European Organisation for Astronomical Research in the Southern Hemisphere
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APPLICATION FOR OBSERVING TIME 111.2547

IMPORTANT NOTICE

Shedding Light on Early Structure Formation: MUSE Unveils the Largest Lyα Nebulae around a z~6.6 QSO

ABSTRACT

Recently a large (>20kpc) and exceptionally luminous (L~2.1x10^43 erg/s) Lyα nebula have been discovered with MUSE around the z=6.6 QSO P323+12. This unique nebula is potentially tracing an enormous reservoir of cool gas that is expected to be the fuel for the growth in both black hole and stellar mass of the first QSOs in the young Universe. However, because of the short integration (45min) and the contamination from the light of a bright star, it is currently impossible to fully constrain the physical properties of the extended Lyα nebula. With this program we propose to observe this spectacular system for 4 additional MUSE hours, reaching a level comparable to z~2-3 studies. This will enable the first detailed characterization of the CGM (potentially reaching IGM scales) of one of the brightest QSOs at z>6. This study will constitute an important step forward in understanding the environment where the first massive galaxies and supermassive black holes can form and evolve.

SCIENTIFIC KEYWORDS

galaxies: high-redshift, galaxies: halos, galaxies: quasars

RUNS

Run	Period	Instrument	Tel. Setup	Constraints	Mode	Type	Propr. Time	Time Constr.	Req. Time
111.2547.001 • Run 1	111	MUSE	UT4	FLI: 80% • Turb.: 100% • pwv: 30.0mm • Sky: Variable, thick cirrus	SM	Normal	12m	✕	04h00m

AWARDED AND FUTURE TIME REQUESTS

Time already awarded to this project

- none -

Future time requests to complete this project

- none -

Special Remarks

P323+12 is one of the brightest QSOs at z>5.5, with a luminosity that rivals with the archetypal z~6.4 QSO J1148+5251. As such, P323+12 has been subject to extensive XShooter (e.g., Farina et al., 2022) and ALMA (e.g., Neeleman et al. 2021) campaigns. The proposed observations will thus be a long-lasting legacy that the ESO community will exploit in the coming decade in synergy with campaigns at world-class observatories like the E-ELT and JWST.

For instance, in combination with the ~20hours of XShooter integration already collected on this target, it will be possible to cross correlate the location of absorption systems with Lyα detected in the MUSE cube opening the possibility of an in-depth investigation of the multi-phase circum-galactic medium of galaxies at z>5 (see for a similar experiment on the z~6.3 QSO J1030+0524, Diaz et al. 2021).

The Rise of the First Massive Galaxies

The present proposal aims at characterizing, via sensitive MUSE observations, the distribution of the ionized gas around the QSO P323+21 at z=6.6, i.e. at the end of the Epoch of Reionization. This object stands out for the presence of a bright [$\mathrm{L(Ly\alpha)}$=2.0×$10^{44}\,\mathrm{erg\,s^{-1}}$] $\mathrm{Ly\alpha}$ nebula with a projected size of approximately 25 kpc. This is, by far, the brightest such emission reported among the 31 z>5.5 QSOs observed with MUSE. However, a detailed investigation of the full nebular emission of P323+21 is hampered by the short exposure time (45 min on source) and by diffraction spikes of a 11 mag star located 30″ away from the QSO. With only 4 hours of MUSE time we will be able to increase the sensitivity of a factor of >2 and, more importantly, to drastically reduce systematics by carefully selecting position angles and dither pattern. These observations are fundamental to firmly pin down the total amount of gas feeding one of the most intensely accreting and star-forming source in the early Universe and to link its growth with the accretion of pristine material from the inter-galactic medium.

The Dawn of Massive Galaxy Formation — QSOs at z>6 (age of the universe: <1Gyr) represent unique laboratories to understand the early formation of massive galaxies and black holes (BHs). Their luminosity, powered by accretion onto massive BHs, makes them lighthouses to study the evolution of the intergalactic medium (IGM, e.g., Bosman et al. 2018; Eilers et al. 2018; Bañados et al. 2018) and the build-up of first large-scale galactic structures (Morselli et al. 2014; Overzier 2016; Decarli et al. 2017; Ota et al. 2018). The host galaxies of these QSOs harbor BHs with masses that can exceed $10^9\mathrm{M_\odot}$ (Farina et al. 2022) and they form stars at high rates (SFR=100–1,000 $\mathrm{M_\odot\,yr^{-1}}$; Venemans et al. 2020). The presence of broad emission lines associated with heavy elements in the broad line region (Onoue et al. 2020), and of large reservoirs of dust in the interstellar medium (Venemans et al. 2018) indicates that these galaxies are already highly metal-enriched. The mass and star formation rates of these early QSO host galaxies exceed by orders of magnitudes the ones of typical star-forming galaxies at z>6 (e.g., Vanzella et al. 2014; Bouwens et al. 2015; Ota et al. 2018). In this respect, QSO hosts are among the most active and evolved objects emerging from the dark ages.

Astronomers, however, still do not understand the detailed process by which these massive highly star-forming galaxies and BHs can form in less than 1 Gyr after the Big Bang and (potentially) evolve into the population of passive elliptical galaxies already in place by $z\sim4$ (500Myr later, Straatman et al. 2014). Cosmological hydro–dynamical simulations (Sijacki et al. 2009; Costa et al. 2014, 2022, Fig. 1) and analytical arguments (Volonteri & Rees 2006) suggest the first QSOs need a continuous replenishment of fresh fuel provided by filamentary streams of T=10^4-10^5 K gas from the intergalactic medium (IGM) and/or by mergers with gas rich haloes (Fig. 1). The goal of this proposal is to put direct observational constraints on this ansatz by **accurately imaging the large scale extended emission around one of the brightest quasars known at z∼7**.

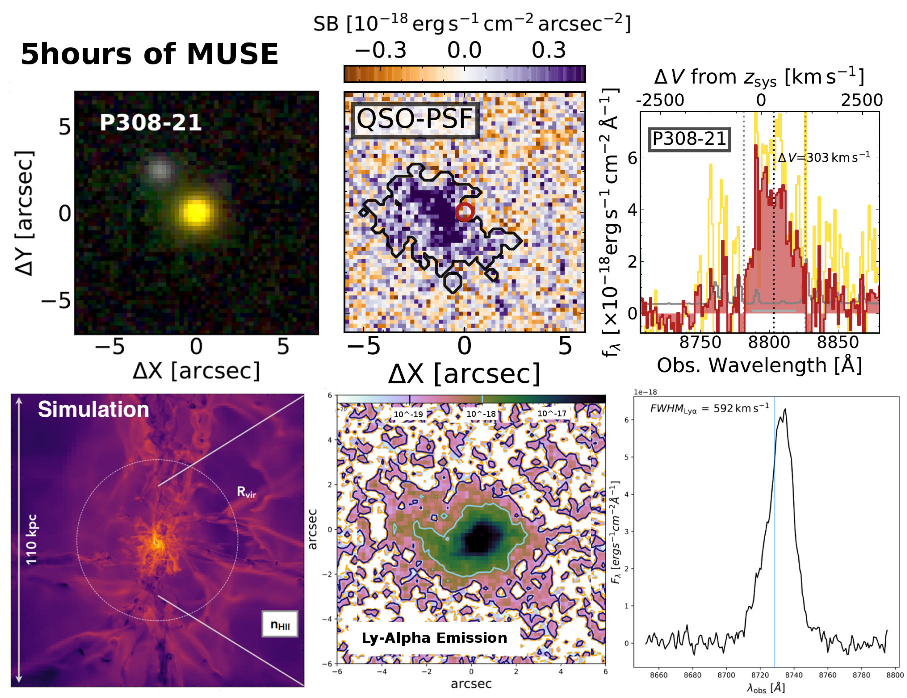

Fig. 1 – Extended Ly-Alpha halos around QSOs at z>6. *Top-Panel*: $\mathrm{Ly\alpha}$ nebula detected around the z=6.23 QSO P308–21 with 5h of MUSE integration. After carefully subtracting the QSO PSF, emission (with SB($\mathrm{Ly\alpha}$) $\sim 10^{-18}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcsec^{-1}}$) extending out to 30 kpc scales has been detected (Farina et al. 2019). This showcases that such deep limits can be reached in an exposure time comparable with that required for this program. *Bottom-Panel*: Dedicated radiation hydro-dynamic zoom simulation of a $\mathrm{M_{Halo}}$=$10^{12.5}\mathrm{M_\odot}$ halo at z=6 (Costa et al. 2022). The simulated QSO host lies at the intersection of a network of gas cold streams that penetrate the halos all the way into the central regions. Once the effects of stellar and QSO photo-ionization are taken into account, the extent and the spectral shape of the central regions of the extended nebula strikingly resemble the observed one (Costa et al. 2022). The unparalleled brightness of P323+12's halo enables the detection of these gas filaments at hundreds of kpcs scales. Thus providing the first direct picture of cold gas accretion at z>4, when this mechanism is predicted to have a pivotal role in feeding the growth of the first massive BHs and galaxies (Costa et al. 2022).

An Enormous Lyman Alpha Nebula around a z=6.6 QSO — In the last years, MUSE has been the workhorse to conduct a statistical survey of 31 luminous $z\sim6$ QSOs in an effort to directly detecting Lyα emission from the circum–galactic medium (CGM, Farina et al. 2019) This study unveiled that $z\sim6$ QSOs are surrounded by low surface brightness Lyα nebulosities with morphologies and (quiescent) kinematics similar to what typically reported around $z\sim2$-3 QSOs, i.e. almost $\sim$2 Gyr later (Arrigoni-Battaia et al. 2019). Among all these nebulae, the one around the z=6.6 QSO P323+12 stands out as the brightest $[\mathrm{L(Ly\alpha)}=2.0\times10^{44}\,\mathrm{erg\,s^{-1}}]$ and most extended one ($\gtrsim$25 kpc, see Fig. 2). These values should be considered as lower limit as the relatively short exposure time (45 min on target) and the contamination from a bright nearby star are hindering the full extent of the emission. This, this could be the high-z counterpart of the so-called *enormous* Lyα *nebulae* (with sizes larger than >200 kpc) reported around $\sim$1% of the $z\sim3$ QSOs (Arrigoni-Battaia et al. 2019). These are tracers of rich proto-cluster environments (e.g. Cantalupo et al. 2014, Hennawi et al. 2015) which are able to power the Lyα emission well beyond their virial radius, literally illuminating the process of gas accretion from the IGM.

Being the largest and brightest such system detected at z>6, the nebula around P323+12 is potentially tracing a similar environment. Thus, this may be pinpointing to **the largest reservoir of cold circum-galactic gas known at the highest redshifts** (with mass of 10^{10}-10^{11} M$_\odot$) and to a **progenitor of the most massive galaxy clusters in the local Universe**. Furthermore, its luminosity makes possible to trace the cool gas at larger scales, potentially all the way into the IGM, providing **the first direct detection of the cold accretion phenomenon at z>4**. However, deeper observations are necessary to compensate for the factor $(1+z)^{-4}$ dimming in surface brightness due to the redshift difference. By reaching 5σ limits of a few$\times10^{-18}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcsec^{-2}}$ we will fully recover the signal from the nebula and be able to accurately quantify its spatial extent, morphology, and kinematics. In addition, current data do not firmly characterize the Lyα line shape because they are not sensitive enough to the line wings. The high-quality of the requested MUSE observations will allow us to spatially-resolve the Lyα line profile, ultimately constraining the cool gas motions on CGM scales. This wealth of information will be decoded with dedicated cosmological simulations ,including radiative transfer models which take into account the well determined photon contribution of the central black hole and of the star forming host (Costa et al. 2022, Fig. 1). Providing, for the first time, stringent constraints on how a star-forming host-galaxy (probed by 0.1 arcsec resolution ALMA observations, Venemans et al. 2020) and an accreting BH (with $\mathrm{M_{BH}}=2\times10^9\,\mathrm{M_\odot}$ and an Eddington ratio of λ_{Edd}=1 as proven by XSHOOTER, Schindler et al. 2020) at z>6.5 are replenished with fresh fuel by pristine gas accretion from the IGM.

Legacy for E-ELT and JWST observations — These observations will go beyond the specific goals of this proposal. By combining high quality observations of one of the brightest $z\sim6.6$ QSO known ($\mathrm{M_{1450}}=-27.1$ mag) collected with three of the most powerful ESO instruments: MUSE, XSHOOTER, and ALMA, we will assemble an unprecedented data–set that will provide a **complete survey for the IGM, CGM and QSO environment around a massive galaxy in the first billion years of cosmic time**. This will become a **legacy for the astronomical community**: providing crucial piece of information to shape current theories on the formation and evolution of galaxies at the highest redshifts and paving the way for future explorations with JWST and the E-ELT.

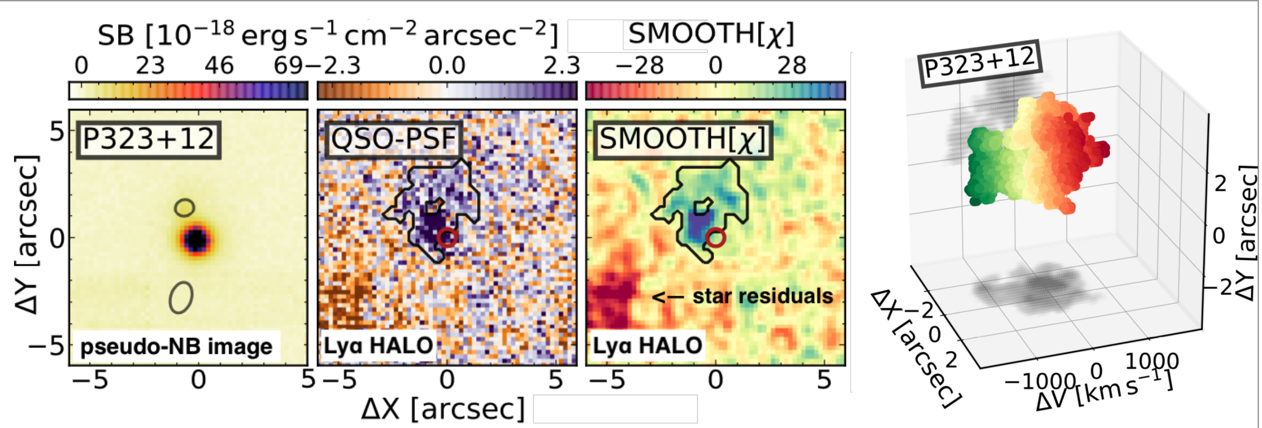

Fig. 2: Detection of the brightest Ly-Alpha halo at z=6.6 Analysis of the 45 min MUSE observations of the QSO P323+12 at z=6.6 (Farina et al. 2019). The different panels show narrow-band images obtained by collapsing the cube where extended emission (highlighted with a black contour) has been detected. From left to right: QSO field, PSF subtracted image, significance of the detection, and 3D visualization of the nebula. The contamination from the saturation spikes of the nearby 11 mag star is apparent in the bottom left corner of the images. The nebula is redshifted from the QSO host galaxy redshift (precisely traced with 0.3″ resolution ALMA observations of the [C II] emission line, Venemans et al. 2020), suggesting an ongoing gas inflow.

References: Arrigoni Battaia et al. 2019, MNRAS, 482, 3162 Cantalupo et al. 2014, Nature, 506, 63 Costa et al. 2022, MNRAS, arXiv:2203.11232 Farina et al. 2019, ApJ, 848, 78 Farina et al. 2022, ApJ, arXiv:220705113 Hennawi et al. 2015, Science, 348 779 Jiang et al. 2007, ApJ, 134, 1150 Matsuoka et al. 2018, ApJS, 237, 5 Mazzucchelli et al. 2017, ApJ, 849, 91 Volonteri & Rees, 2006, ApJ, 650, 669 Volonteri 2010, A&ARv, 18, 279 Wang et al. 2011, ApJ, 739, L34, 2013, ApJ, 773, 44 Wang et al. 2018, ApJL, 869, L9

TARGETS

Name	RA	Dec	Coord	Runs	Comment
P323p12	21:32:33.191	+12:17:55.26	J2000	1	M1450=−27.06, z=6.59
JAB=19.74					

Target Notes

The VLT/MUSE survey of z~6 QSOs presented Farina et al. (2019) revealed the presence of bright [L(Lyα)>20x10^43erg/s] and extended (>20kpc) Lyα emission around the quasar P232p12 at z=6.6. This is the brightest Lyα nebulae known at z>5.5 as such represent a unique laboratory to explore the physical properties of the gas surrounding the first QSOs.

REMARKS & JUSTIFICATIONS

Lunar Phase and Constraints Justification

Please justify here the requested lunar phase and other observing constraints.

Given the little impact of moon illumination at the wavelength of interest (~9000Ang.) we ask for gray time.

Time Justification

Please describe here a detailed computation of the necessary time to execute the observations, including time-critical aspects if any. Parameters used in the ETC should be mentioned so the computation can be reproduced.

This program aims to perform a detailed study of the bright Lyα nebula surrounding the z=6.6 QSO P323+12 powered by UV photons rising both from the star formation activity of the host (derived from ALMA maps of the dust continuum emission) and from accretion on the central BH (directly measured from the rest-frame UV spectroscopy collected with XSHOOTER). The exposure time is tailored to achieve a 5σ Lyα surface brightness limit of ~3x10^−18erg/s/cm^2/arcsec^2 over a 1 arcsec^2 aperture and a 250 km/s bin. In this regime, we will be able to compensate for the (1+z)^-4 redshift dimming factor of the surface brightness and thus to detect this system at a significance level comparable to lower redshift studies (e.g., Arrigoni-Battaia et al. 2019). This is a fundamental step to probe the total extent, morphology and the kinematic of the cool gas surrounding this highly accreting QSO. Coincidentally, at z=6.6 the Lyα emission fall into a region relatively free from strong sky lines making our observations particularly efficient. In addition, the combination of several exposures and the selection of PA aimed at avoiding difractions spikes from the nearby bright star will drastically reduce the systematics that are strongly affecting current data.

Accordingly to the MUSE Exposure Time Calculator (Version P111) considering to observe with 80% FLI, with a seeing=1.3" (85% chance of realization), and at an airmass=1.4, a total of 4.5hours are required to reach the considered sensitivity (of which 45 min have already been collected as part of the program 0101.A-0656). Observations will be split into 2x1500s DIT per 4 OBs each with a different PA (accurately selected to avoid contamination close bright stars). In summary, including overheads (preset, acquisition, offset, and rotation) and considering data already in the archive, we request 4 hours of MUSE to investigate the field of P323+12 at z~6.6 in relatively poor seeing conditions.

Telescope Justification

Please justify why the telescope requested is the best choice for this programme.

The sensitivity requested in this project is only achievable with an 8m-class telescope. Being the most efficient spectrograph on the VLT and with a 1'x1' FoV (corresponding to 2.4x2.4 cMpc^2 at z~6), MUSE is the only instrument able to reach the sensitivity limit necessary to fully characterize the Lyα nebular emission down to a level comparable to their z~2-3 counterpart

Observing Mode Justification

Please justify the choice of SM, VM or dVM.

Given the loose weather conditions required this program can be used as a filler. Service Mode is thus considered.

Calibration Request

If you need any special calibration not included in the instrument calibration plan, please specify it here.

N/A

Duplication with ESO Science Archive

If observations of the same target(s) using the same instrument(s) already exist in the ESO archive, please justify why this programme requests further observations.

For the proposed target a short (~45min) observation has already been collected and published in Farina et al. (2019, see also ESO Science Release #eso1921).

Our proposal aims to reach a sensitivity a factor of >2x higher, improve the spatial resolution, and, more importantly, drastically decrease systematics due to a close by bright star.

GTO Target Duplication Justification

If an instrument GTO team aims at the same target(s), please justify why this programme requests further observations.

N/A

Background and Expertise

Short description of the background, expertise and roles of the various team members in the context of the science case discussed in the proposal. For small teams the applicants may wish to provide a sentence for the qualifications of each member, while for larger teams (e.g. in Large Programmes), only the leading roles need to be specified.

The proposing team discovered more than 200 QSOs at z>6, including the two targets of this proposal. The team is leading an extensive observing campaign using ESO instruments to fully characterize the properties of the first QSOs.

The PI: Dr. Farina reported the highest redshift extended nebula known to date. Dr. Farina is also leading an ESO-VLT/MUSE effort to perform a census of the extended LyAlpha emission around 31 QSOs at 6.0<z<6.6 (Farina et al. 2019, ApJ 887 196F).
Co-Is Dr. Decarli, Prof. Fan, Dr. Mazzucchelli, Dr. Venemans, Dr. Walter, Dr. Yang, and Dr. Wang contributed to the discovery of >200 QSOs at z~6 and of all the z>7 QSOs known to date. They have led several ground breaking studies on the properties of the most distant QSOs with different facilities including HST, ALMA, SPITZER, KECK, and VLT.
Co-Is Prof. Hennawi is an expert in the study of the IGM status at the re-ionization epoch both from an observational and from a theoretical prospect.
Co-I Dr. Arrigoni-Battaia is an experts on extended Lyα emission around intermediate to high-redshift quasars.

The team led more than 200 papers on the topic of high redshift QSOs in the last decade.

REPORT ON PREVIOUS USAGE OF ESO FACILITIES

Run	PI	Instrument	Time	Mode	Comment
0101.A-0656(A)	Emanuele Paolo Farina	MUSE	23.0h	Service	Data published in Farina+19
The Ecosystem of the First QSOs -- A MUSE Snapshot Survey					
0103.A-0562(A)	Emanuele Paolo Farina	MUSE	12.0h	Service	Data published in Farina+19
The Ecosystem of the First QSOs -- A MUSE Snapshot Survey					
0104.A-0948(A)	Emanuele Paolo Farina	MUSE	31.0h	Service	Data published in Farina+19
The Ecosystem of the First QSOs -- A MUSE Snapshot Survey					
0104.A-0948(B)	Emanuele Paolo Farina	MUSE	24.0h	Service	Data published in Farina+19
The Ecosystem of the First QSOs -- A MUSE Snapshot Survey					
099.A-0682(A)	Emanuele Paolo Farina	MUSE	1.0n	Visitor	Data published in Mazzucchelli+19, Drake+19, Farina+19
The build-up of QSOs at the cosmic dawn: a MUSE and ALMA synergy					
0105.A-0006(A)	Emanuele Paolo Farina	MUSE	19.0h	Service	Data reduced, analysis ongoing
The Ecosystem of the First QSOs - A MUSE Snapshot Survey					
0105.A-0007(A)	Emanuele Paolo Farina	KMOS	36.0h	Service	15 out of 36 OBs collected. Analysis ongoing
The birth of a giant: Probing pristine gas accretion on two z~7.5 QSOs					
0106.A-0324(A)	Emanuele Paolo Farina	KMOS	20.0h	Service	Carry-over into period 108
The birth of a giant: Probing pristine gas accretion on the highest redshift QSO known					

RECENT PI/CoIs PUBLICATIONS MOST RELEVANT TO THE SUBJECT OF THIS PROPOSAL

1. Arrigoni Battaia, F., Obreja, A., Prochaska, J. X., et al. (2019) "Discovery of intergalactic bridges connecting two faint z □ 3 quasars," A&A, 631, A18 - 2019A&A...631A..18A

2. Costa, T., Arrigoni Battaia, F., Farina, E. P., et al. (2022) "AGN-driven outflows and the formation of Lyα nebulae around high-z quasars," arXiv, arXiv:2203.11232 - 2022arXiv220311232C

3. Decarli, R., Dotti, M., Bañados, E., et al. (2019) "ALMA and HST Kiloparsec-scale Imaging of a Quasar-galaxy Merger at Z ≈ 6.2," ApJ, 880, 157 - 2019ApJ...880..157D

4. Drake, A. B., Farina, E. P., Neeleman, M., et al. (2019) "Lyα Halos around z □ 6 Quasars," ApJ, 881, 131 - 2019ApJ...881..131D

5. Drake et al. (2022) "The Decoupled Kinematics of High-z QSO Host Galaxies and Their Lyα Halos," ApJ, 929, 86 - 2022ApJ...929...86D

6. Farina, E. P., Arrigoni-Battaia, F., Costa, T., et al. (2019) "The REQUIEM Survey. I. A Search for Extended Lyα Nebular Emission Around 31 z > 5.7 Quasars," ApJ, 887, 196 - 2019ApJ...887..196F

7. Farina et al. (2022) "The X-shooter/ALMA Sample of Quasars in the Epoch of Reionization. II. Black Hole Masses, Eddington Ratios, and the Formation of the First Quasars," arXiv, arXiv:2207.05113 - 2022arXiv220705113F

8. Mazzucchelli, C., Decarli, R., Farina, E. P., et al. (2019) "Spectral Energy Distributions of Companion Galaxies to z □ 6 Quasars," ApJ, 881, 163 - 2019ApJ...881..163M

INVESTIGATORS

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Jinyi Yang, University of Arizona, United States

OBSERVATIONS

In the table below, the repeat factor is applied to the complete observation on that target, including its overhead.

✔ The PI acknowledged that all the telescope times listed below include overheads.

Run 111.2547.001 • Run 1 • P111 • MUSE • SM — Tel. Time: 04h00m

FLI: 80% • Turb.: 100% • pwv: 30.0mm • Sky: Variable, thick cirrus • Airmass: 1.4

Target • P323p12 • 21:32:33.191 • +12:17:55.26 — Tel. Time: 04h00m

OS 1	WFM-NOAO	Observation
Tel. Time: 3600 s	Instrument Mode: WFM-NOAO-N	Integration Time: 0 s
Repeat: 4 x	Telescope Overheads: 360 s	Instrument Overheads: 0 s
Total Tel. Time: 04h00m		Signal/Noise: 0.0