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Dark Energy Survey identification of a low-mass active galactic nucleus at redshift 0.823 from optical variability

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ABSTRACT

We report the identification of a low-mass active galactic nucleus (AGN), DES J0218−0430, in a redshift $z = 0.823$ galaxy in the Dark Energy Survey (DES) Supernova field. We select DES J0218−0430 as an AGN candidate by characterizing its long-term optical variability alone based on DES optical broad-band light curves spanning over 6 yr. An archival optical spectrum from the fourth phase of the Sloan Digital Sky Survey shows both broad Mg II and broad H β lines, confirming its nature as a broad-line AGN. Archival *XMM–Newton* X-ray observations suggest an intrinsic hard X-ray luminosity of $L_{2-12\,\mathrm{keV}} \approx 7.6 \pm 0.4 \times 10^{43}$ erg s^{-1}, which exceeds those of the most X-ray luminous starburst galaxies, in support of an AGN driving the optical variability. Based on the broad H β from SDSS spectrum, we estimate a virial black hole (BH) mass of $M_{\bullet} \approx 10^{6.43}$–$10^{6.72}\,\mathrm{M}_{\odot}$ (with the error denoting the systematic uncertainty from different calibrations), consistent with the estimation from OzDES, making it the lowest mass AGN with redshift > 0.4 detected in optical. We estimate the host galaxy stellar mass to be $M_{*} \approx 10^{10.5 \pm 0.3}\,\mathrm{M}_{\odot}$ based on modelling the multiwavelength spectral energy distribution. DES J0218−0430 extends the $M_{\bullet}$–M_{*} relation observed in luminous AGNs at $z \sim 1$ to masses lower than being probed by previous work. Our work demonstrates the feasibility of using optical variability to identify low-mass AGNs at higher redshift in deeper synoptic surveys with direct implications for the upcoming Legacy Survey of Space and Time at Vera C. Rubin Observatory.

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1 INTRODUCTION

Supermassive black holes (SMBHs) as massive as ∼1–10 billion solar masses were already formed when the universe was only a few hundred Myr old (e.g. Fan et al. 2001; Wu et al. 2015; Bañados et al. 2018). How they were able to form so quickly is an outstanding question in cosmology (Volonteri 2010). At least three channels have been proposed for the formation of the seeds of SMBHs: pop III stellar remnants (e.g. Madau & Rees 2001), direct collapse (e.g. Haehnelt & Rees 1993; Bromm & Loeb 2003; Begelman, Volonteri & Rees 2006), or star cluster evolution (e.g. Gürkan, Freitag & Rasio 2004; Portegies Zwart et al. 2004). Finding small black hole (BH) seeds directly in the early universe represents a major goal of future facilities (e.g. The Lynx Team 2018).

The occupation fraction of BHs in local dwarf galaxies (i.e. $M_* < 10^{10}\,\mathrm{M}_\odot$, Greene, Strader & Ho 2019) and their mass functions hold the fossil record for understanding the mechanisms of seed formation (e.g. Greene 2012; Reines & Comastri 2016). There is growing evidence for the existence of intermediate-mass BHs (IMBHs, $M_\bullet = 10^2-10^6\,\mathrm{M}_\odot$, Greene et al. 2019), including in some globular cluster centres, ultra-luminous X-ray sources (ULXs), and the centre of dwarf galaxies (e.g. Mezcua 2017). However, most of the existing evidence is limited to the low-redshift ($z < 0.15$) universe. Recently, Mezcua (2019) pointed out a problem of using local dwarf galaxies as the hosts for BH seeds, which may be contaminated by mergers and/or AGN feedback and therefore may not be the ideal fossil record for studying seed formation. This underscores the importance of finding small BHs at higher redshift, because they are more 'pristine' (i.e. have gone through fewer mergers and feedback) than those at lower redshift.

Previously, the best strategy for identifying low-mass AGNs at higher redshift was using deep X-ray surveys, such as the Chandra deep fields (CDFs) (e.g. Fiore et al. 2012; Young et al. 2012; Luo et al. 2017; Xue 2017) and the COSMOS survey (Civano et al. 2012) (also see our Fig. 7). For example, Luo et al. (2017) detected ∼1000 objects in CDF-South (484.2 arcmin^2) with total 7 Ms exposure time. Seven hundred eleven are AGNs based on the X-ray and multiwavelength properties. However, deep X-ray surveys are expensive and often plagued by contamination from star formation and/or X-ray binaries. Radio searches for low-mass AGNs in nearby dwarf galaxies have also been conducted with NSF's Karl G. Jansky Very Large Array high-resolution observations (e.g. Reines et al. 2020), although they are subject to the low detection rate of radio cores of AGNs. Alternatively, optical colour selection is much less expensive but is biased against smaller BHs and/or lower Eddington ratios. Optical emission line selection may miss AGNs with line ratios dominated by star formation (e.g. Baldassare et al. 2016; Agostino & Salim 2019), particularly in low-mass galaxies without sufficient spectral resolution (Trump et al. 2015). Furthermore, the standard optical narrow emission line diagnostics used to identify SMBHs may fail when the BH mass falls below $\sim 10^4\,\mathrm{M}_\odot$ for highly accreting IMBHs and for radiatively inefficient IMBHs with active star formation, because the enhanced high-energy emission from IMBHs could result in a more extended partially ionized zone compared with models for SMBHs, producing a net decrease in the predicted [O III]/H β and [N II]/H α emission line ratios (e.g. Cann et al. 2019).

In this work, we present the identification of DES J021822.52−043035.88 (hereafter DES J0218−0430 for short) as a low-mass AGNs at $z = 0.823$ by characterizing its optical variability based on sensitive, long-term light curves from the Dark Energy Survey (DES; Flaugher 2005; The Dark Energy Survey Collaboration 2005; Dark Energy Survey Collaboration 2016) Supernova (SN) fields (Kessler et al. 2015). It serves as a proof of principle for identifying low-mass AGNs (i.e. $M_\bullet \lesssim 10^6\,\mathrm{M}_\odot$) at intermediate and high redshift using deep synoptic surveys with important implications for the Rubin Observatory Legacy Survey of Space and Time (LSST; Ivezić et al. 2019).

Compared to other methods, variability searches should be more sensitive to AGNs with lower Eddington ratios given the anticorrelation between Eddington ratio and optical variability (Ai et al. 2010; MacLeod et al. 2010; Guo & Gu 2014; Rumbaugh et al. 2018; Sánchez-Sáez et al. 2018; Lu et al. 2019). Recently, Baldassare, Geha & Greene (2018) selected several low-mass AGN candidates in the Sloan Digital Sky Survey (York et al. 2000) Stripe 82 (SDSS-S82; Ivezić et al. 2007; Abazajian et al. 2009), but the sample is limited to $z < 0.15$ by the sensitivity of SDSS-S82 light curves. Compared to SDSS-S82, DES-SN provides a factor of 10 increase in single-epoch imaging sensitivity. The higher sensitivity is crucial for discovering AGNs with lower masses at higher redshift.

Our main new findings include the following:

(i) Identification of a low-mass AGN based on optical variability alone. This represents the first low-mass AGN identified from optical variability at intermediate redshift.

(ii) Confirmation that the optical variability is driven by an AGN based on optical spectroscopy, high hard X-ray luminosity, and broad-band spectral energy distribution (SED).

(iii) Estimation of the BH mass $M_\bullet$ using the virial method. Combined with the stellar mass estimate M_* from SED modelling, this puts DES J0218−0430 on the $M_\bullet$–M_* relation in AGN at intermediate redshift and extends it to lower masses than probed by previous work.

(iv) Demonstration that variability searches based on sensitive, long-term optical light curves from deeper synoptic surveys can indeed identify low-mass AGNs at higher redshift (see also Elmer et al. 2020, for a recent study based on NIR variability).

The paper is organized as follows. Section 2 describes the observations and data analysis that identify DES J0218−0430 as a candidate low-mass AGN from optical variability and provides confirmation of its AGN nature based on optical spectroscopy and multiwavelength properties. Section 3 presents our results on the estimation of its virial BH mass and the host galaxy stellar mass. We discuss the implications of our results in Section 4 and conclude in Section 5. A concordance ΛCDM cosmology with $\Omega_\mathrm{m} = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is assumed throughout. We use the AB magnitude system (Oke 1974) unless otherwise noted.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Variability characterization

To distinguish AGN variability from variable stellar sources (e.g. stars, SNe), we follow the method of Butler & Bloom (2011), which represents an easy to implement method for selection of quasars using single-band light curves. We focus on the g band given that AGNs tend to show larger variability amplitudes in bluer bands (Ulrich, Maraschi & Urry 1997). The Butler & Bloom (2011) method first uses the damped random walk model (Kelly et al. 2009) to parametrize the ensemble quasar structure function in SDSS-S82. Then, based on this empirical variable QSO structure function, they classify individual light curves into variable/non-variable objects and QSO/non-QSO with no parameter fitting.

The variability classification is based on two statistics, one describing the fit confidence and the other describing the false alarm probability (FAP), which is tuned to achieve high quasar detection fractions given an acceptable FAP. More specifically, we use the software qso_fit[1] to model the light curve and quantify if a source is variable and if yes, whether the variability is characteristic of AGN. We calculate the following statistics:

(i) $\sigma_{\rm var}$: the significance that a source is variable,

(ii) $\sigma_{\rm QSO}$: the significance that a source is variable and that the fit to the damped random walk model is statistically preferred over that to a randomly variable, and

(iii) $\sigma_{\rm notQSO}$: the significance that a source is variable but is not characteristic of AGN. This parameter is usually anticorrelated with $\sigma_{\rm QSO}$, lending further support to the AGN classification.

Although optimized for quasar variability, the Butler & Bloom (2011) method has been demonstrated to find variability in dwarf galaxies (Baldassare et al. 2018).

2.2 Target selection using the Dark Energy Survey

DES (2013 January–2019 January) was a wide-area 5000 deg^2 survey of the Southern hemisphere in the *grizY* bands. It used the Dark Energy Camera (Flaugher et al. 2015; Bernstein et al. 2017) with a 2.2 deg diameter field of view mounted at the prime focus of the Victor M. Blanco 4m telescope on Cerro Tololo in Chile. The typical single-epoch 5σ point source depths achieved with six-year's data are $g = 24.7$, $r = 24.5$, $i = 23.9$, $z = 23.3$, and $Y = 21.8$ mag (~0.4 mag deeper than three-year's data, Abbott et al. 2018), much deeper than other surveys of larger area (e.g. SDSS-S82 and PanSTARRS1). The data quality varies due to seeing and weather variations. DES absolute photometric calibration has been tied to the spectrophotometric Hubble CALSPEC standard star C26202 and has been placed on the AB system (Oke & Gunn 1983). The estimated single-epoch photometric statistical precision is 7.3, 6.1, 5.9, 7.3, 7.8 mmag in the *grizY* bands (Abbott et al. 2018). DES contains a 30 deg^2 multi-epoch survey DES-SN to search for SNe Ia. It observed in eight 'shallow' and in two 'deep' fields, with the shallow and deep fields having typical nightly point-source depths of 23.5 and 24.5 mag, respectively (Kessler et al. 2015; Brout et al. 2019). DES-SN has a mean cadence of ~7 d in the *griz* bands between mid-August through mid-February from 2013 to 2019.

We have selected DES J0218−0430 as a candidate low-mass AGN by characterizing its long-term optical variability based on DES Y6A1 data. Details of our sample selection will be presented in a forthcoming paper. We briefly describe the selection procedure as follows:

(i) We started from an internal DES variability catalogue in the DES-SN fields. The catalogue includes AGNs, SNe, and artefacts. We applied the damped random walk model to the variable light curves to select AGN-like variability (see the details in Section 2.1).

(ii) We have required that the stellar mass estimates are less than 10^{10} M$_\odot$ based on mass-to-light ratios (M/L) inferred from broad-band colours (Taylor et al. 2011) without more careful SED fitting (see below in Section 3.2), assuming that low-mass AGNs usually reside in low-mass galaxies.

This resulted in ~1, 300 'low-mass' AGN candidates, although the actual number of low-mass AGN candidates is likely to be much smaller considering that our simple colour-derived M/L and stellar masses would have been significantly underestimated due to contamination from a blue AGN continuum. We then cross-matched the candidates with the Million Quasar Catalog.[2] DES J0218−0430 was the only object with both an X-ray detection and obvious broad emission lines with widths of ~500–2000 km s^{-1} from the SDSS spectra. We have also found other low-mass AGN candidates which either show only narrow emission line components in their SDSS spectra, or, with X-ray detections but have no available SDSS spectrum (and therefore without a virial mass estimate). Spectroscopic follow-up observations are still needed for those candidates to measure any broad emission line components to confirm their AGN nature and to infer their virial BH masses.

Fig. 1 shows the g-band light curve of DES J0218−0430 (located in a shallow field) using the point spread function (PSF) magnitudes. There are 142 epochs (175 sec/epoch) of observations in total. Unlike low-mass AGNs at lower redshift, the host galaxy of DES J0218−0430 is unresolved in DES. We therefore adopt the PSF magnitude photometry which is most appropriate for unresolved sources.

Fig. 2 shows $\sigma_{\rm QSO}$ versus $\sigma_{\rm var}$ for DES J0218−0430 compared against spectroscopically confirmed SDSS quasars and stars as well as DES AGN and SNe spectroscopically confirmed by OzDES. It demonstrates that DES J0218−0430 is classified as an AGN based on its characteristic optical variability at a high significance (with $\sigma_{\rm var} \sim 39$ and $\sigma_{\rm QSO} \sim 9$). It occupies the same subregion of parameter space as those of spectroscopically confirmed SDSS quasars and DES AGN.

Fig. 3 shows the dependence of variability significance ($\sigma_{\rm var}$), QSO significance ($\sigma_{\rm QSO}$), and non-QSO significance ($\sigma_{\rm notQSO}$) on the total light-curve baseline T. While DES J0218−0430 can be classified as an AGN when $T \gtrsim 2$ yr, both $\sigma_{\rm var}$ and $\sigma_{\rm QSO}$ continue to increase with increasing T until they start to saturate around $T \sim 4$ yr. This demonstrates the importance of a moderately long time baseline for AGN identification from optical variability.

2.3 Optical spectroscopy

Fig. 4 (upper panel) shows the archival optical spectrum (Plate ID = 8124, Fibre ID = 690, and MJD = 56954) of DES J0218−0430 from SDSS-IV (Blanton et al. 2017). It was targeted as a quasar candidate by the eBOSS survey (Dawson et al. 2016) based on its optical/MIR colour and was included in the SDSS DR14 quasar catalogue (Pâris et al. 2018). Its luminosity is $M_i = -20.5$ mag, which is below the SDSS DR7 quasar catalogue luminosity criterion ($M_i < -22$ mag; Schneider et al. 2010). It is not included in DES OzDES quasar catalogue by Tie et al. (2017), which has $M_i < -22$ mag. Both broad H β and broad Mg II emission are covered in the spectrum.

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[1] http://butler.lab.asu.edu/qso_selection/index.html

[2] https://heasarc.gsfc.nasa.gov/W3Browse/all/milliquas.html

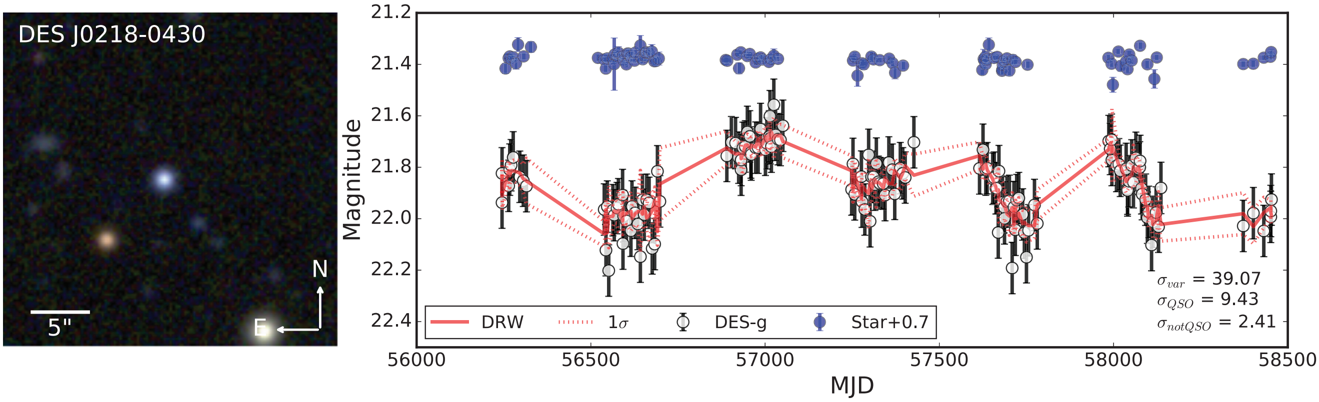

Figure 1. Left-hand panel: DES *gri*-colour composite image (with a 30 arcsec × 30 arcsec field of view) for DES J0218−0430. Right-hand panel: DES *g*-band PSF magnitude light curves for DES J0218−0430 (open filled circles) and a field star (blue filled circles) for comparison. The best-fitting model for DES J0218−0430 (the red solid) and the 1σ confidence levels (the red dashed) assume a damped random walk (Kelly, Bechtold & Siemiginowska 2009). Labelled in the lower right are the variability significance, QSO significance and non-AGN variability significance. See Section 2.1 for details.

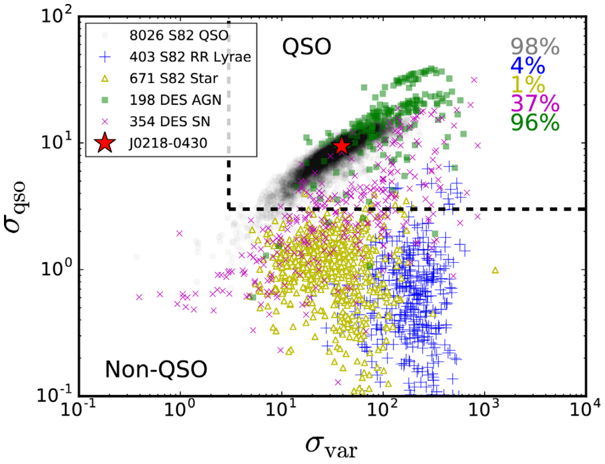

Figure 2. QSO significance ($\sigma_{\rm qso}$) versus variability significance ($\sigma_{\rm var}$) for DES J0218−0430. Also shown for context are spectroscopically confirmed quasars (grey dots) and stars (blue crosses and yellow triangles are for RR lyrae and non-variable stars, respectively) from the SDSS Stripe 82 and spectroscopically confirmed DES AGNs (green squares) and SNe (magenta crosses) from the OzDES survey (Yuan et al. 2015). Numbers indicate the fraction of objects among each population classified as ‘QSO’ using the criteria $\sigma_{\rm var} > 3$ and $\sigma_{\rm qso} > 3$ (Butler & Bloom 2011). DES J0218−0430 is located in the region in which reside by most SDSS Stripe 82 quasars and DES AGN.

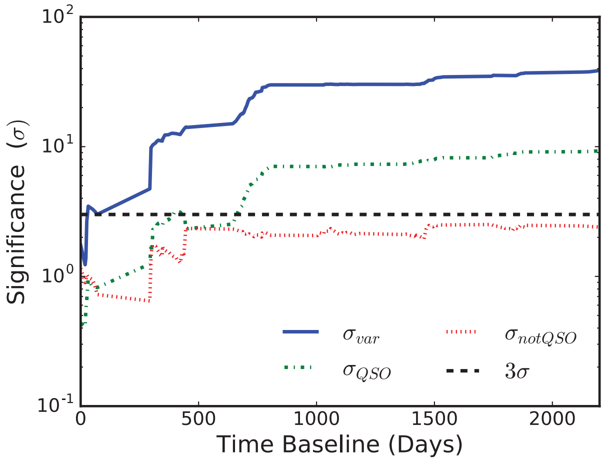

Figure 3. The dependence of variability significance ($\sigma_{\rm var}$), QSO significance ($\sigma_{\rm QSO}$), and non-QSO significance ($\sigma_{\rm notQSO}$) on the total light-curve baseline for DES J0218−0430.

DES J0218−0430 was observed by OzDES[3] twice, once during 2014, and again in 2018. Since 2013, OzDES has used the 2dF positioner and AAOmega spectrograph on the Anglo-Australian Telescope to obtain redshifts for tens of thousands of sources within the 10 deep fields of the DES (Yuan et al. 2015; Childress et al. 2017). The spectra from 2014 and 2018 are combined and shown in Fig. 4 (lower panel). The total integration time for the combined spectrum was 3 h. Further details on how the data were obtained and processed can be found in Yuan et al. (2015), Childress et al. (2017), and Lidman et al. (in preparation).

To determine the significance of the broad emission lines and to measure their profiles for virial BH mass estimates, we fit spectral models following the procedures as described in detail in Shen et al. (2019) using the software PYQSOFIT[4] (Guo, Shen & Wang 2018). The model is a linear combination of a power-law continuum, a third-order polynomial (to account for reddening), a pseudo-continuum constructed from Fe II emission templates, and single or multiple Gaussians for the emission lines. Since uncertainties in the continuum model may induce subtle effects on measurements for weak emission lines, we first perform a global fit to the emission line free region to better quantify the continuum. We then fit multiple Gaussian models to the continuum-subtracted spectrum around the broad emission line region locally.

More specifically, we model the Mg II line using a combination of up to two Gaussians for the broad component and one Gaussian for the narrow component. We impose an upper limit of 1200 km s^{-1} for the FWHM of the narrow lines. For the Hβ line, we use up to three Gaussians for the broad Hβ component and one Gaussian for the narrow Hβ component. We use two Gaussians for the [O III] λ4959 and [O III] λ5007 narrow lines. Considering the low S/N of the spectrum, we only fit single Gaussians to the [O III] $\lambda\lambda$4959, 5007 lines with the flux ratio of the doublet tied to

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[3] Australian Dark Energy Survey.

[4] https://github.com/legolason/PyQSOFit

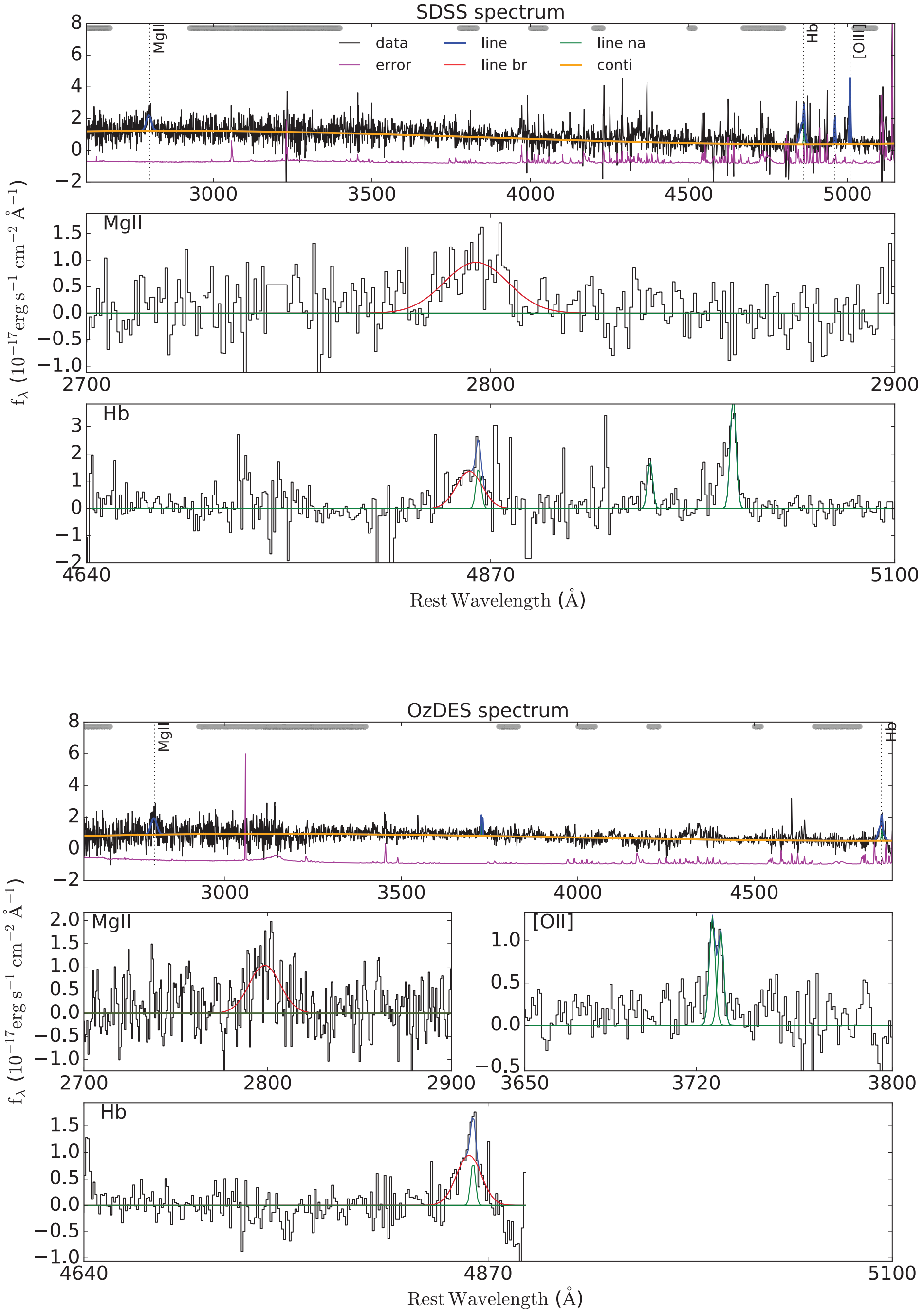

Figure 4. Optical spectrum for DES J0218−0430 from the SDSS-IV/eBOSS and OzDES survey and our spectral modelling analysis. A global fitting is applied to the spectrum having subtracted the host component in the upper panel. Power-law + three-order polynomial and Gaussians are used to fit the continuum and emission lines, respectively. The grey bands on the top are line-free windows selected to determine the continuum emission. The error spectrum has been shifted vertically by -1×10^{-17} erg s^{-1} cm^{-2} Å^{-1} for clarity. The lower panels show the zoomed-in emission line regions of Mg II, [O II], and H β. Broad Mg II and broad H β are both detected at the 2.1(2.0)σ and 3.4(3.6)σ significance levels, yielding virial BH masses $\sim 10^{6.43}$–$10^{6.72}$ M$_\odot$ ($\sim 10^{6.40}$–$10^{6.69}$ M$_\odot$) using H β from SDSS (OzDES).

be $f_{5007}/f_{4959} = 3$. The line widths of [O III] and narrow H β are tied together. Fitting each [O III] line with two Gaussians instead (with an additional component to account for a possible blue wing often seen in [O III]) does not improve the fit significantly. The resulting broad-line H β width is relatively insensitive to our model choice for [O III]. For OzDES spectrum without [O III], we use [O III] $\lambda\lambda$3727, 3729 instead, which is fitted with two Gaussians to decompose the narrow component of H β. We use 100 Monte Carlo simulations to estimate the uncertainty in the line measurements.

Fig. 4 shows our best-fitting spectral model for DES J0218−0430. Table 1 lists the spectral measurements for DES J0218−0430. Both broad H β and broad Mg II are detected. This confirms DES J0218−0430 as a broad-line AGN.

Table 1. Spectral measurements and virial BH mass estimates of DES J0218−0430. Cols. 2 and 3: Broad emission line flux and 1σ uncertainty from Monte Carlo simulations. Cols. 4 and 5: Full width at half-maximum of the broad emission line and 1σ uncertainty measured from our best-fitting spectral model (Section 2.3 and Fig. 4). Cols. 6 and 7: Monochromatic continuum luminosities of the AGN component in our best-fitting spectral model after subtracting the host galaxy contribution from SED modelling. Cols. 8–13: Virial BH mass estimates using the calibrations of Mejía-Restrepo et al. (2016, M16), Shen et al. (2011, S11), and Vestergaard & Osmer (2009, VO09) for Mg II and those of Mejía-Restrepo et al. (2016), Vestergaard & Peterson (2006, VP06), and McLure & Dunlop (2004, MD04) for H β (equations 1 and 2). We assume the same 5100 Å luminosity as that from the SDSS to calculate the BH mass from OzDES.

Spectrum (1)	$F_{\mathrm{Mg\,II}}$ (10^{-17} erg s^{-1} cm^{-2}) (2)	$F_{\mathrm{H}\beta}$ (3)	FWHM$_{\mathrm{Mg\,II}}$ (km s^{-1}) (4)	FWHM$_{\mathrm{H}\beta}$ (km s^{-1}) (5)	log L_{3000} (erg s^{-1}) (6)	log L_{5100} (erg s^{-1}) (7)	$M_\bullet^{\mathrm{Mg\,II,\,M16}}$ (log M$_\odot$) (8)	$M_\bullet^{\mathrm{Mg\,II,\,S11}}$ (log M$_\odot$) (9)	$M_\bullet^{\mathrm{Mg\,II,\,VO09}}$ (log M$_\odot$) (10)	$M_\bullet^{\mathrm{H}\beta,\,\mathrm{M16}}$ (log M$_\odot$) (11)	$M_\bullet^{\mathrm{H}\beta,\,\mathrm{VP06}}$ (log M$_\odot$) (12)	$M_\bullet^{\mathrm{H}\beta,\,\mathrm{MD04}}$ (log M$_\odot$) (13)
SDSS	18.7 ± 3.3	23.5 ± 1.5	1980 ± 360	1060 ± 130	43.69	43.52	7.36 ± 0.12	7.14 ± 0.14	7.30 ± 0.15	6.63 ± 0.14	6.72 ± 0.11	6.43 ± 0.11
OzDES	21.6 ± 4.1	16.5 ± 0.9	2118 ± 410	1025 ± 80	43.77	–	7.47 ± 0.24	7.25 ± 0.15	7.40 ± 0.15	6.60 ± 0.12	6.69 ± 0.07	6.40 ± 0.07

2.4 Multiwavelength observations

To estimate the host-galaxy stellar mass (see Section 3.2 below for details), we queried the archival SED data for DES J0218−0430 using the Vizier tool[5] within 3 arcsec following the procedures of Guo et al. (2020a). We adopt measurements from large systematic surveys to focus on a more homogeneous data set. These include the *Galaxy Evolution Explorer* (*GALEX*; Martin et al. 2005), the Sloan Digital Sky Survey (SDSS; York et al. 2000), the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), the *Wide-field Infrared Survey* (*WISE*; Wright et al. 2010), and the *Spitzer* Wide-Area Infrared Extragalactic survey (SWIRE; Rowan-Robinson et al. 2013). When multi-epoch photometries are available, we take the mean value to quantify the average SED. We assume 20 per cent as the fiducial fractional uncertainty if a proper photometric error is not available.

DES J0218−0430 is included in the Ninth Data Release of the fourth Serendipitous Source Catalog (4XMM-DR9) of the European Space Agency's (ESA) *XMM–Newton* observatory (Rosen et al. 2016). It was detected at $>6\sigma$ significance as a compact source in a 21 ks exposure on 2016 July 1. The EPIC 2–4.5 keV and 4.5–12 keV fluxes are $(2.10 \pm 1.54) \times 10^{-15}$ and $(2.19 \pm 1.14) \times 10^{-14}$ erg cm^{-2} s^{-1} respectively, yielding $L_{2-12\,\mathrm{keV}} = (7.6 \pm 0.4) \times 10^{43}$ erg s^{-1}. The X-ray luminosity exceeds those of the most X-ray luminous starburst galaxies (e.g. Zezas, Alonso-Herrero & Ward 2001), lending further evidence for its AGN nature driving the optical variability.

3 RESULTS

3.1 Black hole mass estimation

We estimate the AGN BH mass using the single-epoch estimator assuming virialized motion in the broad-line region (BLR) clouds (Shen 2013). With the continuum luminosity as a proxy for the BLR radius and the broad emission line width, characterized by the full width at half-maximum (FWHM), as an indicator of the virial velocity, the virial mass estimate is given by

$$\log\left(\frac{M_\bullet}{M_\odot}\right) = a + b\log\left(\frac{\lambda L_\lambda}{10^{44}\,\mathrm{erg\,s^{-1}}}\right) + 2\log\left(\frac{\mathrm{FWHM}}{\mathrm{km\,s^{-1}}}\right), \quad (1)$$

where $L_\lambda = L_{3000}$ for Mg II and $L_\lambda = L_{5100}$ for H β. The coefficients a and b are empirically calibrated either against local reverberation mapped AGNs or internally among different lines. We adopt the calibrations of Mejía-Restrepo et al. (2016),[6] Shen et al. (2011), and Vestergaard & Osmer (2009) for Mg II and those from Mejía-Restrepo et al. (2016), Vestergaard & Peterson (2006), and McLure & Dunlop (2004) for H β. The calibration coefficients are

$$\begin{aligned}
(a,\ b) &= (0.955,\ 0.599),\ \ \mathrm{M16;\ Mg\,II},\\
(a,\ b) &= (0.740,\ 0.62),\ \ \mathrm{S11;\ Mg\,II},\\
(a,\ b) &= (0.860,\ 0.50),\ \ \mathrm{VO09;\ Mg\,II},\\
(a,\ b) &= (0.864,\ 0.568),\ \ \mathrm{M16;\ H}\beta,\\
(a,\ b) &= (0.910,\ 0.50),\ \ \mathrm{VP06;\ H}\beta,\\
(a,\ b) &= (0.672,\ 0.61),\ \ \mathrm{MD04;\ H}\beta.
\end{aligned} \quad (2)$$

Table 1 lists our results on the virial BH mass estimate. We estimate $M_\bullet \sim 10^{6.43}$–$10^{6.72}$ M$_\odot$ using broad H β, or $M_\bullet \sim 10^{7.14}$–$10^{7.36}$ M$_\odot$ using broad Mg II based on the SDSS measurements. The range in the quoted BH mass estimate reflects the systematic uncertainty depending on the adopted calibrations. The total error in the BH mass estimate is dominated by systematic uncertainties in the virial mass estimates which are $\gtrsim$0.4 dex (e.g. Shen et al. 2011). This systematic uncertainty largely accounts for the fact that the empirically calibrated coefficients a and b may not necessarily apply to low-mass AGN at high redshift (e.g. Grier et al. 2017). Table 1 also lists the BH mass estimates based on the OzDES measurements. We adopt the H β-based value from SDSS as our fiducial estimate considering that H β is better known and calibrated by reverberation mapping studies (e.g. Shen 2013) and is believed to be more reliable than Mg II as a virial mass estimator (e.g. Guo et al. 2020b) and OzDES spectrum is incomplete for the H β–[O III] region.

We estimate the Eddington ratio $\lambda_{\mathrm{Edd}} \equiv \frac{L_{\mathrm{Bol}}}{L_{\mathrm{Edd}}}$ as 0.85 ± 0.35 for DES J0218−0430 from its hard X-ray luminosity $L_{2-10\,\mathrm{KeV}}$ assuming a bolometric correction of $L_{\mathrm{Bol}}/L_{2-10\,\mathrm{KeV}} = 10$ (Lusso et al. 2012). Considering the maximum g-band variability of 0.5 mag in Fig. 1, DES J0218−0430 is consistent with the variability–Eddington ratio relation (see their fig. 11) in Rumbaugh et al. (2018), which is produced with normal SDSS quasars of $M_{\mathrm{BH}} \approx 10^9$ M$_\odot$.

3.2 Host galaxy stellar mass estimation

We estimate the host galaxy stellar mass by modelling its multiwavelength SED using the software CIGALE[7] (Noll et al. 2009; Serra et al. 2011; Boquien et al. 2019). CIGALE is designed to reduce computation time and the results are dependent on the parameter space explored by discrete models which can have degenerate

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[5] http://vizier.u-strasbg.fr/vizier/sed/

[6] This calibration is based on a sample of 39 AGNs at $z \sim 1.55$. While it may be more appropriate for high-redshift sources, the sample is biased against low-mass systems and therefore the calibration may not necessarily be better than the other calibrations which do sample the low-mass regime appropriate for DES J0218−0430.

[7] https://cigale.lam.fr/about/

physical parameter values. Mock catalogues are generated and analysed to check the reliability of estimated physical quantities.

We assume an exponential 'delayed' star formation history and vary the *e*-folding time and age of the stellar population model assuming solar metallicity and Chabrier initial mass function (Chabrier 2003) to fit the stellar component. We adopt the single stellar population library from Bruzual & Charlot (2003) for the intrinsic stellar spectrum. We use templates from Inoue (2011) based on CLOUDY 13.01 to model the nebular emission and amount of Lyman continuum photons absorbed by dust. We assume the dust attenuation curve of Calzetti et al. (2000) and a power-law slope of 0 to model dust attenuation. We model the dust emission using the empirical templates from Draine et al. (2007) with updates from Draine et al. (2014). We use the templates from Fritz, Franceschini & Hatziminaoglou (2006) to estimate the contribution from the AGN to the bolometric luminosity. The fractional contribution was allowed to vary from 0.1 to 0.9 along with the option for the object to be either type-1 or type-2 AGN.

Fig. 5 shows the SED data and our best-fitting model. The best fit shown is for a type-1 AGNs with fractional contribution of 0.1 from the AGN to the bolometric luminosity.[8] The resulting stellar mass estimate $M_* = 10^{10.5 \pm 0.3}\,\mathrm{M}_\odot$ can have around 20 per cent systematic uncertainty. More details about accuracy of estimating physical parameters related to stellar mass and fractional AGN contribution can be found in Boquien et al. (2019) and Ciesla et al. (2015).

To further quantify systematic uncertainties in our stellar mass estimate, we have double checked our result by fitting the SED using the software PROSPECTOR[9] (Leja et al. 2018). PROSPECTOR is designed as a new framework for alleviating the model degeneracy and obtaining more accurate, unbiased parameters using the flexible stellar populations synthesis stellar populations code by Conroy, Gunn & White (2009). SED fitting with both broad-band photometries and spectroscopies are available in PROSPECTOR. Our best-fitting stellar mass estimate from the PROSPECTOR analysis is $M_* = 10^{10.8 \pm 0.5}\,\mathrm{M}_\odot$, which is consistent with our CIGALE-based estimate within uncertainties.

3.3 AGN classification using the mass excitation diagnostics

Fig. 6 shows the mass excitation diagnostics diagram for DES J0218−0430. This verifies that the gas excitation as inferred from the narrow emission line ratio [O III]/H β is dominated by the AGN rather than star formation. This is in line with the host galaxy being dominated by old stellar populations as suggested by the SED fitting. The mass excitation diagnostics provide further verification of the AGN classification in addition to direct evidence from the broad-line detection and the hard X-ray luminosity.

4 DISCUSSION

4.1 Comparison to low-mass AGNs in the literature

Fig. 7 shows the BH mass versus redshift for DES J0218−0430 compared against a list of low-mass AGN candidates at different redshift compiled from the literature selected using various techniques. This demonstrates DES J0218−0430 as one of the lowest BH mass objects at similar redshift.[10] The comparison of DES J0218−0430 and known low-mass AGNs in the literature highlights the prospect of using optical variability in deep synoptic surveys to select low-mass AGNs towards higher redshift.

At similar redshifts to DES J0218−0430, all low-mass AGN candidates in the literature are selected from X-ray deep-fields. We complied BH masses and redshifts for the samples noted in the figure caption. We removed duplicate entries during our literature search. We plot the virial BH mass measurements where possible. Individual candidates may have differing BH mass estimates depending on the estimation method and techniques used. Therefore, the individual references should be consulted for details. When measured BH masses are not available, we use the $M_\bullet$–M_* host scaling relation from Reines & Volonteri (2015) to estimate the BH mass. Although there are claims that these scaling relations may flatten-out below $M_* \sim 10^{10}\,\mathrm{M}_\odot$ (e.g. Martín-Navarro & Mezcua 2018) in addition to their large scatter, emphasizing the importance of obtaining broad-line BH mass measurements of low-mass AGNs.

4.2 Comparison to previous optical and near-IR variability searches of low-mass AGNs

Baldassare et al. (2018) used SDSS to select low-mass AGNs ($M_* \sim 10^9 - 10^{10}\,\mathrm{M}_\odot$) with a similar mass range as DES J0218−0430 but was limited to $z < 0.15$. Our identification of a low-mass AGN at $z = 0.823$ is enabled by the factor of 10 increase in single-epoch imaging sensitivity offered by DES-SN and detailed stellar mass estimation beyond the redshift limits of most stellar mass catalogues.

Martínez-Palomera et al. (2020) used DECam imaging to select galaxies with small amplitude ($g < 0.1$ mag) variability characteristic of low-mass AGNs with no stellar mass cut. They confirm three AGNs with broad emission from SDSS spectroscopy in the range $M_\bullet \sim 10^{6.0} - 10^{6.5}\,\mathrm{M}_\odot$. However, their sample is limited to $z < 0.35$.

Sánchez-Sáez et al. (2019) used a random-forest classifier trained on optical light curves (variable features and colours) using the QUEST-La Silla AGN variability survey with high purity. Their sample is dominated by quasars. These authors report the identification of eight low-luminosity AGNs which would not have been found with pure colour selection or other traditional techniques. However, robust BH masses are not quoted in this work.

De Cicco et al. (2019) used the VST survey to select variable AGNs in the COSMOS field. This work also demonstrates variability selection is able to find AGNs with X-ray counterparts missed by colour selection, but BH mass estimates are not reported for their sample.

Elmer et al. (2020) recently used NIR variability selection using *K*-band imaging with the UKIDSS Ultra Deep Survey. These authors demonstrate the very valuable capability of NIR variability to identify AGNs in $M_* \sim 10^9 - 10^{10}\,\mathrm{M}_\odot$ hosts galaxies up to $z \sim 3$, however BH mass estimates are not reported and virial BH masses are increasingly difficult to obtain for high-redshift low-mass AGNs.

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[8] We caution that the SED photometries are measured at different times. This may introduce extra uncertainty to the estimation of the AGN component, considering the variability in DES J0218−0430. In particular, the UV data points are sensitive to the AGN emission component.

[9] https://prospect.readthedocs.io/en/latest/index.html

[10] Our fiducial BH mass is based on broad H β which is believed to be more reliable than Mg II. In comparison, the AGN SDSS J021339.48−042456.4 at redshift $z = 0.656$ has an estimated BH mass of $10^{7.83}\,\mathrm{M}_\odot$ from H β or $10^{6.43}\,\mathrm{M}_\odot$ from Mg II (Sánchez-Sáez et al. 2018).

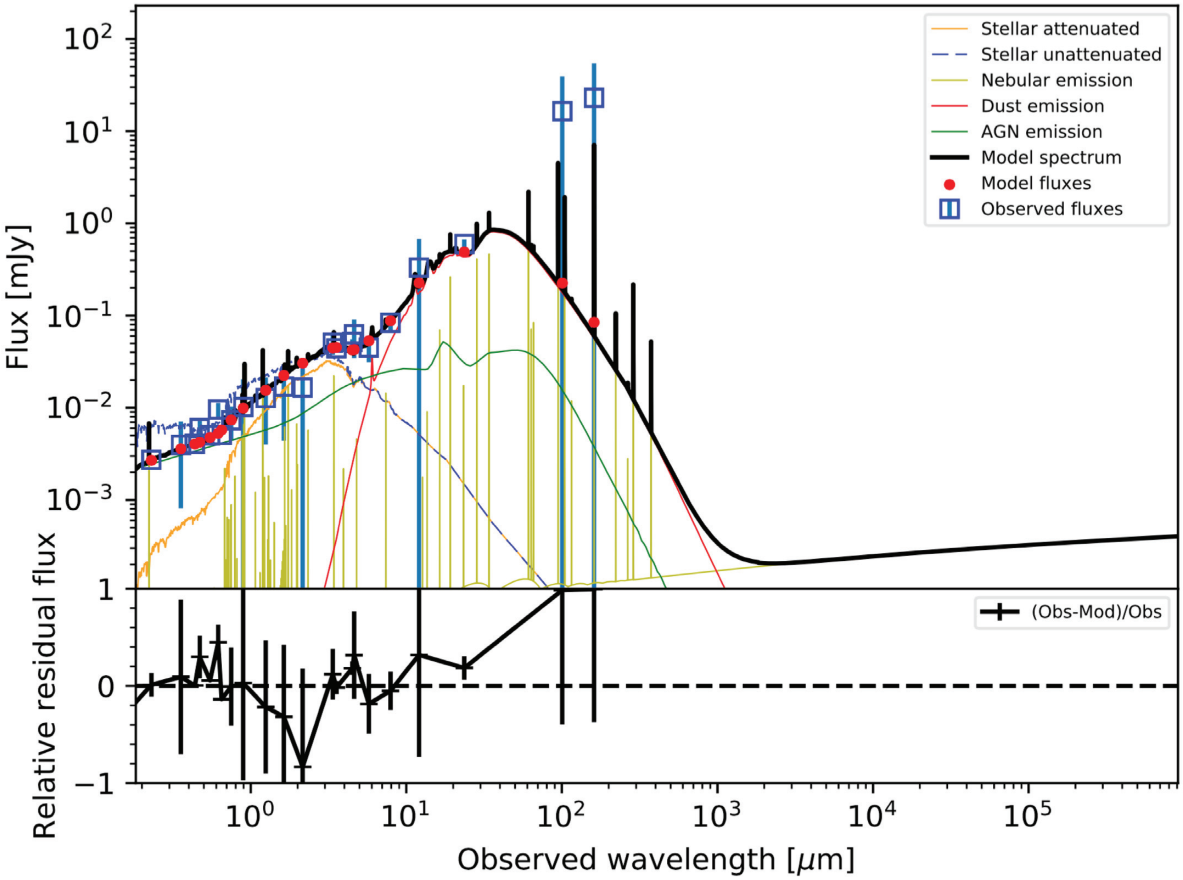

Figure 5. Spectral energy distribution modelling for DES J0218−0430 using CIGALE. All the photometry data from the Vizier service (see Section 2.4 for details) are shown as blue squares. The stellar unattenuated SED component is shown as the blue dotted line with the re-processed component shown as the solid orange line. Nebular emission is shown as the yellow solid line. The cold dust component is shown in red whereas the hot dust component from the AGN is shown in green. The best-fitting model is shown as the solid black line with residuals of observed and modelled flux values in the bottom panel.

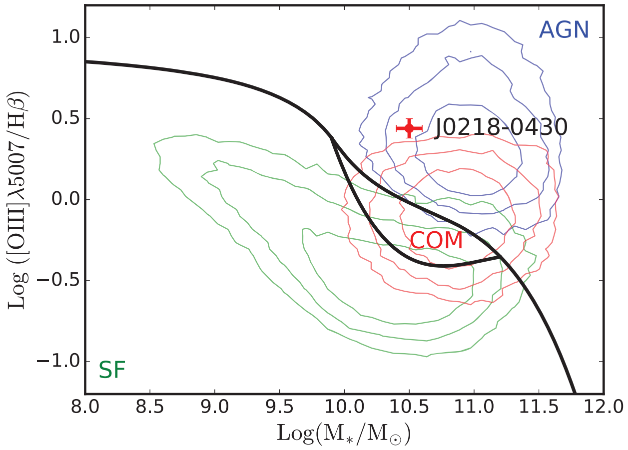

Figure 6. Mass excitation diagnostics for DES J0218−0430. The black lines are boundaries defined by Juneau et al. (2011) to separate AGNs and star-forming galaxies. The green, red, and blue colour contours represent number densities of pure star-forming galaxies, composites, and AGNs classified by the BPT diagram (Kewley et al. 2001; Kauffmann et al. 2003).

4.3 Implications for the BH–host scaling relation at $z \sim 1$

Fig. 8 shows the virial BH mass versus host galaxy stellar mass for DES J0218−0430. Shown for comparison is the X-ray selected AGN sample at median $z \sim 0.8$ from Cisternas et al. (2011), Schramm et al. (2013) re-analysed by Ding et al. (2020). The virial BH masses were estimated based on single-epoch spectra using broad H β and/or broad Mg II. The comparison sample includes 32 objects from Cisternas et al. (2011) and 16 objects from Schramm et al. (2013). The total stellar masses of the Cisternas et al. (2011) sample were estimated by the empirical relation between M_*/L and redshift and luminosity in the *Hubble Space Telescope* (*HST*) *F*814*W* band, which was established using a sample of 199 AGN host galaxies. The total stellar masses for the Schramm et al. (2013) sample were estimated from the galaxy absolute magnitude M_V and rest-frame $(B - V)$ colour measured from *HST* imaging for quasar-host decomposition using the *M*/*L* calibration of Bell et al. (2003). DES J0218−0430 extends the $M_\bullet$–M_* relation at $z \sim 1$ to smaller BH masses. DES J0218−0430 seems to have a BH mass $\sim 3\sigma$ smaller than the median value we would expect from its total stellar mass. This may indicate that variability selection may identify AGNs with lower masses than X-ray selected AGN, although a larger sample is needed to draw a firm conclusion. Note that we also have assumed that low-mass AGNs usually reside in low-mass galaxies in our sample selection.

Also shown for context in Fig. 8 are the best-fitting scaling relations for local samples of inactive galaxies (e.g. Häring & Rix 2004; Kormendy & Ho 2013; McConnell & Ma 2013) and low-redshift AGNs (Reines & Volonteri 2015). While DES J0218−0430

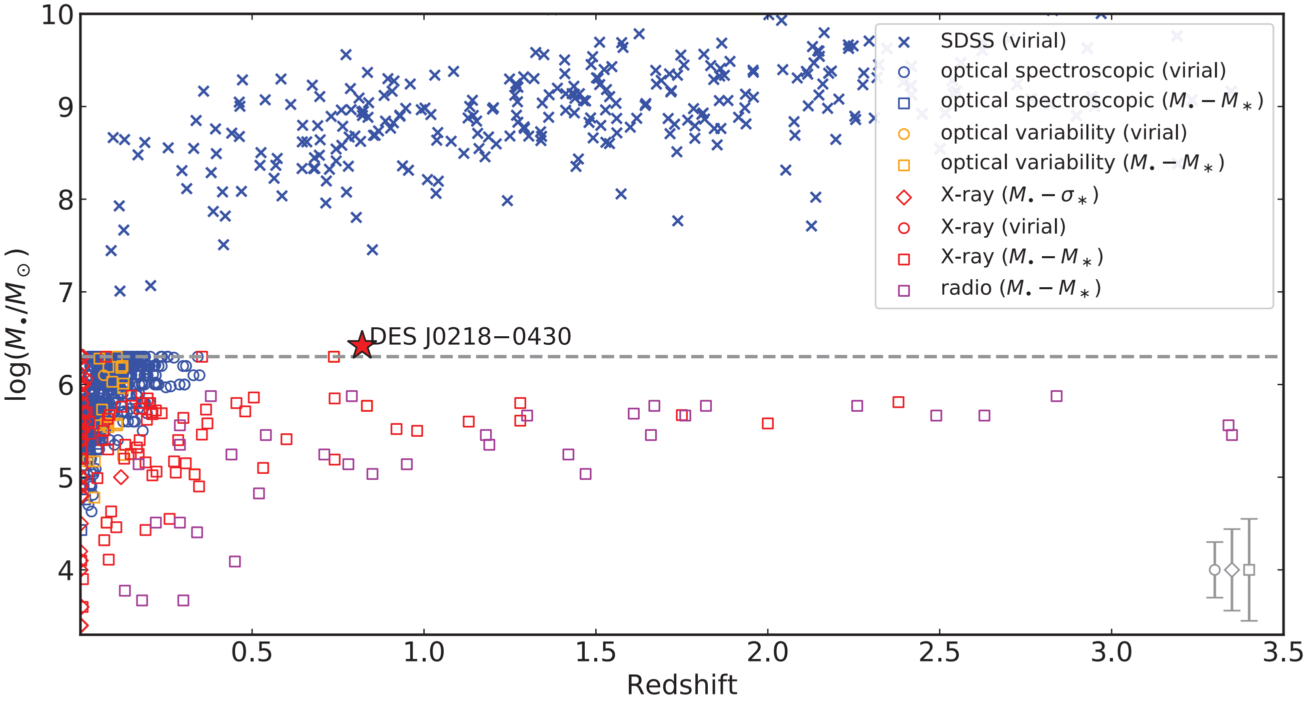

Figure 7. BH mass versus redshift for DES J0218−0430 in comparison to optical and X-ray-selected low-mass AGN candidates in the literature (Filippenko & Ho 2003; Barth et al. 2004; Greene & Ho 2004, 2007; Reines et al. 2011; Dong, Greene & Ho 2012; Ho et al. 2012; Secrest et al. 2012; Reines, Greene & Geha 2013; Schramm et al. 2013; Maksym et al. 2014; Baldassare et al. 2015; Lemons et al. 2015; Reines & Volonteri 2015; Kawamuro et al. 2016; Pardo et al. 2016; Chang et al. 2017; She, Ho & Feng 2017; Baldassare et al. 2018; Chilingarian et al. 2018; Ding et al. 2018; Liu et al. 2018; Mezcua et al. 2018) as well as the low-mass AGNs of the Mezcua, Suh & Civano (2019) radio sample. This demonstrates DES J0218−0430 to be one of the lowest BH mass objects at similar redshift. The higher redshift X-ray selected sources are from the CDF. Additionally, DES J0218−0430 is the highest redshift object in its class identified from an optical survey. We consider objects with BHs mass estimates of $M_\bullet \leq 2 \times 10^6$ M$_\odot$ and DES J0218−0430. For comparison, the more massive sample of SDSS AGNs with BH masses from Shen et al. (2011) is also shown as blue crosses above the dashed line. The typical BH mass uncertainties are shown in grey at the lower right for $M_\bullet$–M_* host scaling relation (0.3 dex), the virial method (0.44 dex), and the $M_\bullet$–σ_* relation (0.55 dex). See Section 4.1 (and references within) for details.

appears to fall below the best-fitting relation of low-redshift AGNs of Reines & Volonteri (2015), the apparent offset is insignificant accounting for systematic uncertainties in the virial BH mass estimate (∼0.44 dex at 1σ; Shen 2013). While based on only one data point, our result on DES J0218−0430 suggests no significant redshift evolution in the $M_\bullet$–M_* scaling relation from redshift $z \sim 1$ to $z \sim 0$ (see also Ding et al. 2020), which is consistent with previous results based on the $M_\bullet$–σ_* relation (e.g. Shen et al. 2015; Sexton et al. 2019).

5 CONCLUSION AND FUTURE WORK

We have identified a low-mass AGN in the redshift $z = 0.823$ galaxy DES J0218−0430 in DES-SN fields based on characterizing its long-term optical variability alone (Figs 1–3). We have not applied any colour selection criterion to avoid bias induced by host galaxy starlight which dominates the optical to near-IR SED (Fig. 5). We have confirmed the AGN nature by detecting broad H β and broad Mg II in its archival optical spectrum (Fig. 4) from the SDSS-IV/eBOSS survey and by measuring its high X-ray 2–10 keV luminosity using archival *XMM–Newton* observations (Section 2.4). We have estimated its virial BH mass as $M_\bullet \sim 10^{6.43}$–$10^{6.72}$ M$_\odot$ based on broad H β from the SDSS (Section 3.1) and its host-galaxy stellar mass as $M_* = 10^{10.5 \pm 0.3}$ M$_\odot$ based on SED modelling (Section 3.2). Comparing DES J0218−0430 to local samples of inactive galaxies and low-redshift AGN, we do not see any evidence for significant redshift evolution in the $M_\bullet$–M_* relation from $z \sim 1$ to $z \sim 0$ (Fig. 8).

DES J0218−0430 is one of the lowest BH mass objects at similar redshift (Fig. 7). At similar redshifts to DES J0218−0430, the literature IMBH candidates are all selected from X-ray deep-fields. Our work highlights the prospect of using optical variability to identify low-mass AGNs at higher redshift (see also Elmer et al. 2020, for a recent study based on NIR variability).

In future work, we will present a systematic variability search of all high-redshift low-mass AGN candidates in the DES-SN and deep fields. We will also systematically search for IMBHs using variability in low-redshift dwarf galaxies over the entire DES wide field based on low cadence but long-term optical light curves. We will measure the BH occupation functions and particularly at low masses to distinguish seed formation mechanisms. Finally, future observations with LSST will discover more small BHs at higher redshift as the more ‘pristine’ fossil record to study BH seed formation.

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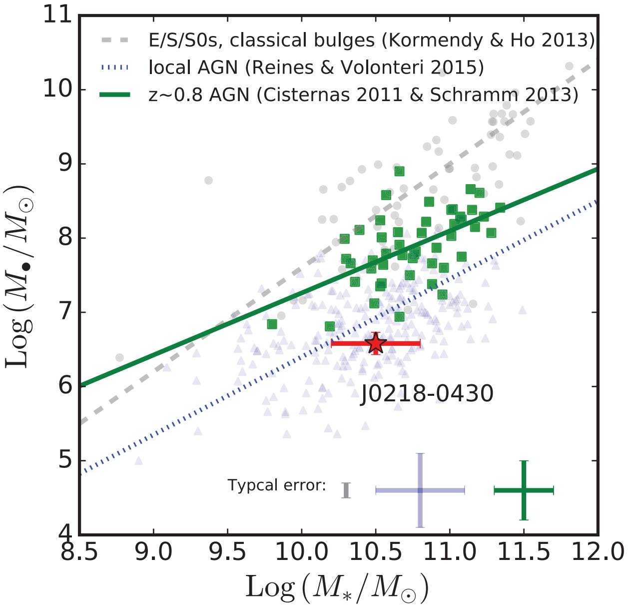

Figure 8. Black hole mass versus host-galaxy total stellar mass for DES J0218−0430 in comparison to X-ray selected intermediate-redshift AGNs and local samples of AGNs and inactive galaxies. The green solid line shows the best-fitting relation of the sample of 48 X-ray selected AGNs with a median $z \sim 0.8$ from Cisternas et al. (2011) and Schramm et al. (2013) re-analysed by Ding et al. (2020). The blue dotted line represents the best-fitting relation in local AGNs from Reines & Volonteri (2015) where the blue triangles show individual objects. The grey dashed line denotes the best-fitting relation using the sample of ellipticals and spiral/S0 galaxies with classical bulges from Kormendy & Ho (2013) with the grey dots showing individual systems. The error bars of DES J0218−0430 includes both statistical and systematic uncertainties. The error bars shown in the lower right corner denote typical uncertainties for the individual measurements in the comparison samples.

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Facilities: DES, Sloan, OzDES

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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