Black Hole – host relationship and NLS1 galaxies

NLS1 Milano 2011
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Black Hole vs. bulge in Active Galaxies

• BH/bulge relationship - quiescent & active galaxies
• $M_{BH}$ from gas dynamics vs. stellar dynamics
• Do NLS1 have lower BH/bulge ratios?
• Where are they in $M_{BH}-\sigma^*$ plane?
History of $M_{BH}$/bulge ratio of NLS1

• Steep soft X-ray excess of NLS1 => accretion disk spectrum of lower BH mass (Wandel & Boller 1997)
• $M_{BH}$-$L_{BLG}$ relation in quiescent galaxies (Maggorian+1997)
• Compare with AGN - Seyfert 1s have a lower $M_{BH}$/L$_{BLG}$ ratio than quasars and quiescent galaxies (Wandel 1999)
• AGN – same $M_{BH}$-$L_{BLG}$ as quiescent galaxies (Wandel 2002, McLure & Dunlop 2002)
• NLS1s and NLQ have $M_{BH}$/bulge by factor 10 lower than BL AGN & quiescent galaxies, (Mathur+2001, Wandel 2002)
• New $M_{BH}$/bulge relationships in AGN: $L_{AGN}$~$L_{blg}^2$, $M_{bh}$/M$_{blg}$~FWHM($H_{\beta}$)$^2$… (Wandel 2002, 2009)
Stellar and gas velocity increase near the center

- indicates the influence of a massive BH
Massive BHs in quiescent galaxies

Stellar and gas velocity increase near the center - indicates the influence of a massive BH
A Massive Black Hole in the center of M84

- Material flowing into a black hole forms a gas disk
- Doppler effect measures gas moving in a disk at nearly 400 km/s within 26 light years of the center of M84
- The central velocity increase provides a "signature" of the black hole's presence.
Jets and disks in active galaxies
Emission line spectrum of AGN

- Broad emission-lines
- Doppler broadened
- Thousands of km/s
- Bulk motion (cannot be thermal)
- Random motions of many clouds
- In the gravitational well of central BH
- Partially ionized by central continuum
Massive central BH
Accretion disk
Broad Line Region
BLR size ~ 0.01-0.3pc
Obscuring torus
Narrow Line Region
NLR size ~ 3-100pc
Reverberation Mapping geometry

Equal time-delay surfaces

Delay vs. $v$ for spherical shells

The Broad-Line Region in AGNs

To observer

$0.01r/c$

$0.5r/c$

$r/c$

$1.5r/c$

$2r/c$

Line-of-sight velocity $V$

Time delay $\tau$
Reverberation Mapping: estimating Black Hole masses in AGN

Light-echo from gas in Broad emission Line Region

Time delay of line variations measures the distance of emitting gas from the central source

Doppler line broadening measures velocity

Is the gas gravitationally bound? If so \( v^2 \sim fGM/r \)
Reverberation Mapping: mathematical formalism

- Line – continuum light curve relation (McKee & Blandford 1982)
- \( L(v,t) = \int \Psi(v,t-\tau) C(\tau) \, d\tau \), \( \Psi \) is the transfer function
- Time delay defined as the centroid of the cross-correlation function \( \text{CCF}(\tau) = \sum C(t)(L(t+\tau)) \)
- BH mass estimated from the virial relation: \( M = fG^{-1}v^2R_{\text{blr}} \)
Reverberation mapping of broad emission-line region in NGC 5548.

Different lines show different time lags \((r)\) and different widths \((v)\)

Radius-velocity relation for different lines: \(v \sim r^{-1/2}\)

Radial range: 2-30 light days (250-4000 Rs)

Strongest case for central BH in AGN
Black Hole Signatures in AGN

- Multiple line mapping in three Seyfert galaxies

BH mass range:

NGC 7469: 8x10^6 Mo
NGC 5548: 7x10^7 Mo
3C 390.3: 3x10^8 Mo
The Photoionization vs. reverberation

Black Hole mass in AGN

Reverb. mapping from multi-year campaigns for 17 Seyfert galaxies (Wandel Peterson & Malkan 1999)

calibrate an empirical photoionization
vs. reverberation Mass relationship

Added 18 quasars (Kaspi et al. 2000;2005)

calibrate an empirical delay-luminosity relation $\tau \sim L^{0.5}$

Then estimate BH mass $M \sim FWHM^2 L^{0.5}$
The empirical BLR size vs. continuum Luminosity relation in AGN

- The Hβ BLR radius in AGN scales as the $L^{0.5-0.7}$ (Kaspi et al. 2001;2005)
- Similar scaling CIV BLR radius (Vestergaard & Peterson 2006)
- The ionization-parameter theory (Wandel 1987;1999;2009)
  $$\xi = \frac{L}{4\pi R^2 n \epsilon c}$$
- Optimally local emission: line emissivity peaks sharply at definite values of the ionization parameter and density (Korista et al 1998) $\xi \sim n^{-1}$ contours giving
- $R_{\text{BLR}} \sim L^{0.5}$
BH Mass - bulge relationship for quiescent galaxies

\[ \rho = \varepsilon^{-1} \int \int \Phi(L, z) L dL dt = 2 \times 10^5 \, \text{MoMpc}^{-3} \]

Richstone et al. 1998, Nature 395, A14
Black Hole Mass Scales with Galaxy Size

Ground

NGC 4649

NGC 4291

NGC 2778

NGC 7157

HST

Black Hole Mass

2 billion suns

200 million suns

20 million suns

3 million suns

Black hole event horizons

75000 light-years

3000 light-years

Diameter of Earth’s Orbit
(186 million miles)

NASA and K. Gebhardt (Lick Observatory) • STScI-PRC00-22
The mass of central black holes is approximately proportional to the luminosity (and mass) of the host galaxy:

\[ M_{bh} \sim (0.001-0.002) \ M_{\text{bulge}} \]

Do massive Black Holes in AGN show a similar relation?
Quasar Light estimate of BH mass

• Integrated quasar light gives density of dead BHs:

\[ \rho = \varepsilon^{-1} \int \int \Phi(L, z) L dL dt = 2 \times 10^5 \text{ Mo Mpc}^{-3} \]

• Comparing to light density of galaxies (10^8 Lo Mpc^3) gives

\[ M_{bh}/L_{gal} \sim 0.002 \text{ Mo/Lo} \]

• \( \Rightarrow \) average bright galaxy (5 \times 10^{10} \text{ Lo}) has a \( \sim 10^8 \text{ Mo} \) BH

• “Eddington limit” \( M > 10^8 (L/ 10^{46} \text{ erg/s}) \) Mo

\( \Rightarrow \) the brightest quasars (L=10^{47} \text{ erg/s}) have \( M_{bh} > 10^9 \text{ Mo} \)
Quiescent galaxies:

\[ M_{\text{BH}} \sim 0.006 \, M_{\text{bulge}} \]
(Magorrian et al. 1997)

Quasars BH/blg similar to galaxies (Laor 1998)

Seyfert galaxies – often smaller \( M_{\text{BH}}/ M_{\text{bulge}} \) than quiescent galaxies and quasars (Wandel 1999):

\[ M_{\text{BH}} \sim 0.0003 \, M_{\text{bulge}} \]
• Corrected BH masses for quiescent galaxies from HST data + improved models (Kormendy & Gebhardt 2001, Merrit & Ferrarese 2001)

• Corrected $L_{\text{bulge}}$ for Seyfert galaxies & quasars (McLure & Dunlop 2001)

• Reverberation $M_{\text{BH}}$ for quasars (Kaspi et al. 2000)

  ➢ Most AGN have same BH/bulge relationship as inactive galaxies $M_{\text{BH}}/M_{\text{bulge}} \sim 0.002$ (Wandel 2002)

  ➢ NLSy1 galaxies have smaller $M_{\text{BH}}/M_{\text{bulge}}$

    (Mathur et al. 2001, Wandel 2002)
Improved data: BLS1s & Quasars have same $M_{BH} - L_{bulge}$ relationship as quiescent galaxies. NLS1 & NLQ (NLAN) $M_{BH}/L_{blg}$ values are ~10 lower.
Mass fraction: \( \frac{M_{BH}}{M_{bulge}} \approx 0.002 \)

Narrow Line AGN (NLAN) have lower \( \frac{M_{BH}}{M_{blg}} \) values

![Graph showing the relationship between \( M_{BH} \) and \( M_{blg} \)]

Wandel 2002
More BH-bulge relationships in AGN

• BH/bulge ratio – broad emission line width - 
  \[ \frac{M_{BH}}{L_{blg}} \sim \nu^2 \]

• Size of Broad Emission-line Region - host bulge luminosity 
  \[ R_{BLR} \sim L_{blg} \]

• AGN luminosity - bulge luminosity 
  \[ L_{AGN} \sim L_{blg}^2 \]

• These relations do not show a difference between ordinary and Narrow-line AGNs.
The $M_{BH}/L_{bulge}$ ratio in AGN is correlated with the broad emission line width – *indep. correlation: $M_{bh}/L_{blg} \sim v^2$*
Eliminating v gives a strong independent relation: the size of the Broad Emission-line Region in AGN scales with the host bulge $R(BLR) \sim L_{\text{bulge}}$.
The $M-\sigma$ relation:

in quiescent galaxies the BH mass is better correlated with bulge stellar velocity dispersion than with bulge luminosity

Is it also in AGN?
A stronger relation?

$M_{\text{bh}}$ is tightly correlated with stellar velocity dispersion in central bulge

(Gebhardt et al. 2000; Ferrarese & Merritt 2000)

$M_{\text{BH}} \sim \sigma^4_{\text{bulge}}$
Narrow Line Seyferts galaxies (solid circles) seem to have a lower $M_{BH}$-L$_{bulge}$ ratio than inactive galaxies yet a similar $M_{BH}$-$\sigma^*$ relation as quiescent galaxies and BLS1?
**Geometrical aspects**

- If the BLR has a flattened geometry,
- the lower $M_{BH}/L_{blg}$ of NLS1 could be an inclination effect (flattened+ near face on)
- BH mass of NLS1 measured by assuming isotropic geometry would be under-estimated
- If so, NLS1 should fall low also in the $M_{BH}-\sigma^*$ relationship
- Unless the bulge is deformed as well (pseudo-bulge?)

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The Faber-Jackson relation as a proxi for $\sigma^*$ in AGN
Do NLS1s have a different FJ relation than broad line AGN? Brighter bulge or lower $\sigma^*$??

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The BH-velocity dispersion relation of AGN: $M_{\text{BH}} \sim \sigma^{4-5}$

$\sigma$ measured or estimated using the F-J relation

Solid symbols - measured $\sigma$
Open symbols - estimated $\sigma$

Wandel 2002
The relation between \( M_{\text{bh}} \) and the gas velocity dispersion in the Narrow Emission Line Region in AGN agrees with the \( M_{\text{bh}} \)-stellar velocity relation in normal galaxies (Nelson 2000).

The size of the NLR (1-100 pc) is comparable to the central bulge region where the stellar velocity dispersion is measured. 

\[ \Rightarrow \text{both velocities measure the potential of the central bulge} \]
**Are NLS1s on or off the $M_{BH} - \sigma_{[OIII]}$ relation?**

- **Off** the BLS1 $M_{BH} - \sigma_{[OIII]}$ relation (Mathur+ 01),
- **“on“** Wang & Lu (2001)
- Few real $\sigma_*$ measurements (Botte+ 05: “on“; Zhou+ 06: “off“; Bian+ 08 “on“ or “off“)
- Few $L_{\text{bulge}}$ measurements (Botte+ 04: “on“; Ryan+ 07, Mathur+ 11, Orban Xivry+11: “off“)

- How reliable is [OIII] as substitute for stellar velocity dispersion?
- **On** the $M_{BH} - \sigma_{[OIII]}$ relation when corrected for outflow (Dawei+ 2007 & this conf.)
Conclusions

• BLR Reverberation in AGN probably gives similar BH masses to $M_{BH}$ from stellar dynamics
• AGN have the same BH-bulge relation’s as inactive galaxies
• Narrow Line AGN have a lower $M_{BH}/L_{blg}$ ratio
• New BH-bulge relations:
  • $R_{BLR} \sim L_{blg}$, $M_{BH}/L \sim v^2$, $L_{AGN} \sim L_{blg}^2$
• $M-\sigma^*$ relation: are NLS1 similar to BLS1 & quiescent galaxies?
• Good measurement of true $\sigma^*$ for AGN problematic, surrogates (gas) uncertain (possibly outflow).
X-ray fluctuation analyses of accreting Black Holes

- Power spectral density (PSD) and structure-function analyses of X-ray fluctuations
- XTE and XMM data of ~ 20 Seyfert nuclei
- Linear correlation: break-timescale in the fluctuation spectrum (Tb) and BH mass (Mbh)
- SF- similar to Tb-Mbh correlation found with PSD
- Extends to lower mass BHs (Cyg X-1 and others)
- Common physical mechanism – scaled by BH mass
X-ray fluctuation analyses of accreting Black Holes

- Power spectral density (PSD) – Fourier-like analyses of time variability
- “Break” in the PSD of Cyg X-1 and other stellar BH-systems
- PSD of Seyfert 1 galaxies also show “break”
- Similar to PSD-break of stellar BH but at lower frequency
- Common physical mechanism produces X-rays in accreting Black Holes?
PSD of Cyg X-1 (high/soft state)
PSDs of Cyg X-1 and AGN

![Graph showing PSDs of Cyg X-1 and AGN](image-url)
Light Curve of NGC 3783

NGC 3783

Date (MJD-50000)

FLUX (c/s)

1200 1600 2000

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PSD of NGC 3783
Structure Function analyses of time-series

\[ S(\tau) = \frac{1}{N(\tau)} \sum_{i<j} [f(t_i) - f(t_j)]^2 \]

\[ S(\tau) = 2[\sigma^2 - ACF(\tau)] \]

\[ S(\tau) = 2 \left[ \int_0^\infty P(f) df - \int_0^\infty P(f) \cos (2\pi \tau f) df \right] \]

**SF: definition**

**Auto-correlation function**

**SF - PSD relation**

power-law section:

defines the range of timescales over which the variations are correlated, and its slope depends on the physical mechanism responsible for the intrinsic variability.

The timescale \( \tau_{\text{char}} \sim \tau_{\text{max}} \) at which the structure function flattens may represent a robust, characteristic timescale determined by fundamental source characteristics, e.g., mass and size; provides...
Structure Function of NGC 3516

Wandel, Markowitz & Malkan 08

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XTE & XMM Light Curves of NGC4051

Figure 1. RXTE long-term 2–10 keV light curve of NGC 4051. Each data point represents an observation of $\sim$1 ks.
PSD of NGC 4051

XMM data
McHardy et al. 2004

2-10 keV
0.1-2 keV

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**SF of NGC 4051**

XTE data
Edelson et al.
2002;

Wandel Markowitz & Malkan
Structure Function of NGC 3516
Structure Functions of AGN

NGC 3516

NGC 3783

Wandel, Markowitz & Malkan 2010

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X-ray fluctuation time scale correlated with BH mass

- 1987 - Einstein data: time-scale of variability of X-rays in AGN prop. to BH mass (Wandel & Mushotzky)
- 2010 - XTE/XMM data: correlation between break-frequency in the fluctuation spectrum and BH mass (McHardy et al., Wandel, Malkan & Markowitz)
- The same correlation extends to lower mass BHs (Cyg X-1 and others)
- Common physical mechanism – scaled by BH mass
PSD $M_{bh}$-$T_b$ correlation

McHardy et al. 2004
**PSD-SF correlation**

Timescale of the break or flattening in the X-ray fluctuation power (SF or PSD)

Wandel, Markowitz & Malkan 2010
Mbh-SFTb correlation

Cyg X-1 PSD extrapolation

Wandel, Markowitz & Malkan

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$M_{BH} - T_b$ correlation (SF)

Wandel, Markowitz & Malkan 2010

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**Extended $M_{bh}-T_b$ correlation**

Common physical mechanism for X-ray variability in BHXRBs and AGNs?
Accretion timescales

• **Light-travel time at** $R_s$: $2GM/c^3 \sim 10^3 \ M_8 \ sec$

• **Orbital time at 5 $R_s$**: $t_{orb} \sim 10^5 \ M_8 \ s \sim 1 \ M_8 \ days$

• **Viscous time at 5 $R_s$**: $t_{visc} \sim 10 \ M_8 (\alpha/0.1)^{-1} \ days$

• **Most of the energy in a thin $\alpha$-disk is produced at a few** $R_s \sim M$
Summary

• Structure-function analyses of X-ray fluctuations
• XTE and XMM data of about 20 Seyfert nuclei
• Doubles the number of objects in the database
• Linear correlation between the break-timescale in the fluctuation spectrum (Tb) and the black hole mass Mbh
• Improves the correlation found between Tb and Mbh with power spectral density (e.g. McHardy 2004;06)
• Extrapolation of the Mbh-Tb relation of Cyg X-1 & GBHs
• ULXs (IMBHs?) and low end SMBHs
• Common physical mechanism for X-ray variability in BHXRBs and AGNs?
• Predicted timescale for Sag A* Tb~1day
Conclusions

• Reverberation Mapping + stratified BLR structure
  >> Kepplerian measurement of BH mass in AGN

• AGN have the same BH-bulge relations as inactive galaxies

• Narrow Line AGN have a lower $M_{BH}/M_{blg}$ ratio

• New relations: $R_{BLR} \sim L_{blg}$, $M_{BH}/L \sim v^2$, $L_{AGN} \sim L_{blg}^2$

• $M_{BH}$ - $T_b$ correlation - between the break-frequency in the fluctuation spectrum and the BH mass

• Extends over 8 orders of magnitude in BH mass

• Common physical mechanism in accreting BHs
Questions

• Do all galaxies have massive black holes (MBHs)?
• Did all galaxies with a MBH have an active phase?
• How is the MBH coupled to its host galaxy?
• Is nuclear activity in AGN related to growing MBHs?
• How is the BH growth related to the halo
New relation between host bulge and BH mass in AGN?

- $M_{BH}/L_{blg}$ depends on the gas velocity in the broad emission line regions $M/L \sim v^{2.0}$
- may be caused because the BH mass in AGN is estimated using the virial relation $M_{BH} \sim v^2 r_{(BLR)}$
- Canceling the v dependence $v^2 r_{(BLR)}/L \sim v^{2.0}$ ...
- we expect no correlation to be left, but actually the remaining correlation, $r_{(BLR)} \sim L_{blg}$ is very strong!
Seyferts galaxies (solid) may have a lower $M_{\text{BH}}$-bulge luminosity relation than normal galaxies (open), (a), -- yet similar $M_{\text{BH}}$-stellar velocity ratios (b)
Non-linear BH-bulge relation?

\[-M_{V \text{ bulg}} \sim M_{\text{BH}}^{(1.2-1.5)}\]

or

\[M_{\text{BH}} \sim L_{\text{bulg}}^{(1.7-2)}\]

\[M_{\text{BH}} \sim M_{\text{bulg}}^{(1.4-1.7)}\]

(Laor 2001,
Wu & Han 2002)
Correlation Between Black Hole Mass and Bulge Mass

- One billion solar masses
- One million solar masses
- No black hole

Mass of central bulge: Increasing
The BH mass - bulge velocity dispersion relation
for Seyfert galaxies (Wu & Han, A&A 2002)
The BH-velocity dispersion relation of AGN: $M_{BH} \sim \sigma^{4.5}$

$\sigma$ measured or estimated using the FJ relation

Solid symbols - measured $\sigma$
open symbols - estimated $\sigma$

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The mass of central black holes is related also to the mass of the host halo (estimated from $v_c$; Ferrarese 2002)

- $M_{bh} \approx 10^{-5} M_{\text{halo}}^{5/3}$
- Does this originate in the formation process?
Possible explanation of R-M relation

* Interstellar gas in the core: $M_{\text{gas}} \sim L_{\text{bulge}}$

* The dynamical friction time scale:

$$\tau_{\text{df}} = 1.2 \frac{r^2 v}{\ln \Lambda} G M R_{\text{blr}} \sim \frac{dM}{dt} \sim \frac{M}{\tau} \sim M^2$$

(assume weak dependence on $r,v$)

* Empirical R-L relation: $R_{\text{blr}} \sim L_{\text{agn}}^{1/2}$

* For a fixed efficiency: $L_{\text{agn}} \frac{dM}{dt} \sim M_{\text{bulge}}^2$