with similar SFR values rather than simply controlling for $M_\star$ when studying how the central star formation property, in particular, relates to AGN activity: if one does not control for SFR (e.g. Bing et al. 2019; Mulcahey et al. 2022; Lammers et al. 2023; Acharya et al. 2024; Gatto et al. 2025), there might be a higher risk of observing artificially suppressed Σ_{SFR} among AGN hosts due to the selection effects as we previously discussed. In our work, we also observe the decreasing optical AGN fraction at the high- $\Sigma_{\text{SFR},1 \text{ kpc}}$ end, but since we controlled for the global SFR when comparing the

⁴ We estimated the H α -based Σ_{SFR} following the method in Sect. 3.1 of Spindler et al. (2018), where the relation from Kennicutt (1998) for a Salpeter (1955) initial mass function was adopted. We note that there are more caveats compared to the advantages of estimating SFR from H α . Due to the complexity in properly decomposing the contribution from AGN and star formation in the H α emission line, which is beyond the scope of this work, we did not adopt H α -based Σ_{SFR} measurements in this study.

⁵ In general, $\log \Sigma_{\text{sSFR}}$ profiles are similar to ΔMS profiles. Since galaxies have higher $\Sigma_\star$ in the central regions, in some cases, one can observe a slightly decreasing Σ_{sSFR} profile toward the center, but a relatively flat ΔMS profile, as the slope of the spatially resolved star formation MS is smaller than one.

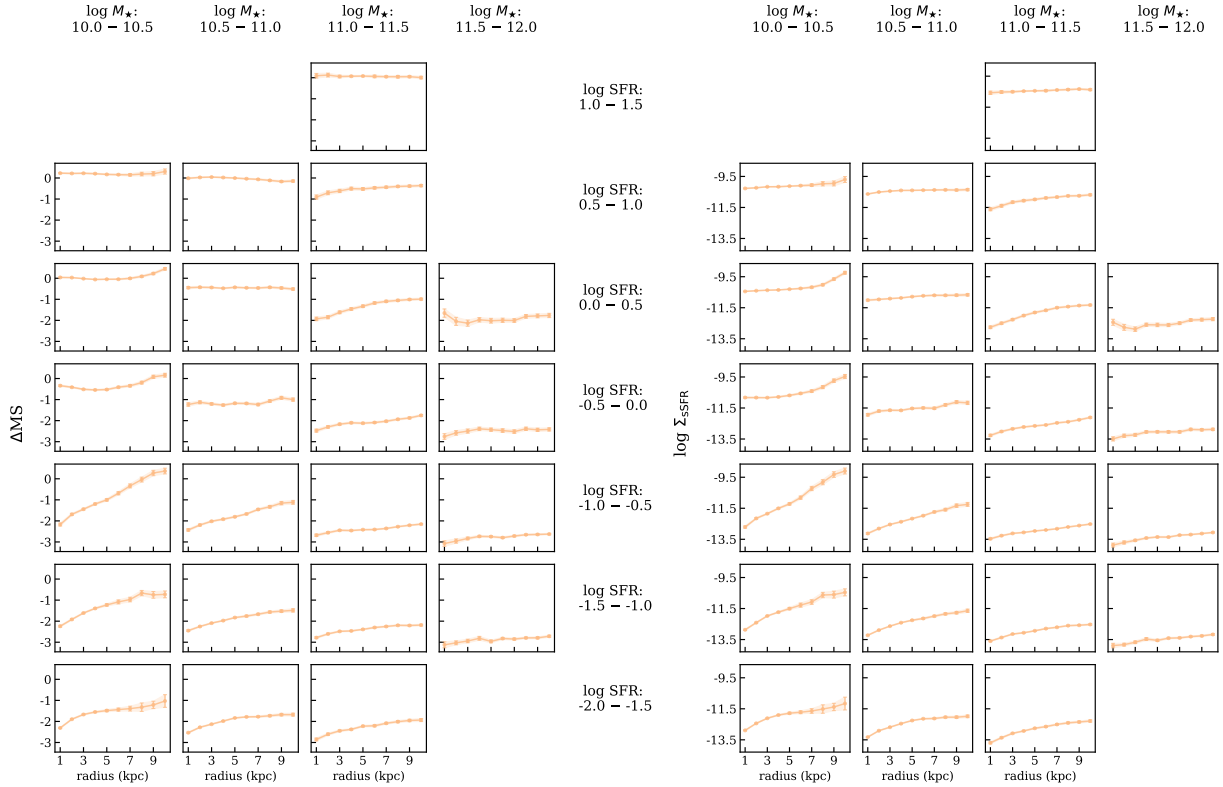


Fig. 16. Left: Mean ΔMS profiles of all the galaxies in the sample grouped according to their $M_\star$ and SFR values. Error bars represent the standard error of the mean. Right: Similar to the left panel, but for Σ_{SFR} profiles.

Σ_{SFR} profiles (the significance of the selection effect varies as a function of both $\Sigma_{SFR,1 \text{ kpc}}$ and total SFR), the high central Σ_{SFR} of optical AGNs compared to normal galaxies can also be observed (though the true difference might be larger, as there are still missing optical AGNs expected among control galaxies). Furthermore, by controlling for the global SFR as well as $M_\star$ through the nearest-neighbour method, we can reliably observe how AGN activity is connected to the availability of gas supply in the center of the galaxy (or the distribution of the gas supply) when the total global gas supply is comparable rather than there simply being more gas in the center when there is more available throughout the whole galaxy.

We therefore advise caution in interpreting previous studies that yield different results in central star formation differences when comparing AGNs with different luminosities to normal galaxies. First, as we discussed in Sect. 4.2, emission-line luminosity cannot safely probe AGN luminosity among low-to-moderate-luminosity AGNs, which is also a challenge for radio luminosity measurements (e.g. Mulcahey et al. 2022; Gatto et al. 2025). Estimation from the X-ray emission, as adopted in the study, is relatively safer, but only when the contamination from the XRB is small. This is also the limitation of the X-ray selection, as the nature of galaxies with $\log L_X < 41$ would be hard to justify, and results established for this type of subsample (e.g. Acharya et al. 2024) should be treated with caution⁶. Second, similar luminosity cannot represent a similar AGN accretion level when probing galaxies with a large range of BH masses, and adding the normalization from $M_\star$ can better approximate

the specific accretion rate. Last but not least, we caution that different mean Σ_{SFR} and/or Σ_{SFR} profiles of AGNs with different luminosity levels (which is commonly adopted in previous studies) or even specific accretion rates do not necessarily mean that their host galaxies are different. Assuming a relatively similar accretion rate distribution throughout the galaxy population (e.g. Aird et al. 2019), one might find that AGNs with higher luminosities or accretion rates have higher $\Sigma_{SFR,1 \text{ kpc}}$ among a limited-size sample, given that the probability of detecting such an AGN among low- $\Sigma_{SFR,1 \text{ kpc}}$ galaxies is very low. It is plausible that the specific accretion rate distribution of AGNs varies with $\Sigma_{SFR,1 \text{ kpc}}$; however, due to the limited sample size of the work, we cannot probe it confidently, and given the results from Aird et al. (2019) that the average specific accretion rate does not vary significantly with SFR at low redshift, which correlates with $\Sigma_{SFR,1 \text{ kpc}}$, one might not expect dramatic variation in the specific accretion rate distribution across different $\Sigma_{SFR,1 \text{ kpc}}$ ranges (except for extreme $\Sigma_{SFR,1 \text{ kpc}}$ values).

5. Conclusions

Utilizing the IFU spectroscopy from SDSS MaNGA, we studied how X-ray and optical AGN fractions vary as a function of $\Sigma_{SFR,1 \text{ kpc}}$ and investigated the spatially resolved properties of X-ray and optical AGN hosts compared to normal galaxies. The main points from this paper can be summarized as follows:

- We built a sample of MaNGA galaxies that have X-ray coverage from *eROSITA*, *XMM-Newton*, or *Chandra*, and identified X-ray AGNs (see Sect. 2.2) and optical AGNs (see Sect. 2.3) among this sample. For all the objects in the sample, we constructed $\Sigma_\star$, Σ_{SFR} , ΔMS , and D_n4000 maps to derive the corresponding radial profiles, and obtained the $\Sigma_{SFR,1 \text{ kpc}}$ measurements (see Sect. 2.4).

⁶ When high-angular-resolution X-ray measurements are available, it is plausible to identify low-power X-ray AGNs more reliably as the offset of the X-ray source to the galactic nucleus can be constrained more precisely. However, current high-angular-resolution X-ray observations from *Chandra* have limited sky coverage.

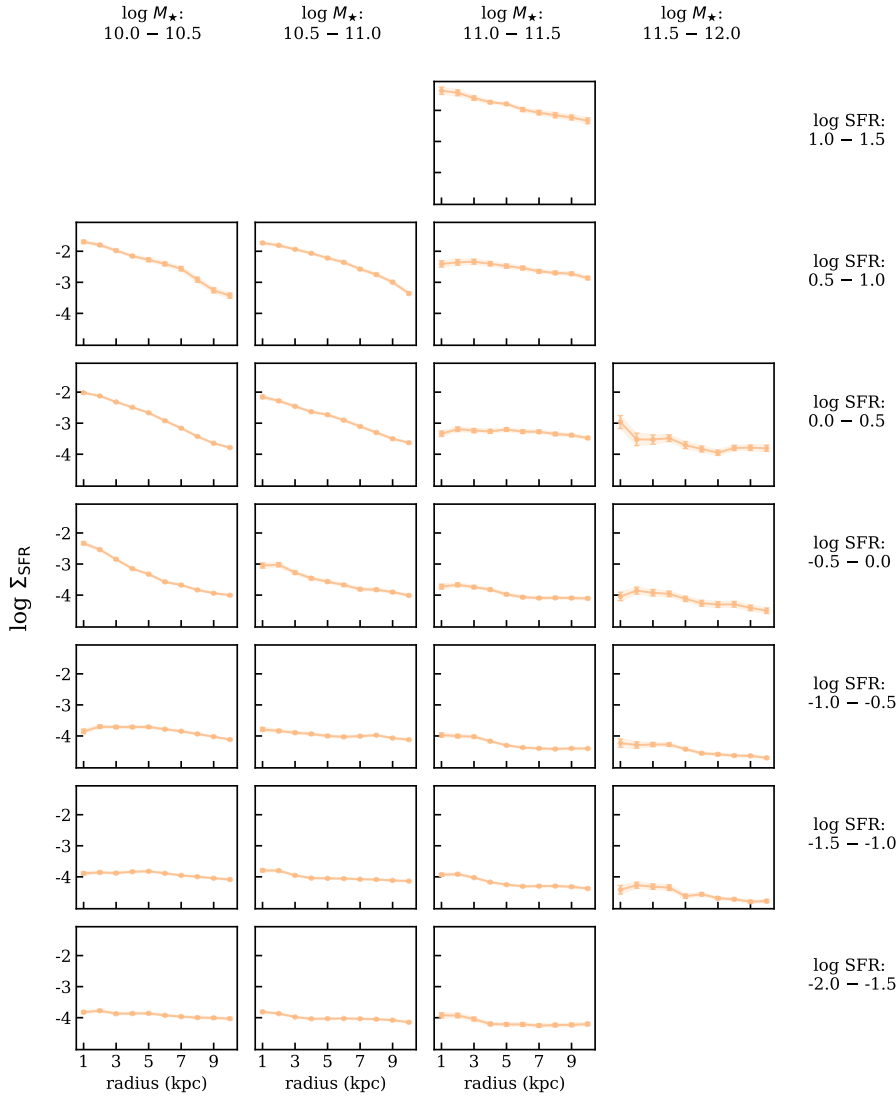


Fig. 17. Mean Σ_{SFR} profiles of galaxies in the sample grouped according to their M_* and SFR values. Error bars represent the standard error of the mean.

- We studied the fractions of X-ray and optical AGNs as a function of $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ (see Sect. 3.1). We found that the fraction of $\log L_X/M_* > 30.5$ AGNs increases with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, while the fraction of $\log L_X/M_* < 30.5$ AGNs decreases with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ among $\log M_* > 11$ galaxies where these X-ray AGNs with negligible levels of accretion can be detected (see Sect. 3.1.1). The optical AGN fraction typically increases with $\Sigma_{\text{SFR}, 1 \text{ kpc}}$, while there is a drop at the high $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ end that is more prominent when the probed M_* range is smaller (see Sect. 3.1.2).
- We further studied the spatially resolved profiles of X-ray/optical AGN hosts and compared them with those of galaxies matched with similar global properties: $\log M_*$, $\log \text{SFR}$, and z (see Sect. 3.2). We found that both X-ray and optical AGNs tend to have higher central Σ_{SFR} , though $\log L_X/M_* < 30.5$ AGNs do not show significant differences in central Σ_{SFR} compared with normal galaxies when the method for measuring Σ_{SFR} is not sensitive to very recent star formation (see Sect. 3.2.1).
- We argue that the observed discrepancy in the results among X-ray AGNs and optical AGNs can be attributed to selection effects. In addition to the well-known limitation of optical selection in picking up weak AGNs among quiescent galaxies, as identifying weak AGNs with BPT diagrams becomes

- harder when the star formation activity is stronger, one might observe a drop in the optically selected AGN fraction at the high- $\Sigma_{\text{SFR}, 1 \text{ kpc}}$ end, which might be misinterpreted as negative AGN feedback (see Sect. 4.1).
- The elevated level of central Σ_{SFR} among AGN hosts we observed is generally consistent with the picture of coeval growth of BHs and central parts of galaxies as a result of a common fuel supply; the difference in Σ_{SFR} is more prominent in the inner regions, which could explain why BH growth is more closely related to host-galaxy properties in the central kiloparsec regions (see Sect. 4.2). While most of the massive galaxies in the local Universe have suppressed sSFR in the center (which can also be misinterpreted as evidence for negative AGN feedback), lower levels of central Σ_{SFR} of AGN hosts compared to normal galaxies on average should not be observed if the AGN and control galaxy samples are carefully selected (see Sect. 4.3).
 - We also note that the picture of coeval growth from a common fuel supply does not contradict AGN feedback in action. For individual objects, it is possible to observe the effects of both positive and negative AGN feedback. We can also observe slight decreases (or flattening) of the mean Σ_{SFR} profiles toward the galaxy center on small scales ($\lesssim$ several kiloparsecs) among AGN hosts in our sample, consistent with

the expectation that AGN feedback can suppress star formation (e.g., via outflows); these features do not contradict our overall finding that AGN hosts in our sample exhibit, on average, elevated central Σ_{SFR} . Among the most massive galaxies, this decreasing trend becomes more noticeable (in both scale and amplitude), consistent with the expectation of jet-related AGN feedback (see Sect. 4.2).

In the future, the accumulation of JWST IFU observations will help to extend the analyses to higher redshifts, where a population of more powerful AGNs can be probed among galaxies with more active star formation, and the dynamic balance between fueling and feedback in the common gas reservoir will have larger variations, so that both effects can be observed more clearly. Combining jet and outflow properties of AGNs into this type of analysis will also help to test the scenario proposed in this study.

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