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Mid-infrared Luminous Quasars in the GOODS–Herschel Fields: A Large Population of Heavily Obscured, Compton-Thick Quasars at $z \approx 2$

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Mid-infrared luminous quasars in the GOODS–Herschel fields: a large population of heavily obscured, Compton-thick quasars at $z \approx 2$

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ABSTRACT

We present the infrared (IR) and X-ray properties of a sample of 33 mid-IR luminous quasars ($\nu L_{6\mu m} \geq 6 \times 10^{44}$ erg s$^{-1}$) at redshift $z \approx 1$–3, identified through detailed spectral energy distribution analyses of distant star-forming galaxies, using the deepest IR data from Spitzer and Herschel in the GOODS–Herschel fields. The aim is to constrain the fraction of obscured, and Compton-thick (CT, $N_{HI} > 1.5 \times 10^{24}$ cm$^{-2}$) quasars at the peak era of nuclear and star formation activities. Despite being very bright in the mid-IR band, $\approx 30$ per cent of these quasars are not detected in the extremely deep 2 and 4 Ms Chandra X-ray data available in these fields. X-ray spectral analysis of the detected sources reveals that the majority ($\approx 67$ per cent) are obscured by column densities $N_{HI} > 10^{22}$ cm$^{-2}$; this fraction reaches $\approx 80$ per cent when including the X-ray-undetected sources (9 out of 33), which are likely to be the most heavily obscured, CT quasars. We constrain the fraction of CT quasars in our sample to be $\approx 24$–48 per cent, and their space density to be $\Phi_1 = (6.7 \pm 2.2) \times 10^{-6}$ Mpc$^{-3}$. From the investigation of the quasar host galaxies in terms of star formation rates (SFRs) and morphological distortions, as a sign of galaxy mergers/interactions, we do not find any direct relation between SFRs and quasar luminosity or X-ray obscuration. On the other hand, there is tentative evidence that the most heavily obscured quasars have, on average, more disturbed morphologies than the unobscured/moderately obscured quasar hosts, which preferentially live in undisturbed systems. However, the fraction of quasars with disturbed morphology amongst the whole sample is $\approx 40$ per cent, suggesting that galaxy mergers are not the main fuelling mechanism of quasars at $z \approx 2$.

Key words: galaxies: active – quasars: general – galaxies: star formation – infrared: galaxies – X-rays: galaxies.

1 INTRODUCTION

Since the discovery that most, if not all, galaxy spheroids in the local Universe host a supermassive black hole (SMBH) whose mass
scales with that of the host-galaxy bulge (e.g. Magorrian et al. 1998; Ferrarese & Merritt 2000; Marconi & Hunt 2003) it has been clear that there is likely to be a tight connection between the evolution of SMBHs and galaxies. Studies of the galaxy population across cosmic time have shown that galaxies were more actively growing in the past, as the star formation rate (SFR) density peaks at redshift $z \approx 2$ and rapidly declines to the present day (e.g. Madau et al. 1996; Hopkins et al. 2006). A similar evolution is seen in the moderate-to-high luminosity active galactic nucleus (AGN) population, where most of the SMBHs accrete more rapidly at high redshift ($z \gtrsim 1$–2), becoming more quiescent at $z = 0$ (e.g. Brandt & Alexander 2015, and references therein). Whether this parallel evolution between galaxies and SMBHs is simply due to a larger gas supply to feed both black hole accretion and star formation (SF) at high redshift, or whether there are other processes that self-regulate the SMBH and galaxy growth is still uncertain (e.g. Alexander & Hickox 2012; Kormendy & Ho 2013). A complete census of AGN is crucial to fully understand the accretion history of the SMBHs and their role in galaxy evolution. However, as the Universe at high redshift is more gas and dust rich, most of the accretion on to SMBHs is expected to be heavily obscured, which makes the identification and study of a large fraction of the AGN population very challenging.

X-ray observations provide arguably the most efficient way to trace the growth of SMBHs, as the high-energy radiation can penetrate large amounts of gas and dust without significant absorption. Moreover, the contamination from galaxy emission at X-ray energies is small as galaxies are typically much fainter than AGN in this band. However, when the column density of the obscuring material becomes Compton thick (CT; $N_H > 1.5 \times 10^{23} \text{cm}^{-2}$) even the deepest X-ray surveys often fail to detect the population of the most obscured, CT AGN (e.g. Xue et al. 2012; see Brandt & Alexander 2015 for a review). A significant fraction of such AGN is predicted by all models of the cosmic X-ray background (CXB) to reproduce the observed background spectrum at high energies ($E \approx 30 \text{keV}$; e.g. Comastri et al. 1995; Gilli, Comastri & Hasinger 2007; Treister, Urry & Virani 2009), however, the actual contribution from CT AGN is not well constrained and varies between the models, due to different assumptions, and the space density of CT AGN is still uncertain.

Since most of the absorbed AGN emission is re-emitted in the mid-infrared band (MIR; $\lambda \approx 3$–40 $\mu$m) by the circumnuclear dust heated by the central SMBH, observations in this band can potentially identify the elusive CT AGN missed by X-ray surveys (e.g. Lacy et al. 2004; Stern et al. 2005; Alexander et al. 2008; Donley et al. 2008, 2012; Fiore et al. 2008; Georgantopoulos et al. 2011a; Mateos et al. 2013). Moreover, since the infrared (IR) band is much less affected by extinction than the UV, optical and soft X-ray bands, the selection of AGN in the IR band is almost unbiased against obscured AGN. The downside of using the IR band to study AGN is that it is strongly contaminated by the SF component. Using the Spitzer MIR colour–colour sample selection, which are generally used to identify AGN within the star-forming galaxy (SFG) population (e.g. Lacy et al. 2004; Stern et al. 2005; Donley et al. 2012; Mateos et al. 2013).

In this paper, we investigate a sample of MIR luminous quasars (hereafter, ‘IR quasars’) at redshift $z \approx 1$–3, i.e. at the peak era of AGN and SF activity. We used the deepest available Spitzer and Herschel data in the GOODS–Herschel North and South fields (hereafter, GH-N and GH-S, respectively; Elbaz et al. 2011) to reliably identify AGN in the MIR band through detailed spectral energy distribution (SED) analyses, which allow us to disentangle the AGN and SF emissions at MIR and FIR wavelengths. The SED analysis is a much more powerful tool than the simple IR colour–colour techniques for identifying AGN, as it can recover the hot dust emission from the AGN even when it does not strongly dominate the SED (e.g. Del Moro et al. 2013; Rovilos et al. 2014); however even the SED analyses have limitations and become incomplete when the AGN component is faint compared to the SF component. Using the deepest Chandra X-ray data available across the sky (2 Ms in CDF-N; Alexander et al. 2003; and 4 Ms in CDF-S; Xue et al. 2011), we investigate the X-ray spectra of the IR quasars to constrain the fraction of obscured and CT sources. We also investigate the properties of their host galaxies to place them in the context of potential SMBH-galaxy evolution scenarios. The paper is organized as follows: in Section 2 the data used in our analyses are described, while Section 3 details the SED analysis method and the selection of our IR quasar sample. Section 4 presents the X-ray spectral analysis and results for our quasars, as well as the properties of their host galaxies assessed by the SFRs derived from our SED analyses, and their morphologies, obtained from visual classification of HST–WFC3 K-band images. In Section 5, the results obtained from our analyses are discussed in the wider context of the CXB models and the SMBH-galaxy evolutionary scenario. A summary and final remarks are given in Section 6. Throughout the paper we assume a cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\Lambda} = 0.73$ (Spergel et al. 2003). All the errors are quoted at a 90 per cent confidence level, unless otherwise stated.

## 2 DATA

### 2.1 IR observations

The GOODS fields have been observed in the IR band by the Spitzer and Herschel space observatories, and include the deepest IR data currently available. The Spitzer observations (Giavalisco et al. 2004) cover the MIR band at 3.6, 4.5, 5.8 and 8.0 $\mu$m with IRAC (Fazio et al. 2004) and at 24 $\mu$m with MIPS (Rieke et al. 2004) as part of the GOODS Legacy programme (PI: M. Dickinson). The 24 $\mu$m source catalogue was created using a point spread function (PSF) fitting technique at the 3.6 $\mu$m source positions as priors ($> 5\sigma$ detections). For details of the observations and catalogue, we refer to Magnelli et al. (2009, 2011). In both fields, the 24 $\mu$m observations reach a point source sensitivity limit of $\approx 30 \mu Jy$ ($5\sigma$).

FIR observations of the GOODS fields were undertaken by Herschel as part of the GOODS–Herschel survey project (GH; Elbaz et al. 2011). The GH survey covers the full $\approx 10 \text{ arcmin} \times 16 \text{ arcmin}$ GOODS-N field with PACS (Poglitsch et al. 2008) at 100 and 160 $\mu$m and with SPIRE (Griffin et al. 2010) at 250, 350, 500 $\mu$m, for a total observing time of 124 h. In GOODS-S a smaller region of $\approx 10 \text{ arcmin} \times 10 \text{ arcmin}$ at the centre of the field was observed by PACS at 100 and 160 $\mu$m and the total exposure was 206.3 h (GH-S; Elbaz et al. 2011). We also used the SPIRE 250 $\mu$m data observed as part of the Herschel Multi-tiered Extragalactic Survey (Oliver et al. 2012) across the GH-S field, to better match the data available in GH-N. We note that since the SPIRE data suffer from significant flux blending issues, we limit our analyses to the 250 $\mu$m band in both the GH-N and GH-S fields, where these issues can still be corrected fairly well. The Spitzer-MIPS 24 $\mu$m source positions were used as priors to estimate the Herschel 100 $\mu$m, 160 $\mu$m and 250 $\mu$m fluxes through
PSF fitting (courtesy of E. Daddi). In the GH-N field 819 sources (≈42 per cent of the 24 µm priors) are detected in at least one of the Herschel bands down to 5σ (3σ) sensitivity limits of ≈1.7 (≈1.2) mJy, ≈4.5 (≈2.3) mJy and ≈6.5 (≈4.0) mJy, respectively. In the GH-S field there are 591 sources (≈34 per cent of the 24 µm priors) detected by Herschel (at 100, 160 or 250 µm); the faintest sources are detected down to 5σ (3σ) flux densities of 1.3 (0.7), 2.7 (1.7), 7.7 (5.0) mJy in the three bands, respectively; however, for general sources the flux densities and errors are higher, depending on the local source density and the de-blending uncertainties. In case of non-detection in any of the Herschel bands, appropriate flux density upper limits were calculated for each prior position.

In our analyses we initially considered all the 24 µm-detected sources within the GH fields, namely 1943 sources in GH-N and 1747 sources in GH-S (for a total of 3690 sources), with or without a Herschel detection. For the sample in GH-N ≈98 per cent of the sources have a redshift identification, of which ≈63 per cent are spectroscopic redshifts, while the remaining are photometric (see Del Moro et al. 2013, hereafter DM13, for a detailed description of the redshift compilation). In the GH-S field, a redshift identification is available for ≈86 per cent of the sources, of which ≈95 per cent are spectroscopic redshifts compiled from multiple catalogues available in the literature (Le Fèvre et al. 2004; Mignoli et al. 2005; Vanzella et al. 2008; Popesso et al. 2009; Balestra et al. 2010; Silverman et al. 2010; Xia et al. 2011) and 5 per cent are photometric redshifts.

### 2.2 X-ray observations

The X-ray counterparts for the 24 µm-detected sources in GH-N and GH-S were found by cross-matching the 24 µm positions with the X-ray source catalogues by Alexander et al. (2003) in the Chandra Deep Field North (CDF-N), constructed from the 2 Ms Chandra observations covering an area of ~448 arcmin² of the sky, and by Xue et al. (2011) in the Chandra Deep Field South (CDF-S), from the 4 Ms Chandra data over a region of 464.5 arcmin². The CDF-N catalogue contains 503 X-ray-detected sources, down to flux limits of $f_{0.5-2\,\text{keV}} \approx 2.5 \times 10^{-17} \text{erg cm}^{-2} \text{s}^{-1}$ and $f_{2-8\,\text{keV}} \approx 1.4 \times 10^{-16} \text{erg cm}^{-2} \text{s}^{-1}$. The CDF-S X-ray source catalogue contains 740 sources down to flux limits of $f_{0.5-2\,\text{keV}} \approx 9.1 \times 10^{-18} \text{erg cm}^{-2} \text{s}^{-1}$ and $f_{2-8\,\text{keV}} \approx 5.5 \times 10^{-17} \text{erg cm}^{-2} \text{s}^{-1}$. For details on the data reduction and the construction of the catalogues we refer to Alexander et al. (2003), Luo et al. (2008) and Xue et al. (2011).

For the X-ray-detected sources in our sample (see Section 3.2), X-ray spectra have been extracted and analysed. The data were processed using the Chandra Interactive Analysis of Observations (CIAO; version 4.3 and CALDB 4.4.1; Fruscione et al. 2006) tools and the ACIS Extract (AE) software package 2 (Broos et al. 2010, 2012). The Chandra spectra were produced using the AE software (version 2011-03-16), extracting source and background spectra in each individual observation, as well as the relative response matrices and ancillary files, and combining them using the ftools 3 addarf and addarf (Blackburn 1995).

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our SED-fitting approach did not provide a reliable measurement of the SF emission, we estimated an upper limit for $L_{\text{SF}}$ by increasing the normalization of the SFG templates until they reached any of the FIR upper limits, without exceeding any of the MIR data point measurements (including errors). An IR luminosity was calculated from each of the five templates and the highest value was then taken as the $L_{\text{SF}}$ upper limit.

3.2 IR quasar sample

From the results obtained from our SED decomposition, we selected a sample of luminous AGN with $vL_{6\,\mu m, \text{AGN}} \geq 6 \times 10^{44}$ erg s$^{-1}$ ($\geq 44.78$ in the logarithmic scale; Fig. 1), defined hereafter as our ‘IR quasar’ sample. Considering the intrinsic relation between the 6 $\mu$m luminosity and the X-ray luminosity observed for unobscured AGN (e.g. Lutz et al. 2004; Fiore et al. 2009; Gandhi et al. 2009; Mateos et al. 2015), our 6 $\mu$m luminosity cut corresponds to an intrinsic X-ray luminosity $L_{2-10\,\text{keV}} \approx 2.5 \times 10^{43}$ erg s$^{-1}$, i.e. clearly in the quasar regime even allowing for the $\pm0.4$ dex scatter in the relation. We also restricted our sample to the redshift range $z = 1–3$ as we aim to investigate the population of luminous quasars at the peak of activity at $z \approx 2$ (Madau et al. 1996; Hopkins et al. 2006; Ueda et al. 2014; Brandt & Alexander 2015). Our sample consists of 33 sources, 19 in the GH-N and 14 in the GH-S fields (see Table 1). The bolometric luminosities ($L_{\text{bol}}$) of these quasars, estimated as $L_{\text{bol}} \approx 2 \times L_{\text{AGN}}$ (assuming a bolometric correction of a factor of $\sim 8$ at 6 $\mu$m, from Richards et al. 2006, and considering the median ratio of $\sim0.3$ between $vL_{6\,\mu m, \text{AGN}}$ and $L_{\text{bol}}$ estimated for our quasars), span the range $\log L_{\text{bol}} = 45.4–46.5$ erg s$^{-1}$ (see Table 1). For all of these sources, we find that the AGN component largely dominates over the SF component at MIR wavelengths, with the AGN contributing $\geq 66$ per cent to the total emission at 6 $\mu$m ($f_{\text{AGN}} = 66–100$ per cent; where $f_{\text{AGN}}$ is defined as the fraction of AGN luminosity over the total at rest-frame 6 $\mu$m; see Table 1). The best-fitting SEDs are reported in Appendix A (Figs A1 and A2). We note that for 13 out of the 33 sources ($\sim40$ per cent) Spitzer-IRS low-resolution spectroscopy is available (e.g. $\lambda \approx 3–20$ $\mu$m; Pope et al. 2008a; Murphy et al. 2009; Kirkpatrick et al. 2012). Although we do not use these spectra to constrain the source SEDs, we find very good agreement between our SED best-fitting solutions and the Spitzer-IRS spectra, which are shown in Figs A1 and A2 (Appendix A), confirming the reliability of our SED-fitting approach.

To explore the completeness of the sample we can take into account that when the AGN is not dominant in the MIR band, i.e. its contribution to the total emission is $< 50$ per cent, our SED-fitting procedure might start failing in identifying the presence of an AGN. We therefore looked for all the sources identified as SFGs from our SED-fitting procedure (i.e. with no significant AGN component) with AGN luminosity upper limits above our IR quasar selection threshold of $\log vL_{6\,\mu m, \text{AGN}} \geq 44.78$ erg s$^{-1}$. There is only one SFG satisfying this condition, having $\log vL_{6\,\mu m, \text{AGN}} < 44.85$ erg s$^{-1}$. This source is classified as an AGN from its X-ray emission ($\log L_X \approx 43.2$ erg s$^{-1}$). Given its modest X-ray luminosity and since the $L_{6\,\mu m, \text{AGN}}$ upper limit is very close to our IR quasar luminosity threshold (only a factor of $\sim1.2$ higher), the AGN within this SFG might still not fulfil our selection criteria, i.e. its intrinsic power could be below our luminosity cut. For this reason we do not include this source in our sample, keeping in mind that our selection might not be 100 per cent complete in identifying IR quasars when the SF luminosity is very high.

We note, however, that our IR quasar selection through the SED analysis is more reliable than the typical MIR colour–colour
from the low-$\lambda$ Spitzer X-ray source. Careful inspection of the multiwavelength images has proved that although the MIR emission, contrary to any of the colour–colour selection techniques. Indeed, despite our sources being the most luminous quasars at MIR wavelengths within the GH fields, the Stern et al. (2005) AGN wedge would miss \approx 20 per cent of them, as well as the majority of the less luminous AGN that we identified from the X-ray band. Careful inspection of the multicolour images has proved that although the Spitzer-IRAC bands are dominated by the low-$\lambda$ galaxy emission, the emission at $\lambda \geq 8 \mu m$ is centred at the X-ray source position rather than the 3.6 $\mu m$ position of the low-$\lambda$ galaxy. We therefore expect the contamination from the low-$\lambda$ galaxy to be very small at the wavelengths used in our SED analyses of this IR quasar (see Section 3.1).
Table 2. X-ray spectral results for all of the X-ray-detected sources. (1) Source number as in Table 1; (2) XID as in Table 1; (3) net counts in the Chandra spectra in the observed 0.5–8.0 keV energy range; (4) photon index, which was left free to vary in our spectral fits (model 1); (5) intrinsic hydrogen column density in units of 10^{22} cm^{-2}; (6) photon index obtained from model 2; (7) hydrogen column density obtained from model 2, in units of 10^{22} cm^{-2}; (8) fraction of the intrinsic power-law emission that is scattered at soft energies (E < 2 keV); (9) logarithm of the rest-frame 2–10 keV luminosity, in units of erg s^{-1}; (10) logarithm of the intrinsic, i.e. corrected for absorption, 2–10 keV luminosity (rest frame), in units of erg s^{-1}.

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<th>N_{H_{mol}}</th>
<th>N_{H_{mol}}</th>
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<td>1.8</td>
<td>43.82</td>
<td>44.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>490S</td>
<td>82</td>
<td>&lt;0.8</td>
<td>1.8</td>
<td>44.03</td>
<td>44.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>518S</td>
<td>4961</td>
<td>&lt;0.8</td>
<td>1.8</td>
<td>44.26</td>
<td>44.26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GH-N and GH-S sources, respectively, using a photon index \( \Gamma = 1.8 \) and appropriate \( k \)-correction. This simple extrapolation was made to have a first idea of the discrepancy between the observed X-ray and the MIR emission of our quasars. We caution, however, that this X-ray luminosity calculation does not account for the possible contribution from SF to the observed X-ray flux (see Table 1 and Section 4.3). Accurate estimates of the observed and intrinsic 2–10 keV luminosity for the X-ray-detected sources, derived from spectral analyses, are obtained in Section 4.1 and reported in Table 2; we use these luminosities for further analyses throughout the paper.

4 ANALYSES AND RESULTS

In this section, we present the X-ray spectral analysis performed on all of the X-ray-detected IR quasars (24 sources) to constrain the absorbing column density \( (N_H) \) and therefore derive the intrinsic X-ray luminosity. We then estimate the obscured quasar \( (N_H > 10^{22} \text{ cm}^{-2}) \) and CT quasar \( (N_HI > 1.5 \times 10^{24} \text{ cm}^{-2}) \) fractions from the X-ray spectral fitting results and from a comparison between the observed (i.e. not corrected for absorption) 2–10 keV luminosity and the \( L_{AGN, \text{rest}} \) (rest-frame), used as a proxy of the intrinsic AGN power. We then investigate in detail the host galaxy properties through the SFRs estimated from the \( L_{SF} \) derived from the SED-fitting analysis, in relation to the AGN intrinsic luminosity and X-ray obscuration. We finally explore the impact of galaxy mergers/interactions in quasar hosts by visually classifying the host galaxy morphology disturbance of our IR quasars using high-resolution HST images.

4.1 X-ray spectroscopy

For all of the 24 IR quasars with an X-ray detection in the CDF-N and CDF-S catalogues (Alexander et al. 2003; Xue et al. 2011), we performed X-ray spectral analyses to investigate the high-energy properties of these sources. For the X-ray-undetected sources, we estimated 3\( \sigma \) flux upper limits through aperture photometry on the Chandra images, assuming a spectral slope of \( \Gamma = 1.4 \) for the count rate to flux conversion. The 2–10 keV luminosity upper limits derived from these fluxes are reported in Table 1.

The spectra were extracted using the AE software package (Broos et al. 2010, 2012) and grouped with a minimum of 20 counts per energy bin in order to adopt \( \chi^2 \)-fitting statistics. The spectra with limited counting statistics (<200 net counts at 0.5–8.0 keV) were binned with a minimum of one count per bin and the Cash statistic (Cash 1979) was adopted for the spectral analysis with XSPEC (v. 12.8.1g; Arnaud 1996).

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Figure 2. Photon index $\Gamma$ versus intrinsic hydrogen column density ($N_H$) for the X-ray-detected IR quasars in our sample, obtained using a simple absorbed power-law model (model 1); the sources XID 243N and XID 320S are not included in the plot because the $\Gamma$ and $N_H$ parameters could not be simultaneously constrained from the spectral fit due to the low numbers of counts ($<50$ cts; see Section 4.1). Sources in GH-N and GH-S are represented by circles and squares, respectively. Red filled symbols indicate sources with more than 200 net counts in the $E = 0.5$–8.0 keV spectra; open symbols are sources with $<200$ net counts (i.e. with poor counting statistics). The grey shaded region represents the intrinsic photon indices typically found for AGN ($\Gamma = 1.8 \pm 0.3$; e.g. Nandra & Pounds 1994; Mainieri et al. 2002; Mateos et al. 2005; Tozzi et al. 2006). The quasars with low numbers of counts have typically flat photon indices ($\Gamma \sim 1.5$), suggesting the presence of additional spectral components, such as soft scattered emission and/or reflection (Section 4.1.1).

4.1.1 Basic spectral model fitting

We initially used a simple absorbed power-law model to characterize the source spectra (model 1), in addition to Galactic absorption, which was fixed to the average values of $N_{H,Gal} = 10^{20}$ cm$^{-2}$ in GH-N and $N_{H,Gal} = 9.0 \times 10^{20}$ cm$^{-2}$ in GH-S (Dickey & Lockman 1990). We left the photon index $\Gamma$ and the intrinsic hydrogen column density ($N_H$) as free parameters. In Fig. 2, we show the $\Gamma$ versus $N_H$ obtained from these fits. For two quasars (XID 243N and XID 320S; see Table 1) with very low numbers of counts ($<50$ net counts, 0.5–8.0 keV), we only fit a simple power-law model with no intrinsic absorption as no useful constraints could be obtained simultaneously on $\Gamma$ and $N_H$ from model 1. These two sources are not plotted in Fig. 2. The results of the X-ray spectral analysis (including errors at 90 per cent confidence level) are reported in Table 2. We note that 14 of the 24 analysed sources ($\sim$58 per cent) have good counting statistics (net counts $>200$; see Table 2). For these sources we obtained good spectral constraints with our simple model, with spectral slopes consistent with the intrinsic values typically found for AGN ($\Gamma = 1.8 \pm 0.3$; e.g. Nandra & Pounds 1994; Mainieri et al. 2002; Mateos et al. 2005; Tozzi et al. 2006). The sources with lower counting statistics (net counts $<200$) have typically flatter spectral indices, ranging between $\Gamma \approx 0.3$–1.4, with large errors. This indicates that the spectra of these sources are harder, and likely more obscured than those measured for the sources with higher numbers of counts; however the poor counting statistics do not allow us to simultaneously place tight constraints on the spectral parameters, $\Gamma$ and $N_H$, as they are degenerate for low-count spectra (e.g. Mateos et al. 2008). The flat $\Gamma$ in these sources might also indicate that a simple absorbed power-law model does not properly characterize their X-ray emission and additional spectral components might be required (e.g. soft scattered component, or reflection).

For the sources with a flat photon index ($\Gamma < 1.5$), we therefore included an extra power-law component in the model to fit the emission at soft energies ($E \lesssim 1$ keV; hereafter model 2). There are several processes that can cause emission at soft X-ray energies, such as thermal emission from star-forming regions, radio jets, atomic processes in partially ionized gas, partial covering by a neutral absorber, or blurred ionized reflection from the inner parts of the accretion disc (e.g. Turner et al. 1997; Gierliński & Done 2004); however, given the limited numbers of counts available in our spectra it is not possible to fit more complex models. We therefore assume a power-law model as an approximation of the soft X-ray emission, with the photon index $\Gamma$ tied to that of the primary power law (e.g. Brightman et al. 2014; Buchner et al. 2014; Lanzuisi et al. 2015) to limit the number of free parameters in the model.$^6$ Fitting the spectra with model 2 constrained the power-law slopes to more typical values for AGN (see Table 2), although the uncertainties on the parameters are still large. Where reasonable constraints on $\Gamma$ could not be obtained, we fixed $\Gamma = 1.8$ to obtain better constraints on the column densities. The $N_H$ values resulting from the fitting of model 2 are typically higher than those obtained from model 1 and in some cases they are very high ($N_H > 8 \times 10^{23}$ cm$^{-2}$) and possibly consistent with CT absorption. In two cases (XID 435S and XID 490S; see Section 4.1.3), the column densities estimated by model 2 even exceed $N_H > 10^{25}$ cm$^{-2}$. Although these $N_H$ values are not reliable because the simple parametrization of the spectra with an absorbed power law is not suitable to constrain column densities of $N_H > 10^{23}$ cm$^{-2}$, they still indicate that these sources might indeed be heavily obscured, possibly CT. We investigate this hypothesis using more suitable models in Section 4.1.2. In model 2, we also estimated the fraction of intrinsic emission scattered at soft energies ($f_{scatter}$), calculated from the ratio between the normalizations of the scattered and intrinsic power-law components, which is on average only a few per cent, typically $\lesssim$5 per cent (e.g. Turner et al. 1997; Ueda et al. 2007). However, in some cases we find higher scattered fractions (see Table 2), which might be due to the contribution from SF emission to the soft energy spectrum ($E < 1$–2 keV).

We also tested model 2 for sources showing significant X-ray absorption ($N_{H,abs} > 10^{22}$ cm$^{-2}$) from the fitting of model 1, but with steeper spectral slopes ($\Gamma > 1.5$); the results are reported in Table 2 for all of the sources where the normalization of the soft scattered power law could be constrained. Although the column densities obtained from these fits are typically higher than those obtained from model 1, the scatter on the parameters ($\Gamma$ and $N_{H,abs}$) is larger and in all cases the results from the two models are consistent. We therefore use the best-fitting solutions from model 1 to estimate the luminosity for these sources.

From the best-fitting models (model 1 for the sources with $\Gamma_{model} > 1.5$, and model 2 for the remainders), we calculated the rest-frame 2–10 keV luminosity of the X-ray-detected IR quasars ($L_{2–10keV}$).
are reported in Table 3. To represent the soft X-ray emission we used self-consistently taking into account Compton scattering and iron appropriate models, such as: (i) PLCABS (Yaqoob 1997), which modelled the intrinsic emission of these sources using more reliably constrain such large column densities, as they do not account for the presence of a reflection component and an emission line at 6.4 keV (observed frame), typical of CT AGN spectra. Indeed, the spectral fit using the Torus model yields a column density lower limit which is well within the CT regime. Georgantopoulos et al. (2009) have also classified this source as a CT AGN. The strong emission line is consistent with the redshifted iron Kα line (E = 6.4 keV) with an equivalent width of EW = 1.2+1.1−1.0 keV; given the limited counting statistics of the spectrum the uncertainties on the line EW are large, but still consistent with CT absorption.

**Table 3. Spectral fits of the heavily obscured AGN**

<table>
<thead>
<tr>
<th>No</th>
<th>XID</th>
<th>PLCABS</th>
<th>Torus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$N_H$</td>
<td>$N_H$</td>
</tr>
<tr>
<td>3</td>
<td>171N</td>
<td>79.1</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>190N</td>
<td>45.0</td>
<td>1.8</td>
</tr>
<tr>
<td>11</td>
<td>307N</td>
<td>43.8</td>
<td>1.8</td>
</tr>
<tr>
<td>16</td>
<td>423N</td>
<td>42.7</td>
<td>1.8</td>
</tr>
<tr>
<td>20</td>
<td>149S</td>
<td>21.9</td>
<td>1.8</td>
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<tr>
<td>22</td>
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<td>1.8</td>
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<tr>
<td>23</td>
<td>320S</td>
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</tr>
<tr>
<td>30</td>
<td>490S</td>
<td>1013.4</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Notes: aTo fit the Torus model, we fixed the opening angle to $\theta_{inc} = 60^\circ$ and the inclination angle to $\theta = 80^\circ$ ; since these sources have typically poor count statistics and these parameters cannot be constrained from the spectra fits. Where sensible constraints could not be obtained simultaneously for the photon index $\Gamma$ and the column density $N_H$, we fixed $\Gamma = 1.8$. bThe column density $N_H$ is expressed in units of $10^{22} \text{ cm}^{-2}$. cFor this source, we did not include any soft power-law component as it is not needed in the fit. dThere is apparently unobscured spectrum (with low numbers of counts) and an X-ray luminosity that is significantly smaller compared to the intrinsic AGN luminosity measured in the MIR band. Assuming a

In general, there is good agreement between the results obtained from the PLCABS and the Torus models. Although the parameters are not tightly constrained, as the errors are relatively large, all the model solutions resulting from our analyses indicate that these quasars are, in fact, heavily obscured and in some cases, as for XID 320S, XID 435S and XID 490S, even CT. We note that three more sources, XIDs 171N, 307N and 423N are consistent with being CT quasars within the uncertainties on the $N_H$ parameter (Table 3).

### 4.1.3 Notes on some individual sources

Although most of the source spectra can be fitted with the simple models described in the previous sections, and sensible results are obtained for their spectral parameters (see Tables 2 and 3), some of the sources show some peculiar characteristics. Here, we describe in more detail the most interesting sources amongst our X-ray-detected IR quasar sample.

**XID 171N.** From the spectral fits using model 2 and PLCABS this $z = 1.995$ source shows a very high level of absorption $N_H \approx 8 \times 10^{23} \text{ cm}^{-2}$ ($\Gamma = 1.8$), although not at CT levels. However, the residuals in the hard band ($E \geq 3 \text{ keV, observed frame}$) suggest the presence of a reflection component and an emission line at $E = 2 \text{ keV (observed frame)}$, typical of CT AGN spectra. Indeed, the spectral fit using the Torus model yields a column density lower limit which is well within the CT regime. Georgantopoulos et al. (2009) have also classified this source as a CT AGN. The strong emission line is consistent with the redshifted iron Kα line ($E = 6.4 \text{ keV}$) with an equivalent width of $EW = 1.2+1.1−1.0$ keV; given the limited counting statistics of the spectrum the uncertainties on the line EW are large, but still consistent with CT absorption.

**XID 243N.** The spectrum of this $z = 2.004$ source has only 12 net counts (0.5–8 keV) therefore a more complex model than a simple power law cannot be fit to the data. The effective photon index measured from the spectrum is $\Gamma = 1.86^{+1.07}_{−0.69}$. Fitting the spectrum with an absorbed power law with $\Gamma = 1.8$ fixed to try to constrain the level of absorption results in an upper limit of $N_H < 8 \times 10^{23} \text{ cm}^{-2}$, which is consistent with the source being unabsorbed. However, the X-ray luminosity of XID 243N is very low compared to the $6 \mu \text{ m}$ luminosity measured from its IR SED (see Table 1) and the typical $L_X - L_{6\mu \text{ m}}$ relations (e.g. Lutz et al. 2004; Fiore et al. 2009; Mateos et al. 2015). The observed X-ray luminosity is consistent with a suppression of a factor of $\sim 300$ with respect to the intrinsic luminosity measured in the MIR (see Table 4), and still more than a factor of $\sim 120$ considering the intrinsic scatter of the $L_X - L_{6\mu \text{ m}}$ relation ($\sim 0.35$ dex; e.g. Mateos et al. 2015). This suggests that XID 243N might be a heavily CT quasar (see Section 4.2 and Fig. 3) and that the X-ray emission seen by Chandra is only the soft scattered component (typically a few per cent of the intrinsic nuclear emission; e.g. Turner et al. 1997; Ueda et al. 2007; Young et al. 2007, and references therein), or some emission due to SF in the host galaxy (see Table 1 and Section 4.3). Another possibility is that this source is intrinsically X-ray weak, as it has been found, for instance, for broad absorption line (BAL) quasars (see e.g. Luo et al. 2014). However, XID 243N has never been identified as a BAL quasar to date. Although the hypothesis of intrinsically weak X-ray emission cannot be ruled out for this quasar, we favour the heavy-obscuration interpretation (see Section 4.2).

**XID 287N.** Similar to XID 243N, this $z = 2.737$ quasar has an apparently unobscured spectrum (with low numbers of counts) and an X-ray luminosity that is significantly smaller compared to the intrinsic AGN luminosity measured in the MIR band. Assuming a
standard value for $L_X/L_{\alpha\text{Fe}}$ (e.g. Lutz et al. 2004; Fiore et al. 2009; Mateos et al. 2015), we estimate that the observed X-ray luminosity is consistent with being suppressed by a factor of ∼35 (see Table 4). This suppression is consistent with the effect of CT absorption, but it is less extreme than that observed for XID 243N. Moreover, no other diagnostics have been found to confirm the intrinsic AGN luminosity measured in the MIR band, therefore the possibility of intrinsic X-ray weakness cannot be ruled out.

**XID 307N.** In the lightly binned spectrum (1 count/bin) of this quasar, clear residuals around the observed ∼2 keV indicate the presence of a strong iron emission line, consistent with being Fe Kα at the source redshift of $z = 2.14$. We therefore added a Gaussian component to the fit, with $E = 6.4$ keV and line width fixed at $\sigma = 50$ eV, to measure the strength of the line. Since the redshift of this source is photometric, we initially left the redshift parameter in the model free to vary. From the X-ray spectral fit we obtained constraints on the redshift of $z = 2.18^{+0.08}_{-0.08}$, in good agreement with the photometric estimate reported in Table 1. Fixing $z = 2.18$ and fitting the spectrum, however, produces a very flat photon index of $\Gamma = 0.70^{+0.95}_{-0.62}$, and no constraints are found on the $N_{\text{H}}$ parameter. Fixing $\Gamma = 1.8$ yields a column density of $N_{\text{H}} = (4.8^{+2.1}_{-0.9}) \times 10^{23}$ cm$^{-2}$ with some residuals in the hard band ($E \gtrsim 2$ keV), suggesting a possible contribution from a reflection component in the spectrum. This hypothesis is supported by the high EW measured for the iron line, $EW = 1.2^{+1.0}_{-0.6}$ keV (rest frame), which is typical of CT AGN. Indeed, fitting the spectrum with the Torus model results in a column density lower limit of $N_{\text{H}} > 6 \times 10^{23}$ cm$^{-2}$ (see Table 3), i.e. in the CT regime. We tested this result also fitting the source spectrum with a pure reflection dominated model (i.e. PEXRAV model; Magdziarz & Zdziarski 1995) with the reflection parameter $R = -1$ fixed, plus a Gaussian line, implying column density in excess of $N_{\text{H}} > 10^{24}$ cm$^{-2}$. This model provides a similarly good fit to the data as the previous models, yielding a spectral index of $\Gamma = 2.07^{+0.31}_{-0.43}$. If XID 307N is really CT, its intrinsic luminosity would therefore be $L_X \sim 10^{26}$ erg s$^{-1}$. **XID 390N.** This z = 1.146 quasar has a relatively strong iron K line (EW = 0.38^{+0.16}_{-0.14}$ keV, rest frame, $\sigma = 50$ eV fixed), which could be broad, as leaving $\sigma$ free to vary in the fit, we obtain $\sigma < 556$ eV. Clear residuals suggest the presence of another emission line at $E \sim 5.9$ keV (rest frame) with $EW \sim 0.28$ keV, which could be a relativistically redshifted iron line from the inner parts of the SMBH accretion disc or an outflow (e.g. Fabian et al. 2000). Although very interesting, more investigation on the emission lines of this quasar is beyond the scope of this paper.

**XID 149S.** This $z = 2.810$ quasar has a column density $N_{\text{H}} \approx 2 \times 10^{23}$ cm$^{-2}$ and a photon index $\Gamma \approx 1.7$ with all the models used to fit the spectrum (i.e. model 1, PLECABS and Torus); none of the models required the addition of a soft scattered power law.
Although the X-ray spectrum does not show signs of any emission line, clear residuals around $E \approx 1.5$–2 keV ($E \approx 5.7$–7.6 keV, rest frame) indicate the presence of a strong absorption feature forming a P-Cygni type profile, which indicates the presence of a high-velocity outflow (e.g. Pounds & Reeves 2009; Tombesi et al. 2010). Indeed, this source has been identified in the optical band as a BAL quasar (Szkokely et al. 2004). A BAL quasar interpretation would help explaining why the intrinsic X-ray luminosity of this quasar, $L_{\text{2–10 keV, intr}} \approx 2 \times 10^{44}$ erg s$^{-1}$, which is corrected for the X-ray absorption derived from the spectral fitting, is lower than that expected from the MIR luminosity $\nu L_{\text{6 \mu m}} \approx 8 \times 10^{45}$ erg s$^{-1}$ (see Fig. 3), as BAL quasars have been found to be intrinsically X-ray weak (e.g. Luo et al. 2014).

**XID 435S.** Fitting this source spectrum with model 2 (see Section 4.1) results in a column density of $N_{\text{H}} \approx (1.1^{+1.2}_{-0.7}) \times 10^{25}$ cm$^{-2}$ (with $\Gamma = 1.89^{+0.7}_{-0.6}$), which is consistent with heavily CT material. Using the PLCABS and Torus models, we obtained smaller $N_{\text{H}}$ values of $N_{\text{H}} \approx (3-7) \times 10^{24}$ cm$^{-2}$ ($\Gamma \approx 1.9$), but still consistent with the source being CT (Table 3). However, the spectrum does not show a clear signature of a strong Fe Kα line. We note that, although these models are too complex for the limited counting statistics to provide tight constraints on the spectral parameters, the intrinsic 2–10 keV X-ray luminosity corrected for the CT column densities derived from the spectral fits is in good agreement with the expectations from the MIR 6 μm AGN luminosity, according to the $L_X-L_{\text{6 \mu m}}$ relation. XID 435S was also classified as a CT AGN also by Brightman & Ueda (2012).

**XID 490S.** This $z = 2.579$ quasar shows evidence for a strong emission line, consistent with the redshifted Fe Kα line at $E = 6.4$ keV, with an equivalent width of $EW > 1$ keV (although the limited counting statistics prevent us from obtaining better constraints on the EW). The spectral-fitting results from model 2 constrained the intrinsic column density largely in the CT regime (see Table 1). As in the previous case, fitting the spectrum with PLCABS or Torus models constrains the column density to lower values than that obtained from model 2 ($N_{\text{H}} \approx (4-10) \times 10^{24}$ cm$^{-2}$), but still consistent with heavily CT columns. Similar results were obtained by Feruglio et al. (2011) and Brightman & Ueda (2012), who identified this source as CT. As for XID 435S, the intrinsic X-ray luminosity estimated by correcting for the high $N_{\text{H}}$ obtained from the spectral fit would place this source on the $L_X-L_{\text{6 \mu m}}$ relation (see Fig. 3).

### 4.2 Obscured AGN fraction

From the X-ray spectral analysis of the X-ray-detected sources, we found that a large fraction of the IR quasars ($\approx 67$ per cent, 16 out of 24 sources) are absorbed in the X-ray band by column densities $N_{\text{H}} > 10^{22}$ cm$^{-2}$. Of these sources, nine can be classified as heavily obscured (reported in Table 3), with $N_{\text{H}} \geq 2 \times 10^{23}$ cm$^{-2}$, of which three (XIDs 320S, 435S and 490S) have CT column densities, in excess of $N_{\text{H}} \approx 1.5 \times 10^{23}$ cm$^{-2}$ in all the models we used (see Section 4.1); three more sources (XIDs 171N, 307N and 423N)

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Footnote:

8 The X-ray weakness of BAL quasars is typically estimated with respect to the optical band ($\alpha_{\text{OX}}$; e.g. Luo et al. 2014). However, since BAL quasars have SEDs consistent with those of typical quasars in the optical-to-IR bands (e.g. Gallagher et al. 2007), we expect to see X-ray weakness relative to the MIR emission too.
are consistent with being CT based on their \(N_\text{H}\), depending on the adopted model (see Tables 3 and 4), and on the detection of a strong iron K\(\alpha\) emission line (EW \(\geq 1\) keV) in the case of XID 171N and 307N. We therefore classify these six sources as CT quasars. Due to the limited numbers of counts in the spectra, however, the strong Fe K\(\alpha\) line expected in CT spectra cannot be detected for all of these CT quasars.

To assess whether our IR quasars are indeed heavily obscured, or CT, we compared the X-ray luminosity (2–10 keV, rest frame) with the AGN 6 \(\mu\)m luminosity measured from the best-fitting SEDs (see Section 3.1). Since the MIR band tends to be much less affected by obscuration than the X-ray band, the MIR luminosity is often used as a proxy for the intrinsic AGN luminosity (e.g. Lutz et al. 2004; Alexander et al. 2008; Gandhi et al. 2009; DM13). Indeed, while unobscured sources are expected to lie on the intrinsic \(L_X - L_{6\mu\text{m}}\) relation (e.g. Lutz et al. 2004; Fiore et al. 2009; Gandhi et al. 2009; Mateos et al. 2015; Stern 2015), heavily obscured and CT sources, where the X-ray luminosity is strongly suppressed, are expected to have weak observed X-ray emission compared to the MIR emission, and therefore lie well below the \(L_X - L_{6\mu\text{m}}\) relation. In Fig. 3, we show the rest frame \(L_{2–10\text{keV}}\) versus \(L_{6\mu\text{m},\text{AGN}}\) for our IR quasars; open symbols represent the observed X-ray luminosity, while the filled symbols represent the intrinsic X-ray luminosity \(L_{2–10\text{keV}}\), i.e. corrected for the \(N_\text{H}\) derived from the X-ray spectral fitting (see Table 2). The unobscured and moderately obscured sources (shown in green) tend to agree with the local intrinsic \(L_X - L_{6\mu\text{m}}\) relation, although possibly showing a flatter slope than that defined by Lutz et al. (2004), more in agreement with Fiore et al. (2009). All of the heavily obscured IR quasars lie well below the correlation, in the region of the plot expected for CT AGN. Correcting their observed X-ray luminosity for absorption brings these sources much closer to the intrinsic \(L_X - L_{6\mu\text{m}}\) relation, although they still lie systematically below. It is important to note that the \(N_\text{H}\) of heavily obscured sources, obtained from spectral analyses of \(E < 10\) keV data alone and with the simple parametrisation used here (i.e. models 1 and 2), could be underestimated, as shown in several X-ray studies of heavily obscured AGN performed using Chandra or XM–Newton data together with hard X-ray data (\(E > 10\) keV) from NuSTARD (e.g. Del Moro et al. 2014; Gandhi et al. 2014; Lansbury et al. 2014, 2015). For the three sources securely identified as CT quasars (XIDs 320S, 435S and 490S), the intrinsic X-ray luminosity results in very good agreement with that expected from the MIR luminosity; this is also true for XID 171N and 307N if we correct the X-ray luminosity for the \(N_\text{H}\) derived from the Torus model, which gives log \(L_{2–10\text{keV,}\text{int}}\approx 45.4\) erg s\(^{-1}\) and log \(L_{2–10\text{keV,}\text{int}}\approx 45.1\) erg s\(^{-1}\), respectively, and possibly for XID 423N considering the large scatter on the \(N_\text{H}\) value. This gives an extra indication that these sources are indeed CT.

We also note that all of the X-ray-undetected IR quasars (nine sources), for which we plot the X-ray luminosity upper limits, lie in the region of the \(L_X - L_{6\mu\text{m}}\) plane expected for CT sources, and therefore can be considered as CT candidates. Two of the X-ray-undetected quasars, #1 and #12, have been already investigated by Alexander et al. (2008) and were identified as CT on the basis of X-ray analyses and \(L_X - L_{6\mu\text{m}}\) analyses. For #12, the intrinsic X-ray luminosity has also been estimated from the optical emission lines (see Alexander et al. 2008) using the average line ratio from Netzer et al. (2006) and the relation between the [O \(\text{III}\)]\(\lambda 5007\) and X-ray fluxes from Mulchaey et al. (1994), yielding log \(L_{\text{X\[O\text{III}\]}}\approx 44.4\) erg s\(^{-1}\) (Table 4), in agreement with that estimated from the MIR emission. This suggests that this source is intrinsically luminous, further confirming the CT nature of this quasar. The evidence found for #12 also support our assumption that the X-ray-undetected IR quasars are CT candidates. We therefore infer that the fraction of X-ray obscured sources (\(N_\text{H}\geq 10^{22}\) cm\(^{-2}\)) in our sample is \(\approx 76\) per cent (25/33 quasars, including the X-ray-undetected quasars), with \(\approx 55\) per cent being heavily obscured quasars (18/33 with \(N_\text{H}\geq 2 \times 10^{23}\) cm\(^{-2}\)) and 15 out of 33 quasars (\(\approx 45\) per cent) are likely to be CT.

From the \(L_X/L_{6\mu\text{m}}\) comparison it also emerged that two sources having unabsorbed X-ray spectra (XID 243N and XID 287N; see Table 2) have much weaker X-ray luminosity than that expected from their MIR luminosity, although for XID 287N the \(L_X/L_{6\mu\text{m}}\) ratio is not as extreme as for XID 243N (see Fig. 3). XID 243N was classified as a candidate CT AGN also by Georgantopoulos et al. (2011b) on the basis of its \(L_X/L_{6\mu\text{m}}\) ratio, similarly to our analysis. The detection of a strong Ly \(\alpha\) emission line in the optical spectrum, which was attributed to AGN emission rather than SF by Adams et al. (2011), allowed us to estimate the expected intrinsic X-ray luminosity (as for source #12) log \(L_{\text{X\[Ly\alpha\]}}\approx 45.7\) erg s\(^{-1}\), calculated assuming the average AGN Ly \(\alpha\) to [O \(\text{III}\)]\(\lambda 5007\) line ratio from Netzer et al. (2006) and the [O \(\text{III}\)]\(\lambda 5007\) to X-ray flux ratio from Mulchaey et al. (1994). Although this luminosity is higher than that inferred from the MIR emission, possibly due to the uncertainties on the optical emission line ratios and perhaps to some contamination from SF emission to the Ly \(\alpha\) flux, it supports the idea of XID 243N being intrinsically X-ray luminous; we therefore consider this source as CT (Table 4). In this case, if we assume that the observed \(E < 8\) keV spectrum is only due to scattering (\(\sim 1–3\) per cent) of the intrinsically heavily obscured emission, we estimate the intrinsic X-ray luminosity to be log \(L_X\approx 43.6\) erg s\(^{-1}\). This is in good agreement with the intrinsic \(L_X - L_{6\mu\text{m}}\) relation, supporting our classification of this quasar as CT. For XID 287N no other diagnostic has been found to establish whether this source is intrinsically X-ray luminous (and therefore likely CT) or X-ray weak (e.g. Luo et al. 2014); we thus do not include this source amongst our CT quasar candidates.

In Table 4, we list all the CT quasars and CT quasar candidates identified in our analyses and the various indicators that point to a CT quasar classification, i.e. primarily the high column density (\(N_\text{H}\geq 1.5 \times 10^{23}\) cm\(^{-2}\)) and/or strong iron line (EW \(\geq 1\) keV) derived from the X-ray spectral analysis, the suppression of the observed X-ray luminosity (more than a factor of \(\sim 30\) for CT sources) compared to the intrinsic X-ray luminosity expected from the 6 \(\mu\)m emission (\(L_X\)), and other indicators found in the literature, such as the X-ray weakness compared to the intrinsic quasar luminosity derived from optical emission lines. The total fraction of CT quasars (and CT quasar candidates) in our sample is therefore \(\approx 24–48\) per cent (8–16 out of 33 quasars) and the total obscured quasar fraction is \(\approx 79\) per cent.

### 4.3 Star formation rates

Using the results from our SED-fitting analyses (Section 3.1) and the X-ray spectral analyses, we explore here the connection between the quasar properties, such as their luminosity and X-ray obscuration, and the host galaxy properties, defined in terms of the SFR. From the IR luminosity (8–1000 \(\mu\)m) of the SFG component, derived from the SED fitting (see Section 3.1), we calculated the SFR of the galaxies hosting our IR quasars. We assumed a Salpeter (1955) initial mass function and used the relation from Kennicutt (1998).

The range of SFRs estimated for our sources is large, SFR \(\approx 17–866\) M\(_{\odot}\)yr\(^{-1}\) (see Table 1). In Fig. 4, we show the SFR versus the X-ray column density \(N_\text{H}\) (left) and the AGN 6 \(\mu\)m luminosity (right) for
the IR quasars in our sample, separating the heavily obscured from the unobscured/moderately obscured quasars (magenta and green symbols, respectively; see Section 4.2). In Fig. 4 (left), we divide our sample in three redshift bins: \( z = 1.0 - 1.5 \), \( 1.5 - 2.5 \) and \( 2.5 - 3.0 \) (green circles, blue triangles and magenta upside-down triangles, respectively), and compare their SFRs with those of typical main sequence (MS) SFGs at redshift \( z \approx 1 - 3 \) (e.g. Elbaz et al. 2011; Mullaney et al. 2012). In the figure, we plot the X-ray-undetected sources, which are CT quasar candidates, with a column density lower limit fixed to \( \log N_{\text{H}} > 24.3 \text{ cm}^{-2} \). On average there is good agreement with the SFRs of our IR quasars and the MS in each redshift bin, however, at \( z = 1.5 - 2.5 \) there is a significant fraction of sources with SFRs more than a factor of 2 above the MS (6/18 sources in this redshift bin, i.e. \( \approx 33 \text{ per cent} \)), which could be classified as starburst galaxies; these sources also tend to have higher X-ray absorption (\( N_{\text{H}} > 2 \times 10^{22} \text{ cm}^{-2} \)). On the other hand at \( z = 2.5 - 3.0 \) only one (heavily obscured) quasar out of 13 has SFR typical of starburst galaxies at similar redshift, while a significant fraction of our IR quasars (5/13 sources, \( \approx 38 \text{ per cent} \)) have SFRs below the MS. This possibly suggests a bias in our sample, as we are likely to miss quasars with very high SFRs (see also Fig. 4, right, and Section 3.2). We caution, however, that given the small number of sources in each redshift bin, these results are only tentative.

Overall, we do not find any significant correlation with the intrinsic AGN luminosity, \( L_{\mu \text{m; AGN}} \), although the range in luminosity for our IR quasars is relatively narrow; this is in agreement with other studies by Harrison et al. (2012) and Stanley et al. (2015). Interestingly, on average we find that the most obscured quasars have higher SFRs than the unobscured quasars (see also Chen et al. 2015). However, as the number of sources in our sample is small, this difference is mainly driven by three heavily obscured sources with very high SFRs (\( \approx 700 - 900 \text{ M}_\odot \text{yr}^{-1} \), \( \sim 16 \text{ per cent} \) of the heavily obscured quasars) that are not representative of the average IR quasar host population, for which there seems to be no significant relation between SFR and X-ray obscuration (e.g. Lutz et al. 2010; Rosario et al. 2012; Rovilos et al. 2012).

From the measured SFRs, we calculate the expected X-ray emission at 2–10 keV (rest frame; \( L_{\text{X, SF}} \)) produced by SF using the Lehmer et al. (2010) relation between SFR and rest-frame 2–10 keV luminosity (equation 4 in their table 4). The values are reported in Table 1. We also estimate what fraction of the observed X-ray luminosity (at 2–10 keV, rest frame) could therefore be due to SF (see Table 1). For the majority of the sources (\( \approx 82 \text{ per cent} \)) the contribution from SF is negligible, of the order of \( < 10 \text{ per cent} \). However, for \( \approx 18 \text{ per cent} \) of the sources more than 10 per cent of the observed X-ray luminosity could be due to SF and for some of them (#1, 6, 9 and 28) this contribution can reach up to \( \approx 20 - 30 \text{ per cent} \). All of these quasars are candidates CT according to our analyses, of which 3 out of 4 are X-ray undetected. The relatively high contribution from SF to the 2–10 keV luminosity (or upper limit) supports the idea that in these quasars we do not detect the intrinsic AGN emission at X-ray energies, which is likely to be very heavily absorbed, as discussed in Section 4.1.3 for XID 243N (#6).

### 4.4 Host galaxy interactions

In order to test the major merger evolutionary scenario for quasars, which predicts that most of the accretion on to the SMBH happens in heavily obscured environments, due to large amounts of gas and dust driven to the centre of galaxies during the merger (e.g. Sanders et al. 1988; Di Matteo, Springel & Hernquist 2005; Hopkins et al. 2006, see also Alexander & Hickox 2012 for a review), we investigate here the connection between the X-ray obscuration and the host galaxy morphology of our IR quasars. In particular, we aim to explore whether the most obscured IR quasars are typically found in interacting/merging systems.

We used the high-resolution HST images to classify the galaxies in terms of disturbance or distortion of their morphology. The
we refer to Kartaltepe et al. (2012). According to the CANDELS
vision classification method and the reliability of the classification and classifiers
9 The CANDELS visual classification is an ongoing programme currently
including morphological and disturbance classifications for all the galaxies
with $H < 24.5$ mag in the GOODS-S and UDS fields, and will soon provide
classifications in all the remaining CANDELS fields. In their catalogue
every source is inspected by at least 5 classifiers who assigned a number to
each source as a measure of their disturbance and interaction/merger level
(or ‘interaction metric’, IM).

The unobscured/moderately obscured quasars reside preferentially
in disturbed systems, while the heavily obscured quasars are equally found
in disturbed and undisturbed systems.

In Fig. 6, we plot the fraction of IR quasar host galaxies be-
longing to each of the three disturbance groups described above
(disturbed, undisturbed and companion). We separated the unob-
scured/moderately obscured sources (green) and the heavily ob-
scured sources (magenta; see Section 4.2). The 1σ
errors in the
plot are calculated following Gehrels (1986). The total fraction of
IR quasars residing in disturbed galaxies is $\approx 60$ per cent, while
that of the sources in disturbed/interacting systems is $\approx 40$ per cent.
These fractions are in good agreement with those found by Ko-
cevski et al. (2012) for samples of AGN ($\approx 56$ per cent undis-
turbed and $\approx 44$ per cent disturbed) and non-AGN hosting galaxies
($\approx 52$ per cent undisturbed and $\approx 48$ per cent disturbed) at similar
redshifts to our sample. This is true also for the fraction of sources
showing a close companion ($\approx 12$ per cent). Separating the sources
between heavily obscured and unobscured/moderately obscured
quasars, we find suggestive evidence that the large majority of the
unobscured quasars reside in disturbed galaxies ($\approx 80$ per cent, as
opposed to $\approx 47$ per cent for the heavily obscured quasars), with only
$\approx 20$ per cent having visible signs of interactions; this fraction seems
to be higher ($\approx 53$ per cent) amongst the heavily obscured quasars.
Consistent results were found for a sample of X-ray-selected
heavily obscured AGN in the COSMOS field by Lanzuisi et al.
(2015). The drop in the number of disturbed galaxies amongst the

![Figure 5. HST F160W (H band) image cutouts (6 arcsec × 6 arcsec) for
three of our IR quasars showing examples of an ‘undisturbed’ galaxy (#14,
left), a ‘companion’ class (#5, centre) and a ‘disturbed’ galaxy (#24, right).
The source numbers are those reported in column (1) in Table 1.]

![Figure 6. Fraction of IR quasar hosts with various disturbance classes,
classified using HST images as described in Section 4.4. The fractions and 1σ
uncertainties for the unobscured/moderately obscured quasar hosts ($N_{H} < 2 \times 10^{21}$ cm$^{-2}$) are plotted as green triangles and for the heavily obscured
quasars ($N_{H} \geq 2 \times 10^{21}$ cm$^{-2}$) as magenta stars (see Section 4.2). The classes
are divided into: ‘undisturbed’, ‘companion’ (which is a sub-class of the
undisturbed galaxies) and ‘disturbed’. For comparison the fractions for $z \approx 2$ AGN and non-AGN samples from Kocevski et al. (2012) are also
shown (filled black triangles and grey squares, respectively). The disturbance
fractions for our IR quasars are in good agreement with Kocevski et al.
(2012). The unobscured/moderately obscured quasars reside preferentially
in disturbed systems, while the heavily obscured quasars are equally found
in disturbed and undisturbed systems.]

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unobscured/moderately obscured quasars might partly be due to the fact that the bright unobscured nucleus might impair the detection of faint signs of interactions, such as tidal features; we note that particular care has been applied to the classification of these sources to minimize this possible bias. Although the errors on the fractions of disturbed and undisturbed galaxies are relatively large, we find that the difference between unobscured/moderately obscured quasars and heavily obscured quasars is significant at 90 per cent confidence level (Fisher exact probability test, \( P = 0.087 \)). However, larger samples are necessary to reliably assess these differences at higher confidence levels.

5 DISCUSSION

We have investigated the X-ray properties of a sample of 33 MIR selected quasars with intrinsic AGN luminosity \( \nu L_{\nu,6\mu m} > 6 \times 10^{44} \text{ erg s}^{-1} \) at redshift \( z \approx 1–3 \). While at MIR wavelengths these quasars are very luminous, the majority have low X-ray luminosities, and a significant fraction of them (\( \sim 30 \) per cent) are undetected in the deep Chandra data available in the GH fields, suggesting they are heavily obscured in the X-ray band. Indeed, the X-ray spectral analysis and the comparison between the X-ray and MIR luminosities indicate that the vast majority of these IR quasars are obscured (up to \( \sim 79 \) per cent, 26 out of 33 sources), of which a large fraction are candidates to be CT (up to \( \sim 48 \) per cent, i.e. 16 out of 33 quasars). The fractions of obscured and potentially CT quasars are much higher than those typically found for optically and X-ray-selected quasar fractions (\( \sim 30 \) per cent) are undetected in the deep Chandra data available in the GH fields, suggesting they are heavily obscured in the X-ray band. Indeed, the X-ray spectral analysis and the comparison between the X-ray and MIR luminosities indicate that the vast majority of these IR quasars are obscured (up to \( \sim 79 \) per cent, 26 out of 33 sources), of which a large fraction are candidates to be CT (up to \( \sim 48 \) per cent, i.e. 16 out of 33 quasars). The fractions of obscured and potentially CT quasars are much higher than those typically found for optically and X-ray-selected quasar samples (see Section 5.1). We have reliably identified eight of these sources as CT from the X-ray spectral analyses (\( N_{\text{H}} \) and strong Fe K\alpha line), although some ambiguity still remains for three of them (XIDs 171N, 307N and 423N) due to the large uncertainties on the estimated \( N_{\text{H}} \), from the suppression of the X-ray luminosity (a factor of \( \approx 30–1000 \)) compared to the 6 \( \mu m \) luminosity derived from the SED analyses and from the optical emission line luminosity. Further diagnostics are needed for the remaining eight CT quasar candidates to confirm their nature. Eight of our CT quasar candidates have also been classified as CT (or CT candidates) in previous studies (see Table 4, for reference), however, the remainders have never been identified to date. Our results therefore indicate that there is a large population of obscured and heavily obscured quasars at \( z \approx 2 \) and confirm that the selection of sources in the MIR band allows us to find even the most obscured, CT quasars, that are missing in the optical and X-ray bands.

5.1 Obscured quasar fraction: comparison with previous studies

Several studies conducted in the optical and X-ray bands have shown that the fraction of obscured AGN decreases with luminosity (e.g. Lawrence & Elvis 1982; Steffen et al. 2003; Ueda et al. 2003, 2014; Hasinger 2004, 2008; La Franca et al. 2005; Simpson 2005; Treister & Urry 2005). For instance, Hasinger (2008) found that the obscured fraction (\( f_{\text{obsc}} \)), defined as the number of obscured, Compton-thin AGN (Cthin; \( N_{\text{H}} \approx 10^{22–10^{25} \text{ cm}^{-2}} \)) over the total with \( N_{\text{H}} \approx 10^{24} \text{ cm}^{-2} \), amongst quasars is more than a factor of 2 lower (\( f_{\text{obsc}} < 25 \) per cent at \( L_X > 10^{44} \text{ erg s}^{-1} \)) than that for the less-powerful AGN (\( f_{\text{obsc}} \approx 50 \) per cent at \( L_X = 10^{43} \text{ erg s}^{-1} \)). This trend is also seen when selection biases are accounted for (due to the fact that unobscured bright quasars are easier to detect out to larger comoving volumes, e.g. Della Ceca et al. 2008). The obscured AGN fraction seems to evolve with redshift, becoming larger at high redshift (e.g. La Franca et al. 2005; Ballantyne, Everett & Murray 2006; Treister & Urry 2006; Hasinger 2008; Ueda et al. 2014). The trend of decreasing \( f_{\text{obsc}} \) at high luminosity, however, is found at all redshifts (e.g. Hasinger 2008; Ueda et al. 2014). To compare the obscured fraction in our sample with those found in previous studies we consider here the Compton-thin quasars only, i.e. excluding sources with \( N_{\text{H}} > 10^{24} \text{ cm}^{-2} \). Amongst our IR quasars \( f_{\text{obsc}} \approx 59–72 \) per cent, where the range is determined by the lower and upper limit on the number of candidate CT quasars in our sample. These fractions are higher than those found by Hasinger (2008) for X-ray and optically-selected \( L_X \approx 10^{41} \text{ erg s}^{-1} \) quasars at \( z = 1–3 \), \( f_{\text{obsc}} \approx 40–55 \) per cent. However, we find good agreement with the Ueda et al. (2014) estimates in the same redshift range, \( f_{\text{obsc}} \approx 60–65 \) per cent at \( L_X \approx 10^{42} \text{ erg s}^{-1} \), where they apply a correction for detection biases to the observed X-ray absorbed AGN fraction.

Taking into account the CT sources in our sample the obscured quasar fraction reaches \( \approx 79 \) per cent (see Section 4.2), with CT quasars being up to \( \sim 62 \) per cent of the total obscured quasars. This fraction is consistent with those found for Seyfert galaxies (\( L_X < 10^{43} \text{ erg s}^{-1} \)) in the local Universe, where \( \approx 50 \) per cent of the AGN population shows CT absorption (e.g. Risaliti, Maiolino & Salvati 1999; Guainazzi, Matt & Perola 2005; Tozzi et al. 2006), possibly suggesting that the relative ratio of Cthin and CT sources remains constant across all redshifts and luminosities. Our results also support the assumptions of the CXB synthesis models by Gilli et al. (2007) and Ueda et al. (2014) of an equal number of Cthin and CT AGN across all luminosities and redshifts. However, we note that different population synthesis models (e.g. Ballantyne et al. 2006; Treister et al. 2009) use different assumptions on the relative numbers of Cthin and CT AGN (see table 6 of Ueda et al. 2014). Buchner et al. (2015) found that obscured AGN (\( N_{\text{H}} > 10^{21} \text{ cm}^{-2} \)) at \( L_X > 43.2 \text{ erg s}^{-1} \) contribute \( \approx 75 \) per cent of the luminosity density at \( z = 1–3 \), with CT AGN and obscured Cthin AGN contributing in equal fractions, while unobscured AGN only making up \( \approx 25 \) per cent of the luminosity density. We found consistent results for quasars (\( L_X > 10^{41} \text{ erg s}^{-1} \)).

In the context of galaxy evolution, where the most massive galaxies, hosts of the most luminous quasars, form earlier and evolve more rapidly than the less luminous systems (cosmic ‘downsizing’, e.g. Cowie et al. 1996; Franceschini et al. 1999), a decreasing fraction of obscured sources with luminosity can be explained with the most luminous AGN being more efficient than their less luminous analogues in consuming their surrounding gas and blowing off their dusty cocoon (through AGN feedback; e.g. Hopkins et al. 2006; Menci et al. 2008) becoming unobscured, bright quasars. This means that the probability of seeing obscured high-luminosity quasars is smaller than for lower luminosity AGN, as the fast accreting SMBHs spend a shorter time in this ‘obscured phase’. However, at high redshifts we might expect to see more of these bright obscured quasars as they have not yet expelled or consumed all their surrounding material. Indeed, Assef et al. (2015) found that the space density of very luminous obscured quasars at high redshift (\( 2 \leq z < 4 \)) is comparable to that of unobscured quasars of similar luminosities. In this scenario it is perhaps not surprising to find such a high fraction of obscured quasars (\( \sim 80 \) per cent, including CT sources) in our sample at \( z \approx 2 \). In fact, there is indication that CT AGN have a similar evolution with redshift to Cthin AGN (e.g. Brightman & Ueda 2012; but see also Buchner et al. 2015). The selection in the IR band tends to find the most obscured, CT AGN more efficiently than in the optical and X-ray bands, and previous studies of MIR-selected AGN have indeed found high fractions of obscured and CT sources, consistent with our results (e.g. Maiolino...
scured/unobscured quasars are in green (as in Fig.3). The dashed line marks
ily obscured quasars are represented in magenta, while the moderately ob-
in GH-N are shown as circles and the sources in GH-S as squares; heav-
µ+ can be classified as DOGs is $39\pm10^4$; e.g. Fiore et al. 2008). The fraction of IR quasars in our sample that
the fraction are estimated from the errors in the $F(24\ \mu m)$/$F(R)$

5.2 Comparison with the dust obscured galaxy population
X-ray obscured AGN have often been found to show extreme MIR-
to-optical colours ($F(24\ \mu m)$/$F(R)$; where $F(24\ \mu m)$ is the flux
density at 24 $\mu m$ (observed frame) and $F(R)$ is the flux density in the
$R$ band), due to strong reddening typically affecting the optical
bands (e.g. Fiore et al. 2009; Georgantopoulos et al. 2009).
Fiore et al. (2008) identified an MIR-to-optical colour selection,
$F(24\ \mu m)$/$F(R)$ > 1000, as an efficient way to select heavily ob-
sured, CT AGN, finding a large fraction ($\approx$80 per cent) of such
sources in their sample. Objects with these extreme MIR-to-optical
colours have often been called dust obscured galaxies (DOGs; e.g.
Dey et al. 2008; Pope et al. 2008b).
To investigate how our IR quasar selection, and our obscured quasar
collection for this work with compare it with those found in previous
studies. Our results are consistent with the space density of $L_X =
10^{43} - 10^{45}$ erg s$^{-1}$ (intrinsic) CT quasars at $z \approx 1.2 - 2.2$ found
by Fiore et al. (2009), who based their estimates on IR selected sources
in the COSMOS field. Alexander et al. (2008) calculated the
volume density of CT quasars at $z \approx 2 - 2.5$ in the CDF-N based on
four sources identified in the X-ray and IR bands; their estimate is
somewhat higher than ours, but it is in broad agreement given their
large uncertainties. Our estimate is in good agreement with the CT
quasars space density predicted by the Gilli et al. (2007) model for
intrinsic $L_X > 10^{44}$ erg s$^{-1}$ at $z \approx 2$ and also with the values found
by Tozzi et al. (2006) and Brightman & Ueda (2012), from X-ray
spectral analyses in the CDF-S (Fig. 8).
For a more direct comparison with the X-ray studies of Tozzi et al.
(2006) and Brightman & Ueda (2012), we limit our sample here to the CT quasars (and candidates) identified in the GH-S field
(eight sources, three of which are detected in the X-rays). The space
density estimated by Tozzi et al. (2006) for CT AGN at $z \approx 2$, is
based upon four CT AGN identified from X-ray spectral analysis in the
central 95 arcmin$^2$ in CDF-S (1 Ms). Brightman & Ueda (2012)
identified ~10 CT AGN in the CDF-S ($\approx 460$ arcmin$^2$) at $z \approx 1 - 3$
and intrinsic $L_X > 10^{44}$ erg s$^{-1}$, yielding a similar volume density
to Tozzi et al. (2006) and to ours. However, it is important to note that
there is no overlap between the CT AGN identified by Tozzi et al.
(2006) and those identified in this work through spectral analysis
(i.e. the three X-ray-detected sources in GH-S). Two of our three
X-ray-detected CT quasars were undetected in the 1 Ms Chandra
observations analysed in Tozzi et al. (2006), while the third source
was mis-classified as a low-luminosity, unobscured AGN. On the

5.3 Space density of CT quasars
Considering the full IR quasar sample, we calculate the sky density
of our sources ($vL_{6,\mu m} > 6 \times 10^{44}$ erg s$^{-1}$ at $z = 1 - 3$) within the GH
fields (North and South; $\approx 260$ arcmin$^2$ in total) to be $\approx 460$ deg$^{-2}$.
CT quasars constitute up to $48$ per cent of our sources, i.e. up to
$62$ per cent of the obscured quasars in our sample (26 objects with
$N_{\nu} > 10^{22}$ cm$^{-2}$). Calculating the space density of CT quasars (and
candidates) in our sample ($\approx$8 - 16 sources) in the comoving
volume between $z = 1 - 3$ we find $\Phi = (6.7 \pm 2.2) \times 10^{-6}$ Mpc$^{-3}$,
where the errors are estimated from the lower and upper limits on
the number of CT quasars in our sample.
In Fig. 8, we plot the comoving CT quasar space density estimated
in this work and compare it with those found in previous
studies. Our results are consistent with the space density of $L_X =
10^{43} - 10^{45}$ erg s$^{-1}$ (intrinsic) CT quasars at $z \approx 1.2 - 2.2$ found
by Fiore et al. (2009), who based their estimates on IR selected sources
in the COSMOS field. Alexander et al. (2008) calculated the
volume density of CT quasars at $z \approx 2 - 2.5$ in the CDF-N based on
four sources identified in the X-ray and IR bands; their estimate is
somewhat higher than ours, but it is in broad agreement given their
large uncertainties. Our estimate is in good agreement with the CT
quasars space density predicted by the Gilli et al. (2007) model for
intrinsic $L_X > 10^{44}$ erg s$^{-1}$ at $z \approx 2$ and also with the values found
by Tozzi et al. (2006) and Brightman & Ueda (2012), from X-ray
spectral analyses in the CDF-S (Fig. 8).
5.3 Space density of CT quasars
Considering the full IR quasar sample, we calculate the sky density
of our sources ($vL_{6,\mu m} > 6 \times 10^{44}$ erg s$^{-1}$ at $z = 1 - 3$) within the GH
fields (North and South; $\approx 260$ arcmin$^2$ in total) to be $\approx 460$ deg$^{-2}$.
CT quasars constitute up to $48$ per cent of our sources, i.e. up to
$62$ per cent of the obscured quasars in our sample (26 objects with
$N_{\nu} > 10^{22}$ cm$^{-2}$). Calculating the space density of CT quasars (and
candidates) in our sample ($\approx$8 - 16 sources) in the comoving
volume between $z = 1 - 3$ we find $\Phi = (6.7 \pm 2.2) \times 10^{-6}$ Mpc$^{-3}$,
where the errors are estimated from the lower and upper limits on
the number of CT quasars in our sample.
In Fig. 8, we plot the comoving CT quasar space density estimated
in this work and compare it with those found in previous
studies. Our results are consistent with the space density of $L_X =
10^{43} - 10^{45}$ erg s$^{-1}$ (intrinsic) CT quasars at $z \approx 1.2 - 2.2$ found
by Fiore et al. (2009), who based their estimates on IR selected sources
in the COSMOS field. Alexander et al. (2008) calculated the
volume density of CT quasars at $z \approx 2 - 2.5$ in the CDF-N based on
four sources identified in the X-ray and IR bands; their estimate is
somewhat higher than ours, but it is in broad agreement given their
large uncertainties. Our estimate is in good agreement with the CT
quasars space density predicted by the Gilli et al. (2007) model for
intrinsic $L_X > 10^{44}$ erg s$^{-1}$ at $z \approx 2$ and also with the values found
by Tozzi et al. (2006) and Brightman & Ueda (2012), from X-ray
spectral analyses in the CDF-S (Fig. 8).
For a more direct comparison with the X-ray studies of Tozzi et al.
(2006) and Brightman & Ueda (2012), we limit our sample here to the CT quasars (and candidates) identified in the GH-S field
(eight sources, three of which are detected in the X-rays). The space
density estimated by Tozzi et al. (2006) for CT AGN at $z \approx 2$, is
based upon four CT AGN identified from X-ray spectral analysis in the
central 95 arcmin$^2$ in CDF-S (1 Ms). Brightman & Ueda (2012)
identified ~10 CT AGN in the CDF-S ($\approx 460$ arcmin$^2$) at $z \approx 1 - 3$
and intrinsic $L_X > 10^{44}$ erg s$^{-1}$, yielding a similar volume density
to Tozzi et al. (2006) and to ours. However, it is important to note that
there is no overlap between the CT AGN identified by Tozzi et al.
(2006) and those identified in this work through spectral analysis
(i.e. the three X-ray-detected sources in GH-S). Two of our three
X-ray-detected CT quasars were undetected in the 1 Ms Chandra
observations analysed in Tozzi et al. (2006), while the third source
was mis-classified as a low-luminosity, unobscured AGN. On the

\[10\] We note that the optical and near-IR photometry of the source #6 (XID
243N) is contaminated by a nearby low-$\alpha$ galaxy (see also note in Table 1),
and therefore its $F(24\ \mu m)$/$F(R)$ ratio, which results to be well below the
DOG selection threshold, might not be reliable.
other hand, all the CT AGN identified by Tozzi et al. (2006) have lower MIR AGN luminosity than our IR quasars (although still consistent with the scatter of the \( L_X - L_{6\mu m} \) relation), and therefore are not selected in our sample, as we are only probing the most luminous IR quasars. Two out of the three X-ray-detected CT quasars, we identified in the GH-S field were also classified as CT by Brightman & Ueda (2012), using the same \textit{Chandra} data as in this work; the third source was not included in the Brightman & Ueda (2012) sample, but was analysed by Brightman et al. (2014) and classified as a CT quasar. Nevertheless, the overlap between our CT quasar candidates and those found by Brightman & Ueda (2012) is small (\( \approx 20-25 \) per cent, only two sources), as most of our CT candidates are X-ray undetected, while the CT quasars (with intrinsic \( L_X > 10^{44} \) erg s\(^{-1} \)) identified by Brightman & Ueda (2012) have MIR AGN luminosities below our IR quasar threshold (according to our SED analyses). This is perhaps just a selection effect due to the scatter of the \( L_X - L_{6\mu m} \) relation; however, it might also suggest that the quasar selection approaches in the MIR and X-ray bands are complementary, and tend to identify different source populations (e.g. Brightman & Ueda 2012), where the MIR selected CT quasars are brighter at MIR wavelengths and more obscured (e.g. \( N_H \gtrsim (5-10) \times 10^{22} \) cm\(^{-2} \), as the majority are X-ray undetected) than the X-ray-selected CT quasars, possibly because of a larger dust content in the circumnuclear regions. If we combine the number of CT quasars identified in our work over the GH-S field with those found by Brightman & Ueda (2012) within the same area (\( \lesssim 7 \) sources within the GH-S area, of which two are in common with ours), we would obtain a total CT quasar space density of \( \Phi = (1.9 \pm 0.6) \times 10^{-5} \) Mpc\(^{-3} \). This is in agreement with the predictions by Shi et al. (2013) based on a joint model of the X-ray and IR backgrounds. This suggests that the best estimate of the true space density of CT quasars is possibly obtained from a combination of the CT populations identified in the IR and in the X-ray bands.

5.4 IR quasars and BH-galaxy co-evolution

According to some evolution scenarios, the most luminous AGN, hosted in the most massive systems, experience a different evolutionary path than that of smaller, less luminous systems. Major mergers are predicted to play a significant role in driving gas into the centre of the most massive galaxies, causing violent episodes of starbursts and rapid SMBH growth (e.g. Di Matteo et al. 2005; Hopkins et al. 2006), especially at high redshifts (e.g. Hopkins, Kocevski & Bundy 2014). On the other hand, secular processes, such as disc instabilities and galaxy bars, are expected to be the main mechanisms driving the gas into the centre of smaller, low-luminosity systems, where the SMBH and the galaxy experience a slower and more steady growth (see also Alexander & Hickox 2012, for a review). To place the IR quasars, which are the brightest MIR sources detected in the GH fields, into this evolution scenario, we investigated the host galaxy properties in terms of the SFR and the level of disturbance in the galaxy morphology to detect signs of possible recent interactions/mergers. Our quasars have typically SFRs consistent with those of MS SFGs at redshift \( z \approx 1-3 \), with no indication of unobscured quasars having suppressed SF (i.e. below the star-forming MS) compared to the most obscured ones (Fig. 4).

As the morphology of the majority of our sources does not show any strong distortion features (\( \lesssim 60 \) per cent), we can infer that mergers are not the main fuelling process amongst the IR quasars (Fig. 6). This is in good agreement with the merger/interaction fractions found in less luminous AGN and non-AGN hosting galaxies at similar redshifts by Kocevski et al. (2012), but it is in contrast with the evolution scenario proposed for quasars (e.g. Di Matteo et al. 2005; Hopkins et al. 2006). However the fraction of disturbed/interacting systems (~40 per cent) is on average higher than those found for sources at lower redshifts (~15–20 per cent at \( z < 1 \); e.g. Cisternas et al. 2011), in agreement with the observed increase of the galaxy merger rate with redshift (e.g. Conselice et al. 2003; Karaltepe et al. 2007).

Interestingly, the fraction of unobscured/moderately obscured quasars hosted in disturbed systems is significantly lower (~20 per cent) than those in undisturbed galaxies (~80 per cent; see Fig. 6), while the heavily obscured quasars are equally found in disturbed and undisturbed galaxies, suggesting that the merger fraction in the most heavily obscured systems might be higher (see also Kocevski et al. 2015). The difference between the two quasar populations is significant at the 90 per cent confidence level (~0.087, see Section 4.4). If unobscured quasars represent a later stage of the SMBH-galaxy evolution compared to the heavily obscured quasars, the distortion/interaction features due to mergers or galaxy interactions might have faded by the time these quasars are observed as unobscured, as the relaxation time of the galaxy is typically \( \approx 200-400 \) Myr (e.g. Lotz et al. 2010). This might...
explain the smaller fraction of disturbed systems we found for the unobscured/moderately obscured quasars. On the other hand, the most heavily obscured quasars might still be at a younger stage of evolution after the merger, and therefore their hosts still show the signatures of the recent interactions. We note, however, that we did not find any direct connection between the SFR and X-ray obscuration in our quasars, and thus no evidence for an enhancement of SFR in the heavily obscured quasars in disturbed systems, challenging the predictions from the quasar evolution scenarios. However, as the size of our sample is small, we cannot derive any strong conclusion from our results. Further analyses of larger quasar samples and comparisons with well selected control samples of galaxies are needed to accurately test the SMBH-galaxy evolution scenarios.

6 SUMMARY AND CONCLUSIONS

Through detailed SED decomposition analyses of the 24 µm-detected sources in the GH-N and GH-S fields we identified a sample of 33 luminous IR quasars with AGN MIR luminosity $L_{\text{MIR}} > 6 \times 10^{44}$ erg s$^{-1}$ at redshift $z \approx 1$–3. Considering typical intrinsic $L_X - L_{\text{MIR}}$ relations, this luminosity corresponds to an intrinsic X-ray luminosity of $L_X > 2 \times 10^{44}$ erg s$^{-1}$, i.e. in the quasar regime. We investigated the X-ray properties of these IR quasars through X-ray spectral analysis for the X-ray-detected sources to accurately derive the obscured quasar fraction and constrain the CT quasar population at $z \approx 2$. Through our SED analyses, which provide reliable measurements of the intrinsic AGN luminosity and of the host galaxy SFR, and through visual classification of the galaxy disturbance morphology using high-resolution HST images, we also investigated the host galaxy properties in relation to the quasar luminosity and the X-ray obscuration to understand the SMBH-galaxy connection in the context of the evolution scenarios. Our main results can be summarized as follows.

1. X-ray spectral analyses of the X-ray-detected IR quasars (~70 per cent of the sample) show that the majority of the sources (16 out of 24) are obscured by column densities $N_H > 10^{22}$ cm$^{-2}$, with more than half of them (9/16) being heavily obscured ($N_H > 2 \times 10^{23}$ cm$^{-2}$). Given that the fraction of obscured AGN decreases at high luminosity (Section 5.1), the number of obscured quasars in our sample is high; however, we find it is consistent with those expected from an increase of the obscured fraction with redshift (after accounting for detection biases, e.g. Ueda et al. 2014).

2. Despite being the brightest quasars at MIR wavelengths detected in the GH fields, about 30 per cent of our IR quasars are not detected in the deepest 2 and 4 Ms Chandra X-ray data. Their X-ray luminosity upper limits imply a suppression of the X-ray emission by factors of ~30–1000 compared to the intrinsic MIR AGN luminosity. From the comparison of the MIR and observed X-ray luminosities for all the IR quasars in our sample, we constrain the fraction of CT quasars to be ~24–48 per cent (8–16 quasars, six of which are robustly identified through X-ray spectral analyses), i.e. up to ~62 per cent of all the obscured quasars in the sample (Section 4.2).

3. The space density of CT quasars at $z = 1$–3 estimated from our sample is $\Phi = (6.7 \pm 2.2) \times 10^{-8}$ Mpc$^{-3}$, which is in general agreement with previous results for quasars identified in the X-ray or MIR bands (Tozzi et al. 2006; Alexander et al. 2008; Fiore et al. 2009; Brightman & Ueda 2012) as well as with the predictions from the population synthesis models (e.g. Gilli et al. 2007). However, the small overlap between the CT quasars identified through our analyses and those found in the X-rays within the same fields (e.g. Brightman & Ueda 2012) suggests that the space density of CT quasars is likely to be higher than that estimated in this work (or those found in previous studies based on X-ray-detected sources), and that the combination of X-ray and MIR-detected CT populations possibly provides the best constraints on their true space density in the Universe (Section 5.3).

4. The SFRs of the IR quasar hosting galaxies are broadly consistent with those of MS galaxies at $z \approx 1$–3. In general, we do not find any direct correlation between the SFR and the quasar luminosity or with the X-ray obscuration, with only tentative indication for the heavily obscured quasars ($N_H > 2 \times 10^{23}$ cm$^{-2}$) to have higher SFRs than the less obscured ones (in particular at $z = 1.5$–2.5). The limited number of sources in our sample, however, does not allow us to derive any strong conclusion from this result (Section 4.3).

5. From visual classification of the galaxy morphology to identify signs of interactions/mergers we find that ~40 per cent of our quasars have a distorted morphology, while ~60 per cent do not show any sign of distortions, indicating that mergers are not the main mechanism fuelling the SMBH in luminous quasars. This is consistent with the results found for lower luminosity AGN (e.g. Kocevski et al. 2012). However, the interaction/merger fraction seems to be lower for unobscured/moderately obscured quasars than for heavily obscured quasars, possibly suggesting that large amounts of gas and dust in the galaxy, as a result of recent merger or galaxy interactions, are partly responsible for the high level of obscuration in these quasars, while the unobscured/moderately obscured quasars might be at a later evolutionary stage, where the signatures of galaxy interactions/mergers have already faded (Section 4.4).

Further progress can be made in the near future to constrain the CT quasar population using the extremely deep 7 Ms Chandra data recently obtained in the CDF-S (PI: W. Brandt). These data will allow us to confirm the CT nature of the CT quasar candidates we identified in the GH-S field (e.g. providing better spectra and detecting some of the X-ray-undetected systems), further validating our analyses and results. Moreover, the advent of the new X-ray and MIR observatories, such as eROSITA, ATHENA and the James Webb Space Telescope (JWST) will provide unprecedentedly large samples of high-$z$ quasars to allow studies of MIR- and X-ray-selected CT quasars, placing tighter constraints of their space density and on the different properties characterizing sources selected in the MIR versus those selected in the X-ray bands.

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MIR selected heavily obscured quasars at $z \approx 2$

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APPENDIX A: INFRARED SEDS OF THE IR QUASARS

Figure A1. SED of the IR quasars in GH-N. Filled circles are the Spitzer 8.0, 16 and 24 \( \mu \)m and Herschel 100, 160 and 250 \( \mu \)m data used to constrain the SEDs. The Spitzer-IRAC 3.6, 4.5 and 5.8 \( \mu \)m data (open triangles) and the Herschel 350 and 500 \( \mu \)m (open circles) are also shown, although these data are not used in the SED-fitting process (Section 3.1). For 8 out of 19 IR quasars in GH-N (\( \sim \)42 percent) Spitzer-IRS spectra are available and they are shown here (cyan line) to demonstrate the agreement with the best-fitting SEDs. The dotted curves and the dashed curves represent the AGN and SFG templates, respectively, while the solid curve is the total best-fitting SED. The purple stars, which are only shown for the X-ray-detected IR quasars, represent the 6 \( \mu \)m flux we would expect from the observed X-ray luminosity adopting the Lutz et al. (2004) relation (for XID 243N the star falls below the plotted flux range). On the top-left corner of each plot we report the source number and the redshift, while on the top-right corner there is the XID from Alexander et al. (2003) for the X-ray-detected quasars.
MIR selected heavily obscured quasars at $z \approx 2$

Figure A2. SED of the IR quasars in GH-S. Symbols are the same as in Fig. A1. The Spitzer-IRS spectra, which are available for 4 out of the 14 IR quasars in GH-S (≈29 per cent) are shown (cyan lines) to demonstrate the agreement with the best-fitting SEDs. For XIDs 320S, 435S and 490S, which we robustly identified as CT quasars, the purple stars, which represent the 6 µm flux we would expect from the observed X-ray luminosity adopting the Lutz et al. (2004) relation, falls below the plotted flux range. On the top-left corner of each plot we report the source number and the redshift, while on the top-right corner there is the XID from Xue et al. (2011) for the X-ray-detected quasars.

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