Time Allocation Committee for
MPG time at the ESO 2.2m-telescope
c/o MPI für Astronomie
Königstuhl 17
D-69117 Heidelberg / Germany

Application No.	
Observing period	Spring 2021
Received	

APPLICATION FOR OBSERVING TIME

from [X] MPIA [ ] MPG institute [ ] other

1. Telescope: 2.2-m [X]

2.1 Applicant

Eduardo **Bañados**	MPIA
Name	Institute
Königstuhl 17	69117 Heidelberg
street	ZIP code - city
banados	banados@mpia.de
ESO User Portal username	e-mail

2.2 Collaborators

Schindler, Venemans, Onoue, Xie, Davies	MPIA
name(s)	institute(s)
Walter, Andika, Rojas, Mazzucchelli, Decarli	MPIA, ESO, OABo
name(s)	institute(s)

2.3 Observers

Rojas	Xie
name	name

By specifying the names under item 2.3 it is obligatory to also send out these observers to La Silla, if required. Correspondence on the rating of this application will be sent to the applicant (P.I.) as quoted under 2.1 above.

3. Observing programme: Category: B

Title : **The search for the first QSOs: NIR imaging of $z \gtrsim 7$ QSO candidates**

Abstract : QSOs at redshifts $z \gtrsim 7$ are crucial tools for understanding the timing of the Epoch of Reionization and the formation mechanisms of the first massive galaxies and supermassive black holes. Our goal is to build a statistical sample of QSOs at $z \gtrsim 7$; of which only a small handful are currently known. Our $z \gtrsim 7$ QSO candidates are detected in NIR public surveys while they are invisible in the optical surveys. Unavoidably, a large fraction of our candidates are artifacts in the NIR surveys or interlopers scattered into our selection. We here propose deep GROND follow-up photometry of our $z \gtrsim 7$ QSO candidates. This will be crucial to confirm and extend the photometric information of our candidates, which will allow an efficient selection of our targets for spectroscopic confirmation.

4. Instrument: [ ] WFI [ ] FEROS [X] GROND

5. Brightness range of objects to be observed: from 20.0 to 22.0 J-band [mag]

6. Number of hours:

applied for			already awarded	still needed
	70		210	140
no restriction	grey	dark		

May Sep 7. Optimum date range for the observations: .... May – Sep
Usable range in local sideral time LST: .... 11h – 21h

Astrophysical context

QSOs at the highest redshifts, $z \gtrsim 7$, are direct probes of early supermassive black hole growth and provide invaluable insight into early structure formation and the reionization of the Universe. As one of the most luminous, powerful, and energetic sources in the Universe, QSOs can be studied in detail at the earliest cosmic times with current instrumentation. They also promise unprecedented studies of the epoch of reionization and supermassive black hole growth with *JWST* and the next generation of extremely large telescopes like the E-ELT. These QSOs are so bright that even a 2-meter-class telescope can detect them all the way to $z = 7.5$ in just a few minutes (Fig. 1). However, despite exhaustive use of resources and extensive efforts from the community, the most distant QSO until recently was at $z = 7.08$ for more than half a decade [12], emphasizing the challenge of identifying such objects.

The golden age for high-z QSO searches: The advent of various wide-area optical/NIR photometric surveys such as PS1, DECals, DES, VST-ATLAS, VISTA, VIKING, UKIDSS, and *WISE* has radically accelerated the search for high-z QSOs. Indeed, just in the last year three new QSOs at $7.0 < z < 7.08$ have been reported [25, 28, 9]. Our group has been at the forefront of this field by almost tripling the number of QSOs known at $z > 6$ over the last few years [1, 3, 10, 21, 22] and, recently, *discovered the two most distant QSOs ever seen at* $z > 7.5$ [4, 29] (Fig. 1).

The brightness of these $z \sim 7.5$ QSOs makes them superb targets for multiwavelength follow-up. The existence of these billion-solar-mass black holes just 680 Myr after the Big Bang sets one of the strongest constraints on models of early black hole formation and growth (Fig. 2 left), challenges models of early star formation and supernova yields [23, 13], reveals the earliest galaxy merger known [6], places the earliest limits on black hole accretion [5, 30], and shows evidence that their surroundings are ∼50% neutral [7, 8, 29], indicating that we are probing well within the reionization epoch (Fig. 2 right). *This sample of two is providing key insights about the early Universe and highlights the need to find more of these objects at similar or higher redshifts.*

Immediate aim

Now is arguably the best time to perform an exhaustive search for $z > 7.5$ and perhaps even $z > 8$ QSOs for the first time since a number of public surveys recently released are ideal to exploit our new search. According to the most up-to-date luminosity function of $z > 6$ QSOs we expect ∼7 $z > 7.5$ and ∼2 $z > 8$ QSOs in the area of our search [26]. At MPIA we are in a privileged position to find these first QSOs: we have both the expertise [3, 4, 19] and the required facilities to carry out such an ambitious enterprise.

The immediate objective of this proposal is to obtain GROND *grizJHK* photometry to continue our successful program to confirm the nature of our best $z > 7$ QSO candidates. The strategy consists of three steps. **i)** Candidate selection mining all public large area NIR/optical surveys available. **ii)** NIR follow-up imaging, crucial for the success of this project, to efficiently remove our main contaminants: a) spurious detections (most probably artifacts or moving objects in the NIR surveys); b) cool L- and T-dwarfs through a flat $J-H$ and $H-K$ color (Fig. 3); and c) high-redshift dusty galaxies, which can be identified via SED fitting of the GROND photometry. All these items can be successfully and efficiently addressed with GROND and are a key part of our project. **iii)** NIR spectroscopy to confirm the nature of our best $z > 7$ QSO candidates that are left after all the previous steps.

We emphasize that the initial selection is based solely on *public data*. The existence of the bright QSOs at $z = 7.5$ is now widely known and we already published their selection method [4, 29]. It is therefore crucial to act quickly and efficiently. We have already submitted ESO and LBT proposals to obtain optical and NIR spectroscopy of our best $z \gtrsim 7$ candidates. Thus, the proposed GROND observations are key to maximize the return of our on-going campaigns.

Previous work

Our team has considerable expertise in the selection of high-z QSOs using color selections, SED fitting, and machine learning methods [19, 16]. We have discovered more than half of the known QSOs at $z \sim 6$ and the most distant QSO currently known [4]. The GROND instrument at the 2.2m MPG telescope has played a key role in a large fraction of our discoveries (see e.g., [1, 2, 3, 10, 11, 22]).

Strategic importance for MPIA

MPIA is a world-renowned center for studies of the earliest QSOs (e.g., MPIA press releases 2017–05–27, 2017–12–06, 2019–10–31, and 2019–12–19). MPIA also hosts some of the most talented early-career quasar experts in the world (Bosman, Meyer, Onoue, Schindler; see e.g., [15, 16]) as well as promising PhD students working on this area (Andika, Rojas, Xie). Furthermore, Bañados recently started as a group leader of the *supermassive black holes and galaxies in the epoch of reionization* group at MPIA while Davies just started as a group leader on *theoretical aspects of supermassive black hole growth and the epoch of reionization.* This proposal is an integral part of the long-term success and global visibility for the two newest groups in the GC department. **MPIA is uniquely positioned for searches of the highest-redshift QSOs** and these observations are crucial to keep us at the forefront of this competitive field.

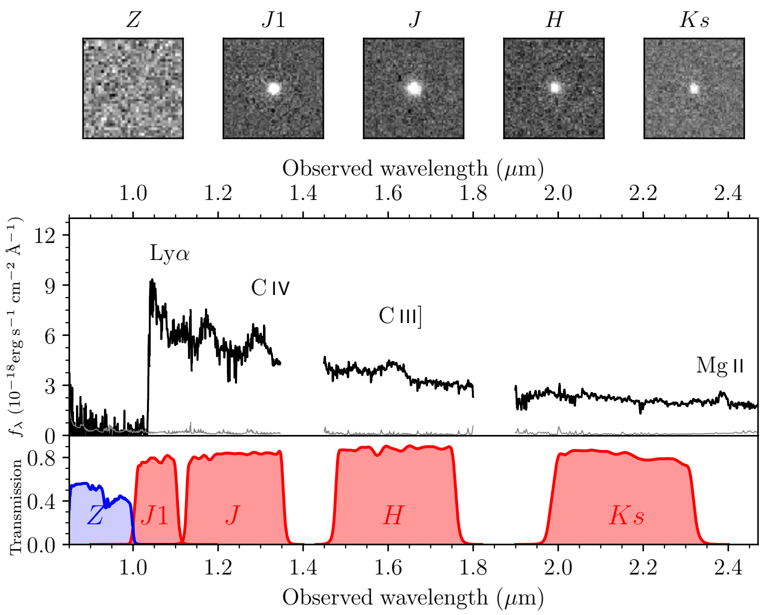

Fig 1. **The most distant QSO known to date at z = 7.54** [4]. The black line shows the NIR spectrum and the gray line its 1σ error vector. Prominent emission lines are highlighted. The bottom panel shows the transmission curves of the filters used for follow-up imaging, while the top panel shows $10'' \times 10''$ postage stamps of the QSO in the same filters. This QSO is so bright (J_{AB} = 20.7, K_{AB} = 20.1) that can be detected at high S/N in ~10 min with a 2m-class telescope. QSOs at z > 7 are virtually invisible in the optical bands.

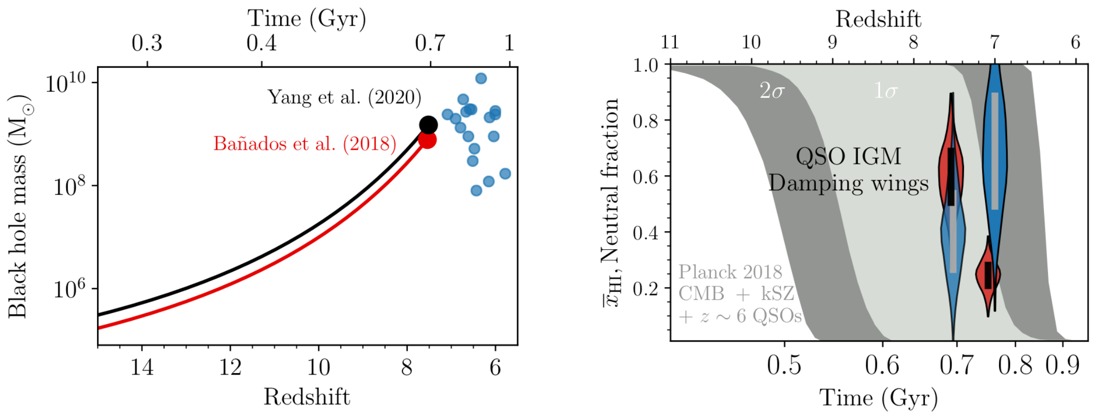

Fig 2. *Left:* **Early black hole growth.** Distribution of supermassive black hole masses in $z > 6$ QSOs. Thick lines show their growth history assuming Eddington-limited accretion. The two most distant QSOs at z = 7.51 [29] and z = 7.54 [4] set the strongest challenges for black hole formation theories. *Right:* **Constraints on the history of reionization in terms of hydrogen neutral fraction**. The contours are the constraints from [17]. The red violin plots show the constraints from the QSO IGM damping wings from [8], but see also [4, 7]. The blue violin plots are recent constraints from QSOs at $z = 7.0-$ and $z = 7.51$ [27,29]. The vertical lines represent the 68% credible intervals. The QSO IGM damping wings provide one of the strongest constraints existing on the history of reionization.

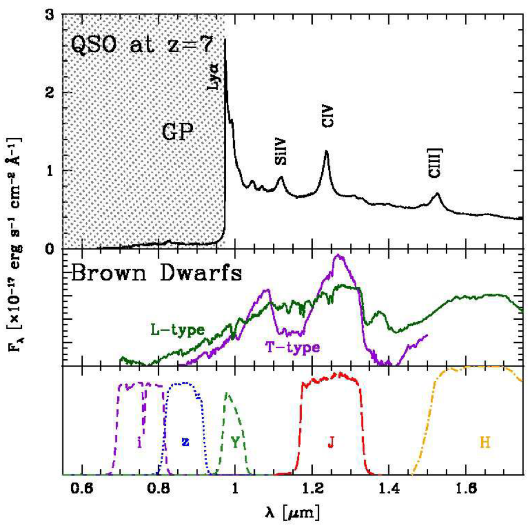

Fig 3. **Comparison among the expected spectra for a QSO at z = 7 (*top panel*), L- and T-type brown dwarfs (*middle panel*) and the throughput of various optical and NIR filters (*bottom panel*).** Because of the Gunn-Peterson effect, the flux at $\lambda < \lambda_{\mathrm{obs}}(\mathrm{Ly}\alpha)$ is absorbed by the IGM (shaded region). Therefore the optical bands (< 1μm) are practically blind to QSOs at $z \gtrsim 7$. Such a steep flux decline in broad-band filters towards bluer wavelengths is also observed in brown dwarfs, which are one of our main contaminants. However, at longer wavelengths, brown dwarfs show redder NIR continuum than quasars. Hence, color-color diagrams using GROND photometry represent an efficient tool to select the best candidates.

9. Objects to be observed

(Objects to be observed with high priority should be marked in last column)

Designation	α (2000)	δ (2000)	magnitude in spectral range to be observed	priority
QSO1[a]	$00^{\mathrm{h}}\,00^{\mathrm{m}}\,00\overset{\mathrm{s}}{.}00$	$00^\circ\,00'\,00''$	20-22.5 mag	1

[a]The goal of this proposal is to observe our best 70 candidates of QSOs at $z > 7$. We will update our list using the latest survey databases before our observing runs. This strategy has been successful in the past years as the public surveys have frequent public releases.

10. `Justification of the amount of observing time requested:`

Deep JH photometry (S/N$\sim$ 10) for all our $z \gtrsim 7$ candidates and 3σ limiting magnitudes of $\sim$23 in i and z bands are required to (a) weed out objects that scattered into our selection based on the photometry of public optical/NIR surveys and to (b) distinguish between promising QSO candidates and late-type stars or lower-redshift dusty galaxies. For QSO candidates at $z \geq 7$ we seek to confirm the sharp break between the z- and the J-band and a flat color between the J- and H-bands (Fig. 3).
Our targets are typically red sources with near-infrared magnitudes of $J_{\mathrm{AB}} \sim 20-22$. We base our exposure time estimates on the 3σ limiting magnitudes reached in the 8-minute OBs from Table 2 of the GROND instrument paper (Greiner et al. 2008), which has been confirmed to be adequate for $izJH$ by our previous observations. The 8-minute OBs present the lowest overhead for the necessary infrared exposure time (based on our experience 8-minute on-source requires an execution time of 16-20 minutes due to target acquisition, readout and dithering).
The number of OBs that is needed to confirm the nature of a candidate varies depending on the apparent magnitude of the candidates. Our candidates have apparent magnitudes of $J_{\mathrm{AB}} \sim 20-22$ and thus require 2–5 OBs per candidate to reach the S/N$\sim$ 10 necessary for our science goals. To observe 70 of our high-priority $z > 7$ candidates with 2–5 8-minute OBs per target, we thus request a total observing time of 70 hours.

11. `Constraints for scheduling observations for this application:`

Due to the R.A. of our objects we would prefer to have our run in August-September 2021

12. `Observational experience of observer(s) named under 2.3:`
`(at least one observer must have sufficient experience)`

The team has wide experience in the reduction and analysis of optical and NIR data of high-z QSOs (Bañados et al. 2014-2018, Venemans et al. 2013-2015, Mazzucchelli et al. 2017, Onoue et al. 2017-2019, Schindler et al. 2017-2019). Over the past years we have led > 200 observing nights at various facilities (LBT, ESO, Magellan, MMT, Subaru). S. Rojas has already successfully observed with GROND for this program in the past.

13. `Observing runs at the ESO 2.2m-telescope (preferably during the last 3 years)`
`and publications resulting from these`

Telescope	instrument	date	hours	success rate	publications
2.2m	GROND	Jan 2020	70	50%	Data reduced/paper in prep.
2.2m	GROND	May 2020	11	0%	COVID-19
2.2m	GROND	Dec 2020	15	N/A	N/A
2.2m	GROND	Mar 2021	55	N/A	N/A

Between 2012 and 2017, we used GROND, the Calar Alto 3.5m, and the LBT to follow-up high redshift QSO candidates selected from both Pan-STARRS1 and VIKING. These observations allowed us to dramatically increase the number of $z > 5.7$ QSOs known to date [1, 2, 12, 23]. We are now pushing this search to the next frontier at $z > 7$, our first observing run for this search was on January 2020. The data were reduced by S. Rojas using the M. Schirmer's THELI pipeline.

14. References for items 8 and 13:

[1] Bañados et al. 2014, AJ, 148, 14

[2] Bañados et al. 2015, ApJ, 804, 118

[3] Bañados et al. 2016, ApJS, 227, 11

[4] Bañados et al. 2018, Nature, 553, 473

[5] Bañados et al. 2018, ApJ, 861, L14

[6] Bañados et al. 2019, ApJL, 881, L23

[7] Davies et al. 2018, ApJ, 864, 142

[8] Durovčíková et al. 2020, MNRAS 493, 4256

[9] Matsuoka et al. 2019, ApJ, 872, L2

[10] Mazzucchelli et al. 2017, ApJ, 849, 91

[11] Morganson et al. 2012, AJ 143, 142

[12] Mortlock et al. 2011, Nature, 474, 616

[13] Novak et al. 2019, ApJ, 881, 63

[14] Onoue et al. 2017, ApJ, 847, 15

[15] Onoue et al. 2019, ApJ, 880, 77

[16] Schindler et al. 2019, ApJS, 243, 5

[17] Planck Collaboration 2018 arXiv:1807.06209

[18] Schindler et al. 2017, ApJ, 851, 13

[19] Schindler et al. 2018, ApJ, 863, 144

[20] Schindler et al. 2019, ApJ, 871, 258

[21] Venemans et al. 2013, ApJ, 779, 24

[22] Venemans et al. 2015, ApJ, 801, L11

[23] Venemans et al. 2017, ApJ, 851, L8

[24] Walter et al. 2009, Nature 457, 699

[25] Wang et al. 2018, ApJ, 869, L9

[26] Wang et al. 2019, ApJ, 884, 30

[27] Wang et al. 2020, ApJ, 896

[28] Yang et al. 2019, AJ, 157, 236

[29] Yang et al. 2020, ApJ, 897, L14

[30] Davies et al. 2019, ApJ, 884, L19

Tolerance limits for planned observations:

maximum seeing:	2.0″	**minimum transparency:**	70%	**maximum airmass:**	2.0
photometric conditions:	no	**moon: max. phase / ∠ :**	0.5/30°	**min. / max. lag:**	0/90 nights