The coevolution of the AGNs and their host galaxies

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A thesis submitted to Aristotle University of Thessaloniki in accordance with the regulations for admission to the Degree of Doctor of Philosophy.
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Dedicated to my beloved and inspiring family...
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Vasileia−Aspasia Masoura

Submitted for the degree of Doctor of Philosophy

Abstract

This thesis is a contribution to the understanding of the correlation between the Active Galactic Nuclei (AGNs) and their host galaxies. There is growing evidence supporting the coeval growth of galaxies and their resident supermassive black hole (SMBH). Most studies also claim a correlation between the activity of the SMBH and the star formation of the host galaxy. It is unclear, though, whether or not this correlation extends at all redshifts and X-ray luminosities. We use data from the X-ATLAS and XMM-XXL North fields, compiling the largest X-ray sample up to date (3336 AGNs) to investigate how X-ray selected AGNs affect the star formation of their host galaxies, in a wide redshift and X-ray luminosity ($L_X$) baseline of $0.03 < z < 3$ and $\log L_X(2-10 \text{ keV}) = (41 - 45.5) \text{ erg s}^{-1}$. 1872 of our sources have spectroscopic redshifts. For the remaining sources we calculate photometric redshifts using TPZ, which is a machine-learning algorithm. We estimate stellar masses $M_*$ and star formation rates (SFRs) by applying spectral energy distribution (SED) fitting through the CIGALE code, using optical, near-IR, and mid-IR photometry (SDSS, VISTA, and WISE). Of our sources, 608 also have far-IR photometry (Herschel). We use the latter sources to calibrate the SFR calculations of our remaining X-ray sample. Our results show a correlation between $L_X$ and SFR of the host galaxy at all redshifts and luminosities spanned by our sample. We also find a dependence of the specific SFR (sSFR) on redshift, while there are indications that the X-ray luminosity enhances the sSFR even at low redshifts. Then, taking into account the evolution of SFR with stellar mass and redshift, we explore whether the AGN power correlates with any deviation of the host galaxy’s place, with respect to the star forming Main Sequence (MS). To do so, we estimate the SFRs of main-sequence galaxies that have the same stellar masses and redshifts with our X-ray AGNs and compare them with the SFRs of our X-ray AGNs. The latter is described by the SFR$_{\text{norm}}$ value. Our analysis reveals that the AGN presence is linked with an enhanced star formation in the host galaxy, regardless of the position of the host galaxy on the main sequence. Furthermore, using 3,213 Active Galactic Nuclei from the XMM-XXL northern field we investigate the relation of AGN type with host galaxy properties. Specifically, we apply
an advanced statistical method to derive the hardness ratios (HRs) for the examined sample and through them the hydrogen column density (N_H) for each source. We consider as absorbed those sources with N_H > 10^{21.5} \text{ cm}^{-2}. We examine the star formation rate as well as the stellar mass distributions for both absorbed and unabsorbed sources. Our work indicates that there is no significant link between the AGN type and these host galaxy properties. Next, we investigate whether the AGN power correlates with any deviation of the host galaxy’s place from MS, for the obscured and the unobscured AGN populations. We find that the correlation between L_X and SFR_{\text{norm}}, follows approximately the same trend for both absorbed and unabsorbed sources. This behaviour suggests that the AGN type does not have a significant impact on the relation between SFR and AGN power, as expected by the standard AGN unification models. Finally, we explore the connection between column density, N_H, and SFR. We find that there is no correlation between these quantities, suggesting that the AGN obscuration is unrelated to the large scale SFR in the galaxy. Motivated by our results, in the third part of this study, we explore the obscuration properties of red AGNs with both X-ray spectroscopy and SEDs. The combination of optical and mid-infrared (MIR) photometry has been extensively used to select red AGNs. In the last part of this work we re-visit the relation between optical/MIR extinction and X-ray absorption. To do so, we use IR selection criteria, specifically the W1 and W2 WISE bands, to identify 4798 AGNs in the XMM-XXL area (∼ 25 deg^2). Selection via optical/MIR colours (r – W2 > 6) reveals 561 red AGNs (14%). Of these, 47 have available X-ray spectra with at least 50 net (background-subtracted) counts per detector. For these sources, we construct SEDs from the optical to the MIR using the CIGALE code. The SED fitting shows that 44 of these latter 47 sources present clear signs of obscuration based on the AGN emission and the estimated inclination angle. Fitting the SED also reveals ten systems (∼ 20%) which are dominated by the galaxy. In these cases, the red colours are attributed to the host galaxy rather than AGN absorption. Excluding these ten systems from our sample and applying X-ray spectral fitting analysis shows that up to 76% (28/37) of the IR red AGNs present signs of X-ray absorption. Thus, there are nine sources (∼ 20% of the sample) that although optically red, are not substantially X-ray absorbed. Approximately 50% of these sources present broad emission lines in their optical spectra. We suggest that the reason for this apparent discrepancy is that r – W2 criterion is sensitive to smaller amounts of obscuration relative to the X-ray spectroscopy. In conclusion, it appears that the majority of red AGNs present considerable obscuration levels as shown by their SEDs. Their X-ray absorption is
moderate with a mean value of $N_H \sim 10^{22} \text{ cm}^{-2}$. 
Μελέτη της αλληλεπίδρασης των ενεργών γαλαξιακών πυρήνων με τον περιβάλλοντα γαλαξία

Βασιλεία–Ασπασία Μασούρα

Περίληψη

Η παρούσα διδακτορική διατριβή, πραγματεύεται τη μελέτη της σχέσης του Ενεργού Γαλαξιακού Πυρήνα (AGN) με τον περιβάλλοντα γαλαξία. Μελέτες των τελευταίων δεκαετιών έχουν οδηγήσει στο συμπέρασμα ότι υπάρχει άρρητη σχέση ανάμεσα στους γαλαξίες και στις υπερμεγέθεις μελανές οπές (SMBHs) που φιλοξενούν στο κέντρο τους. Εντούτοις, είναι ακόμη ασαφές εάν και πώς η δραστηριότητα της SMBH επηρεάζει τις ιδιότητες του περιβάλλοντα γαλαξία. Το πρώτο μέρος αυτής της μελέτης, έχει ως στόχο την διερεύνηση του εν λόγω ζητήματος και πιο συγκεκριμένα, πραγματεύεται τη σχέση ανάμεσα στη δραστηριότητα του AGN και του ρυθμού παραγωγής αστέρων (SFR) του εκάστοτε γαλαξία. Για το σκοπό αυτό, συνθέτουμε το μεγαλύτερο δείγμα πηγών ακτίνων -Χ (μεγαλύτερο σε σχέση με μελέτες που άπτονται του εν λόγω θέματος). Το δείγμα μας αποτελείται από ~ 3,500 AGNs, σε ένα μεγάλο φάσμα ερυθρομετατοπίσεων καθώς και φωτεινότητων στις Ακτίνες -Χ, 0.03 < z < 3 και log Lx(2-10 keV) = (41 - 45.5) erg s⁻¹, χρησιμοποιώντας τα πεδία X-ATLAS και XMM-XXL North. Πιο συγκεκριμένα, η σύνδεση μεταξύ του AGN (χρησιμοποιώντας ως δείκτη την Lx), και του σχηματισμού άστρων, διερευνάται, απαντώντας στα ακόλουθα ερευνητικά ερωτήματα: σύνδεση SFR-Lx, εξέλιξη του SFR με την αστρική μάζα του γαλαξία (M*) και την ερυθρομετατόπιση, αποδέσμευση του SFR από τις επιδράσεις της M* και της ερυθρομετατόπισης και σύγκριση με την κύρια ακολουθία. Οι γαλαξιακές ιδιότητες (p.χ. M*, SFR) υπολογίζονται μέσω της ανάλυσης της φασματικής ενεργειακής κατανομής (Spectral Energy Distribution, SED), με τη χρήση εξειδικευμένου λογισμικού (CIGALE). Σύμφωνα με τα αποτελέσματα μας, υπάρχει συσχέτιση ανάμεσα στον AGN και το SFR του περιβάλλοντα γαλαξία, ανεξάρτητα από τη θέση του σε σχέση με την κύρια ακολουθία. Το δεύτερο μέρος της διατριβής πραγματεύεται ένα επίσης αναλογικό ζήτημα, αυτό της σχέσης του τύπου του AGN (απορροφημένος ή μη) με τον περιβάλλοντα γαλαξία. Είναι υπό διερεύνηση το εάν η απορρόφηση, εξαιτίας μεσοαστρικού αερίου και κονιορτού, που παρατηρούσε τον περιβάλλοντα γαλαξία. Είναι υπό διερεύνηση το εάν η απορρόφηση, εξαιτίας μεσοαστρικού αερίου και κονιορτού, που παρατηρούσε τον περιβάλλοντα γαλαξία. Είναι υπό διερεύνηση το εάν η απορρόφηση, εξαιτίας μεσοαστρικού αερίου και κονιορτού, που παρατηρούσε τον περιβάλλοντα γαλαξία. Είναι υπό διερεύνηση το εάν η απορρόφηση, εξαιτίας μεσοαστρικού αερίου και κονιορτού, που παρατηρούσε τον περιβάλλοντα γαλαξία.
AGN, καθώς επίσης στη σχέση της αστρογένεσης με το $L_x$, για διαφορετικούς τύπους AGN. Χρησιμοποιώντας το προαναφερθέν δείγμα, αυτή τη φορά μόνο τις πηγές που προέρχονται από το πεδίο XMM-XXL North, μελετώντας οι ιδιότητες του περιβάλλοντα γαλαξία (M*, SFR) καθώς επίσης, επανεξετάζεται η σχέση του SFR με τον AGN λαμβάνοντας υπόψη και στις δύο περιπτώσεις, την απορρόφηση του κάθε συστήματος. Τα αποτελέσματα μας φαίνεται να συμφωνούν με τις προβλέψεις του ενοποιημένου μοντέλου, δεδομένου ότι αφενός οι κατανομές των ιδιοτήτων των γαλαξιών δεν επηρεάζονται σημαντικά από τον τύπο του AGN, αφετέρου διότι η σχέση ανάμεσα στο AGN και στο SFR παραμένει ίδια σε διερευνητική απορρόφηση. Με αφορμή τα αποτελέσματα μας, στο τρίτο και τελευταίο μέρος της έρευνας, εξετάζεται η σχέση οπτικής/υπέρυθρης και X-ray απορρόφησης. Για το σκοπό αυτό, χρησιμοποιούμε, και πάλι, πηγές του πεδίου XMM-XXL. Εφαρμόζοντας συγκεκριμένα κριτήρια ($r - W2 > 6$, Yan et al.) εντοπίζουμε ~ 600 απορροφητικούς (κόκκινους) AGNs στο υπό μελέτη πεδίο. 50 από αυτούς έχουν διαθέσιμα ύψιστα ακτίνων X και επιτρέπουν τη μελέτη των X-ray ιδιοτήτων των εν λόγω πηγών (XSPEC). Επιπροσθέτως, πραγματοποιείται ανάλυση της φασματικής ενεργειακής κατανομής, με τη χρήση του CIGALE και εξετάζονται τα οπτικά τους φάσματα, όπου αυτά είναι διαθέσιμα. Σύμφωνα με τα αποτελέσματα μας το 76% (28/37) των κόκκινων πηγών παρουσιάζει απορρόφηση και στις Ακτίνες X.
Preface

The current work was undertaken between October 2016 and December 2020 whilst the author was a PhD student under the supervision of Dr. Ioannis Georgantopoulos & Prof. Manolis Plionis at IAASARS of National Observatory of Athens in collaboration with the Department of Physics of Aristotle University of Thessaloniki. This work has not been submitted for any other degree at this (or any other) university.

Results from this thesis have appeared in the following papers:


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“The copyright of this thesis rests with the author. No quotations from it should be published without the author’s prior written consent and information derived from it should be acknowledged.”
I would like to express my sincere appreciation to my supervisor, Dr. Ioannis Georgantopoulos, for giving me the opportunity to start my journey as a PhD student at the National Observatory of Athens, sharing his scientific ideas with me. Without him this research would not have been possible. I would also like to thank my co-supervisors Prof. Manolis Plionis and Prof. Padelis Papadopoulos. I heartily thank my day-to-day supervisor Dr. Georgios Mountrichas for his kindness and assistance. Dr. Amalia Corral was one of my first collaborators and I would like to thank her for the generosity and support she offered me. My sincere thanks to Dr. Antonis Georgakakis and Dr. Angel Ruiz with whom, the last years, I have been sharing not only the office but also my concerns and questions regarding the projects I have been working on as well as to Dr. Thanasis Akylas. They were all, helpful and generous to me. I thank, the Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, for supporting, financially, the major part of my research, as well as the Aristotle University of Thessaloniki.

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“Κτῆσαι ἀίδια”

Pittacus of Mytilene (650 - 578 BC)
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Prologue

The results and analysis in this thesis have already been written as separate papers. Chapters 3, 4 and 5 of this thesis are presented largely in the form that they are published in the following papers:

Chapter 1

Introduction

1.1 Active Galactic Nuclei

Active Galactic Nuclei (AGNs) are among the most luminous objects in the Universe. They radiate across the entire electromagnetic spectrum, from radio up to γ rays, with bolometric luminosities up to $L_{\text{bol}} \approx 10^{48}$ erg s$^{-1}$ (see Padovani et al., 2017, for a review). The source of their power is claimed to be the gravitational accretion of material onto supermassive black holes (SMBHs), with masses $M_{\text{SMBH}} \geq 10^6 M_\odot$ (see Figure 1.1), located in the centre of their host galaxies (e.g. Hoyle and Fowler, 1963; Schmidt, 1963; Salpeter, 1964; Lynden-Bell and Rees, 1971). Where $M_\odot$, is the solar mass ($\approx 1.99 \cdot 10^{30}$ kg). In short, when the interstellar gas, present in the galaxy, is in a state that allows rapid loss of angular momentum, it can trigger the central black hole and “turn” the normal galaxy into an “active” one. SMBHs grow in mass, via the aforementioned mechanism (accretion of cold gas), shining as AGNs (e.g. Sotan, 1982).

Despite the difference in physical scale between the SMBH and the galaxy spheroid (e.g. Hickox et al., 2011), based on observational (e.g. Magorrian et al., 1998; Ferrarese and Merritt, 2000) and theoretical studies (e.g. Hopkins and Hernquist, 2006; Hopkins et al., 2008; Di Matteo et al., 2008), there has been evidence of a causal connection between the growth of the SMBH and the host galaxy evolution (e.g. Alexander and Hickox, 2012). Figure 1.2, presents the general concept of the AGN - host galaxy interaction. Both, black hole and star formation are fuelled by the same gas reservoir inside the galaxy halo. This reservoir can be fed by different mechanisms (e.g. gas - rich mergers, recycling material from internal galactic processes). The amount of gas and its ability to cool, determines the amount of usable fuel that can be used for
1.1. Active Galactic Nuclei

Figure 1.1: The first direct image taken of a SMBH. This SMBH is located at the galactic centre of Messier 87. The dark centre is the event horizon and its shadow (Goddi et al., 2019).

feeding, on one hand star formation, on the other hand the black hole located in the galaxy’s centre. The extraordinary amount of energy, released by AGNs, is believed to regulate star formation of their host galaxies, via AGN feedback. However, the details of how and when this occurs remain uncertain from both an observational and theoretical perspective. Based on simulation studies, AGN feedback, can trigger (e.g. Bicknell et al., 2000; Silk and Nusser, 2010; Zubovas et al., 2013) and suppress (e.g. Di Matteo et al., 2005; Hopkins et al., 2005; Dubois et al., 2016) star formation of its host galaxy (Figure 1.3).

This thesis is divided into six chapters. Chapter 1 is a general introduction related to the AGN structure, based on the predominant models, and the role of obscuration in terms of these models. Furthermore, in the same chapter, is presented the state-of-the-art regarding the open issues investigated in this work. In Chapter 2 are presented the data and the used tools to carry out this study along with the overview of the thesis. The main scope of this work is to investigate on one hand, how AGNs co-evolve with their host galaxies and on the other hand, if there is a link between the AGN type and the host galaxy properties. This is the major part of the analysis and is described in Chapters 3, 4. Motivated by the involvement of the AGN type, in Chapter 5 we investigate the AGN classification based on different obscuration criteria. Finally, in Chapter 6, are presented the main conclusions of this study along with some future prospects.
1.1. Active Galactic Nuclei

Figure 1.2: Both AGN and SF are fuelled by cold gas that originates from a shared gas reservoir inside the galaxy halo. This reservoir can be fed by gas-rich mergers, by recycled material from internal galactic processes and by accretion of gas from intergalactic material. The amount of gas and its ability to cool determines the amount of usable fuel that can be used for feeding black hole growth and SF (Harrison, 2017).

Figure 1.3: Based on simulation studies, AGN feedback, can trigger (e.g. Bicknell et al., 2000; Silk and Nusser, 2010; Zubovas et al., 2013) and suppress (e.g. Di Matteo et al., 2005; Hopkins et al., 2005; Dubois et al., 2016) star formation of its host galaxy.
1.2 History and Taxonomy

The first studies of AGN took place fifty years ago and led to the definition of some of the main classes (e.g. Seyfert, 1943; Baade and Minkowski, 1954; Schmidt, 1963), Seyfert galaxies, radio galaxies, and quasars, respectively. There is a wide range of AGN classes and subclasses, appearing in literature, based on their special properties (see Padovani et al., 2017, for a review).

On the basis of their radio loudness (the ratio of the radio flux to the optical flux; Kellermann et al., 1989), they are divided into radio-loud (RL) and radio-quiet (RQ) systems with RQ AGNs making up the large majority (> 90%) of the AGN class (Padovani, 2010). Regarding their optical emission line properties, they are classified as type 1 (Broad line, BL) and type 2 (Narrow line, NL) AGNs. The latter classification is based upon the presence or absence of broad emission lines (full width at half maximum; FWHM > 1000 km s$^{-1}$) from the various elements, at optical wavelengths. In Figure 1.11 are presented two typical AGN optical spectra. Two other fundamental subclasses of AGNs are Seyfert galaxies and quasars. The main difference between these two subclasses is in the magnitude of power emitted by the nuclear source. In the case of a typical Seyfert galaxy, the total power emitted by the nuclear source (at optical wavelengths) is comparable to that emitted by all of the stars of the host galaxy ($\sim 10^8 - 10^{11}$ L$_\odot$).

Seyfert (1943) was the first to realise that there are several galaxies forming a distinct class with unusually bright point-like nuclei with prominent emission lines. Specifically, selected a group of galaxies on the basis of high central surface brightness, obtained spectra of these systems and reported the presence of strong and broad emission lines in the nuclei of six of them (NGC 1068, NGC 1275, NGC 3516, NGC 4051, NGC 4151 and NGC 7469).

Nevertheless, the latter study remained in the shadows until Baade and Minkowski (1954) identified the similarities between the spectra of the latter galaxies and that of the galaxy they associated with the Cygnus A radio source. Woltjer (1959) made the first attempt to understand the physics of Seyfert galaxies. Based on his study, the nucleus is unresolved, thus its size is less than 100 pc. An extreme scenario is that Seyfert galaxies have always been Seyferts so their lifetime is the age of the Universe. Another scenario, is that all spiral galaxies pass through a Seyfert phase or phases. The third main point of this work is that if the material in the nucleus is gravitationally bound, the mass of the nucleus is approximately equal to $u^2 r / G$, where $u$ the velocity dispersion obtained from the widths of the emission lines (typical velocities $\sim 500 - 1000$ km s$^{-1}$), $r$ the radius of the central source and $G$ the gravitational constant.
In the case of quasars, the central source is brighter than all the stars of the host galaxy by factors of \( \gtrsim 100 \). These sources look “quasi-stellar” because the star-like, luminous, central source is prominent. The light from the host galaxy, due to its small angular size and faintness, is diluted by the strong emission of the nucleus. Quasars are among the most luminous objects in the sky at every wavelength at which they have been observed. They were discovered, in the late 1950s, as a result of the first radio surveys. By this time, the angular resolution of radio observations was good enough to identify the strongest radio sources with individual optical objects, often galaxies, but sometimes stellar-appearing sources. Based on Schmidt (1969) quasars are “star-like” objects identified with radio sources at high redshifts, with large UV flux. Additionally, they show time-variable continuum flux as well as broad emission lines.

Another special AGN class is “Blazar”. Blazars, are RL AGNs with a relativistic jet pointing towards the Earth. Their emission is dominated by the non thermal continuum produced within the jet (Urry and Padovani, 1995), mainly synchrotron and inverse Compton \( \gamma \) rays. As mentioned, there is a variety of AGN subclasses with characteristic properties, for a detailed classification see Table 1 in Padovani et al. (2017).

In Figure 1.4, taken from Dermer and Giebels (2016), is presented the observational classi-
1.3 Fundamental quantities

1.3.1 “Feeding” the black hole

As mentioned in Section 1.1, the source of the AGN power is claimed to be the gravitational accretion of material onto SMBHs. The reason of this accretion is the gravitational force of the black hole (with a mass $M_{BH}$) acting on the surrounding material, which is mainly hydrogen gas (with a mass $m$). A good way to quantify the efficiency of power generation via accretion on a black hole is with the efficiency $\eta$, so $E = \eta mc^2$, where $m$ is the mass of the surrounding material, $c$ the speed of light ($\simeq 2.99 \cdot 10^8$ m s$^{-1}$) and $E$ the released energy. The energy rate, $\dot{E}$, is equal to the AGN luminosity ($L$), thus:

$$L = \dot{E} = \frac{d(\eta mc^2)}{dt} = \eta \dot{m}c^2 \quad \text{(or \, \,} \eta = \frac{L}{\dot{m}c^2}) \quad (1.1)$$

where $\dot{m} = \frac{dm}{dt}$ the black hole accretion rate (BHAR).

1.3.2 Accretion efficiency and black hole mass

As the surrounding gas supplies the central source, the gravitational potential energy is:

$$|E_G| = G \frac{m \cdot M_{BH}}{r} \quad (1.2)$$

(where $G \simeq 6.67 \cdot 10^{-11}$ m$^3$ kg$^{-1}$ s$^{-2}$). The rate at which the potential energy can be converted into radiation is given by:

$$L = \frac{dE_G}{dt} = G \frac{\dot{m} \cdot M_{BH}}{r} \quad (1.3)$$

Using Eq. 1.1 and Eq. 1.3, we find that the accretion efficiency is:

$$\eta = \frac{G}{c^2} \cdot \frac{M_{BH}}{r} \quad \text{(or \, \,} \eta \sim \frac{M_{BH}}{r}) \quad (1.4)$$

The accreting gas is gravitationally bound and orbits the black hole thus, for a $\delta m$ gas mass:
1.3. Fundamental quantities

\[ |F_c| = \delta m \cdot \alpha_{\text{rad}} = \frac{\delta m \cdot u^2}{r} \]  \hspace{1cm} (1.5)

and,

\[ |F_G| = G \frac{\delta m \cdot M_{\text{BH}}}{r^2} \]  \hspace{1cm} (1.6)

where \( r \) the distance of the \( \delta m \) from the black hole, \( u \) its velocity and \( \alpha_{\text{rad}} \) its radial acceleration.

It is required \( |F_c| = |F_G| \), thus one can infer the mass of the central object (i.e. \( M_{\text{BH}} \)) using basic classical physics. In this case

\[ M_{\text{BH}} \approx u^2 \cdot r / G \]  \hspace{1cm} (1.7)

The latter can be derived, assuming that broad line clouds (see Section 1.4.5) are obeyed with the virial theorem, i.e. \( T = -1/2 \vec{F} \cdot \vec{r} \), (e.g. Krolik et al., 1991; Wandel et al., 1999).

If we consider Eq. 1.7, we need to determine \( r \) and \( u \) to have a black hole mass estimation. Radius, \( r \) (\( \equiv R_{\text{BLR}} \), radius of the broad line region, see Section 1.4.5), can be estimated through different approaches. For instance, applying reverberation mapping technique (Blandford and McKee, 1982; Netzer and Peterson, 1997; Peterson, 1993, 1998) or via \( R_{\text{BLR}} \) - luminosity correlation (Koratkar and Gaskell, 1991; Wandel et al., 1999; Kaspi et al., 2000).

Velocity, \( u \), is measured based on the optical spectrum either as the mean of the full width at half maximum (FWHM) derived from each line or as the FWHM from the root mean square (rms) spectrum. According to Kaspi et al. (2000) those velocity estimates are similar, however their difference has an impact on the black hole mass uncertainties. For instance, considering an isotropic distribution of the BL clouds, \( u = \sqrt{3/2} \cdot \text{FWHM} \) (Netzer, 1991).

There are many possible factors (e.g. magnetic fields, radiation pressure) that can affect the dynamics of the region and thus have an impact on the gas velocity fields and the emerging line spectrum or the associate line spectrum (Krolik, 2001). In this case applying the virial theorem will overestimate the central source mass. There are several studies presenting and discussing the assumption above (Gaskell, 1988; Wandel et al., 1999; Peterson and Wandel, 1999). Based on previous results different assumptions (e.g. regarding the orbital shape) contribute to the total uncertainty of the black hole mass estimation (e.g. McLure and Dunlop, 2001; Kaspi et al., 2000). There are studies that combined broad-line velocities (measured from spectra), with \( R_{\text{BLR}} \) (estimated through reverberation mapping) and calculated black hole masses (e.g. Wandel et al., 1999; Onken and Peterson, 2002). However, only in very few
cases the estimation of the central object have been measured with spatially resolved dynamics close to it (see Gebhardt et al., 2000).

At this point it should be mentioned that we can also estimate the $M_{\text{BH}}$, through stellar velocity dispersion. Specifically, $M_{\text{BH}} \propto \sigma^{3.75}$ or $M_{\text{BH}} \propto \sigma^{4.8}$, based on Gebhardt et al. (2000) and Ferrarese and Merritt (2000), respectively.

### 1.3.3 Eddington limit

The bolometric luminosity of an AGN is directly linked to the mass accretion rate, $\dot{m}$ (see Eq. 1.1). A basic question is what is the maximum luminosity of an AGN and what is the role of the black hole mass?

As the mass accretes onto the black hole, the inward gravitational force ($F_G$) due to $M_{\text{BH}}$, on an electron-proton pair is $\simeq G \cdot M_{\text{BH}} \cdot m_p / r^2$. Furthermore, the outward radiation force ($F_R$) on a single electron is equal to $P_R \cdot \sigma_e$, where $P_R = L / 4 \pi r^2 \cdot c$ (radiation pressure) and $\sigma_e$ the Thomson cross-section. Taking into account that the gravitational force has to balance or exceed the outward radiation force, it is required $|F_G| \geq |F_R|$. From the latter we can derive the **Eddington limit** which is:

$$L \leq 4\pi \cdot G \frac{M_{\text{BH}} \cdot m_p \cdot c}{\sigma_e}$$

(1.8)

Thus, $M_{\text{BH}}$ sets an approximate upper limit to AGN energetics (via the Eddington limit). Based on Eq. 1.8, **Eddington luminosity** (the maximum luminosity of a source of mass $M_{\text{BH}}$ that is powered by spherical accretion) is equal to:

$$L_{\text{Edd}} = 4\pi \cdot G \frac{M_{\text{BH}} \cdot m_p \cdot c}{\sigma_e}$$

(1.9)

So, for the idealised case of spherical accretion

$$L_{\text{Edd}} \approx 1.26 \cdot 10^{38} \cdot \frac{M_{\text{BH}}}{M_\odot} \text{ ergs}^{-1}$$

(1.10)

Using Eq. 1.8 we can identify the mass which corresponds to the minimum $M_{\text{BH}}$ for a given $L$, this quantity is called **Eddington mass** ($M_{\text{Edd}}$). Based on the Eq. 1.1 we can derive the required mass accretion rate to power a source with $L_{\text{Edd}}$ (**Eddington accretion rate**),

$$\dot{m}_{\text{Edd}} = \frac{L_{\text{Edd}}}{\eta c^2}$$

(1.11)

and

$$\text{Eddington ratio} = \frac{L_{\text{bol}}}{L_{\text{Edd}}}$$

(1.12)
1.4 AGN structure and emission mechanisms

In Figure 1.5 is presented the basic structure of a radio quiet AGN. The main AGN components are the central engine, and the dusty torus that surrounds it. The central engine consists of the SMBH and the accretion disk. According to the unification model (e.g. Antonucci, 1993; Urry and Padovani, 1995; Netzer, 2015), optical and UV emission is produced by the accretion disk around the SMBH. As matter accretes onto the black hole, forming the accretion disk, emits radiation due to the viscosity of the material, ionising the gas in the surrounding environment. Both, broad and narrow line regions (BL and NL) contain photoionized gas. The BL region is located in between the dusty torus and the accretion disk. This region contains much more denser gas with much more higher orbital speeds compared to that in NL region, which is located further out from the central engine. AGN signature is a strong X-ray emission. The intrinsic X-ray radiation originates in the vicinity of the SMBH. Specifically, is claimed to be produced by the interaction of UV/optical photons, from the accretion disk, with high energy electrons in corona (above the SMBH), via inverse Compton scattering. This emission follows a power law continuum with a typical slope of 1.9 (Haardt and Maraschi, 1991).

All the aforementioned components have different characteristics (e.g. temperature, density, kinematics), thus they emit through different mechanisms at different wavelengths. Below are presented the most common emission mechanisms along with a detail description of the different AGN regions.

1.4.1 Main emission Mechanisms

* Thermal emission (e.g. accretion disk, torus): Thermal emission is directly related to the temperature of the emitting body. The majority of the AGN components are well modelled by black body (BB) emission across a range of temperatures. BB is a body in thermal equilibrium with no reflected radiation, since it is a perfect absorber and emitter, its spectrum depends only on its temperature. In reality, there is no such a body (ideal BB), nevertheless many objects behave approximately like BBs. BB radiation is described by Planck's law:

$$B_\nu(T) = \frac{2\hbar\nu^3}{c^2} \left( e^{\hbar\nu/kT} - 1 \right)$$  \hspace{1cm} (1.13)
1.4. AGN structure and emission mechanisms

Figure 1.5: The basic structure of a radio quiet AGN. The main AGN components are the central engine, and the dusty torus that surrounds it. The central engine consists of the SMBH and the accretion disk. Above the SMBH is located a corona of hot electrons, and this is where the hard X-ray emission of an AGN is produced. Both, broad and narrow line regions (BL and NL) contain photoionized gas. The BL region is located in between the dusty torus and the accretion disk and contains much more denser gas with much more higher orbital speeds compared to that in NL region, which is located further out from the central engine. All these components have different characteristics (e.g. temperature, density, kinematics), thus they emit through different mechanisms at different wavelengths. The relative distances are expressed in relation to the Schwarzschild radius ($r_s$). For a black hole with mass $M_{BH} \approx 10^8 M_\odot \rightarrow r_s \approx 3 \cdot 10^{13}$ cm.
where \( v \) the frequency of the radiation, \( T \) the temperature of the body, \( c \) the speed of light, \( k \) is the Boltzmann constant \((\simeq 1.38 \cdot 10^{-23} \text{ J K}^{-1})\) and \( h \) is the Planck constant \((\simeq 6.63 \cdot 10^{-34} \text{ J s})\). The radiation curve of a BB, for different \( T \) (temperatures), peaks at different \( \lambda_{\text{max}} \) (wavelengths) that are inversely proportional to the temperature (Wien’s displacement law):

\[
\lambda_{\text{max}} \cdot T \simeq 2.9 \cdot 10^{-3} \text{ m K}
\]

The total energy \((E)\) radiated per unit surface area of a BB (across all wavelengths) per unit time is:

\[
E = \sigma \cdot T^4 \text{ (Stefan – Boltzmann law)}
\]

where \( \sigma \simeq 5.7 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \) (Stefan–Boltzmann constant).

\* Inverse Compton scattering (e.g. corona): Inverse Compton scattering refers to the opposite of the standard Compton effect. Specifically, is the scattering of low energy photons to high energies by ultra-relativistic electrons. Via this interaction the photons gain energy (electrons lose energy) and this is why is called “inverse” Compton (the opposite mechanism of the Compton scattering). Assuming that the electrons in a regime have a thermal distribution of velocities at temperature \( T_e \) and the electron density of the region is \( N_e \) with size \( dl \). The average change of photon energy per collision is:

\[
\Delta E/E = \frac{4kT_e - hv}{m_e c^2}
\]

if \( hv < 4kT_e \), energy is transferred to photons. The optical depth for Thomson scattering is \( \tau_e = N_e \sigma_T dl \). The normal condition for inverse Compton scatter to change significantly the spectrum of the photons is (for a detailed proof see Peterson, 1997):

\[
\frac{kT_e}{m_e c^2} \cdot \tau_e^2 \leq 1/4
\]

where \( k \simeq 8.6 \cdot 10^{-5} \text{ eV K}^{-1} \) (Boltzmann constant). For \( \Delta E = 0 \) (no energy transfer) \( \rightarrow hv = 4kT_e \) (photon saturation), thus if the photons are heated to temperatures of \( hv = 4kT_e \), no net energy is transferred on average from electrons to photons. Thus, the maximum energy of the emitted photons (after the inverse Compton interaction) can be derived, for a given \( T_e \). For instance, for a spherical plasma cloud (corona) having \( kT_e = 25 \text{ keV} \), the energy (photon energy) cut-off would be equal to 100 keV. In other words, the cut-off of the X-ray spectrum depends only on the temperature of the corona. Furthermore, the slope of the spectrum decreases with increasing optical depth, \( \tau_e \).
1.4.2 Accretion disk

Accretion disk emission is well modelled by BB emission across a range of temperatures. From the virial theorem, half of the gravitational potential energy goes into heating the gas and the other half is radiated at rate $L$ (see 1.3.2). So,

$$L = \frac{dE_G}{dt} = G \frac{\dot{m} \cdot M_{BH}}{2r} = 2\pi r^2 \cdot \sigma \cdot T^4$$  \hspace{1cm} (1.18)

Taking into account the viscosity and assuming that the inner edge of the disk $r_{in} << r$, Eq. 1.18 becomes:

$$T(r) \propto M_{BH}^{-1/2} \cdot (r/r_s)^{-3/4}$$  \hspace{1cm} (1.19)

where $r_s$ the Schwarzschild radius. Based on the latter equation, the temperature in the disk increases inwards and at a fixed ratio $r/r_s$, it decreases with increasing mass of the black hole. This implies that the maximum temperature in the disk is lower for more massive black holes.

The predominant accretion disk model is described by a geometrically thin and optically thick structure (Shakura, 1973; Lynden-Bell and Pringle, 1974). In terms of this model, hydrodynamic equilibrium and steady accretion towards the SMBH are assumed. The gravitational potential energy is converted into radiation via viscous dissipation and/or magnetic processes. The geometrically simplest case of accretion is the spherical accretion. In this case of accretion (Bondi, 1952), the motion is steady and symmetrical with the gas being at rest and accretion rate given by: $\dot{m}_B \propto \rho_B \cdot r_B^2$, where $r_B^2$ the radius in which the escape velocity is equal to the speed of sound and $\rho_B$ the corresponding gas density. Accretion activity is significant not only for explaining the huge amounts of the released power, but also for the mass growth of the central source itself.

Accretion flows can be divided into two main classes, the “cold” and the “hot”. For accretion rates ($\sim 0.01 \cdot \dot{m}_{Edd} - \dot{m}_{Edd}$), gas density is enough for the gas to radiate in an efficient way and remain “thin” (geometrically thin accretion disks). Optically thick disks can be geometrically thin or thick. Optically thin accretion disks or flows are occasionally advection dominated. Such structures are referred to as radiation inefficient accretion flow (RIAF), or advection dominated accretion flow (e.g. Narayan and Yi, 1994, 1995, ADAF). On the other hand when the density is low, the gas may be unable to radiate energy at a rate that balances viscous heating. In this case, the heat generated by viscosity will be “advected” inwards with the flow.
instead of being radiated. The disk becomes “hot”, hence geometrically thick, low density, and radiatively inefficient (for a review see Yuan and Narayan, 2014). For instance, ADAF, introduced to explain the lower than expected luminosities of galaxies (Fabian and Rees, 1995).

1.4.3 Corona

A corona of hot electrons is located above the black hole. This is where the hard X-ray ($\gtrsim 2$ keV) spectral component is claimed to be produced, via inverse Compton scattering (Haardt and Maraschi, 1991). This emission follows a power law continuum, with a typical slope (photon index) of $\Gamma \sim 1.9$ (e.g. Nandra and Pounds, 1994; Mateos et al., 2005a; Tozzi et al., 2006). Photon index, is strongly correlated to the optical depth. Specifically, smaller optical depths correspond to steeper X-ray spectra. At this point it should be noted that, based on observations, X-ray power law index spans a limited range, roughly between 1.5 - 2.5 (e.g. Reeves and Turner, 2000; Shemmer et al., 2006, 2008).

Based on Lusso and Risaliti (2016), AGN radiation, at hard X-ray energies, has a tight correlation with the UV and the optical emission originating in accretion disk. The high energy electrons in corona interact with the optical/ UV photons, produced by the accretion disk, and the latter emission is transformed into X-ray radiation due to Inverse Compton scattering. This process is the opposite of the standard Compton effect since the electrons loose energy rather than the photons (for details see “inverse Compton”, 1.4.1).

1.4.4 Torus

To account for the strong infrared (IR) emission (Sanders et al., 1989; Elvis et al., 1994), unification models, include a torus of dust and gas that forms around the central engine. This emission is consistent with thermal emission of dust and molecular gas heated by the radiation of the central engine (SMBH and accretion disk). In particular, the dust grains (see Draine, 2003) of the toroidal structure, are heated by the radiation from the central engine, which is then re-emitted at larger wavelengths (IR emission; Barvainis, 1987). Torus emission ($L_T$) is a reprocessed fraction of that emitted by the accretion disk.

There is a wide range of tori models in the literature. For instance, smooth toroidal structures (e.g. Pier and Krolik, 1992; Granato and Danese, 1994; Schartmann et al., 2005; Fritz et al., 2006), clumpy tori (e.g. Risaliti et al., 2002; Nenkova et al., 2008b,a; Hönig et al., 2010; Stalevski et al., 2012; Markowitz et al., 2014; Liu and Li, 2014; Buchner et al., 2019; Stalevski
1.4. AGN structure and emission mechanisms

1.4.5 BLR

The region of the dense photoionized rotating gas clouds in between the dusty torus and the accretion disk is called broad line region (BLR) (for a review see Netzer, 2015). This AGN component produces the broad emission lines (e.g. Hydrogen Balmer lines and the Lyman Series) which are presented in the optical spectra of unobscured AGNs. Regarding the size of this region, it is a compact one with a typical radial distance from the central black hole $r \sim 0.01$ pc (e.g. Peterson, 1993; Kaspi et al., 2000). The radius of the BLR, $R_{\text{BLR}}$, can be derived through direct and indirect methods and can be used for the estimation of the central black hole (see Section 1.3.2)

Figure 1.6: Schematic of a clumpy torus. On thermodynamical grounds, such a structure is more realistic (in comparison to a “smooth” torus), since it is consistent with Jeans-instability. Credits: Bill Saxton, NRAO/AUI/NSF.

et al., 2016). On thermodynamical grounds, the former structure (smooth torus) would fragment, due to the Jeans-instability. Specifically, the inevitable Jeans-instability acting on the strongly cooling interstellar medium (ISM), will fragment it towards ever smaller ISM clumps, which continue on to star-form, even in the vicinity of luminous AGNs (see Wada et al., 2009). MIR observations provided strong evidence supporting the existence of a clumpy structure (e.g. Tristram et al., 2007). In Figure 1.6 is presented a schematic of such a structure.
The formation of this region is under debate and there are several models trying to explain the origin of the material that consists of. Some of them are inflow models, disk winds/outflows or disk instabilities. The temperature and the density of the ionised gas can reach $T \sim 3.7 \cdot 10^4$ K and $n \sim 10^{14}$ cm$^{-3}$ (optically thin emission plasma in the BLRs), respectively (e.g. Popović, 2003).

1.4.6 NLR

The typical AGN model places a narrow line region (NLR) much further out from the central engine, $10^3$ pc in size in the case of the most luminous AGN (Hagai, 2013), where orbital speeds are relatively low ($\sim 200-900$ km s$^{-1}$). This region contains photoionized, though, relatively low-density gas ($n \sim 10^3$ cm$^{-3}$). Its spectra includes only narrow permitted (e.g. Hydrogen Balmer lines) as well as some forbidden lines and in contrast with the BL they appear in both AGN types (optically-obscured and -unobscured).

1.5 Selection / Identification

To identify an AGN there is a wide range of criteria at different wavelengths. Each of these wavelengths has different advantages and disadvantages, and obtains samples with different biases. In this section are presented some common AGN selection techniques along with those adopted in our analysis.

1.5.1 X-ray selected AGNs

As already mentioned, AGN signature is a strong X-ray emission. Observations at X-ray wavelengths provide a quite efficient way of selecting AGNs, over a wide luminosity baseline and almost independent of obscuration. Specifically, regarding obscuration, emission above 2 keV suffers low X-ray absorption in the host galaxy ($N_H \lesssim 10^{22}$ cm$^{-2}$).

These wavelengths, directly, detect the activity of the central SMBH. Thus, X-ray luminosity is a proxy of the AGN power. In Figure 1.7 are presented the X-ray and optical images of NGC 3783, as an example of the “contrast” between the radiation produced by the accretion activity and the starlight (Brandt and Alexander, 2015).
Apart from the AGNs there are also other systems in the host galaxy producing X-rays. For instance, supernova remnants, stars, binary stars. X-ray binaries or Ultra luminous X-ray sources (ULXs) can have luminosities up to $L_X \sim 10^{41} \text{ erg s}^{-1}$. To alleviate the contamination of the aforementioned objects, AGNs, are commonly selected as those sources having hard X-ray luminosity $L_X > 10^{42} \text{ erg s}^{-1}$. Only the most powerful star forming galaxies have $L_X \sim 10^{41-42} \text{ erg s}^{-1}$. Nevertheless the contamination of X-ray selected AGN samples, from the latter systems, is not significant (Bernhard et al., 2018). It should be mentioned that Galaxy contribution could be significant in deep fields, however, in the present survey is negligible. In this study we consider as X-ray selected AGNs, those objects with $\log L_X(2 - 10 \text{ keV}) > 41.0 \text{ erg s}^{-1}$.

**X-ray telescopes and surveys:** The remarkable improvement of the X-ray Astronomy, over the last decades, has allowed the detection and study of the X-ray emission from both galactic and extra galactic sources. High energy phenomena play a crucial role in the formation, chemical and dynamical evolution of systems at all redshifts (see Giacconi, 2010, for a review). X-ray observations have proved of great importance in discovering significant features of these phenomena.

There is a wide range of X-ray surveys providing us large datasets to investigate the accretion
history of the Universe. Two essential characteristics of a survey are the width and the depth. Wide fields, provide large datasets and allow the improvement of the statistics, however, they lack faint objects. On the other hand, deep surveys provide us information for fainter sources but they do not offer large samples and suffer from variance and low number statistics at the highest luminosities (extreme sources are not well sampled).

In the following paragraphs are described some of those surveys and in Figure 1.8 is presented the solid angle of sky coverage versus sensitivity for different X-ray surveys. Many of those surveys, thanks to their high sensitivity, they are capable in revealing large populations of AGNs in galaxies where the accretion activity is either obscured or dominated by the host galaxy (see Brandt and Alexander, 2015, for a review). Thus they contribute in our understanding of the co-evolution of SMBHs and galaxies.

All data used in the present work were obtained by the XMM—Newton (for details regarding the corresponding surveys, see section 2). XMM—Newton (0.2 - 12 keV) is an X-ray space observatory launched (1999) by the European Space Agency. “XMM” stands for X-ray Multi-Mirror Mission and it is named after Sir Isaac Newton. The effective area of each of the co-aligned X-ray telescopes is over $\sim 1500 \text{ cm}^2$. The spacecraft holds a set of three X-ray CCD cameras, comprising the European Photon Imaging Camera (EPIC). Two of them are MOS (Metal Oxide Semi-conductor) and the third one is the pn camera. These cameras, perform extremely sensitive imaging observations over the telescope’s field of view (FOV) of 30 arcmin and in the energy range $\sim 0.15$-15 keV with angular resolution, PSF (6 arcsec FWHM). For a circular aperture of diameter D, the first minimum in the diffraction pattern occurs at $\theta = 1.22\lambda/D$ (where $\lambda$ the wavelength of the emitting source). In Table 1.1 are presented selected X-ray surveys with XMM—Newton. Second and third columns refer to the exposure time (ks) and the solid angle (arcmin$^2$), respectively.

NASA’s Chandra X-ray Observatory (0.3 - 8 keV) was launched the same year as XMM-Newton and they both generated up to thousands of AGN detections contributing to the characterisation of the $\sim 0.2$ - 12 keV cosmic X-ray background sources (the majority are AGNs). Nevertheless there are more galactic systems producing X-rays, such as supernova remnants, stars or binary stars, as mentioned above. Galaxy clusters as well as ultra-luminous X-ray sources (ULXs) are extragalactic systems contributing in the X-ray part of the electromagnetic spectrum, too.

Two of the deepest Chandra surveys are the CDF-North and CDF-South. Specifically,
Table 1.1: Selected extragalactic X-ray Surveys with XMM – Newton (0.2 - 12 keV). Taken from Table 1 of Brandt and Alexander (2015).

<table>
<thead>
<tr>
<th>Survey</th>
<th>Exposure time (ks)</th>
<th>Solid angle (arcmin²)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra Deep Field-South (CDF-N)</td>
<td>180</td>
<td>752</td>
<td>Miyaji et al. 2003</td>
</tr>
<tr>
<td>ELAIS-S1</td>
<td>90</td>
<td>2,160</td>
<td>Puccetti et al. 2006</td>
</tr>
<tr>
<td>COSMOS</td>
<td>68</td>
<td>7,670</td>
<td>Cappelluti et al. 2009</td>
</tr>
<tr>
<td>XMM-XXL</td>
<td>10</td>
<td>180,000</td>
<td>Pierre 2012</td>
</tr>
<tr>
<td>Chandra Deep Field-South (CDF-S)</td>
<td>2,820</td>
<td>830</td>
<td>Ranalli et al. 2013</td>
</tr>
</tbody>
</table>

The CDF-N survey, consists of 20 individual ACIS-I (Advanced CCD Imaging Spectrometer) pointings, covering an area of 448 arcmin² and is centred at α = 12°36'49'', δ = +62°12'58''. CDF-S survey covers an area of 436 arcmin² and the average aim point is α = 03°32'28'', δ = −27°48'23'' (J2000). The Extended Chandra Deep Field North survey (ECDF-S) consists of 4 Chandra 250 ks ACIS-I pointings, covering ∼ 0.3 deg² and surrounding the original CDF-S. In 2012 was launched the Nuclear Spectroscopic Telescope Array (NuSTAR). The latter telescope focuses in the higher energy range of the X-ray radiation (3-79 keV).

**X-rays produced by AGNs:** As described in Section 1.4 (see corona), the intrinsic X-ray emission originates in the vicinity of the SMBH. Specifically, the hard X-ray (≥ 2 keV) spectral component is claimed to be produced in corona via Comptonization (see Section 1.4.1). Reprocessing of the “primary” X-ray emission by the accretion disk, the broad line region (BLR) and the dusty torus (e.g. Pringle and Rees, 1972), produces reflection features. The part reflected by the disk, produces Compton reflection and several fluorescence lines, for instance, Fe Kα at 6.4 keV for neutral Fe and Fe in the most highly ionised states at ∼ 6.7 - 6.9 keV (e.g. George and Fabian, 1991). The line Fe Kα at 6.4 keV is found to be ubiquitous in all AGN types (Nandra and Pounds, 1994; Shu et al., 2010). Thus, the latter lines can be used to probe the properties of the obscuring gas. Reflection can also occur on larger scales in the torus. The
1.5. Selection / Identification

Figure 1.8: Solid angle of sky coverage versus sensitivity in both the 0.5 - 2 keV (left panel) and 2 - 10 keV (right panel) bands for selected X-ray surveys. Green and blue colours refer to the XMM-Newton and Chandra, respectively. A few surveys from previous X-ray missions are shown in red. The circles around some of the points indicate serendipitous surveys. Some of the surveys are labeled by name (sometimes abbreviated) in regions where symbol crowding is not too strong. The vertical dotted line shows the solid angle for the whole sky. Each of the surveys has a range of sensitivity across its solid angle, and different authors use different methodologies for computing and quoting sensitivity, this leads to small uncertainties in the precise relative locations of the data points. Source: Brandt and Alexander (2015).
1.5. Selection / Identification

Figure 1.9: Primary and reprocessed X-ray radiation in AGNs. Taken from https://www.isdc.unige.ch/ricci/Website/AGN_in_the_X-ray_band.html.

line profile gives valuable information about the emitting processes and the regions where they occur. In Figures 1.10 and 1.9 are presented a typical 0.1-1000 keV spectrum of an unabsorbed AGN and the schematic representation of the X-ray production, respectively.

1.5.2 UV/Optical selected AGNs

Optical and UV radiation is thermal emission, produced by the accretion disk around the SMBH (see Section 1.4). For these wavelengths, the most prominent feature is the “big-blue-bump”, peaking in the UV, around 100 nm (Shields, 1978). For an indicative temperature of the emitting region, taking into account the latter wavelength and using 1.14, the corresponding temperature is $\sim 10^4$ K.

The emission lines of an optical spectrum of an AGN, are stronger and broader compared to those of a normal galaxy or a starburst. The emitting material is rotating around the black hole with high speeds causing a range of Doppler shifts of the emitted photons, as a result, the emission lines are broadened. Apart from the presence of broad emission lines, AGNs, exhibit characteristic narrow lines. The latter are present not only in the spectrum of an unobscured AGN, but also when the central source is “hidden”. In section 1.4 are described in detail, both, broad and narrow line regions of the AGN structure. In Figure 1.11 are presented the optical spectra of an obscured and an unobscured AGN.

Optical and UV colours (e.g. $U - B < -0.50$; Boyle et al., 1985) is a means to, efficiently,
Figure 1.10: The typical 0.1-1000 keV X-ray spectrum of an AGN. 1) Direct emission (main power-law) 2) reflected emission 3) soft excess. The power-law is cut off at 300 keV. Credit: N. Torres-Alba (CCTAGN project).

Figure 1.11: Composite optical spectrum of Type 1 (blue) and Type 2 (red) AGN from SDSS, adapted from DiPompeo et al. (2018).
select AGN candidates, since stars (normal galaxies) exhibit lower temperatures compared to those associated with AGN accretion disks (apart from the white dwarfs). This technique is efficient only when the AGN is unobscured (so we are able to, directly, see the accretion disk) and up to redshifts \( \sim 2.5 \), since intergalactic absorption presents a significant barrier for more distant sources. Nevertheless, when the AGN is not very luminous, the system (AGN-host galaxy) will be dominated by the galactic emission (stars). As mentioned above, AGNs exhibit characteristic narrow and broad (when unobscured) lines in their optical spectra. An efficient means of AGN selection at this wavelengths, for local sources, is the emission-line diagnostics (e.g. “BPT diagrams” Baldwin et al., 1981; Kewley et al., 2006). Based on this technique, the comparison of the ratios of high to low ionisation lines (e.g. \([\text{OIII}]/\text{H} \beta \) versus \([\text{OI}]/\text{H} \alpha \), \([\text{OIII}]/\text{H} \beta \) versus \([\text{NII}]/\text{H} \alpha \) determine the class of the source (large ratios imply the existence of an AGNs). Specifically, AGNs can be distinguished from star forming regions (HII region) and LINERs (low-ionization nuclear emission region sources), based on the aforementioned ratios, since large ratios mean “hotter” (i.e. shorter wavelength) radiation field. High ionisation narrow lines, e.g. forbidden lines \([\text{NeV}] \) at \( \lambda = 3426 \text{Å} \) and \( \lambda = 3346 \text{Å} \) \([\text{OIII}] \) at \( \lambda = 5007 \text{Å} \), \([\text{OIV}] \) at \( \lambda = 26 \mu \text{m} \) can be also used as AGN tracers (e.g. Maiolino et al., 1998; Dudik et al., 2007; Dasyra et al., 2008; Torres-Albà et al., 2018). However, this is not applicable for high redshift sources since the optical lines that uses are redshifted outside the wavelength range of the optical spectrum (this is the case for BPT diagrams too). The reason their presence indicates AGN activity is that high energy photons (>97 eV) are required for ionisation (Schmidt et al., 1998). Since ionisation potential from stellar emission is < 55 eV (Haehnelt et al., 2001) the aforementioned lines can be luminous only because of the harder ionisation fields of AGNs.

### 1.5.3 IR AGN candidates:

There are several criteria to characterise a source as IR selected AGN (e.g. Stern et al., 2005; Donley et al., 2012; Assef et al., 2018). *WISE* Wright et al. (2010) completed an all-sky coverage in four MIR bands: 3.4, 4.6, 12, and 22 \( \mu \text{m} \) (\( W1, W2, W3 \) and \( W4 \) bands, respectively). Various colour criteria used these IR bands to efficiently identify AGN candidates. For instance, Mateos et al. (2012) suggested a selection method using three *WISE* colours. Stern et al. (2012) used the \( W1 \) and \( W2 \) bands and applied the criterion \( W1 - W2 \geq 0.8 \) to select AGNs with \( W2 < 15.05 \) in the COSMOS field. Assef et al. (2013) extended the latter criterion and provided a selection of AGNs for fainter *WISE* sources using the *WISE* All-Sky data release.
catalogue. Assef et al. (2018) modified these criteria to incorporate data obtained during the post-cryogenic main mission extension (AllWISE catalogue). The underlying principle of these criteria is distinguishing between the IR emission originated by the AGN (torus emission) and that due to the host galaxy (star formation). In this study, to select IR AGN candidates, we apply Assef et al. (2018) criterion, i.e.:

\[ W_1 - W_2 \geq \alpha_R, \quad W_2 \leq \gamma_R, \]  
\[ W_1 - W_2 > \alpha_R \exp \left[ \beta_R (W_2 - \gamma_R)^2 \right], \quad W_2 > \gamma_R, \]  

where \((\alpha_R, \beta_R, \gamma_R) = (0.650, 0.153, 13.86)\), to select AGNs with 90% reliability.

1.5.4 Radio AGNs

Radio emission is, in most cases, only a small amount of the total AGN luminosity. Approximately, only, \(\sim 10\%\) of the total AGN population are radio loud systems (Begelman et al., 1984), so the majority do not contribute significantly in these wavelengths. The source of their radio emission could be related to a persistent jet, the magnetised corona and the wind-like outflows. In the case of a RL AGN, the radio emitting regions are usually located at large distances from the AGN (e.g. kpc or even Mpc scales). On the other hand RQ systems exhibit pc scale (central) radio emission (see Panessa et al., 2019, for a review). The radio spectrum is well described with a power law (indicating a non thermal origin) with the spectrum of the jets being steeper compared to that of the central source. It is generally accepted that relativistic jet outflows produce non-thermal synchrotron emission, irrespective of their nature, leptonic (i.e. positron and electron pairs) or hadronic (protons and electrons).

Apart from the aforementioned AGN characteristics, variability (\(\sim\) hours to years) is another means to classify a source as AGN (e.g. Ulrich et al., 1997; Paolillo et al., 2004). There are several studies that explore this AGN feature at different wavelengths, to understand better the nature of these system see Pouliaias et al. (2019) and references therein.
1.6 Obscuration

An important challenge for uncovering the complete AGN population: Despite the huge radiative power of AGNs, obscuration presents an important challenge for uncovering their complete population and explaining the complicated mechanisms that regulate these systems in a unified way. Most of the radiation emitted by AGNs is obscured from our view, due to the presence of material between the central source and the observer (Fabian, 1999; Treister et al., 2004). Obscured AGNs consist up to \( \sim (70\% - 80\%) \) of the total AGN population (e.g. Akylas et al., 2006; Ueda et al., 2014; Georgakakis et al., 2017). As a result, obscuration presents a significant obstacle in revealing the complete AGN population and the understanding of cosmic evolution of SMBHs.

The main reasons of obscuration are, both, the fuelling of the SMBH (inflows of gas) and the AGN feedback (for a review see Hickox and Alexander, 2018). In Figure 1.2 is presented a schematic diagram to illustrate the feedback mechanisms and relationships between fuel supply, galaxy growth and black hole growth (Harrison, 2017). In terms of the different obscuring material, X-ray energies are obscured by gas and metals (e.g. Fe, Si), whereas ultraviolet (UV), optical, and infrared wavelengths are extinct by dust.

In this study with the general term “obscured” we may refer to i) optically-obscured AGNs based on their optical spectra (only narrow lines) ii) optical/IR obscured AGNs (or “red” AGNs), based on Yan et al. (2013) \((r - W2 > 6)\) criteria and iii) X-ray absorbed AGNs. A typical characteristic of an obscured AGN is the absence of emission from the BLR in the optical waveband. This corresponds to a typical extinction from dust \((A_V = 5-10\) mags\) (e.g. Schnorr-Müller et al., 2016) and to a hydrogen column density, \(N_H > 10^{22}\) cm\(^{-2}\) (for typical dust-to-gas ratios as measured in the Galaxy, e.g. Predehl and Schmitt, 1995). The NLR can be detected in both obscured and unobscured sources while the BLR is only detected in unobscured ones.

Obscuration can occur on different regions. For a hydrogen cloud with constant number density \(n_H\) distributed over a sphere of radius \(R\), the average hydrogen column density is equal to \(n_H R\). Thus gas mass is given by \(M_H = m_H n_H V_R \propto N_H R^2\), where \(m_H\) the mass of the hydrogen atom and \(V_R = \frac{4}{3} \pi R^3\). As a result, for a given gas mass, \(N_H \propto R^{-2}\). Based on the latter, highest \(N_H\) values will occur on relatively small scales. Nevertheless, instabilities and disturbances (e.g. galaxy mergers) can increase the gas density on larger scales (\(\sim 100\) pc to kpc) and, temporarily, produce larger columns, near the AGN and thus larger scale obscuration. In Figure 1.12 are presented the different scales of obscuration.
1.6. Obscuration

Host galaxy
\( (R > 1 \text{ kpc}, M_H < 10^{10} M_\odot) \)
\( N_H < 10^{23} \text{ cm}^{-2} \)

Nuclear torus
\( (R < 10 \text{ pc}, M_H < 10^{8} M_\odot) \)
\( N_H < 10^{25} \text{ cm}^{-2} \)

Circumnuclear starburst
\( (R \sim 10-100 \text{ pc}, M_H < 10^{9} M_\odot) \)
\( N_H < 10^{24} \text{ cm}^{-2} \)

\[ M_H \propto R^2 N_H \]

Figure 1.12: Different scales of AGN obscuration, for a Milky Way-type galaxy in the local Universe, for a given gas mass \( M_H \), \( N_H \propto R^{-2} \) (Hickox and Alexander, 2018).

A geometrical effect or an evolutionary phase? Based on the Unification model (e.g. Antonucci, 1993; Urry and Padovani, 1995; Netzer, 2015), obscuration is a geometrical effect. Specifically, the orientation of the dusty torus determines the amount of obscuring material along the observer’s line of sight to the central regions. Thus, type 1 refers to the face-on (unobscured) and type 2 to the edge-on (obscured) AGNs. One of the main predictions of the simple unification model is that type 1 and type 2 AGNs should live in similar environments and thus have similar host galaxy properties. In the context of the unification model, AGN obscuration is related, basically, to the region of the toroidal structure (e.g. Mateos et al., 2016, 2017).

An observational evidence, supporting this model, is the discovery of large columns of X-ray absorbing gas in type 2 AGNs (e.g. Awaki et al., 1991; Risaliti et al., 1999) and the lack of this absorbing material in type 1 AGNs. However, there is a significant number of observational results that cannot be explained in terms of the simple unification model: a) there is a number of type 1 AGNs detected with significant X-ray absorption (e.g. Fiore, 2001; Mainieri et al., 2002; Brusa et al., 2003; Mateos et al., 2005b) and b) Seyfert 2 galaxies unabsorbed in X-rays have been found (e.g. Pappa et al., 2001; Panessa and Bassani, 2002; Barcons et al., 2003a,b; Mateos et al., 2005b).

In the case of a smooth toroidal structure (e.g. Pier and Krolik, 1992; Granato and Danese, 1994; Schartmann et al., 2005; Fritz et al., 2006), the viewing angle is considered to be the only
1.6. Obscuration

Figure 1.13: Obscuration based on the Unification model (e.g. Antonucci, 1993; Urry and Padovani, 1995; Netzer, 2015). Type 1 AGNs are seen at inclinations ∼ 0°-60°, while type 2 AGNs at ∼ 60°-90°. The central black point represents the SMBH, the surrounding X-ray corona is in violet, the accretion disc is shown with the colour pattern of a rainbow. The BLR is in red and light brown, the circumnuclear dust is in dark brown, the polar ionised winds are in dark green. NLR is in yellow-green and a kpc jet is added to account for radio-loud AGNs. Credits: Marin (2016); Lobos et al. (2018).
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Different levels of obscuration correspond to different stages of the growth of the SMBH. The main idea is that the AGN growth coincides with host galaxy activity which is likely to obscure the AGN, “type 2 – phase”. Eventually, the powerful AGN pushes away the surrounding material (“blowout”), revealing the unobscured AGN, “type 1 – phase”.

Figure 1.14: Evolutionary model (Ciotti and Ostriker, 1997, 2001; Page et al., 2004; Stevens et al., 2005; Di Matteo et al., 2005; Hopkins et al., 2006; Bournaud et al., 2007; Gilli et al., 2007; Somerville et al., 2008; Treister et al., 2009; Fanidakis et al., 2011).
1.6. Obscuration

Obscuration criterion. However, as mentioned in Section 1.4.2 on thermodynamical grounds, such a structure would immediately fragment, due to the Jeans-instability. On the other hand, if we consider a clumpy torus (e.g. Risaliti et al., 2002; Nenkova et al., 2008b,a; Hönig et al., 2010; Stalevski et al., 2012; Markowitz et al., 2014; Liu and Li, 2014; Buchner et al., 2019; Stalevski et al., 2016), see Figure 1.6, then both AGN types can be observed at any viewing angle. The only difference being the statistics (i.e. much fewer type 1 would be observed in edge-on tori than type 2). Regardless the nature of the toroidal structure, it determines the amount of obscuring material along the observer’s line of sight to the central regions.

It should be noted, that although the two types of AGN are determined by different viewing angles, this does not necessarily imply that the two populations do not have some other elemental differentiation. It has been suggested that type 1 sources have a thin accretion disk while the accretion disk of type 2 systems is thick (Antonucci, 1983). This is based on the observation that in type 1 sources the optical polarization is aligned to the large-scale radio structure of the galaxy (e.g. NGC4151) while in type 2 systems the optical polarization is perpendicular to the inner radio contours (e.g. NGC1068).

Evolutionary model (see Figure 1.14) is another popular scenario which interprets the nature of AGN obscuration based on the different stages of the AGN evolution, i.e. different stages of the growth of the SMBH (Ciotti and Ostriker, 1997, 2001; Page et al., 2004; Stevens et al., 2005; Di Matteo et al., 2005; Hopkins et al., 2006; Bournaud et al., 2007; Gilli et al., 2007; Somerville et al., 2008; Treister et al., 2009; Fanidakis et al., 2011). The main idea is that the AGN growth coincides with host galaxy activity which is likely to obscure the AGN (type 2−phase). Eventually, the powerful AGN pushes away the surrounding star forming material revealing the unobscured AGN (type 1−phase).

In the context of this model the same galaxy material (dust and gas), that obscures the AGN, may also fuel the star formation and it has even been claimed that obscuration can occur not only at the region around the accretion disk, but also in galaxy scale (e.g. Maiolino and Rieke, 1995; Malkan et al., 1998; Matt, 2000; Netzer, 2015; Circosta et al., 2019; Malizia et al., 2020). This large-scale caused extinction, is typical in models where SMBH−galaxy co-evolution is driven by mergers (e.g. Hopkins et al., 2008; Alexander and Hickox, 2012; Buchner and Bauer, 2016). Early studies indicated large scale morphological differences between type 2 and type 1 AGN, in Seyfert galaxies, with the former having more frequent asymmetric/disturbed morphologies (Maiolino et al., 1997). While an asymmetry between average
molecular gas conditions has been found and attributed to type 2 hosting starbursts, more frequent than type 1 (Papadopoulos and Seaquist, 1998).

Many different approaches are used in the literature to examine the aforementioned theoretical picture of the AGN obscuration, and its possible relation with large scale properties of the host galaxy. Investigating the relation between AGN type and host galaxy properties presents a popular approach to achieve that.

1.7 Motivation

1.7.1 AGN – host galaxy coevolution

A popular approach: A straightforward and popular method to study the AGN–galaxy coevolution is via examining the correlation, if any, of the SMBH activity, and the star formation of the host galaxy, at different epochs. Observational results on the AGN luminosity in relation to the star formation activity can place important constraints on the corresponding theoretical models. X-rays detect the activity of the central SMBH, and therefore the X-ray luminosity is often used as a proxy of the AGN power (e.g., Lusso et al., 2012). As mentioned, in previous section, observations at X-ray wavelengths provide a quite efficient way of selecting AGNs over a wide luminosity range nearly independent of obscuration. Infrared observations provide a good measure of star formation rate, as these long wavelengths are dominated by dust emission from itself reradiated starlight from newly formed OB stars. Some studies claim positive relation at all $L_X$ (e.g. Rovilos et al., 2012; Chen et al., 2013; Lanzuisi et al., 2017; Brown et al., 2018), while others find proportional relation only at highest $L_X$ (Lutz et al., 2010; Bonfield et al., 2011; Rosario et al., 2012). On the other hand, there are groups that find no evidence of correlation between $L_X$ and $L_{IR}$ (Mullaney et al., 2011; Stanley et al., 2015; Scholtz et al., 2017; Ramasawmy et al., 2019). In the next paragraphs are presented the examined samples as well as the main results of those studies along with recent works related to the explored issue.

First studies: Starting from the less recent studies, Lutz et al. (2010) used Chandra X-ray selected AGN (895 sources), in the Extended Chandra Deep Field South (ECDFS), with median redshift $z \sim 1$. They observed a trend of star formation rate increasing with redshift, furthermore, an increase of star formation rate with AGN luminosity is indicated at the highest $L_{2-10keV} \gtrsim 10^{44}$ erg s$^{-1}$ luminosities only. On the other hand, Mullaney et al. (2011), used X-ray
selected, moderate luminosity (i.e, $L_X = 10^{42} - 10^{44} \text{ erg s}^{-1}$) AGNs up to $z \sim 3$ and found no evidence of any correlation between the X-ray and infrared luminosities at any redshift. Their findings suggest that star formation is decoupled from nuclear activity in their examined sample. Furthermore, they claimed that the majority of moderate nuclear activity is fuelled by internal mechanisms rather than mergers. The latter indicates that high redshift disk instabilities could be an important AGN fuelling mechanism.

**Quenching:** Many theoretical models require powerful AGNs to suppress star formation of their host galaxies. This quenching is in agreement with theoretical models in which the AGN outflows expel the interstellar medium of the host galaxy (Di Matteo et al., 2005; Springel et al., 2005; Sijacki et al., 2007). A model that has received particular interest, proposes that AGN are triggered by mergers (Hopkins et al., 2008). According to this model, the main phase of AGN growth coincides with host activity, which is likely to obscure the AGN. However, eventually the powerful AGN pushes away the surrounding star forming material, further arresting star formation (quenching) and revealing the now unobscured AGN. Different physical processes have been proposed to provide this quenching. The dominant mechanisms can be divided into two main categories (Gabor et al., 2010). Those that heat gas which then cannot collapse to form stars (preventative feedback), for instance virial shock heating (e.g. Birnboim and Dekel, 2003) or galaxy interactions (e.g. Di Matteo et al., 2005) and those that expel the gas that could be used to form stars (ejective feedback, Keres et al., 2009). Different mechanisms prevail at high and low redshifts (Hopkins et al., 2010). This possible suppression of the star-formation due to the AGN activity may also be the reason for the galaxies’ transition from the blue to the red group Georgakakis et al. (2008). Page et al. (2012) based on *Herschel*-SPIRE observations claimed a significant decrease in the mean SFRs of the most luminous AGNs ($L_X > 10^{44} \text{ erg s}^{-1}$) at $z \approx 1-3$ in the *Chandra* Deep Field-North (CDF-N). However, when Harrison et al. (2012) extended the latter results using *Herschel*-SPIRE 250 $\mu$m data in the COSMOS and CDF-S fields, they found no strong evidence for quenching in $L_X > 10^{44} \text{ erg s}^{-1}$ AGNs at $z \approx 1-3$. The same year, Rosario et al. (2012), used a combination of deep FIR and X-ray data in GOODS-South, GOODS-North and COSMOS, with a wide range of X-ray luminosities and spanning redshifts from the Local Universe to $z=2.5$. Based on their findings, the relation between SFR and accretion luminosity depends, both, on the AGN luminosity and redshift. Specifically, at low AGN luminosities, accretion and SFR show no relation at all redshifts. The latter finding is consistent with a scenario where low-luminosity AGNs are primarily fuelled
by secular processes in their hosts. For higher luminosities, they detected a strong correlation, though, only among AGNs at low and moderate redshifts ($z < 1$). They interpreted this trend as a consequence of the increasing importance of major-mergers in driving both the growth of the SMBHs and global star-formation in their host galaxies at high AGN luminosities. Additionally, they claimed that the enhancement of SFR in luminous AGNs weakens or disappears at high redshifts ($z > 1$), suggesting that at these epochs, the role of mergers is not significant.

**Flat relation between SFR and AGN power:** Stanley et al. (2015) used $\sim 2000$ X-ray detected AGN, with X-ray luminosities $10^{42} < L_X < 10^{45.5}$ erg s$^{-1}$ and redshift range $z = 0.2-2.5$. To decompose the IR spectral energy distributions into AGN and star formation components, they used IR photometry (8-500 µm), including Spitzer and Herschel images and taking into account photometric upper limits. They claimed that the relationship between the average SFR and AGN luminosity is broadly flat at all $L_X$ and $z$. Scholtz et al. (2017) used $\sim 86$ X-ray selected AGN in the CDF-S and COSMOS fields, 63 with ALMA constraints at $z = 1.5-3.2$. The redshift range of their sample is $z = 1.5 - 3.2$ with stellar masses $> 2 \cdot 10^{10}$ M$_\odot$. They compared their measurements with predictions of the EAGLE model and they concluded that even with AGN feedback, no strong relationship between the specific star formation rates (sSFR) distribution parameters and instantaneous AGN luminosity is expected. In addition to that, a signature of AGN feedback is a broad distribution of sSFRs for all galaxies, regardless if they AGN hosts, with stellar masses above $\sim 10^{10}$ M$_\odot$. In a recent study, Ramasawmy et al. (2019), used deep 850 µm observations from the SCUBA-2 Cosmology Legacy survey (S2CLS) to investigate star formation in a sample of X-ray selected AGN, probing galaxies up to $L_{0.5-7 \text{ keV}} = 10^{46}$ erg s$^{-1}$. Their sample consists of 1957 galaxies at $1 < z < 3$ and based on their results, the average AGN resides in a star-forming host galaxy, with SFRs ranging from 80-600 M$_\odot$ yr$^{-1}$. Within each redshift bin, they did not detect any relation between SFR and the X-ray luminosity. Instead they claimed a flat distribution of SFR across $\sim 3$ orders of magnitude of AGN luminosity. Overall, they found no evidence that AGN activity affects star formation in host galaxies.

**Positive relation:** Chen et al. (2013), presented a measurement of the average BHAR as a function of SFR for 1767 (far-IR selected), star-forming galaxies, in the redshift range 0.25 $< z < 0.8$, in the 9 deg$^2$ Boötes multi-wavelength survey field. Based on their findings, there is an almost linear relation between the average BHAR (in M$_\odot$ yr$^{-1}$) and the SFR (in M$_\odot$ yr$^{-1}$) for
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galaxies across a wide SFR range. Specifically, for SFRs $0.85 < \log \text{SFR} < 2.56$ they claimed that $\log \text{BHAR} = (-3.72 \pm 0.52) + (1.05 \pm 0.33) \log \text{SFR}$. Their results are consistent with a scenario in which SFR and AGN activity are tightly linked over galaxy evolution timescales. Other recent studies that claim a positive correlation are Lanzuisi et al. (2017) and Brown et al. (2018). Both of the latter groups have used large samples of X-ray selected AGNs. Specifically, Lanzuisi et al. (2017) used 692 sources in the COSMOS field, with redshift range $0.1 < z < 4$. They detected a strong relation between the $L_X$ and the host’s $L_{(8-1000)\mu m}$ luminosity which is powered by star formation (even after disentangling the effect of redshift). Similarly, Brown et al. (2018) used 703 AGNs with $\log L_{(2-10)\text{keV}} = (42 - 46) \text{erg s}^{-1}$ at $0.1 < z < 5$ from the Chandra XBoötes X-ray Survey. They also found a dependence of the star-formation of the host galaxy on X-ray luminosity. Based on Stemo et al. (2020), there is a positive trend between star formation rate and AGN luminosity, in individual redshift bins and across all redshift bins, and that both are correlated with the stellar mass of their galaxies. The latter group used X-ray and/or IR selected AGN (Spitzer and Chandra data) and composed a sample of 2585 sources with redshift range $0.2 < z < 2.5$. Their compiled data come from the GEMS, COSMOS, GOODS and AEGIS surveys.

Evolution of SFR with $M_*$ and $z$: Some of the aforementioned groups take into account the evolution of SFR with redshift, by splitting their results into redshift bins, though, SFR also coevolves with the stellar mass of the host galaxy. Rovilos et al. (2012) used AGNs from the 3 Ms XMM-Newton survey and measure the star formation rates of their host galaxies using data from deep $100 \mu m$ and $160 \mu m$ Herschel observations, as well as from Spitzer MIPS-70 $\mu m$. The redshift range of their sample consists of sources with $z \approx 0.5 - 4$. To take into account the evolution of SFR with $M_*$ and redshift they divided the star formation rates by the stellar masses of the host galaxies, to derive sSFR, and they split their sample into redshift bins. They found evidence for a positive correlation between the AGN activity and the sSFR for the most active systems with X-ray luminosities exceeding $L_x \simeq 10^{43} \text{erg s}^{-1}$ and redshifts $z \gtrsim 1$. Nevertheless they do not detect such a correlation for lower luminosity systems or those at lower redshifts, consistent with previous studies.

Comparison with the MS: SFR follows the cosmic evolution of the so-called Main Sequence (MS) relation of galaxies, i.e. the tight relation between galaxy SFR and stellar mass (Noeske et al., 2007). As mentioned, since star formation rate evolves with stellar mass
and redshift, some studies disentangled the effects of these properties on SFR. However, the majority of them do not compare their findings with the MS. To normalise SFR measurements for an AGN sample, one can compare SFRs of the AGNs with the SFR of main sequence galaxies with the same stellar masses and redshifts. The latter can be estimated using Eq. 9 in Schreiber et al. (2015):

$$\log_{10}(\text{SFR}_\text{MS}[\text{M}_\odot/\text{yr}]) = m - m_0 + a_0 r - a_1 \left[ \max(0, m - m_1 - a_2 r) \right]^2,$$

(1.22)

with $m_0 = 0.5 \pm 0.07$, $a_0 = 1.5 \pm 0.15$, $a_1 = 0.3 \pm 0.08$, $m_1 = 0.36 \pm 0.3$ and $a_2 = 2.5 \pm 0.6$. $r$ and $m$ are defined as: $r \equiv \log_{10}(1 + z)$ and $m \equiv \log_{10}(M_*/10^9 \text{M}_\odot)$. Thus, the normalised SFR ($\text{SFR}_{\text{norm}}$) can be defined as the ratio of the SFR of an AGN to the SFR of a galaxy in the main sequence (e.g. Mullaney et al., 2015; Bernhard et al., 2018; Grimmett et al., 2020). Mullaney et al. (2015), used X-ray selected AGN at $0.5 < z < 4$, from Chandra Deep Field South and Chandra Deep Field North. According to their results, 34%-55% of AGNs have SFRs at least a factor of two below that of the average MS galaxy. Despite the fact that X-ray AGNs and MS galaxies have different SFR distributions, they derive a linear-mean SFR of AGNs consistent with that of MS galaxies. The apparent contradiction claimed to be due to the linear-mean SFR being biased by bright outliers, and thus does not represent a true characterisation of the typical SFR of X-ray AGNs. In another recent study, Bernhard et al. (2018), used data from COSMOS field and found that the SFR$_{\text{norm}}$ of powerful AGN has a narrower distribution that is shifted to higher values compared to their lower X-ray luminosity counterparts. However, the mean SFRs are consistent with a flat relationship between SFR and $L_X$.

Furthermore, based on Stemo et al. (2020), AGN hosts tend to lie below the MS, with X-ray-selected AGN host galaxies being more offset than IR-selected AGNs. Their findings suggest that there is some process, possibly negative feedback, in AGN hosts causing decreased star formation.

There are also studies using simulations to investigate the AGN-host galaxy coevolution. According to Aird et al. (2017), the probability of a quiescent galaxy hosting an AGN is generally lower than that of a star-forming galaxy, shows signs of suppression at the highest stellar masses, and evolves strongly with redshift. Aird et al. (2019) investigated this coevolution by measuring the incidence of AGN in galaxies as a function of SFR and redshift. They combined large samples with deep Chandra X-ray imaging and measured the probability distribution of specific black hole accretion rates ($L_X$ relative to stellar mass) and derived AGN fractions as
well as average specific accretion rates. They claimed that fuelling mechanisms differ, depending on the galaxy’s place in terms of the MS. Specifically, for galaxies along the MS they found a linear correlation between the average SFR and both the AGN fraction and average specific accretion rate across a wide range in stellar mass ($M_\star \sim 10^{8.5-11.5} M_\odot$), indicating that AGNs in main sequence galaxies are driven by the stochastic accretion of cold gas. In the case of quiescent galaxies, though, they found higher AGN fractions than their predictions (given their low SFRs) indicating that AGN in quiescent galaxies are fuelled by additional mechanisms, such as stellar winds. They also claimed that the AGN fraction is elevated for star-forming galaxies, with SFRs below the main sequence, suggesting further triggering mechanisms as well as that the incidence of more powerful AGNs is enhanced in starbursts and evolves more mildly with redshift. The latter indicates that mergers play a role in driving AGN activity in starbursts.

Before drawing any conclusions when comparing results from different studies, it is important to consider parameters such as the size of the sample (some studies suffer from low number statistics), the $L_X$ the $z$ distributions as well as the followed analysis. In addition to the aforementioned parameters, for observational studies, it has been pointed out that different observed trends could be the consequence of different binning (Volonteri et al., 2015b,a; Lanzuisi et al., 2017). A possible explanation could be the differences, in timescales, between the black hole accretion rate and the SFR. Specifically, AGNs may be expected to vary on a wide range of timescales that are extremely short compared to the typical timescale for star formation (100 Myr) (Hickox et al., 2014). Recently, Grimmett et al. (2020) presented a novel technique that removes the need for binning, by applying a hierarchical Bayesian model. Their results confirmed those of Bernhard et al. (2018), that higher X-ray luminosity AGNs have a tighter physical connection to the star-forming process than lower luminosity AGNs, in the redshift range probed by their dataset.

1.7.2 AGN type – host galaxy properties

As mentioned before, several different approaches are used in the literature to examine the nature of the AGN obscuration, and its possible relation with large scale properties of the host galaxy. The most common way, is to examine whether or not there are differences in various host galaxy properties of obscured and unobscured AGN. Increasing trends with obscuration (e.g. SFR versus X-ray absorption, SFR versus optical/IR obscuration) or significant different distributions of galaxy properties (for obscured and unobscured populations) are expected in
AGN evolutionary scenarios. On the other hand, if AGN obscuration is a geometrical effect (i.e. simple unification model), then we do not expect any connection between the aforementioned properties, neither differences between obscured and unobscured AGNs in terms of their galaxy properties. Studies that used X-ray selected sources found that the correlation of SFR and X-ray absorption is either non-existent or mild (e.g. Rovilos and Georgantopoulos, 2007; Rovilos et al., 2012; Rosario et al., 2012; Stemo et al., 2020). Therefore, it is still an open question, whether there is a connection between X-ray absorption levels and host galaxy properties.

**Obscuration and stellar mass:** Merloni et al. (2014), studied the incidence of nuclear obscuration using ∼1300 X-ray selected AGNs from the XMM-COSMOS survey, in the redshift range 0.3 < z < 3.5. In that study, the X-ray population was split into obscured and unobscured AGN, using the same N$_H$ cut that is applied in our analysis (N$_H$=10$^{21.5}$ cm$^{-2}$). They found no remarkable differences between the mean M$_*$ of obscured and unobscured AGNs. On the other hand, Lanzuisi et al. (2017), used approximately 700 X-ray selected AGNs, in the COSMOS field in the redshift range 0.1 < z < 4, and found that unobscured AGNs tend to have lower M$_*$ than obscured sources. However, they considered as X-ray absorbed sources with N$_H$ > 10$^{22}$ cm$^{-2}$.

There are a few recent studies, related to this open issue. Zou et al. (2019) used 2463 X-ray selected AGNs in the COSMOS field and found that unobscured AGNs tend to have lower M$_*$ than their obscured counterparts. However, in their analysis they divided their sample into type 1 and type 2 AGNs based on their optical spectra, morphologies, and variability. Thus, one should take into account the selection effect when comparing with populations split based on their X-ray absorption. An apparent disagreement could be attributed to the different method applied in the characterisation of a source as obscured/unobscured.

**Obscuration and SFR:** According to Lutz et al. (2010), obscuration, is not linked to the global star formation rate of the host galaxy. However, based on the same study, increasing trends with X-ray absorption, may be present for higher luminosity (intrinsic) AGNs L$_{2-10keV}$ ≥ 10$^{44}$ erg s$^{-1}$. This behaviour suggests a transition between two modes in the AGN-host galaxy coevolution. Rosario et al. (2012) used a sample of AGNs from GOODS-South, GOODS-North and COSMOS fields, spanning the redshifts 0.2 < z < 2.5. The N$_H$ values were estimated using either spectral fits for X-ray sources with sufficient counts or scalings based on hardness ratios for faint X-ray sources. They found a mild dependence between the mean far IR luminosity (SFR proxy) and the X-ray obscuring column, N$_H$. On the other hand, Rovilos et al. (2012)
used AGNs from the 3Ms XMM – Newton survey with $z \simeq 0.5–4$ and reported that there is no correlation between SFR and $N_H$. They claimed that the absorption is likely to be linked to the nuclear region rather than the host galaxy. Chen et al. (2015) used AGN from the B"ootes field and claimed that type 2 sources have higher IR star formation luminosities by a factor of $\sim 2$ than type 1. However, their dataset consists of mid-IR selected, luminous quasars. Moreover, they have divided their sample into type 1 and type 2 AGNs using optical/mid-IR colour criteria $R-[4.5] = 6.1$ (e.g. Hickox et al., 2007), where $R$ and [4.5] are the Vega magnitudes in the R and IRAC 4.5$\mu$m bands, respectively. Stemo et al. (2020), recently, confirmed Rovilos et al. (2012) findings. Specifically, they used X-ray and/or IR selected AGN (Spitzer and Chandra data) and composed a sample of 2585 sources, from the GEMS, COSMOS, GOODS and AEGIS surveys, with redshift range $0.2 < z < 2.5$. They used extinction parameter, $E_{B-V}$, values (estimated through SED fitting) to infer the $N_H$ values, using a conversion factor of $E_{B-V}/N_H = 1.80\pm0.15\cdot10^{-23}$. Based on their findings, the relation between the SFR and $N_H$ is flat, up to $z = 2.5$. According to their interpretation, this behaviour indicates a difference in fuelling processes or timescales between SMBH growth and host galaxy star formation.

### 1.7.3 AGN classification based on different wavelength

The combination of optical and IR data provides a powerful tool to search for obscured AGNs. The optical emission of a SMBH is attenuated by dust and is re-emitted in the NIR to MIR wavelengths. In this case the galaxy appears faint in the optical but bright in the IR. Various optical and IR colour criteria have been used in the literature to identify red AGNs, using either Spitzer (e.g. Fiore et al., 2009; Hickox et al., 2007; LaMassa et al., 2016; Donoso et al., 2014) or WISE (Yan et al., 2013) IR bands. Previous studies investigated the correlation between the optical/IR colours and X-ray absorption (e.g. Civano et al., 2012; Merloni et al., 2014; Koutoulidis et al., 2018; Ruiz et al., 2021). In some cases their results are contradictory. Different selection criteria or sample selection could explain those discrepancies. In Figure 1.15 are presented the relative fractions of AGN versus AGN power, for a redshift range $\sim 0.3-3.5$, based on Merloni et al. (2014). We note here, that fractions are distinguished based on their X-ray and optical classifications. Koutoulidis et al. (2018), found that reddened AGNs are equally divided into X-ray absorbed and unabsorbed. Specifically, these latter authors used about 1500 X-ray AGNs from five deep Chandra fields (CDF-N, CDF-S, ECDF-S, COSMOS, AEGIS) and divided them into obscured and unobscured sources using X-ray (Hardness Ratio).
1.8 Thesis Overview

The scope of this thesis is to investigate and shed light on all the aforementioned contradictory results (see sections 1.7.1, 1.7.2 and 1.7.3), by answering the following questions.

- How AGNs co-evolve with their host galaxies?

In the first part of our analysis, we are addressing the contradictory results from previous studies regarding the AGN-host galaxy coevolution (see section 1.7.1), by compiling multi-wavelength data from both the XMM-XXL and X-ATLAS surveys. Both surveys are wide and provide us the opportunity to carry out a study with a particularly large sample, that spans a wide range of luminosities and redshifts. The addition of the X-ATLAS field,
allows us to increase the available number of lower luminosity sources in our sample. Our goal is to study the effect of AGN on the SFR of the host galaxy, by using the largest X-ray sample up to date. To achieve that, we measure the SFR and sSFR as a function of X-ray luminosity, we examine the evolution of SFR with stellar mass and redshift and, finally, we explore whether the AGN power correlates with any deviation of the host galaxy’s place, with respect to the main sequence.

- Is there a link between the AGN type and the host galaxy properties?

In chapter 4, we use AGNs from the XMM-XXL North field (same data as in Chapter 3 without including X-ATLAS sources) to investigate the relation, if any, between X-ray absorption and galaxy properties. Applying an advanced statistical method, we derive the hardness ratios (HRs; see 4.1.2) and based on these calculations we derive the hydrogen column density ($N_H$) for each source. We consider as absorbed sources, type 2, those with $N_H > 10^{21.5}$ cm$^{-2}$. We examine the star formation rate (SFR) as well the stellar mass ($M_*$) distributions for both absorbed and unabsorbed sources. Nevertheless, we disentangle the effects of $M_*$ and redshift on SFR and examine the SFR-L$_X$ relation, as a function of AGN type and explore whether the SFR varies as a function of the absorbing column density. Additionally, we divide our sample into obscured and unobscured populations based on their optical-IR obscuration. Specifically, we apply Yan et al. (2013) criterion (r-W2) and we follow the same analysis to investigate if the different obscuration criteria affect our results.

- Do different obscuration criteria applied, affect the AGN type?

As mentioned, in section 1.7.3, there are different obscuration criteria such as optical/IR as well as X-ray. Motivated by these contradictory results as well as by the comparison of the impact of different obscuration criteria (4) on the host galaxy properties, in the last part of this research (Chapter 5), we re-visit the X-ray properties of red AGNs.

To this aim, we use X-ray AGNs in the XXL survey (Pierre et al., 2016, hereafter XXL paper I) and select IR AGN candidates by applying the criteria of Assef et al. (2018). We use optical and MIR colours (Yan et al., 2013) to select optically red sources. The final sample is restricted to those AGNs for which X-ray spectroscopy is available (47 sources).
We fit the X-ray spectra to quantify the X-ray absorption of the sources. Additionally, we construct spectral energy distributions (SEDs) using optical, near-infrared (NIR), and MIR photometry. We use the CIGALE code (Ciesla et al., 2015) to fit the SEDs and get an estimation of various absorption indices (AGN emission, torus inclination). We also complement our analysis with available optical spectra. Finally, we compare the results of different wavelengths and techniques for each red AGN.

In the calculations, throughout this thesis, we assume a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km $s^{-1}$Mpc$^{-1}$. 
Chapter 2

Data & Analysis

In this study we use X-ray selected AGN from different fields. Specifically, our data come from both the \textit{XMM − Newton-XXL} (\textit{XMM-XXL}; Pierre et al., 2016) and XMM-ATLAS (Ranalli et al., 2015) fields. In this Chapter are presented these fields as well as the surveys related to our examined subsamples.

2.1 X-ray data

\textbf{XMM-XXL:} The \textit{XMM − Newton XXL} (\textit{XMM-XXL}; Pierre et al., 2016), is the largest \textit{XMM − Newton} project approved to date (> 6 Msec) with median exposure at 10.4 ks and a depth of \(\sim 6 \cdot 10^{-15}\) erg sec\(^{-1}\) cm\(^{-2}\) for point sources at the 90% completeness limit in the [0.5-2] keV band (XXL paper I). It refers to the \textit{XMM − Newton} observations and source catalogue in XXL area. \textit{XMM − Newton} observatory, is suited to map large areas of the sky thanks to its collecting area (\(\sim 2000\) cm\(^{2}\) at 1 keV) and large field of view (\(\sim 30\) arcmin (for more details regarding \textit{XMM − Newton} telescope, see Section 1.5.1). The XXL survey is a medium-depth X-ray survey covering a total area of 50 deg\(^{2}\) split into two fields equal in size, the \textit{XMM-XXL} North (XXL-N) and the \textit{XMM-XXL} South (XXL-S). It builds, mainly, on the developments and findings of the XMM-LSS pilot project (Pierre et al., 2004). The source detection algorithm and classification rely on the fact that, at high galactic latitude and medium X-ray sensitivity, the vast majority of sources are point-like AGNs (95%), extended groups and clusters of galaxies. The coverage of the XXL survey, enables the detection of a large number of AGNs (more than \(\sim 20,000\) and \(\sim 10,000\) in the [0.5-2.0] and [2.0-10] keV bands, respectively. In Section 2.3.1, are described, in details, the used catalogues for the present research. In this work we use
Figure 2.1: XMM-XXL north area with sky coordinates of XMM-Newton sources and associated BOSS spectrograph (SDSS) observed targets. 8445 point-like X-ray sources were extracted (grey) over a $\sim 18$ deg$^2$ area of the XMM-XXL north. At the time of the reduction (January 2012), the pointing of XMM-Newton in the XMM-XXL north area was not yet completed. The spectroscopic follow-up of the XMM-Newton sources with BOSS has been performed during two ancillary programmes (1st: dashed line circle / light blue markers, 2nd: solid black line circle / dark blue markers) and completed by former targets from BOSS-DR10 (purple markers). Source: Menzel et al. (2016) & X-ray Group MPE, https://www.mpe.mpg.de/XraySurveys/XMM-XXL/.

data from XXL-North area. In Figure 2.1 is presented the latter area with sky coordinates of XMM-Newton sources and associated BOSS spectrograph (SDSS) observed targets.

**XMM-ATLAS:** XMM-ATLAS (or X-ATLAS) refers to the XMM – Newton observations and source catalogue in the H-ATLAS area (see Section 2.2). Specifically, refers to the XMM – Newton observed area (7.1 deg$^2$) within the H-ATLAS SDP region (see Section 2.2), centred at 9h 4m 30.0s+0d 34m 0s, with a total exposure time of 336 ks (in the MOS1 camera). The flux limits of the survey are $2 \cdot 10^{-15}$, $6 \cdot 10^{-15}$ 9 $\cdot 10^{-15}$ erg sec$^{-1}$ cm$^{-2}$ in the 0.5-2, 0.5-8, and 2-8 keV bands, respectively. X-ATLAS consists one of the largest contiguous areas of the sky with
both XMM – *Newton* and *Herschel* coverage. The catalogue is comprised by 1,816 X-ray AGN (Ranalli et al., 2015).

### 2.2 Optical & IR data

**SDSS:** The Sloan Digital Sky Survey (SDSS) is a wide-field photometric and spectroscopic survey over a large area of the sky (York et al., 2000). It uses a dedicated 2.5-m wide-angle optical telescope, equipped with a large format mosaic CCD camera imaging the sky in five optical bands, and two digital spectrographs obtaining the spectra of multiple sources. The SDSS telescope is located at the Apache Point Observatory (APO) in New Mexico. Data collection began in 2000 creating the most detailed three-dimensional maps of the Universe so far, with deep multicolour images of one third of the sky, and spectra for more than $\sim 10^6$ objects (latest data release is DR16). Its photometric system includes five filters (Fukugita et al., 1996; Gunn et al., 1998). The five filters in the imaging array of the camera, [u, g, r, i and z] have effective wavelengths of $\lambda = 3590\AA$, $\lambda = 4810\AA$, $\lambda = 6230\AA$, $\lambda = 7640\AA$, $\lambda = 9060\AA$, respectively. The median 5-sigma depth for SDSS photometric observations is: $u = 22.15$, $g = 23.13$, $r = 22.70$, $i = 22.20$, $z = 20.71$. This is based upon the formal errors from photo PSF photometry on point sources. To obtain optical photometry for this study, we cross-match our X-ray catalogue with the SDSS-DR13 (u, g, r, i, z; Albareti et al., 2015).

**VISTA:** The Visible and Infrared Survey Telescope for Astronomy (VISTA), is part of ESO’s (European Southern Observatory) Paranal Observatory and is the largest telescope dedicated to surveying the sky at near-infrared. There are six large public surveys conducted by VISTA (UltraVISTA, VIKING, VMC, VVV, VHS, VIDEO), covering different areas of sky in different depths. VISTA telescope is a wide-field reflecting telescope with a 4.1 metre mirror, located at the Paranal Observatory in Chile. It has one instrument, VIRCAM (Vista InfraRed CAMera). This camera contains 16 special detectors sensitive to IR, with a combined total of 67 million pixels. We make use of VISTA-VIKING (J, H, K; Emerson et al., 2006; Dalton et al., 2006) catalogues, to obtain near infrared for photometry for the examined AGNs.

**WISE:** The Wide-field Infrared Survey Explorer (WISE), is a complete mid-infrared survey of the entire sky, in four IR bands. These are W1, W2, W3, W4, centred at 3.4, 4.6, 12 and 22 $\mu$m, respectively (Wright et al., 2010). The angular resolution for the latter are 6.1”, 6.4”, 6.5”
and 12", and the astrometric precision for high SNR (signal-to-noise ratio) sources is better than 0.15". Sensitivity improves toward the ecliptic poles due to denser coverage and lower (zodiacal) background. WISE, is a space telescope launched in 2009 and placed in hibernation mode in 2011 (re-activated in 2013).

**H-ATLAS:** The Herschel Space Observatory, named after Sir William Herschel and Caroline Herschel, was a space observatory operated by the European Space Agency (ESA). It was the largest infrared telescope ever launched, activated from 2009 to 2013, and the first space observatory to observe from the far-infrared to the sub-millimetre waveband. It carried three detectors, PACS (Photo-detecting Array Camera and Spectrometer), SPIRE (Spectral and Photometric Imaging Receiver) and HIFI (Heterodyne Instrument for the Far Infrared). The H-ATLAS survey is the largest Open Time Key Project carried out with the Herschel Space Observatory (Eales et al., 2010), covering an area of $\sim 600 \, \text{deg}^2$ (with both SPIRE and PACS instruments) in five far-infrared and sub-mm bands, 100, 160, 250, 350 and 500 $\mu$m (Valiante et al., 2016). 16 $\text{deg}^2$ have been presented in the Science Demonstration Phase (SDP) catalogue (Rigby et al., 2011) and lie within one of the regions observed by the Galaxy And Mass Assembly (GAMA) survey (Driver et al., 2011; Baldry et al., 2010).

### 2.3 Source-matching

#### 2.3.1 Source-matching/ Data reduction

**XXL-N AGNs**

In Chapters 3 and 4, we use the XXL-N sample that consists of 8445 X-ray sources. 5294 of these X-ray sources have SDSS counterparts and 2512 have reliable spectroscopy (Menzel et al., 2016; Liu et al., 2016). mid-IR and near-IR is obtained following the Likelihood Ratio method (Sutherland, 1992) as implemented in Georgakakis and Nandra (2011). For more details on the reduction of the XMM observations and the IR identifications of the X-ray sources, see Georgakakis et al. (2017). The XXL field was partially observed by Herschel ($\sim 70\%$ of the XXL area) in the context of the Herschel Multi-tiered Extragalactic Survey (HerMES, Oliver et al., 2012). We use the SPIRE xID250 catalogue from the HERMES-DR4 (http://hedam.lam.fr/HerMES/index/dr4), a band-merged catalogue (250, 350 and 500 $\mu$m) extracted on blind 250 $\mu$m positions. We crossmatch this catalogue with the list of XXL
2.3. Source-matching

X-ray sources using xmatch (Pineau et al., 2017). For a proper performing of xmatch, all the crossmatched catalogues must cover the same footprint. Hence, before the crossmatch, we select only X-ray and Herschel sources in the footprint resulting of the intersection of the XXL and HERMES areas. xmatch estimates the probability that a subsample of sources from different catalogues corresponds to the same real source. Specifically, it uses a Bayesian approach to estimate this probability. It takes into account the likelihoods and priors of all possible hypotheses. Likelihoods depend on multiple factors (e.g. the corresponding hypothesis, the number of cross-matched catalogues). Priors depend on the density of sources for each catalogue in the cross-matched area. Hence, to obtain meaningful probabilities the software has to be able to correctly estimate these densities. Less than 10% of the cross-matched sources are expected to be spurious (Ruiz et al., 2018).

There are 6,790 X-ray sources and 54,823 Herschel sources in the common area. We use an average positional error for the Herschel sources of 15 arcsec. After the crossmatch with xmatch, we reject sources with a low probability of association (< 68%). In those cases where the same X-ray source is associated with several Herschel counterparts, we simply select the association with the highest probability. Photometric bands with upper limits have been excluded. After applying these filtering criteria, we find 600 X-ray sources with a Herschel counterpart. In our analysis, we make SFR estimates, through SED fitting. For this reason, we require our sources to have at least, WISE (W1-W4) or Herschel detection, in addition to optical photometry. SFR estimates for sources without Herschel photometry have been calibrated, see Section 2.5.3. The dataset consists of 3,213 X-ray selected AGN from the XXL-N field, within a redshift range of 0.03 < z < 3. 1849 sources have spectroscopic redshift (Menzel et al., 2016) and 1364 have photometric redshift (photoz). Photometric redshifts were estimated using the machine-learning algorithm TPZ (Carrasco Kind and Brunner, 2013) (for details see 2.4) and following the process described in Mountrichas et al. (2017) and Ruiz et al. (2018). In Table 2.2, we present the number of sources based on the available photometry and spectroscopy.

In Chapter 5, we use the XXL-N sample that consists of 14,168 sources, including extended objects. To identify the X-ray detections at other wavelengths, the X-ray counterparts have been crossmatched with optical, NIR, and MIR surveys (for more details see Chiappetti et al., 2018, hereafter XXL paper XXVII). Firstly, we use approximately 500,000 WISE detections included in the latest WISE catalogue (AllWISE) that lie within the XMM-XXL area to select IR AGN candidates, applying the criteria of Assef et al. (2018). For details see Section 1.5.3. To
2.3. Source-matching

select optically red sources from the IR AGN candidates, we apply the Yan et al. (2013) criterion \((r - W2 > 6)\). This analysis reveals 561 red AGNs. We cross-match this subsample with the XXL catalogue to identify the X-ray counterparts of these sources. For the cross-match, we use a radius of 3 arcsecs. Within this radius and given the X-ray source sky density, we find that a fraction of \(\sim 0.2\%\) of spurious matches is expected (Mountrichas et al., 2017). To study the X-ray absorption of the optically red AGN population, we apply an X-ray spectral fitting analysis. As one of our main goals is to quantify the obscuration in the red AGNs, we chose to analyse only the X-ray spectra of the sources with reliable photon statistics. For this reason, we keep only the sources with 50 or more net counts per detector (see Corral et al., 2015). There are 47 red AGNs that meet the aforementioned X-ray criteria. Table 2.3 presents the number of sources in the various subsamples. As mentioned, the XXL field has been observed by the SPIRE instrument. To identify the FIR counterparts, we used the ARCHES cross-correlation tool XMATCH (Pineau et al., 2017), as for Chapters 3 and 4. We find nine sources with Herschel photometry. Furthermore, optical spectra are available for 33 out of the 47 red AGNs. The vast majority of them (30 out of 33) come from the SDSS (DR15) survey. The remaining optical spectra are from the Galaxy And Mass Assembly (GAMA; Driver et al., 2011; Baldry et al., 2010) and the VIPERS (Guzzo et al., 2014; Scodeggio et al., 2018) surveys. We use spectroscopic redshifts for 33 sources. For the remaining AGNs we use their photometric redshifts, estimated in Fotopoulou et al. (2016, hereafter XXL paper VI). The photometric redshift accuracy is 0.095 (for the full XMM-XXL catalogue). In our analysis, we incorporate the full probability density function (PDF) of the photometric redshifts when we calculate the uncertainties of the various parameters.

X-ATLAS AGNs

In Chapter 3, in addition to the XXL sources we also include 123 X-ATLAS sources. To obtain optical, mid-IR and far-infrared photometry for the X-ATLAS data (1,816 X-ray AGN, Ranalli et al. (2015)), we cross-match the X-ray catalogue with the SDSS-DR13 (u, g, r, i, z; Albareti et al., 2015), the WISE (W1, W2, W3, W4; Wright et al., 2010) and the VISTA-VIKING (J, H, K; Emerson et al., 2006; Dalton et al., 2006) catalogues. From the SDSS catalogue, we use psf magnitudes for point like sources (star like sources, number 6 in Menzel et al. (2016)) and model magnitudes for extended sources (galaxy like sources, number 3 in Menzel et al. (2016)). We consider as point like any extended source at z>1. The crossmatch with SDSS,
Figure 2.2: XMM-XXL and X-ATLAS. In Chapter 3, we use X-ray selected AGNs from both XMM-XXL and X-ATLAS fields Pierre et al. (2016) and Ranalli et al. (2015), respectively.

VISTA and WISE was performed using the ARCHES cross-correlation tool xmatch (Pineau et al., 2017). This tool matches symmetrically an arbitrary number of catalogues providing a Bayesian probability of association or non-association. The cross-match reveals 1,031 sources with at least optical photometry (for more details see Mountrichas et al., 2017). To improve the accuracy of our star formation rate estimates, we also include, wherever available, far-IR photometry in our SED fitting analysis. For that purpose, we cross-match the 1,031 sources with the Herschel Terahertz Large Area sample (H-ATLAS). Figure 2.2 and Table 2.1 describe the latter sample.

<table>
<thead>
<tr>
<th></th>
<th>XMM-XXL</th>
<th>X-ATLAS</th>
<th>Total sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>specz sources</td>
<td>1849(338)</td>
<td>23(3)</td>
<td>1872(341)</td>
</tr>
<tr>
<td>photoz sources</td>
<td>1364(262)</td>
<td>100(5)</td>
<td>1464(267)</td>
</tr>
<tr>
<td>Total sources</td>
<td>3213(600)</td>
<td>123(8)</td>
<td>3336(608)</td>
</tr>
</tbody>
</table>

Table 2.1: AGNs used in Chapter 3. The number of AGNs with spectroscopic (specz) and photometric (photoz) redshifts, in the XMM-XXL and X-ATLAS fields. In the parentheses we quote the number of X-ray sources with available Herschel photometry.
2.4 Photometric redshifts

<table>
<thead>
<tr>
<th>X-ray selected AGN</th>
<th>Total number</th>
<th>Specz</th>
<th>Photoz</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS</td>
<td>5294</td>
<td>2512</td>
<td>2782</td>
</tr>
<tr>
<td>SDSS + WISE or Herschel</td>
<td>3213</td>
<td>1849</td>
<td>1364</td>
</tr>
</tbody>
</table>

Table 2.2: AGNs used in Chapter 4. Number of spectroscopic and photometric sources with SDSS, WISE or Herschel photometry in our sample. The number of AGNs used in this thesis appear in bold.

<table>
<thead>
<tr>
<th>Total number</th>
<th>X-ray Detections</th>
<th>X-ray Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR AGNs</td>
<td>4798</td>
<td>1503</td>
</tr>
<tr>
<td>IR AGNs with SDSS</td>
<td>2652</td>
<td>1268</td>
</tr>
<tr>
<td>Red AGNs</td>
<td>561</td>
<td>135</td>
</tr>
</tbody>
</table>

Table 2.3: AGNs used in Chapter 5. Number of IR-selected AGNs with X-ray and optical observations and spectra in the XMM-XXL field.

2.4 Photometric redshifts

2.4.1 TPZ

We estimate photometric redshifts (photoz) through TPZ (Trees for Photo-Z). TPZ is a publicly available, machine learning algorithm which calculates photoz. The code and the technique it incorporates are described in detail in Carrasco Kind and Brunner (2013). In summary, the algorithm uses prediction trees (see Figure 2.3) and random forest techniques to generate photometric redshift Probability Density Functions (PDFs). The basic idea of a random forest method is to use bootstrap samples from the training data to build a set of prediction trees. As an empirical technique it requires a dataset with reliable spectroscopy to train the algorithm before it is applied to our photometric X-ray sample.

2.4.2 Accuracy of photoz

The accuracy of the photometric redshifts estimated by TPZ is quantified by two widely used statistical parameters, the normalised absolute median deviation, $\sigma_{nmad}$, and the percentage of
outliers, $\eta$. $\sigma_{\text{nmad}}$ is defined as:

$$\chi = \Delta(z_{\text{norm}}) = \frac{z_{\text{spec}} - z_{\text{phot}}}{1 + z_{\text{spec}}},$$

$$MAD(\chi) = \text{Median}(|\chi|),$$

$$\sigma_{\text{nmad}} = 1.4826 \cdot MAD(\chi).$$

(2.1)

The percentage of outliers, $\eta$, is defined as:

$$\eta = \frac{100}{N} \cdot \text{(Number of sources with } |\Delta(z_{\text{norm}})| > 0.15)$$

(2.2)

To check the performance of TPZ in estimating accurate photoz, Mountrichas et al. (2017) split their training set into two subsamples. One is used to train the algorithm and the other is used as a test case for which they estimate photometric sources. This is an ideal scenario since both subsamples share the same region of the parameter space and the same quality of spectroscopic data, i.e. the same distribution in redshift and magnitude as well as the same photometric errors. Table 2.4 presents their results.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Point-like</th>
<th>Extended</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{\text{nmad}}$ / $\eta$ (%)</td>
<td>$\sigma_{\text{nmad}}$ / $\eta$ (%)</td>
</tr>
<tr>
<td>SDSS</td>
<td>0.08 / 27.0</td>
<td>0.06 / 19.0</td>
</tr>
<tr>
<td>SDSS+WISE</td>
<td>0.07 / 17.4</td>
<td>0.07 / 13.0</td>
</tr>
<tr>
<td>SDSS+WISE+VISTA</td>
<td>0.07 / 14.2</td>
<td>0.05 / 10.2</td>
</tr>
<tr>
<td>SDSS+VISTA</td>
<td>0.07 / 21.3</td>
<td>0.06 / 12.0</td>
</tr>
</tbody>
</table>

Table 2.4: The performance of the TPZ algorithm, estimated by splitting our spectroscopic sample (see Section 3.2) into train and test files. The accuracy of the photometric redshifts is quantified by the estimation of the normalised absolute median deviation, $\sigma_{\text{nmad}}$ and the percentage of outliers, $\eta$. Table: Mountrichas et al. (2017).

Using only optical photometry (SDSS) the number of outliers is high, especially in the case of point-like sources. Adding MIR colours (WISE) the results improve significantly while TPZ performs best when they also include NIR magnitudes in the training process of the algorithm. Figure 2.4 compares the estimated photometric redshifts with the available spectroscopic redshifts of the sources.

We use the same training sample that Mountrichas et al. (2017) used to estimate photoz for the X-ray sources in the X-ATLAS field and follow their analysis (see their Section 3 for more details). Based on their results, the estimated photometric redshifts have a normalised absolute median deviation, $\text{nmad} \approx 0.06$, and a percentage of outliers, $\eta = 10-14\%$ (see Table), depending upon whether the sources are extended or point-like. For the samples, used in this thesis, we exclude sources that have been optically classified as extended and their photometric redshift is photoz > 1 (Salvato et al., 2011).

### 2.5 Spectral Energy Distribution fitting

#### 2.5.1 CIGALE

The continuum spectra of AGNs are quite complex. Unlike spectra of stars or galaxies, AGN spectrum cannot be described in terms of blackbody emission at a single temperature, or as a stellar continuum composite over a limited range of temperatures. It is even more challenging
Figure 2.4: The performance of TPZ using the ten available photometric bands (SDSS+WISE+VISTA). The training sample has been split into train and test files to compare the estimated photometric redshifts with the spectroscopic redshifts of the sources. Figure taken from (Mountrichas et al., 2017).
A typical Spectral Energy Distribution (SED) of an AGN is characterised by the broad energy range, since they emit over the entire electromagnetic spectrum (from $\gamma$ rays to radio emission), with several typical features observed. In Figure 2.5 is presented the schematic of the SED of an unobscured AGN.

To calculate the contribution of the AGNs to the power output of the host galaxy as well as host galaxy properties (e.g. star formation rates, stellar masses), we use the Code Investigating GALaxy Emission Burgarella et al. (CIGALE; 2005); Noll et al. (CIGALE; 2009). We provide the CIGALE code version 2018.0 (Boquien et al., 2019) with multi-wavelength flux densities, using optical, NIR, MIR and FIR (where available) photometry.

The stellar population synthesis is modelled using the Bruzual and Charlot (2003) template, adopting the Salpeter template. The double-exponentially-decreasing ($2\tau$-dec) model is
2.5. Spectral Energy Distribution fitting

assumed to convolve star formation histories (Ciesla et al., 2015). \( \tau \) is the e-folding time of the main stellar population model in millions of years. Age is defined as the age of the main stellar population, also in millions of years. Calzetti et al. (2000) and Dale et al. (2014) templates are utilised for the dust extinction law and the absorbed dust reemitted in the IR. The Fritz et al. (2006) library of templates is used to model the AGN emission. The AGN fraction, refers to the IR (1 – 1000 \( \mu m \)) AGN emission (\( L_{\text{IR,AGN}} \)) divided by the total IR emission (\( L_{\text{IR,TOTAL}} = L_{\text{IR,AGN}} + L_{\text{IR,GALAXY}} \)).

\[
\text{frac}_{\text{AGN}} = \frac{L_{\text{IR,AGN}}}{L_{\text{IR,TOTAL}}} \tag{2.3}
\]

The extinction of a source based on the SED fitting, is derived from the viewing angle (of the torus), \( \Psi \): \( \Psi \leq 30^\circ \) for type 2 (edge-on), \( 40^\circ \leq \Psi = 60^\circ \) for intermediate, and \( \Psi \geq 70^\circ \) for Type 1 AGNs (face-on; Ciesla et al., 2015), respectively.

2.5.2 Modules

The modules and the values for their free parameters used by CIGALE, for the SED fitting of our X-ray sample, are presented in Table 2.5.

Our SFR calculations assume that all the FIR emission is due to dust heated by stars (the AGN contribution is ignored). However, this is not the case for powerful AGNs (e.g. Symeonidis et al., 2016; Duras et al., 2017). This introduces a maximum offset of 30\% to our SFR calculations (for more details see Section 3.2.3 in Ciesla et al., 2015).

We take into account only those sources that have the most accurate star formation rate estimates. For that purpose, we include only AGNs with available at least WISE or Herschel photometry, in addition to optical photometry. In section 2.5.3 we calibrate the SFR estimates for the total sample, using a subsample of 608 sources with available Herschel photometry. Furthermore, we exclude AGNs that their SED fitting has estimated reduced \( \chi^2 \), \( \chi^2_{\text{red}} > 5 \). This criterion is based on visual inspection of the SED fits. Table 2.5 presents the models and the parameters used by CIGALE for the SED fitting of our samples.

2.5.3 Using Herschel photometry to calibrate SFRs

Figure 2.6 presents the SED fitting of an AGN with (left panel) and without (right panel) Herschel photometry. Using sources that have additional Herschel photometry available (PACS and SPIRE; 100, 160, 250, 350 and 500 \( \mu m \)) we calibrate the SFR estimates for all samples.
### Table 2.5: The modules and the values for their free parameters used by CIGALE for the SED fitting of our X-ray samples.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model/values</th>
</tr>
</thead>
<tbody>
<tr>
<td>stellar population synthesis model</td>
<td></td>
</tr>
<tr>
<td>initial mass function</td>
<td>Salpeter</td>
</tr>
<tr>
<td>metallicity</td>
<td>0.02 (Solar)</td>
</tr>
<tr>
<td>single stellar population library</td>
<td>Bruzual &amp; Charlot (2003)</td>
</tr>
<tr>
<td>double exponentially decreasing (2τ dec) model</td>
<td></td>
</tr>
<tr>
<td>τ</td>
<td>100, 1000, 5000, 10000</td>
</tr>
<tr>
<td>age</td>
<td>500, 2000, 5000, 10000, 12000</td>
</tr>
<tr>
<td>burst age</td>
<td>100, 200, 400</td>
</tr>
<tr>
<td>Dust extinction</td>
<td></td>
</tr>
<tr>
<td>dust attenuation law</td>
<td>Calzetti et al. (2000)</td>
</tr>
<tr>
<td>reddening E(B-V)</td>
<td>0.01, 0.1, 0.3, 0.5, 0.8, 1.2</td>
</tr>
<tr>
<td>E(B-V) reduction factor between old and young stellar population</td>
<td>0.44</td>
</tr>
<tr>
<td>Fritz et al. (2006) model for AGN emission</td>
<td></td>
</tr>
<tr>
<td>ratio between outer and inner dust torus radii</td>
<td>10, 60, 150</td>
</tr>
<tr>
<td>9.7 µm equatorial optical depth</td>
<td>0.1, 0.3, 1.0, 2.0, 6.0, 10.0</td>
</tr>
<tr>
<td>β</td>
<td>-0.5</td>
</tr>
<tr>
<td>γ</td>
<td>0.0, 2.0, 6.0</td>
</tr>
<tr>
<td>Θ</td>
<td>100°</td>
</tr>
<tr>
<td>Ψ</td>
<td>0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°</td>
</tr>
<tr>
<td>AGN fraction</td>
<td>0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9</td>
</tr>
</tbody>
</table>

τ is the e-folding time of the main stellar population model in Myr, age is defined as the age of the main stellar population in the galaxy in Myr, and burst age is the age of the late burst in Myr. Here, β and γ are the parameters used to define the law for the spatial behaviour of density of the torus density. The functional form of the latter is \( \rho(r, \theta) \propto r^\beta e^{-\gamma |\cos \theta|} \), where \( r \) and \( \theta \) are the radial distance and the polar distance, respectively. Θ is the opening angle and Ψ the viewing angle of the torus. Type 2 AGNs have Ψ ≤ 30° (edge-on) and type 1 AGNs have Ψ ≥ 70° (face-on). 40° ≤ Ψ ≤ 60° corresponds to intermediate type AGNs. The AGN fraction is measured as the IR AGN emission relative to the total IR emission (1 – 1000 µm).
Figure 2.6: SED fitting of an AGN with (left panel) and without (right panel) Herschel photometry. The star-formation component is plotted in red, the AGN component in orange, the attenuated and the unattenuated stellar component described by the yellow and the blue dashed line, respectively. The black solid line shows the best fit from CIGALE. The source lies at $z = 0.825$. When FIR photometry is included in the fitting analysis, CIGALE yields: $\chi^2_{\text{red}} = 1.1$, log SFR = $1.26 \, M_\odot \, \text{yr}^{-1}$ and $M_* = 11.32 \, M_\odot$. Without Herschel the corresponding values are: $\chi^2_{\text{red}} = 1.3$, log SFR = $1.12 \, M_\odot \, \text{yr}^{-1}$ and $M_* = 11.31 \, M_\odot$. Stellar mass estimates for AGN may suffer from large uncertainties, in particular in the case of unabsorbed sources. The AGN emission can outshine the optical emission of the host galaxy, thus rendering stellar mass calculations uncertain.
2.5. Spectral Energy Distribution fitting

For details regarding the available photometry see table 2.1. Specifically, we perform an SED fitting, following the analysis described in the previous Section and estimate their SFR with and without the Herschel bands. In the latter case, only SDSS and WISE bands are used in the SED fitting. The comparison is shown in Figure 2.7. Although there is a small scatter in the measurements, that could be due to statistical errors (CIGALE estimations) and/or the usage of photometric redshifts for some sources, among others, we notice a systematic offset in the measurements. SFR estimated without Herschel are underestimated compared to SFR calculations including Herschel. Applying a \( \chi^2 \) fit we find that this offset is best described by the following equation:

\[
\log \text{SFR}_{\text{Herschel}} = \frac{\log \text{SFR}_{\text{noHerschel}} + 0.12 \pm 0.01}{0.87 \pm 0.03}.
\]  

(2.4)

The errors on the best-fit parameters represent the 1\( \sigma \) uncertainties. Based on the above equation, the corresponding uncertainty on the calculated SFR\(_{\text{Herschel}}\) due to the scatter is <10%. Although, in our analysis, we use this equation to correct the SFR estimates for those sources that do not have FIR photometry available, we also present separately our results for sources with and without available Herschel photometry. The inclusion of the (calibrated) non-Herschel SFR estimates significantly increase the size of our X-ray sample without affecting our results.
Figure 2.7: Comparison of the SFR estimates with and without Herschel, for the 608 sources with available Herschel photometry. The black solid line is the 1-1 line and the blue dashed line the best-fit calibration line. Sources with photoz are shown by blue, empty circles and spectroscopic sources by filled circles.
Chapter 3

AGN – host galaxy coevolution

In this chapter we explore the effect of the AGN power on the SFR of the host galaxy, using the largest X-ray sample up to date. We first, measure the SFR as well as the sSFR as a function of X-ray luminosity. Then, motivated by the evolution of SFR with stellar mass and redshift we disentangle the effects of the latter galaxy properties on the SFR and re-visit the AGN power–SFR relation (see Section 1.8 for an overview).

In our analysis we use data from both the XMM-XXL and X-ATLAS surveys. For details, regarding the examined sample, see Section 2. The final number of AGNs are presented in Table 2.1. All our X-ray sources have log $L_X(2−10\text{ keV}) > 41.0\text{ erg s}^{-1}$ which minimises contamination from inactive galaxies. The redshift distribution along with the X-ray luminosity distribution, for the whole sample, are presented in Figure 3.1.

In Figure 3.2 we present the X-ray luminosity as a function of redshift, for our final sample. Our dataset lacks low luminosity sources (log $L_X(2−10\text{ keV}) < 42.5\text{ erg s}^{-1}$) at $z > 1$. Restricting our X-ray catalogue to AGN with log $L_X(2−10\text{ keV}) > 43.5\text{ erg s}^{-1}$, reduces the number of sources to 2067, but our sample is complete up to $z \sim 2.5$. Various selection biases are introduced in our X-ray sample, for instance requirement for optical and mid-IR photometry, usage of photometric redshifts and data from wide area surveys compared to deeper fields (e.g. COSMOS, Chandra Deep Fields). It is not straightforward how these affect our measurements. For instance, the SDSS requirement biases our sample against low luminosity sources, whereas the XMM-XXL allow us to include more high luminosity AGN in our dataset. Therefore, when presenting our measurements we also include estimates for the individual AGN, using different symbols/colours depending on available spectroscopy and/or photometry. Furthermore, we split our final sample into many redshift bins to minimise any effect of possible incompleteness.
3.1 Analysis

To perform SED fitting analysis we need redshift information for our X-ray sources. 2,512/5,294 AGNs in the XMM-XXL field have available spectroscopic redshifts (specz), while for the ∼1000 sources in the X-ATLAS field we use the photoz catalogue presented in Mountrichas et al. (2017). We estimate photoz for the remaining 2,782 AGNs (in the XMM-XXL field), through TPZ (see Section 2.4). Although, we estimate photometric redshifts for the total of the 2,782 sources, as mentioned in Section 2.4, in our SED fitting analysis we include only sources that have available at least WISE or Herschel photometry, in addition to optical photometry.

Among the different galaxy properties the SFR and stellar mass are of great importance, since they provide a measure of the SFH (star formation history) of the host galaxy either averaged in the last few tens to hundred million years (instantaneous SFR) or integrated over...
3.2 Results

We use the X-ray luminosity as a proxy of the AGN power to study how an active supermassive black hole affects the star formation of its host galaxy. For that purpose we estimate the dependence of SFR on X-ray luminosity. Then, we divide the SFR of the galaxy by its stellar mass to derive the sSFR and study its dependence on the AGN power. Previous works have estimated the evolution of SFR with $M_*$ for star-forming galaxies (e.g. Schreiber et al., 2015). We perform a similar analysis using our X-ray sources and compare our findings with those from galaxy studies. To facilitate a better comparison with previous works (e.g. Lanzuisi et al., 2017; Brown et al., 2018) we follow their analysis and do not account for the Lx-z incompleteness of our sample (see Figure 3.2). However, we split our sample into redshift bins, which significantly

Figure 3.2: The X-ray luminosity as a function of redshift for the 3336 X-ray AGNs in our final sample. Sources in the XMM-XXL field are shown in blue. AGNs in the X-ATLAS field are presented with green symbols. Sources with photoz are shown by empty points and specz sources by filled points. AGNs with available Herschel photometry are presented with squares whereas those without Herschel by circles.
3.2. Results

reduces the effect of incompleteness on our calculations. Finally, we disentangle the effect of stellar mass and redshift to test how this affects the dependence of SFR on $L_X$.

3.2.1 SFR–$L_X$

In this Section, we study how the X-ray luminosity, used as a proxy of the AGN power, affects the star-formation rate of the host galaxy. SFR are estimated by CIGALE through the SED fitting. $L_X$ (observed) are estimated in the hard energy band ($2 - 10$ keV) using the available flux estimates of the sources. Our measurements are presented in the left panel of Figure 3.3. Individual sources are shown with small circles and squares for sources with and without Herschel photometry available, respectively. We also compute median $L_X$ in bins of SFR, indicated by the filled squares (median SFR values are shown). Our results show a dependence of the SFR on $L_X$, in the whole redshift and luminosity range, spanned by our sample.

In the same Figure, we also plot the binned SFR versus $L_X$ measurements from Brown et al. (2018) (polygons) and Lanzuisi et al. (2017) (triangles). Brown et al. (2018) used 703 AGNs with log $L_X(2 - 10$ keV) = (42 – 46) erg s$^{-1}$ at $0.1 < z < 5$ from the Chandra XBoötes X-ray Survey and found a dependence of the star-formation of the host galaxy on X-ray luminosity. Their SFR measurements are consistent with our estimates. Lanzuisi et al. (2017) used 692 AGNs from the COSMOS field in the redshift range $0.1 < z < 4$. Their results are in qualitative agreement with our findings, i.e., they detect a dependence of the SFR with X-ray luminosity at all redshifts and luminosities. However, their SFR calculations appear higher compared to our results and those from Brown et al. (2018). This difference could be due to the different methods applied to estimate SFR. Lanzuisi et al. (2017) calculates SFR using IR luminosities and adopting a Kennicutt (1998) law. We should mention that although we have split our measurements into five redshifts intervals, there could be some redshift evolution of SFR, within each redshift bin. However, the primary purpose of these measurements is to compare our results with previous similar studies. The main conclusions of our work are not drawn from these results.

Next, in the right panel of Figure 3.3 we compare our observational SFR versus $L_X$ results with the theoretical predictions of the model presented in Hickox et al. (2014). In this model a population of star-forming galaxies across a range of redshifts from 0 to 2 is created, with a redshift dependent distribution in SFR taken from the far-IR. Then, the far-IR luminosity is converted to SFR and each galaxy is assigned an average BH accretion rate. Finally, the instantaneous accretion rate is converted to a bolometric AGN luminosity (for more details see...
3.2. Results

Figure 3.3: Left: AGN X-ray Luminosity versus SFR. Dots are individual AGNs. Sources with photoz are shown by empty points and specz sources by filled points. AGNs with available Herschel photometry are presented with squares whereas those without Herschel by circles. Big squares refer to our binned results (median SFR and $L_X$ values are shown, in bins of SFR) and the error bars represent the $1\sigma$ dispersion of each bin. Triangles and polygons show the results from Lanzuisi et al. (2017) and Brown et al. (2018), respectively. The symbols are colour coded based on their redshifts $z > 0.4$ blue, $0.4 < z < 0.8$ green, $0.8 < z < 1.2$ red, $1.2 < z < 2.0$ magenta, $z > 2.0$ cyan. Right: Distribution of AGN X-ray luminosity versus SFR. Squares present our binned results. The solid lines are the extrapolated trends from the Hickox et al. (2014). They are colour coded based on their redshift range.

Hickox et al., 2014). The curves are colour coded based on the redshift bins. Although our results agree with the theoretical curves, in the sense that the average estimates of the binned measurements are consistent with the model, our measurements show a stronger dependence of the SFR on $L_X$.

3.2.2 $s\text{SFR} - L_X$

In this Section, we explore the dependence of the specific star-formation rate ($s\text{SFR}$; defined as the ratio of the SFR to the $M_*$) on X-ray luminosity. In Figure 3.4 we plot the results of our measurements. Squares indicate the average binned $s\text{SFR}$ as a function of the mean $L_X$.
Figure 3.4: Specific star-formation rate against X-ray luminosity for our AGN sample. The black, blue, red and cyan symbols refer to $z < 1.120$, $1.120 < z < 1.615$, $1.615 < z < 2.455$ and $z > 2.455$, respectively. Solid lines present the Rovilos et al. (2012) estimates while the dashed lines show their extrapolation to higher luminosities.

of each bin, for different redshift ranges. We choose to use mean sSFR and $L_X$ values instead of median, to facilitate comparison with previous studies. Specifically, we overlay the best-fit lines from the Rovilos et al. (2012). Rovilos et al. (2012) used X-ray data from the 3Ms CDFS XMM – Newton survey and found a significant correlation between the sSFR and X-ray luminosity for redshifts $z > 1$. They do not detect a significant correlation at lower redshifts though. Our X-ray sample consists of more luminous sources compared to the Rovilos et al. dataset. This is due to the large area of the XMM-XXL field used in our study. Towards this end, we extrapolate the best-fit lines of Rovilos et al. (2012) to higher X-ray luminosities (dashed lines). Our binned measurements are in good agreement with their results, at $1 < z < 2.455$.

At higher redshifts ($z > 2.5$), our estimates (cyan point) appear lower compared to the Rovilos et al. measurements. However, as previously mentioned, their sample spans lower redshift and X-ray luminosities compared to ours and only a small fraction of their sources resides at $z > 2.5$. At lower redshifts our sSFR measurements are lower but in statistical agreement with the Rovilos et al. sSFR estimates. Our measurements clearly show a dependence of the sSFR with redshift. In our lowest redshift bin, although the individual measurements have a large scatter, there is a hint of a mild sSFR dependence on $L_X$, even at $z < 1$. 
3.2.3 Evolution of SFR with $M_*$ and $z$

In this Section, we examine the evolution of the average SFR of the host galaxies of X-ray luminous AGNs with stellar mass and redshift. The motivation is to compare this evolution for X-ray AGNs and star-forming galaxies. Schreiber et al. (2015), used a sample of star-forming galaxies in four extragalactic fields, the GOODS North, GOODS South, UDS, and COSMOS obtained within the GOODS Herschel and CANDELS Herschel key programs. Their analysis revealed a universal, nearly linear slope of the $\log(SFR) - \log(M_*)$ relation, with evidence for a flattening at high masses ($\log(M_*/M_\odot) > 10.5$) that is less prominent at higher redshifts and almost vanishes at $z > 2$.

Figure 3.5 presents our measurements for the evolution of the average SFR of X-ray AGNs with average stellar mass and redshift (filled squares). Average values have been chosen to allow a fair comparison with the results of Schreiber et al. (2015) (open squares). Although our mean SFR estimates for the X-ray AGNs are higher compared to the SFR of star-forming galaxies, with the exception of low redshifts ($z < 0.7$), our results are in very good agreement with the trends found by Schreiber et al. for the star-forming galaxies. Specifically, at low redshifts ($z < 1.8$) SFR increases with $M_*$ for low stellar masses and then reaches a plateau for higher $M_*$. At higher redshifts the SFR increases nearly linearly with $M_*$.

3.2.4 Disentangling the effects of $M_*$ and redshift on the SFR

Motivated by the results of the previous Sections, i.e., the strong dependence of SFR on $M_*$ and redshift, we disentangle the effects of these parameters on SFR. Towards this end, we compare the SFR of our X-ray AGNs with the SFR of main sequence galaxies with the same stellar mass and redshift. The latter is estimated using Eq. 9 in Schreiber et al. (2015):

$$\log_{10}(\text{SFR}_{\text{MS}}[M_\odot/\text{yr}]) = m - m_0 + a_0 r - a_1 \left[ \max(0, m - m_1 - a_2 r) \right]^2,$$

(3.1)

with $m_0 = 0.5 \pm 0.07$, $a_0 = 1.5 \pm 0.15$, $a_1 = 0.3 \pm 0.08$, $m_1 = 0.36 \pm 0.3$ and $a_2 = 2.5 \pm 0.6$. $r$ and $m$ are defined as: $r \equiv \log_{10}(1 + z)$ and $m \equiv \log_{10}(M_*/10^9 M_\odot)$.

We, then, define the normalised SFR, as the ratio of the SFR of the host galaxies of our X-ray selected AGNs to the SFR of galaxies in the main sequence (see also Mullaney et al., 2015; Bernhard et al., 2018; Grimmett et al., 2020).
3.2. Results

Figure 3.5: Mean star formation rate versus $M_*$ for our sample (filled squares) and for observed star-forming galaxies (open squares; Schreiber et al., 2015).

As shown in Figure 3.1 our sample lacks low-luminosity sources at high redshifts ($z > 1$). Thus, in Figure 3.6, we plot the $\text{SFR}_{\text{norm}} - L_X$, for the whole sample using three redshift bins ($z < 0.5, 0.5 < z < 1.2$ and $z > 1.2$). Results are presented in $L_X$ bins. Median SFR and $L_X$ values are shown. The error bars represent the $1\sigma$ dispersion of each bin. Our measurements show evolution of the $\text{SFR}_{\text{norm}}$ with redshift. This evolution does not appear statistical significant for redshift below $z < 1.2$ ($\leq 1\sigma$), but its statistical significance increases between the lowest and highest of our redshift bins. This result suggests, that as we move to higher redshifts, galaxies that host AGN tend to have a higher increase of their SFR compared to star-forming galaxies. At high redshifts, the SFR and the amount of dust in galaxies increase (e.g. Santini et al., 2014). Our result may indicate that at $z > 1.2$, galaxies that host an AGN are more efficient to convert the increased amount of gas in stars compared to star-forming galaxies with the same stellar mass. Mullaney et al. (2015), used X-ray AGN from Chandra Deep Field South and Chandra Deep Field North and found no evolution of $\text{SFR}_{\text{norm}}$ with redshift. However, their sample does not include sources below $z < 0.5$. Based on our results, $\text{SFR}_{\text{norm}}$ evolves with $L_X$, at all luminosities spanned by our sample. However, our previous measurements showed evolution of $\text{SFR}_{\text{norm}}$ with redshift. Although, we have split our measurements into three redshift intervals,
3.2. Results

Figure 3.6: SFR$_{\text{norm}}$–$L_X$ for different redshift. Median SFR and $L_X$ values are shown. The error bars represent the 1σ dispersion of each bin. Our measurements show evolution of the SFR$_{\text{norm}}$ with redshift. This evolution does not appear statistical significant for redshift below $z < 1.2$ ($\leq 1\sigma$), but its statistical significance increases between the lowest and highest of our redshift bins. This result suggests, that as we move to higher redshifts, galaxies that host AGN tend to have a higher increase of their SFR compared to star-forming galaxies. At high redshifts, the SFR and the amount of dust in galaxies increase (e.g. Santini et al., 2014). Our result may indicate that at $z > 1.2$, galaxies that host an AGN are more efficient to convert the increased amount of gas in stars compared to star-forming galaxies with the same stellar mass.
3.2. Results

Figure 3.7: The ratio $\text{SFR}_{\text{norm}}$ to $L_X$ versus $z$. The individual sources are presented by the black squares and the binned results by the blue circles. They are presented in bins of 0.1 redshift. The errors, both on redshift and $\text{SFR}_{\text{norm}}/L_X$ are the $1\sigma$ dispersion in each bin.

we further investigate whether the observed trends hide redshift evolution within each redshift bin. For that purpose, in Figure 3.7, we present the ratio of $\text{SFR}_{\text{norm}}$ over $L_X$ as a function of redshift. Based on this plot, we conclude that at $z>0.5$, the $\text{SFR}_{\text{norm}}/L_X$ does not evolve with redshift. At lower redshifts, there is an evolution which, however, does not appear statistical significant ($<1\sigma$). Thus, we conclude that the $\text{SFR}_{\text{norm}}$ evolution observed in Figure 3.6 is driven by the X-ray luminosity.
Chapter 4

AGN type – host galaxy properties

Most of the radiation directly emitted by AGNs is obscured from our view (see Section 1.6). In this chapter we investigate the relation between the AGN type and the host galaxy properties as well as if the SFR-L\(_X\) relation changes with absorption. We apply our analysis for both X-ray absorbed/unabsorbed and red/unobscured populations, to compare the results for the different obscuration criteria (for details see Section 1.8).

In table 4.1, is presented the number of sources based on the available photometry, spectroscopy and X-ray absorption. The observed L\(_X\), is estimated in the hard energy band (2–10 keV) and, as mentioned, our X-ray sources are selected to have L\(_X\) (2–10 keV) > 10\(^{41}\) erg s\(^{-1}\) (see Section 2).

The observed X-ray luminosity as a function of redshift is presented in Figure 4.1. Based on the latter plot, there is a selection bias against low luminosity sources (log L\(_X\) < 43 erg s\(^{-1}\)) at high redshifts (z > 1). To account for this effect we adopt the \(\frac{1}{V_{\text{max}}}\) method (e.g. Schmidt, 1968; Akylas et al., 2006, see Section 4.2).

<table>
<thead>
<tr>
<th>X-ray selected AGN</th>
<th>Total number</th>
<th>Specz</th>
<th>Photoz</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS</td>
<td>5294</td>
<td>2512</td>
<td>2782</td>
</tr>
<tr>
<td>SDSS + WISE or Herschel</td>
<td>3213 (808)</td>
<td>1849 (454)</td>
<td>1364 (354)</td>
</tr>
</tbody>
</table>

Table 4.1: Number of spectroscopic and photometric sources with SDSS, WISE or Herschel photometry in our sample. The number of AGNs used in this study appear in bold. The sources are classified as absorbed or unabsorbed based on their N\(_H\). We consider as absorbed those sources with N\(_H\) > 10\(^{21.5}\) cm\(^{-2}\). The numbers in parentheses refer to the absorbed AGNs.
4.1 Analysis

In this Section, we describe the steps we follow in our analysis. The AGN host galaxy properties have been estimated through SED fitting (section 4.1.1). Section 4.1.2 describes the estimation of the X-ray properties of our sample and the methodology we have followed to account for selection biases.

4.1.1 Host galaxy properties

SFR and $M_*$ were estimated using the CIGALE code. The emission associated with AGN is modelled using the Fritz et al. (2006) library, as described in Ciesla et al. (2015). This allows us to disentangle the AGN IR emission from the IR emission of the host galaxy and derive more accurate SFR measurements. For more details regarding SED fitting, see 2.5.

Masoura et al. (2018) (see their Figure 7), found that the average SFR of AGN host galaxies of the X-ray selected AGNs has a similar evolution with stellar mass and redshift with that of star-forming systems (e.g Brinchmann et al., 2004; Elbaz et al., 2007; Daddi et al., 2007; Magdis et al., 2010; Salmon et al., 2015; Schreiber et al., 2015).

To account for the evolution of the MS, we follow the approach of (see also e.g., Bern-
4.1. Analysis

hard et al., 2018) and make use of the SFRs_{norm} parameter to examine whether the AGN type plays any systematic role in deviations (or dispersion) around it. This quantity is equal to the observed SFR, divided by the expected SFR at a given M_\ast and redshift (SFRs_{norm} = SFR/SFR_{MS}). To estimate the SFR_{MS} we use equation 9 of Schreiber et al. (2015).

4.1.2 X-ray absorption

To classify the AGN as X-ray absorbed and unabsorbed we need to estimate their hydrogen column density. For that purpose, we first apply an advanced statistical method to calculate the HR and then infer the N_H of each source. A detailed description of this process is provided below:

X-ray colours

Hardness ratio (HR) or X-ray colour, is used to quantify and characterise weak sources and large samples. To alleviate the downsides of the classical definition (e.g. Gaussian assumption for the error propagation of counts for faint sources with a significant background, background subtraction), we apply the Bayesian Estimation of Hardness Ratios code (BEHR; Park et al., 2006). This method applies a Bayesian approach to account for the Poissonian nature of the observations. For the estimates, we use the number of photons in the soft (0.5−2.0 keV) and the hard (2.0−8.0 keV) bands, provided in Liu et al. (2016) catalogue. The hardness ratio calculations are based on the following equation:

\[
HR = \frac{H - S}{H + S},
\]

where S and H the counts in the soft and the hard bands, respectively.

Hydrogen column density

The N_H values for all the sources in our sample are estimated using the calculated HRs. PIMMS tool (Portable, Interactive, Multi-Mission Simulator; Mukai, 1993) is used to create a grid of HR and N_H values and convert the HR values from BEHR into N_H. PIMMS is also used to estimate the correction factor, that is applied for the calculation of the intrinsic fluxes of our sources (see next paragraph).

In our calculations we assumed that the power law X-ray spectrum has a fixed photon index (\Gamma) of 1.8 (Nandra and Pounds, 1994). The value of galactic N_H used is \log N_{H,gal}/\text{cm}^{-2} = 20.25.
4.2 Results

The AGN sample is split into X-ray absorbed and unabsorbed sources, using a N\textsubscript{H} cut at log N\textsubscript{H}/ cm\textsuperscript{-2} = 21.5. This value has been chosen in a number of previous studies since it provides a good agreement between the X-ray and optical classification of type 1 and 2 AGNs (e.g. Merloni et al., 2014; Masoura et al., 2020).

Figure 4.2 presents the distribution of the hydrogen column density for the examined sources. Its bimodal nature, was observed in previous works, too (e.g. Civano et al., 2016; Stemo et al., 2020). N\textsubscript{H} values lower than the adopted galactic N\textsubscript{H} are due to the Bayesian approach we have followed in the estimation of HRs. Specifically, the Bayesian method we use for the HR estimates does not impose a hard limit on the N\textsubscript{H} values. The Probability Density Function (PDF) of the each HR may extent to lower values than that which corresponds to the Galactic absorption. Thus, in some cases, the mean HR values estimated by these PDFs may be lower than the Galactic absorption value.

Having estimated N\textsubscript{H}, we compute the correction factor, defined as \( f_{\text{int}}/f_{\text{abs}} \), where \( f_{\text{abs}} \) is the absorbed flux and \( f_{\text{int}} \) the intrinsic flux. The latter has been estimated using PIMMS and assuming an unabsorbed power law with \( \Gamma = 1.8 \). Then, each observed X-ray luminosity is corrected using this factor, to estimate the intrinsic X-ray luminosity. The mean value of the correction factor is 0.16 dex with a dispersion of 0.04, in terms of the X-ray luminosity.

Figure 4.3 presents the distribution of redshift (left panel) and intrinsic X-ray luminosity (right panel) of absorbed (red line) and unabsorbed (blue line) AGN. We notice that the distributions of the two AGN subsamples are similar. This can be explained by the low X-ray absorption limit we adopt in our analysis. Adoption of a higher N\textsubscript{H} cut (log N\textsubscript{H}/ cm\textsuperscript{-2} = 22), results in different redshift and X-ray luminosity distributions between absorbed and unabsorbed sources, in agreement with the predictions of X-ray luminosity function studies (e.g. Aird et al., 2015). Adopting a higher N\textsubscript{H} cut does not affect our results and conclusions.

4.2 Results

In this section, we present our main results and compare them with previous studies. Specifically, we examine, whether absorbed and unabsorbed AGN have different host galaxy properties as well as if obscuration affects the SFR-L\textsubscript{X} relation.
4.2. Results

Figure 4.2: Hydrogen column density, \( N_{\text{H}} \), distribution of the AGN sample. The vertical, dashed line presents the \( N_{\text{H}} \) cut applied in our analysis to split the sources into absorbed and unabsorbed.

Figure 4.3: Left: Redshift distribution of the examined sample. Right: Intrinsic, X-ray luminosity distribution of the examined sample. Blue and red colours refer to the unabsorbed and absorbed sources, respectively. Both histograms have been normalised to the total number of sources.
4.2. Results

4.2.1 Host galaxy properties of absorbed and unabsorbed AGNs

As presented in Figure 4.3, the redshift and \( L_X \) distributions of X-ray absorbed and unabsorbed classified AGN in our sample are similar. However, we account for the small differences between them, to facilitate a better comparison of the host galaxy properties of the two populations. For that purpose, we join the redshift distributions of the two populations and normalise each one by the total number of sources in each redshift bin (bin size of 0.1). We repeat the same process for the \( L_X \) distributions of the two subsamples (bin size of 0.2 dex). This procedure provides us with the probability density function (PDF) in this 2−D parameter space (i.e., redshift and \( L_X \) space). Then, we use the redshift and \( L_X \) of each source to weigh it based on the estimated PDF (see also Mendez et al., 2016; Mountrichas et al., 2016). This correction method is similar to that applied in previous studies (e.g. Zou et al., 2019) and allows a fair comparison with their results. Additionally, each source is weighted based on the statistical significance of its stellar mass and SFR measurements (see next Sections for details).

**KS-test**

In the following sections we apply a two-sample Kolmogorov-Smirnov test (KS-test) to examine whether or not the distributions differ. We note that the characterisation of two populations as similar because of e.g. a 99% KS-test probability (i.e. 99% probability that two samples are drawn from the same underlying population) is not equally strong as deducing dissimilarity because of an 1% probability.

For instance, supposing two populations whose average is different but only in some low level of a few%. If the samples are small or large but noisy and the KS-test reveals 99% probability that these two populations are drawn from one common underlying one, it is possible for larger samples (or less noisy) the KS-test to uncover that the two populations are really different, with their KS similarity estimator dropping to a few%. If, on the other hand, a KS probability is initially found to be small even with a small sample, this is unlikely to be revised upwards by a larger sample.

In other words, population differences uncovered by the KS-test are more secure than similarities. In that sense the magnitude of our sample yields some good confidence to our conclusions.
Stellar mass distribution

Stellar mass estimations for AGN may suffer from large uncertainties, in particular in the case of unabsorbed sources (type 1 AGN $\sim 70\%$). The AGN emission can outshine the optical emission of the host galaxy, thus rendering stellar mass calculations uncertain. The median stellar mass measurements and the median uncertainties, estimated by CIGALE are $10.6 \pm 0.4$ and $10.9 \pm 0.6$, for unabsorbed and absorbed AGN, respectively. Restricting our sample to the most X-ray luminous ($L_X \geq 10^{44} \text{ergs}^{-1}$), unabsorbed AGN ($\sim 20\%$ of our total sample) gives $11.1 \pm 0.8$. Figure 4.5 presents the distributions of stellar mass uncertainties for absorbed (red shaded area) and unabsorbed (blue line) AGN. The two populations have similar distributions, with the bulk of the measurements to have errors $\leq 0.5 - 0.6 \text{dex}$. We choose not to exclude sources with large stellar mass errors to avoid reducing the size of the dataset. Instead we account for the $M_*$ uncertainties, by estimating the significance (value/uncertainty), $\sigma$, of each stellar mass measurement and weigh each source based on its $\sigma$ value (in addition to the weight presented in the previous paragraph). We confirm, that excluding from our analysis those sources that have stellar mass uncertainties larger than $0.6 \text{dex}$ ($\sim 25\%$ of unabsorbed and $\sim 33\%$ of absorbed AGN) does not change our results and conclusions compared to those presented, using the weighting method described above.

Figure 4.4 presents the distribution of $M_*$ for both absorbed and unabsorbed AGNs. We apply a two-sample Kolmogorov-Smirnov test (KS-test) to examine whether or not the two distributions differ. The KS-test reveals that the distributions are similar for both AGN populations ($p$-value $= 0.89$). We also split the AGN sample into low and high redshift subsamples, using a redshift cut at $z = 1.0$ and repeat the process. KS-test shows no statistical significant difference of the $M_*$ distribution of absorbed and unabsorbed sources, at any redshift. Specifically, at $z < 1.0$ KS-test gives $p = 0.99$ and at $z > 1.0$, $p = 0.36$. Our findings are in agreement with Merloni et al. (2014) who used 1310 X-ray selected AGN from the XMM-COSMOS survey with redshift range $0.3 < z < 3.5$. In that study, the X-ray population was split into obscured and unobscured AGN, using the same $N_H$ cut that is applied in our analysis ($N_H=10^{21.5} \text{cm}^{-2}$). They found no remarkable differences between the mean $M_*$ of obscured and unobscured AGNs.

On the other hand, Lanzuisi et al. (2017), used approximately 700 X-ray selected AGNs, in the COSMOS field in the redshift range $0.1 < z < 4$, and found that unobscured AGNs tend to have lower $M_*$ than obscured sources. However, they considered as X-ray absorbed sources with $N_H > 10^{22} \text{cm}^{-2}$. To be consistent with Lanzuisi et al. (2017), we apply the KS-test adopting
the same $N_H$ with them. The estimated $p$-value, although is reduced to 0.56 still indicates that the $M_*$ distribution is similar, for the two AGN populations. Furthermore, Zou et al. (2019) used 2463 X-ray selected AGNs in the COSMOS field and found that unobscured AGNs tend to have lower $M_*$ than their obscured counterparts. However, in their analysis they divided their sample into type 1 and type 2 AGNs based on their optical spectra, morphologies, and variability. Thus, the disagreement with our results could be attributed to the different method applied in the characterisation of a source as obscured/unobscured.

**Star formation rate distribution**

For the comparison of the SFR distributions of absorbed and unabsorbed AGN, we follow the process presented in the previous Section. Specifically, each source is weighted based on its X-ray luminosity and redshift as well as the $\sigma$ value of its SFR measurement. Figure 4.6 presents the distributions of the star formation rate, for the two AGN populations. Application of the two-sample KS-test reveals that the SFR distributions are similar for both AGN populations, with $p$−value equals to 0.95. This is also the case when we split the AGN sample into low and high redshift subsamples, using a redshift cut at $z = 1.0$ (for $z < 1.0$, $p = 0.99$ and for $z > 1.0$, $p = 0.95$ for $z < 1.0$).
Figure 4.5: Distributions of the error of the log \( M_\ast \) for absorbed (red shaded histogram) and unabsorbed (blue line) AGN. The two populations have similar error distributions, with the bulk of the measurements to have errors \( \leq 0.5 \) – 0.6 dex.

\[ p = 0.86 \].

In Fig 4.7, we present the star formation rate distributions only for those AGN that have available Herschel photometry. The results are similar to those for the full sample, i.e. the SFR distributions of X-ray absorbed and unabsorbed AGN present no significant differences \((p – value = 0.86)\). Further restricting the sample to those sources with signal-to-noise ratio greater than 3 for the SPIRE bands (216 AGN), does not change the results.

Our findings agree with most previous studies (Merloni et al., 2014; Lanzuisi et al., 2017; Zou et al., 2019). On the other hand, Chen et al. (2015) used AGN from the Böotes field and claimed that type 2 sources have higher IR star formation luminosities (a proxy of star formation) by a factor of \( \sim 2 \) than type 1. However, their dataset consists of mid-IR selected, luminous quasars. Moreover, they have divided their sample into type 1 and type 2 AGNs using optical/mid-IR colour criteria \( R - [4.5] = 6.1 \) (e.g. Hickox et al., 2007), where \( R \) and \([4.5]\) are the Vega magnitudes in the R and IRAC 4.5\( \mu\)m bands, respectively.
Figure 4.6: Star formation rate distribution. Blue and red colours refer to the unabsorbed and absorbed sources, respectively. Histograms have been normalised to the total number of sources. Distributions for the total number of sources. The two populations have similar SFR distributions ($p$-value = 0.95).

Figure 4.7: Star formation rate distribution. Blue and red colours refer to the unabsorbed and absorbed sources, respectively. Histograms have been normalised to the total number of sources. Distributions for the 1,276 AGN with Herschel photometry available. We confirm that the X-ray absorbed and unabsorbed AGN have similar SFR distributions ($p$-value = 0.86).
Normalised star formation rate distribution

We calculate the SFR$_{\text{norm}}$, to take into account the evolution of SFR with stellar mass and redshift (see section 4.1.1). The distribution of SFR$_{\text{norm}}$ of absorbed and unabsorbed AGN is presented in Figure 4.8, in bins of 0.2 dex. Each source is weighted based on its redshift and luminosity, as well as based on the significance of its stellar mass and star formation rate measurement. The KS-test results in a $p$-value equal to 0.71, i.e., the two populations have similar SFR$_{\text{norm}}$ distributions. We notice that both distributions are bimodal. Further investigation reveals that, both for the absorbed and the unabsorbed sources, the first peak is due to low redshift systems ($\text{mean} \ z \approx 0.7$), while the second peak is due to AGN that lie at high redshifts ($\text{mean} \ z \approx 1.5$). This may suggest evolution of the SFR$_{\text{norm}}$ with redshift. To investigate this scenario further, we split the AGN sample into two redshift bins, at $z = 1.2$. The SFR$_{\text{norm}}$ distributions are presented in Figure 4.9. The results confirm that the SFR$_{\text{norm}}$ distribution peaks at different values at low and high redshifts. AGN in the lower redshift bin have SFR comparable with galaxies in the star-forming main sequence ($\log \text{SFR}_\text{norm} = 0$), whereas AGN at higher redshift have enhanced SFR compared to galaxies in the main sequence. We discuss this in more detail in the next section.

Bernhard et al. (2018) examined the SFR distribution of X-ray AGN, taking into consideration its evolution with $M_*$ and redshift. Specifically, they used X-ray sources in the COSMOS field and investigated the SFR$_{\text{norm}}$ distribution as a function of $L_X$. Based on their analysis, more powerful AGN present a narrower SFR$_{\text{norm}}$ distribution that peaks close to that of the MS galaxies. Their sample consists of AGN at intermediate redshifts, i.e., $0.8 < z < 1.2$. Based on the mean redshift values of the systems contained in the two peaks of our SFR$_{\text{norm}}$ distributions presented above, this would place their sources in between our two peaks and close to SFR of MS galaxies. Furthermore, Bernhard et al. sample spans a narrower $L_X$ range and lacks sources both at low and in particular at high $L_X$ compared to the sample used in our analysis (see our Figure 4.1 and their Figure 1). There are only $\sim 500$ AGN in our dataset that are within the redshift and luminosity range of Bernhard et al. Further restricting the sample to only obscured sources, in accordance with Bernhard et al., results in less than 200 sources. Applying their luminosity cut ($L_X = 2 \times 10^{43} \text{ ergs}^{-1}$) we divide AGN into high and low luminosity systems. We note that there are less than 30 low luminosity sources in our sample. The SFR$_{\text{norm}}$ distribution of high (green) and low (blue) $L_X$ AGN is presented in Figure 4.10. High luminosity AGN still present a two-peaked SFR$_{\text{norm}}$. We note, however, that although we have matched the redshift
4.2. Results

Figure 4.8: Normalized star formation rate distribution. Blue and red colours refer to the unabsorbed and absorbed sources, respectively. The histogram has been normalised to the total number of sources. The two populations have similar normalised SFR distributions ($p-$value = 0.71). Both distributions are bimodal.

and $L_X$ range with that of Bernhard et al., the $L_X$ distributions of the two datasets are still different. Nevertheless, the two results agree that higher X-ray luminosity AGN exhibit higher SFR$_{norm}$ values. We conclude, that the different results between our study and Bernhard et al. could be due to the different $L_X$, redshift plane probed by the samples of the two studies and in particular the different luminosity distributions between the two datasets.

4.2.2 SFR$_{norm}$ − $L_X$ correlation for different AGN types

In this section, we study the effect of obscuration on the SFR−$L_X$ relation. To account for the evolution of SFR with stellar mass and redshift (see also section 4.1.1), we plot SFR$_{norm}$ versus $L_X$. Luminous sources are observed within a larger volume compared to their faint counterparts, in flux limited surveys (Figure 4.1). This introduces a selection bias to our analysis. To account for this effect, we adopt the $\frac{1}{V_{\text{max}}}$ correction method (Akylas et al., 2006; Page and Carrera, 2000). Specifically, we estimate for each source of a given $L_X$, the maximum available volume that it can be observed, using the following equation:

$$V_{\text{max}} = \int_{0}^{z_{\text{max}}} \Omega(f) \frac{dV}{dz} dz,$$  \hspace{1cm} (4.2)
4.2. Results

Figure 4.9: Normalized star formation rate distribution for sources at $z < 1.2$ (blue line) and at $z > 1.2$ (green, dashed line). The histogram has been normalised to the total number of sources. AGN in the lower redshift bin have SFR comparable with galaxies in the star-forming main sequence ($\log SFR_{\text{norm}} = 0$), whereas AGN at higher redshift have enhanced SFR compared to galaxies in the main sequence. This suggests evolution of the $SFR_{\text{norm}}$ with redshift (see text for more details).

Figure 4.10: $SFR_{\text{norm}}$ distribution for low ($L_\text{X} < 2 \times 10^{43}$ ergs$^{-1}$, blue line) and high ($L_\text{X} > 2 \times 10^{43}$ ergs$^{-1}$, green line) X-ray luminosities. Redshift and $L_\text{X}$ range have been restricted to match that of Bernhard et al. (2018). We only present measurements for the X-ray absorbed AGN.
where $\Omega(f)$ is the value of the sensitivity curve at a given flux, corresponding to a source at a redshift $z$ with observed luminosity $L_X$. $z_{\text{max}}$ is the maximum redshift at which the source can be observed at the flux limit of the survey. The area curve used in our calculations is presented in Liu et al. (2016) (see their Figure 3). The area curve or sensitivity map is an estimate of the probability that a source with a certain X-ray flux, in a certain energy band, will be detected across the detector. Each source is weighted by the $\frac{1}{V_{\text{max}}}$ value, depending on their $L_X$ and redshift. An additional weight is also considered, based on the $\sigma$ value of the $M_*$ and SFR measurements.

In Figure 4.11, we present our measurements in $L_X$ bins, for absorbed and unabsorbed AGNs. In the plot are presented the median values of $\text{SFR}_{\text{norm}}$ and $L_X$. The error bars represent the 1 $\sigma$ dispersion of each bin. The number of sources varies in each bin, but bins with fewer than 30 sources are disregarded from our results. Based on our findings, both X-ray absorbed and unabsorbed AGNs present a similar SFR-$L_X$ relation, at all X-ray luminosities spanned by our sample.

Additionally, we examine, if and how the redshift range affects our estimates. The $N_H$ values, estimated in section 4.1.2 could be considered less secure, as we move to higher redshifts. This is because the absorption redshifts out of the soft-Xray band in the observed frame. Moreover, as shown in Figure 4.1 our sample lacks low-luminosity sources at high redshifts ($z > 1$). Thus, in Figure 4.12, we plot the $\text{SFR}_{\text{norm}}-L_X$, for the whole sample (left), the absorbed (middle) and unabsorbed (right) subsamples using three redshift bins ($z < 0.5, 0.5 < z < 1.2$ and $z > 1.2$). Results are presented in $L_X$ bins. Median SFR and $L_X$ values are shown. The error bars represent the 1 $\sigma$ dispersion of each bin. For X-ray absorbed sources we find no difference in the dependence of the SFR on the AGN power, at all redshifts. However, X-ray unabsorbed sources at high redshift ($z > 1.2$) present a flat $\text{SFR}_{\text{norm}}-L_X$ relation.

4.3 Star formation—$N_H$

SFR is a galaxy scale quantity while X-ray obscuration occurs in the region around the black hole. However, it has been claimed that obscuration can also occur in galaxy scale (e.g. Fabbiano et al., 2017; Malizia et al., 2020). In the latter case, the two properties may be correlated. Thus, in this part of our analysis, we investigate whether there is a dependence of SFR with the X-ray absorption.
4.3. Star formation—$N_{\text{HI}}$

Figure 4.11: The SFR$_{\text{norm}}$–$L_X$ correlation in $L_X$ bins, for absorbed and unabsorbed sources. Based on our measurements, the AGN correlates with the SFR of the host galaxy, at all X-ray luminosities spanned by our sample, regardless of whether the source is X-ray absorbed or not. Red and blue triangles refer to the absorbed and unabsorbed sources, respectively. The dashed line corresponds to the star forming main sequence. Here are presented median SFR and $L_X$ values. The error bars represent the 1σ dispersion of each bin.
Figure 4.12: The SFR$_{norm}$–$L_X$ correlation in $L_X$ bins, for different redshift intervals ($z < 0.5$, $0.5 < z < 1.2$ and $z > 1.2$). Left and right panels refer to the absorbed and unabsorbed populations, respectively. The dashed line corresponds to the star forming main sequence. Trends are similar in all redshift bins. The error bars represent the dispersion $1 \sigma$ of each bin.
Rosario et al. (2012) used a sample of AGNs from GOODS-South, GOODS-North and COSMOS fields, spanning the redshifts 0.2 < z < 2.5. The $N_H$ values were estimated using either spectral fits for X-ray sources with sufficient counts or scalings based on hardness ratios for faint X-ray sources. They found a mild dependence between the mean far IR luminosity (SFR proxy) and the X-ray obscuring column, $N_H$. On the other hand, Rovilos et al. (2012) used AGNs from the 3Ms XMM – Newton survey with $z \approx 0.5–4$ and reported that there is no correlation between SFR and $N_H$. They claimed that the absorption is likely to be linked to the nuclear region rather than the host galaxy.

Their findings were recently confirmed, by Stemo et al. (2020). This group used X-ray and/or IR selected AGNs (Spitzer and Chandra data) and composed a sample of 2585 sources with redshift range 0.2 < z < 2.5. They compiled data come from the GEMS, COSMOS, GOODS and AEGIS surveys. They used extinction parameter, $E_{B-V}$, values (estimated through SED fitting) to infer the $N_H$ values, using a conversion factor of $E_{B-V} / N_H = 1.80 \pm 0.15 \cdot 10^{-23}$. Based on their findings, the relation between the SFR and $N_H$ is flat, up to $z = 2.5$. According to their interpretation, this behaviour indicates a difference in fuelling processes or timescales between SMBH growth and host galaxy star formation.
4.4 Obscuration based on the r-W2 criterion

In this part of our analysis we follow the same analysis described in Sections 4.1-4.3, this time dividing our sample into obscured and unobscured based on their optical-IR obscuration, applying Yan et al. (2013) criterion (r-W2). We do that to examine the relation between the AGN type and the host galaxy properties as well as if the SFR-L_X relation changes with absorption.

We follow the same process as in the previous Section, i.e., we match the redshift and X-ray luminosity distributions of the two AGN populations and we also weigh each source based on the error of each measurement. Then, we compare their host galaxies properties (Figures 4.15-4.18). Based on our results and the p-values of the KS-test, red and non red AGNs have different host galaxy properties.
4.4. Obscuration based on the r-W2 criterion

Figure 4.15: Left: Stellar mass distribution. Blue and red colours refer to the unobscured and obscured sources based on the r-W2 criterion, respectively. The histogram has been normalised to the total number of sources. Based on the KS-test, $p$-value $= 7.7 \times 10^{-16}$, that implies that the stellar mass distributions of the two AGN populations are drawn by different parent samples. Right: Star formation rate distribution (r-W2). Blue and red colours refer to the unobscured and obscured sources based on the r-W2 criterion, respectively. The histogram has been normalised to the total number of sources. Based on the KS-test, $p$-value $= 1.2 \times 10^{-6}$, i.e. red and non red X-ray AGN have different SFR distributions.

Figure 4.16: Left: Cumulative distributions of stellar mass (left panel) and SFR (right panel) for red (red line) and non red (green line) X-ray AGNs.
4.4. Obscuration based on the r-W2 criterion

Figure 4.17: Normalised star formation rate distribution. Blue and red colours refer to the unobscured and obscured sources based on the r-W2 criterion, respectively. The histogram has been normalised to the total number of sources. KS-test gives $p-$value $= 1.3 \times 10^{-20}$. Therefore the two AGN populations have SFR$_{\text{norm}}$ distributions that are statistically impossible to have been drawn from the same parent sample.

Figure 4.18: Cumulative distributions of SFR$_{\text{norm}}$ for red (red line) and non red (green line) X-ray AGNs.
Chapter 5

X-ray properties of red AGNs

In this Chapter, we explore the obscuration properties of red AGNs, with both X-ray spectroscopy and SED fitting (for a review see 1.8).

5.1 Analysis

The examined sample consists of 47 red AGNs (Yan et al. criterion; r-W2>6). The parent sample consists of 2706 IR selected AGNs in the footprint of the XXL. 1594 of them have SDSS detection and when we apply Yan et al. criterion from those sources (1594), 369 are red AGNs. 47 out of 369 AGNs have available X-ray spectra, see Section 2.3. Table 5.1 presents the identity (ID), the redshift and the magnitudes r and W2 (in the Vega system) for the 47 optically red AGNs.

In addition to optical and MIR photometry, 45 out of the 47 red AGNs have also been detected in the NIR (VISTA; Emerson et al., 2006; Dalton et al., 2006). In the following sections we study their X-ray absorption, the obscuration based on their SED fitting and when available we also study their optical spectra to investigate if and how all these different obscuration criteria agree.

5.1.1 X-ray spectra

In this section we examine the X-ray absorption of our sample. To achieve that, we apply X-ray spectral-fitting using the XSPEC v12.10 software (Arnaud, 1996). We use the Cash statistical analysis (C-stat; Cash, 1979) on the spectra binned to 1 count/bin, which has been shown to recover the actual spectral parameters in the most accurate way even for very low-
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Table 5.1: General properties of the red AGN sample. r is the SDSS photometric band (SDSS DR15; Aguado et al., 2019). r and W2 magnitudes are on the Vega system. We use three decimal points for spectroscopic redshifts and photometric redshifts are in italics with two decimal points.
Table 5.2: X-ray properties of the red AGN sample. When $\Gamma \leq 1.2$, we quote the $N_{\text{H}}$ calculations with $\Gamma$ fixed to $\Gamma = 1.8$ and present the $N_{\text{H}}$ estimates in column 4. Sources classified as X-ray obscured based on our strict criteria (see text for more details) are presented in bold. Sources that satisfy the loosened X-ray criteria (see text) are shown in italics. The energy band of $L_X$ is [2-10 keV].
5.1. Analysis

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Table 5.3: SED properties of the red AGN sample. The extinction of a source is derived from the viewing angle, Ψ, of the torus: Ψ ≤ 30° for type 2 (edge-on), 40° ≤ Ψ ≤ 60° for intermediate, and Ψ ≥ 70° for Type 1 AGNs (face-on; Ciesla et al., 2015), respectively. The AGN fraction is measured as the IR AGN emission relative to the total IR emission (1 − 1000 μm).
### Table 5.4: Optical properties of the red AGN sample.

Optically-unobscured sources (type 1) are considered to be those with broad emission lines (BL). Whereas obscured sources (type 2) exhibit only narrow emission lines (NL) or a red continuum. The AGNs are characterised as obscured, unobscured, or intermediate type (IMD) based on visual inspection of their optical spectra. We note that in the optical spectra of sources 13 and 22, while the MgII lines are broad, all other lines are narrow. This is attributed to the wider area from which the MgII originates with respect to the Balmer lines. These sources are characterised as IMD.

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Figure 5.1: $N_H$ as a function of X-ray luminosity for the 47 optical red AGNs. Those sources for which the X-ray spectral fitting could not constrain their $N_H$ are presented with a triangle (upper limit estimates). The 21 AGNs that satisfy our X-ray absorption criteria are presented with filled symbols (see text for more details).

The model applied to the spectral data is a simple power law, $A(E) = KE^{-\Gamma}$, absorbed by both the Galactic photoelectric absorption and the intrinsic absorption. $\Gamma$ is the photon index of the power law and $K$ is the flux at 1 keV in units of photons/keV/cm$^2$/s. The Galactic absorption is taken from the Leiden/Argentine/Bonn (LAB) Survey of Galactic HI Kalberla et al. (2005). The X-ray spectra for the 47 AGNs are presented in Figures A.1- A.47. The best-fit values are presented in Table 5.2. In Figure 5.1 we present $N_H$ versus X-ray luminosity.

Figure 5.2 presents the $N_H$ distribution of the sources, taking into account the $N_H$ upper limits (Isobe et al., 1986). For that purpose, we use the Astronomical SURVival Statistics (ASURV; Lavalley et al., 1992) software package, which adopts the maximum-likelihood Kaplan-Meier estimator to take into account censored data (Feigelson and Nelson, 1985). The derived mean value is $\log N_H$/cm$^{-2} = 21.80 \pm 0.13$. The distribution shows that the red sources are almost equally divided between obscured ($N_H > 10^{22}$cm$^{-2}$) and unobscured AGNs. The limit of $N_H = 10^{22}$cm$^{-2}$ is often used in X-rays because lower column densities can be produced by dust lanes in the galaxy instead of the torus (Malkan et al., 1998). However, we note that Merloni
et al. (2014) propose an alternative dividing line of $3 \cdot 10^{21} \text{cm}^{-2}$ in the sense that this provides a much better agreement when compared with the optical classification between type 1 and type 2 AGNs. From Figures 5.3 and 5.4 it appears that the red r-W2 colour alone cannot guarantee that the source will be classified as obscured in X-rays.

### 5.1.2 SED fitting

The extinction of a source is derived from the viewing angle, $\Psi$, of the torus: $\Psi \leq 30^\circ$ for type 2 (edge-on), $40^\circ \leq \Psi \leq 60^\circ$ for intermediate, and $\Psi \geq 70^\circ$ for Type 1 AGNs (face-on; Ciesla et al., 2015), respectively. No intermediate values are used. The results from these fits appear in Table 5.5 and the SEDs are shown in Figures A.1- A.47 (for more details on the SED fitting, see also Masoura et al., 2018).

As mentioned in the previous section, Herschel photometry is available for nine of the sources in our sample. We fit the SEDs of these sources with and without FIR data to check whether the lack of FIR photometric bands affects the SED fitting measurements. Specifically, we are interested in the inclination angle $\Psi$, since this parameter is used as a proxy to determine the obscuration of an AGN. We find that the inclusion of FIR photometry in the SED fitting does not change the AGN emission or the estimated inclination angle of the sources. Based on these results and the fact that X-ray sources observed by Herschel have similar properties ($L_x$ and $z$) with sources without Herschel detection, we conclude that SFR estimates of the non-Herschel sources of our sample, are reliable.

### 5.1.3 Optical spectra

The optical spectra for 33 out of 47 sources are presented in Figures A.1- A.47. Optically-unobscured sources are considered to be those with broad emission lines (BL), whereas obscured sources exhibit only narrow emission lines (NL) or a red continuum. The AGNs are characterised as obscured, unobscured, or intermediate (IMD) type, based on visual inspection of their optical spectra. Table 5.4 contains the classification according to the optical spectrum for each object.

To verify the redshift of our sources and assess their obscuration in the optical band we used the optical spectra provided by the SDSS. We recomputed the spectroscopic redshift and for a small number of cases we provide in Table 5.1 a different measurement from the one in SDSS.
Figure 5.2: $N_H$ distribution taking into account $N_H$ upper limits; see text for more details.

Figure 5.3: i-band distribution of our sample. Red sources occupy the faint part of the i-band distribution.
Table 5.5: Comparison of the X-ray, SED, and optical properties. Sources classified as X-ray obscured based on our strict criteria (see text for more details) are presented in bold. Sources that satisfy the loosened X-ray criteria (see text) are shown in italics. Numbers 1 (unobscured) and 2 (obscured) are used to denote the classification of the sources based on the various criteria. Numbers 0 and 3 refer to optical spectra that are too noisy to allow us to classify them and are IMD type, respectively. The first number refers to the X-ray classification, while the second and the third numbers correspond to the SED- and optical-based characterisation.
5.2 Results

Our IR selection criteria, Assef et al. (2018), identify 4798 AGN candidates (Table 2.3). Of these, 2652 have been observed by SDSS. Approximately 20% of these sources are optically red using the criteria of Yan et al. (2013), see Table 2.3. Figures 5.3 and 5.4 show the i-band and the $r-W_2$ distributions of the various samples. As expected, red sources occupy the faint part of the i-band distribution while the AGN sample with available X-ray spectra lacks sources with the highest $r-W_2$ values.

In our analysis, we explore the X-ray spectral properties of the 47 optically red AGNs and examine whether these sources are also X-ray absorbed. Furthermore, we search for indications of extinction either on their SEDs or in their optical spectra. The results of the X-ray spectral fitting are presented in Table 5.2. For those cases where the photon index ($\Gamma$) is unphysically low ($\Gamma < 1.2$) we quote the $N_H$ estimations with $\Gamma$ fixed to $\Gamma = 1.8$ (Nandra and Pounds, 1994). The latter $N_H$ estimation is used to characterise the X-ray absorption of the source. Our analysis reveals 18 sources with best-fit intrinsic column densities $N_H > 10^{22} \text{cm}^{-2}$. We also consider as possibly absorbed a source whose upper limit lies above the arbitrary chosen...
The vast majority of our optically red AGNs have SEDs that show clear signs of obscuration in their AGN emission (green lines in Figures A.1-50). However, the AGN emission of the source J022809.0-041235 (no. 4 in Table 5.3) extends to the optical part of the spectrum without presenting signs of even mild obscuration. This source has also large $\Psi$ ($\Psi = 80^\circ$) that also indicates a type 1 AGN (X-ray and optical spectra also confirm this is an unobscured AGN). There are two more sources with a large $\Psi$ value (i.e. observed face-on), namely sources J020517.3-051024 and J021808.8-055630 (no. 11 and 28 in Table 5.3). Their SEDs reveal that even though the AGN emission extends to the optical part of the SED, the emission of the galaxy is a dominant component of the SED at the optical wavelengths. We refer to the latter two systems as galaxy dominated. We attribute this term to sources that satisfy the following criteria: (i) the IR (W2) emission of the system is due to the AGN emission, and (ii) there is a strong galaxy emission in the optical part of the SED even though the AGN emission is only mildly obscured (or not obscured at all). Specifically, the ratio of the galaxy emission to the AGN emission in the r band is $\geq 1$. Although source no. 28 is not X-ray absorbed, source no. 11 presents signs of mild X-ray absorption ($N_H = 0.78^{+1.10}_{-0.70} \cdot 10^{22} \text{ cm}^{-2}$). The optical spectra of these two systems have broad emission lines, corroborating the assertion that these are unobscured sources. We conclude that the SEDs for 44 out of the 47 sources in our sample present clear signs of obscuration based on their AGN emission and their $\Psi$ values ($\Psi \leq 30^\circ$).

In addition to these two AGNs (i.e. sources 11 and 28 in Table 5.3), there are eight more sources that satisfy our aforementioned criteria and are therefore considered galaxy-dominated systems (nos. 5, 7, 10, 26, 35, 39, 44, and 47). In these systems, the galaxy and/or AGN emission in the r band, ranges from $\approx 1$ (e.g. no. 28) to $\geq 10$ (e.g. nos. 10, 39, and 47). Five of these sources are among the AGNs that are also X-ray absorbed (nos. 10, 26, 35, 39, and 47).
5.2. Results

in Table 5.5). Their AGN fraction, $\text{frac}_{\text{AGN}} = 40 - 80\%$ (Table 5.3). These suggest that these systems are galaxy dominated because the AGN is obscured and not because the active SMBH is intrinsically weak. However, for the remaining three galaxy-dominated systems (nos. 5, 7, and 44) that are not X-ray absorbed, it could be that they are characterised as optically red ($r$-$\text{W2} > 6$) due to an intrinsically weak AGN ($\text{frac}_{\text{AGN}} = 20 - 30\%$, Table 5.3) rather than an obscured AGN. Galaxy-dominated systems are known to confuse optical and MIR criteria (Koutoulidis et al., 2018), as expected and in extremely obscured systems would not be accessible to such criteria.

Excluding the ten galaxy-dominated systems from our sample of red IR AGNs reduces the total number of red sources to 37. Of these, 17 (46% of the total sample) and 28 (76% of the total sample) are X-ray absorbed using the strict and loose criteria, respectively. Therefore, there are nine ($\sim 20\%$) IR red AGNs in our sample that present no signs of X-ray absorption. We must note here that the realistic (Jeans Instability fragmented) tori around AGN can present such contradictory behaviours. The applied obscuration criterion (Yan et al.) is an emission based selection criterion, on the other hand the $N_H$ based criterion is an absorption one (Ogawa et al., 2021). The optical spectra for two of these sources present narrow emission lines (nos. 16 and 20 in Table 5.5), four present broad emission lines (nos. 1, 3, 9, and 25 in Table 5.5) and two are of intermediate type (nos. 17 and 18 in Table 5.5) based on our visual inspection. The optical spectrum of source no. 23 is too noisy to extract any information. Previous studies have found that selection of obscured AGNs based on optical and/or MIR colours are 80% reliable (Hickox et al., 2007). This could explain why at least some of these nine AGNs, although optically red, present broad emission lines in their spectra and no substantial X-ray absorption.

Recently, Jaffarian and Gaskell (2020) studied the optical E(B-V) reddening versus the X-ray absorbing column density for a large sample of Seyfert galaxies with both E(B-V) and X-ray absorption column density measurements. These latter authors find a significant correlation between E(B-V) and $N_H$, albeit with a large scatter of ±dex, which they claim could be attributed to X-ray column density variability. Regardless of the origin of the physical interpretation, the presence of such a large scatter can readily explain why some of our red sources show no sign of significant absorption in X-rays. The fact that the average absorbing column density derived for the red $r$-$\text{W2} > 6$ sources is only $N_H = 21.8 \pm 0.13$ suggests that the above obscuration criterion selects sources with lower absorption compared to those selected in X-rays using $N_H > 10^{22}\text{cm}^{-2}$ (e.g. Akylas et al., 2006; Ueda et al., 2014). In other words, the optically
red source selection does not correspond to the same level of obscuring column densities as those seen for X-ray wavelengths. Hickox et al. (2017) proposed an additional criterion for the selection of obscured AGNs based on the combination of the $u$ and WISE W3 band. Since there is not a unique definition of how obscured an AGN must be to be classified as absorbed, the various selection criteria target different ranges of obscuration. Specifically, the application of the ‘usual’ X-ray criterion $N_H > 10^{22}\text{cm}^{-2}$ selects the most obscured part of the obscured AGN distribution, while the r-W2 criterion extends to lower levels of obscuration. Finally, the Hickox et al. $u$-W3 criterion is sensitive to the lowest levels of obscuration. This is due to the use of the $u$ band that is easily affected by even small amounts of reddening. The different selection criteria indeed result in different obscured AGN samples. This is most probably the reason why only 76% (at most) of the red AGN sample is absorbed in X-rays with column densities $\log N_H/\text{cm}^{-2} > 21.5$. 

Chapter 6

Conclusions & Future prospects

6.1 Main Conclusions

In this Chapter are discussed the main conclusions of this thesis. To have a clear view of our findings and the future prospects, the Chapter is divided into four sections. Accordingly to the three investigated open issues (see Chapter 1.8) and the future prospects.

AGN – host galaxy coevolution: In the first place we investigate the coevolution between AGN and host galaxy. Specifically, we combine data from, both, the X-ATLAS and XMM-XXL North fields, that cover more than \( \sim 30 \text{ deg}^2 \), composing the largest X-ray AGN sample in the literature to perform SED fitting analysis and study the effect of X-ray AGNs on the star formation rate of their host galaxies. This is done in a wide redshift and \( L_X \) range \( (0.03 < z < 3, \log L_X (2-10 \text{ keV}) = 41-45.5 \text{ erg s}^{-1}) \). The examined sample consists of 3,336 X-ray sources, 608 of which have available Herschel photometry and 1,872/3,336 have spectroscopic redshifts. We estimate star formation rates and stellar masses using the CIGALE code. We use far-IR photometry (Herschel) and derive a relation to calibrate the SFR estimates of those sources without Herschel observations (see 2.5.3). Prompted by the work of Mullaney et al. (2015) and Bernhard et al. (2018), we examine if there is a relation of the AGN power with the SFR of the host galaxy and its dependence on redshift, taking into account the position of the AGN relative to the star-forming main sequence (SFR\(_{\text{norm}}\)). The aforementioned studies find no evolution of SFR\(_{\text{norm}}\) with redshift (Mullaney et al., 2015) and a dependence of the SFR\(_{\text{norm}}\) with the X-ray luminosity, in the sense that the SFR\(_{\text{norm}}\) distribution of higher \( L_X \) AGNs is narrower and peaks at higher values compared to the SFR\(_{\text{norm}}\) distribution of lower \( L_X \) AGNs (Bernhard
et al., 2018). Our dataset probes a significantly larger redshift and luminosity range compared to these studies. Our analysis revealed a correlation between SFR$_{\text{norm}}$ and AGN power, at all redshifts spanned by our sample (Figure 3.6). We note, however, that this correlation does not necessarily imply that the two parameters are connected. For instance, a fuelling mechanism (e.g. mergers) could trigger both the SFR of the host galaxy and the SMBH at its centre. Furthermore, our results suggest evolution of the SFR$_{\text{norm}}$ for sources that lie at $z < 0.5$ compared to higher redshift AGNs ($z > 1.2$; Figure 4.9).

The relation between AGN type and host galaxy properties: The second open issue, discussed in this thesis, is the relation between AGN type and host galaxy properties. We use 3,213 AGNs from the XMM-XXL northern field to investigate this relation. About 60% of our sources have available spectroscopic redshift while for the remaining we use photometric redshifts estimated through a machine learning technique (TPZ). The host galaxy properties, SFR and stellar mass are estimated via the SED fitting code CIGALE. A statistical method, based on bayesian statistics (BEHR), is applied to derive the HRs for the examined sample. AGN with $N_{\text{H}} > 10^{21.5}\,\text{cm}^{-2}$ are considered as absorbed. First, we study whether there is a connection between AGN type and the properties of the host galaxy. We estimate the SFR and $M_*$ distributions of both X-ray absorbed and unabsorbed AGN. A KS-test reveals that the galaxy properties of the two AGN populations are similar. Next, we disentangle the effects of $M_*$ and redshift on SFR and examine the SFR$_{\text{norm}}$-$L_X$ relation, as a function of AGN type. Based on our findings, the SFR-$L_X$ relation is similar for absorbed and unabsorbed AGN, at all redshifts spanned by our sample. This behaviour indicates that the interplay between AGN and its host galaxy is independent of the obscuration level. Finally, we explore whether SFR varies as a function of the absorbing column density. Based on our results there is no relation between these two properties, suggesting that a) the two processes take place in different scales or b) even if absorption extents to galactic scales it does not relate with the SFR of the host galaxy. The latter, is unlikely given that SFR is expected to correlate strongly with the fuel (gas) present in the galaxy and therefore with the average column of gas and dust spanning the galaxy (Schmidt, 1959). Overall, our results suggest that there is no connection between X-ray absorption and the properties of the host galaxy nor the AGN-galaxy co-evolution. This, provides support to the unification model, i.e. X-ray absorption seems to be a torus inclination local effect and not a phase in the lifetime of the AGN. We note, however, that in our analysis we have adopted a rather low X-ray absorption limit. XMM-XXL is a shallow exposure field,
and thus there is only a small number of heavily absorbed sources ($N_H \sim 10^{23}\text{ cm}^{-2}$).

**X-ray properties of red AGNs:** Motivated by our findings in Chapter 4 and the contradictory results from previous studies (see 1.7.3), in the third part of this study, we explore the obscuration properties of red AGNs with both X-ray spectroscopy and SEDs. We apply the Assef et al. (2018) criteria based on the W1 and W2 WISE bands to select IR AGNs in the XXL-North 25 deg$^2$ survey area. The above criteria yield 4798 AGNs. Furthermore, we apply the optical MIR colour criterion $r - W2$ (Yan et al., 2013) in order to select obscured AGNs. We identify 561 red AGNs, of which 135 are detected in X-rays while 47 have good photon statistics (at least 50 net counts per detector), and derive a reliable estimate of the absorbing column density. We used XSPEC to fit the X-ray spectra of the 47 sources and quantify their X-ray absorption. Of these 47 sources, 76% may show signs of absorption higher than log$N_H$/cm$^{-2} = 21.5$. Additionally, we applied the CIGALE code in order to study the SEDs of our 47 red sources. The SED analysis revealed that 10/47 sources are galaxy-dominated systems as the red colours are attributed to the host galaxy rather than absorption. In the vast majority of the remaining 37 sources, the SEDs confirm the presence of significant obscuration. The exact nature of the red sources that show low levels of X-ray absorption (25%) in apparent contradiction with their SEDs is unclear. The large scatter in the $r - W2$ colour versus column density, possibly caused by variation of the column density, is likely to offer an explanation. Our findings shows that the $r - W2$ selection provides a robust method for selecting obscured AGNs. However, it may also identify sources that present lower levels of obscuration when compared with the widely used X-ray spectroscopic criteria which usually define obscured sources as those with log$N_H$/cm$^{-2} > 21.5$.

Finally, we must note that realistic tori (i.e. Jeans-unstable and fragmented) will naturally yield a non-trivial percentage of red AGN (under the $r - W2$ criterion) but which are also X-ray unabsorbed. This is simply because the emission from a dusty optically thin (or nearly so) torus will be there to have it selected as red, irrespective of its inclination angle, while a dust-clear single line of sight between AGN-observer, which can happen through a dusty but fragmented torus, will make that AGN appear as an X-ray-unabsorbed system. This clearly shows the need for realistic tori models to be used from now on in the study of such AGN samples.
6.2 Future prospects

Host galaxy properties as a function of AGN type, using different obscuration criteria: This work has studied the host galaxy properties of different AGN types, classifying sources using (mostly) X-ray criteria. Although, there are studies that found a correlation between X-ray absorption and optical/IR obscuration (e.g. Civano et al., 2012), these correlation presents a large scatter (e.g. Jaffarian and Gaskell, 2020). This scatter could be due to e.g. i) absorbing material located at galactic scales (e.g. Malizia et al., 2020), ii) X-ray column density variability (e.g. Yang et al., 2016), iii) dust-to-gas ratio that is different from the Galactic and iv) the fact that different obscuration criteria are sensitive to different amounts of obscuration (e.g. Masoura et al., 2020), among others. Thus, the analysis presented in the previous Chapters could be used to study whether the properties of host galaxies differ for AGN classified into type 1 and type 2 using their optical spectra. Furthermore, a detailed SED fitting analysis could be applied to help us investigate the possible reason for the different classifications between optical spectra and optical/mid-IR colour criteria.

Extend the range to lower luminosities/higher X-ray absorption: In this thesis, we used data from XMM – Newton-XXL and XMM-ATLAS fields. These are wide fields that provided large datasets and allowed us to improve the statistics of our analysis. However, they lack faint objects. On the other hand, deep surveys provide us information for fainter objects (e.g. Comastri et al., 2011; Ranalli et al., 2013). In the context of this research, “faint objects”, refer to either intrinsically weak or obscured AGNs. Since the vast majority of our data come from the XMM-XXL North field, there is only a small number of heavily absorbed sources ($N_H \sim 10^{23} \text{cm}^{-2}$). Future surveys that will provide larger datasets of obscured AGN and/or with higher column densities (eROSITA, ATHENA) will allow us to study whether this picture holds also for the most heavily absorbed AGN.

More realistic torus models, inclusion of polar dust and addition of X-ray flux: In our analysis, we used the SED fitting code CIGALE (i.e. CIGALE code version 0.12; 2018.0 Noll et al., 2009; Boquien et al., 2019), to calculate the properties of AGN host galaxies. A new branch of this code was recently published, named X-CIGALE (Yang et al., 2020) that implements some important new features. X-CIGALE allows the inclusion of X-ray flux in the SED fitting process. Addition of X-ray flux improves the estimation of important SED
fitting parameters (e.g. AGN fraction, classification Mountrichas et al., 2020). X-CIGALE also quantifies the dust extinction found in all AGN (polar dust). Finally, the new code includes an addition AGN module, called SKIRTOR that is based on the clumpy torus model of Stalevski et al. (2012, 2016). The toroidal structure surrounding the accretion disk of the AGN, in the previous version (the one used in this work), is considered to be “smooth” (Fritz et al., 2006). In this case, the viewing angle is the only obscuration criterion. Nevertheless, if we consider a different torus model, such as a clumpy structure, then both AGN types can be observed at any viewing angle. On thermodynamical grounds, models including smooth tori around AGNs, are not realistic. Jeans-instability acting on the strongly cooling ISM, would fragment such structures towards ever smaller ISM clumps, which would continue on to star-form, even in the vicinity of luminous AGN Wada et al. (2009). Thus, applying SED fitting through the updated version of CIGALE will improve our measurements, in the sense that our calculations will be the result a more realistic modelling.

**ALMA data:** Correlate X-ray absorption criteria with high resolution ALMA imaging (0.1 arcsec) data, that measure AGN obscuring dust columns and the corresponding H$_2$, more directly.

**Local X-ray AGN:** In chapter 4 is investigated the relation of the AGN type on the host galaxy, using a sample of X-ray selected AGNs at high redshifts. However, the dataset lacks sources in the local Universe ($z < 0.1$). Using local X-ray AGN would allow us explore whether our results and conclusions are also valid at low redshifts. A sample that would meet this criterion could consist of AGNs from the C-GOALS dataset. The latter sample is the *Chandra* component of the GOALS dataset and is divided into two subsamples, C-GOALS I (Iwasawa et al., 2011) and C-GOALS II (Iwasawa et al., 2011). This project will shed light in the open issue of AGN obscuration - host galaxy, in the local Universe.
Appendix A

X-ray, optical spectra, and SEDs

In this section, we present the X-ray, SEDs, and the optical spectra (when available) for each one of the 47 optically red sources in our sample. Numbers 1 and 2 are used to denote the classification of the sources based on the various criteria. Specifically, 1 refers to unobscured and 2 to obscured sources. Number 0 is used in those cases where the optical spectrum is too noisy to extract any useful information. Number 3 is used to denote IMD type of classification. The numbers in parentheses refer to the classification based on the X-ray spectrum, the SED, and the optical spectrum, respectively. We use three decimal points for spectroscopic redshifts and two decimal points for photometric redshifts.

Figure A.1: J021835.7-053758 (1,2,1), z=0.387
Figure A.2: J022848.4-044426 (2,2,1), $z=1.046$

Figure A.3: J022928.4-051124 (2,2,1), $z=0.307$

Figure A.4: J022809.0-041235 (1,1,1), $z=0.879$

Figure A.5: J020654.9-064552 (1,2,2), $z=1.412$
Figure A.6: J020410.4-063924 (2,2,2), z=0.414

Figure A.7: J023315.5-054747 (1,2,2), z=0.598

Figure A.8: J021337.9-042814 (2,2,1), z=0.419

Figure A.9: J020436.4-042833 (1,2,1), z=0.827
Figure A.10: J020543.0-051656 (2,2,1), z=0.653

Figure A.11: J020517.3-051024 (2,0,1), z=0.792

Figure A.12: J022244.3-030525 (2,2,2), z=0.637

Figure A.13: J022323.4-031157 (2,2,3), z=0.691
Figure A.14: J022209.6-025023 (2,2,2), z=0.400

Figure A.15: J022750.7-052232 (2,2,3), z=0.804

Figure A.16: J022758.4-053306 (1,2,2), z=0.956

Figure A.17: J022453.2-054050 (2,2,3), z=0.488
Chapter A. X-ray, optical spectra, and SEDs

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