A model for the black hole mass and halo mass correlation

Course 689 Final Presentation
by Yan Shi
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Second part presentation.
First part Nov 5, 2009.
The $M_{\text{SMBH}} - M_{\text{tot}}$ relation is verified by two independent methods.

Ferrarese: Circular velocity at flat rotation curve

Bandara: Gravitational lensing
How does the entire galaxy know what is the mass of the SMBH at the center?
An Engineer’s view: Servo loop

• **If there is no initial relation** between $M_{SMBH}$ and $M_{tot}$, to build the universal $M_{SMBH} - M_{tot}$ relation there needs to be
  – Communications (between SMBH and rest of the system)
  – Feedback (able to add or reduce mass from the SMBH)
• There is no efficient way to remove matter from a BH. The servo loop idea does not work.

The $M_{SMBH} - M_{tot}$ relation must be set at the early stage of a galaxy.
Universal DM Halo Density Profile

• Gravitational force is scale invariant

→ Universal mass density profile (NFW)

\[ \rho (r) \propto \frac{1}{\left(\frac{r}{r_s}\right)(1 + \frac{r}{r_s})^2} \]

with a scale length \( r_s \) determined by the total mass \( M_{\text{tot}} \) (or \( r_s \propto \sqrt{M_{\text{tot}}} \)).

The Newtonian force \( F \propto \frac{M}{r^2} \) is scale invariant.
Unique property of Universal Profile

- The ratio of the mass inside the same scaled length to the total mass is the same for different mass DM halos.

\[
\frac{m(< r_{\text{scaled}})}{m_{\text{tot}}} = \frac{M(< r_{\text{scaled}})}{M_{\text{tot}}}
\]

Universal relation for \( M( r_{\text{scaled}} ) \) to \( M_{\text{tot}} \) ratio.
SMBH at the DM halo Center

- If there is a black hole at the center, it can be viewed as a delta density function at $r = 0$.
  \[
  \rho(r) \propto \delta(r), \text{ for } |r| \ll r_s,
  \]
  or
  \[
  \rho(r) = \frac{M_{SMBH}}{r} (r).
  \]

- In order to meet the universal profile condition,
  \[
  M_{SMBH} \propto M_{tot}.
  \]

A BH behaves similarly to weakly interacting dark matter particles. It will Virialize with dark matter particles.
How Does a SMBH Develop at the center?

• At the early universe, the primordial gas was first able to cool and collapse into dark matter mini-halos.
• The first stars were very massive (~ 100 M\(_\odot\)), owing to the limited cooling properties of primordial gas.
• After the main sequence lifetime, the first stars collapsed to BH’s.

The mini-halos with BH’s (collapased from the first stars) are the initial building blocks of galaxies.
How Does a SMBH Develop at the center?
(continued)

• DM halos form hierarchically. Small halos form first and merge into bigger halos.
• Larger number of identical building blocks merge and form into a galaxy. They provide seed black holes to coalesce into a single, massive black hole in the center of the galaxy.

The mass of the SMBH at the center is always proportional to $M_{\text{tot}}$. 
Building Block $M_{BH}$ to $M_{Halo}$ ratio

- In a CDM flat cosmology, primordial gas with $M_b \sim 10^6 \, M_\odot$ would be collapsing from $3-\sigma$ fluctuations.\(^1\)
- Assuming only one black hole of mass $m_\bullet \sim 100 \, M_\odot$ in each mini-halo\(^1\),

$$
\frac{M_{BH}}{M_{Halo}} = \frac{m_\bullet}{(M_b + M_{DM})} \sim 1.5 \times 10^{-5}
$$

$$(M_b : M_{DM} = 15\% : 85\%)$$

$$
\frac{M_{SMBH}}{M_{tot}} \sim 5 \times 10^{-5} \quad \text{(Bandara, Ferrarese)}
$$

Note 1: Johnson et al 2008, Spolyar et al 2009

The building block $M_{BH}$ to $M_{Halo}$ ratio is the same order of magnitude as the observed $M_{SMBH}$ to $M_{tot}$ ratio.
Summary

• The massive first stars collapsed into BH’s at the early universe.
• The BH’s behave similarly to weakly interacting DM particles.
• They virialize with DM particles and sink to the center of the DM halo to form a massive BH.
• The peak of BH’s merging activity leads to the quasar stage of a galaxy (z = 2 ~ 4).
• The gas accreted by the SMBH at late stages (z<1) is insignificant (< 5% in mass)*.

* Stated as “radio mode” in Croton, 2006
Presented by Sharon on Nov 12, 2009
The $M_{SMBH}$ and $M_{tot}$ correlation is probably established by the building blocks (mini-halos with first star BH's) at the early universe.
Further Question

How does the $M_{SMBH}$ to $M_{tot}$ ratio evolve with time according to this model?

Increase? decrease? or remain constant?