X-ray observations of highly obscured $\tau_{9.7\mu m} > 1$ sources: an efficient method for selecting Compton-thick AGN?

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Received 16 December 2010 / Accepted 22 April 2011

ABSTRACT

Observations with the IRS spectrograph onboard \textit{Spitzer} have found many sources with very deep Si features at 9.7 $\mu m$, that have optical depths of $\tau > 1$. Since it is believed that a few of these systems in the local Universe are associated with Compton-thick active galactic nuclei (hereafter AGN), we set out to investigate whether the presence of a strong Si absorption feature is a good indicator of a heavily obscured AGN. We compile X-ray spectroscopic observations available in the literature on the optically-thick ($\tau_{9.7\mu m} > 1$) sources from the 12 $\mu m$ IRAS Seyfert sample. We find that the majority of the high-$\tau$ optically confirmed Seyferts (six out of nine) in the 12 $\mu m$ sample are probably Compton-thick. Thus, we provide direct evidence of a connection between mid-IR optically-thick galaxies and Compton-thick AGN, with the success rate being close to 70\% in the local Universe. This is at least comparable to, if not better than, other rates obtained with photometric information in the mid to far-IR, or even mid-IR to X-rays. However, this technique cannot provide complete Compton-thick AGN samples, i.e., there are many Compton-thick AGN that do not display significant Si absorption, with the most notable example being NGC 1068. After assessing the validity of the high 9.7 $\mu m$ optical-depth technique in the local Universe, we attempt to construct a sample of candidate Compton-thick AGN at higher redshifts. We compile a sample of seven high-$\tau$ \textit{Spitzer} sources in the Great Observatories Origins Deep Survey (GOODS) and five in the \textit{Spitzer} First-Look Survey. All these have been selected to have no PAH features (EW_{2.2\mu m} < 0.3 $\mu m$) to maximise the probability that they are bona-fide AGN. Six out of the seven GOODS sources have been detected in X-rays, while for the five FLS sources only X-ray flux upper limits are available. The high X-ray luminosities ($L_X > 10^{42}$ erg s$^{-1}$) of the detected GOODS sources corroborates that these are AGN. For FLS, ancillary optical spectroscopy reveals hidden nuclei in two more sources. SED fitting can support the presence of an AGN in the vast majority of sources. Owing to the limited photon statistics, we cannot derive useful constraints from X-ray spectroscopy on whether these sources are Compton-thick. However, the low $L_X/L_{9.7\mu m}$ luminosity ratios, suggest that at least four out of the six detected sources in GOODS may be associated with Compton-thick AGN.

Key words. X-rays: general – X-rays: diffuse background – X-rays: galaxies – infrared: galaxies

1. Introduction

Hard X-rays (2–10 keV) are extremely efficient in detecting AGN, as they can penetrate large columns of dust and gas. This allowed the \textit{Chandra} and \textit{XMM-Newton} missions to map the AGN universe with unprecedented detail. In particular, about 90\% of the X-ray background has been resolved (Alexander et al. 2003; Luo et al. 2008), revealing a sky density in the CDF-N of $>5000$ deg$^{-2}$ (Bauer et al. 2004). The majority of these sources are obscured AGN, presenting column densities $>10^{22}$ cm$^{-2}$ (e.g. Tozzi et al. 2006; Akylas et al. 2006).

However, even the hard X-ray surveys may be missing a substantial fraction of the most heavily obscured sources, the Compton-thick AGN, which have column densities $>10^{23}$ cm$^{-2}$. Although this population remains elusive (see Comastri 2004 for a review), there is concrete evidence for its presence. The peak of the X-ray background at 20–30 keV (e.g. Frontera et al. 2007; Churazov et al. 2007; Moretti et al. 2009) can be reproduced only by invoking a significant number of Compton-thick sources at moderate redshifts. However, the exact density of Compton-thick sources required by X-ray background synthesis models still remains an open issue (Gilli et al. 2007; Sazonov et al. 2008; Treister et al. 2009a). Additional evidence of a numerous Compton-thick population comes from the directly measured space density of black holes in the local Universe (see Soltan 1982). It is found that the black hole space density is a factor of 1.5–2 higher than that predicted from the X-ray luminosity function (Marconi et al. 2004; Merloni & Heinz 2008). The exact number depends on the assumed efficiency of the conversion of gravitational energy to radiation. Direct searches in
the ultra-hard 20–70 keV band by Swift and INTEGRAL did not detect large numbers of Compton-thick sources (e.g. Ajello et al. 2008; Tueller et al. 2008; Paltani et al. 2008; Winter et al. 2009). Nevertheless, it is possible that even these ultra-hard surveys are biased against the most heavily obscured reflection-dominated Compton-thick sources (Burlon et al. 2011). Owing to the limited imaging capabilities of these missions, the flux limit probed is very bright (∼10−11 erg cm−2 s−1) allowing only the detection of AGN in the local universe. At higher redshifts, some Compton-thick AGN have been reported in the deepest XMM-Newton and Chandra observations in the Chandra deep fields (Tozzi et al. 2006; Georgantopoulos et al. 2009; Comastri et al. 2011; Feruglio et al. 2011).

Mid-IR wavelength observations have attracted much attention because they provide an alternative way of detecting heavily obscured systems. This is because the absorbed radiation by circumnuclear dust is re-emitted in the IR part of the spectrum. Martínez-Sansigre et al. (2005) argue that a population of bright 24 μm AGN with no 3.6 μm detections is as numerous as unobscured QSOs at high redshift (z > 2). On the basis of X-ray stacking analysis, Daddi et al. (2007); Fiore et al. (2008); Georgantopoulos et al. (2008); Treister et al. (2009b); Eckart et al. (2010); Donley et al. (2010) propose that a fraction of infrared excess, 24 μm-bright sources are associated with Compton-thick AGN. These sources are found at high redshift (z ~ 2), and their contribution to the X-ray background is expected to be small (<1%; Treister et al. 2009a). In contrast, the bulk of the contribution to the X-ray background is produced at redshifts z ~ 0.7–1 (Gilli et al. 2007).

At high redshifts, mid-IR spectroscopy with Spitzer-IRS, has detected a number of sources with large columns of obscuring material, as inferred from their 9.7 μm Si features (τ > 1; hereafter called high-τ sources; Dasyra et al. 2009). These systems could be associated with Compton-thick AGN. A local analog system is the nearby ULIRG NGC 6240 (Armus et al. 2006), which is well known in X-ray wavelengths to host a Compton-thick AGN (Vignati et al. 1999). There is little information available at X-ray wavelengths for these high-τ systems at higher redshift (Bauer et al. 2010).

The primary goal of this paper is to investigate whether an efficient way to identify Compton-thick AGN is indeed to look for sources with deep silicate absorption at 9.7 μm. The structure of the paper is as follows: we first compile a local sample of high optical-depth (τ9.7 μm > 1) sources from the Wu et al. (2009) flux-limited Spitzer-IRS observations of the 12 μm Seyfert sample of Rush et al. (1993). We investigate the X-ray spectra available in the literature, to deduce how many of these high-τ objects are heavily obscured or Compton-thick. Finally, we compile a sample of high-τ AGN at higher redshift with available X-ray observations, using the Chandra Deep Fields, as well as the Spitzer FLS sample. Although these sources are faint in X-ray wavelengths (and thus it is difficult to derive with great certainty their X-ray spectral properties), we attempt to estimate whether they are heavily absorbed from their Lx/Lbol μm luminosity ratio.

We adopt H0 = 70 km s−1 Mpc−1, ΩM = 0.3, and ΩΛ = 0.7 throughout the paper.

2. Sample selection

2.1. The local sample

We employ a sample of local galaxies with a deep Si absorption feature in the mid-IR, that are known to definitely host an AGN and also have X-ray data, so that the fraction of Compton-thick AGN among them can be quantified. An ideal data set for this purpose is the Spitzer IRS spectroscopic sample of Wu et al. (2009). These authors present low-resolution Spitzer 5.5–35 μm spectra for 103 galaxies from the 12 μm Seyfert sample (Rush et al. 1993). This is a complete, unbiased, flux-limited sample of local Seyfert galaxies, selected from the IRAS Faint Source Catalog by means of optical spectroscopy.

To identify sources with high optical depth at 9.7 μm (τ9.7) due to Si absorption, we use the 6 and 13 μm continuum flux to interpolate the intrinsic AGN unobscured flux at 9.7 μm in a similar way to Spoon et al. (2007). We subsequently measure τ9.7 by calculating the natural logarithm of its observed to intrinsic value. For screen extinction, this corresponds to τ9.7. For sources without spectral coverage at 13 μm, we use the 6 and 7 μm continuum values to extrapolate at 9.7 μm. We reject all sources with optical depths smaller than one. Nonetheless, various spectral fitting techniques can lead to different τ9.7 values due to different continuum assumptions, e.g. the small differences in our measurements of τ9.7 and those derived by Bauer et al. (2010) in the FLS sources. For this reason, we also run PAHFIT (see Smith et al. 2007) for all sources for which it is possible, using the parameters presented in Dasyra et al. (2009). We confirm that all of the sources selected with our primary technique also have τ9.7 > 1 based on PAHFIT. The above re-analysis of the Wu et al. (2009) Spitzer spectra shows that τ9.7 > 1 for eleven AGN (see Table 1). The IRS spectra of many of these sources were also discussed in Armus et al. (2007).

2.2. High-τ 9.7 μm AGN at higher redshift

To identify sources in the distant Universe that are deeply obscured in the mid-IR, we used all the Spitzer-IRS spectra available for the 4 deg2 field of the First Look Survey (FLS), as well as for the CDF-N and CDF-S (<900 arcmin2 in total) of the Great Observatories Origins Deep Survey (GOODS). The two surveys are complementary in targeting sources for our analysis. The FLS is a shallow 24 μm survey, whose spectra were limited to a depth of 0.9 mJy (Yan et al. 2007; Sajina et al. 2007; Dasyra et al. 2009), targeting luminous high-z galaxies. This is ideal for identifying many high-τ systems, as the highest amounts of obscuration are found in the sources with the highest infrared luminosity (Inamishi et al. 2010). However, the GOODS area has the most sensitive mid-IR and X-ray observations available. We select again sources with τ9.7 μm > 1, using the methodology described above.

Since the initial sample selection is made at infrared wavelengths, we expect to find a significant number of non-AGN sources, which owe their infrared emission to dust heated by star-formation processes. To minimize the contamination by pure star-forming systems, we exclude sources with significant PAH emission at 6.2 or 11.3 μm (see Fig. 1), since it has been demonstrated that AGN lack strong PAH features (e.g. Genzel et al. 1998; Hernán-Caballero et al. 2009). We define as PAH-poor sources (mostly AGN dominated) those that have EW(6.2 μm) < 0.3 μm, or EW(11.3 μm) < 0.3 μm where the 6.2 Å wavelength is not covered.

There are 220 sources with IRS spectroscopy in the FLS sample, and we end up with 20 high-τ AGN in FLS using the method described above. Among these, there are six sources with Chandra observations available. Five of them have no obvious PAH features (see Fig. 1 and Table 3), while one (FLS-283) has EW(11.3 μm) = 0.68 μm and is therefore not included in our sample. Pope et al. (in prep.) have consistently reduced and
analysed all publicly available IRS spectra in both GOODS-N and ECDFS fields. For this paper, we search through the 150 GOODS IRS spectra database to find AGN with high $\tau_9$, selecting 15 sources. Eight of these sources are excluded because they have prominent PAH features with $EW$ larger than 0.3 $\mu m$ (see Table 5). The properties of the 12 sources in the high-redshift sample (seven GOODS and five FLS sources) are given in Table 3, while their IRS spectra are shown in Fig. 1.

### 2.3. Comparison between the high and low redshift samples

It is important to highlight the differences between the selection at low and high redshift. In the former, all sources are bona-fide AGN according to optical spectroscopy. Many sources would be classified as composite AGN/star-forming systems, on the basis of the $EW$ of the 6.2 $\mu m$ PAH feature.

Since there is no optical spectroscopy available for many sources in the high redshift sample, the AGN classification is based on the absence of strong PAH features. As discussed in Sect. 4.3.2, our AGN selection criterion is shown to be effective for at least eight out of twelve sources based on their high X-ray luminosities, and optical spectra and most probably all sources based on the measured MIR excess in their SED fitting. Therefore, the local and the high-redshift samples have different relative contributions to the star-formation in the total IR energy budget. Four sources in our local sample (Mrk 938 NGC 3079, Mrk 266, Arp 220) would not satisfy the $EW(6.2 \mu m) < 0.3 \mu m$ selection criterion imposed in the high redshift sample.

### 3. Analysis

#### 3.1. The local sample

##### 3.1.1. X-ray observations

X-ray photometric observations exist for all sources in the local AGN sample. For one source (NGC 1125) only Swift-BAT observations are available at very high energies (>15 keV; Cusumano et al. 2010), and no X-ray spectrum can be derived. For another source (IRAS 08572+3915) there are Chandra observations available (Iwasawa et al. 2009), but unfortunately they are not sensitive enough to allow the derivation of the X-ray column through X-ray spectroscopy. For the remaining nine sources, we compile the X-ray spectroscopic results available in the literature in Table 2.

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**Table 1. Spitzer IRS properties of the high-$\tau$ 9.7 $\mu m$ AGN in the 12 $\mu m$ sample.**

<table>
<thead>
<tr>
<th>Name</th>
<th>$z$</th>
<th>Type</th>
<th>$\tau$</th>
<th>$\log([L_\nu_{6.2}\mu m}]$</th>
<th>AGN</th>
<th>$EW(6.2\mu m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrk 938</td>
<td>0.020</td>
<td>Sy2</td>
<td>1.2</td>
<td>10.09</td>
<td>0</td>
<td>0.440</td>
</tr>
<tr>
<td>NGC 1125</td>
<td>0.011</td>
<td>Sy2</td>
<td>1.0</td>
<td>9.12</td>
<td>0.81</td>
<td>0.258</td>
</tr>
<tr>
<td>108572+3915</td>
<td>0.058</td>
<td>Sy2</td>
<td>3.5</td>
<td>11.51</td>
<td>0.98</td>
<td>&lt;0.021</td>
</tr>
<tr>
<td>UGC 5101</td>
<td>0.039</td>
<td>Sy1</td>
<td>1.4</td>
<td>10.52</td>
<td>0</td>
<td>0.229</td>
</tr>
<tr>
<td>NGC 3079</td>
<td>0.004</td>
<td>Sy2</td>
<td>1.3</td>
<td>9.10</td>
<td>0</td>
<td>0.458</td>
</tr>
<tr>
<td>Mrk 266</td>
<td>0.028</td>
<td>Sy2</td>
<td>1.0</td>
<td>10.03</td>
<td>0</td>
<td>0.608</td>
</tr>
<tr>
<td>Mrk 273</td>
<td>0.038</td>
<td>Sy2</td>
<td>1.7</td>
<td>10.51</td>
<td>0</td>
<td>0.192</td>
</tr>
<tr>
<td>Arp 220</td>
<td>0.018</td>
<td>Sy2</td>
<td>2.4</td>
<td>9.86</td>
<td>0</td>
<td>0.344</td>
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<tr>
<td>I 08572-7245</td>
<td>0.062</td>
<td>Sy2</td>
<td>1.2</td>
<td>11.03</td>
<td>0.88</td>
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<td>NGC 7172</td>
<td>0.009</td>
<td>Sy2</td>
<td>1.9</td>
<td>9.75</td>
<td>0.2</td>
<td>0.045</td>
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<tr>
<td>NGC 7582</td>
<td>0.005</td>
<td>Sy2</td>
<td>1.0</td>
<td>9.56</td>
<td>0</td>
<td>0.274</td>
</tr>
</tbody>
</table>

**Notes.** The columns are: (1) Name; (2) Redshift; (3) Optical AGN type; (4) Optical depth at 9.7 $\mu m$; (5) Logarithm of $vL_\nu$ IR monochromatic luminosity; at 6 $\mu m$ in units of solar luminosity; at 6 $\mu m$ in units of 10$^{22}$ cm$^{-2}$. (4) X-ray spectroscopy reference: 1) Guainazzi et al. (2005); 2) Cusumano et al. (2010); 3) Iwasawa et al. (2009); 4) Imanishi et al. (2003); 5) Akylas & Georgantopoulos (2009); 6) Brassington et al. (2007); 7) Iwasawa et al. (2005); 8) Braito et al. (2003); 9) Dadina (2008); 10) Iwasawa et al. (2011); 11) González-Martín et al. (2009); 12) Ptak et al. (2003); 13) Georgantopoulos et al. (2010); 14) Clements et al. (2002); 15) Bianchi et al. (2009); 16) Brightman & Nandra (2011). (6) X-ray mission. (7) X-ray criterion on which the source is classified as Compton-thick: a. detection of the absorption turnover; b. high-equivalent width Fe 14) Clements et al. (2002); 15) Bianchi et al. (2009); 16) Brightman & Nandra (2011). (6) X-ray mission. (7) X-ray criterion on which the source is classified as Compton-thick: a. detection of the absorption turnover; b. high-equivalent width Fe.
3.1.2. X-ray spectra

The classification of a source as Compton-thick is based on one of the following criteria (see Georgantopoulos et al. 2009):

(a) The most reliable criterion is the detection of the absorption turnover at high energies. These are the transmission-dominated Compton-thick sources with relatively ‘mild’ column densities of a couple of times $10^{24} \text{cm}^{-2}$. In these sources, we can directly view the obscured component through the torus, even at energies below 10 keV (e.g. NGC 3079; Akylas & Georgantopoulos 2009).

(b) The detection of a high ($\sim 1$ keV) equivalent-width ($\text{EW}$) Fe line.

(c) A “hard” spectrum with $\Gamma \sim 1$ or flatter. This is considered to be the signature of a reflection dominated Compton-thick source, where the X-ray emission comes solely from reflection from the backside of the torus (see e.g. Murphy & Yaqoob 2009).

Six of the nine sources for which X-ray spectra can be derived probably host a Compton-thick nucleus based on one of the above criteria (see Table 2). Out of these, UGC 5101 is probably the most debatable case: in a study of ULIRGs with large amounts of molecular gas, Georgantopoulos et al. (2010) detect a flat spectrum ($\Gamma \sim 1.2$) using Chandra, together with a high $\text{EW}$ ($\sim 3.6$ keV) FeK$\alpha$ line, in agreement with Ptak et al. (2003). The combination of a flat spectrum with a high $\text{EW}$ FeK$\alpha$ line suggests a Compton-thick AGN. Imanishi et al. (2003) analyzed both the XMM-Newton and the Chandra data and found a considerably lower $\text{EW}$ ($\sim 400$ eV). González-Martin et al. (2009), using Chandra, claim the direct detection of a mildly Compton-thick AGN with a column density of $N_H \approx 1.4 \pm 0.4 \times 10^{24} \text{cm}^{-2}$. Finally, Brightman & Nandra (2011) report a column density of $10^{23} \text{cm}^{-2}$ by re-analyzing the available XMM-Newton data. We note that the same authors report a much lower column density ($2 \times 10^{23} \text{cm}^{-2}$) for Mrk266 (NGC 5256) than the one derived by Guainazzi et al. (2005). NGC 7582 is one of the few known “changing-look” AGN, i.e. sources with past X-ray
Table 3. High-\( r \) 9.7 \( \mu m \) AGN at higher redshift

<table>
<thead>
<tr>
<th>Name ( (1) )</th>
<th>( \alpha ) ( (2) )</th>
<th>( \delta ) ( (3) )</th>
<th>( \zeta ) ( (4) )</th>
<th>( S_8 ) ( (5) )</th>
<th>( \tau ) ( (6) )</th>
<th>PAH ( \text{EW} ) ( (7) )</th>
<th>( \log[L_{\text{PAH}}] ) ( (8) )</th>
<th>( \log[L_{\text{IR}}] ) ( (9) )</th>
<th>AGN ( (10) )</th>
<th>Comment ( (11) )</th>
<th>AGN ( (12) )</th>
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<td>12:35:55:1</td>
<td>+62:09:01</td>
<td>1.87(^b)</td>
<td>0.097</td>
<td>2.43</td>
<td>&lt;0.18</td>
<td>11.37</td>
<td>12.62</td>
<td>0.75</td>
<td>a, b, d, e</td>
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<td>GN IRS-29</td>
<td>12:36:56:5</td>
<td>+62:19:37</td>
<td>2.2(^b)</td>
<td>0.048</td>
<td>2.54</td>
<td>&lt;0.11</td>
<td>11.83</td>
<td>12.62</td>
<td>0.91</td>
<td>a, d, e</td>
<td>Y</td>
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<td>GN IRS-30</td>
<td>12:37:26:5</td>
<td>+62:20:26</td>
<td>1.76(^c)</td>
<td>0.175</td>
<td>3.6</td>
<td>&lt;0.07</td>
<td>11.92</td>
<td>12.74</td>
<td>0.96</td>
<td>a, d, e</td>
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<td>1.8</td>
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<td>-27:52:33</td>
<td>1.87(^b)</td>
<td>0.026</td>
<td>2.22</td>
<td>&lt;0.20</td>
<td>11.16</td>
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<td>p</td>
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<td>1.88(^b)</td>
<td>0.02</td>
<td>1.78</td>
<td>&lt;0.28</td>
<td>10.99</td>
<td>12.25(^a)</td>
<td>0.32</td>
<td>a, d</td>
<td>Y</td>
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<td>GS IRS-60</td>
<td>03:32:40:0</td>
<td>-27:47:55</td>
<td>2.0(^a)</td>
<td>0.045</td>
<td>1.35</td>
<td>&lt;0.17</td>
<td>11.78</td>
<td>13.25</td>
<td>0.57</td>
<td>a, d, e</td>
<td>Y</td>
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<td>FLS-8196</td>
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<td>2.59(^a)</td>
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<td>1.32</td>
<td>&lt;0.05</td>
<td>12.50</td>
<td>13.40</td>
<td>0.74</td>
<td>d, e, f</td>
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<td>12.7</td>
<td>1.49</td>
<td>&lt;0.04</td>
<td>12.71</td>
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<td>p</td>
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<td>24</td>
<td>2.13</td>
<td>&lt;0.05</td>
<td>12.38</td>
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<td>p</td>
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<td>2.60(^a)</td>
<td>71</td>
<td>2.17</td>
<td>&lt;0.08</td>
<td>11.76</td>
<td>12.85</td>
<td>0.71</td>
<td>c, d, e</td>
<td>Y</td>
</tr>
<tr>
<td>FLS-8550</td>
<td>17:18:14:6</td>
<td>+59:56:05</td>
<td>0.87(^a)</td>
<td>255</td>
<td>2.74</td>
<td>&lt;0.27</td>
<td>11.10</td>
<td>12.09(^a)</td>
<td>0.70</td>
<td>d, e</td>
<td>p</td>
</tr>
</tbody>
</table>

Notes: The columns are: (1) Name; (2), (3) Equatorial \textit{Spitzer} coordinates; (4) Redshift: (1) Chapman et al. (2005); (2) IRS from Pope et al. (2008) or Murphy et al. (2009) in the case of GOODS, or Sajina et al. (2007) in the case of FLS.; (3) Barger et al. (2008); (4) 8 \( \mu m \) flux in units of \( \mu Jy \); (5) optical depth at 9.7 \( \mu m \); (6) PAH equivalent-width at 6.2 \( \mu m \); (7) PAH equivalent-width at 6.2 \( \mu m \) in units of \( \mu m \) (except in the case of FLS-8550 where the 11.3 \( \mu m \) \text{EW} \) is quoted); (8) Logarithm of the \textit{V} \( \mu m \) monochromatic luminosity at 6 \( \mu m \) in units of solar luminosity as derived by IRS spectroscopy; (9) Logarithm of the 8–1000 \( \mu m \) IR luminosity in units of solar luminosity as derived from the SED fitting; (10) No photometry at rest-frame wavelengths >30 \( \mu m \) which constrains the far-IR luminosity; (10) fraction of AGN contribution at 6 \( \mu m \) according to the spectral decomposition; (11) evidence for the presence of an AGN: a) X-ray luminosity, b) radio-emission, c) broad optical line, d) absence (or weakness) of PAH feature, e) SED, f) broad-ish (>500 km s\(^{-1}\)) [OIII] line; (12) AGN classification: (Y) secure on the basis of the X-ray luminosity or optical spectroscopy, (p) probable on the basis of the mid-IR diagnostics i.e. low-EW PAHs and SED fitting.

In both a Compton-thin and a reflection-dominated state (Bianchi et al. 2009). The three high-\( r \) AGN that are definitely not Compton-thick are Mrk 938, Mrk 273, and NGC 7172. These have column densities between \( N_{HI} = 8\times 10^{23} \) cm\(^{-2}\) and \( 4\times 10^{23} \) cm\(^{-2}\). For Mrk 273, Iwasawa et al. (2011) note that the X-ray emission may come from a different location than the IR nucleus. They also point out that the IR nucleus may be associated with a Compton-thick source, although the evidence for this remains weak.

### 3.2. Sources at high redshift

#### 3.2.1. The X-ray observations

The FLS has few (and shallow; ~30 ks) X-ray data points, which are presented in Bauer et al. (2010). Their X-ray observations targeted primarily ULIRGs. There are X-ray observations available (all of them yielding upper limits) for only five out of the 20 high-\( r \) AGN in FLS. However, the GOODS survey for the \textit{Chandra} Deep Fields has the deepest X-ray images to date. The CDF-N was observed for 2 Ms (see Alexander et al. 2003). We examine the 2Ms CDF-N X-ray images and find that all sources are detected in the total (0.3–8 keV) band. Three of the sources are in the catalog of Alexander et al. (2003), while the other one is marginally below the detection threshold of these authors. The CDF-S was originally observed for 2 Ms (Luo et al. 2008), while the field was observed for an additional 2 Ms. Here, we use the entire set of 4 Ms images. In the CDF-S, two sources (out of the three high-\( r \) sources in this field) are detected in the total (0.3–8 keV) band.

#### 3.2.2. X-ray spectra

Among the X-ray detections, we can derive low-quality X-ray spectra in five cases but in only three we can constrain both the photon-index and the hydrogen column density. We use XSPEC (Arnaud 1996) for the spectral fitting. We use the C-statistic (Cash 1979), leaving the data ungrouped. The errors correspond to the 90% confidence level. We fit a simple power-law with photoelectric absorption from cold material in all cases. First, leave both the photon index and column density as free parameters for the three sources with the highest quality photon statistics. The results are given in Table 4. There is no clear evidence of a Compton-thick source. GN IRS-30 presents a very flat spectrum, with \( \Gamma = 0.54 \), but very large errors. To obtain more stringent constraints on the absorbing column density, we fix the photon-index to the commonly observed value of \( \Gamma = 1.8 \) (Dadina 2008). We see that the spectra of the sources GN IRS-19 and GN IRS-30 are heavily obscured with column densities \( \sim 10^{23} \) cm\(^{-2}\).

#### 3.2.3. Spectral energy distributions

To estimate the total infrared emission of the sources in the high redshift sample, and assess the possibility that they host an AGN, we fit their broad-band spectra with combinations of starburst and AGN templates. The starburst templates we use come from the SWIRE template library 1 (Polletta et al. 2007), which is a compilation of observed SED of nearby galaxies, and from the sample of Chary & Elbaz (2001). The AGN templates we use come from Silva, Maiolino & Granato (2004), who combine nuclear SEDs of Seyferts with a range of absorption columns. We also construct a sample of AGN templates using the type-1 QSO SED from Richards et al. (2006) and applying dust absorption following Rosenthal et al. (2000), to account for the 9.7 \( \mu m \) absorption feature.

1 \textit{www.iaps-milano.inaf.it/~polletta/templates/swire_templates.html}

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Murphy et al. (2009) in the case of GOODS or Sajina et al. (2007) in the case of FLS; (5) optical depth at 9.7 μm, in units of erg s⁻¹ cm⁻², has been estimated from the X-ray spectral fits. Where there is no spectral fit, we assume \( \Gamma = 2 \). (3) Logarithm of the X-ray luminosity \( \log L_X \). (4) Rest-frame column density in units of 10²² cm⁻². (5) Rest-frame column density in units of 10²⁵ cm⁻², where \( \Gamma = 1.8 \).

### Table 4. X-ray properties of the high-redshift sample.

<table>
<thead>
<tr>
<th>Name</th>
<th>( L_X )</th>
<th>( \Gamma )</th>
<th>( N_H )</th>
<th>( N_H )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-19 &amp; 43.5 &amp; 1.44±0.07 &amp; 12.1±6.9 &amp; 16.8±4.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-29 &amp; 42.3 &amp; –</td>
<td>&lt;7.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-30 &amp; 43.1 &amp; 0.54±0.18 &amp; &lt;17.5 &amp; 17.0±16.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-55 &amp; 42.3 &amp; 2.15±2.16 &amp; &lt;5.8 &amp; &lt;4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDFS-S</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GS_IRS-14 &amp; &lt;42.9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>GS_IRS-42 &amp; 42.3 &amp; –</td>
<td>&lt;1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GS_IRS-60 &amp; 42.1 &amp; –</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLS</td>
<td>8196</td>
<td>&lt;43.8 &amp; –</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>78</td>
<td>&lt;44.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>8245 &amp; &lt;43.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>16080 &amp; &lt;43.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>8550 &amp; &lt;43.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Notes. The columns are: (1) Name; (2), (3) Equatorial coordinates; (4) Redshift: (1) Chapman et al. (2005); (2) IRS from Pope et al. (2008), Murphy et al. (2009) in the case of GOODS or Sajina et al. (2007) in the case of FLS; (5) optical depth at 9.7 μm. (6) PAH equivalent-width at 6.2 μm, in units of μm (except in the case of FLS-283 where the 11.3 μm EW is quoted); (7) Logarithm of the IR luminosity \( \log L_{IR} \), in units of solar luminosity as derived by IRS spectroscopy; (8) X-ray luminosity (uncorrected for obscuration) in the 2–10 keV band in units erg s⁻¹.

### Table 5. High-τ 9.7 μm sources not included in our sample because of a high PAH EW.

<table>
<thead>
<tr>
<th>Name</th>
<th>( \alpha )</th>
<th>( \delta )</th>
<th>( z )</th>
<th>( \tau )</th>
<th>PAH EW</th>
<th>( \log L_{IR} )</th>
<th>( \log L_X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN_IRS-4 &amp; 12:36:53.4 &amp; +62:11:39 &amp; 1.27</td>
<td>1.12 &amp; 0.67 &amp; 11.40 &amp; 41.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-11 &amp; 12:36:21.3 &amp; +62:17:08 &amp; 1.99</td>
<td>1.55 &amp; 1.18 &amp; 11.41 &amp; &lt;42.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-13 &amp; 12:37:34.5 &amp; +62:17:23 &amp; 0.64</td>
<td>1.37 &amp; 0.48 &amp; 11.27 &amp; 41.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-14 &amp; 12:36:22.5 &amp; +62:15:44 &amp; 0.63 &amp; 3.00 &amp; 0.63 &amp; 10.39 &amp; 41.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-15 &amp; 12:37:11.4 &amp; +62:13:31 &amp; 1.99</td>
<td>1.09 &amp; 0.78 &amp; 10.74 &amp; 42.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-16 &amp; 12:36:37.0 &amp; +62:08:52 &amp; 2.02</td>
<td>3.97 &amp; 0.57 &amp; 11.27 &amp; 42.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-20 &amp; 12:36:03.2 &amp; +62:11:10 &amp; 0.64</td>
<td>2.32 &amp; 0.60 &amp; 10.68 &amp; 41.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN_IRS-21 &amp; 12:36:18.3 &amp; +62:15:50 &amp; 2.00</td>
<td>1.96 &amp; 0.66 &amp; 11.19 &amp; 42.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLS-283 &amp; 17:14:58.3 &amp; +59:24:11 &amp; 0.94</td>
<td>1.12 &amp; 0.68 &amp; 11.46 &amp; &lt;43.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. The columns are: (1) Name; (2), (3) Equatorial Spitzer coordinates; (4) Redshift: (1) Chapman et al. (2005); (2) IRS from Pope et al. (2008), Murphy et al. (2009) in the case of GOODS or Sajina et al. (2007) in the case of FLS; (5) optical depth at 9.7 μm. (6) PAH equivalent-width at 6.2 μm, in units of μm (except in the case of FLS-283 where the 11.3 μm EW is quoted); (7) Logarithm of the IR, monochromatic luminosity at 6 μm in units of solar luminosity as derived by IRS spectroscopy; (8) X-ray luminosity (uncorrected for obscuration) in the 2–10 keV band in units erg s⁻¹.

The photometry we use for the GOODS-N and GOODS-S sources comes from the IRAC (3.6, 4.5, 5.8, and 8.5 μm) public GOODS data release and the SIMPLE survey (Spitzer IRAC/MUSYC Public Legacy in ECDF-S; Damen et al. 2011) respectively. MIPS photometry at 24 and 70 μm, comes from the FIDEL survey (Far-Infrared Deep Extragalactic Legacy survey; see Magnelli et al. 2009) and the 850 μm photometry in the GOODS-N from Pope et al. (2005). The FLS sources have IRAC and MIPS (70 μm) photometric values published in Sajina et al. (2007), while their MIPS (24 μm) and 1.2 mm fluxes are published in Sajina et al. (2008). In the IRS wavelength range, we bin the data every five datapoints and average their flux values, which gives us 30 photometric data points per source.

We use a \( \chi^2 \) minimisation method to select the optimum combination of a starburst and an AGN template to fit our data. The results can be seen in Fig. 2. We calculate the 8–1000 μm luminosity by integrating the best-fit SED; the results are listed in Table 3. We note that six of the GOODS-N sources have their infrared luminosities published in Murphy et al. (2009), where a similar procedure was used in their calculation. Our \( L_{IR} \) values agree within a factor of 2 with the \( L_{IR} \) values of Murphy et al. (2009). Most of the sources of Table 3 require both a star-forming and an AGN template to fit the photometric points. The spectral decomposition (Fig. 2) suggests that the bulk of the mid-IR emission is produced by the AGN component. The exception is GS_IRS-42. In the case of this source, an F-test gives only an 8% probability that the AGN component is needed.

### 3.2.4. \( L_X/L_6 \) ratio

For faint sources such as those in the CDFs, it is difficult to apply X-ray spectroscopy diagnostics owing to the limited photon statistics. Alternatively, the \( L_X \) to \( L_6 \) ratio could be used to identify any highly obscured, Compton-thick AGN. One of the most reliable proxies of the intrinsic power of an AGN is considered to be the mid-IR 6 μm luminosity (e.g. Lutz et al. 2004; Maiolino et al. 2007). This wavelength region can contain significant emission from the hot dust heated by the AGN, and thus...
provides a reliable diagnostic of the AGN power. On the basis of this, Alexander et al. (2008) and Goulding et al. (2011) claim that very low X-ray to $L_{6\mu m}$ ratios, typically 30–40 times lower than those of unobscured AGN, is indicative of very strong attenuation at X-ray wavelengths and thus of Compton-thick sources.

We present the 2–10 keV luminosity, uncorrected for absorption, against the monochromatic 6 $\mu$m IR luminosity for both the 12 $\mu$m sample and the higher redshift sources in Fig. 3. We define very roughly a region where Compton-thick AGN reside, by scaling down the relation of Fiore et al. (2009) for the AGN in the COSMOS fields by 0.03. This is very roughly the amount of reflected emission in a type-2 AGN (Comastri 2004). Moreover, we show the scaled down $L_X - L_{6\mu m}$ relation, by the same amount, of AGN in the local Universe found by

Fig. 2. Mid-IR rest-frame SEDs of the GOODS and FLS sample. The blue and red line denote the torus and star-forming contribution while the purple line denotes the sum of the two.
Our selection criterion (low $EW$) is chosen to minimise the number of star-forming galaxies (non-AGN) in our sample. The $EW$ upper limits of our FLS sources are consistent with a high AGN contribution, close to 100% according to the $L_X/L_{6 \mu m}$ diagnostic, i.e. GN_IRS-29, GN_IRS-55, GS_IRS-42, and GN_IRS-60. Taking into account only the X-ray detections, the fraction of possible Compton-thick sources would be 66% (4/6). The X-ray upper limits are all situated unconventionally above the Compton-thick regime. Under the extreme assumption that all upper limits are either associated or not with Compton-thick sources, the fraction of Compton-thick AGN could vary between 33% and 83%.

### 3.2.5. Contamination by star-forming galaxies.

Our selection criterion (low $EW$ PAH) is chosen to minimise the number of star-forming galaxies (non-AGN) in our sample. The $EW$ upper limits of our FLS sources are consistent with a high AGN contribution, close to 100% according to the $L_X/L_{6 \mu m}$ diagnostic, i.e. GN_IRS-29, GN_IRS-55, GS_IRS-42, and GN_IRS-60. Taking into account only the X-ray detections, the fraction of possible Compton-thick sources would be 66% (4/6). The X-ray upper limits are all situated unconventionally above the Compton-thick regime. Under the extreme assumption that all upper limits are either associated or not with Compton-thick sources, the fraction of Compton-thick AGN could vary between 33% and 83%.

**Fig. 3.** Rest-frame (uncorrected for absorption) $L_X$ versus $L_{6 \mu m}$ luminosity diagram. The filled triangles correspond to the Compton-thick AGN in the 12 $\mu m$ sample, while the open triangles correspond to the three heavily obscured but not Compton-thick AGN in the same sample. The red (blue) filled circles or upper limits denote the high-$\tau$ sources in the CDF-N (CDF-S). The black upper limits denote the FLS points. Finally, the green points (filled squares and small upper limits) denote the sources with considerable PAH emission that have not been included in our sample. The dash line (magenta) denotes the low $L_X/L_{6 \mu m}$ area that should be populated by Compton-thick AGN. This line is derived from the average $L_X/L_{6 \mu m}$ relation derived for the COSMOS AGN (Fiore et al. 2009) by scaling it down by a factor 0.03, which corresponds to the average flux of the reflection component in the 2–10 keV band relative to the intrinsic power-law component in local Compton-thick AGN (Comastri 2004). The solid line (green) corresponds to the luminosity-dependent Compton-thick line based on the Maiolino et al. (2007) relation, scaled down by the same amount. Finally, the horizontal dotted line at $L_X = 10^{42}$ erg s$^{-1}$ denotes the upper limit to X-ray emission due to star-forming processes (Tzanavaris et al. 2006).

Lutz et al. (2004). Finally, we show the luminosity-dependent line predicted by Maiolino et al. (2007). The luminosity error bars do not play a major role relative to the uncertainties introduced by the use of different Compton-thick lines. We present a typical error-bar for one source. This includes both the photon statistics error as well as the uncertainty in the spectral model used for the conversion from flux to luminosity. Therefore, the uncertainties in this diagnostic are quite large.

Using as a guide our AGN in the local Universe for which we have reliable X-ray spectroscopy, we see that there is one Compton-thick source (NGC 7582) that lies above the local Compton-thick AGN regime. Moving to our AGN at higher redshift, there are four GOODS sources that could be classified as Compton-thick according to the $L_X/L_{6 \mu m}$ diagnostic, i.e. GN_IRS-29, GN_IRS-55, GS_IRS-42, and GN_IRS-60. Taking into account only the X-ray detections, the fraction of possible Compton-thick sources would be 66% (4/6). The X-ray upper limits are all situated unconventionally above the Compton-thick regime. Under the extreme assumption that all upper limits are either associated or not with Compton-thick sources, the fraction of Compton-thick AGN could vary between 33% and 83%.

In agreement with the above classifications, two of our sources (GN_IRS-19 and GN_IRS-55) have additional evidence of an AGN via excess of radio emission (Del Moro et al., in prep.). FLS-8196 presents an [OII] line with a FWHM of $\approx 800$ km s$^{-1}$ (Sajina et al. 2008), which is typical of emission from the AGN narrow-line-region (Zakamska et al. 2003). FLS-16080 displays a broad CIV 1550 Å emission line, with
with intrinsic luminosities around the "knee" of the luminosity function, i.e., $\approx (10^44 - 10^45 \text{ erg s}^{-1})$. The presence of a broad-line argues against this source being Compton-thick. There are cases of course of broad-line QSOs associated with Compton-thick AGN but these cases are rare (Braito et al. 2004).

4. Discussion

4.1. The efficiency of the high-$\tau$ method for finding Compton-thick AGN

Silicate absorption features in a few (U)LIRGS in the local Universe known to be associated with Compton-thick AGN (e.g. NGC 6240; Armus et al. 2006), prompts us to investigate whether a high optical depth at 9.7 $\mu$m could provide a reliable diagnostic for the presence of these nuclei. We can reliably identify Compton-thick AGN in the nearby Universe by means of X-ray spectroscopy, owing to their high X-ray brightness. We argue that six out of nine highly absorbed sources at 9.7 $\mu$m ($\tau_{9.7} > 1$), in the 12 $\mu$m IRAS Seyfert sample, with X-ray spectra available in the literature are probably associated with Compton-thick nuclei. In any case, all nine sources are heavily obscured AGN.

Since these are nearby AGN ($z < 0.06$), they should contribute only a small fraction to the X-ray background. The peak of the X-ray background is produced at $z \approx 0.7-1$ from objects with intrinsic luminosities around the “knee” of the luminosity function, i.e., $\sim 10^{45}-10^{46} \text{ erg s}^{-1}$ (Gilli et al. 2007). The median X-ray luminosity (uncorrected for absorption) of our six local Compton-thick AGN is $\sim 0.5 \times 10^{42} \text{ erg s}^{-1}$. Assuming a correction of about 33 for the intrinsic X-ray luminosity (Comastri 2004), this translates to $\approx 2 \times 10^{40} \text{ erg s}$. Hence, AGN with comparable luminosity, but at higher redshift, are the typical AGN responsible for the peak of the X-ray background.

At higher redshift, the fraction of candidate Compton-thick AGN is more uncertain. This fraction can be derived indirectly from the X-ray to IR luminosity ratio. If we take only the X-ray detections into account, this is close to 66%. When we also consider the upper limits, we find that the uncertainty becomes larger: the fraction of Compton-thick sources could vary between 33% and 83%.

The frequency of Compton-thick AGN measured above is comparable to or higher than derived by other mid-IR methods for finding Compton-thick sources. For example, on the basis of X-ray stacking analyses, several authors (e.g. Daddi et al. 2007; Fiore et al. 2008; Georgantopoulos et al. 2008) proposed that the 24 $\mu$m-excess sources are good candidates for hosting Compton-thick nuclei. However, because of the lack of X-ray spectroscopy the fraction of Compton-thick sources cannot be readily quantified. Based on brighter sources with X-ray spectroscopy in the GOODS (Georgantopoulos et al. 2011), AEGIS (Georgakakis et al. 2010) and SWIRE fields (Lanzuisi et al. 2009), the fractions of Compton-thick sources found among IR-excess AGN range between 0% and 50%. Another widely applied mid-IR method for the selection of Compton-thick AGN (Alexander et al. 2008) relies on low X-ray to IR ratios. The principle behind this method is that a low $L_X/L_{IR}$ ratio is a sign of heavy obscuration (but see Yaqoob & Murphy 2011; Georgakakis et al. 2010).

Although we have shown that the success rate of our technique in finding Compton-thick AGN is close to 70%, at least among optically confirmed Seyferts in the local Universe, there are two caveats. First, the detection of this feature alone does not imply the presence of an AGN in these systems. There are star-forming systems with large absorption features at 9.7 $\mu$m that are associated instead with star-forming galaxies. One case is NGC 3628 for which $\tau_{9.8} = 1.64$ (Brandl et al. 2006), although the X-ray emission in this system does not come from an AGN (Dahlem et al. 1996). In other words, the high $\tau_{9.7}$ optical depth characterises systems with large amounts of dust but does not necessarily prove the presence of an AGN. The second caveat has to do with the completeness of our method. There are well-known Compton-thick sources in the literature that contain no significant 9.7 $\mu$m absorption. We discuss this in detail in the following section.

4.2. Si optical depth versus X-ray column density

Shi et al. (2006) described observations of 9.7 $\mu$m features in 97 AGN including a wide range of types. They found that the strength of the silicate feature correlates with the hydrogen column density, derived from X-ray observations in the sense that the low column densities correspond to silicate emission, while high columns correspond to silicate absorption. They point out that the column densities derived from X-ray spectral fitting are always higher than those estimated on the basis of the Si optical depths. Moreover, there appears to be a large scatter between the X-ray and the 9.7 $\mu$m column density in the sense that the same $\tau_{9.7}$ corresponds to X-ray column densities that could differ by as much as an order of magnitude. This result can be seen more clearly in Fig. 4, where we plot the 9.7 $\mu$m optical depth as a function of the X-ray column density for both the 12 $\mu$m sample as well as the sample of Shi et al. (2006). We note that the latter is based mainly on the optically selected sample of Risaliti et al. (1999). Some column densities in this sample were revised by Malizia et al. (2009) and we include these updated values in Fig. 4. This figure clearly shows that the majority of the optically thick sources detected in the mid-IR display Compton-thick absorption at X-ray wavelengths. In addition we see that there are numerous Compton-thick AGN according to X-ray spectroscopy that have optical depths $\tau_{9.7} < 1$.

Perhaps the most well studied case of a low Si $\tau$ Compton-thick source is NGC 1068. The X-ray column density of this

Fig. 4. Optical depth at 9.7 $\mu$m versus X-ray hydrogen column density for the Shi et al. (2006) sample (black points) and the optically-thick AGN in the IRAS sample of Wu et al. (2009) (red points). The solid line marks the region where the X-ray $N_H$ equals that inferred from $\tau_{9.7}$, assuming a Milky-Way extinction curve.

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The goal of this work has been to investigate whether the presence of high absorption at mid-IR wavelengths (τ$_{9.7}$ > 1) can be used as an efficient means for identifying highly obscured or even Compton-thick AGN. Our conclusions can be summarised as follows:

- Our re-analysis of Spitzer-IRS spectra show that there are eleven AGN with τ$_{9.7\mu m}$ > 1 in the 12μm Seyfert IRAS sample. For nine sources X-ray spectroscopic observations are available in the literature. The X-ray spectra show that a large fraction (six of nine) is probably associated with Compton-thick AGN. The success rate of this method is comparable to or even higher than those of other methods using either mid-IR photometric information or the X-ray to IR luminosity ratio.

- Even though optical thickness in the MIR, as determined by 9.7 micron Si absorption with τ > 1 can be efficiently used to identify Compton-thick sources in the local Universe with a high success rate, this method cannot provide complete samples of these sources. This is because a large fraction of Compton-thick sources do not have large high Si optical depths. This could possibly be explained within the framework of a clumpy torus model.

- Using Spitzer-IRS spectra in the CDF and the FLS surveys, we have compiled a sample of 12 sources in total, with τ$_{9.7}$ > 1 at higher redshift (z = 0.87–2.70). These are selected to have weak PAH features to maximise the probability that they host an AGN. The vast majority of sources in the CDFs (six out of seven) are detected in the X-rays, while all five FLS sources remain undetected. For the X-ray detections, the high X-ray luminosities (>2×10$^{42}$ erg s$^{-1}$) confirm that all these sources are AGN. For two FLS sources, their optical line emission also indicates that an AGN is present. Because our sources are faint in X-rays, we are unable to ascertain from X-ray spectroscopy whether at least some of our sources are Compton-thick.

- The use of the L$_{X}$/L$_{6\mu m}$ ratio indicates that the success rate of the high-τ method in identifying Compton-thick AGN could be about 66% (4/6), if we consider X-ray detections only. However, it can be as low as 33% (4/12), or as high as 83% under the extreme assumptions that all the X-ray upper limits are either associated or not associated with Compton-thick sources. Deeper X-ray spectroscopy will be needed to properly constrain the exact fraction of Compton-thick AGN among high-τ, high-τ sources.

In the future, observations with the JWST will be able to identify numerous galaxies with deep Si features that could be used to compile large candidate Compton-thick AGN samples.

Acknowledgements. I.G. and A.C. acknowledge support by the European Community through the Marie Curie fellowship FP7-PEOPLE-IEF-2008 Prop. 235285 under the Seventh Framework Programme (FP7/2007-2013). K.D. also acknowledges support by the European Community through a Marie Curie Fellowship (PIEF-GA-2009-235038) awarded under the Seventh Framework Programme (FP7/2007-2013) The Chandra data were taken from the Chandra Data Archive at the Chandra X-ray Center. This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA.

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