Revealing Massive Black Holes in Dwarf Galaxies with X-rays

Amy Reines
Einstein Fellow at NRAO           Hubble Fellow at Univ. of Michigan
The importance of supermassive black holes (SMBHs)

- SMBHs are fundamental components of today’s massive galaxies

\[ M_{BH} \sim 1.4 \times 10^8 \, M_{\text{sun}} \]

Bender et al. (2005)
The importance of supermassive black holes (SMBHs)

- SMBHs are fundamental components of today’s massive galaxies
- SMBHs power AGN, which are a source of feedback in galaxies

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NASA/CXC/CfA/R.Kraft et al.
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- SMBHs are thought to play an important role in the evolution of galaxies

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\[ \text{Bulge velocity dispersion (km s}^{-1}\text{)} \]
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\[ \text{Black hole mass (M}_{\text{sun}} \text{)} \]
McConnell & Ma (2013)
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The origin of these SMBHs is far from understood!
**Motivation:** The origin of supermassive black holes

**Directly observing the first BH seeds is currently not feasible**

- High-z galaxies from the sample of Bouwens et al. NOT detected in 4 Ms *Chandra* Deep Field South (individually or stacked) (Willott 2011; Cowie et al. 2012; Treister 2013)

- star-forming, blue, compact galaxies 600-800 Myr after the Big Bang (Bouwens et al. 2010)

- intrinsic sizes < 1 kpc (Oesch et al. 2010)

- masses ~ $10^9$-$10^{10} \, M_{\odot}$ (Labbe et al. 2010)

*Image: HUDF09 WFC3/IR Image with z~7 and z~8 Galaxies* (Credit: NASA, ESA, G. Illingworth, R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team)
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Present-day dwarf galaxies offer another avenue to observationally constrain the origin of supermassive BH seeds

(e.g., masses, host galaxies, and in principle, even the formation mechanism)
Motivation: The origin of supermassive black holes

Observations of high-redshift quasars:

- $M_{\text{BH}}>10^9 \, M_{\odot}$ less than a Gyr after the Big Bang
  (e.g. Fan et al. 2001; Mortlock et al. 2011)

Seeds almost certainly started out with masses considerably in excess of normal stellar-mass BHs
Motivation: The origin of supermassive black holes

Possible seed formation mechanisms
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Possible seed formation mechanisms

Motivation:
The origin of supermassive black holes remnants from Pop III stars

Gas cools very slowly forming a stable disc

First stars: maybe one star per galaxy, up to several hundred times larger than the sun

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

Volonteri 2012, Science
Motivation: The origin of supermassive black holes

Possible seed formation mechanisms

- Remnants from Pop III stars:
  - Gas cools very slowly forming a stable disc
  - Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms

- Direct collapse:
  - First stars: maybe one star per galaxy, up to several hundred times larger than the sun
  - The stellar core collapses into a small black hole, embedded in what is left of the star

- If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun
  - The black hole swallows the envelope growing up to ~one million solar masses

Volonteri 2012, Science
**Motivation:** The origin of supermassive black holes

**Possible seed formation mechanisms**

- **Dark matter**
  - Gas
  - Collisions in dense star clusters
    - Locally unstable gas flows toward the galaxy center
    - Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms
  - Direct collapse
    - Gas cools very slowly forming a stable disc
    - Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms
  - Remnants from Pop III stars
    - First stars: maybe one star per galaxy, up to several hundred times larger than the sun
    - Gas fragments into stars, and a dense star cluster forms
    - The stellar core collapses into a small black hole, embedded in what is left of the star
    - The black hole swallows the envelope growing up to ~one million solar masses
    - If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of the Sun
    - Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

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Volonteri 2012, *Science*
Motivation: The origin of supermassive black holes

Models of black hole growth in a cosmological context

Greene 2012, *Nature Communications*; also see review in Volonteri 2010
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Models of black hole growth in a cosmological context

- Direct collapse
- Remnants of Pop III stars

Greene 2012, *Nature Communications*; also see review in Volonteri 2010
Observationally, very few dwarf galaxies known to host massive black holes
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Until now...
Dwarf galaxies with optical signatures of active massive BHs

Largest sample of dwarfs hosting massive BHs to date

35 AGN
101 Composites

25 broad-line AGN candidates
(with BH mass estimates)

Reines, Greene & Geha 2013
Dwarf galaxies with optical signatures of active massive BHs

Largest sample of dwarfs hosting massive BHs to date

Least-massive black holes known
(median \( M_{BH} \sim 2 \times 10^5 \, M_{\odot} \))

Reines, Greene & Geha 2013
Dwarf galaxies with optical signatures of active massive BHs

Examples of host galaxies

Reines, Greene & Geha 2013
Dwarf galaxies with optical signatures of active massive BHs

~0.5% of dwarfs have **optical signatures** of accreting massive BHs

... but only sensitive to the most actively accreting BHs in galaxies with low SF

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Reines, Greene & Geha 2013
Dwarf galaxies with optical signatures of active massive BHs

\[ 10^7 < M_{\text{stellar}} < 10^{9.5} M_\odot \]

\( \sim 0.5\% \) of dwarfs have \textit{optical signatures} of accreting massive BHs

... but only sensitive to the most actively accreting BHs in galaxies with low SF

Reines, Greene & Geha 2013

\textbf{Need other diagnostics!}
High-resolution X-ray and radio observations

• More sensitive to weakly accreting BHs
• Can pick out AGN in galaxies with lots of star formation (common in dwarfs)
A massive BH in the dwarf starburst galaxy Henize 2-10

Reines et al. 2011, *Nature*

First example of a dwarf starburst galaxy with a massive BH ($\sim 10^6 \, M_{\odot}$)
A massive BH in the dwarf starburst galaxy Henize 2-10

VLBI follow-up with the Long Baseline Array (LBA)

nuclear radio source: \( \leq 3 \times 1 \) pc

HST imaging of central \( \sim 250 \) pc

Reines & Deller 2012
Motivation to look for additional examples of massive BHs in star-forming dwarf galaxies with Chandra and the VLA.
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

SDSS image (RGB=zrg)

$M_\star \sim 1.1 \times 10^9 M_{\odot}$

Mrk 709 N

$M_\star \sim 2.5 \times 10^9 M_{\odot}$

Mrk 709 S

metallicity $\sim 10\%$ solar

Reines et al. 2014

Masegosa et al. (1994)
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

*Chandra* ~ 21 ks

*VLA, A-configuration, C-band* ~ 1 hr on-source
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

SDSS z-band image of Mrk 709 S with position of hard X-ray source and radio contours

Reines et al. 2014
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

\[ L_{(2-7 \text{ keV})} = (5.0 \pm 2.9) \times 10^{40} \text{ erg s}^{-1} \]

(90% confidence interval)

\[ L_{(2-10 \text{ keV})} \sim 9 \times 10^{39} \text{ erg s}^{-1} \]

(3 sigma upper limit)

\[ L_{\text{gal}}^{\text{HX}} = \alpha M_* + \beta \text{SFR} \]

Lehmer et al. (2010)
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

*Chandra* hard (2-7 keV) X-ray image

Expected contribution from X-ray binaries within 3” spectroscopic fiber:

\[ L_{\text{gal}}^{\text{HX}} = \alpha M_* + \beta SFR \]

Lehmer et al. (2010)

\[ L_{(2-10 \text{ keV})} \sim 9 \times 10^{39} \text{ erg s}^{-1} \]

(3 sigma upper limit)

Measured value (within ~1” *Chandra* PSF) is a factor of ~5x higher, suggesting the presence of an AGN

\[ L_{(2-10 \text{ keV})} = (5.0 \pm 2.9) \times 10^{40} \text{ erg s}^{-1} \]

(90% confidence interval)
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

Chandra hard (2-7 keV) X-ray image

Minimum Black Hole Mass:

\[ \frac{M_{\text{BH}}}{M_\odot} \geq \frac{\kappa L_{2-10\text{keV}}}{(1.3 \times 10^{38} \text{ erg s}^{-1})} \]

Assuming BH radiating at Eddington limit and X-ray bolometric correction = 1,

\[ M_{\text{BH}} > 385 \, M_\odot \]

(or >160 \( M_\odot \) at 95% confidence)

\[ L_{(2-10 \text{ keV})} = (5.0 \pm 2.9) \times 10^{40} \text{ erg s}^{-1} \]

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**A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709**

*Chandra* hard (2-7 keV) X-ray image

**Minimum Black Hole Mass:**

\[
\frac{M_{\text{BH}}}{M_\odot} \geq \left( \kappa L_{2-10\text{keV}} \right) / \left( 1.3 \times 10^{38} \text{ erg s}^{-1} \right)
\]

Assuming BH radiating at Eddington limit and X-ray bolometric correction = 1,

\[
M_{\text{BH}} > 385 \, M_\odot
\]

(or >160 \( M_\odot \) at 95% confidence)

BH mass may be orders of magnitude larger

\[
L_{(2-10 \text{ keV})} = (5.0 \pm 2.9) \times 10^{40} \text{ erg s}^{-1}
\]

(90% confidence interval)
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

Central radio source (#2)

$S_{7.4\text{GHz}} \sim 40 \pm 10 \text{ uJy}$
$S_{5.0\text{GHz}} \sim 60 \pm 20 \text{ uJy}$

$L_{\text{radio}} = (1.6 + 0.6) \times 10^{37} \text{ erg s}^{-1}$
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

Merloni et al. 2003

\[ \log L_R (5 \text{ GHz}) \, \text{erg s}^{-1} = 0.60 \log L_X (2-10 \text{ keV}) \, \text{erg s}^{-1} + 0.78 \log M \]

“fundamental plane of black hole activity”

\[ \log L_R = 0.60 \log L_X + 0.78 \log M + 7.33 \]

order-of-magnitude estimate of BH mass: \( M_{BH} \sim 6 \times 10^6 \, \text{M}_\odot \)
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

X-ray luminosity alone suggests a massive BH or super-Eddington accretion onto a stellar-mass BH

If the radio point source emission is also from the accreting BH, a stellar-mass BH is firmly ruled out

Reines et al. 2014
X-ray + radio observations suggest the presence of a massive BH at the center of Mrk 709 S that is hidden at optical wavelengths.

Among the most metal-poor galaxies with evidence for an AGN.

Underscores the power of utilizing Chandra and the VLA to search for massive BHs in low-mass star-forming galaxies that can be missed by optical diagnostics.

Larger-scale surveys are needed to determine how common these objects are, and to ultimately help constrain the BH occupation fraction in dwarfs and the origin of supermassive BH seeds.
Summary

• Dwarf galaxies can help reveal the origin of supermassive BHs

• Found largest sample of massive BHs in dwarf galaxies to date using optical diagnostics (Reines, Greene & Geha 2013)

• Also using X-ray + radio diagnostics to search for BHs in dwarf galaxies: Henize 2-10 (Reines et al. 2011, Reines & Deller 2012), Mrk 709 (Reines et al. 2014)

• Host galaxies have stellar masses comparable to the Magellanic Clouds, a mass regime where very few massive BHs have previously been found

• Future work:
  Follow-up on existing samples, new searches to probe a different parameter space, constrain seed masses, host galaxies, and models for BH seed formation