Black Holes in the center of Galaxies

Luis Padilla

Advanced Extragalactic Astronomy
Universidad de Valparaíso

October 24,2022

Overview

Introduction

Discovery that quasars are not stellar in nature but are rather extremely luminous, compact objects located in the center of distant galaxies led to an intensive effort to identify and measure supermassive black holes (SMBHs) energetically favored to power them. Some Questions:

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- Is the mass of the black hole, the rate at which matter is accreted onto it, or the efficiency of the mechanism which is generatin the energy?
- What are the effects of central SMBHs on the lensing configurations?

Schwarzschild Radius

Recalling Newton:

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Schwarzschild metric:

$$ds^2 = -(1 - \frac{2GM}{c^2 r})c^2 dt^2 + \frac{1}{1 - \frac{2GM}{c^2 r}} dr^2 + r^2(d\theta^2 + sin^2\theta d\phi^2) \tag{2}$$

Coordinate singularity defines the event horizon:

$$r_s = \frac{2GM}{c^2} \sim 2.95 \cdot 10^5 cm \left(\frac{M}{M_\odot}\right) \tag{3}$$

Radius of influence

Considering mass concentration $M_\bullet$ in the center of a galaxy with velocity dispersion σ_v. For distances smaller than:

$$r_{BH} = \frac{GM_\bullet}{\sigma_v^2} \sim 0.4 \left(\frac{M_\bullet}{10^6 M_\odot}\right) \left(\frac{\sigma_v}{100\ km/s}\right)^{-2} pc \tag{4}$$

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the SMBH will significantly affect kinematics of stars and gas in the galaxy. The corresponding angular scale is:

$$\theta_{BH} = \frac{r_{BH}}{D} \sim 0.1'' \left(\frac{M_\bullet}{10^6 M_\odot}\right) \left(\frac{\sigma_v}{100 \ km/s}\right)^{-2} \left(\frac{D}{1 \ Mpc}\right)^{-1} \tag{5}$$

Increasing distance D, mass $M_\bullet$ has to increase for a SMBH to be detectable at a given angular resolution.

Kinematic evidence

The presence of a SMBH inside r_{BH} is revealed by an increase in the velocity dispersion for $r \lesssim r_{BH}$. Behaving as:

- $\sigma_v \propto r^{-\frac{1}{2}}$
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Problems in detecting these signatures:

- Angular resolution
- Projection effects
- Kinematics of stars can be rather complicated.

Despite this difficulties, detection of SMBH has been achieved in recent years. More than 70 nearby galaxies and upper limits on $M_\bullet$ obtained for about 30 galaxies.

Masses chart for dead stars and black holes

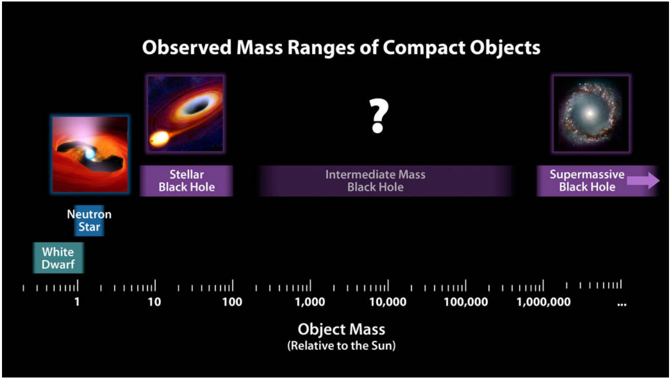

Figure 1: relative masses of super-dense cosmic objects. Image credit: NASA/JPL-Caltech

Examples for SMBHs in galaxies: M84

- Member of Virgo Cluster. $\sim$15 Mpc away from us.
- Long-slit spectrum. $\delta\lambda \propto v_{radial}$
- v_{rot} steeply increases inwards and change sign on the other side of center
- Kepler rotation in SMBH gravitational field estimated as $M_\bullet \sim 3 \cdot 10^8 M_\odot$

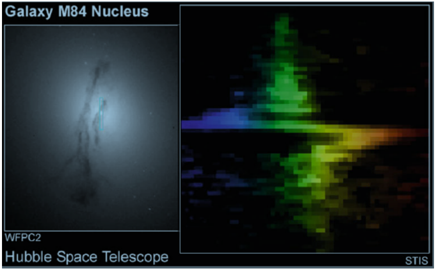

Figure 2: Nucleus galaxy M84 and Relative wavelength change of light. Credit: Gary Bower, Richard Green (NOAO), the STIS Instrument Definition Team, and NASA/ESA

Examples for SMBHs in galaxies: NGC3115

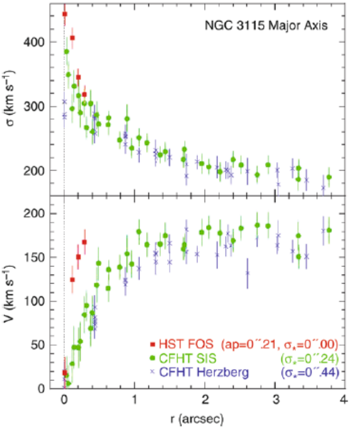

Figure 3: Velocity dispersion and rotational velocity. Source: J.Kormendy , Supermassive Black Holes in Inactive Galaxies, astroph/0003268, p.5

- Lenticular Galaxy. ∼4.2 MPc away
- Correcting Projection effects: $\sigma \sim 600$ km/s $\rightarrow M_\bullet \sim 10^9 M_\odot$
- Measurability of kinematical evidence for SMBH depends on achievable angular resolution of observation.

Examples for SMBHs in galaxies: M87

- Central galaxy of Virgo Cluster. D $\sim$ 7Mpc
- Increase of rotation curve and broadening $[O_{II}]$-line at $\lambda = 3727\text{Å}$ towards center
- Results shows a central mass concentration $M_\bullet \sim 3 \cdot 10^9 M_\odot$ in a region less than 3pc

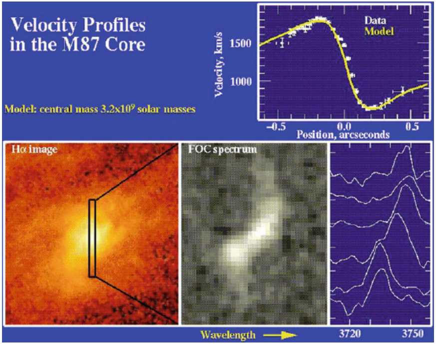

Figure 4: H_α image of galaxy. $[O_{II}]$ spectrum line. Spectras at different positions along the slit. Credit: STScI, NASA, ESA, W.Keel and Macchetto. 1997. FOC data

Examples for SMBHs in galaxies: NGC4258

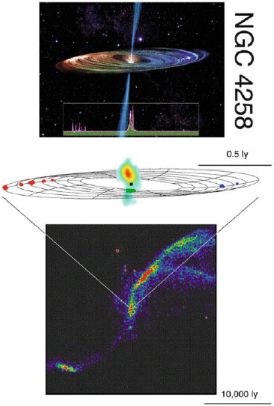

Figure 5: NGC4258. Line spectrum of maser sources. 20 cm map of Large-scale radio structure.Credit: M. Inoue (NAOJ), National Radio Astronomical Observatory and C. De Pree, Agnes Scott College

- Seyfert Galaxy. $D \sim 7Mpc$
- Accretion disk with several water masers embedded
- Position and velocities mapped by Very Long Baseline Interferometry (VLBI).
- Kepler law: $M_\bullet \sim 3.5 \cdot 10^7 M_\odot$

Examples for SMBHs in galaxies

Hence, there are three different probes of gravitational potential in the center of galaxies:

- Stars
- Gas
- Masers

All three employed for identifying a SMBH in galaxies and to determine their masses.

Examples for SMBHs in galaxies: Sgr A*

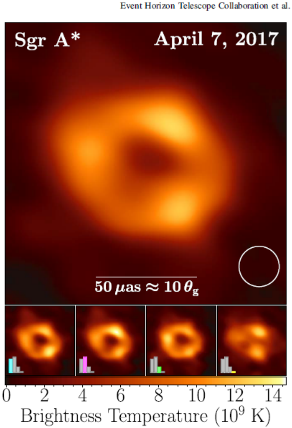

Figure 6: EHT image of Sgr A* average over different reconstruction methods. Color denotes specific intensity in units of brightness temperature.

- High-resolution observations, have traced out the three-dimensional orbits of several stars within the innermost arcsec around Sgr A*
- These orbits jointly determine the ratio M/D that determines the angular size of the black hole in the sky

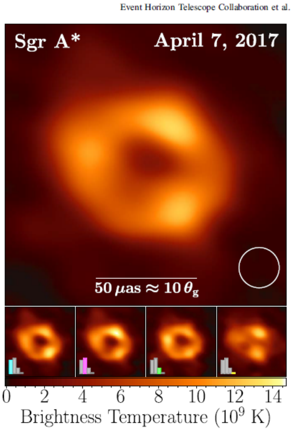

Figure 7: EHT image of Sgr A* average over different reconstruction methods. Color denotes specific intensity in units of brightness temperature.

- $M_\bullet \approx 4 \cdot 10^6 M_\odot$
- located nearly motionless with respect to the dynamical center of galaxy ($D \approx 8kpc$)
- Does not present a clear jet structure
- X-ray measurements confirmed that SgrA* has lowest Eddington ratio (L/L_{Edd}) for any black hole ($\sim$ 9 orders of magnitude)
- Flaring emission at most wavelengths. Daily flares at X-ray an NIR.

Examples for SMBHs in galaxies: Sgr A*

What can we learn from these images and their variability properties?

- EHT images are consistent with the expected appearance of a Kerr black hole.
- Ring-like structure, similar to M87
- SMBH Sgr A*, can be scrutinized in ways that are impossible for other sources, making it a unique Laboratory for exploring astrophysics of black holes and testing predictions of GR.

Examine whether and in what way $M_\bullet$ is related to the properties of the host galaxy.
Discovery: $M_\bullet$ is correlated with the absolute magnitude of the bulge component (sphere of influence).

$$M_\bullet = 1.7 \cdot 10^9 \left(\frac{L_V}{10^{11} L_{V\odot}} \right)^{1.11} \quad (6)$$

Bulge component is either the bulge of a spiral/S0 galaxy or an elliptical galaxy as a whole.

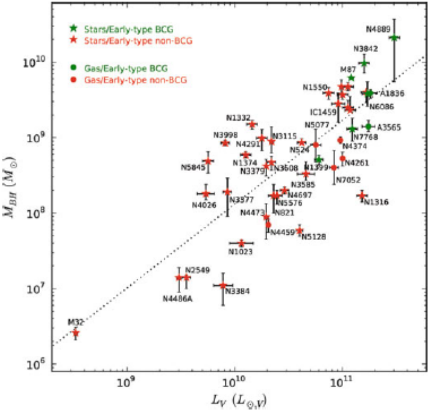

Figure 8: $M_\bullet$ as a function of optical luminosity of bulge component for early type galaxies with photometry.

Instead of the bulge luminosity, one can also study correlation with the mass of the bulge. Best power-law fit:

$$M_\bullet = 2.9 \cdot 10^8 \left(\frac{M_{bulge}}{10^{11} M_\odot} \right)^{1.05} \quad (7)$$

$$M_\bullet \approx 3 \cdot 10^{-3} M_{bulge} \quad (8)$$

0.3% of baryon mass used to make stellar population in the bulge of these galaxies was transformed into a central black hole.

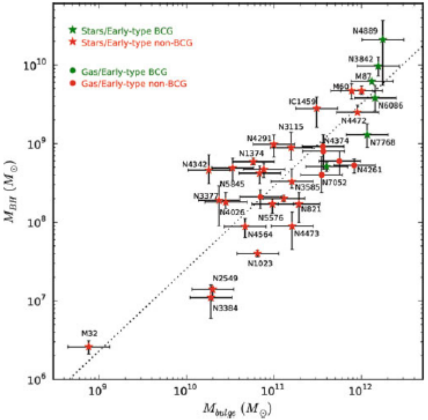

Figure 9: $M_\bullet$ as a function of bulge stellar mass, from dynamical measurements.

Correlation Between SMBH mass and galaxy properties

Fitting early- and late-type galaxies separately, the correlation between $M_\bullet$ and velocity dispersion is:

$$M_\bullet = 2.1 \cdot 10^8 M_\odot \left(\frac{\sigma_v}{200\ km/s}\right)^{5.64} \quad (9)$$

Scatter of this relation is smaller than relations with mass and luminosity about a factor of ~ 2.5. Scatter decreases slightly with increasing σ_v

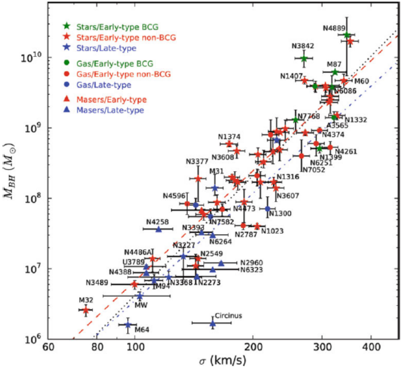

Figure 10: $M_\bullet$ as a function of velocity dispersion of spheroidal component for full sample of 72 galaxies. Source:NJ.McConnel, Revisiting the Scaling Relations of Black Hole Masses and Host Galaxy Properties. ApJ 764,184.

Correlation Between SMBH mass and galaxy properties

In conclusion, galaxies with a bulge component host a supermassive black hole, whose mass is tightly correlated with the properties of the stellar component; in particular, black hole mass amounts to about 0.3% of stellar mass in the bulge component.
(The spheroidal component of a galaxy evolves together with the SMBH)

Referencias

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Thanks for your attention