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

$M_{BH} \sim 1.4 \times 10^8\ M_{sun}$
Bender et al. (2005)

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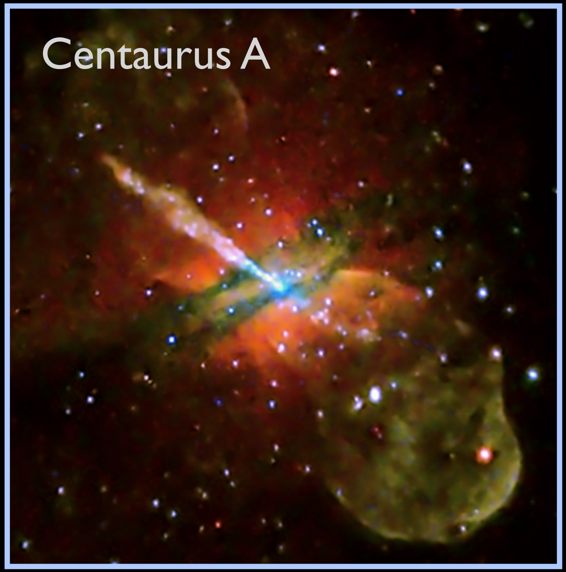

NASA/CXC/CfA/R.Kraft et al.

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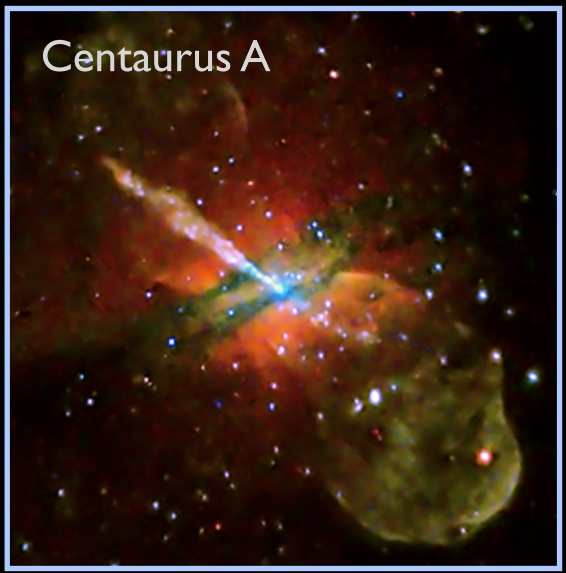

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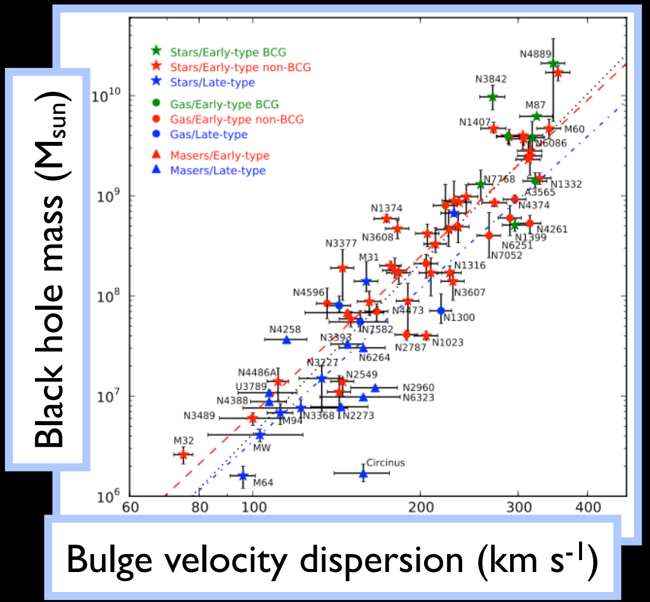

McConnell & Ma (2013)

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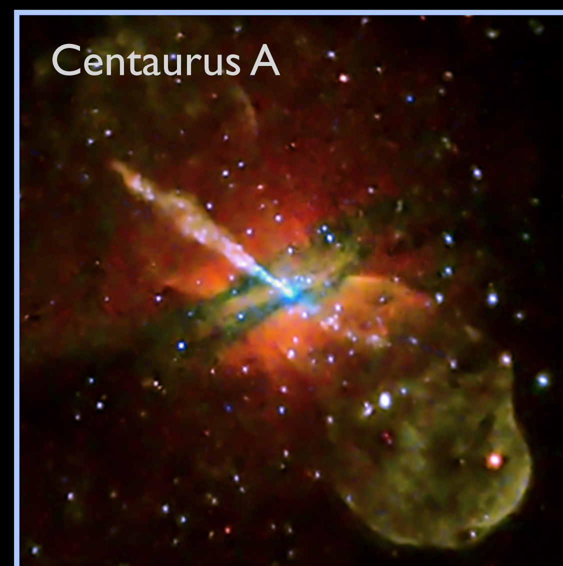

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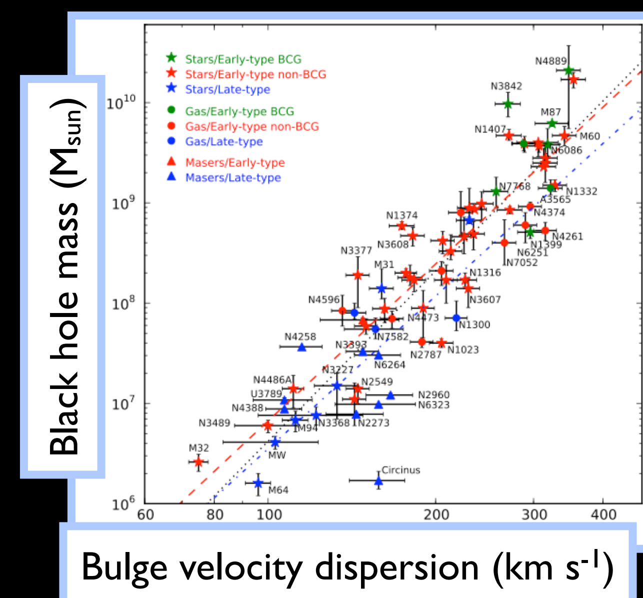

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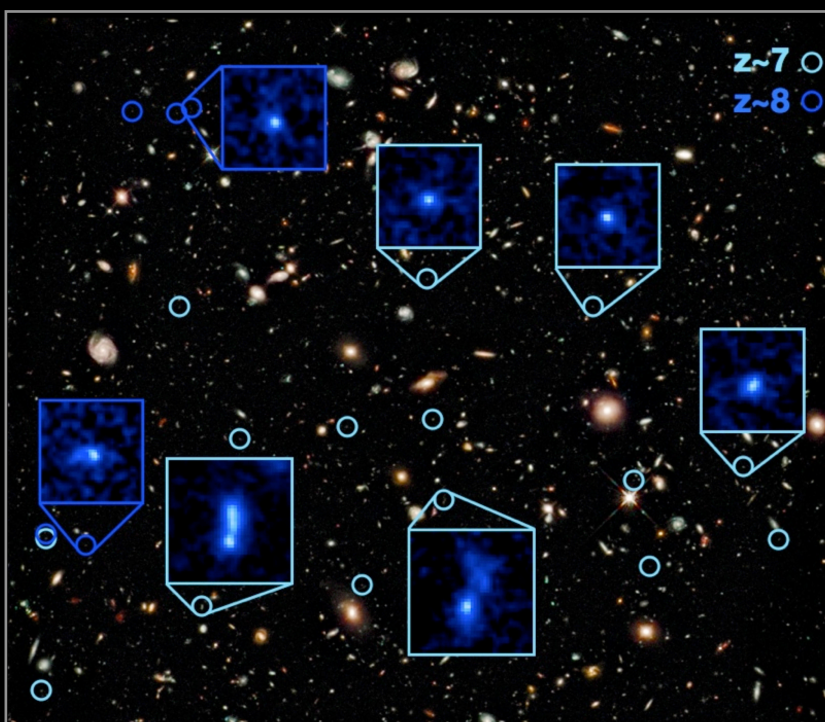
The origin of these SMBHs is far from understood!

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 (individully or stacked) (Willott 2011; Cowie et al. 2012; Treister 2013)



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.

• 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_{sun} (Labbe et al. 2010)

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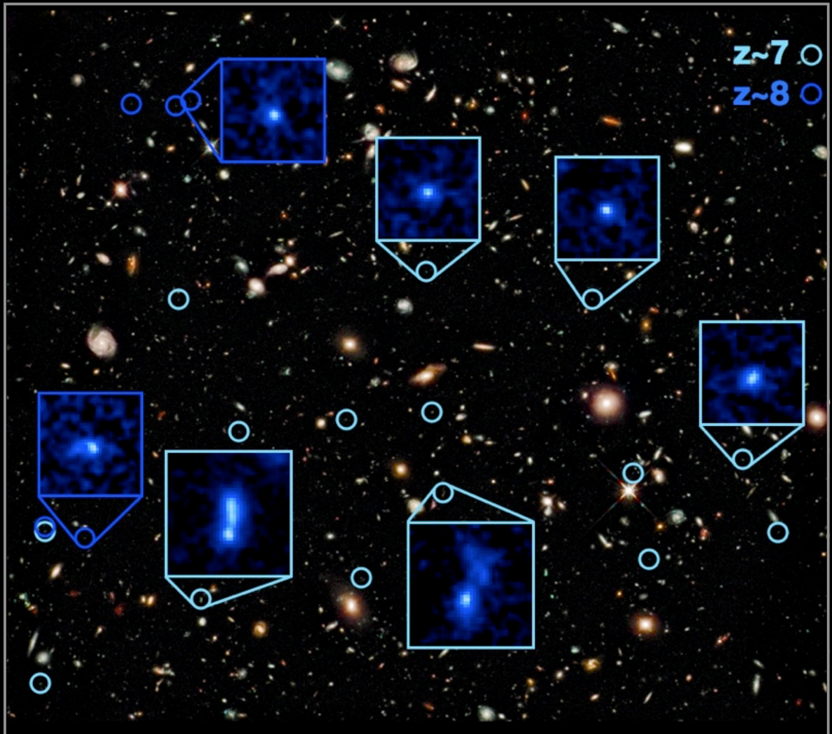

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Present-day dwarf galaxies offer another avenue to observationally constrain the origin of supermassive BH seeds

(e.g., masses, host galaxies, and in principle, even the formation mechanism)

Motivation: The origin of supermassive black holes

Observations of high-redshift quasars:

- $M_{BH} > 10^9\ M_{sun}$ 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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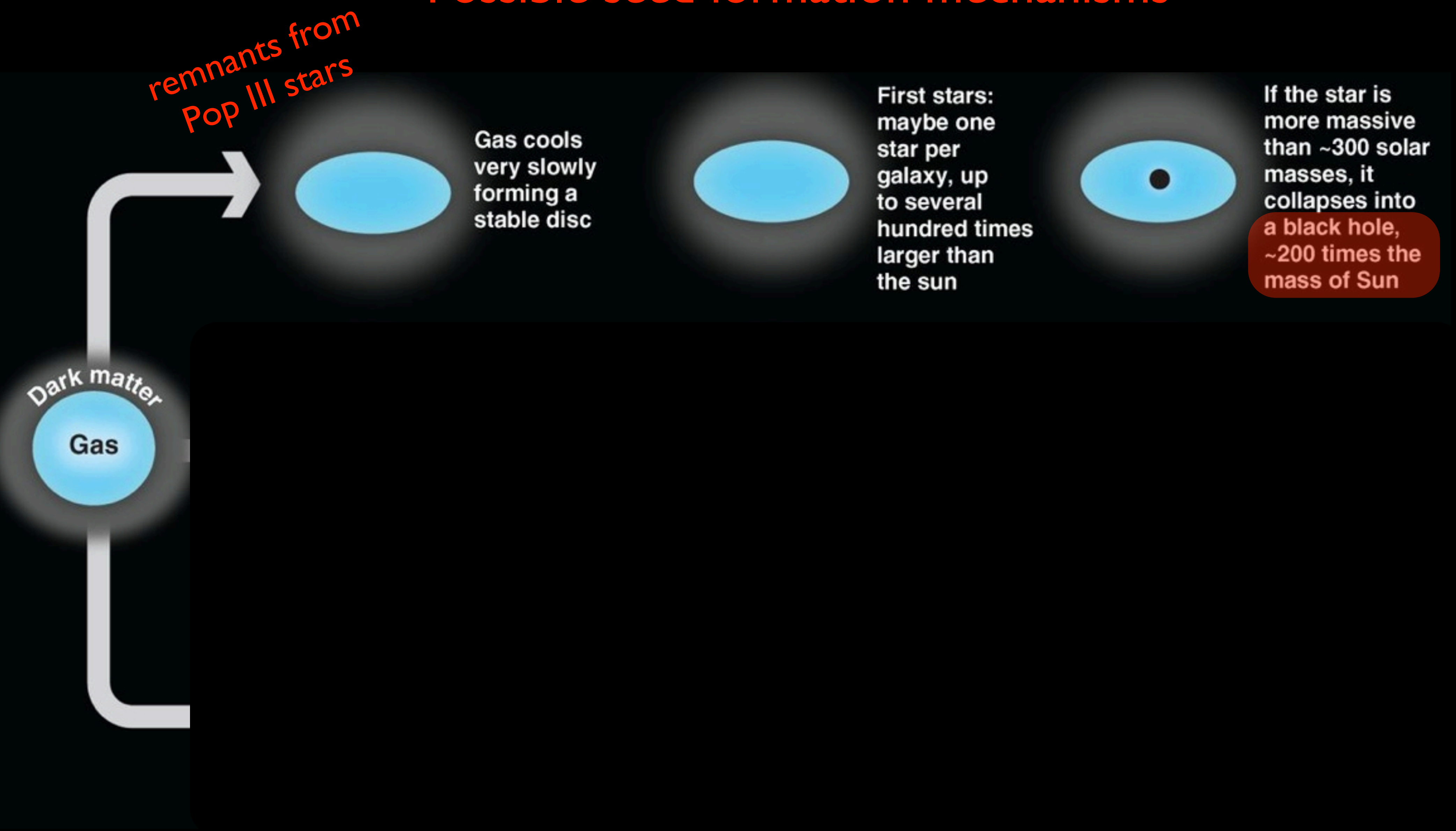

Volonteri 2012, *Science*

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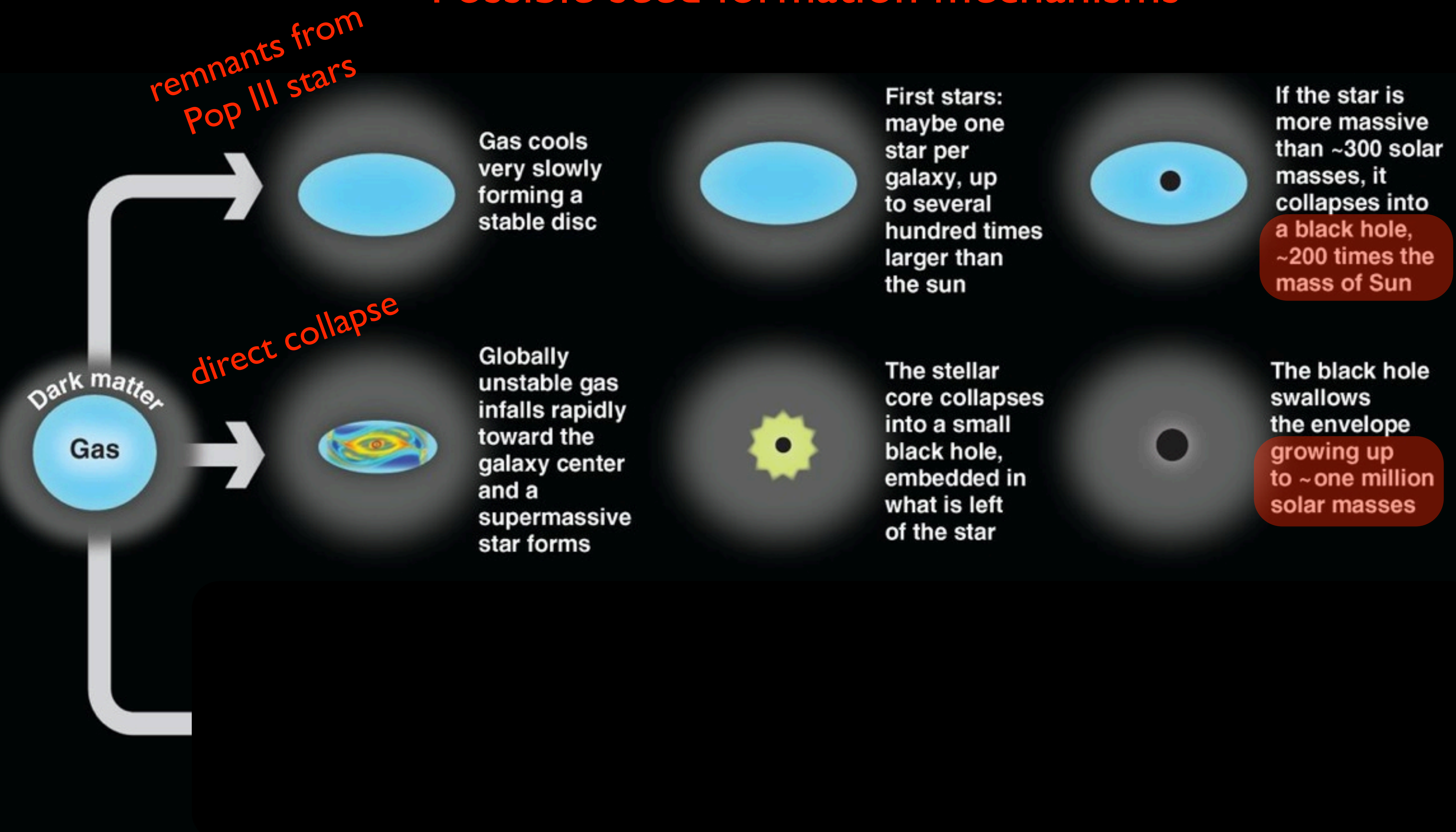

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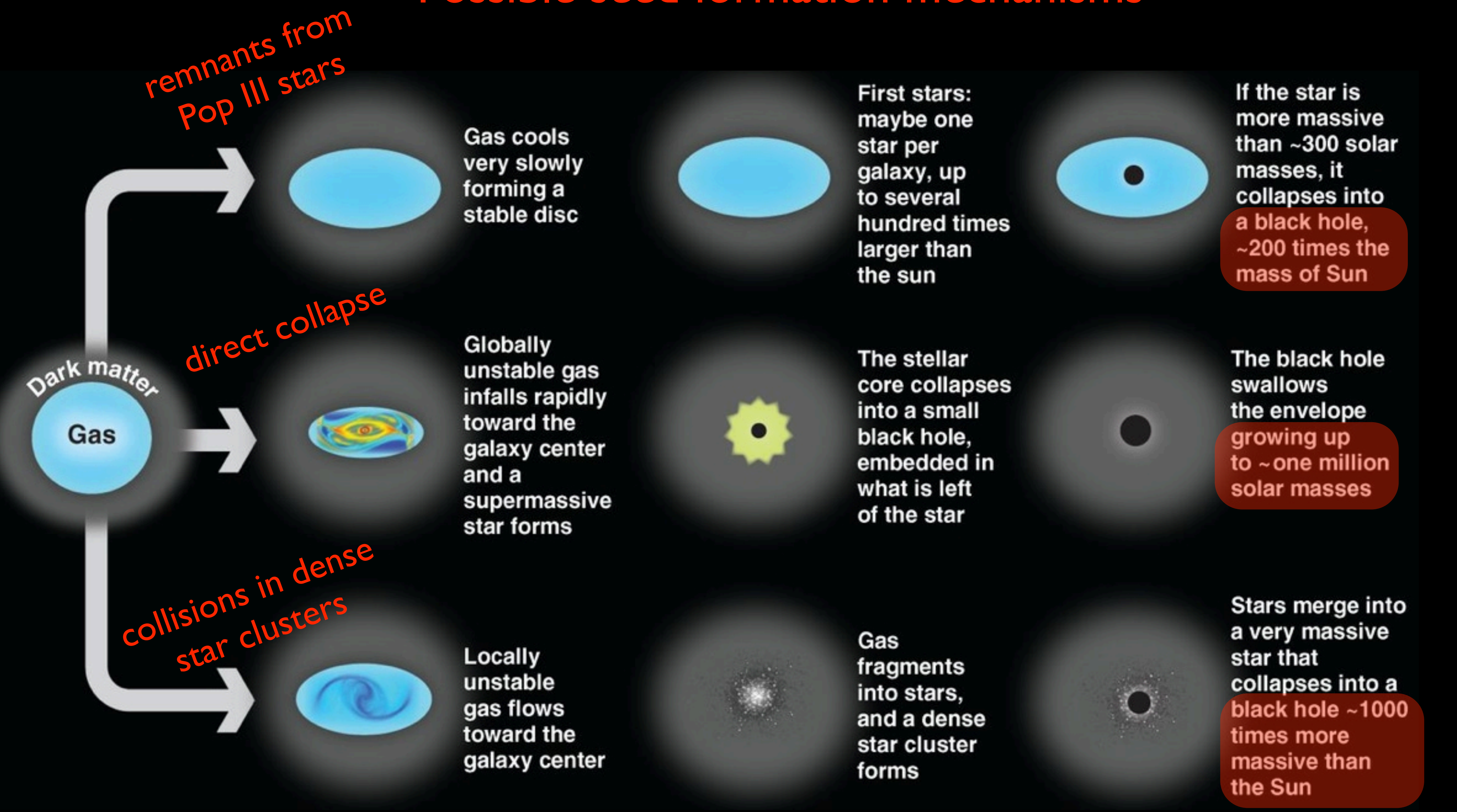
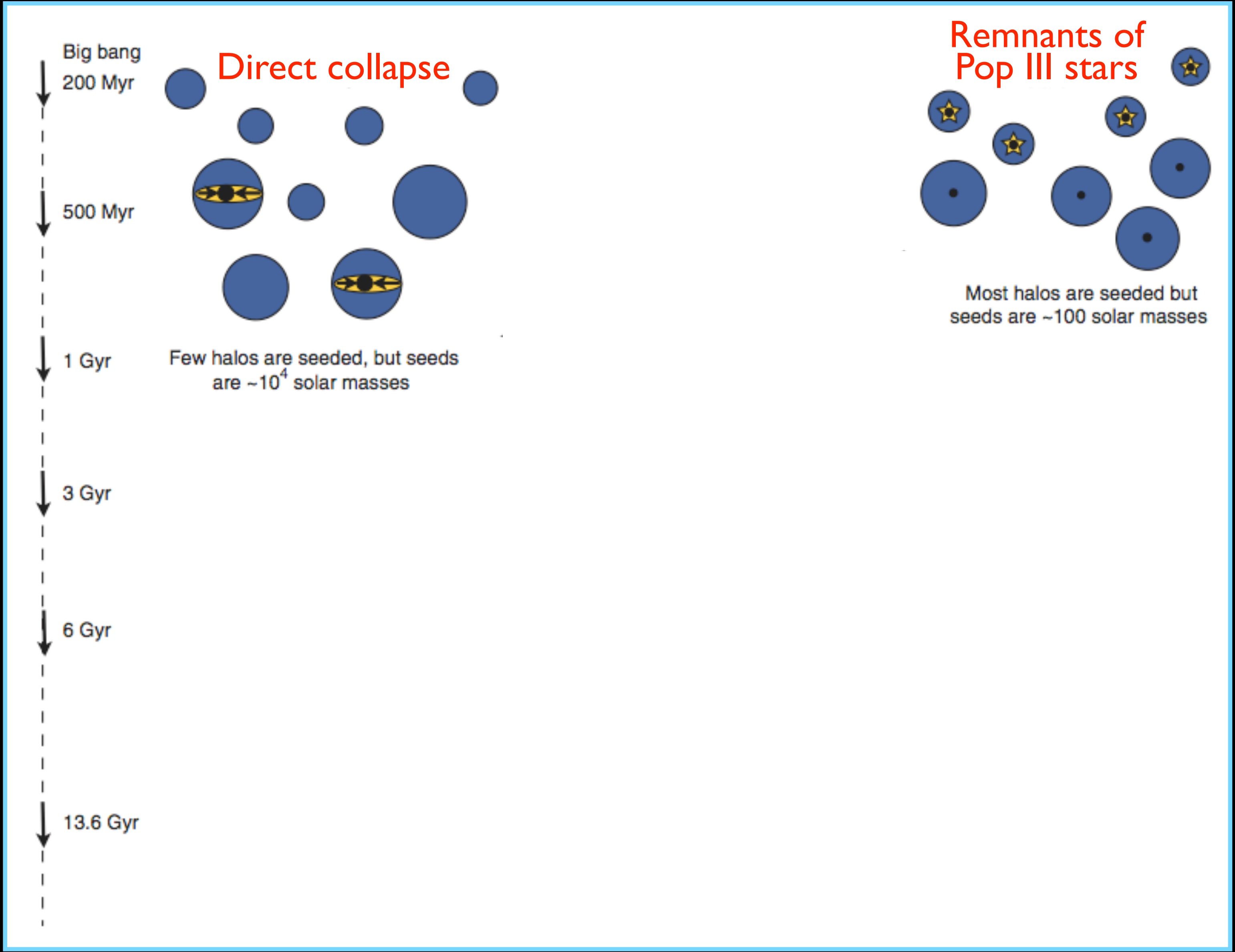


Volonteri 2012, *Science*

Motivation: The origin of supermassive black holes

Models of black hole growth in a cosmological context

time



Greene 2012, *Nature Communications*; also see review in Volonteri 2010

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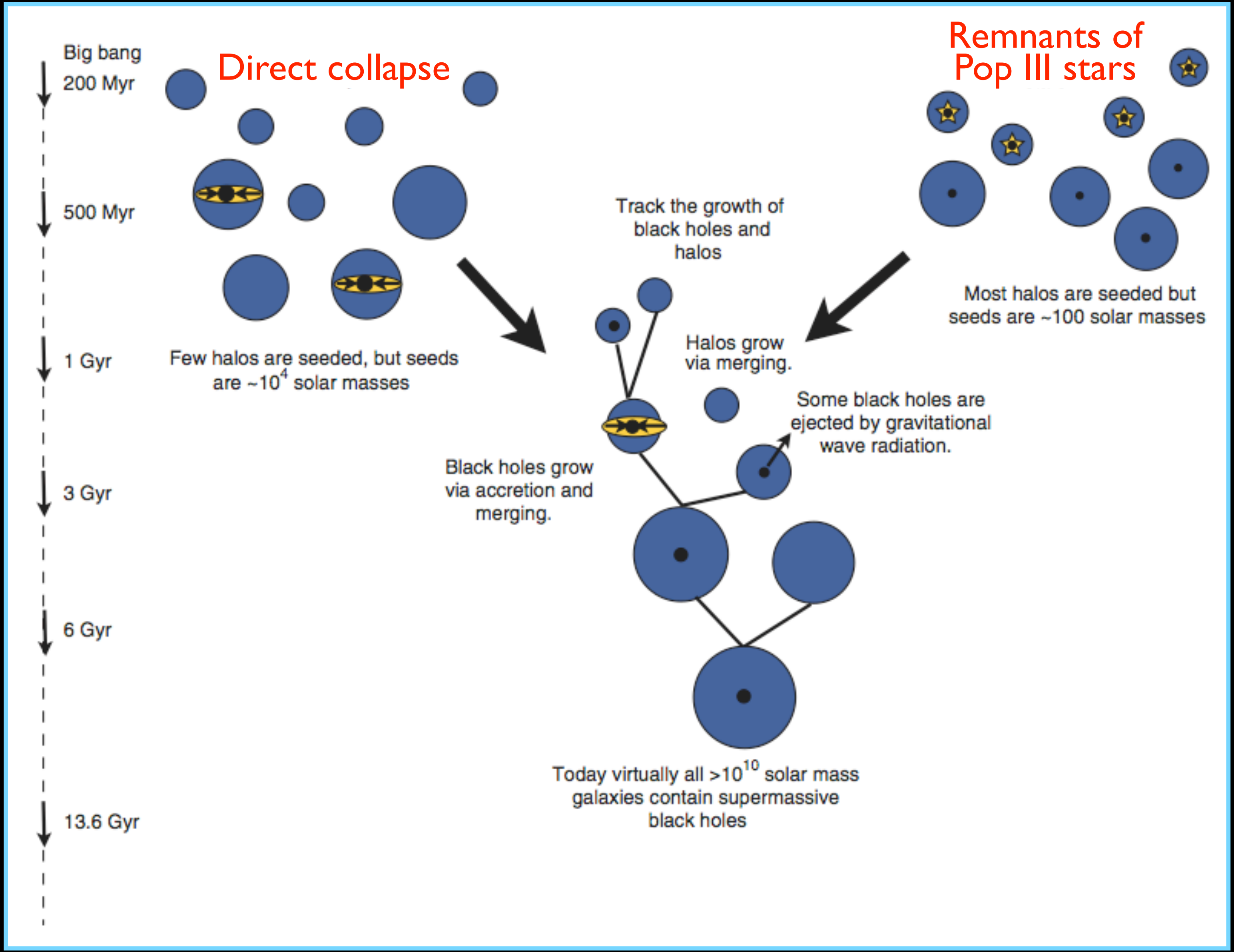

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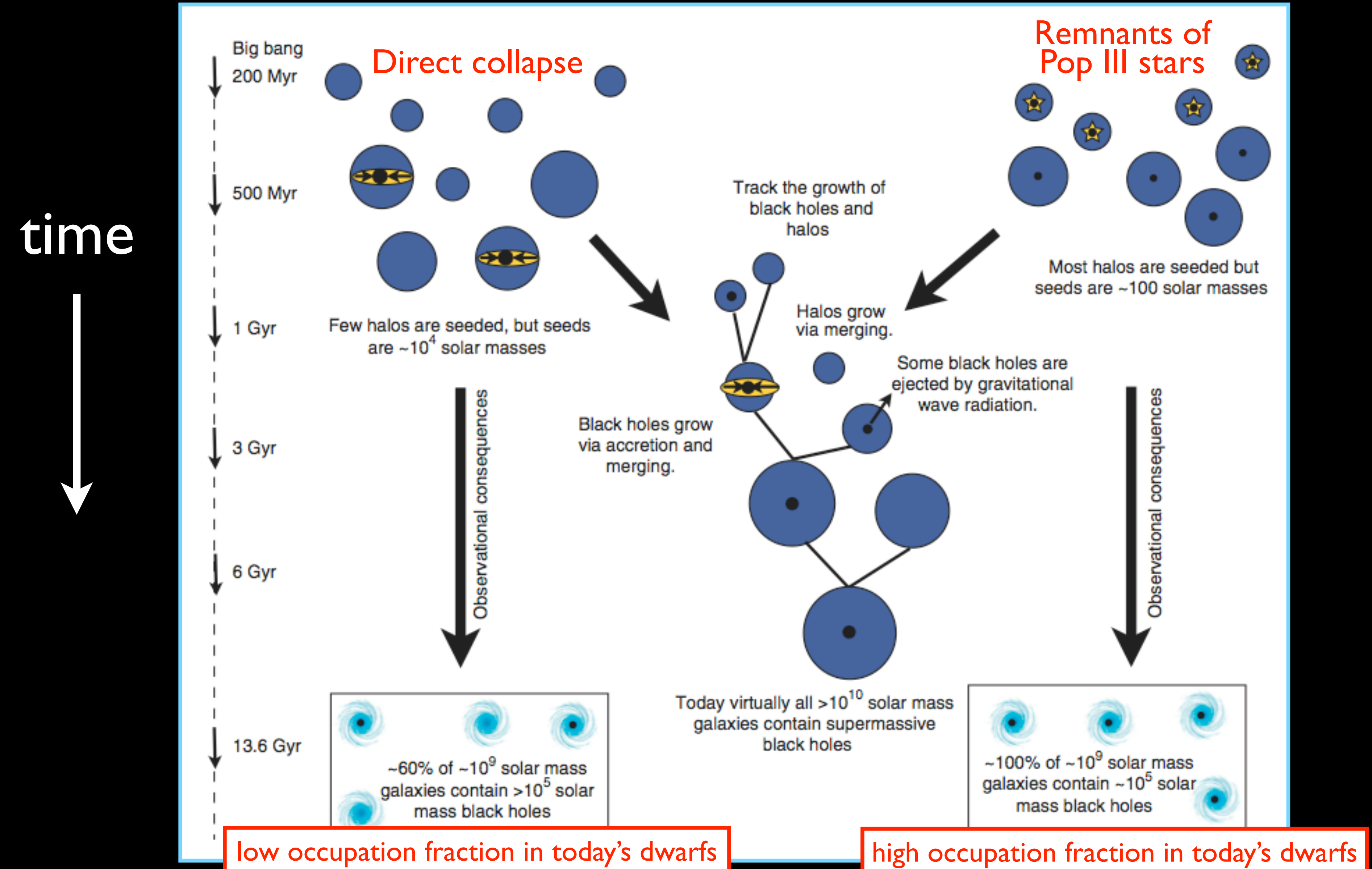

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Observationally, very few dwarf galaxies known to host massive black holes

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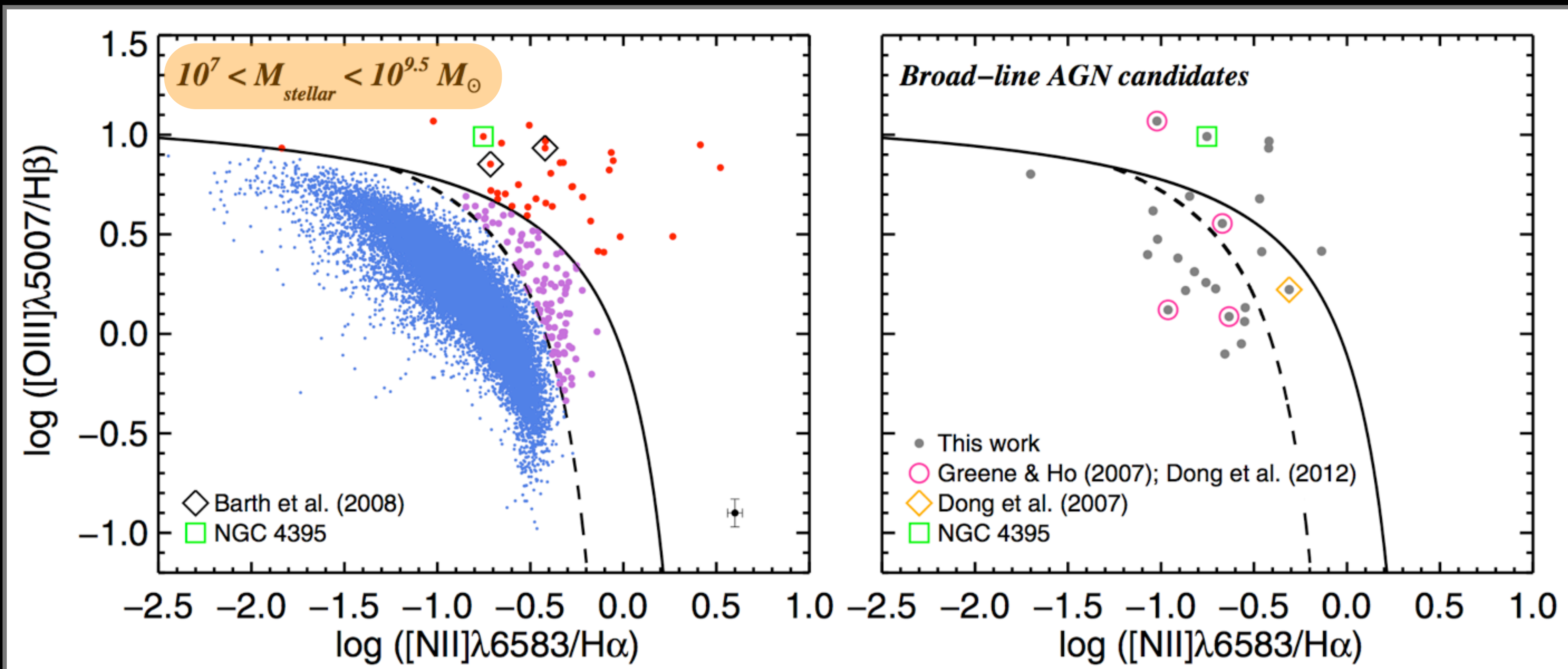
Until now...

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

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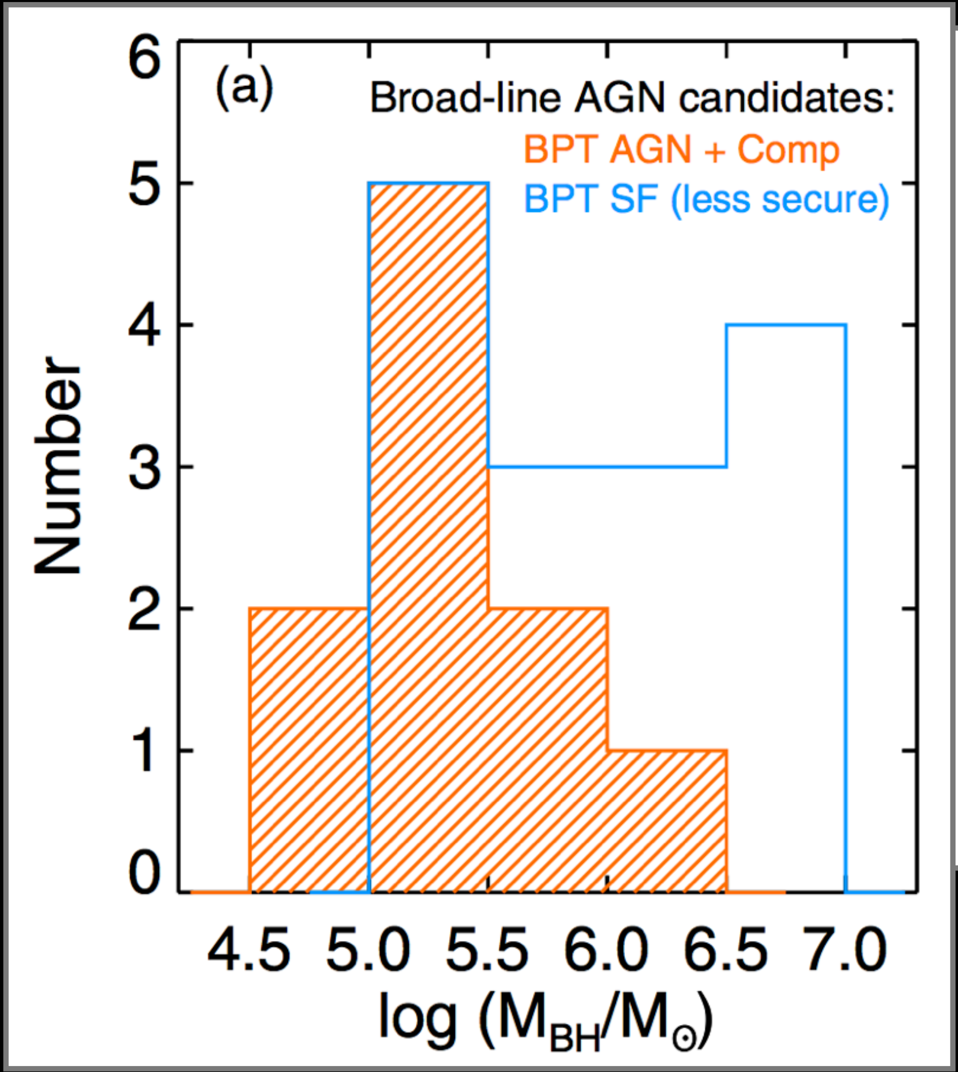
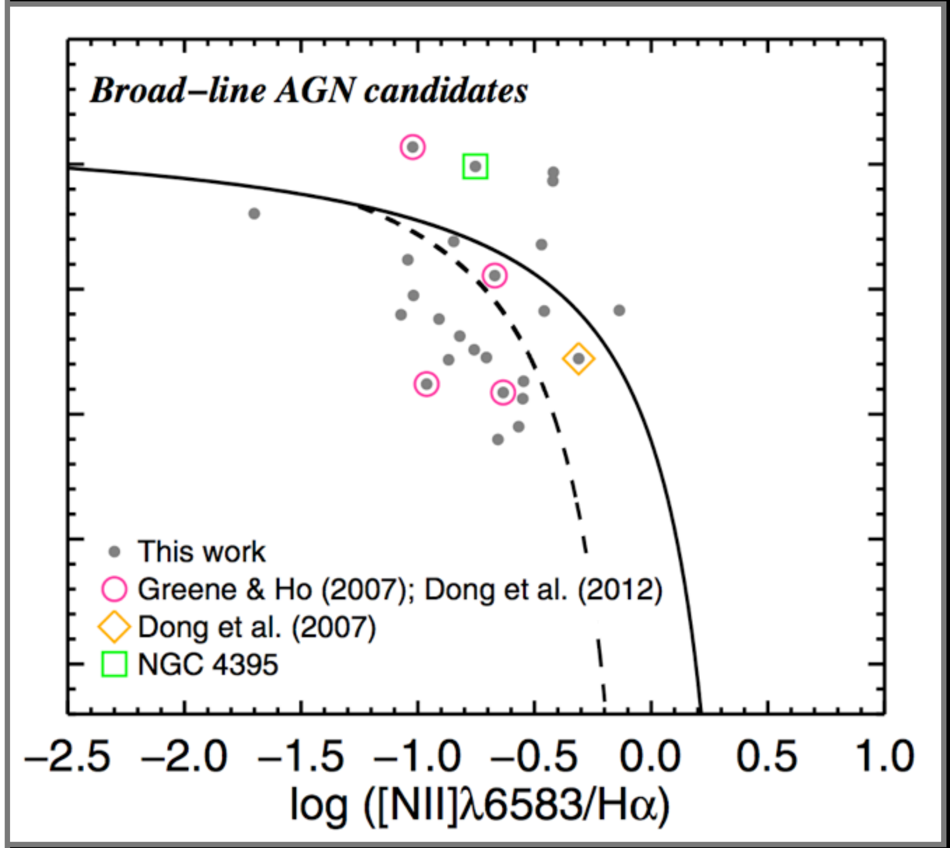




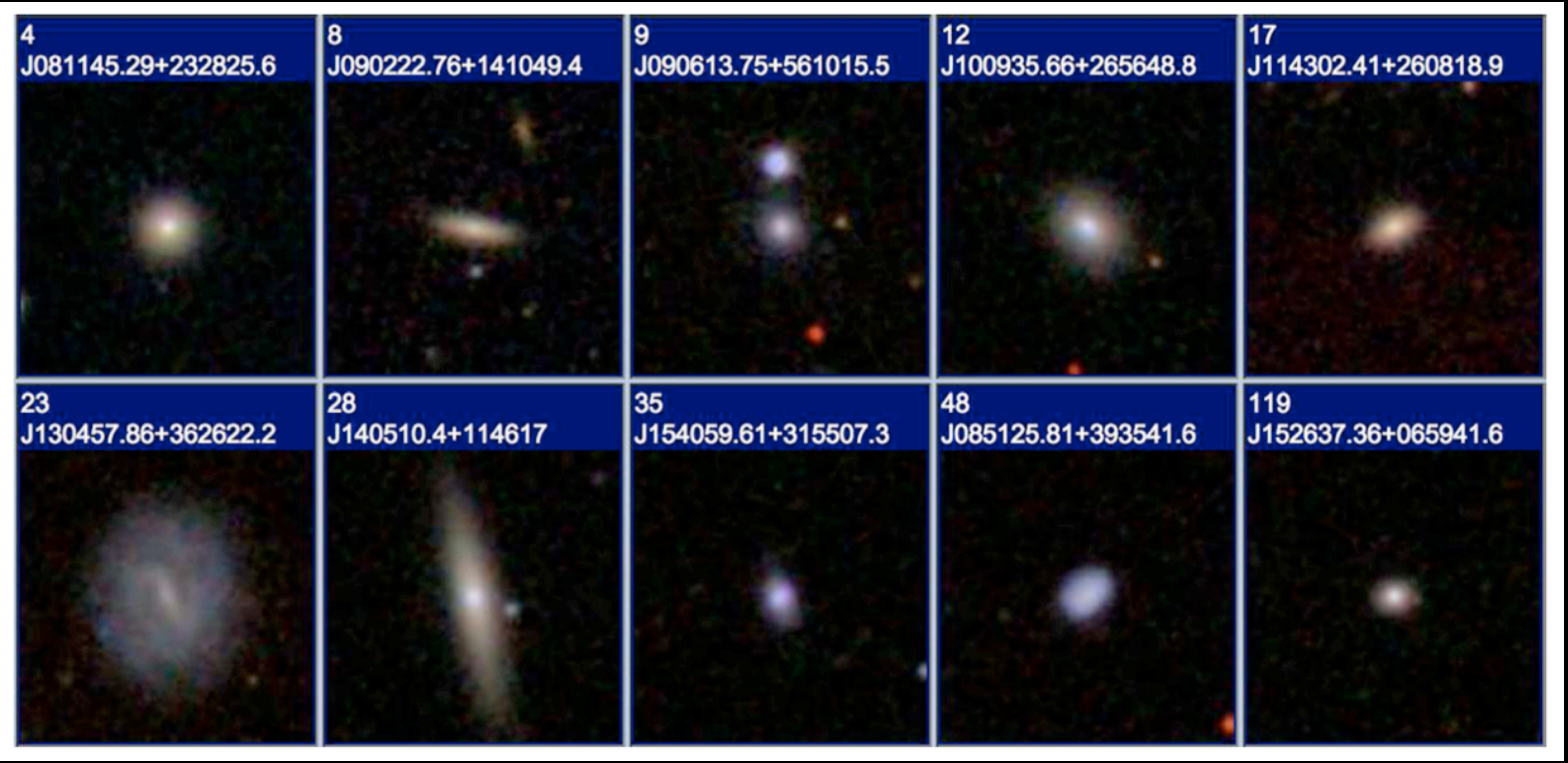
Least-massive black holes known

(median M_{BH} ~ 2 x10^5 M_{sun})

Reines, Greene & Geha 2013

Dwarf galaxies with optical signatures of active massive BHs

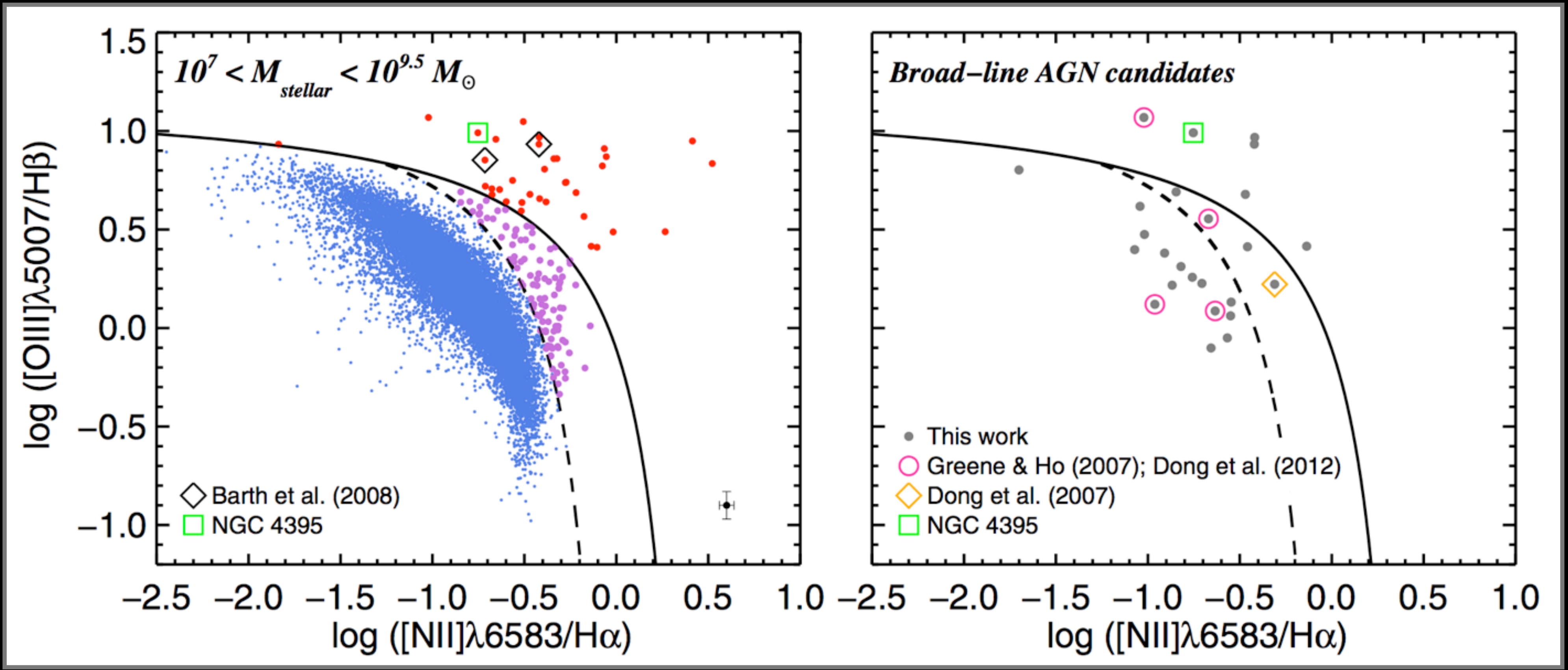
Examples of host galaxies



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

Reines, Greene & Geha 2013

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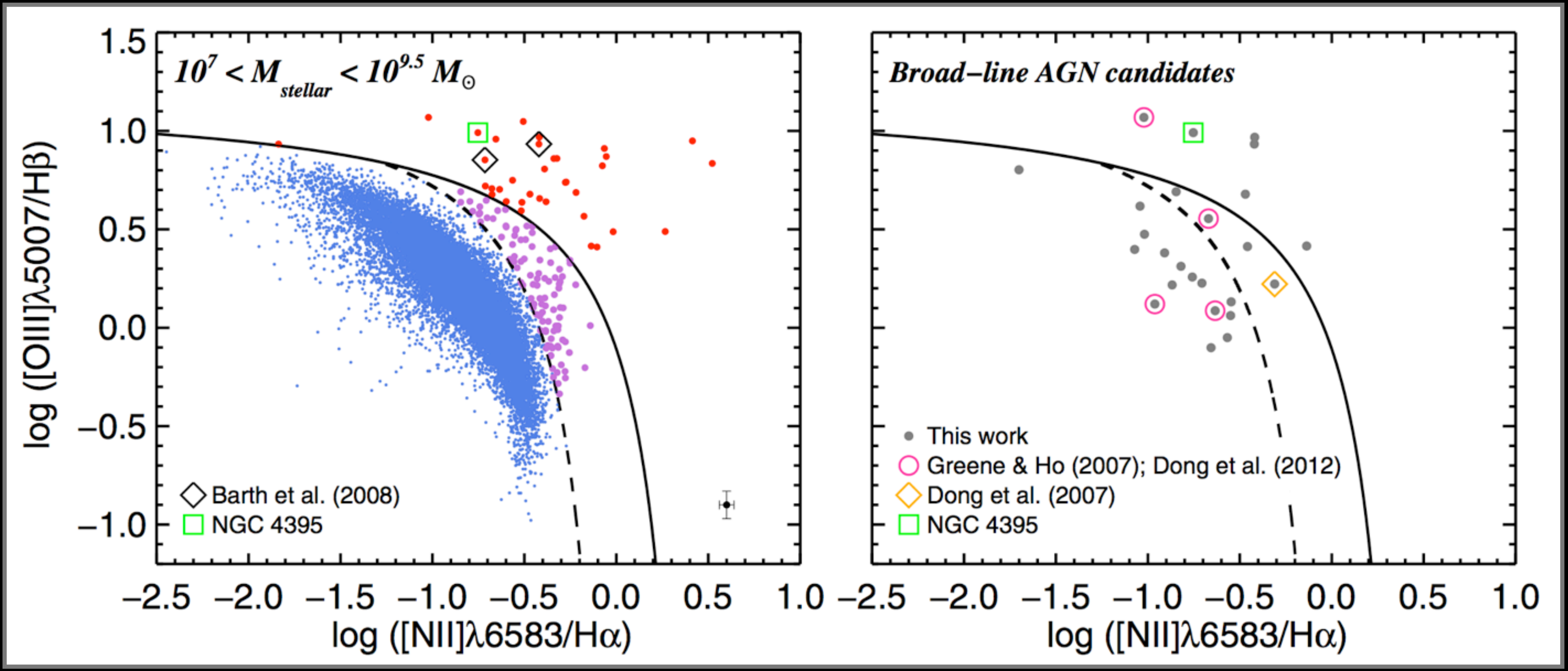

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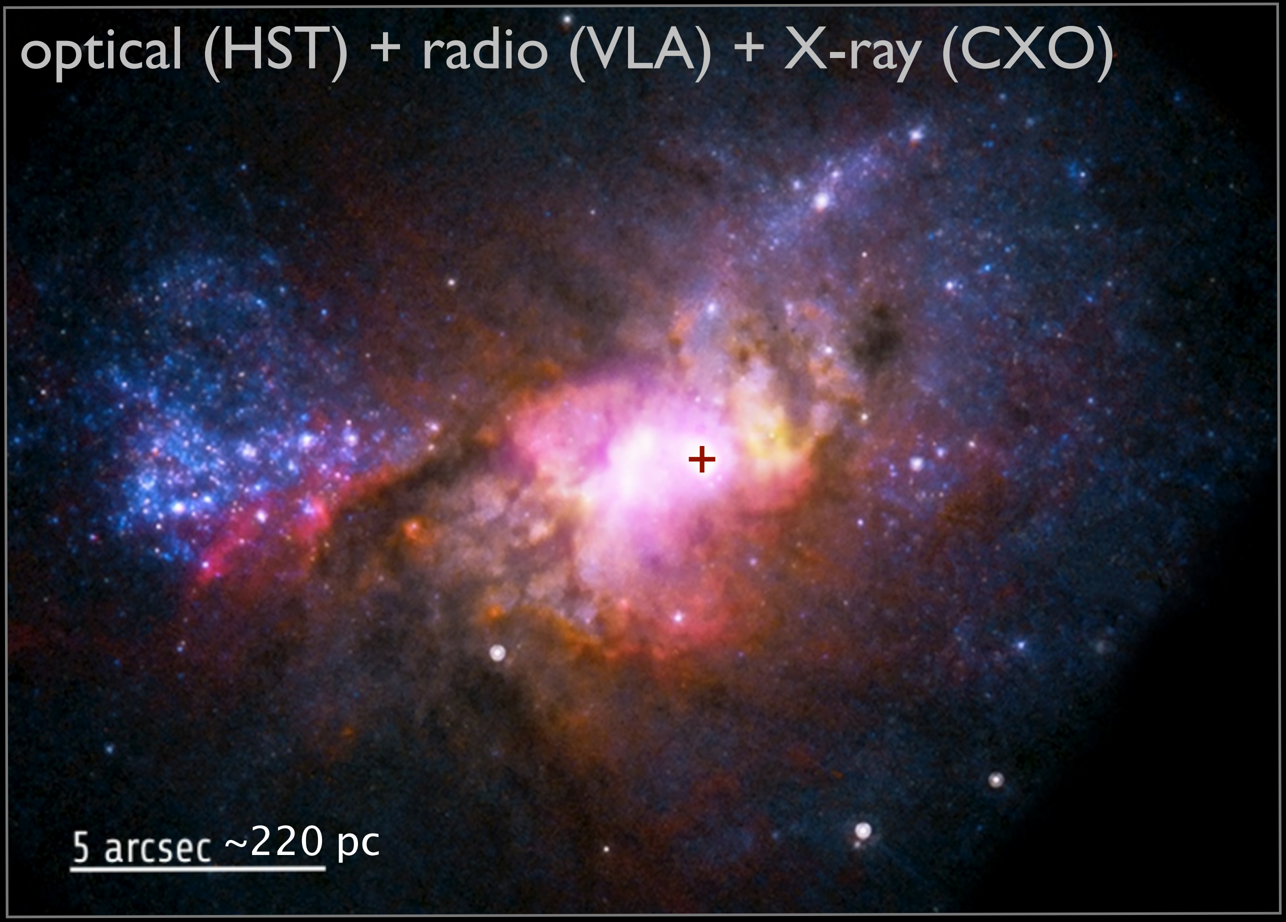
Reines, Greene & Geha 2013

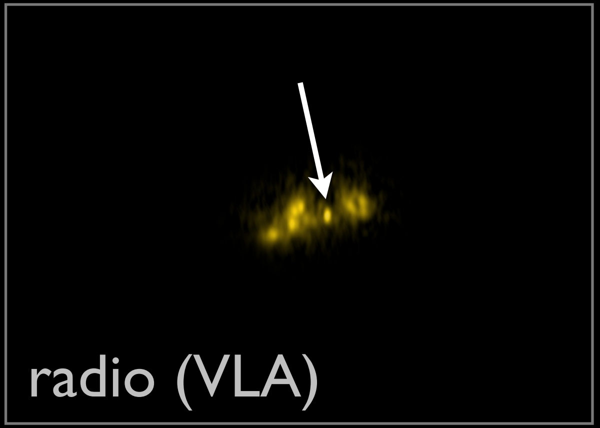
Need other diagnostics!

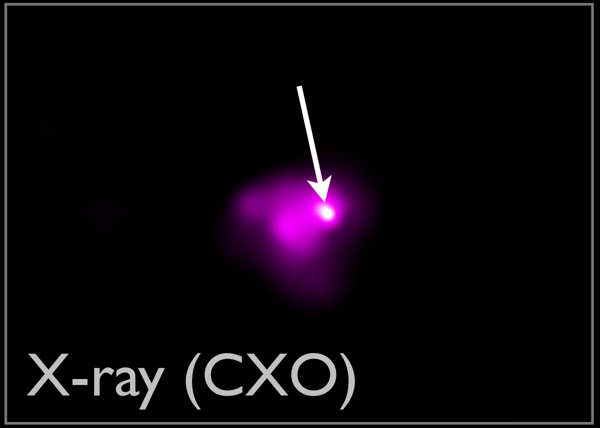
High-resolution X-ray and radio observations

- 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







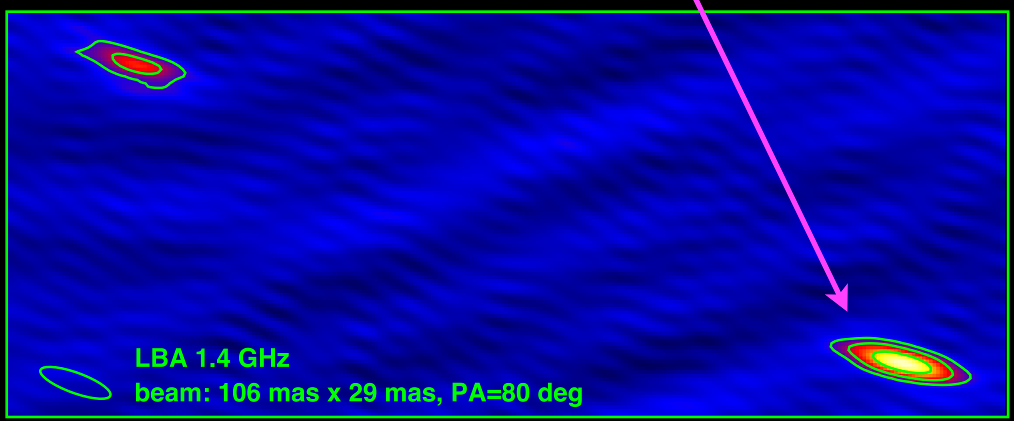
Reines et al. 2011, *Nature*

First example of a dwarf starburst galaxy with a massive BH (~10^6 M_{sun})

A massive BH in the dwarf starburst galaxy Henize 2-10

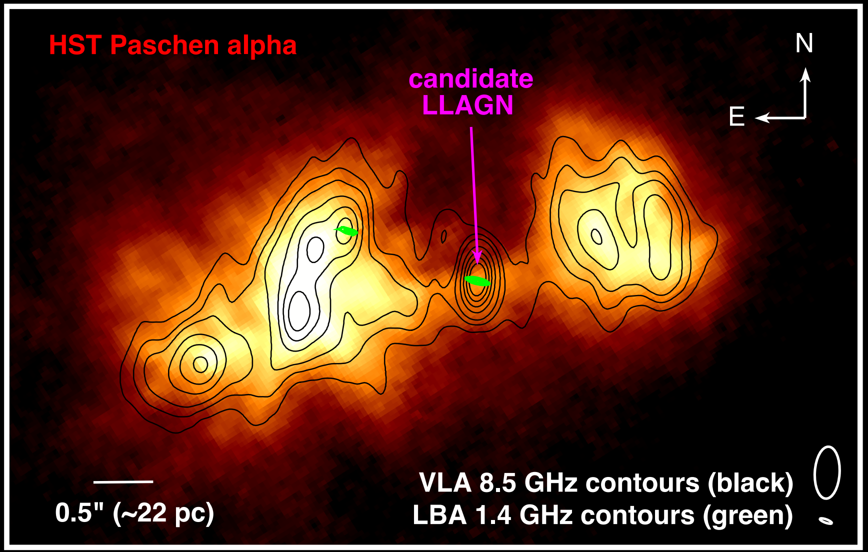
VLBI follow-up with the Long Baseline Array (LBA)

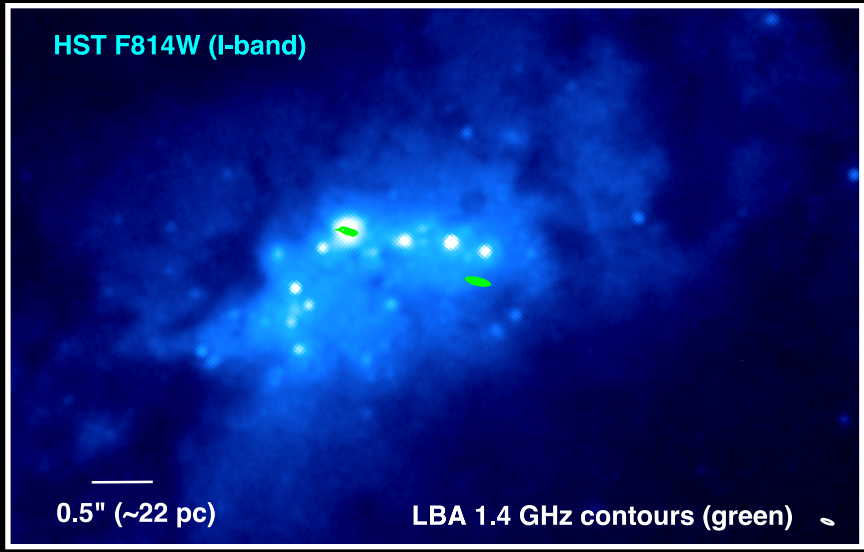
nuclear radio source:
$\lesssim$ 3 x 1 pc



Reines & Deller 2012

HST imaging of central ~ 250 pc





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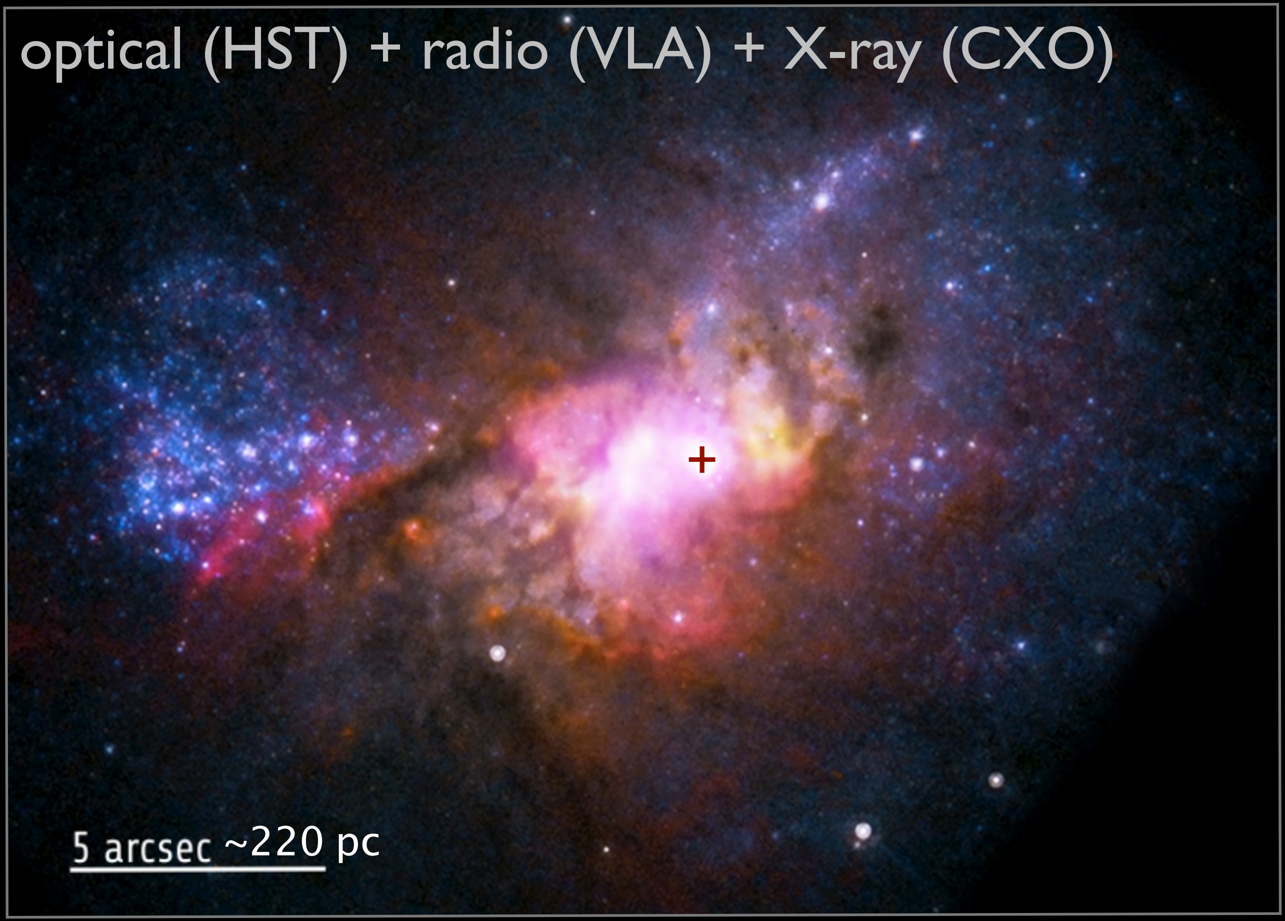
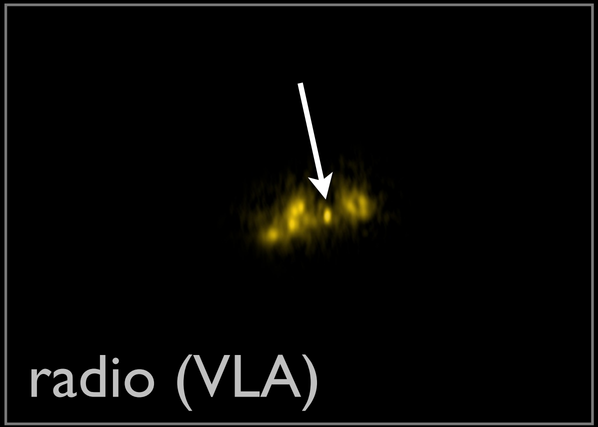
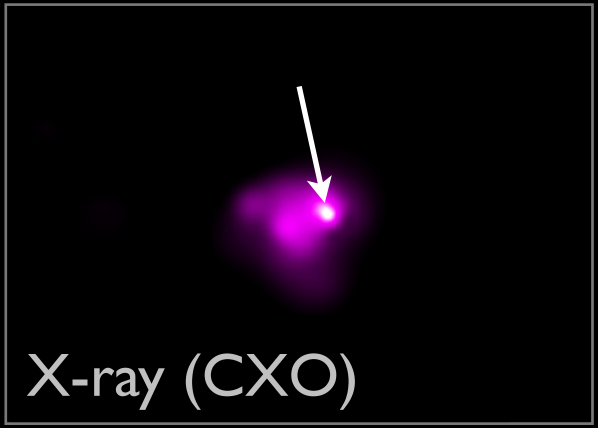
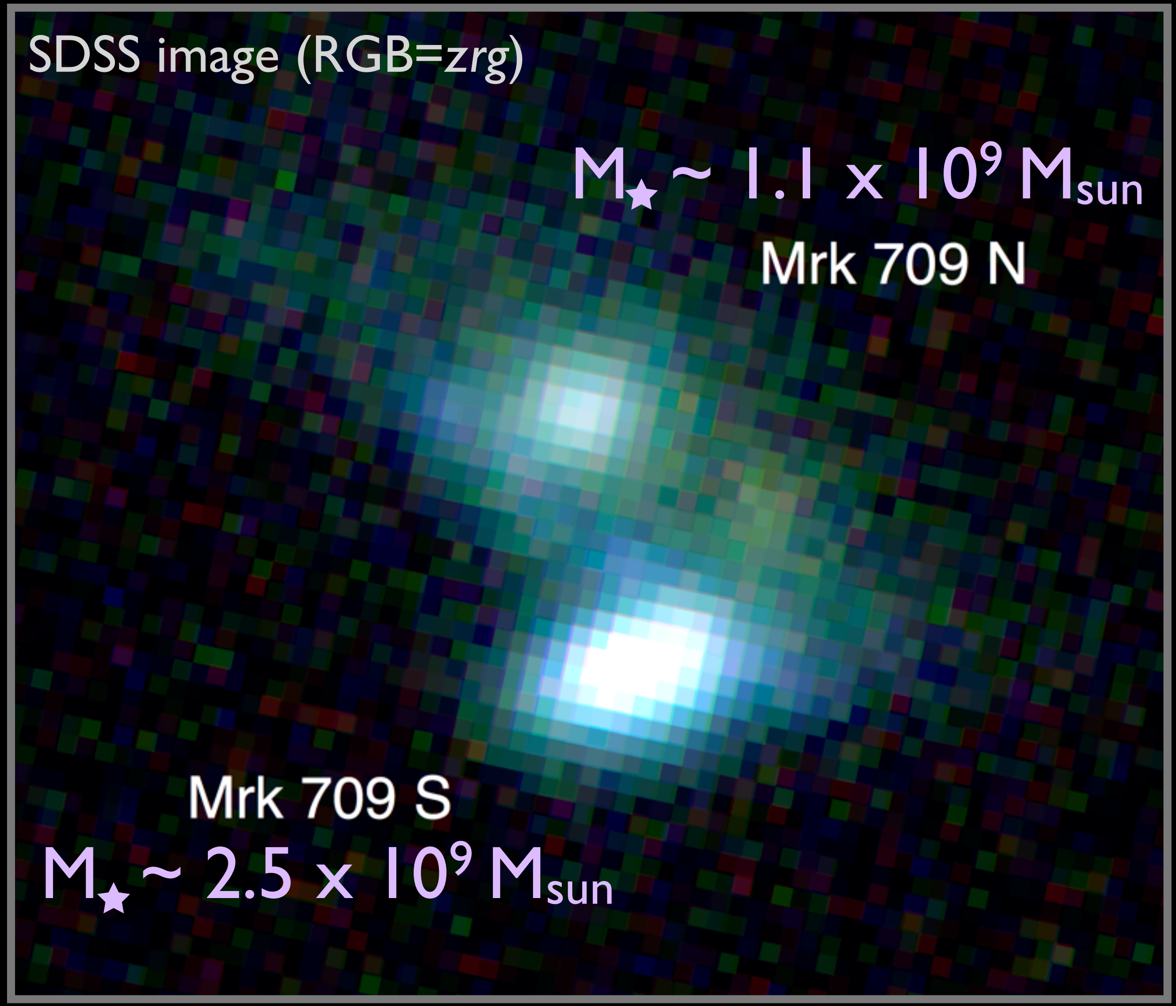






Motivation to look for additional examples of massive BHs in star-forming dwarf galaxies with Chandra and the VLA

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



metallicity ~ 10% solar

Masegosa et al. (1994)

Reines et al. 2014

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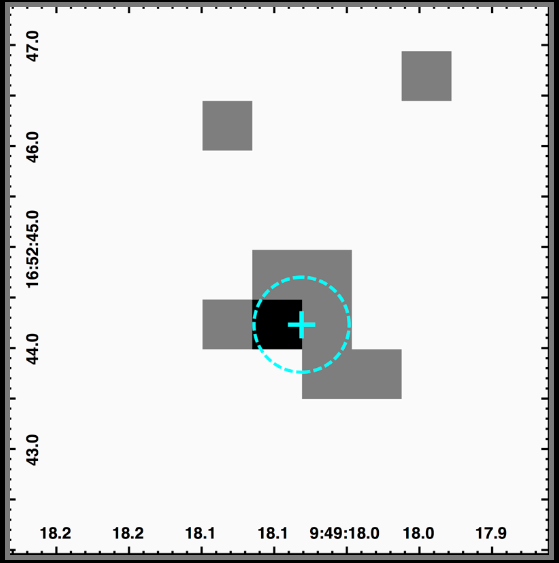
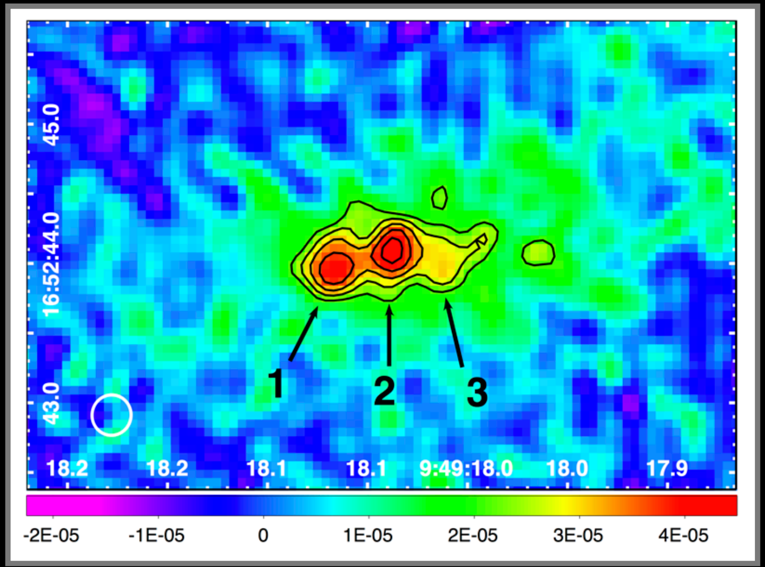
+

Chandra ~ 21 ks

VLA, A-configuration, C-band ~ 1 hr on-source





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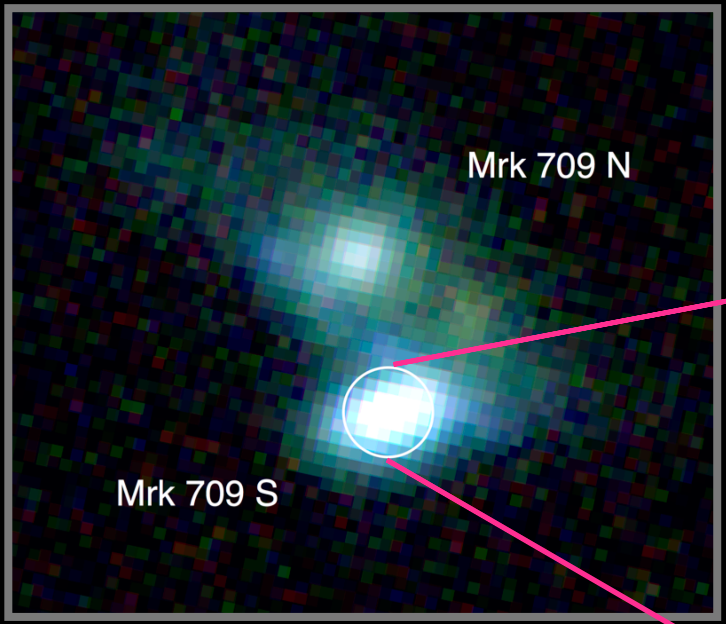

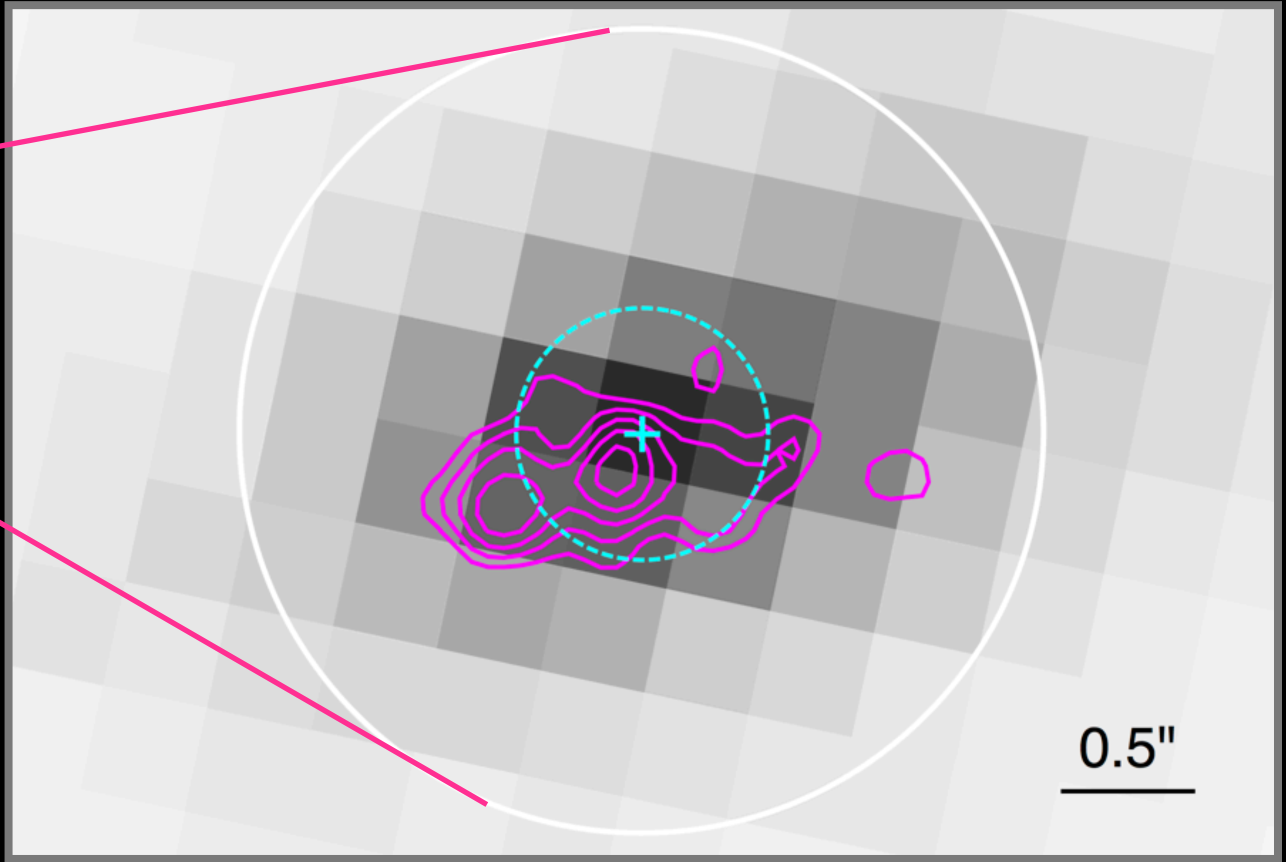

SDSS z-band image of Mrk 709 S with position of hard X-ray source and radio contours

Reines et al. 2014

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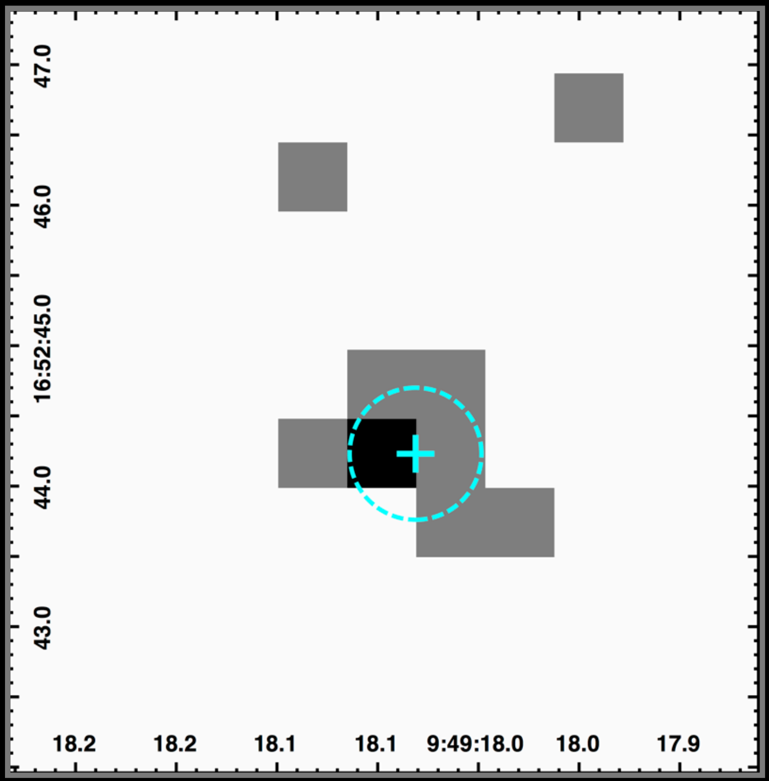
Chandra hard (2-7 keV) X-ray image



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

(90% confidence interval)

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

$$L_{\mathrm{HX}}^{\mathrm{gal}} = \alpha M_\star + \beta \mathrm{SFR}$$

Lehmer et al. (2010)

$L_{(2\text{-}10\ \mathrm{keV})} \sim 9 \times 10^{39}$ erg s^{-1}
(3 sigma upper limit)

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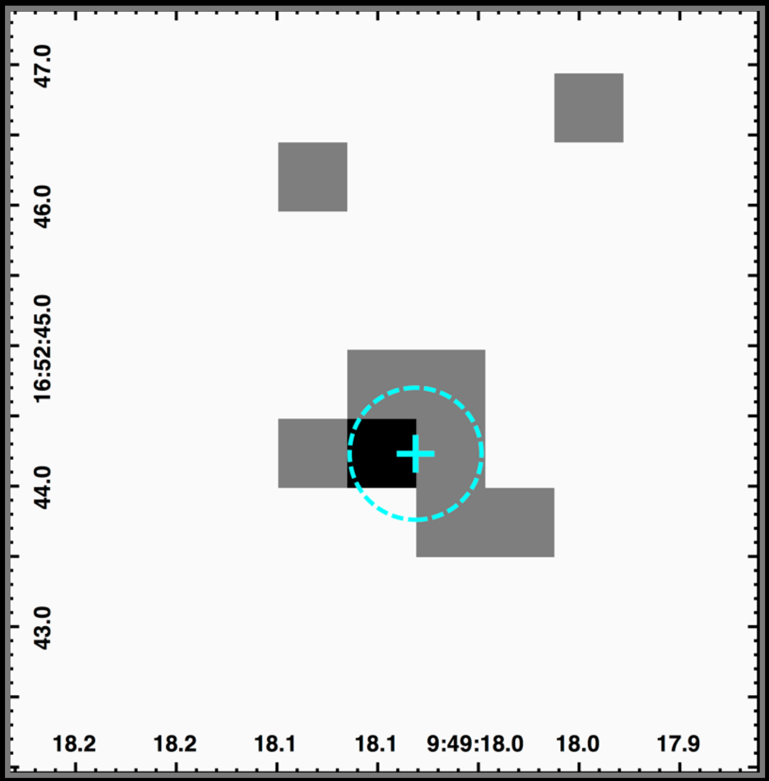

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Measured value (within ~1" *Chandra* PSF) is a factor of ~ 5x higher, suggesting the presence of an AGN

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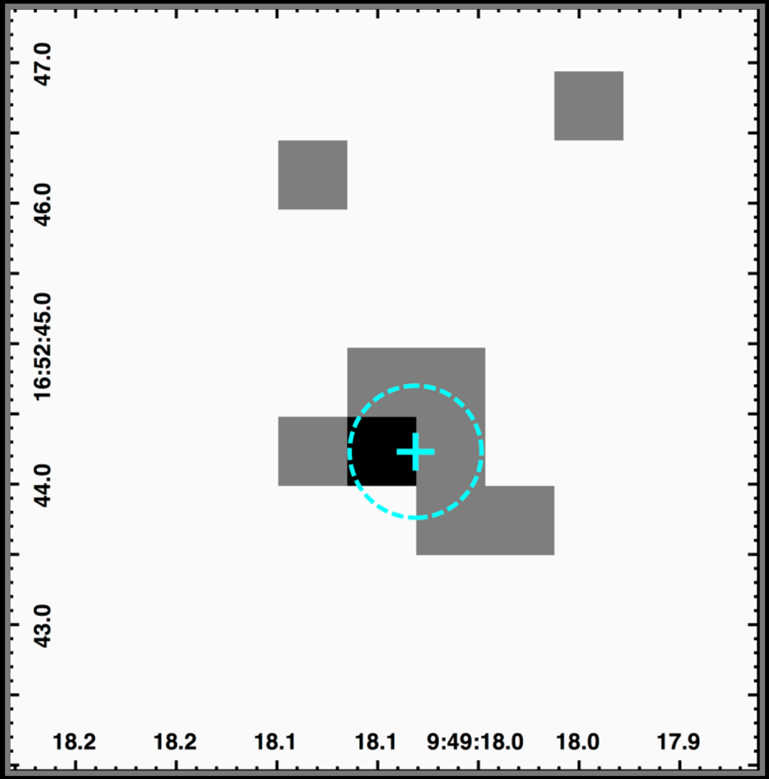

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(90% confidence interval)

Minimum Black Hole Mass:

$$M_{\mathrm{BH}}/M_{\odot} \geq (\kappa L_{2-10\mathrm{keV}})/(1.3\times10^{38}\ \mathrm{erg\ s^{-1}})$$

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

$M_{BH} > 385\ M_{sun}$

(or >160 M_{sun} at 95% confidence)

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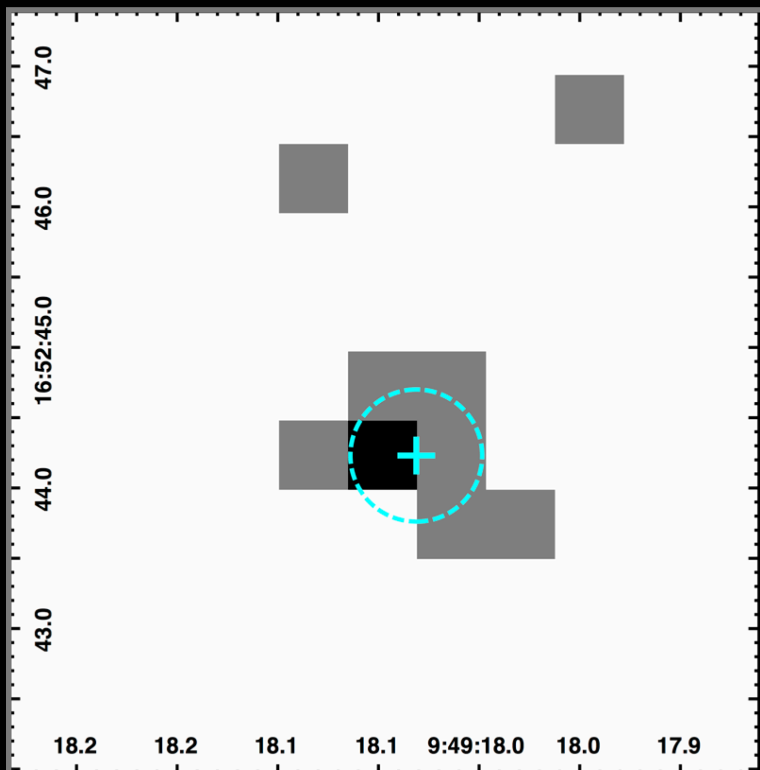

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BH mass may be orders of magnitde larger

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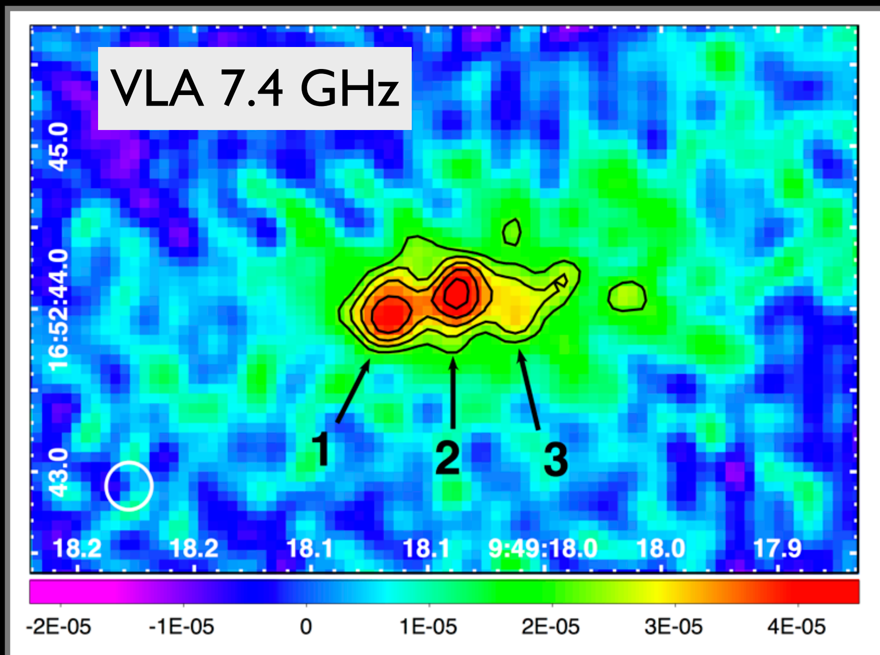
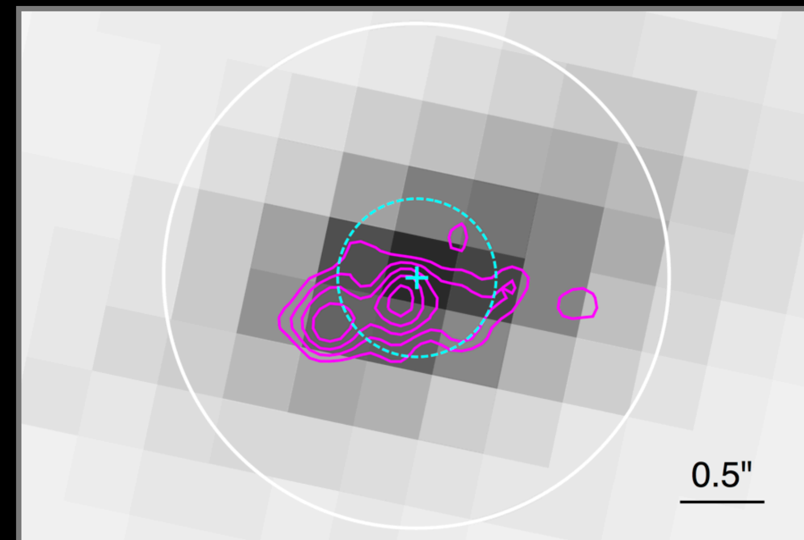




SDSS *z*-band image of Mrk 709 S with position of hard X-ray source and radio contours

Central radio source (#2)

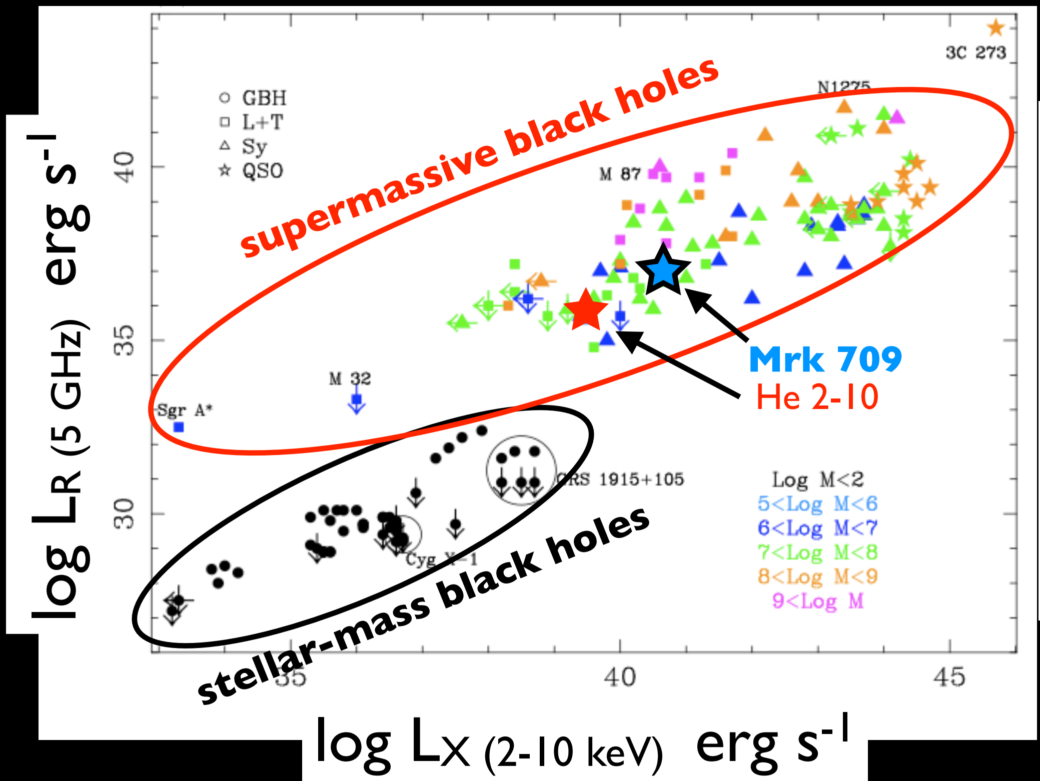
$S_{7.4GHz}$ ~ 40 +/- 10 uJy

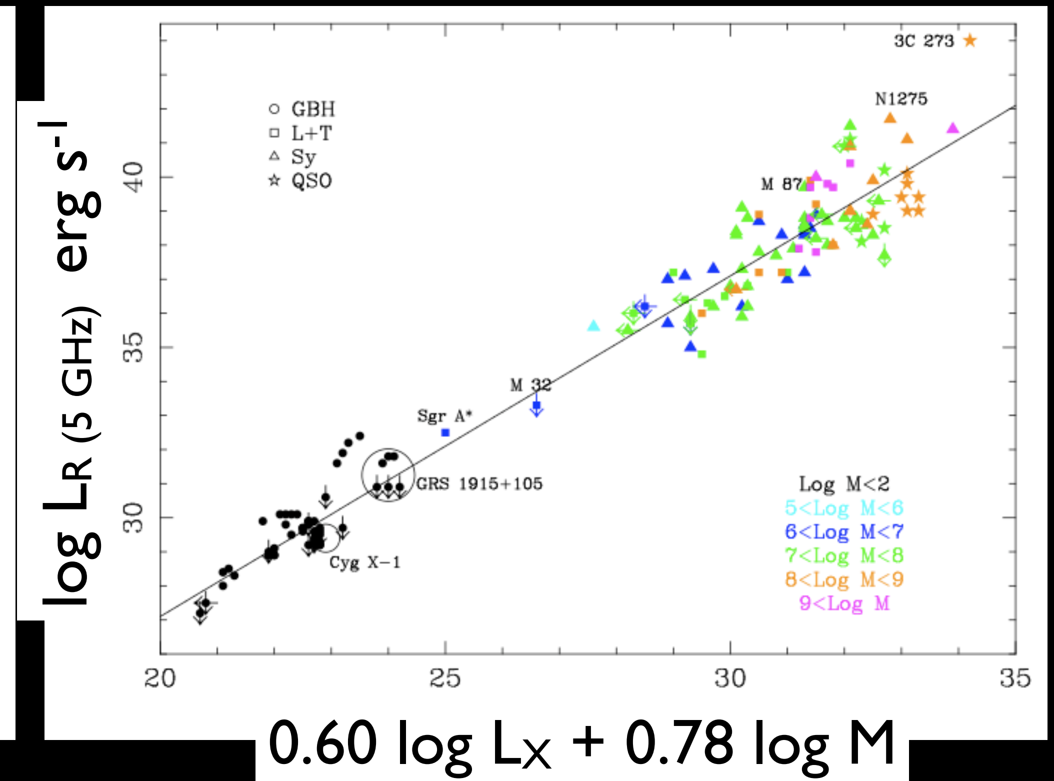
$S_{5.0GHz}$ ~ 60 +/- 20 uJy

$L_{radio} = (1.6 + 0.6) \times 10^{37}$ erg s^{-1}

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

Merloni et al. 2003





"fundamental plane of black hole activity"

$\log L_R = 0.60 \log L_X + 0.78 \log M + 7.33$

order-of-magnitde estimate of BH mass: $M_{BH} \sim 6 \times 10^6 M_{sun}$

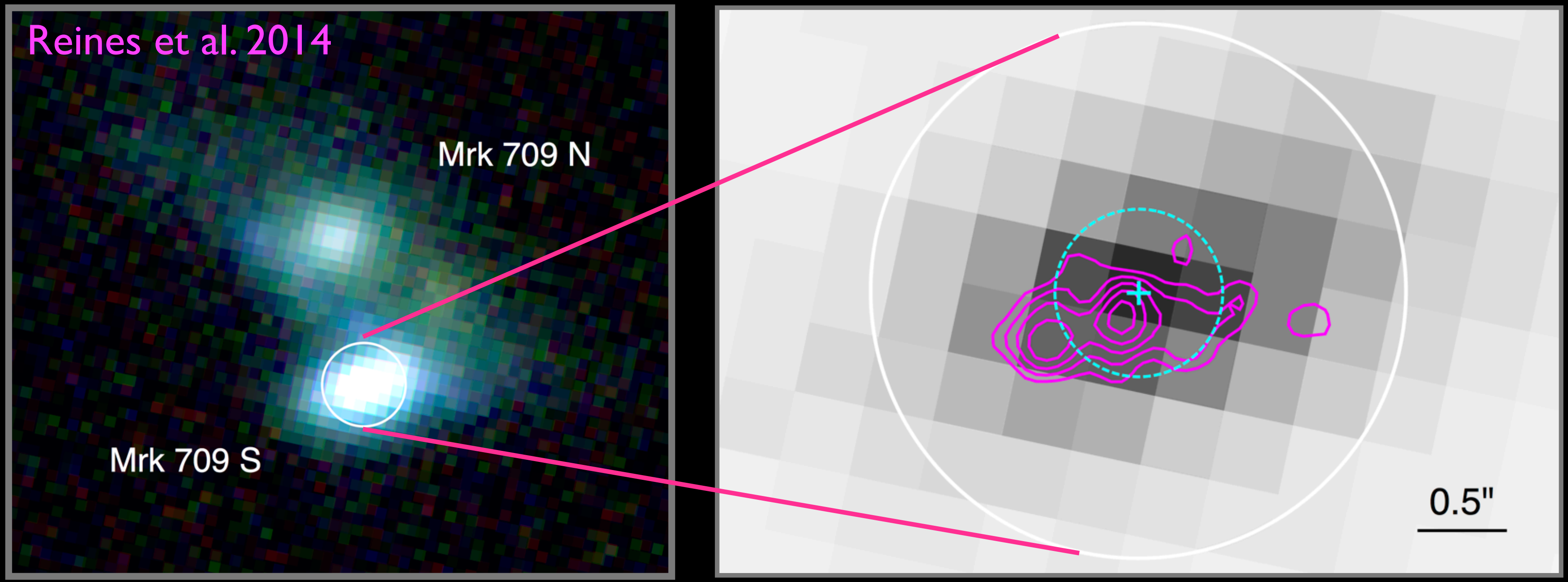
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

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

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



- 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