

JWST Simulation from Im & Stockman (1998)

Super-massive Black Holes of Quasars at World's End

[Rest-frame Optical Spectra of Quasars at $4.5 < z < 6.5$]



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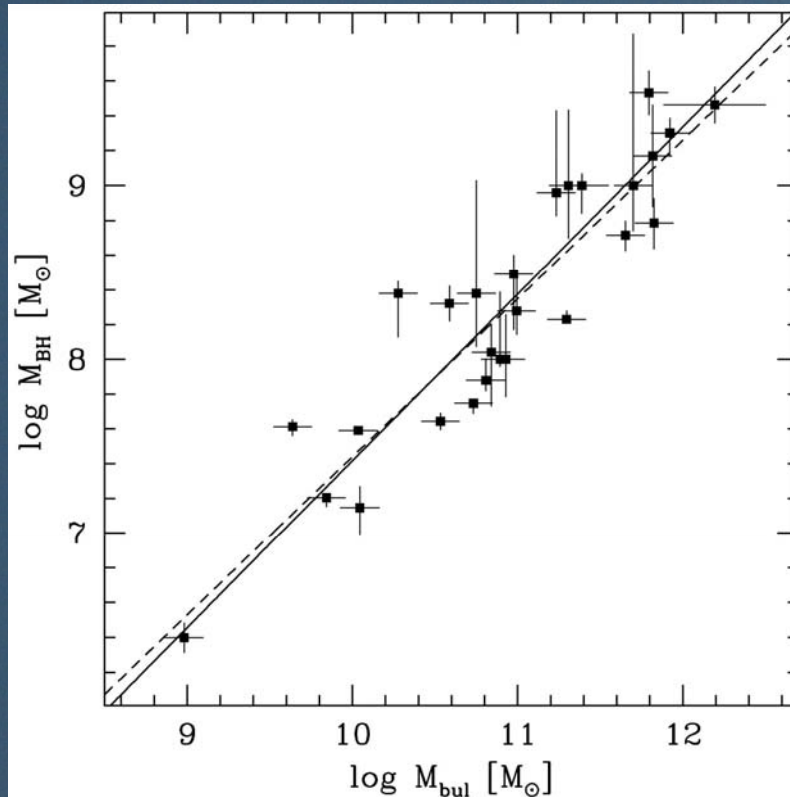
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T. Wada, T. Nakagawa (ISAS/JAXA), Xiaohui Fan (U. Arizona)

Supermassive Black Holes in Nearby Galaxies

- Supermassive black holes (SMBHs) at the centers of massive galaxies (bulges)
- SMBH mass tightly correlates with, mass, velocity dispersion, and K-band luminosity of the host galaxies (e.g., Gebhardt et al. 2000; Ferrarese & Merritt 2000; Marconi & Hunt 2003)



But why?

Which was born first?

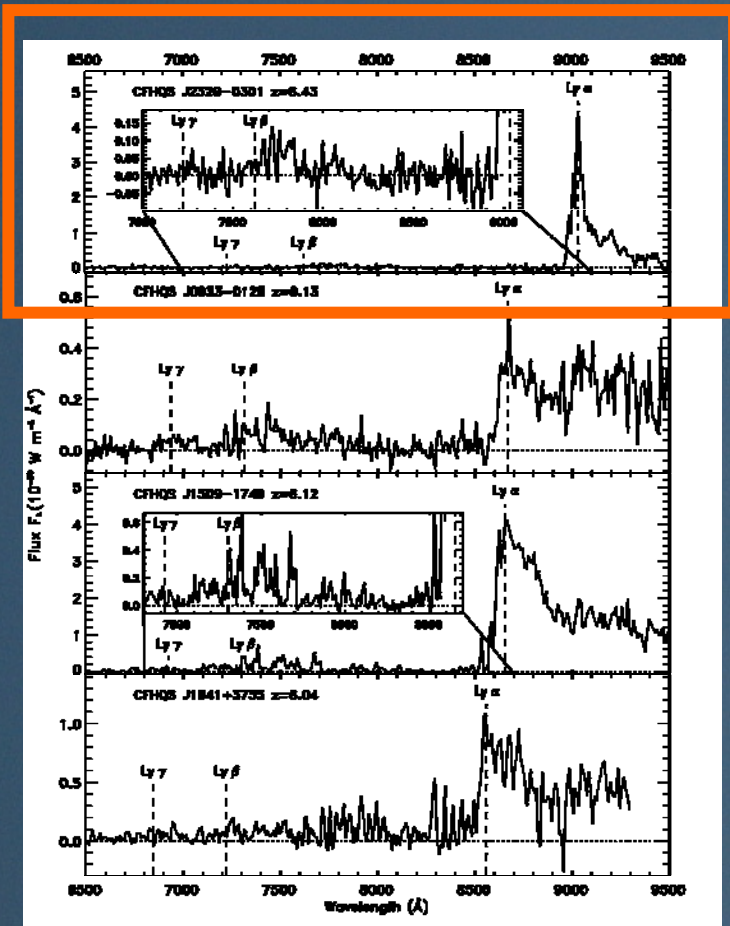
When did the massive SMBHs appear?

: Important questions for the galaxy formation and evolution.

Marconi & Hunt (2003)

Supermassive Black Holes in Early Universe

- Quasars are powered by matters accreted to SMBHs.
- Quasars have been discovered out to $z \sim 6.43$ (Fan et al; Willott et al. 2007).



Luminous quasars existed out to $z \sim 6.4$.

But, how massive were they, and can you grow such SMBHs in short time scale?

Understanding the nature of SMBHs in QSOs in the early universe is very important!

QSO at $z=6.43$ (Willott et al. 2007)

Measuring (or estimating) SMBH mass

- Direct measurement from stellar motion
- Reverberation mapping: BLR size correlation with $L(5100) \rightarrow L(5100)$ and H. width can be used for M_{BH} measurement (Kaspi et al. 2000)!
- Single epoch measurements using optical or UV spectra (e.g., Vestergaard et al. 2005; Greene & Ho 2005)

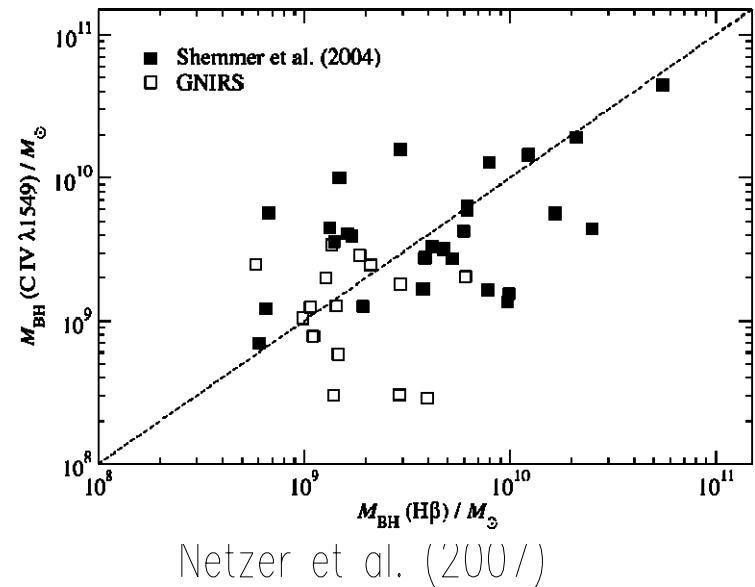
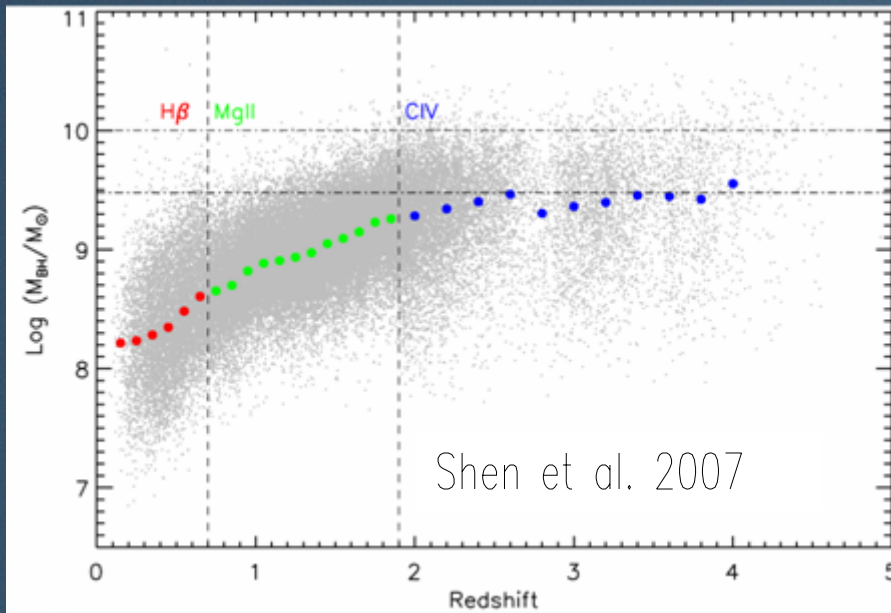
$$M_{\text{BH}}(H\beta) = 10^{6.91} \left[\left(\frac{\text{FWHM}(H\beta)}{1000 \text{ km s}^{-1}} \right)^2 \left(\frac{\lambda L_{\lambda}(5100 \text{ \AA})}{10^{44} \text{ erg s}^{-1}} \right)^{0.57} \right].$$

$$M_{\text{BH}}(\text{CIV}) = 10^{6.66} \left[\left(\frac{\text{FWHM}(\text{CIV})}{1000 \text{ km s}^{-1}} \right)^2 \left(\frac{\lambda L_{\lambda}(1350 \text{ \AA})}{10^{44} \text{ erg s}^{-1}} \right)^{0.51} \right].$$

$$[M = f \cdot R \cdot v^2 / G ; \text{Vestergaard (2008)}]$$

Masses of SMBHs at high redshift

- M_{BH} measurements for high redshift QSOs rely on the UV-lines (CIV: 0.1549 micron, MgII: 0.2798 micron).

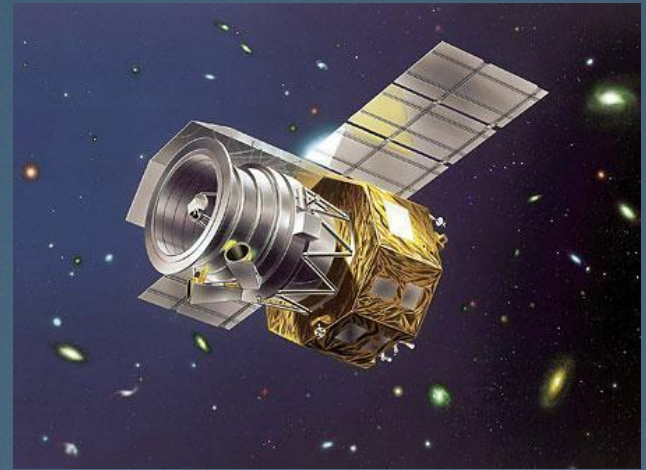


✓ But the reliability of CIV measurement has been in question (or even MgII – outflow contribution, asymmetric profile, etc).

✓ Need for a well-calibrated, independent measure of M_{BH} using optical spectra such as H. or H. (e.g., Greene & Ho 2005).

AKARI Spectroscopy

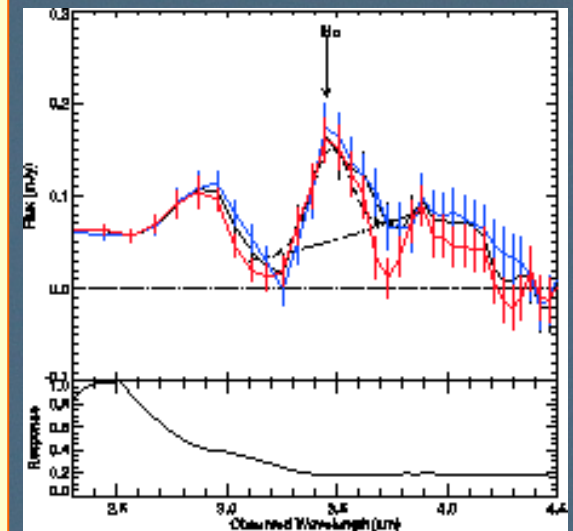
- ✓ Japanese 68cm IR telescope optimized for FIR all-sky survey.
- ✓ Participation from ESA and Korea (mainly Seoul National Univ. group).
- ✓ Launched in Feb., 2006.
- ✓ Cold mission ended in late August, 2007.



NIR Grism and Prism Spectroscopy

- NP (Prism): Slit-less spectroscopy at 2 – 5 micron. $R=19$ at 3.5 micron, FWHM=15000 km/sec.
- NG (Grism): Slit-less or with slit-aperture at 2.5 – 5 micron. $R=120$ at 3.6 micron, FWHM=2500 km/sec.

➔ The only facility in the world capable of studying Balmer lines at $4 < z < 7$!



Detection of H. (Prism data) of QSO at $z=4.3$ (Oyabu et al. 2007)

AKARI Open Time Program HZQSO (PI: Im)

Program Summary

Observation of rest-frame optical lines of QSOs at $z > 4.5$ (mainly H.) using AKARI NG & NP.

Mass of super-massive black holes in the early universe.

Test the empirical relations of line luminosity/continuum.

Study the metallicity evolution (Fe abundance, OIII lines, etc).

Targets

14 Known QSOs at $z > 4.5$.

← Good visibility (stringent orbital constraint of AKARI).

← 3.6 micron flux $> \sim 100 \mu\text{Jy}$ (for detection of H-alpha).

← Not in the crowded region to avoid the confusion of spectra.

Observations & Targets

Observations were carried out in 2006 – 2007.

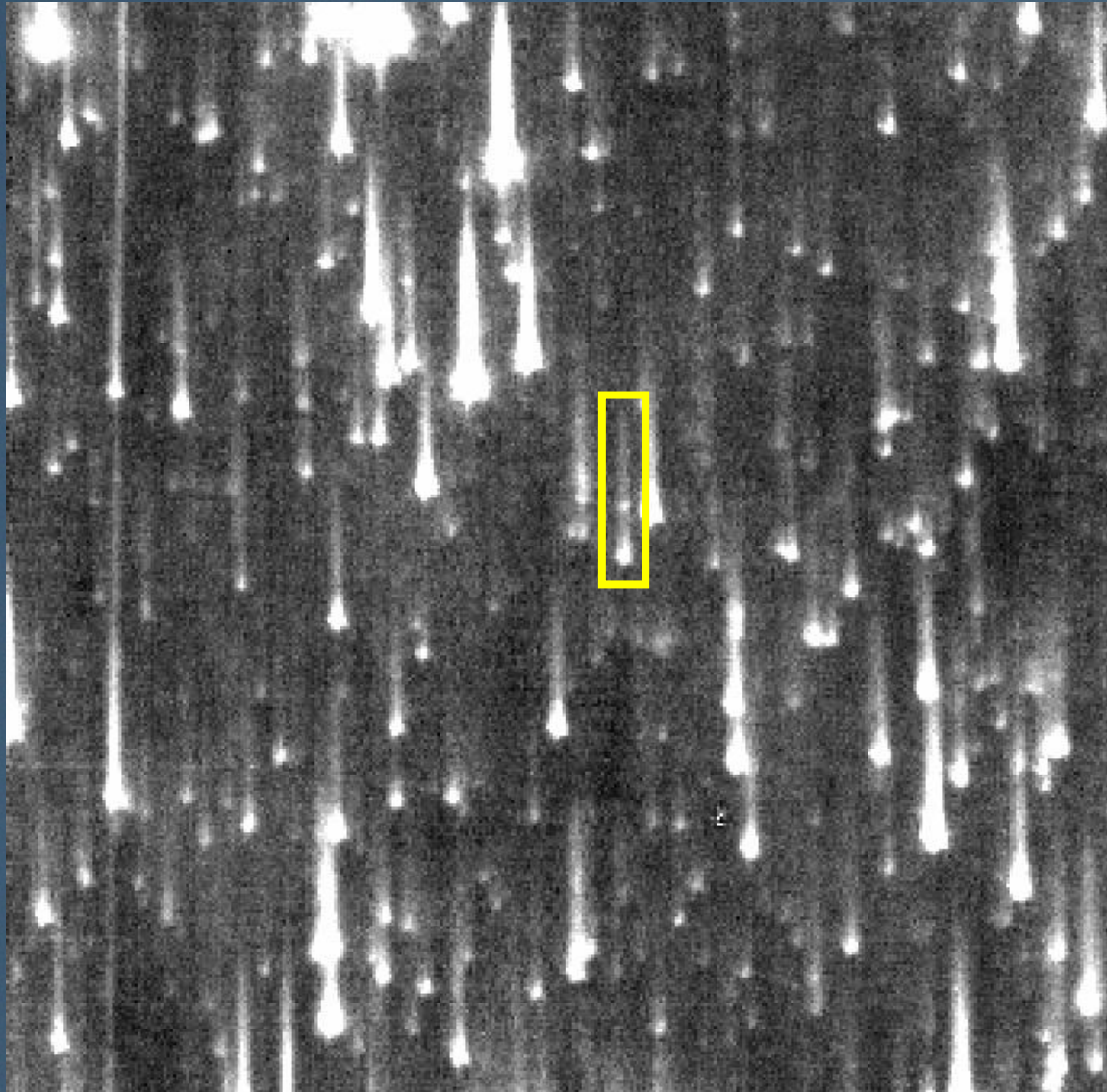
3 QSOs have both NG/NP data.

8 QSOs out of 14 show H. detection.

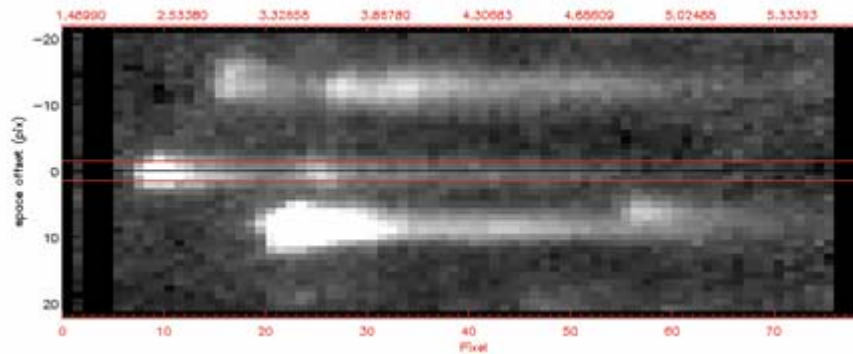
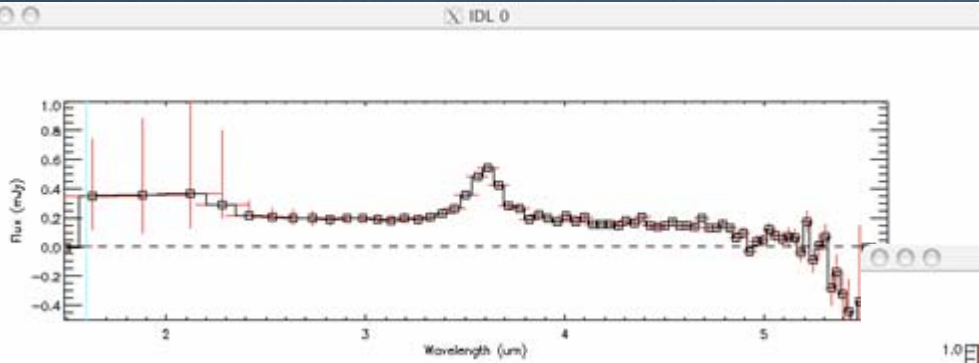
1 pointing ~ 10 min.

Name	z	NG	NP	H.?
BR 0006-6208	4.51	3	2	Yes
BR 1202-0727	4.694	1	0	Yes
SDSS J 165354+405402	4.97	2	0	Yes
SDSS J 161705+443522	5.50	2	0	No
SDSS J 162100+515548	5.59(5.71)	4	0	Yes
SDSS J 172100+601721	5.799	4	0	No
SDSS J 000239+255034	5.80	3	2	Yes
SDSS J 000552-006555	5.85	0	1	No
SDSS J 113717+354956	6.01	0	1	No
SDSS J 160253+422824	6.07	0	1	Yes
FLX J 1427386+331241	6.10	0	2	No
SDSS J 125051+313021	6.13	0	1	Yes?
SDSS J 162331+311200	6.22	0	3	Yes?
SDSS J 114816+525150	6.42	7	2	No?

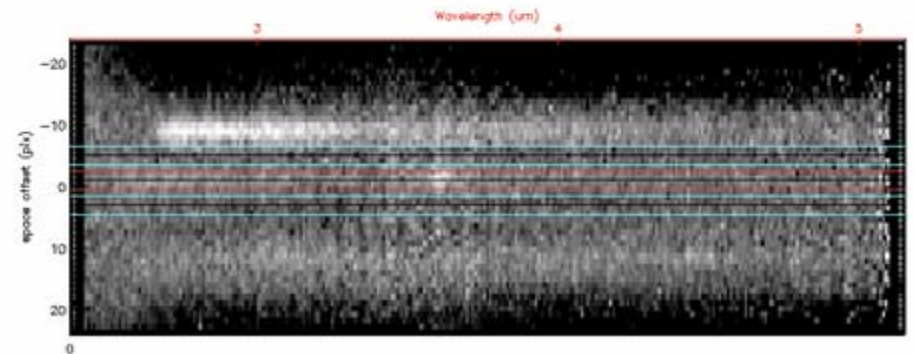
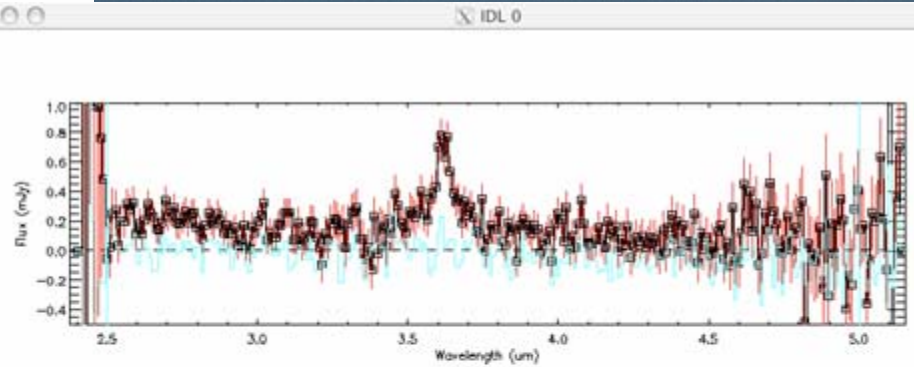
NIR Prism Observation



BR 0006-6224 ($z=4.51$)



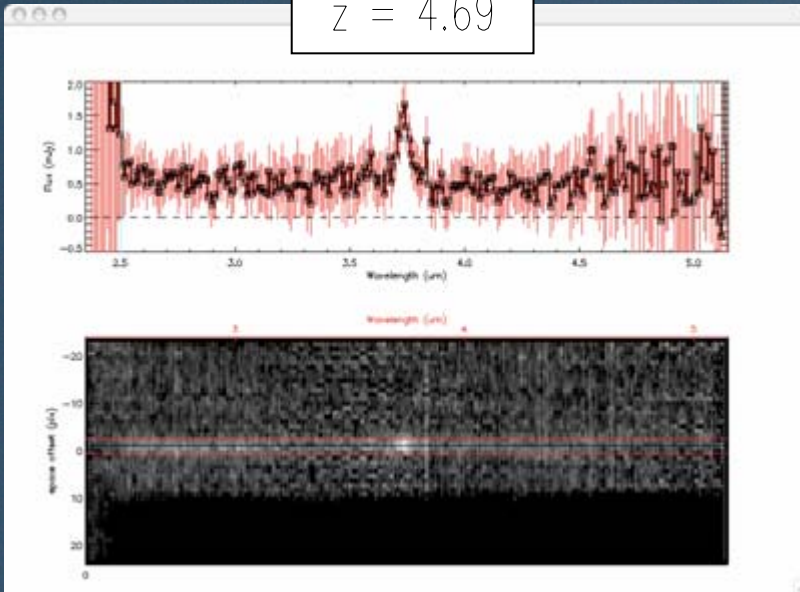
NP



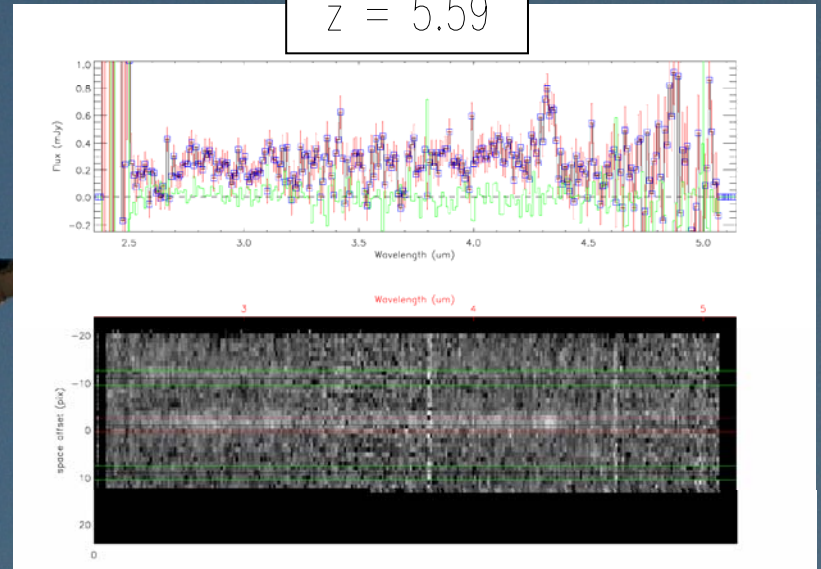
NG

H. Detections (NG)

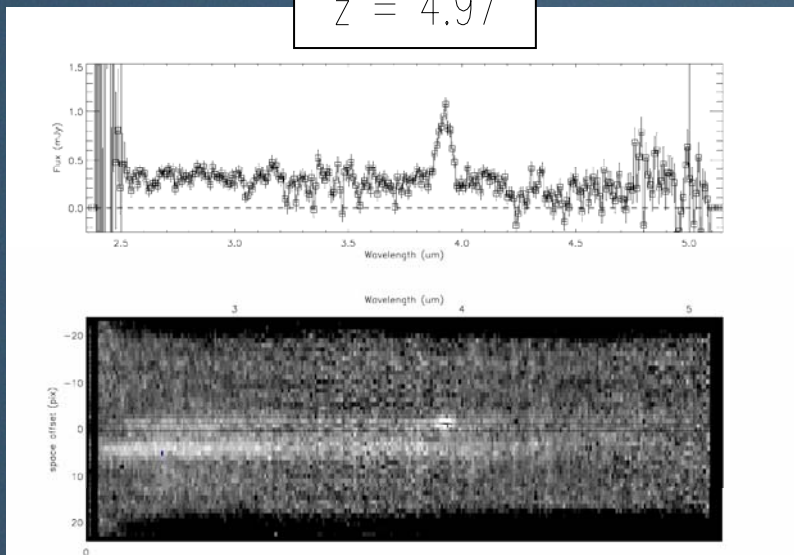
$z = 4.69$



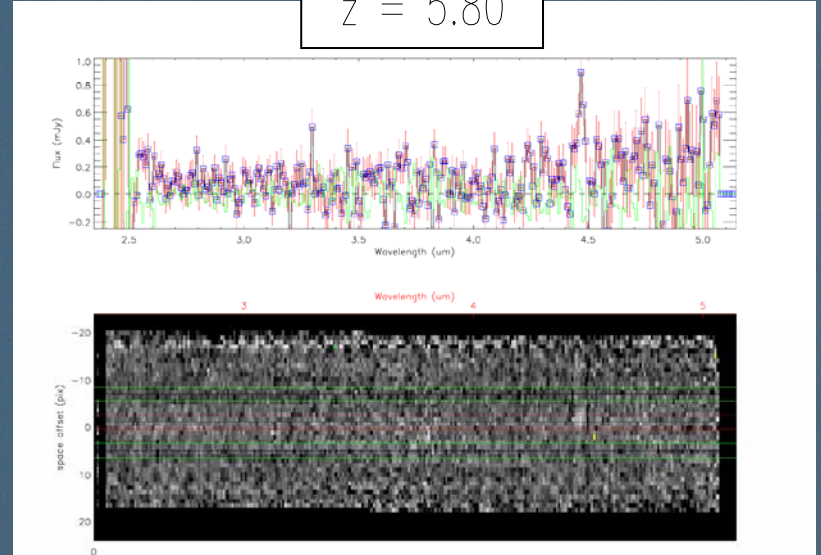
$z = 5.59$



$z = 4.97$

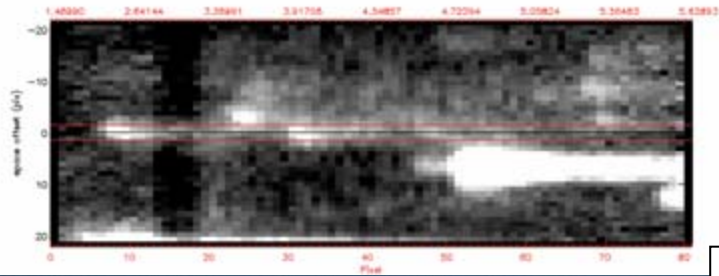
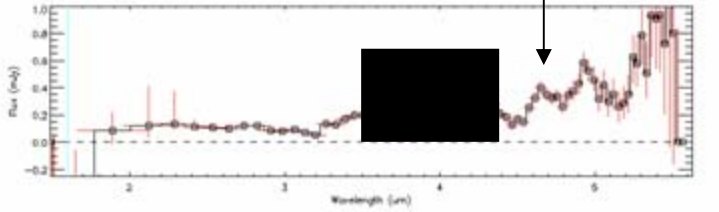


$z = 5.80$

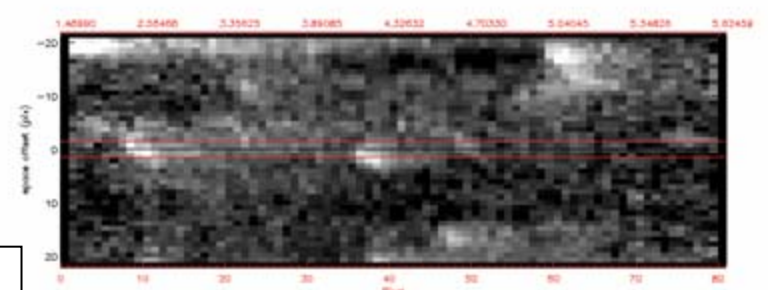
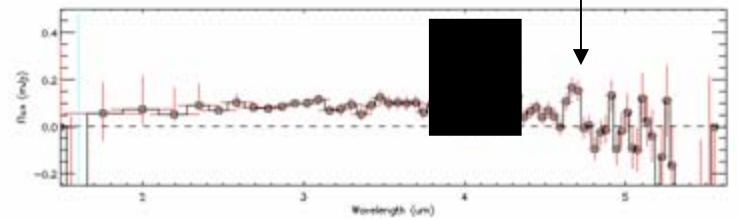


H. Detections (NP)

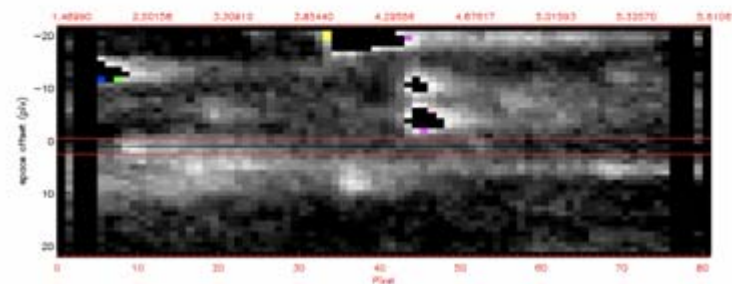
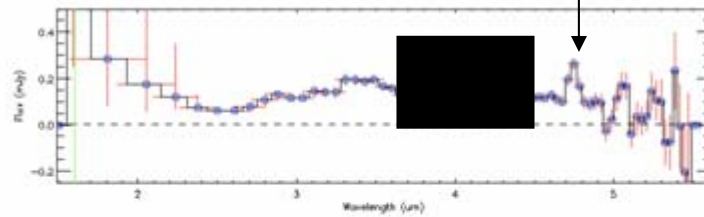
$z = 6.07$



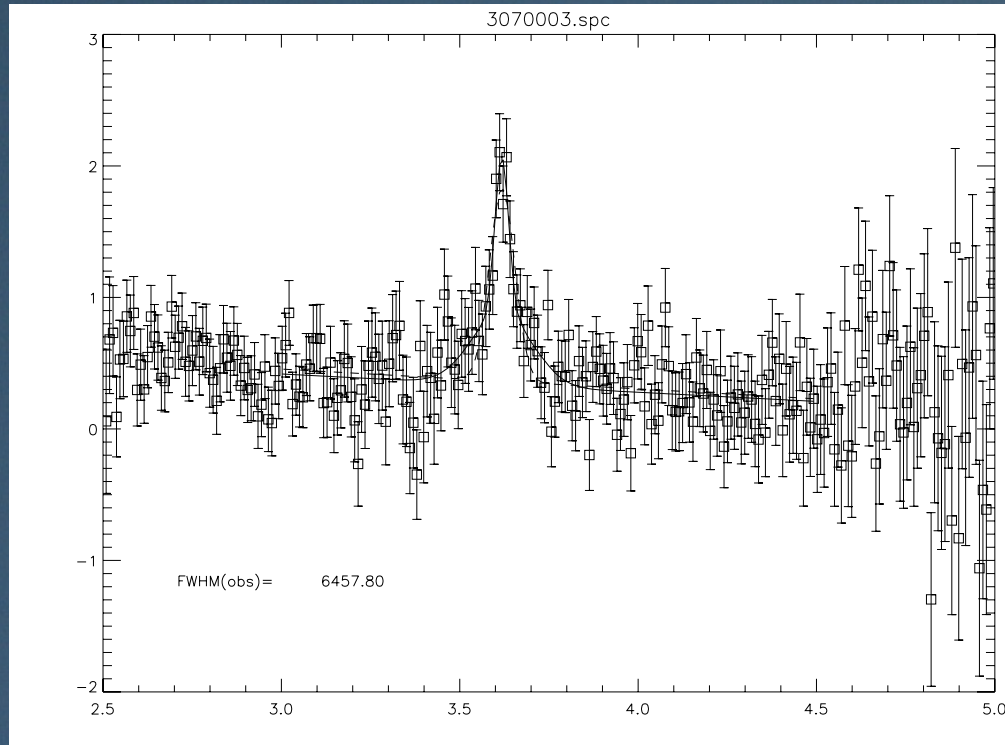
$z = 6.13$



$z = 6.22$



Line Luminosity/Width, Black Hole Mass



- ✓ $\text{Log}(L(\text{H.}) \text{ erg/sec}) \sim 45.5 \text{ erg/sec}$
- ✓ $\text{FWHM} \sim 2500 - 5000 \text{ km/sec.}$
- ✓ $\text{Log}(M_{\text{BH}} M_{\odot}) \sim 9.2 - 10.1$ (H. method from McGill, Woo, Treu & Malkan 2007).
- ✓ When no FWHM available (NP data), $\text{FWHM}=4000 \text{ km/sec}$ was assumed to calculate M_{BH} .

Redshifts of Quasars

- BR0004–6224: $z=4.51$ vs 4.49 in the literature (e.g., Storrie–Lombardi et al. 2004) \rightarrow our measurement shows $z=4.51 \pm 0.01$
- SDSS J1621+5155: Tentative redshift of 5.71 from the ground–based observation (not published) \rightarrow our measurement shows $z=5.59 \pm 0.01$
- In all other cases, the literature values and our measurements agree well

Comparison with other M_{BH} estimators

- Two objects have independent CIV and/or MgII based measurements

1. SDSS J000552-000655 ($z=5.85$)

No detection in H. $\rightarrow M < 1.5 \times 10^9 M_{\odot}$

vs.

$0.7 \times 10^9 M_{\odot}$ (CIV) or $0.3 \times 10^9 M_{\odot}$ (MgII)
(Both from Kurk et al. 2007)

2. SDSS J162331+311200 ($z=6.22$)

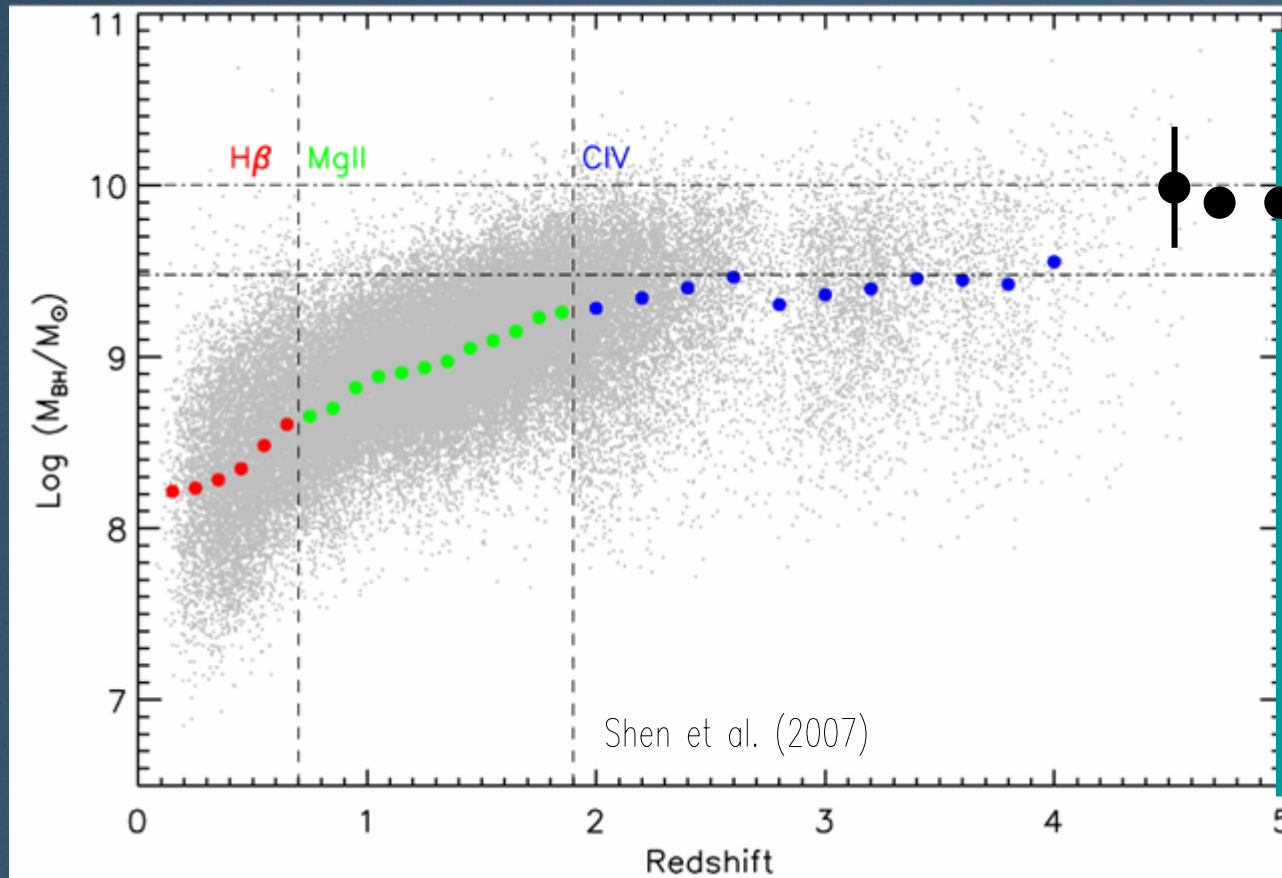
$3.5 \times 10^9 M_{\odot}$ (our measurement)

vs.

$1.5 \times 10^9 M_{\odot}$ (MgII; Jiang et al. 2007)

SMBH Mass

●: Our work



✧ :Jiang et al. (2007)
Kurk et al. (2007)

6

6.5

- BH Mass $\sim 10^{9.3} - 10^{10.1} M_{\odot}$
 \rightarrow A few $\times 10^9 M_{\odot}$ SMBHs existed at $z \sim 6$ (0.95 Gyr)
- $10^{10} M_{\odot}$ SMBHs existed at $z \sim 5$ (1.2 Gyr)
- No $M \sim 10^{10} M_{\odot}$ SMBHs at $z > 5.5$ ($t_{\text{univ}} \sim 1$ Gyr) ???

Conclusion

- The first detection of H. from QSOs at $z > 4.5$ out to $z=6.22$ using AKARI
- Supermassive black holes with $10^{9.2} - 10^{10} M_{\odot}$ existed in the early universe. (confirmed with a well-calibrated method using H.)
- Lack of $10^{10} M_{\odot}$ SMBHs at $z > 5.5$: They are emerging at $z \sim 5.5$?
- QSONG (Study of QSOs with NIR Grism): New AKARI mission program will extend this study to 130 quasars at $z > 3.3$ (observation started in June this year).

