High-z Quasar Survey with IMS: Are Quasars Growing Fast in the Early Universe?

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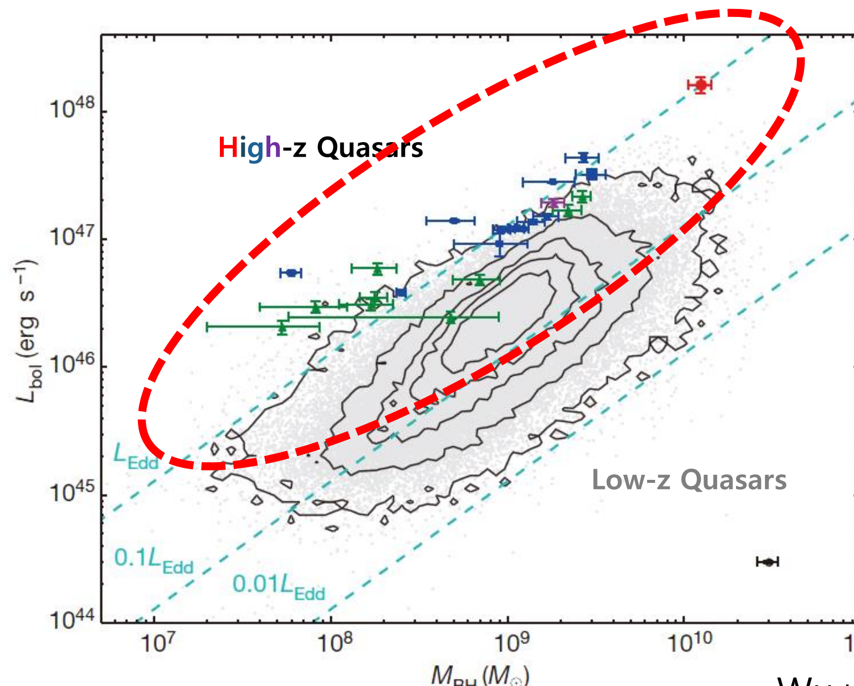
Introduction

- **Why High Redshift Quasars?**
  - Quasars are energetic sources in the universe
    - **A unique sample to study formation of the first supermassive black holes** (SMBHs)
- **Properties of High Redshift Quasars**
  - Compared to low redshift quasars,
    - No evolution in UV/optical spectra
    - Larger fraction of dust poor hosts
    - Existence of SMBHs with **$10^{8\text{-}10}$ M_{sun}**
    - Higher Eddington ratio of **λ_{Edd}~1**



Wu+15

Introduction

- **Theoretical Challenge for SMBH Formation**
  - Time requirements for growing to 10^9 M_{sun} SMBH
    - **0.8 Gyr** for seed BH of 100 M_{sun} with λ_{Edd}=1
    - But only **0.5 Gyr** from the first formation of seed BH (z~10) to z~6
  - To solve this problem,
    - **Super-Eddington accretion** (λ_{Edd}>1) of stellar mass (~100 M_{sun}) BHs
    - BH growth from **massive seed BHs** with 10^{4-6} M_{sun}

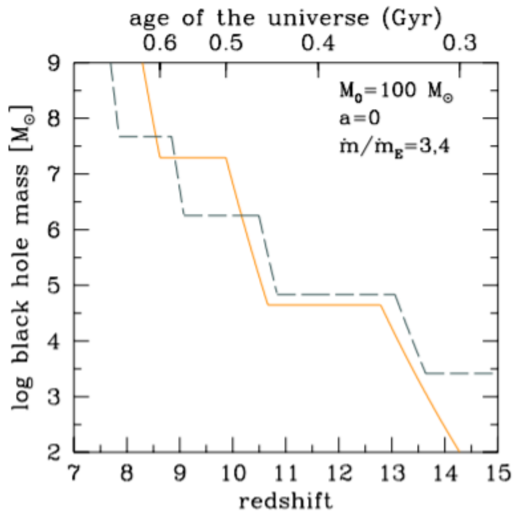
0.8 Gyr!

10^9 M_{sun} **100 M_{sun}**

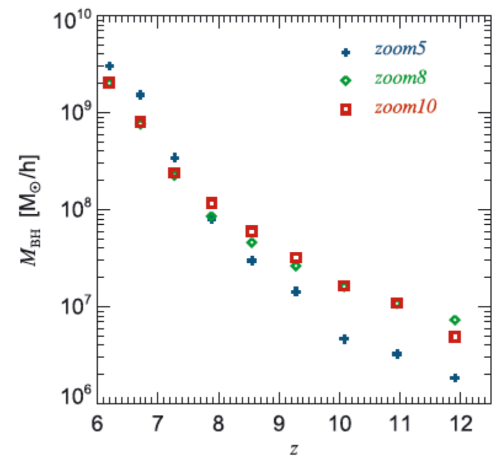
$$M_{\mathrm{BH}}(t) = M_{\mathrm{BH},0} \times \exp[\lambda_{\mathrm{Edd}} \mathrm{f}_{\mathrm{Duty}} \frac{(1-\epsilon)}{\epsilon} \frac{\mathrm{t}-\mathrm{t}_0}{\mathrm{t}_{\mathrm{Edd}}}]$$

$\lambda_{\mathrm{Edd}} = 1$ $\epsilon = 0.1$

f_{Duty}=1.0 $t_{\mathrm{Edd}} = 450$ Myr



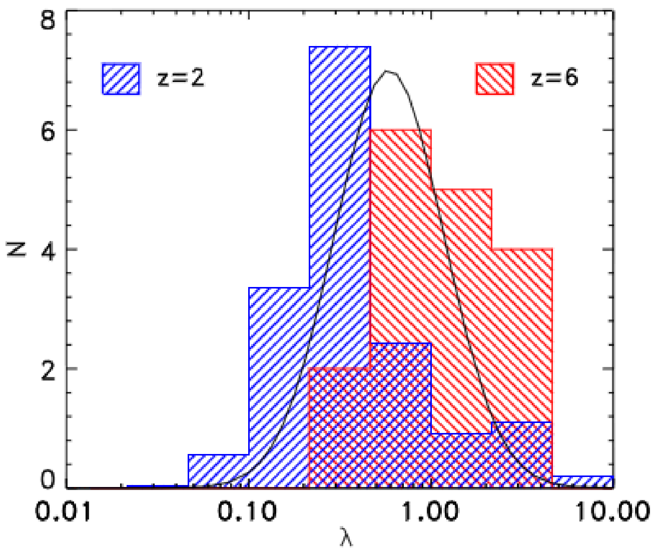
Madau+14



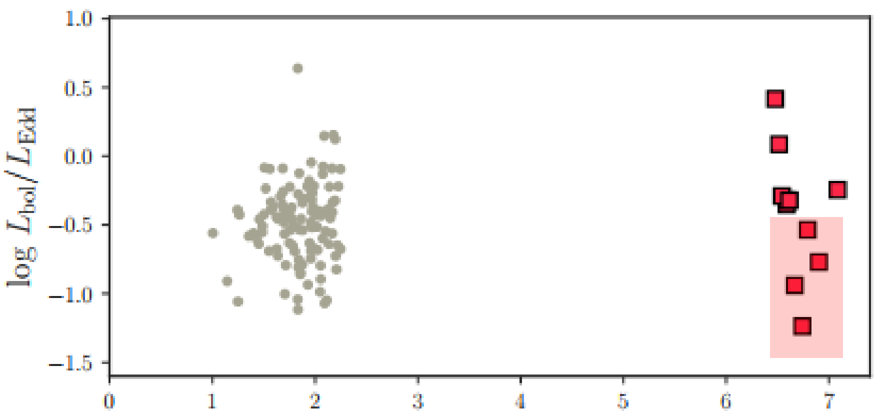
Sijacki+09

Introduction

- **For Testing the Scenarios,**
  - **Understanding intrinsic λ_{Edd} of High-z quasars is required**
  - Intrinsic λ_{Edd} distribution of z~6 quasars (Willott+10)
    - Using 17 bright quasars (L_{bol} > 10^{47} erg s^{-1}) ➔ log λ_{Edd} = -0.22 ± 0.30 dex (black line)
    - **Biased sample toward luminous ones!**
  - Extending the luminosity range is required
    - Low λ_{Edd} quasars (L_{bol}=$10^{46.5\text{-}47}$ erg s^{-1}) are discovered at z~6.5 (Mazzucchelli+17)
    - Possible L_{bol}-λ_{Edd} correlation found at low redshift



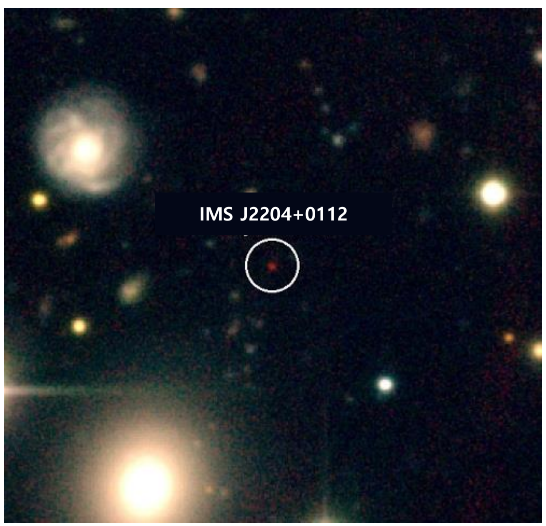
Willott+10a

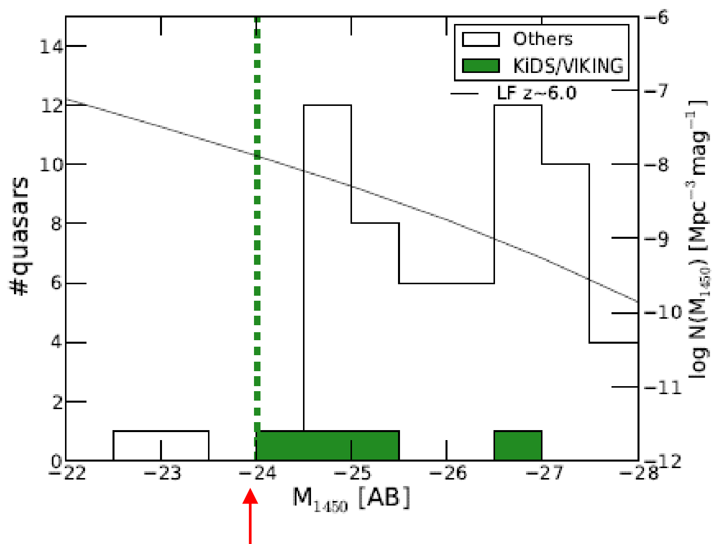


Mazzucchelli+17

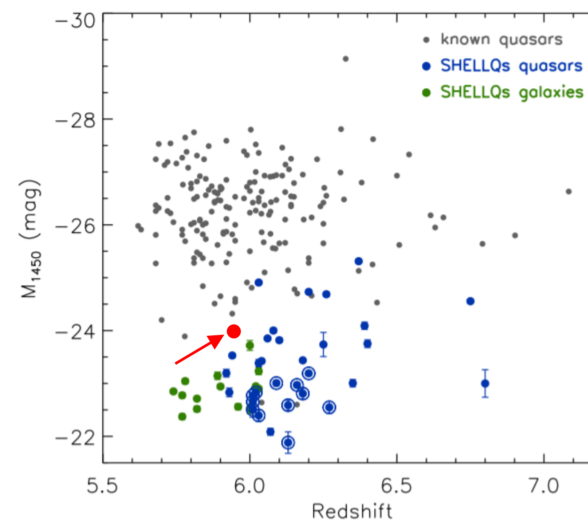
Introduction

- **IMS J2204+0112**
  - One of the low luminous quasars at z~6 (Kim+15)
    - **M_{1450}=-23.99 mag, z=5.926**
  - Supported by K-GMT Science Program by KASI (PID: gemini_KR-2015A-023)
  - A good starting point to see the BH growth of quasar population at z~6





Venemans+15

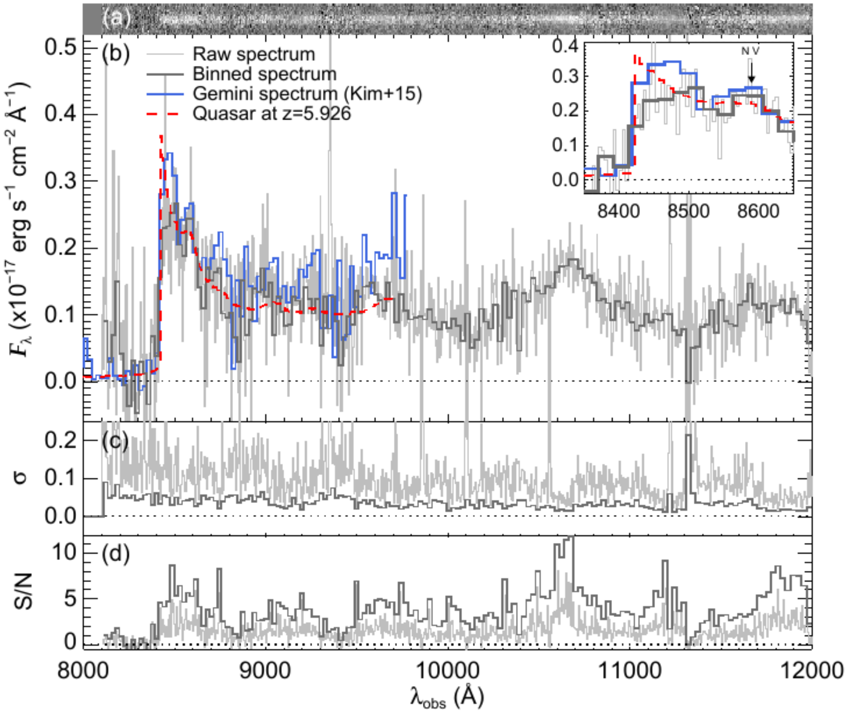


Matsuoka+17

Observation

- **Magellan/FIRE Observation (Sep. 2015)**
  - **Magellan Baade 6.5 m Telescope** at Las Campanas Observatory, Chile
  - Folded-port InfraRed Echellette (**FIRE**)
- **Technical Description**
  - Focus on **C IV λ1549**, instead of Mg II λ2798
  - **Longslit observation** at λ < 12,000 Å
  - Resolution: R_J~500 (600 km/s)
- **Exposure Time**
  - 26 sequences of 908.8s (~6.7 hrs)
  - Use 20 frames (**~5.0 hrs**) with seeing < 1″

Magellan Baade 6.5 m Telescope

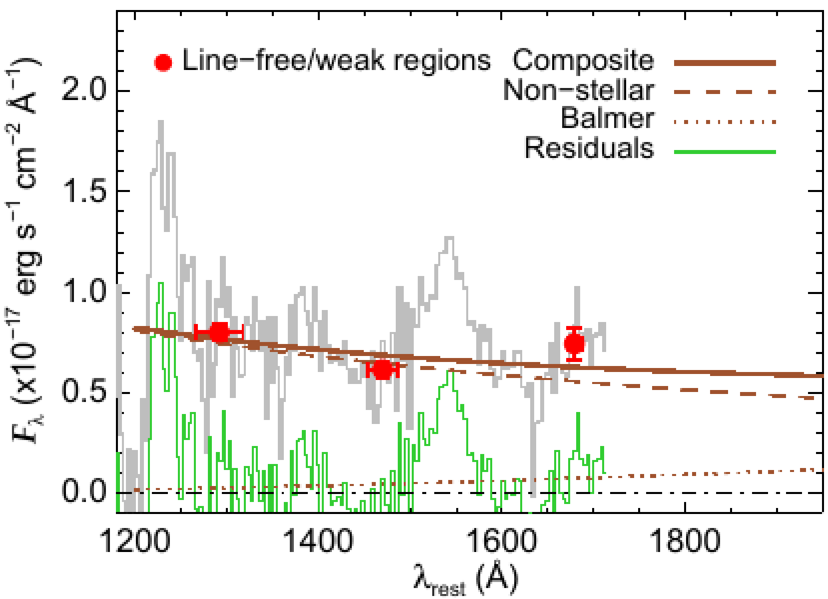


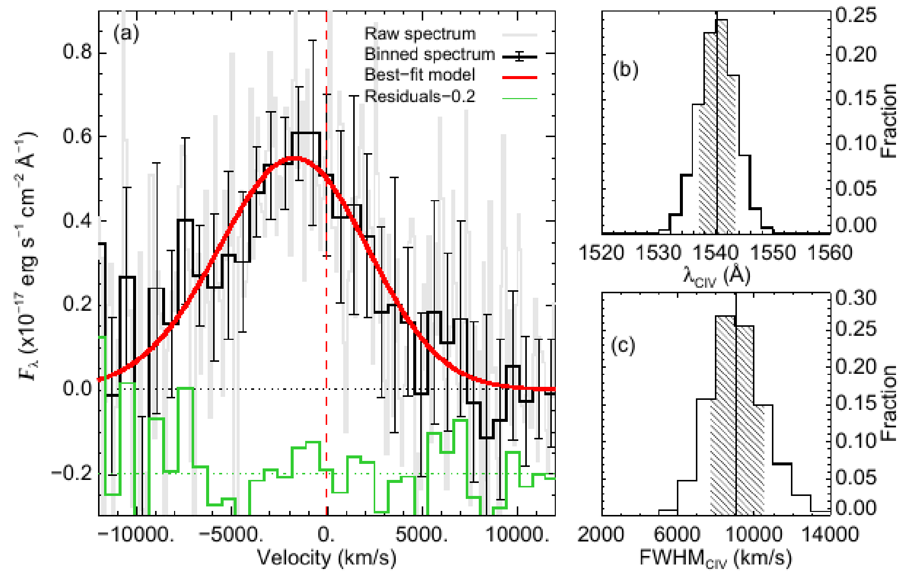
Spectral Modeling

- **Continuum Components**
  - Non-stellar power law + Balmer pseudo-continuum
    - $\alpha_{\mathrm{P}} = -1.12^{+0.38}_{-0.40}$
    - $\log(L_{\mathrm{bol}}/\mathrm{erg\,s^{-1}}) = 46.21^{+0.12}_{-0.16}$

$$F_\lambda = F_{\mathrm{P}} \left(\frac{\lambda}{1000\mathrm{\AA}}\right)^{\alpha_{\mathrm{P}}} + F_{\mathrm{B}} B_\lambda(T_e) \left(1 - e^{-\tau_{\mathrm{BE}}(\lambda/\lambda_{\mathrm{BE}})^3}\right), \; \lambda < \lambda_{\mathrm{BE}}$$

- **C IV Line Measurement**
  - Single Gaussian Fitting
    - $\lambda_{\mathrm{CIV}} = 1540.32^{+3.14}_{-3.20}$ Å, $\mathrm{FWHM_{CIV}} = 9046^{+1499}_{-1305}\ \mathrm{km\,s^{-1}}$





Black Hole Mass ($M_{BH,CIV}$)

- **Using $FWHM_{CIV}$ + L_{1350} as a M_{BH} estimator**
  - Assuming virial motion of CIV emitting gas

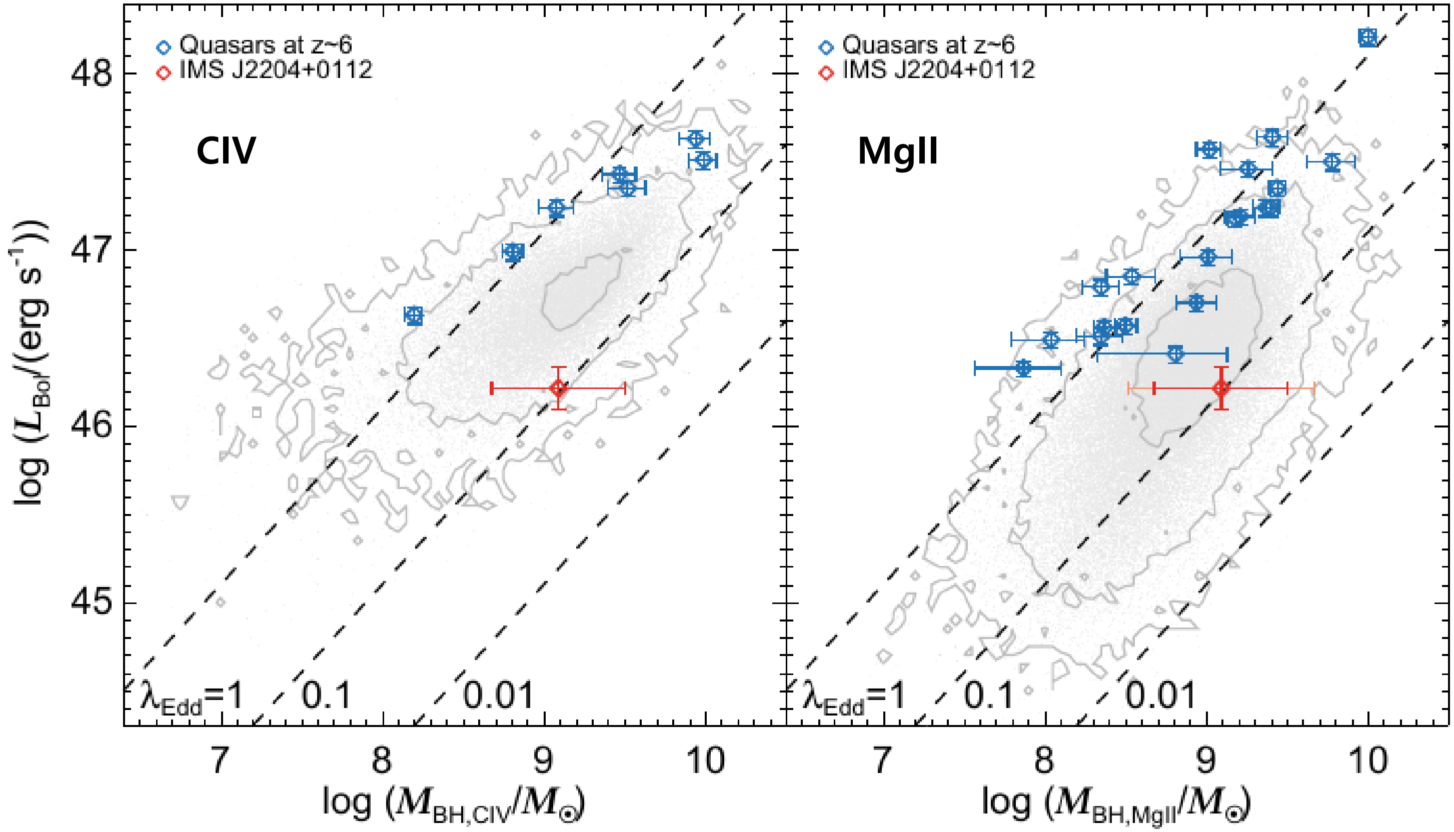
$$\log\left(\frac{M_{\rm BH,CIV}}{M_\odot}\right) = A + \log\left\{\left(\frac{L_{1350}}{10^{44}\ {\rm erg\ s^{-1}}}\right)^{\beta}\left(\frac{\rm FWHM_{CIV}}{1000\ {\rm km\ s^{-1}}}\right)^{\gamma}\right\}$$

- **Various Assumptions Considering Uncertain $M_{BH,CIV}$ Measurements**
  - Simple viralized gas with γ=2
    - $\log M_{\rm BH,CIV}$ = 9.27-9.55 (Vestergaard+06; Jun+15; Park+17)
  - Considering non-virial components with γ=0.5
    - $\log M_{\rm BH,CIV}$ = 8.72 (Park+17)
  - $FWHM_{CIV}$ correction with CIV blueshift ($v_{bs,CIV}$)
    - $\log M_{\rm BH,CIV}$ = 9.05-9.27 (Coatman+17; Jun+17)
  - Instead of $FWHM_{CIV}$, using line dispersion (σ_{CIV} or σ_G)
    - $\log M_{\rm BH,CIV}$ = 8.59 (Park+17)

➔ **We use a weighted-mean M_{BH} value ($10^{9.09\pm0.41}$ M_{sun}) as a proxy!**

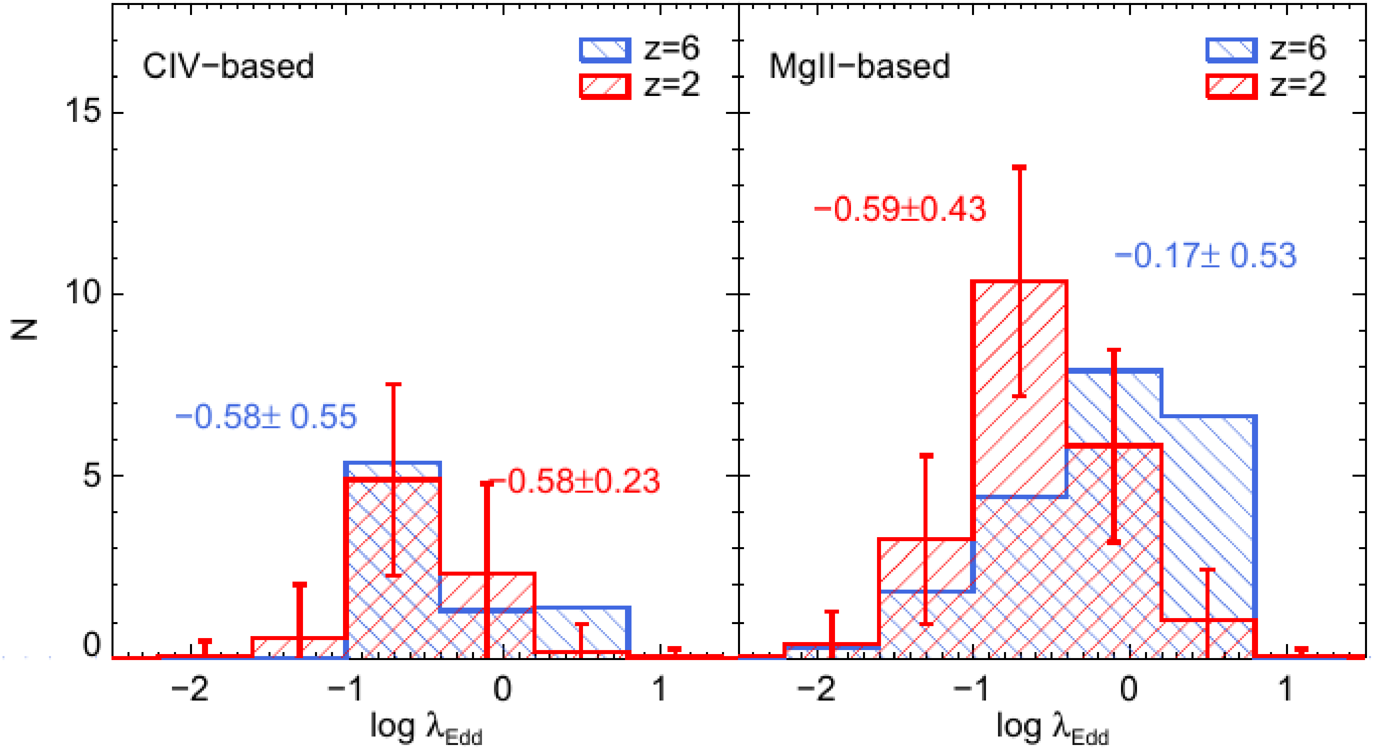
Eddington Ratio (λ_{Edd})

- **λ_{Edd} Measurements**
  - For IMS J2204+0112, $\boldsymbol{\lambda_{Edd} = 0.11}$
    - **Only chance of 0.03% (3.5σ)** with the intrinsic λ_{Edd} distribution from Willott+10 **(-0.10 ± 0.26 dex for IMS depth)**



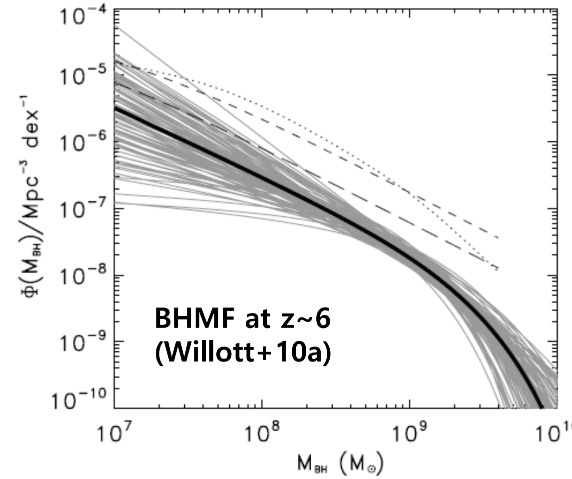
Eddington Ratio (λ_{Edd})

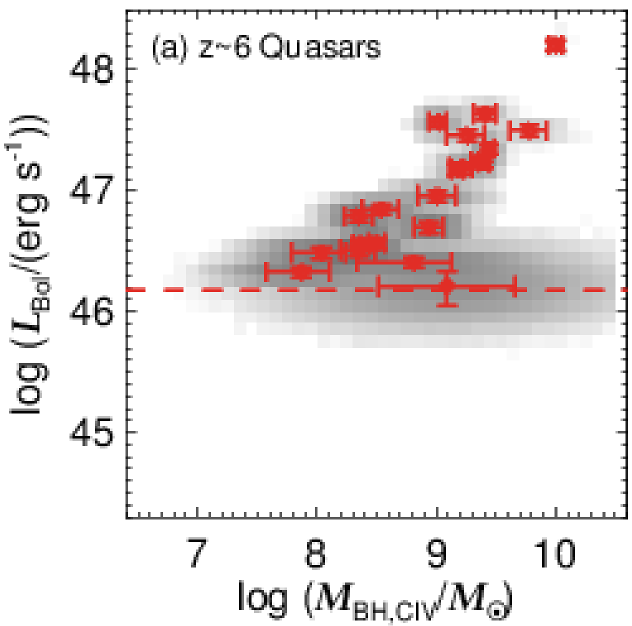
- **Comparison with Low Redshift Counterparts**
  - For completeness, scaling with **quasar luminosity function (QLF)**
  - 10,000 sets of **luminosity-matched z~2 quasars** from Shen+11
    - Comparable (CIV) or larger by 0.42 dex (MgII)
    - Considering small number (7) of CIV, we concentrate on MgII-based sample



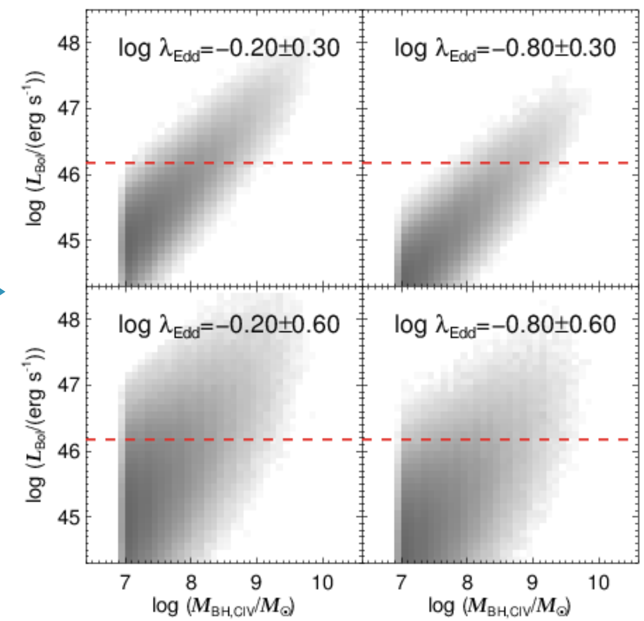
Low λ_{Edd} for z~6 Quasars?

- **Intrinsic λ_{Edd} Distribution of Quasars at z~6**
  - **2D Fitting for density map on M_{BH}-L_{bol} plane**
    - 21 observed quasars
    - Mock 10^6 quasars
      - BH mass function (Willott+10a)
      - Log-normal λ_{Edd} distribution
    - Minimum χ^2_{red} value (M_{1450} < -24 mag)



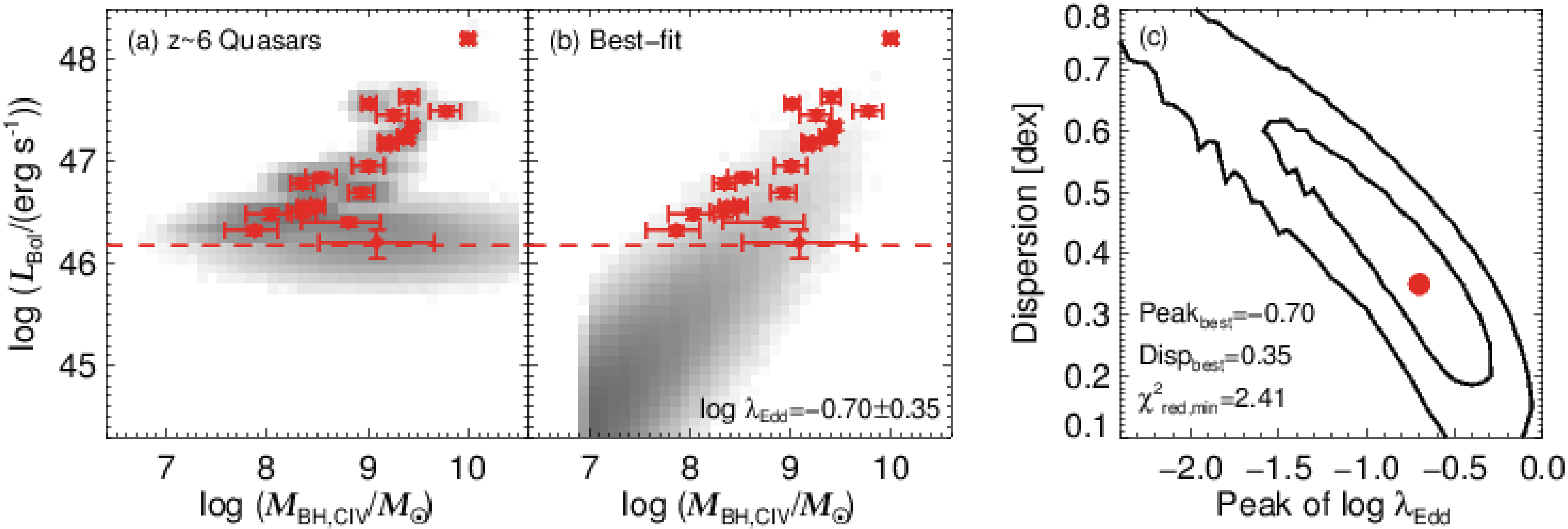


$$\chi^2_{red} = \frac{1}{\nu}\sum \frac{(D_{obs,i}-D_{mock,i})^2}{D_{obs,i}}$$



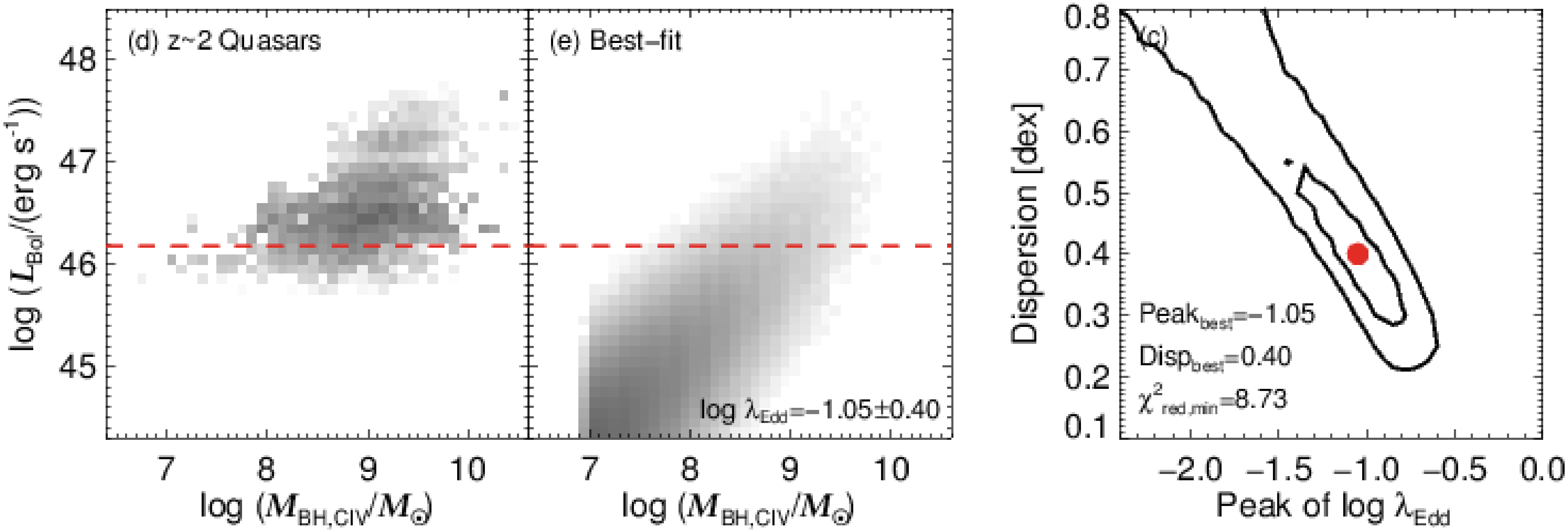
Low λ_{Edd} for z~6 Quasars?

- **Intrinsic λ_{Edd} Distribution of Quasars at z~6**
  - **Best-fit** Parameters:
    - Peak of $\log(\lambda_{\rm Edd}) = -0.70^{+0.40}_{-0.90}$ with dispersion of $0.35^{+0.25}_{-0.15}$ dex
- **Inclusion of IMS J2204+0112 reduces λ_{Edd} at z~6**
  - $\log(\lambda_{Edd})$ = -0.22 ± 0.30 dex (Willott+10) ➔ **$\log(\lambda_{Edd})$ = -0.70 ± 0.35 dex**



Low λ_{Edd} for z~6 Quasars?

- **Intrinsic λ_{Edd} Distribution of Quasars at z~2**
  - For z~2 luminosity-matched quasar sample,
    - Generate Density map of the z~2 quasar sample
    - Peak of $\log(\lambda_{\mathrm{Edd}}) = -1.05^{+0.30}_{-0.35}$ with dispersion of $0.40^{+0.15}_{-0.10}$ dex
  - But λ_{Edd} at z~6 is still slightly **higher (0.35 dex)** than λ_{Edd} at z~2



Implications for SMBH Evolution

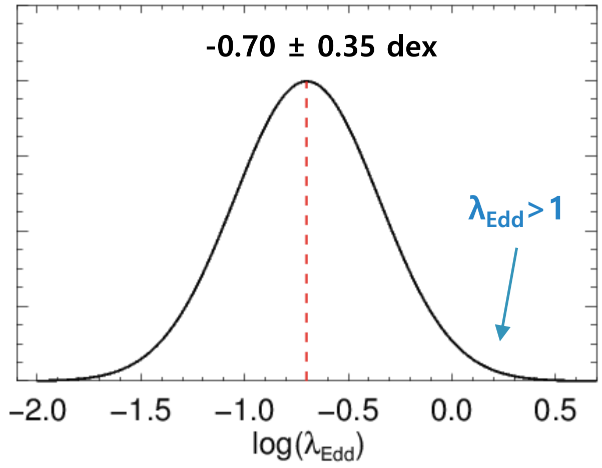
- **Low λ_{Edd} for z~6 Quasars?**
  - Significantly worse situation if λ_{Edd} = 0.2
  - For stellar mass seed BHs (100 M_{sun}),

$$M_{BH}(t) = M_{BH,0} \times \exp[\lambda_{Edd} f_{Duty} \frac{(1-\epsilon)}{\epsilon} \frac{t - t_0}{t_{Edd}}]$$

$$\log M_{BH,0} + \log e \times 10 \times \lambda_{Edd}\ f_{Duty} = 9$$

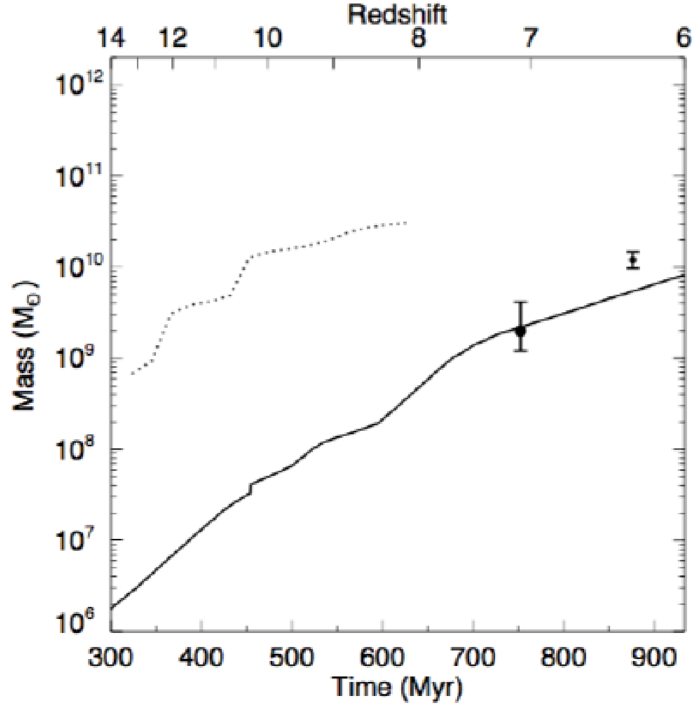
$$\lambda_{Edd}\ f_{Duty} \simeq 1.6$$

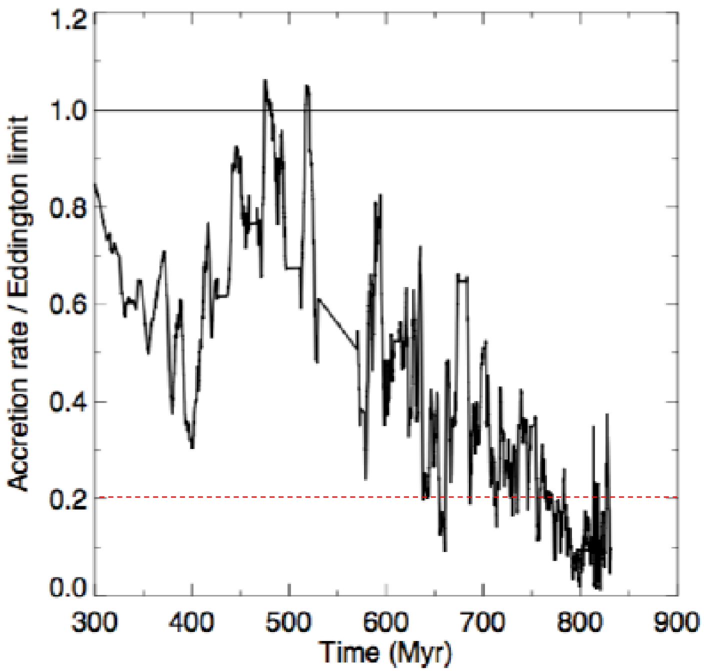
    - For λ_{Edd} = 3, f_{Duty} = 0.53, inconsistent with the intrinsic λ_{Edd} distribution
    - **Episodic high super-Eddington accretion (λ_{Edd} > 10) with f_{Duty} << 0.1**



Implications for SMBH Evolution

- **Low λ_{Edd} for z~6 Quasars?**
  - For heavy seed BHs (10^5 M_{sun}),
    - Reduce accretion time scale by factor of 2 (~2.3 Gyr for λ_{Edd} = 0.2 with f_{Duty} = 1.0)
    - **Eddington-limited accretion until z~7 and then reduces to λ_{Edd} ~ 0.2** when cold gas flows feed the massive seed BHs (Di Matteo+12; Smidt+17)
    - Possible cosmological gas density evolution as $(1+z)^3$ (Di Matteo+12; De Graf+12)





Smidt+17

Summary

- **IMS J2204+0112: The Lowest λ_{Edd} Quasar at z~6**
  - Deep NIR spectroscopy with FIRE on Magellan 6.5 m Telescope
  - $M_{BH,CIV}$ = $10^{9.1}$ M_{sun}, L_{bol} = $10^{46.2}$ erg s^{-1}, λ_{Edd} = 0.11
  - The lowest Eddington ratio quasar at z~6
- **Intrinsic λ_{Edd} Distribution of z~6 Quasars**
  - Inclusion of IMS J2204+0112 (M_{1450}<-24 mag) reduces the intrinsic λ_{Edd}
  - But still slightly higher (0.35 dex) than z~2 quasars
- **Possible Scenarios for the Formation of First SMBHs**
  - Episodic super-Eddington ratio accretion (λ_{Edd} >10) with $M_{BH,seed}$=100 M_{sun}
  - λ_{Edd}~1 accretion until z~7 and then reduces to λ_{Edd}~0.2 with $M_{BH,seed}$=10^5 M_{sun}