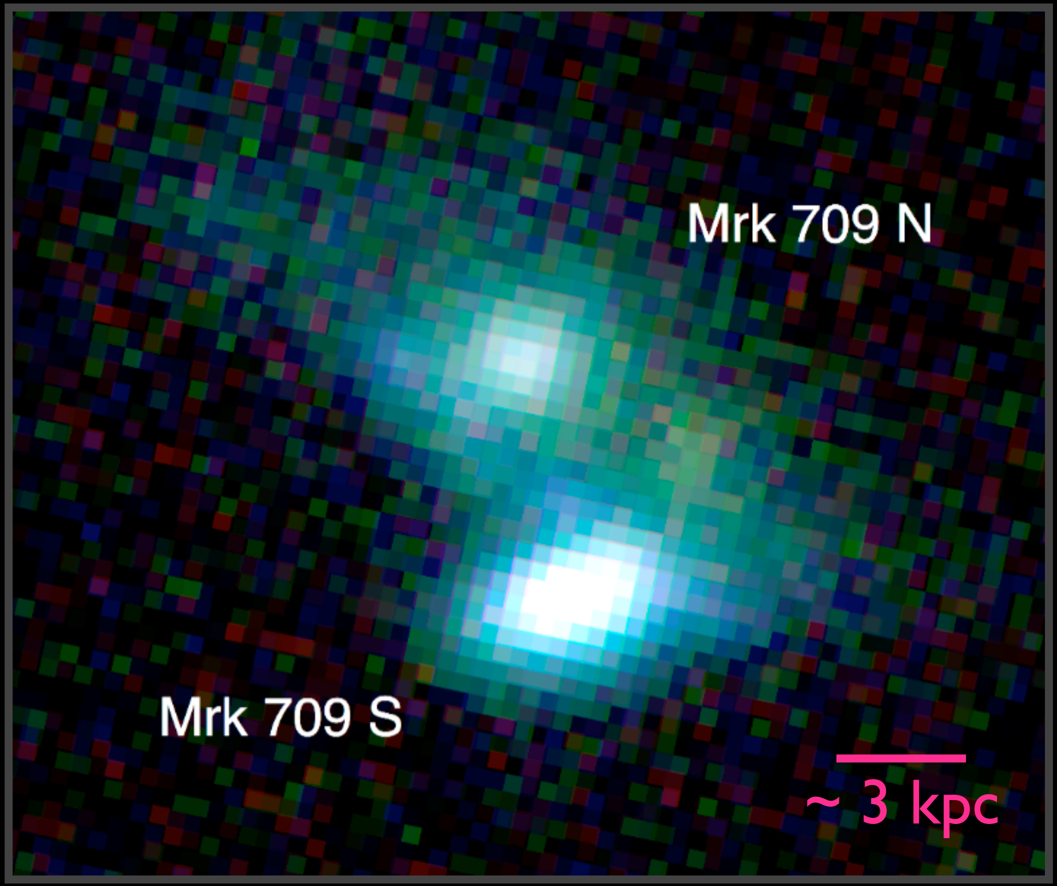
AGN and Star Formation in Dwarf Galaxies



Amy Reines

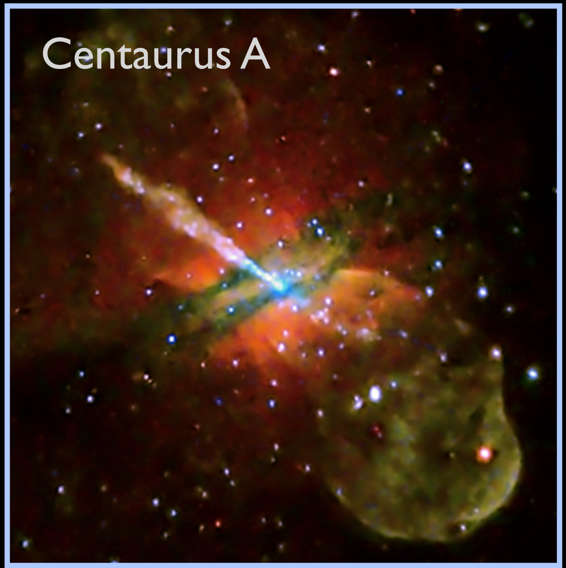
Einstein Fellow at NRAO ⟶ Hubble Fellow at Univ. of Michigan (starting Friday)

Supermassive black holes and galaxy evolution

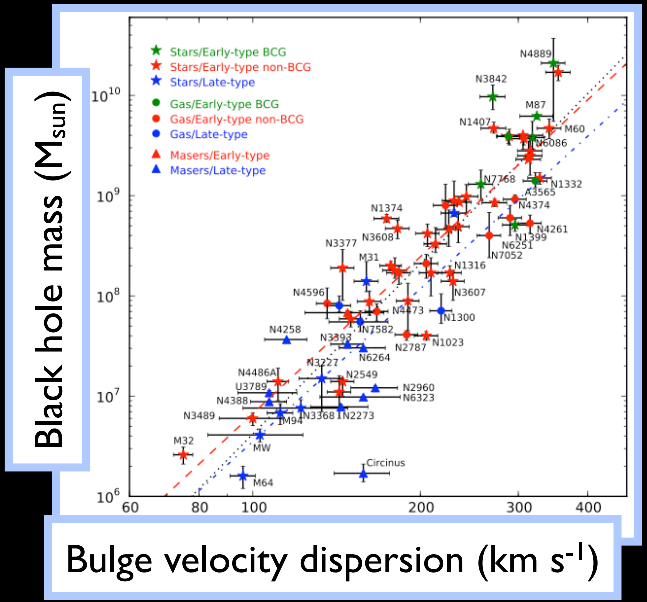
- SMBHs are fundamental components of today's massive galaxies
- SMBHs power AGN, which are a source of feedback in galaxies
- SMBHs are thought to play an important role in the evolution of galaxies

$M_{BH} \sim 1.4 \times 10^8\ M_{sun}$

Bender et al. (2005)



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



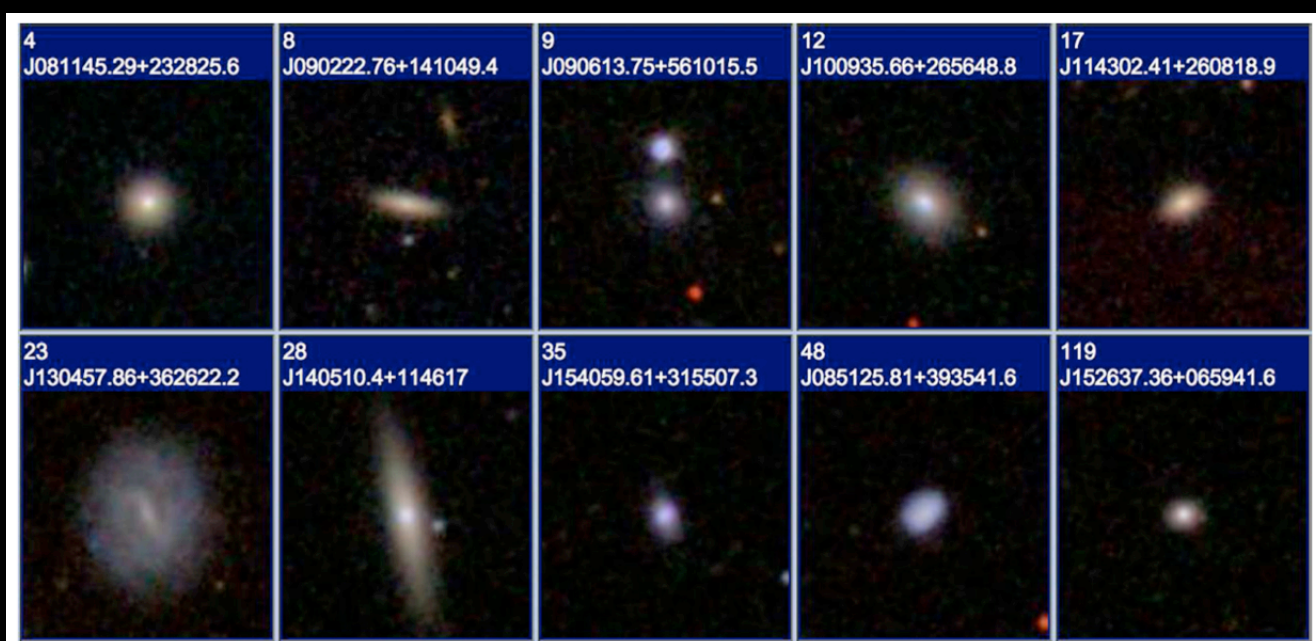
McConnell & Ma (2013)

... usually thought about in the context of massive galaxies with bulges

Dwarf galaxies can also host massive black holes!

(and a large fraction of dwarfs are forming stars)

>100 SDSS dwarfs (Reines, Greene & Geha 2013)



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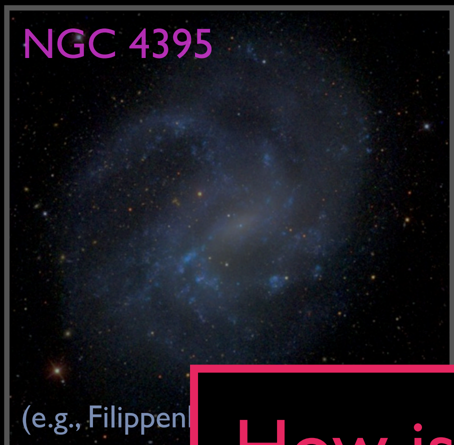


How is AGN activity connected to star formation in dwarf galaxies?

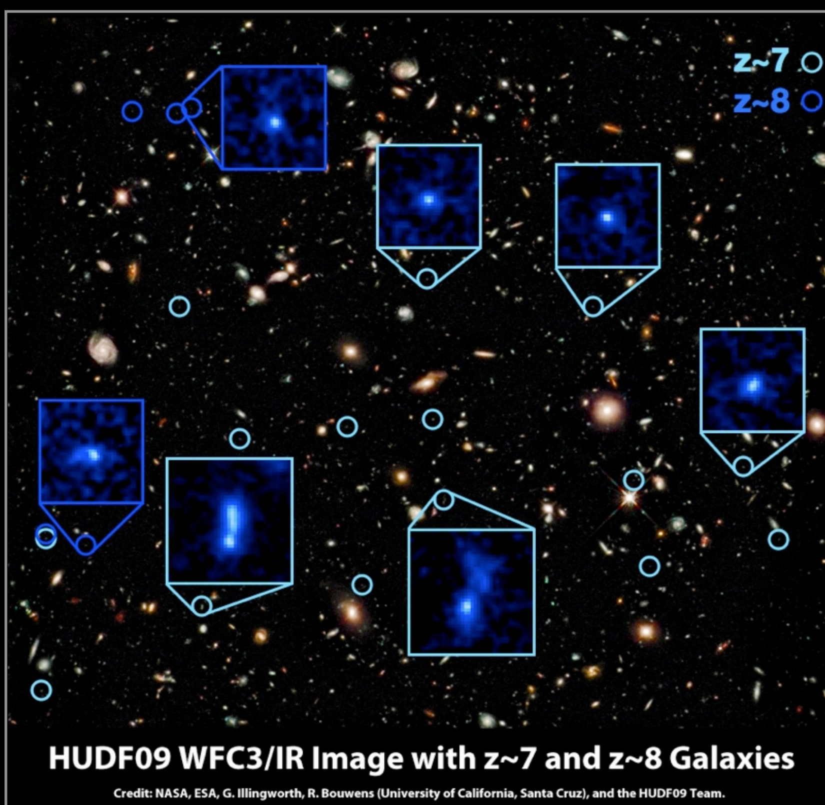
★ *Evidence for BH accretion in dwarf galaxies*

★ *Constraints on the origin of SMBH seeds*

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)

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)

The origin of supermassive black holes

Observations of high-redshift quasars:

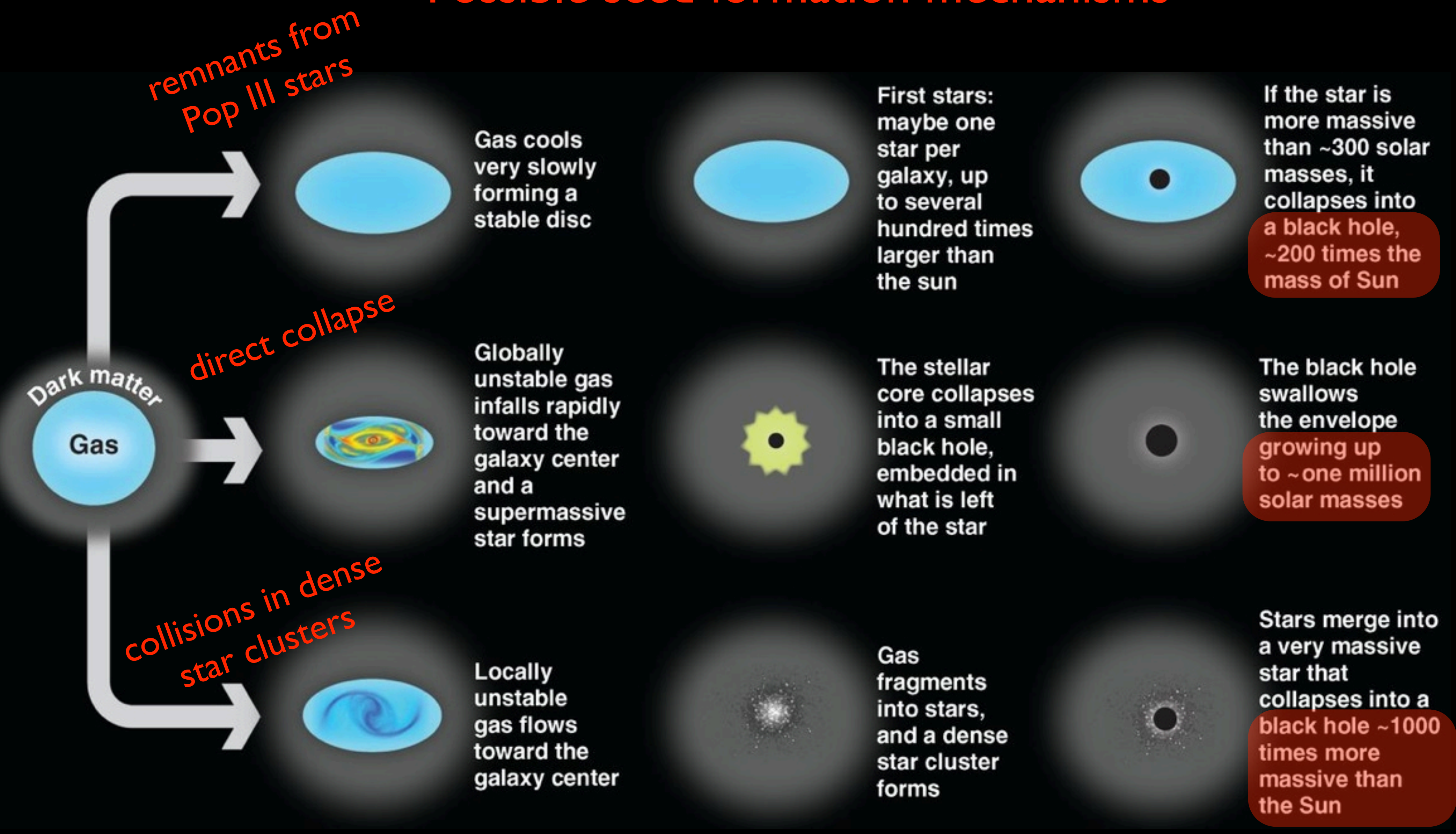
- $M_{BH} > 10^9\ M_{sun}$ less than a Gyr after the Big Bang

(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

The origin of supermassive black holes

Possible seed formation mechanisms

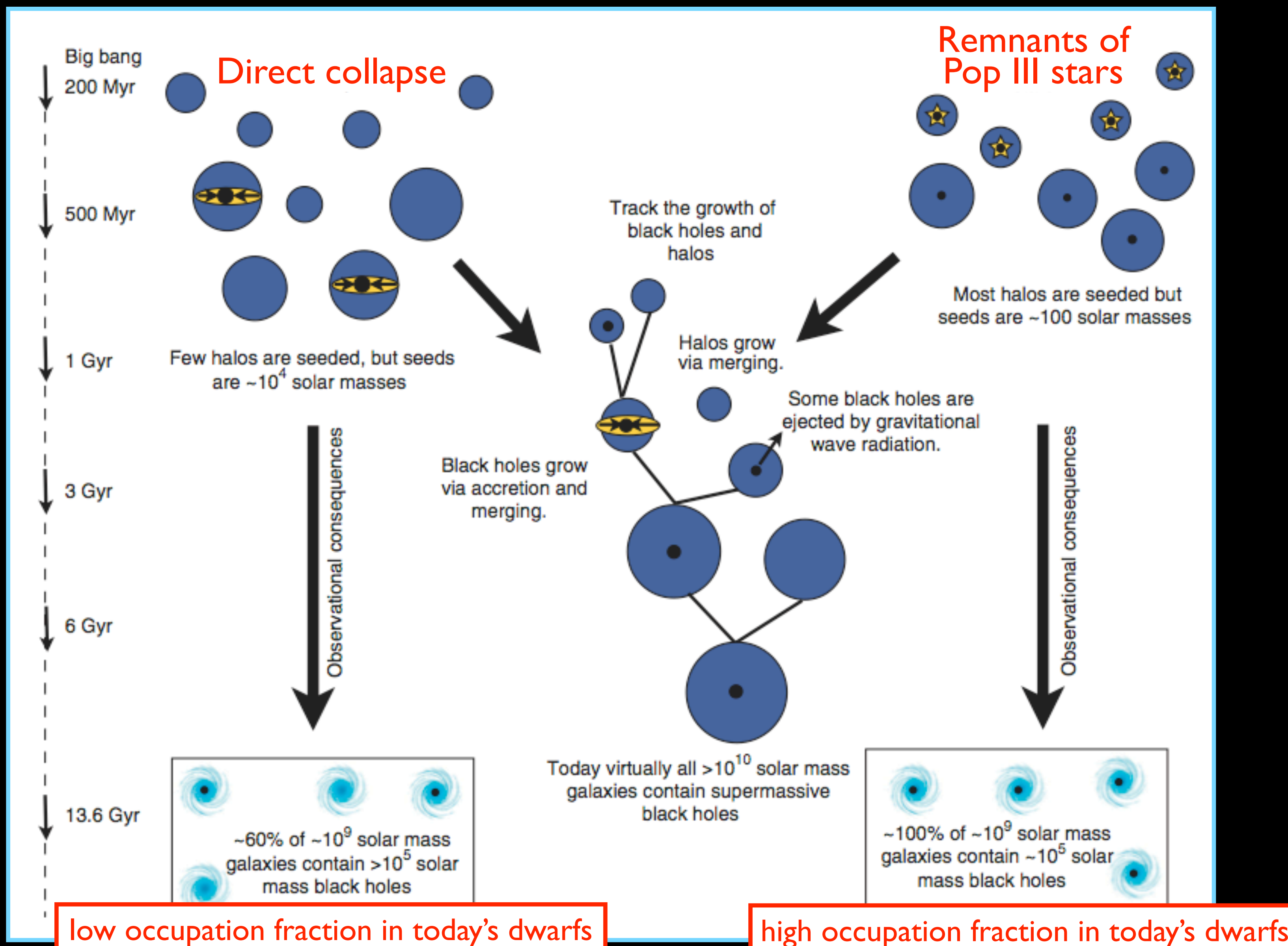


Volonteri 2012, *Science*

The origin of supermassive black holes

Models of black hole growth in a cosmological context

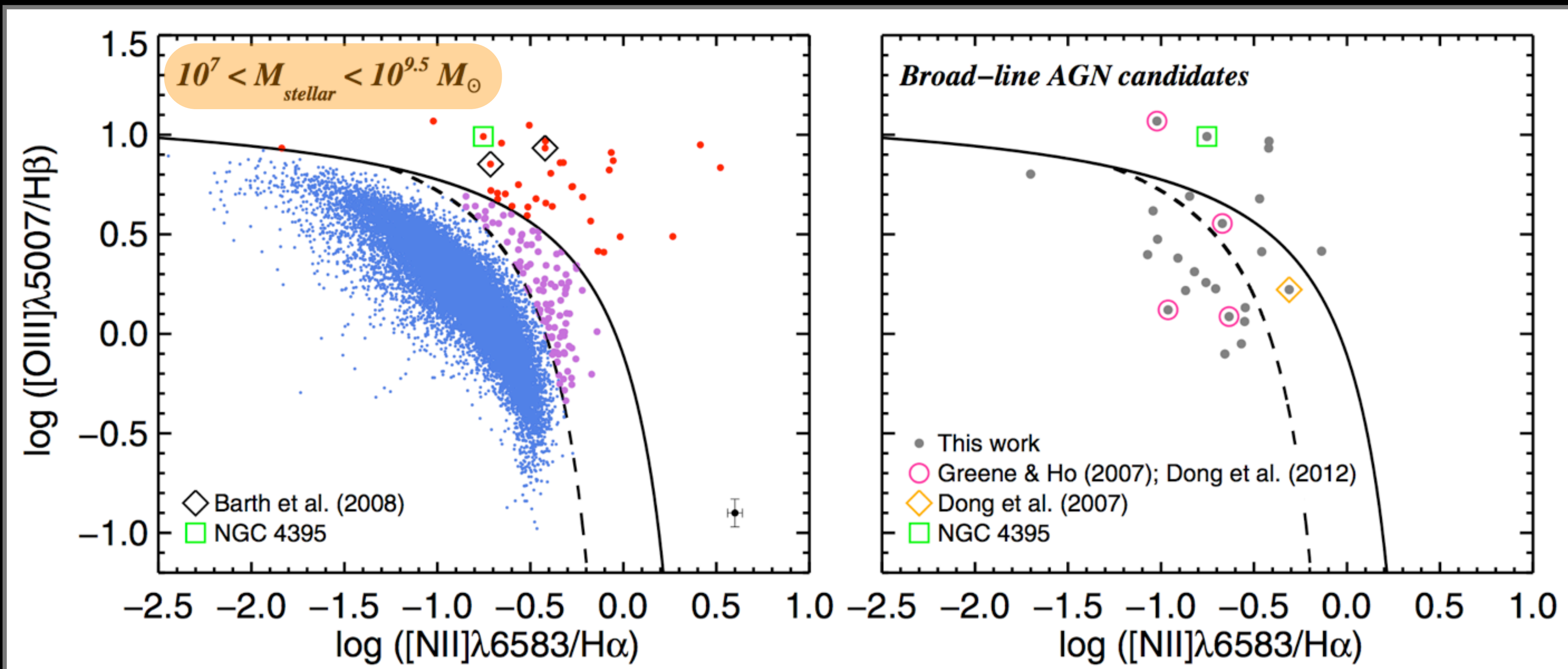
time



Greene 2012, *Nature Communications*; also see review in Volonteri 2010 *and now some recent evidence for dwarf galaxies hosting massive BHs...*

Dwarf galaxies with optical signatures of active massive BHs

Largest sample of dwarfs hosting massive BHs to date



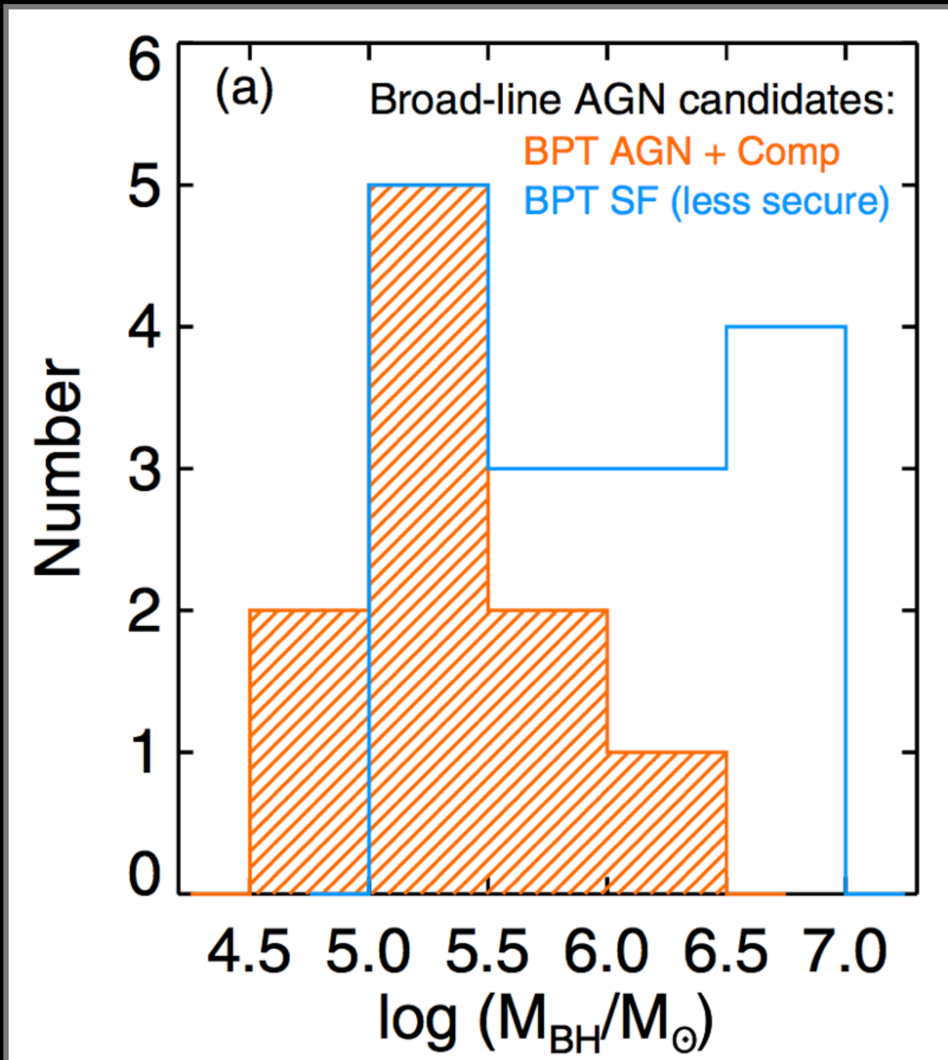
35 AGN
101 Composites

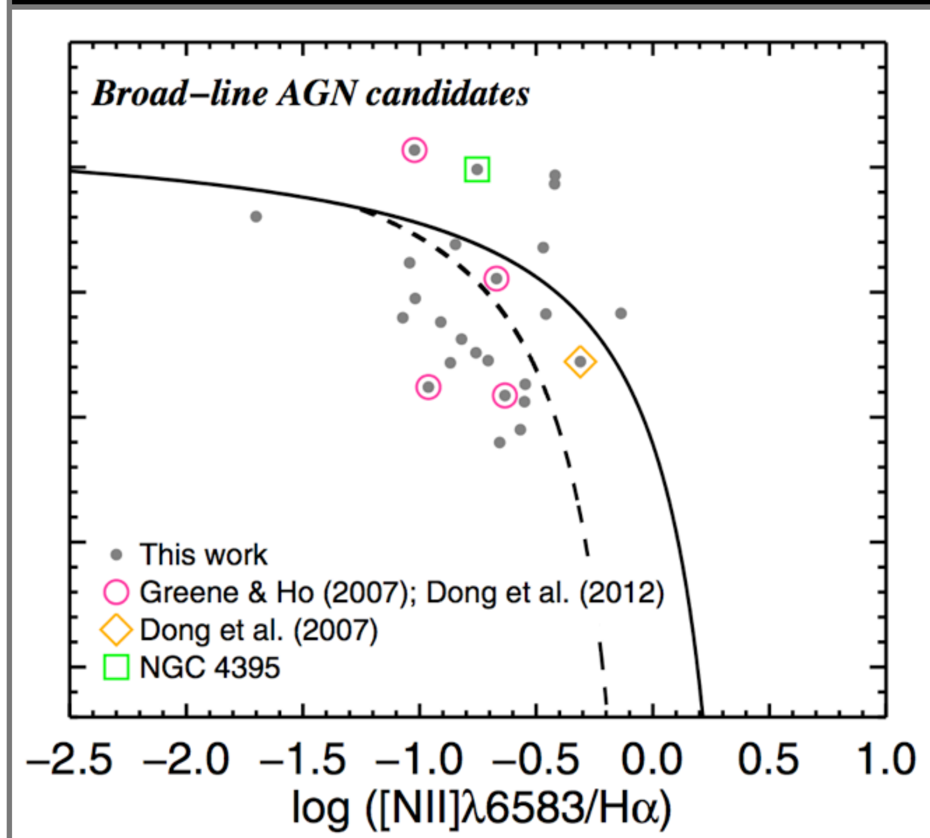
25 broad-line AGN candidates
(with BH mass estimates)

Reines, Greene & Geha 2013

Dwarf galaxies with optical signatures of active massive BHs

Largest sample of dwarfs hosting massive BHs to date





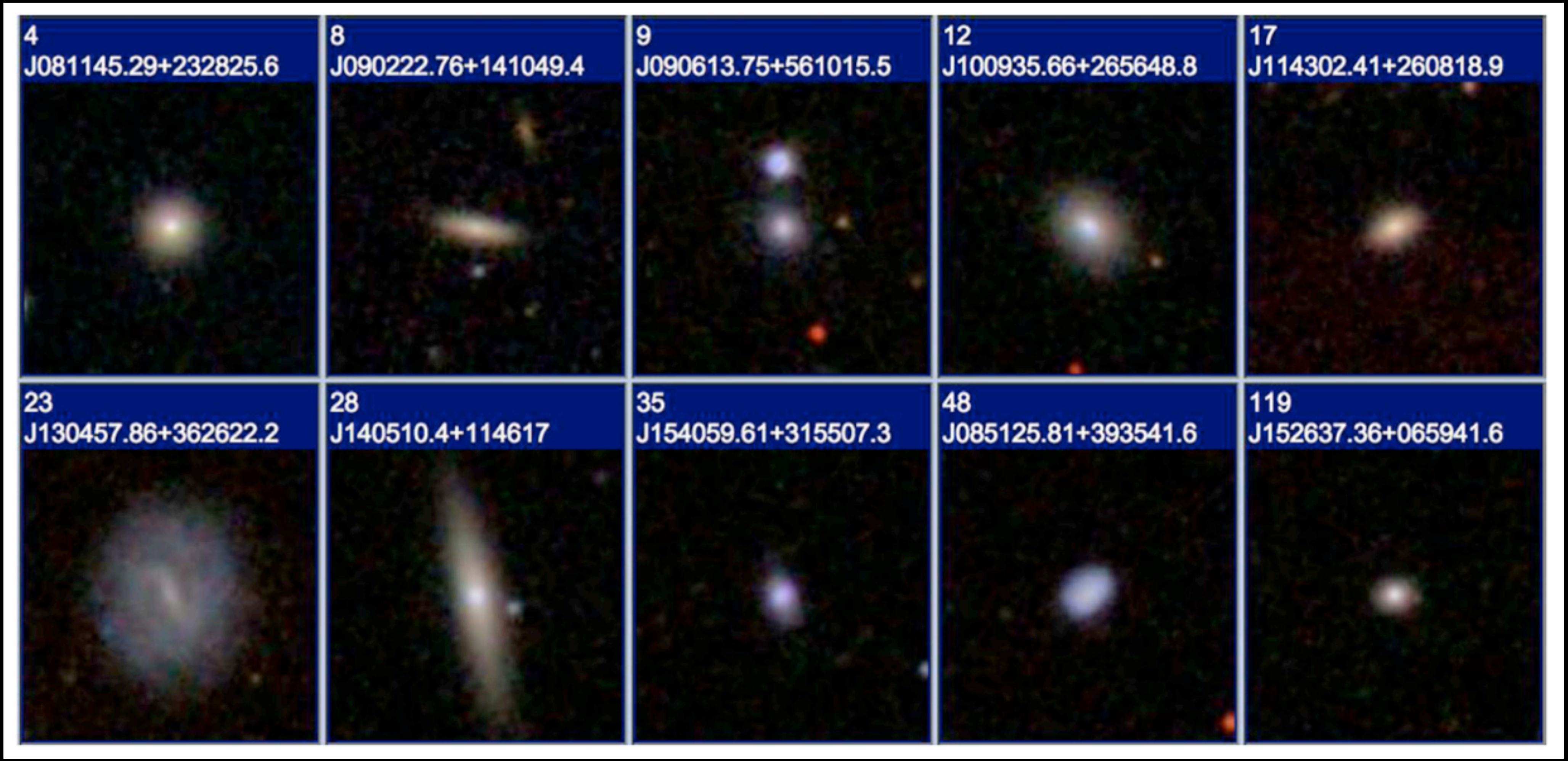
Least-massive black holes known

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

Reines, Greene & Geha 2013

Dwarf galaxies with optical signatures of active massive BHs

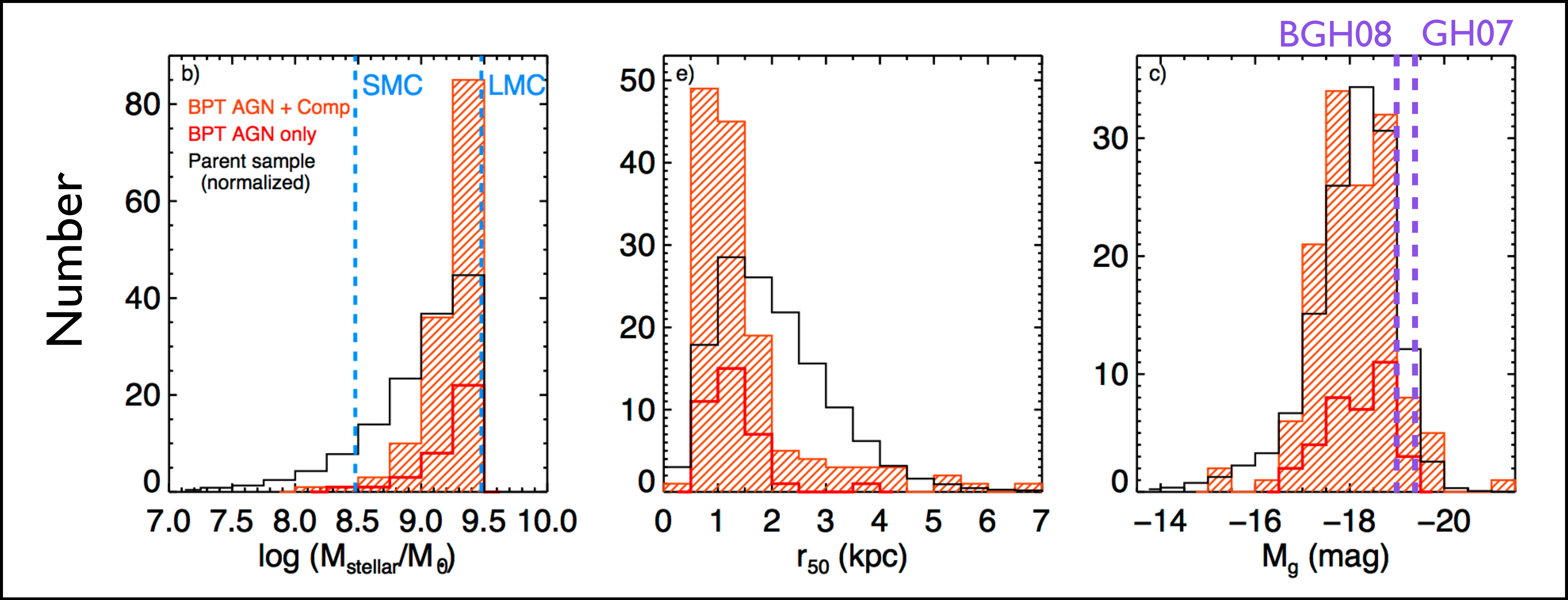
Examples of host galaxies



Reines, Greene & Geha 2013

Dwarf galaxies with optical signatures of active massive BHs

Smallest and least-massive galaxies known to host masssive BHs

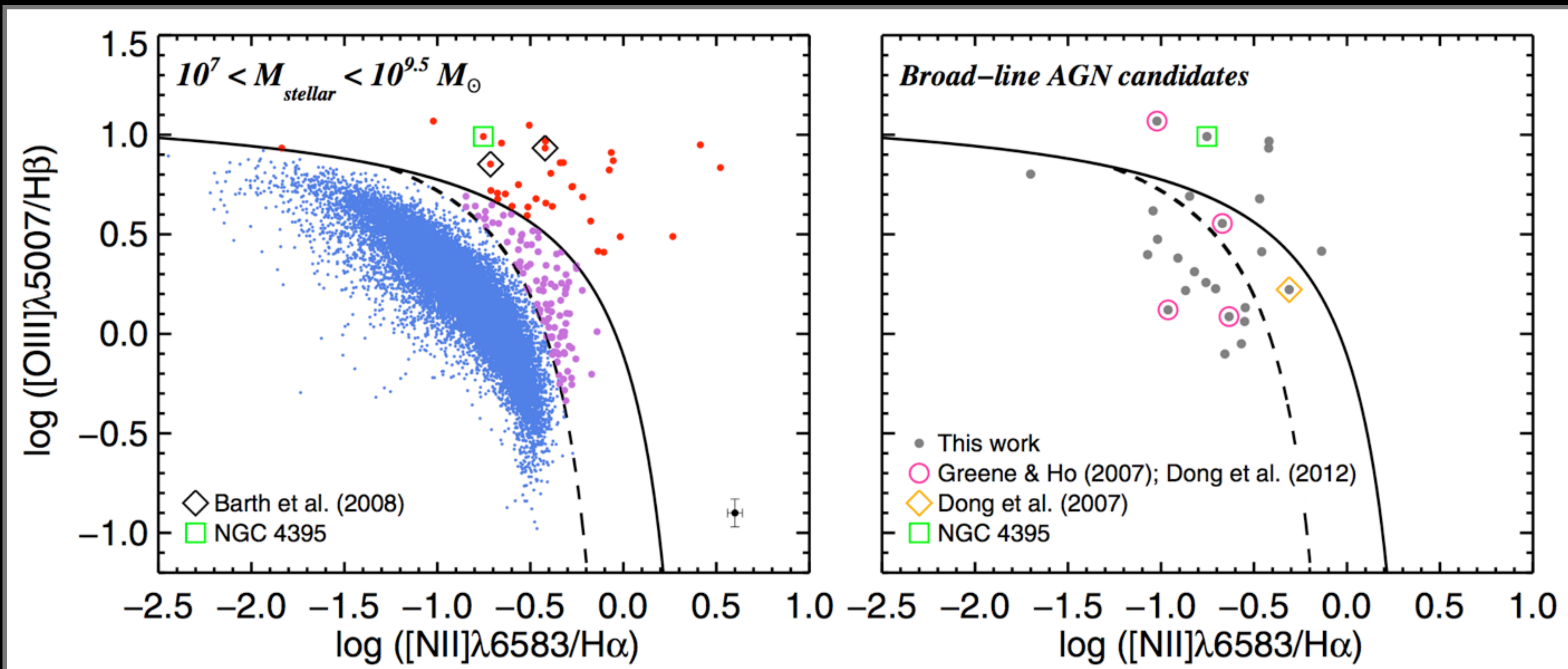


stellar mass   half-light radius   *Mg*

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

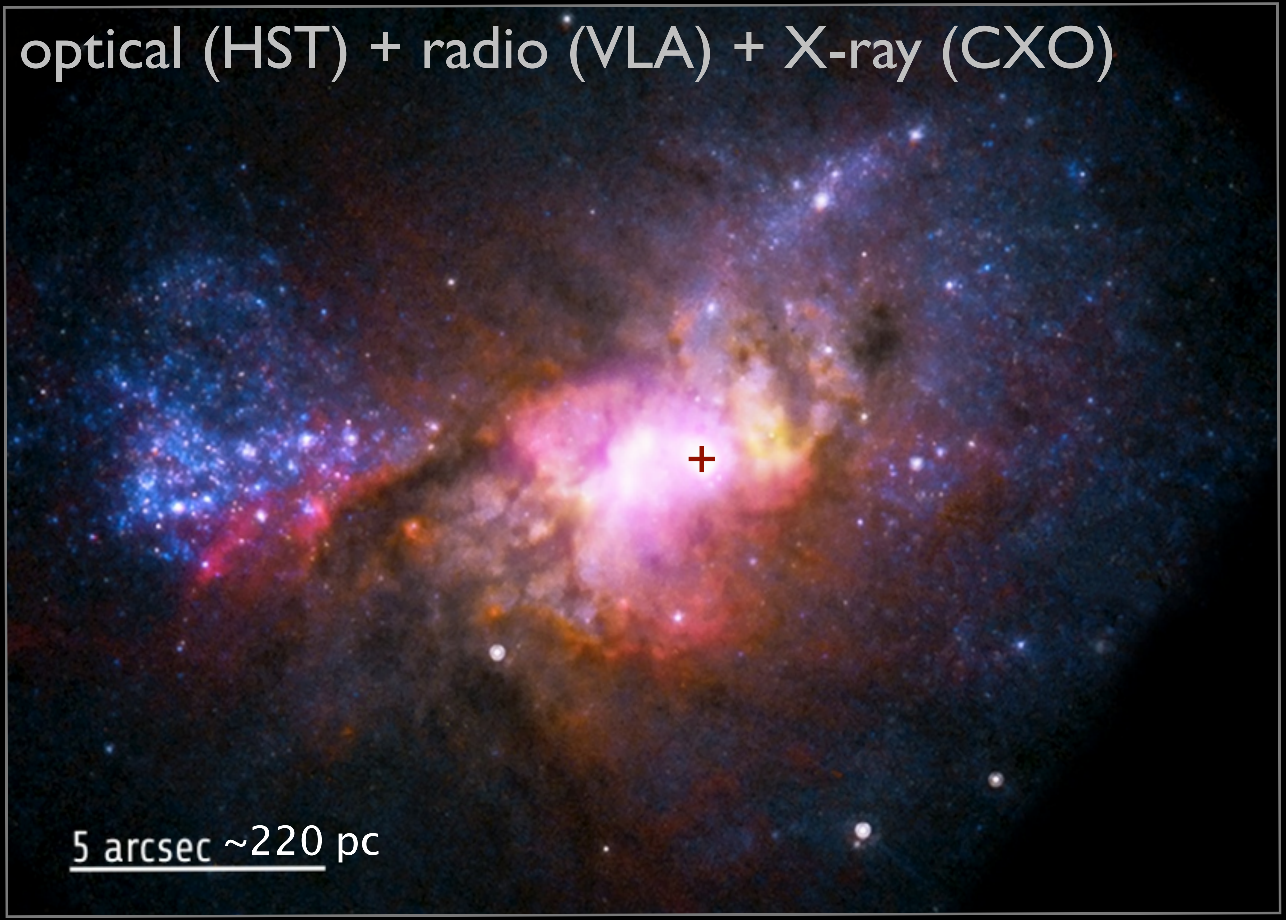
Reines, Greene & Geha 2013

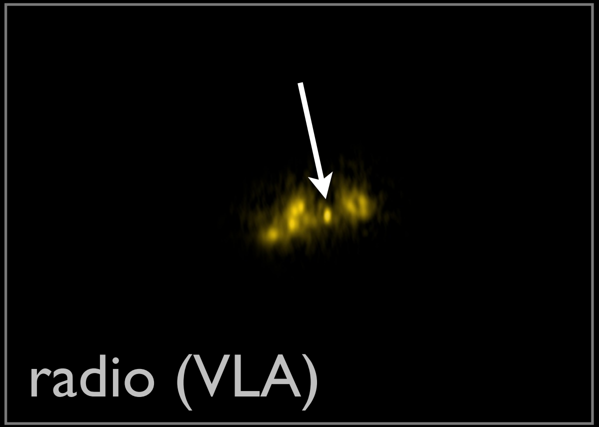
Need other diagnostics!

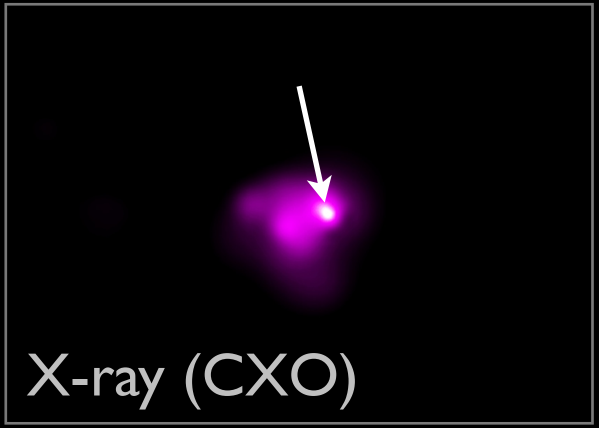
High-resolution X-ray and radio observations

- 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







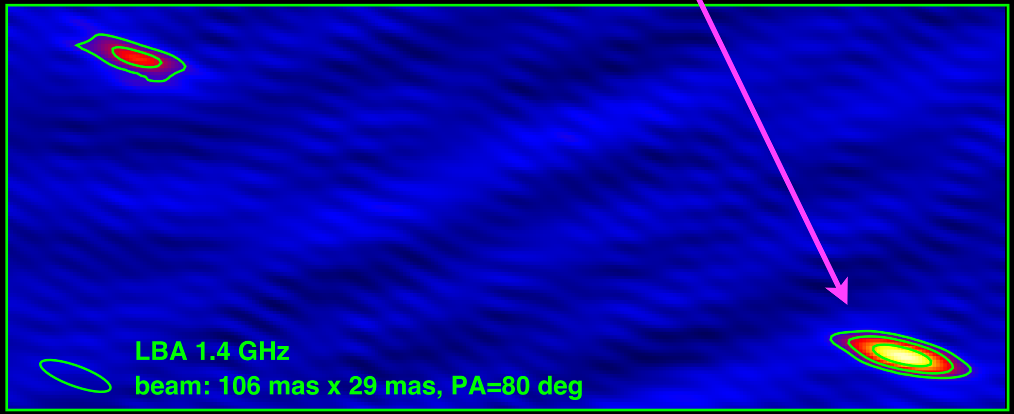
Reines et al. 2011, *Nature*

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

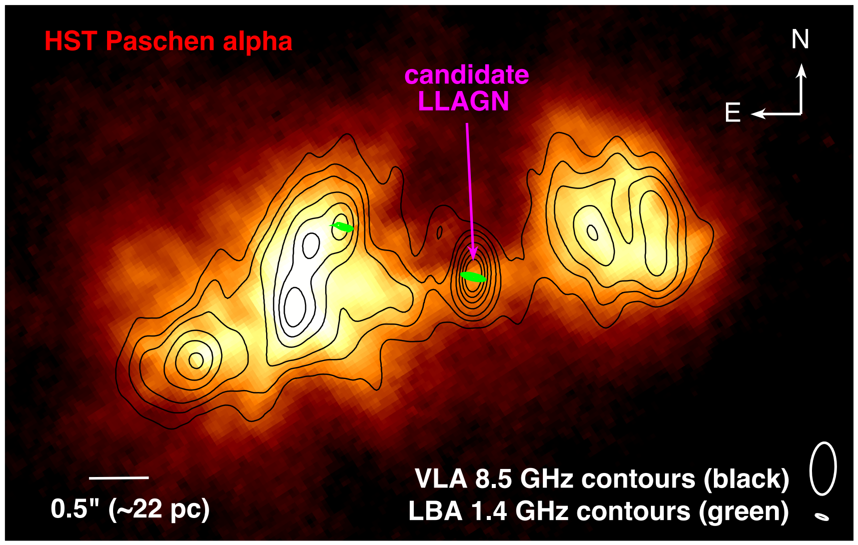
VLBI follow-up with the Long Baseline Array (LBA)

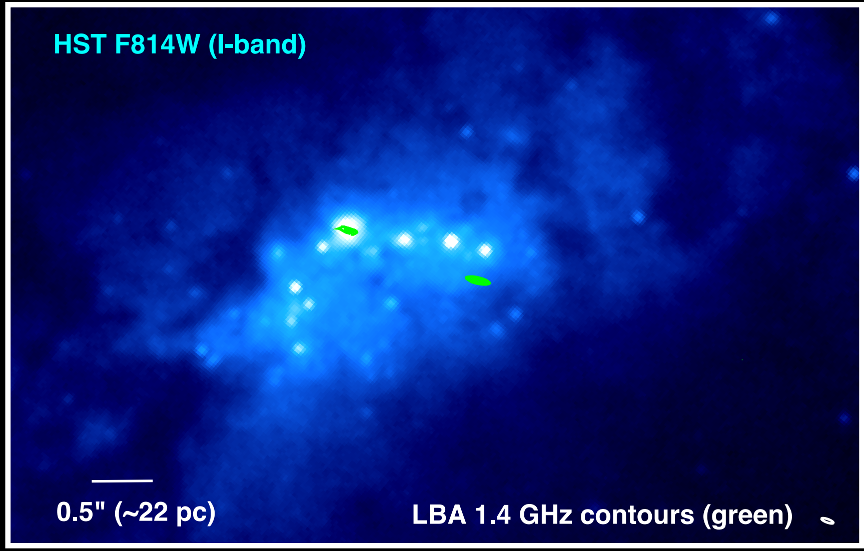
nuclear radio source:
$\lesssim$ 3 x 1 pc



Reines & Deller 2012

HST imaging of central ~ 250 pc





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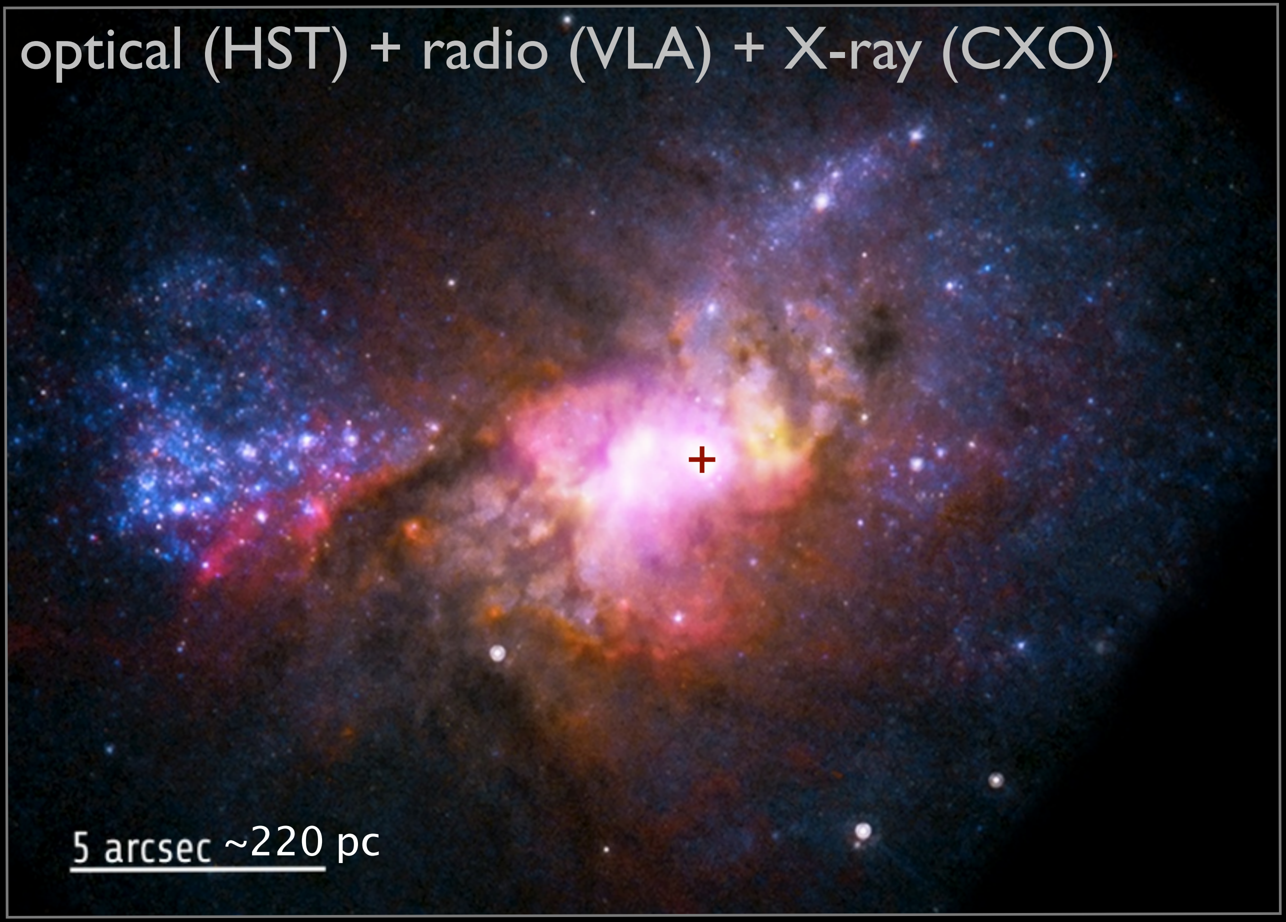
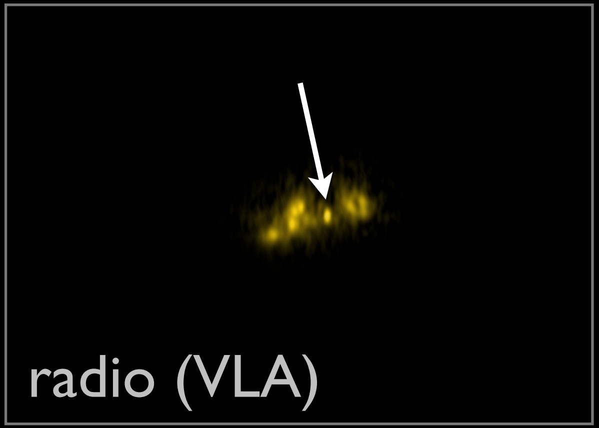
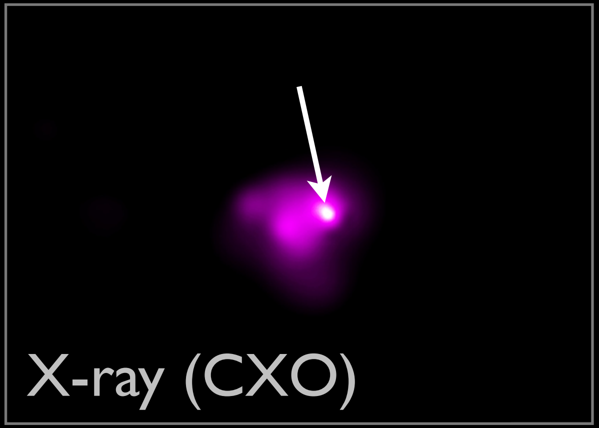
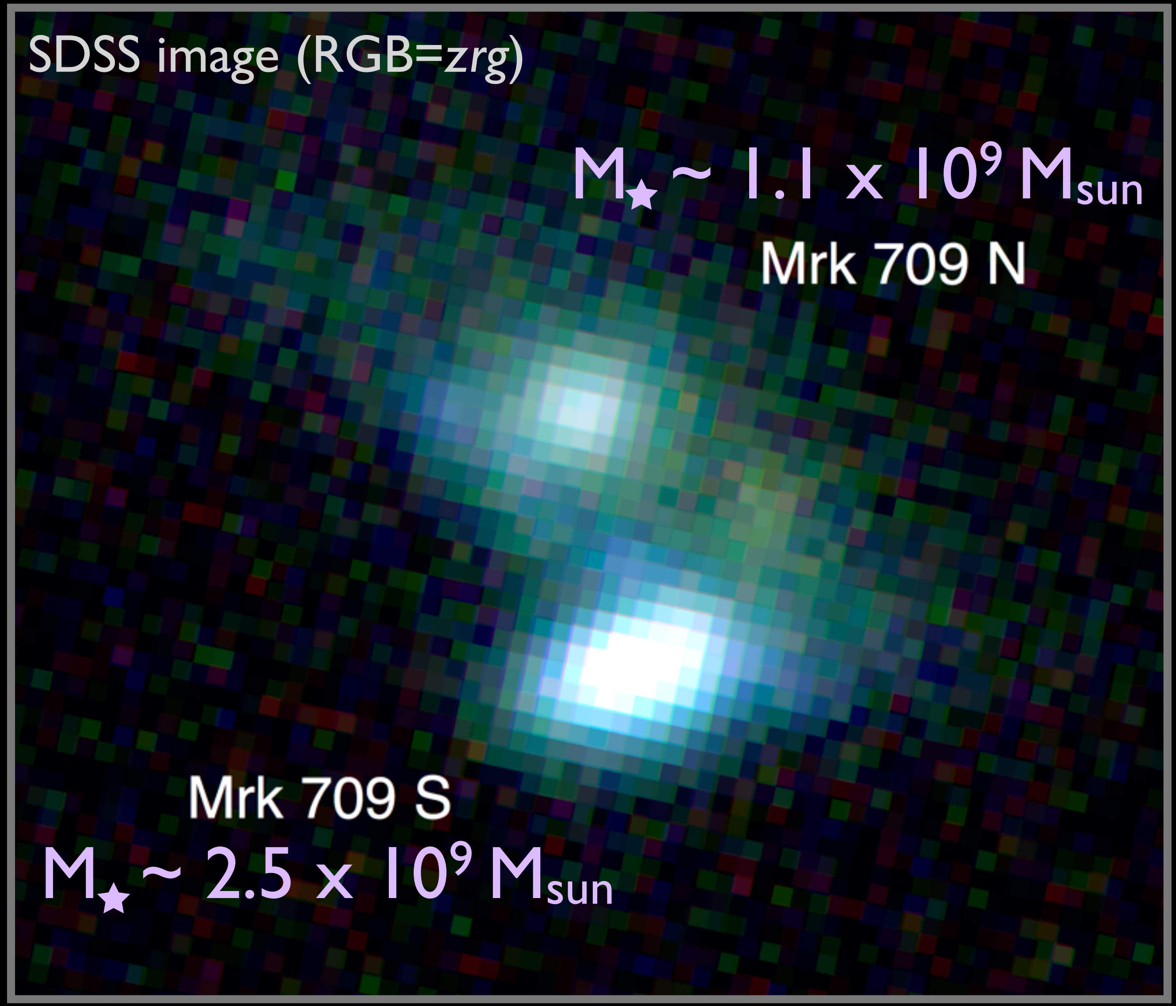






Motivation to look for additional examples of massive BHs in star-forming dwarf galaxies with Chandra and the VLA

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



metallicity ~ 10% solar (Masegosa et al. 1994)
active star formation

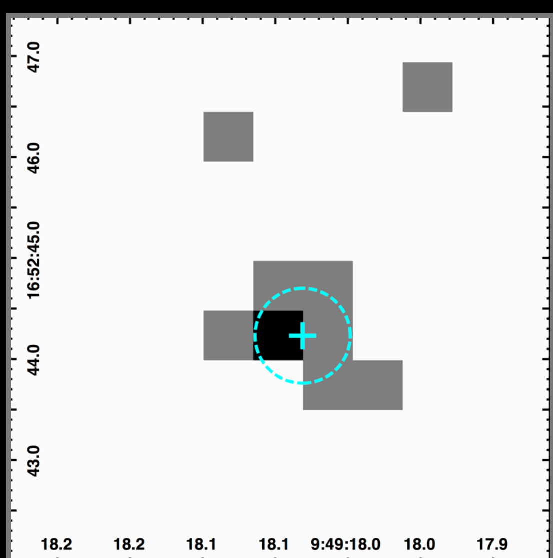
Reines et al. 2014

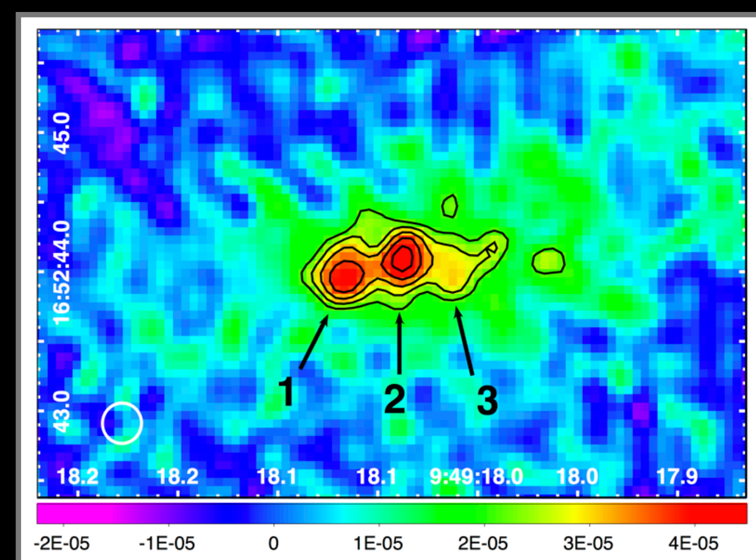
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

\+

Chandra ~ 21 ks

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





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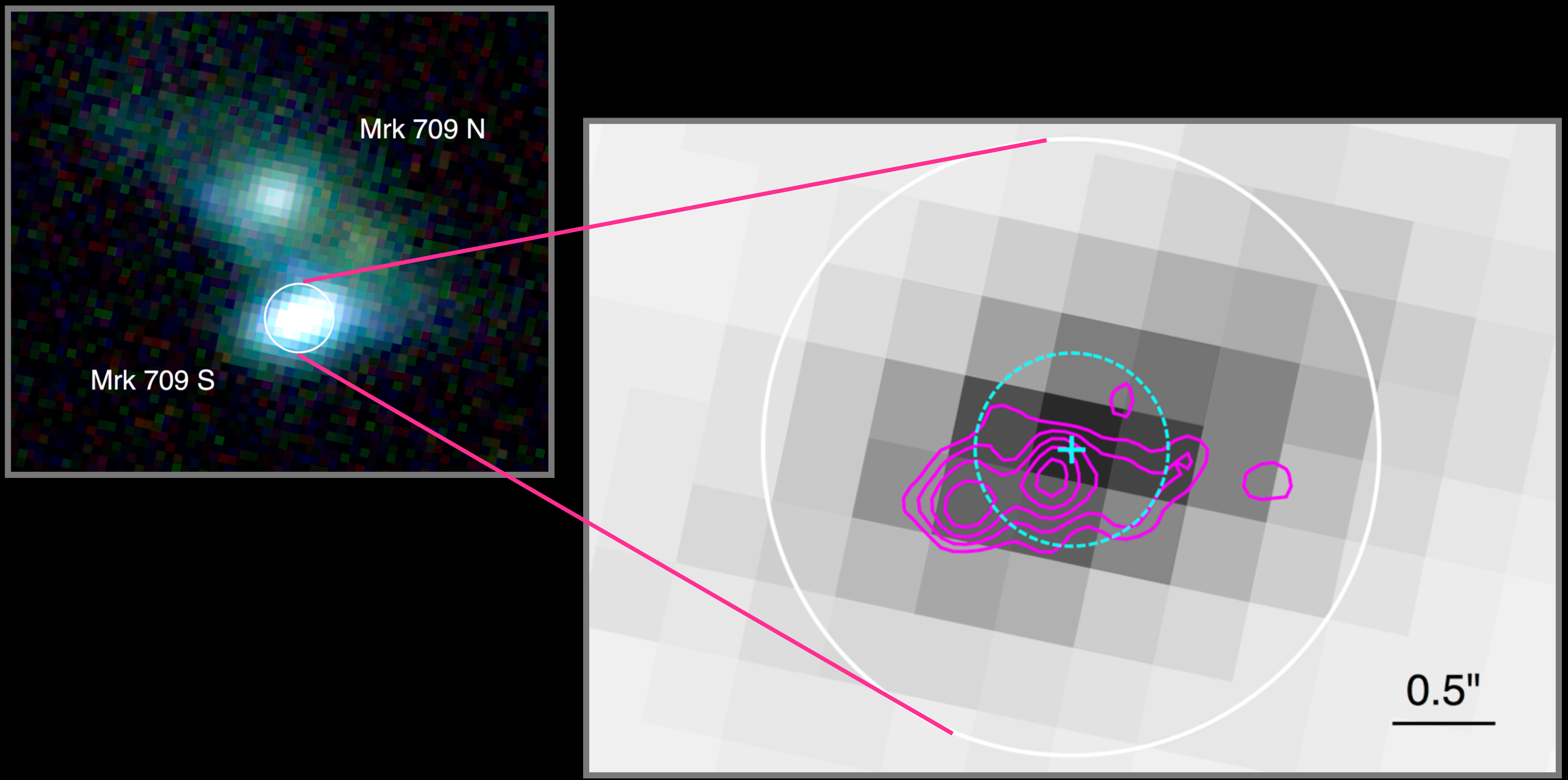
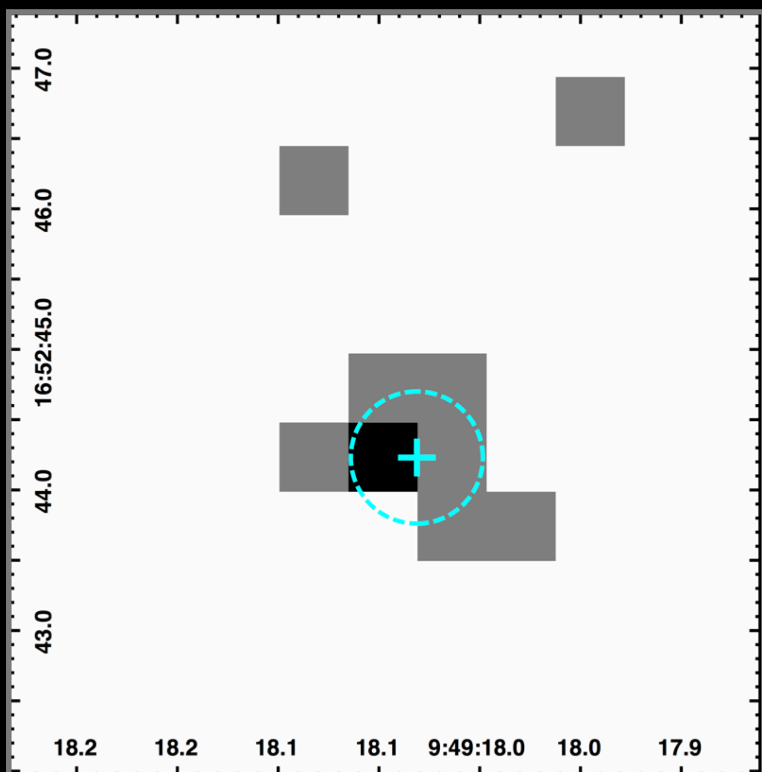


SDSS z-band image of Mrk 709 S with position of hard X-ray source and radio contours

Reines et al. 2014

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

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:

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

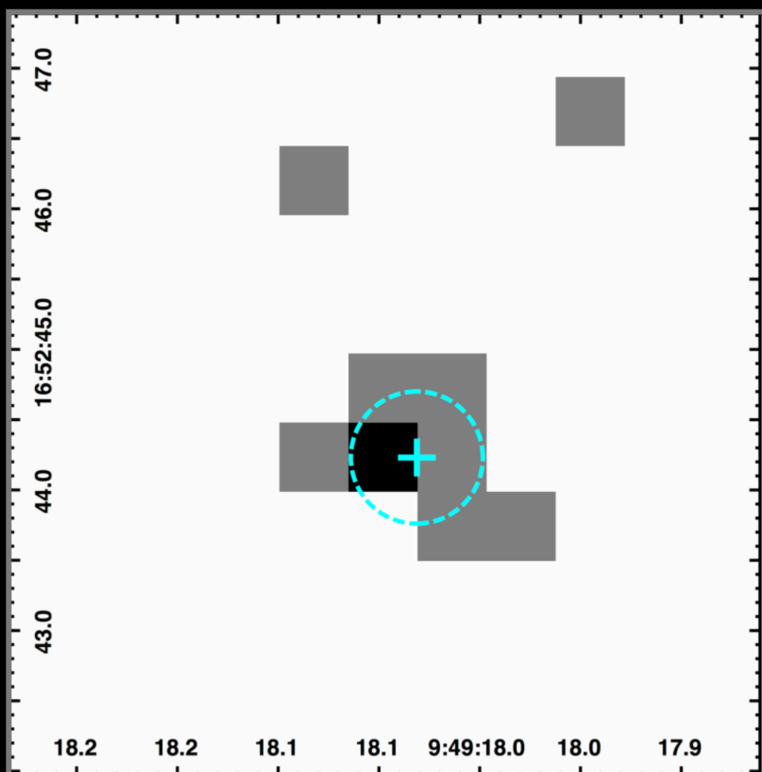
Lehmer et al. (2010)

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

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

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

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



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

(90% confidence interval)

Minimum Black Hole Mass:

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

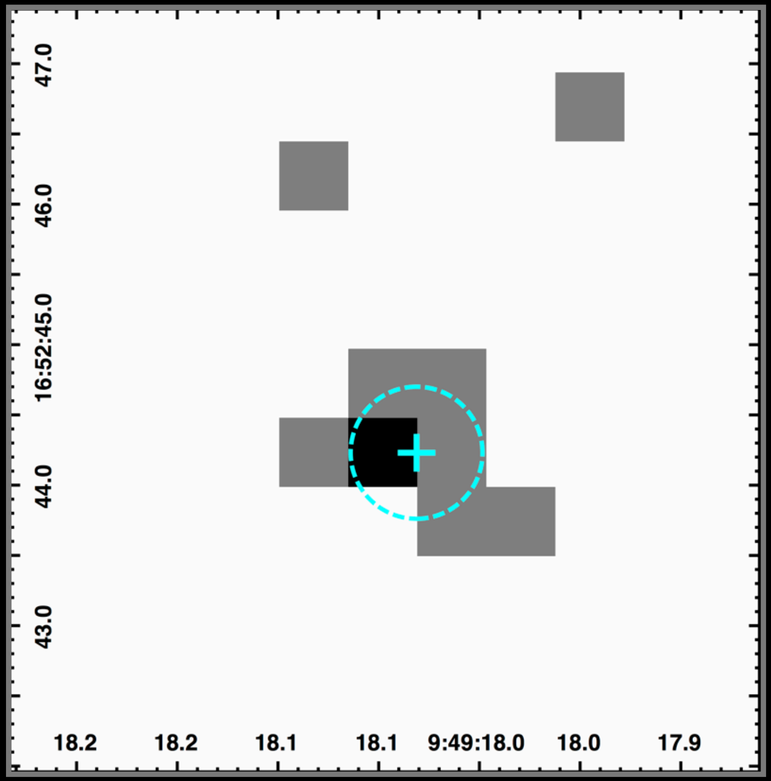
Assuming BH radiating at Eddington limit and X-ray bolometric correction = 1,

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

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

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

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



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

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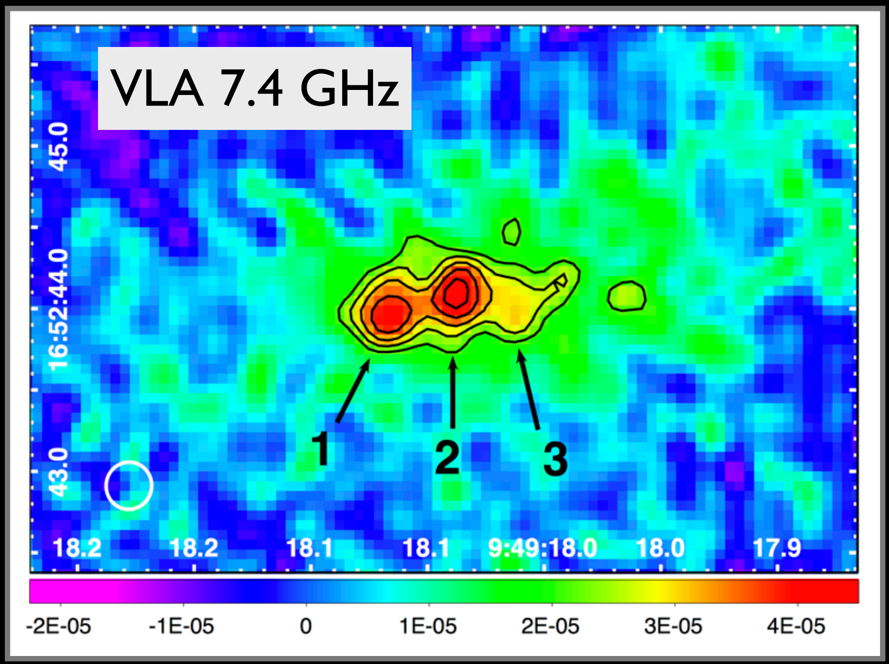
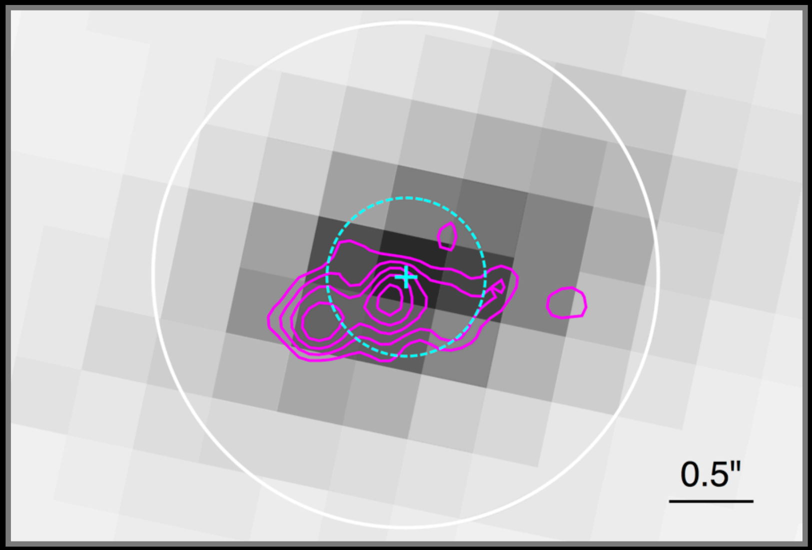
M_{BH} > 385 M_{sun}

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

BH mass may be orders of magnitde larger

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

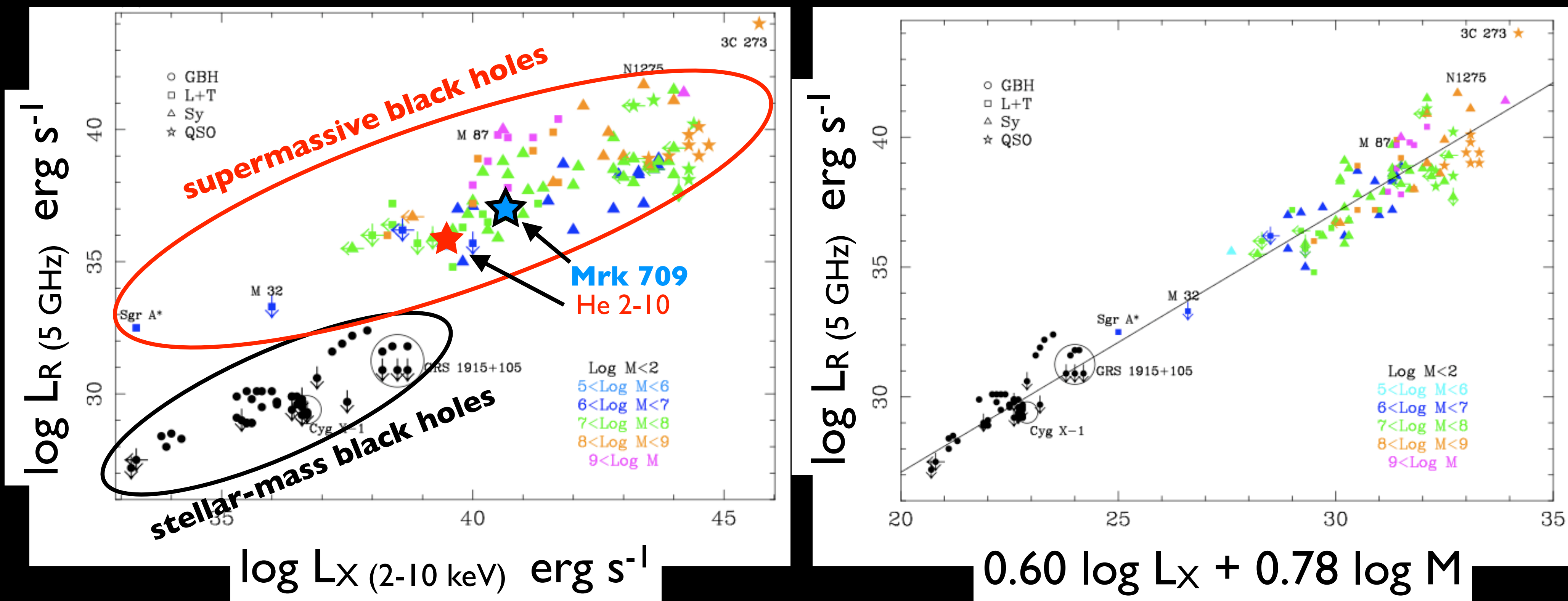
Central radio source (#2)

$S_{7.4GHz}$ ~ 40 +/- 10 uJy
$S_{5.0GHz}$ ~ 60 +/- 20 uJy

L_{radio} = (1.6 + 0.6) x 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: $M_{BH} \sim 6 \times 10^6\ M_{sun}$

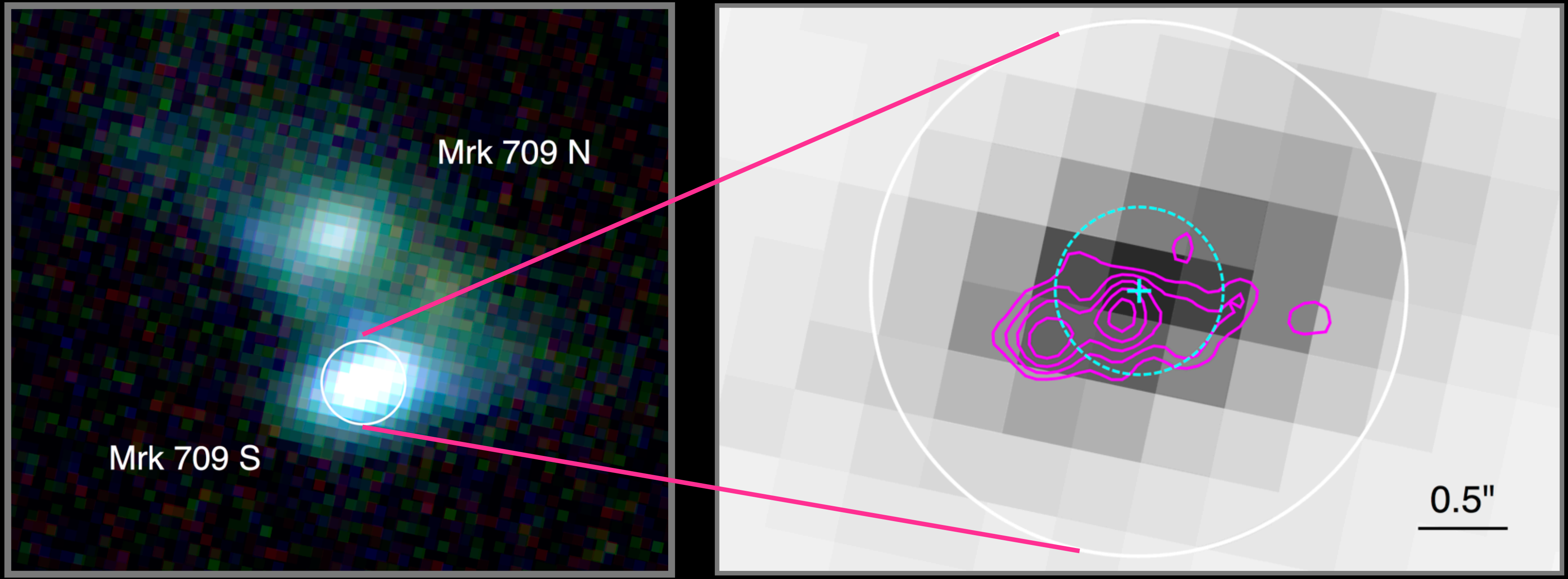
A Candidate Massive Black Hole in the Low-Metallicity Dwarf Galaxy Pair Mrk 709

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, and the only known BH-hosting dwarf in an interacting pair
- Systems like this may have been more common at higher redshifts

Reines et al. 2014

Summary

• 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

• New searches are underway and following-up on existing samples

• Implications for galaxy formation models and the connection between AGN activity and star formation at low masses, as well as the origin of supermassive black hole seeds