The Radiative Efficiencies of the Most Massive, Highest-Redshift Black Holes

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With:

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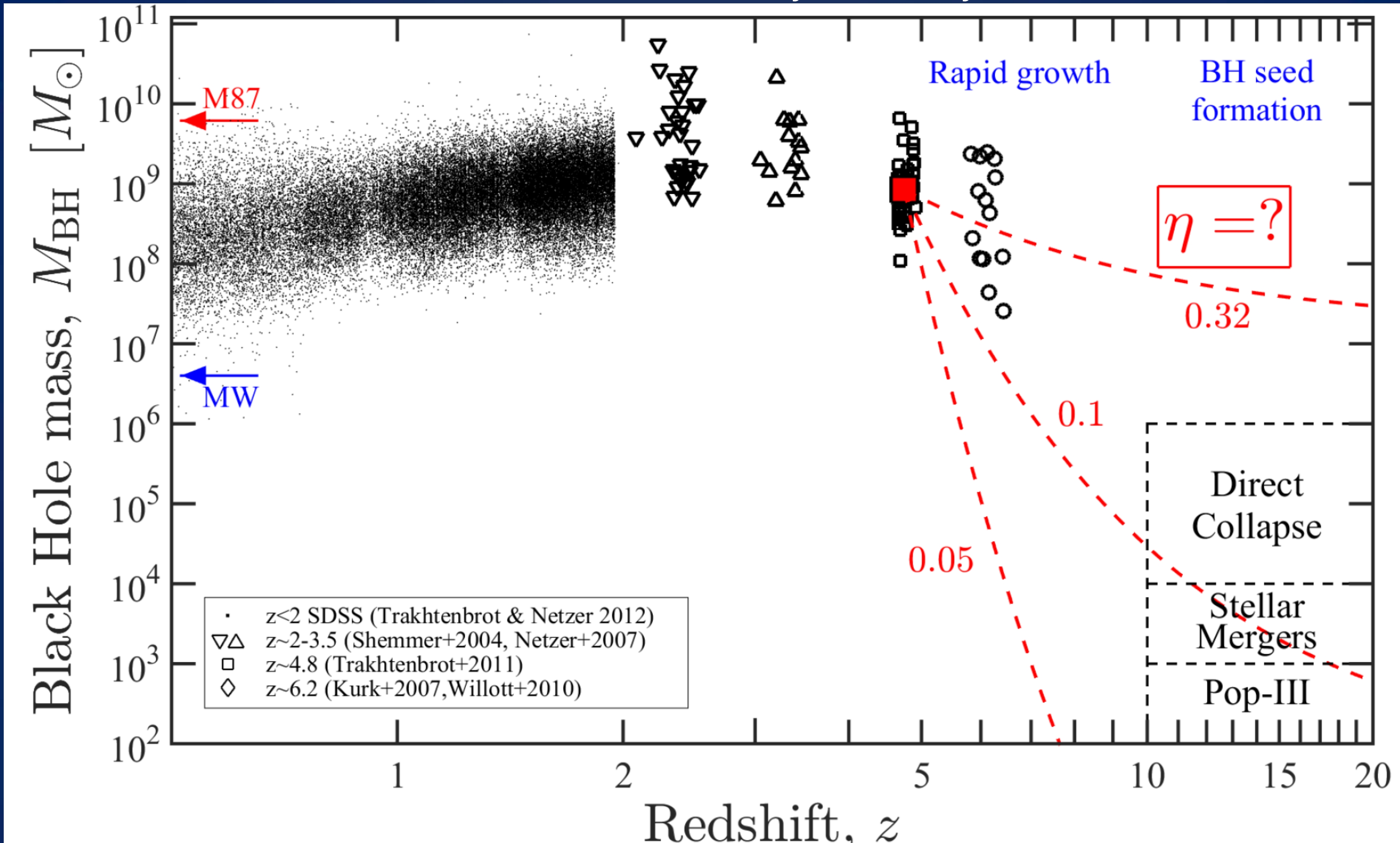
Breaking the Limits, Arbatax, September 19 2016

3 2 Gyr 1 Gyr after

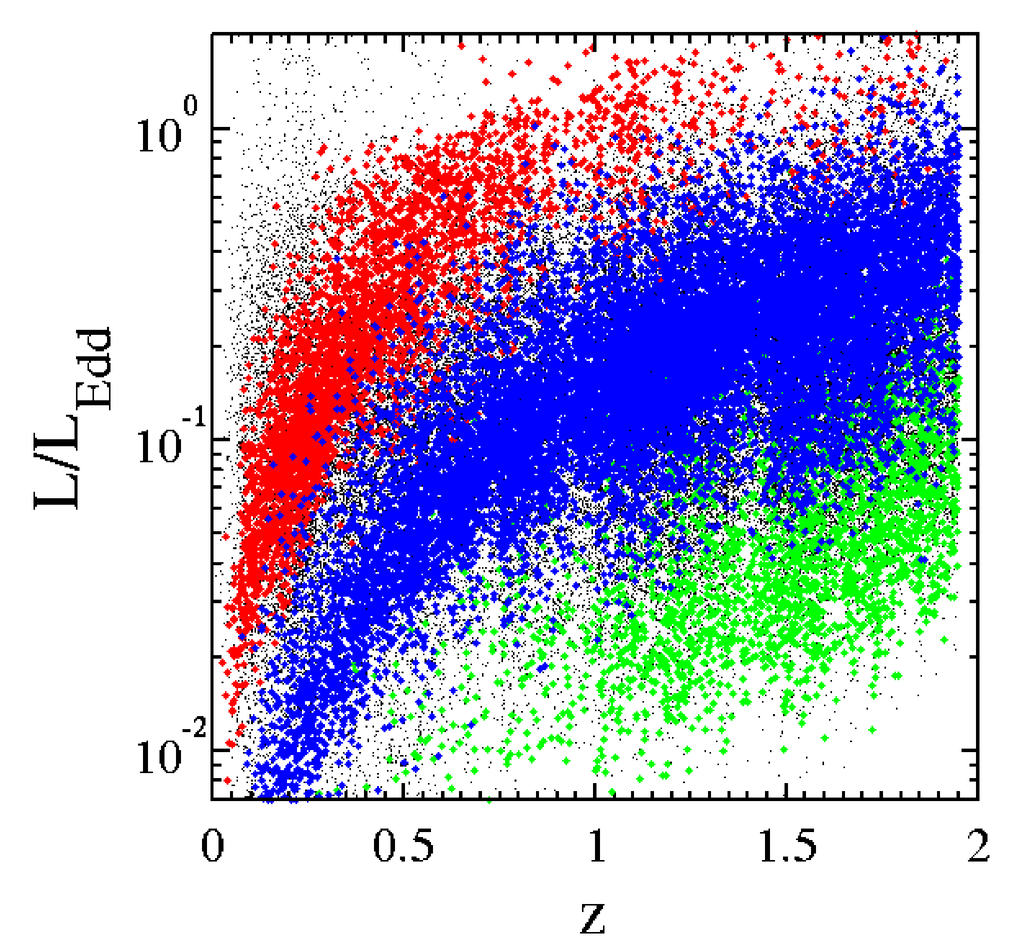


$$\tau_\bullet \simeq 0.4\,\mathrm{Gyr}\ \frac{\eta}{(1-\eta)}\ \frac{1}{L/L_{\rm Edd} \times f_{\rm active}}$$

Figure adapted from:
Trakhtenbrot & Netzer (2012)

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

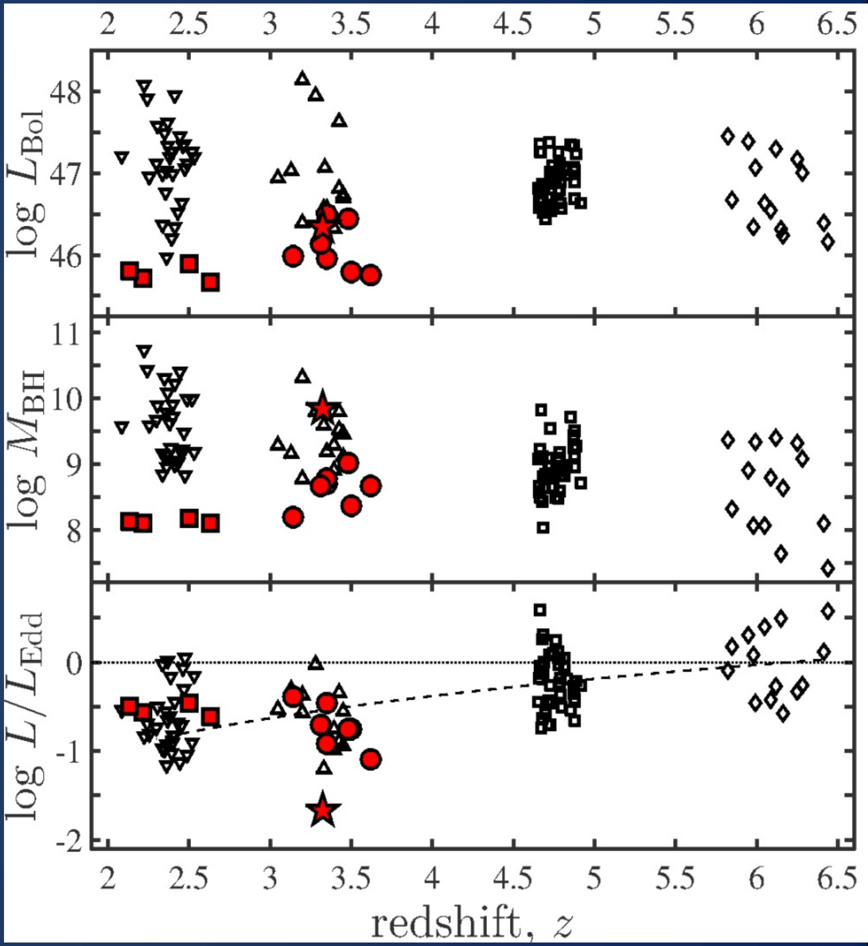
SDSS - out to z ~ 2



M_{BH} = 4×10^7 4×10^8 1.5×10^9

Trakhtenbrot & Netzer (2012)

NIR studies - z ~ 2 – 7



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

Radiative efficiency: controls SMBH growth

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

$$L_{\mathrm{Bol}} = \eta \dot{M}_{\mathrm{AD}} c^2$$

- In the thin-disk regime:

$$\eta \sim 0.04 - 0.4$$

- "Soltan's argument":

$$\eta \sim 0.1$$

- BH "growth efficiency":

$$\dot{M}_{\mathrm{BH}} = (1 - \eta) \dot{M}_{\mathrm{AD}}$$

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

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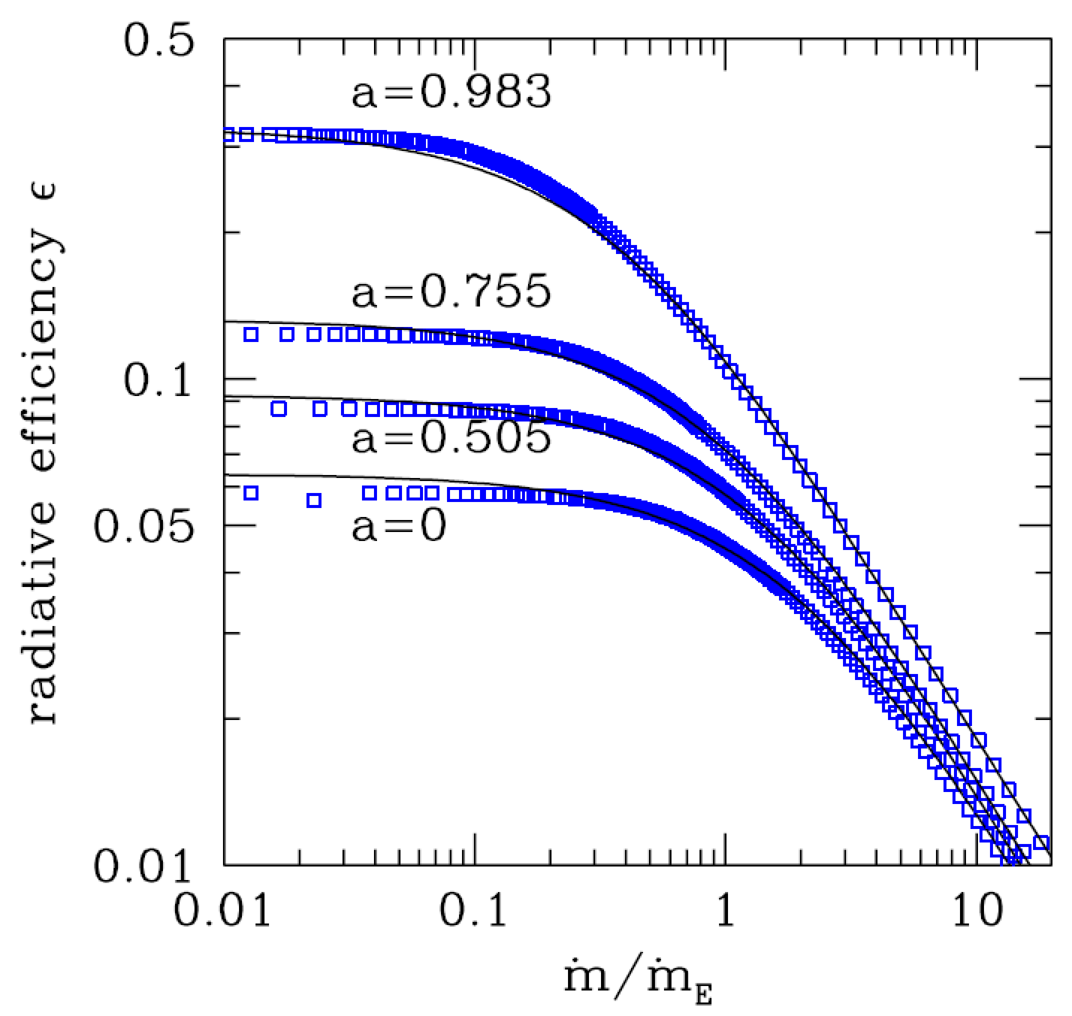
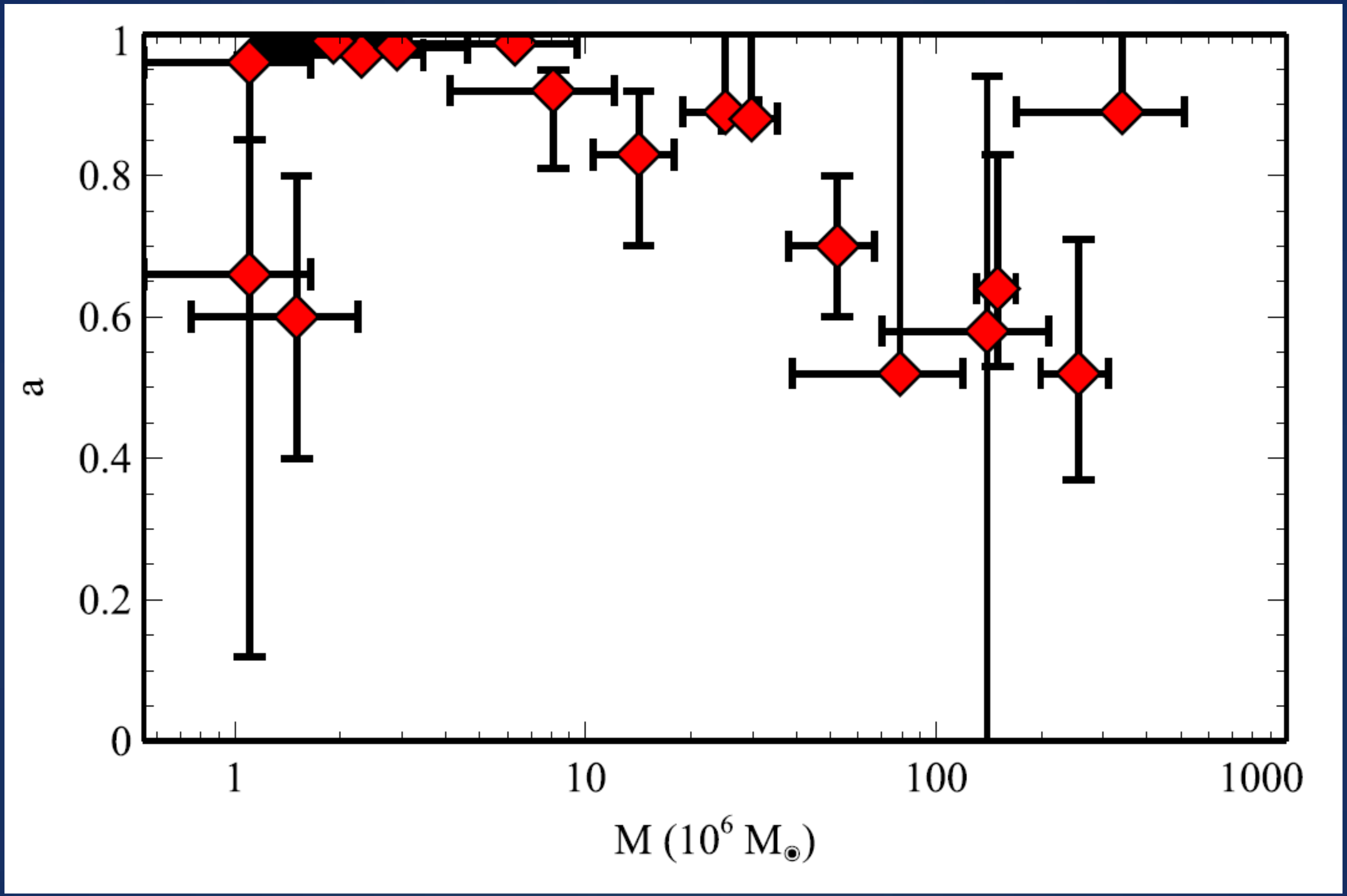


Madau, Haardt & Dotti (2014)

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

Census of (local) SMBH spin estimates



Gravitationally broadened Iron Kα line at ~6.7 keV

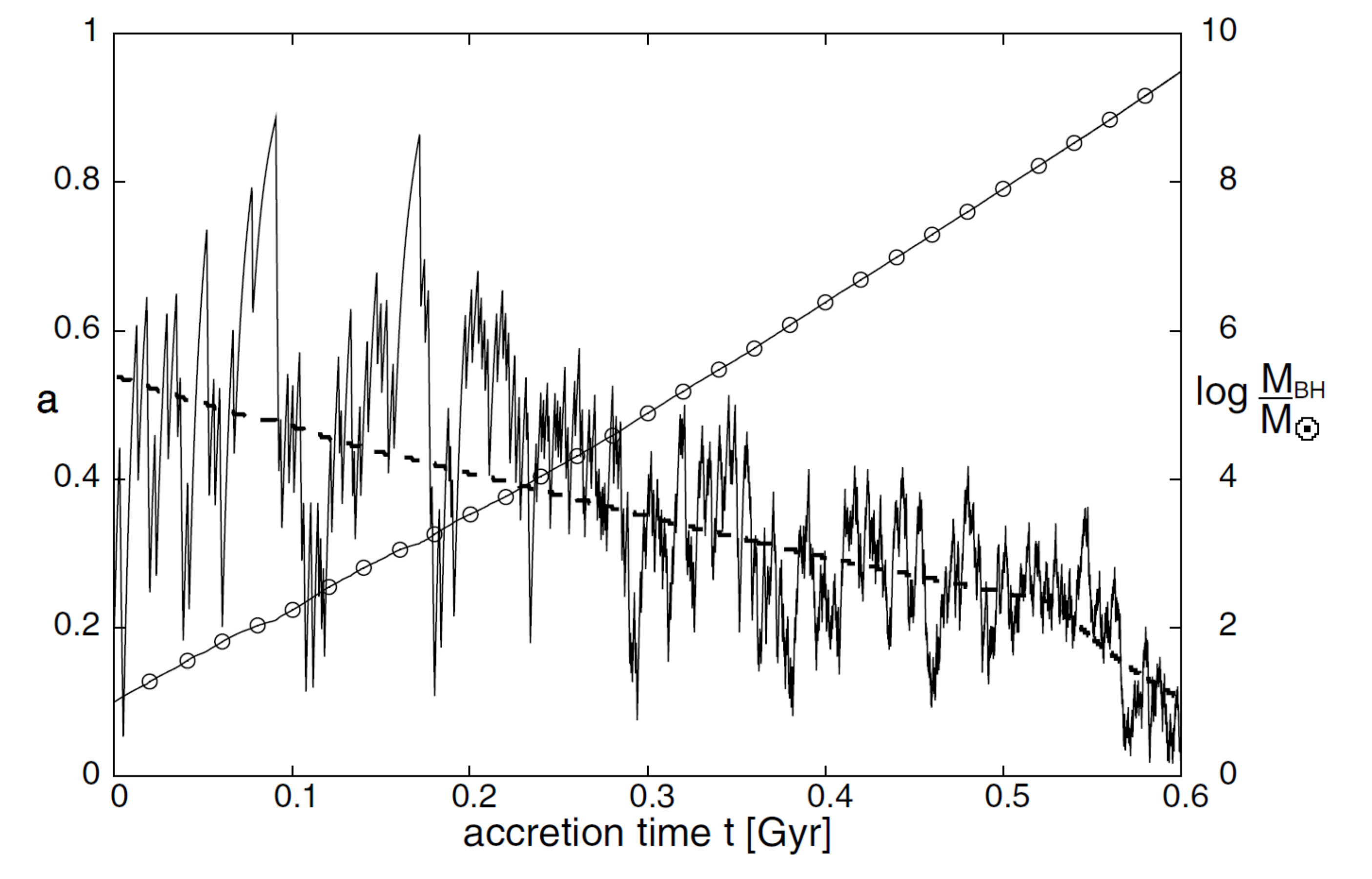
Spin estimates for ~20 local, low-luminosity and low-M_{BH} AGN

No non-spinning SMBHs ?

Brenneman & Reynolds (2006), Brenneman et al (2011), Gallo et al (2011), Patrick et al (2012), Fabian et al (2013), Walton et al (2013) …

review by Reynolds (2014)

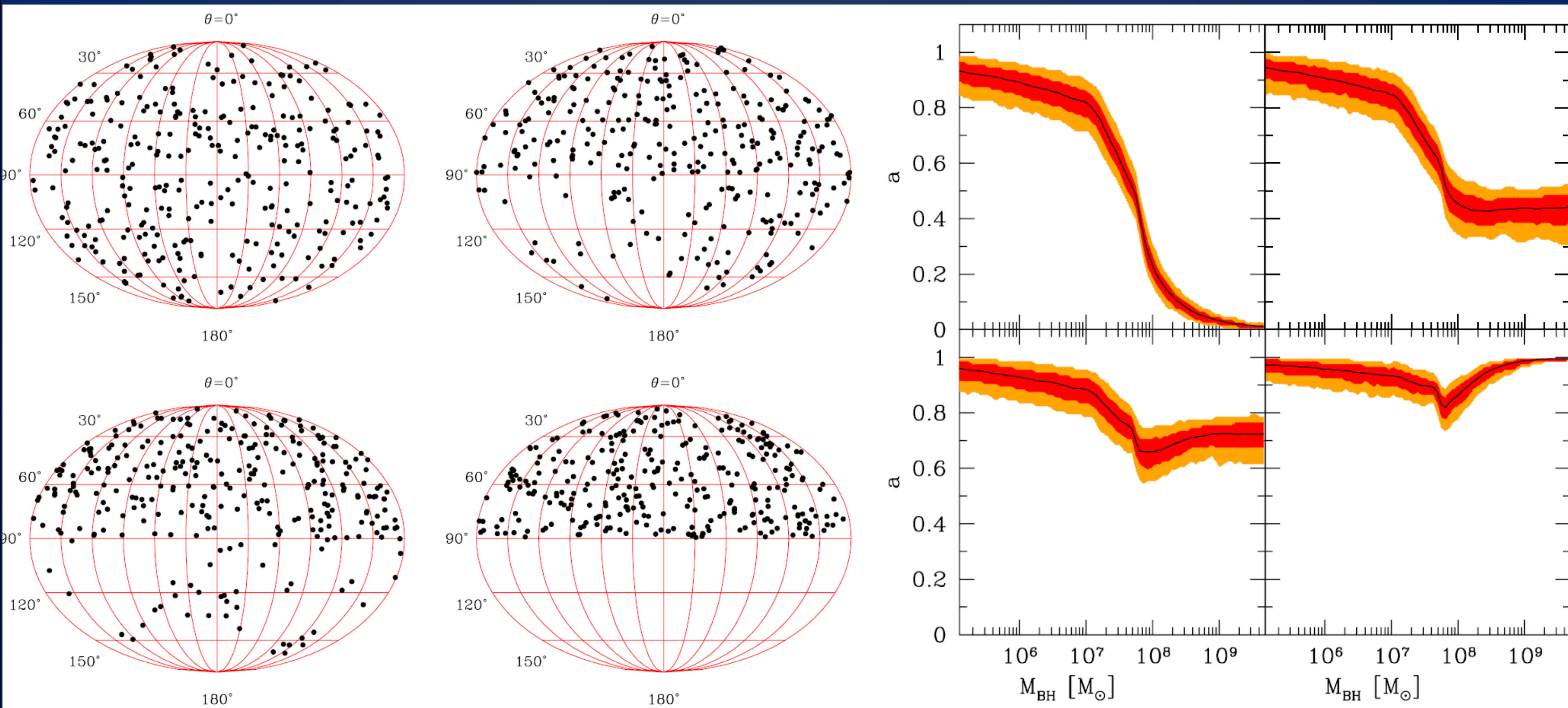
BH spin evolution: “spin down” scenario



A large number of accretion events (disks), randomly oriented w.r.t. the SMBH → “spin down” (King et al. 2008)

Coalescence events also lead to spin-down: $a \propto M_{\rm BH}^{-2.4}$ (Hughes & Blandford, 2003)

BH spin evolution: the role of (an)isotropy

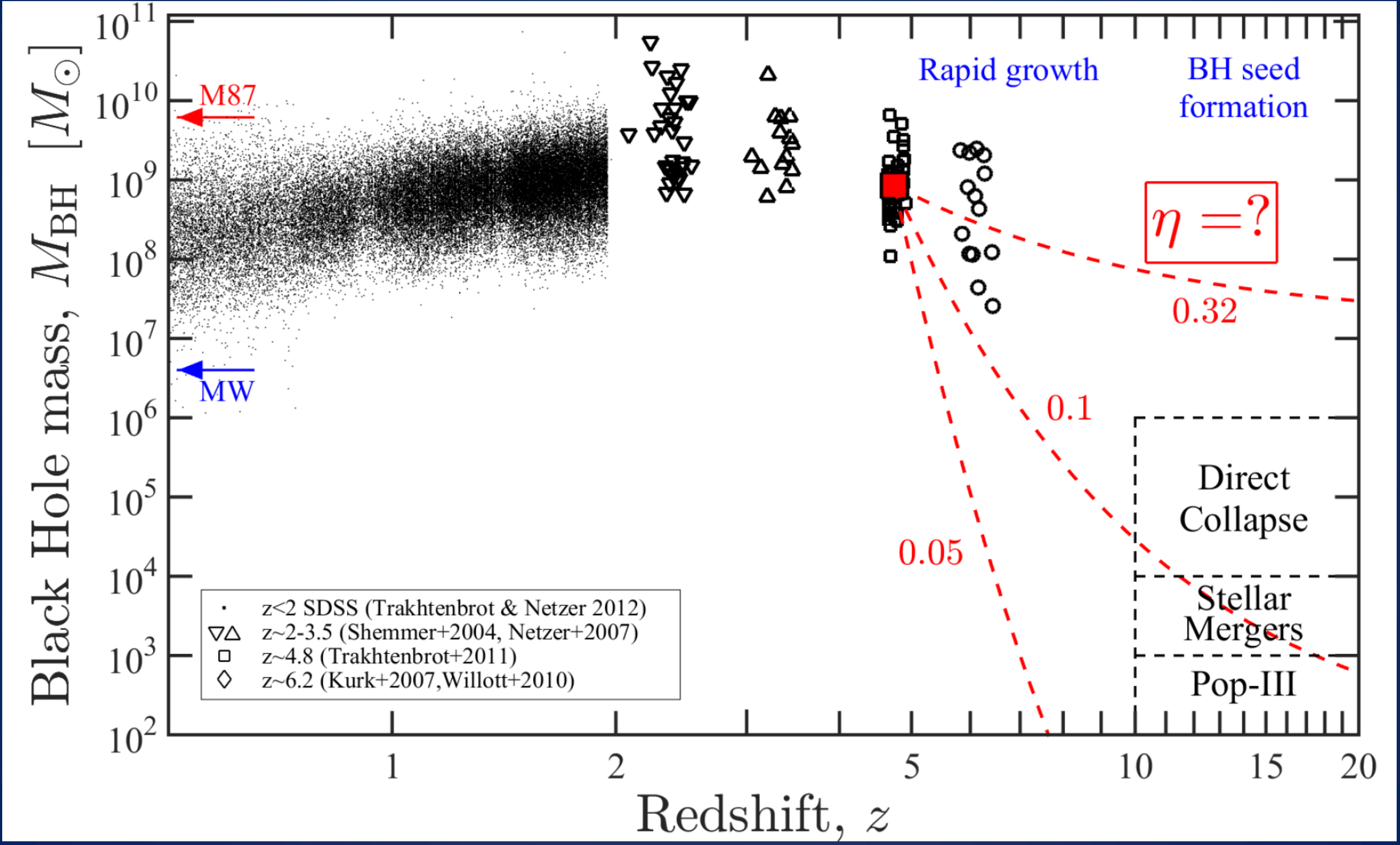


More isotropy → lower spins

prolonged accretion / anisotropy → "spin up"

Dotti et al. (2013)

Where are the most massive *active* BHs?



BH spin estimates: a different approach

$$L_{\rm Bol} = \eta \dot{M}_{\rm AD}\, c^2$$

Davis & Laor (2010), Wu+2013,
Trakhtenbrot (2014, ApJL, 789, 9)

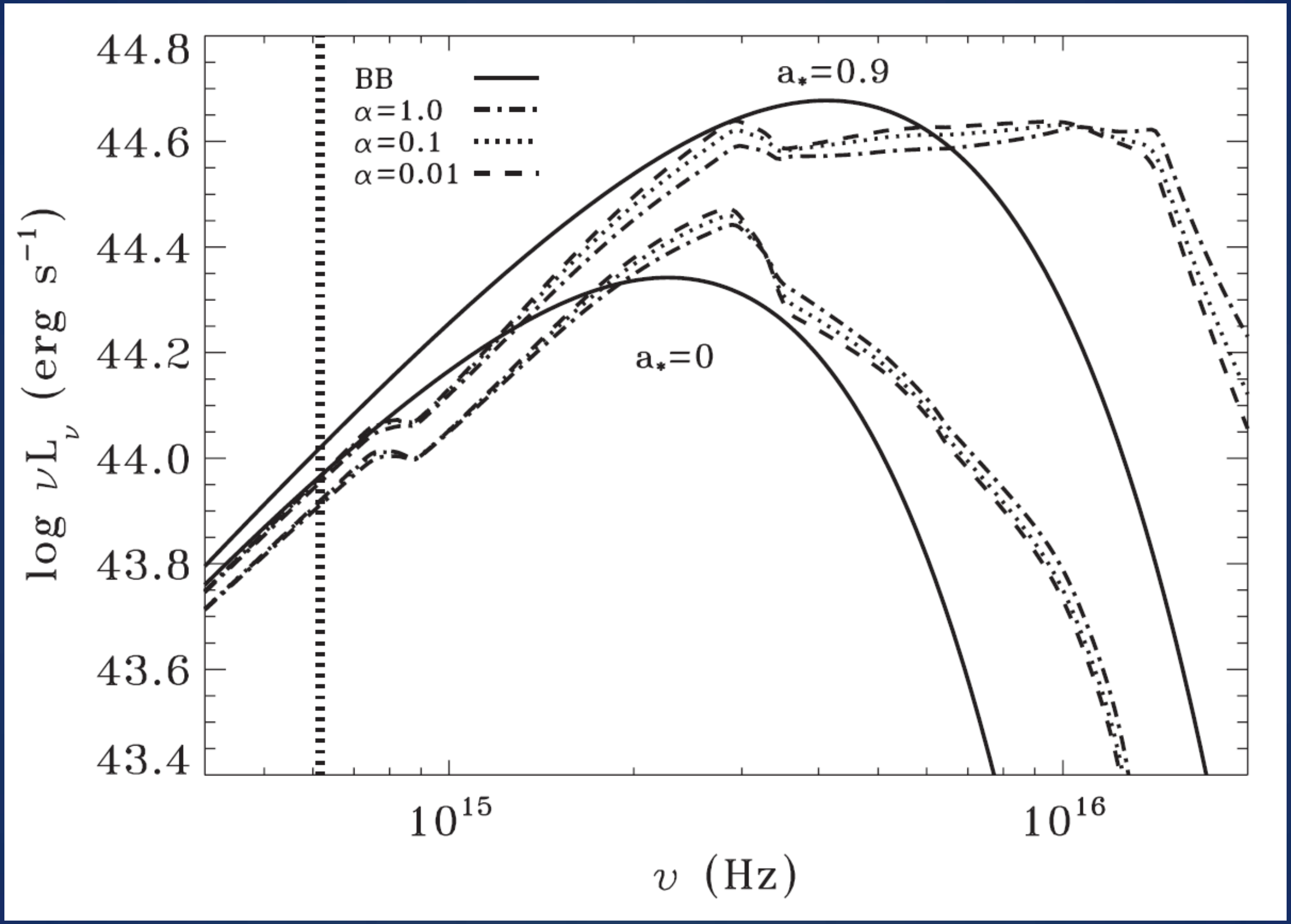
Basic assumptions

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:

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

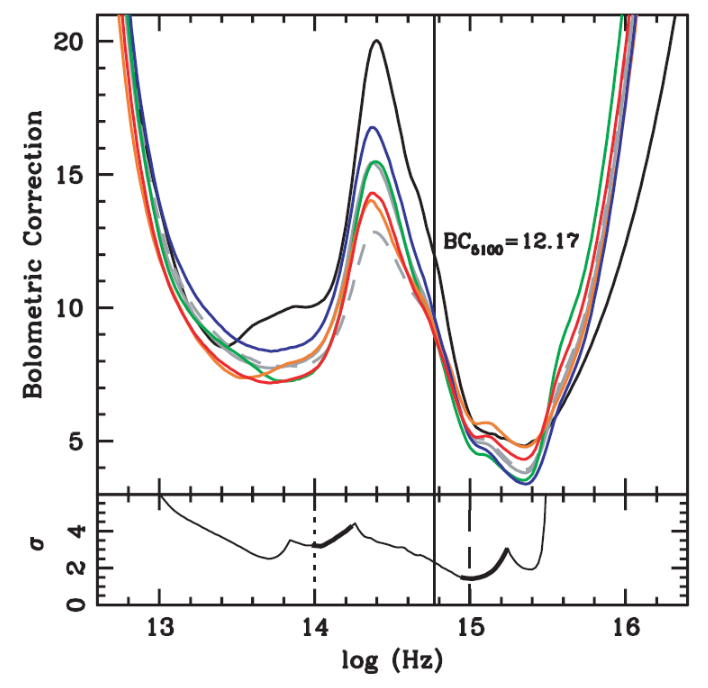
Thin accretion disks: estimating accretion rates

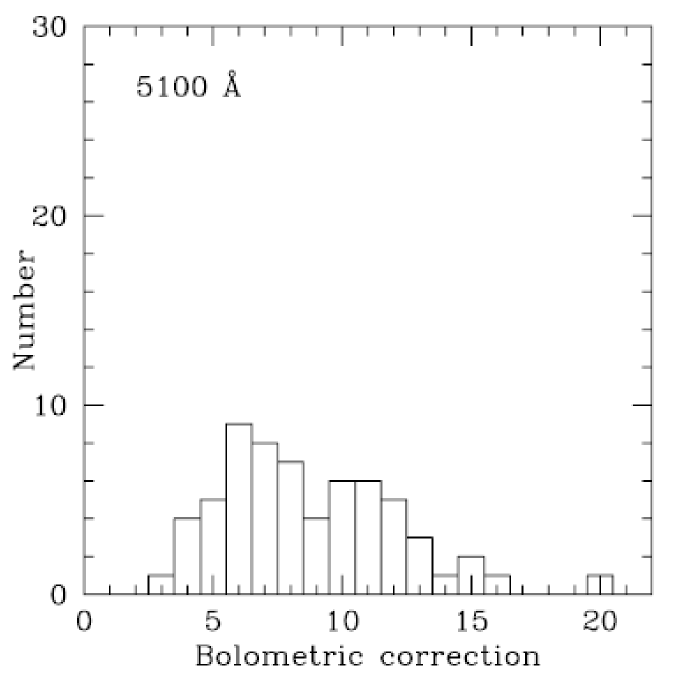


$$\dot{M}_{\rm AD} = 2.4 \left(\frac{\lambda L_\lambda}{10^{45}\ {\rm erg/s}}\right)^{3/2} \left(\frac{\lambda}{5100 \text{Å}}\right)^{2} \left(\frac{M_{\rm BH}}{10^{8} M_\odot}\right)^{-1} M_\odot/{\rm yr}$$

Bechtold et al. (1987)
Collin et al. (2006)
Davis & Laor (2011)

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 et al (1994), Marconi et al. (2004), Richards et al. (2006),
Jin et al. (2012), Runnoe et al. (2012)

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

- 72 quasars at z~1.5–3.5

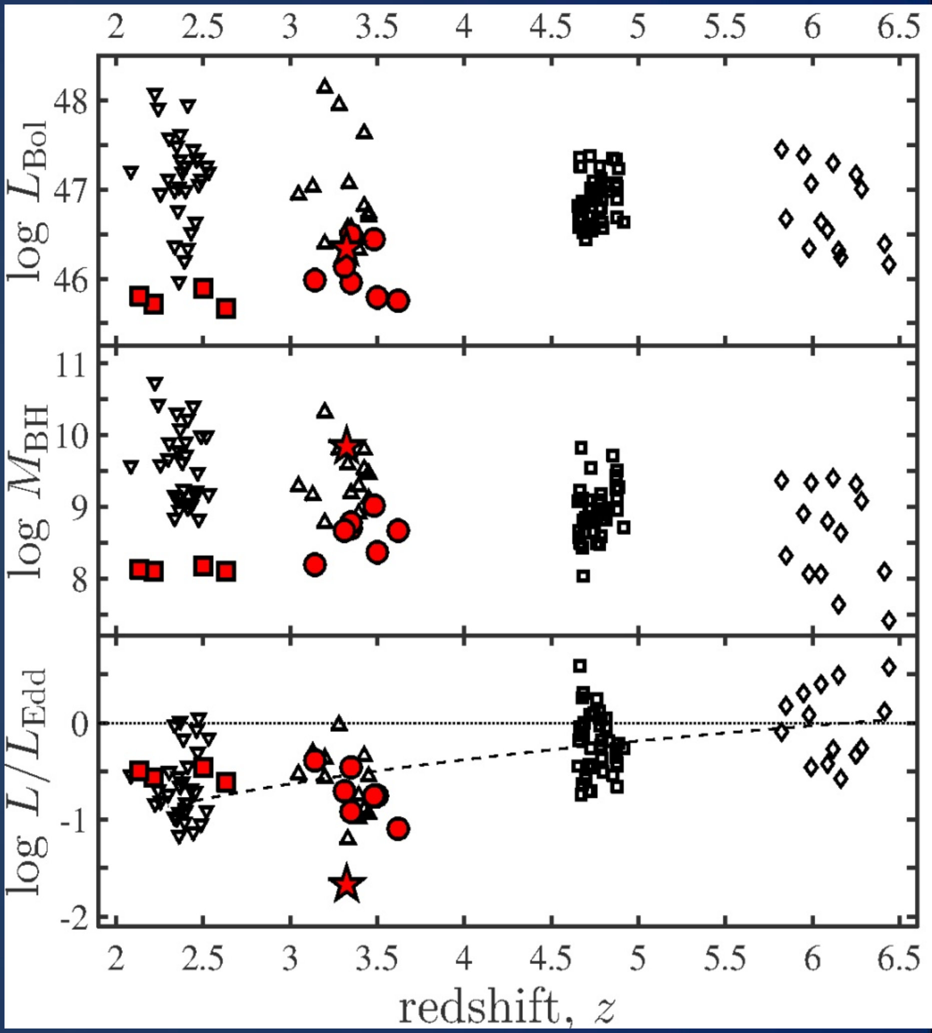
  Shemmer+2004, Netzer+2007, Marziani+2009, Dietrich+2009

- 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)

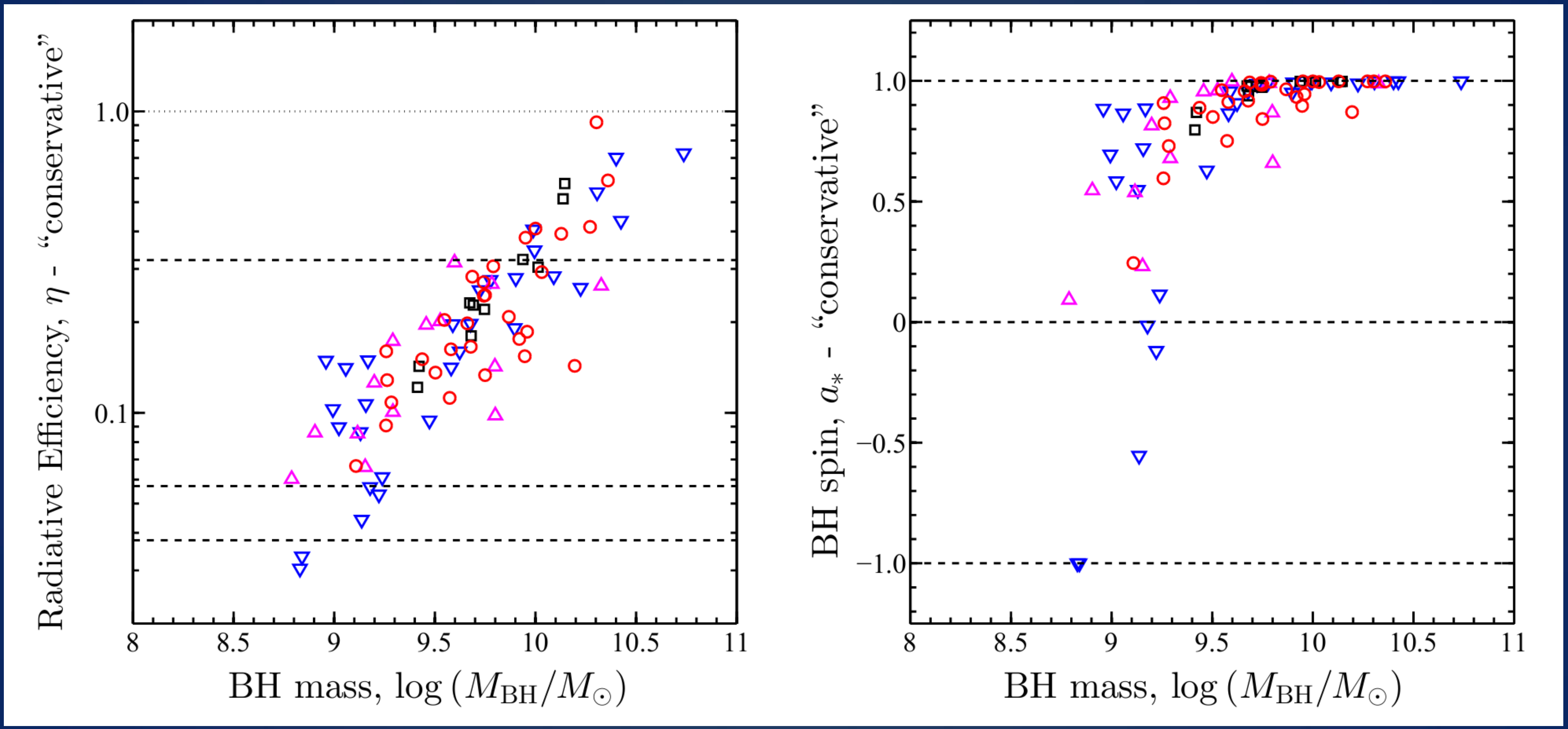
  $\longrightarrow$ M_{BH} and $\dot{M}_{AD}$



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

Results, z~1.5-3.5: conservative lower limits on η

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



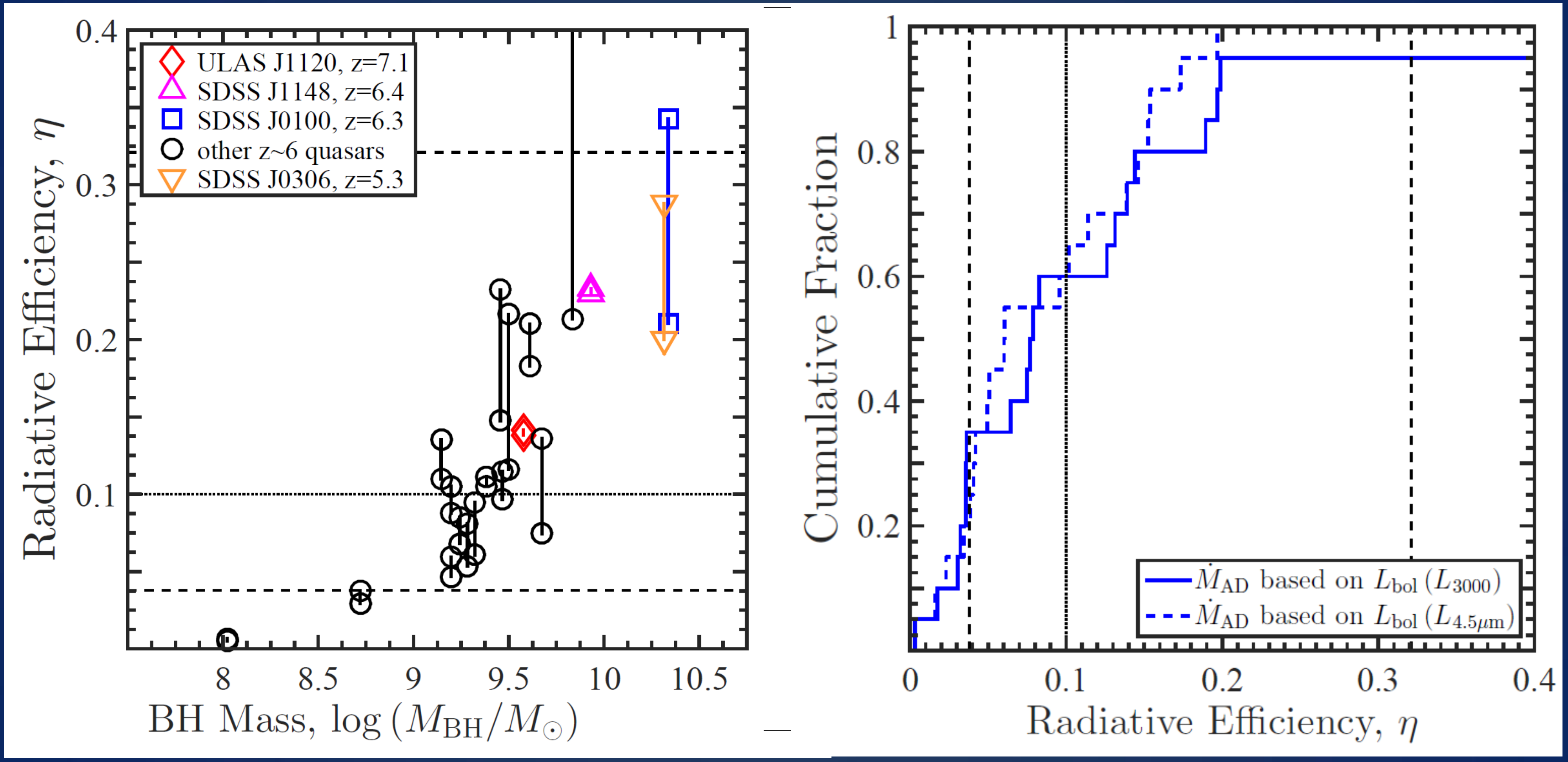
the most massive BHs have high radiative efficiencies

… and high spins ➔ low growth efficiencies

Trakhtenbrot (2014)

Results, z~6-7: conservative lower limits on η

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

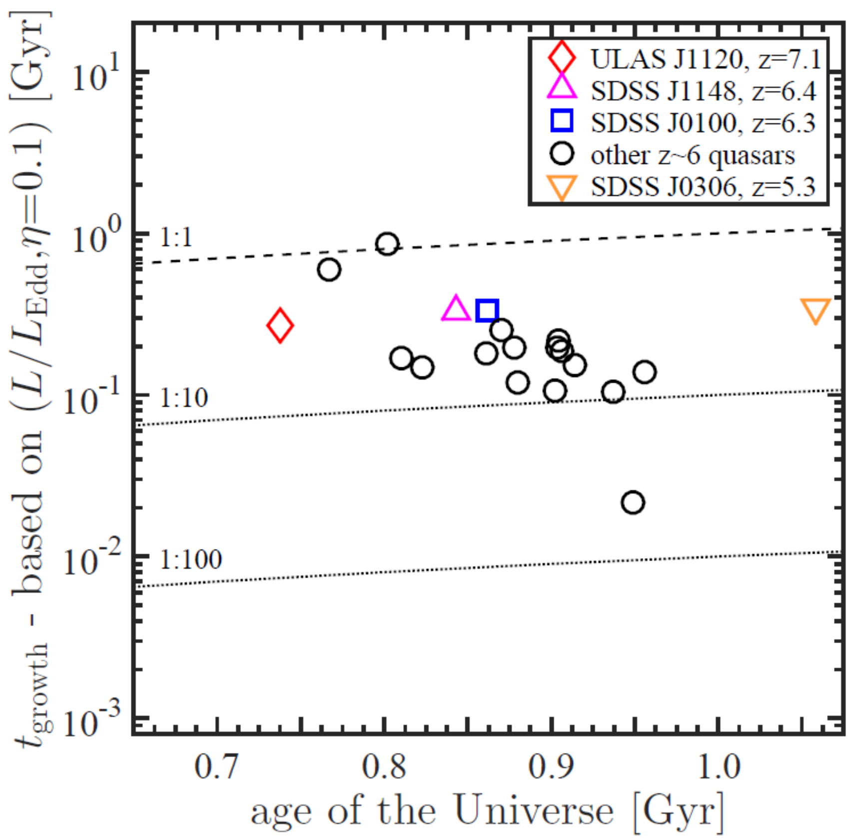


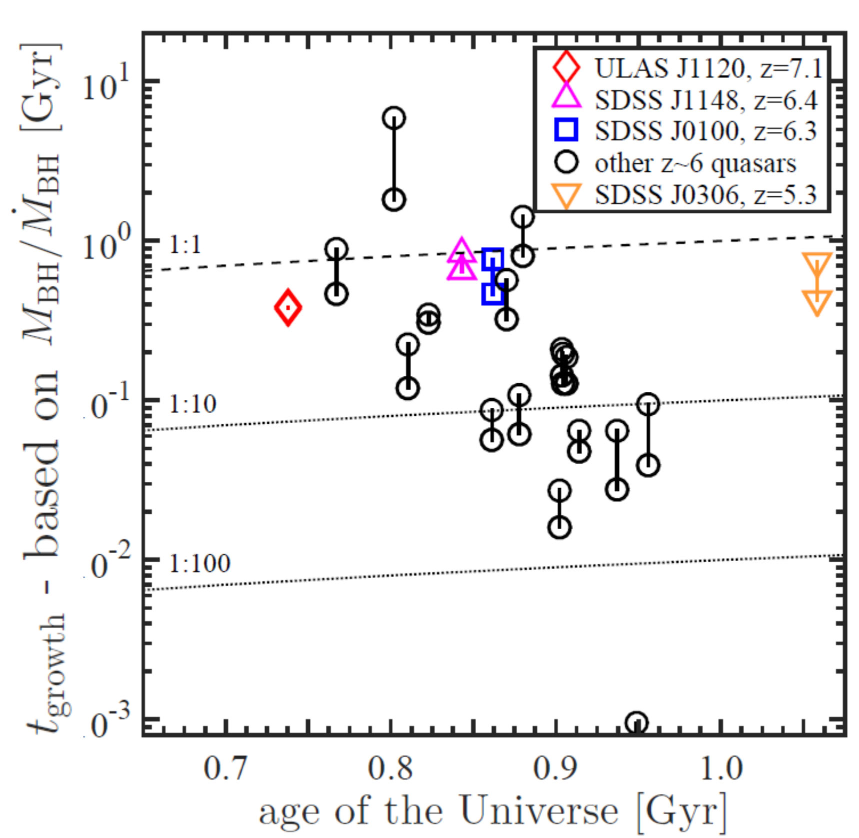
the highest-redshift quasars are consistent with efficient, thin accretion disks

Trakhtenbrot, Volonteri & Natarajan (in prep.)

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

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





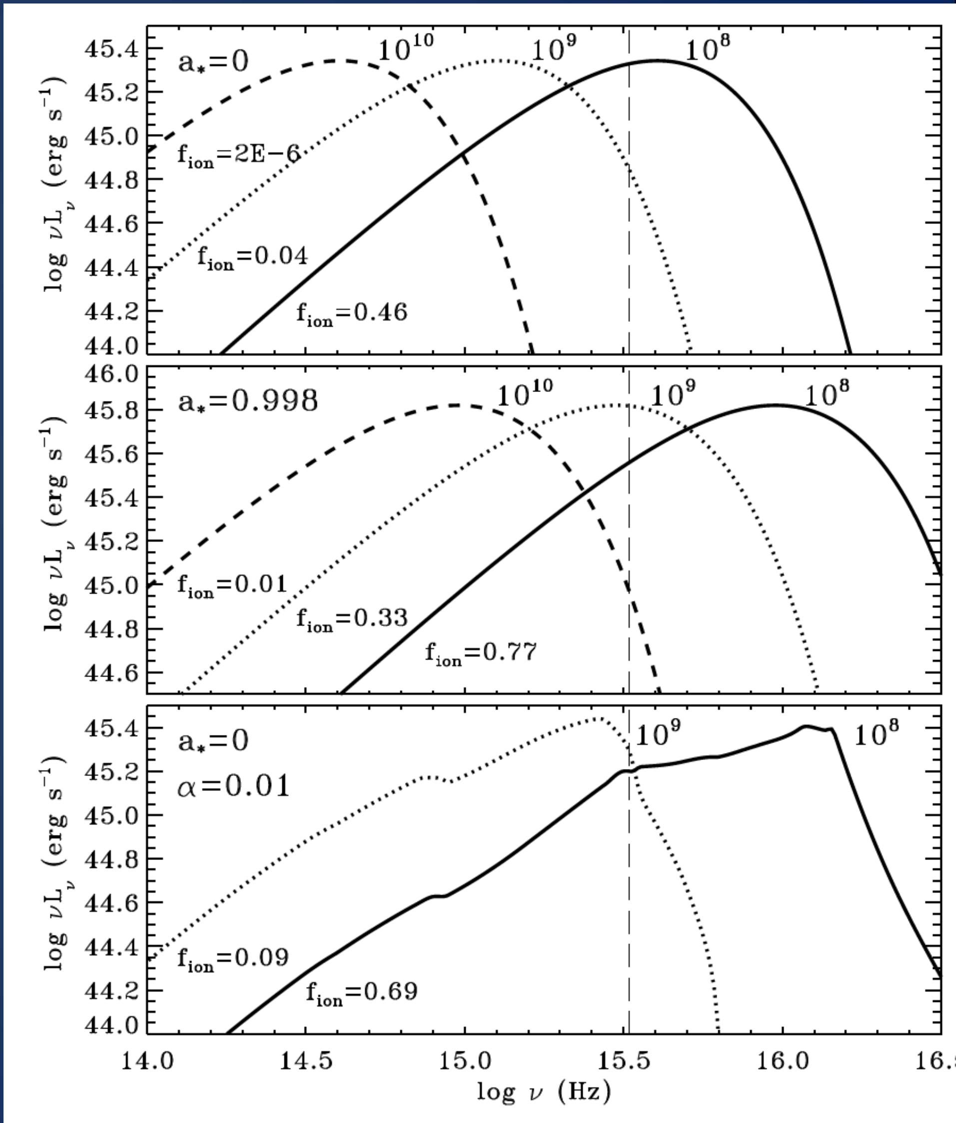
the highest-redshift quasars are consistent with efficient, thin accretion disks; time for ~1-10 mass e-folds

Trakhtenbrot, Volonteri & Natarajan (in prep.)

Additional evidence for high spins at high M_{BH}

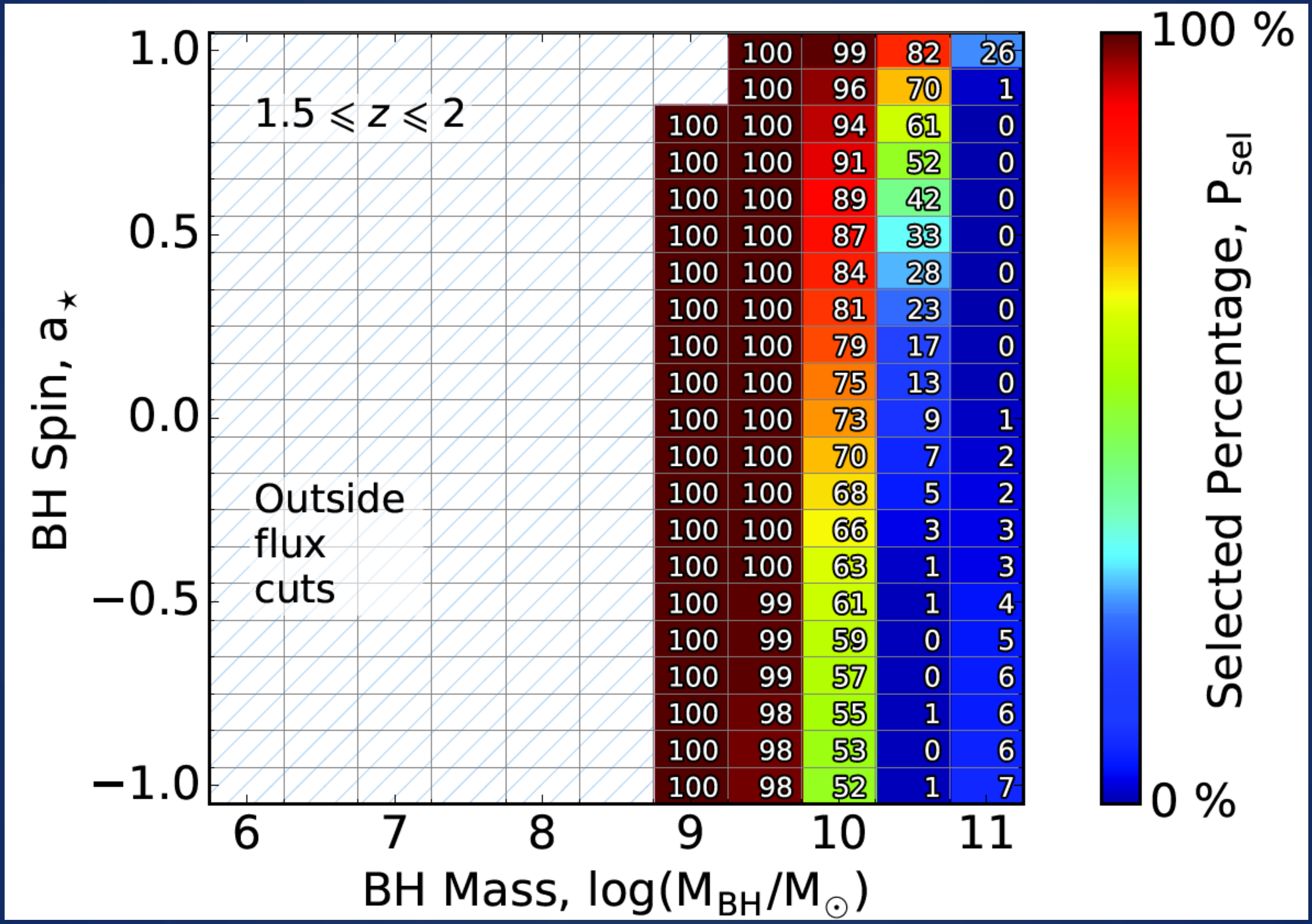
- Two new Kα measurements at significant redshifts, $z\sim1$-2
  (Reis+2014, Reynolds+2014)
- UV-Optical SED fitting for $z\sim1.5$ AGN with known BH mass
  (Capellupo+2015, 2016)
- Requirement of significant ionizing radiation (for lines)

  → About 75% of massive $z\sim0.7$ SDSS quasars have $a_* > 0.7$
  (Netzer & Trakhtenbrot 2014)
- are we missing a population of high-mass, slow- or retrograde spinning SMBHs?



Laor & Davis(2011)

Are we missing a population of high-mass, slow-spinning and/or retrograde SMBHs?



testing SDSS color-color selection for thin-disk models

Bertemes et al (arXiv:1609.00376)

Conclusions …

1. Radiative efficiencies and/or BH spins are key to understanding early SMBH growth (and seed BH formation)

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

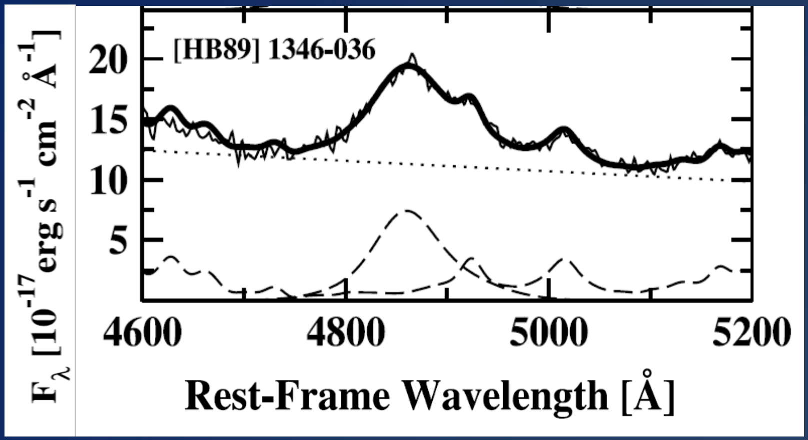
3. Available data for the highest-z quasars, at z~6, consistent with thin-disk accretion
   if one assumes a thin-disk optical SED, most have $\eta > 0.04$

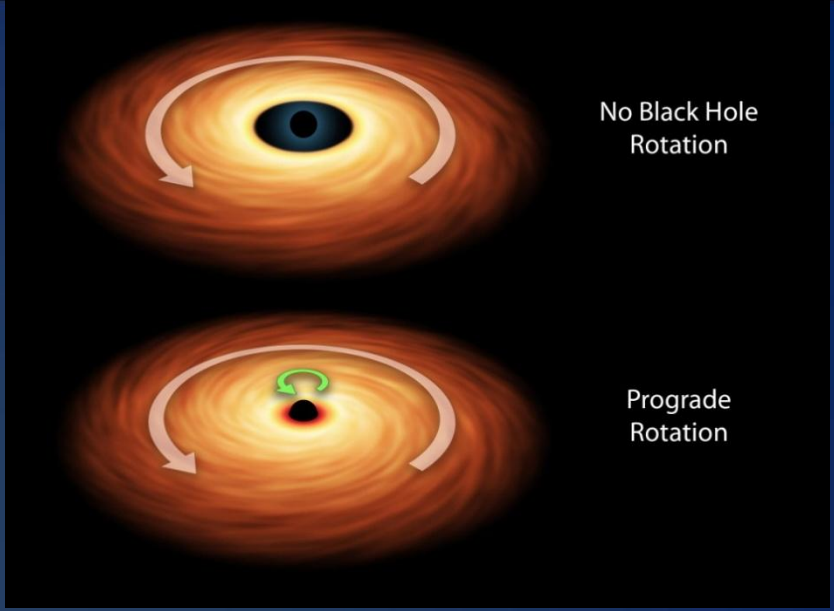
4. Still possible that they accreted with lower η at earlier epochs

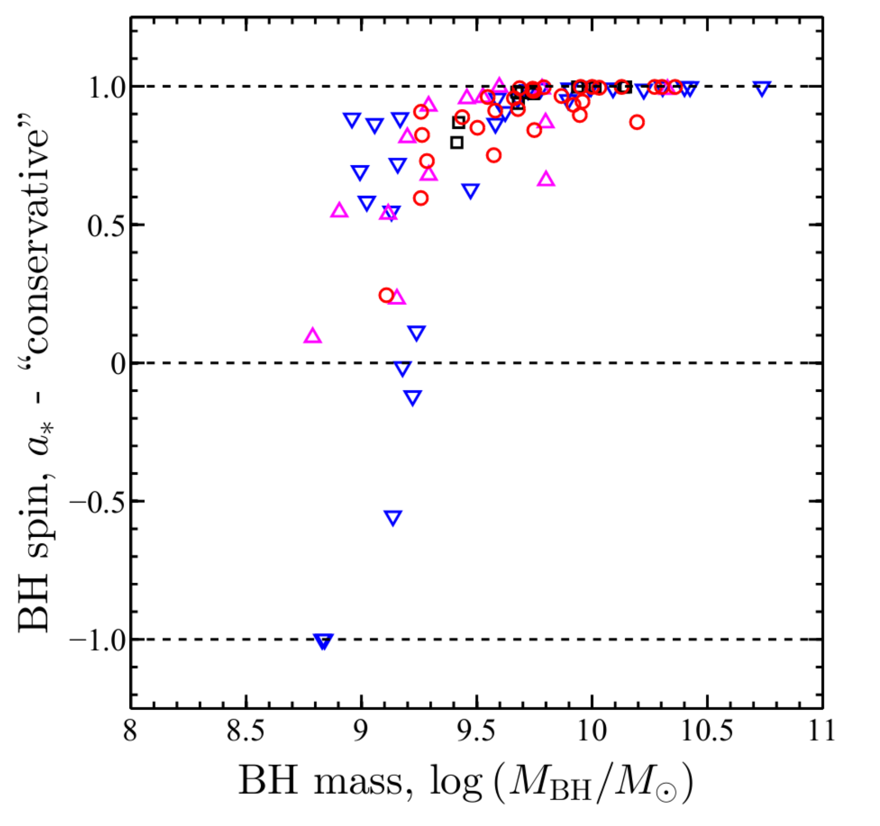
… and consequences / open issues

- Most massive relic, local SMBHs should have high spins *(EHT ? …)*
- Are we missing the non-spinning, retro-grade spinning and/or radiatively-inefficient SMBHs? *(eROSITA, Athena, …)*

Thank you!


[HB89] 1346-036
F_λ [10^{-17}erg s^{-1} cm^{-2} Å^{-1}]
Rest-Frame Wavelength [Å]
4600
4800
5000
5200
5
10
15
20


No Black Hole Rotation
Prograde Rotation


BH spin, a_* - "conservative"
BH mass, $\log(M_{BH}/M_\odot)$
1.0
0.5
0
−0.5
−1.0
8
8.5
9
9.5
10
10.5
11