OBSERVING REQUEST
University of Arizona Observatories

Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term⋆

A Survey of Luminous Quasars at $z \gtrsim 7$: Early Black Hole Growth and Reionization History

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Abstract of Scientific Justification

This is a continuation of our survey of reionization-era quasars at $z \gtrsim 7$. Luminous quasars at $z > 6 - 7$ provide direct probes of the evolution of supermassive black holes (BHs) and the intergalactic medium (IGM)at early cosmic time. More than 100 quasars have been discovered at $z \gtrsim 6$. Detections of such objects indicate the existence of billion $M_{\odot}$ BHs merely a few hundred Myrs after the Big Bang. Absorption spectra of the highest redshift quasars reveal complete Gunn-Peterson absorption with a rapid increase in the IGM neutral fraction, marking the end of the reionization epoch at $z > 6$. However, only one quasar was previously known at $z > 7$, due to difficulties in near-IR spectroscopic follow-up observations. The UKIRT Hemisphere Survey (UHS) is a new deep near-IR J-band imaging survey, which covers the whole northern sky with declination from 0° to 60° by combing UKIRT Deep Sky Survey (UKIDSS). Together with Pan-STARRS 3π data, DECalS survey in z-band, MzLS survey in z-band, and the mid-IR WISE all sky survey, we have a new dataset that covers ∼12,000 deg^2 high Galactic latitude sky area with both z, y, J and WISE bands to the depth of $J_{AB} \sim 20.5$, allowing a first systematic search for reionzation-era quasars. Our goal is to discover ~ 10 new $z \gtrsim 7$ quasars, which will provide the most powerful probes to the earliest supermassive black hole growth and to map the history of reionization. In the first year of our survey, we already had a major breakthrough: we have discovered a redshift record break quasar at $z \sim 7.5$, which shows a significant Lyα damping wing, indicative of high IGM neutral faction at $z \sim 7.5$, as well as four new quasars at $6.5 < z < 7.0$. In 2017B, we require additional IR imaging (UKIRT) and spectroscopy time (MMT/MMIRS and Magellan/FIRE), aiming at finding 2-4 new quasars at $z \gtrsim 7$.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	UKIRT		WFCAM			3.0	grey/bright	Aug-Sep	Aug-Oct	yes	yes
2	Magellan		FIRE			2.0	grey/bright	Sep-Oct	Sep-Nov	yes	no
3	MMT		MMIRS			2.0	grey/bright	Oct-Nov	Oct-Dec	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We will carry out imaging follow-up first with UKIRT and then do spectroscopy with Magellan/FIRE and MMT/FIRE. So we need the UKIRT observation run to be scheduled at least half month before our Magellan and MMT runs, in order to get enough time to reducing and analysis UKIRT imaging data.

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A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	$z \gtrsim 7.0$ quasar candidates	$RA = 19h - 05h,$	$-30° \sim 50°$	$J_{AB} \sim 19 - 20.5$

Approval for Instrument Use from PI: ________________________

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Jan-Torge Schindler	Xiaohui Fan		no	no

Scientific Justification

Luminous quasars at high redshift provide direct probes of the evolution of supermassive black holes (BHs) and the intergalactic medium (IGM) at early cosmic time. Over the last decade, more than 100 quasars have been discovered at $z > 6$ (e.g. Fan et al. 2001; Jiang et al. 2007; Willott et al. 2010; Venemans et al. 2013,2015; Banãdos et al. 2014), with the highest redshift at $z = 7.1$ (Mortlock et al. 2011). Two main results emerge from the studies of these quasars:

- Detections of such objects indicate the existence of billion $M_\odot$ BHs merely a few hundred Myrs after the first star formation in the Universe. The existence of such massive objects, including the recent discovery of the first ten billion $M_\odot$ BH by our group (Figure 1a, Wu et al. 2015), challenges the theory of BH growth and places the strongest constraints on the BH-galaxy coevolution at early epoch.
- Absorption spectra of the highest redshift quasars reveal complete Gunn-Peterson absorption, indicating a rapid increase in the IGM neutral fraction, marking the end of the reionization epoch at $z > 6$ (e.g. Fan et al. 2006). Combined with results from the most recent constraints on the declining Lyα visibility and abundance among high-redshift galaxies and revised measurements of CMB polarization measurements, current data strongly suggest a peak of reionization activity and emergence of the earliest galaxies and AGNs at $7 < z < 11$ (Figure 1b, Robertson et al. 2015), highlighting the need to expand our search to higher redshift.

A New Survey of $z \gtrsim 7$ Quasars. At $z \gtrsim 7$, Lyα emission line is redshifted to beyond 1μm, requiring near-IR observations for both their selections and spectroscopic identifications. However, efforts to find such objects have proven to be difficult. So far, only one quasar have been discovered at $z \gtrsim 7$, and a handful at $z > 6.5$, compared to the large number of available objects at $z \sim 6$. It is due to a combination of their declining spatial density, limited sky coverage of near-IR photometry, and low efficiency in spectroscopic follow-up observations. For example, Venemans et al. (2013) discovered three $z > 6.5$ quasars in the Visible and Infrared Survey Telescope for Astronomy (VISTA) Kilo-Degree Infrared Galaxy (VIKING) survey. We recently discovered several $z > 6.5$ quasars from Panoramic Survey Telescope & Rapid Response System 1 (Pan-STARRS1, PS1; Kaiser et al. 2002, 2010) 3-π sky survey (Venemans et al. 2015). But PS1 could only find $z \lesssim 6.8$ quasars without near-IR band. Mortlock et al. (2011) found the only known $z > 7.0$ quasar with UKIRT Large Area Survey (LAS) in about 4,000 deg^2 high galactic latitude sky area.

This situation is finally changing, with the availability of new deep near-IR sky surveys. In particular, PS1 survey provides deep z and y observations over 3-π area of the sky; its depth and sky coverage are well matched to both the UKIRT Hemisphere Survey (UHS) and VISTA Hemisphere Survey (VHS) in J band, and the latest WISE survey mid-IR data. The DECalS and BASS+MzLS NOAO public survey is covering the SDSS/WISE footprint with high quality, deep photometry in g, r and z bands, in particular a z-band depths of ~ 23 in AB mag, deeper than the PS1 survey. In addition, the DES survey covers 5000 square degree area in $grizY$ survey of the Southern sky to even fainter flux level. The combination of these surveys enables near-IR selection of quasars at $z \gtrsim 7$ in $\sim 20,000$ deg^2 of high-galactic latitude sky at $DEC < +60$ degree. **We have started a major effort in establishing the first large luminous $z \gtrsim 7$ quasar sample. Our goal is to find ~ 10 quasars at this redshift in the next two years. Our new sample will provide the most powerful probe to early BH growth and reionization history.** This proposal aims at carry out imaging follow-up and spectroscopic identifications of bright $z \gtrsim 7$ quasar candidates in the Fall Sky.

Quasar Selection. High redshift quasars are usually selected by using dropout technique, because of the strong IGM absorptions at the blueward of $Ly\alpha$ emission line. Our group has pioneered the high-redshift quasar selection using a combination of deep optical, near-IR and mid-IR data. We will use the VHS and UHS and UKIDSS J-band as the detection band and use PS-1 z_{p1} and y_{p1}, DECaLS/MzLS z, DES i and z, as the dropout bands to select high redshift quasar candidates. This step will exclude most of stars except cold dwarf (mainly T dwarfs). Finally, we will combine WISE $W1$ and $W2$ bands to further exclude cold dwarfs (e.g. $J - W1/W1 - W2$ color-color diagram).

Recent Record Breaking Discoveries. In 2016 to 2017A, our group has made major progress in our survey of $z \gtrsim 7$ quasars: **we have discovered a luminous quasar at $z = 7.54$.** This is a highly significant discovery: it not only broke the previous redshift record of $z = 7.09$, more importantly, its spectrum shows a pronounced IGM neutral hydrogen damping wing feature (Figure 2), strongly suggesting a very high neutral fraction at $z \sim 7.5$, thus places the strongest constraint yet on the history of reionization at $z > 7$. In addition, we have discovered four other new quasars at $z = 6.5 - 7.0$ in the spring sky. This demonstrates both the effectiveness of our survey strategy, and highlights the unique value of these high-redshift quasars in probing reionization history.

Plans for 2017B. According to our previous selection and scale to the Fall sky coverage, we expect to have $\sim$ 200 candidates after the procedure mentioned above. During our previous runs, we found that many candidates ($\sim 15\%$) are fake objects due to the fact that we only have J-band and W1 band as our detection bands. Such kind of objects can be rejected easily from near IR imaging follow-up. Thus, we ask for UKIRT/WFCAM to do deeper J-band ($\sim$ 20 in VEGA) follow-ups of our candidates. For those J-band detected candidates, we will further carry out the Y-band imaging ($\sim$ 21 in Vega) in order to further reject cold T dwarfs using $Y - J$ colors. Then we will use MMT/MMIRS (northern objects) and Magellan/FIRE (southern objects) to carry out the spectroscopic identification for the remaining candidates. There is $\sim 8,000$ deg^2 available photometric data at –30 $<$ DEC $\lesssim$ +50 deg in the Fall sky and we expect to find 2-4 new $z \gtrsim 7$ quasars in this area.

Our two main science goals are:

- **What is the accretion history of the earliest supermassive BHs in the Universe?** At $z \sim 7$, the Universe was only $\sim$ 20 Salpeter times old. Our new survey will for the first time measure the density of luminous quasars and their BH masses at $z \gtrsim 7$, and place constraint on the existence of $z > 8$ quasars. These measurements will test whether super-Eddington accretion or direct formation of intermediate-mass BHs are needed for early BH growth, and constrain models of quasar formation.
- **Does the IGM become mostly neutral by z $\sim 7 - 8$?** Earlier quasar observations indicate the neutral fraction of the IGM to be $> 10^{-2 \sim -3}$ at $z \sim 6$. Measurements of the near-zone size and Lyα damping wing profile of the lone $z \gtrsim 7$ quasar is highly suggestive that neutral fraction has increased to the order 10% at $z \sim 7$ (Bolton et al. 2011), consistent with the results from new $z \gtrsim 7$ galaxy observations (Stark et al. 2010, Robertson e al. 2015). As shown in the example of the new $z \sim 7.5$ quasar, we will extend these tests to large $z \gtrsim 7$ quasar samples, which will definitively measure the IGM neutral fraction at $z \sim 7 - 8$, and probe whether the reionization process resembles a phase transition of the IGM or follows a more gradual pattern in this crural cosmic epoch.

References: •Banãdos et al. 2014, AJ, 148, 14 •Bolton, J. S., et al. 2011, MNRAS, 416, L70 •Fan, X., et al. 2001, AJ, 122, 2833 •Fan, X., et al. 2003, AJ, 125, 1649 •Fan, X., et al. 2006, ARA&A, 44, 415 •Kaiser, N. et al. 2002, SPIE, 4836, 154 •Kaiser, N. et al. 2010, SPIE, 7733, 12 •McGreer, I. D., et al. 2015, MNRAS, 447, 499 •Mortlock, D. J., et al. 2011, Nature, 474, 616 •Robertson, B. E., et al. 2015, arXiv:1502.02024 •Saumon, D. et al. 2012, ApJ, 750, 74 •Simcoe, R. A., et al. 2012, Nature, 492, 79 •Stark, D. P., et al. 2010, MNRAS, 408, 1628 •Venemans, B. P., et al. 2013, ApJ, 779, 24 •Venemans, B. P., et al. 2015, arXiv:1502.1927 •Willott, C. J., et al. 2010, AJ, 139, 906 •Wu, X.-B., et al. 2015, Nature, 518, 512

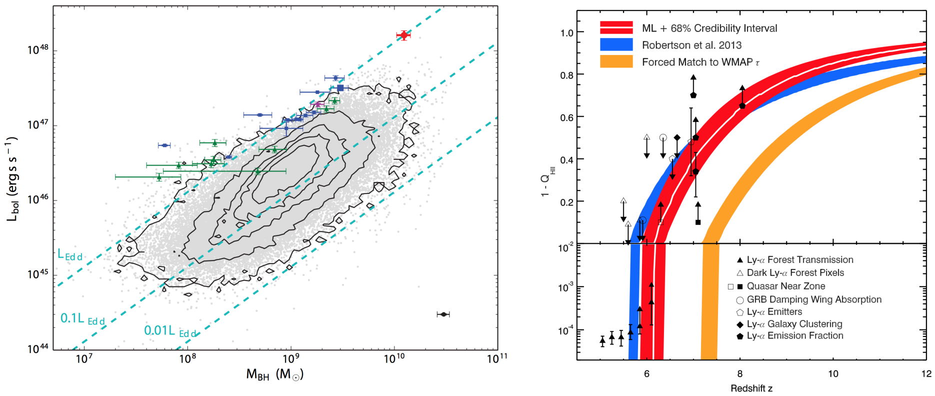

Figure 1: $Left$: Distribution of quasar bolometric luminosities, L_{bol}, and BH masses, M_{BH}, estimated from the Mg II lines. The red circle at top right represents J0100+2802, the only known ten billion solar mass BH. The existence of such massive object along with other billion solar mass BHs at $z \gtrsim 6$ challenge the theory of BH growth and places the strongest constraints on the BH-galaxy coevolution at early epoch. Our survey will extend quasar BH measurements to $z \gtrsim 7$. Adapted from Wu et al. (2015). $Right$: Measures of the neutral Hydrogen fraction of the IGM as a function of redshift. Adapted from Robertson et al. 2015. Different colors represent different cosmic reionization history models. The redshift range at $7 \lesssim z \lesssim 8$ marks the rapid transition era from a mostly neutral to mostly ionized IGM and the peak of reionization activity.

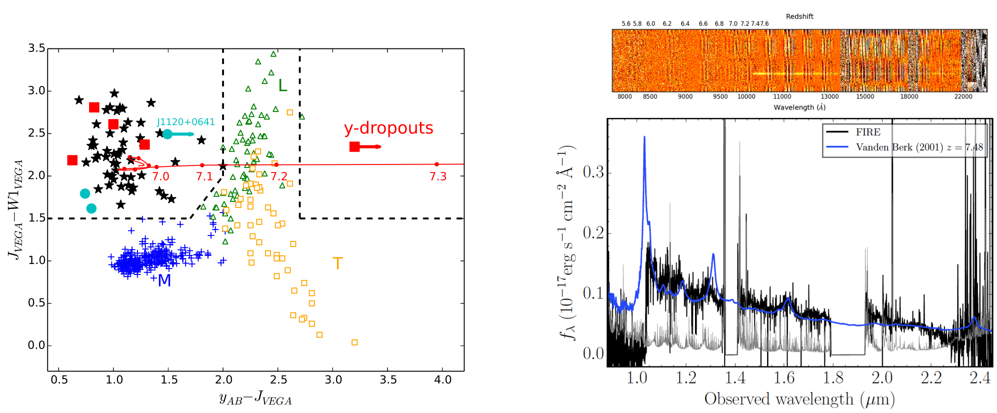

Figure 2: $Left$: y−J versus J−W1 color-color diagram. The red solid line denotes colors of quasars at different redshift derived from quasar composite template after considering neutral hydrogen absorptions. The black stars represent $z \sim 6$ quasars, and the cyan points are $z > 6.5$ quasars. The red squares denotes our four newly discovered $z > 6.5$ quasars and one $z \sim 7.5$ quasar. The blue crosses, green triangles and brown squares denote M-, L- and T-dwarfs. The black dashed lines mark the expected colors of $z \lesssim 7.1$ and $z \gtrsim 7.3$ quasars. The z-dropout technique will reject most of M, L dwarfs and $z < 6.5$ quasars. This diagram can further reject most of T dwarfs. $Right$: Upper panel shows the low resolution near-IR 2D spectrum (background-subtracted and flux-calibrated) of the new discovered $z = 7.5$ quasar. There is essentially zero flux bluewards of 1.03 μm, implying that it is a quasar at z ~7.5. The discovery spectrum was taken with FIRE in longslit mode (five minutes on-source exposure). This spectrum suggest that we can identify whether a candidate is a quasar or not with $\sim 5 - 8$ minutes exposure using FIRE longslit mode. Lower panel shows the high dispersion FIRE spectrum, overplot with a quasar template at $z \sim 7.5$. Note that the Lyα emission is almost completely absorbed away by the IGM, indicating a high neutral fraction which provides the strongest constraint yet on reionziation history. *Figure taken from Bañados et al., in prep, it is presented here for the sole purpose of this proposal. We ask to treat it as confidential and do not distribute.*

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

New IR Sky Surveys. We aim to discover $z \gtrsim 7$ quasars selected from various wide-field sky surveys mentioned in the scientific justification: The PS1 3π survey has deep z and y observations, and will provide the dropout band for $z \sim 7$ quasar selection. The survey has completed. Our group is part of the PS1 quasar survey team. We are also part of the NOAO/DESI DECalS and BASS+MzLS survey team. The year one data of DES survey have been published and will also be used to further to reject contaminations using the deep i and z-bands. The UKIDSS, UHS and VHS will provide deep J-band continuum measurements for our quasar candidate. They have completed the majority of their observations and data are available through public data releases. The mid-IR WISE data will provide crucial selection against both stellar contaminations, especially red cool dwarfs, and contaminations from red low-redshift galaxies. The WISE all-sky survey has mapped the whole sky and currently depth is good enough for our science goal; over the next two years, it will double its exposure time, allowing more efficient mid-IR selection. **Remarkably, We have discovered four new $6.5 < z < 7.0$ quasars with previous observation runs and one redshift record break quasar at $z \sim 7.5$.** In 2017B, we propose to continue our program, selecting $z \sim 7$ quasar candidates from about 8,000 deg^2 of high galactic latitude sky in the Fall sky at –30 < DEC $\lesssim$ 50 deg, with deep DECaLS + DES + PS1optical imaging and new UKIDSS + UHS + VHS near-IR imaging and focus on bright candidates at $J_{VEGA} = 19 - 20$. We expect to have ~ 200 candidates available in 2017B.

Observing Request. Our observations will have three steps:

- Firstly, we will carry out the Y- and J-bands imaging follow-up observations for our candidates. We will first carry out the J-band imaging observations. In order to get better photometry than UHS and VHS, we request to reach $J_{VEGA} \sim 20$ at 5σ. With the typical seeing conditions, we need 3mins exposures. We need about 13 hours for this step and will get rid of 40-50 junk objects. In order to further reject L/T dwarfs, we will perform deeper Y-band imaging and to reach $Y_{VEGA} \sim 21$ at 5σ which corresponds to $\sim$ 5 mins on-source exposure time. Considering overheads on reading out and changing positions, we need $\sim$ 15 hours for this step. In total, we need three nights for $\sim$ 200 candidates. After this step, we expect to reject ~ 100 candidates.
- For those survived candidates, we will do the near-IR spectroscopy directly, as the $Ly\alpha$ redshifted to beyond $1\mu m$ at $z \gtrsim 7.0$. FIRE is the most effective instrument in the south and MMIRS is the most effective instrument in the north. With the FIRE/MMIRS longslit mode, we can distinguish quasars from cool dwarfs with only $\sim 3-7$ minutes exposure for each target at $J_{VEGA} = 19-20$ (See Figure 2). We use another 2 minutes to put the faint target into the slit and about one minutes to move the telescope/readout. Thus we need about $\sim$10 minutes for each target, including all overheads. In this way, we can observe about $\sim$40 candidates per night. Thus, we ask for three nights to do the longslit observations (two MMT/MMIRS nights and one Magellan/FIRE night). Extrapolating from $z \sim 6$ quasar luminosity function to higher redshift, we expect $2 - 4$ quasars at $z \gtrsim 7$ over this area.
- For the confirmed objects with DEC$< +30$ deg, we will carry out longer FIRE Echelle exposures to increase the S/N. The high S/N FIRE Echelle spectra will be used to measure for a number key quantities: the profile of $Ly\alpha$ near zone profile, the Lyα damping wing profile, CIV and MgII emission lines for BH mass measurements, and weak IGM metal absorption lines. In order to study the near zone profile and the weak absorption systems (e.g. $log(N_{HI}) \lesssim 21.0$), an additional $\sim$ 4 hours exposure per quasar is required. Assuming we can identify two $z > 7.0$ quasars at DEC$< +30$ deg and one $z > 7$ quasar at DEC$\sim$ +30 – +50 deg, we need another about $\sim$8 hours of Magellan/FIRE integration time to get good Echelle spectra of new quasars at DEC$< +30$ deg. For the confirmed objects with DEC$> +30$ deg, we will propose additional IR spectroscopy time for high resolution data.

Altogether, we request three UKIRT/WFCAM nights, two Magellan/FIRE nights and two MMT/MMIRS, including overheads. Since some key features that we are interested in, Lyα and CIV in particular, are in Y and J bands at this redshift, we would like to avoid full moon condition and prefer grey time.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

Our long-term goal is to establish a sample of ~ 10 quasars at $z \gtrsim 7$ in 3–4 years. So far, our team has discovered a record breaking $z \sim 7.5$ quasar (Bañados et al. in preparation), and four new quasars at $6.5 < z < 7.0$ (one has been published in Wang et al. 2017). Our group have also been carrying out MMT observations of PS1 and DECaLS quasars at $z \sim 6$ in a different program. The MMT red channel observation is limited to $z \lesssim 6.5$ and the goal is to complete our census of $z \sim 6$ quasars using existing mature selection technique. This $z \sim 7$ program is aiming at the scientifically new and technically more challenging $z \sim 7$ territory, with our newly developed selection technique.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

In past two years. Fan is PI of the following programs:

- ⋆ 2017A: Three nights on UKIRT/WFCAM, two nights on Magellan/FIRE and one night on MMT/MMIRS on $z \sim 7$ quasar survey. Observations to be carried out.
- 2017A: one night on LBT for spectroscopic identification of a $z \sim 11$ galaxy candidate. Some good data taken; to be combined with upcoming Keck run data.
- ⋆ 2016B, 2016A, 2015B: Five nights on Magellan on $z \sim 7$ quasar survey. Four new quasars with redshift $6.5 < z < 7.0$ were discovered. One paper accepted by ApJ, one more in preparation.
- 2017A, 2016B: eight nights on Bok, four nights on LBT for survey of high-redshift protoclusters. 2016B data analyzed; 2017A observations later in the semester.
- 2016A: Two nights on LBT for survey of high-redshift protoclusters. Observations successful. Two papers published, one submitted.
- 2015B: One night on LBT/LBC for deep imaging high-redshift quasar field. Analysis done, one paper in preparation.
- 2015A, 2016A, 2017A : 150 nights on Bok/90prime for the Beijing Arizona Sky Survey. This is a long-term project to provide imaging survey for DESI spectroscopy. Survey is on-going. Two papers on survey description and data processing published.
- 2015A, 2014B, 2014A: four nights on Magellan/FIRE for $z \sim 5$ quasar follow-up. Three papers, including one Nature paper published, one more in preparation.
- 2016B, 2015B, 2015A, 2013B, seven nights on MMT for PS1 quasar follow-up. More than 60 quasars at $z \sim 6$ quasar discovered in the PS1 quasar followup program. Eight papers published.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*