Supermassive Black Holes and the Evolution of Galaxies

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In the beginning...
Simulated dark-matter distribution today

Intensity indicates surface density,

color indicates velocity dispersion.
Simulated galaxy light distribution today

Intensity indicates surface brightness,
color indicates light color.
What is wrong with simple DM collapse?

1) There are no $10^{14} \, M_{\odot}$ galaxies
2) The biggest galaxies are “red and dead”
Feedback from supermassive black holes: 
1. Radiative mode

Galaxy binding energy: \[ E_{\text{gal}} \sim M_{\text{gal}} \sigma^2 \]
Energy released by black hole: \[ E_{\text{bh}} \sim 0.1 M_{\text{bh}} c^2 \]

If \( \sigma \sim 10^{-3} c \) and \( M_{\text{gal}} \sim 10^3 M_{\text{bh}} \), then \( E_{\text{bh}} \sim 10^2 E_{\text{gal}} \)

Eddington’s luminosity limit: radiation force on surrounding ionized gas cannot exceed gravity.

\[ \frac{L_{\text{Edd}}}{L_\odot} \sim 3 \times 10^4 \frac{M_{\text{bh}}}{M_\odot} \]

Dusty galaxy luminosity limit: \( L_{\text{gal}} \sim 500 L_{\text{Edd}} \) for typical dust/gas ratio can limit \( M_{\text{bh}} \leq M_{\text{gal}} / 500 \), retard growth of \( M_{\text{gal}} \) and star formation.
Feedback from supermassive black holes: 
II. Kinetic mode

Radio jets can inject $E_{\text{kin}} \sim 10^{61}$ ergs of kinetic energy into the intracluster gas in clusters of galaxies, retarding the growth of the most massive galaxies in the centers of clusters of galaxies.
How to weigh a black hole

\[ M = \frac{R \, v^2}{G} \] is total enclosed mass

\[ R = \theta \, D \quad \theta \text{ from VLBA, } \quad D = \text{Hubble distance} \]

\[ v = \frac{v_r}{\sin i} \quad v_r = \text{Doppler velocity, } \quad i = \text{inclination} \]
\[ \lambda = 1.3 \text{ cm imaging with HSA = GBT + VLBA} \]

Resolution: \[ \frac{\lambda}{D} \approx 0.0003 \text{ arcsec} \]

Relative astrometric accuracy:
\[ > 0.000002 \text{ arcsec} \approx 10^{-11} \text{ radians} \]
UGC 3789
D ~ 50 Mpc

Zoom 300,000 x

$\theta_y$ (mas)

$\theta_x$ (mas)

UGC 3789

VLBA beam

NRAO

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$D_A \sim 50 \text{ Mpc}$ so
$0.1 \text{ mas} \sim 0.024 \text{ pc}$

$M_* = \frac{v^2 \theta}{G} D_A$
$= 1.12 \times 10^7 M_\odot$
$x \left( \frac{D_A}{50 \text{ Mpc}} \right)$
## Accurate SMBH masses

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$R_{\text{maser}}$ (pc)</th>
<th>$M_\bullet / 10^6 M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1194</td>
<td>0.58 – 1.41</td>
<td>66</td>
</tr>
<tr>
<td>NGC 2273</td>
<td>0.03 – 0.08</td>
<td>7.6</td>
</tr>
<tr>
<td>UGC 3789</td>
<td>0.08 – 0.30</td>
<td>11</td>
</tr>
<tr>
<td>NGC 2960</td>
<td>0.05 – 0.30</td>
<td>7.5</td>
</tr>
<tr>
<td>NGC 4388</td>
<td>0.24 – 0.29</td>
<td>8.4</td>
</tr>
<tr>
<td>NGC 6264</td>
<td>0.23 – 0.78</td>
<td>25</td>
</tr>
<tr>
<td>NGC 6323</td>
<td>0.11 – 0.29</td>
<td>10</td>
</tr>
</tbody>
</table>

SMBH masses in Seyfert galaxies lie below the line defined by SMBH’s in elliptical galaxies
Real SMBH or just a dense star cluster?

\[ \rho = \rho_0 (1 + r^2/a^2)^{-5/2} \]

\[ a < 0.02 \text{ pc} \]

\[ \rho_0 \geq 4 \times 10^{11} \, M_\odot \, \text{pc}^{-3} \]

\[ N_* \geq 10^8 \]

\[ M_* < 0.08 \, M_\odot \]

\[ \tau \leq 2 \times 10^6 \text{ yr} \]
Most large galaxies contain SMBHs. What happens when they merge?
Inspiraling, Binary, and Recoiling SMBHs

- Dynamical friction inspiraling time scale
  \[ \tau_{\text{df}} \sim 1.7 r^2 \sigma_v / (Gm^2 \ln \Lambda) \]
  where \( r = \) distance to galaxy center, \( \sigma_v = \) rms stellar velocity dispersion, \( m = \) black hole mass, and \( \ln \Lambda \sim 5 \) is the Coulomb logarithm.
  For \( r = 1 \) kpc, \( \sigma_v = 200 \) km/s, and \( m = 10^8 M_\odot \), \( \tau_{\text{df}} \sim 10^8 \) years

- Binary SMBH maximum orbit diameter
  \[ d_b = 3 G (m_1 + m_2) / \sigma_v^2 \]
  where \( m_1 \) and \( m_2 \) are the black hole masses.
  For \( m_1 = m_2 = 10^8 M_\odot \), \( d_b \sim 10^2 \) pc
Inspiraling, Binary, and Recoiling SMBHs

The “last parsec problem”

- Binary SMBH “stalling” orbit diameter
  \[ d_s \sim 0.2 \, d_b \left( \frac{m_1}{m_2} \right) / (1 + \frac{m_1}{m_2})^2 \]
  For \( m_1 = m_2 = 10^8 \, M_\odot \), \( d_s \sim 10 \, \text{pc} \)

- Binary orbit diameter for gravitational coalescence within Hubble time
  \[ d_g = 8 \left[ H_0^{-1} \, G^3 \, (m_1 m_2)^3 \, (m_1 + m_2)^3 / (5 c^5) \right]^{1/4} \]
  where \( H_0^{-1} = 13.6 \, \text{Gyr} \).
  For \( m_1 = m_2 = 10^8 \, M_\odot \), \( d_g \sim 0.2 \, \text{pc} \)
How can we find them?

Make a high-resolution 8.6 GHz VLBA search for off-nuclear and binary SMBHs in a complete sample of $\sim 10^3$ nearby ($<D_A> \sim 200$ Mpc) massive galaxy bulges to:

(1) discover off-nuclear inspiraling SMBHs predicted by the “merger tree” theory for massive galaxy evolution
(2) resolve “stalled” binary SMBHs in tight ($d \sim 10$ pc) orbits
(3) discover off-nuclear recoiling SMBHs kicked out by the strong anisotropic gravitational radiation sought by LISA and NANOgrav
(4) discover currently active nearby SMBHs (no dust bias)
Nearby galaxy sample

2MASS $K_{20fe} < 12.25$
NVSS $S_{1.4} > 100$ mJy
$\delta \geq -40^\circ$, $|b| \geq 5^\circ$
$N = 923$ galaxies

$<D_A> \sim 200$ Mpc so
1 mas $\sim 1$ pc
$<L_{1.4} > \sim 10^{24}$ W Hz$^{-1}$
$> 90\%$ are radio-loud AGN
The VLBA observations

Fig. 3.—Top: Example of BC 191 X-band CLEAN images for three objects of different parsec-scale morphology. The image of 1801+007 was reconstructed from two scans observed within two separate segments from August 3 and 21, 2010. Dynamic range of the image is greater than 100:1.

Bottom: Correlated flux density versus projected spacings corresponding to the images shown on top.

Fig. 4.—SDSS image of a promising candidate for an off-set black hole in the highest cluster galaxy Zw 8193 (J1717+4226) with VLBA-2MASS offset of 2.4″. The radio source lies north of the SDSS and 2MASS position.
First results

![Graph showing distribution of offsets in RA and DEC with a concentration of points in the center.]
Summary

Black holes regulate the growth and evolution of galaxies.

Accurate masses of black holes in disk galaxies were measured via classical physics and modern technology.

They fall below the linear black hole/bulge mass relation for massive elliptical galaxies, as expected.

The maser galaxies contain supermassive black holes, not just dense star clusters.

Galaxy mergers yield inspiraling, binary, and recoiling black holes that may be detectable in current surveys.