A demographic view on the active black hole growth history out to z=2

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Subaru Seminar, Hilo Base Facility, Hawaii
19.05.2015
Black hole - galaxy coevolution

$M_\bullet - \sigma_*$ relation

AGN Feedback required to shut off SF in massive galaxies

McConnell & Ma (2013)

⇒ $M_\bullet - \sigma_*$: AGN Feedback? Central limit? Both?

⇒ what effect has the black hole on its host galaxy?
Black hole - galaxy coevolution

integrated cosmic BH accretion history parallel to SF history

Zheng et al. (2009)

⇒ link between black hole growth and galaxy evolution

⇒ how are black holes growing?

Rosario et al. (2012)

Chen et al. (2013)
AGN demographics: The AGN LF

AGN Luminosity function is main demographic quantity

\[ \log \Phi \]

\[ 0.0 < z < 0.3 \]
\[ 0.3 < z < 0.5 \]
\[ 0.5 < z < 0.7 \]

\[ 0.7 < z < 1.0 \]
\[ 1.0 < z < 1.5 \]
\[ 1.5 < z < 2.0 \]

\[ 2.0 < z < 2.5 \]
\[ 2.5 < z < 3.0 \]
\[ 3.0 < z < 3.5 \]

\[ 3.5 < z < 4.0 \]
\[ 4.0 < z < 4.5 \]
\[ 4.5 < z < 5.0 \]

\[ M_i(z = 2) [\text{mag}] \]

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AGN demographics: AGN LF evolution

AGN Luminosity function is main demographic quantity

- space density of bright QSOs peaks at $z \approx 2 - 3$

optical: SDSS (Richards et al. 2006)

X-rays: Hasinger et. al (2005)
AGN demographics: AGN LF evolution

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- space density of bright QSOs peaks at $z \approx 2 - 3$
- peak is shifted towards lower $z$ for fainter AGN

$\Rightarrow$ AGN cosmic downsizing

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X-rays: Hasinger et al. (2005)
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\( \Rightarrow \) AGN cosmic downsizing

optical: various surveys

X-rays: Hasinger et. al (2005)
Implications for BH growth

- BH mass density accreted during QSO phases = local BH mass density (Soltan argument)
- most BH growth takes place in luminous AGN phase

⇒ AGN downsizing implies anti-hierarchical BH growth

Constraints on theoretical models

- SAMs & numerical simulations able to reproduce AGN LF and downsizing

**SAMs**

- Menci et al. (2014)

**Numerical simulations**

- Hirschmann et al. (2014)
How can we trace black hole growth?

Limitation of AGN LF:

Physical quantities of black holes:
- black hole mass $M_\bullet$
- accretion rate / Eddington ratio $\lambda = \frac{L_{\text{bol}}}{L_{\text{Edd}}}$
How can we trace black hole growth?

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$\Rightarrow$ additional $M_\bullet$ information able to break this degeneracy
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Active black hole mass function - $\Phi_\bullet(M_\bullet)$
Eddington ratio distribution function - $\Phi_\lambda(\lambda)$

- well-defined AGN sample
- black hole mass estimates
for virial motion in BLR:

\[ M_\bullet = f \frac{R_{BLR} \Delta V^2}{G} \]
Black hole masses for broad line AGN

- for virial motion in BLR:
  \[ M_\bullet = f \frac{R_{\text{BLR}} \Delta V^2}{G} \]
- \(\Delta V\) from broad line width

\[ \text{BLR size (light days)} \]
\[ \text{log } \frac{\lambda L_\lambda (5100 \text{ Å})}{10^5} \]

\[ \text{log } H_\beta \]

Bentz et al. (2009)

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Black hole growth history
Black hole masses for broad line AGN

- for virial motion in BLR:
  \[ M_\bullet = f \frac{R_{\text{BLR}} \Delta V^2}{G} \]
- \( \Delta V \) from broad line width
- scaling relation between BLR size and continuum luminosity (via reverberation mapping)
  \[ R_{\text{BLR}} \propto L_{5100}^{0.5} \]

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- scaling relation between BLR size and continuum luminosity (via reverberation mapping)
  \[ R_{BLR} \propto L_{5100}^{0.5} \]

- estimate \( M_\bullet \) from spectrum
  \[ M_\bullet \propto L_{5100}^{0.5} \Delta V^2 \]

\[ \Rightarrow \] feasible to estimate \( M_\bullet \) for large samples of broad line AGN out to high \( z \)

Bentz et al. (2009)
define active BH:

⇒ active BHs limited to broad line AGN
⇒ luminosity limit poor criteria for BHMF (incompleteness at low mass by definition)
⇒ define active black hole by Eddington ratio limit
⇒ active BH: type-1 AGN with $\log \lambda > -2$
The bivariate distribution function of BH mass and Eddington ratio

- model DF via fitting of bivariate distribution function of $M_\bullet$ and $\lambda$
  - Black hole mass function (BHMF) and Eddington ratio distribution function (ERDF) determined jointly by fitting probability distribution in $M_\bullet - \lambda$-plane
  - via Maximum likelihood method (Schulze & Wisotzki 2010) or via Bayesian framework (Kelly et al. 2009)

**ML approach**

- BHMF
- $+$ ERDF
- $+$ survey selection function
- $=$ probability distribution
The local active black hole mass function and Eddington ratio distribution function

Local ($z < 0.3$) BHMF and ERDF from the Hamburg/ESO Survey

Active black hole mass function

Eddington ratio distribution function

Schulze & Wisotzki (2010)

⇒ No evidence for downturn at low black hole mass or at low Eddington ratio
Active fraction of local black holes

compare to quiescent BHMF of Marconi et al. 2004

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compare to quiescent BHMF of Marconi et al. 2004

- significant decrease of active fraction toward higher $M_\bullet$
- indication for cosmic downsizing in black hole mass
at $z > 0.4$ BHMF and ERDF determined from SDSS QSO sample
⇒ evidence for black hole mass downsizing
⇒ only high mass end of BHMF, high $\lambda$ end of ERDF

Kelly & Shen (2013)
BH demographics from VVDS, zCOSMOS and SDSS

combine bright, large area surveys (SDSS) with deep, small area AGN surveys (VVDS, zCOSMOS)

SDSS: \( i < 19.1 \) \( \Omega_{\text{eff}} = 6248 \text{ deg}^2 \) color selection

VVDS: wide: \( I_{\text{AB}} < 22.5 \) \( \Omega_{\text{eff}} = 4.5 \text{ deg}^2 \)
depth: \( I_{\text{AB}} < 24.0 \) \( \Omega_{\text{eff}} = 0.6 \text{ deg}^2 \) random selection

zCOSMOS: \( I_{\text{AB}} < 22.5 \) \( \Omega_{\text{eff}} = 1.6 \text{ deg}^2 \) random + X-ray selection
BH demographics from VVDS, zCOSMOS and SDSS

⇒ 1.1<z<2.1
⇒ use MgII BH masses

⇒ SDSS: ~ 28000 AGN
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⇒ 1.1<z<2.1
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⇒ SDSS: \( \sim 28000 \) AGN
⇒ VVDS: \( 86 + 61 \) AGN
⇒ zCOSMOS: 145 AGN

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Active black hole demographics at $1 < z < 2$

active black hole mass function

Eddington ratio distribution function

Schulze et al. (2015)
Bivariate distribution function of $M_\ast$ and $\lambda$ at $1 < z < 2$
Comparison with $M_\bullet - \lambda$ plane and AGN LF

By construction the BHMF & ERDF is consistent with observed $M_\bullet - \lambda$ plane and with bolometric AGN LF.
Evolution of the active black hole mass function and Eddington ratio distribution function comparison with local distribution functions

⇒ strong downsizing in the active BHMF
⇒ decrease of average Eddington ratio towards $z = 0$
Evolution of the AGN space density

⇒ strong downsizing in the active BHMF
⇒ moderate evolution in ERDF
compare to quiescent BHMF derived from stellar mass function

at $z \approx 1.5$ broad line AGN active fraction almost independent of $M_\bullet$. 
The evolution of the active black hole fraction

week evolution at $\sim 10^7 \, M_\odot$

strong evolution at $> 10^9 \, M_\odot$

$\Rightarrow$ witness shutoff of black hole growth at the high mass end between $z = 2$ and $z = 0$
Constraints on theoretical models

⇒ comparison with galaxy evolution models
⇒ discriminate between different models of galaxy evolution, AGN feedback, SMBH seeds

Hirschmann et al. (2012)

Natarajan & Volonteri (2012)
Comparison with numerical simulations

- comparison with simulation from Hirschmann et al. (2014)
  \[ \Rightarrow \] good match at \( z > 1 \) and \( M_\bullet < 10^{9.5} \)
  \[ \Rightarrow \] disagreement at low-\( z \) and high \( M_\bullet \) => caused by radio-mode AGN feedback implementation

Schulze et al. (2015)
Implications for the BH-bulge relations

⇒ cosmic evolution of the black hole-bulge relations provides constraints for coevolution models
⇒ understanding of biases on evolution of BH-bulge relations requires knowledge of distribution functions

Schulze & Wisotzki (2011)

Bongiorno et al. (2014)
Implications for the BH-bulge relations

⇒ selection effects can account for observed apparent trend of increasing $M_\bullet/M_\ast$ ratio

⇒ no statistically significant evidence for positive evolution in $M_\bullet$—bulge relation with redshift, out to $z \sim 6$

Schulze & Wisotzki (2014)
Conclusions

- active BHMF and ERDF provide additional observational constraints on BH growth and galaxy evolution
- established at $z < 2$
  - downsizing in AGN LF mainly driven by downsizing in the BHMF
  - shutoff of black hole growth at the high mass end from $z = 2$ to $z = 0$
  - new observational constraints for theoretical models of galaxy formation and BH growth