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

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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

2. The quasars we don’t know (yet?)

Radiative efficiency:

\[ L_{bol} = \eta \dot{M}_{acc} c^2 \]

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:
  \[ L_{\text{bol}} = \eta \dot{M}_{\text{acc}} c^2 \]
- In the thin-disk regime:
  \[ \eta \sim 0.04 - 0.4 \]
- “Soltan’s argument”:
  \[ \eta \sim 0.1 \]
- BH “growth efficiency”:
  \[ \dot{M}_{\text{BH}} = (1 - \eta) \dot{M}_{\text{acc}} \]
  \[ t_{\text{growth}} \propto \eta / (1 - \eta) \]

\[ \rightarrow \text{Fast-spinning BHs grow slowly} \]
1 Gyr after

2 Gyr

3 Gyr

Figure adapted from Trakhtenbrot & Netzer 12
BH spin evolution: “spin down” scenario

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

coalessness events also lead to spin-down: \( a \propto M_{BH}^{-2.4} \)  

(Hughes & Blandford 03)
BH spin evolution: the role of (an)isotropy

more isotropy → lower spins
prolonged accretion / anisotropy → “spin up”

Dotti+13
Census of (local) SMBH spin measurements

Gravitationally broadened Iron Kα line at ~6.7 keV
Spin estimates for ~20 local, low-luminosity and low-$M_{\text{BH}}$ 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

\[ L_{\text{bol}} = \eta \dot{M}_{\text{disk}} c^2 \]

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. \( M_{\text{BH}} \) can be reliably estimated from broad emission lines
   for example:

\[
M_{\text{BH}}(H\beta) = 1.05 \times 10^8 \left( \frac{L_{5100}}{10^{46} \text{ erg s}^{-1}} \right)^{0.65} \left[ \frac{\text{FWHM}(H\beta)}{10^3 \text{ km s}^{-1}} \right]^2 \text{ M}_\odot.
\]
Thin accretion disks: estimating accretion rates

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

Bechtold+87, Collin+06
Davis & Laor 11
Estimating bolometric luminosities

Elvis+94, Marconi+04, Richards+06, Jin+12, Runnoe+12
Sample & data: the most massive BHs at \( z \approx 2–7 \)

- **72 quasars at \( z \approx 1.5–3.5 \)**

- **20 quasars at \( z \approx 5.8–7 \)**

- Near-IR spectra to cover \((H\beta, L_{5100})\) or \((\text{MgII}, L_{3000})\)

- 2MASS, Spitzer and/or WISE data covers (rest-frame) optical cont.

\[ \rightarrow M_{\text{BH}} \text{ and } M_{\text{disk}} \]

- **Most sources have** \( M_{\text{BH}} > 3 \times 10^9 M_\odot \)
Most massive BHs, $z \sim 1.5-3.5$: lower limits on $\eta$

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

the most massive BHs have high radiative efficiencies
... and high spins $\Rightarrow$ low growth efficiencies

Trakhtenbrot 14
Highest-z quasars, $z \sim 6-7$: lower limits on $\eta$

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

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

Trakhtenbrot, Volonteri & Natarajan 17
Recent $K\alpha$ results at $z \sim 1-2$ (e.g., Reis+14, Reynolds+14)

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

UV-Optical SED fitting for $z \sim 1.5$ AGN with known BH mass
   (Capellupo+15, 16)
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 $\eta$, 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 $\eta > 0.04$

... but what about “elusive” AGN?
We are missing faint AGN at $z \sim 5-7$

we expect to observe them...

... but we do not

are the missing AGN obscured? radiatively inefficient?

Fig. from Trakhtenbrot+16

Weigel+15
Most massive BHs, $z \sim 1.5-3.5$: lower limits on $\eta$

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

the most massive BHs have high radiative efficiencies
... and high spins $\Rightarrow$ 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”
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. value</th>
<th>Max. value</th>
<th>Step size</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH mass, log (M_{BH}/M_{\odot})</td>
<td>6</td>
<td>11</td>
<td>0.5</td>
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<tr>
<td>BH spin, a_+</td>
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<td>0.998</td>
<td>0.1</td>
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<tr>
<td>Accretion rate, L/L_{Edd}</td>
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<tr>
<td>Redshift, z</td>
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<td>0.1</td>
</tr>
<tr>
<td>Inclination, inc</td>
<td>10°</td>
<td>50°</td>
<td>10°</td>
</tr>
</tbody>
</table>
Are we missing high-mass, high-z SMBHs with low or retrograde spins? testing SDSS color-color selection for thin-disk models

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

SDSS J0945+1009
WLQ at $z=1.66$
EW(CIV) = 1.5 Å

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 $\rightarrow$ 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 $z\sim1.5-3.5$ have high spins. Their luminosities require high $\eta$, given the virial masses.

3. The highest-z quasars, at $z\sim6$, 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

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

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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

SDSS color-color selection misses high-mass, low spin BHs
We are missing faint AGN at $z \sim 5-7$
$L/L_{\text{Edd}}$ Evolution in Luminous, Unobscured AGN

SDSS - out to $z \sim 2$

NIR studies - $z \sim 2 - 7$

$M_\text{BH} = 4 \times 10^7, 4 \times 10^8, 1.5 \times 10^9$

Trakhtenbrot & Netzer (2012)

BH spin evolution: expectations for extremely massive BHs

**spin-up** (Dotti et al. 2013)  
**spin-down** (King et al. 2008)

The most massive SMBHs ($M_{\text{BH}} > 10^9 M_\odot$) experience more accretion episodes $\rightarrow$ 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 $K\alpha$ method

Gravitationally broadened Iron $K\alpha$ line at $\sim6.7$ keV, reflected from the accretion disk,

review by Reynolds (2013)
BH spin estimates: the $K\alpha$ method at high $z$?

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

Reynolds et al. (2014) - $z = 1.695$, $M_{BH} = 3 \times 10^9 M_\odot$, $a_*=0.74$
BH spin estimates: the $K\alpha$ method

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

No non-spinning SMBHs (publication bias?)

review by Reynolds (2013)
Luminous AGNs at $z \approx 1.5$ 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. $M_{\text{BH}}$ can be reliably estimated from broad emission lines at $z>0$, we use empirical calibrations, based on reverberation mapping

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

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Kaspi et al. (2005)  
Woo et al. (2013)
Thin accretion disks: spectral energy distributions

- Original theory by Shakura & Sunyaev (1973)...

Basic ingredients:

\[ M_{\text{BH}}, M_{\text{AD}}, \text{ and spin} \]

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

\[ L_\nu \propto (M_{\text{AD}} \cdot M_{\text{BH}})^{2/3} \nu^{1/3} \]

- More elaborate models, with comptonization, GR etc ...

Hubney et al. (2000), Davis & Laor (2011)
Results: BH spin distributions

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

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

Trakhtenbrot (2014)
Results, $z \sim 6-7$: accretion time-scales

“standard”: $L/L_{\text{Edd}}$ and $\eta = 0.1$ vs. “new”: $M_{\text{AD}}$ and $L_{\text{Bol}}$

The highest-redshift quasars are consistent with efficient, thin accretion disks; time for $\sim 1-10$ mass e-folds

Trakhtenbrot, Volonteri & Natarajan (in prep.)
Additional evidence for high spins at high $M_{\text{BH}}$:
Direct evidence for M87

- One of the most massive BHs in the local Universe
  \[ M_{\text{BH}} = 6.2 \times 10^9 M_\odot \]
  (Gebhardt et al. 2011)

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

- Direct measurement of ISCO
  \[ R_{\text{ISCO}} = 5.5 \pm 0.4 \ R_{\text{Sch}} \]
  \[ \Rightarrow a_* \approx 0.5-0.8 \]