Measuring the Mass and Accretion-rate of Super-Massive Black Holes in AGN

Benny Trakhtenbrot

School of Physics and Astronomy,
Tel-Aviv University, Israel

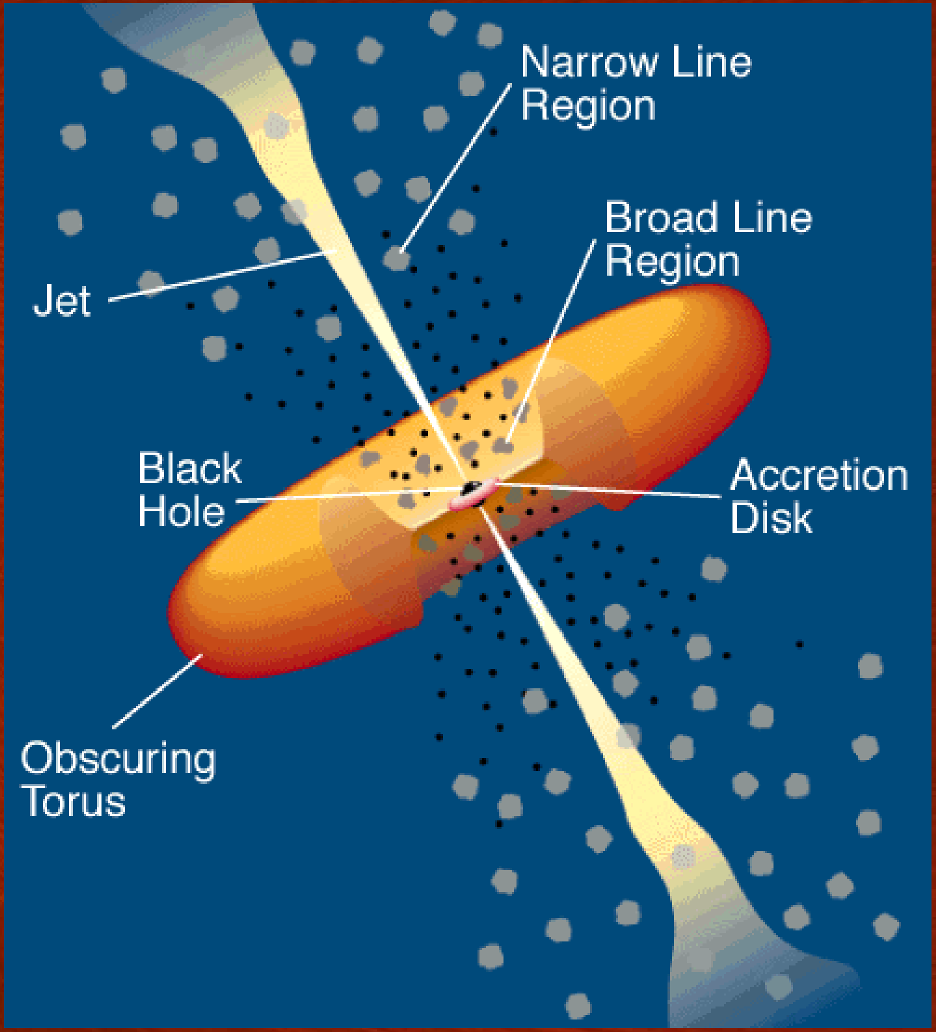
with Hagai Netzer,

Paulina Lira (U. de Chile) and Ohad Shemmer (Penn. State)

Outline

- Motivation
- How to measure Black-Hole mass and accretion
- Results from a large z<0.75 sample
- Results from a small z~2-3 sample
- Moving to higher redshifts
  - Using the MgII line
  - Our new z~4.8 program
- Conclusions

Introduction - AGN



Motivation

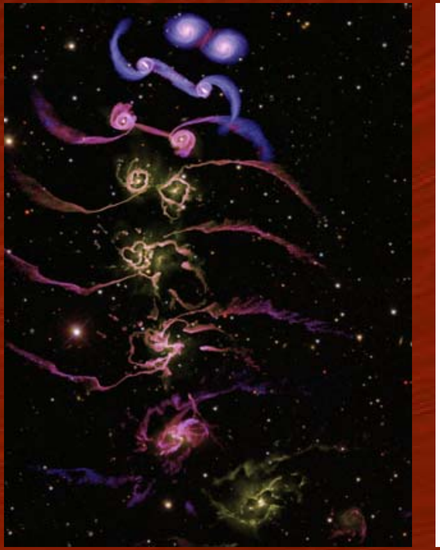
- Basic questions:
  - – What is the mass of the central BH?
  - – How much matter does it accrete? (L/L_{Edd})
  - – In which phase of the duty cycle is the AGN?
  - – What *is* the duty cycle?
- How do all these evolve with cosmic time?

(from a seed BH, through mergers to the local population…)

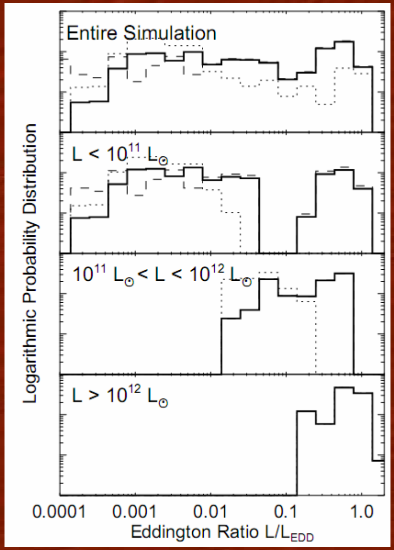
Theoretical Concepts

- Basic BH evolution:
  - Seed black hole
    $M_{\rm seed} = 10^2\text{-}10^5 M_\odot$
  - Cold gas infall due to merger (or just bars)
  - Accretion as fast as $\sim L_{\rm Edd}$

- Duty cycle would be:
  - Fraction of active galaxies
    ➔ ~1% of lifetime
  - Time scale of gas infall
    ➔ ~1 Gyr
  - Simulations of mergers
    ➔ ~0.1-1 Gyr



Di-Matteo+05



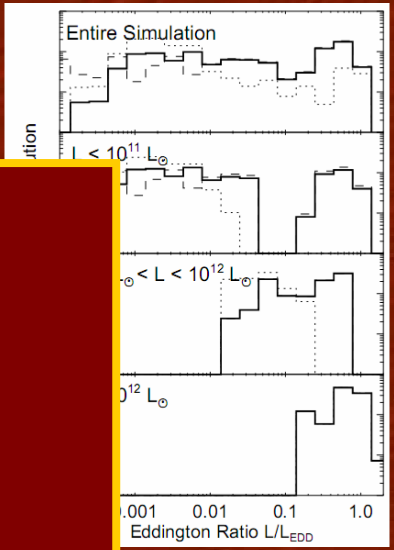
Hopkins+05

$$f_{\rm Edd}(z) = \begin{cases} 1 & z \geqslant 6 \\ 0.078(1+z)^2 - 0.623(1+z) + 1.545 & 3 \leqq z < 6 \\ f_{\rm Edd,0}[(1+z)/4]^{1.4} & z < 3, \end{cases}$$

Volonteri+06

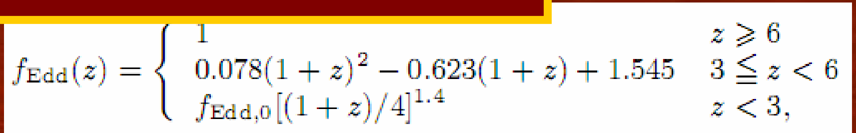
Theoretical Concepts

- Basic BH evolution:
  - Seed black hole
    $M \quad = 10^2 - 10^5 M$
  - C
    r
  - A
- Dut
  - F
    T
  - T
    ➔ ~1 Gyr
  - Simulations of mergers
    ➔ ~0.1-1 Gyr



opkins+05

How can we *measure* any of these properties?

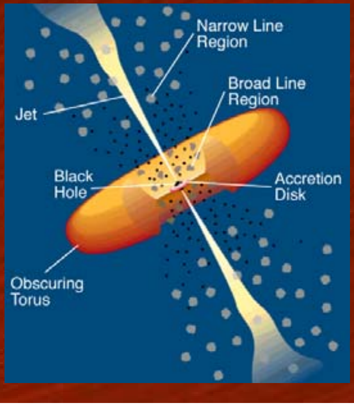


$$f_{\rm Edd}(z) = \begin{cases} 1 & z \geqslant 6 \\ 0.078(1+z)^2 - 0.623(1+z) + 1.545 & 3 \leqq z < 6 \\ f_{\rm Edd,0}[(1+z)/4]^{1.4} & z < 3, \end{cases}$$

Volonteri+06

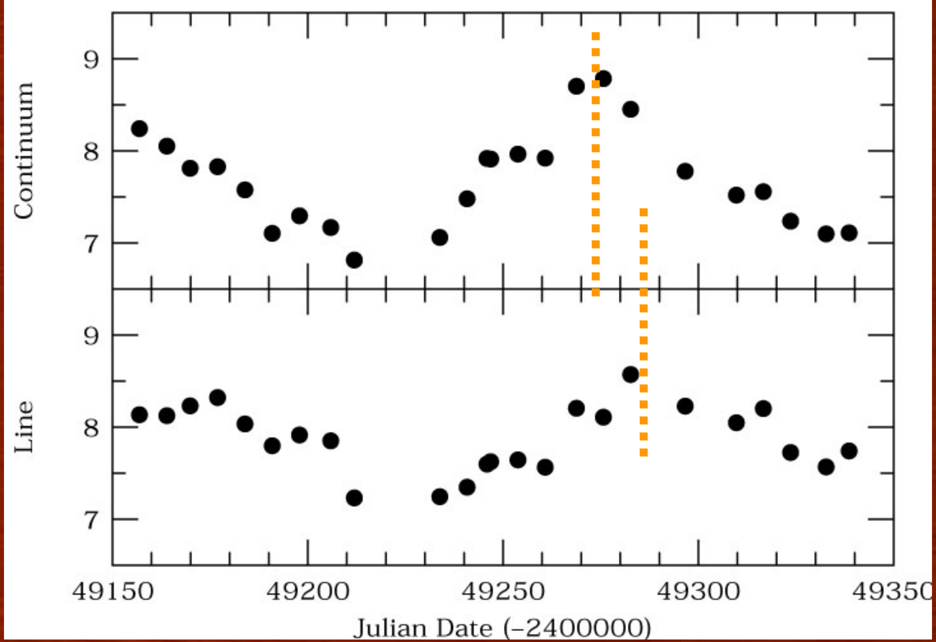
Basic Reverberation Mapping

- AGNs are variable sources



- Time lags between different emission components indicate physical separations:

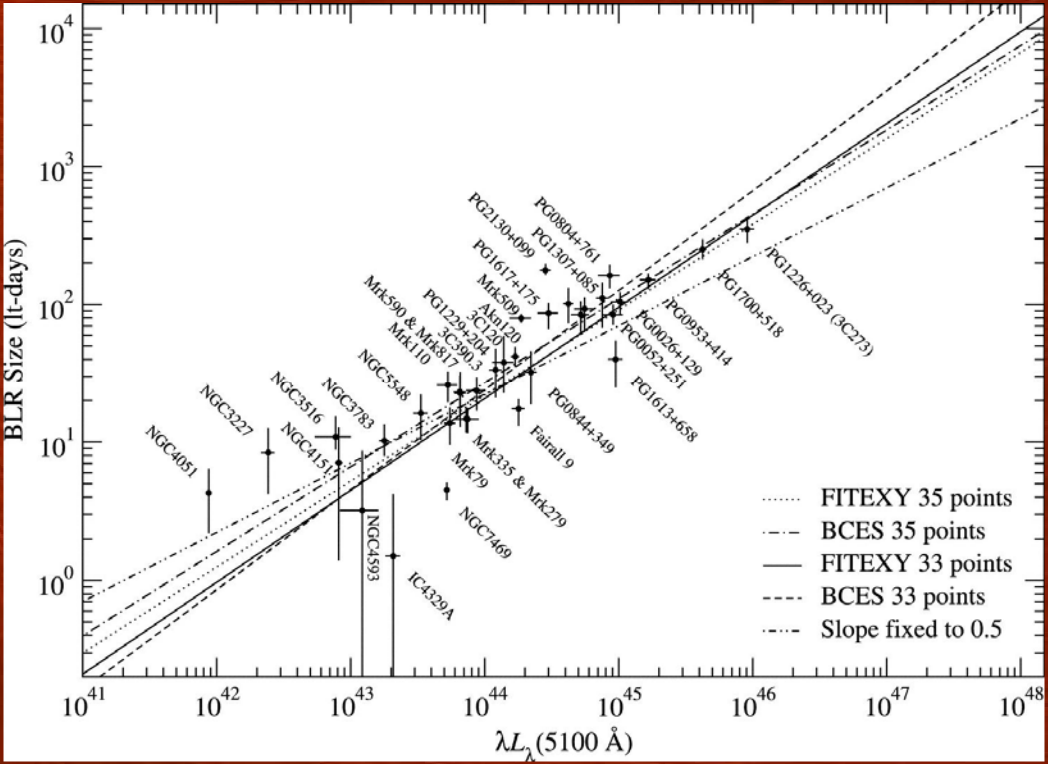
$$\boxed{R \simeq c \cdot \Delta t}$$



Basic Reverberation Mapping

- Kaspi et al. (2000, 2005), from reverberation mapping:

$$\boxed{R_{BLR} \propto \lambda L_{\lambda}(5100\text{Å})^{0.65\pm0.05}}$$



About a decade for 35 low-z low-L AGN

Estimating the Black Hole Mass

- Since the BLR is (generally) virialized, a “single epoch” mass estimation is now possible.

  The best example is <u>“The Hβ method”</u>:

$$\boxed{M_{BH} = G^{-1} R_{BLR} f \cdot V_{BLR}^2 \rightarrow 1.05\times10^{8}\left(\frac{L_{5100}}{10^{46}\ \mathrm{erg\ s^{-1}}}\right)^{0.65}\left[\frac{\mathrm{FWHM(H}\beta)}{1000\ \mathrm{km\ s^{-1}}}\right]^{2} M_{\odot}}$$

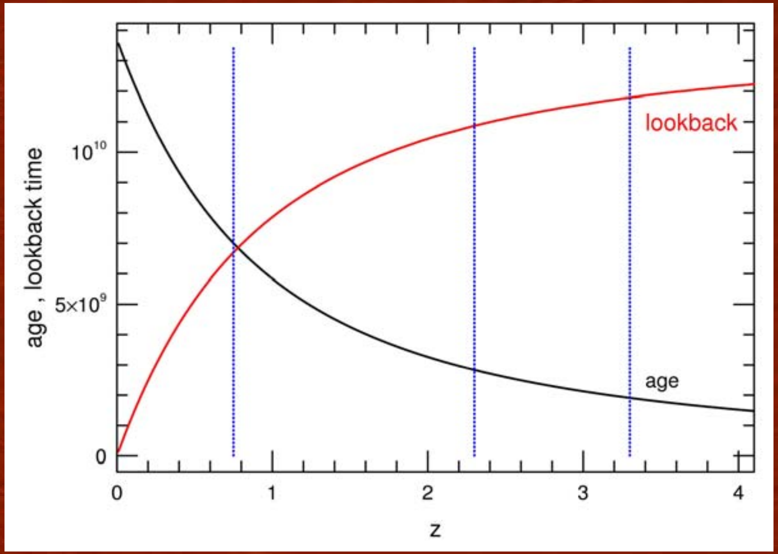
- L/L_{Edd} is a probe of the accretion rate:

$$\boxed{L_{Edd} \simeq 1.5\times10^{38}\left(\frac{M_{BH}}{M_{\odot}}\right)\mathrm{erg\ s^{-1}} \rightarrow \quad {L_{Bol}}\big/{L_{Edd}} \simeq {7L_{5100}}\big/{1.5\times10^{38} M_{BH}}}$$

Note: Estimating the Growth Time

- from the *mass accretion rate*, we can estimate how long would it take to grow such a BH (Salpeter 1964)

$$t_{grow} = 4\times10^{8}\,\frac{\eta(1-\eta)}{L/L_{Edd}}\,\log\left(\frac{M_{BH}}{M_{\odot}}\right)\frac{1}{f_{active}}\ \mathrm{yr}$$



- We'll assume:

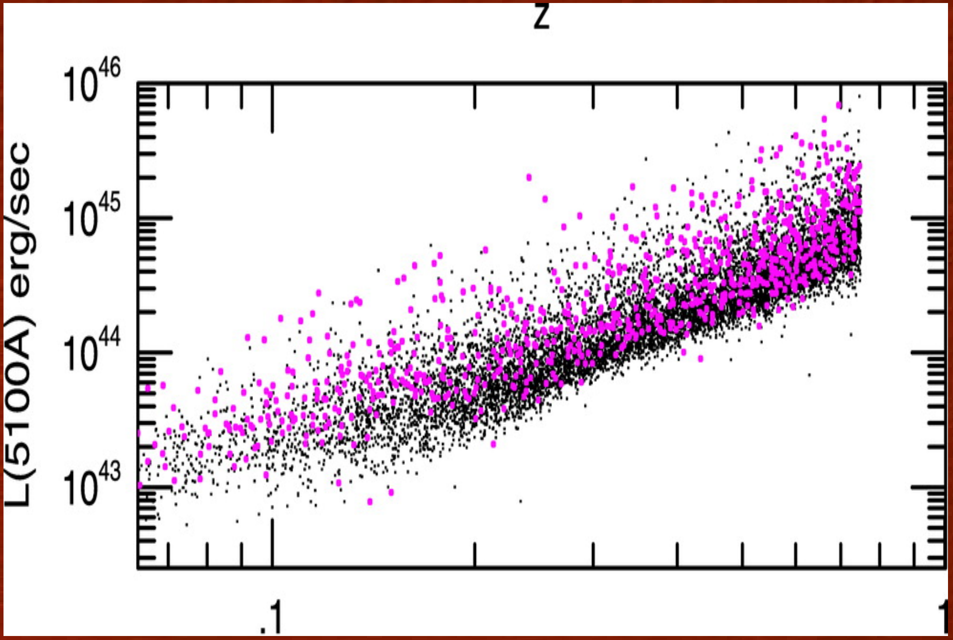
$\eta = 0.1$ (common)

$f_{active} = 1$ ("best case")

Estimating the Black Hole Mass

- We have an observational bias due to the flux limited selection.

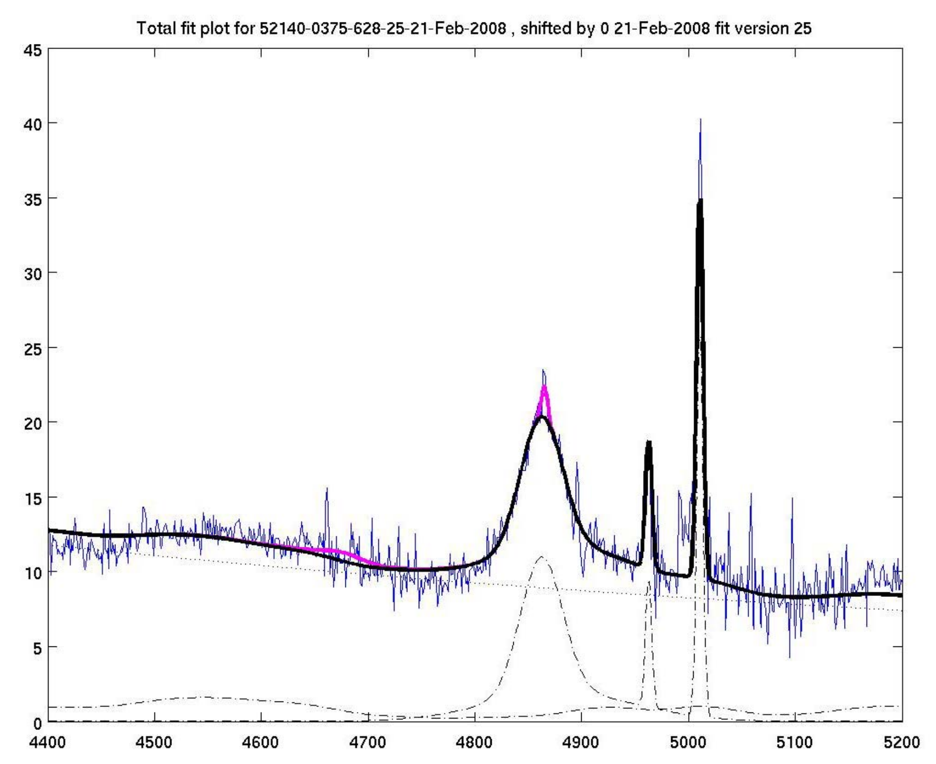
- Both M_{BH} and L/L_{Edd} correlate with luminosity, so most massive and/or fast-accreting BHs are "easy targets".



→ Choose the faintest targets which are feasible to observe, to better probe the entire population

Results for $z<0.75$

- Any observed spectrum with $\mathrm{H}\beta$ and L_{5100} is suitable.
- The SDSS has ~10,000 AGNs with $z<0.75$, where the $\mathrm{H}\beta$ is measurable.
- We have fitted them <u>automatically</u> and analyzed statistical trends



Netzer & Trakhtenbrot (2007), *ApJ 645*, 754

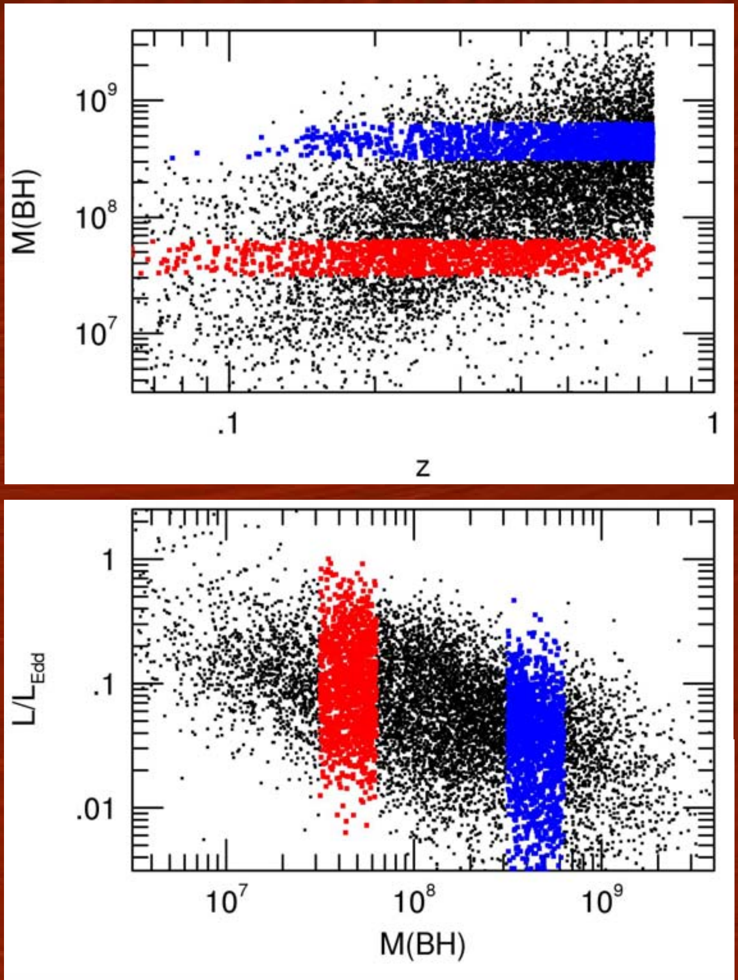
Results for $z<0.75$

Netzer & Trakhtenbrot (2007)

Some “well known truths”…

- Smaller AGNs are currently active

- More massive BHs accrete slower



🟥 $M_{BH}=10^{7.6}$

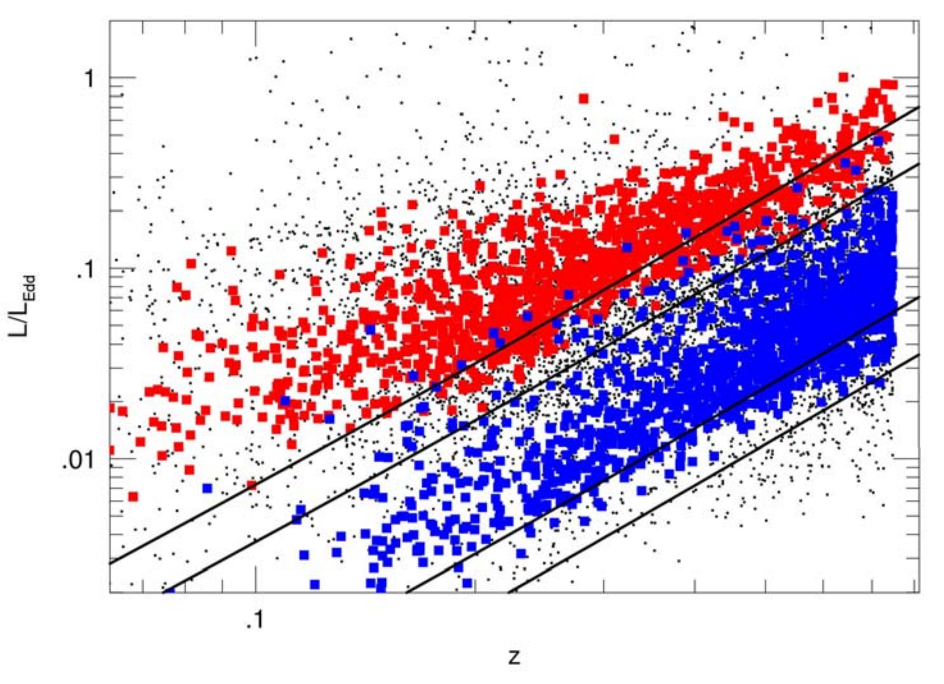
🟦 $M_{BH}=10^{8.6}$

Results for $z<0.75$

Netzer & Trakhtenbrot (2007)

…some new results…

- Accretion rate increases with z for all M_{BH} values



🟥 $M_{BH}=10^{7.6}$

🟦 $M_{BH}=10^{8.6}$

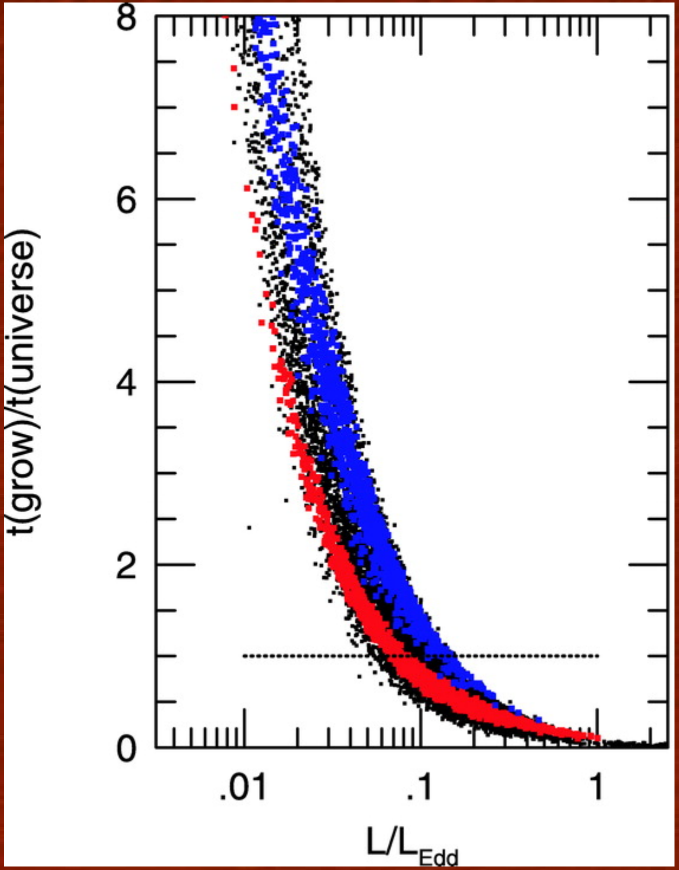
Results for $z<0.75$

Netzer & Trakhtenbrot (2007)

… and a small "problem":

- A large fraction (~2/3) of BHs did not have enough time to gather their mass by current accretion rate.
- recall this is without "cycles"!
- They have probably accreted at a higher rate in the past…
  ("L/L_{Edd} rises with z")

➔ **We need a sample with higher redshift!**



$$t_{grow} = 4\times10^{8}\,\frac{\eta(1-\eta)}{L/L_{Edd}}\log\left(\frac{M_{BH}}{M_{\odot}}\right)\frac{1}{f_{active}}\ \mathrm{yr}$$

The $z\sim2\text{-}3$ sample

- The Hβ line may also be observed in one of the NIR bands:
  - *H*-band (1.6 μm) ⇔ $z\sim2.3$
  - *K*-band (2.2 μm) ⇔ $z\sim3.4$
- We have a well-defined sample of 44 sources

29 very luminous QSOs
($47 < \log L_{\rm Bol} < 48$)

15 moderate QSOs
($46 < \log L_{\rm Bol} < 47$)

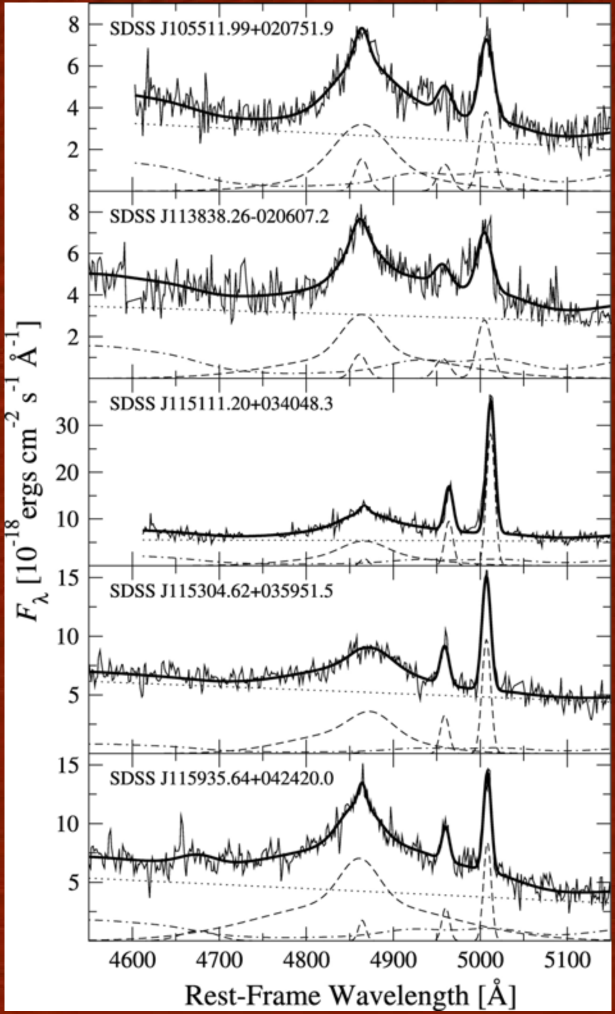
Observed by 4m class telescopes
(Shemmer et al. 2004)

Observed by GNIRS on the
Gemini-South 8m telescope

Results from the *z*~2-3 sample

Netzer, Lira, Trakhtenbrot, Shemmer & Cury 2007, *ApJ 671*, 1256

GNIRS on Gemini-S

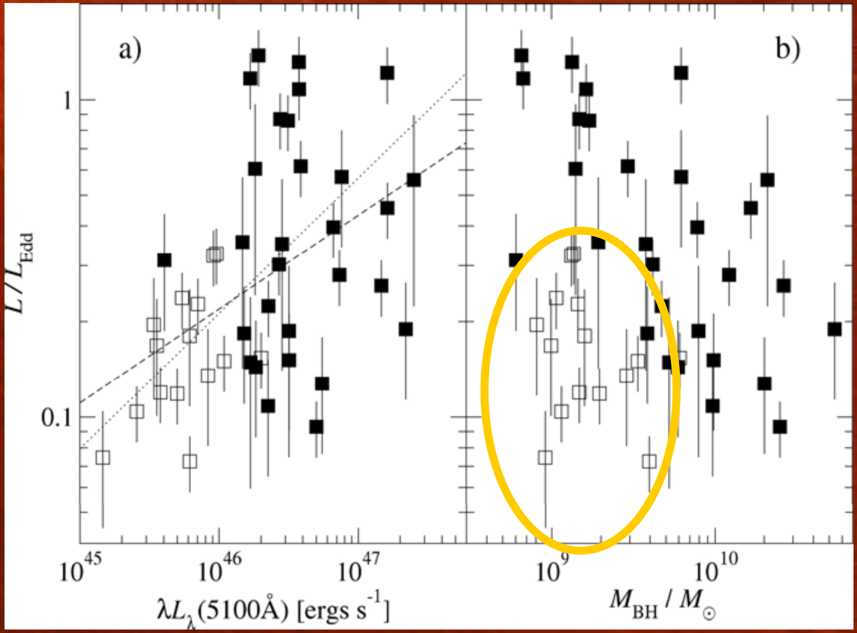


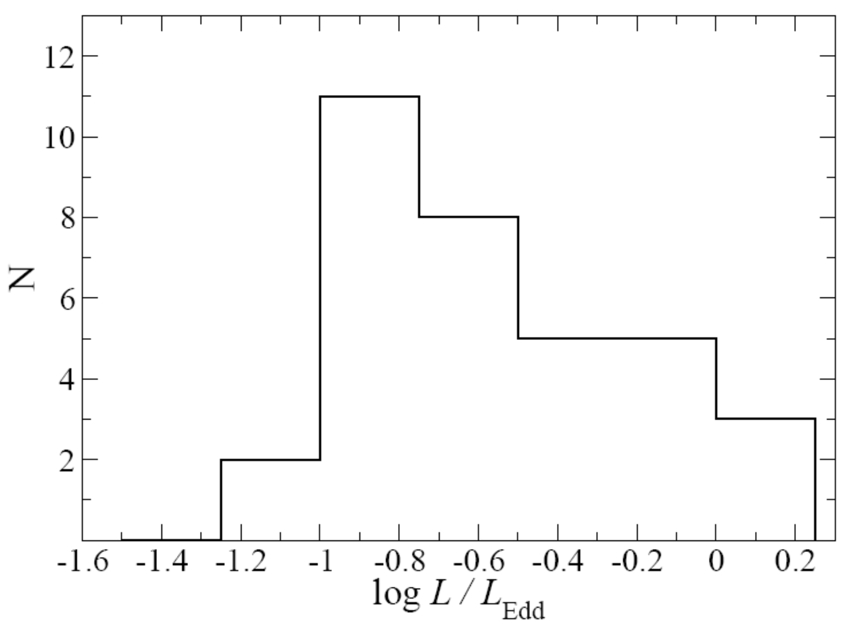
Results from the z~2-3 sample

Netzer et al. (2007)

1. We find low-M_{BH}, low-L/L_{Edd} sources

2. A broad range of L/L_{Edd}
   - certainly not around 1
   - probably not log-normal





Results from the $z\sim2$-3 sample

Netzer et al. (2007)

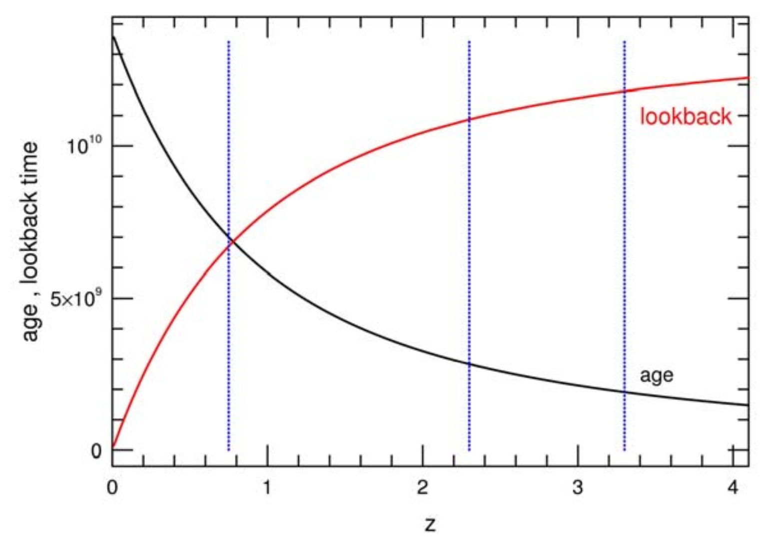
- And what about the time it took to grow *these* BHs?

$$t_{grow} = 4\times10^{8}\,\frac{\eta(1-\eta)}{L/L_{Edd}}\,\log\left(\frac{M_{BH}}{M_{\odot}}\right)\frac{1}{f_{active}}\ \mathrm{yr}$$

- Again, most of the sample (and all the lower L/L_{Edd} sources) has t_{grow} larger than the age of the universe.

➔ So again, they "must have accreted more rapidly in the past…"

(but when? Time is getting short!)



What's Next?
Using MgII to measure M_{BH}

- Our faithful Hβ line has taken us to z~3.4, so what can we do in order to extend the studied redshift?

- Mclure & Dunlop (2004) established an alternative M_{BH} estimator, based on

  $\lambda L_\lambda(3000\text{Å})$ & FWHM(MgII λ2800Å)

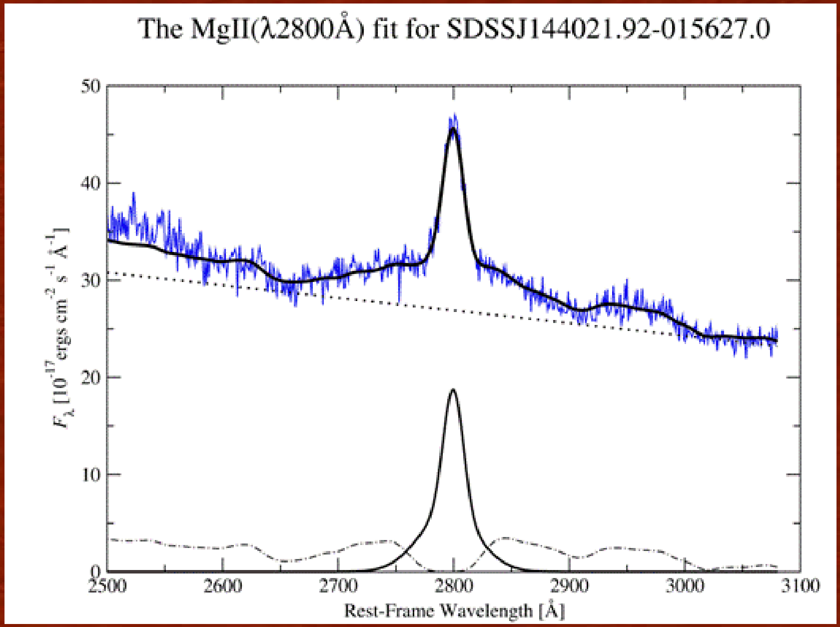
  (same form as Hβ estimator, but with other parameters)

- Has a few drawbacks:
  1. *What IS* L_{3000}? Balmer continuum, blended FeII/III lines ….
  2. NIR bands don't always allow observing broad MgII & L_{3000}.

Using MgII to measure M_{BH}

- We have developed another method, based on the line Luminosity itself, instead of continuum. (Trakhtenbrot & Netzer, in prep.)

- As accurate as McLure & Dunlop (2004), more usable for high-z studies.



What's Next? Using SDSS

- With the MgII method, we can extend our SDSS study to $z<2.1$

- This should provide us with M_{BH} and L/L_{Edd} measurements for ~40,000 QSOs

- Similarly, smaller samples have been studied by McLure & Dunlop (2004), Shen et al. (2008) and others…

What's Next? Moving to z~4.8

- Lets repeat the same strategy – observe MgII in one of the NIR bands
- We place the MgII in the *H*-band ➔ z~4.8
- Why not *K*-band? There are numerous $z > 6$ QSOs (Kurk et al. 2007), but these are only the few ultra-luminous ones and do not represent the population.
- We aim at a flux-limited sample of ~50 sources

What's Next? Moving to $z{\sim}4.8$

- We are observing the first duty cycle / first merger.

- A combined effort of the largest telescopes and best instruments:

Bright sample

Gemini-N / NIRI

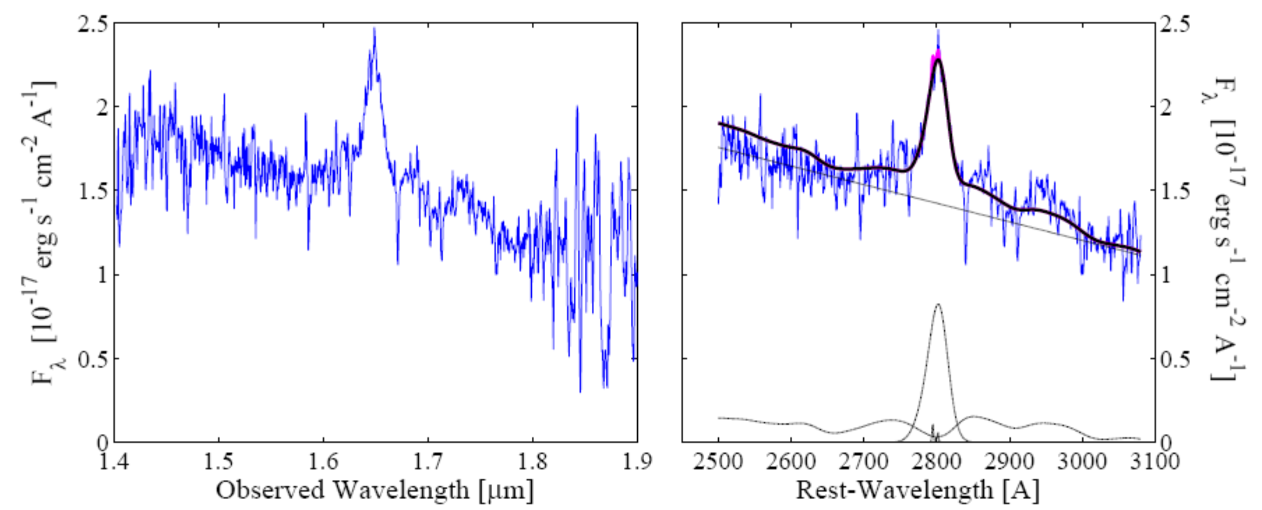
Faint sample

VLT / SINFONI

What’s Next? Moving to $z\sim4.8$

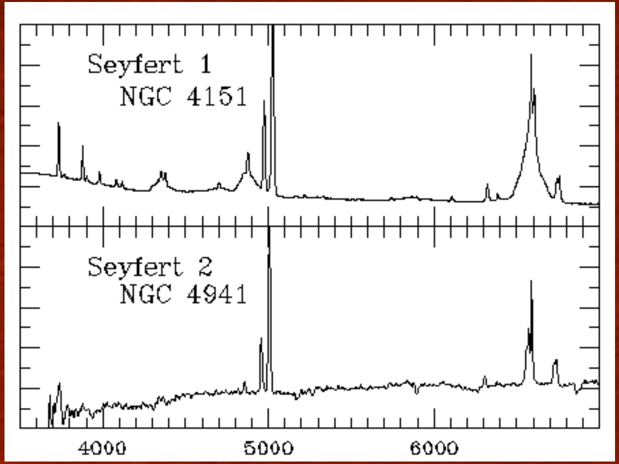
- We have already observed 15 targets
- Got time for total of ~40
- First results, for “J2225”:

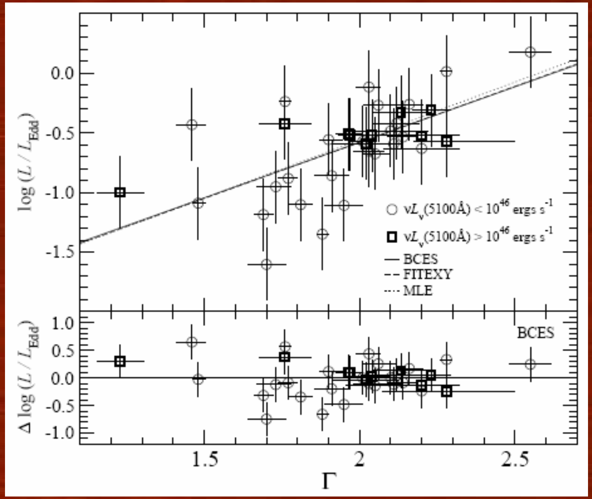
$M_{\mathrm{BH}} = 1.8\text{-}2.6\times10^{9}\,M_{\odot}$ $L/L_{\mathrm{Edd}} \approx 0.65\text{-}0.95$



What's Next? Type-2 AGN

- In type-2 AGN we can't see the BLR ➔ all M_{BH} estimators would not work.
- Shemmer et al. (2008) have developed an estimator for L/L_{Edd}, based on the hard X-ray spectrum.
- Usable for 100s of type-2 AGN in deep *Chandra / XMM* fields.
- Given $L/L_{Edd,}$ you can also deduce M_{BH}, with some probe of $L_{Bol.}$





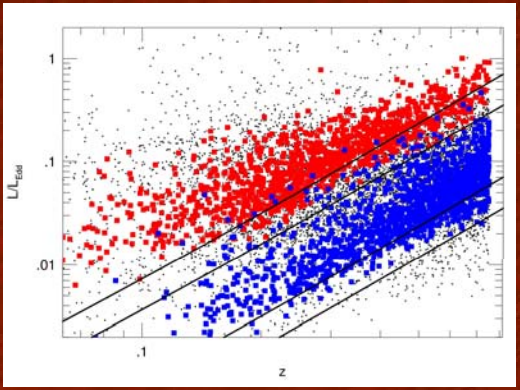
Conclusions

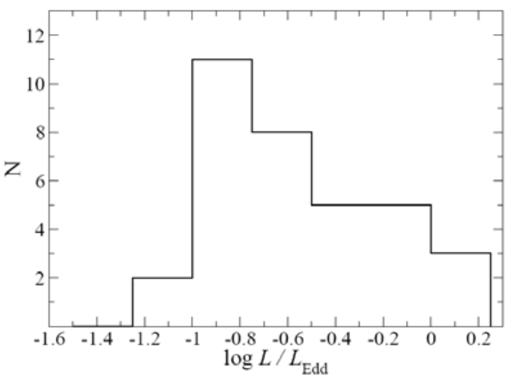
- We have good estimators of $M_{\rm BH}$ & $L/L_{\rm Edd}$

- From large, low-z samples:
  - $L/L_{\rm Edd}$ correlates with z, for every $M_{\rm BH}$
  - Most BHs have “too low” $L/L_{\rm Edd}$
  - ➔ BHs accreted more rapidly in the past

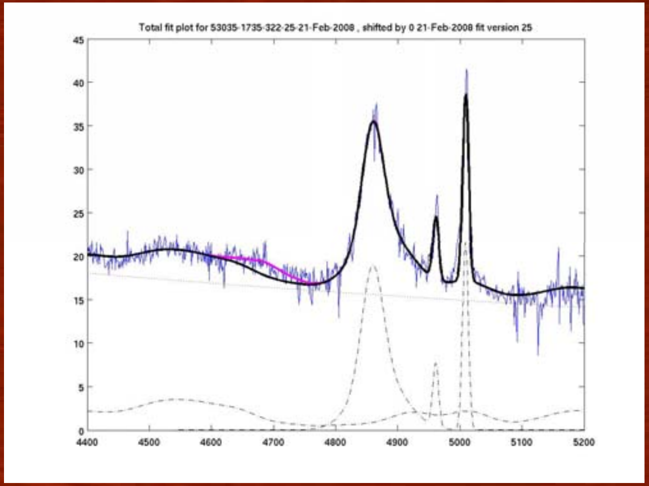
- From small, z~2-3 sample:
  - Broad dist. of $L/L_{\rm Edd}$, far from unity
  - Most BHs have “too low” $L/L_{\rm Edd}$

- Observing a well defined sample at z~4.8 would probe first cycle
  (“we need more telescope time…”)





Thank You!


Total fit plot for 53035-1735-322-25-21-Feb-2008 , shifted by 0 21-Feb-2008 fit version 25
45
40
35
30
25
20
15
10
5
0
4400
4500
4600
4700
4800
4900
5000
5100
5200