Exploring Gravitationally Lensed $z \gtrsim 6$ X-Ray Active Galactic Nuclei Behind the RELICS Clusters

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Abstract

Although observations of high-redshift quasars demonstrate that many supermassive black holes (BHs) reached large masses within one billion years after the Big Bang, the origin of the first BHs is still a mystery. A promising way to constrain the origin of the first BHs is to explore the average properties of $z \gtrsim 6$ BHs. However, typical BHs remain hidden from X-ray surveys, which is due to their relatively faint nature and the limited sensitivity of X-ray telescopes. Gravitational lensing provides an attractive way to study this unique galaxy population as it magnifies the faint light from these high-redshift galaxies. Here, we study the X-ray emission originating from 155 gravitationally lensed $z \gtrsim 6$ galaxies that were detected in the Reionization Lensing Cluster Survey. We utilize Chandra X-ray observations to search for active galactic nuclei (AGNs) in the individual galaxies and in the stacked galaxy samples. We did not identify an individual X-ray source that was undoubtedly associated with a high-redshift galaxy. We stack the signal from all galaxies and do not find a statistically significant detection. We split our sample based on stellar mass, star formation rate, and lensing magnification and stack these subsamples. We obtain a 2.2σ detection for massive galaxies with an X-ray luminosity of $(3.7 \pm 1.6) \times 10^{42} \text{erg s}^{-1}$, which corresponds to a $(3.0 \pm 1.3) \times 10^5 M_\odot$ BH accreting at its Eddington rate. Other stacks remain undetected and we place upper limits on the AGN emission. These limits imply that the bulk of BHs at $z \gtrsim 6$ either accrete at a few percent of their Eddington rate and/or are 1–2 orders of magnitude less massive than expected based on the stellar mass of their host galaxy.

Unified Astronomy Thesaurus concepts: High-redshift galaxies (734); Active galactic nuclei (16); X-ray active galactic nuclei (2035); Galaxy clusters (584); Gravitational lensing (670)

1. Introduction

In recent decades, deep surveys have detected more than 200 optically bright quasars at high ($z \gtrsim 6$) redshifts. These discoveries demonstrate that accretion-powered black holes (BHs) with masses of $\sim 10^9 M_\odot$ were in place merely one billion years after the Big Bang (e.g., Fan et al. 2006; Willott et al. 2007; Jiang et al. 2008; Mortlock et al. 2011; Venemans et al. 2013; Bañados et al. 2014; Wang et al. 2017; Yang et al. 2017; Wang et al. 2019; Yang et al. 2019, 2020). The origin and rapid assembly of BHs can be explained by a number of seeding models, which are usually grouped into “light seed” and “heavy seed” models. The light-seed scenario involves the collapse of Population III stars leading to BH seeds with masses of $\sim 10^4 M_\odot$. The masses of these X-ray-detected BHs is $\sim 10^5 M_\odot$, hence they do not represent average AGNs, which are likely several orders of magnitude less massive. However, these relatively low-mass and high-redshift accreting BHs remained hidden from X-ray observations and, hence, our understanding of the average properties of $z \sim 6$ AGNs is still lacking despite the substantial efforts over the past decade.

Understanding the origin and early growth of BHs is arguably one of the most thrilling quests of modern astrophysics. However, to constrain the formation scenarios and early growth of BHs, it is essential to probe BHs residing at high redshift. Indeed, only these objects can provide the much-needed observational constraints. However, observations of these distant BHs are exceptionally demanding with present-day X-ray observatories. The main difficulty in detecting the “average” high-redshift accreting BHs is due to their low luminosities and the relatively low sensitivity of present-generation X-ray telescopes. Despite the challenging nature, several studies have attempted to detect high-redshift BHs in the X-ray wave band. X-ray follow-up of optically identified quasars has led to the detection of high-redshift active galactic nuclei (AGNs). Specifically, Chandra detected several AGN at $z \sim 6$ (e.g., Ai et al. 2016; Gallerani et al. 2017; Nanni et al. 2017; Vito et al. 2019; Connor et al. 2020; Pons et al. 2020; Wang et al. 2021). The masses of these X-ray-detected BHs is $\sim 10^9 M_\odot$, hence they do not represent average AGNs, which are likely several orders of magnitude less massive. However, these relatively low-mass and high-redshift accreting BHs remained hidden from X-ray observations and, hence, our understanding of the average properties of $z \gtrsim 6$ AGNs is still lacking despite the substantial efforts over the past decade.

To characterize the average properties of AGNs at medium redshift ($z = 2–5$) and high redshift ($z = 5–6$), most studies have focused on the Chandra Deep Field South (CDF-S; e.g., Giacconi et al. 2001; Luo et al. 2017). By stacking the X-ray...
photons of a large number of galaxies, Vito et al. (2016) detected signals from accreting BHs at \( z \approx 4 \) and \( z \approx 5 \), but \( z \approx 6 \) galaxies remained undetected. Recently, Liu et al. (2021) utilized the Cluster Lensing And Supernova survey with Hubble (CLASH) clusters (Postman et al. 2012) to search for AGNs in medium- to high-redshift galaxies. They detected a handful of individual AGNs in the redshift range of \( 2.8-5 \) behind the CLASH clusters; they also stacked their galaxy sample, which led to detections in these redshifts. While these authors demonstrated the feasibility and the powerful nature of using lensing clusters to study high-redshift AGNs, their study did not constrain AGNs at \( z \gtrsim 6 \).

In this work, we utilize gravitational lensing, which brings into focus fainter sources by magnifying them. Specifically, we rely on the rich X-ray data from the Chandra X-ray Observatory, optical data from the Hubble Space Telescope (HST), and infrared data obtained from the Spitzer Space Telescope for galaxies identified by the Reionization Lensing Cluster Survey (RELICS; Salmon et al. 2020). Through gravitational lensing, these massive galaxy clusters magnify the faint light from high-redshift galaxies behind them. Due to gravitational lensing, only the X-ray photons associated with the source are magnified, while the sky and instrumental background components and—most importantly—the cluster emission is not enhanced. Despite the enhanced signal, the bulk of individual AGNs may be too faint to be detected individually. To this end, we boost the signal-to-noise ratios by coadding (i.e., stacking) the X-ray photons from the individual galaxies. Due to the stacking approach, the combined exposure time will be increased, which allows us to probe the X-ray flux of high-redshift accreting BHs to very low limits. Therefore, this technique could reveal a stacked detection if the individual AGNs remain hidden.

This paper is structured as follows. In Section 2 we introduce the analyzed high-redshift galaxy sample and describe its properties. The analysis of the Chandra data is described in Section 3. The results of our paper, including the potential individual detections and the lower and upper limits on the stacked samples are presented in Section 4. In Section 5, we place our results into context, where we compare our results with previous studies and discuss the overall importance of our results. We summarize the results of our study in Section 6. Throughout the paper we assume \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( \Omega_M = 0.27 \), and \( \Omega_\Lambda = 0.73 \). The error bars are 1\( \sigma \) uncertainties and the presented upper limits are also 1\( \sigma \) limits.

2. The Analyzed Galaxy Sample

The lensing magnification caused by the RELICS clusters provides an incredible opportunity to study high-redshift AGNs behind these galaxy clusters. The RELICS survey is a HST Treasury program (PI: Coe) and a Spitzer Space Telescope program (PI: Bradač), which studied 41 massive galaxy clusters that serve as exceptional gravitational lenses. The galaxy clusters reside in the redshift range of \( z = 0.18-0.97 \), which is ideal to utilize the lensing magnification from the clusters and study high-redshift AGNs. To study the X-ray emission from the lensed high-redshift AGNs, high-resolution X-ray observations with Chandra are essential. Although Chandra did not carry out a systematic study of the RELICS clusters, 35 of the 41 clusters have been observed with Chandra. Of these galaxy clusters, we excluded El Gordo (ACT-CLJ0102-49151) whose intracluster medium (ICM) is extremely bright and would outshine possible detections of faint high-redshift AGNs and would dominate the overall emission in the galaxy stacks. Therefore, in this work, we study lensed galaxies that are behind the remaining 34 galaxy clusters. The basic properties of this sample are given in Table 1.

The detailed analysis of HST and Spitzer data identified 207 galaxies with redshifts of \( 6 \lesssim z \lesssim 8 \) (Strait et al. 2021). Of these galaxies, 174 are behind the studied 34 galaxy clusters. Based on the HST and Spitzer data, the physical characteristics of the galaxies were computed using two spectral energy distribution (SED) fitting methods. In the first method (dubbed as Method A), the redshift of each galaxy was computed using the Easy and Accurate Redshifts from Yale code (EAZY; Brammer et al. 2008). The resulting photometric redshift probability distribution functions and stellar population synthesis templates were used to calculate the stellar properties of the galaxies. In the second method (dubbed as Method B), the Bayesian Analysis of Galaxies for Physical Inference and Parameter Estimation code (BAGPIPES; Carnall et al. 2018) was used to fit the redshift and the physical properties of the galaxies using the MultiNest nested sampling algorithm. While both of these methods utilize the SEDs of galaxies, they apply a different methodology and template set to obtain the galaxies’ properties. These differences result in different galaxy properties and distributions of these properties (for details, see Strait et al. 2021). Following Strait et al. (2021), we use the values obtained via Method A as our default throughout this paper. We note that using the redshift-fitting procedure of Method A, 19 galaxies were demoted to low-redshift systems. We excluded these galaxies from our study. Therefore, our final galaxy sample consists of 155 \( z \gtrsim 6 \) galaxies. In Figure 1, we present the stellar mass, star formation rate, redshift, and lensing magnification distributions of the 155 lensed galaxies in our sample.

The lensing magnification of the galaxies plays an essential role in our study. In this work, we rely on the magnifications published in Strait et al. (2021). To compute the magnifications, they used three different lens models (if available) to derive lensing maps of the clusters, thereby deriving the lensing magnification for each galaxy. Since the individual lensing magnifications vary, they applied bootstrapping for each lensing model and created multiple lensing constraints for the position of each galaxy. Then the median of these realizations was computed. Since multiple methods were used to obtain the lensing maps, the final lensing magnification was the average of the medians obtained from the different methods. Further details about the analysis are provided in Strait et al. (2021). The derived lensing magnifications are in the range of \( \mu = 1-95 \), with only 10 galaxies having \( \mu > 15 \). The distribution of magnifications is shown in Figure 1. As a caveat, we note that magnifications \( \gtrsim 10 \) typically have large uncertainties (Meneghetti et al. 2017), therefore such sources need to be treated with caution.

3. Analysis of the Chandra Data

The analysis of the Chandra data was carried out using standard CIAO tools (version 4.13) and the CALDB (version 4.9.4). All Chandra data were obtained from the public archive. We analyzed 105 high-resolution imaging observations (Table 2). While most of these were taken with ACIS-I array, eight observations were done with the ACIS-S array. To maximize the signal-to-noise ratios of our analysis, we include
data from both ACIS-I and ACIS-S observations. The total exposure time of the observations was 3.53 Ms.

The first step of the analysis was to reprocess all observations. Since the observations were taken in a broad timeframe (from 2000 to 2019), it is essential to apply the same calibration data for each observation. Therefore, we used the chandra_repro tool on all observations. Following this step, we filtered the high background time periods. We produced light curves in the 2.3–7.3 keV energy range in 200 s bins and excluded those time periods where the count rate exceeded the mean value by 2σ. Because ACIS-I is only weakly sensitive to high-background periods, the total exposure times were not affected significantly.

To account for vignetting effects, we constructed exposure maps for each observation. Because the main goal of this work is to study the characteristics of high-redshift AGNs, we assumed a power-law model with a slope of $\Gamma = 1.9$, which is appropriate to describe the spectrum of high-redshift AGNs (Nanni et al. 2017). These exposure maps were used to convert the counts to flux units. Since several clusters were observed in multiple pointings, the individual observations and exposure maps were coadded to obtain merged event files and images of the clusters.

Although our main goal is to identify high-redshift AGNs, it is expected that there will be many lower-redshift AGNs in the field of view that could contaminate the sample. To identify point sources in the individual galaxy clusters, we used the CIAO WAVDETECT tool. We searched for point sources in the merged images in the 0.5–7 keV (broad band), 0.5–2 keV (soft band), and 2–7 keV (hard band) energy ranges. We derived point-spread function (PSF) maps for each observation using the MKSPFMAP tool, which is used by WAVDETECT to look up the size of the PSF for each pixel in the images. To detect both small and more extended features in the images, we used the square-root two series of 2 from $\sqrt{2}$ to 16. In addition, we set the ELLSIGMA parameter to 4, which assures that $\geq 90\%$ fraction of counts associated with the point sources are encircled. Therefore, the residual counts from point sources are not expected to significantly contribute to the large-scale diffuse emission. The significance threshold of the source detection was set to $10^{-6}$, which is expected to result in one false detection per each $1024 \times 1024$ pixel image. We identified 3558 point sources within the footprint of the galaxy.
clusters. Given the applied significance threshold of the WAVDETECT tool and the area covered by the detectors, we estimate that about 4% of the sources are of a spurious nature. This source list was used to probe whether individual high-redshift AGNs at the known coordinates of lensed galaxies are detected in the Chandra images. Finally, we excluded the detected point sources when carrying out the stacking analysis.

We extracted images in the broad, soft, and hard bands. These images were used to cross-correlate the X-ray source list with the galaxy positions and to stack the individual galaxies. To carry out the stacking, we cut out 100 × 100 pixel regions of the images and exposure maps around each galaxy, and coadded the image and exposure map cutouts.

The lensing magnification affects the fluxes that we observe from the high-redshift AGNs. Since the gravitational lensing is achromatic, photons in the optical and X-ray wave band are magnified by the same factor. To account for the magnification factors, we rely on the average lensing magnifications derived by Strait et al. (2021), who used a substantial set of lensing models to derive the median magnification factor at the individual galaxy’s position and redshift (see Section 2). Because the lensing magnification only affects the emission from the source and not from the instrumental or sky background, we applied the magnification correction on the background-subtracted count rates. Specifically, we multiplied each exposure map associated with the individual galaxies with the corresponding median lensing magnification taken from Strait et al. (2021). To compute the fluxes and upper limits of the stacked AGNs, we used the exposure maps, which were convolved with the lensing magnification.

4. Results
4.1. Individual Detections

We first investigated whether the merged Chandra images of individual RELICS clusters can detect an AGN associated with the high-redshift galaxies. To this end, we cross-correlated the coordinates of the detected X-ray sources with those of the
lensed galaxies. To maximize the likelihood of the search, we carried out the cross-correlation in all three energy ranges. We searched for counterparts within a $2.5'$ radius. This fairly large search radius was chosen to conservatively account for any differences between the astrometric accuracy of HST and Chandra (Liu et al. 2021) and to consider the broader Chandra PSF at the edges of the detectors.

We identified two X-ray sources that are in the proximity of high-redshift lensed galaxies. The galaxies are located in MACS0553-33 and PLCKG287+32 and their IDs in the high-redshift galaxy catalog are 830 and 792, respectively. The redshifts of these galaxies are $z = 6.55$ and $z = 7.82$ for IDs 830 and 792. The coordinates and properties of the X-ray source-lensed galaxy pairs are given in Table 3. The offsets between the positions of the X-ray sources and the lensed galaxies are

| Obs. ID | $t_{exp}$ (ks) | Detector | Obs. Date  |
|---------|----------------|----------|------------|
| 520     | 67.41          | ACIS-I   | 2000-08-18 |
| 528     | 9.47           | ACIS-I   | 2000-10-10 |
| 531     | 9.01           | ACIS-I   | 1999-12-29 |
| 532     | 7.97           | ACIS-I   | 1999-10-21 |
| 545     | 9.45           | ACIS-I   | 2000-07-29 |
| 913     | 36.48          | ACIS-I   | 2000-09-08 |
| 926     | 44.23          | ACIS-I   | 2000-06-11 |
| 1653    | 71.15          | ACIS-I   | 2001-06-16 |
| 1654    | 19.85          | ACIS-I   | 2000-10-03 |
| 2213    | 58.31          | ACIS-S   | 2001-08-28 |
| 3251    | 19.33          | ACIS-I   | 2002-11-11 |
| 3262    | 21.36          | ACIS-I   | 2003-01-22 |
| 3265    | 17.90          | ACIS-I   | 2002-10-02 |
| 3268    | 24.45          | ACIS-I   | 2002-03-10 |
| 3274    | 14.32          | ACIS-I   | 2002-11-06 |
| 3276    | 13.91          | ACIS-I   | 2002-06-14 |
| 3284    | 17.74          | ACIS-I   | 2002-10-08 |
| 3581    | 18.47          | ACIS-I   | 2003-08-23 |
| 3586    | 29.72          | ACIS-I   | 2002-12-28 |
| 3587    | 17.88          | ACIS-I   | 2003-02-23 |
| 3591    | 19.60          | ACIS-I   | 2003-08-28 |
| 4215    | 66.27          | ACIS-I   | 2003-12-04 |
| 4217    | 19.52          | ACIS-I   | 2002-12-15 |
| 4962    | 36.19          | ACIS-S   | 2004-09-09 |
| 4993    | 23.40          | ACIS-I   | 2004-06-08 |
| 5010    | 24.83          | ACIS-I   | 2004-08-09 |
| 5012    | 23.79          | ACIS-I   | 2004-03-08 |
| 5813    | 9.94           | ACIS-I   | 2005-01-08 |
| 6106    | 35.30          | ACIS-I   | 2004-12-04 |
| 7000    | 5.08           | ACIS-I   | 2006-12-30 |
| 7003    | 5.08           | ACIS-I   | 2007-01-01 |
| 7110    | 6.97           | ACIS-I   | 2007-07-12 |
| 7111    | 6.96           | ACIS-I   | 2007-01-13 |
| 9372    | 38.51          | ACIS-I   | 2008-08-11 |
| 9376    | 19.51          | ACIS-I   | 2008-10-03 |
| 9409    | 19.91          | ACIS-I   | 2008-02-02 |
| 9424    | 109.66         | ACIS-I   | 2008-01-01 |
| 9425    | 113.52         | ACIS-I   | 2007-12-24 |
| 9426    | 110.69         | ACIS-I   | 2008-01-09 |
| 9430    | 113.52         | ACIS-I   | 2008-01-11 |
| 10413   | 75.64          | ACIS-I   | 2008-10-16 |
| 10786   | 13.91          | ACIS-I   | 2008-10-18 |
| 10797   | 23.85          | ACIS-I   | 2008-10-21 |
| 11719   | 9.65           | ACIS-I   | 2009-10-18 |
| 12244   | 74.06          | ACIS-I   | 2011-06-23 |
| 12260   | 19.79          | ACIS-I   | 2012-01-06 |
| 12286   | 47.10          | ACIS-I   | 2012-01-10 |
| 12300   | 29.66          | ACIS-I   | 2010-11-26 |
| 13194   | 19.97          | ACIS-I   | 2010-11-28 |
| 13201   | 48.71          | ACIS-I   | 2011-01-06 |
| 13997   | 27.64          | ACIS-I   | 2012-09-27 |
| 14017   | 15.01          | ACIS-I   | 2012-11-03 |
| 14018   | 35.60          | ACIS-I   | 2012-09-15 |

Table 2
List of Analyzed Chandra Observations

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Interestingly, the median lensing magnifications at the positions of the galaxies are among the largest in our sample: they are $\mu = 16.87$ for the source in MACS0553-33 and $\mu = 9.83$ for PLCKG287+32, respectively.

In Figure 2, we show the broadband Chandra and HST images of the two X-ray sources and the high-redshift galaxies. The sources in MACS0553-33 and PLCKG287+32 have $6.5 \pm 3.6$ and $16.0 \pm 7.2$ net counts in the broad band, respectively. Both sources lie relatively close to the aim point, implying a narrow PSF. The offset between the X-ray source–galaxy pairs is about 2″. At the redshift of the galaxies, the...
projected offset corresponds to ~10 kpc, which is nearly an order of magnitude larger than the typical half-light radius of typical galaxies at z ~ 6 (Bouwens et al. 2004). Astrometric uncertainties cannot explain the large offset since the typical offset between Chandra and HST astrometry is 0′′.35 (Liu et al. 2021). This suggests that the X-ray sources are not associated with the high-redshift galaxies.

Given the large number of X-ray sources detected on the Chandra images, it is possible that the association is due to coincidence. To estimate the likelihood of random matches, we carried out Monte Carlo simulations. We generated random coordinates within the footprint of the galaxy clusters. For each cluster, the number of random coordinates was the same as the number of high-redshift galaxies in the given cluster. Based on these sets of coordinates, we searched for matches between the simulated “high-redshift galaxies” and the X-ray sources. To obtain a statistically meaningful sample, we generated 10,000 random sets of “high-redshift” galaxies, which amounts to 155 × 10^4 = 1.55 × 10^6 randomly selected coordinates. We identified 2373 random matches for all these coordinates, which suggests that the likelihood of chance coincidence is ≈0.15%. Thus, we expect ≈0.23 random matches. While this number is lower than two X-ray source–galaxy pairs, it is also possible that the X-ray sources are spurious detections (Section 3).

The other X-ray sources in our sample do not have a high-redshift galaxy in their proximity. This suggests that most point sources are associated with AGNs at lower redshifts or they may be foreground objects.

### 4.2. Stacking the High-redshift Galaxies

To increase the signal-to-noise ratios and the likelihood of detecting high-redshift AGNs, we stacked the X-ray photons associated with the individual galaxies. This approach, combined with the lensing magnifications, allows us to probe relatively faint AGNs. Indeed, the sensitivity of our study is nearly compatible with that achieved in the 7 Ms Chandra Deep Field South regions (see Section 5.1).

A major difference between the present work and previous stacking analyses (e.g., Vito et al. 2016) is that we are coadding galaxies that reside behind rich galaxy clusters. Therefore, emission from the ICM contributes to the overall emission and elevates the background level. In addition, the ICM exhibits notable structure across galaxy clusters, particularly in merging systems. In our analysis, we do not specifically account for the varying level of ICM emission associated with the individual lensed galaxies. Because the regions that were cut around individual galaxies are small (Section 3) relative to the angular size of the galaxy clusters, variations in the ICM emission are negligible on these small scales and average out across the stacked images.

We carried out the stacking analysis in all three energy ranges using multiple approaches. First, we coadded all 155 galaxies in our sample. In Figure 3, we present the broadband stacked X-ray images of the galaxies. Visual inspection of the galaxies does not reveal a bright point source at the center of the images. When investigating the images extracted in the soft and hard bands, we also did not identify a point source. To constrain the flux associated with the stacked AGNs, we extracted the counts from the stacked images and applied the stacked lensing-corrected exposure maps. The source and background regions were described with a circular region with a 1′′5 radius and with an annulus with 5′′–10′′ radii, respectively. We did not detect a statistically significant signal associated with the stacked high-redshift AGNs. In the absence of a detection, we place an upper limit on the flux. To be consistent with previous works (e.g., Vito et al. 2016), we report the upper limits in the 0.5–2 keV energy range. Taking into account the lensing-corrected exposure maps, the upper limit on the flux is F_{0.5-2 keV} < 2.1 × 10^{-18} erg s^{-1} cm^{-2}, which corresponds to a luminosity of L_{0.5-2 keV} < 9.1 × 10^{41} erg s^{-1} using the mean redshift of z = 6.11.

Although the entire galaxy sample does not reveal a detection, we further split our sample to increase the likelihood of a detection. We used three criteria to divide our sample. First, we split the galaxies based on their stellar mass. It is well established that the stellar bulge mass of galaxies is proportional with the BH mass in the local universe (e.g., McConnell & Ma 2013; Saglia et al. 2016). Recently, this correlation was investigated for dwarf galaxies and it was found that the M_{BH} – M_{bulge} relation can be extended to these low-mass galaxies (Schutte et al. 2019). While this relation may be different for galaxies at z ~ 6, it is reasonable to assume that more massive galaxies, even in the low-mass regime, host more massive BHs, which, in turn, are expected to shine brighter as AGNs. Hence, by dividing our sample by mass, we expect that the average luminosity of the AGNs in the high-mass sample will become detectable. The luminosity of AGNs in low-mass galaxies will be lower than that of the entire sample, implying that this sample will remain undetected. To split the sample based on mass, we applied 4 × 10^8 M_⊙ as our threshold, which approximately splits our sample into two equal-sized groups. After stacking the galaxies in the two subsamples, we obtained a 2.2σ detection in the high-mass sample (Figure 3, top-left panel), while the low-mass sample remained undetected.
Specifically, we detected $59.4 \pm 26.5$ net counts in the broad band, which corresponds to a weak detection. We note that the level of the detection significance does not exhibit notable variation if different background regions are used. We derive fluxes of $F_{0.5-2\text{ keV}} = (8.1 \pm 3.6) \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ and $F_{0.5-2\text{ keV}} < 2.5 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ for the two samples, which correspond to $L_{0.5-2\text{ keV}} = (3.7 \pm 1.6) \times 10^{42} \text{ erg s}^{-1}$ and

Figure 4. Stacked 0.5–7 keV band Chandra images of lensed high-redshift galaxies using different binning criteria. We split the galaxies based on stellar mass (top row), star formation rate (middle), and lensing magnification (bottom). We obtained a weak, 2.2σ detection for the high-mass subsample, while other subsamples remained undetected. The physical criteria used to divide the galaxies into bins are shown on the stacked images.
and B in Strait et al. 

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Table 4

Properties of the Stacked Samples

| Bin          | $N_{gal}$ | $z$  | $\mu$ | $M_\star$ (#A) | $M_\star$ (#B) | SFR (#A) | SFR (#B) | $F_{\text{obs},0.5-2\text{ keV}}$ (erg s$^{-1}$ cm$^{-2}$) | $L_{\text{obs},0.5-2\text{ keV}}$ (erg s$^{-1}$) |
|--------------|-----------|------|-------|----------------|---------------|----------|----------|-------------------------------------------------|----------------------------------|
| High mass    | 73        | 6.22 | 3.6   | $2.6 \times 10^6$ | $4.7 \times 10^6$ | 16.8     | 22.0     | $(8.1 \pm 3.6) \times 10^{-18}$ | $(3.7 \pm 1.6) \times 10^{22}$ |
| Low mass     | 82        | 6.01 | 7.9   | $1.4 \times 10^6$ | $9.2 \times 10^6$ | 4.4      | 3.8      | $<2.5 \times 10^{-18}$ | $<1.0 \times 10^{22}$ |
| High SFR     | 105       | 6.17 | 5.8   | $1.8 \times 10^6$ | $3.6 \times 10^6$ | 13.7     | 16.7     | $<2.7 \times 10^{-18}$ | $<1.1 \times 10^{22}$ |
| Low SFR      | 50        | 5.99 | 6.2   | $2.6 \times 10^6$ | $8.3 \times 10^6$ | 3.0      | 3.2      | $<3.3 \times 10^{-18}$ | $<1.4 \times 10^{22}$ |
| $\log \mu > 0.5$ | 48    | 6.37 | 13.8  | $1.3 \times 10^6$ | $3.1 \times 10^6$ | 10.6     | 17.3     | $<2.6 \times 10^{-18}$ | $<1.2 \times 10^{22}$ |
| $\log \mu < 0.5$ | 107  | 5.99 | 2.4   | $1.3 \times 10^6$ | $2.5 \times 10^6$ | 10.1     | 10.1     | $<3.4 \times 10^{-18}$ | $<1.4 \times 10^{22}$ |
| All RELICS   | 155       | 6.11 | 5.91  | $1.3 \times 10^6$ | $2.7 \times 10^6$ | 10.3     | 12.3     | $<2.1 \times 10^{-18}$ | $<9.1 \times 10^{21}$ |

$N_{gal}$ All galaxies in the Chandra Deep Field South (CDF-S) field with $5.5 < z < 6.5$. The stellar mass and star formation rates (SFRs) for the CDF-S galaxies are based on Santini et al. (2015). Because these values were not computed following the method described in Strait et al. (2021), we opt to show the range of these parameters. Columns are as follows. (1) Binning method; (2) number of galaxies in the bin; (3) mean redshift of galaxies; (4) median lensing magnification factor; (5) and (6) mean stellar mass of galaxies obtained via Methods A and B in Strait et al. (2021), respectively; (7) and (8) mean star formation rate of galaxies computed via Methods A and B in Strait et al. (2021); (9) and (10) observed flux and luminosity of the galaxies in the 0.5–2 keV band, respectively.

Note.

$\mu_{0.5\text{ keV}} < 1.0 \times 10^{19}$ erg s$^{-1}$. We further discuss this possible detection in Section 5.

The second approach to split the galaxies into two samples was based on the star formation rate. It is believed that the stellar population of galaxies coevolves with their central BH as they are feeding from the same gas supply (e.g., Hopkins et al. 2006). This, in turn, suggests that galaxies with high star formation rate may host BHs that are growing at a more rapid pace and hence are more luminous. Additionally, galaxies with high star formation rates are expected to host a more numerous population of high-mass X-ray binaries, whose total luminosity is proportional to the star formation rate of the host galaxy (Mineo et al. 2012; Fragos et al. 2013). Finally, actively star-forming galaxies are also more likely to host ultraluminous X-ray sources, which can have luminosities comparable to low-luminosity AGNs (Kovlakas et al. 2020). Taken all together, galaxies with high star formation rates may exhibit a higher X-ray luminosity and could be detected in the stacked sample. We split our galaxy sample into two groups using $4 M_\star$ yr$^{-1}$ as the threshold. We did not detect a statistically significant signal from either subsamples. Therefore, we derived 1σ upper limits on the fluxes and luminosities of the galaxies.

As the third approach, we split the galaxy sample based on their median lensing magnification. The advantage of this method is that the lensing magnification only boosts the signal from the high-redshift galaxies (i.e., the luminosity of the AGNs), while it does not increase the galaxy cluster emission and the overall background level. Hence, the high-lensing-magnification sample should result in improved signal-to-noise ratios from the AGNs. We selected $\log \mu = 0.5$ as our threshold to split the galaxies. After stacking the two subsamples and measuring the count rates, we found that none of the two subsamples exhibit detections. Therefore, we derived upper limits on the flux and luminosity of the AGNs.

We present the stacked 0.5–7 keV band images in Figure 4 and we tabulated the results of the stacking analysis in Table 4. This table includes the number of galaxies, fluxes, and luminosities for each subsample. While we relied on Method A to split the galaxies into subsamples, for completeness we also list the mean physical properties of the galaxies obtained through Method B. The results are further discussed in Section 5.

5. Discussion

5.1. Comparison with Chandra Deep Field South

So far the most powerful constraints on the average properties of high-redshift AGNs were obtained by Vito et al. (2016), who carried out a stacking analysis using the deep, 7Ms observations of the CDF-S field. Vito et al. (2016) stacked AGNs in three redshift bins: $3.5 < z < 4.5$, $4.5 < z < 5.5$, and $5.5 < z < 6.5$. They obtained a statistically significant detection in the lowest-redshift bin, a tentative detection in the $4.5 < z < 5.5$ bin, but AGNs in the highest-redshift bin remained undetected. Due to the large galaxy sample and the deep observations, the total stacked exposure time of galaxies in the $5.5 < z < 6.5$ redshift bin was about $1.35 \times 10^{5}$ s and the derived flux upper limit was $<4.4 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to a luminosity of $<1.8 \times 10^{41}$ erg s$^{-1}$ assuming $z = 6$ (Table 4).

Although the number of high-redshift galaxies in our sample is similar to that studied in Vito et al. (2016), the stacked exposure time of the galaxies in the RELICS sample is nearly 2 orders of magnitude shorter and is about $2.0 \times 10^{5}$ s. However, the lensing magnification of the galaxy clusters significantly improves our signal-to-noise ratios. Since the gravitational lensing is achromatic, it increases the signal from the high-redshift galaxies but not the background emission (including the X-ray emission originating from the ICM).

Similarly to the galaxies in CDF-S, we also did not detect a statistically significant signal from high-redshift galaxies when stacking all galaxies in the sample. The 0.5–2 keV band flux upper limits are about a factor of $\sim 4$ times higher than those obtained in the CDF-S footprint. Similarly to Vito et al. (2016), we divided our sample based on the stellar mass of the host galaxies. Interestingly, we obtained a weak ($\sim 2.2\sigma$) detection in the stacked galaxy sample, with fluxes of $8.1 \times 10^{-18}$ erg s cm$^{-2}$, which exceeds the CDF-S flux upper limit by factor of $\sim 8$. However, due to the relatively low signal-to-noise ratio of the detection, we cannot exclude that this detection is an upward fluctuation. This detection is further discussed in the next section.
5.2. Detection in the High-mass Subsample

Our sample of massive high-redshift galaxies exhibited a 2.2σ detection. The corresponding X-ray flux is a factor of about 8 times higher than the upper limit obtained for z ∼ 6 galaxies in the CDF-S field. This result may appear controversial, especially when comparing the stellar masses of the galaxies in the CDF-S and RELICS samples. The median stellar mass of the RELICS galaxies is lower than that of the CDF-S galaxies (Table 4). However, this difference is likely due to systematic effects associated with the determination of stellar masses at high redshifts.

The SED fitting of the CDF-S galaxies was done by 10 independent teams (Santini et al. 2015). The stellar masses presented in Vito et al. (2016) correspond to the median of the stellar masses obtained from these 10 different groups. At z < 5.5, the stellar mass estimates obtained through different methods are in good agreement with each other. However, at high redshift (5.5 < z < 6.5) there are large differences, which are mostly caused by the inclusion (or omission) of nebular line emission in the models. Specifically, only three teams included the nebular line emission in their SED-fitting procedure, which, however, is essential to accurately fit the SED of high-redshift galaxies. Indeed, emission lines, such as H-β and [O iii], can substantially contaminate the observed rest-frame window and drastically alter the SED fitting. The net effect of this is that the stellar mass of high-redshift galaxies can be overestimated. According to Santini et al. (2015), the omission of nebular lines in young and/or high-redshift galaxies can result in stellar masses that are overestimated by up to a factor of 25. Based on Santini et al. (2015), we estimate that not accounting for nebular emission lines will result in factor of ~3 too high stellar masses for the overall 5.5 < z < 6.5 galaxy population with ~15% of the galaxies having a factor of ~5 too high stellar masses. Since the stellar masses presented in Santini et al. (2015) are the median\(^6\) of the values obtained by the different teams and most of the teams did not include emission from the nebular emission lines, the stellar masses for the 5.5 < z < 6.5 galaxies presented in Santini et al. (2015) and employed in Vito et al. (2016) are overestimated.

As opposed to this, nebular emission lines were included in the SED-fitting procedure for the RELICS galaxies (Strait et al. 2021), which therefore provides more accurate stellar masses. Thus, the large offset between the stellar masses of the CDF-S and RELICS samples can be explained with the different SED-fitting methods, in particular by the inclusion of nebular emission lines. Taking this difference into account, it is feasible that the RELICS high-mass sample includes—on average—more massive galaxies than the CDF-S field. In addition, we note that in the present work we utilize the stellar masses obtained through Method A in Strait et al. (2021). However, the stellar masses derived through Method B are systematically higher than those in Method A; for example for the high-mass sample the stellar masses are a factor of ~2 higher (Figure 5).

Therefore, the stacked detection of high-redshift galaxies behind the RELICS clusters is not incompatible with the nondetection of high-redshift galaxies in the CDF-S field. Indeed, the analysis of Vito et al. (2016) pointed out for the 3.5 < z < 5.5 stacked samples that the detected X-ray signal from AGNs is most sensitive to the stellar mass of the host galaxies and the most massive galaxies dominate the signal.

To further probe whether the 2.2σ detection is caused by the more massive nature of galaxies in the high-mass bin or other, randomly selected galaxies can reproduce the observed signal, we carried out jackknife resampling. To this end, we randomly selected the coordinates of 73 high-redshift galaxies (which is identical with the number of galaxies in the high-mass bin) from the sample, coadded the X-ray photons associated with them, and derived the detection significance in the 0.5–7 keV energy range. We repeated this analysis 10\(^5\) times to obtain a statistically meaningful sample. The detection significances of the randomly selected and stacked galaxies show a normal distribution that has a peak-detection significance distribution at ≈0.16σ. We found that only ≲0.3% of the random resampling simulations show >2.2σ detections. This is less frequent than that suggested by the 2.2σ detections, hinting that the detection in the massive high-redshift galaxies is unlikely to be the result of chance coincidence.

5.3. Comparison with Individual Detections

Over recent decades, wide-area optical and infrared surveys have identified a substantial population (>200) of extremely luminous quasars at z > 5.5 (e.g., Fan et al. 2006; Willott et al. 2007; Jiang et al. 2008; Mortlock et al. 2011; Venemans et al. 2013; Bañados et al. 2014; Wang et al. 2017; Yang et al. 2017; Wang et al. 2019; Yang et al. 2019, 2020). A fraction of these sources were followed up using X-ray observatories, which allowed the determination of the X-ray properties of these high-redshift AGNs (e.g., Nanni et al. 2017; Vito et al. 2019; Pons et al. 2020; Wang et al. 2021). These studies established that the X-ray luminosities of these sources range from several times 10\(^{43}\) erg s\(^{-1}\) to a few times 10\(^{45}\) erg s\(^{-1}\).

\(^6\) The median of the stellar masses in Santini et al. (2015) was computed using the Hodges–Lehmann estimator.
Clearly, the luminosity of the quasars studied in Nanni et al. (2017) surpasses the X-ray upper limits obtained in our stacking analysis by about 1.5–3.5 orders of magnitude. Although the source-detection sensitivity strongly varies in our galaxy cluster sample due to the different exposure times and spatially varying lensing magnifications, we estimate the typical detection sensitivity of our study. To this end, we rely on the average Chandra exposure time ($t_{\text{exp}} = 104$ ks) of the RELICS galaxy cluster sample (Table 1), use the median lensing magnification factor of $\mu = 3$, apply the median redshift ($z = 5.9$) of the lensed galaxies, and assume that an X-ray AGN can be detected with 10 counts. We thus obtain an average source-detection sensitivity of $\sim 10^{44}$ erg s$^{-1}$, which implies that the bulk of the quasars in the sample of Nanni et al. (2017) could be individually detected behind the RELICS clusters.

In the sample of RELICS galaxies, we did not identify a conclusive X-ray source–galaxy pair. In the absence of detection, we place an upper limit on the number of luminous AGNs in high-redshift galaxies using the Bayesian formalism for Poisson-distributed data (Kraft et al. 1991). The 95% confidence interval for nondetection yields an upper limit of three sources, which implies that $<1.9\%$ of $z \geq 6$ galaxies host AGNs with luminosities of $\geq 4 \times 10^{43}$ erg s$^{-1}$. This result is also in line with our stacking analysis, which suggests that no more than a few percent of galaxies may host AGNs with such high luminosities.

### 5.4. High-mass X-Ray Binaries

Although the primary goal of our study is to constrain the X-ray emission from luminous high-redshift AGNs, other sources also contribute to the overall X-ray emission. Most notably, high-mass X-ray binaries (HMXBs) also present a major source of X-ray emission. The X-ray emission from these sources is proportional to the star formation rate of the galaxy. Taking into account the $L_X$–SFR relation (Fragos et al. 2013), the redshift evolution of the relation (Lehmer et al. 2016), and assuming a power-law slope with $\Gamma = 2$, the average expected 0.5–2 keV band luminosity from HMXBs is $1.4 \times 10^{41}$ erg s$^{-1}$.

This average HMXB luminosity is about an order of magnitude below our detection limit. Therefore, given the sensitivity of our stacking analysis, it is unlikely that HMXBs can be detected in the present data set, even in our high-SFR subsample. Therefore, the nondetection of X-ray emission from HMXBs is consistent with the estimated X-ray luminosity from these sources. As a caveat, we note that the $L_X$–SFR scaling relation has only been probed up to $z \sim 2.5$ and it cannot be excluded that $z \approx 6$ galaxies exhibit a different relation. However, based on the observed redshift evolution of this relation, it seems unlikely that their contribution will be close to the sensitivity of our stacking analysis. Additionally, we note that the X-ray emission from HMXBs are also not expected to play a significant role in the obtained $2.2\sigma$ detection in the high-mass bin. Specifically, HMXB are expected to account for $\sim 6\%$ of the total emission in the 0.5–2 keV energy range.

The predicted X-ray luminosity associated with high-redshift galaxies with the highest star formation rates ($\sim 100 M_\odot$ yr$^{-1}$) is about $1.5 \times 10^{42}$ erg s$^{-1}$. While these luminosities are comparable with the average sensitivity of the stacks, these values remain below the individual source-detection limits, which is also consistent with the fact that none of the galaxies with high star formation rate were individually detected on the Chandra images. The metallicity of galaxies strongly influences the number of HMXBs (e.g., Linden et al. 2010; Lehmer et al. 2016). Specifically, the number of HMXBs per unit stellar mass is significantly higher in galaxies with low ($\sim 20\%$) metallicities (Douna et al. 2015), with the excess sources being mostly present at the bright end of the X-ray luminosity function (Lehmer et al. 2021). While the effect of decreasing metallicity at higher-redshift galaxies was incorporated in the model of Lehmer et al. (2016), galaxies with extremely low metallicities and high star formation rates could be individually detected in other lensed high-redshift galaxies. Additionally, future, more sensitive X-ray surveys will be able to detect the X-ray emission from HMXBs in high-redshift galaxies.

### 5.5. Constraining the Properties of $z \sim 6$ Black Holes

Based on the data from the stacked galaxies, we can constrain the characteristics of the typical $z \sim 6$ AGN. The X-ray upper limit on the luminosity of the BHs in the RELICS galaxy sample is $L_X < 8.4 \times 10^{41}$ erg s$^{-1}$ (Table 4). Assuming a bolometric correction of $K_{\text{bol}} = 10$ (Lusso et al. 2012; Duras et al. 2020), the upper limit on the bolometric luminosity is $L_\text{bol} < 8.4 \times 10^{42}$ erg s$^{-1}$. If BHs accrete at their Eddington rate, this upper limit corresponds to a mean BH mass of $M_{\text{BH}} < 6.7 \times 10^6 M_\odot$. Clearly, this average BH mass is about 4 orders of magnitude lower than those detected in the most luminous quasars.

If we assume that galaxies at $z \sim 6$ obey the BH mass–bulge mass scaling relation obtained in the local universe (Schute et al. 2019) and consider the mean stellar mass of our sample ($1.3 \times 10^{10} M_\odot$), we expect a mean BH mass of $M_{\text{BH}} = 2.6 \times 10^6 M_\odot$. This implies that the BH mass calculated from the mean stellar mass is $\sim 40$ times larger than the upper limit assuming Eddington accretion. Thus, our results imply that BHs are either much less massive at $z \sim 6$ than expected from the local scaling relation or they accrete at a few percent of their Eddington rate. We note that the former possibility is incompatible with some observational studies. Specifically, Merloni et al. (2010) suggested that BHs at high redshift may be over-massive relative to their host galaxies, and Bogdán et al. (2012) hinted that some BHs may grow faster than their host galaxies at high redshift. However, the relatively low mean accretion rate is feasible if most BHs originate from the heavy-seed scenario. In this picture, BHs may experience episodic periods with high accretion rates, while most times they accrete at low Eddington rates. Obscuration of AGNs by gas and dust may also play an important role in the nondetection, as it could hide the X-ray emission from these sources (see Section 5.6 for details). Finally, it is also feasible that the BH occupation fraction of galaxies is not 100%, implying that a fraction of low-mass systems do not host a BH (Lippai et al. 2009; Bellovary et al. 2011).

Performing a similar calculation for the high-mass subsample that has a weak X-ray detection results in the same conclusion. The bolometric X-ray luminosity for these BHs is $L_\text{bol} = 3.7 \times 10^{42}$ erg s$^{-1}$, which corresponds to a mean BH mass of $M_{\text{BH}} = 3.0 \times 10^5 M_\odot$ assuming Eddington accretion. The average stellar mass of our high-mass sample is $2.6 \times 10^9 M_\odot$, which would imply that the mean BH mass is $6.5 \times 10^6 M_\odot$ if they follow the local scaling relation. The latter value is $\sim 22$ times lower than that obtained assuming the Eddington accretion rate. Therefore, it is likely that even these more massive BHs do not accrete at the Eddington limit, but the average accretion rate remains at the $\sim 5\%$ level.
The low average accretion rate is not surprising when compared to theoretical studies. Most of the BH accretion, and hence BH growth, is expected to happen in the most luminous AGNs, and it is expected that BHs with low accretion rates will have a small contribution to the overall BH growth. For example, Volonteri et al. (2016) established, based on the Horizon-AGN simulations, that at high redshifts (z > 4), the bulk of the BH growth takes place in the most luminous (L_{bol} > 10^{44}\text{ erg s}^{-1}) and most rapidly accreting (f > 0.1f_{edd}) AGNs. Because the sensitivity of our stacking analysis is well below this limit, the nondetection of the AGNs in the full stacked RELICS galaxy sample is consistent with this. Since the observed luminosity of an AGN depends both on the Eddington ratio and the BH mass, the detection of AGNs in the high-mass galaxy subsample may be attributed to the more massive BH sample even though the mean accretion rates are still low.

5.6. Obscuration

A fraction of AGNs remains hidden behind gas and dust that absorbs the emission from the accretion disk of the BH. Because the obscured fraction of these AGNs may depend on both the luminosity and the redshift, our understanding of the complete census and evolution of AGNs depends on the obscured fraction of AGNs. A wide range of studies have explored the obscuration of high-redshift AGNs, which found that about 50% of 3 < z < 6 AGNs are obscured by a column density N_H > 10^{21}\text{ cm}^{-2} (Vito et al. 2013; Hickox & Alexander 2018; Vito et al. 2018).

To assess the importance of obscuration, we follow Vito et al. (2016) and assume that 50% of the AGNs are obscured by a column density N_H = 3.2 \times 10^{20}\text{ cm}^{-2} and assume that all sources have the same intrinsic luminosity. Given these conditions, the transmission factor for typical z = 6 AGNs is e = 0.3, yielding a correction factor of F_{0.5-2\text{ keV,total}}/F_{0.5-2\text{ keV,obs}} = 1.3. While this factor is not applied for the observed X-ray fluxes and luminosities, the total—obscuration corrected—fluxes and luminosities can be computed by using this correction factor.

5.7. Outlook

This work represents the first attempt to utilize gravitational lensing to constrain the average characteristics of AGNs in z ~ 6 galaxies. We obtained a 2.2\sigma detection of galaxies in the high-mass subsample, while other subsamples remained undetected. This initial result is encouraging: it emphasizes the powerful nature of our approach and highlights that future detections with higher statistical significance are feasible.

To further advance our understanding of high-redshift AGNs, the advancement of both optical/infrared observatories and deeper X-ray observations are required. The James Webb Space Telescope ( JWST) will completely revolutionize our understanding of the early universe by detecting large samples of faint and high-redshift galaxies. Two instruments on board JWST, the Near InfraRed Camera and the Mid InfraRed Instrument, will provide broadband photometry that will allow probing the rest-frame UV, optical, and near-infrared SEDs of high-redshift galaxies. Thanks to its large collecting area, superb angular resolution, and infrared sensitivity, JWST will explore a vast population of galaxies at z = 6–10 and will even identify the first galaxies at z ~ 15. By utilizing existing, upcoming, and proposed deep Chandra observations of lensed galaxy clusters, the sample of high-redshift AGNs can be significantly increased, thereby improving the signal-to-noise ratios, which may lead to further detection of AGNs and/or the population of HMXBs in distant galaxies, both individually and in stacks.

On a longer timescale, more sensitive high-resolution X-ray telescopes could provide an edge in detecting high-redshift galaxies that were identified by JWST. For example, the proposed Lynx observatory would be able to reach sensitivities to even individually detect some of the lensed AGNs and would be able to probe the average luminosity of HMXBs. Indeed, Lynx could drastically change the landscape of high-redshift AGNs studies as it will detect AGNs with luminosities with 10^{41}\text{ erg s}^{-1} in deep fields and at even lower luminosities by utilizing the lensing magnification of galaxy clusters. While JWST and Lynx would not operate simultaneously, X-ray follow-up observations of JWST targets will revolutionize our understanding about high-redshift AGNs.

6. Conclusions

In this work, we analyzed Chandra X-ray observations of 34 RELICS galaxy clusters and probed the X-ray emission originating from 155 gravitationally lensed galaxies that reside at z ~ 6. We probed the emission from high-redshift AGNs both individually and in stacks. Our results can be summarized as follows:

1. To search for individually detected AGNs associated with the high-redshift galaxies, we cross-matched the coordinates of the detected X-ray sources with those of the lensed galaxies. We did not identify an X-ray source that was undoubtedly associated with a high-redshift galaxy.

2. To probe the average X-ray luminosity from high-redshift galaxies, we coadded the X-ray signal from the 155 lensed galaxies, but did not obtain a statistically significant detection. In the absence of detection, we placed a flux upper limit on the high-redshift AGNs, which was <2.1 \times 10^{41}\text{ erg s}^{-1}\text{ cm}^{-2}, and which corresponded to a luminosity upper limit of <8.4 \times 10^{41}\text{ erg s}^{-1}.

3. Assuming that z ~ 6 galaxies follow the local BH mass–bulge mass scaling relation, we estimate that the typical BH mass is ~2.6 \times 10^8 M_{\odot}. Given the upper limit on the luminosity, this implies that typical BHs at high redshift accrete at 5%–10% of their Eddington rate.

4. We split galaxies based on their stellar mass, star formation rate, and lensing magnification and stacked galaxies in these subsamples. We obtained a weak, 2.2\sigma detection for massive galaxies. Taken at face value, the luminosity of the AGNs in the high-mass group is 3.7 \times 10^{42}\text{ erg s}^{-1}. We did not obtain a statistically significant detection in other subsamples.

5. We find that emission from HMXBs is well below the sensitivity of the stacking analysis given the star formation rate of the sample.

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