Observational Constraints on the Growth of Supermassive Black Holes at the Edge of the Universe

Myungshin Im
CEOU/Department of Physics & Astronomy,
Seoul National University

Hyungsun Jun, Yiseul Jeon, Jihoon Kim, Won-Kee Park, Changsu Choi, Dohyeong Kim,
Hyung Mok Lee, Myung Gyoon Lee, Jonghak Woo **(SNU), Y. Ohyama (ASIAA), Minjin Kim** (NRAO/SNU),
T. Nakagawa, H. Matsuhara, S. Oyabu, T. Takagi, T. Wada (ISAS/JAXA), **X. Fan** (Steward Observatory),
Y. Urata (NCU), T. Sakamoto, N. Gehrels (NASA/GSFC), P. Choi (Pomona College), **T. Kruehler,**
J. Greiner (MPE), Soojong Pak (Kyunghee Univ.)

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Origin of the Black Hole

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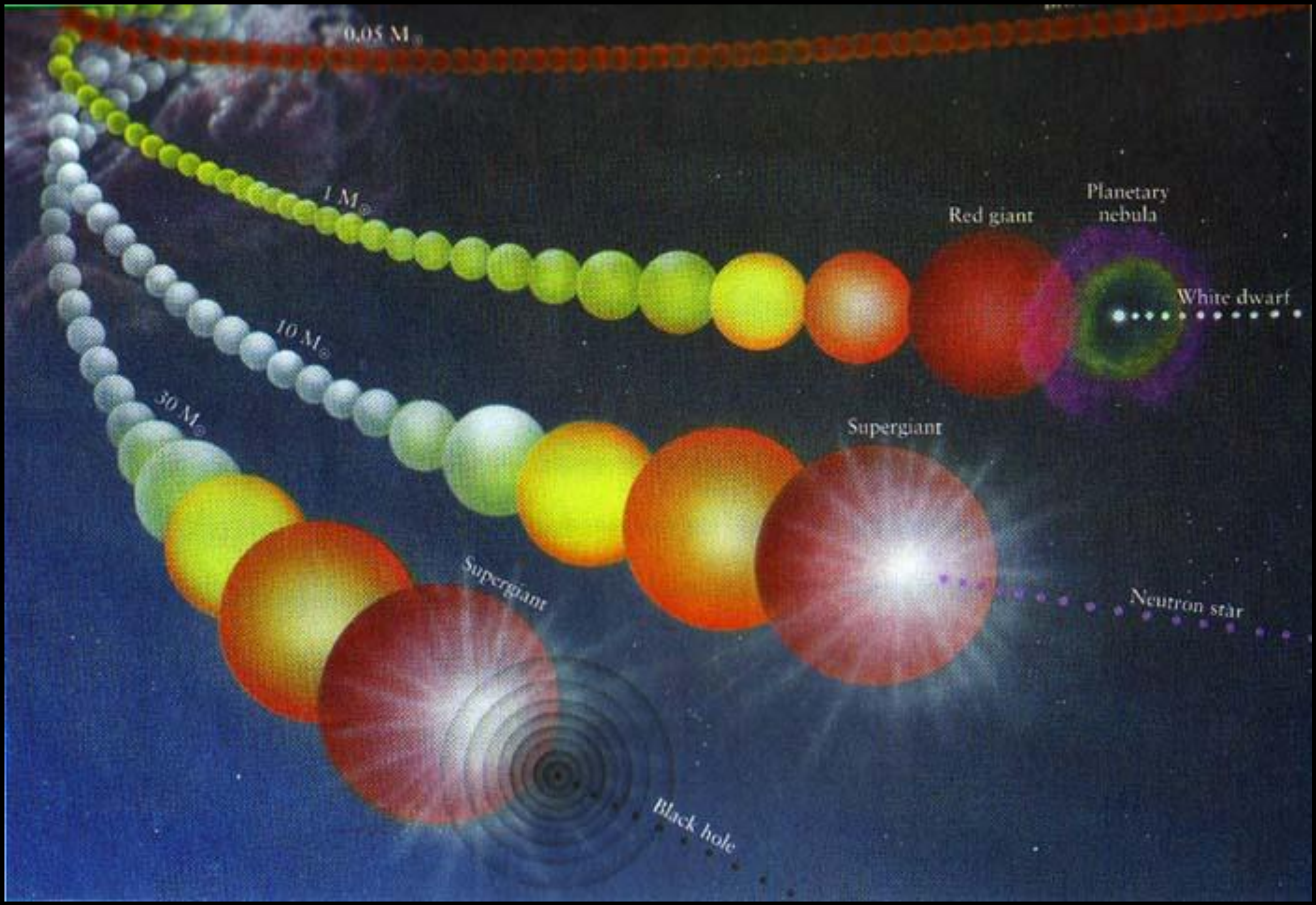

Black holes with ~ 10 $M_\odot$

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Supermassive Black Holes (SMBH)

- What are they?

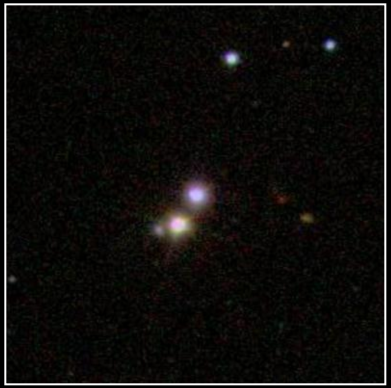
- Black Holes with masses ~ 10^5 – 10^{10} $M_\odot$

- Where are they ?

- Centers of massive spheroids/bulges or quasars

Elliptical galaxy

Bulges of Spirals



Quasars/AGNs

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Super-massive Black Holes in Inactive Galaxies

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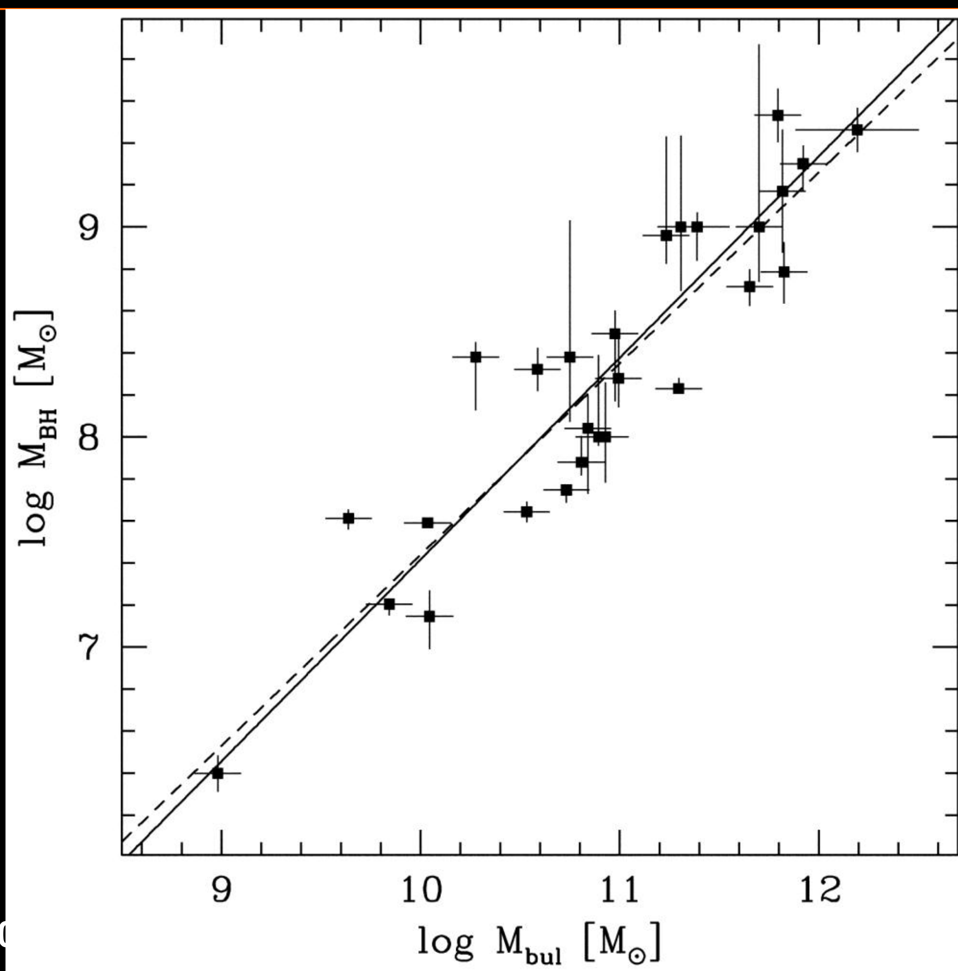
SMBH mass ∝
mass, velocity dispersion, and luminosity of the host galaxy
(e.g., Gebhardt et al. 2000; Ferrarese & Merritt 2000; Marconi & Hunt 2003)



But why?

Which was born first?

When did the massive SMBHs appear?

Marconi & Hunt (2003)

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Quasars (Active galaxies)

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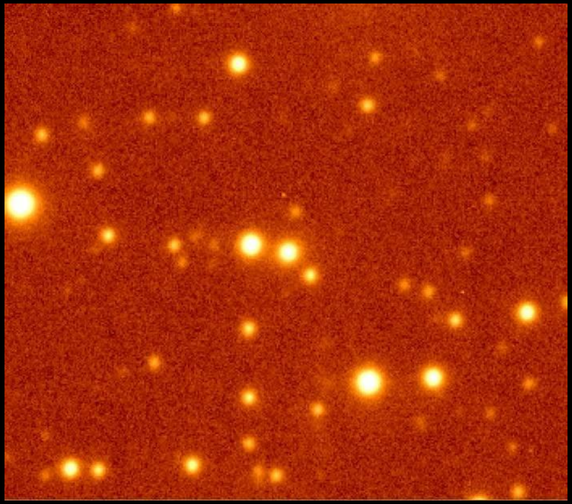
- Quasars = QUASi-stellAR radio sources
- $10^{12}\ L_\odot$ in a sphere with d < 2.5 x 10^{17}cm (3 light-months) ➔ powered by SMBHs!



Im, Lee, et al. 2007,
Lee, Im, et al. 2008

Reverberation Mapping or Single Epoch Measurement

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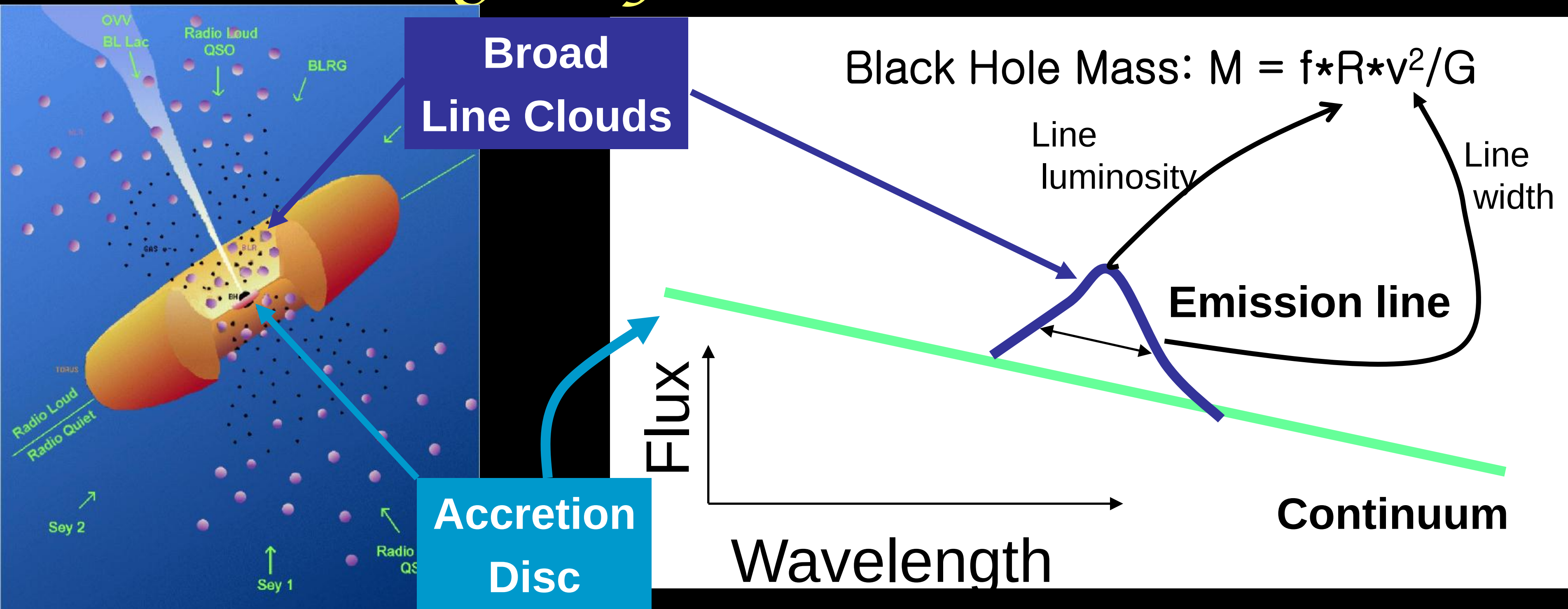

Variability in the Central Light Source

Time Lag = Distance to BL Clouds

Variability in the Line Flux

Width of the Emission Line Due to Doppler Motion
= Velocity of BL Clouds

Single Epoch Measurement

- Reverberation mapping ➔ Long-term monitoring needed (months – decades)

- $R_{BLR} \propto$ L(Continuum) or Line Flux
  ➔ BH measurement with a single-epoch spectrum is possible ! (Kaspi et al. 2000; Vestergaard et al. 2005; Greene & Ho 2005; Kim, Im, & Kim 2010)

$$M_{\rm BH} = (2.0^{+0.4}_{-0.3}) \times 10^6 \left(\frac{L_{\rm H\alpha}}{10^{42}\ {\rm ergs\ s^{-1}}}\right)^{0.55\pm0.02} \left(\frac{\rm FWHM_{H\alpha}}{10^3\ {\rm km\ s^{-1}}}\right)^{2.06\pm0.06} M_\odot$$

Greene & Ho 2005

Masses of SMBHs at high redshift

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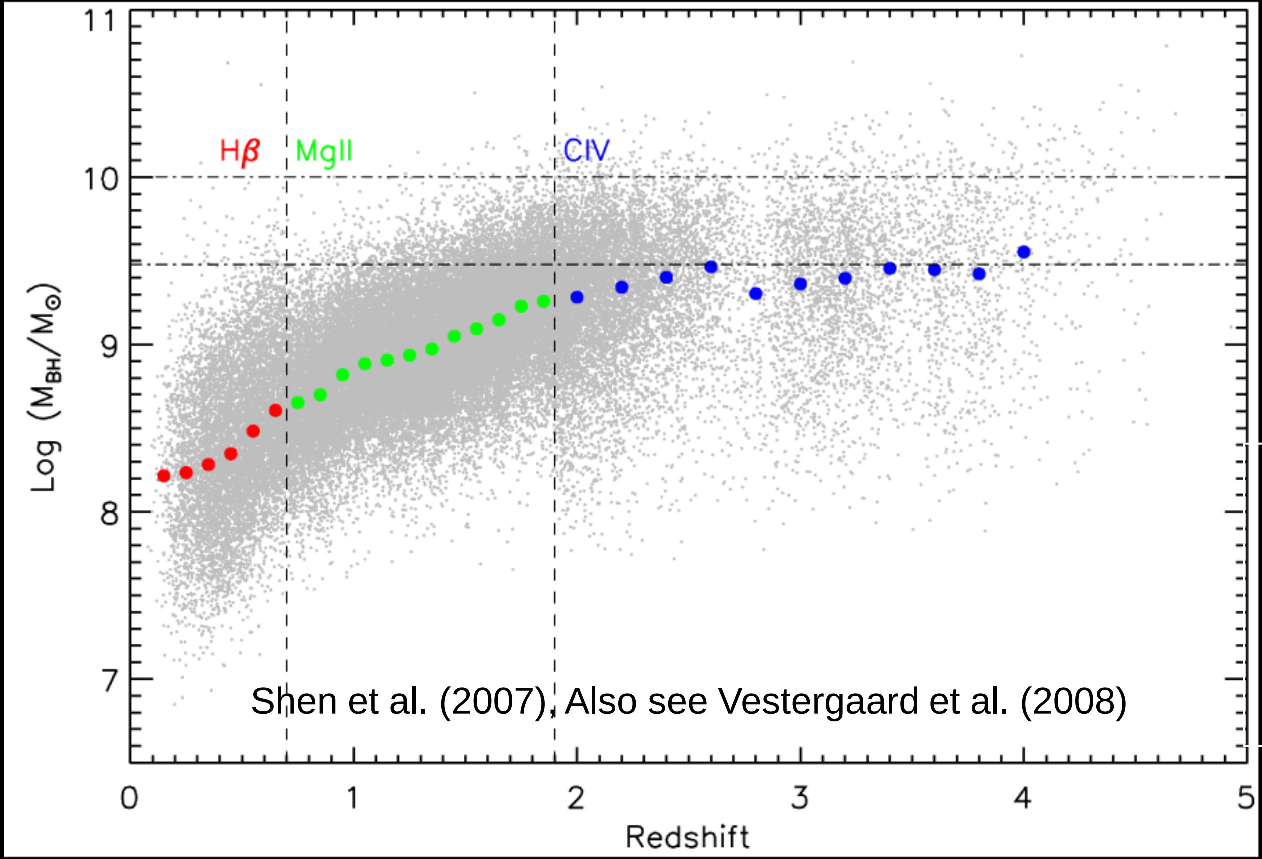
- The most massive SMBHs ($M \sim 10^{10}\ M_\odot$ or more) at $2 < z < 4.5$, $10^9\ M_\odot$ BHs at $z \sim 6.42$ ($t_{univ} < 1$ Gyr)



Shen et al. (2007), Also see Vestergaard et al. (2008)

A few more points here from ground-based NIR spectroscopy (Jiang et al.; Kurk et al. 2007)

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Supermassive Black Holes in Early Universe

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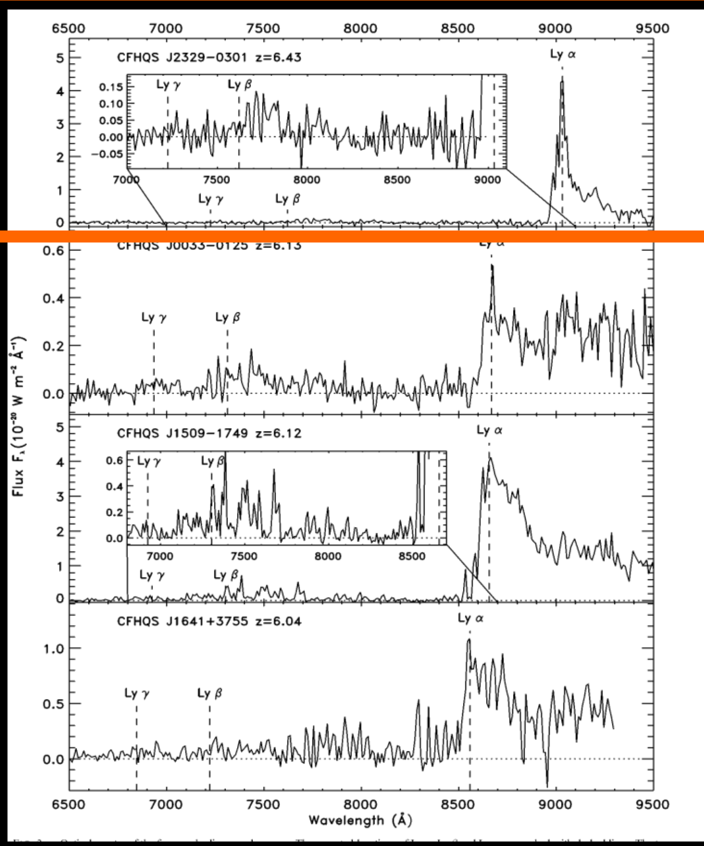
- Quasars have been discovered out to z ~ 6.43 (Fan et al. 2003; Willott et al. 2007).



Luminous quasars exist out to z ~ 6.4 →
10^9 $M_\odot$ SMBHs in place at t_{univ} ~ 1 Gyr

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

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Growing SMBHs

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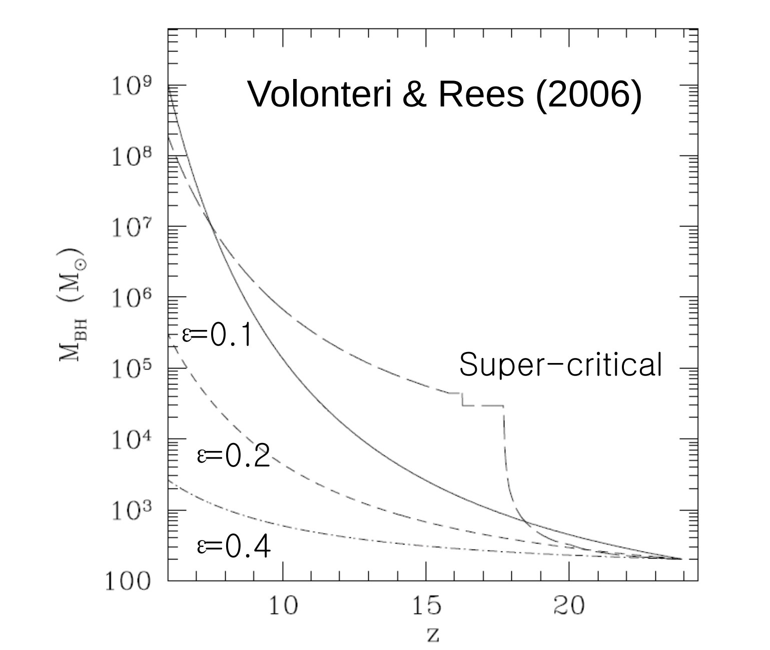

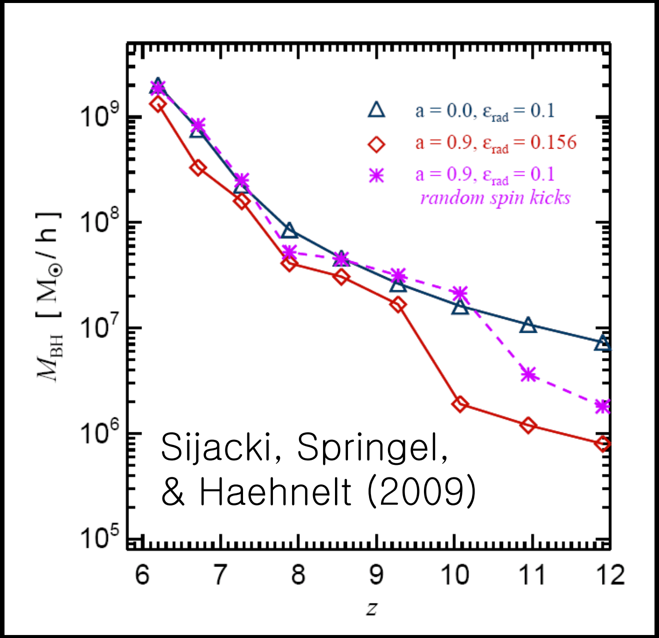

- M(t)=M(0) exp[(1-ε)/ε (t/t_{Edd})]=M(0) exp(t/τ), with τ ~ 4.5 x 10^7 (ε/0.1) yrs
- Not enough time (only ~0.64 Gyr between z= 6 and 15)
- Previous measurements with CIV and MgII ➔ Prone to errors, Better if we can use Hα or Hβ

Need for Better Mass Measurement

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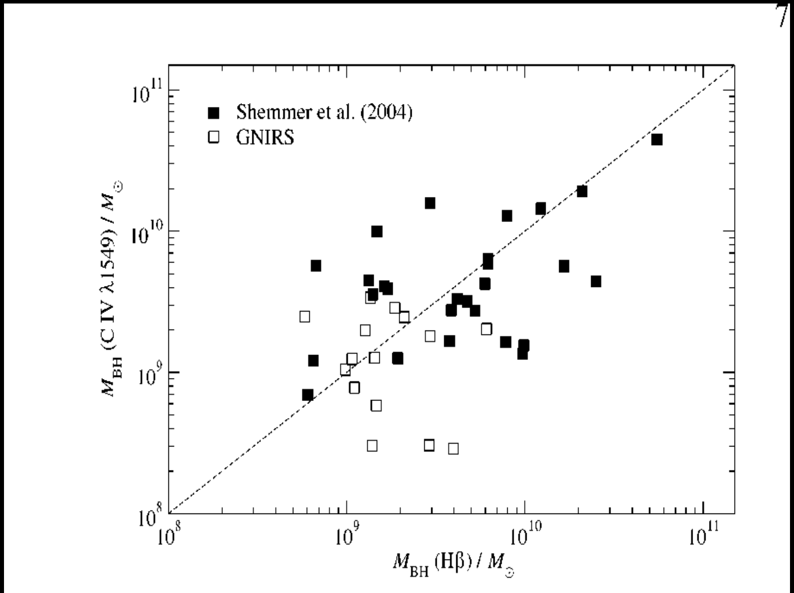
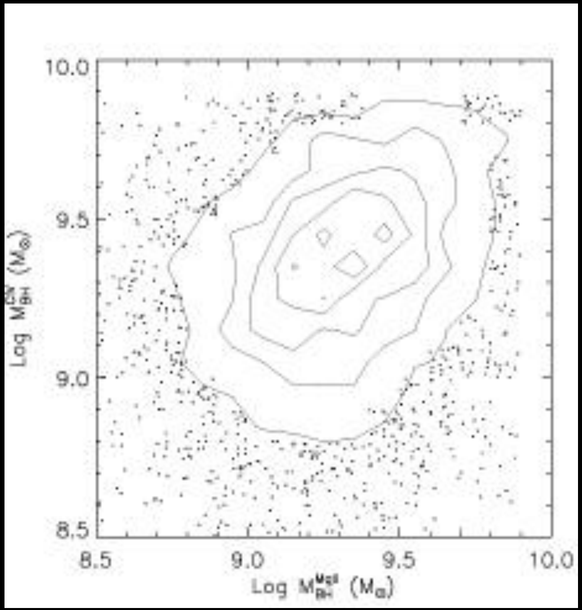


Netzer et al. (2007)



Shen et al. (2008)

✓ **Reliability of CIV measurement has been in question (or even MgII – outflow contribution, asymmetric profile, etc)**

✓**At higher z, metal abundance may decrease + extinction**

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

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AKARI Spectroscopy at 2.5-5 μm

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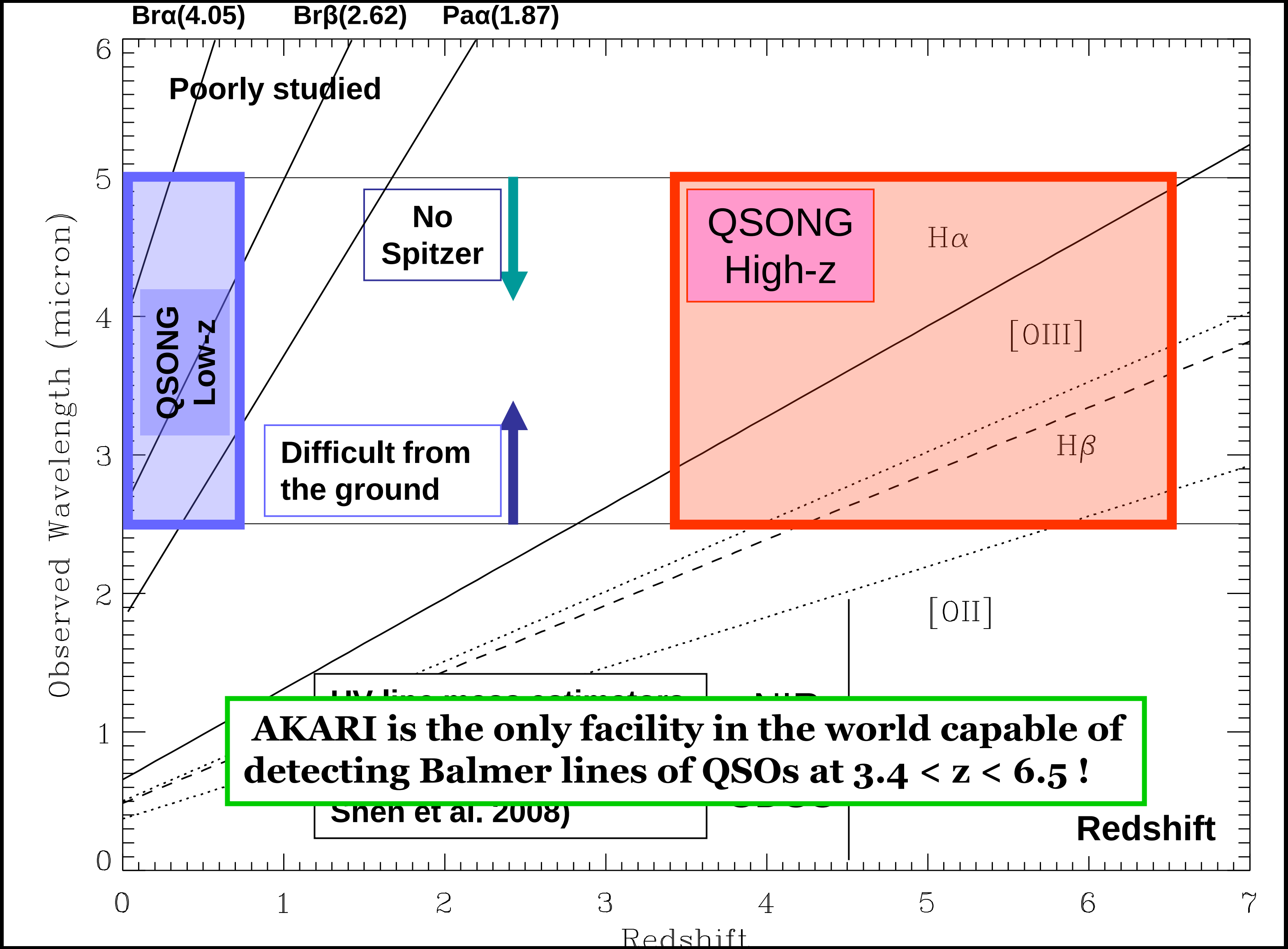
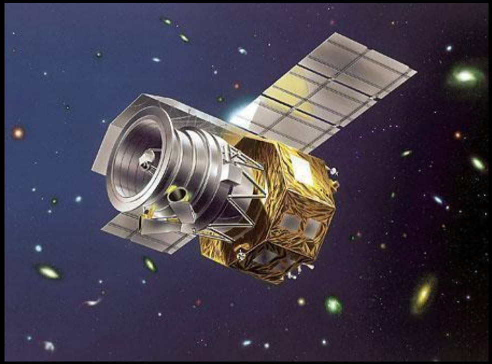


AKARI is the only facility in the world capable of detecting Balmer lines of QSOs at 3.4 < z < 6.5 !

QSONG

- **Q**uasar **S**pectroscopic **O**bservation with **N**IR **G**rism (AKARI Mission Program)
- NIR Spectroscopic Study of high-z and low-z AGNs at 2.5 – 5.0 μm with NIR grism of AKARI (R ~ 120, FWHM ~ 2500 km/sec)
- High-z study (HQSONG): 200+ QSOs at 3.4 < z < 6.42
- Low-z study (LQSONG): 102 nearby AGNs + red AGNs



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High-z QSONG Sample (HQSONG)

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- 200+ Type-1 QSOs at $3.4 < z < 6.4$ (mostly SDSS QSOs)

- z-band magnitude limit:
  $z_{AB} < \sim 19$ for $z < 5.5$
  $z_{AB} < \sim 20$ for $z > 5.5$

- L_{bol} limit ~ 10^{47} erg s^{-1}
- M_{BH} limit ~ 10^{9} $M_{\odot}$

- BH mass from well-calibrated Hα line (Greene & Ho 2005; McGill et al. 2008; versus CIV/MgII) → evolution of the most massive QSOs at high-z

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NIR Prism Observation

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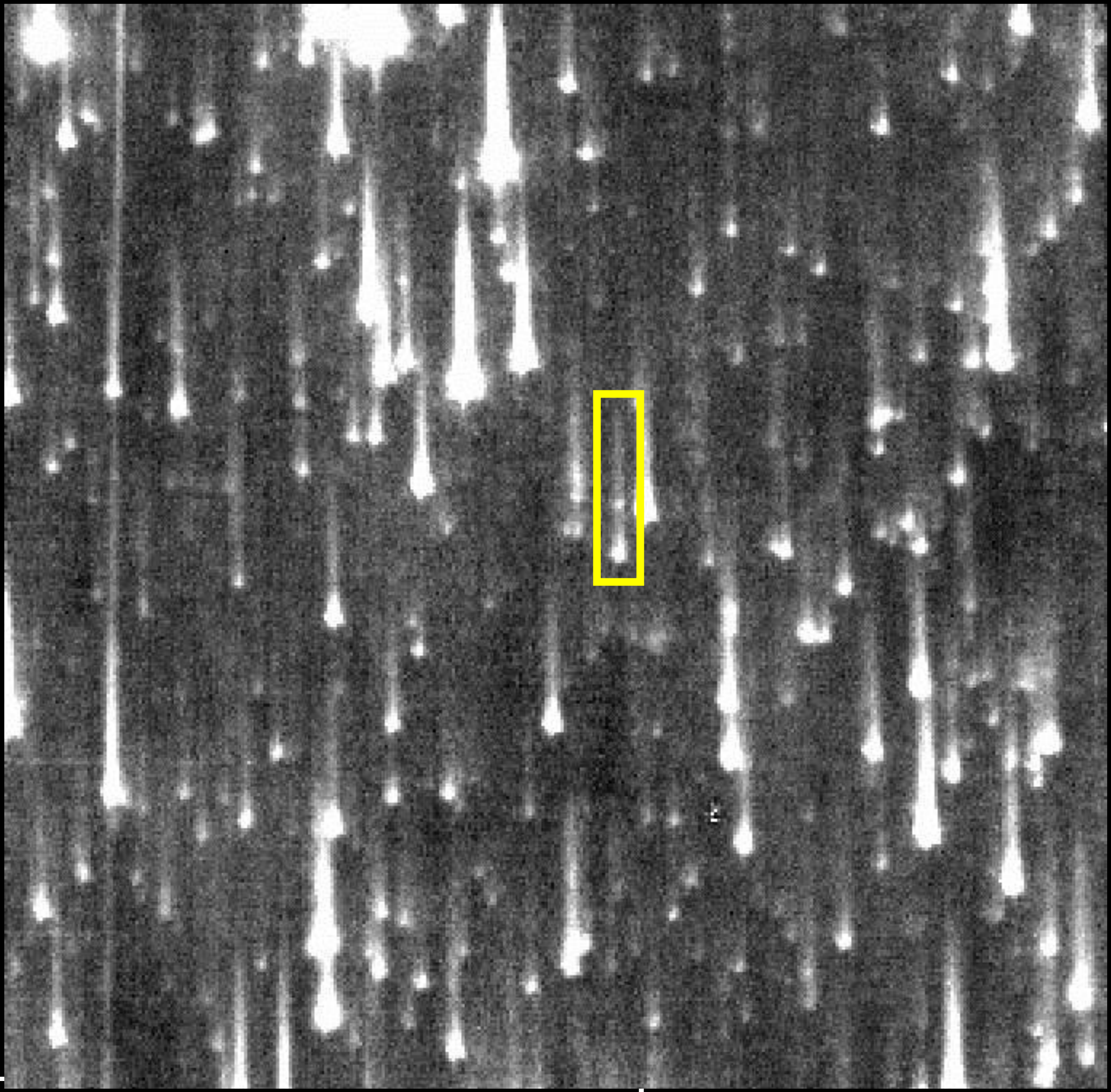

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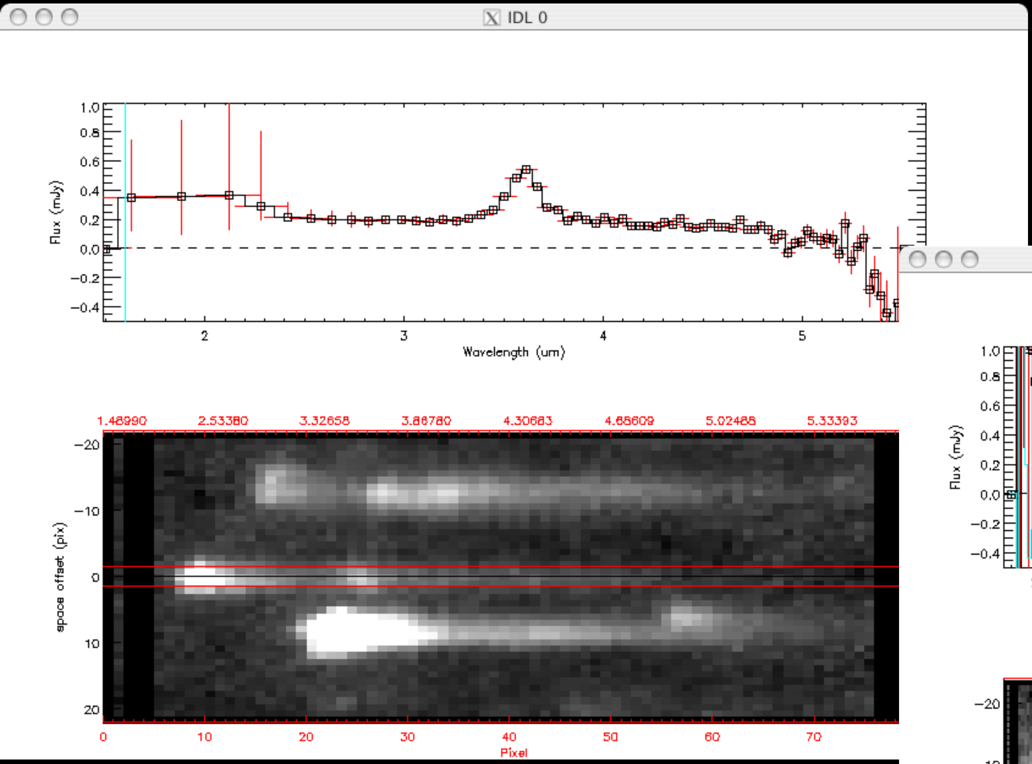
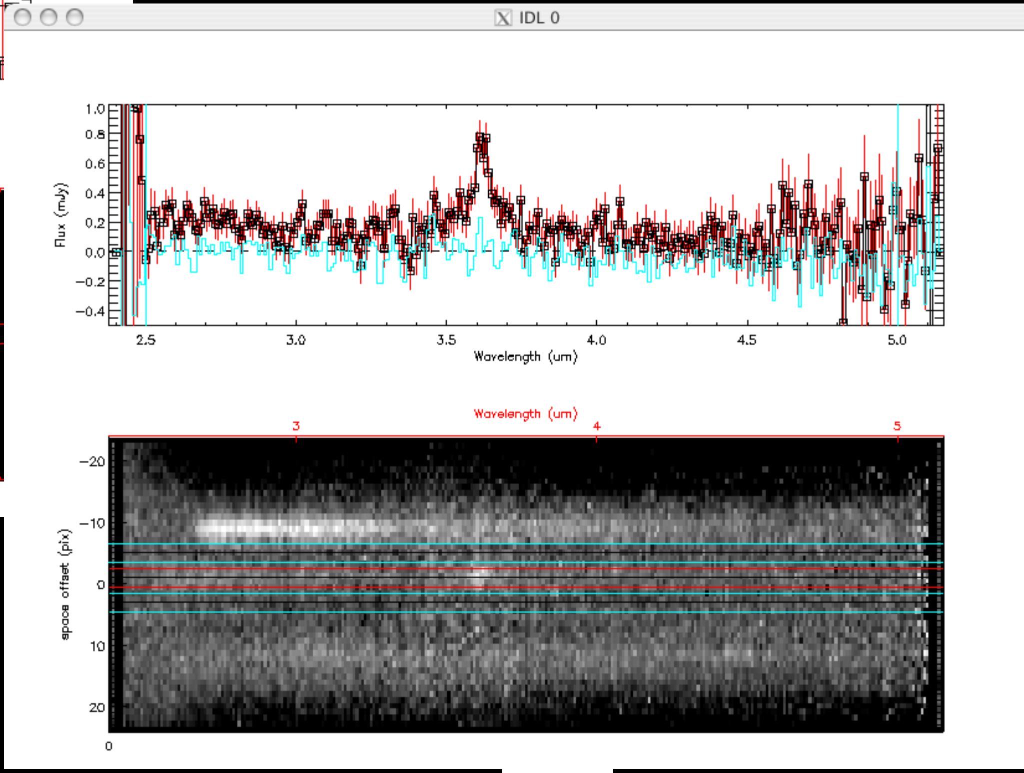
BR 0006-6224 (z=4.51)



NP



NG

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Pilot Study: Hα lines of 14 QSOs at $4.5 < z < 6.22$

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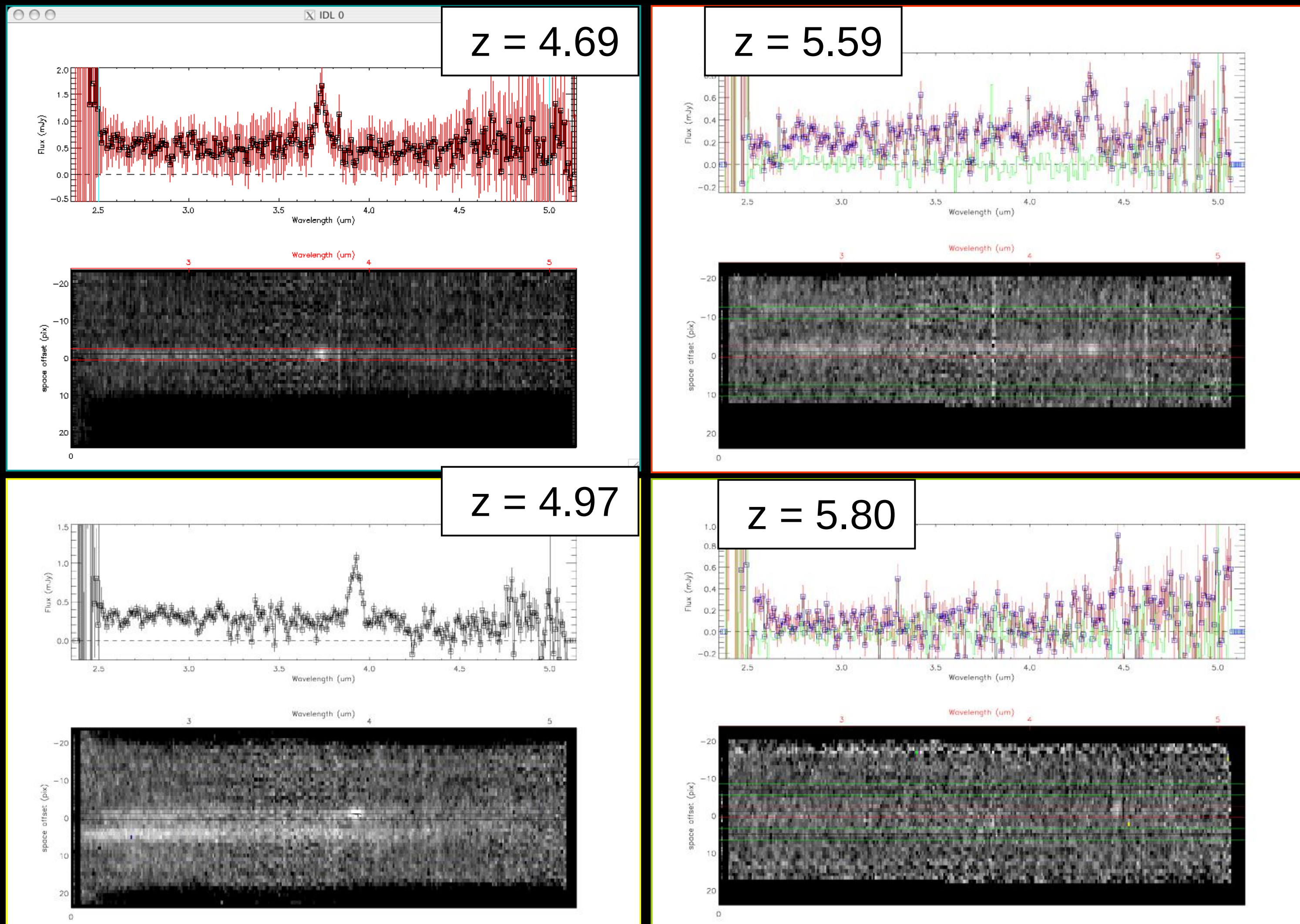
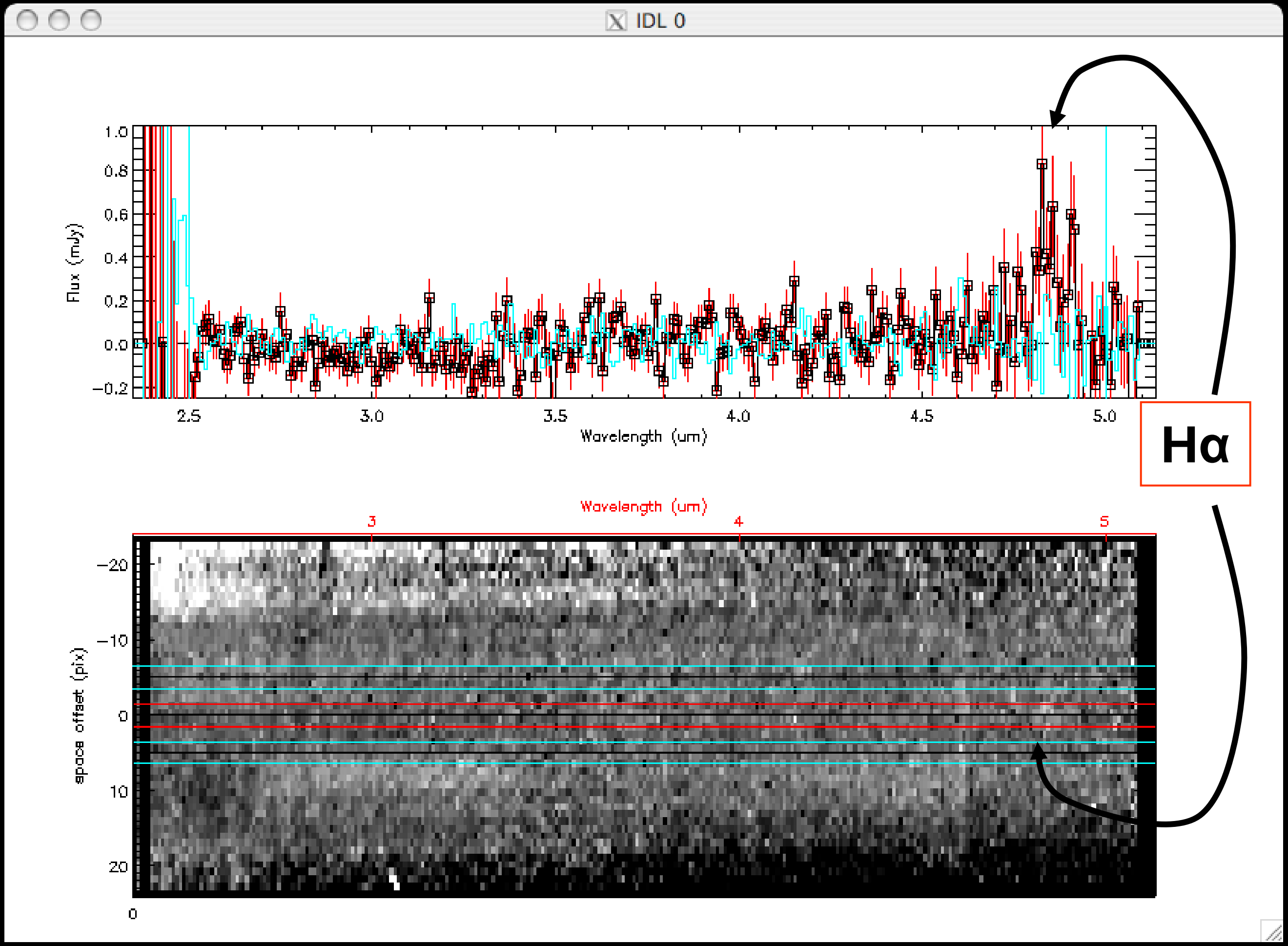


SDSS J 114816+525150 at z=6.42



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Hα Detections (NP)

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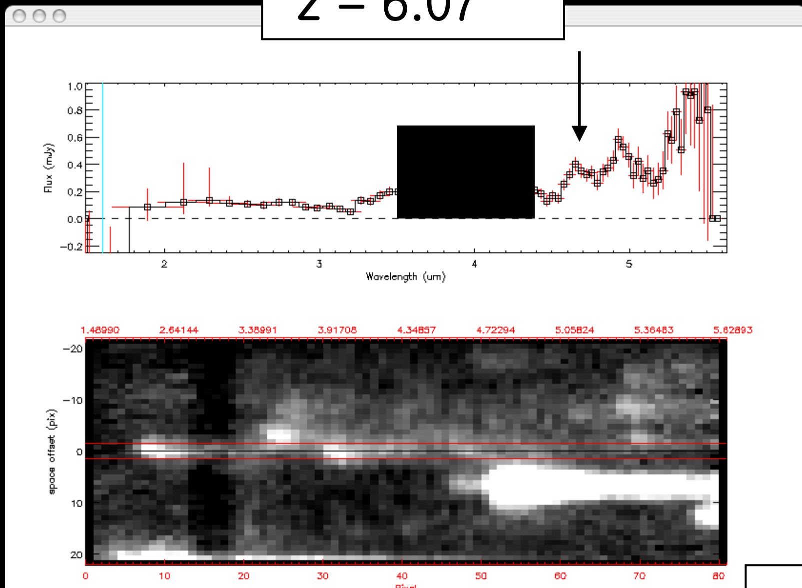
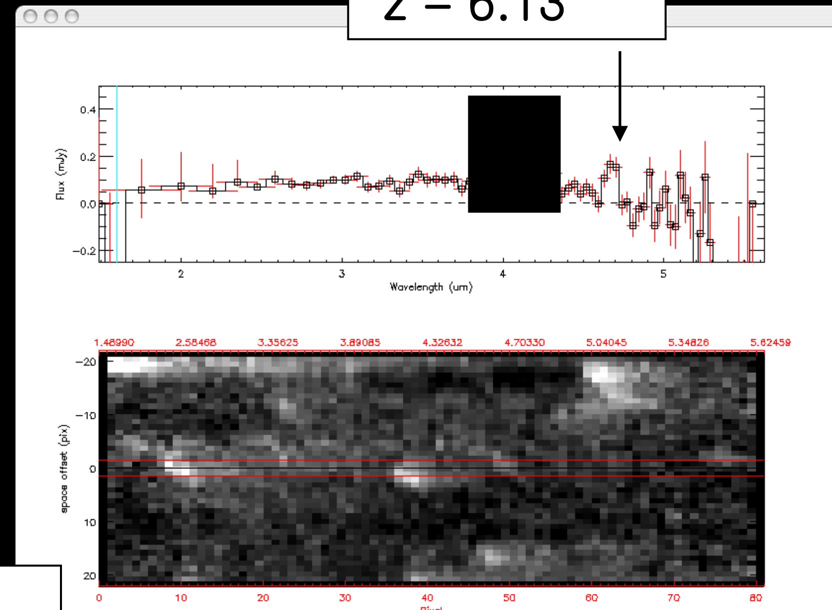
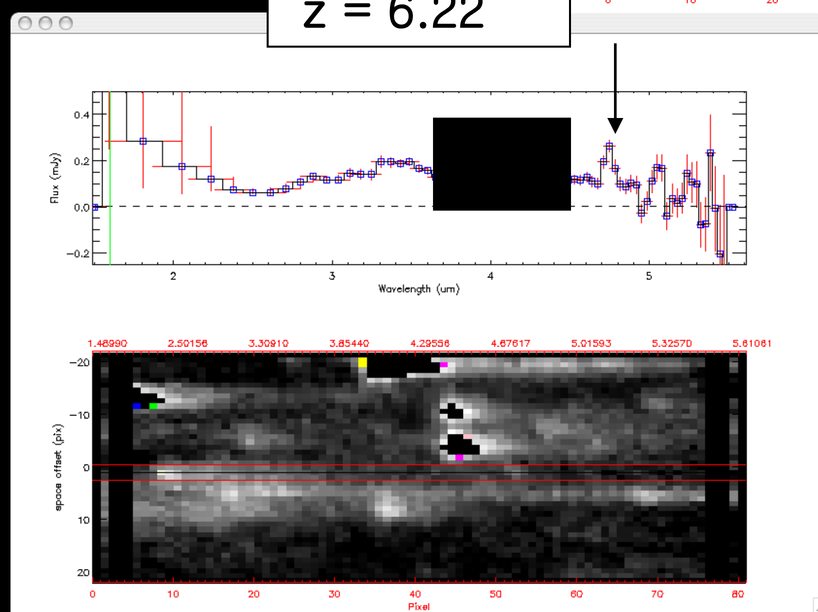
z = 6.07



z = 6.13



z = 6.22



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SMBH Mass Evolution

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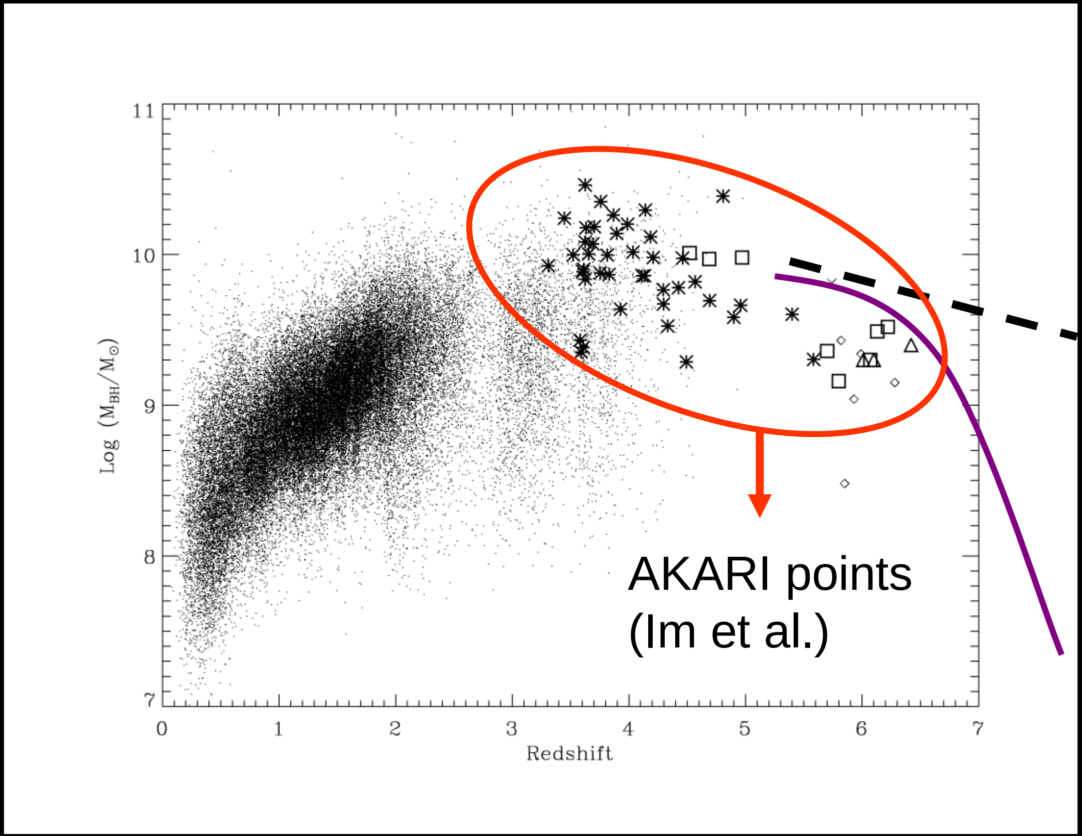

- $10^{9.3} – 10^{10.1}\ M_\odot$ ➔ A few x $10^9\ M_\odot$ SMBHs existed at z ~ 6 (0.95 Gyr)
- L_{bol}/L_{Edd} ~ 0.4 – 1.8 [0.8] ➔ Eddington-limited accretion
- No M ~ $10^{10}\ M_\odot$ SMBHs at z > ~6 (t_{univ} ~ 0.9 Gyr) - they are growing!

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How should they evolve?

- Accretion at Eddington limit
- Dustless quasars (Jiang et al. 2010)

- $M(t)=M(0)\exp[(1-\varepsilon)/\varepsilon\,(t/t_{Edd})]=M(0)\exp(t/\tau)$, with $\tau \sim 4.5 \times 10^7\,(\varepsilon/0.1)$ yrs

- X 10^8 growth ➔ 18 e-fold time ➔ t ~ 0.8 Gyr ~ age of the universe
- Luminosity evolution with $L(t) \sim \exp(t/\tau)$

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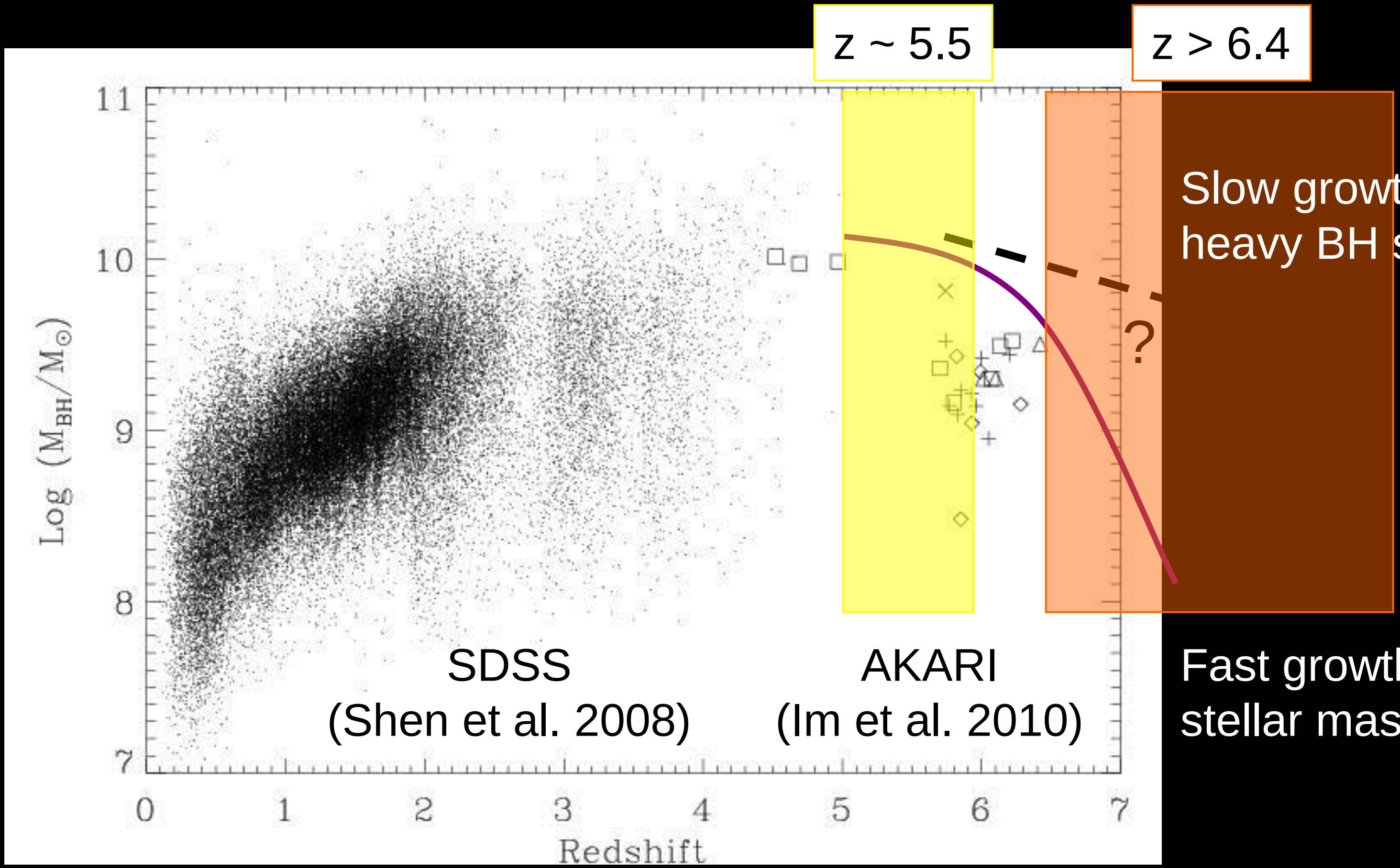
How did SMBHs grew?



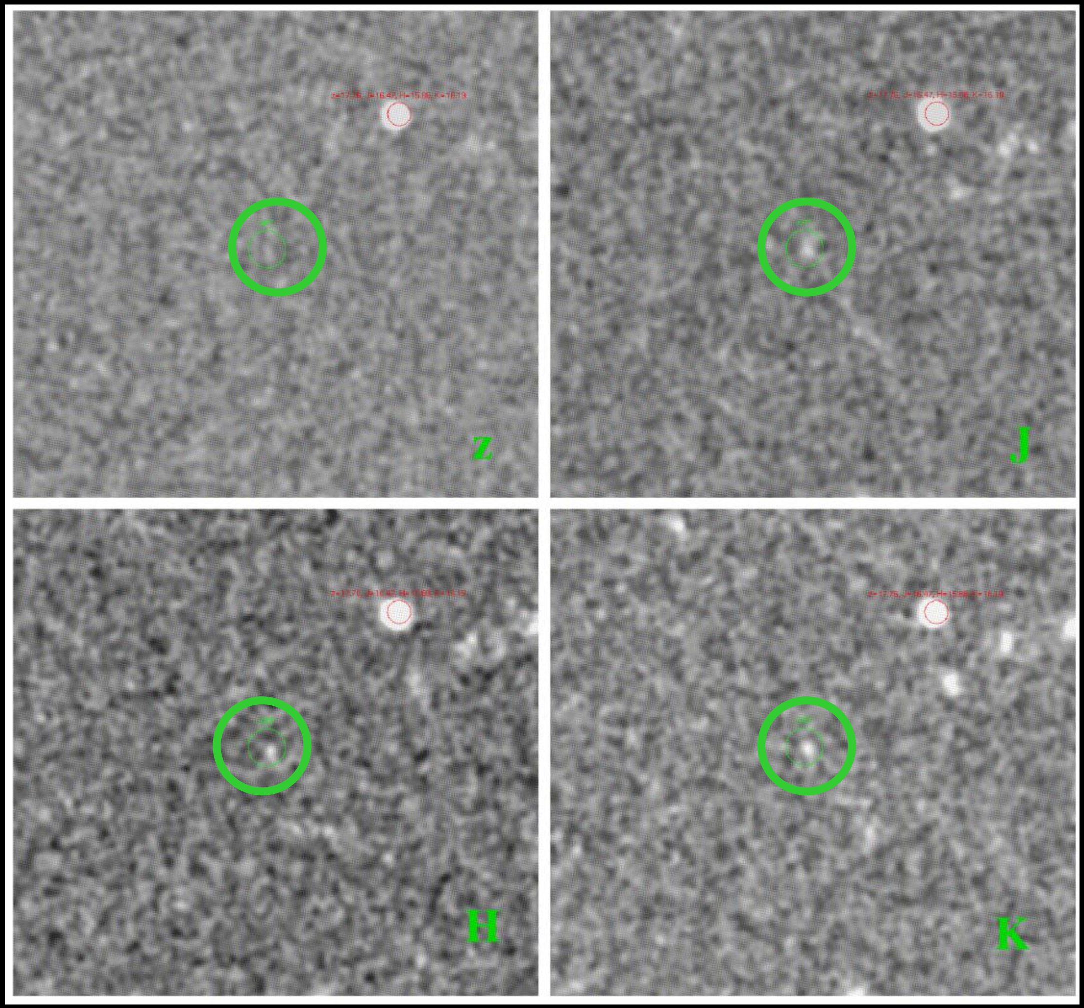
Slow growth with heavy BH seeds

Fast growth from stellar mass BHs

Infrared Medium-Deep Survey (IMS)

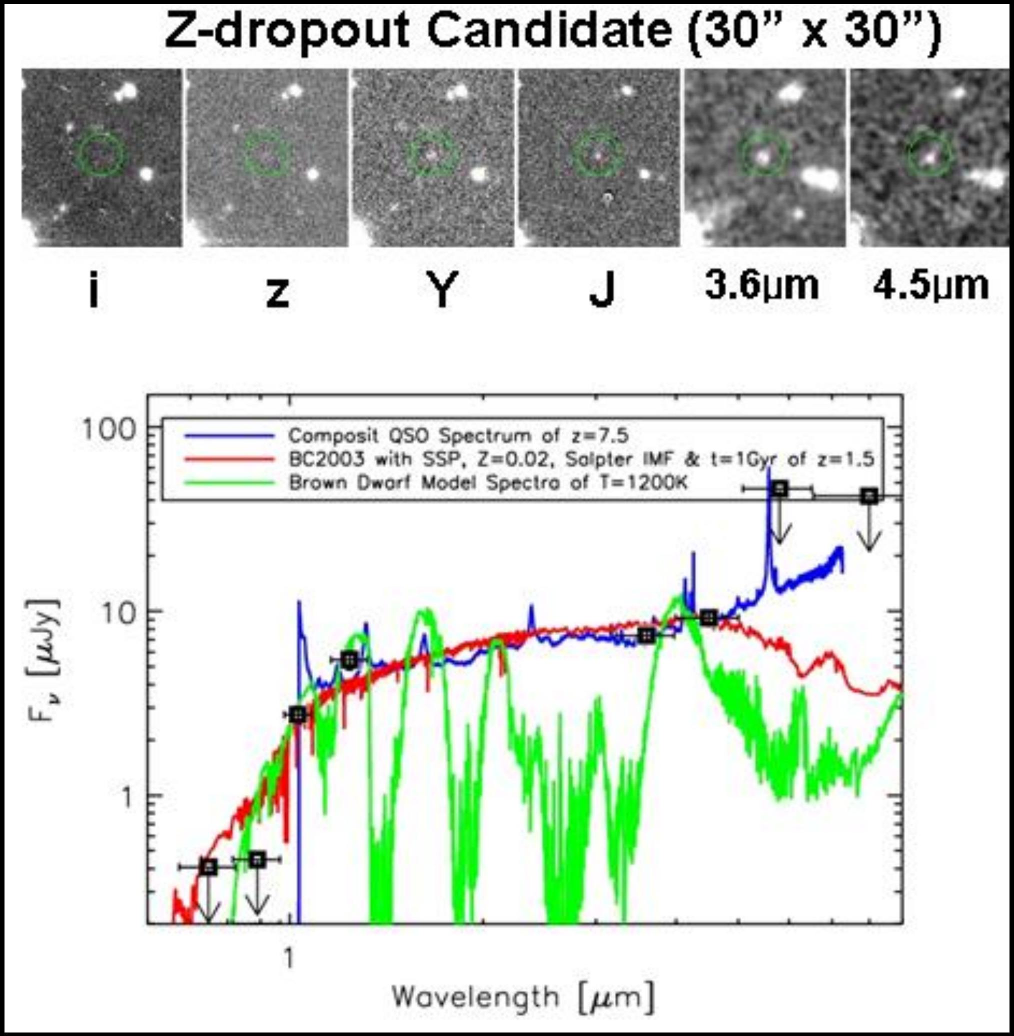
- J-band Imaging over 200 deg^2 to ~23 AB mag (+I,z,Y,…) to identify and study z > 6.5 quasars
- Currently, ~55 deg^2 covered
- Collaborative agreement with NCU (Taiwan), NASA/GSCF/Pomona College (USA) for GRB study

GRB 100905A at z ~ 7.5

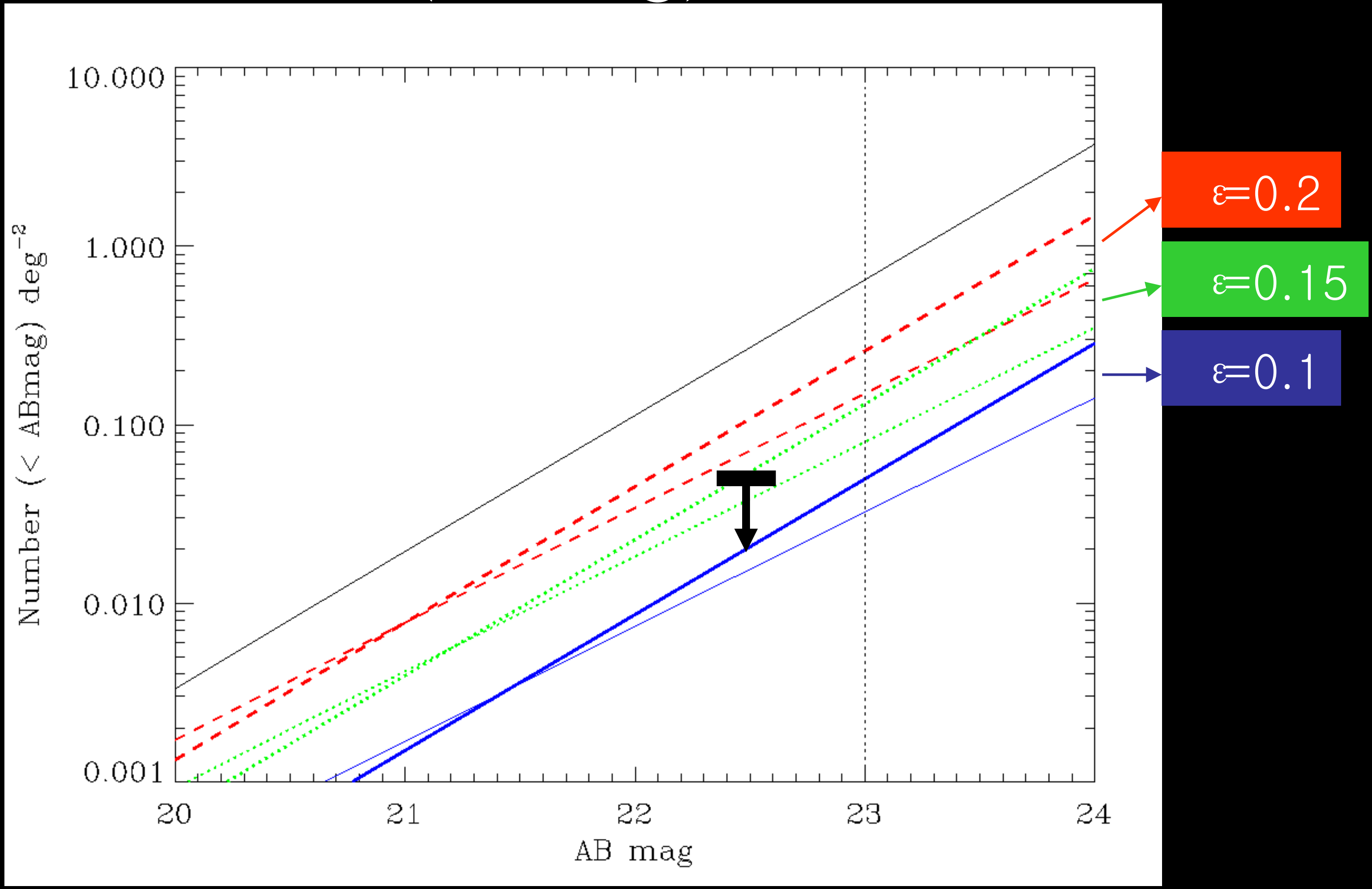


- UKIRT zJHK imaging from 15 min after the burst (Im et al. 2010, GCN Circular 11222)
- z-dropout at redshift ~ 7.5
- Third of three GRBs with short duration

Quasars at z ~ 7?



Current Limit: Luminosity Evolution (z > 6.5)



- L ~ exp[t/τ(ε)]
- Radiation eff. ε ~0.1-0.3

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Summary

- QSONG: AKARI NIR (2.5-5 micron) Spectroscopy Study of ~200 high redshit QSOs ($3.4 < z < 6.4$) and 102 low redshfit AGNs
- Rest-frame optical spectra for high redshift QSOs – Evolution of mass of SMBHs at high redshift – first detection of Hα lines at QSOs $z > 4.5$ (before JWST)
- There are ~10^9 $M_\odot$ SMBHs out to $z \sim 6$, but the most massive QSOs (10^{10} $M_\odot$) disappears beyond $z \sim 6$
- Limit on number density of quasars at $z > 6.5$