Observing the Fast Growth of Black Holes at $z \sim 4.8$

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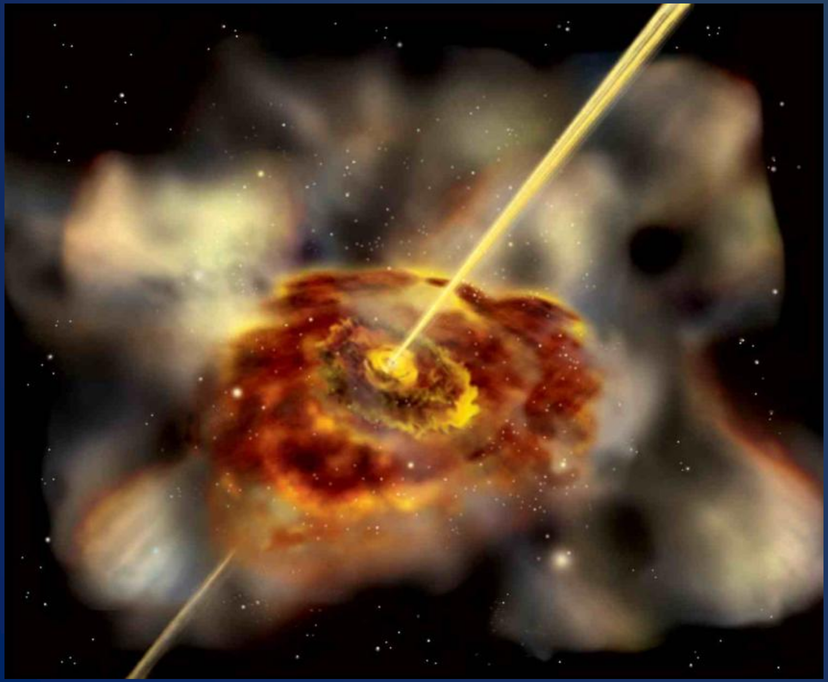
Growing Super Massive Black Holes

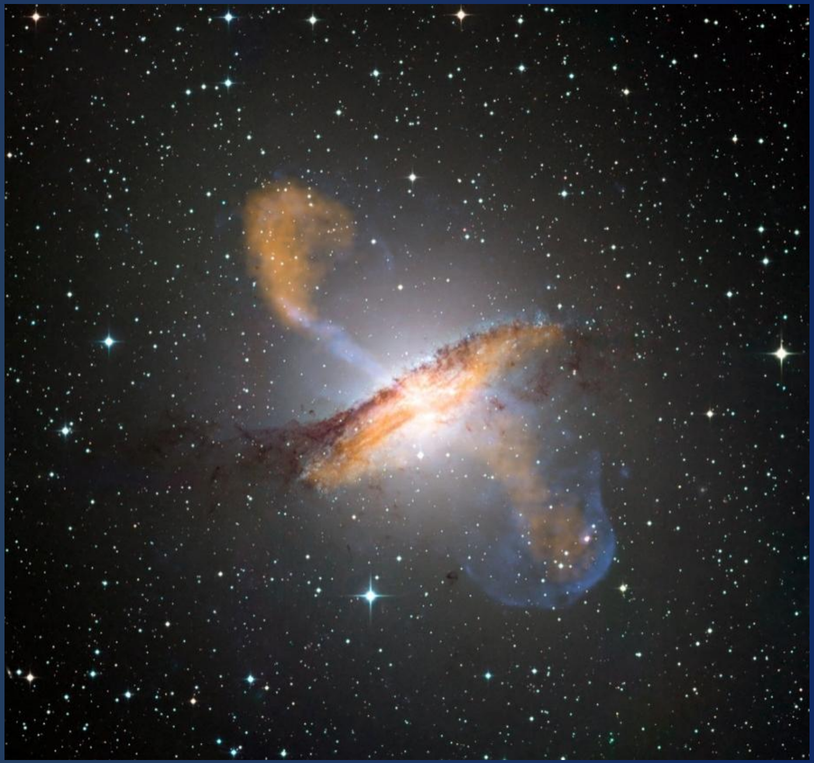
- Most galaxies host a super-massive black hole (SMBH)

$$M_{BH} \sim 10^{6} - 10^{10}\ M_{\odot}$$

- Accreting mass – “active”

$$L_{Bol} = \eta \dot{M}_{BH} c^{2} \sim 10^{42} - 10^{48}\ \mathrm{erg/s}$$



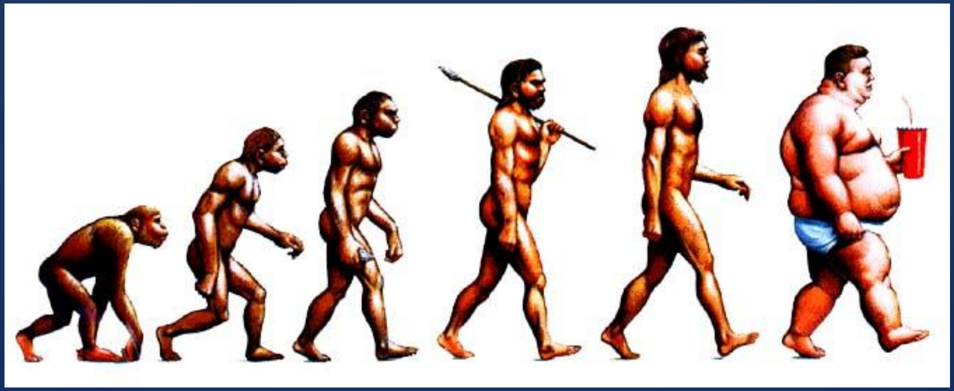


Observed from γ-rays to radio, up to z ~ 7

focus on UV-optical spectra of un-obscured, point-like sources

Motivation

- Basic questions:
  - What are their masses ?
  - What is the accretion rate ($L_{\mathrm{Bol}}/L_{\mathrm{Edd}}$) ?
- How do these properties evolve ?
  (from a seed BH, through mergers to the local population…)
- When did SMBHs accumulate most of their mass?



Outline

- Measuring BH masses and growth rates
- Clues from large optical surveys ($z < 2$)

  … and small samples at $z \sim 2$ - 3.5
- A new sample at $z \sim 4.8$:
  - Observations
  - Growth from seed BHs
  - Forward evolution
- Testing the merger-driven scenario at high z
- Overall evolution of BH masses

When do SMBHs Gain Most of Their Mass?

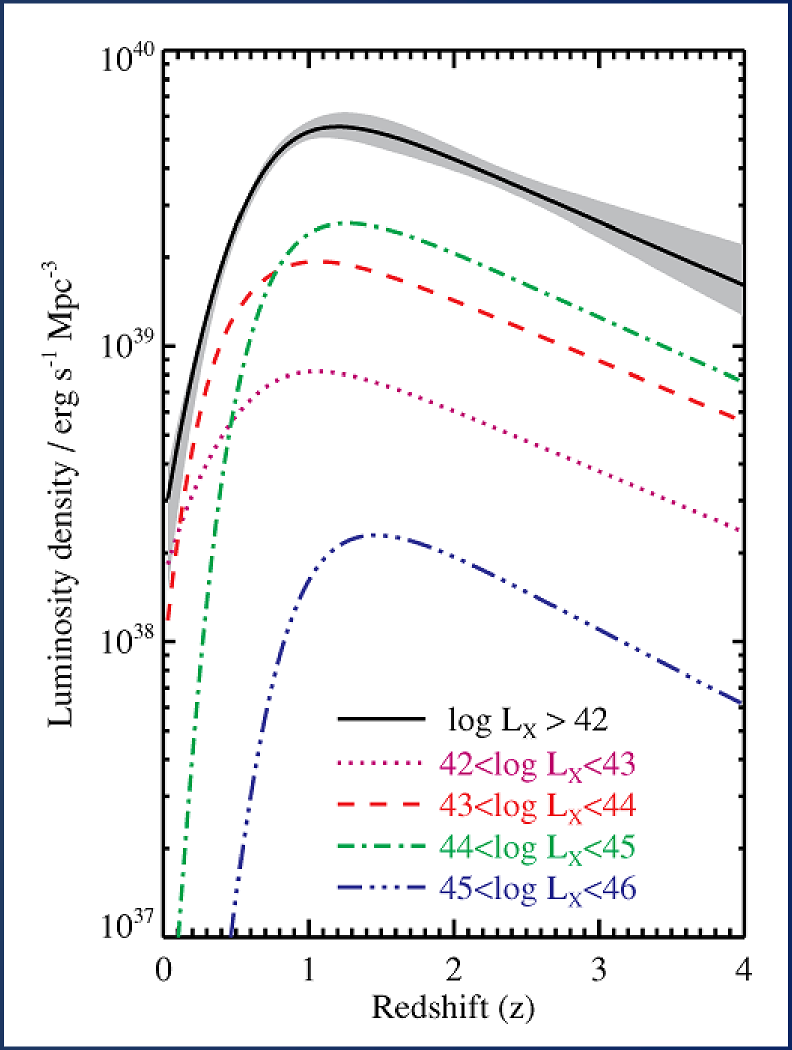
- Observed distribution of luminosities traces accretion

- The accretion history AGNs peaks at z~1-2

- Integrating over Quasar Luminosity Function:

  ➔ smaller BHs grow at lower z

- Problem Solved ?



Aird et al.(2009)

When do SMBHs Gain Most of Their Mass?

- Not really…
  unfortunately, the luminosity is degenerate:

$$\boxed{L_{Bol} = M_{BH} \times \left({L_{Bol}}\big/{M_{BH}} \right) \propto M_{BH} \times \left({L_{Bol}}\big/{L_{Edd}} \right)}$$

- $L_{\mathrm{Bol}}/L_{\mathrm{Edd}}$ ➔ growth times
  accretion disk structure
  feedback models

➔ Measure M_{BH} and $L_{\mathrm{bol}}/L_{\mathrm{Edd}}$ across redshift space

Measuring BH Masses and Growth Rates

1. Observe either the Hβ or MgII(2800Å) broad emission lines

   - Measure their width and the adjacent continuum
   - Estimate the distance to the line-emitting region - $R_{BLR} \sim (L_\lambda)^\gamma$
     (e.g., Kaspi et al. 2000, 2005; Peterson et al. 2004; ...)

2. Combine observables to a virial product

$$\boxed{M_{BH} = 3.2 \times 10^6 \left(\frac{L_{3000}}{10^{44}\,\mathrm{erg\,s^{-1}}} \right)^{0.62} \left(\frac{\mathrm{FWHM(MgII)}}{1000\,\mathrm{km/s}} \right)^2 M_\odot}$$

McLure & Dunlop (2004)

3. Accretion rate:

   f_{Bol} ~ 3.5-6 (decreases with L)

$$\boxed{\frac{L_{Bol}}{L_{Edd}} \simeq \frac{f_{Bol} \cdot L_{3000}}{1.5 \times 10^{38} \left(M_{BH} / M_\odot \right)}}$$

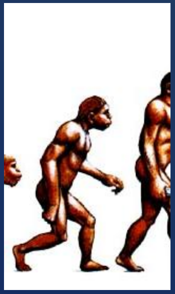
Measuring BH Masses and Growth Rates

1. Observe either the Hβ or MgII(2800Å) broad emission lines

   other lines are unreliable (Baskin & Laor 2005; Netzer et al. 2007; Shen et al. 2008; Trakhtenbrot & Netzer in prep.)

➔ Optical surveys (SDSS, 2QZ, …) can cover $z < 2$

➔ Higher redshifts must be observed in restricted NIR bands ➔ $z \sim 2.4, 3.3, 4.8$ and 6.2



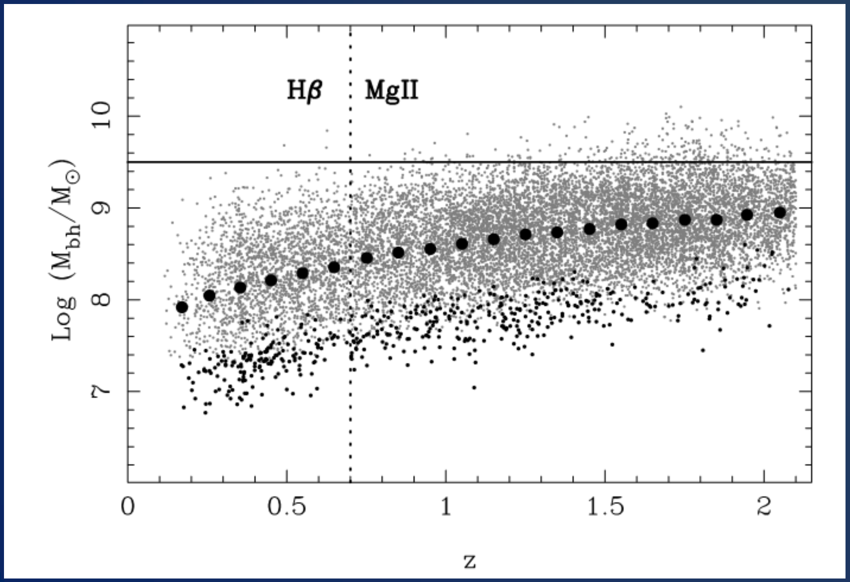
… ? …

… ? …

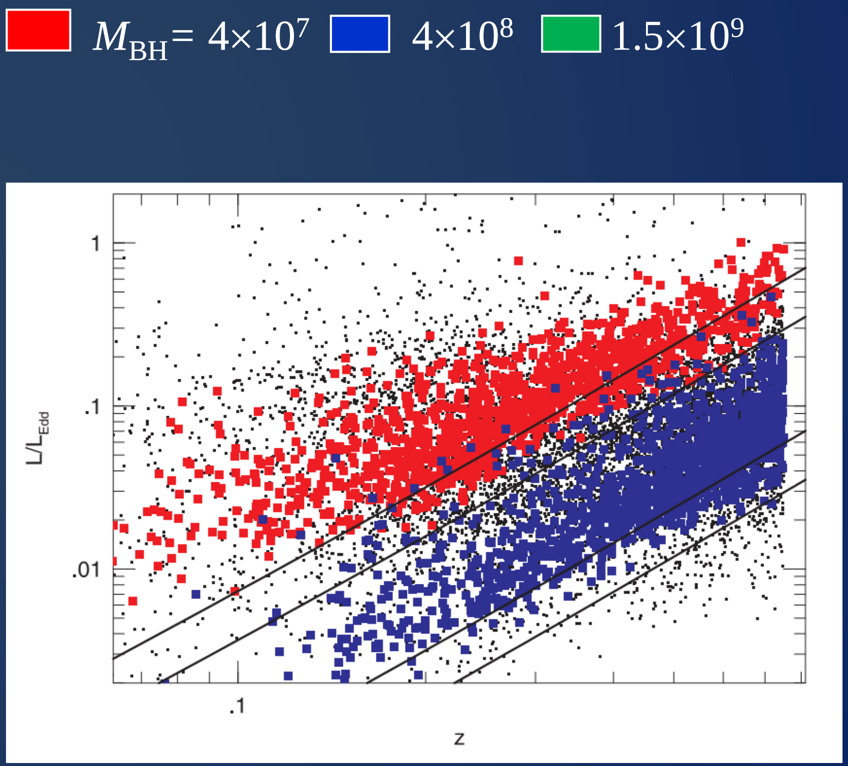
Clues from large optical surveys ($z < 2$)

At low redshift very massive BHs ($M_{BH} \geq 10^9\, M_{\odot}$) exist, but:

1. Only the less-massive BHs are accreting, and at a slow rate



McLure & Dunlop (2004)

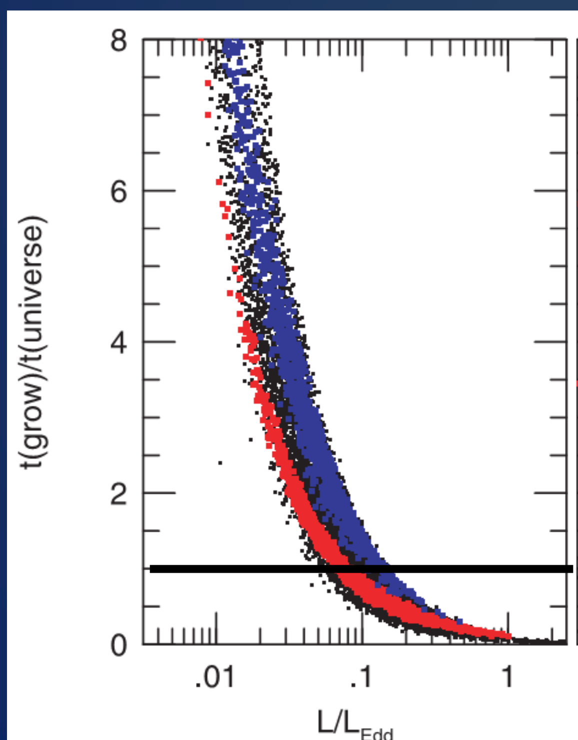


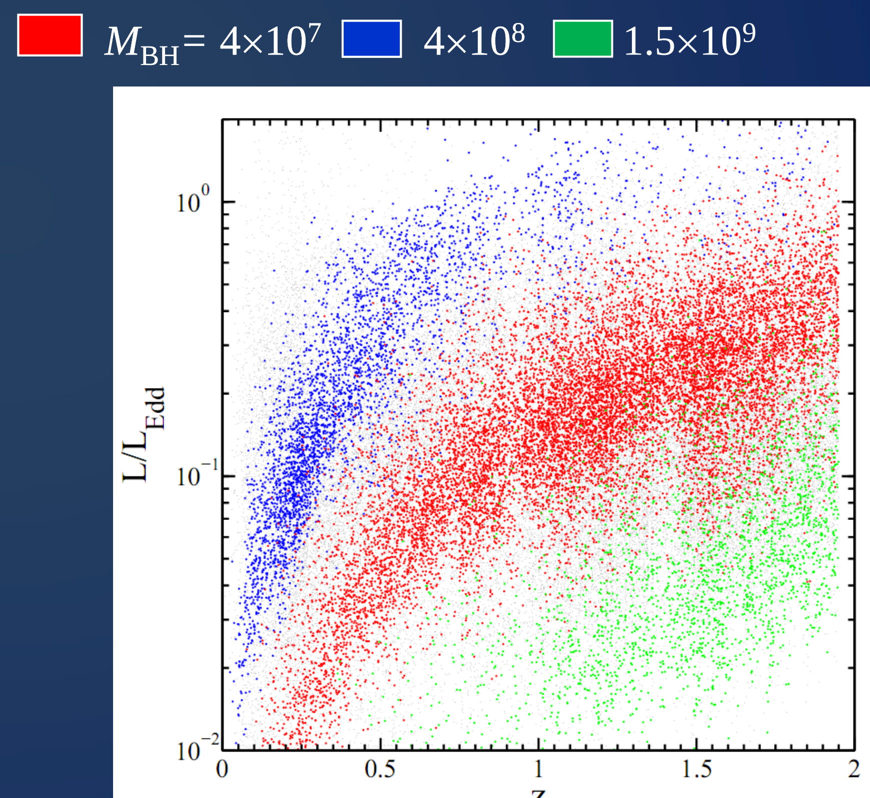
Netzer & Trakhtenbrot (2007) ; Trakhtenbrot, in prep.

Clues from large optical surveys (z < 2)

At low redshift very massive BHs ($M_{BH} \geq 10^9\,M_\odot$) exist, but:

1. Only the less-massive BHs are accreting, and at a slow rate
2. Most BHs did not have enough time to grow , given the observed rates



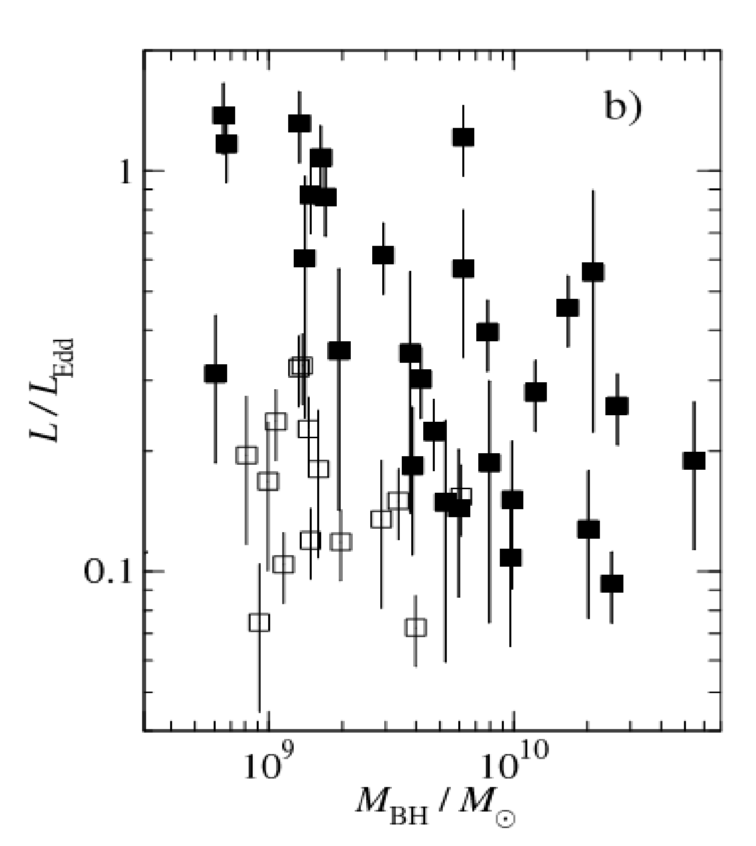


Netzer & Trakhtenbrot (2007) ; Trakhtenbrot, in prep.

More Clues from $z \sim 2.2 - 3.5$


...


- In Netzer et al. (2007; inc. B.T.) we studied 44 AGNs at z~2.2-3.5 (Hβ in *H*- and *K*-band)
- Many SMBHs with $M_{BH} > 5\times10^{9} M_{\odot}$
- Over 60% of sources have $L/L_{Edd} < 0.2$
- Most SMBHs did not have time to grow



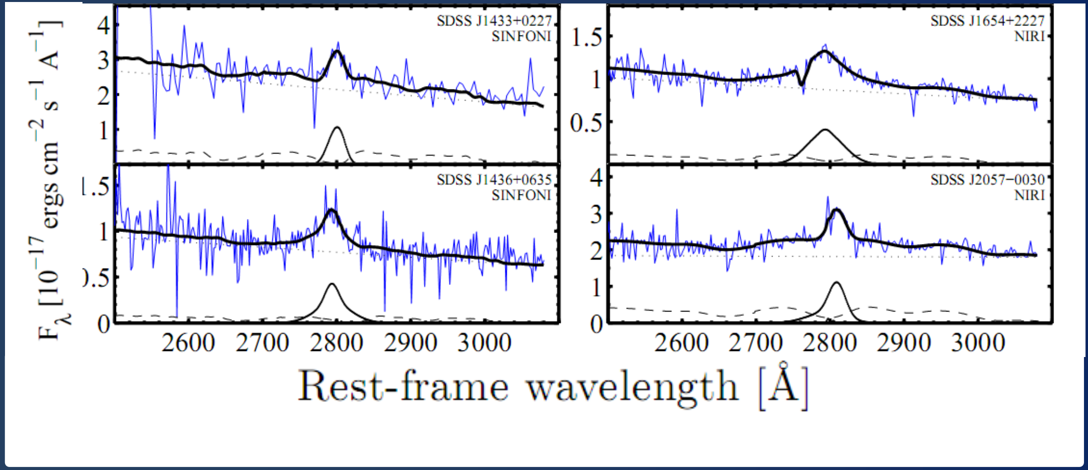
➔ We have to observe beyond z~3.5

A New Spectroscopic Sample at $z \sim 4.8$

- **40 AGNs at z = 4.65 – 4.95**

(Trakhtenbrot et al. 2011; ApJ, 730, 7)

- Optically (rest-UV) selected from SDSS, and further flux limited. ~1/4 of all such SDSS sources.
- *H*-band (~1.65 μm) spectroscopy with VLT and Gemini-N ~100 hrs
- Up to 3 hours on-source



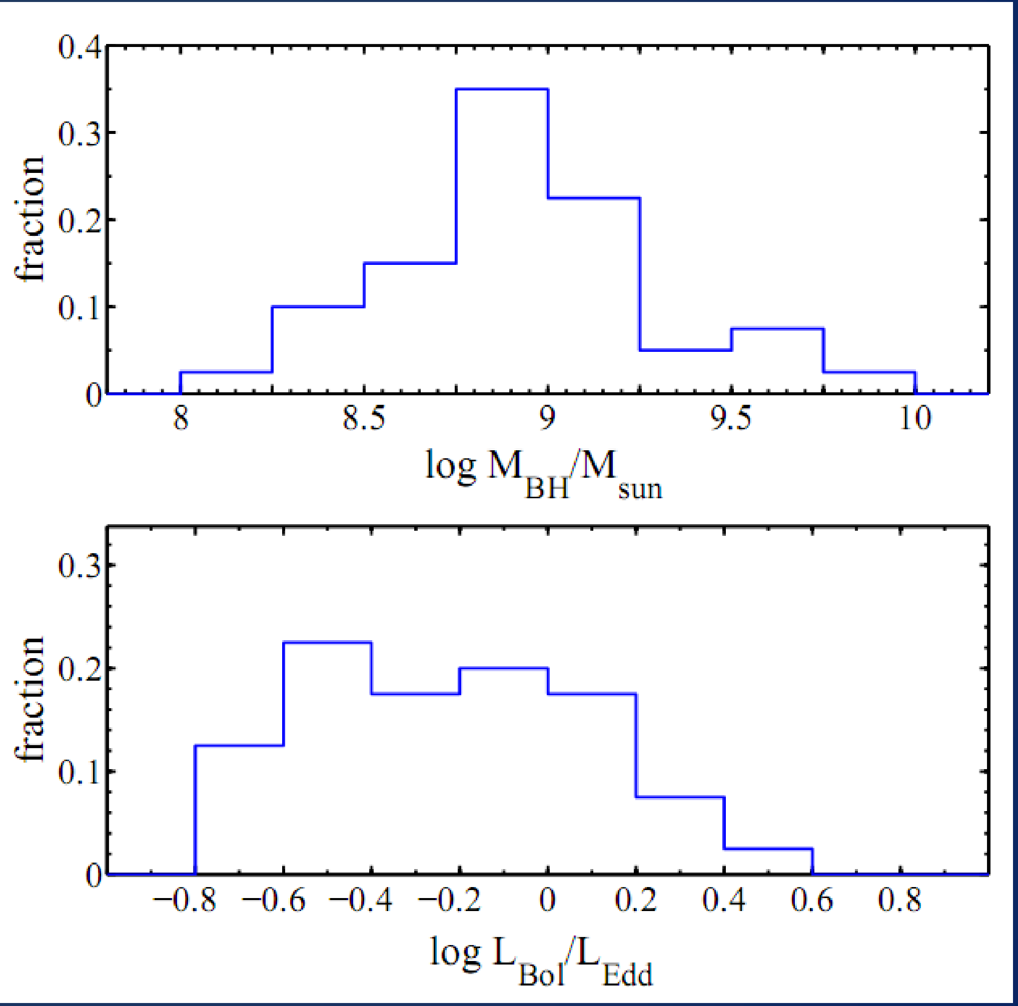
A New Spectroscopic Sample at $z \sim 4.8$

- Black hole masses:

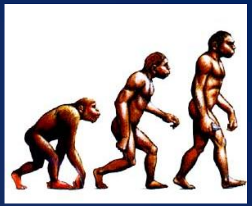
$$10^8 \leq M_{\rm BH} \leq 6.6 \times 10^9\, M_\odot$$
$$\langle M_{\rm BH} \rangle \simeq 8.4 \times 10^8\, M_\odot$$

- Accretion rates:

$$0.2 \leq L / L_{\rm Edd} \leq 3.9$$
$$\langle L / L_{\rm Edd} \rangle \simeq 0.6$$



Growth from Seed BHs



- SMBHs grow from a broad range of seeds:

1. Stellar remnants

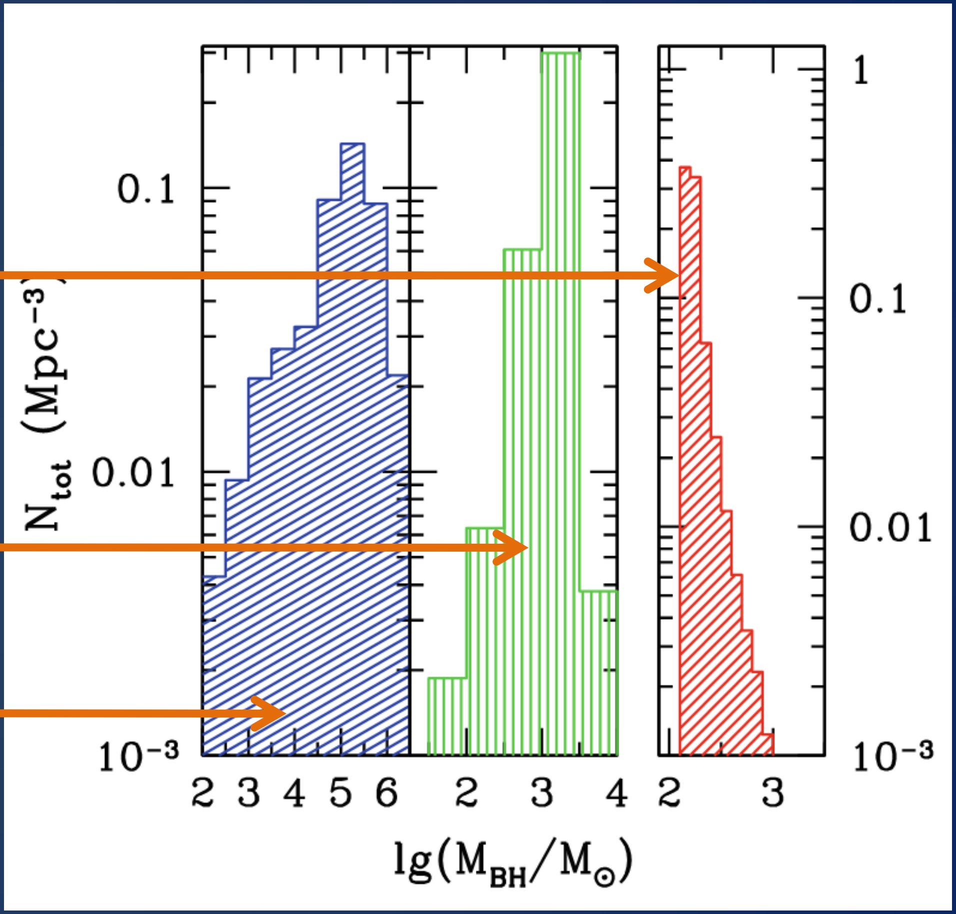
$$100 < M_{\rm seed} < 1000\, M_\odot$$

2. "Runaway" stellar mergers

$$10^2 < M_{\rm seed} < 10^4\, M_\odot$$

3. Direct collapse of gas halos

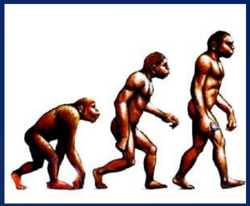
$$10^3 < M_{\rm seed} < 10^6\, M_\odot$$



~20-25% ~20-25% ~50-60%

review by Volonteri (2010)

Growth from Seed BHs



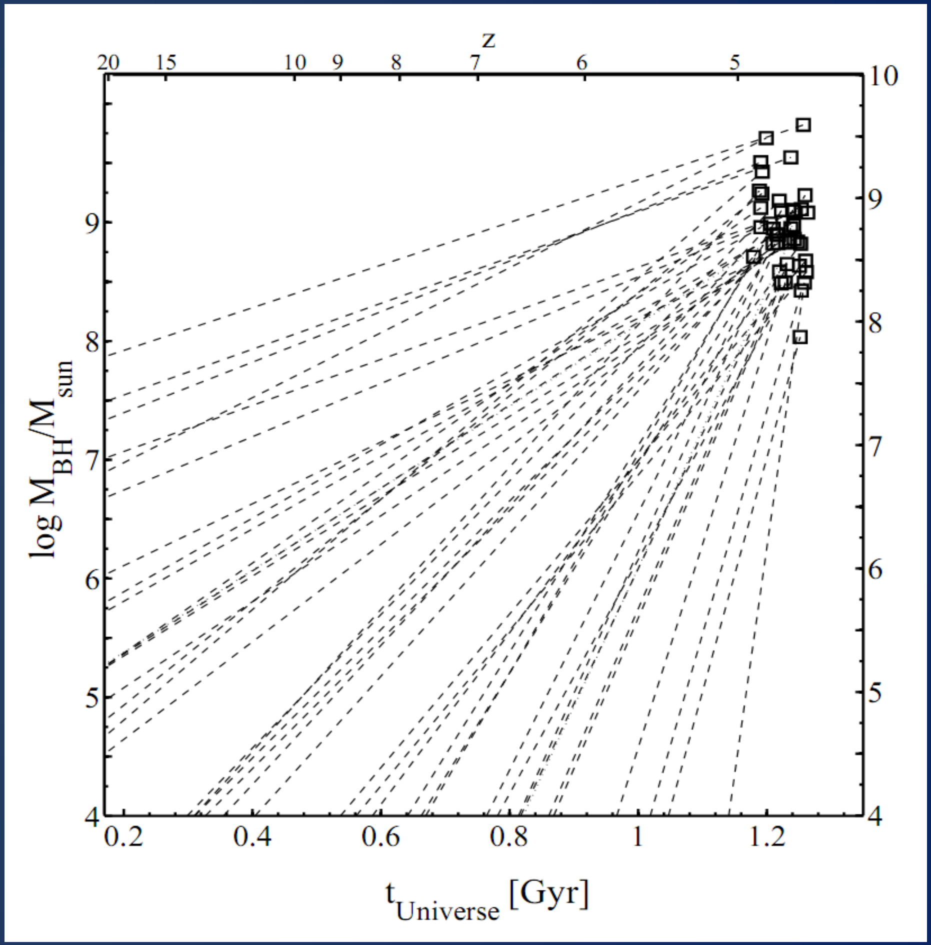
- Constant L/L_{Edd}
  ➔ exponential growth

➔ ~40% of $z \sim 4.8$ SMBHs may have grown from stellar remnants.

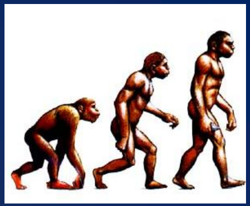
➔ Another ~20% may have grown from seeds with

$$10^3 < M_{seed} < 10^5\, M_\odot$$

- We have to assume a certain radiative efficiency: $\eta = 0.1$



Growth from Seed BHs



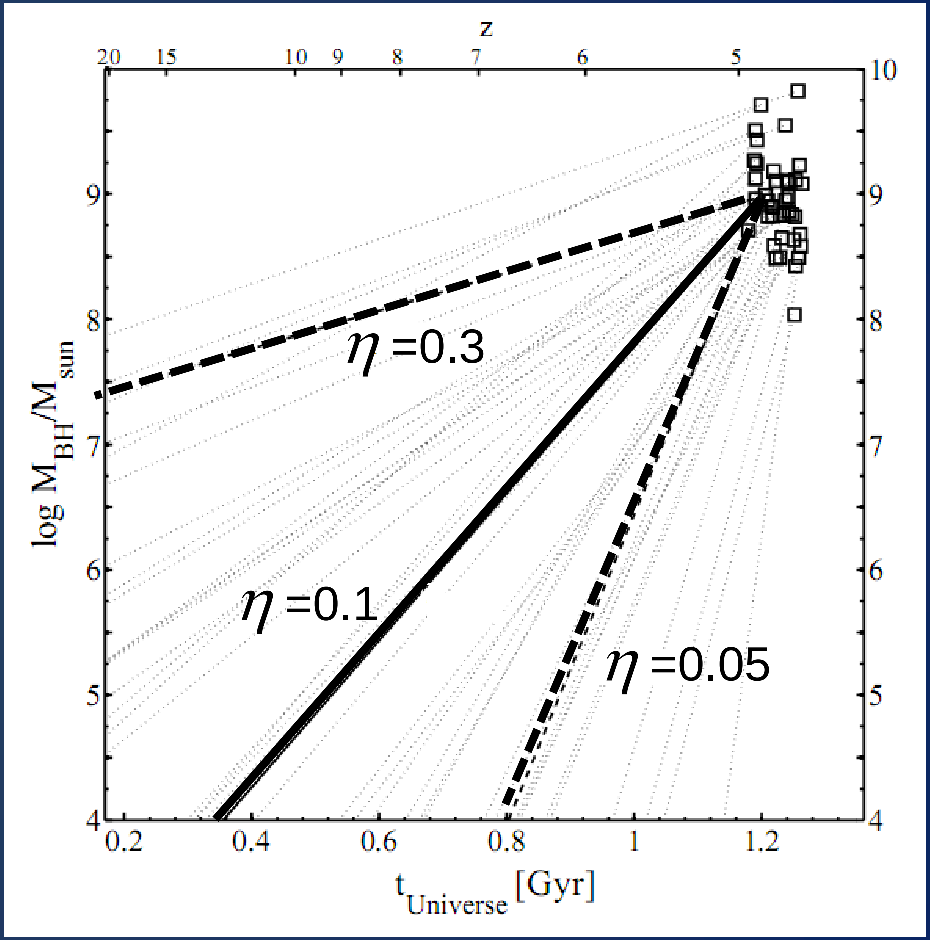
- Some models suggest much higher or lower efficiencies (e.g. Wang et al. 2009; King et al. 2008)

- If we assume $\eta = 0.3$ then all seeds have $M_{\rm seed} > 500\, M_\odot$

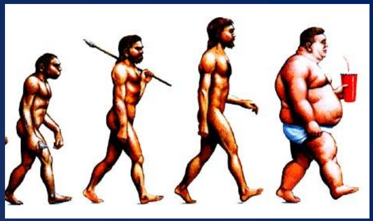
  ➔ high η means stellar remnants are not required

- If we assume $\eta = 0.05$ then all seeds have $M_{\rm seed} \leq 10^6\, M_\odot$

  ➔ very low spins are required to match seed models



A Sequence of Growing M_{BH}



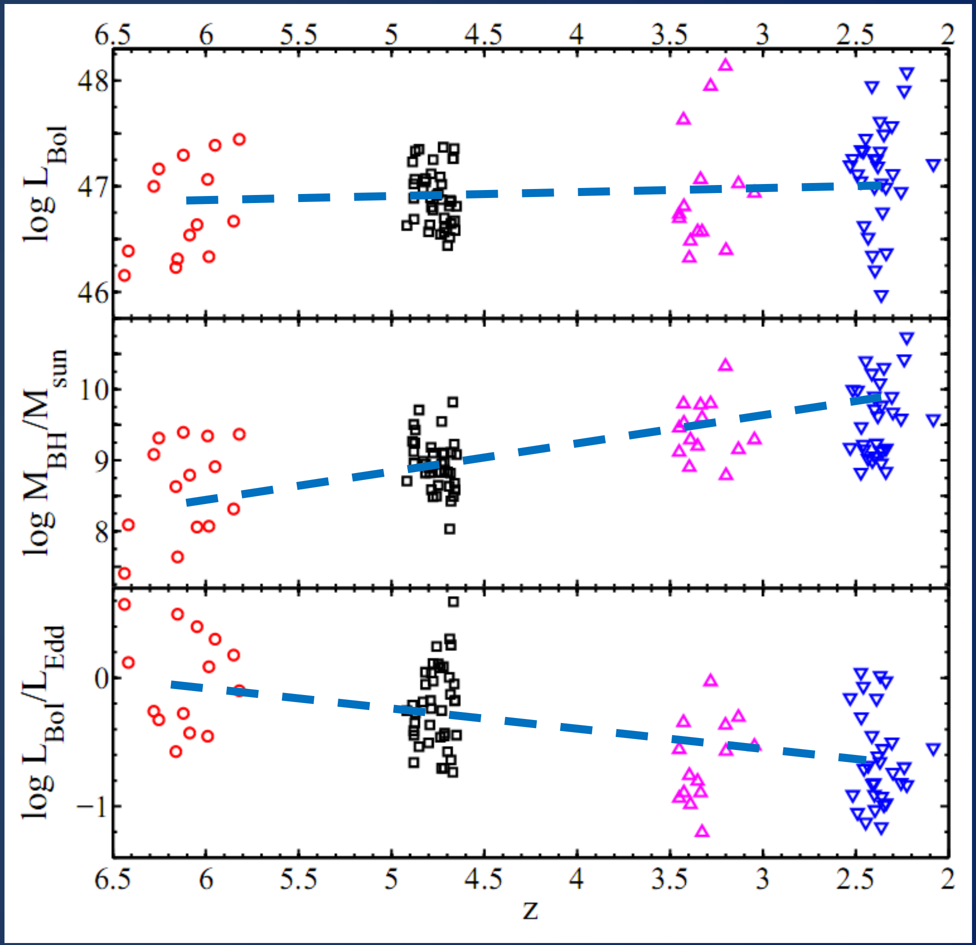
- We focus on the most massive BHs at all epochs:
    1. 44 sources at $z\sim2.4$ and $z\sim3.3$
    2. 14 sources at $z\sim 6 - 6.5$

    Kurk et al. (2007), Willott et al. (2010)

- Similar luminosities

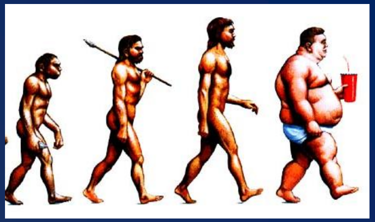
➔ M_{BH} increases with time

➔ L/L_{Edd} decreases with time



$t_{(z\,=\,4.8\,\rightarrow\,3.3)} \simeq 680\,\mathrm{Myr}$ $\quad$ $t_{(z\,=\,3.3\,\rightarrow\,2.4)} \simeq 790\,\mathrm{Myr}$

A Sequence of Growing M_{BH}



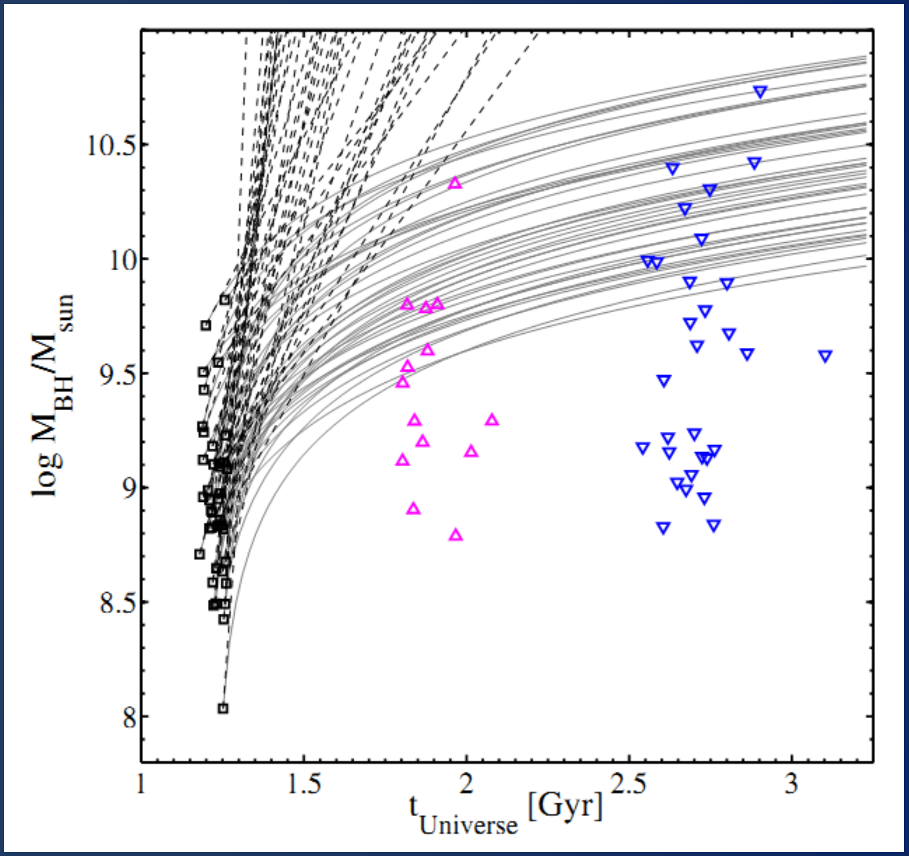
- Two basic scenarios:

  1. Constant L/L_{edd} – exp. growth
  2. Constant L_{bol} – linear growth

- Evolved masses are higher than observed

➔ The accretion is not continuous, **duty cycle must be <100%**

A “shut down” of activity after a given fraction of the time.



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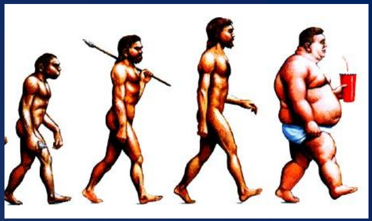


- The derived duty cycles are:

  1. 5-15% (constant L/L_{Edd})
  2. 15-25% (constant L_{Bol})

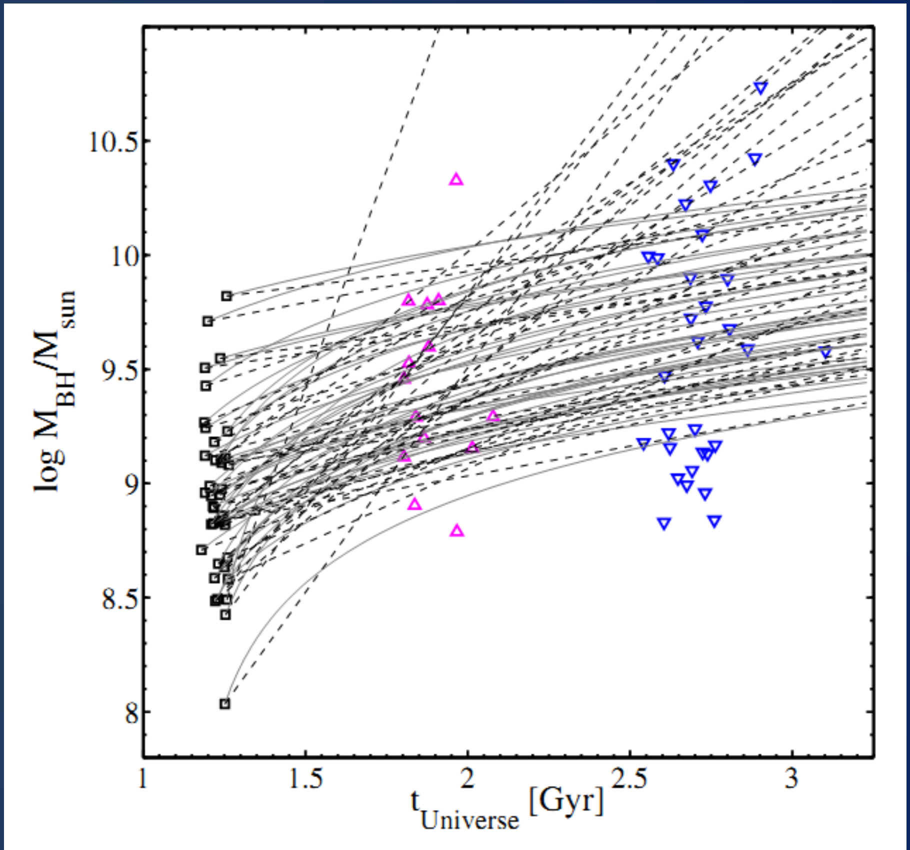
- Equivalent to periods of **~70-150 Myr**

→ Consistent with merger-driven accretion epochs

(e.g. Hopkins et al. 2006)

→ Much lower than some models, which suggest duty cycles of ~70-100%

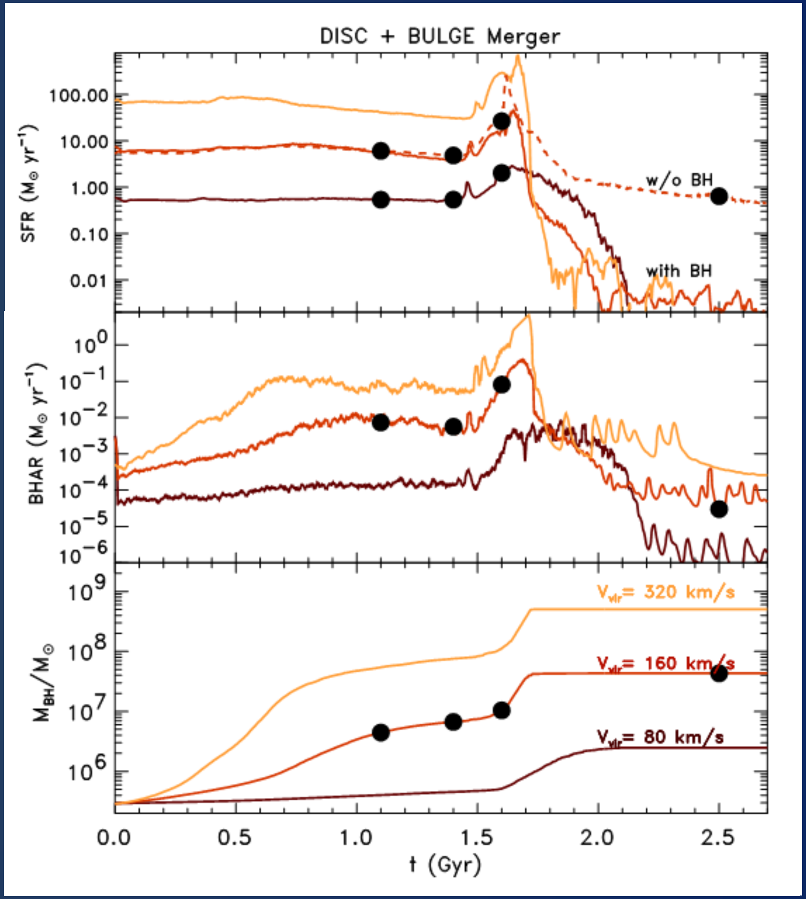
(White et al. 2008; Wyithe & Loeb 2009; Shen et al. 2010; Shankar et al. 2010...)



To do: use proper BHMFs and more realistic scenarios (e.g., Hopkins & Hernquist 2009)

Growing BHs by Mergers

- SMBHs may grow by a factor ~100-1000 following a merger
- Each merger lasts ~2 Gyr (depending on redshift)
- High merger rate at high z
- Explain BH-host co-evolution
- Can we relate the observed sequence to merger activity?



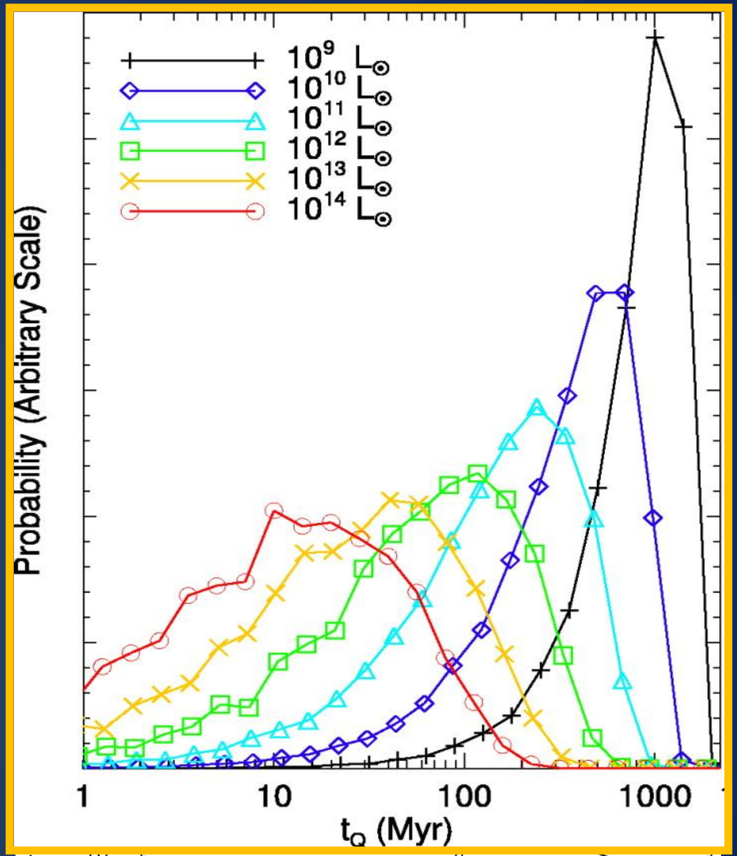
Di-Matteo et al. (2005)

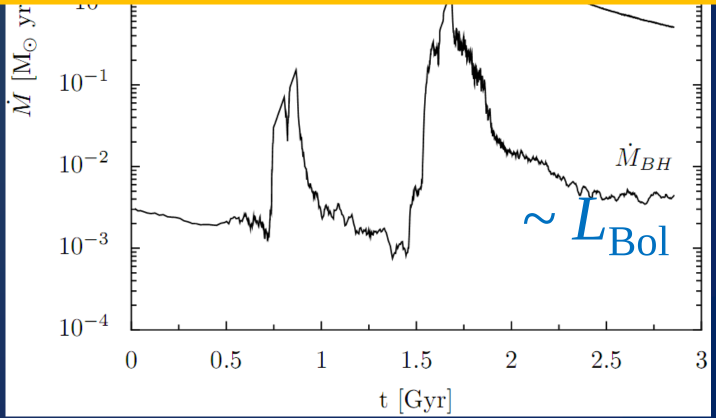
Growing BHs by Mergers - Predictions

1. Luminous ("quasar") accretion only lasts a few 100's Myr

- Hopkins et al. (2006) suggest only **~100 Myr** above our limiting luminosity ($L_{\mathrm{Bol}} > 2.7\times10^{46}$ erg/s)

- Our analysis implies an accretion period of **~70-150 Myr**





Hopkins et al. (2006)

DeBuhr et al. (2011)

Growing BHs by Mergers - Predictions

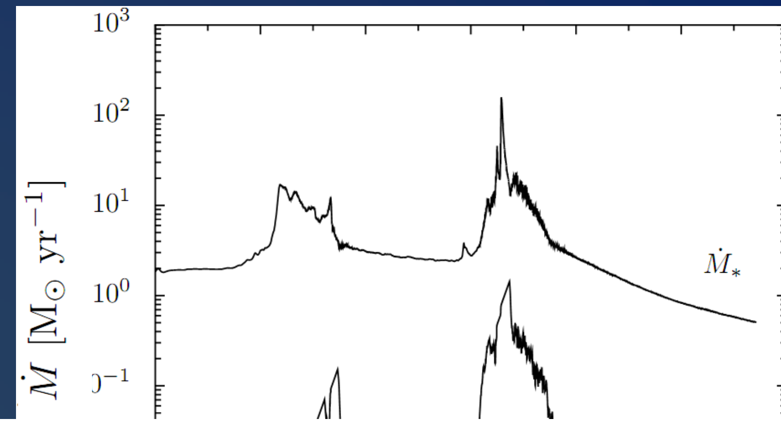
2. BH accretion goes hand in hand with intense SF

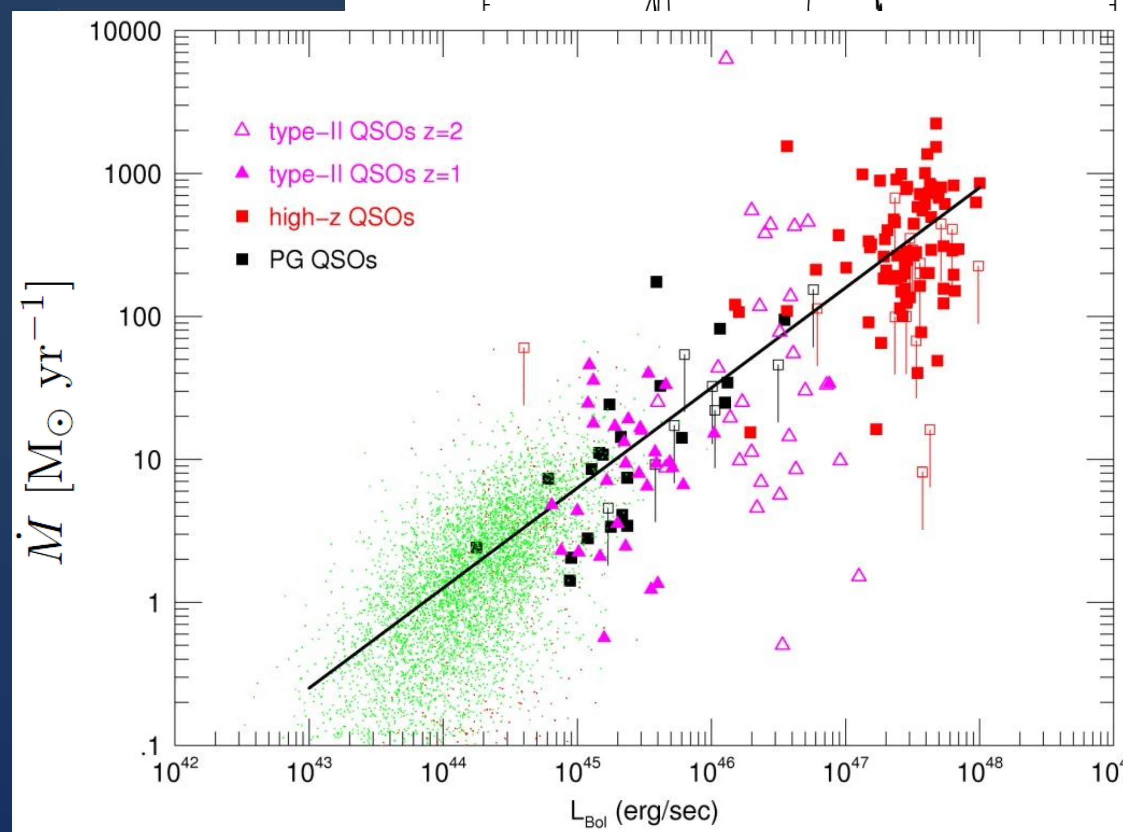
- Observed for many $z < 3$ sources:

$$\boxed{L_{SF} \propto L_{Bol}^{\;0.7}}$$

(Trakhtenbrot & Netzer 2010)

Can we observe this at z~4.8 ?





Current and Future Follow-up Observations

- ✓ Herschel photometry to detect high SFR in hosts

  Peak of SF-heated dust flux is redshifted to ~350 μm

- ❑ Use HST imaging to detect merging or nearby companions

  Angular scale at z~4.8 is same as at z~0.55 , ~640 pc/pix !

- ❑ Use ALMA or IRAM to detect the [CII] 158μm Line

  Probe hosts' morphology and dynamical mass

- ❑ Use Chandra to constrain X-ray –to- UV SED

  may also detect extreme dual AGNs (luminous but obscured…)

Overall Evolution of M_{BH}

z~6.2
Willott+10, Kurk+07

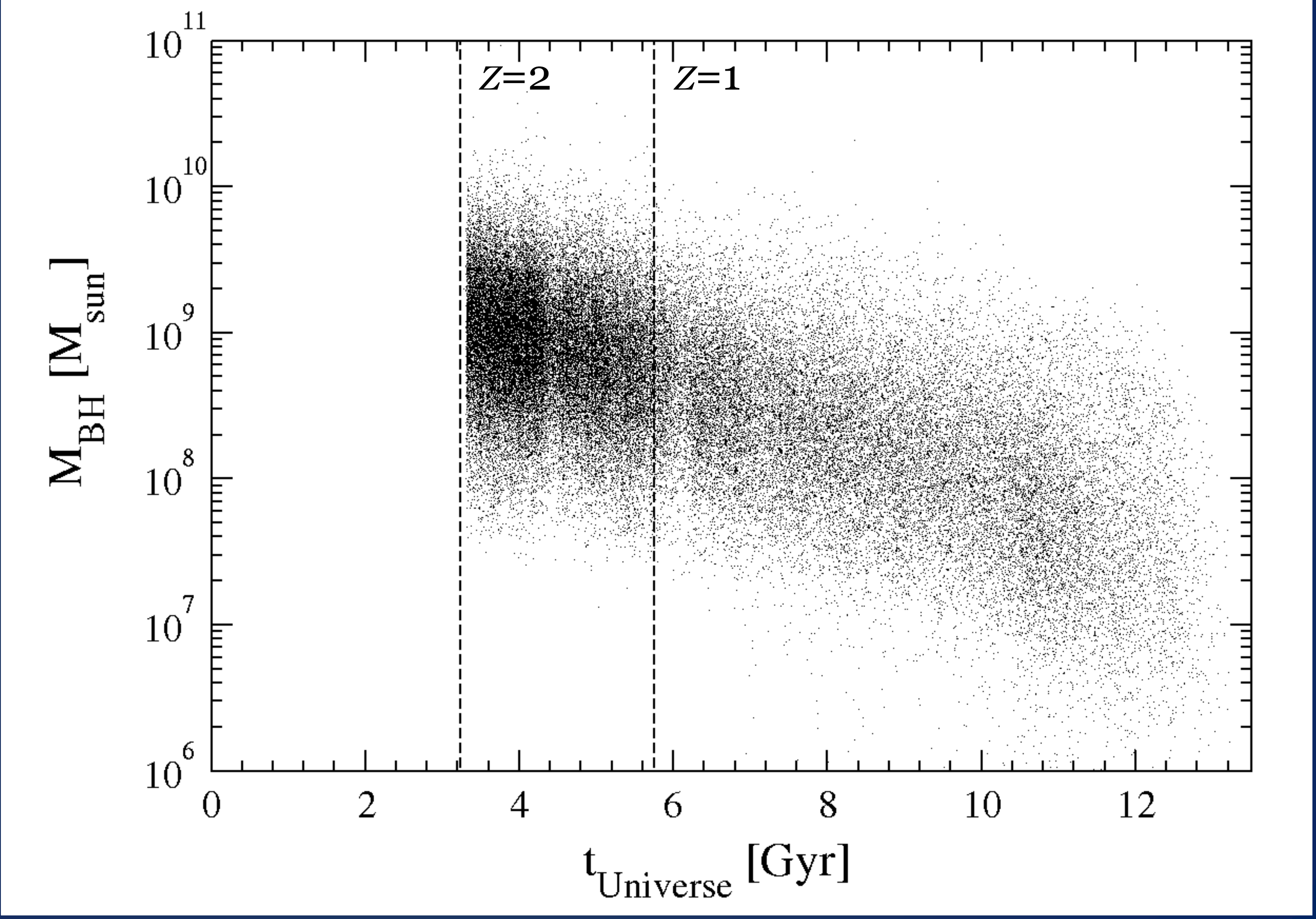
z~4.8
Trakhtenbrot+2011

z~3.3
Netzer+07,Shemmer+04

z~2.4
[**Netzer+07**,Shemmer+04]

z<2
SDSS; Netzer & **Trakhtenbrot** (2007)
Trakhtenbrot in prep.

faint surveys
2QZ, 2SLAQ, VVDS, zCOSMOS
homogeneous analysis in **Trakhtenbrot** , in prep.



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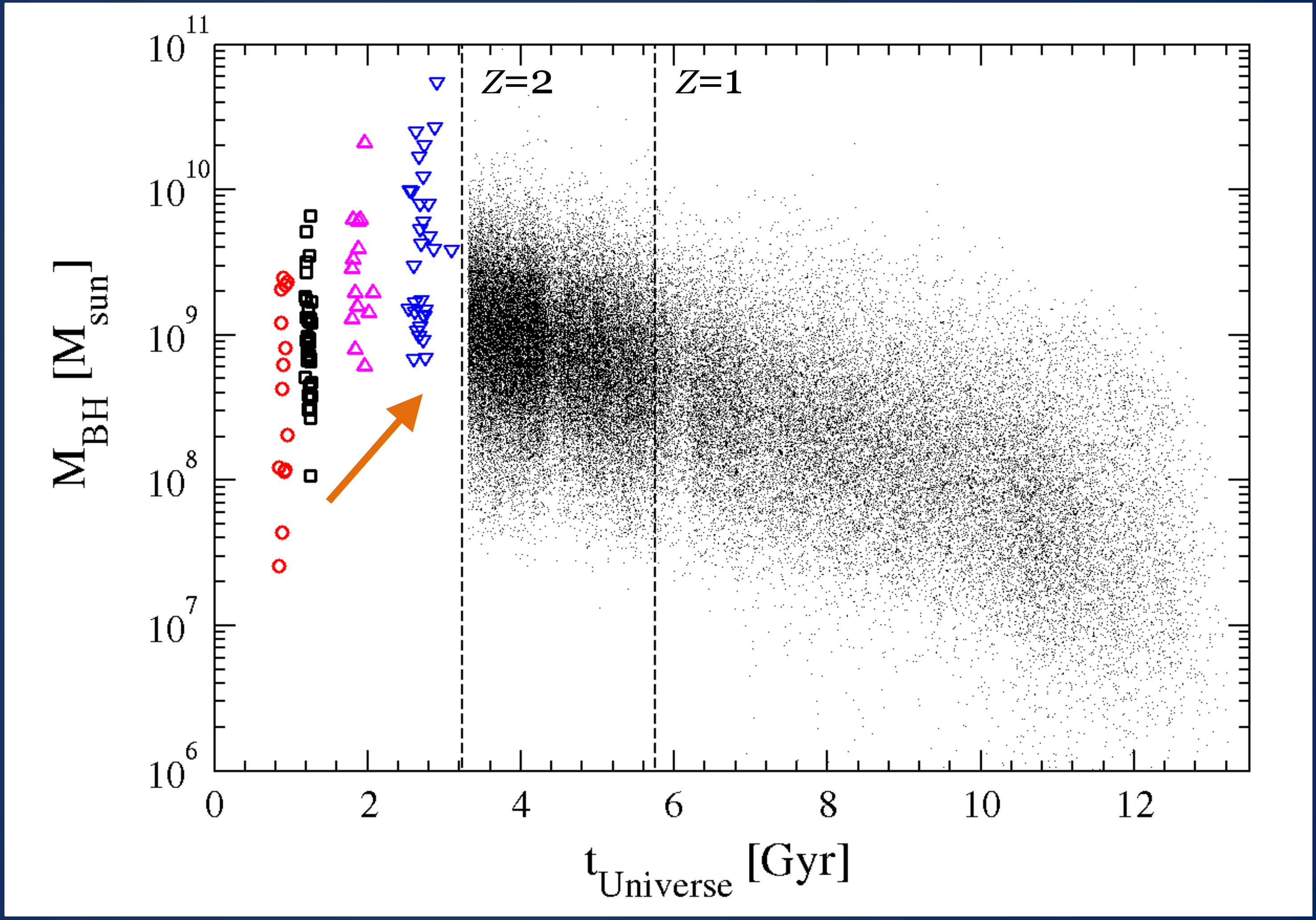

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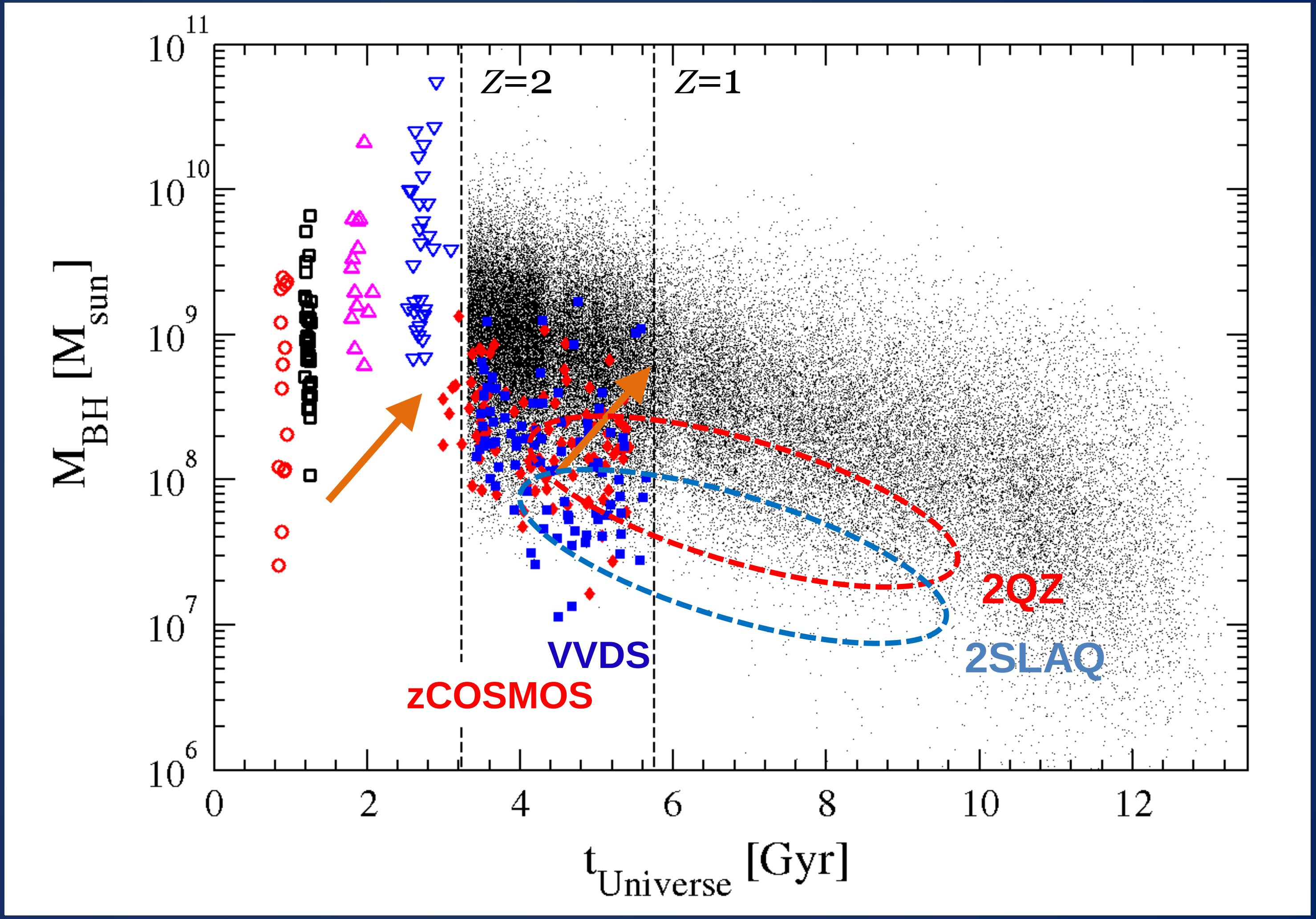


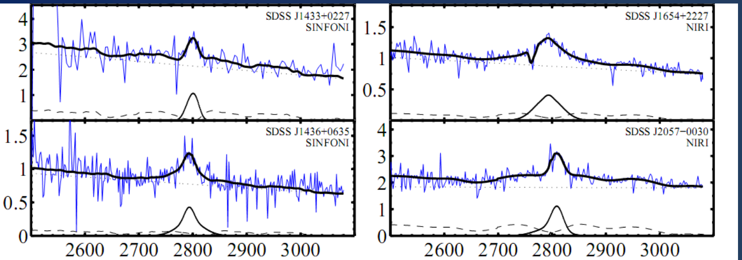
faint surveys

2QZ, 2SLAQ,
VVDS, zCOSMOS
homogeneous analysis in
Trakhtenbrot , in prep.

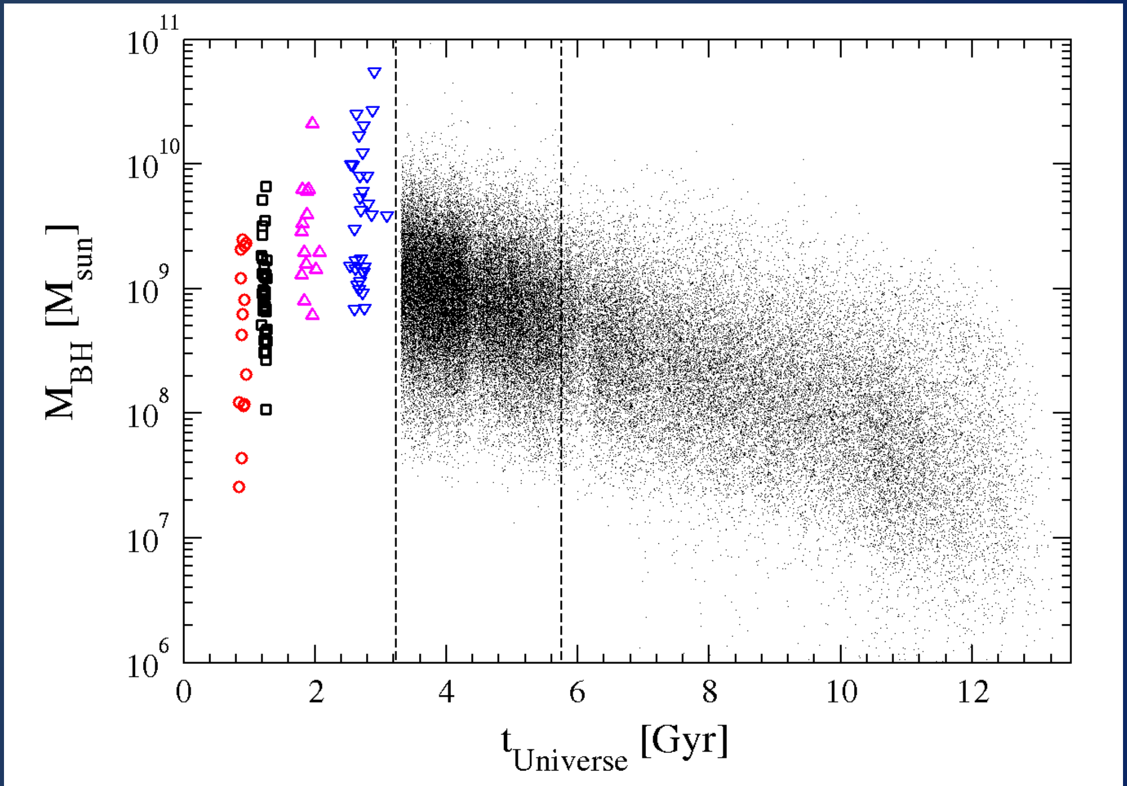
Summary

1. A new, large and flux-limited sample with reliable M_{BH} and L/L_{Edd} estimates
2. Masses are lower, and accretion rates are higher, than lower-z samples ➔ epoch of fast growth of the most massive BHs
3. A broad range of seed masses is required, but ~40% of sources may have grown from stellar remnants
4. Growth to later epochs proceeds at a low duty cycle of ~10-20% , or during ~70-150 Myr
5. The unique sequence of rising M_{BH} provides a natural test-bed for the merger-driven BH growth scenario

Thank you!



SDSS J1433+0227
SINFONI
SDSS J1654+2227
NIRI
SDSS J1436+0635
SINFONI
SDSS J2057−0030
NIRI
2600
2700
2800
2900
3000



M_{BH} [M_{sun}]
$t_{Universe}$ [Gyr]