Black Hole Mass of the Most Luminous Quasar in the Early Universe

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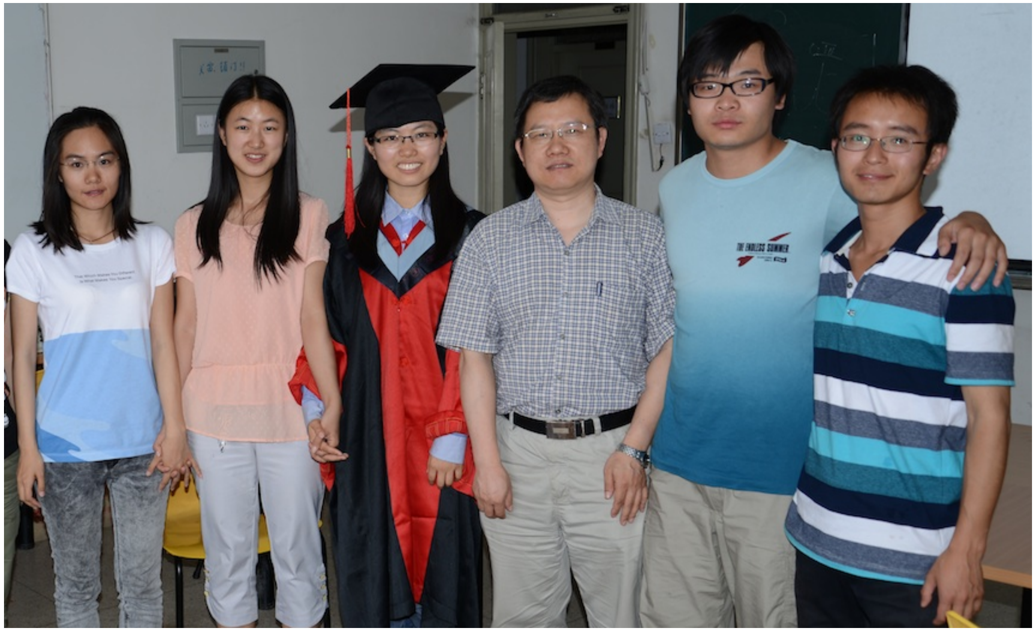
Our Team



(From right: Yi Weimin, Wang Feige, WXB, Zuo Wenwen, Yang Qian, Yang Jinyi)

Fan Xiaohui (UA/KIAA)

Jiang Linhua (KIAA)

Wang Ran (KIAA)

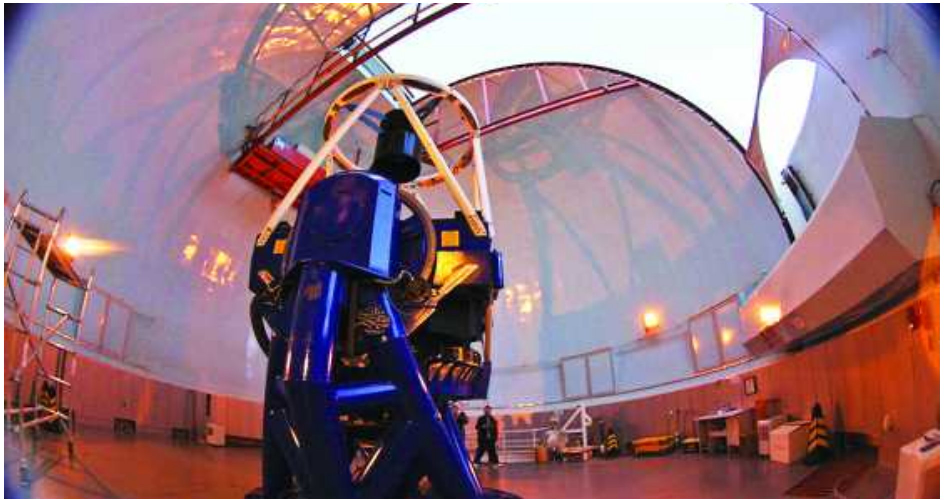
Bian Fuyan (ANU)

Ian McGreer (UA)

D. Thompson (UA)

Yuri Beletsky (LCO)

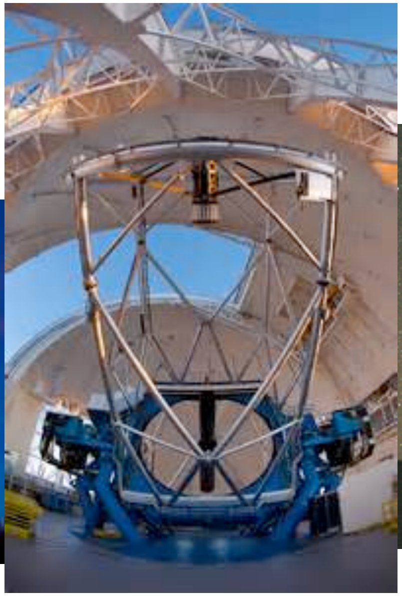
Telescopes we used



2.4-m telescope, Lijiang, Yunnan, China

MMT(6.5-m)

LBT(2*8.4-m)



Gemini-N(8.1-m)

Magellan(6.5-m)

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LETTER

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An ultraluminous quasar with a twelve-billion-solar-mass black hole at redshift 6.30

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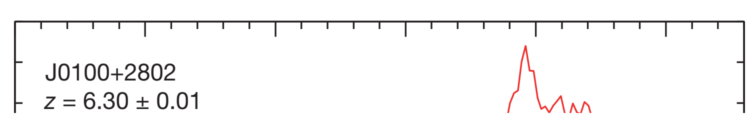
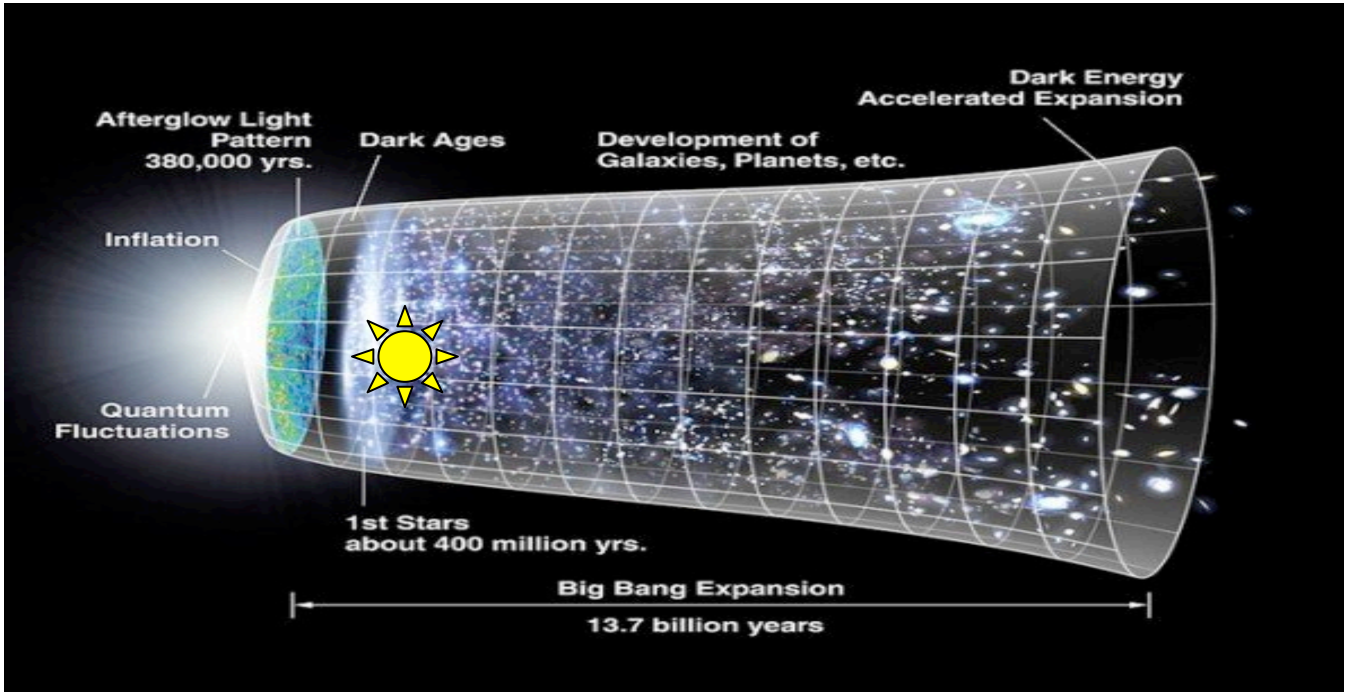
So far, roughly 40 quasars with redshifts greater than $z = 6$ have been discovered[1–8]. Each quasar contains a black hole with a mass of about one billion solar masses ($10^9\ M_\odot$)[2,6,7,9–13]. The existence of such black holes when the Universe was less than one billion years old presents substantial challenges to theories of the formation and growth of black holes and the coevolution of black holes and galaxies[14]. Here we report the discovery of an ultraluminous quasar, SDSS J010013.02+280225.8, at redshift $z = 6.30$. It has an optical and near-infrared luminosity a few times greater than those of previously known $z > 6$ quasars. On the basis of the deep absorption trough[15] on the blue side of the Lyman-α emission line in the spectrum, we estimate the proper size of the ionized proximity zone associated with the quasar to be about 26 million light years, larger than found with other $z > 6.1$ quasars with lower luminosities[16]. We estimate (on the basis of a near-infrared spectrum) that the black hole has a mass of $\sim 1.2 \times 10^{10}\ M_\odot$, which is consistent with the $1.3 \times 10^{10}\ M_\odot$ derived by assuming an Eddington-limited accretion rate.

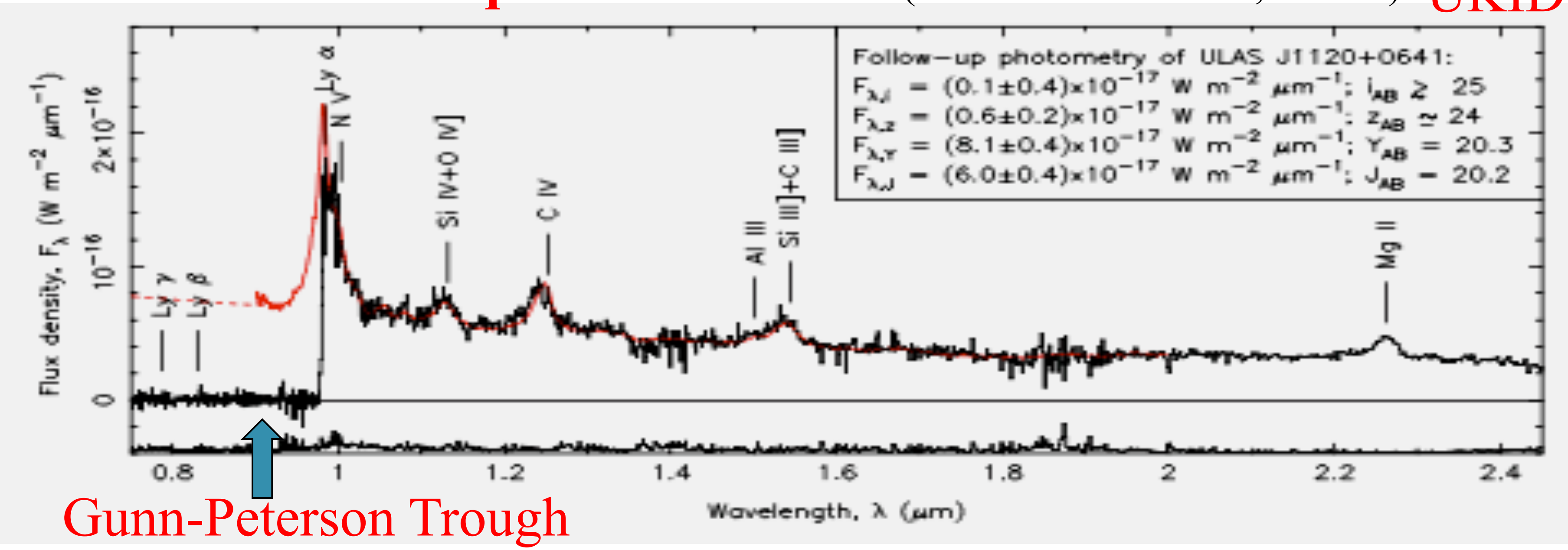
We use the multiwavelength photometry to estimate the optical luminosity at rest-frame wavelength 3,000 Å ($L_{3,000}$), which is consistent with that obtained from K-band spectroscopy (see below). The latter gives a more reliable value of $(3.15 \pm 0.47) \times 10^{47}$ erg s^{-1}, adopting a ΛCDM cosmology with Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}, matter density parameter $\Omega_M = 0.30$ and dark energy density parameter $\Omega_\Lambda = 0.7$. Assuming an empirical conversion factor from the luminosity at 3,000 Å to the bolometric luminosity[21], this gives $L_{\rm bol} = 5.15 \times L_{3,000} = 1.62 \times 10^{48}$ erg s^{-1} $= 4.29 \times 10^{14}\ L_\odot$ (where $L_\odot$ is the solar luminosity). We obtain a similar result when estimating the bolometric luminosity from the Galactic extinction corrected absolute magnitude at rest-frame 1,450 Å, which is $M_{1450,\rm AB} = -29.26 \pm 0.20$. The luminosity of this



Distant quasars can help probe the cosmic reionization



The most distant quasar at z=7.085 (Mortlock et al. 2011, Nature) UKIDSS

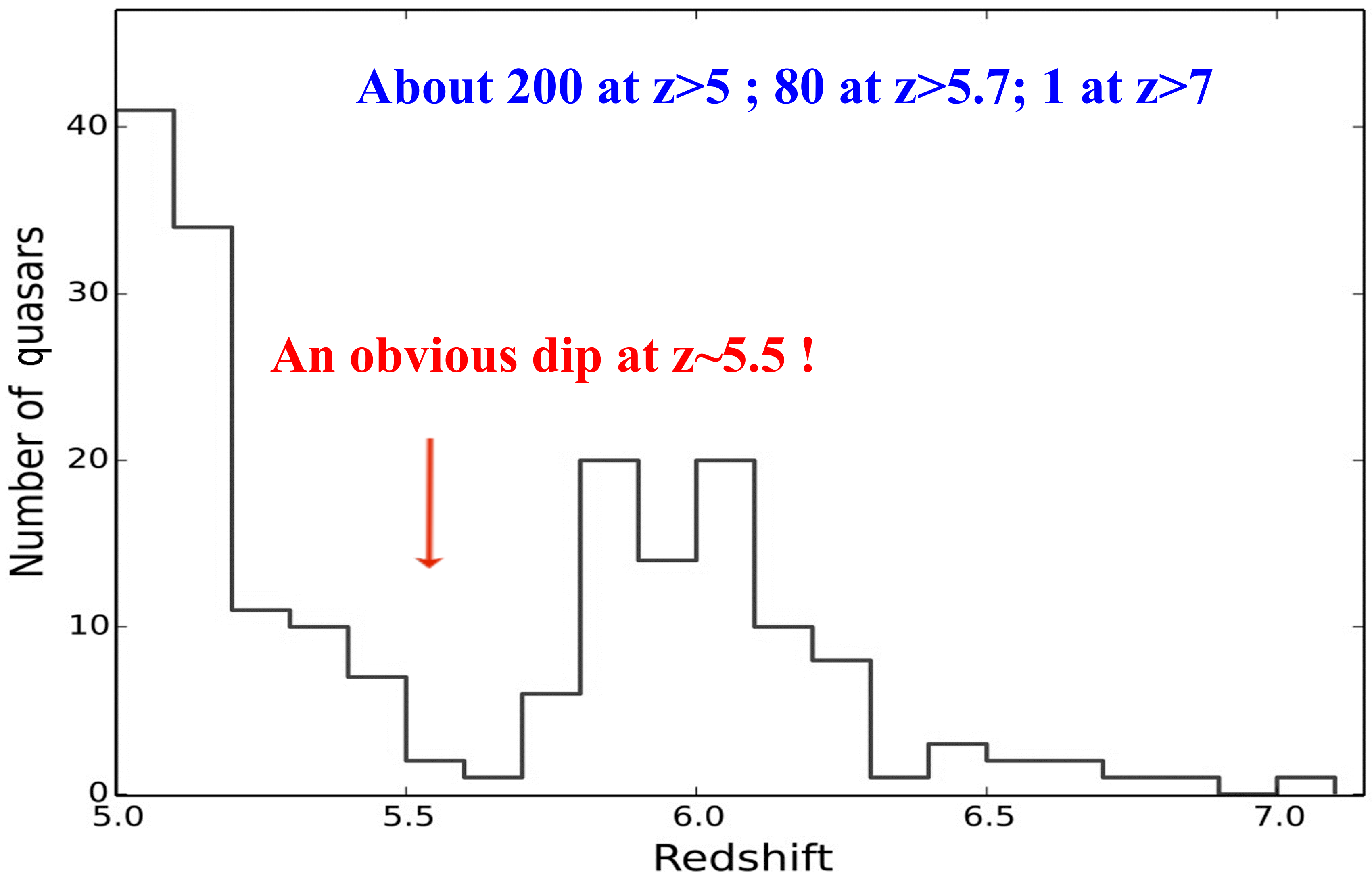


Gunn-Peterson Trough

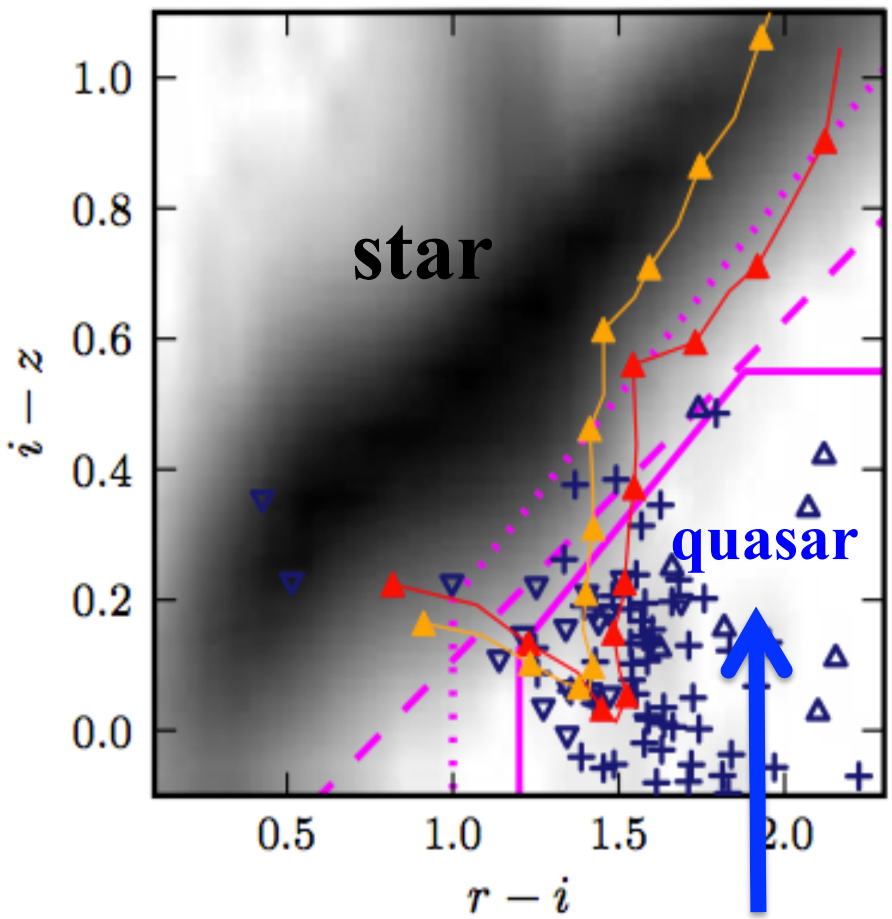
Weighing BH in distant quasars

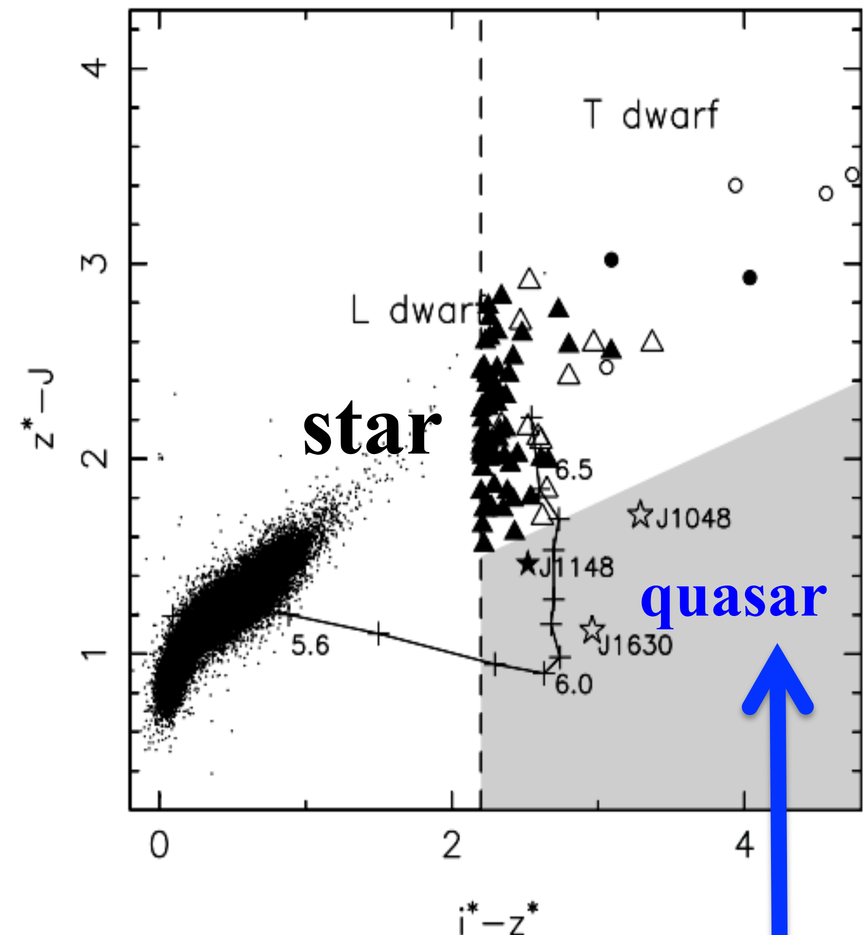
- **BH mass can be estimated with some empirical relations（$M \sim V^2R \sim V^2L^{1/2}$, V and L can be measured from the broad emission line width and continuum luminosity in quasar spectrum）**
- **Quasar at z=6-7 host SMBHs with masses of about one billion solar masses. How can the SMBHs grow in a time within 1 Gyr ? This is a big challenge to theorist**

Redshift distribution of z>5 quasars



Why it is so difficult to find z>5 quasars?

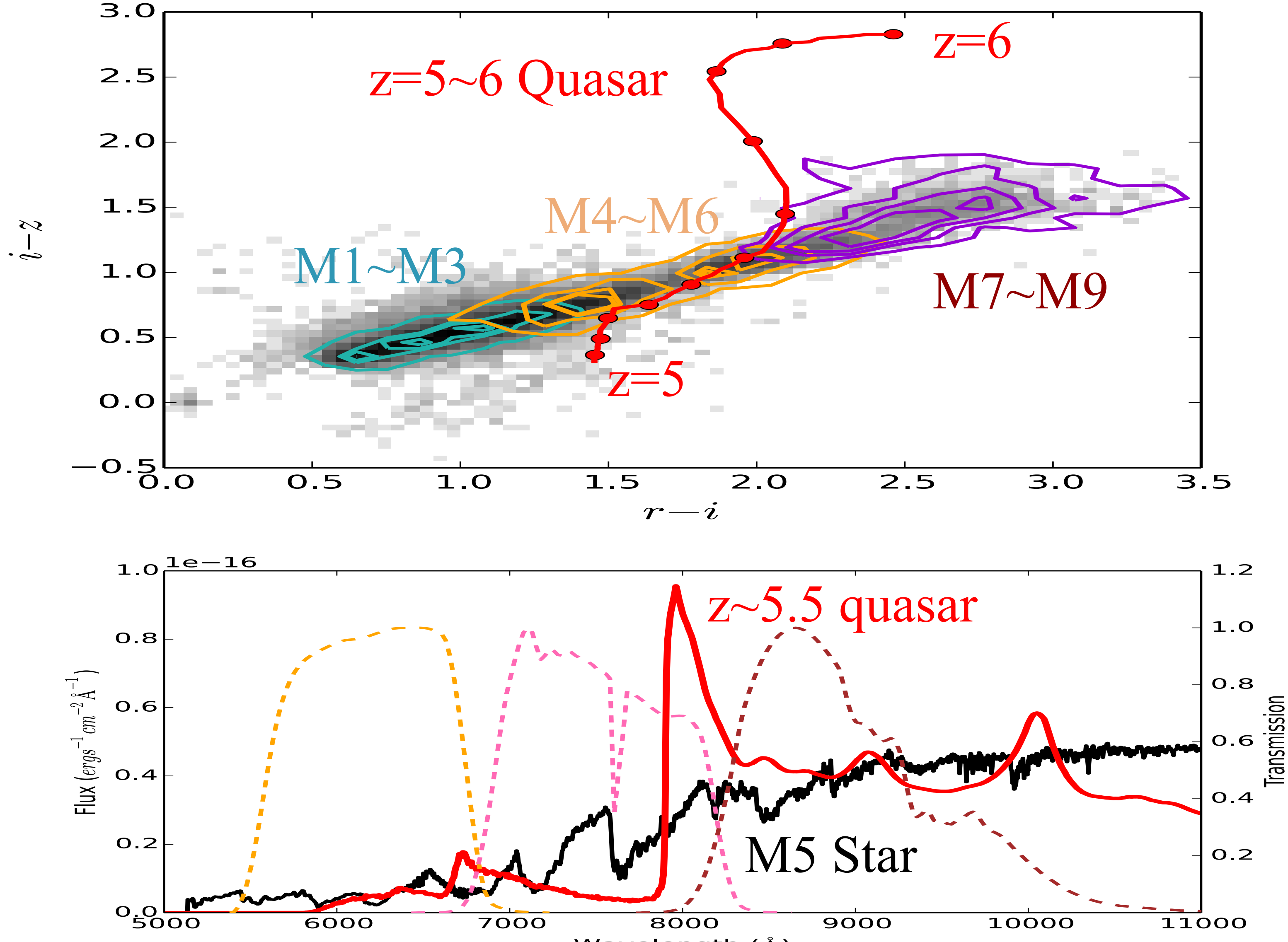




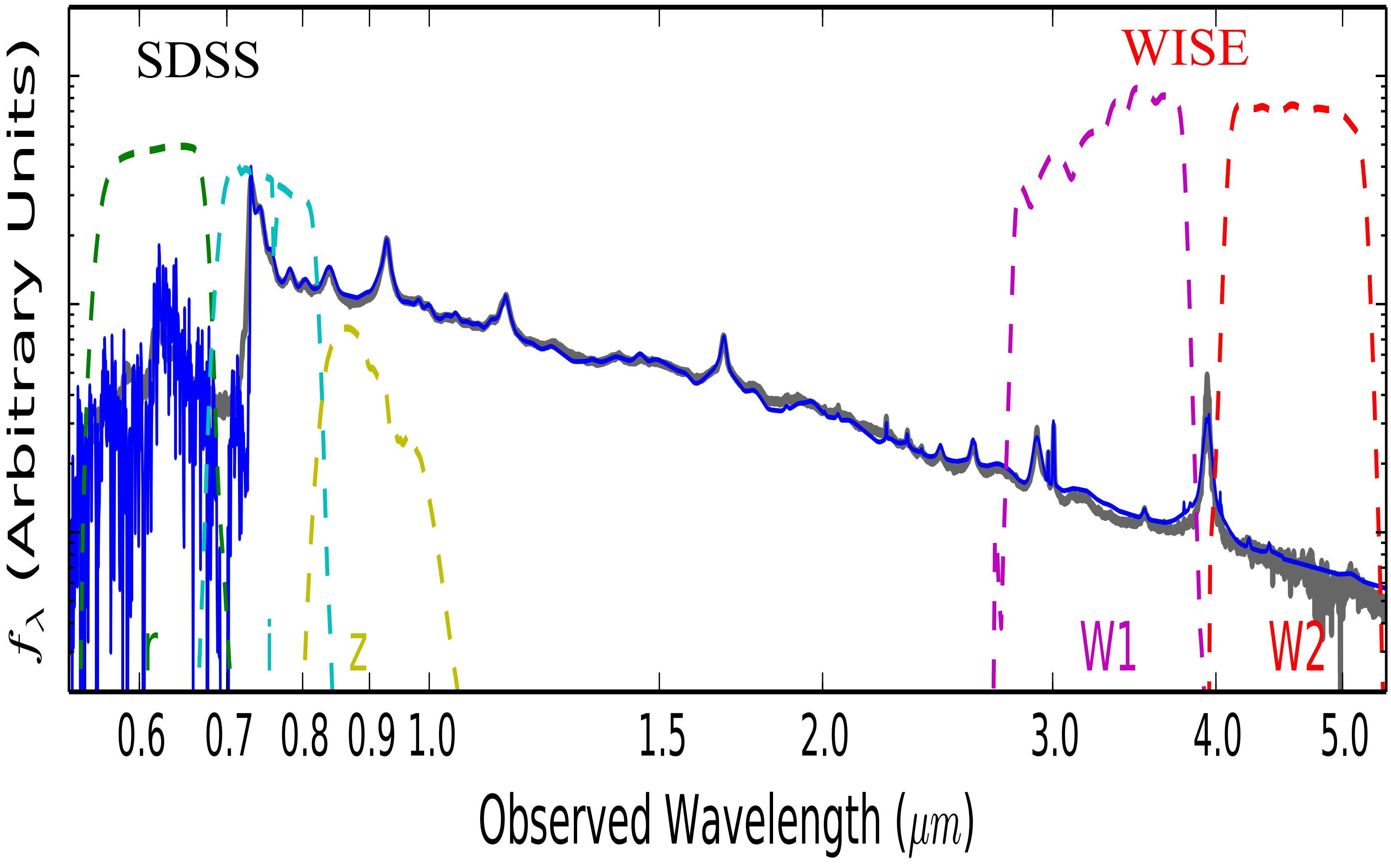
McGreer et al. 2013; Effective: 4.7< z < 5.1

Fan et al. 2001, 03, 04, 06
Jiang et al. 2008, 09;
Effective: z > 5.8

Using optical colors can hardly separate z~5.5 quasars and M stars (Yang, Fan, Wu, et al., 2016)

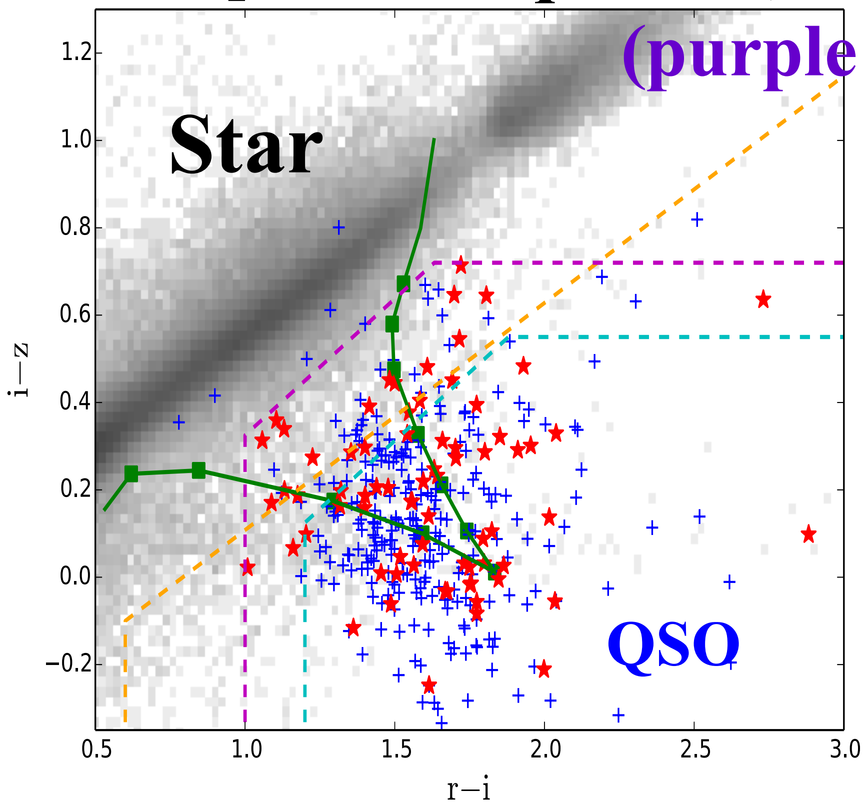


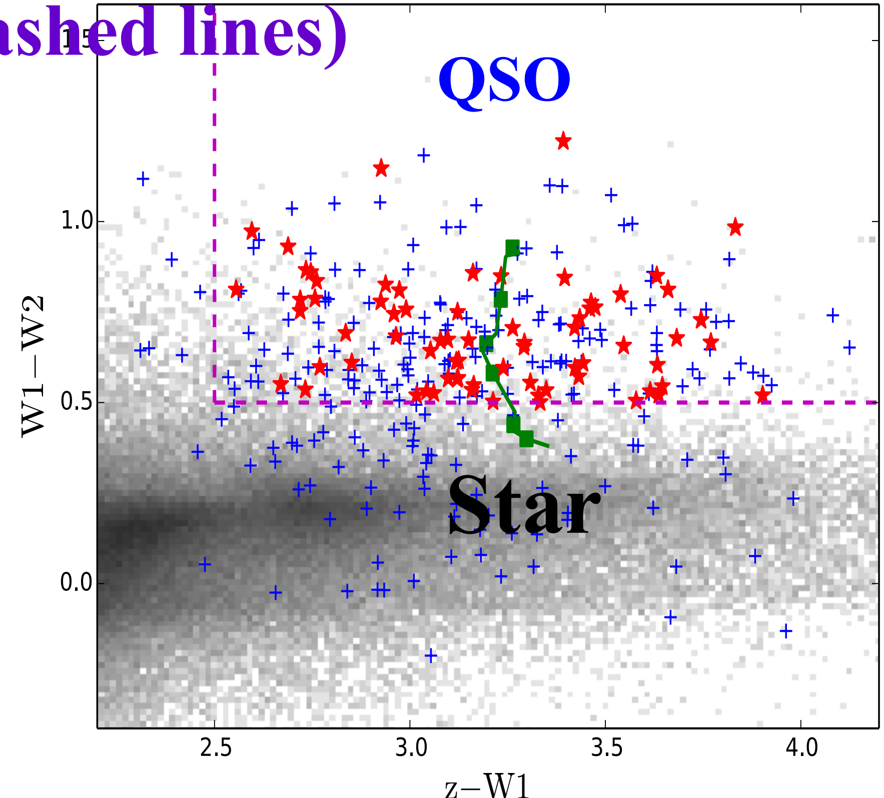
z~5 quasar spectrum

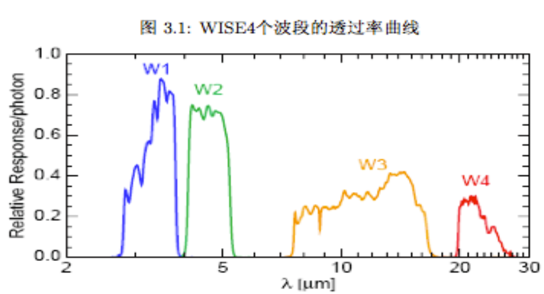


Select high-z quasar candidates with SDSS-WISE

Because WISE detection rate of z>4.5 quasars is 75%, using WISE can help find z~5 quasars; revised selection criteria (purple dashed lines)

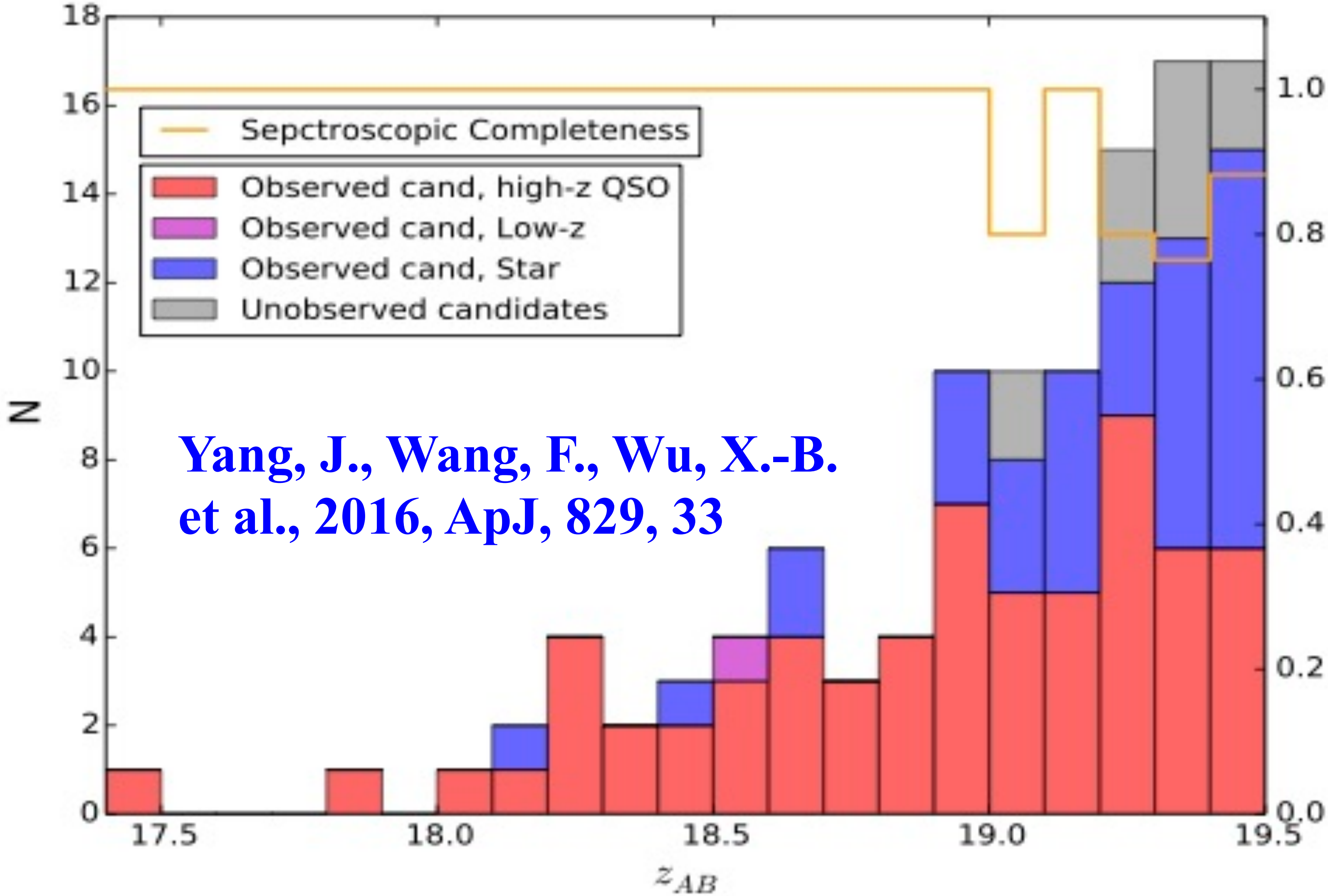






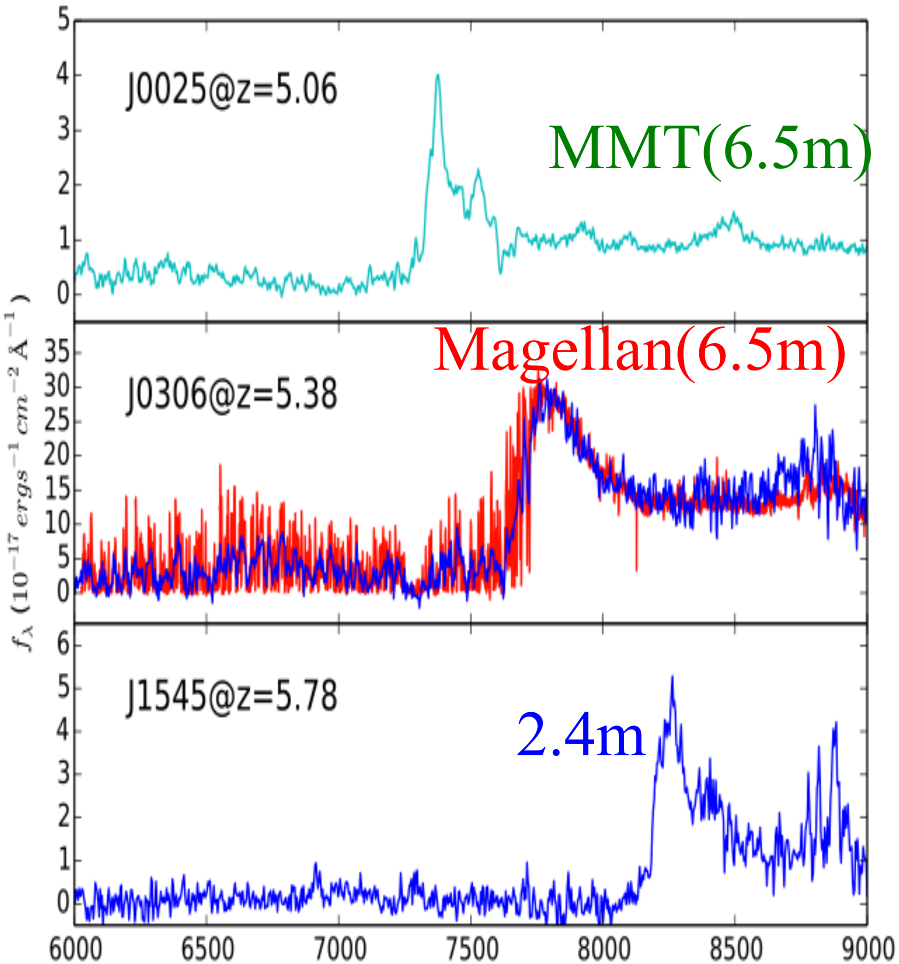
(Wang F., Wu, X.-B., Fan, X. et al. 2016, ApJ，819, 24)

Observational Results of 110 candidates (z_{AB}<19.5)

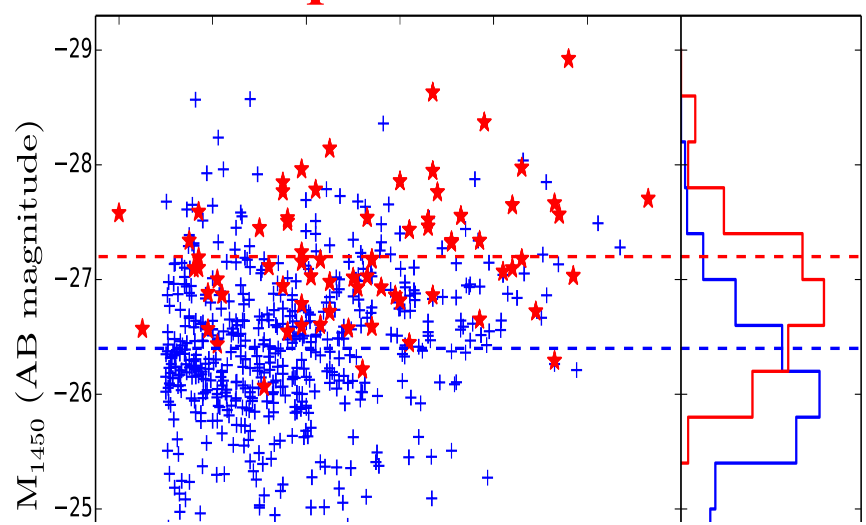


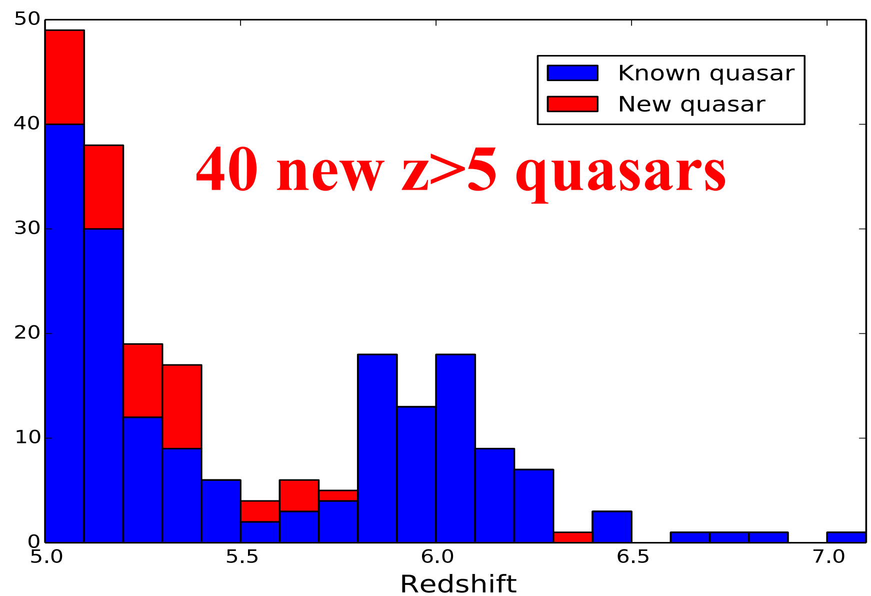
Yang, J., Wang, F., Wu, X.-B. et al., 2016, ApJ, 829, 33

SDSS-WISE High-z Quasar Candidates



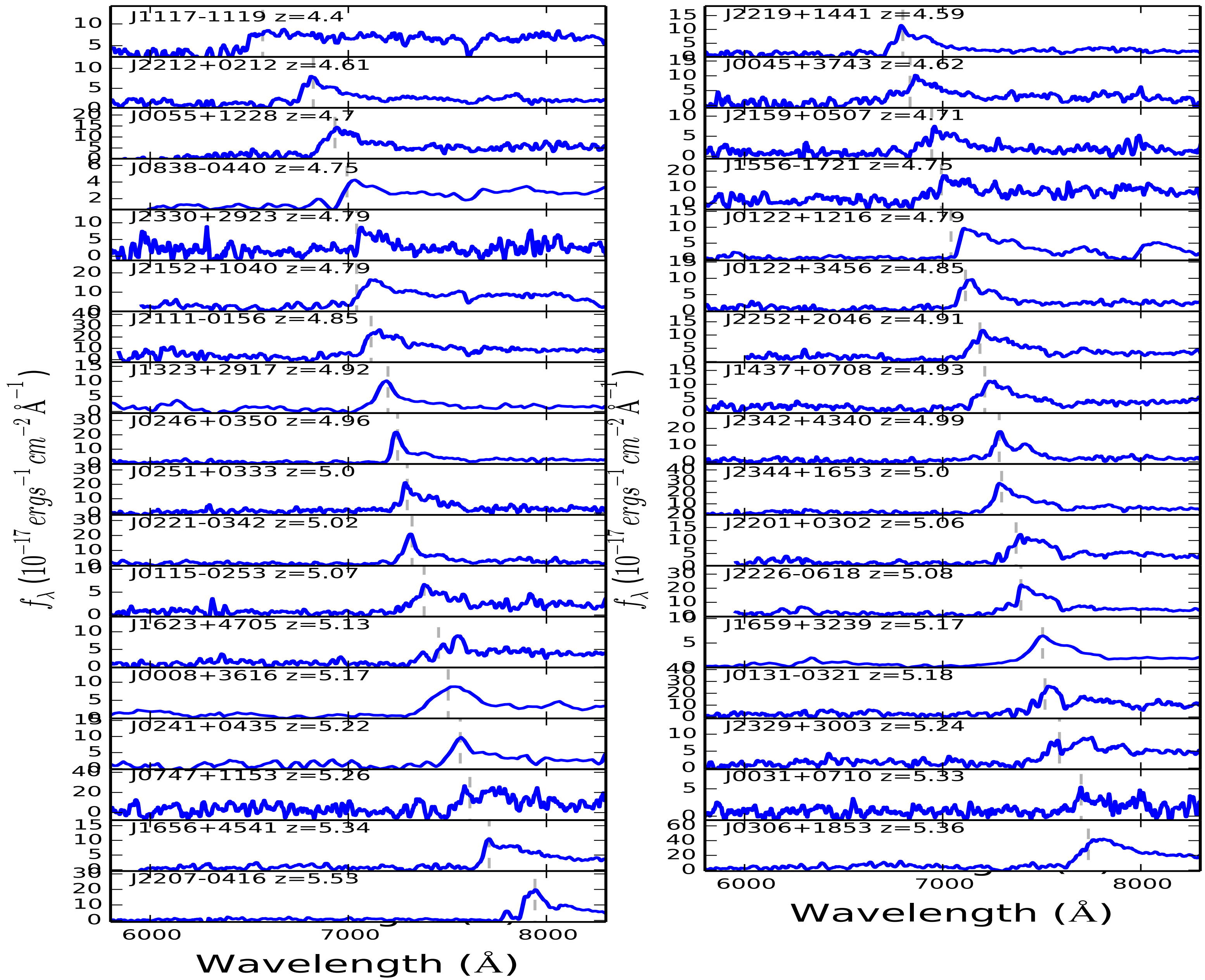
76 new quasars



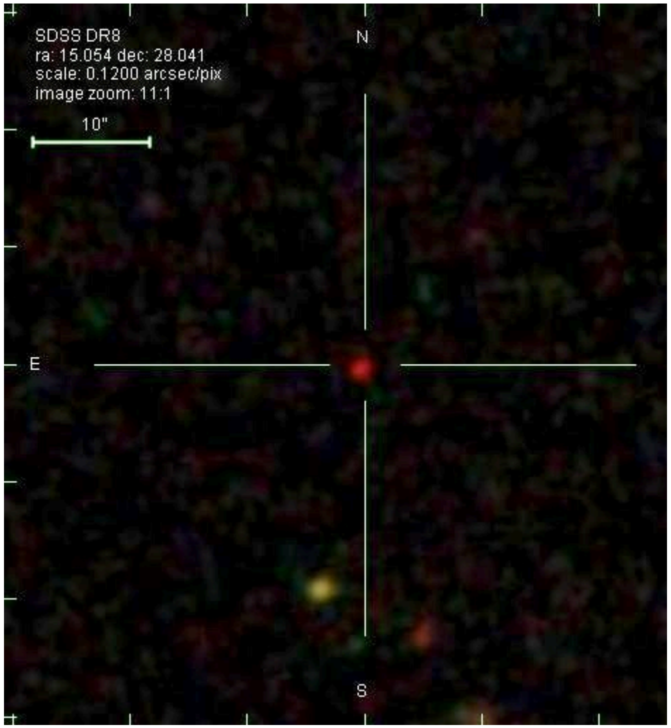


(Wang F., Wu, X.-B., Fan, X. et al. 2016, ApJ, 819, 24)

35 z~5 quasars found by 2.4m Lijiang Telescope

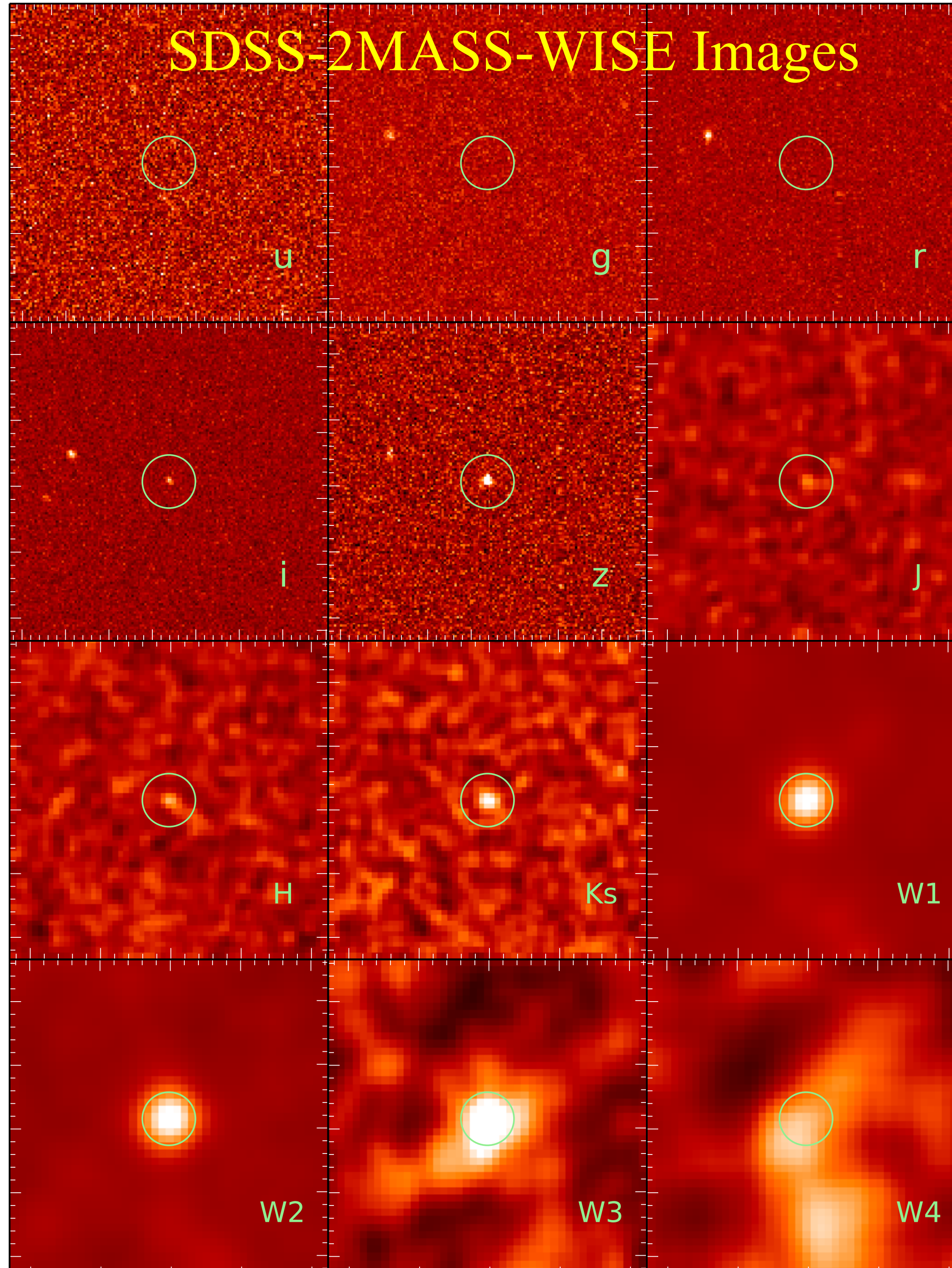


One interesting target

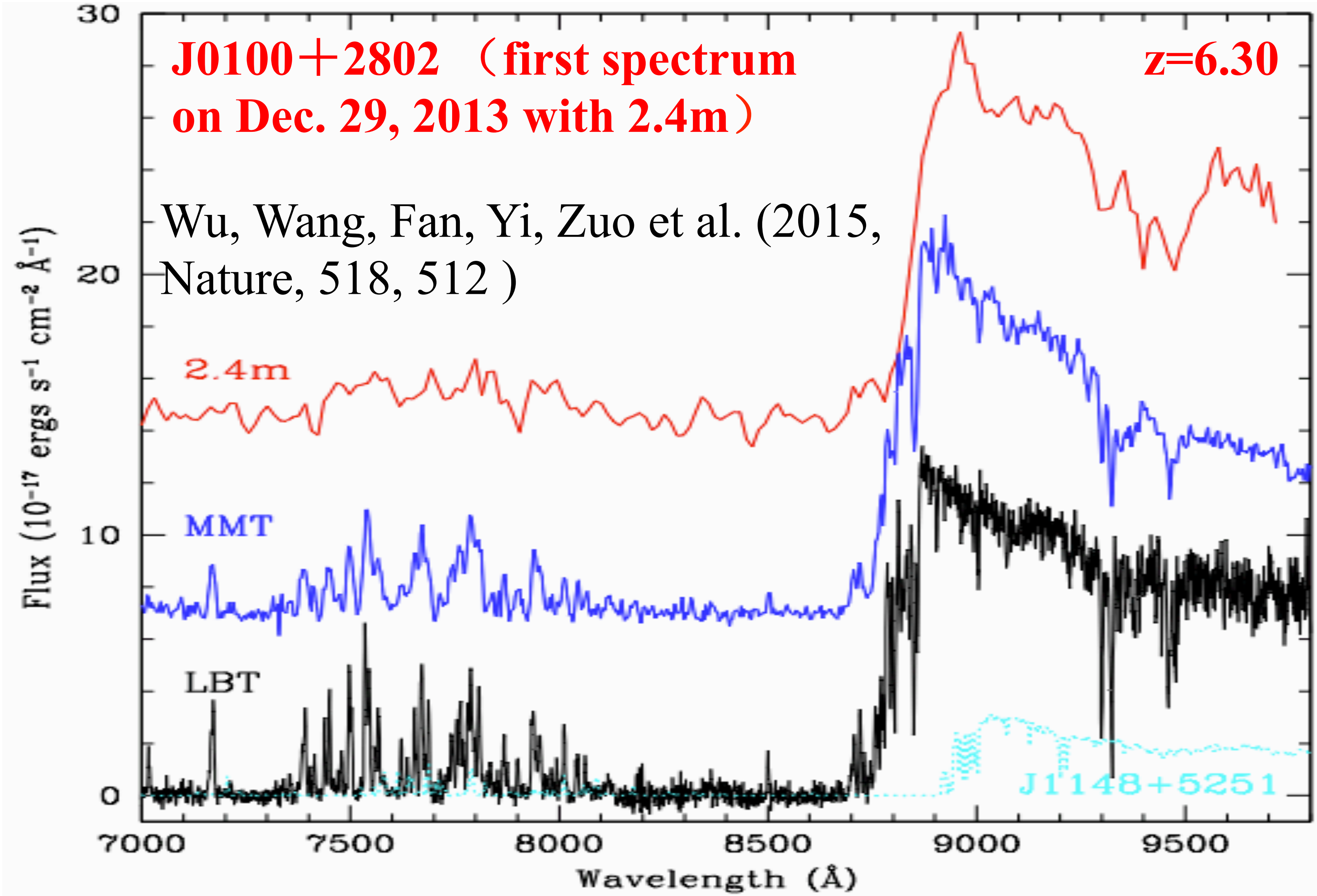


i=20.84 z=18.33
J=17.00 H=15.98
Ks=15.20
W1=14.45 W2=13.63
W3=11.71 W4=8.98

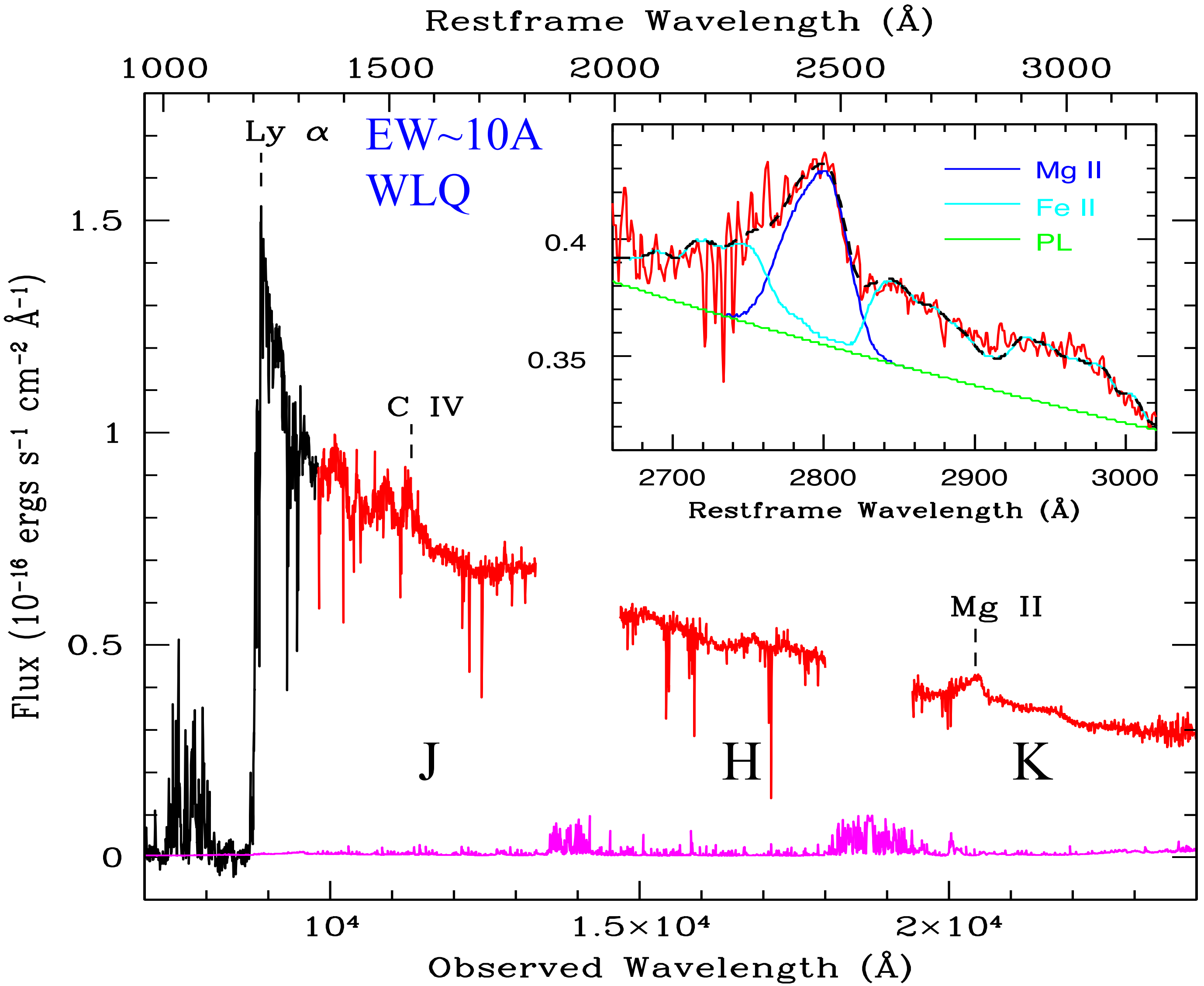
Photo-z ~ 6.3!



The highest redshift quasar we discovered with 2.4m telescope



Near-IR Spectroscopy (Jan.-Oct., 2014)

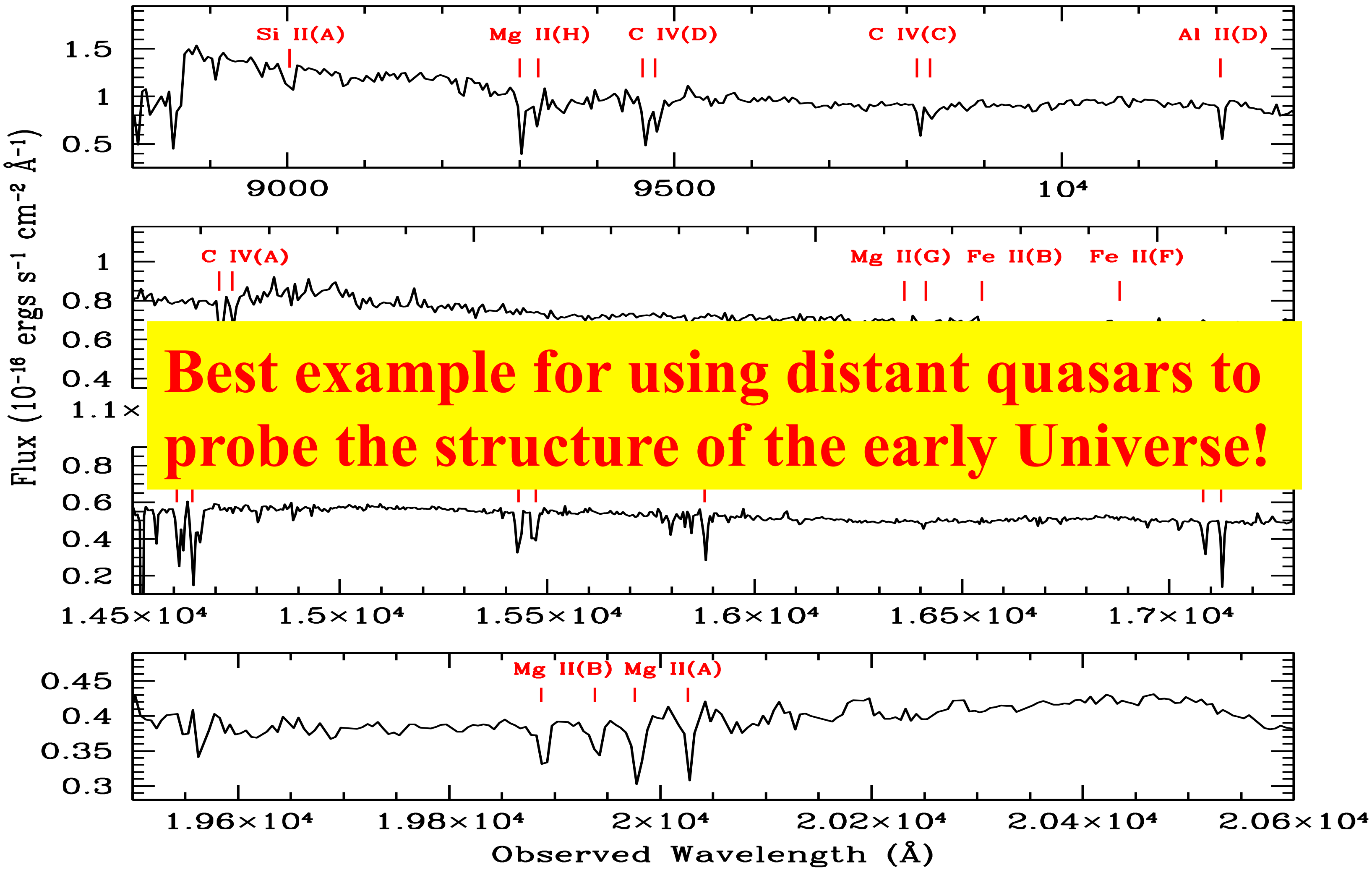


LBT(8.4-m; Jan.)
Gemini (8.1-m;Aug.)
Magellan(6.5m; Oct.; R~6000, S/N>30)

MgII FWHM ~ 5130 km/s
L_{3000}~3.15E47 erg/s

Following MD04 & VP06
-->BH mass ~ **12 billion solar masses**

Many Absorption Systems at z=2.2 to 6.1 !

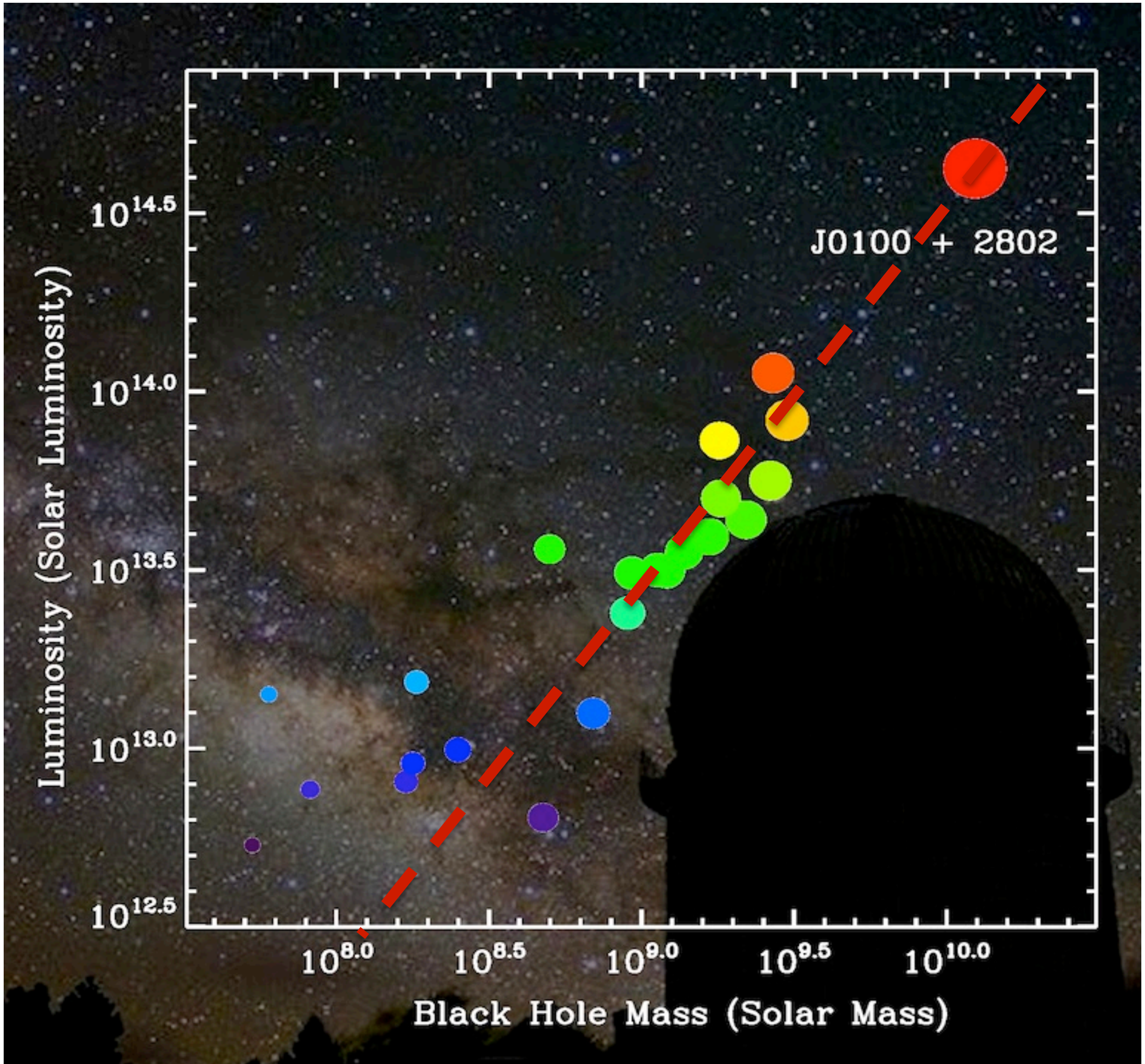


Best example for using distant quasars to probe the structure of the early Universe!

SDSS J0100+2802, a quasar with largest BH mass and highest luminosity at z>5.7

$L_{bol} = 5.15 \times L_{3000} = 1.62 \times 10^{48}$ erg/s

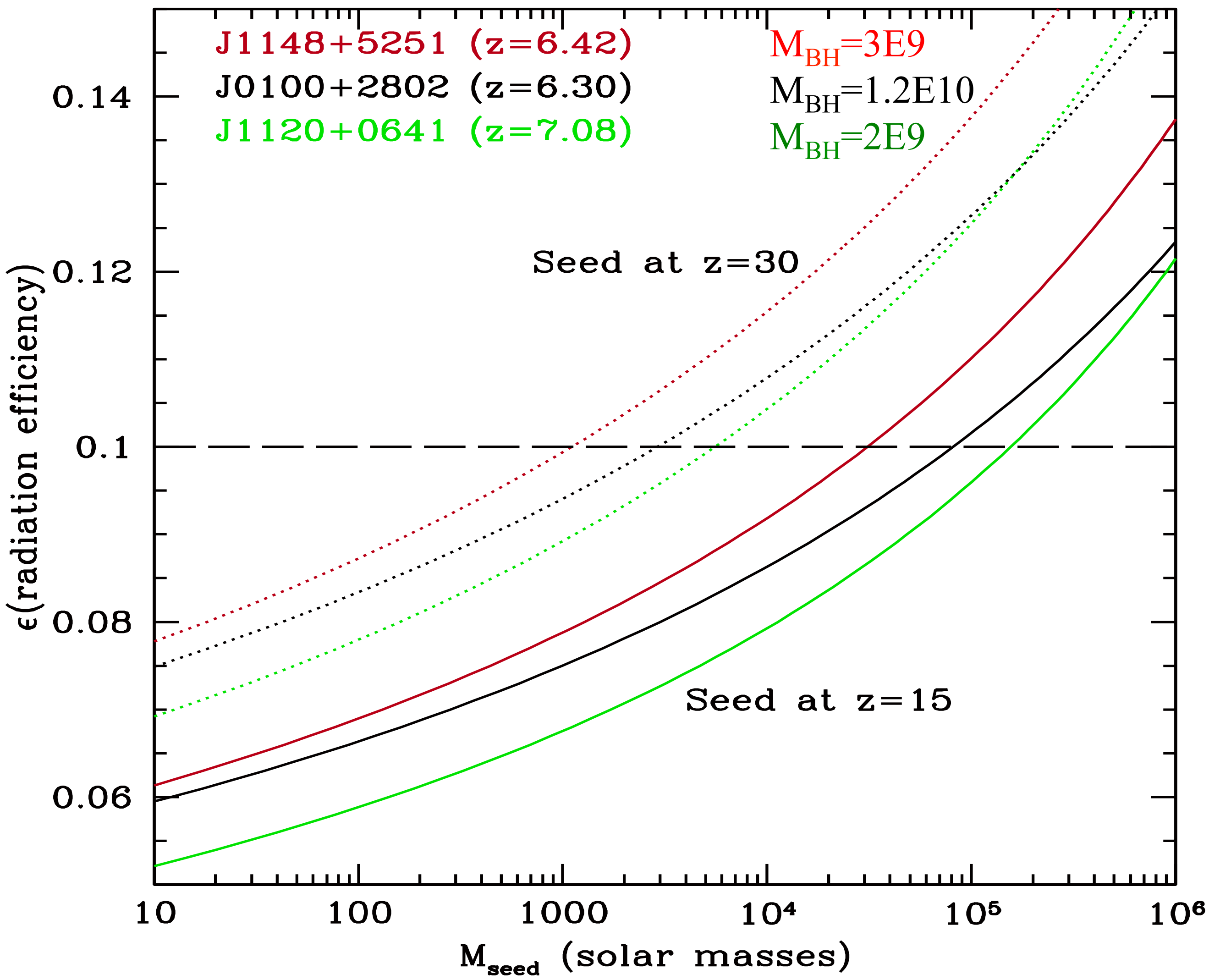
$M_{1450} = -29.26$



--- Eddington Luminosity

Credits: Zhaoyu Li (SHAO); background photo (2.4m dome) provided by YNAO

Constraints on seed BH & growth



Assumptions: Eddington accretion; Duty cycle=1

Seed BH mass >10^5 solar masses! (direct collapse)?

Or super-Eddington accretion?

X-ray fellow up observation of J0100

- Chandra 14.8ks on Oct. 16, 2015

(Ai, Du, Fan, et al., 2016, ApJ, 823, L37)

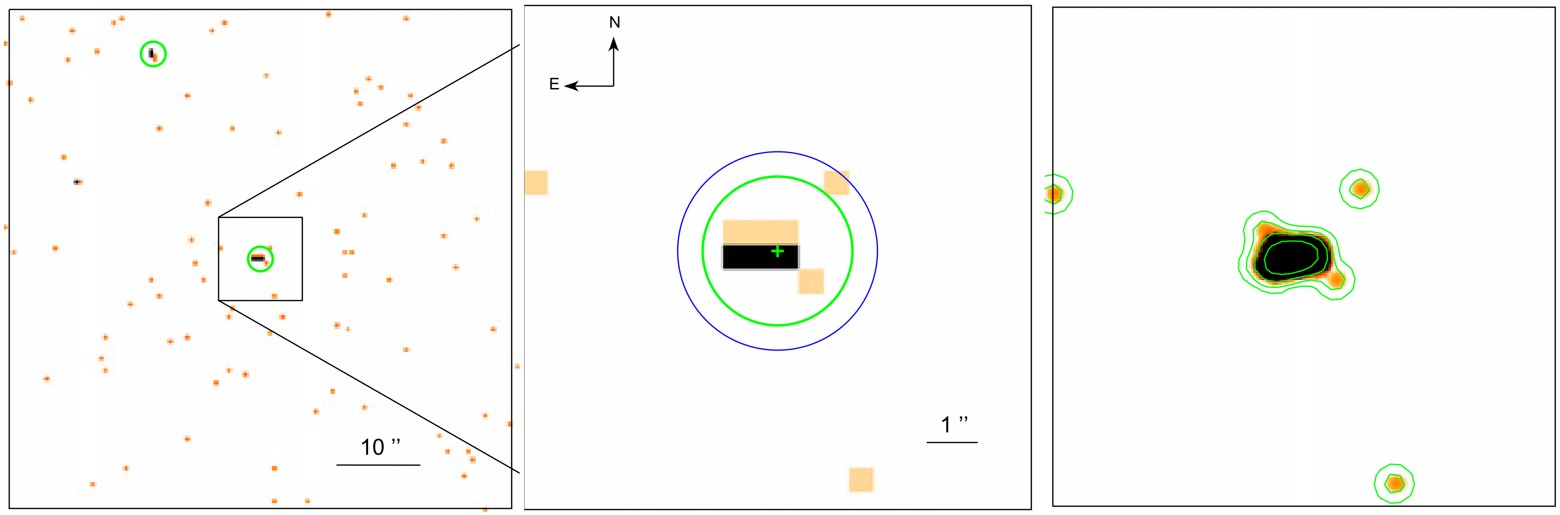


Figure 1. Detection of X-ray emission of J0100+2802. Left: $1' \times 1'$ *Chandra* image centered on J0100+2802 in 0.5–7 keV. The circles show the two sources detected by CIAO task WAVDETECT; Middle: central $10'' \times 10''$ of the image. The plus sign shows the optical position given by SDSS. 14 counts are detected in the 3 pixel radius aperture (green), and one more count in the 4 pixel radius aperture (blue). Right: rebinned image in the middle panel to 0.1 ACIS pixel and smoothed with a $0\farcs492$ Gaussion filter. The size of the ACIS CCD pixel is $\sim 0\farcs492$.

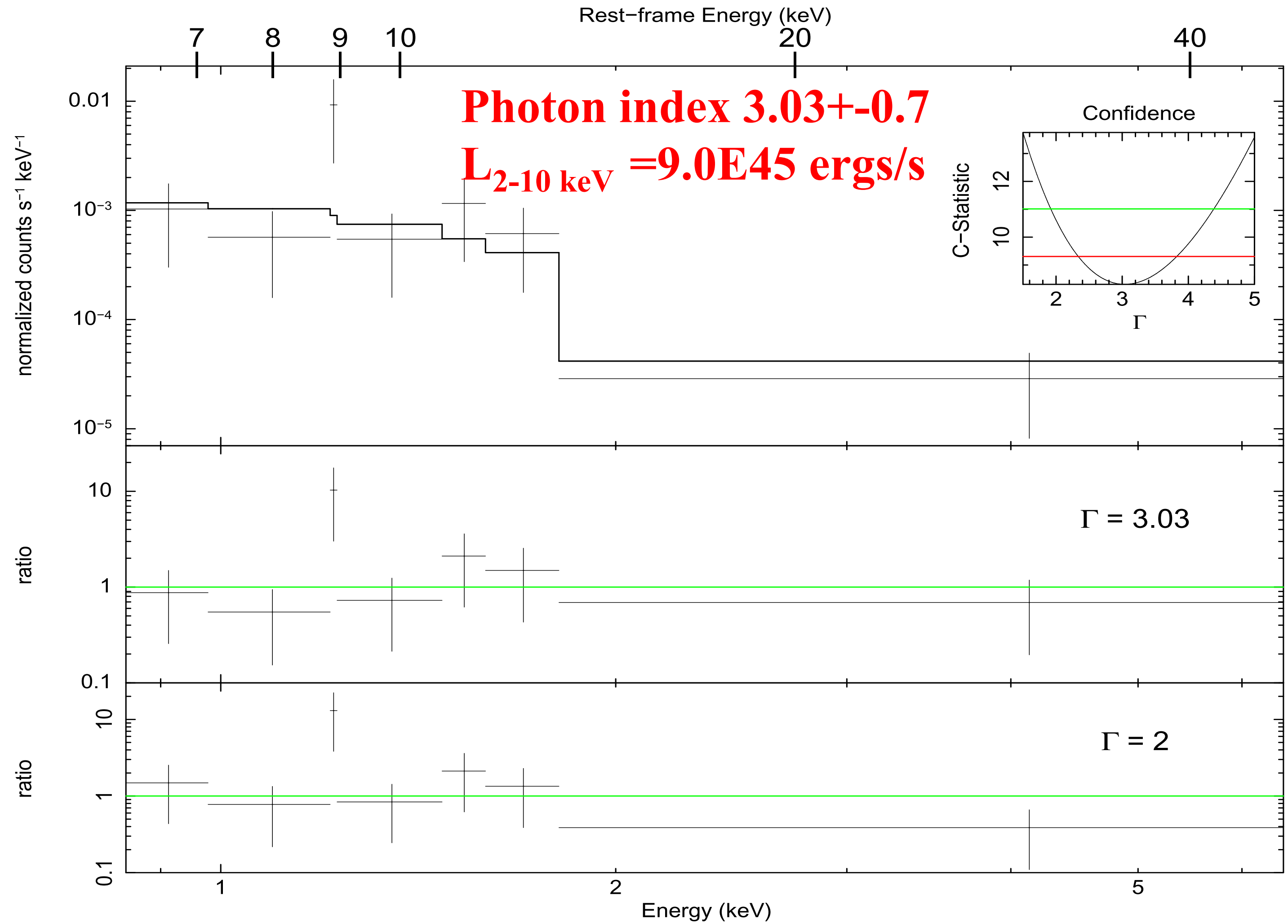


Figure 2. Upper panel: *Chandra* spectrum of J0100+2802 and the best-fit power-law model with $\Gamma = 3.03$ ($N_{\rm H}$ fixed at Galactic $N_{\rm H}^{\rm Gal}$). Inset, confidence curve for the fitted photon index. Middle: data to model ratio of the best-fit model. Significant residual at $\sim$1.2 keV (8.8 keV at rest-frame) is present in the fitting with different photon indices. Lower: data to model ratio, where a power law with fixed $\Gamma = 2.0$ is assumed.

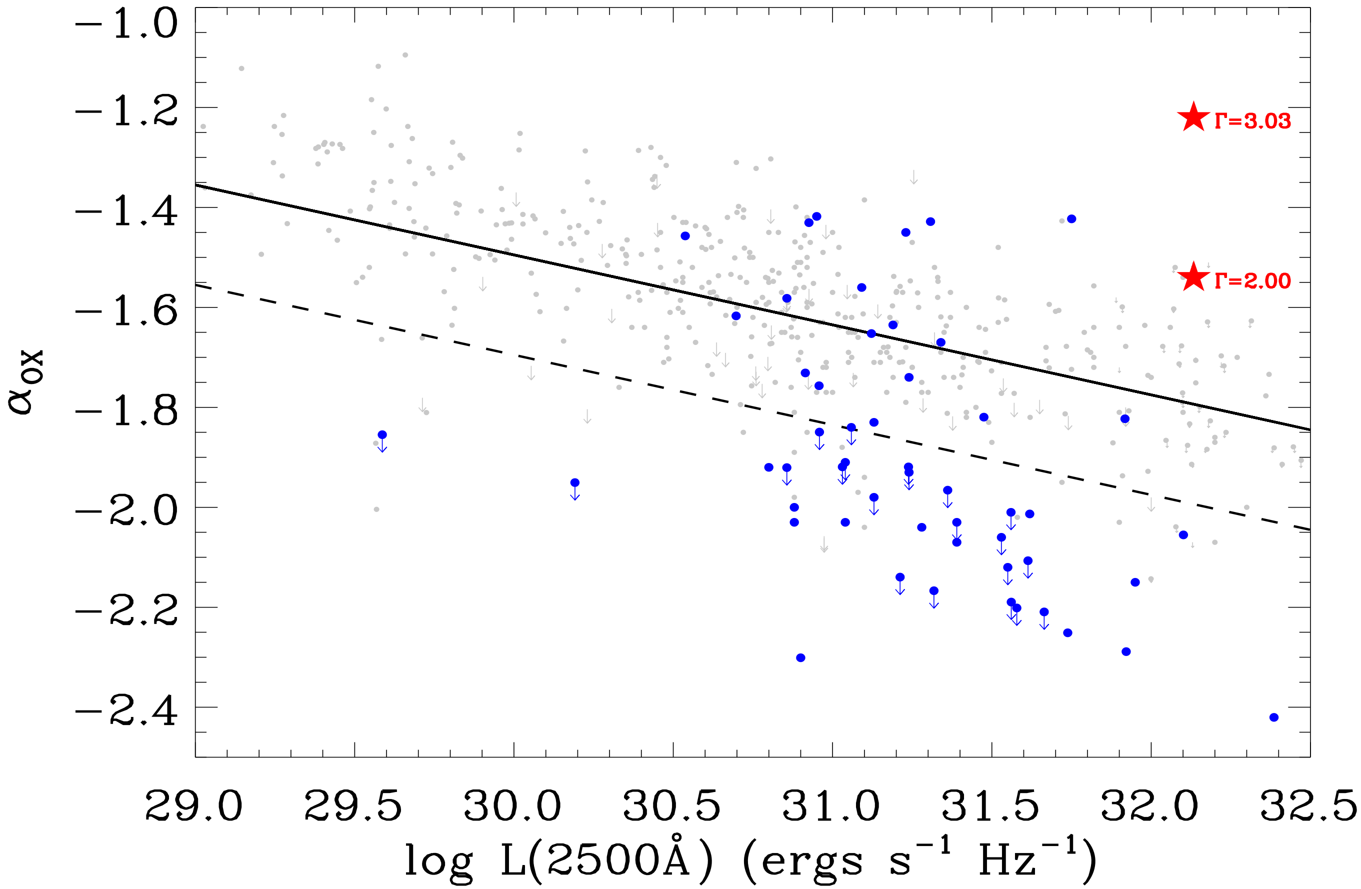


Figure 4. Location of J0100+2802 (red stars) in the X-ray-to-optical power-law slope parameter $\alpha_{\rm ox}$ vs. 2500 Å monochromatic luminosity. The gray dots are the quasars from the samples of Just et al. (2007), Steffen et al. (2006), and Gibson et al. (2008). The blue dots are the weak-line quasars and PHL 1811 analogs from Luo et al. (2015). The solid line represents the Just et al. (2007) $\alpha_{\rm ox}$–$L_{2500\text{Å}}$ relation, and the dashed line marks the devision between X-ray weak and X-ray normal quasars adopted in Luo et al. (2015). For J0100+2802 the two red stars represent the values of $\alpha_{\rm ox}$ derived with X-ray photon index of 3.03 and 2.0, respectively.

Summary

- **Discovering more high-z quasars is crucial to study the evolution of quasars/galaxies and BH growth in the early Universe**
- **We proposed new selection criteria in finding high-z quasars, and are carrying out a large program in identifying quasars at z>5**
- **An ultra-luminous z=6.3 quasar with the most massive BH (12 billion solar masses) was discovered, which challenges the theories of black hole growth and galaxy formation in the epoch of cosmic reionization**
- **A lot of follow-up observations are ongoing and will reveal more secrets on these distant black holes**

Thanks !