Discovery of a Faint Quasar at z~6:

Implications to Cosmic Reionization
&
Black Hole Growth in the Early Universe

2017. 3. 3

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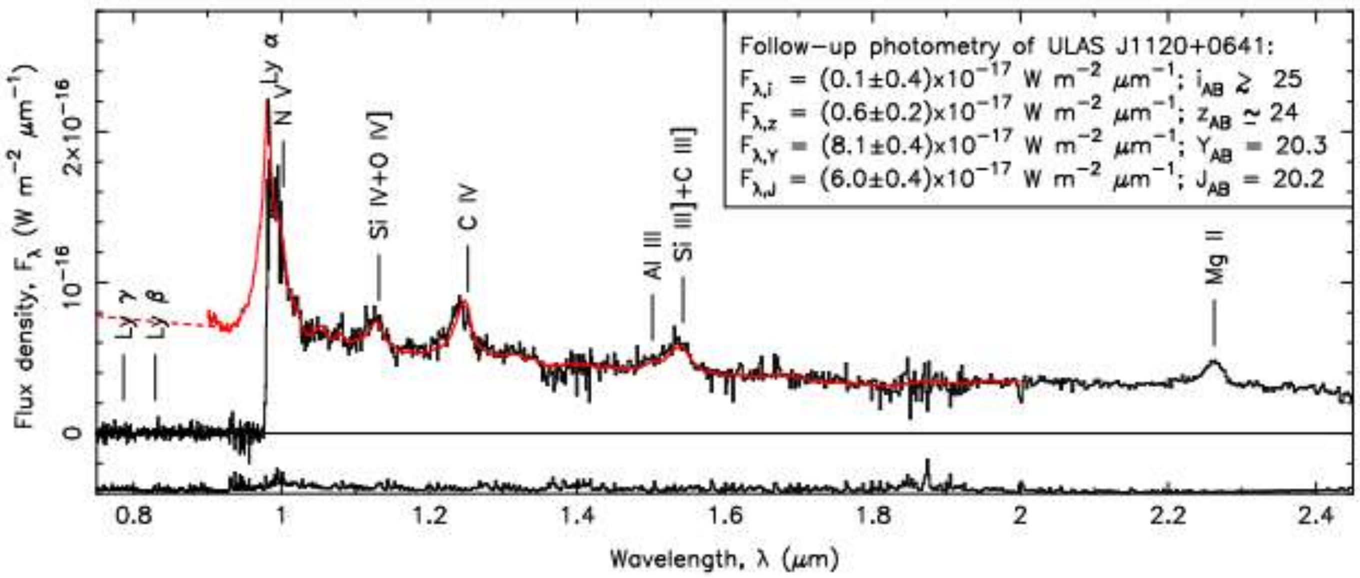
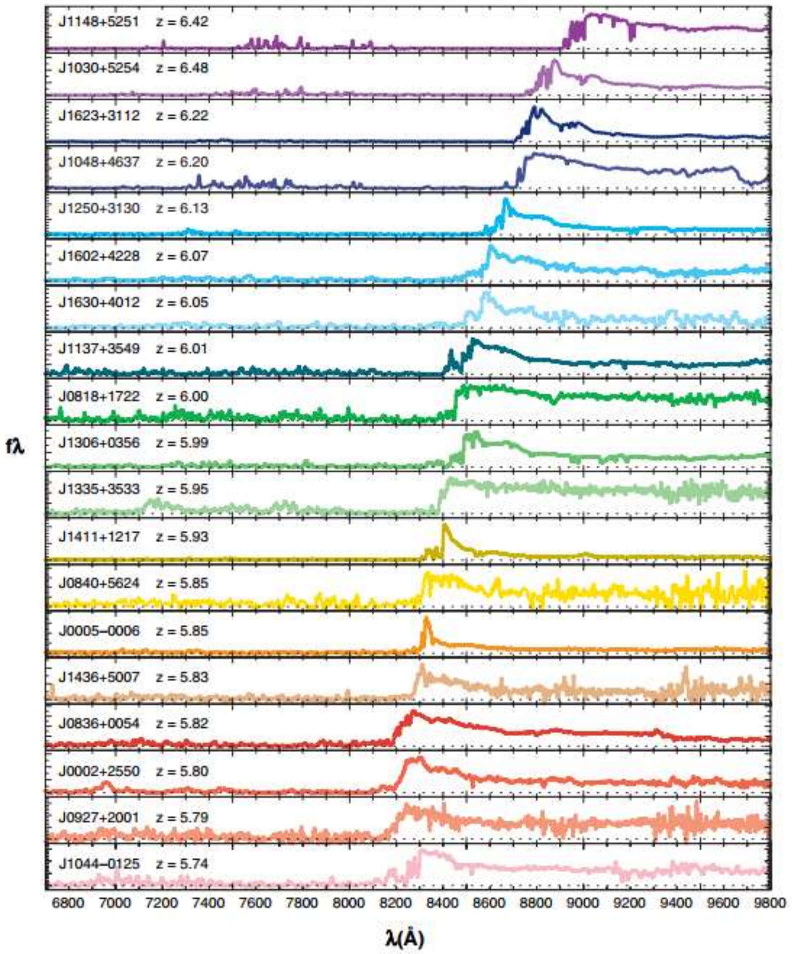
Introduction

- **Quasars in the Early Universe**
  - Energetic sources in the universe
  - A unique sample to study
    - Contribution of quasars to cosmic reionization
    - Formation of the first supermassive black holes (SMBHs)

  ➔ Various optical/NIR surveys (e.g., SDSS, CFHQS)



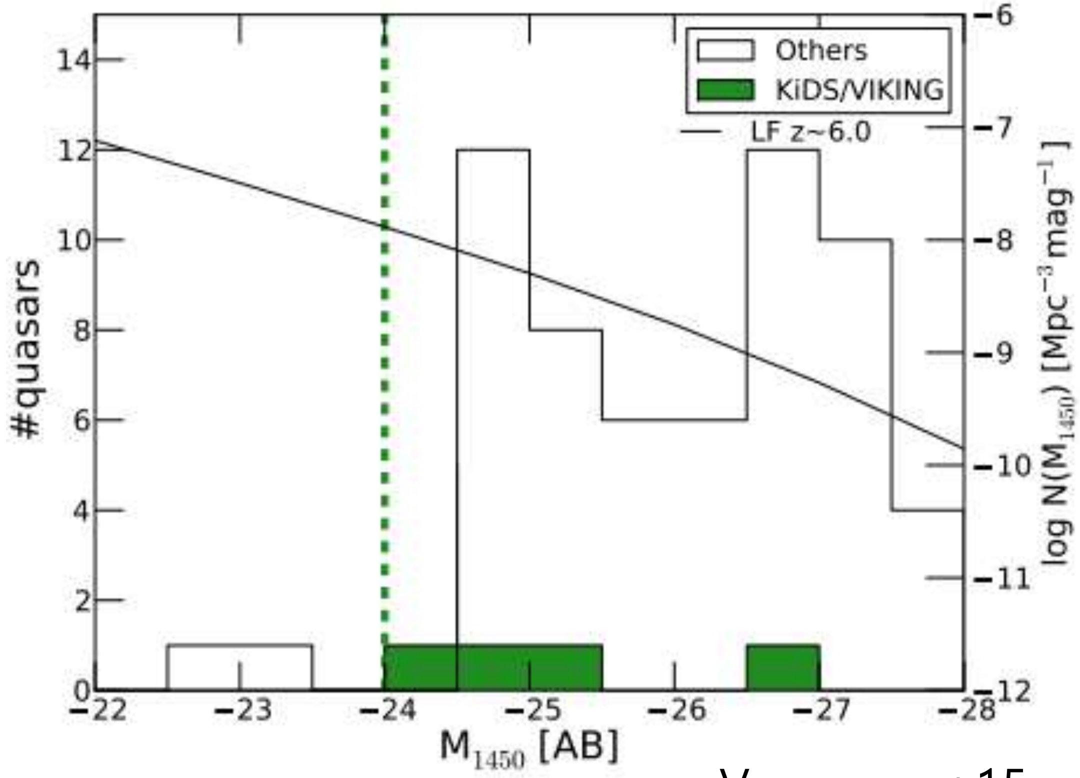
Mortlock+11



Fan+06

Introduction

- **Lack of Faint Quasars at z > 6 (M_{1450} > -24 mag)**
  - How did high-z quasars **contribute to cosmic reionization**?
    - Are main contributors or not?



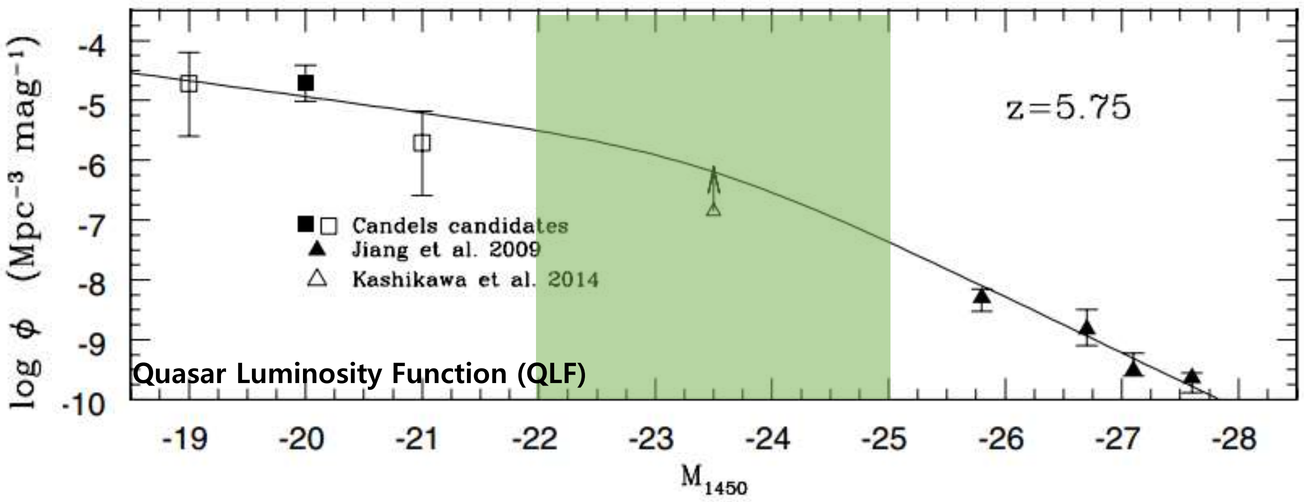
Venemans+15

UV Emissivity

$\epsilon \propto \phi \times L$

ϕ: QLF L: luminosity

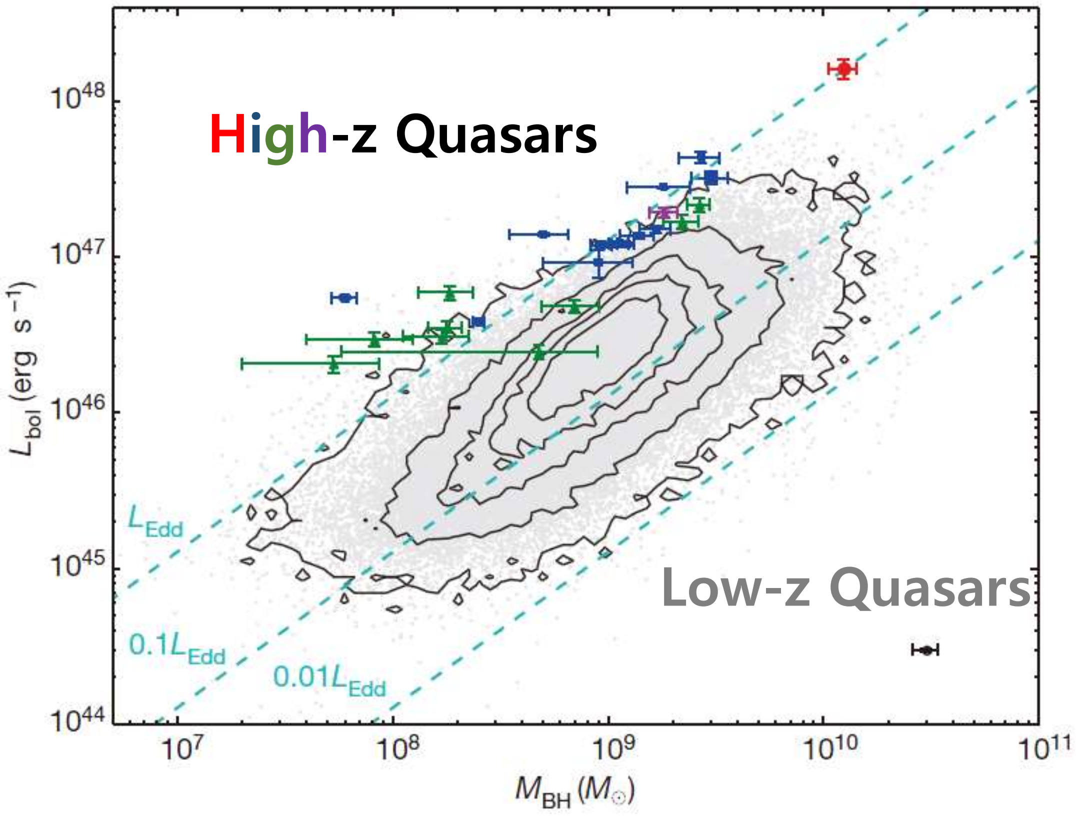
Maximum at M_{1450} ~ -23.5 mag



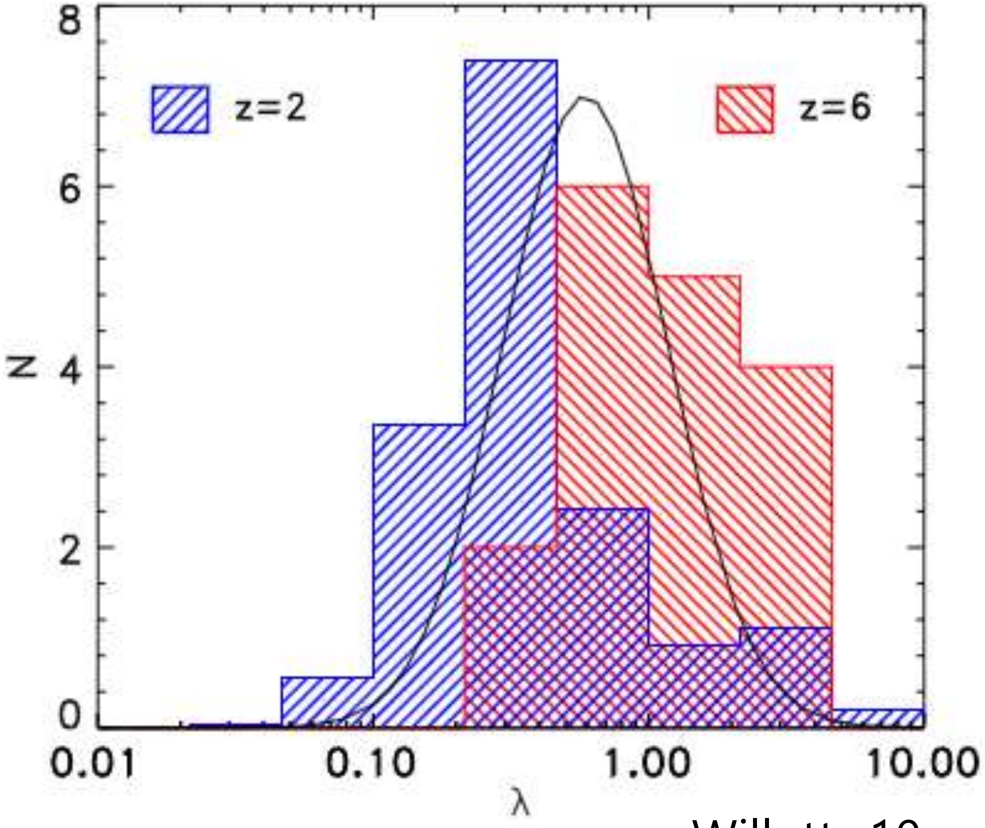
Giallongo+15

Introduction

- **Lack of Faint Quasars at z > 6 (M_{1450} > -24 mag)**
  - Are **Quasars Growing fast**?
    - An order of magnitude?



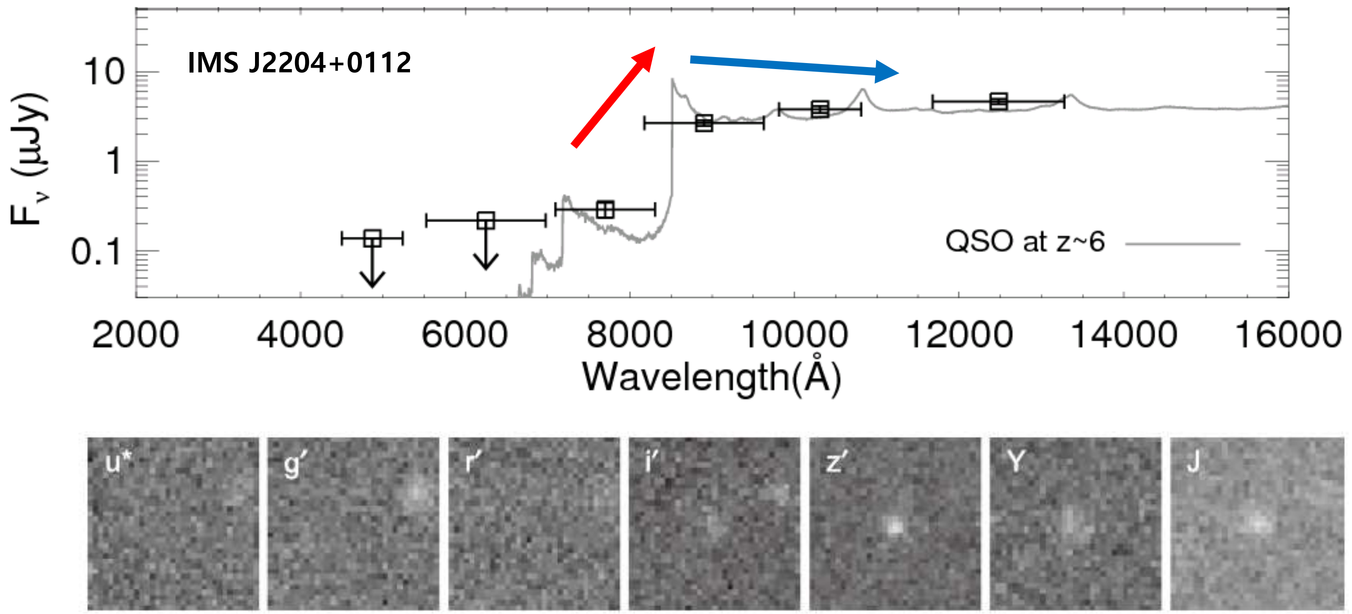
Wu+15

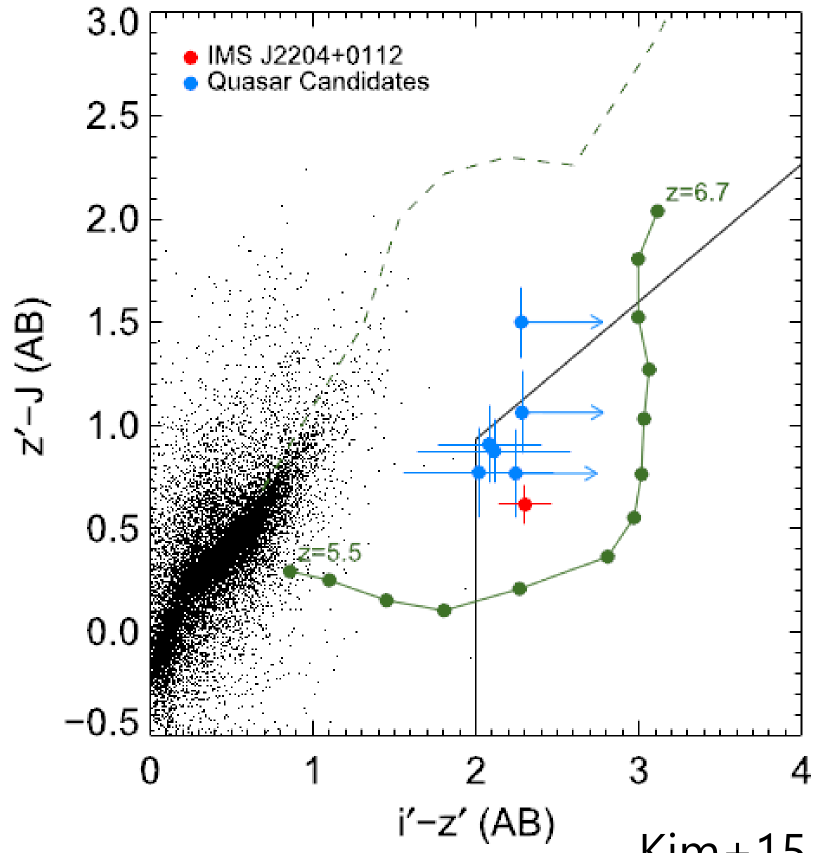


Willott+10a

Discovery of IMS J2204+0112

- **High Redshift Quasar Survey with**
  - Infrared Medium-deep Survey (**IMS**) – Near-Infrared (YJ)
  - Canada-France-Hawaii Telescope Legacy Survey (**CFHTLS**) – Optical (ugriz)
- **Quasar Candidate Selection**
  - Using red i-z color due to Lyman break





Kim+15

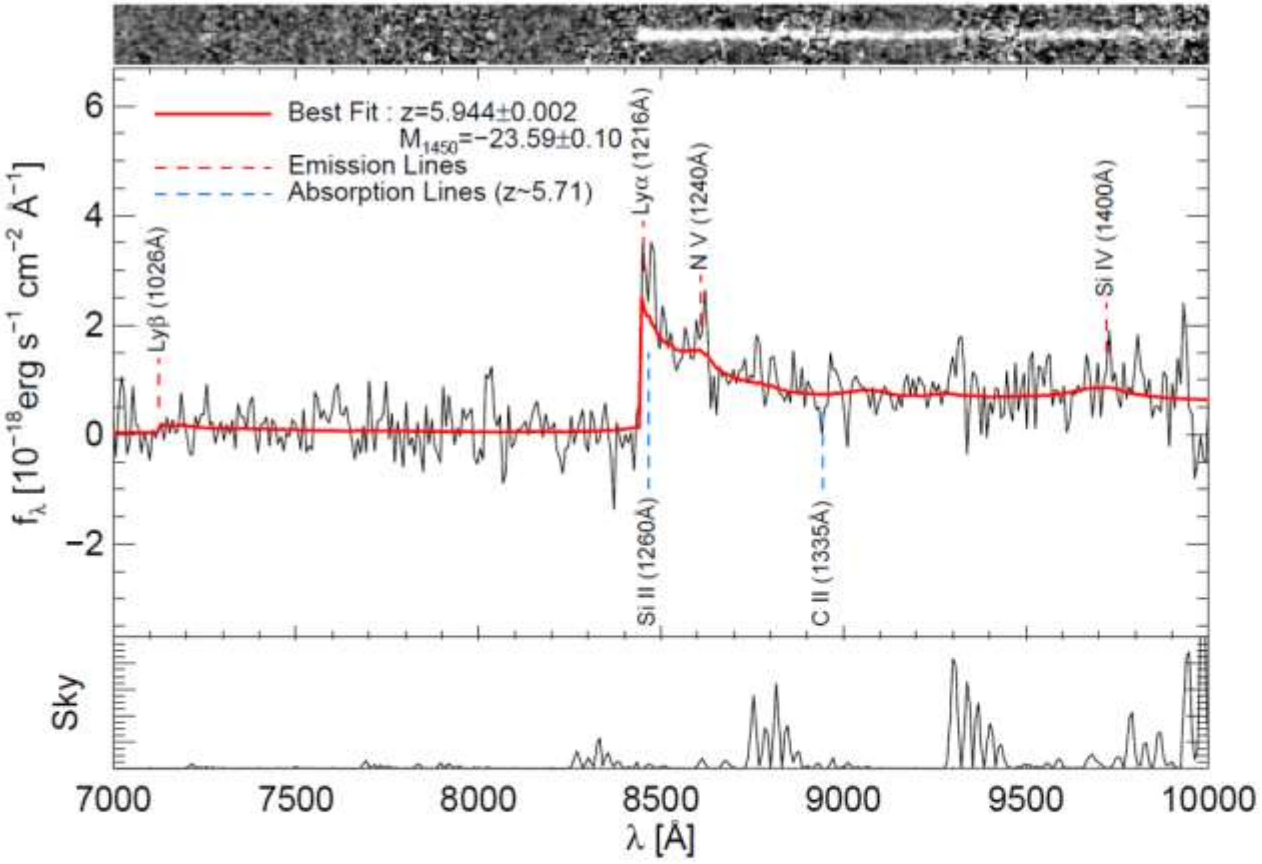
Discovery of IMS J2204+0112

- **Gemini/GMOS-S Observation**
  - Supported by **K-GMT Science Program** of KASI
  - Instrument: Gemini Multi-Object Spectrograph (**GMOS**)
- **Technical Description**
  - **Nod & Shuffle longslit** mode with R150_G5326 grating
  - 4x4 binning → 7.72 Å/pixel (~290 km/s)
  - RG610_G0331 filter to avoid the order-overlap
- **Exposure Time**
  - 12 sequences of 968 s (~3 hr)
  - Use five frames (**~1.3 hr**) with seeing < 1″

Gemini South 8 m Telescope

Discovery of IMS J2204+0112

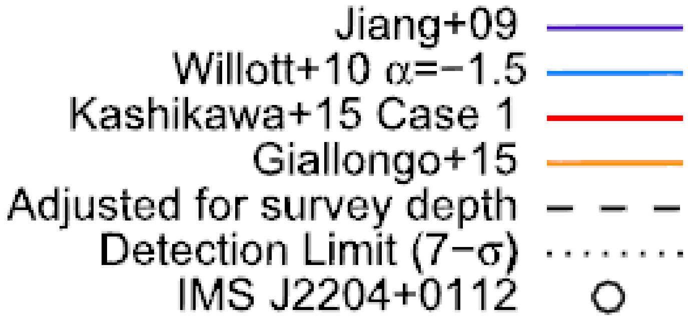
- **Spectrum of IMS J2204+0112**
  - Clear Lyman break at ~8443 Å
    - Fit the SDSS composite quasar spectrum + IGM attenuation (Vanden Berk+01; Madau+96)
    - **$z = 5.944 \pm 0.002$**
    - **$M_{1450} = -23.59 \pm 0.10$ mag**
  - Emission & absorption lines
  - $M_{BH} > 10^8 M_{sun}$ (if $\lambda_{Edd}=1$)

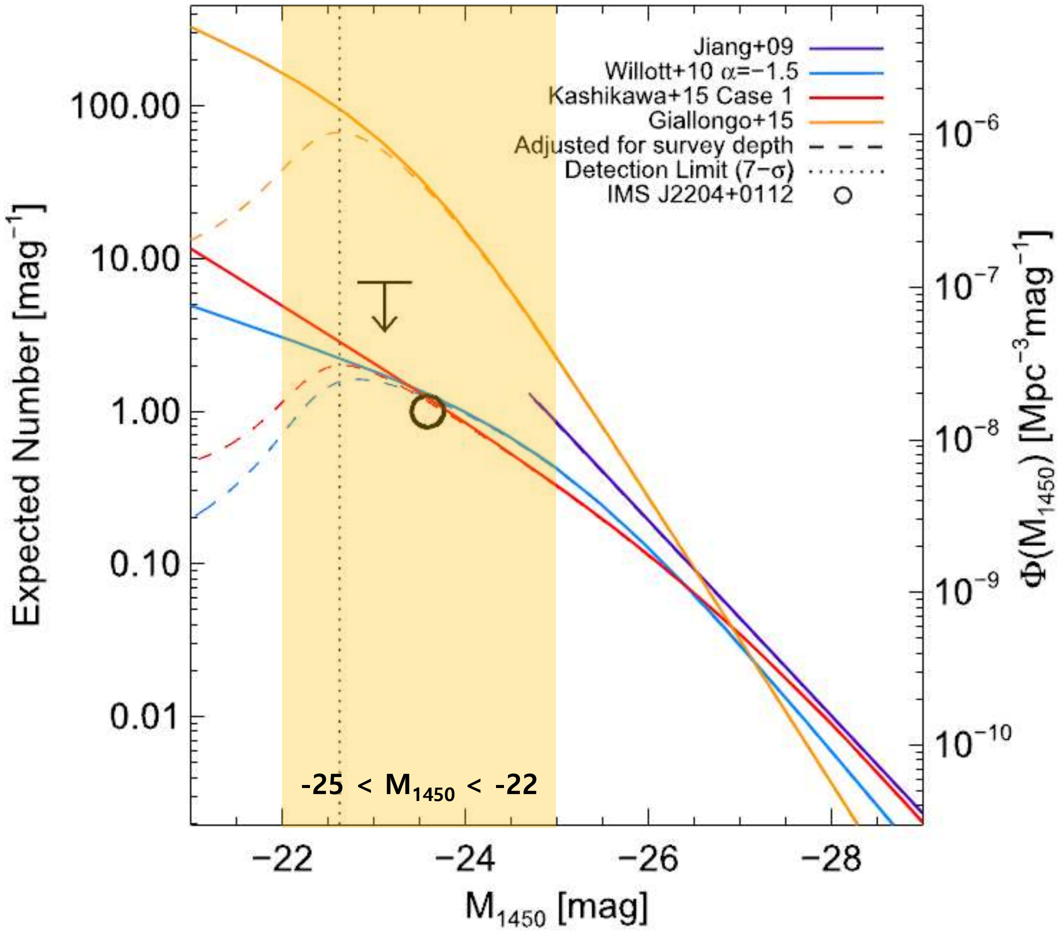


Kim+15

Contribution to Cosmic Reionization

- **Expected Number of Quasars in SA22**
  - Estimated with different QLFs
    - Willott+10 & Kashikawa+15 → 1.4
    - Giallongo+15 → ~40
- **Required UV Photons for Reionization**
  - AGNs at M1450 ~ 23.5 mag
    - Willott+10 & Kashikawa+15: ~3%
    - Giallongo+15: ~60%
    - **Our result: <15%**





Kim+15

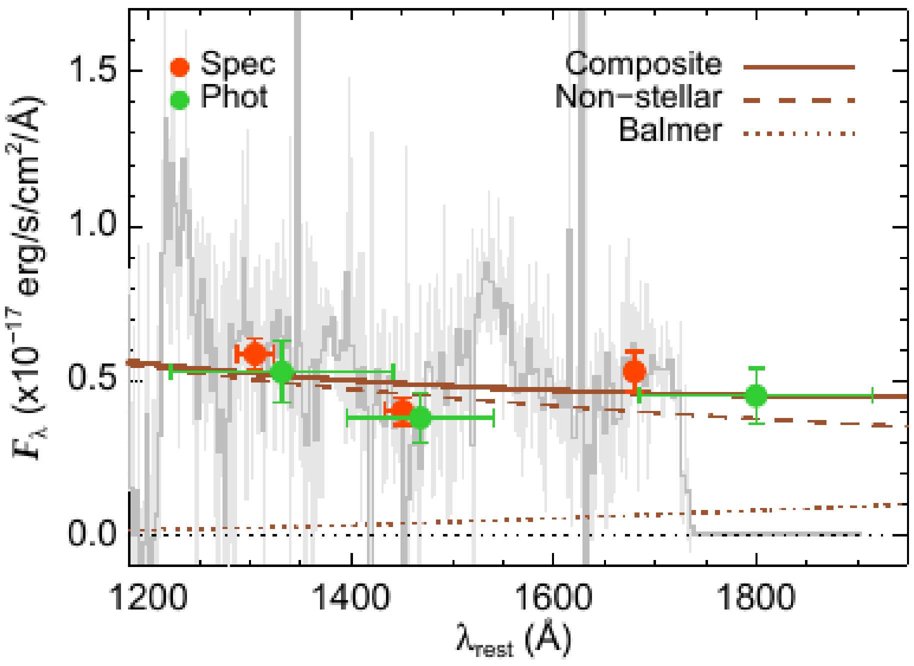
Supermassive Black Hole of IMS J2204+0112

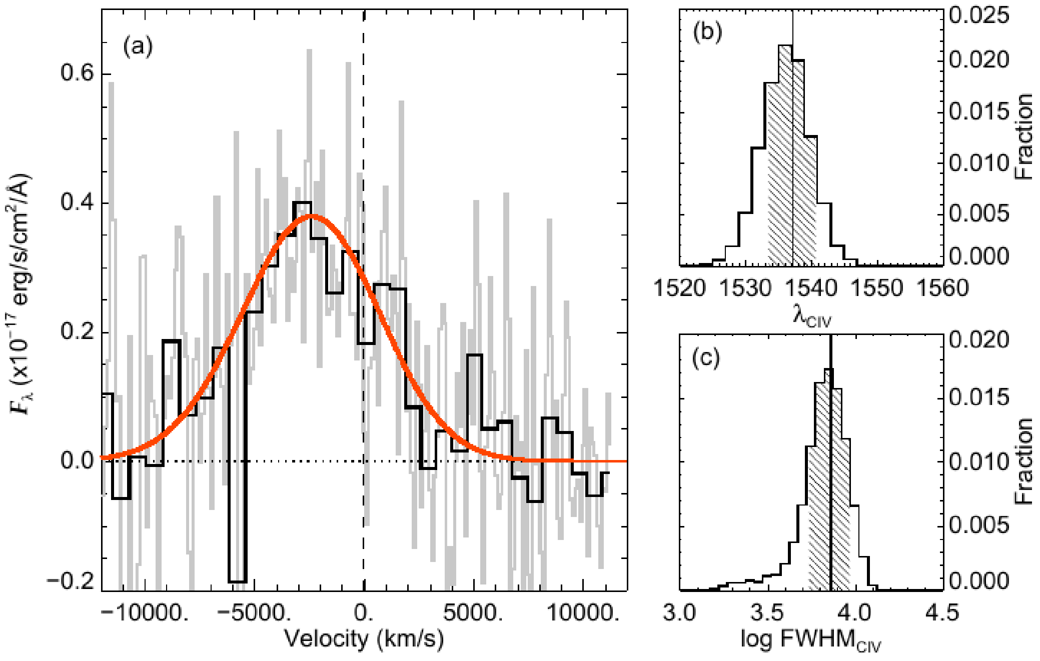
- **Magellan/FIRE Observation**
  - **Magellan Baade 6.5 m Telescope** at Las Campanas Observatory, Chile
  - Folded-port InfraRed Echellette (**FIRE**)
- **Technical Description**
  - **Longslit observation** at λ < 12,000 Å
  - Resolution: R_J~500 (600 km/s)
- **Exposure Time**
  - 26 sequences of 908.8s (~6.7 hr)
  - Use 20 frames (**~5.0 hr**) with seeing < 1″

Magellan Baade 6.5 m Telescope

Supermassive Black Hole of IMS J2204+0112

- **M_{BH} & λ_{Edd} Measurements**
  - Continuum Modeling (Non-stellar power law + Balmer)
  - Assuming **virial motion of C IV gas** (Vestergaard+06),
    - log ($M_{BH,CIV}/M_{sun}$) = 9.15 ± 0.24
    - log (λ_{Edd}) = -1.18 ± 0.27





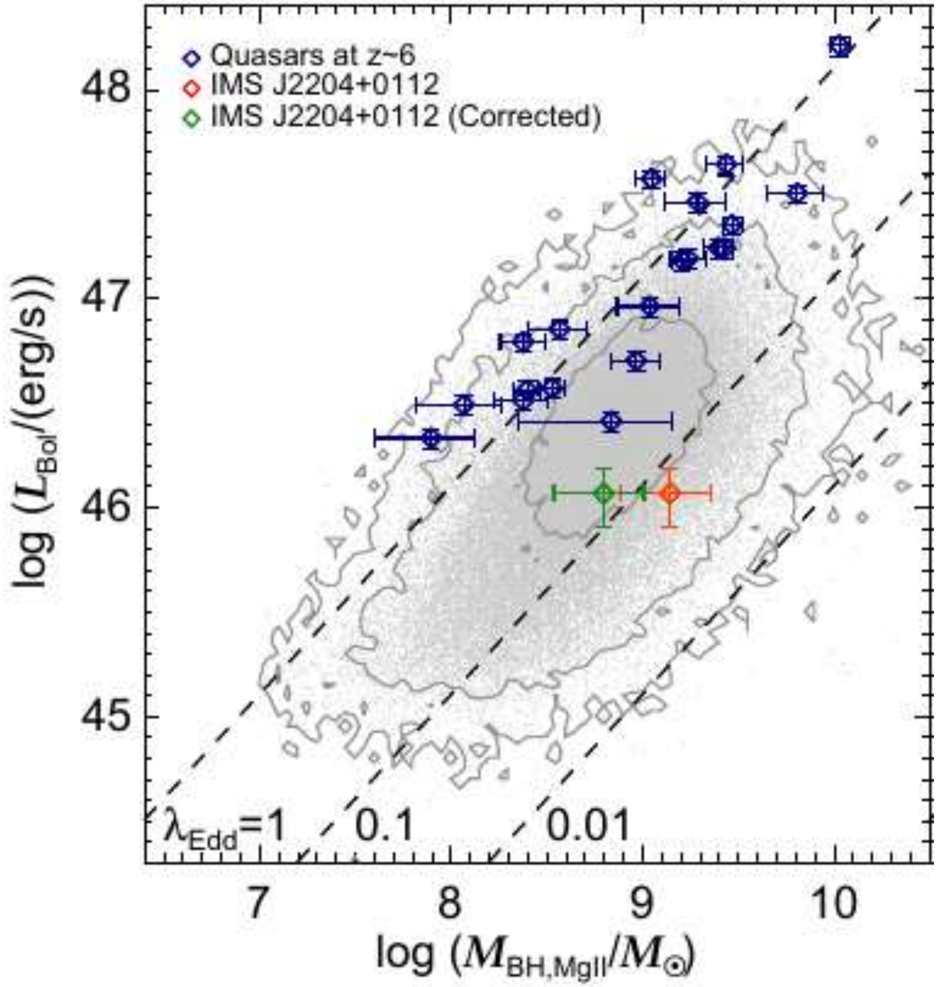
Kim+17 in prep

Supermassive Black Hole of IMS J2204+0112

- **Correction for $M_{BH,CIV}$**
  - Shape of C IV line (Runnoe+13)
  - Non-virial C IV gas (Shen&Liu12; Park+13)
  - Blueshift of C IV line (Coatman+16)
  - ➔ log ($M_{BH,CIV}/M_{sun}$) ~ 8.8 & log (λ_{Edd}) ~ -0.8

Table 3. M_{BH} and λ_{Edd} of IMS J2204+0112

Reference	Correction	$\log(M_{BH,CIV}/M_{\odot})$	σ_{int}	$\log \lambda_{Edd}$	Section
(1)	(2)	(3)	(4)	(5)	(6)
Vestergaard & Peterson (2006)	-	$9.15^{+0.26}_{-0.21}$	0.36	$-1.18^{+0.29}_{-0.25}$	4.1
Jun et al. (2015)	-	$9.26^{+0.33}_{-0.30}$	0.40	$-1.30^{+0.35}_{-0.33}$	4.1
Runnoe et al. (2013)	Peak(λ1400/C IV)	> 8.4	0.45	< -0.5	4.2.1
Shen & Liu (2012)	$\gamma = 0.24$	$8.90^{+0.05}_{-0.05}$	0.28	$-0.93^{+0.15}_{-0.15}$	4.2.2
Park et al. (2013)	$\gamma = 0.56$	$8.69^{+0.48}_{-0.50}$	0.35	$-0.72^{+0.50}_{-0.52}$	4.2.2
Coatman et al. (2016b)	$v_{bs,CIV}$	$8.75^{+0.26}_{-0.21}$	0.50	$-0.78^{+0.33}_{-0.30}$	4.2.3



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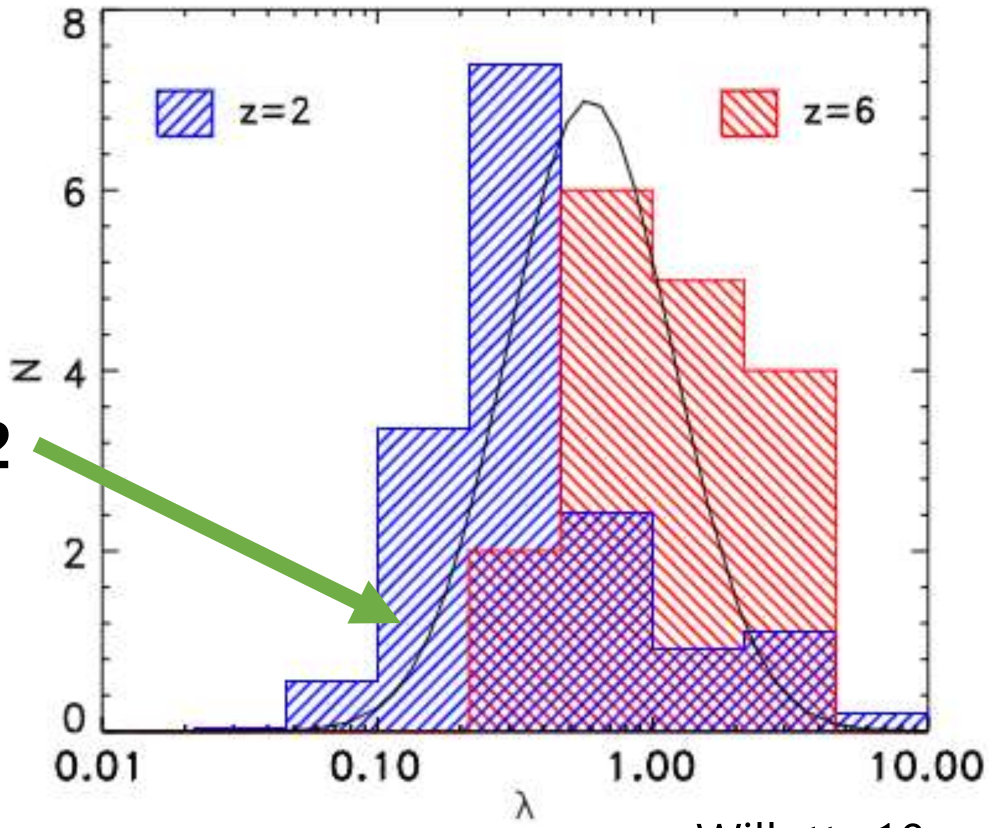
Are Quasars Growing Vigorously at z~6?

- **Eddington Ratio Distribution**
  - Previous suggestion with 17 luminous quasars (L_{bol} > $10^{46.6}$ erg/s; Willott+10a)
    - log $\lambda_{Edd,z6}$ = 0.03 ± 0.28 dex & log $\lambda_{Edd,z2}$ = -0.43 ± 0.39 dex
    - **log $\lambda_{Edd,z6,int}$ = -0.22 ± 0.30 dex**

IMS J2204+0112

$P_{det,IMS}$ = 0.3%!!



Willott+10a

Are Quasars Growing Vigorously at z~6?

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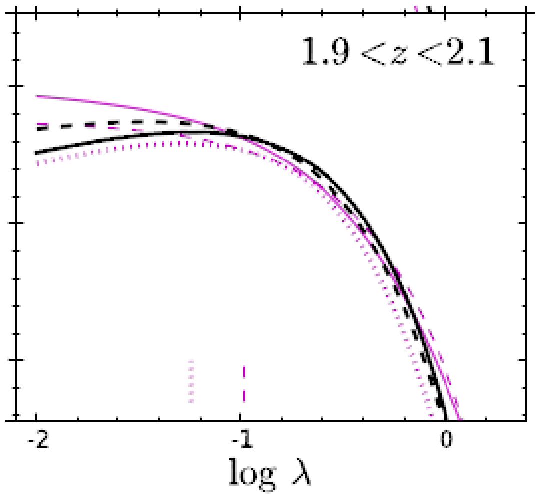
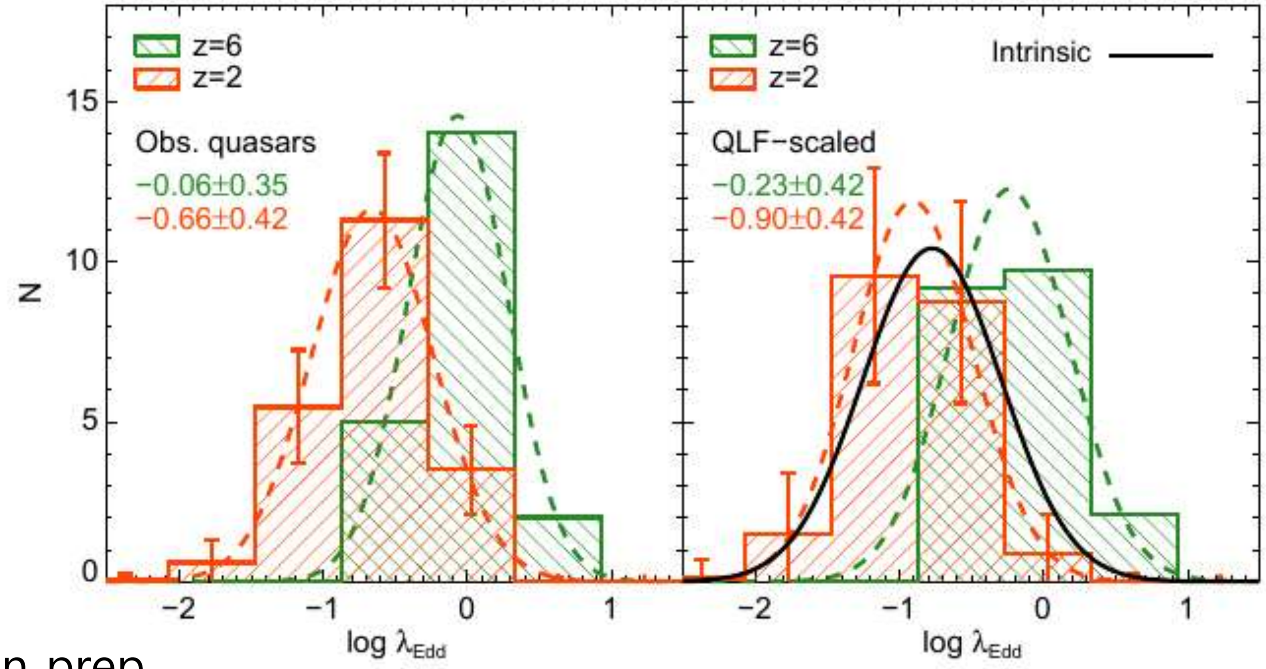
  - Previous suggestion with 17 luminous quasars ($L_{bol} > 10^{46.6}$ erg/s; Willott+10a)
    - $\log \lambda_{Edd,z6} = 0.03 \pm 0.28$ dex & $\log \lambda_{Edd,z2} = -0.43 \pm 0.39$ dex
    - **$\log \lambda_{Edd,z6,int} = -0.22 \pm 0.30$ dex**
  - Considering 21 quasars & QLFs ($L_{bol} > 10^{45.8}$ erg/s; This work)
    - $\log \lambda_{Edd,z6} = -0.23 \pm 0.42$ dex
    - $\log \lambda_{Edd,z2} = -0.90 \pm 0.42$ dex
    - **$\log \lambda_{Edd,z6,int} = -0.78 \pm 0.48$ dex**



Schulze+15



Kim+17 in prep

Summary

- **Discovery of IMS J2204+0112**
  - Thanks to K-GMT science program, IMS J2204+0112 was discovered
  - Very faint & the lowest Eddington ratio quasar to date
- **Contribution to Cosmic Reionization**
  - z~6 quasars might not be main contributors (<15%)
- **SMBH Growth with Quasar at z~6**
  - May not be accreting much faster than low-z counterparts
- **What are the Nominal Quasars at z~6?**
  - Moderately luminous quasars with moderate accretion rates
  - Need more sample of faint quasars
  - \+ Upcoming ALMA observation..!