European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **97Z**

DDT

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title

Category: **A–1**

First insights onto the build-up of QSOs at the cosmic dawn: a MUSE and ALMA synergy

2. Abstract / Total Time Requested

Total Amount of Time:

Luminous QSOs at $z>6$ are among the most massive objects at these early cosmic times, and are expected to reside in prominent overdensities. However, so far observational studies failed to achieve conclusive evidence of such overdensities. Our on-going ALMA survey of [CII] and dust emission in $z>6$ QSOs has now revealed five cases (out of 18 sources delivered so far) in which the QSO has a close companion, gas-rich galaxy. This is the first unambiguous evidence of galaxies associated with $z>6$ QSOs. Characterizing these sources is crucial for our understanding of early black hole and galaxy growth. Here we propose to use MUSE to search for Lyα and rest-frame UV continuum emission associated with the most extreme of the [CII]-bright QSO companions in our sample, J2100-1715 at z=6.087, and to investigate the QSO's environment. With these observations, we will have for the first time a quantitative insight of the build-up of QSOs at the dawn of cosmic time.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	97	MUSE	4h	any	g	1.0	CLR	s	

4. Number of nights/hours

	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

In the last years, ESO has consistently supported our effort to discover and characterize QSOs at $z>6$. Follow-up imaging (NTT; PI: Decarli) and spectroscopy (FORS2, PI: Venemans; XSHOOTER, PI: Farina) allowed our group to triple the number of southern QSOs known to date. Moreover, this project builds on our on-going ALMA Cycle 3 program (PI: Walter) aimed at surveying the [CII] emission in a large sample of $z>6$ QSOs. Thanks to the unprecedented statistical power of our search, we were able to find rare gas-rich companions around a handful of high-z QSOs and thus to quantitatively investigate the build-up of the first QSOs.

6. Principal Investigator: deky

6a. Co-investigators:

E.P.	Farina	1498
C.	Mazzucchelli	1498
B.	Venemans	1498
F.	Walter	1498

Following CoIs moved to the end of the document ...

7. Description of the proposed programme

A – Scientific Rationale:

QSOs at the dawn of cosmic time — The very presence of luminous QSOs within 1 Gyr from the Big Bang challenges our understanding of early black hole and galaxy formation. Over the last 15 years, numerous studies have established a sample of ∼180 QSOs at z>5.5 (half of them discovered by our group, Bañados et al. 2014,15a,16; Venemans et al. 2013,15a,b; Mazzucchelli et al. in prep). These QSOs are powered by accretion onto $\sim 10^9\,M_\odot$ black holes, which are already in place less than a Gyr after the Big Bang, during the epoch of reionization. Observations at [sub-]mm wavelengths revealed that their host galaxies are intensely forming stars (e.g., Bertoldi et al. 2003a; Walter et al. 2009; Leipski et al. 2014). Star formation is supported by large reservoirs of molecular gas, resulting in bright CO and [CII] emission (e.g., Bertoldi et al. 2003b; Walter et al. 2003,04,09; Maiolino et al. 2005; Venemans et al. 2012; Wang et al. 2013; Willott et al. 2015, Venemans et al. 2016). To explain such a rapid build-up of both stellar and black hole mass, models require that the host galaxies of QSOs at z>5.5 are among the most massive galaxies in the early Universe (e.g., Narayanan et al. 2008, Volonteri 2012), are highly clustered (e.g., Bonoli et al. 2009), and reside in the high-density peaks of the dark matter distribution (Volonteri 2012, Bonoli et al. 2009, 2014). To date, however, firm observational constraints of these theoretical predictions are still missing.

Gas-rich galaxies around QSOs <1 Gyr after the Big Bang — Searches for direct evidence of companion galaxies around z>5.5 QSOs at optical/NIR wavelengths have so far led to controversial results. Some studies reported indications of overdensities of Lyman Break Galaxies (LBGs) selected via broad-band optical/NIR colors (e.g., Stiavelli et al. 2005; Zheng et al. 2006; Morselli et al. 2014); these searches, however, are highly contaminated by foreground, intrinsically red sources. Narrow-band studies, which are less sensitive to contaminants, failed so far to find any galaxy overdensity around z>5.5 QSOs (e.g., Decarli et al. 2012; Bañados et al. 2013; Mazzucchelli et al. submitted). In ALMA Cycle 3 we undertook a survey of dust continuum and [CII] 158μm fine-structure emission line in 35 QSOs at z>6 (project 2015.1.01115.S, PI: Walter). **This marked a transformational step from studies on individual targets to first statistical samples**. This project is currently on-going, but the (recently-delivered) first data already demonstrate the success of our survey: fifteen (out of 18 delivered) QSOs are clearly detected in both [CII] and the underlying dust continuum with only 8 min of integration. Intriguely, **five QSOs show [CII]-bright companion galaxies with similar redshift and projected separations of only 6-60 kpc** (Fig. 1). These findings provide unprecedented clues on the early growth of the first QSOs.

This proposal — It is of paramount importance that we characterize these new gas-rich companions. We need to **a)** measure their rest-frame UV continuum emission, in order to assess which kind of spectral energy distribution these galaxies have, and measure their unobscured star formation rate; **b)** measure their Lyα emission line, in order to map the extent and kinematics of the ionized gas reservoir, to compare with the neutral medium explored with our ALMA observations. Additionally, **c)** we will investigate the presence of galaxy overdensities via a blind search for Lyα Emitters (LAEs) and LBGs in the cube. This will allow us to directly link the presence of gas-rich companions with the (rest-frame UV bright) galactic environment of the QSO (Fig. 4). The excellent sensitivity and integral field capabilities offered by MUSE represent an ideal combination in order to simultaneously reach these goals (Figs. 2-3). For this proposal, we selected J2100-1715 at z=6.087, when the Universe was 840 Myr (Fig. 1 and Box 11).

B – Immediate Objective:

We propose to obtain sensitive MUSE observations of the field of the z=6.087 QSO J2100-1715. We will validate our strategy by focusing on a clear-cut example of a FIR- and [CII]-luminous QSO companion galaxy with a small ($\sim 30\,\mathrm{km\,s^{-1}}$) line-of-sight velocity separation (see Box 11). Our custom-built set of routine for data analysis will allow us to improve illumination correction and sky subtraction in the MUSE data (as already demonstrated in Fumagalli et al. 2014, Farina et al. in prep.), allowing us to stretch the capabilities of MUSE to their limits at longer wavelengths (Fig. 2). We will collapse the MUSE datacube at wavelengths λ>862 nm (the observed wavelength of Lyα) in order to get a sensitive image of the rest-frame UV emission of the companion source of J2100-1715. The bright dust continuum emission revealed by ALMA requires that the star formation rate of the companion source is $\sim 100\,M_\odot\,\mathrm{yr^{-1}}$, yielding intrinsically bright UV emission, that we expect to detect even in presence of substantial dust reddening (Fig. 3). Additionally, we will map the Lyα emission of the companion source and use it to trace the morphology and kinematics of the $T\sim 10^4$ K ionized gas, compared with the [CII] line which is mostly associated with the cold (T<300 K) gas phase. Finally, we will search for Lyα and UV continuum emission from other sources in the field. Our clustering analysis suggests that at least 1 additional LAE will be detected within the MUSE field of view if the QSO-galaxy clustering is the same as observed at $z\sim 1$ (Zheng et al. 2013), and up to ∼10 if the LAE clustering evolves as expected from structure formation theory (Fig. 4; Bonoli et al. 2009; Shen et al. 2009). **With a single, sensitive observation we will shed light on the properties of the companion galaxies of the first QSOs, thus exposing the formation and early growth of the first massive galaxies and black holes**. The outcome of the proposed observations will be instrumental in shaping our plan for a follow-up campaign of the other four sources in our sample (and possibly more, as new ALMA data are currently being delivered) in the next observing semesters.

7. Description of the proposed programme and attachments

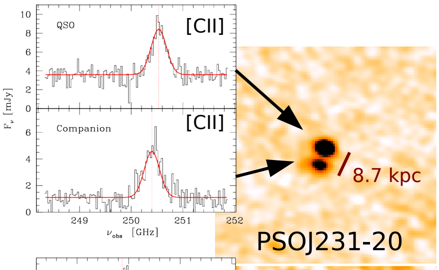
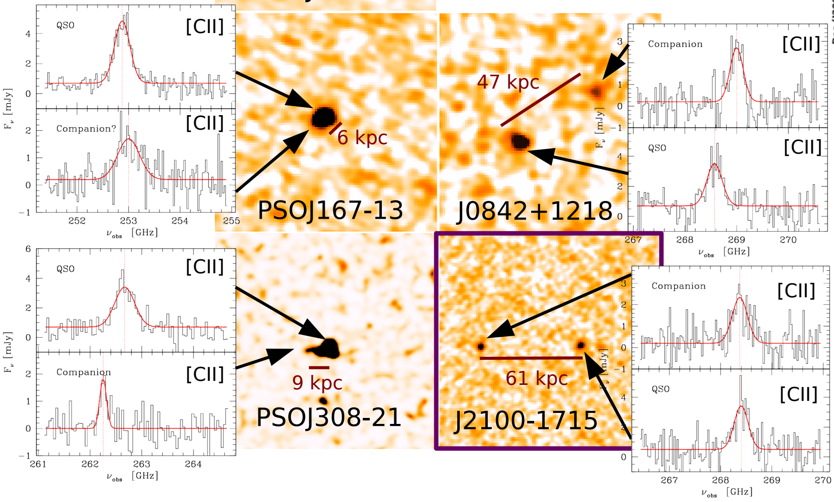


Figure 1: ALMA dust continuum images of the z>6 QSOs with gas-rich companions (color scales) in our ALMA survey. Each image is 20"x20". The on-sets show [CII] spectra. The target chosen here is J2100-1715, which shows a [CII]- and FIR-luminous companion at a separation of only 61 kpc on the sky plane, and a bulk line-of-sight velocity difference of only ~30 km s^{-1} (see Box 11 for further details on the target selection).



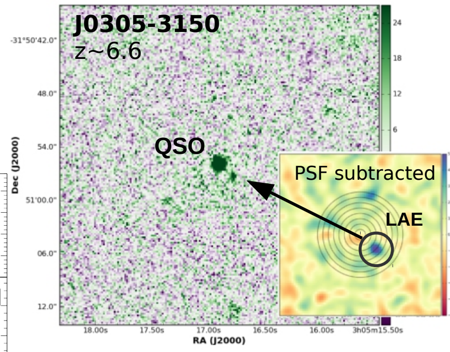


Figure 2: MUSE IFU images of the QSO J0305-3150 z~6.6 (part of our project to map the Lyα emission around high-z QSOs, Farina et al. in prep., see Box 9). The analysis of the field with our newly developed routines reveals the presence of a Lyα emitter located only 2" (12.5 kpc) and ~550 km s^{-1} from the QSO, thus showcasing MUSE potential in detecting faint galaxies at these high redshifts.

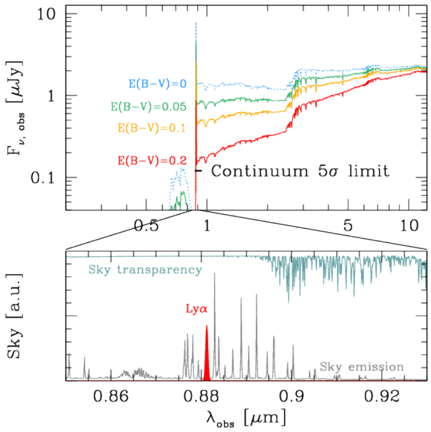


Figure 3: The expected spectral energy distribution of the galaxy companion of J2100-1715. We assume a stellar population with a SFR~100 Mo yr^{-1}, required to power the bright dust emission, and apply various degrees of reddening (parametrized by the E(B-V) value). Even in the case of high dust extinction (E(B-V)=0.2 mag, yielding a IR luminosity even higher than the one estimated based on the ALMA observations) we expect a >5-σ continuum detection by collapsing the MUSE observations red-ward of the observed Lyα wavelength (8812Ang) into a single continuum image. Additionally, the Lyα line coincidentally falls in a wavelength window that is free of significant atmospheric absorption and that is not contaminated by any bright sky emission line, thus enabling sensitive measurements of the Lyα emission in our target.

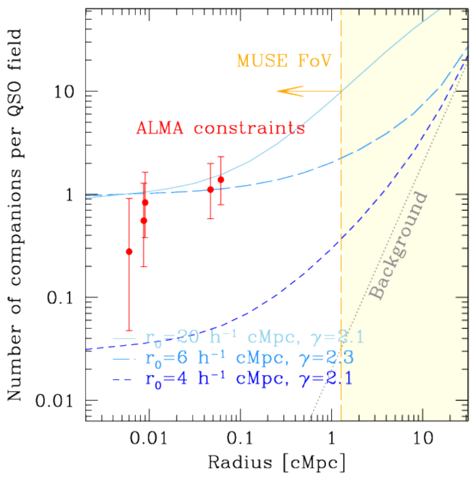


Figure 4: Expected number of LAEs in the field of J2100-1715, assuming the z~6.6 luminosity function by Kashikawa et al. (2011) and the QSO-galaxy 2 point correlation function by Zhang et al. (2013), calibrated at z~1 (r_0=4 h^{-1} cMpc, γ=2.10; dashed line). The commonality of ALMA companions suggests a strong evolution of the clustering with redshift, consistent with the known evolution of the QSO-QSO clustering (i.e., the higher z, the higher both r_0 and γ; see solid and long-dashed blue lines, respectively). From the number of LAEs detected in our field, we will be able to quantify the clustering in this system.

REFERENCES — Bañados et al. 2013, ApJ, 773, 178; 2014, AJ, 148, 14 • Bertoldi et al. 2003a, A&A, 406, L55; 2003b, A&A, 409, L47 • Bonoli et al. 2009, MNRAS, 396, 423; 2014, MNRAS, 437, 1576 • Decarli et al. 2012, ApJ, 756, 150 • Kashikawa et al. 2011, ApJ, 734, 119 • Leipski et al. 2014, ApJ, 785, 154 • Maiolino et al. 2005, A&A, 440, L51 • Morselli et al. 2014, A&A, 568, 1 • Narayanan et al. 2008, ApJS, 174, 13 • Venemans et al. 2012, ApJ, 751, L25; 2013, ApJ, 779, 24; 2015a, ApJ, 801, L11; 2015b, MNRAS, 453, 2259; 2016, ApJ 816, 37 • Volonteri et al. 2003, ApJ, 582, 559; 2012, Science, 337, 544 • Walter et al. 2003, Nature, 424, 406; 2004, ApJ, 615, L17; 2009, Nature, 457, 699; 2011, ApJ, 730, 18 • Wang et al. 2013, ApJ, 773, 44 • Willott et al. 2005, ApJ, 626, 657; 2015, ApJ, 801, 123 • Zhang et al. 2013, ApJ, 773, 155

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: Given that the Lyα emission in J2100-1715 is redshifted at λ=862 nm (where the moon has small effect on the data quality) we ask for gray time. Bright time would require ∼2.5× more integration time.

Time Justification: (including seeing overhead) The main goal of this program is to detect the Lyα emission line and rest-frame UV continuum arising from the companion galaxy of the z>6 QSO J2100-1715. Additionally, we aim to constrain the QSO-galaxy clustering at z>6 via a sensitive search for Lyα emitters and Lyman break galaxies in the field. We base our estimates on the online *MUSE Exposure Time Calculator* (Version 6.0.1) assuming a seeing of 1″ (87% chance of realisation at the Cerro Paranal site) and an airmass of 1.5. At wavelengths >870 nm the sky emission affects the S/N of the observations, but our line observations are well accommodated in a feature-free region of the atmospheric spectrum (see Fig. 3).

IR–bright companion source: The ALMA–detected companion of J2100-1715 has a IR luminosity $L_{\rm IR}$=(3-10)$\times 10^{11}\,L_\odot$, corresponding to a star formation rate SFR∼100 $M_\odot\,{\rm yr}^{-1}$. The expected UV rest-frame continuum emission from the stellar population is shown in Fig. 3. If we assume an extinction E(B-V)=0.2 mag, the dust-absorbed power is $\sim 10^{12}\,L_\odot$, i.e., more than sufficient to explain the observed ALMA 263 GHz flux density, assuming energy balance. Our sensitivity request is driven by the need to detect such a galaxy at >5-σ at λ=(881-930) nm (the range encompassed in the proposed MUSE observations). By taking into account the actual S/N wavelength dependence predicted by the MUSE ETC, and collapsing over the 881-930 nm range, we infer that 8 DITs×1200 sec will yield the requested 5-σ sensitivity of 0.12 μJy (AB=26.2 mag).

Expected number of LAEs in the field: At the proposed sensitivity, we achieve a 5-σ Lyα line sensitivity of $0.7\times 10^{-17}\,{\rm erg\,s^{-1}\,cm^{-2}}$, or L(Ly$\alpha$)=$3.1\times 10^{42}\,{\rm erg\,s^{-1}}$. This is a factor 1.6× fainter than the knee of the LAE luminosity function estimated by Kashikawa et al. (2011) at $z\sim 6.6$. By integrating the LAE luminosity function down to our luminosity limit, we estimate a volume density of n=$3.1\times 10^{-4}\,{\rm cMpc^{-3}}$. The expected number of LAEs is then N=$n\int dV(1+\xi(r))$, where $\xi(r)$=$(r/r_0)^{-\gamma}$ is the correlation function. The volume integral is extended over 20 cMpc along the line of sight (the typical distance used in clustering studies), and over the $1'\times 1'$ MUSE field of view. The results are shown in Fig. 4 for various values of r_0 and γ, and yield 1-10 expected LAE detections in our field at the requested sensitivity.

Overheads (preset, acquisition, offset, and rotation) sum up to ∼20 min per OB. In summary: we request 4 hours of MUSE to characterize the gas-rich companion and probe the environment of J2100-1715 at z=6.087.

8a. Telescope Justification:

The sensitivity requested in this project is only achieved with an 8m-class telescope. The IFU capabilities offered by MUSE are ideal for our goals as we will be able to search for Lyα emitting galaxies in the environment of these QSOs in an area as large as $\sim 2.4\times 2.4\,{\rm cMpc^2}$ (i.e., sufficient to fully encompass the typical size of the overdensities expected at these early cosmic times, and to cover the area of our ALMA observations).

8b. DDT Justification:

The recently-delivered [CII] and dust observations from our on-going ALMA Cycle 3 survey of z>6 QSOs have provided us with *the first unambiguous evidence of gas-rich companion galaxies* in the field of these QSOs. **For the first time, we can directly test models for early massive black hole and galaxy growth**. The proposed MUSE observations will demonstrate the robustness of our strategy and show-case the power of the synergy between MUSE and ALMA observations, as we need the capabilities of MUSE to put these ALMA-discovered sources into the larger framework of galaxy formation. We start by exploring the case with the lowest line-of-sight velocity difference between the QSO and its companion source. Based on this pilot program we will assess the best strategy to characterize the full sample in the upcoming cycle. This pilot project will already give us an unprecedented insight on the formation of the first massive galaxies and their environment, a result that would certainly deserve high visibility and possibly become material for press release, and would shape more in-depth observational campaigns focused on these unique sources.

8c. Calibration Request:

Standard Calibration

9. Report on the use of ESO facilities during the last 2 years

In the last years, ESO has consistently supported our effort to discover and characterize QSOs at $z \gtrsim 6$. Follow up imaging with EFOSC2 and SOfI at the NTT (PI: R.Decarli) and spectroscopy with FORS2 at the VLT (PI: B.Venemans) have allowed our group to discover more than 80 new z$\gtrsim$6 QSOs (nearly triple the number of southern QSOs known to date), 12 of which at z>6.4 (see Venemans et al. 2013,15a,b; Mazzucchelli et al. 2016 in prep; Bañados et al. 2014,15,16 in prep.).

092.A-0150, **093.A-0574**, **094.A-0079**, **095.A-0535**, **096.A-0291**: *Identification of new 5.5<z<7.5 quasars in the Southern sky* SOFOSC imaging, 25n, PI: R. Decarli. **092.A-0339, 093.A-0863, 094.A-0053, 095.A-0375**: *The most distant quasars: probes of the early universe* – FORS2 spectroscopy, >30h, PI: B. Venemans. Results published in Bañados et al. 2014; Venemans et al. 2015a; Mazzucchelli et al. (in prep.).

097.B-1070 and **098.B-0537**: *The Properties of the First QSOs: new Insights from X-SHOOTER and ALMA* – PI: E.P.Farina, 80h to obtain high-quality X-SHOOTER spectra of a homogeneous sample of 36 z>6 QSOs.

094.B-0893: *Extended Lyman alpha emission around a z=6.6 quasar* – PI: B.Venenans, 3h of MUSE at VLT to investigate the environmental properties of the [CII] bright QSO J0305-3150 at z=6.6 (Farina et al. in prep.).

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

None of the data requested here is present in the ESO archive.

9b. GTO/Public Survey Duplications:

None of the proposed observations duplicate an on-going GTO program.

10. Applicant's publications related to the subject of this application during the last 2 years

Venemans B.P., et al. 2016, ApJ, 816, 37:
Bright [CII] and Dust Emission in Three $z > 6.6$ Quasar Host Galaxies Observed by ALMA.

Venemans B., et al. 2015b, MNRAS, 453, 2259:
First discoveries of z∼6 quasars with the Kilo-Degree Survey and VISTA Kilo-Degree Infrared Galaxy survey.

Venemans B., et al. 2015a, ApJ, 801, L11:
The Identification of Z-dropouts in Pan-STARRS1: Three Quasars at 6.5<z<6.7.

Bañados E., et al. 2015, ApJ, 805, L8:
Bright [CII] 158μm Emission in a Quasar Host Galaxy at z=6.54.

Bañados E., et al. 2015, ApJ, 804, 118:
Constraining the radio-loud fraction of quasars at z>5.5.

Bañados E., et al. 2014, AJ, 148, 14:
Discovery of 8 z∼6 quasars from Pan-STARRS1.

Walter F., et al. 2014, ApJ, 782, 79:
A molecular scan in the Hubble Deep Field North: Constraints on the CO luminosity function and the cosmic H_2 abundance.

Decarli R., et al. 2014b, ApJ, 782, L17:
Varying [CII]/[NII] Line Ratios in the Interacting System BR1202-0725 at z=4.7.

Decarli R., et al. 2014a, ApJ, 782, 78:
A molecular scan in the Hubble Deep Field North.

Farina E.P., et al. 2014, MNRAS, 441, 886:
The extent of the MgII absorbing circumgalactic medium of quasars.

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	J2100-1715	21:00:54.616	-17:15:22.50	4	21.6		6.0870	

Target Notes: The additional info column lists the QSO redshift. The quoted magnitude refers to the QSO y-band (AB system). Out of the five QSOs shown in Fig. 1, PSOJ167-13 and PSOJ308-21 are not considered here because they appear to be advanced stages of galaxy mergers; for these, MUSE observations with Adaptive Optics will be required. Out of the remaining three fields, J2100-1715 is chosen because it shows the smallest line-of-sight velocity difference between the QSO and the companion, and because of its optimal visibility in the proposed period.

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
97	MUSE	A	WFM-NOAO-N	-

6b. Co-investigators:

...continued from box 6a.

E.	Banados	1188