A QSO host galaxy and its Lyα emission at \( z = 6.43 \)

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ABSTRACT
Host galaxies of highest redshift quasi-stellar objects (QSOs) are of interest; they provide us with a valuable opportunity to investigate physics relevant to the starburst–active galactic nuclei (AGN) connection at the earliest epoch of the Universe, with the most luminous black holes.

Here, we report an optical detection of an extended structure around a QSO at \( z = 6.43 \) in deep \( z' \)- and \( z_r \)-band images of the Subaru/Suprime-Cam. Our target is CFHQS J2329-0301 (\( z = 6.43 \)), the highest redshift QSO currently known. We have carefully subtracted a point spread function (PSF) constructed using nearby stars from the images. After the PSF (QSO) subtraction, a structure in the \( z' \) band extends more than 4 arcsec on the sky (\( R_e = 11 \) kpc), and, thus, is well resolved (16 \( \sigma \) detection). The PSF-subtracted \( z_r \)-band structure is in a similar shape to that in the \( z' \) band, but less significant with a 3 \( \sigma \) detection. In the \( z' \) band, a radial profile of the QSO+host shows a clear excess over that of the averaged PSF in 0.8–3 arcsec radius.

Since the \( z' \) band includes a Lyα emission at \( z = 6.43 \), we suggest the \( z' \) flux is a mixture of the host (continuum light) and its Lyα emission, whereas the \( z_r \)-band flux is from the host. Through a SED modelling, we estimate 40 per cent of the PSF-subtracted \( z' \)-band light is from the host (continuum) and 60 per cent is from Lyα emission. The absolute magnitude of the host is \( M_{1450} = -23.9 \) (cf. \( M_{1450} = -26.4 \) for the QSO). A lower limit of the SFR(Lyα) is \( 1.6 \, M_\odot \, \text{yr}^{-1} \) with stellar mass ranging from \( 6.2 \times 10^8 \) to \( 1.1 \times 10^{10} \, M_\odot \) when 100 Myr of age is assumed. The detection shows that a luminous QSO is already harboured by a large, star-forming galaxy in the early Universe only after \( \sim 840 \) Myr after the big bang. The host may be a forming giant galaxy, co-evolving with a super-massive black hole.

Key words: black hole physics – galaxies: high-redshift – early Universe.

1 INTRODUCTION
There have been accumulating evidence that galaxies and active galactic nuclei (AGNs) co-exist. Evidence of starburst features have been detected in numerous AGNs (Maiolino et al. 1997; Cid Fernandes et al. 2005). Half of the ultraluminous infrared galaxies contain simultaneously an AGN and starburst activity (Genzel et al. 1998; Goto 2005). Post-starburst signatures have been found in AGNs (Brotherton et al. 1999; Dewangan et al. 2000; Goto 2006).

The discovery of tight correlation between black hole mass and bulge velocity dispersion provides another evidence that the formation of bulge and the central black hole may be closely linked (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Granato et al. 2001; Heckman et al. 2004; Onken et al. 2004). The correlation implied the co-evolution of a super-massive black hole and its host galaxy. To understand galaxy formation theory and the AGN mechanisms, it is important to characterize a possible relationship between the galaxy formation and AGNs.

At high luminosity end of the AGN, quasi-stellar objects (QSOs) are not exception; at low redshift, QSOs are predominantly hosted by luminous, massive and bulge-dominated galaxies (Hamilton, Casertano & Turnshek 2002; Dunlop et al. 2003; Pagani, Falomo & Treves 2003; Floyd et al. 2004), irrespective of radio power. At high redshift, evolution of the QSO host has been reported; Schramm,
Wisotzki & Jahnke (2008) found hosts with stellar populations indicating recent massive star formation at \( z \approx 3 \). Aretxaga, Boyle & Terlevich (1995) and Aretxaga, Terlevich & Boyle (1998) found star formation rate (SFR) of \( >100-200 \, \text{M}_\odot \, \text{yr}^{-1} \) for \( z \approx 2 \) QSO hosts. Villforth, Heidt & Nilsson (2008) also found moderate rate of SFR for QSO hosts at \( z = 0.87 \) and 2.85. Hutchings et al. (2002, 2006) found that high-redshift QSO host galaxies are irregular and highly disturbed. Hutchings (2005) reported a significant young stellar population with a possible spiral structure in two hosts at \( z = 5 \). However, also note that some luminous QSOs are reported to reside in luminous massive early-type galaxies at \( 1 < z < 2 \) (Kotilainen et al. 2007) and at \( 2 < z < 3 \) (Falomo et al. 2008). The host galaxies of radio-quiet QSOs are on average less luminous than the ones of radio-loud QSOs (e.g. Kukula et al. 2001; Kotilainen et al. 2007). The apparent co-evolution of QSO and host galaxies leads to the question if QSO activity and star formation are caused by the same physical mechanism, or one triggers the other.

Although a proper investigation of high-\( z \) QSO hosts would shed light on the QSO–galaxy co-evolution, QSO host galaxies at highest redshifts of \( z > 6 \) have not yet been studied extensively, since due to high QSO-to-host light ratios, extremely deep, high-resolution images are required to assure a sufficiently high signal-to-noise ratio. A pioneering attempt by Hutchings (2005) did not resolve host galaxies of QSOs at \( z = 6.23 \) and \( z = 6.35 \).

In this paper, we investigate a host galaxy of a QSO at \( z = 6.43 \) using deep optical images taken with the Suprime-Cam/Subaru equipped with new red-sensitive CCDs. This is the highest redshift QSO as of the date of writing, and thus provides us with an unprecedented opportunity to shed light on the co-evolution of galaxy and QSO at the massive end of super-massive black holes with \( \sim 10^9 \, \text{M}_\odot \), at the earliest epoch when the age of the Universe was only \( \sim 840 \, \text{Myr} \) old.

Unless otherwise stated, we adopt the *Wilkinson Microwave Anisotropy Probe* (WMAP) cosmology: \( (h, \Omega_m, \Omega_b) = (0.7, 0.3, 0.7) \) (Komatsu et al. 2009).

### 2 OBSERVATION

Our target is CFHQS J2329-0301, which is a QSO at \( z = 6.43 \) (Willott et al. 2007). Characteristics of the target are summarized in Table 1. Assuming the Eddington luminosity, its black hole mass is estimated to be \( 1.0 \times 10^9 \, \text{M}_\odot \) (Fan et al. 2001).

Observations were carried out on 2008 August 1, 26 and 27 with the Suprime-Cam (Miyazaki et al. 2002), on which new red sensitive CCDs have been just installed (Utsumi et al., in preparation). The sensitivity of the new CCDs is 1.3 times better in \( z' \) band and 1.9 times better in \( z_c \) band (\( \lambda_{\text{effective}} = 988 \, \text{nm} \)). The data were originally taken to investigate the QSO environment, which will be presented elsewhere (Utsumi et al. in preparation). Since the observation was partly for an engineering purpose to test the new CCDs, we used various exposure times with \( 300 \, \text{s} \times 2, 400 \, \text{s} \times 3, 500 \, \text{s} \times 6, 700 \, \text{s} \times 2 \) in \( z' \) and \( 500 \, \text{s} \times 19 \) in \( z_c \). The dithering patterns were mostly circular with separations of 0.5-2 arcmin. The total exposure time on the target was 3600 s in \( z' \), 6900 s in \( z_c \) and 9500 s in \( r' \) bands. We used a nearby field observed by both the Sloan Digital Sky Survey (SDSS) and us for a photometric calibration. A slight difference between the SDSS and the Subaru filters is compensated using the Gunn & Stryker (1983) stellar spectral library. The data are reduced using the modified version of the pipeline. The details of the reduction is described in Utsumi et al. (in preparation). The 2σ limiting magnitudes are \( i' = 26.73, z' = 25.79 \) and \( z_c = 25.09 \, \text{AB} \) magnitude within 2 arcsec aperture. Here, 1σ sky magnitudes are computed by randomly placing a 2 arcsec aperture in the blank (sky) part of the image (Yagi et al. 2002; Ouchi et al. 2004).

The pixel scale of the Suprime-Cam is 0.2 arcsec pixel\(^{-1}\). The seeing size of the images is \( \sim 0.5 \, \text{arcsec} \) (see Table 2). An \( i' \), \( z' \) and \( z_c \) composite image of the QSO is shown in Fig. 1, where the RGB (red, green and blue) colours are assigned to \( z', z_c \), and \( r' \) bands, respectively. Without even subtracting the central PSF, it is

| Object       | RA        | Dec       | \( z \) | \( i'_{\text{AB}} \) | \( z'_{\text{AB}} \) | \( J \) | \( M_{1450} \) |
|--------------|-----------|-----------|--------|-------------------|-------------------|------|------------|
| CFHQS J232908-030158 | 23:29:08.28 | -03:01:58.8 | 6.43 | >25.08 | 21.76±0.05 | 21.56±0.25 | -26.4 |

**Table 1.** Target information adopted from Willott et al. (2007).

The figures are north up, east left.

**Table 2.** Basic properties of the constructed PSFs. The pixel scale is 0.2 arcsec pixel\(^{-1}\). The FWHM is obtained through a Gaussian fit.

| Filter | FWHM (pixel) | Ellipticity |
|--------|--------------|-------------|
| \( i' \) (\( \lambda_c = 768 \, \text{nm} \)) | 2.45 (=0.49 arcsec) | 0.04 |
| \( z' \) (\( \lambda_c = 911 \, \text{nm} \)) | 2.25 (=0.45 arcsec) | 0.06 |
| \( z_c \) (\( \lambda_c = 988 \, \text{nm} \)) | 2.69 (=0.54 arcsec) | 0.07 |

**Figure 1.** Composite pseudo-colour image of the QSO (CFHQS J2329-0301). The RGB colours are assigned to \( z', z_c \) and \( r' \) bands, respectively. The figures are north up, east left.
immediately noted that the QSO has an extended structure in the $z'$ band (red in the composite).

3 RESULTS

3.1 PSF subtraction

In this section, we subtract a PSF from the QSO image to investigate a possibly extended structure around the QSO. In this process, it is critical to carefully construct the PSF model using the observed data since at such a high redshift the PSF has to be known very precisely to be able to see a marginally extended host galaxy. Using observed stars instead of analytical functions is especially important for $z_r$ band where 0.5 per cent of the flux is known to bleed in horizontal spikes due to the filter characteristics. In each band, we have carefully picked ~20 nearby stars within 200 arcsec in the mosaic image to avoid a possible PSF variation across the image. These stars are picked to be relatively isolated, and ambiguous stars according to their radial profile. Stars blended with a nearby object are excluded from the selection. We have specifically picked stars as bright as, but not brighter than, the QSO itself to avoid a possible non-linearity effect at the central pixels of bright stars. We have checked that a choice of a different set of PSF stars does not affect results. Then we used DAOPHOT in IRAF to construct an average PSF. The constructed PSF models in each band are shown in the middle panels of Fig. 2. Basic properties of the PSF in each band are presented in Table 2.

Then, we use GALFIT (Peng et al. 2002) to subtract the constructed PSFs from the QSO images shown in the left-hand panels of Fig. 2. At first, GALFIT was set to fit only the PSF and any remaining sky. The residuals are shown in the right-hand panels of Fig. 2. We discuss results from each band in the following sections.

3.1.1 $i'$ band

In the $i'$ band (the top panels), no flux is left on the residual image, i.e. the QSO is consistent with a PSF in the $i'$ band. This is not surprising since bluewards of the Lyman break, little light from the host galaxy can escape from the heavy absorption by the neutral hydrogen. The detection limit is summarized in Table 3.

3.1.2 $z'$ band

In the $z'$ band shown in the middle panels of the Fig. 2, there clearly remains an extended structure, subtending 4 arcsec after the PSF subtraction. There is a little oversubtraction at the very centre, making the structure look like a doughnut shape, perhaps because the PSF fit is affected by the extended structure. We have applied the same PSF subtraction to nearby stars for consistency check (in Appendix A). None of the PSF fits to stars yielded such an extended structure in Appendix A. We performed an aperture

Figure 2. The upper, middle and lower panels are for $i'$, $z'$ and $z_r$ band, respectively. In each line, the left-hand panels are reduced images. The middle panels are PSFs constructed using nearby stars. The right-hand panels show residuals from the PSF subtraction. All figures are north up, east left.
Table 3. Magnitudes and results of the fit.

| Object     | $i'_{AB}$          | $z'_{AB}$          | $z_{AB}$          |
|------------|--------------------|--------------------|--------------------|
| QSO+host   | 25.54 ± 0.02       | 21.165 ± 0.003     | 21.683 ± 0.007     |
| Host       | > 25.34 (1σ limit) | 23.5 ± 0.3 (16σ)  | 24.3 ± 0.2 (3σ)   |
| 1σ sky     | 25.44 (26 pixel diameter) | 24.90 (26 pixel diameter) | 25.46 (18 pixel diameter) |

Figure 3. Radial profiles of QSO+host (blue solid line), the constructed PSF (red dashed line) and the PSF+Sérsic model (green short-dashed line) in the $z'$ band (left). The right-hand panel is for the $z_r$ band. Profiles are normalized at a maximum value. The pixel scale is 0.2 arcsec pixel$^{-1}$.

photometry using 13 pixel (= 2.6 arcsec) of radius on the structure. The measured magnitude is $z' = 23.5 ± 0.3$ as summarized in Table 3. We have computed a 1σ of the sky by randomly placing the same size aperture on the blank regions of the image. The 1σ sky noise is estimated to be 24.90 in $z'$ band. Compared to the sky noise, the detection is 16σ, i.e. the structure is well resolved and detected.

In addition to the PSF subtraction, in the left-hand panel of Fig. 3, we show $z'$-band radial profiles of QSO+host in the blue solid line, and of the constructed PSF in the red-dashed line. The profiles are normalized to be unity at a maximum. The solid, dashed and short-dashed lines connect median in each sample. The error bars denote the errors in determining the median at each radii. At above the radius of 4 pixel (> 0.8 arcsec), the figure shows that the QSO+host is clearly more extended than the PSF, showing the extended structure is well resolved.

We note that there may be a point-source-like structure to the right of the residual image in the $z'$ band in the middle-right panel of Fig. 2. However, this is not likely a contamination from a foreground star since the possible point-source is not detected in $i'$ band, and, thus is quite red. Instead, it is more likely to be a star-forming region/substructure associated with the QSO.

3.1.3 $z_r$ band

In the $z_r$-band image in the bottom-left panel of Fig. 2, there may be a possible elongation from north-east to south-west, in a similar orientation to the extended structure in the $z'$ band. Although the residual image on the bottom-right panel is much less obvious than in the $z'$ band, there is a hint of remaining flux. We performed an aperture photometry with an optimal 18 pixel diameter, obtaining 24.3±0.2 mag of flux (Table 3). The 1σ sky noise measured by randomly placing the same size apertures on the blank regions of the image is 25.46 mag, i.e. the extended structure is at a 3σ level. The errors on the PSF subtraction are 0.2 mag, and thus smaller. We also run the source extractor on the PSF subtracted image, detecting the host at a 2.6σ level over the local background.

The radial profiles in the $z_r$ are shown in the right-hand panel of Fig. 3. Although the extended structure is less obvious, the QSO+host has a 1σ excess over the PSF in three consecutive radii at 6–9 pixel.

The extended structure becomes more visible in a 10-pixel box-car-smoothed image in Fig. 4. For a sanity check, we fit the PSF to nearby stars in Appendix A, where we do not see any clear excess in the residuals even after box-car smoothed.

Because the Ly$\alpha$ emission at $z = 6.43$ is redshifted into the $z'$-band wavelength range, the extended structure in the $z'$ band could be an extended nebula of Ly$\alpha$ emission (Ly$\alpha$ blob) extensively searched

Figure 4. Both panels show residuals from the PSF subtraction in the $z_r$ band. The right-hand panel is box-car smoothed with 10 pixel. The figures are north up, east left.

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at $z \sim 3$ (Matsuda et al. 2004; Saito et al. 2008). However, in this QSO image, the extended structure is also found in the $z_r$-band where the Lyα emission does not contaminate the flux. Therefore, it is more likely that at least some $z'$-band flux stems from the host galaxy (continuum), and the $z'$-band flux is a mixture of host and its Lyα emission. We estimate the relative strength of the flux of the host (continuum) and Lyα emission in detail in Section 3.2.

### 3.2 SED, stellar mass, SFR

In Fig. 5, we show the SED of the QSO (the black-filled circles) and the host (the red rectangles). Since the host was not detected in the $i'$-, $1\sigma$ upper limits are shown at the effective wavelength. We computed the $1\sigma$ of the sky noise by randomly placing an aperture of the same size on the blank region of the images, following the prescription by Yagi et al. (2002) and Ouchi et al. (2004).

Overlaid are constant star formation and delta burst models (Bruzual & Charlot 2003) with the ages of 100 Myr scaled to the $z_r$-band flux. Assumed are the Salpeter initial mass function, solar metallicity and no dust extinction. Flux bluewards of the Lyα emission is attenuated using the prescription given by Fan, Carilli & Keating (2006). These models are often used to compute colours of Lyman break galaxies at $z \sim 6$.

Comparing the colours of the host to the galaxy models, one immediately notices that the $z'$-band flux is not consistent with the flat continuum of the SED models, regardless of the star formation history. Perhaps this is because the host galaxy has some Lyα emission in the $z'$-band. In the past, Davies et al. (2008) detected extended line emission in high-redshift galaxies on scales of $\sim 4$ kpc. Such extended Lyα emission nebulae, called Lyα blobs, have been extensively searched at $z \sim 3$ (Matsuda et al. 2004; Saito et al. 2008). A QSO BR1202-0725 has a Lyα emitting companion, possibly ionized by the QSO (Hu, McMahon & Egami 1996; Ohyama, Taniguchi & Shioya 2004). A typical FWHM of Lyα blobs is 300 km s$^{-1}$ (Matsuda et al. 2004; Saito et al. 2008). If the Lyα emission around the QSO is extended, it may be theoretically predicted infalling gas to form a galaxy, illuminated by a central QSO (Rees 1988). If so, quantifying this will provide us with an important constraint on the formation of galaxies such as gas fraction, AGN geometry and covering factors in the early Universe.

Both of the SED models show an almost flat continuum slope at this small wavelength range between $z'$ and $z_r$ bands. Thus, scaling from the $z_r$-band flux and the SED models in the $z'$-band, $\sim 2.5 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ flux is estimated to be the light from the continuum of the host galaxy. Subtracting this from the observed flux in the $z'$-band (6.0 $\times$ 10$^{-19}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$), $\sim 3.5 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ of flux is estimated to originate from Lyα emission of the host galaxy, i.e. in the $z'$-band, the continuum-to-Lyα flux ratio is 4:6.

If such flux came through the Lyα emission of 300 km s$^{-1}$, then the Lyα luminosity would be $1.6 \times 10^{42}$ erg s$^{-1}$, which are comparable luminosity to Lyα emitters at $z \sim 6$ (Kashikawa et al. 2006; Ouchi et al. 2009) and Lyα blobs at $z = 3.1$ (Matsuda et al. 2006). Based on the Lyα luminosity, we estimate the SFR(Lyα) is $> 1.6 M_{\odot}$ yr$^{-1}$ (Kennicutt 1998). However, the SFR estimated here are lower limits because significant fraction of bluer side of the Lyα emission could be absorbed by the neutral hydrogen.

We can also estimate SFR of the host galaxy based on the UV luminosity using Kennicutt (1998). Since the UV continuum of the host is relatively bright $M_{1450} = -23.9$, we obtain SFR 50 $M_{\odot}$ yr$^{-1}$. It has been suggested that SFR derived from UV continuum is often larger than that from Lyα, especially for Lyα emitters (Ajiki et al. 2003; Hu et al. 2004; Kodaira et al. 2003), as is the case here. Even though this is quite a large number compared to that obtained through Lyα ($> 1.6 M_{\odot}$ yr$^{-1}$), and thus suggests the nature of the host galaxy, its UV continuum is brighter than typical Lyα emitters. The host may be a massive galaxy that is decreasing its star formation activity.

In the literature, Jahnke et al. (2004) reported 2–30 $M_{\odot}$ yr$^{-1}$ for $z = 1.8$–2.6 QSO hosts. Villforth et al. (2008) measured 0.03–33 $M_{\odot}$ yr$^{-1}$ for QSO hosts at $z = 0.87$ and $z = 2.75$. The SFR estimated by UV light, however, is also subject to reddening uncertainties since a possible presence of dust has not been taken into account.

With the lack of infrared photometry, it is difficult to constrain age/stellar mass through the SED. However, in the literature, a very young age of 5–100 Myr for high-redshift galaxies at $5 < z < 7$ has been reported (Egami et al. 2005; Lai et al. 2007). If we assume an age of 100 Myr and scale models to $z_r$-band flux, we obtain a stellar mass of $1.1 \times 10^{11} M_{\odot}$ for the delta burst model, and $6.2 \times 10^{9} M_{\odot}$ for the constant SFR model. Considering the age of the Universe is 840 Myr, the host may be a forming massive galaxy, possibly co-evolving with the super-massive black hole.

### 3.3 Sérsic fit

Since we have a clear detection of extended structure in the $z'$-band, we attempted to fit the $z'$-band image with a PSF+Sérsic+sky model using the GALFIT. The $z_r$-band image does not have enough signal-to-noise ratio to include the Sérsic profile in the fit. Results are shown in Fig. 6. The middle panel of Fig. 6 shows the PSF+ Sérsic (PSF convolved) model, which is subtracted from the original image shown in the left-hand panel. Some residuals can be seen in the right-hand panel, possibly implying an irregular morphology of the host, being consistent with Hutchings et al. (2006) who pointed out that high-redshift QSO host galaxies are found to be irregular and highly disturbed. Measured Sérsic parameters are $R_e = 2.0 \pm 0.1$ arcsec, axis ratio of $b/a = 0.74 \pm 0.03$ and $n = 0.019$, suggesting that the host possesses a flatter profile than the PSF, and even than de Vaucouleurs. In the left-hand panel of Fig. 3, we show the

![Figure 5. SEDs of QSO and its host galaxy. Overplotted are SED models of constant SFR and delta starburst with 100 Myr of age. The host is not detected in $i'$ band, where $1\sigma$ upper limit is shown.](https://academic.oup.com/mnras/article-abstract/400/2/843/1017835)

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The extended structure has an effective radius of $R_e = 2.0\,\text{arcsec}$ according to the Sérsic fit. Even in the image, one can easily recognize the light distribution beyond 13 pixel (=2.6 arcsec). At the distance of $z = 6.43$, 2.0 arcsec corresponds to 11 kpc. As a reference, in the Great Observatories Origins Deep Survey (GOODS) fields, a mean size of $z \sim 5$ galaxies with $1 - 5 L^*$ is 0.3 arcsec (~2 kpc) in rest frame 1500 Å (Ferguson et al. 2004). In the UDF, a mean size of $z \sim 6$ galaxies with 0.1–1.0 $L^*$ is 0.15 arcsec (~1 kpc) in rest frame 1600 Å (Bouwens et al. 2004).

On the size of QSO hosts in the literature, Kukula et al. (2001), who observed in $J$ and $K_s$, found a mean of $11.1 \pm 5.7$ kpc for their $z \approx 1$ sample. For their $z \approx 1.5$–2 sample, they found a value of $9.78 \pm 6.58$ kpc for objects where it could be determined and upper limits (<10 kpc) for the remaining sources. Kotilainen et al. (2007) found values of $6.7 \pm 1.7$ kpc for their $z \approx 1$–2 sample (observed in K and H). Falomo et al. (2008) found values between 2.6 and 11.3 kpc for a sample of three high-redshift QSOs ($z \approx 2$–3) observed in $K_s$. Villforth et al. (2008) found 1.5–3.9 kpc at $z = 0.9$ and 1.5–3.9 kpc at $z = 2.8$ in the Focal Reducer and Low Dispersion Spectrograph (FORS) deep field.

However, direct interpretation of our results is difficult; in the last section we estimated that the $z'$-band flux is a mixture of 40 per cent continuum light and 60 per cent Ly$\alpha$ emission. Therefore, this extension of 11 kpc scale can be either extended Ly$\alpha$ emission or the extended stellar population of the host. Clear morphological separation of these two has to await high-resolution near-infrared imaging, or specially resolved IFU spectroscopy in the red end of the optical CCD. A spectro-polarization is also important to constrain contribution from dust scattered light (Young et al. 2009).

### 4 DISCUSSION

In Section 3, we detected an extended light in the $z'$ and $z_	ext{b}$ band, and suggested that this was the QSO host galaxy at $z = 6.43$. However, it is always a possibility that the extended light could be from a foreground-lensing galaxy, which also explains the bright magnitude of the QSO by lensing magnification. However, we believe it is not very likely in this case; using the 1σ limit of $i' > 25.34$, the $i' - z'$ colour of the host is $>2.1$, which is very red and is hard to be explained unless the host has a break between $i'$ and $z'$. One possibility is a Balmer break at $z = 1.25$. However, the colour of the Balmer break is bluer, at approximately $0.64 < u - g < 1.99$ (Fukugita, Shimasaku & Ichikawa 1995). The size, absolute magnitude and nuclear-to-host flux ratio all do not seem to be unreasonable for the structure to be at $z = 6.43$. In addition, no significant flux is detected at $6500 < \lambda < 8900$ Å in the GMOS spectrum with 1 hour of exposure time (Willott et al. 2007). Therefore, it is more plausible to consider that the extended emission is from the host galaxy of the QSO at $z = 6.43$.

We have estimated the host luminosity to be $M_{1450} = -23.9$, i.e. the QSO-to-host flux ratio in rest-frame UV is 8.8. This is a higher ratio compared to the previous work. Hutchings (2005) found a nuclear-to-extended ratio of 2.3 in rest 2100 Å. Guyon, Sanders & Stockton (2006) report a flux ratio of 2.5 (note their passbands are in NIR). If the mass of the black hole is proportional to that of the host (Magorrian et al. 1998; Ivanov & Alonso-Herrero 2003), and if the QSO emits at a fixed fraction of the Eddington luminosity, then one would expect a correlation between the luminosities of the host and QSO. However, a number of reasons can explain the deviation; the host may be more actively star forming at earlier epoch; the Eddington ratio may be different at $z = 6.43$; the amount of nuclear obscuration may be different. Hutchings et al. (2006) reported a higher a QSO-to-host flux ratio for more luminous QSOs among their sample. Since this is only one example based on the rest-frame UV photometry, it is important to obtain infrared photometry to accurately measure the stellar mass/luminosity ratio of more hosts. High-resolution spectroscopy is also important to examine $M - \sigma$ relation at $z > 6$.

Comparing the morphology of the host to those in the literature, Hutchings (2003) resolved the host galaxies of four high-redshift QSOs ($z \sim 4.7$) and found heavily disturbed galaxies, partially showing signs of ongoing merging. Guyon et al. (2006) reported that 30 per cent of PG QSO host galaxies showed obvious sign of disturbances, with strongly disturbed hosts favouring more luminous QSOs. In this work, there were some residuals after the host was fit with a Sérsic profile in the right-hand panel of Fig. 6, suggesting a possible non-smooth morphology. Further morphological investigation, however, is difficult due to the limited depth and spatial resolution of our ground-based data. It is necessary to take high-resolution near-infrared AO or Hubble Space Telescope data to investigate the morphology of the host galaxy.

### 5 SUMMARY

We have detected an extended structure around a QSO at $z = 6.43$ in the $z'$ and $z_	ext{b}$-band images of the Subaru/Suprime-Cam. The QSO is the highest redshift QSO currently known. After a careful PSF subtraction, the structure is detected at a 16σ level in $z'$ band and at a 3σ level in the $z$ band. In the $z'$ band, the radial profile of

![Figure 6](https://academic.oup.com/mnras/article-abstract/400/2/843/1017835/figure6)
the QSO+host shows clear excess at >4 pixel of radius over the carefully constructed PSF. There is a marginal excess in the $z'$-band profile at 6–10 pixel of radius as well. Through the SED modelling, we estimate 40 per cent of the PSF-subtracted $z'$-band light is from the host (continuum) and 60 per cent is from Lyα emission of the galaxy.

The host is a bright, large galaxy with $M_{1450} = -23.9$. Its extended structure has an effective radius of $>11$ kpc. The lower limit on the SFR(Lyα) is $>1.6 M_\odot$ yr$^{-1}$, the stellar mass of the host ranges from $6.2 \times 10^{8}$ to $1.1 \times 10^{10} M_\odot$ depending on the star formation history when 100 Myr of age is assumed. Therefore, the host is a large, star-forming galaxy, with a moderate amount of stellar mass.

These results present an important example that indeed a supermassive black hole resides in a large galaxy even in the early epoch when the Universe is $\sim840$ Myr old. Quantifying the host mass and fraction of ionized gas in more detail will provide us with an important constraint on how galaxies and AGN form in the early Universe, such as gas fraction, AGN geometry and covering factors.

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APPENDIX A: PSF SUBTRACTION TEST

Fitting the constructed PSF (Section 3.1) to the observed stars around QSO provides a sanity check of the PSF subtraction. In this exercise, we first select stars within 200 arcsec around the QSO as objects with source extractor’s starlist of ≥0.97. We have specifically picked stars as bright as, but not brighter than, the QSO itself to avoid a possible non-linearity effect at the central pixels of bright
Figure A1. Reliability of the PSF subtraction is tested by fitting the constructed PSF from five nearby stars, in i' and z' bands. In each band, the left-hand panels show actual stellar images. The right-hand panels show residuals from the PSF subtraction.

stars. These are the stars used to construct a composite PSF in Section 3. In Fig. A1, we show five images of stars (left-hand panels) and PSF-subtracted images (right-hand panels) in i' (left) and z' (right) bands. Fig. A2 shows the same PSF subtraction for z_r band, but the rightmost panels show 10-pixel box-car smoothed images of residuals (the middle panels) in the z_r band.

None of the residuals in Fig. A1 shows an extended structure, such as seen in the z_r in the middle-right panel of Fig. 2. In the z_r band, no obvious residuals are seen even after the images are box-car smoothed (cf. Fig. 4). These sanity checks suggest that the extended structures found in Figs 2 and 4 are not artefacts from the PSF subtraction.

Figure A2. Reliability of the PSF subtraction is tested by fitting the constructed PSF to five actual stars in the z_r bands. The left-hand panels show actual stellar images. The middle panels show residuals from the PSF subtraction. The right-hand panels are 10-pixel box-car smoothed images of the residual.

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