Supermassive Black Holes in Galactic Nuclei: Demography and relation with AGN activity

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A brief history

- 1783 - 1796: John Michell and Pierre-Simon Laplace hypothesized the existence of "dark stars": objects with $\rho = \rho_{\odot}$ with $R = 500 \, R_{\odot}$ would have escape speed larger than $c$. $M_{\text{Dark Star}} = 1.1 \times 10^8 \, M_{\odot}$!

- WRONG assumptions (corpuscolary theory of light; Newtonian mechanics) but CORRECT formula for the "Schwarzschild" radius.

- 1916: Schwarzschild solves Einstein equations and find the "Black Hole" solution.

- 1968: John Wheeler coins the term "Black Hole"

- Beginning of 1970s: X-ray source Cygnus X-1 is the first BH candidate with $M \sim 12 \, M_{\odot}$

- 1978: Sargent et al. showed that images and spectra of the central region of M87 could be explained only with the presence of a BH with $M \sim 3 \times 10^9 \, M_{\odot}$
What types of BHs?

**Stellar mass Black Holes**
(~1-10 \( M_\odot \))
- Endpoints of the life of massive stars

**Intermediate Mass Black Holes**
(~\(10^2-10^5\) \( M_\odot \))

**Supermassive Black Holes**
(~\(10^6-10^9\) \( M_\odot \))
- in galactic nuclei
Active Galactic Nuclei

- Mass accretion onto a massive BH ($>10^6 \, M_\odot$) is widely accepted as the powering mechanism of AGNs.

- It satisfies observational requirements:
  - high efficiency ($\varepsilon \sim 0.1$)
  - relativistic motions (e.g. superluminal jets)
  - rapid time variability (e.g. $c\Delta \tau < 1$ light-day)
  - compactness (e.g. Cen A, $r < 10$ light-days)

- If the Eddington limit applies an AGN with $L = 10^{12} \, L_\odot$ must have
  $$M_{BH} \geq 2.6 \, \Delta 10^7 \, M_\odot$$

Urry & Padovani
Why Black Holes in Normal Galaxies?

- Accretion onto a massive BH is the powering mechanism of Active Galactic Nuclei
- Observed evolution of AGNs (at z~2-3 luminous quasars where ~2 orders of magnitude more numerous than they are now)
- Significant fraction of luminous galaxies should host a BH in their nuclei as a "remnant of past glory"
Why Black Holes in Normal Galaxies?

- **Integrated comoving energy density from AGNs:**
  \[ u = \int_{0}^{\infty} \int_{0}^{\infty} dz \Phi(L,z) L dL \frac{dt}{dz} = 1.3 \times 10^{-15} \text{erg cm}^{-3} \]

- **Accretion efficiency } \varepsilon \Rightarrow \text{present day mass density:}**
  \[ \rho_u = \frac{u}{\varepsilon c^2} = 2.2 \times 10^4 \varepsilon^{-1} \text{M}_\odot \text{Mpc}^{-3} \]
  Soltan 1982; Chokshi & Turner 1992

- **Mass density of bulges**
  \[ \rho_{\text{Bulges}} \approx 5.3 \times 10^8 h \text{M}_\odot \text{Mpc}^{-3} \]

  \[ \frac{M_{\text{BH}}}{M_{\text{Bulge}}} \approx 4.2 \times 10^{-5} \varepsilon^{-1} h^{-1} = 6 \times 10^{-4} \text{ [} h=0.7; \varepsilon=0.1 \text{]} \]
How can we find a BH?

Use Gas/Stars as tracers to get velocity field $V$ around the BH

Determine gravitational potential $\phi$ which gives rise to observed $V$

\[ \phi = \phi_{\text{Stars}} + \phi_{\text{BH}} \]

Get $\phi_{\text{Stars}}$ from observed light distribution in galaxy nucleus $(L \Rightarrow M)$

\[ \phi_{\text{BH}} = G M_{\text{BH}} R^{-1} \]

(R > $R_{\text{Schwarzschild}}$)
Black Hole Sphere of Influence

- Gravitational field of BH = Galactic gravitational field

\[ r_{BH} = \frac{GM_{BH}}{\sigma_*^2} = 4.3 \text{ pc} \left( \frac{M_{BH}}{10^7 M_\odot} \right) \left( \frac{\sigma_*}{100 \text{ km/s}} \right)^{-2} \]

- For a galaxy at distance D, \( r_{BH} \) corresponds to an angular size:

\[ \theta_{BH} = 0.1'' \left( \frac{M_{BH}}{10^7 M_\odot} \right) \left( \frac{\sigma_*}{100 \text{ km/s}} \right)^{-2} \left( \frac{D}{10 \text{ Mpc}} \right) \]

- Need high spatial resolution to probe within the BH sphere of influence and detect its effects! This is why the Hubble Space Telescope has produced such a major impact in the field.
Gas Kinematics vs Stellar Dynamics

**Gas:**
- high surface brightness, short integration times
- easy interpretation

**Stars:**
- completely gravitational motions
- available in all galaxies

- but not in all galaxies
- only if system is a circularly rotating disk
- but interpretation difficult (complex orbital structure)
- but observations require long integration times
The Galactic Center

\[ M_{\text{BH}} = 2.6 \times 10^6 M_\odot \]

Genzel et al. 2000; Schodel et al. 2002
Extragalactic BHs: NGC 4258

High spatial resolution VLBI observations of H$_2$O maser emission at the nucleus of NGC4258

$M_{BH} = 4 \times 10^7 M_\odot$

Miyoshi et al. 1995; Greenhill et al. 1995
Hubble Space Telescope longslit rotation curve from emission line [OII] $\lambda$ 3727 Å (0.1” spatial resolution)

To account for the observed rotation curve one requires $M_{BH} = (3.2 \pm 0.9) \times 10^9 M_\odot$

$L/L_{Edd} < 10^{-6}$; quasar relic?

Centaurus A

- $A_v \sim 7$ toward nuclear region require near-IR spectroscopy which is not possible from the Hubble Space Telescope!
- We used the ESO-VLT to get medium resolution spectra in the J band with good seeing (0.5")
- Fit of the rotation curve requires: $M_{\text{BH}} \sim 2 \times 10^8 M_\odot$
- $L/L_{\text{Edd}} \sim 10^{-3}$, low level of activity!
Cygnus A

Keck/NIRSPEC

\( M_{\text{BH}} = 2.7^{+0.7}_{-1.3} \times 10^9 \, M_\odot \)

First time that the BH mass is measured in an AGN with Quasar-like luminosity (\( L \sim 10^{12} \, L_\odot \))

\( L/L_{\text{Edd}} = 0.02; \) is it the relic of an even more powerful AGN?

HST/STIS
NGC 4258

- In NGC 4258 a BH has been detected from kinematics of H$_2$O masers ($M_{BH} = 4 \times 10^7 M_\odot$).
- Second best case for a SMBH after our galactic center and is a crucial test for the gas kinematical method!

- HST observations, 3 parallel slits
- $M_{BH} = 4^{+4}_{-2} \times 10^7 M_\odot$ in agreement with maser data!
- Gas Kinematics and Stellar Dynamics give the same answer!

Miyoshi et al. 1995

Axon, Marconi, et al. 2003
Massive Black Holes in Galactic Nuclei

Observations currently suggest that massive Black Holes are present in ALL galaxies.

The BH mass correlates with the luminosity of the host spheroid and stellar velocity dispersion.

Kormendy & Richstone 1995; Merritt & Ferrarese 2000; Gebhardt et al. 2000
BH Mass vs Host Galaxy Properties

- $M_{\text{BH}} - \sigma_e$ is believed to be tighter than $M_{\text{BH}} - L_{B,\text{bul}}$ (rms 0.25 vs 0.5 in log $M_{\text{BH}}$) suggesting that bulge dynamics (mass) drives the correlations (e.g. Tremaine et al. 2002).

- What is the reason of the larger scatter of $M_{\text{BH}} - L_{B,\text{bul}}$?

- Marconi & Hunt (2003) have investigated the $M_{\text{BH}} - L_{\text{bul}}$ relation in the near-IR (reduce reddening and M/L effects on scatter).

- Sample is 37 galaxies with DIRECT BH mass determination (ALL with stellar dynamics or gas kinematics).

- Measure near-IR galaxy structural parameters using J, H and K images from 2MASS using 2D image analysis.

- Divide sample in 2 Groups: in Group 1 place galaxies with reliable BH masses (e.g. BH sphere of influence resolved, BH mass well constrained by data).
B band (literature) vs K band (new)

B band: rms 0.5
K band: rms 0.5

Marconi & Hunt 2003
B band vs K band: only Group 1 galaxies

B band: rms 0.3

K band: rms 0.3

Marconi & Hunt 2003
Tight correlation between $M_{BH}$ and virial bulge mass

\[
M_{bul} \propto R_e \sigma_e^2
\]

- linear slope (0.96+/-0.07)
- Average ratio
  \[
  \frac{M_{BH}}{M_{bul}} \approx 0.002
  \]
- Merritt & Ferrarese (2001) find -2.9 (estimate $M_{BH}$ in sample of galaxies using $M_{BH} - \sigma_e$). With their method we find -2.8.
What is the origin of the correlations?

- $M_{\text{BH}} - L_{\text{bul}}$: from $M_{\text{BH}} - M_{\text{bul}}$
  
  - $M_{\text{BH}} \sim L_{\text{bul}}^{1.15}$ and $M_{\text{BH}} \sim M_{\text{bul}}$ are consistent if $(M/L)_{\text{bul}} \sim L_{\text{bul}}^{0.15}$ consistent with literature data

- Are $M_{\text{BH}} - \sigma_e$ and $M_{\text{BH}} - R_e \sigma_e^2$ the same? i.e. is $M_{\text{BH}} - R_e \sigma_e^2$ a consequence of $M_{\text{BH}} - \sigma_e$ combined with the known $\sigma_e - R_e$ correlation?

- Partial correlation analysis shows that $M_{\text{BH}}$ correlates with both $\sigma_e$ and $R_e$ (after removing the effects of $\sigma_e - R_e$), i.e. $M_{\text{BH}}$ depends on both $\sigma_e$ and $R_e$!
A weak, but significant correlation between the residuals of $M_{\text{BH}} - \sigma_e$ and the effective radius $R_e$. With these data we can not say more!

- $M_{\text{BH}} - L_{\text{NIR, bul}}$ correlate and, if only secure BH masses are considered, the spread of $M_{\text{BH}} - L_{\text{bul}}$ is similar to that of $M_{\text{BH}} - \sigma_e$ regardless of photometric band (B, J, H and K)

- $M_{\text{bul}}$ tightly correlates with $M_{\text{BH}}$ ($M_{\text{BH}} / M_{\text{bul}} \sim 0.002$)

- $M_{\text{BH}}$ depends on both $\sigma_e$ and $R_e$ and both variables are necessary to drive the correlations between BH mass and other bulge properties.
Are they really massive BHs?

In reality, stellar and gas kinematical observations detect *Massive Dark Objects* (MDO), not Black Holes!

Only in a few cases (e.g. GC, NGC 4258) an alternative explanation to a BH can be confidently ruled out.

The proof that a MDO is a BH is the detection of relativistic motions close to the Schwarzschild radius (Kormendy & Richstone 1995)!
MDO: are they SMBH?

\( \tau_{\text{MAX}} \) is the Survival Time for a Cluster of dark objects (stellar remnants, brown dwarfs, planets).

In \( \tau_{\text{MAX}} \) core collapse or collisions will produce a massive BH, eventually embedded in a dark cluster.
Fe Kα at 6.4 keV: broad red wing from relativistic effects!

Fabian et al. 2000
A broad red wing in Fe Kα at 6.4 keV

ASCA - Tanaka et al., 1995

XMM - Fabian et al., 2002

But this is not conclusive yet!
Relic Black Holes

- Are local BHs relics of past AGN activity?
- One needs to compare past AGN activity with local BHs: this can be achieved by comparing local BH mass function with the BHMF of AGN relics.
- From the comparison of the two (not only densities!) one can find if there are inconsistencies.
- Recently various authors have been saying that there are inconsistencies at large masses, $M_{\text{BH}} > 10^8 M_\odot$ (e.g. Ferrarese 2002, Yu & Tremaine 2002)!
Local BH mass function \[ dN = \phi(M_{BH}) \, dM_{BH} \]

- There are \(~30\) galaxies with a DIRECT BH mass determination and these are not enough to estimate the BHMF.

- One can use galaxy Luminosity/Velocity functions \([\phi(L) \text{ or } \phi(\sigma)]\), apply the known correlations between BH mass and galaxy properties and obtain the BHMF

\[ \phi(M_{BH}) = \phi(L) \frac{dL}{dM_{BH}} \quad \text{with } \log M_{BH} = a + b \log L_{\text{bul}} \]
\[ \text{and } L_{\text{bul}} = f L \]

\[ \phi(M_{BH}) = \phi(\sigma) \frac{d\sigma}{dM_{BH}} \quad \text{with } \log M_{BH} = c + d \log \sigma \]

(this is thought to be more “reliable”)

Salucci et al. 1998; Marconi & Salvati 2001; Ferrarese 2002; Aller & Richstone 2002
The Local BH Mass Function

Galaxy Luminosity Function per Morphological Type
Marzke et al. 1994 (CFA)

Galaxy Velocity Function

Bulge/Total Correction
(Simien & de Vaucouleurs)

Faber-Jackson Relation
$L = k \sigma^\alpha$

$M_{\text{BH}} - \sigma$ relation
e.g. Tremaine et al. 2002

Black Hole Mass Function

Ferrarese 2002; Aller & Richstone 2002
The Local BH Mass Function

\[ \rho_{BH} = 2.1 \times 10^5 \, M_\odot \, \text{Mpc}^{-3} \]

Cosmology:
- \( h = 0.7 \)
- \( \Omega_M = 0.3 \)
- \( \Omega_\Lambda = 0.7 \)

Aller & Richstone 2002
Continuity equation

We use the Small & Blandford (1982) formalism and write the continuity equation for the BH mass function $N(M,t)$ as

$$\frac{\partial N(M,t)}{\partial t} + \frac{\partial}{\partial M} \left[ N(M,t) \langle \dot{M}(M,t) \rangle \right] = 0$$

Note that no source term is present, i.e. no merging of BHs.

Assume that a BH with mass $M$ at time $t$ accretes at the Eddington rate ($L = M c^2 / t_E$) with a duty cycle $\delta(M,t)$, thus

$$\langle \dot{M} \rangle N = \frac{1}{\varepsilon \tau_E} \delta(M,t) MN(M,t) = \frac{1}{\varepsilon \tau_E} \left[ \phi(L,t) \right]_{L = \frac{M c^2}{t_E}}$$

$\phi(L,t)$ is the AGN luminosity function $\varepsilon$ is the accretion efficiency ($\varepsilon = 0.1$ fixed)
Evolution of BH mass function

Finally we get

$$\frac{\partial N(M, \tau)}{\partial \tau} = -\frac{c^2}{\epsilon \tau_E^2} \left. \left( \frac{\partial \phi(L, \tau)}{\partial L} \right) \right|_{L=\frac{M}{t_E}}$$

which can be easily integrated given the AGN luminosity function AND the initial conditions.

For the initial conditions we assume that at the starting redshift $z_0$ [$t_0=t(z_0)$] **ALL** Black Holes are active, i.e. $\delta(M, t(z_0))=1$

$$M N(M, \tau_0) = \left[ \phi(L, \tau_0) \right]_{L=\frac{M}{t_E}}$$
Luminosity Functions

- LF of optically selected quasars (Boyle et al. 2000)
- LF of X-ray selected AGNs (Miyaji et al. 2000; these are mostly type 1s, ~80%)
- These 2 LFs refer only to type 1 objects!
- With bolometric corrections from B and 0.5-2 keV one can get the AGN LF $\phi(L,t)$.
Apply continuity equation...
Local BHMF vs Relic BHMF

- The relic BHMF has an excess at large masses!
- Are the Bolometric corrections too high or is the Efficiency (0.1) too low?
- Yu & Tremaine (2002) conclude that:
  - high M BHs must be rapidly rotating
  - low M BHs are either “obscured” or emitting at low efficiency.
Where is the problem?

- Is the $M_{BH}-\sigma$ relation as good as we think (i.e. rms=0)?
- Is the $M_{BH}$-L$_{bul}$ not usable because it is less “tight”?
- SDSS has produced $\phi(\sigma)$ and $\phi(L)$ for 9000 Early type galaxies (Bernardi et al. 2003, Sheth et al. 2003) which can be used to test the correlations.
- $M_{BH}-\sigma$ ($\sim 0$-0.3) and $M_{BH}$-L$_{bul}$ (0.5?) have dispersions to be taken into account: $\rho_{BH} = \rho_0 \exp[0.5 \text{ (rms ln10)}^2]$!
- But Marconi & Hunt (2003) have shown that $M_{BH}-\sigma$ and $M_{BH}$-L$_{bul}$ have similar dispersion ($\sim$0.3)!
- Indeed they give the same BHMF only if they have the same dispersion!
The Local BH Mass Function: use of $M_{BH} - \sigma$

- Galaxy Luminosity Function per Morphological Type
  Marzke et al. 1994 (CFA)

- Galaxy Velocity Function

- Bulge/Total Correction
  (Simien & de Vaucouleurs)

- Faber-Jackson Relation
  $L = k \sigma^\alpha$

- $M_{BH}-\sigma$ relation
  e.g. Tremaine et al. 2002

Ferrarese 2002; Aller & Richstone 2002
The Local BH Mass Function: use of $M_{BH} - L_{bul}$

Galaxy Luminosity Function per Morphological Type

Spheroid Lum. Function

Black Hole Mass Function

Bulge/Total Correction (Simien & de Vaucouleurs)

Faber-Jackson Relation $L = k \sigma^{\alpha}$

$M_{BH} - L_{bul}$ relation e.g. Hunt & Marconi 2003
\[ \rho_{\text{BH}} = 3.1^{\text{def}} 0.1 \times 10^5 \ M_\odot \ Mpc^{-3} \]

\[ \rho_{\text{BH}} = 4.1^{\text{def}} 0.3 \times 10^5 \ M_\odot \ Mpc^{-3} \]

\[ \rho_{\text{BH}} = 2.5 \ (\text{Aller & Richstone})! \]
AGNs: bolometric corrections

- For AGNs ... bolometric corrections!
- Elvis et al. (1994) overestimated by a factor 2!
- SEDs for Seyferts and QSOs compiled by Maiolino & Granato (2003, in prep.)
- Elvis et al. 1994 (used previously) overestimated $L/(\nu L_\nu + B)$ by roughly a factor 2!
The disagreement at high masses have disappeared (mostly due to Bol. Corr.)!

- Quasars produce $M_{\text{BH}} > 10^8 M_\odot$
- The relic BHMF is from type 1 AGN only!
- The assumptions on initial conditions are not important.
- Putting in type 2 AGNs, all is consistent with BH mass growth during AGN activity!
Local BHMF vs Relic BHMF “reloaded”

- Combining LFs (X-ray at low L, Optical at high L) and assuming Type2/Type1=3 we get a reasonable agreement between Local and Relic BHMF.

- Remember the underlying assumption that BH growth take place in AGNs emitting at Eddington L with 0.1 efficiency!
Local BHMF vs Relic BHMF “reloaded”

\[ \delta = \text{fraction of 'Active' BHs} \]

\[ \text{Accretion rate onto BHs} \]
Future: the X-ray Backgr. constrain

- Elvis, Risaliti & Zamorani (2002) from a reanalysis of Fabian & Iwasawa (1999) argument find that the density in relics BHs is \( \geq (7.5-16.8) \times 10^5 (\epsilon/0.1) \, \text{M}_\odot \, \text{Mpc}^{-3} \) much higher than the density in local BHs (4.1\( \equiv 0.3 \)).

- The further development is to use the luminosity functions and Type2/Type1 ratios (with their \( z \) dependence) needed to fit the X-ray background and number counts.

- If it is not possible to fit the XRB with the a small number of type 2's then we might really need to conclude that the efficiency is larger than 0.1 and that “Most supermassive Black Holes must be rapidly spinning” (Elvis, Risaliti & Zamorani)
Conclusions

- Current observational evidence suggests that most, possibly all, luminous galaxies host a massive Black Hole in their centers.
- The Black Hole mass correlates with mass/luminosity of the bulge in which it resides and ALL correlations are equally good!
- Hypothesis that AGNs are powered by accretion onto a massive BH combined with the observed redshift evolution of AGNs suggests that these massive BHs are relics of past activity.
  - Local BHs have density \((4.1 \pm 0.3) \times 10^5 \, M_\odot \, \text{Mpc}^{-3}\)
  - Quasars make \(M > 10^8 \, M_\odot\) BHs
  - The majority of BH mass is produced during AGN activity
  - Type 1/Type \(\sim 3\)
- With "reasonable" values of the free parameters compatible with current knowledge, accretion on AGNs can reproduce the local BH mass function!
Thanks very much to the organizers!