Black Hole
Demographics:
Observations, Theory and Extrapolation to Intermediate-Mass

Roeland van der Marel
Active Galaxies

Some galaxies show active phenomena in their centers:

- radio emission
- X-rays / gamma-rays
- Jets of material
- Superluminal motion
- Broad emission lines
- ...

→ Supermassive black holes (BHs) ($\sim 10^6$-$10^9 \ M_\odot$)
Quiescent Galaxies

☆ Quasar and Active Galaxy Population Statistics as function of redshift

⇒ many normal galaxies were active in the past

⇒ BHs common in quiescent galaxies

[Fan et al. 2001]
BH Detections and Mass Measurements

☆ A BH reveals itself through the gravitational pull it exerts on surrounding material.
☆ Close to a black hole material will move rapidly
  ☆ Kepler: $V^2 \sim GM/r$
☆ Detection: Massive Dark Object (MDO)
☆ If an MDO can be demonstrated to be very small $\Rightarrow$ density must be enormous $\Rightarrow$ assumed to be a BH
Dynamical Tracers and Complications

☆ Stars:
☆ Pro: Available in all galaxies; motions completely gravitational.

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Hubble Space Telescope

WITHOUT BLACK HOLE     WITH BLACK HOLE
The Milky Way Galaxy Center

Near-infrared images show **proper motions** of stars that move rapidly around a central black hole (Sgr A*) with $M_{BH} = 3 \times 10^6 M_\odot$

[Ghez et al.]
Dynamical Interpretation of Stellar Motions

🌟 Stars:

🌟 **Con**: Interpretation often complicated, because generally only projected motions are observed, and the 3D orbital structure is unknown

🌟 Various codes exist to do the necessary modeling, but discussion continue about interpretation and error analysis
Dynamical Tracers and Complications

✈ Gas:

✈ Pro: Rapid gas motions observed in many AGN (narrow-line regions and broad-line regions).

✈ Con: Interpretation often complicated, because hydrodynamical forces, outflow, inflow, etc. may be as important as gravity.

[Bower, Green, et al.]
BH Masses From Gas Kinematics

Rotating **nuclear gas disks** in (active) galaxy centers:

- Water maser disks (VLBI)
- Optical emission-line gas disks

[NGC 4258]

[NGC 7052]
BH Masses From Gas Kinematics

BLR reverberation mapping  X-ray iron K emission lines

[Welsh et al.]  [Reynolds]
Black Hole Demographics

☆ BH mass relation to
☆ galaxy properties? (do all galaxies have BHs?)
☆ galaxy activity and quasar statistics?
☆ galaxy formation and galaxy interactions?
Back-of-the-Envelope Demographics

☆ Insights from some well-studied galaxies:

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Type</th>
<th>$M_{\text{gal}}$ ($\log_{10}$)</th>
<th>$M_{\text{BH}}$ ($\log_{10}$)</th>
<th>$M_{\text{bulge}}$ ($\log_{10}$)</th>
<th>$\frac{M_{\text{BH}}}{M_{\text{gal}}}$ ($\log_{10}$)</th>
<th>$\frac{M_{\text{BH}}}{M_{\text{bulge}}}$ ($\log_{10}$)</th>
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<td>NGC 4258</td>
<td>Sbc</td>
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<td>7.6</td>
<td>10.0</td>
<td>-3.5</td>
<td>-2.4</td>
</tr>
</tbody>
</table>
Back-of-the-Envelope Demographics

☆ Faber-Jackson : $L_{\text{bul}} \propto \sigma^{3.5}$

Π Fundamental Plane : $M_{\text{bul}}/L_{\text{bul}} \propto L_{\text{bul}}^{0.2}$

$\Rightarrow M_{\text{bul}} \propto \sigma^{4.2}$

Π BH Demographics : $M_{\text{BH}} \propto M_{\text{bul}}$

$\Rightarrow M_{\text{BH}} \propto \sigma^{4.2}$
$M_{\text{BH}} - \sigma$ relation

- ~30 trustworthy MBH determinations
- Good correlation with $\sigma$
- Scatter $\sim 0.3$ dex
- Slope $= 4.0 \pm 0.3$ (but lots of discussion about the exact value; Gebhardt et al., Ferrarese & Merritt, etc.)

[Tremaine et al., 2002]
$M_{BH} - M_{bul}$ relation

- Long history, e.g.,
  - Kormendy & Richstone (1995)
  - Magorrian et al. (1998)
- Recent work
- Scatter $\sim 0.3$ dex
  - similar as $M_{BH} - \sigma$ relation!
- Slope = $1.0 \pm 0.1$
- Correlation with $L_{bul}$ not much worse ...

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[Marconi & Hunt 2003]
$M_{BH} - M_{DM}$ relation

- **Demographics**: $M_{BH} \propto \sigma^{4.0}$
- **Bulges**: $\sigma \propto V_{circ}^{1.2}$
- **Assume**: $V_{circ} \sim V_{vir}$
- **Cosmology**: $M_{DM} \propto V_{circ}^{3}$

$\Rightarrow M_{BH} \propto M_{DM}^{1.6}$

[Ferrarese 2002]
\( M_{\text{BH}} \) – concentration relation

\( M_{\text{BH}} \) also correlates with a measure of galaxy light concentration (Graham et al. 2001)

\( \text{Scatter} \sim 0.3 \text{ dex} \)

also similar as \( M_{\text{BH}} - \sigma \) relation ...

[Graham et al. 2001]
Comparison of BH Demographics Relations

☆ What fundamentally drives $M_{\text{BH}}$?
☆ At present there is little reason to consider any of the relations more “fundamental” than the others

☆ Important for extrapolations, e.g,
☆ $M_{\text{BH}}$ driven by $\sigma$: globular clusters could have IMBHs
☆ $M_{\text{BH}}$ driven by $M_{\text{DM}}$: globular clusters may not have IMBHs

☆ $M_{\text{BH}} - \sigma$ is popular because
☆ $\Pi \sigma$ is a directly observed quantity (and emission line width can be used as a proxy)
☆ $\sigma$ can be theoretically related to dark halo properties ($M_{\text{gal}}, L_{\text{gal}},$ and light concentration relate to)
Evolution of the $M_{BH} - \sigma$ relation for AGNs

★ **BLR:** $M_{BH} \sim V^2 R / G$
  ★ $V$: line-width(BLR)
  ★ $R$: reverberation mapping, photoionization modeling
  $R \propto L_{\text{cont}}^{0.5}$

★ **NLR:** $\sigma \propto \text{FWHM}[\text{OIII}]$

Π **Shields et al. (2003):** no sign of evolution with redshift ($z < 3$)
The Link between Nearby Galaxies and Distant AGN

« Integral over $M_{BH} - \sigma$ relation $\Rightarrow$
Local BHs: $\rho \sim 3 \times 10^5 \, M_\odot \, \text{Mpc}^{-3}$

↷ Energy density in QSO radiation + assumed accretion efficiency $\sim 0.1 \Rightarrow$
Integrated luminous QSO accretion:
$\rho \sim 2 \times 10^5 \, M_\odot \, \text{Mpc}^{-3}$

↷ X-ray background + corrections $\Rightarrow$
Integrated obscured accretion:
$\rho \sim 2 \times 10^5 \, M_\odot \, \text{Mpc}^{-3}$

↷ All BHs (more-or-less) accounted for ....
The Questions of BH Formation

How is a BH formed initially?

A small seed BH is formed originally

From Population III evolution
[Madau & Rees; Volonteri et al.; Schneider et al; Islam et al.]

From Evolution of a dense star cluster
[Quinlan & Shapiro; Lee; Portegies Zwart & McMillan; Baumgarth et al; Gurkan et al]

A massive BH is formed by direct collapse of a gas cloud
H2 cooling must be suppressed

Rees (1984)
The Questions of BH Formation

☆ When is a BH formed initially?
  ☆ Before galaxy/bulge formation
  ☆ During galaxy/bulge formation
    [Adams et al.]
  ☆ After galaxy/bulge formation

☆ When do BHs gain their mass?
  ☆ Early on
  ☆ Intermittent over time (e.g., during mergers)
  ☆ Slowly over time (e.g., adiabatic growth)
The Questions of BH Formation

☆ What do BHs accrete to grow in mass?

☆ **Gas** [Kauffmann & Haehnelt; Di Matteo et al; Bromley et al]

☆ **Stars** [Zhao et al]

☆ **BHs** [Volonteri et al.; Schneider et al; Islam et al.; Hughes & Blandford]

☆ **Dark Matter** [Ostriker]
The Questions of BH Formation

☆ How does galaxy merging affect the BHs?

☆ Trigger accretion/activity
  [Kauffmann & Haehnelt; Di Matteo et al; Bromley et al]

☆ Changes both galaxy and BH properties

☆ Merging timescale

☆ Slingshot ejection

☆ Gravitational Wave Recoil

[NGC 6240]
The Questions of BH Formation

☆ What mechanism regulates BH mass/growth?

☆ Availability of material to accrete

☆ Feedback/Self-Regulation

☆ Competition between star formation and BH growth
  [Burkert & Silk]

☆ Accretion limited by mechanical feedback
  [Silk & Rees; King]

☆ Accretion limited by heating due to the BH
  [Ciotti & Ostriker]
Comparison of Models to BH Demographics

 Scaling arguments in many models give $M_{BH} \propto \sigma^k$ (k~4)

 Cosmologically motivated (semi-analytical) models fit $M_{BH} \propto \sigma^4$ and many other observations, but require fine-tuning of ad-hoc assumptions

 Our improved understanding of BH demographics hasn’t really reduced the number of plausible scenarios.

 [Haehnelt & Kauffmann 2000]
Are there IMBHs in Galaxy Centers?

- BHs detected so far in
  - Hot stellar systems
    - With $\sigma > 70$ km/s
- Do all galaxies have BHs?
- Do intermediate-mass BHs (IMBHs) exist in galaxy centers with $\sigma < 50$ km/s?
Does Theory suggest a Minimum $M_{\text{BH}}$?

☆ Most models make no definitive statement about this

☆ Models that address this face difficulties for low-mass galaxies
  ☆ Star formation and feedback critically important
  ☆ High-redshift physics critical
  ☆ Cosmological simulations lack resolution

☆ If supermassive BH formation involves growth from seeds $< 10^6 \, M_\odot$, it is easy to imagine that some BHs may not have had the opportunity to grow supermassive

→ Observational study of late-type galaxies needed
Central Structure of Late Type Spiral Galaxies

- Late-type galaxies (Sc-Sd) generally host a nuclear star cluster
  - HST imaging (Boeker et al)
    - in 75% of a large sample
    - Barely resolved (<0.1")
  - VLT spectroscopy (Walcher et al)
    - Age ~ $10^{8-9}$ years
    - $M \sim M_\odot$

[Boeker et al. 2002]
Central Structure of Dwarf Elliptical (dE) Galaxies

- dEs brighter than $M_V = -16$ generally host a **nuclear star cluster** ("nucleated")
  - Keck spectroscopy (Geha et al)
    - Age $\sim 5$ Gyrs
    - $M \sim 10^6 M_\odot$
  - dEs may have formed from harassment of late-type spirals

$\Rightarrow$ **Evolutionary Connection?**
Relation of Nuclear Clusters to Other Hot Stellar Systems

In **Fundamental-Plane space**, nuclear star clusters are most similar to Globular Clusters; they have similar size, but are more massive and denser.

\[ M/L \sim I^3 \]
Some very late-type galaxies are active, e.g., NGC 4395 (Sm), POX52 (dE)

- BH mass estimated at $M_{\text{BH}} \sim 10^5 M_\odot$
- Both galaxies have a nuclear star cluster

Questions:

- How typical are these galaxies?
- Did the BH form because of the galaxy potential well? or
- Did the BH form because there is a cluster? and if so
- Do such BHs also form/exist in isolated star clusters?
Stellar Kinematical BH studies in Late-Type Galaxies

☆ Stellar kinematics: only $M_{BH}$ upper limits
  - Irregulars ?? Dwarf Spheroidals ??
  - Dwarf Ellipticals (Geha, Guhathakurta & vdM)
    \[ \pi \sigma = 20-50 \text{ km/s}; \ M_{BH} < 10^7 \ M_\odot \]
  - Late-Type spirals (IC 342 Boeker, vdM & Vacca)
    \[ \pi \sigma = 33 \text{ km/s}; \ M_{BH} < 10^{5.7} \ M_\odot \]

☑ Interesting BH limits/detections:
  - Requires spatial resolution of cluster
  - Restricted to HST data for Local Group galaxies
Case Study: IC 342

\[ \pi \sigma = 33 \text{ km/s} \Rightarrow M_{\text{BH}} < 10^{5.7} M_\odot \text{ (upper limit)}. \]
M33

- Nucleus/star cluster dominates central few arcsec

HST/STIS:

- Gebhardt et al., Merritt et al.
- $\sigma = 24$ km/s
- $M_{\text{BH}} < 1500-3000 M_\odot$ (upper limit)
IMBHs in Globular Clusters?

- Studies of Globular Cluster kinematics are probing an interesting mass range
- Controversial results/upper limits
  - G1
  - M15
- Interestingly, consistent with $M_{\text{BH}} - \sigma$ relation...
Conclusions:

- BH demographics well mapped for supermassive BHs

- $M_{BH} \propto M_{bul} \propto \sigma^4$ can be explained by many scenarios

- BH studies in late-type galaxies are emerging; IMBHs exist there but may not be ubiquitous

- There may be a continuum in central structure from early-type galaxies to late-type galaxies to Globular Clusters