Galaxies and the Universe

Figures + Tables for Lecture 19 on Tu Apr 15
Figures + Tables for Lecture 20 on Th Apr 17

(Black holes in Galaxies)
Supermassive Black hole at Center of Milky Way
Radio image of the central region of the Milky Way

Wide-Field Radio Image of the Galactic Center
\[ \lambda = 90 \text{ cm} \]
(Kassim, LaRosa, Lazio, & Hyman 1999)

Sgr A* = compact radio source believed to coincide with SMBH in center of the Milky Way

K-band nearinfrared image shows compact star cluster centered on Sgr A*

Fig. 2.34. Left: A VLA wide-field image of the region around the Galactic center, with a large number of sources identified. Upper right: a 20 cm continuum VLA image of Sgr A East, where the red dot marks Sgr A*. Center right: Sgr A West, as seen in a 6-cm continuum VLA image. Lower right: the circumnuclear ring in HCN line emission

(Credit: EAC)
Fig. 2.35. Mosaic of X-ray images of the Galactic center, taken by the Chandra satellite. The image covers an area of about 130 pc $\times$ 300 pc ($48' \times 120'$). The actual GC, in which a supermassive black hole is suspected to reside, is located in the white region near the center of the image. Furthermore, on this image hundreds of white dwarfs, neutron stars, and black holes are visible that radiate in the X-ray regime due to accretion phenomena (accreting X-ray binaries). Colors code the photon energy, from low energy (red) to high energy (blue). The diffuse emission, predominantly red in this image, originates in diffuse hot gas with a temperature of about $T \sim 10^7$ K.
Infrared image of Galactic Center

NIR image shows a compact stellar cluster, centered on Sgr A* radio source.

Keck observations with adaptive optics were taken over 15 years to map out complete orbits of individual stars in the cluster.
Map Proper Motion and Orbits of Stars around Sgr A*

Fig. 2.37. At left, the orbit of the star S2 around Sgr A* is shown as determined by two different observing campaigns. The position of Sgr A* is indicated by the black circled cross. The individual points along the orbit are identified by the epoch of the observation. The right-hand image shows the orbits of some other stars for which accelerations have already been measured.

(Credit: EAC)
Supermassive Black Hole at center of Milky way

Estimated mass: ~ 3.6 million solar masses!
Supermassive Black Hole at center of Milky way

Fig. 2.38. Determination of the mass $M(r)$ within a radius $r$ from Sgr A*, as measured by the radial velocities and proper motions of stars in the central cluster. Mass estimates obtained from individual stars (S14, S2, S12) are given by the points with error bars for small $r$. The other data points were derived from the kinematic analysis of the observed proper motions of the stars, where different methods have been applied. As can be seen, these methods produce results that are mutually compatible, so that the mass profile plotted here can be regarded to be robust. The solid curve is the best-fit model, representing a point mass of $2.9 \times 10^6 M_\odot$ plus a star cluster with a central density of $3.6 \times 10^6 M_\odot/pc^3$ (the mass profile of this star cluster is indicated by the dash-dotted curve). The dashed curve shows the mass profile of a hypothetical cluster with a very steep profile, $n \propto r^{-5}$, and a central density of $2.2 \times 10^{17} M_\odot pc^{-3}$.
Supermassive Black Holes in External Galaxies
**Supermassive Black Holes in External Galaxies**

Fig. 3.24. An HST image of the nucleus of the galaxy M84 is shown in the left-hand panel. M84 is a member of the Virgo Cluster, about 15 Mpc away from us. The small rectangle depicts the position of the slit used by the STIS (Space Telescope Imaging Spectrograph) instrument on-board the HST to obtain a spectrum of the central region. This long-slit spectrum is shown in the right-hand panel; the position along the slit is plotted vertically, the wavelength of the light horizontally, also illustrated by colors. Near the center of the galaxy the wavelength suddenly changes because the rotational velocity steeply increases inwards and then changes sign on the other side of the center. This shows the Kepler rotation in the central gravitational field of a SMBH, whose mass can be estimated as $M_* \sim 3 \times 10^8 M_\odot$.

(Credit: EAC)
Supermassive Black Holes in External Galaxies

Fig. 3.26. M87 has long been one of the most promising candidates for harboring an SMBH in its center. In this figure, the position of the slit is shown superimposed on an Hα image of the galaxy (lower left) together with the spectrum of the [OII] line along this slit (bottom, center), and six spectra corresponding to six different positions along the slit, separated by 0.14 arcseconds each (lower right). In the upper right panel the rotation curve extracted from the data using a kinematical model is displayed. These results show that a central mass concentration with $\sim 3 \times 10^9 M_\odot$ must be present, confined to a region less than 3 pc across – indeed leaving basically no alternative but a SMBH.
Supermassive Black Holes in External Galaxies

Fig. 3.27. The Seyfert galaxy NGC 4258 contains an accretion disk in its center in which several water masers are embedded. In the top image, an artist’s impression of the hidden disk and the jet is displayed, together with the line spectrum of the maser sources. Their positions (center image) and velocities have been mapped by VLBI observations. From these measurements, the Kepler law for rotation in the gravitational field of a point mass of $M_\bullet = 25 \times 10^6 M_\odot$ in the center of this galaxy was verified. The best-fitting model of the central disk is also plotted. The bottom image is a 20-cm map showing the large-scale radio structure of the Seyfert galaxy.

(Credit: EAC)
Fueling the Central BH: The Angular Momentum Problem

Before gas in the outer disk at a radius $R$ of $\sim 5$ kpc can feed a black hole, its specific angular momentum $L$ must be lowered by a factor of $10^5$. Interactions or mergers can help at least partly.

(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)
Mass accretion rate to power high and low luminosity AGN

Table 1. Typical $L_{\text{bol}}$ and $\dot{M}_{\text{bh}}$ for QSOs and local AGN

<table>
<thead>
<tr>
<th>Type of AGN</th>
<th>$L_{\text{bol}}^a$ (ergs s$^{-1}$)</th>
<th>Typical $L_{\text{bol}}$ (ergs s$^{-1}$)</th>
<th>Typical $\dot{M}<em>{\text{bh}}^b$ (M$</em>\odot$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QSOs</td>
<td>$10^{46}$–$10^{48}$</td>
<td>$10^{47}$–$10^{48}$</td>
<td>10–100</td>
</tr>
<tr>
<td>Seyferts</td>
<td>$10^{40}$–$10^{45}$</td>
<td>$10^{43}$–$10^{44}$</td>
<td>$10^{-3}$–$10^{-2}$</td>
</tr>
<tr>
<td>LINERs</td>
<td>$10^{39}$–$10^{43.5}$</td>
<td>$10^{41}$–$10^{42}$</td>
<td>$10^{-5}$–$10^{-4}$</td>
</tr>
</tbody>
</table>

Notes to Table – a. The full range in bolometric luminosity ($L_{\text{bol}}$) for Seyfert and LINERS is taken from Ho, Filippenko, & Sargent 1997a, while for QSOs different sources in the literature are used; b. The typical $\dot{M}_{\text{bh}}$ in column (4) is derived from the typical $L_{\text{bol}}$ in column (3) assuming a standard radiative efficiency $\epsilon \sim 0.1$

(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)
Correlation between BH mass and Bulge velocity dispersion

Fig. 1. Correlation between central BH mass and circumnuclear velocity dispersion — Black hole mass versus bulge luminosity (left) and the luminosity-weighted aperture dispersion within the effective radius (right). Green squares denote galaxies with maser detections, red triangles are from gas kinematics, and blue circles are from stellar kinematics. Solid and dotted lines are the best-fit correlations and their 68\% confidence bands. (From Gehhardt et al. 2000)

(Fig from Gehhardt et al 2000)
**Why do galaxies obey the BH Mass-Bulge $\sigma$ relation?**

1. Gravity of BH does not affect bulge: $R_g \gg R_{\text{bulge}}$

2. But BH does impact bulge in terms of energy!

   Energy $E_{BH}$ generated by mass accretion onto BH $\gg$ Binding energy of bulge  
   (See in class calculations)

   even if a few % of $E_{BH}$ is injected into bulge it can cause bulge to dissolve!  
   a bulge of given velocity dispersion can only survive if mass of BH $< \text{some limit}$

3. Major mergers may cause concurrent growth of BH and some types of bulges  
   called classical bulges … see next slides
Growth of Classical Bulge and Central BH via major merger

- Classical bulge defined as a bulge with a de Vaucouleurs $R^{1/4}$ surface brightness profile and low $v/\sigma$

- Believed to form main via major merger of two disks. During the merger
  - Gas is compressed to high density and converted to stars
  - Violent relaxation acts on stars and redistributes them into a classical bulge

Torques drive gas to low radii, causing BH to grow

Feedback: AGN jet heat/expel gas
Feedback from Black Holes quench SF and BH growth

Di Matteo et al 2005

Show merger of two spiral galaxies that host central supermassive black holes. Only the gas distribution is shown. Brightness represents gas density. Color hue shows gas temperature. Gas inflows feed central SF and BH until energy generated by mass accretion onto BH heat/expel gas, quenching both SF and BH growth
But... the synchronous growth of BH and bulges via major mergers cannot fully explain the relationship between BH Mass—Bulge $\sigma$ as not all bulges on this relation are classical bulges. Some are disky or boxy bulges: these do not grow via major mergers but via mechanisms that cannot efficiently cause the BH to grow. Should disky and boxy bulges have a different BH-bulge relation compared to classical bulges?

Fig. 1. Correlation between central BH mass and circumnuclear velocity dispersion — Black hole mass versus bulge luminosity (left) and the luminosity-weighted aperture dispersion within the effective radius (right). Green squares denote galaxies with maser detections, red triangles are from gas kinematics, and blue circles are from stellar kinematics. Solid and dotted lines are the best-fit correlations and their 68% confidence bands. (From Gebhardt et al. 2000)
**Disky bulges (pseudobulges)**

*Disky bulges* are stellar components that lie in the inner kpc of galaxies, have a high $v/\sigma$, and a surface brightness profile that is often exponential.

Believed to form when bars or minor mergers drive gas into inner kpc gas settled into a disk and forms stars get central stellar disks of high $v/\sigma$ in central kpc, called pseudobulge.
Boxy “bulges” are thickened bars viewed edge-on

- Buckling instability and vertical resonances (ILRs) in a bar cause it to thicken.
- If this bar is viewed in an edge-on galaxy, it appears as a peanut or boxy bulge.
- Milky Way has boxy bulge

Recurrent Buckling of Galactic Bars

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University of Kentucky, USA

Isaac Shlosman
University of Kentucky, USA

&
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Martinez-Valpuesta, Shlosman, & Heller 2005