Radiative Efficiencies, BH spins, and Elusive AGN among High-Mass Quasars

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With:

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Elusive AGN in the Next Era, Fairfax, September 19 2016

1. The quasars we know
2. The quasars we don’t know (yet?)

1. The quasars we know

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2. The quasars we don't know (yet?)

Radiative efficiency:

$$L_{\rm bol} = \eta \dot{M}_{\rm acc} c^2$$

Bolometric AGN luminosity

Mass accretion rate (through disk)

Radiative efficiency: controls SMBH growth

- BH spin sets inner edge of accretion disk/flow …
- … which sets the radiative efficiency:

$$L_{\rm bol} = \eta \dot{M}_{\rm acc} c^2$$

- In the thin-disk regime:

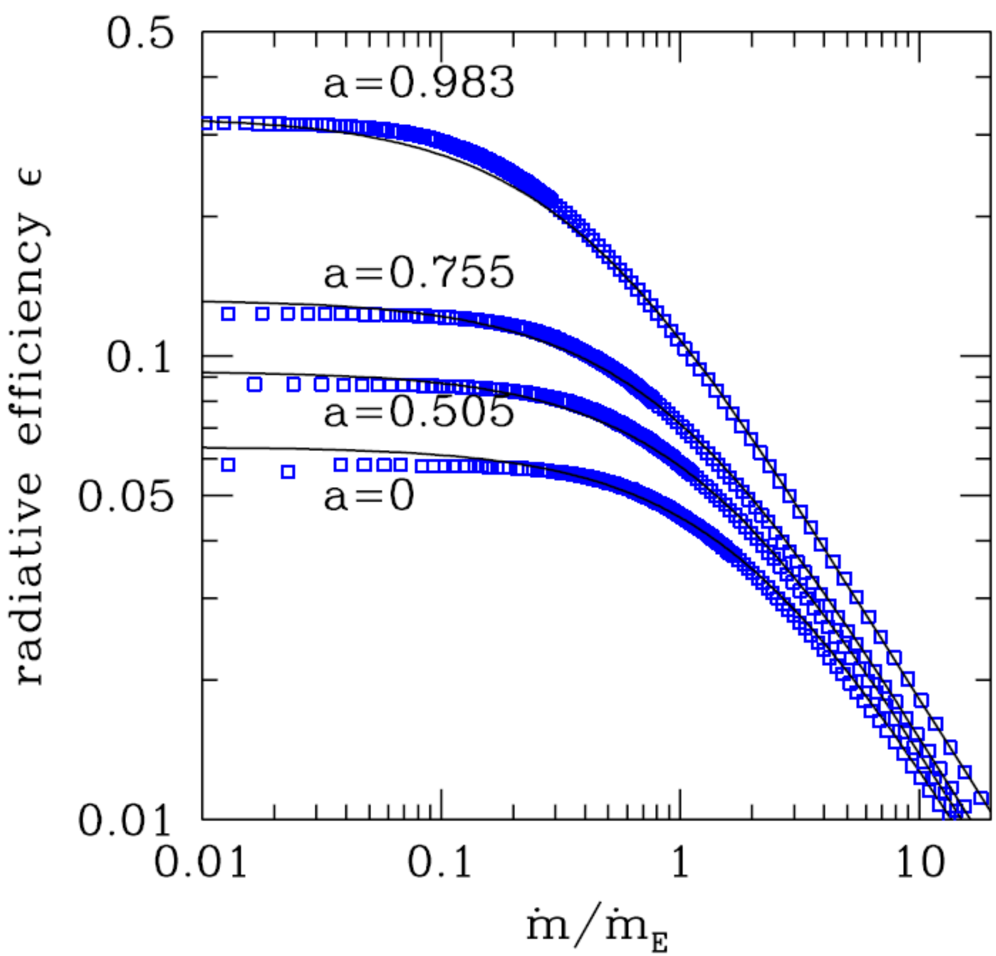
$$\eta \sim 0.04 \text{ - } 0.4$$

- "Soltan's argument":

$$\eta \sim 0.1$$

- BH "growth efficiency":

$$\dot{M}_{\rm BH} = (1-\eta)\dot{M}_{\rm acc}$$



Madau, Haardt & Dotti 14

$$t_{\rm growth} \propto \eta/(1-\eta)$$ → Fast-spinning BHs grow slowly

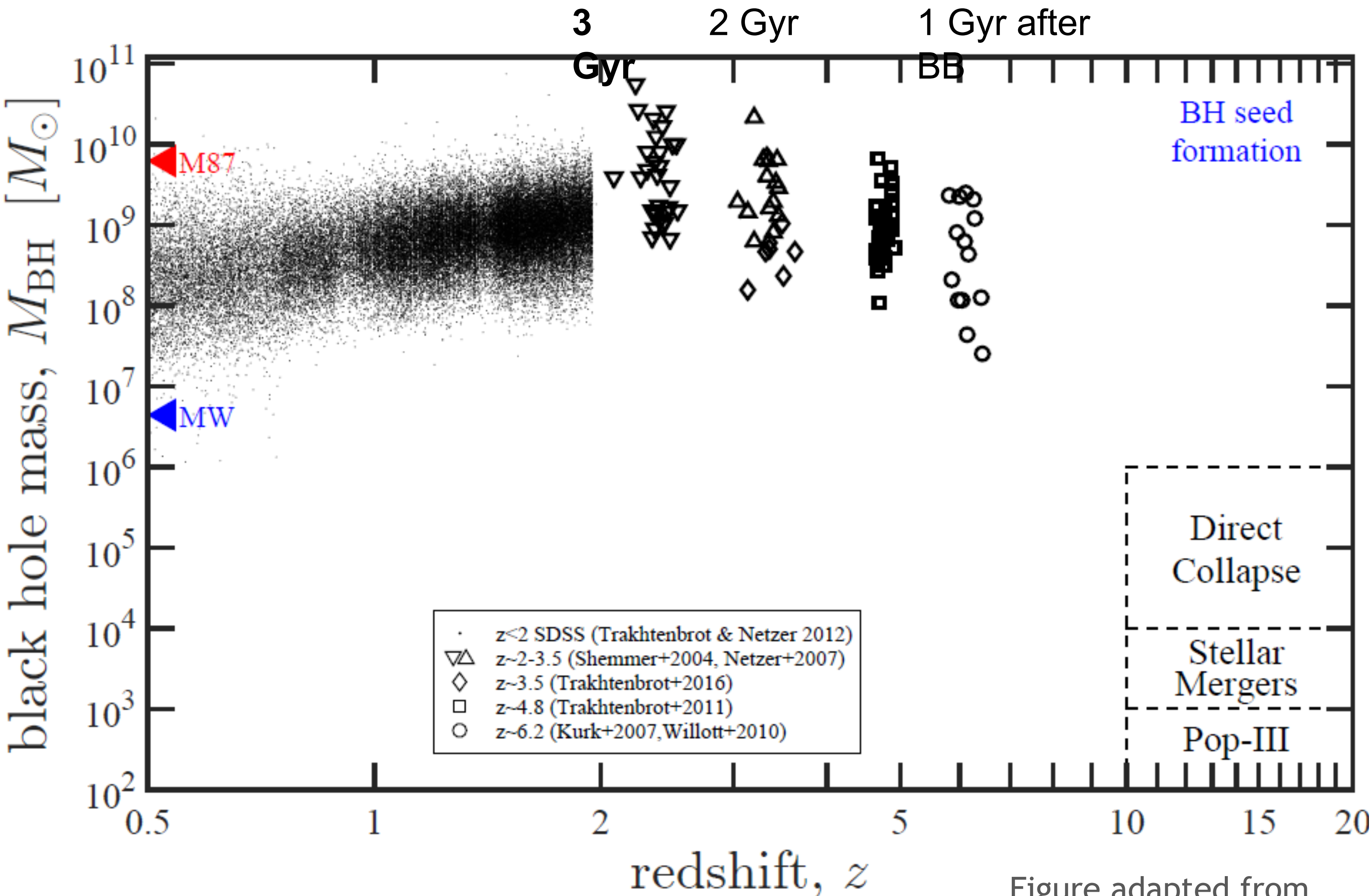


Figure adapted from Trakhtenbrot & Netzer 12

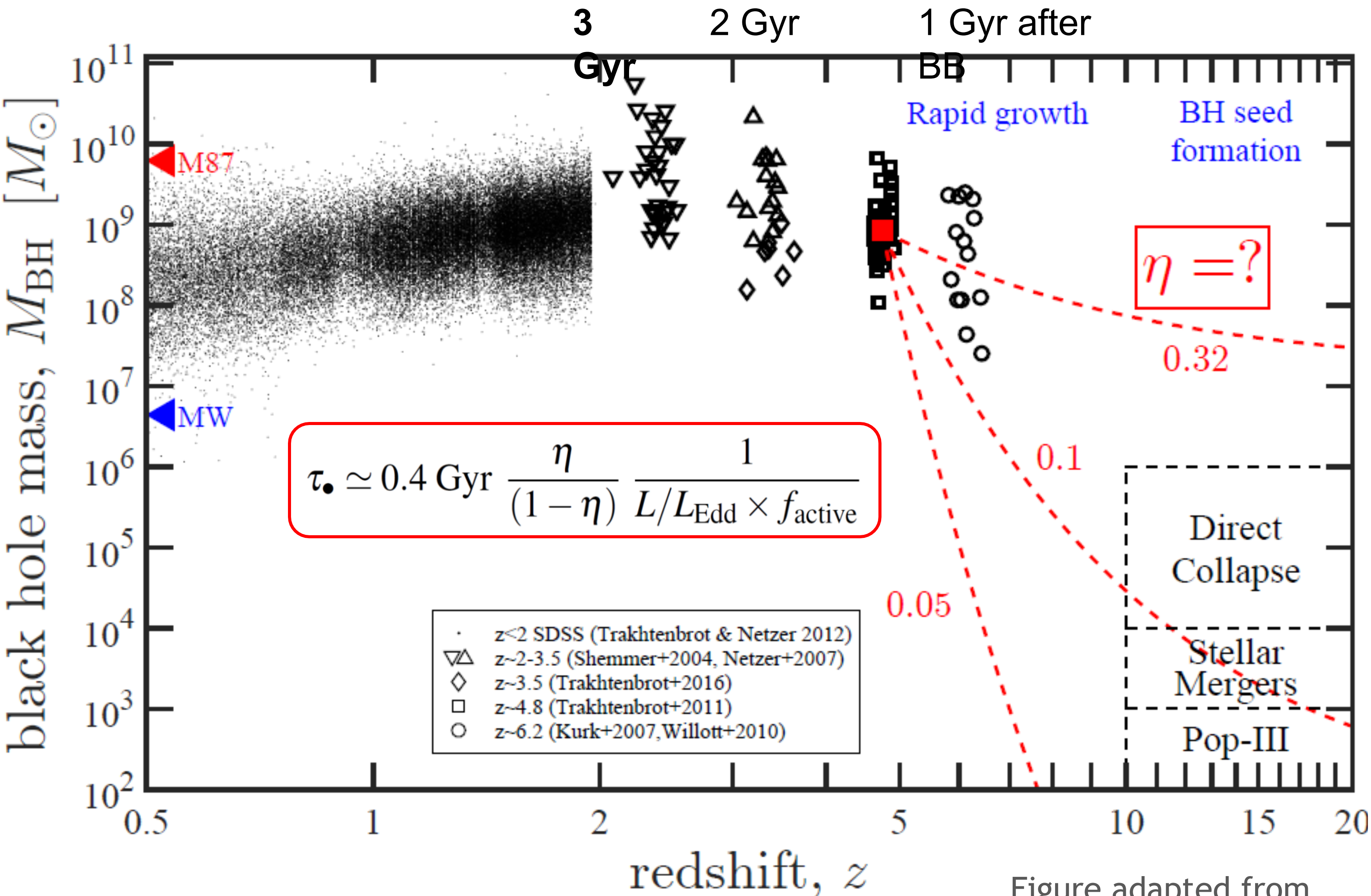
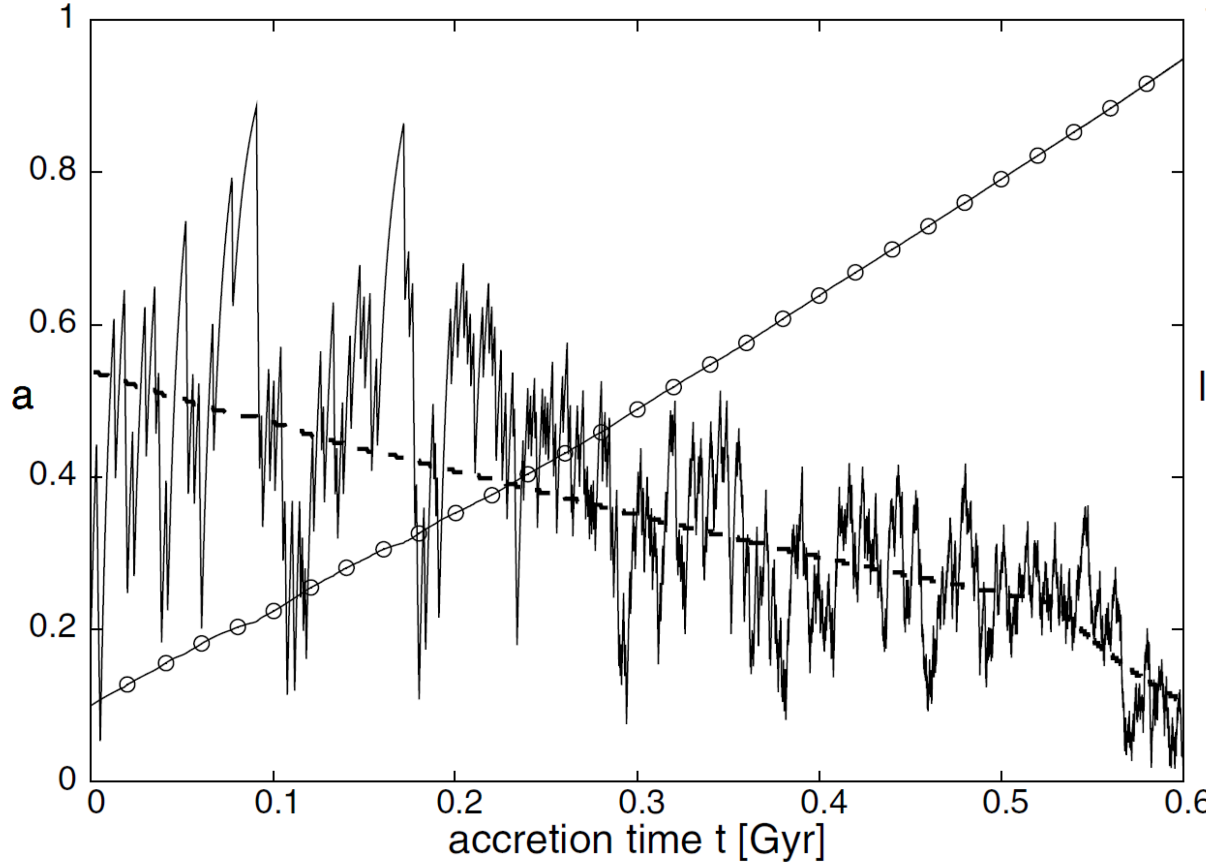


Figure adapted from Trakhtenbrot & Netzer 12

BH spin evolution: “spin down” scenario

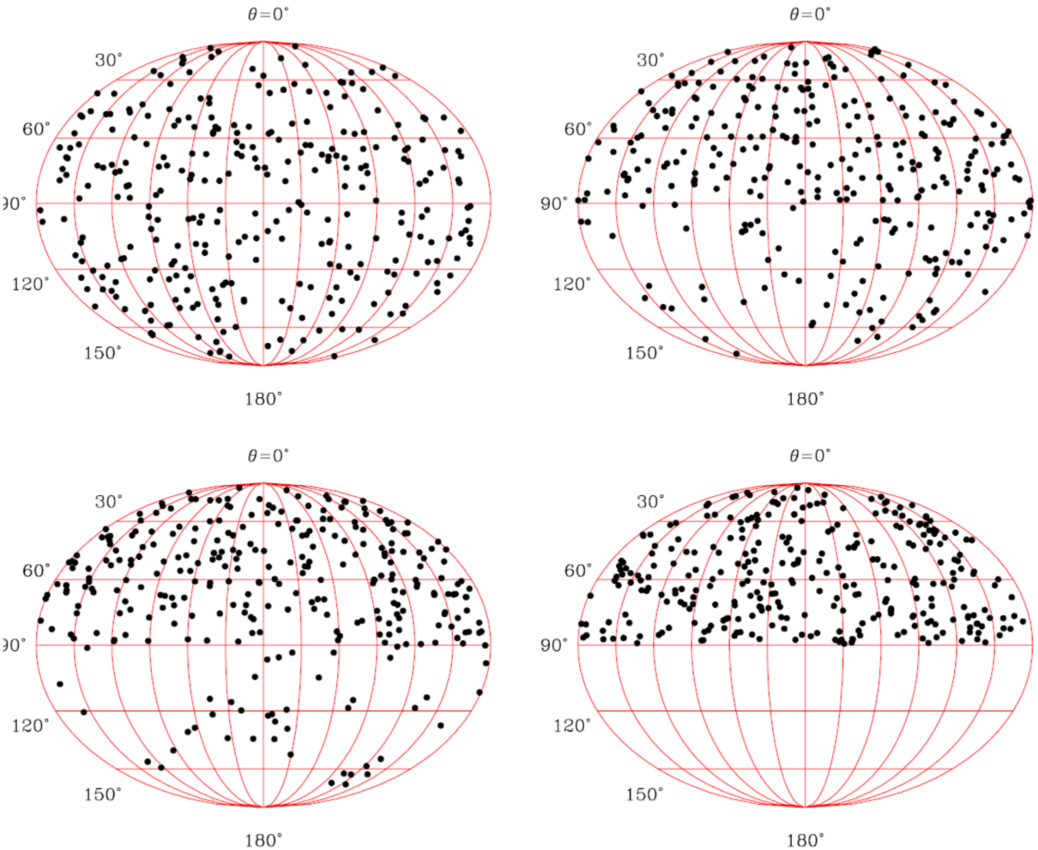


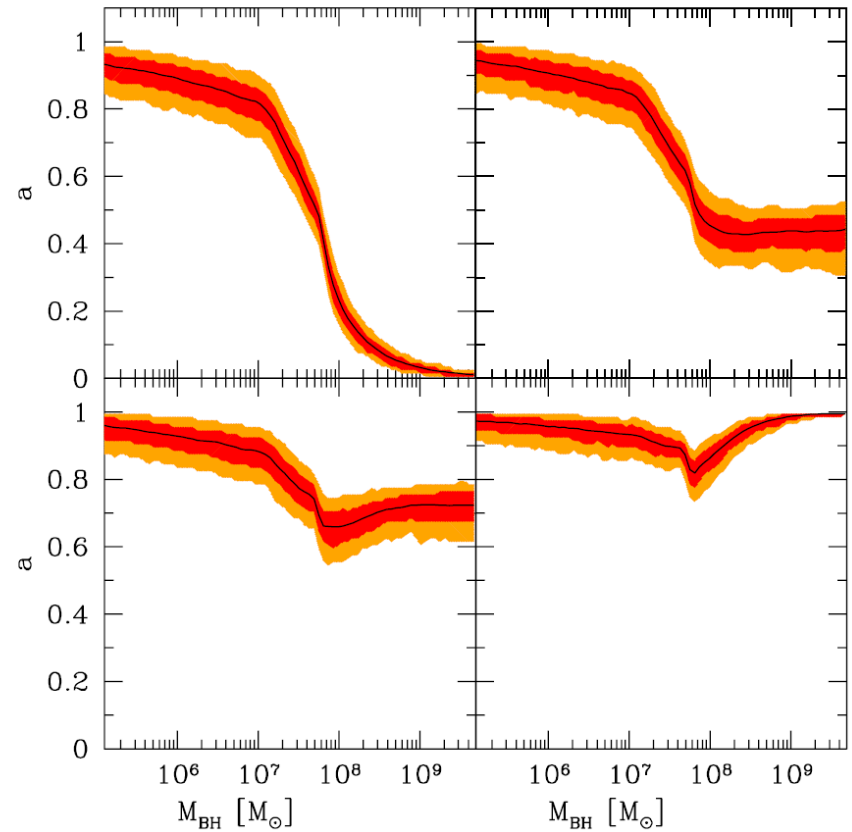
King+08

A large number of accretion events (disks), randomly oriented w.r.t. the SMBH → **“spin down”**

coalescence events also lead to spin-down: $a \propto M_{\rm BH}^{-2.4}$ (Hughes & Blandford 03)

BH spin evolution: the role of (an)isotropy



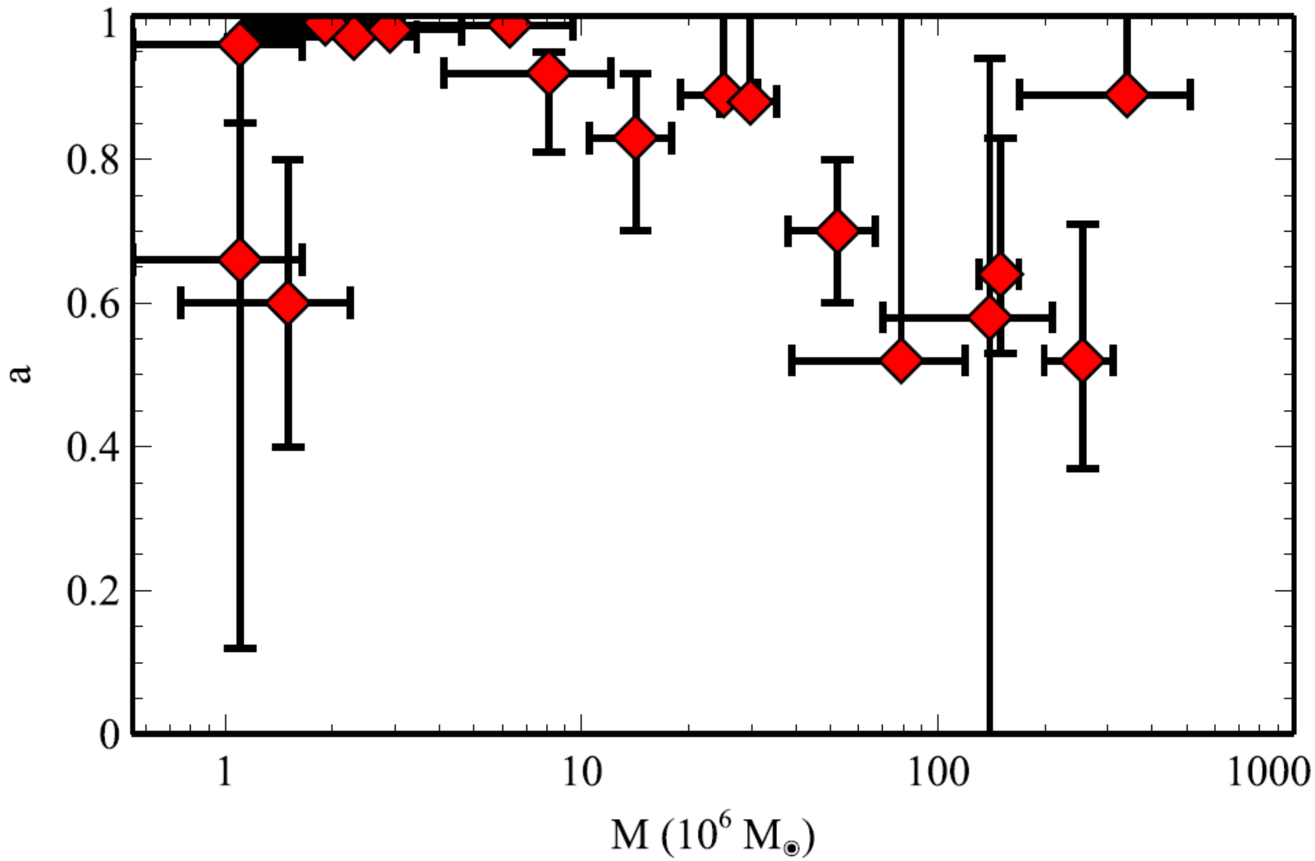


Dotti+13

more isotropy → lower spins

prolonged accretion / anisotropy → **"spin up"**

Census of (local) SMBH spin measurements



review by Reynolds 14

Gravitationally broadened Iron Kα line at ~6.7 keV

Spin estimates for ~20 local, low-luminosity and low-M_{BH} AGN

No non-spinning SMBHs ?

Brenneman & Reynolds 06, Brenneman+11, Gallo+11, Patrick+12, Fabian+13, Walton+13 …

Where are the most massive active BHs?

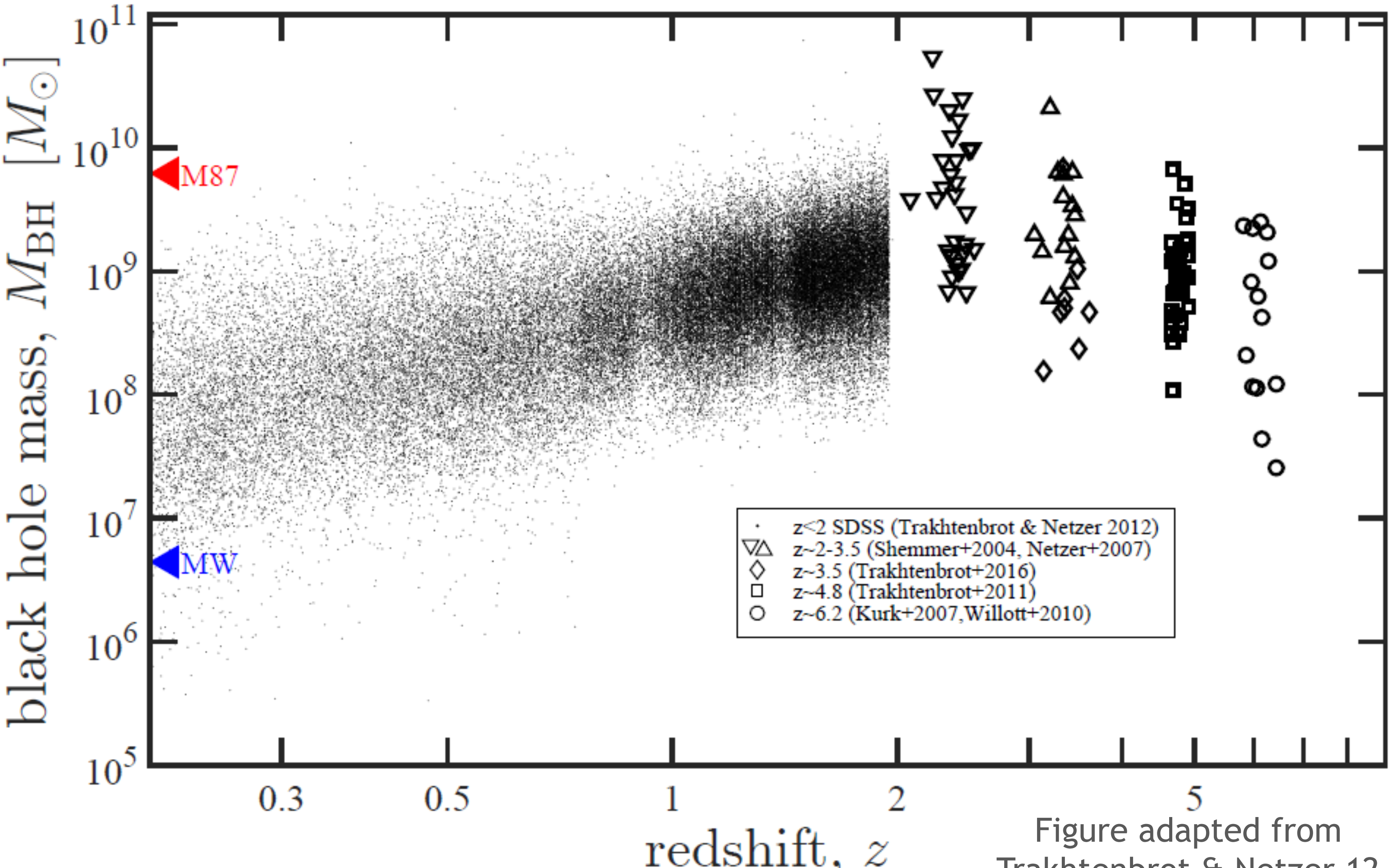


Figure adapted from Trakhtenbrot & Netzer 12

Constraints on radiative efficiencies of high-z quasars

$$L_{\rm bol} = \eta \dot{M}_{\rm disk} c^2$$

Trakhtenbrot 14,
Trakhtenbrot, Volonteri & Natarajan 17
method described in Davis & Laor 10, Wu+13

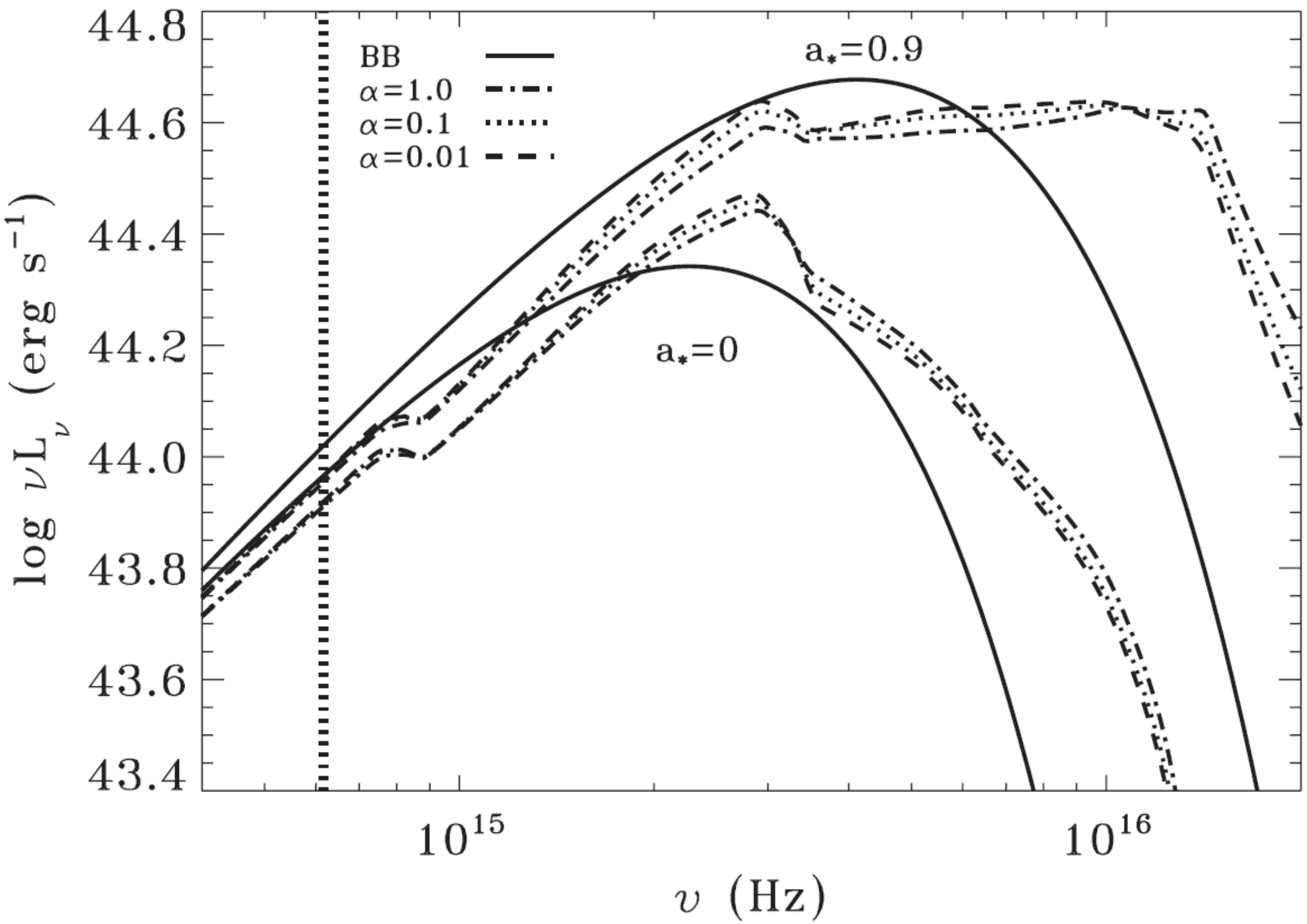
Basic assumptions

1. Luminous AGNs accrete matter through geometrically thin, "Shakura-Sunyaev-*like*" accretion disks

2. $M_{\rm BH}$ can be reliably estimated from broad emission lines
   for example:

$$M_{\rm BH}({\rm H}\beta) = 1.05 \times 10^8 \left(\frac{L_{5100}}{10^{46}\,{\rm erg\,s^{-1}}} \right)^{0.65} \left[\frac{{\rm FWHM(H}\beta)}{10^3\,{\rm km\,s^{-1}}} \right]^2 {\rm M}_\odot .$$

Thin accretion disks: estimating accretion rates

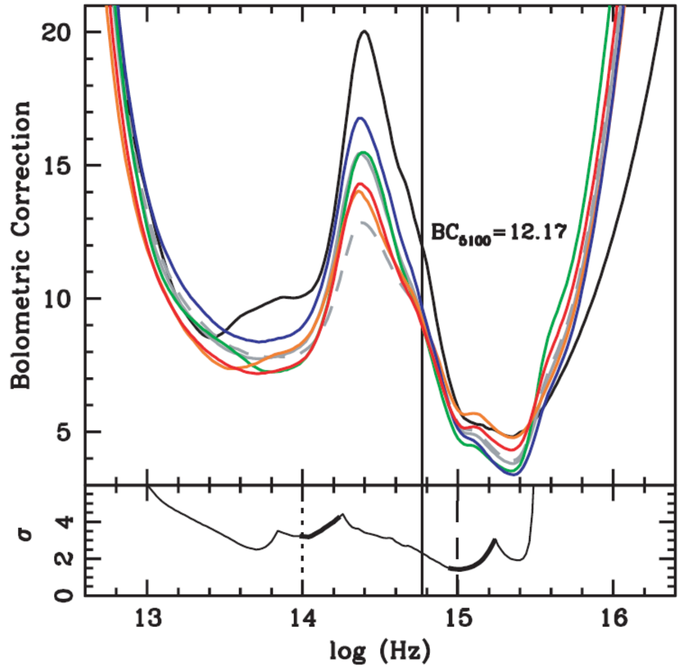


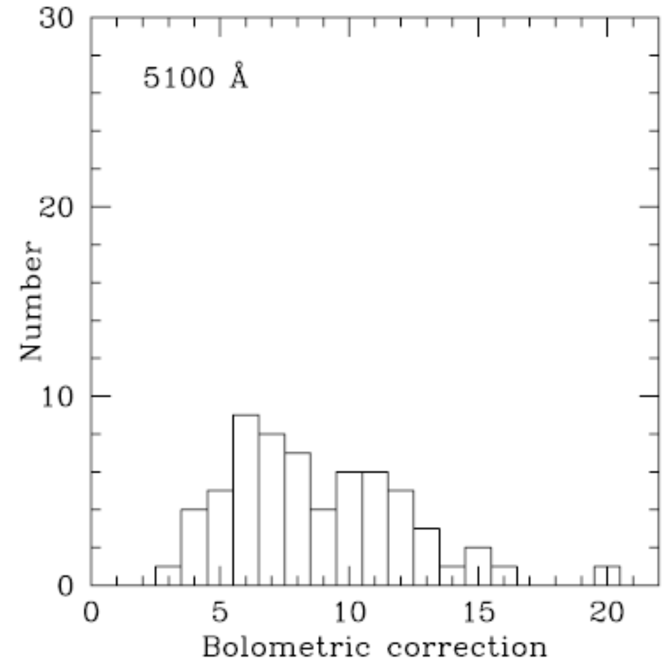
$$\dot{M}_{\rm disk} \simeq 2.4 \left(\frac{\lambda L_\lambda}{10^{45}\cos i}\right)^{3/2} \left(\frac{\lambda_{\rm cont}}{5100\text{Å}}\right)^2 \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right) M_\odot/{\rm yr}$$

Bechtold+87, Collin+06

Davis & Laor 11

Estimating bolometric luminosities





Reference	ζ_{1450}	ζ_{3000}	ζ_{5100}	Number of sources	Range in $\log(L_{\rm bol})$	Standard error in mean for 1450/3000/5100 Å
Elvis et al. (1994)[a]	5.12	6.19	12.45	47	44.86–46.92	–
Recalculated Elvis et al. (1994)[b]	3.15	3.82	7.68	–	–	–
Richards et al. (2006)	–	5.62	10.33	259	45.06–47.43	…/0.07/0.13
Recalculated Richards et al. (2006)[c]	2.33	3.11	5.53	–	–	–
Nemmen & Brotherton (2010)[d]	3.0	5.9	7.6	280	44.60–48.50	0.3/0.8/1.9
This work	4.2	5.2	8.1	63	45.13–47.30	0.1/0.2/0.4

Elvis+94, Marconi+04, Richards+06, Jin+12, Runnoe+12

Sample & data: the most massive BHs at z~2–7

- **72 quasars at z~1.5–3.5**

  Shemmer+2004, Netzer+2007, Marziani+2009, Dietrich+2009

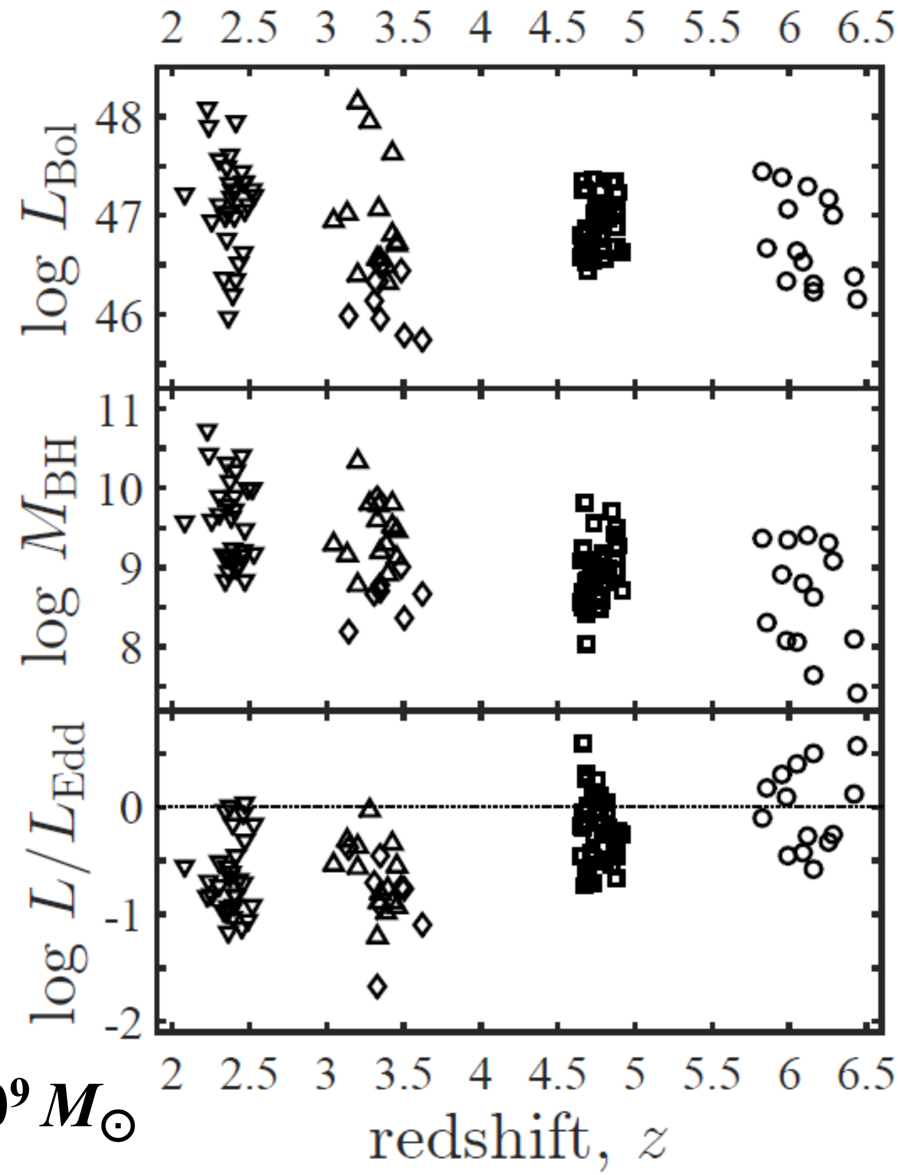
- **20 quasars at z~5.8–7**

  Iwamuro+2004, Kurk+2007,2009, Jiang+2007, Willott+2010, De Rosa+2011

- Near-IR spectra to cover (Hβ,L_{5100}) or (MgII,L_{3000})
- *2MASS, Spitzer* and/or *WISE* data covers (rest-frame) optical cont. (Jiang+2006, 2010, Leipski+2014)

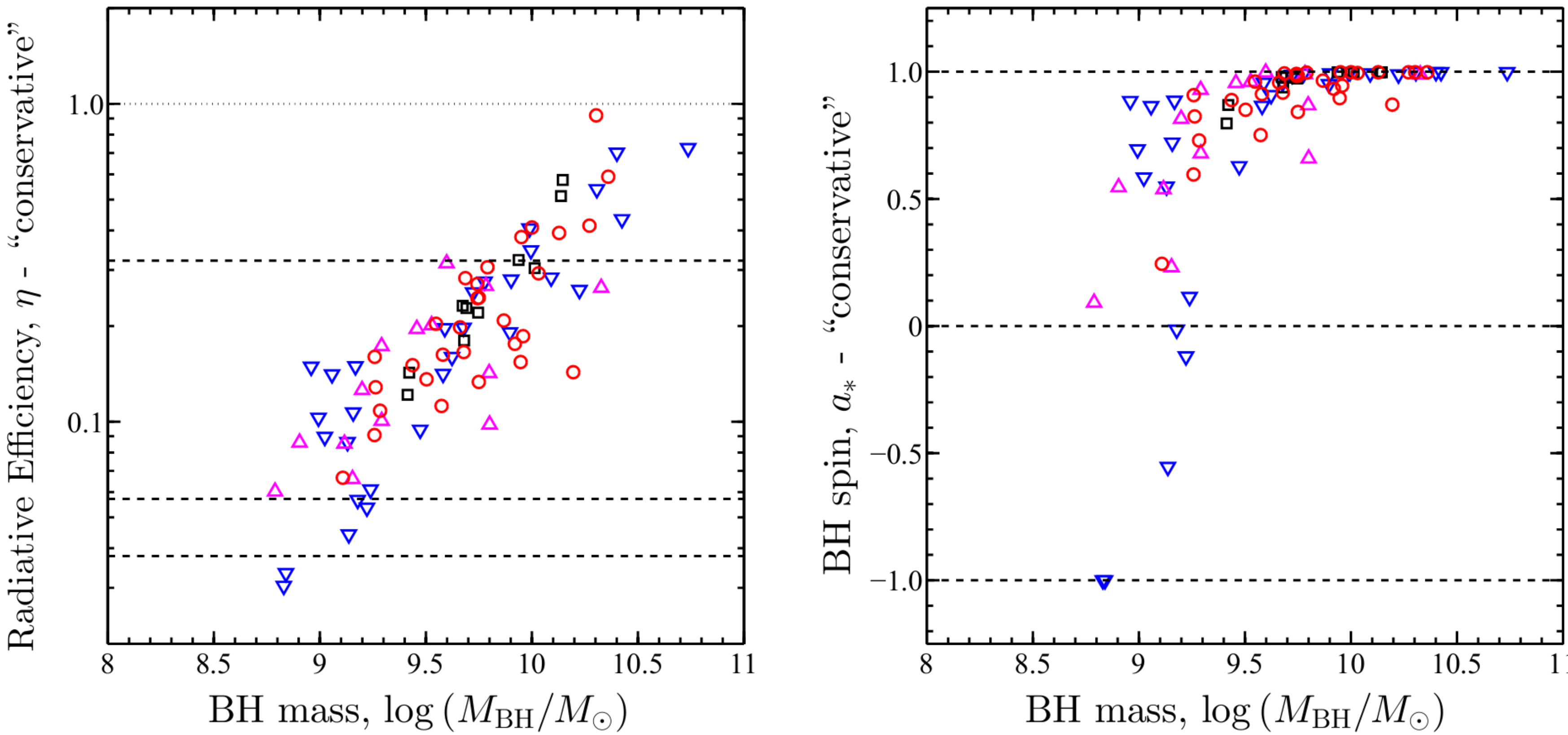
  $\rightarrow M_{\rm BH}$ and $\dot{M}_{\rm disk}$

- **Most sources have $M_{\rm BH} > 3\times10^9\, M_\odot$**



Most massive BHs, z~1.5-3.5: lower limits on η

Highest $\dot{M}_{disk}$ and *lowest* L_{bol} $(= 3 \times L_{5100})$



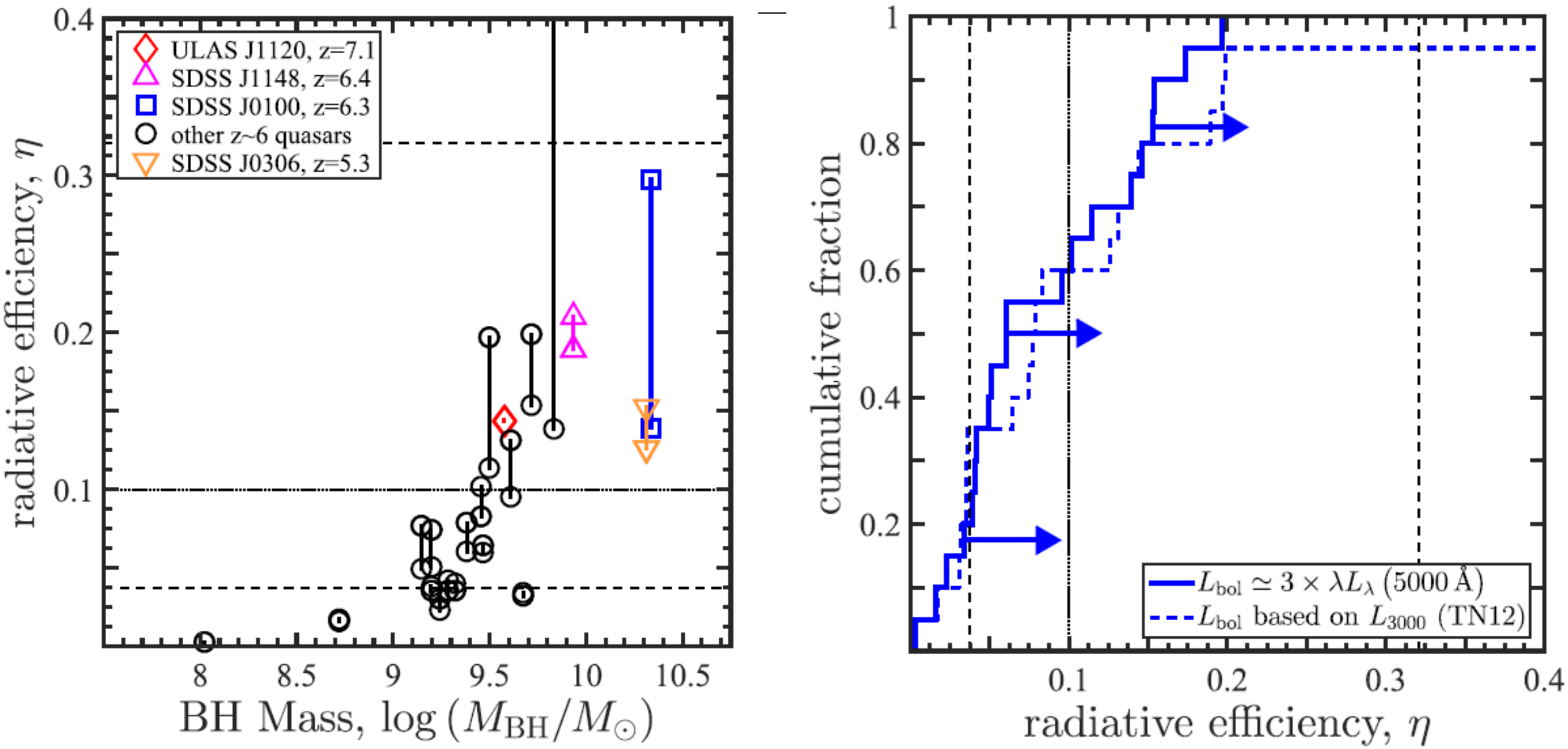
the most massive BHs have high radiative efficiencies

… and high spins ➔ low growth efficiencies

Trakhtenbrot 14

Highest-z quasars, z~6-7: lower limits on η

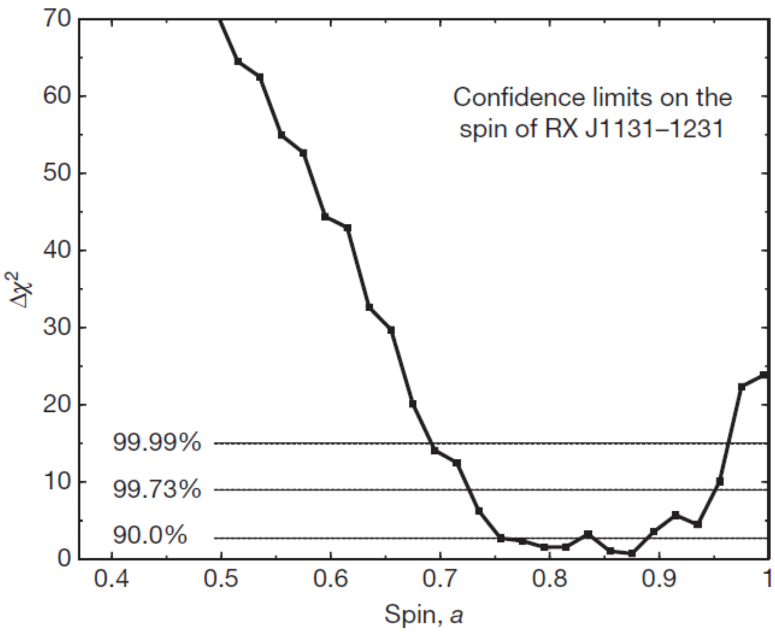
Highest $\dot{M}_{\rm disk}$ and *lowest* $L_{\rm bol}$ $(= 3 \times L_{5100})$

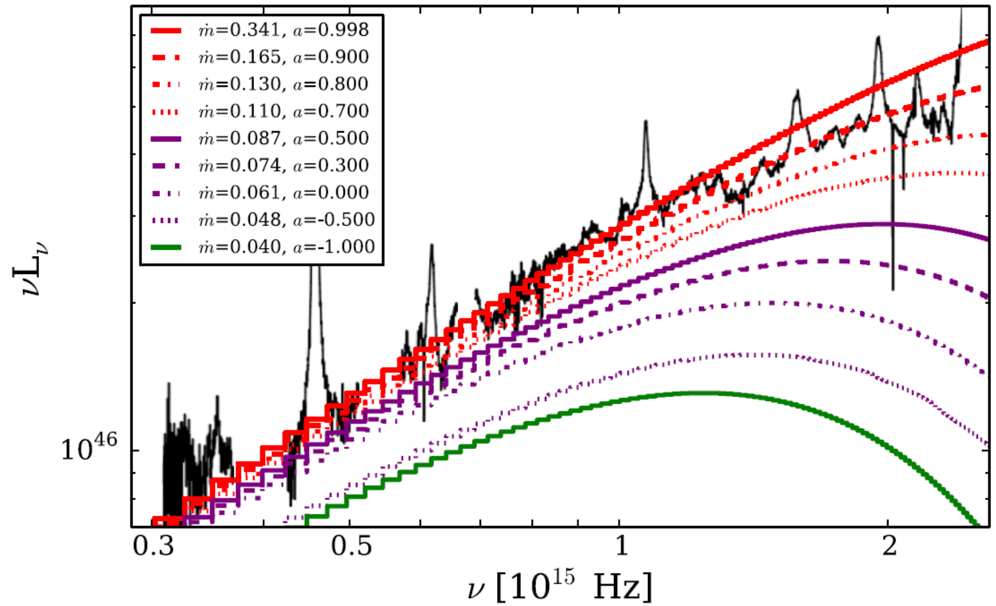


the highest-redshift quasars are consistent with Eddington-limited, radiatively efficient, thin-disk accretion

Trakhtenbrot, Volonteri & Natarajan 17

Additional evidence for high spins at high M_{BH}





- Recent Kα results at $z \sim 1$-2
  (e.g., Reis+14, Reynolds+14)

- UV-Optical SED fitting for $z \sim 1.5$ AGN with known BH mass
  (Capellupo+15, 16)

- Requirement for significant ionizing radiation (for lines)
  → About 75% of massive $z \sim 0.7$ SDSS quasars have $a_* > 0.7$
  (Netzer & Trakhtenbrot 14)

Summary – 1. the quasars we know

1. Radiative efficiencies and BH spins are important for understanding SMBH growth

2. The most massive BHs, at z~1.5-3.5 have high spins
   Their luminosities require high η , given the virial masses

3. The highest-z quasars, at z~6, can be explained self-consistently with thin-disk, sub-Eddington accretion
   if one assumes a thin-disk optical SED, most have η > 0.04

… but what about "elusive" AGN?

We are missing faint AGN at z~5-7

we *expect* to observe them… … but we do *not*

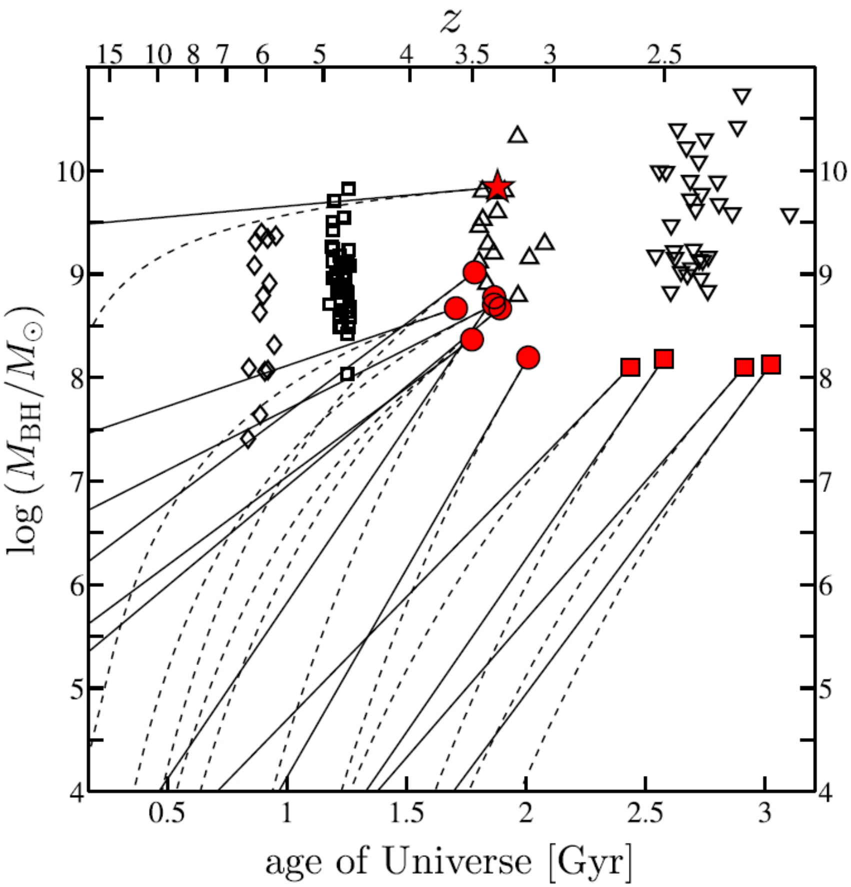
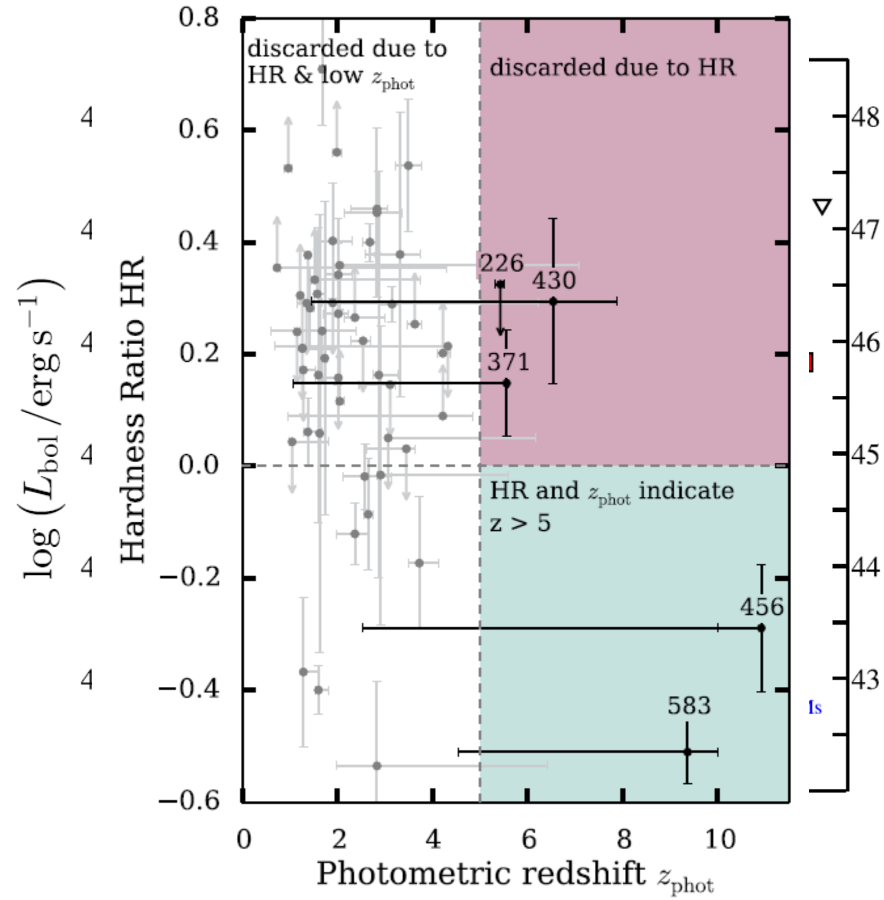


Fig. from Trakhtenbrot+16

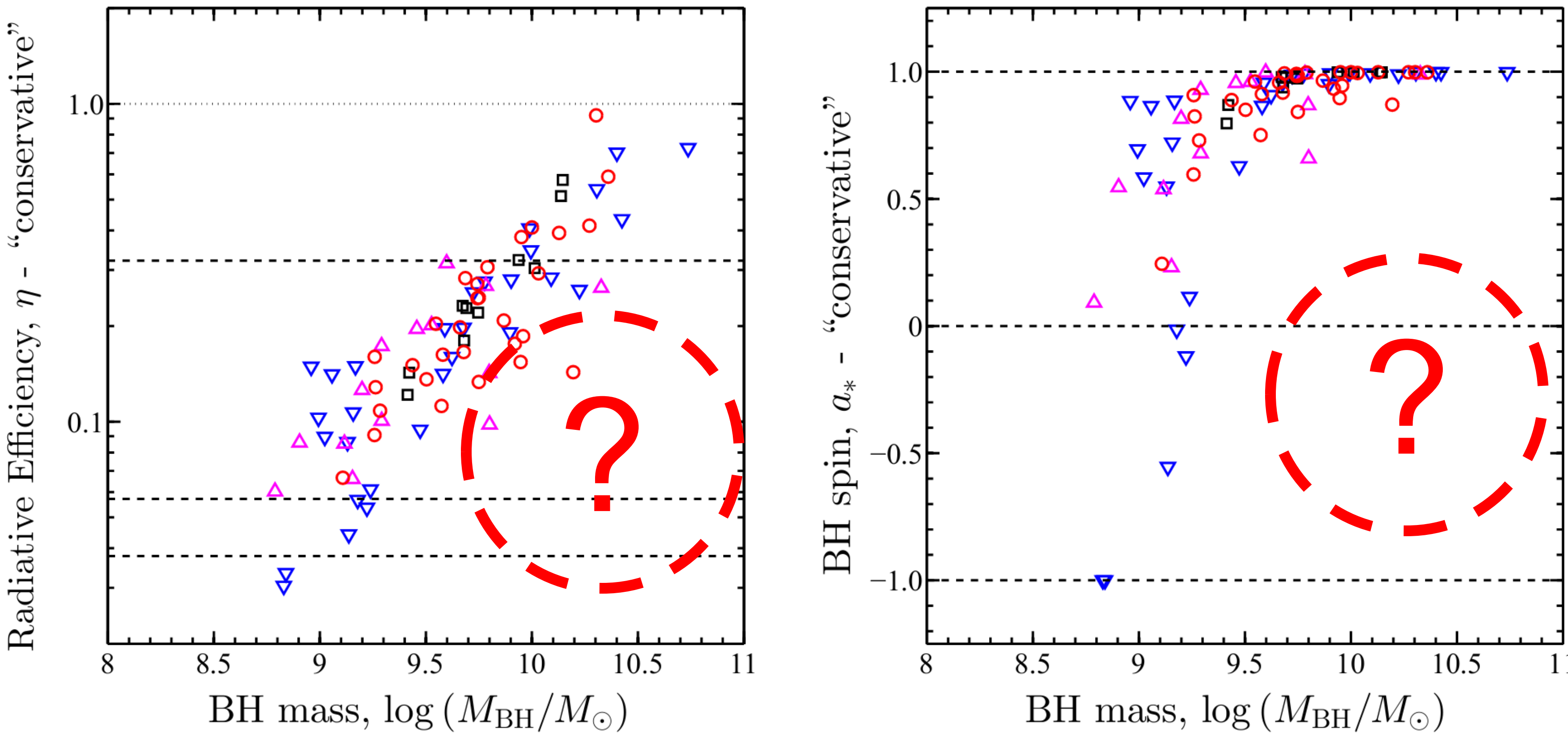


Weigel+15

are the missing AGN obscured? radiatively inefficient?

Most massive BHs, z~1.5-3.5: lower limits on η

Highest $\dot{M}_{\rm disk}$ and *lowest* $L_{\rm bol}$ $(= 3 \times L_{5100})$



the most massive BHs have high radiative efficiencies

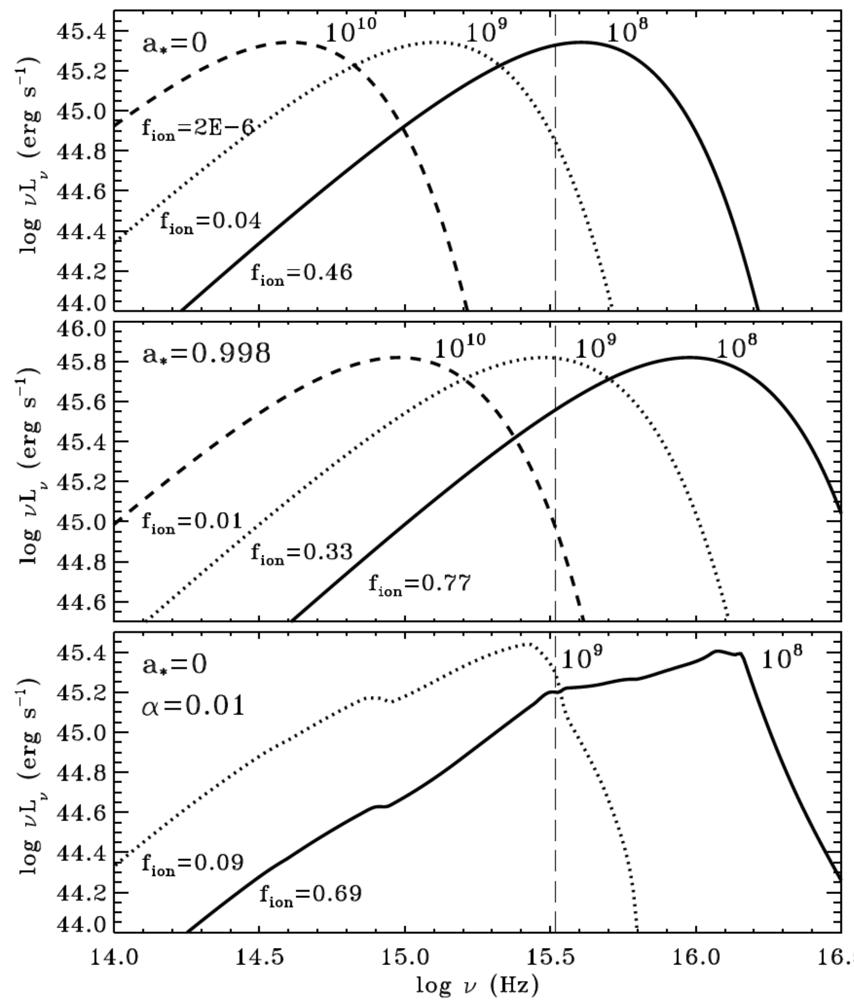
... and high spins ➔ low growth efficiencies

Trakhtenbrot 14

Are we missing high-mass, high-z SMBHs with low or retrograde spins?

In thin disk models, UV radiation decreases for high-mass and/or low spin SMBHs:

1. UV-optical SED becomes “red”



Laor & Davis 11

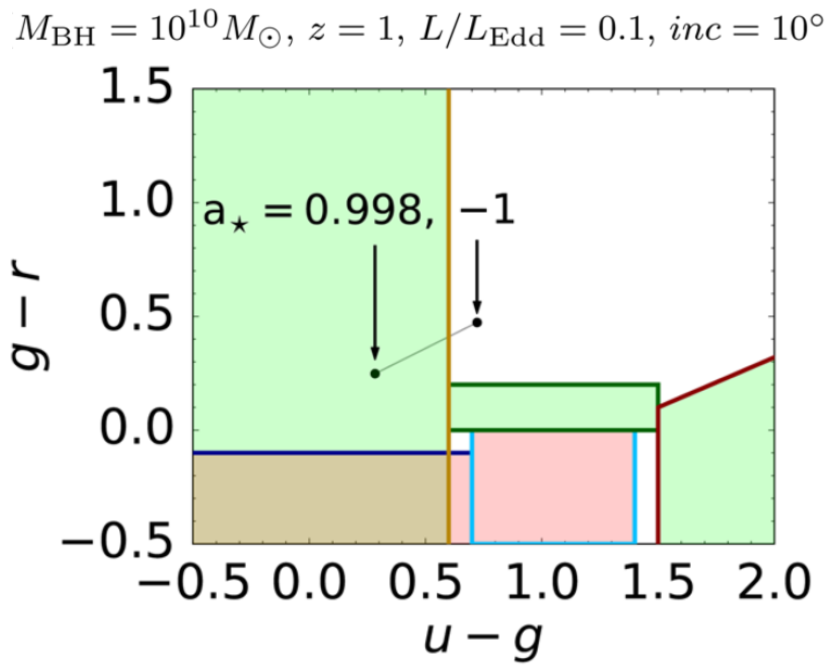
Are we missing high-mass, high-z SMBHs with low or retrograde spins?

testing SDSS color-color selection for thin-disk models

Bertemes, BT +16

a grid of thin disk models:
~400,000 SEDs

Parameter	Min. value	Max. value	Step size
BH mass, $\log(M_{BH}/M_{\odot})$	6	11	0.5
BH spin, a_*	−1	0.998	0.1
Accretion rate, L/L_{Edd}	0.05	1	0.05
Redshift, z	0.5	2	0.1
Inclination, inc	10°	50°	10°



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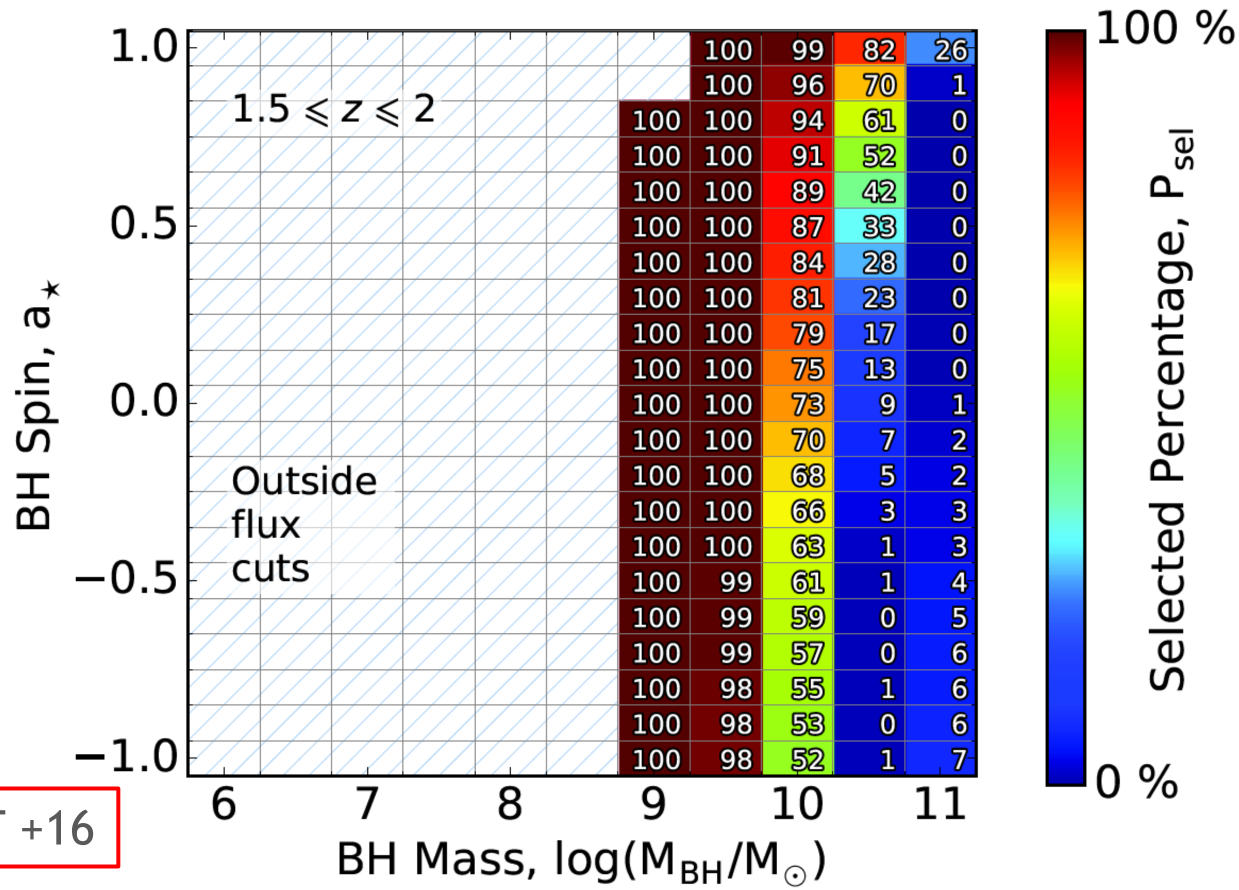

Bertemes, BT +16

SDSS color-color selection misses high-mass, low spin BHs

Are we missing high-mass, high-z SMBHs with low or retrograde spins?

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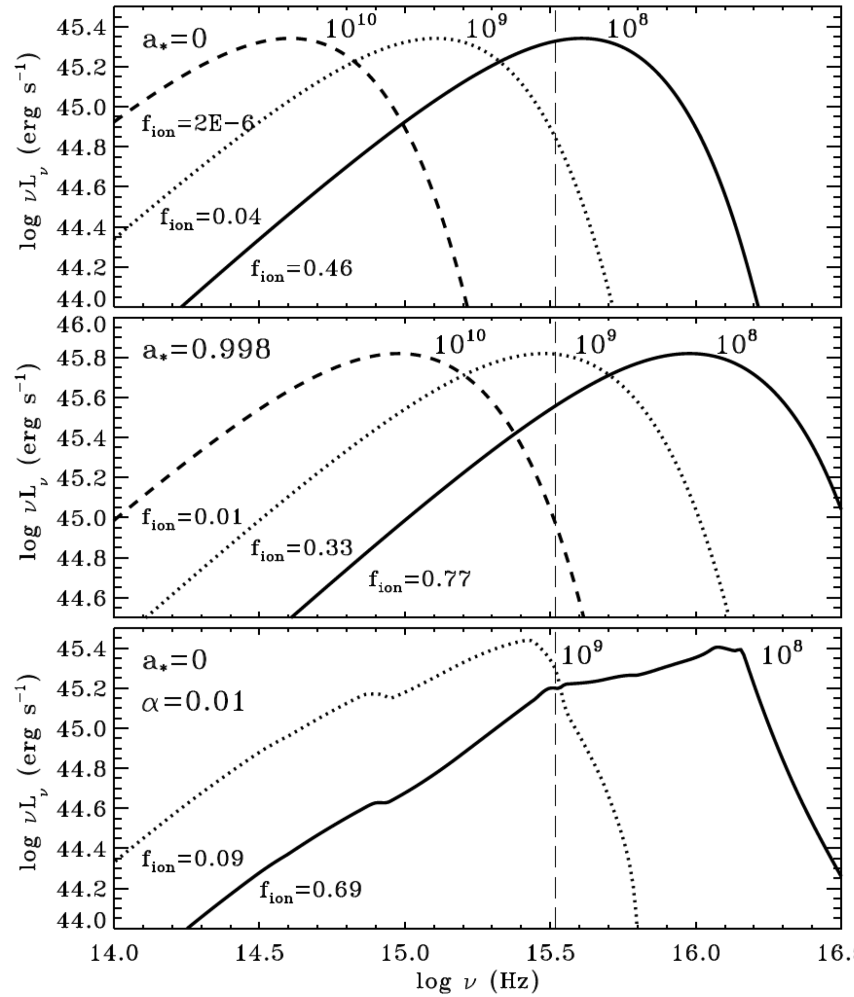
2. Insufficient ionizing radiation for emission lines

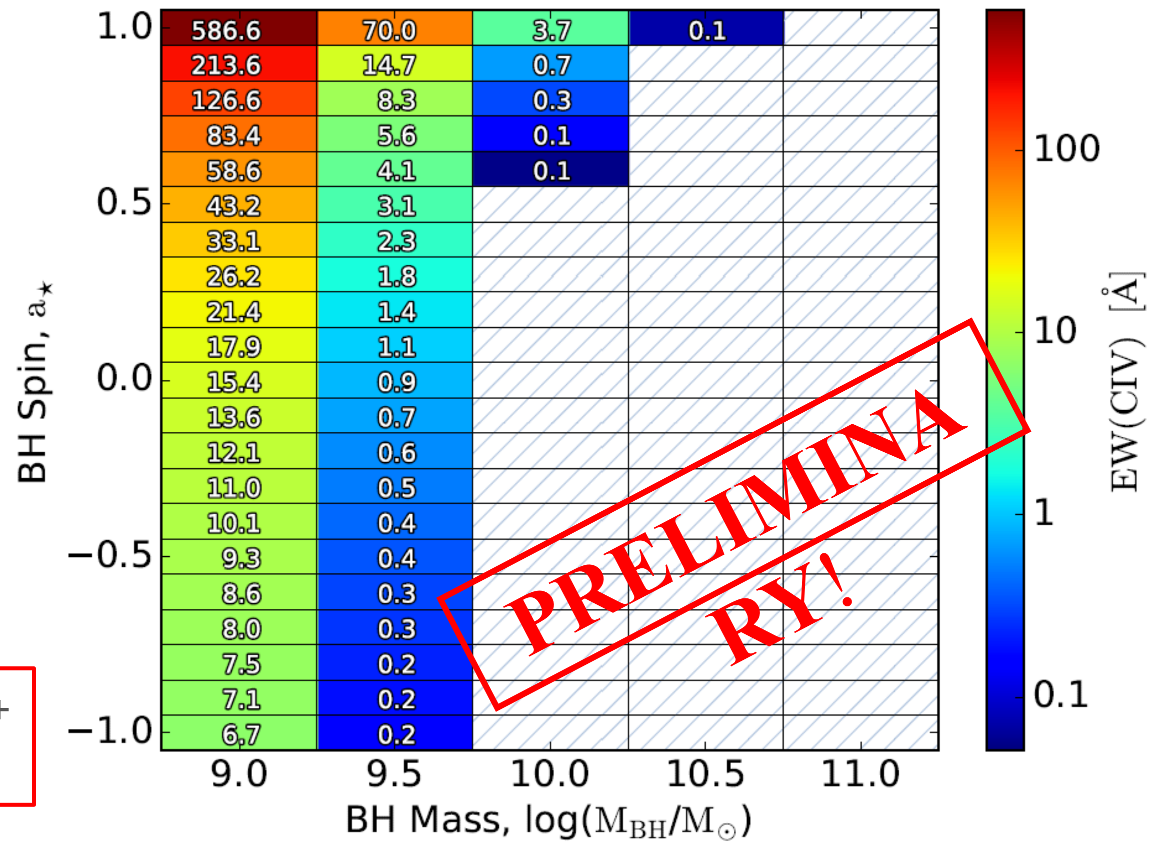


Laor & Davis 11

Are we missing high-mass, high-z SMBHs with low or retrograde spins?

modeling broad-line emission with thin-disk SEDs & CLOUDY

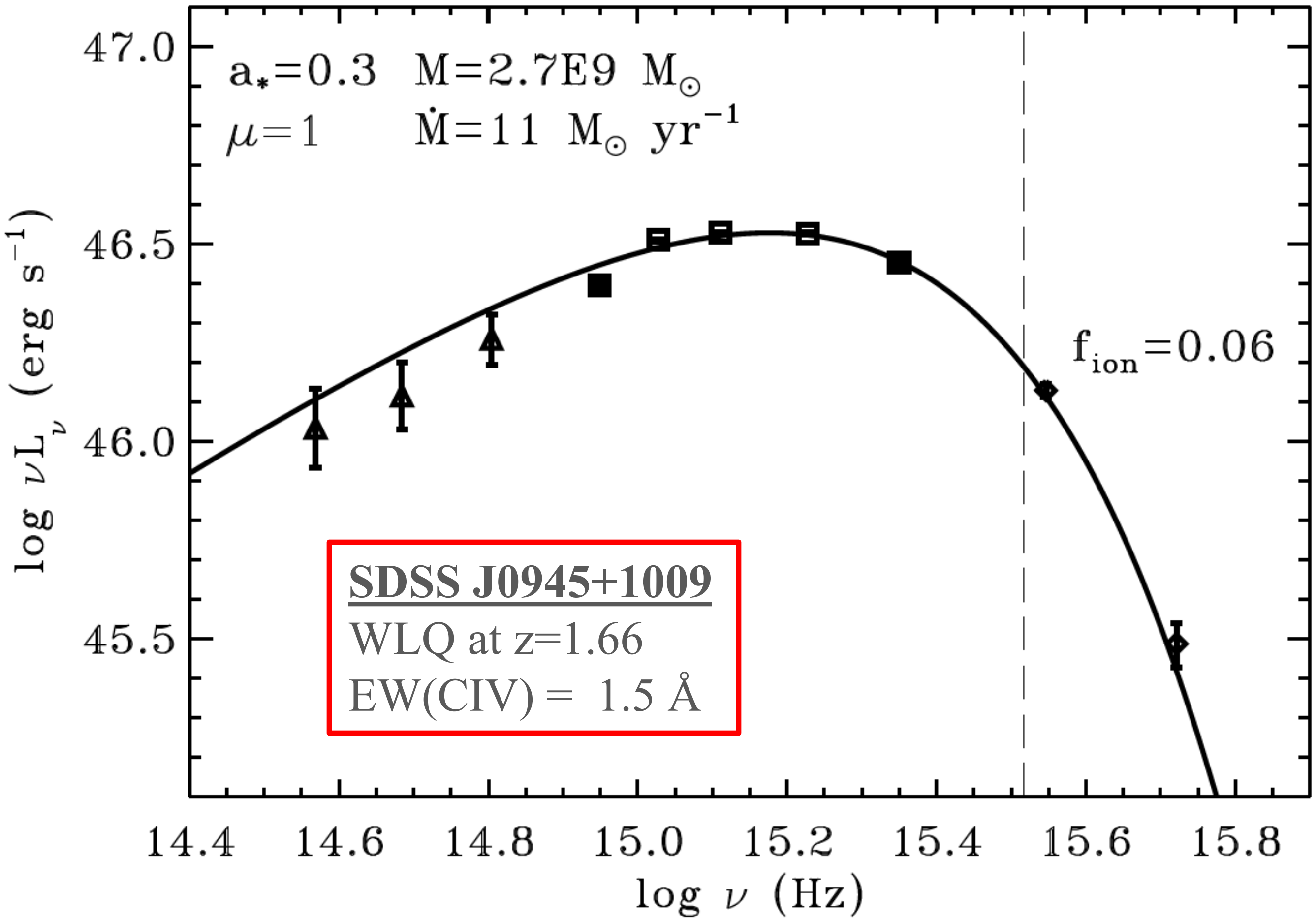
10 $M_\odot$/yr
CIV 1549



Bertemes, BT+
(in prep.)

high-mass, low-spin BHs would have weak high-ion. lines

Are we missing high-mass, high-z SMBHs with low or retrograde spins?



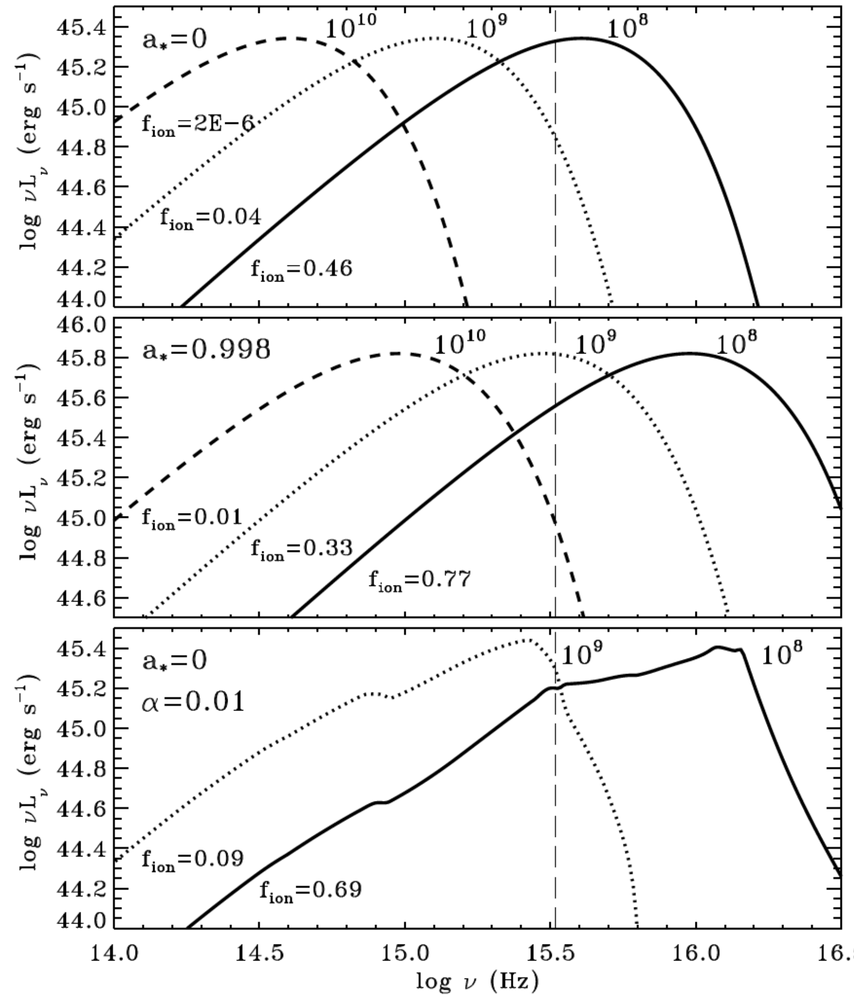
an example for a cold accretion disk in the SDSS

Hryniewicz+11, Laor & Davis 11 (more WLQs in Shemmer+10, Plotkin+15)

Are we missing high-mass, high-z SMBHs with low or retrograde spins?

In thin disk models, UV radiation decreases for high-mass and/or low spin SMBHs:

1. UV-optical SED becomes "red"
2. Insufficient ionizing radiation for emission lines
3. **Disk outflows and/or super-Eddington accretion can make it worse**
4. **No UV → no X-rays? No (M)IR?**



Laor & Davis 11

Conclusions

1. Radiative efficiencies and/or BH spins are important for understanding SMBH growth

2. The most massive BHs, at z~1.5-3.5 have high spins
   Their luminosities require high η , given the virial masses

3. The highest-z quasars, at z~6, can be explained self-consistently with thin-disk, sub-Eddington accretion
   if one assumes a thin-disk optical SED, most have $\eta > 0.04$

4. We might be missing the high-mass, non-spinning, retro-grade spinning, and/or radiatively inefficient SMBHs

5. "UV-poor AGN" might be elusive in emission lines, X-rays & IR

Thank you!

Conclusions

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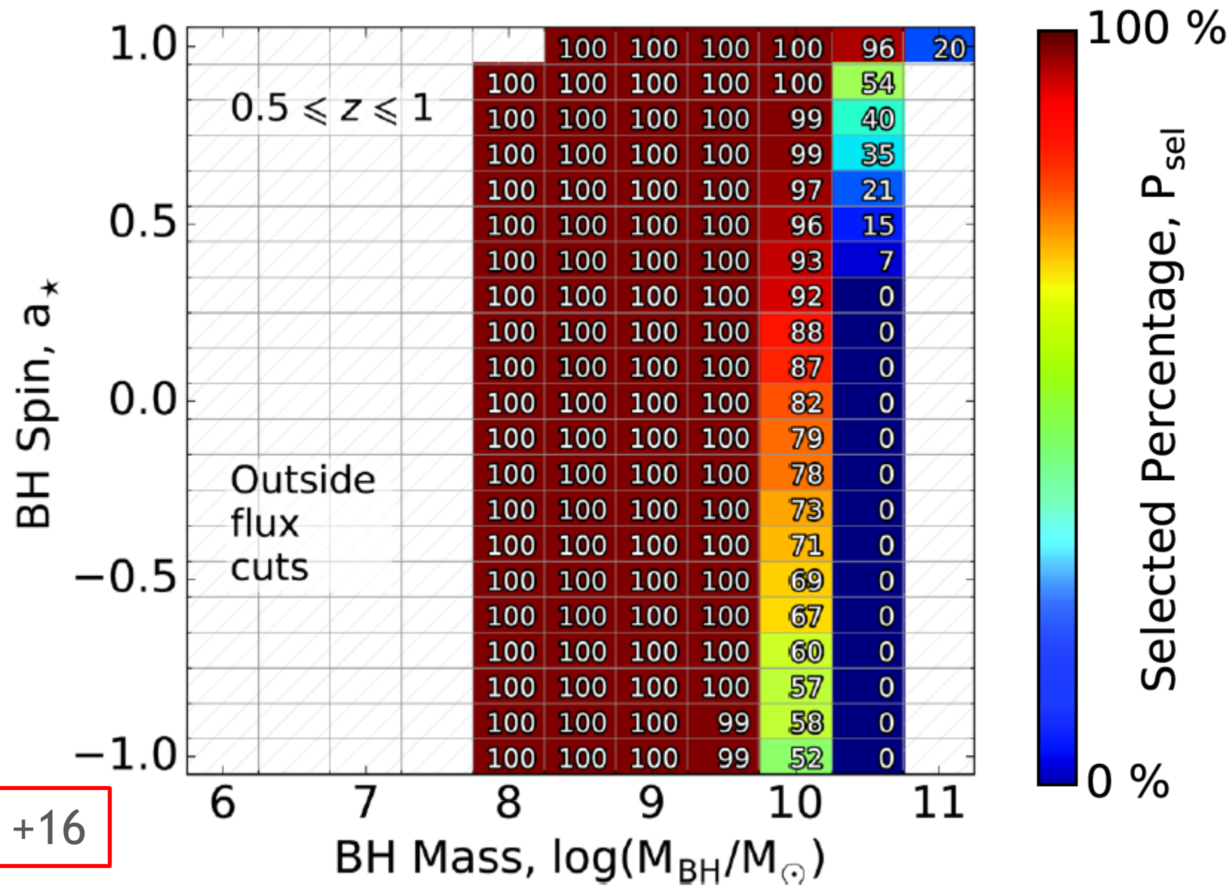
Thank you!

Are we missing high-mass, high-*z* SMBHs with low or retrograde spins?

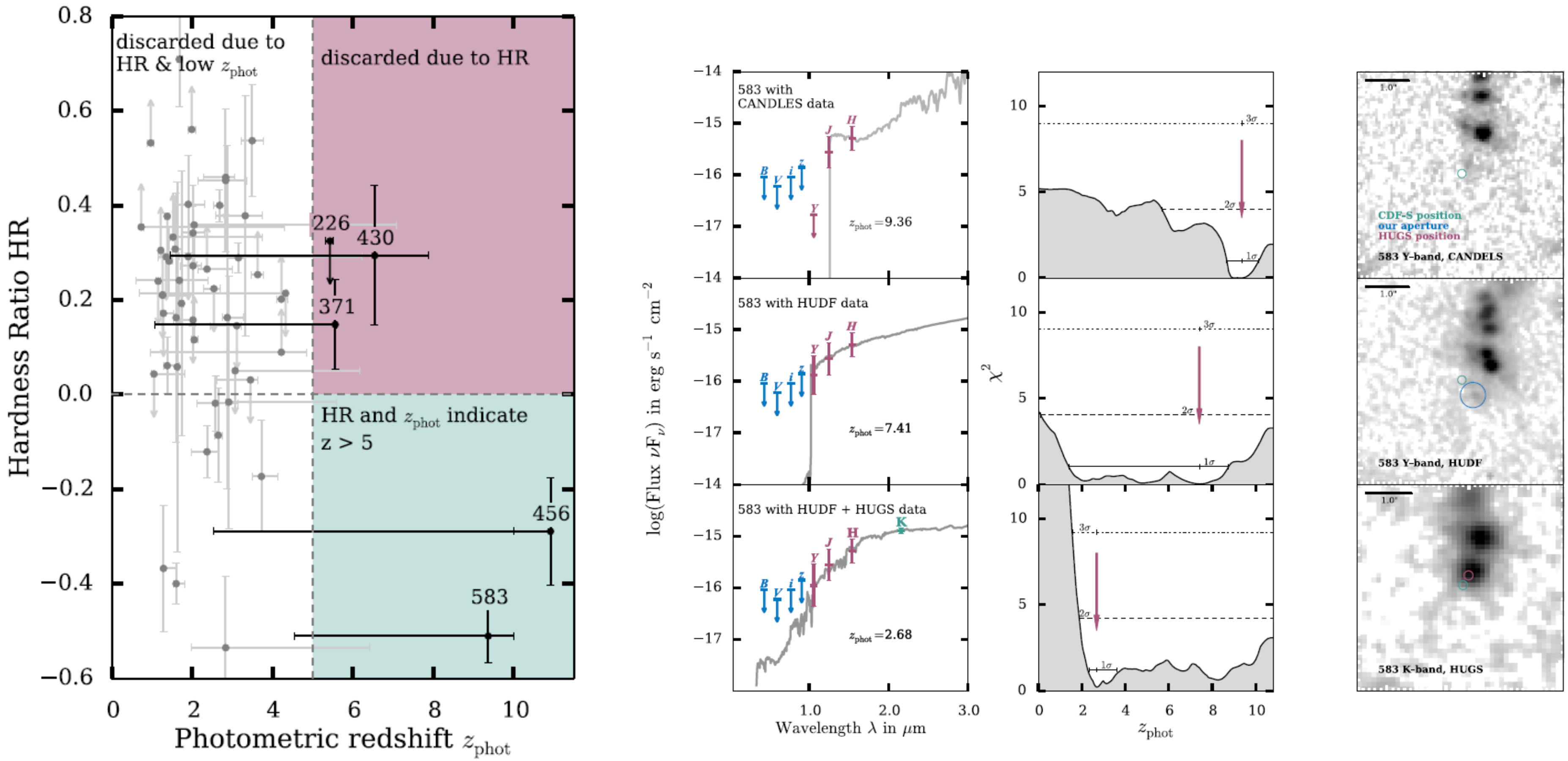
testing SDSS color-color selection for thin-disk models



Bertemes, BT +16

SDSS color-color selection misses high-mass, low spin BHs

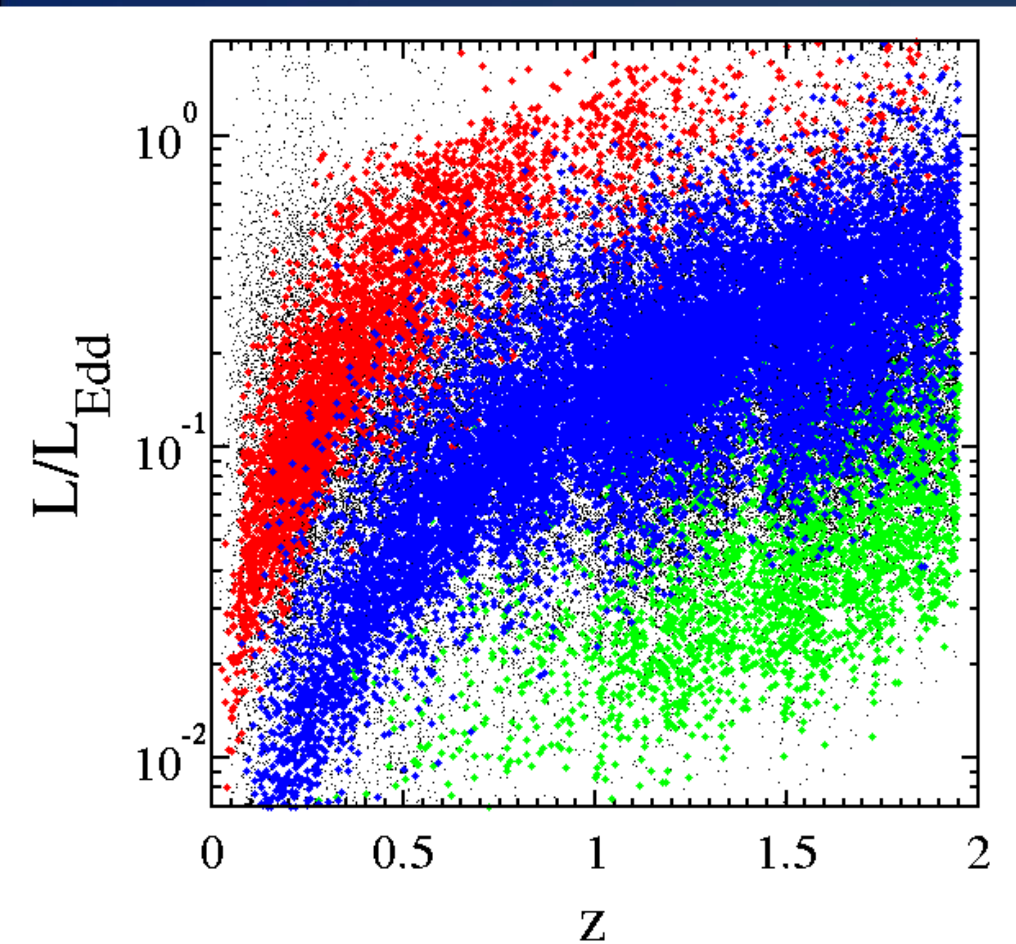
We are missing faint AGN at z~5-7



Weigel+15

L/L_{Edd} Evolution in Luminous, Unobscured AGN

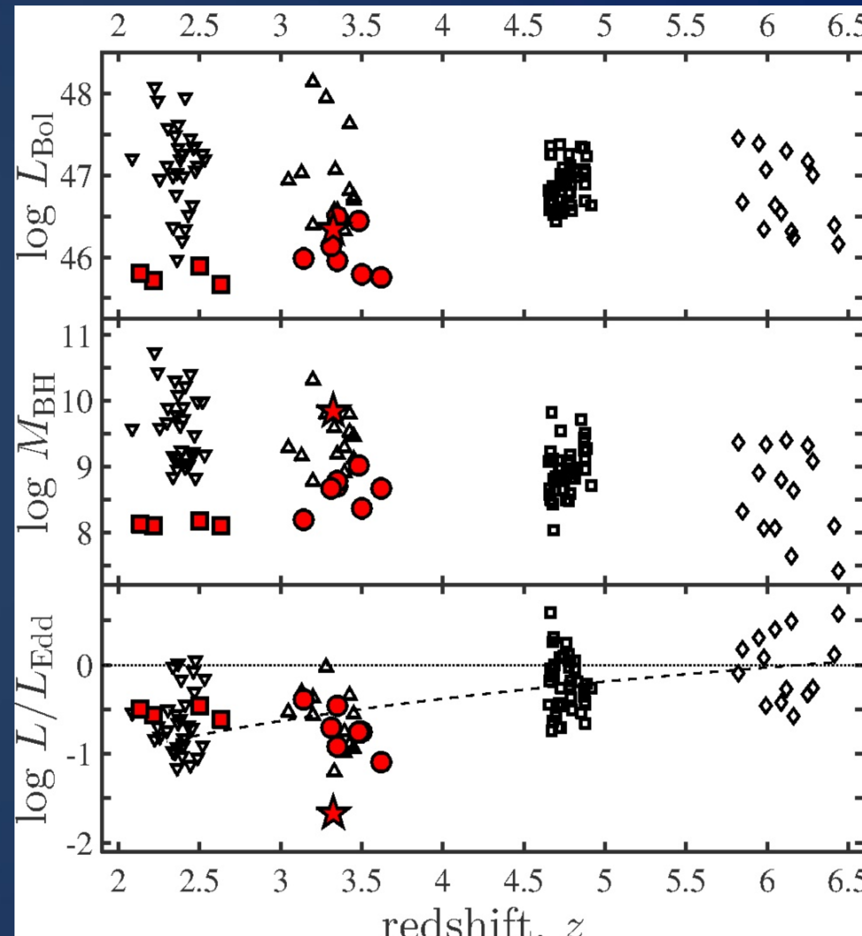
SDSS - out to $z \sim 2$



$M_{BH} = 4\times10^{7}$ 4×10^{8} 1.5×10^{9}

Trakhtenbrot & Netzer (2012)

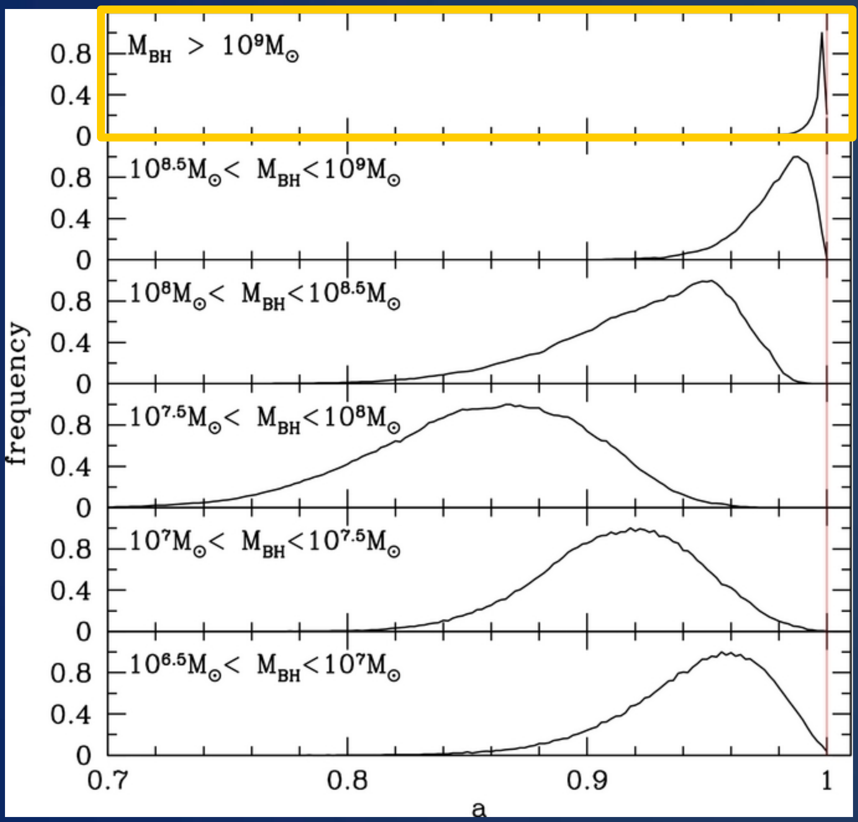
NIR studies - $z \sim 2 - 7$



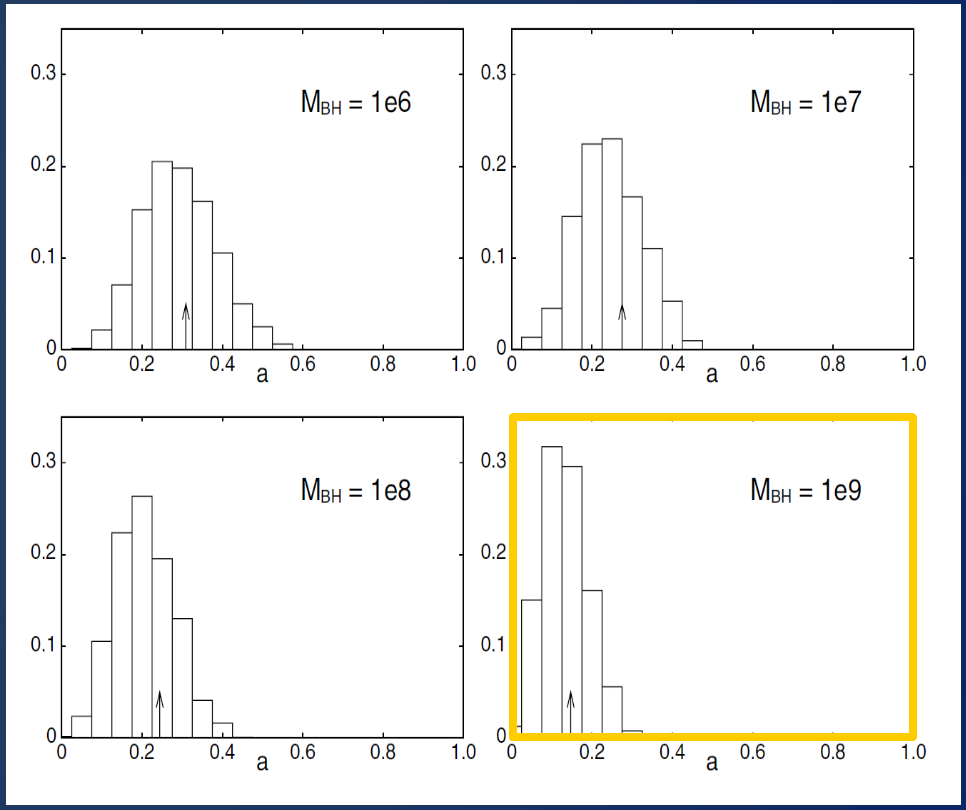
Netzer+2007, Kurk+2007, Willott+2010, Trakhtenbrot+2011, Trakhtenbrot+2016

BH spin evolution:
expectations for extremely massive BHs

spin-up (Dotti et al. 2013)



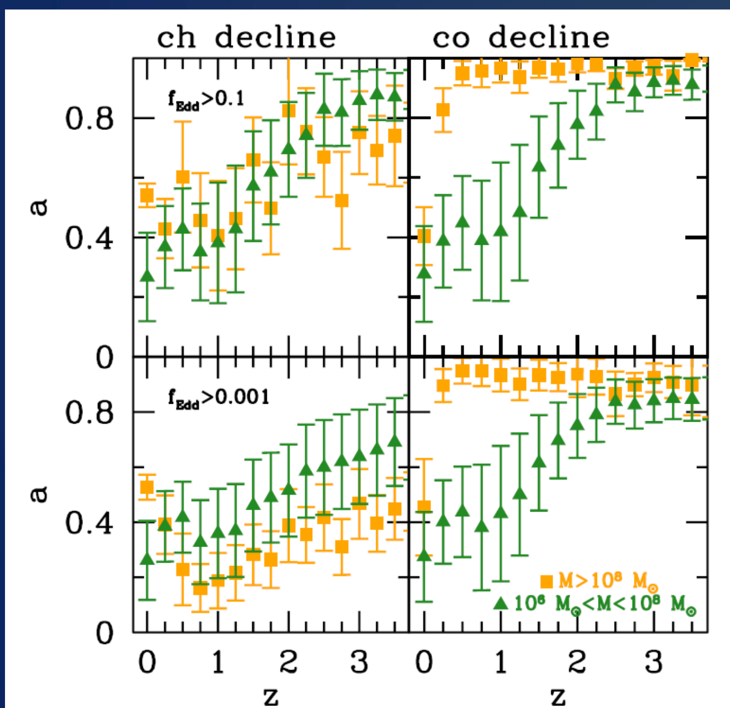
spin-down (King et al. 2008)



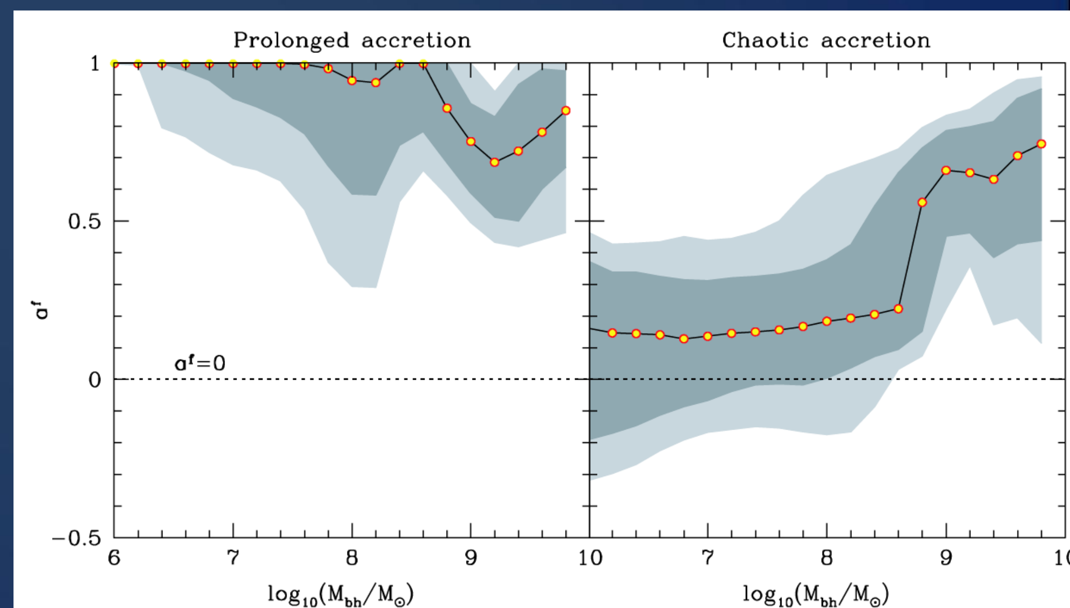
The most massive SMBHs ($M_{BH} > 10^9 M_\odot$) experience more accretion episodes → largest difference in spins

BH spin evolution:
expectations for extremely massive BHs

Embedding accretion prescriptions in SAMs provide evolutionary tracks and distributions of BH spin

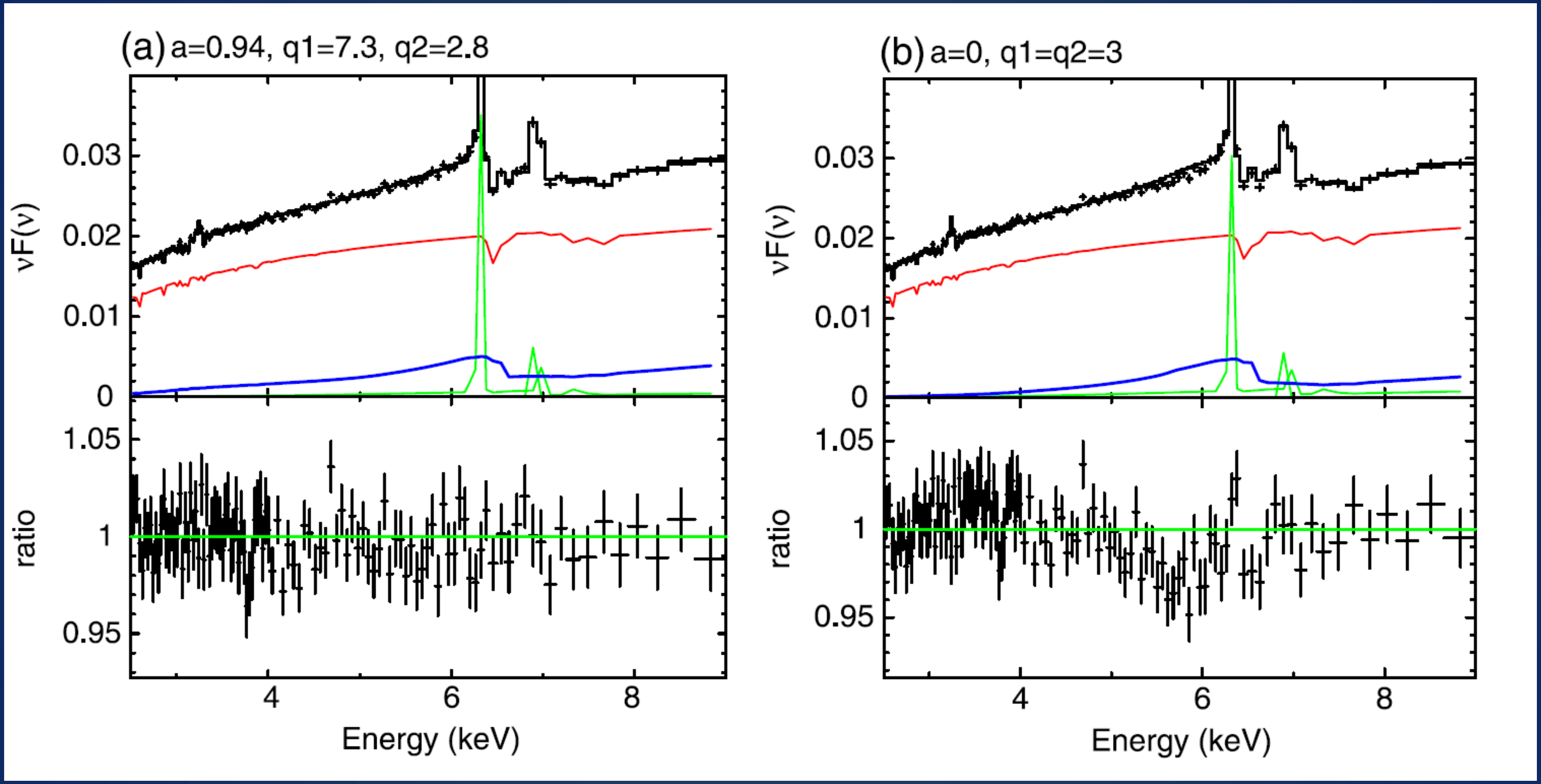


Volonteri et al. (2013)



Fanidakis et al. (2011)

BH spin estimates: the Kα method

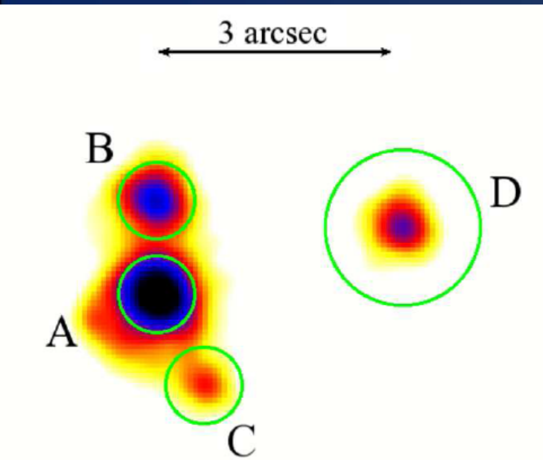


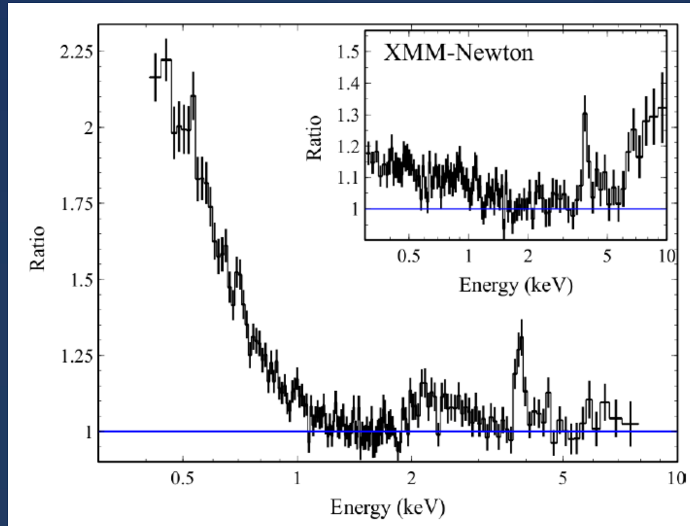
Gravitationally broadened Iron Kα line at ~6.7 keV,
reflected from the accretion disk,

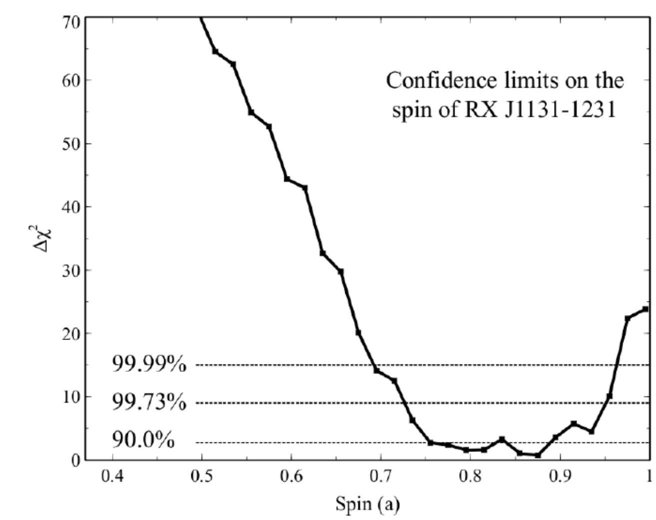
review by Reynolds (2013)

BH spin estimates: the Kα method at high z ?

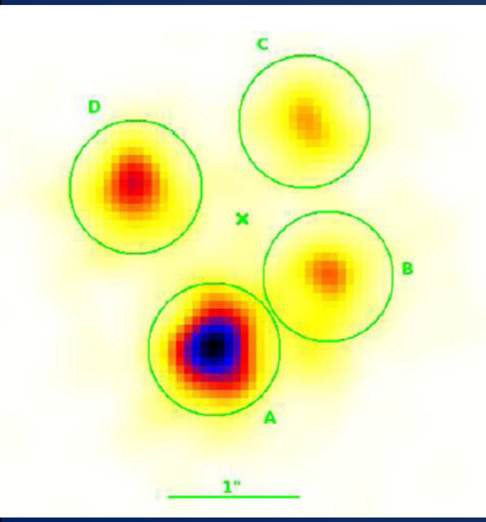
Reis et al. (2014, *Nature*) - z = 0.658 , $M_{\rm BH} \approx 10^8 M_\odot$, a_*=0.87

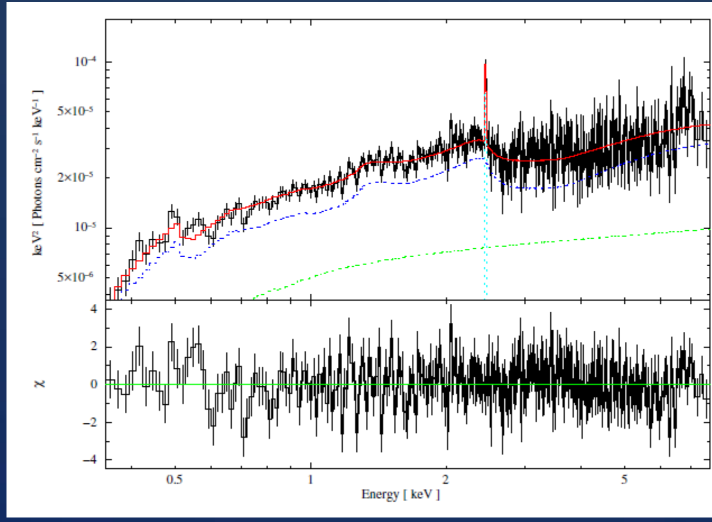


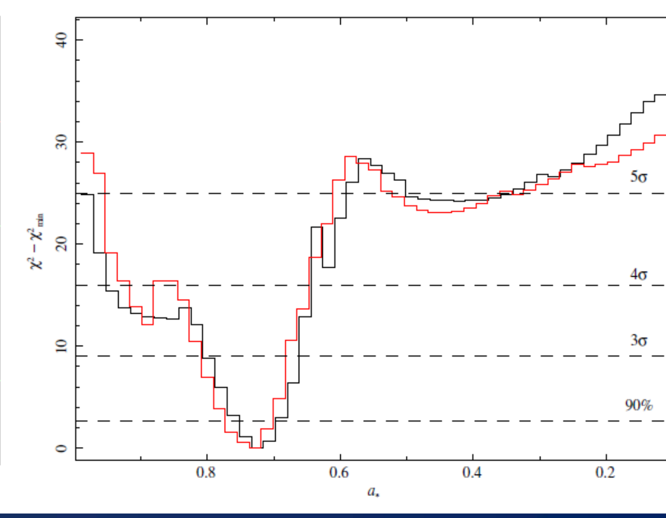




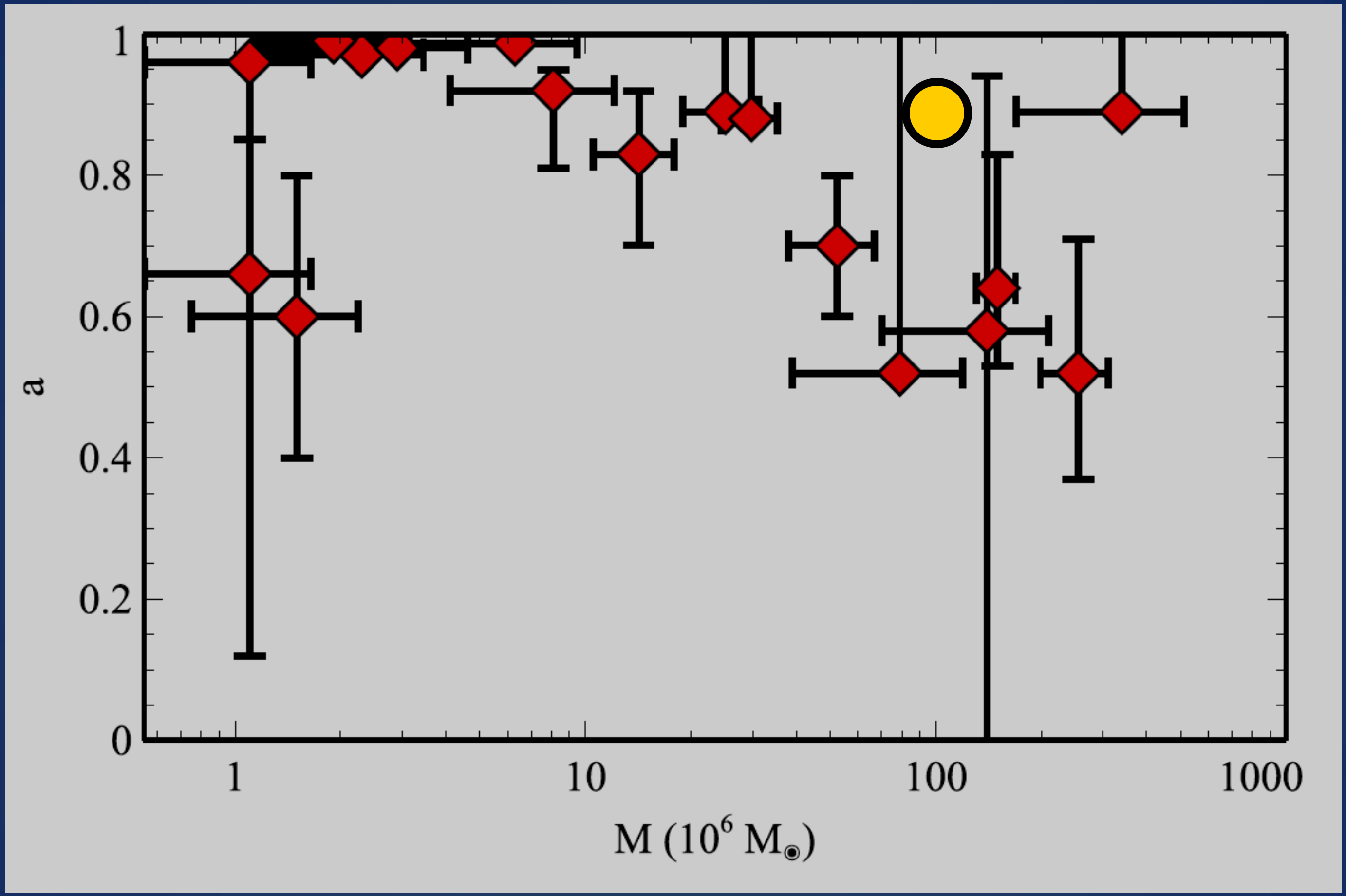
Reynolds et al. (2014) - z = 1.695 , $M_{\rm BH} = 3\times10^9 M_\odot$, a_*=0.74







BH spin estimates: the Kα method



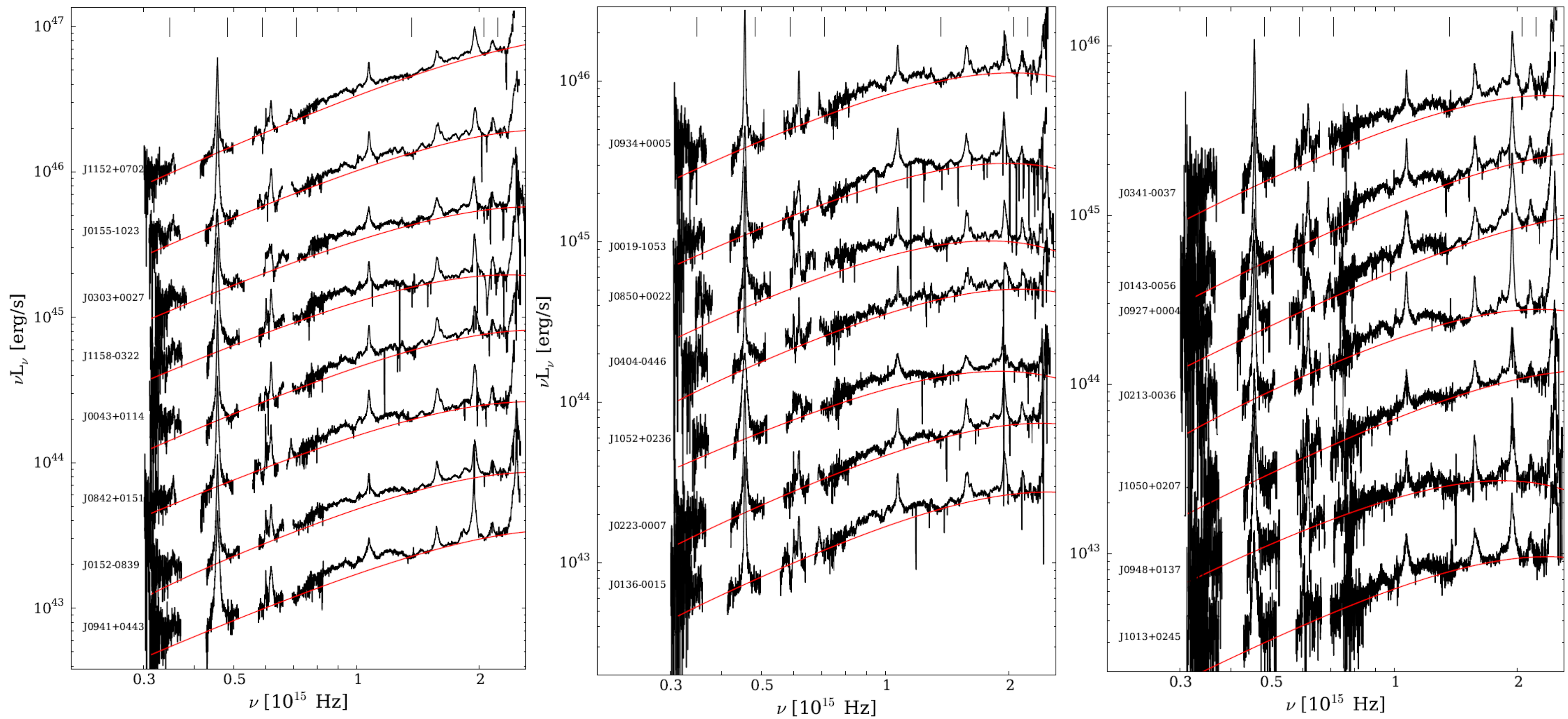
Spin estimates for ~20 local, low-luminosity and low-M_{BH} AGNs

No non-spinning SMBHs (publication bias?)

review by Reynolds (2013)

BH spin estimates: a different approach

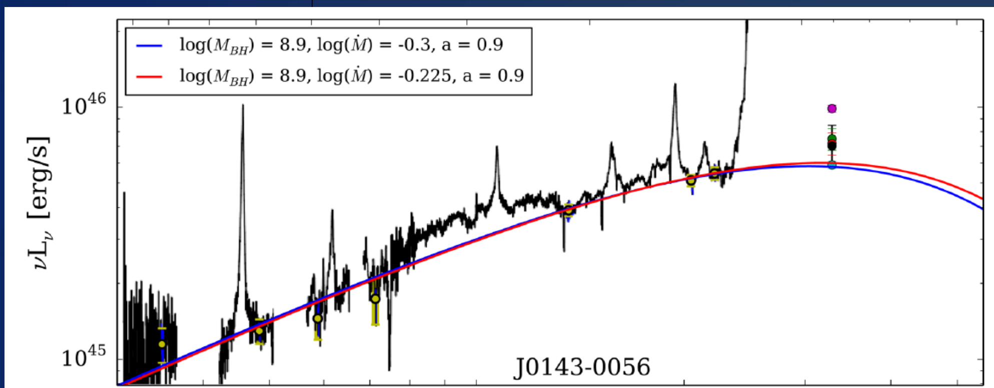
Luminous AGNs at z~1.5 accrete matter through geometrically thin, Shakura-Sunyaev-*like* accretion disks

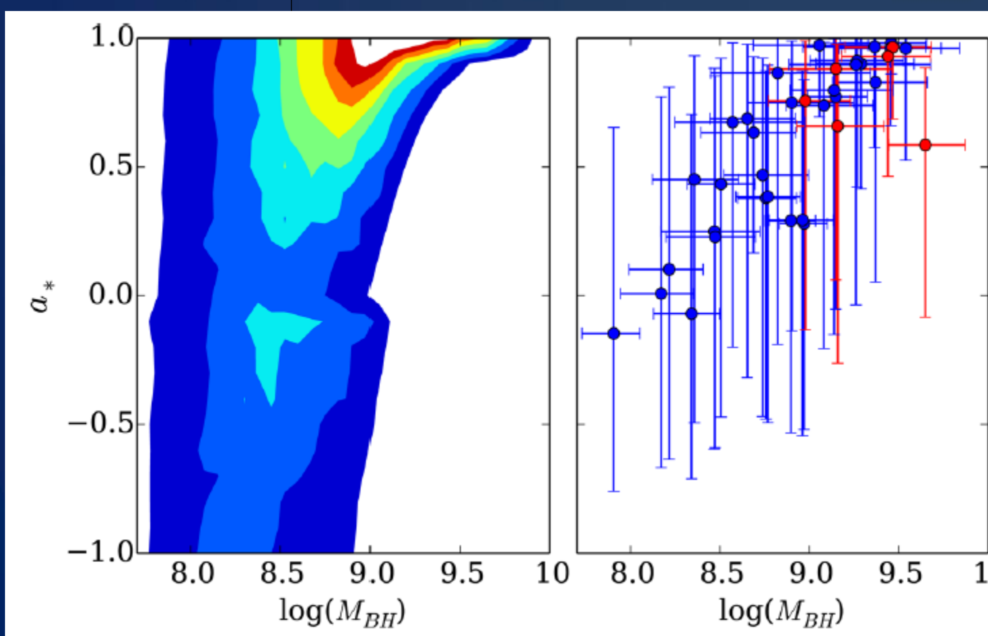


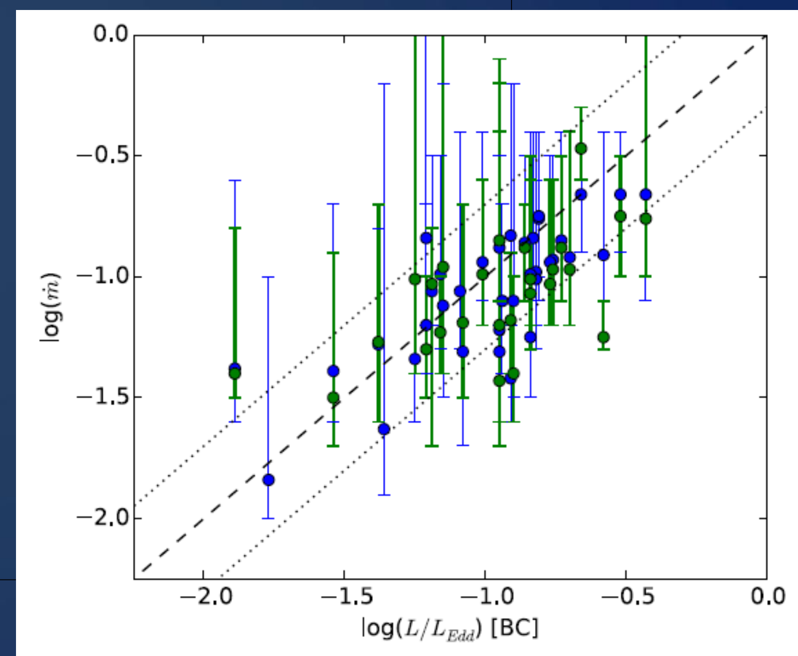
Capellupo et al. (2014)

BH spin estimates: a different approach

~45 Luminous AGNs at z~1.5 with X-Shooter – fit SEDs of geometrically thin, Shakura-Sunyaev-*like* accretion disks







Capellupo et al. (2014,2016)

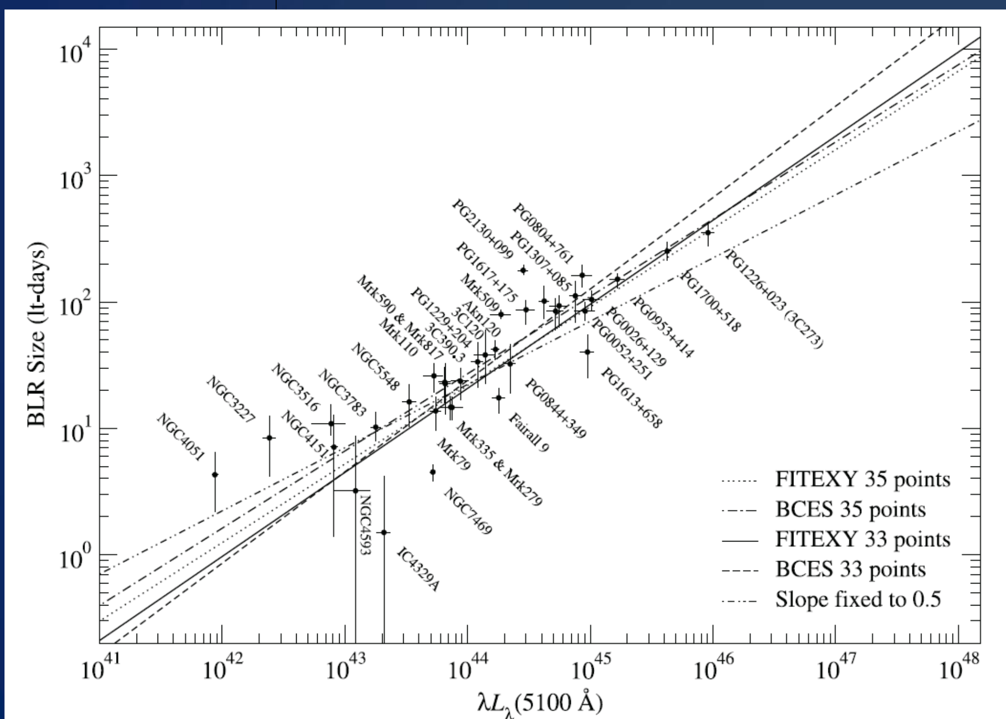
BH spin estimates: a different approach

Basic assumptions

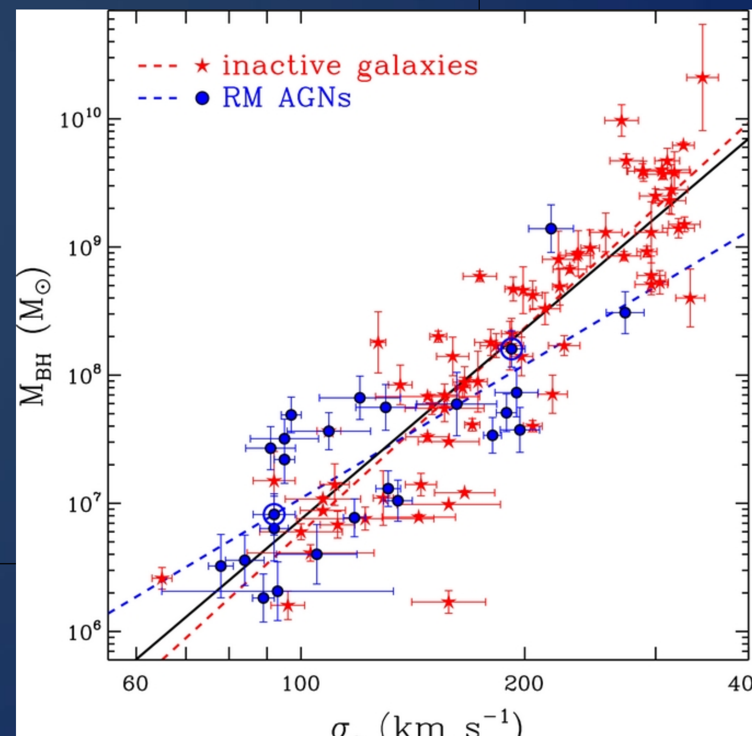
2. M_{BH} can be reliably estimated from broad emission lines

at z>0, we use empirical calibrations, based on reverberation mapping

$$M_{BH} = 1.05 \times 10^{8} \left(\frac{\lambda L_{\lambda}[5100\text{Å}]}{10^{46}\ \text{km/s}} \right)^{0.65} \left(\frac{\text{FWHM}[\text{H}\beta]}{1000\ \text{km/s}} \right)^{2} M_{e}$$



Kaspi et al. (2005)



Woo et al. (2013)

Thin accretion disks: spectral energy distributions

- Original theory by Shakura & Sunyaev (1973)…

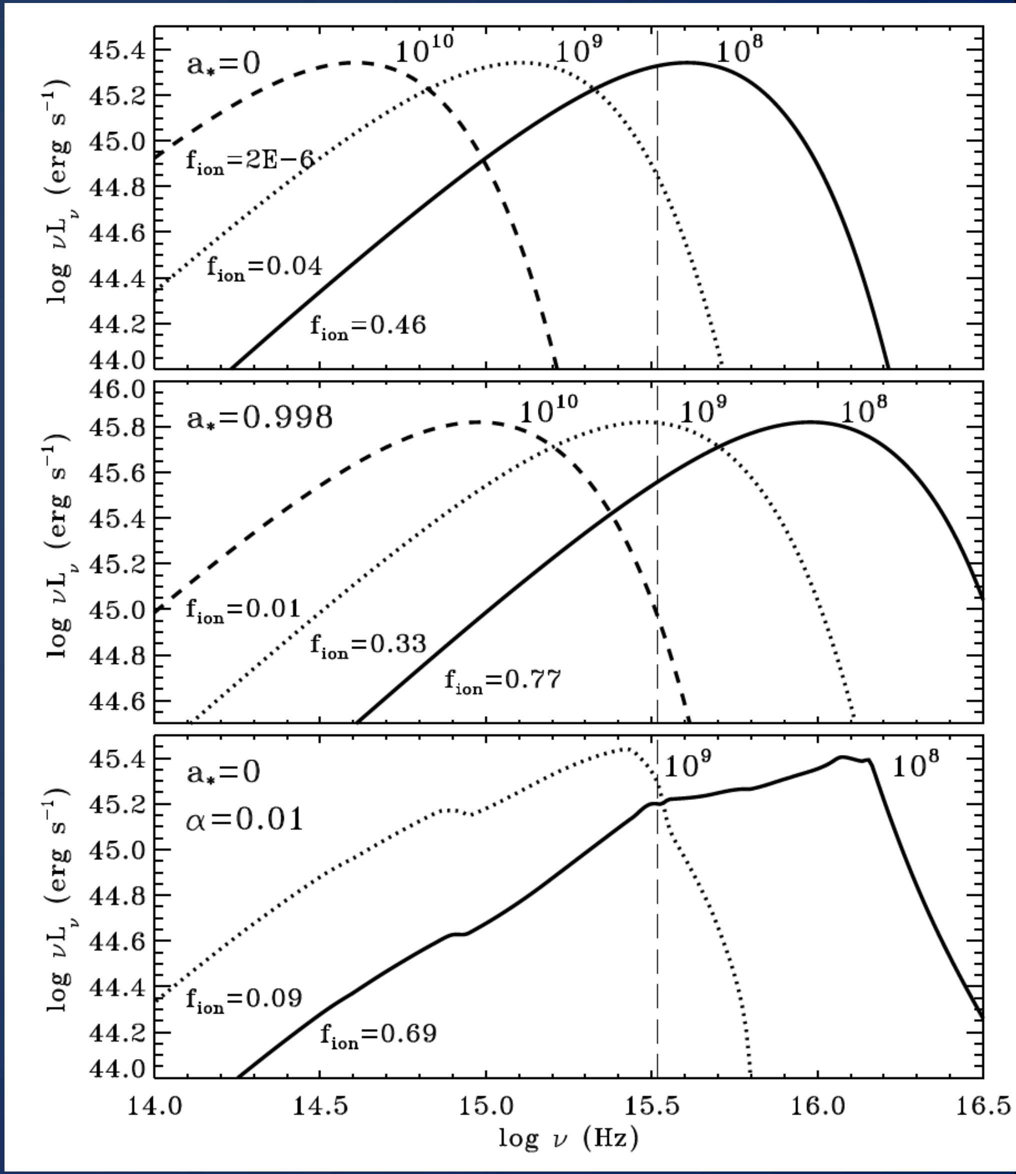
  Basic ingredients:

  M_{BH}, $\dot{M}_{AD}$ and spin

- "multi-color" shape with a low-frequency tail, due to outer (colder) region:

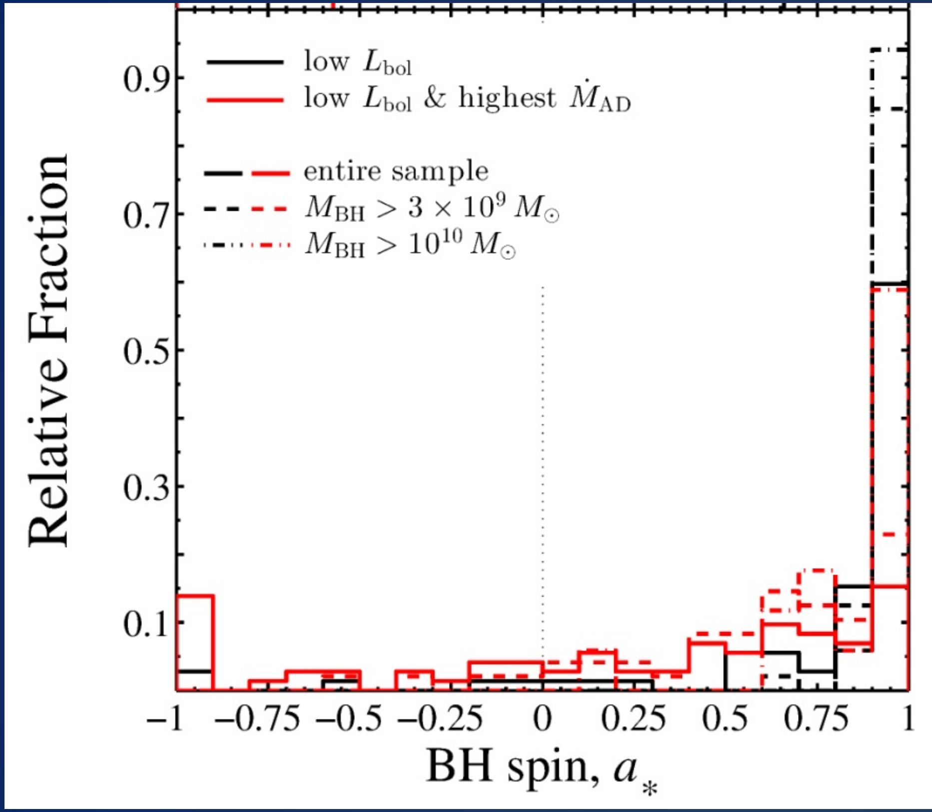
$$L_\nu \propto \left(\dot{M}_{AD} \cdot M_{BH}\right)^{2/3} \nu^{1/3}$$

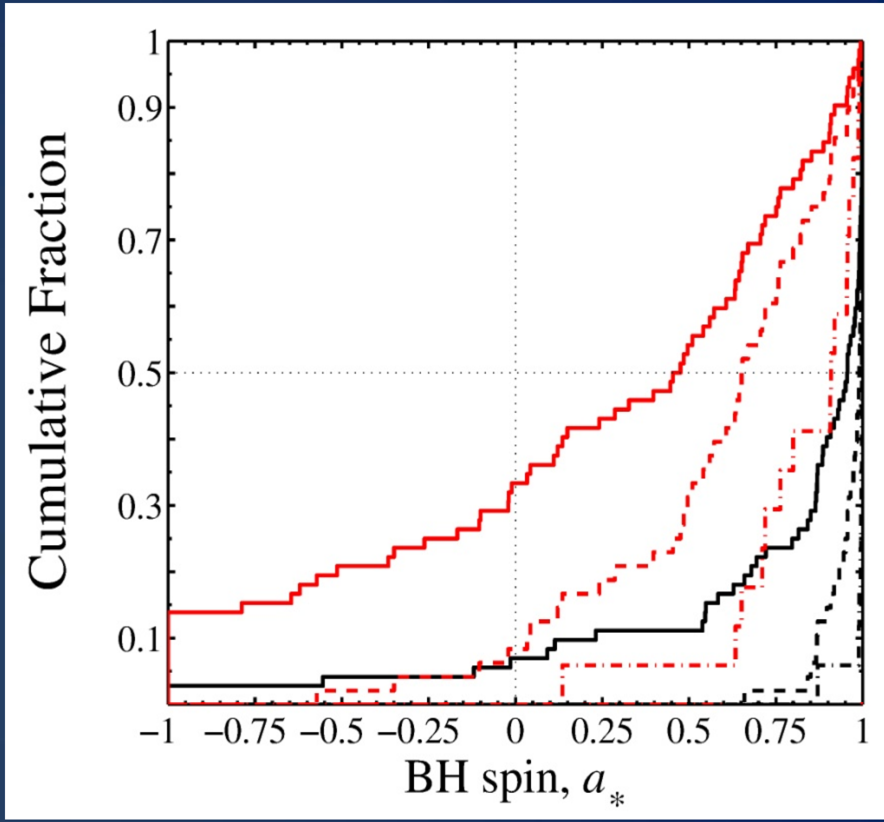
- More elaborate models, with comptonization, GR etc …



Hubney et al. (2000), Davis & Laor (2011)

Results: BH spin distributions





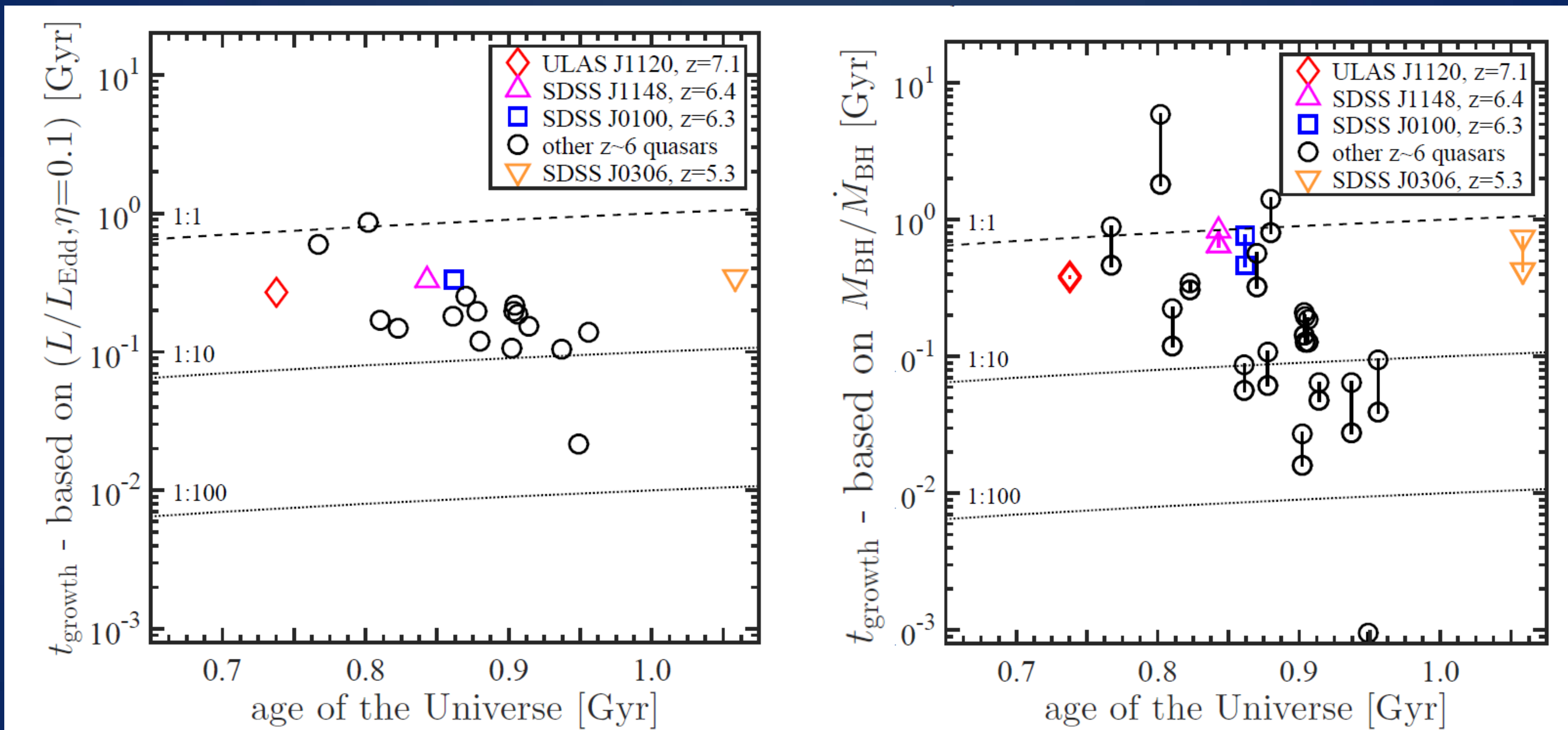
- Red lines: most conservative (lowest $L_{\rm Bol}$ and highest $\dot{M}_{\rm AD}$)
- Dashed lines: $M_{\rm BH} > 3 \times 10^9\, M_\odot$

→ 2/3 of BHs have a>0.5, 2/3 of BHs with $>10^{10}\, M_\odot$ have a>0.8

Trakhtenbrot (2014)

Results, z~6-7: accretion time-scales

"standard": L/L_{Edd} and $\eta = 0.1$ vs. "new": $\dot{M}_{AD}$ and L_{Bol}



the highest-redshift quasars are consistent with efficient, thin accretion disks; time for ~1-10 mass *e*-folds

Trakhtenbrot, Volonteri & Natarajan (in prep.)

Additional evidence for high spins at high M_{BH} :

Direct evidence for M87

- One of the most massive BHs in the local Universe

  $$M_{BH} = 6.2 \times 10^9 \, M_\odot$$

  (Gebhardt et al. 2011)

- New sub-mm VLBI data resolved the jet-launching site (Doelman et al. 2012, *Science*)

- Direct measurement of ISCO

  $$R_{ISCO} = 5.5 \text{ +/- } 0.4 \; R_{Sch}$$

  $$\rightarrow \; a_* \approx 0.5\text{-}0.8$$