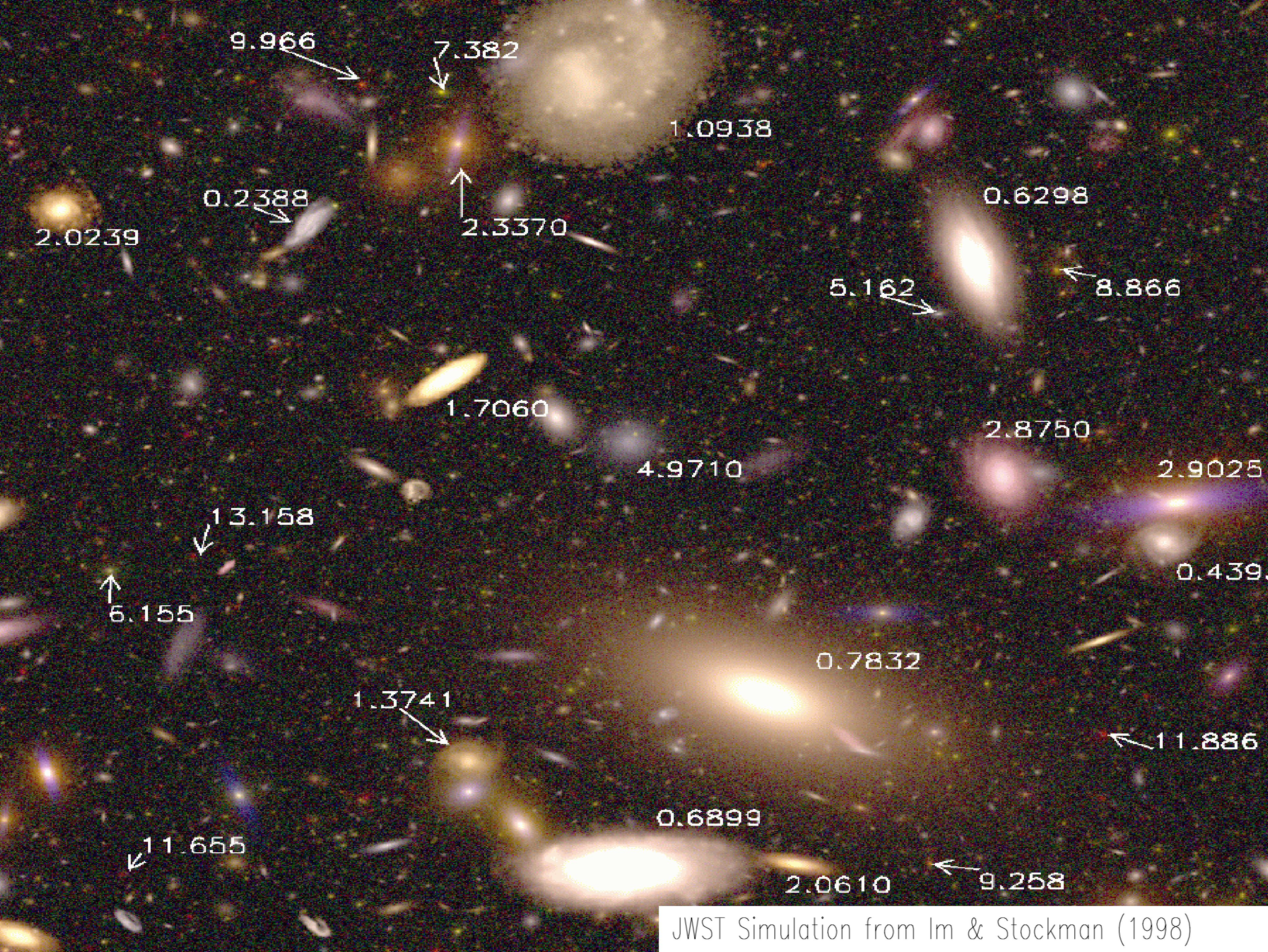


JWST Simulation from Im & Stockman (1998)

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

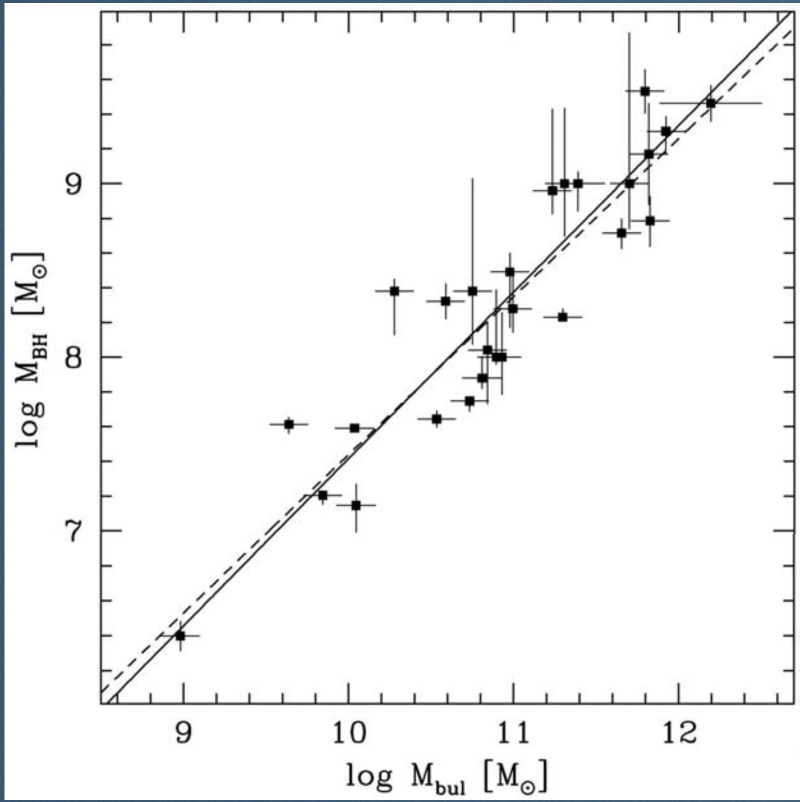
[Rest-frame Optical Spectra of Quasars at 4.5 < z < 6.5]

Myungshin Im
(Seoul National University)

Youichi Ohyama (ISAS & ASIAA)
Minjin Kim, Induk Lee, H. M. Lee, M. G. Lee (SNU),
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?

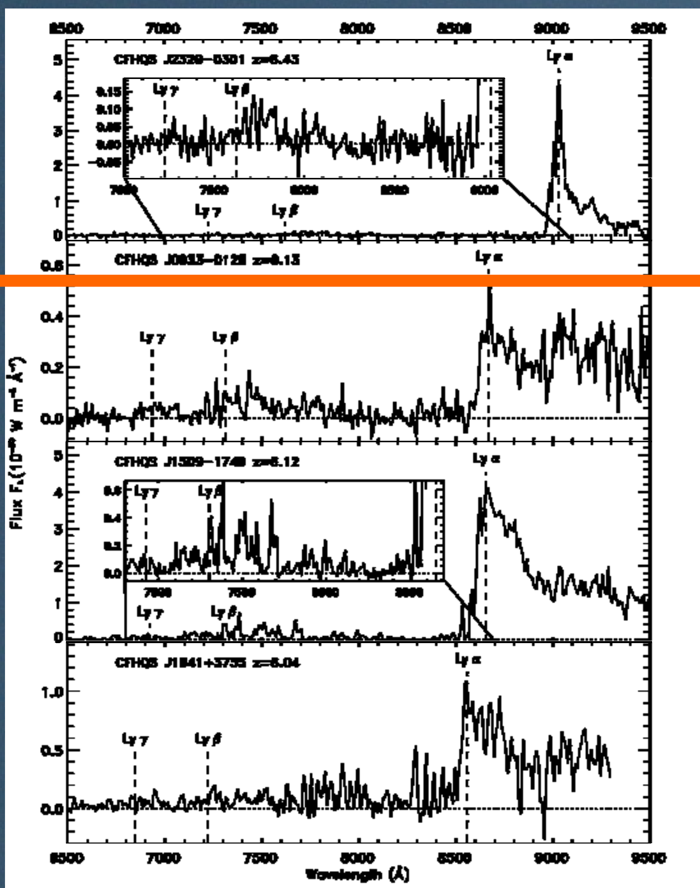
When did the massive SMBHs appear?

: 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 ~ 6.43 (Fan et al; Willott et al. 2007).



Luminous quasars existed out to z ~ 6.4.

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

Undertanding 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) → 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)

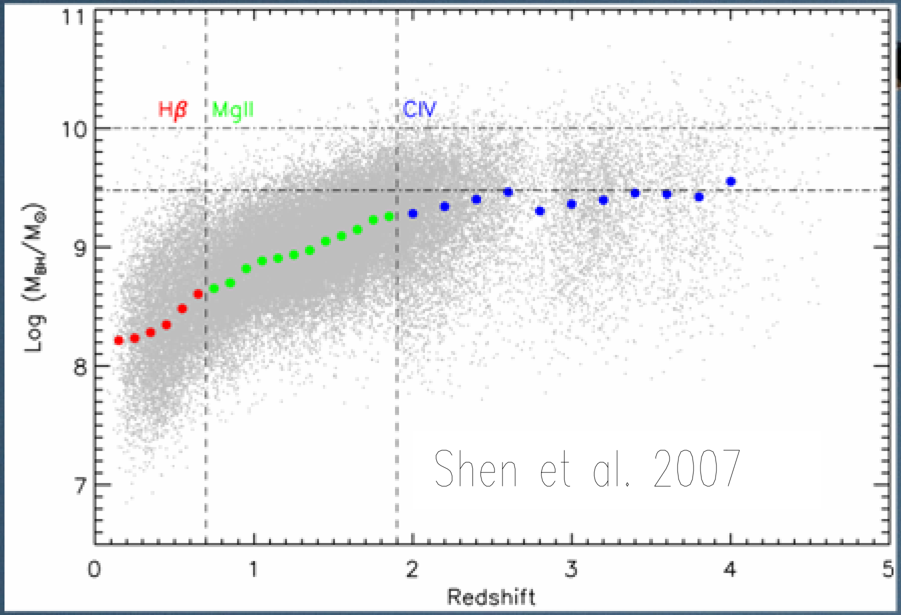
$$M_{BH}(H\beta) = 10^{6.91}\left[\left(\frac{\mathrm{FWHM}(H\beta)}{1000\ \mathrm{km\ s^{-1}}}\right)^{2}\left(\frac{\lambda L_{\lambda}(5100\ \mathrm{\AA})}{10^{44}\ \mathrm{erg\ s^{-1}}}\right)^{0.50}\right].$$

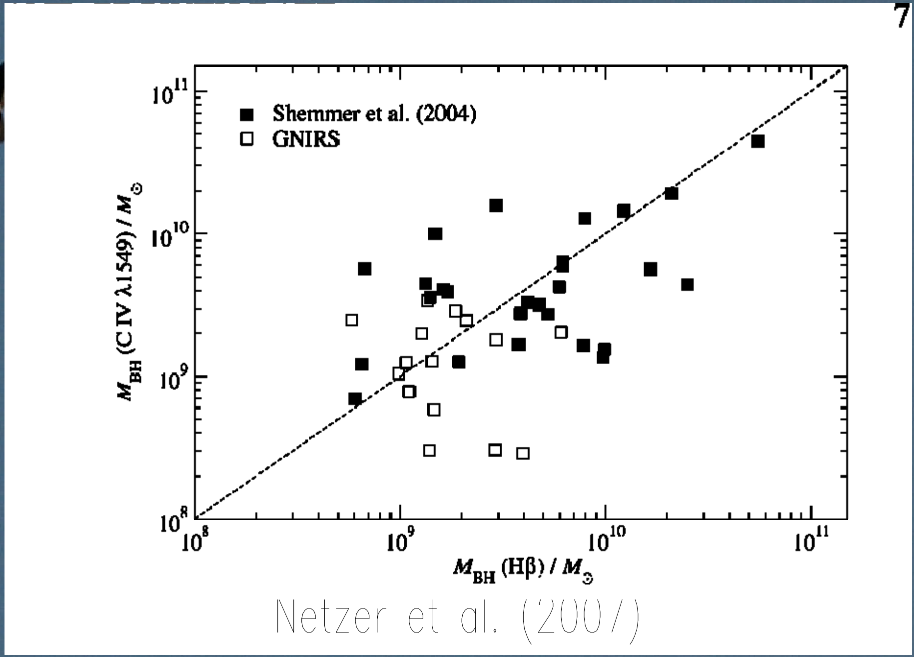
$$M_{BH}(\mathrm{CIV}) = 10^{6.66}\left[\left(\frac{\mathrm{FWHM}(\mathrm{CIV})}{1000\ \mathrm{km\ s^{-1}}}\right)^{2}\left(\frac{\lambda L_{\lambda}(1350\ \mathrm{\AA})}{10^{44}\ \mathrm{erg\ s^{-1}}}\right)^{0.53}\right].$$

[M = f*R*v^2/G ; 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 micon).



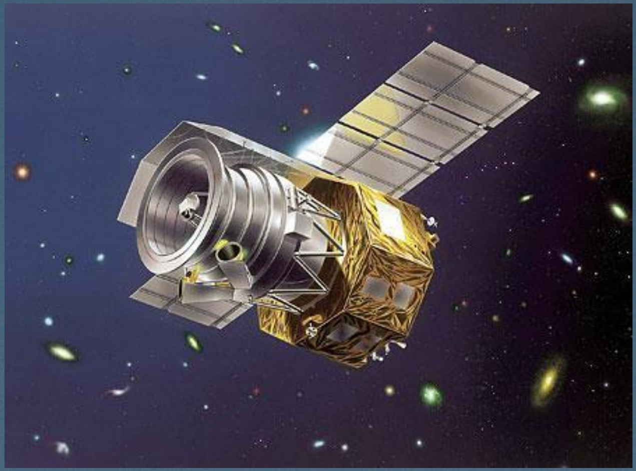


✓ But the reliability of CIV measurement has been in question (or even MgII – outflow contribution, asymmetric profile, etc).

✓ 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.

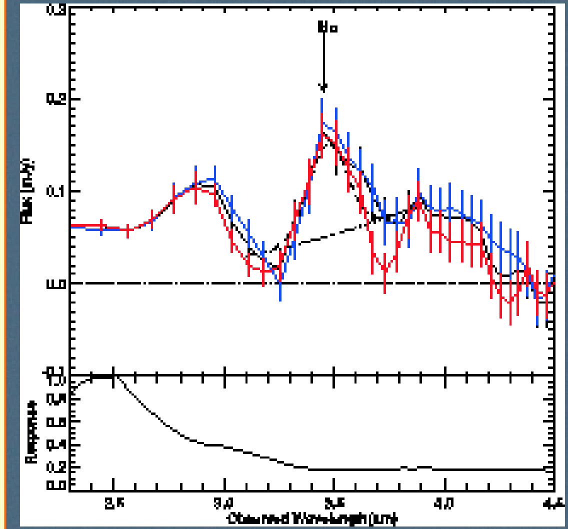


NIR Grism and Prism Spectroscopy

– 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 > ~ 100 uJy (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.

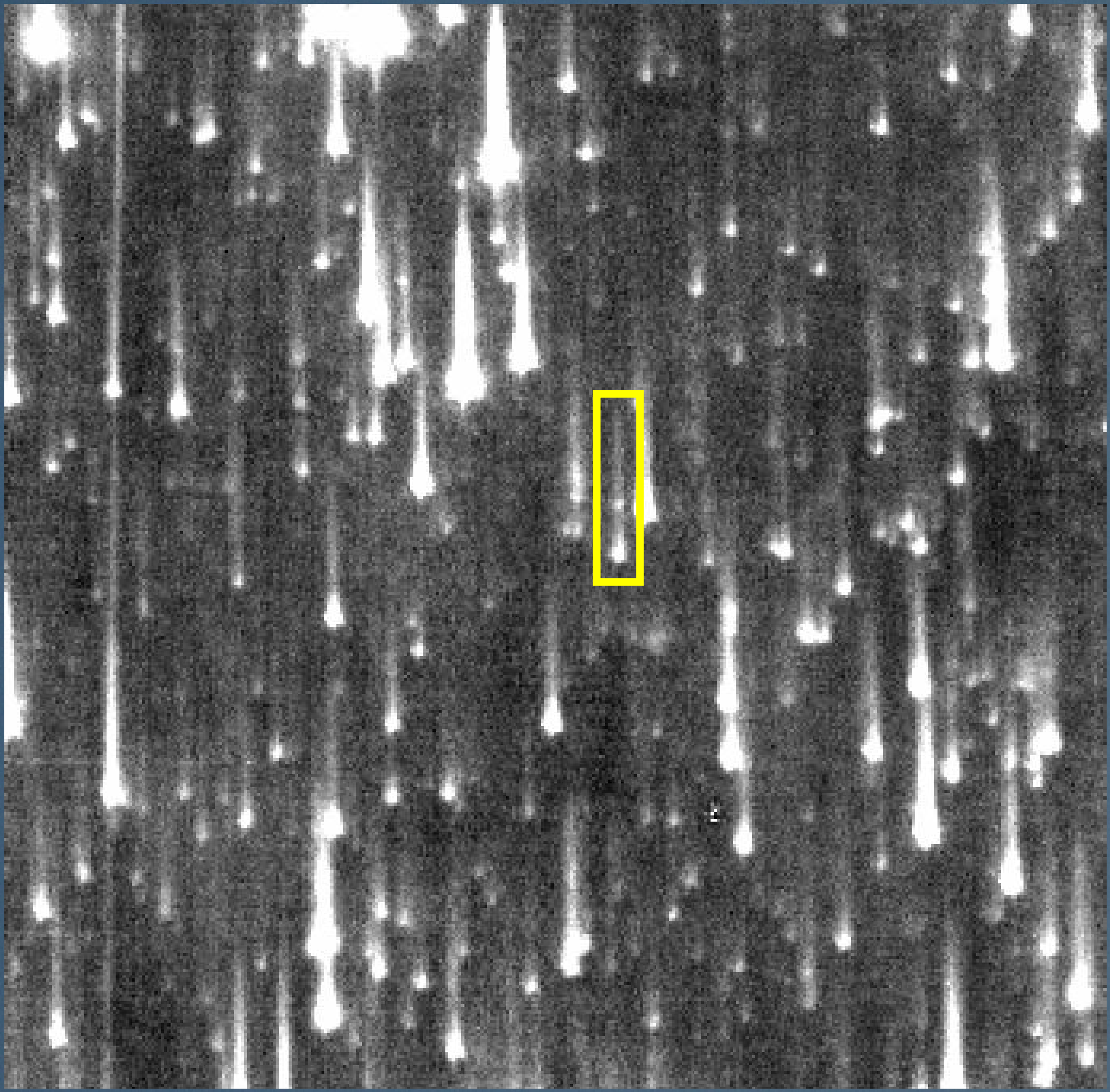
3 QSOs have both NG/NP data.

8 QSOs out of 14 show H. detection.

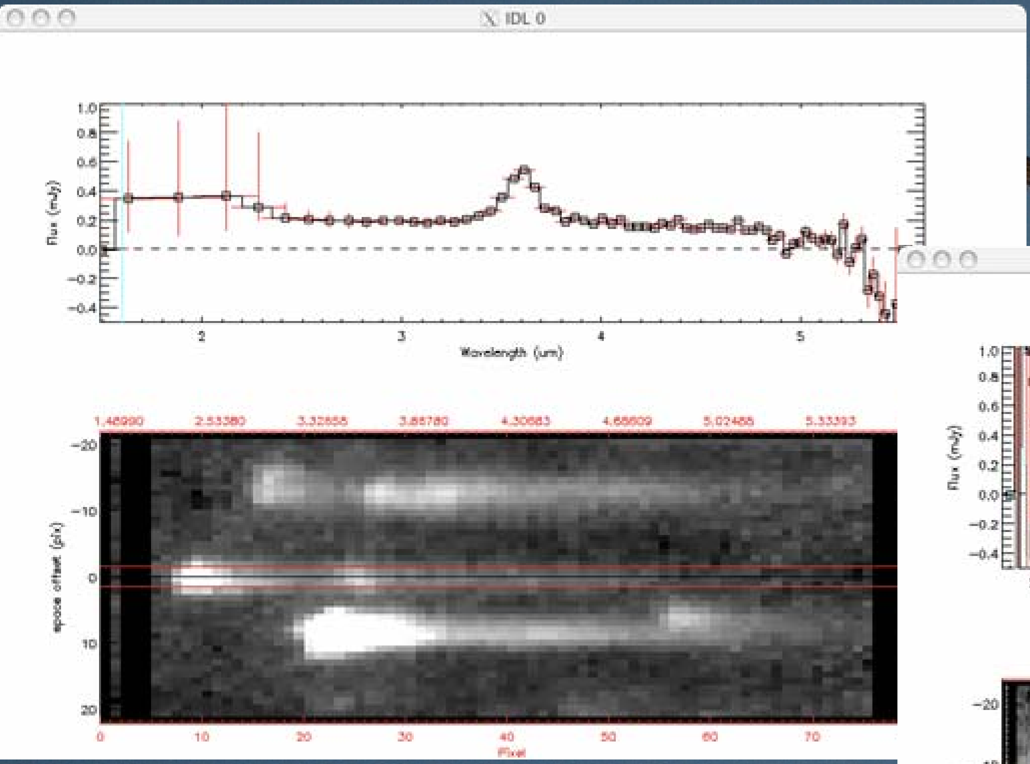
1 pointing ~ 10 min.

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?

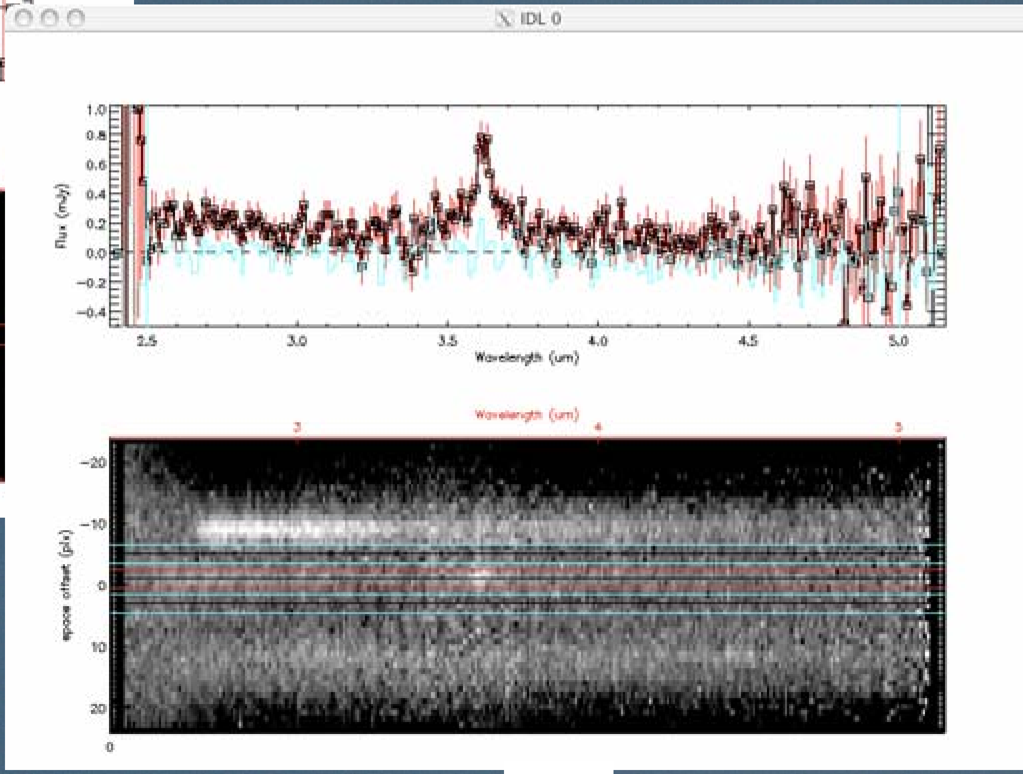
NIR Prism Observation



BR 0006-6224 (z=4.51)



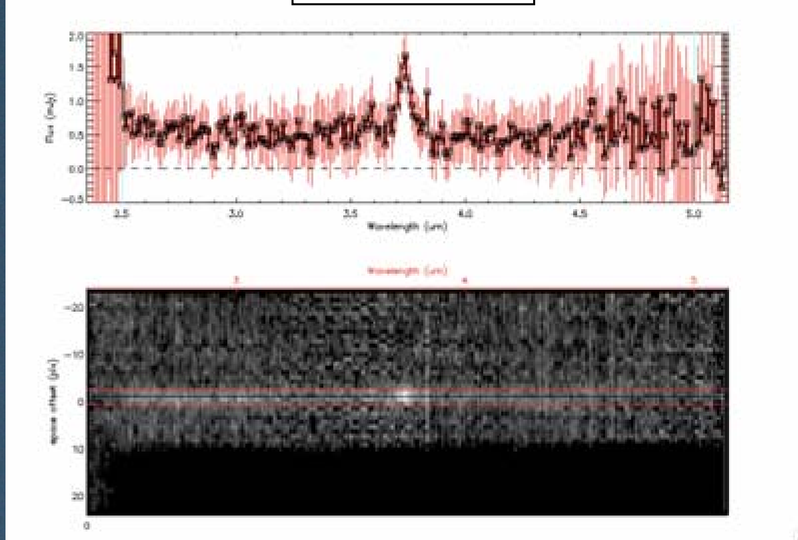
NP



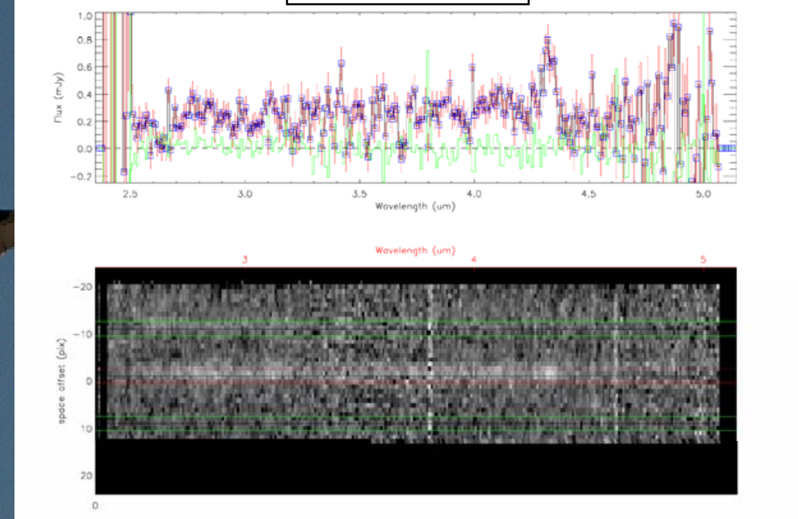
NG

H. Detections (NG)

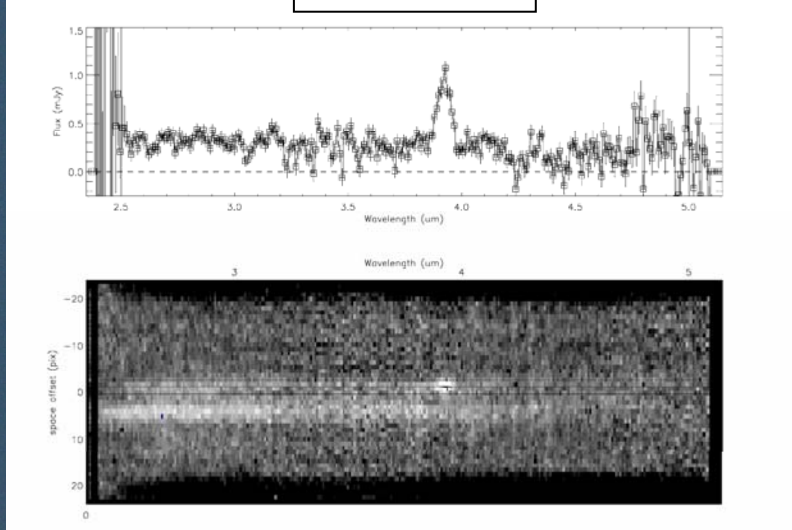
z = 4.69



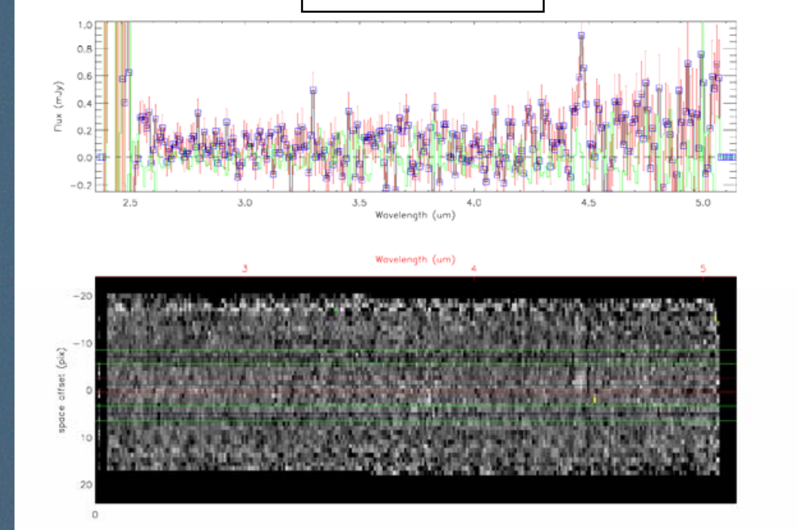
z = 5.59



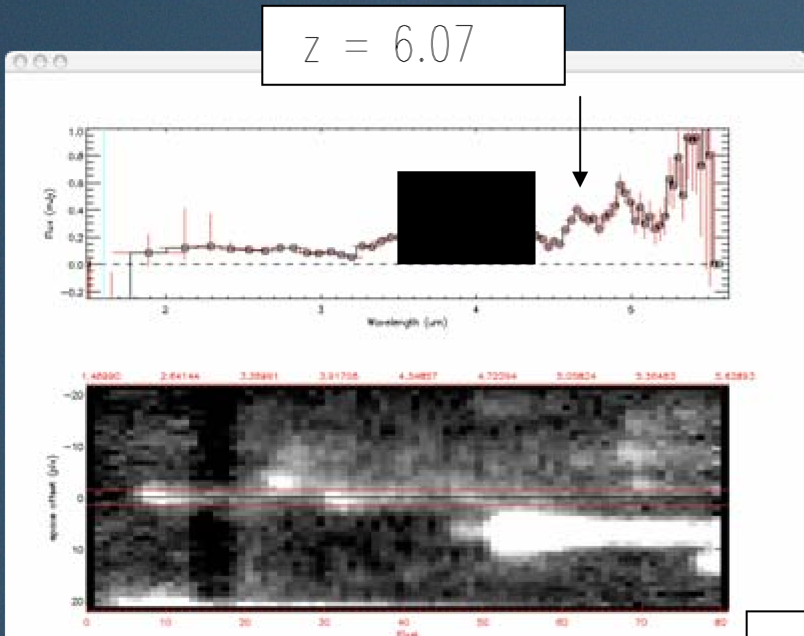
z = 4.97

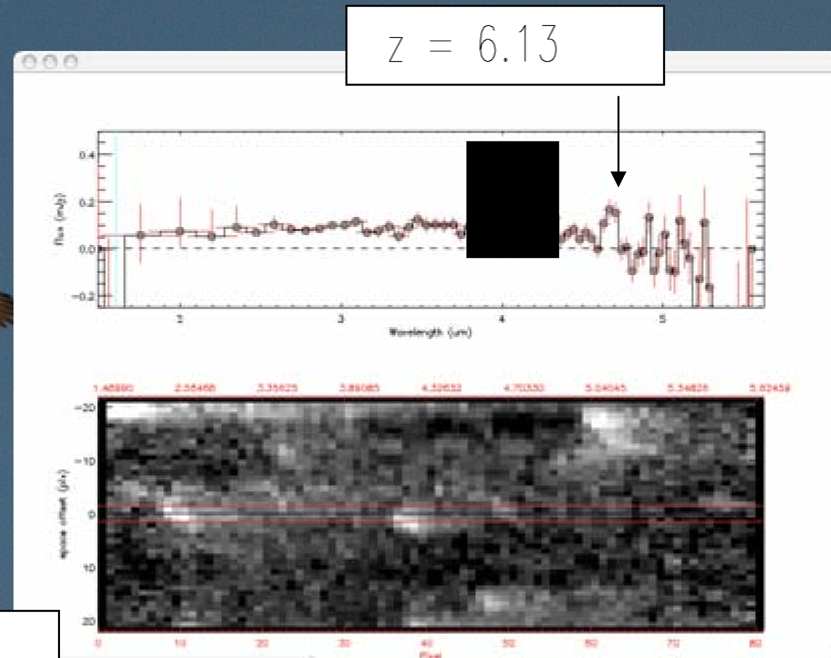


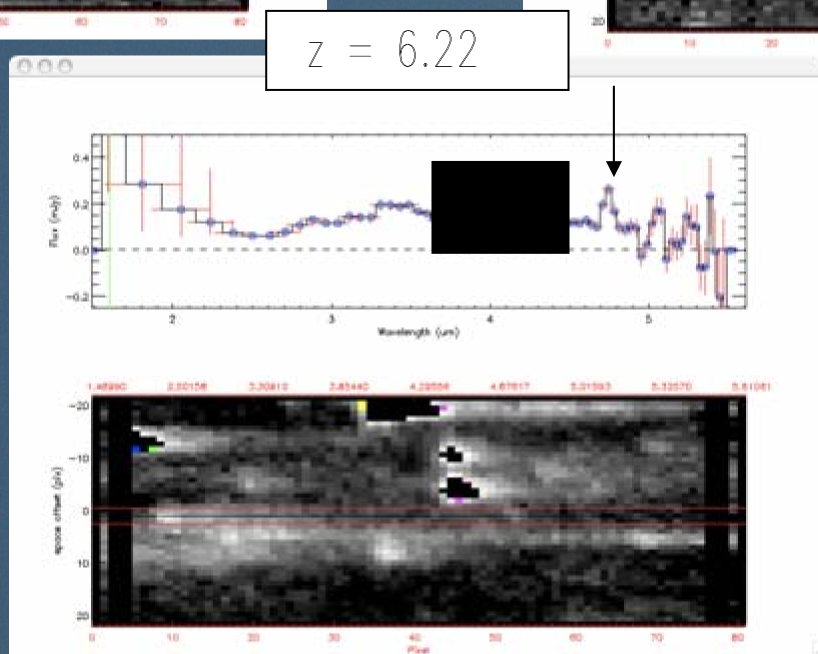
z = 5.80



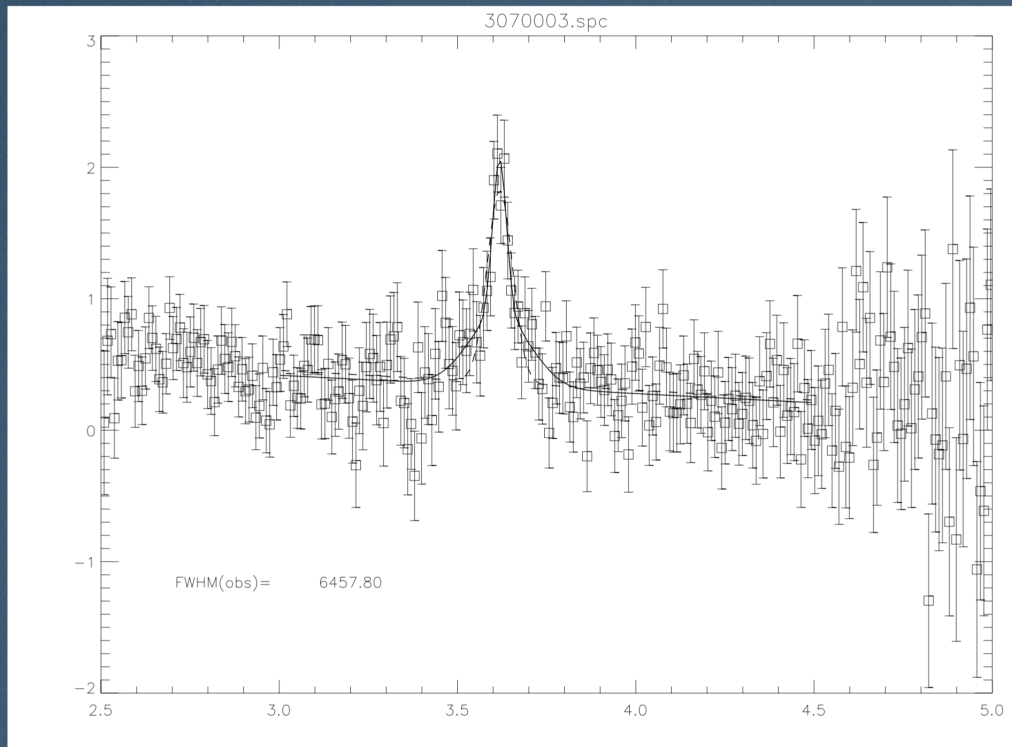
H. Detections (NP)







Line Luminosity/Width, Black Hole Mass



z = 4.51

- Log(L(H.) erg/sec) ~ 45.5 erg/sec
- FWHM ~ 2500 – 5000 km/sec.
- Log(M_{BH} M.) ~ 9.2 . 10.1 (H. method from McGill, Woo, Treu & Malkan 2007).
- When no FWHM available (NP data), FWHM=4000 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) → our measurement shows z=4.51 +-0.01
- SDSS J1621+5155: Tentative redshift of 5.71 from the ground-based observation (not published) → our measurement shows z=5.59 +-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

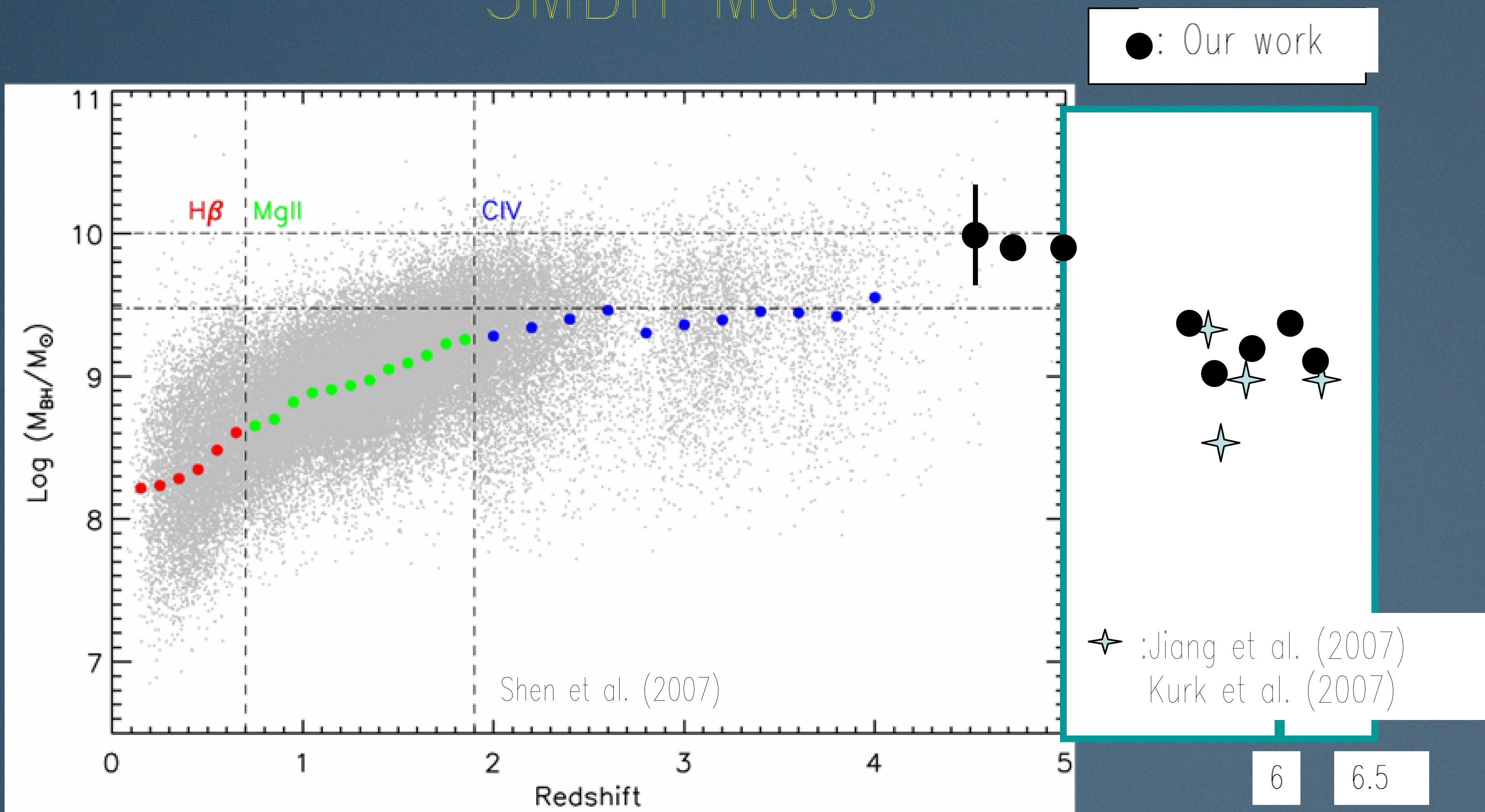
1. SDSS J000552–000655 (z=5.85)

No detection in H. ➔ $M < 1.5 \times 10^9\ M_.$
vs.
$0.7 \times 10^9\ M_.$ (CIV) or $0.3 \times 10^9\ M_.$ (MgII)
(Both from Kurk et al. 2007)

2. SDSS J162331+311200 (z=6.22)

$3.5 \times 10^9\ M_.$ (our measurement)
vs.
$1.5 \times 10^9\ M_.$ (MgII; Jiang et al. 2007)

SMBH Mass



- BH Mass ~ $10^{9.3}$ – $10^{10.1}$ M
  ➔ A few x 10^{9} M SMBHs existed at z ~ 6 (0.95 Gyr)

- 10^{10} M SMBHs existed at z ~ 5 (1.2 Gyr)

- No M ~ 10^{10} M SMBHs at z > 5.5 (t_{univ} ~ 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).