■ Scientific Justification

As the Chandra X-ray Observatory looks towards its 20th year of operation, its scientific legacy is secure and includes a deeper understanding of the physics of black holes, accretion and AGN. We propose to build on this legacy in the area of the highest redshift quasars $z > 6$, which will not be accessible again until the Lynx/Athena era in the 2030s. We aim to observe four recently discovered $z > 6$ quasars, which have high luminosities and massive black holes ($M_{BH} \approx 1 - 6 \times 10^9 M_\odot$). All 4 quasars have been detected in ALMA $850\mu m$ imaging. We shall: measure the full photon budget of luminous $z > 6$ quasars; correlate the strength of Lyman-α and X-ray absorption; look for quasar X-ray variability; and study the link between the accretion disc and coronal emission in quasars. This final science aim will allow the extension of the Quasar Hubble diagram to $z > 6$, significantly further than the $z < 1.2$ extent of the Type Ia SNe Hubble diagram.

Introduction: Very high redshift quasars with $z \gtrsim 6$ are excellent probes of the early Universe. This includes studies of the Epoch of Reionization for hydrogen (see Fan et al. 2006 and Mortlock 2016 for reviews) the formation and build-up of supermassive black holes (e.g., Rees 1984, Wyithe & Loeb 2003, Volonteri 2010, Agarwal et al. 2016, Valiante et al. 2018, Latif et al. 2018) and early metal enrichment (e.g., Simcoe et al. 2012, Chen et al. 2017, Bosman et al. 2017). Indeed the search for $z \gtrsim 6$ quasars has been a large motivation for new optical and infrared wide-field surveys, and projects including PanSTARRS, DES, VST ATLAS, UKIDSS, VHS and WISE have led to a large increase in the number of $z \gtrsim 6$ QSOs identified (e.g., Willott et al. 2010; Venemans et al. 2013; Matsuoka et al. 2016; Bañados et al. 2016; Tang et al. 2017; Yang et al. 2017, Bañados et al. 2018)

Recenlty, our team (Carnall et al. 2015; Chehade et al. 2018) reported the discovery of four bright high-redshift quasars using the combination of the VST ATLAS and WISE surveys (see Figure **??** and Table 1). Preliminary virial mass estimates based on the C IVand Mg IIemission lines give supermassive black hole (SMBH) masses in the range $M_{\rm BH} \approx 1 - 6 \times 10^9 M_\odot$ for the four ATLAS quasars. As such, Chehade et al. (2018) claim, along with Wu et al. (2015) that ∼0.1-0.6 and $\sim 1.2 \times 10^{10}$ $M_\odot$ SMBHs exist at $z \approx 6.0$ and $z \approx 6.3$, respectively. *These are the most luminous quasars, with the most massive black holes at any redshift.*

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"Understanding First Light & Reionization", that is, aiming to understand the $z \gtrsim 6$ galaxy and quasar population is a key science goal of *JWST*.

We propose to obtain NIRSpec Long Slit data on four $z \gtrsim 6$ luminous quasars that were identified cleanly by their optical-to-WISE colours (the only such selection in the literature). With these data, plus our we will be able to:

- Characterise the full rest UV-optical spectrum of the $z \gtrsim 6$ quasar population, from blueward of Ly$\alpha$to redward of H-α ($\approx 1160 - 7330$Å rest);

Quasar	Redshift	z (AB mag)	$M_{1450\text{Å}}$	Reference
ATLAS J025.6821-33.4627	6.31 ± 0.03	19.63 ± 0.06	-27.50 ± 0.06	[?]
ATLAS J029.9915-36.5658	6.02 ± 0.03	19.54 ± 0.08	-26.97 ± 0.08	[?]
VIKINGKiDS J0328-3253	5.86 ± 0.03	19.75 ± 0.12	-26.60 ± 0.04	[?]
ATLAS J332.8017-32.1036	6.32 ± 0.03	19.75 ± 0.06	-26.79 ± 0.06	This paper
ATLAS J158.6938-14.4211	6.07 ± 0.03	19.44 ± 0.08	-27.23 ± 0.08	This paper
PSO J340.2041-18.6621	5.98 ± 0.03	19.67 ± 0.10	-26.42 ± 0.10	[?]

Table 1: Absolute magnitudes for the four quasars discovered and the two quasars rediscovered in VST ATLAS+WISE. The ATLAS quasar absolute magnitudes are estimated via the X-Shooter spectra in Fig. **??** and the other two from the above sources.

- measure to 0.3dex (TBC!) the mass of the supermassive black hole;
- infer continuum shape, including measuring the contiuum slope at both shorter and longer than $\lambda_{\rm rest} = 4000$Å;
- infer the metalicity of the immediate environment of the quasar;
- by linking to the GTO High-z quasar programs, extend the baseline and challenge BH-formation models; how do you have $\sim 6{\times}10^9$ $M_{\rm BH}$ in place $\lesssim$1.2 Gyrs after the Big Bang?

Questions to answer/things to address::

- Why not *HST*??
- Why not *ALMA*?? Have ALMA data...

General Sample::

We propose to obtain ...sec exposures from *JWST* NIRSpec on each of these four ATLAS $z > 6$ quasars, for a total of sec. With these observations, plus our current multiwavelength data, our main science goals are:

- Challenge SMBH formation models; how do you have $\sim 6 - 10 \times 10^9$ $M_\odot$ SMBHs in place $\lesssim$0.9 Gyrs after the Big Bang?
- Measure the full photon budget of luminous $z > 6$ quasars putting strict limits on the Eddington limit and radiative efficiency;
- Check for variability (as is expected for super-Eddington accretion);

- Link the gas content of $z > 6$ quasar hosts via Ly-α, dust emission and X-ray absorption;

Science Case

The full photon budget of luminous $z > 6$ quasars. These $z > 6$ ATLAS quasars are amongst the brightest quasars with the most massive black holes seen at any redshift and yet appear less than 1 Gyr after the Big Bang. The paradox is that in their rest optical spectra they look very similar in e.g. metallicity to their lower redshift counterparts. The M_{BH} of these 4 quasars are close to the theoretical maximum black hole mass achievable by luminous accretion ($\approx 10^{10} M_{\odot}$, see Natarajan & Treister 2009, King 2016; Gallerani et al. 2017), and the challenge is to understand how these SMBHs have formed in less than $\approx$1 Gyr. This has led to various speculations about how to seed black holes: either the seeds have to be small and grow fast, or, they have to start big and grow at a normal rate. The former scenario could mean that the proto-quasars have frequently to accrete at super-Eddington rates to speed their growth. The latter scenario suggests that to explain the existence of SMBHs at high redshift, might include the possibility of direct collapse black holes (DCBHs) where gas collapses without fragmenting into stars to form an $\approx 10^{5} M_{\odot}$ black hole seed. This has led to searches for these proto-quasars in multi-wavelength surveys including X-rays.

Here we are proposing to measure X-ray fluxes for 4 quasars whose black hole mass is most difficult to explain and that we are seeing shortly after their seeding phase. Clearly determining the full photon budget at all wavelengths is vital in establishing their origin and the nature of their host galaxies. Because of their high luminosity, already these are some of the best studied quasars with optical and NIR spectroscopy available from VLT XShooter, and ALMA observations of the dust continuum and [CII] emission of the host galaxies. *Adding X-ray luminosities to their multi-wavelength spectra will directly help infer how such large mass objects appeared in the early Universe (e.g. Valiante et al., 2018a; Valiante et al 2018b).*

Variability of luminous high-z Quasars. We have now entered the "time-domain" astronomy era, where we now have large samples of variable quasars (e.g. SDSS-IV: TDSS with 100,000 objects). Considering the rapid build-up of BH mass, luminous $z > 6$ quasars might have some of the largest $\dot{M}$ changes. However, we have not conclusively observed this.

Nanni et al. (2018) report on the $z = 6.31$ quasar SDSS J1030+0524. They note that when compared with data obtained by XMM-*Newton* in 2003, the *Chandra* observations in 2017 show a harder ($\Delta\Gamma \approx -0.6$) spectrum and $\times 2.5$ fainter flux. Although this is consistent with accretion disc state changes i.e. faint-hard, bright-soft, *the timespan of $\sim$2 yrs rest-frame, is unexpected for such a luminous quasar powered by a $>10^{9} M_{\odot}$* SMBH. Nanni et al (2017) note that ATLAS J025.6821-33.462 has a survey observation in 2007 by the NASA *Swift* XRT and $\sim 3\sigma$ detections in the 0.5-7, 0.5-2 and 2-7keV bands. Thus making a measurement again, e.g. $\sim$2 years later in the rest-frame, is now timely. Very high-z quasars potentially build-up their mass via super-Eddington accretion; if so, we should observe these objects to be variable.

The gas content of $z > 6$ quasar hosts via LyA, dust emission and X-ray absorption: All 4 ATLAS quasars are strong ALMA 850μm continuum sources at the ≈ 0.5mJy level (Figure 2). The detection of X-ray emission by *Swift* XRT of J025-33 clearly shows that $z > 6$ quasars can be strong X-ray (and UV) emitters while being hosted by a dusty star-forming galaxy. Indeed $z > 6$ quasars seem characterised by strong dust and $[CII]$ emission. (see e.g. Decarli et al 2018). Given this prevalence of dust emission and $[CII]$ in high redshift quasars it seems natural to search for absorbed X-ray emission to test for the presence of neutral gas. In lower redshift quasars there has also been some evidence seen for the presence of sub-mm emission from X-ray absorbed quasars (e.g., Lutz et al 2010; Hill & Shanks 2011; Bielby et al 2012; Heywood et al 2013) further motivating this search for X-ray absorption at $z > 6$.

Why James Webb? Why Now?

References

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■ Technical Justification

- **Special Requirements (if any)**

- **Justify Coordinated Parallel Observations (if any)**

- **Justify Duplications (if any)**

- **Data Processing & Analysis Plan (AR only)**

- **Management Plan (AR only)**

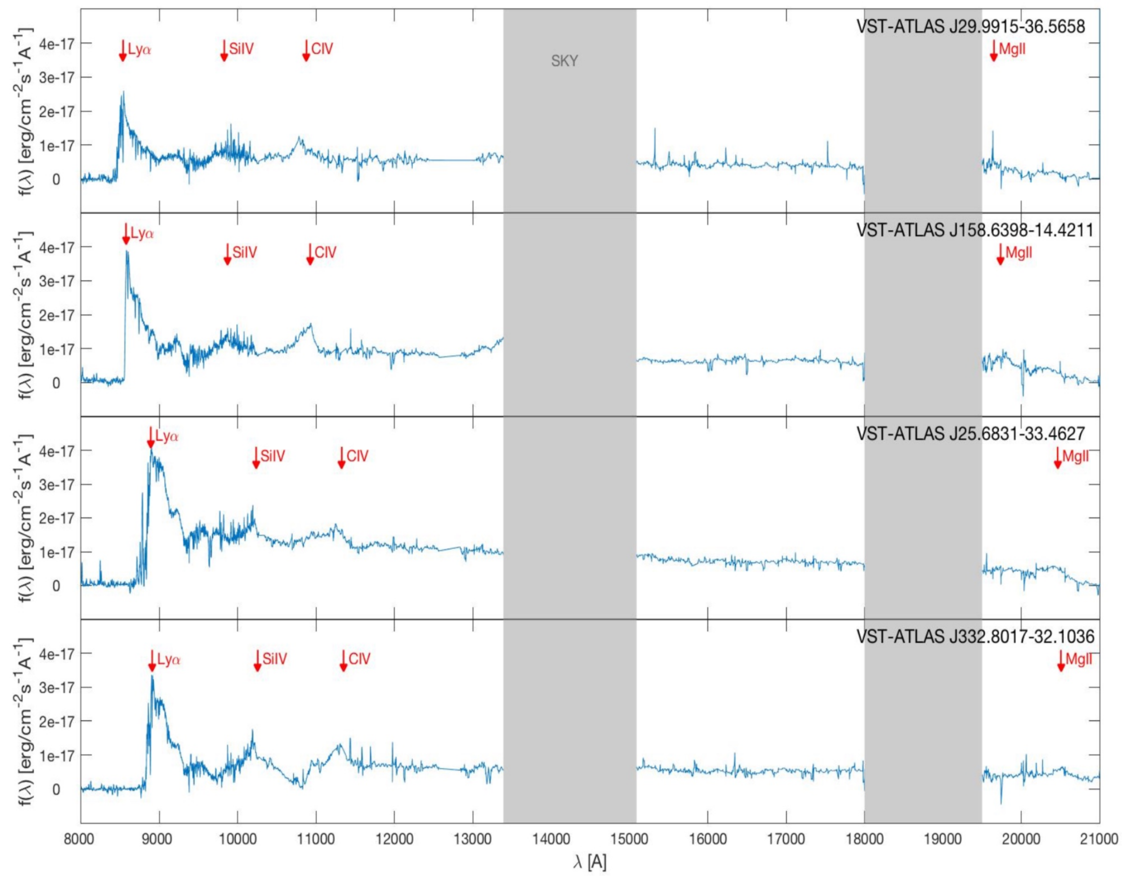

Figure 1: The VLT X-shooter spectra for our 4 ATLAS quasars. The spectra were flux calibrated to the observed z-band magnitudes from VST ATLAS and corrected for telluric absorption. The positions of the Lyα, Si IV, C IV and MgII emission lines are marked (and the redshifts given in Chehade et al. 2018). We note that higher ionisation lines such as C IV are frequently found to be blueshifted with respect to lower ionisation lines like Lyα and this is seen to be the case for all four quasars.

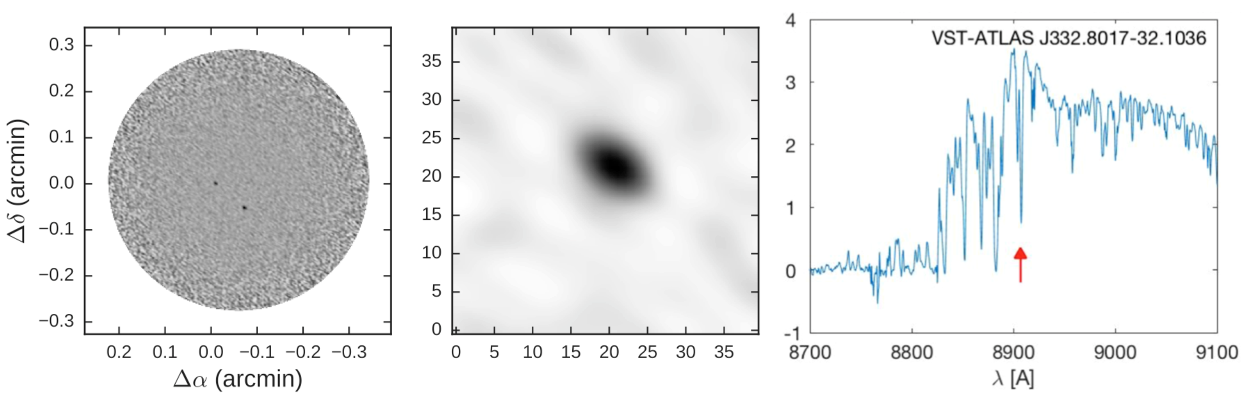

Figure 2: *Left:* ALMA 850 micron dust continuum images for J332 showing an integrated flux density of ≈ 0.5mJy. The lower of the two ALMA sources is the quasar. The other source could also be associated with the quasar. *Right:* Also the XShooter spectra of Chehade et al (2018) showing the complicated neutral gas pattern around this quasar via the Lyman-α absorption lines. Fig. 3 of Chehade et al shows the wide variety of Lyman-α absorption around the 4 ATLAS quasars. We propose to test for correlations between the presence of X-ray absorption, the pattern of the Lyman-α absorption and the strength of dust emission.

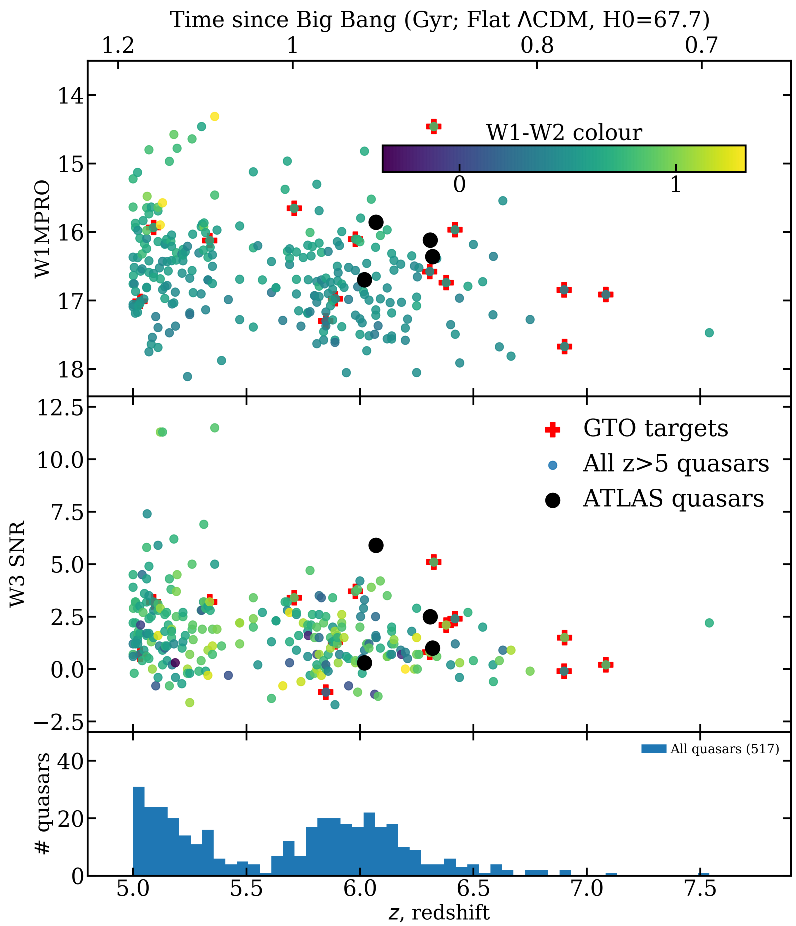

Figure 3: Ned Wright's talk; https://www.ipac.caltech.edu/exgal2011/sched.shtml