Probing the Origin of Supermassive Black Hole Seeds with Nearby Dwarf Galaxies

Amy Reines
Einstein Fellow
National Radio Astronomy Observatory

Motivation: The origin of supermassive BH seeds

- 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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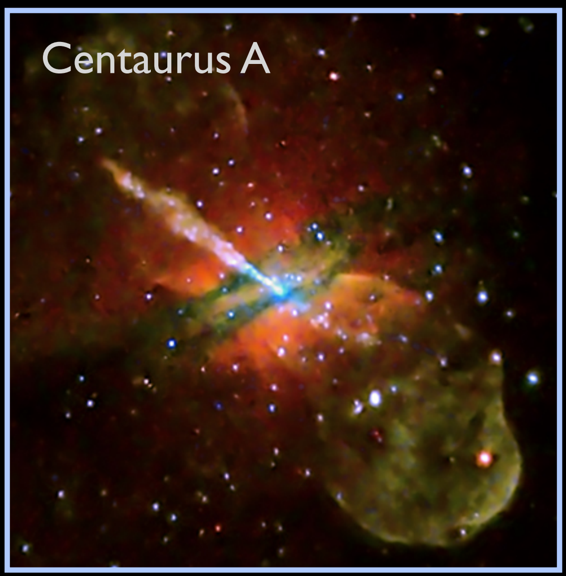

NASA/CXC/CfA/R.Kraft et al.

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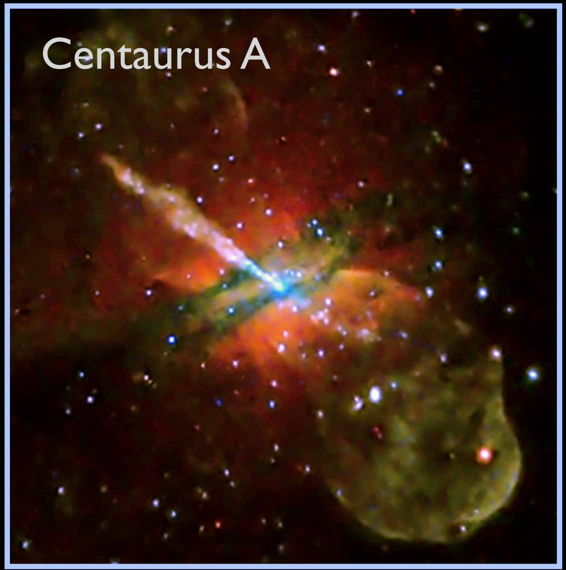

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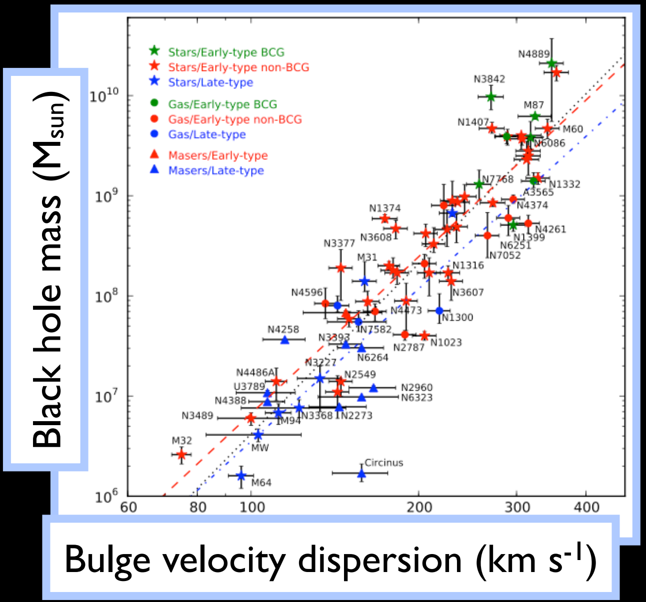

McConnell & Ma (2013)

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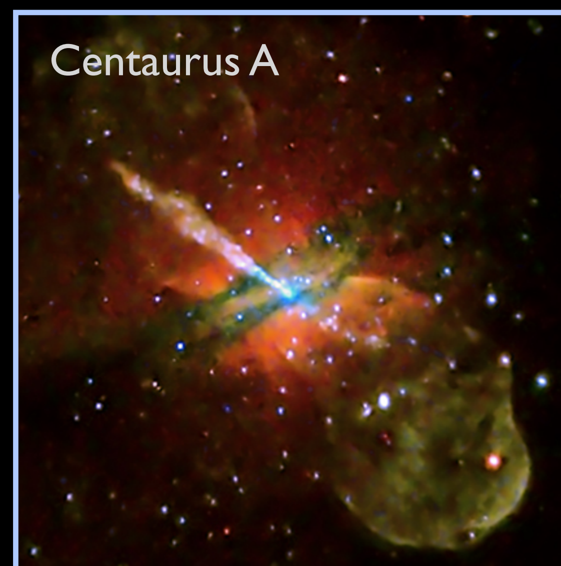

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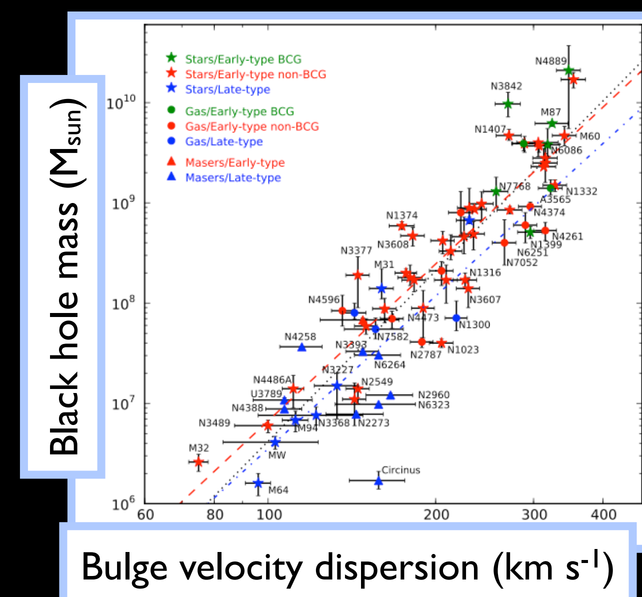

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We don't know how these SMBHs get started in the first place

Motivation: The origin of supermassive BH seeds

Constraints on BH seed formation come from:

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★ *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 must start out with masses considerably larger than normal stellar-mass BHs

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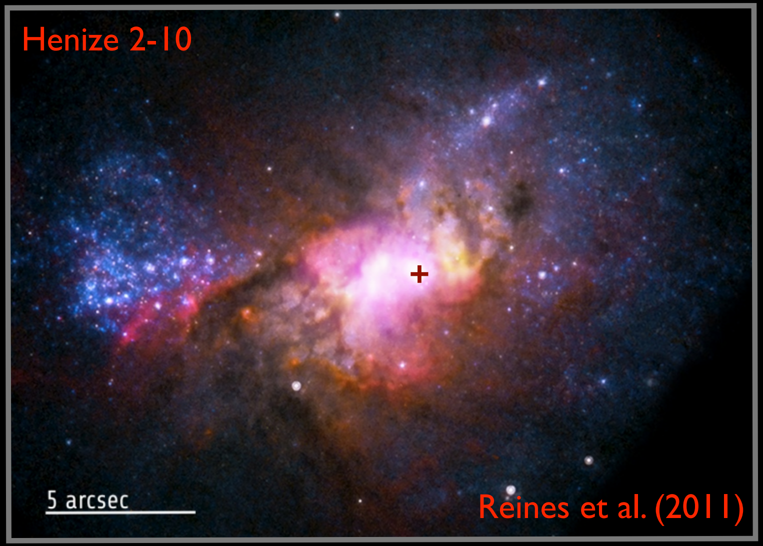
★ *Low-redshift dwarf galaxies*



- dwarfs have relatively quiet merger histories and may host BHs not so different from the first seed BHs

e.g. Filippenko & Ho (2003); Barth et al. (2004); Reines et al. (2011)

- properties and prevalence of massive BHs in dwarfs can help distinguish between various formation mechanisms

e.g. Volonteri 2010 and references therein

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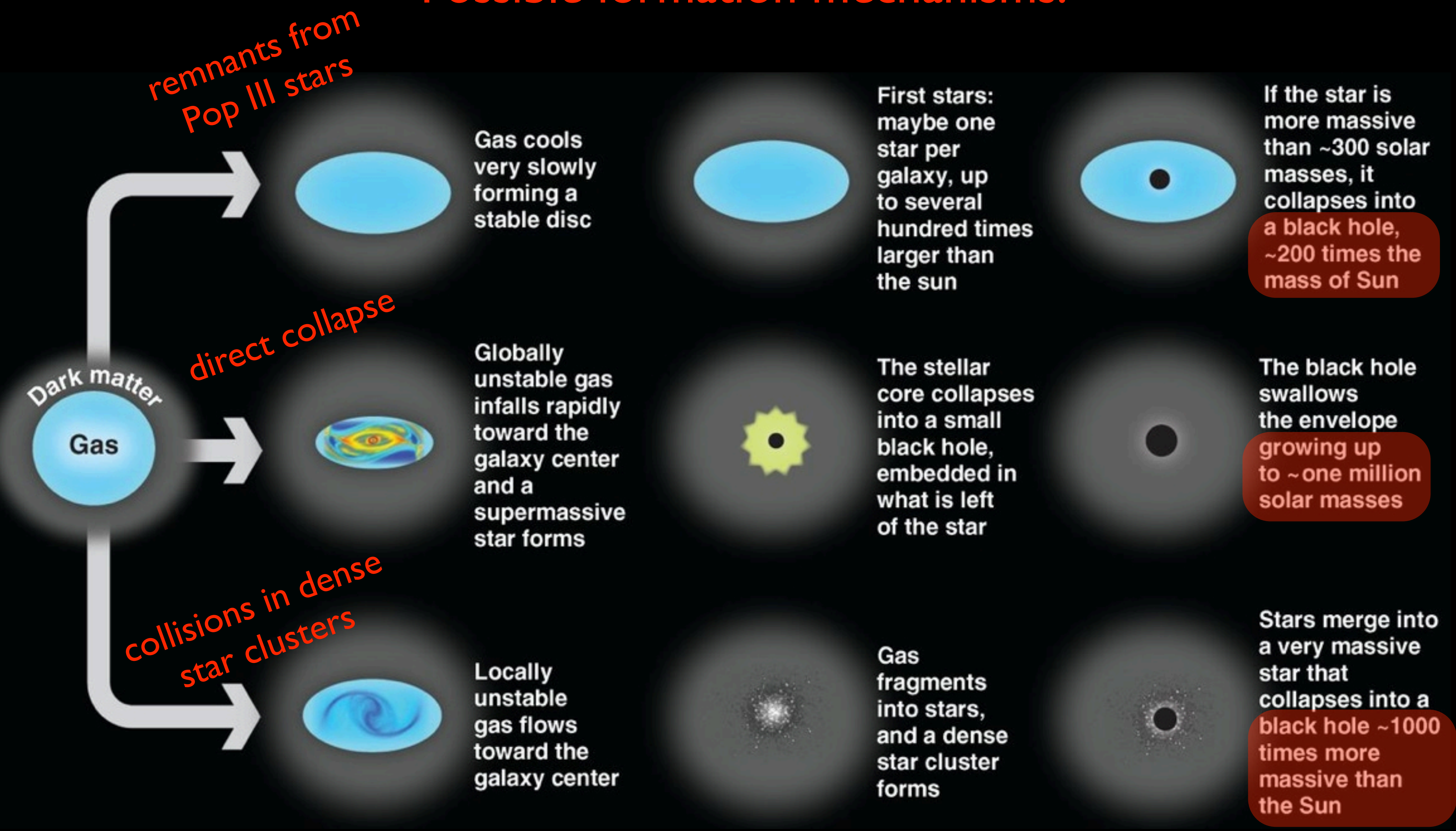
Possible formation mechanisms:



Volonteri 2012, *Science*

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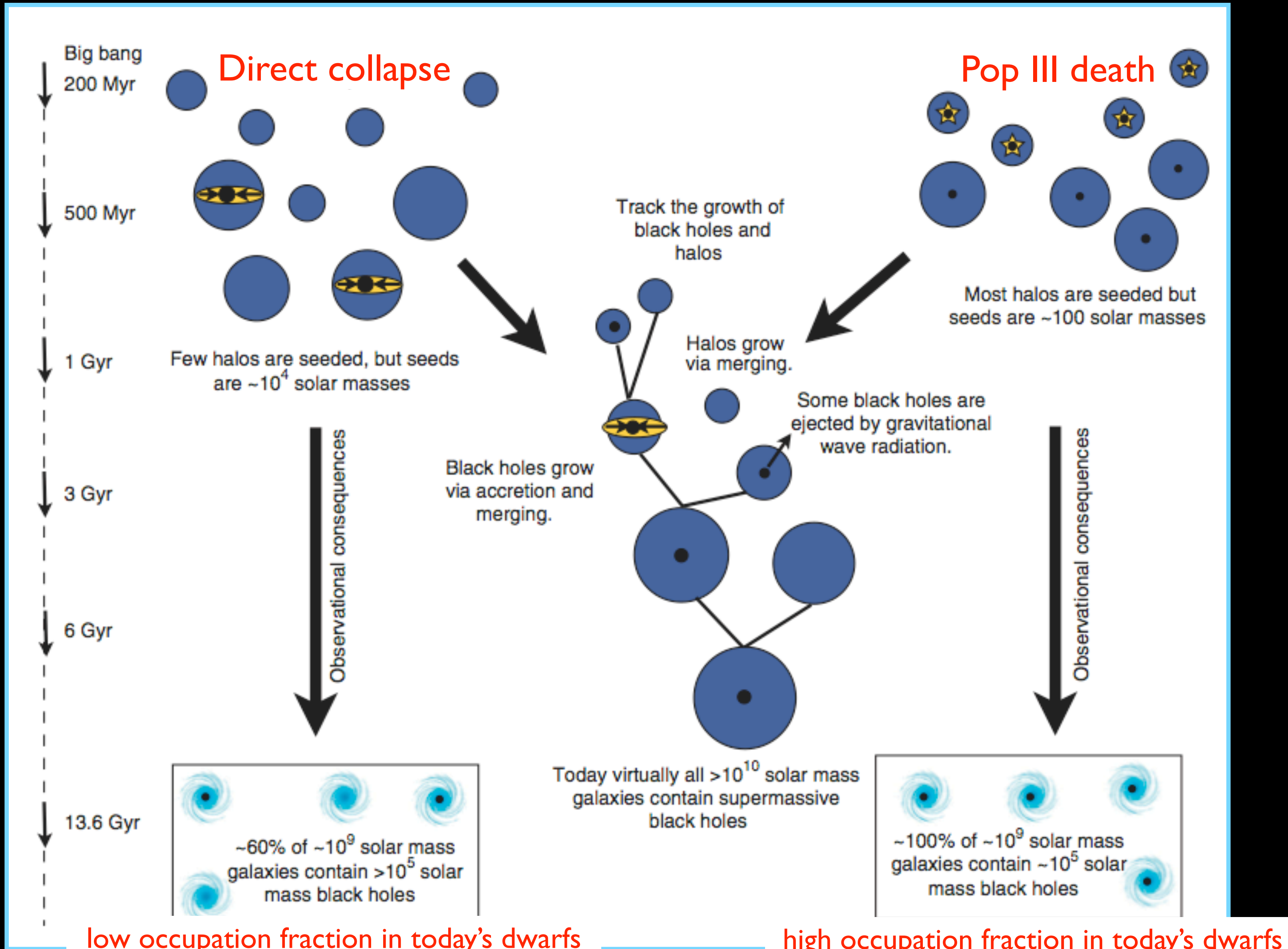
Evolution of seed BHs

time



Greene 2012, *Nature Communications*

Observations in the low-mass regime

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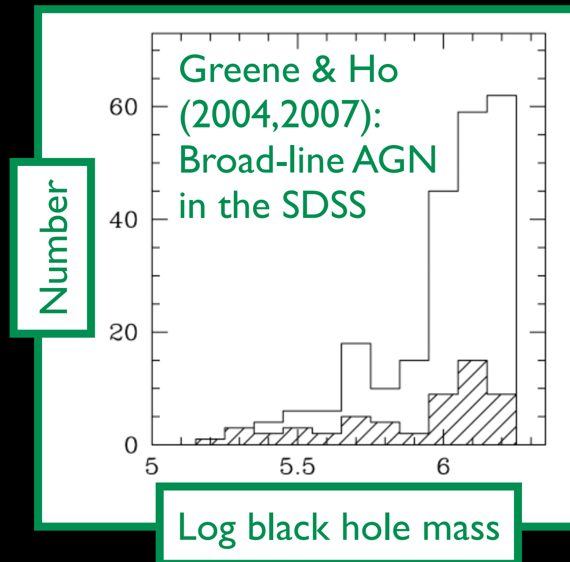
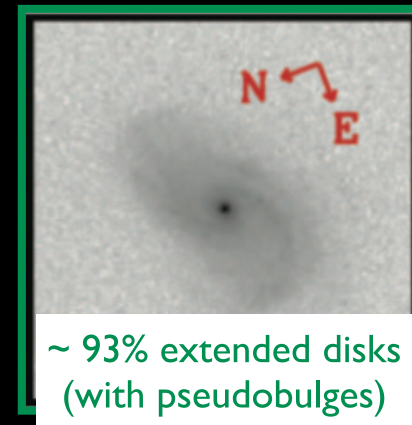
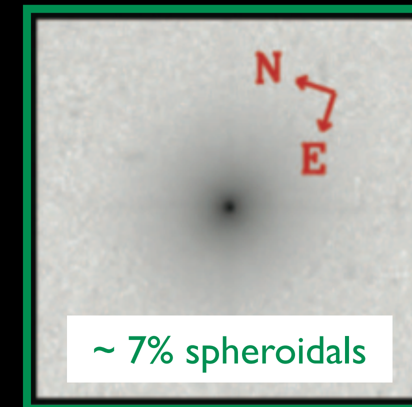


Also see Dong et al. (2007)
1 BLAGN in SDSS dwarf





Greene et al. (2008); Jiang et al. (2011), Xiao et al. (2011)

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Narrow-line AGN
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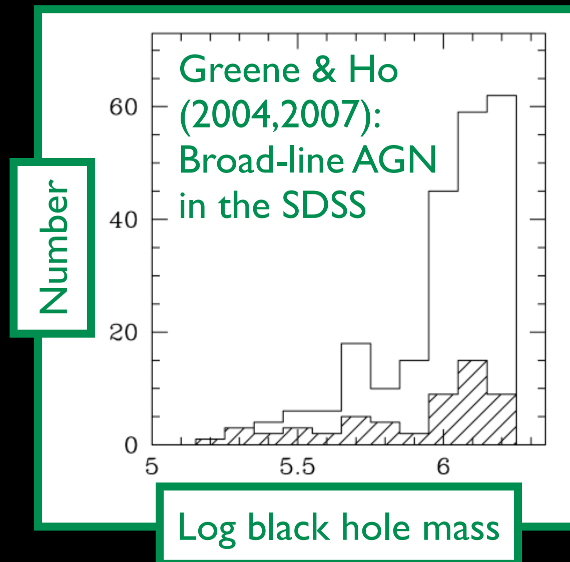

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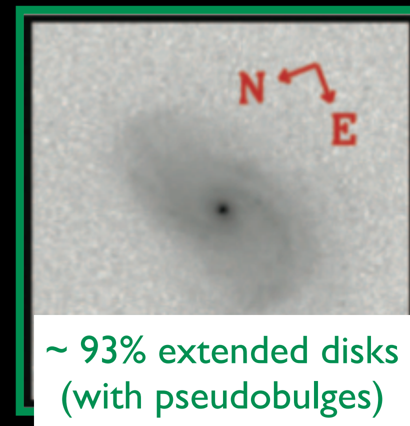

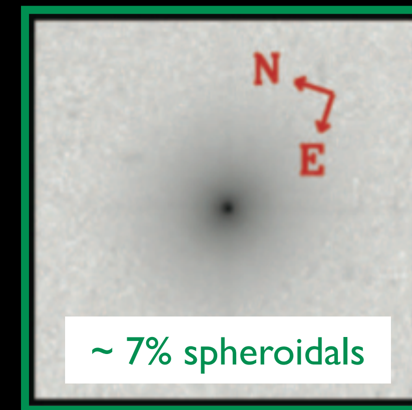

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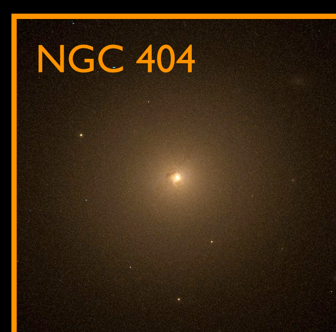
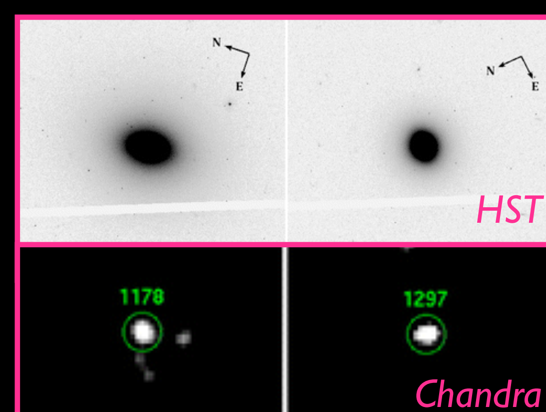


Seth et al. (2010):
dynamics
Nyland et al. (2012):
radio detection



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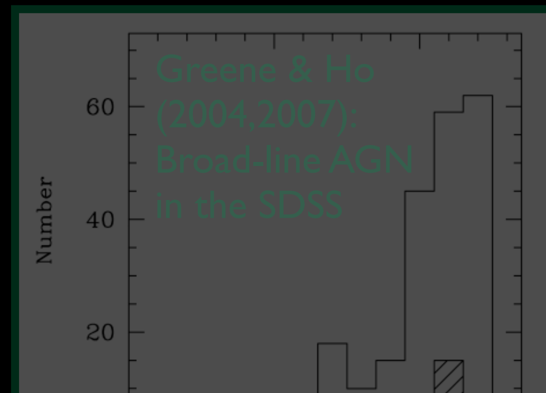

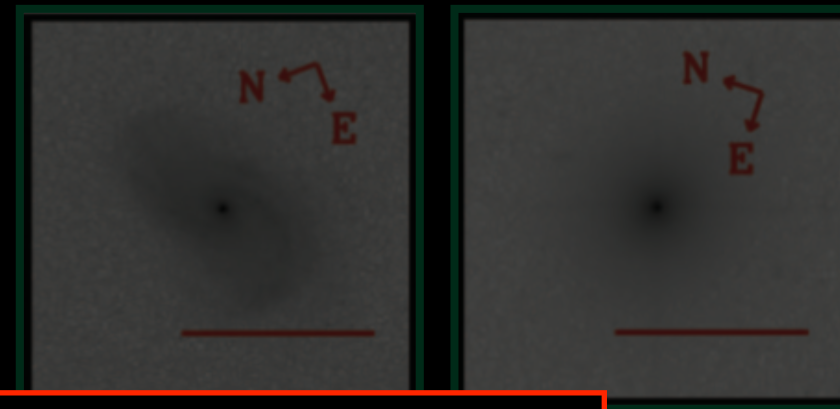

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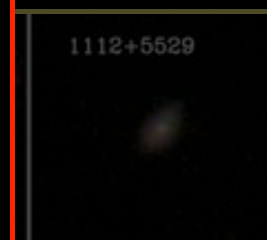

Need larger samples of dwarf galaxies hosting massive BHs

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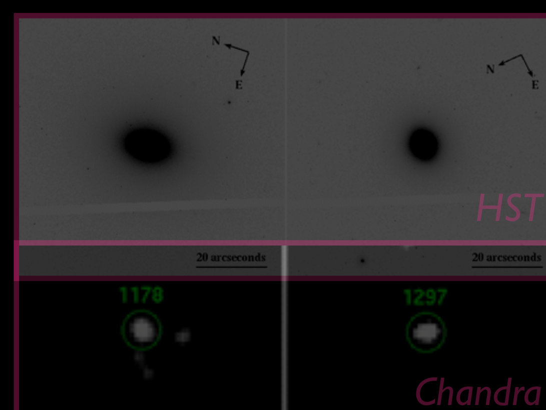

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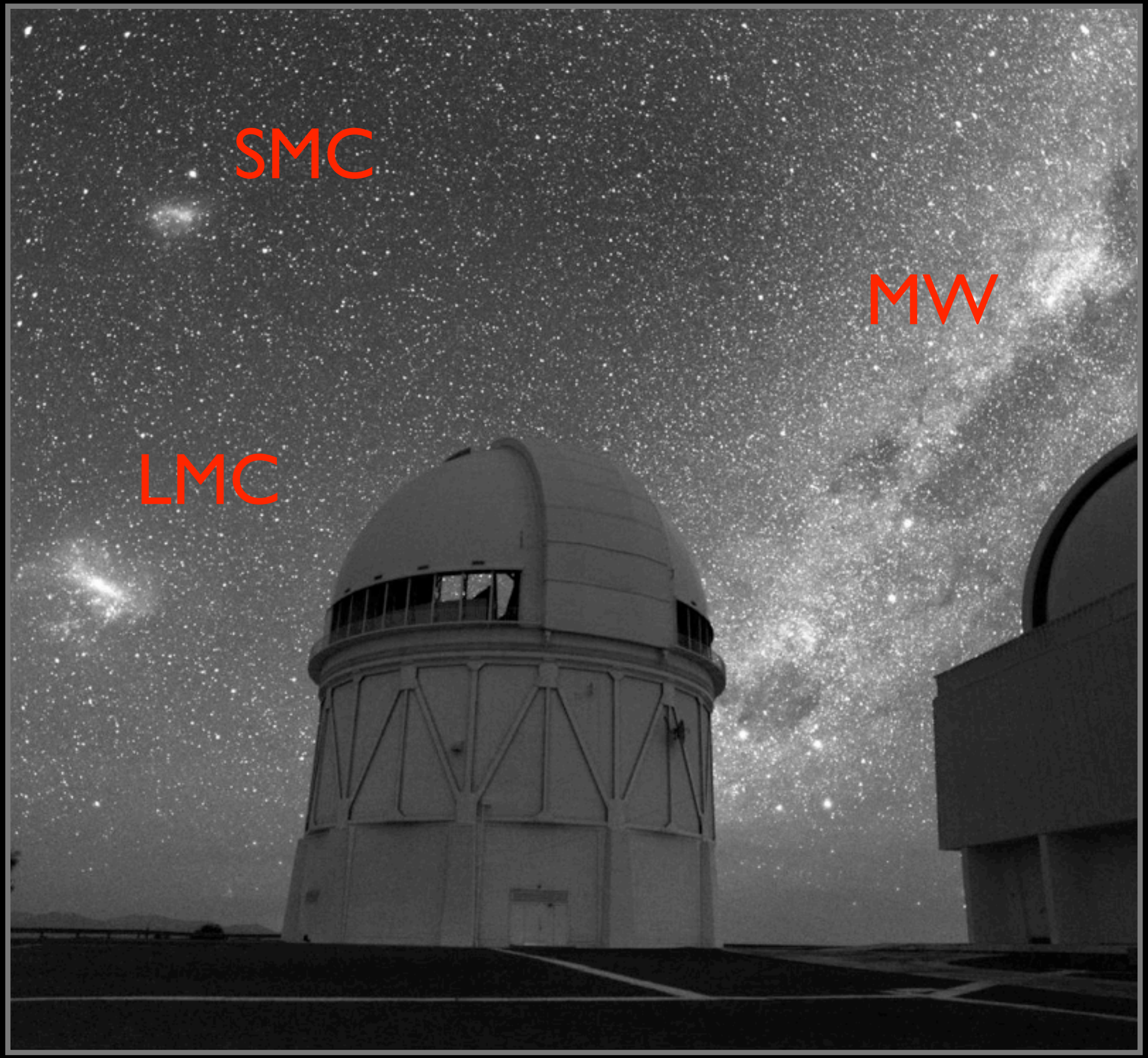
Dwarf galaxies with optical signatures of active massive BHs

Reines, Greene & Geha 2013

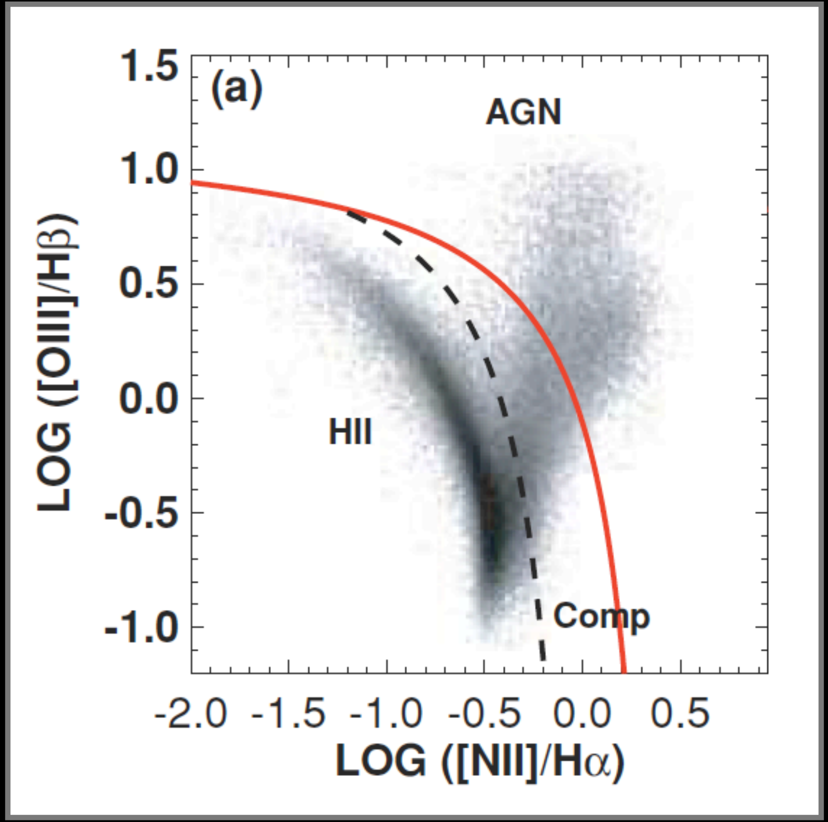
Dwarf galaxies with optical signatures of active massive BHs

~25,000 SDSS emission-line galaxies with $M_\star \lesssim 3 \times 10^9 M_{sun}$ (~LMC)



Dwarf galaxies with optical signatures of active massive BHs

Narrow-line ratios (BPT diagrams)



(Kewley et al. 2006)

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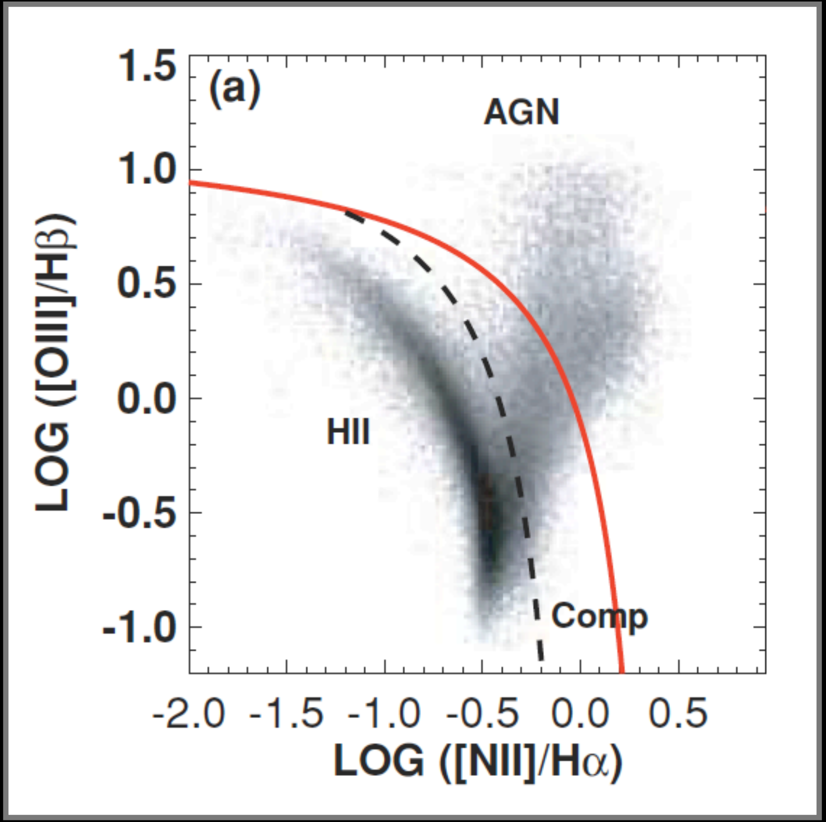

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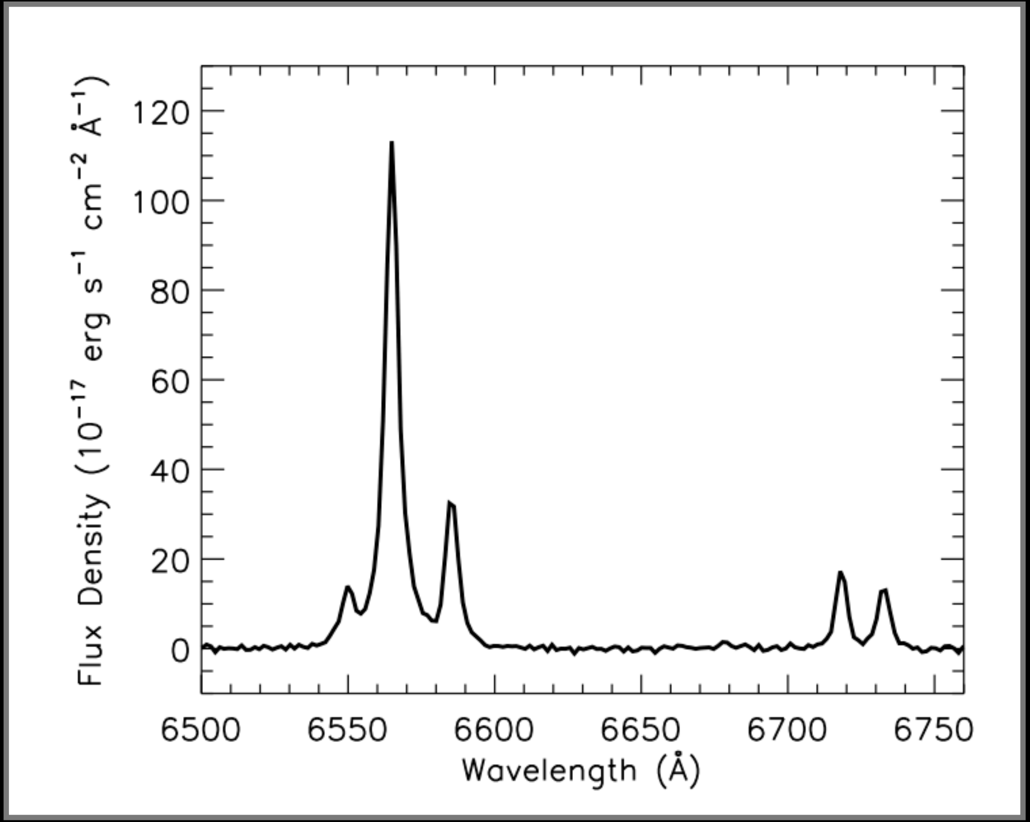
Broad H-alpha



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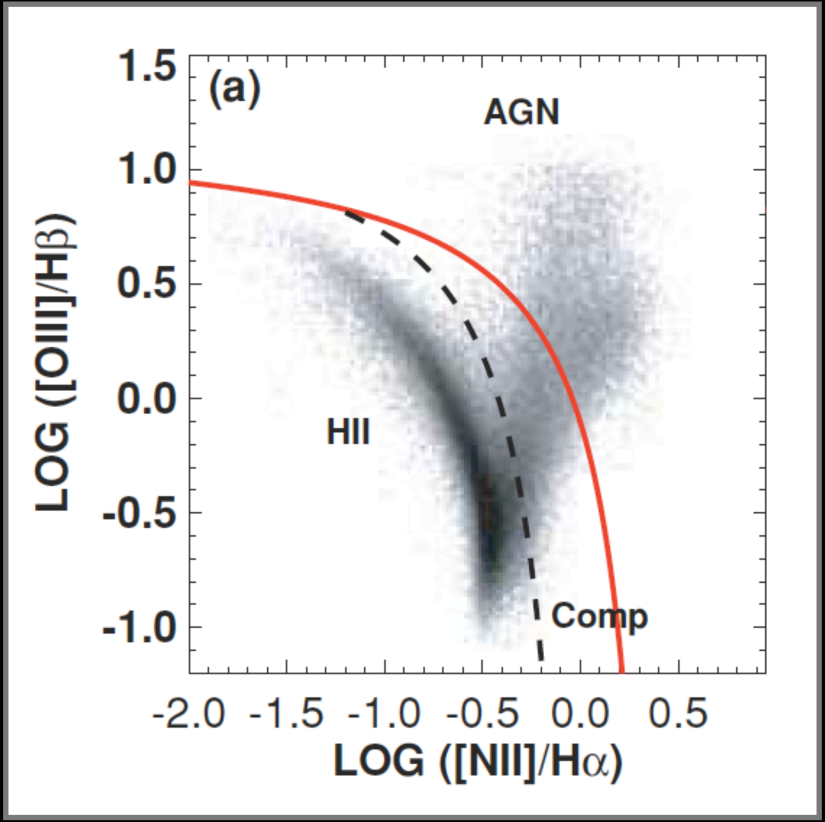

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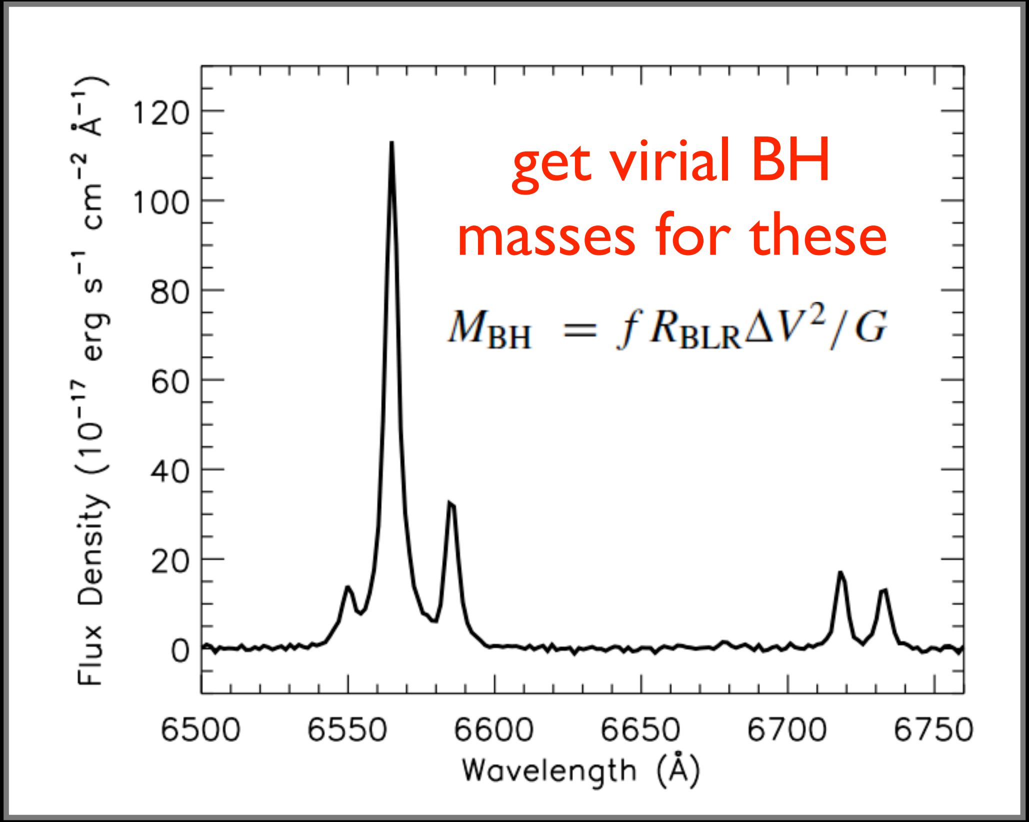


(method from Greene & Ho 2005)

Overview of the method

1. Select dwarf emission line galaxies from NSA and get SDSS spectra

- stellar mass $\lesssim 3 \times 10^9$ M_{sun} (~LMC)
- $z \lesssim 0.05$ ($D \lesssim 200$ Mpc)

~ 25,000 galaxies

2. Remove the stellar continuum and absorption lines

- use BC03 models for 10 ages (5 Myr - 11 Gyr) and 3 metallicities, allowing for dust attenuation (general approach from Tremonti et al. 2004)

3. Fit emission lines with Gaussians

- model the narrow line profile using the [SII] doublet
- look for line ratios indicating an AGN
- check for broad component of H-alpha

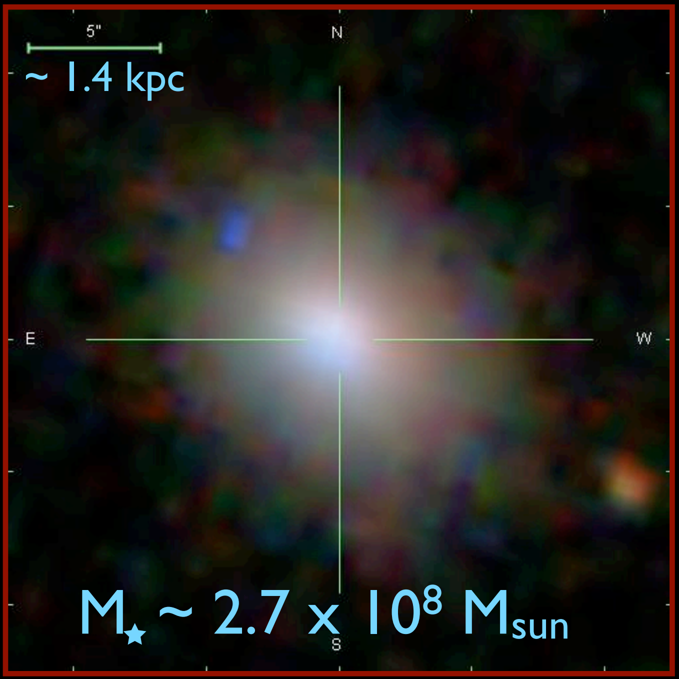
4. Calculate virial black hole masses from broad H-alpha

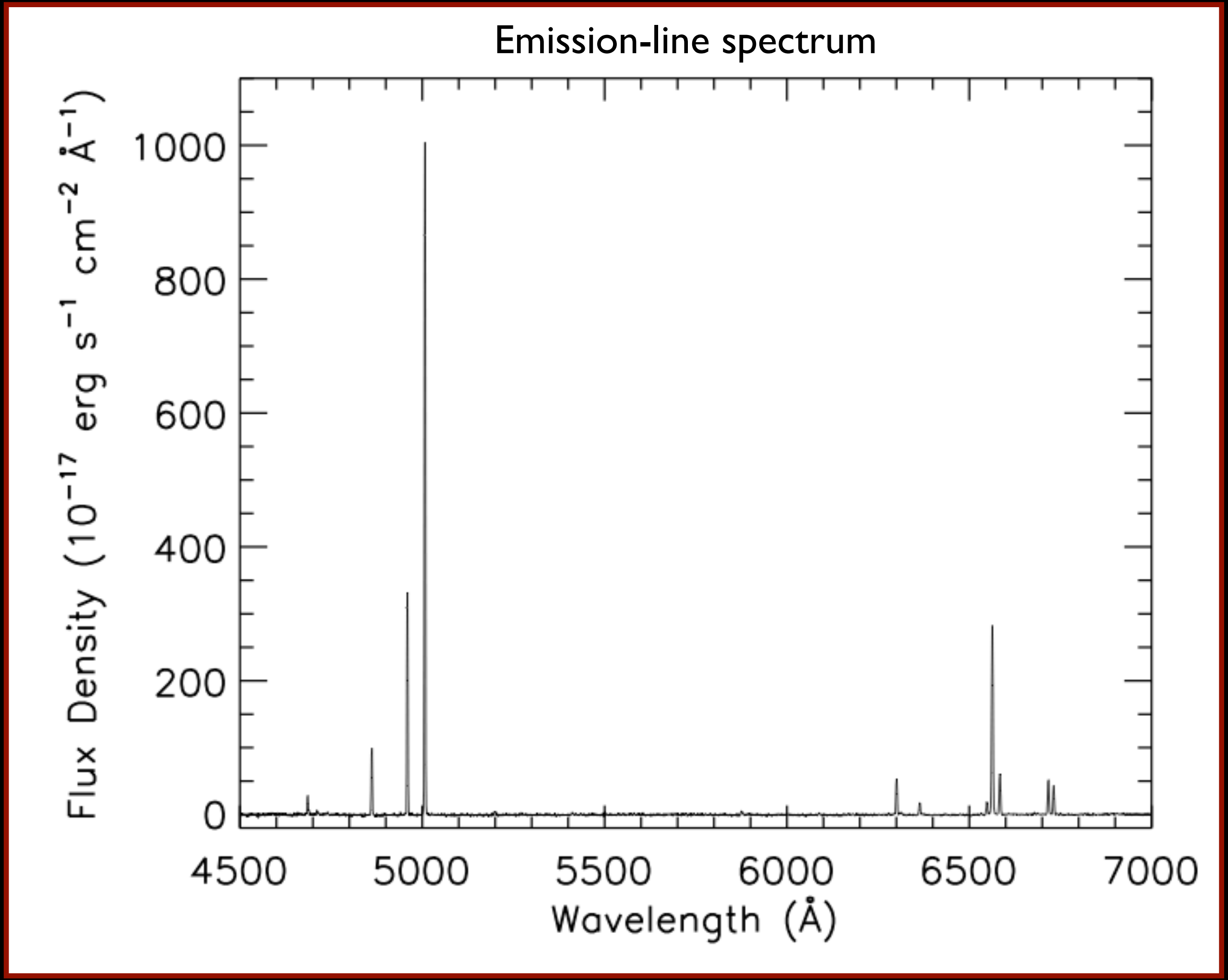
$$M_{\rm BH} = \epsilon \left(\frac{R_{\rm BLR} {\rm FWHM}_{\rm H\beta}{}^2}{G} \right)$$

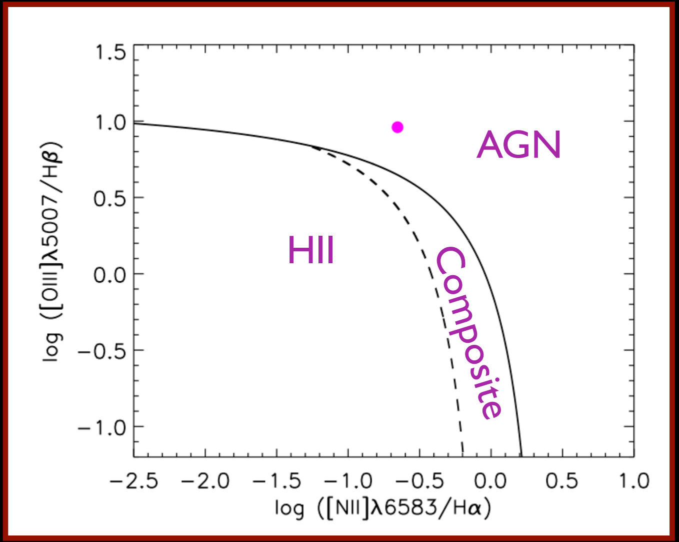
$$\log \left(\frac{M_{\rm BH}}{M_\odot} \right) = \log \epsilon + 6.57 + 0.47 \log \left(\frac{L_{\rm H\alpha}}{10^{42} {\rm ~erg~s^{-1}}} \right) + 2.06 \log \left(\frac{\rm FWHM_{H\alpha}}{10^3 {\rm ~km~s^{-1}}} \right)$$

(Reines et al. 2013; method from Greene & Ho 2005 with updated R-L relation from Bentz et al. 2013)

Example 1: Narrow-line AGN







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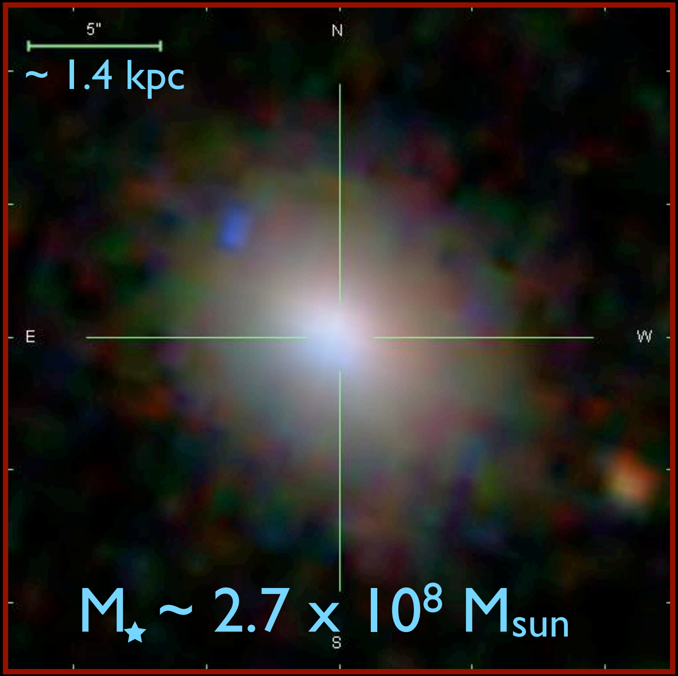

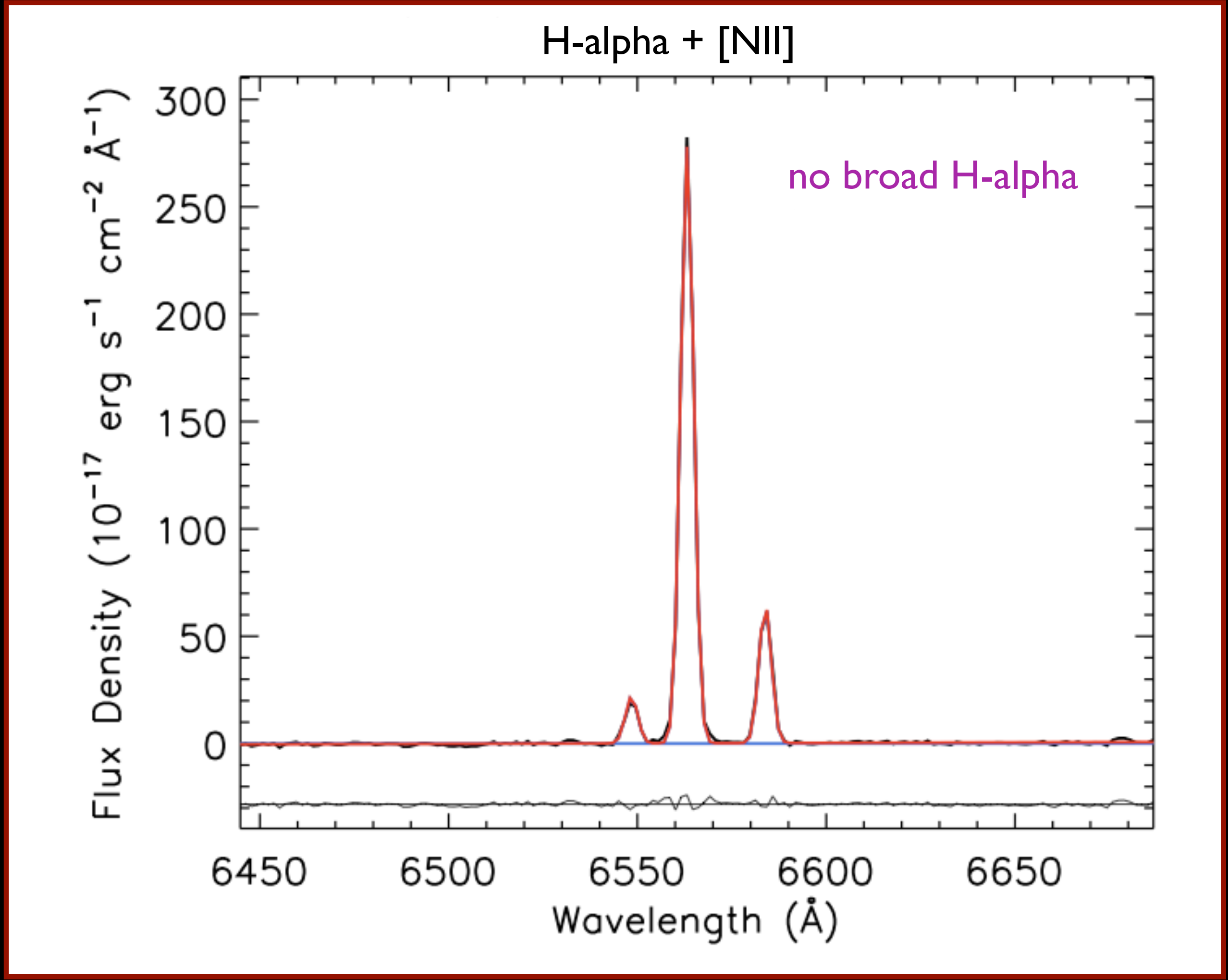

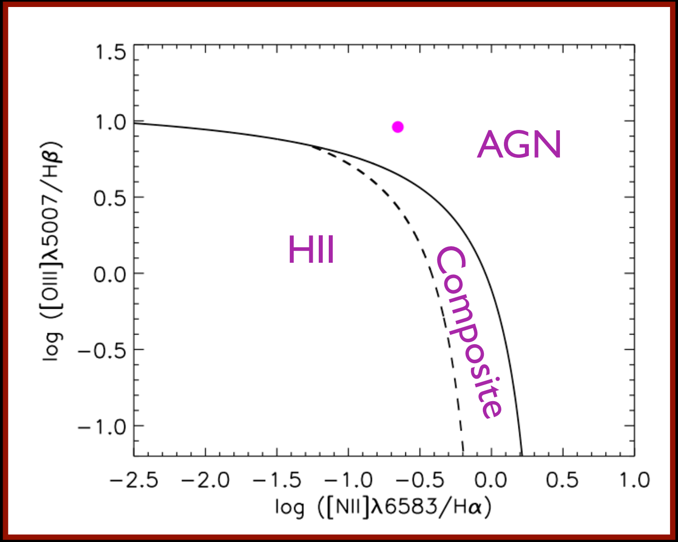

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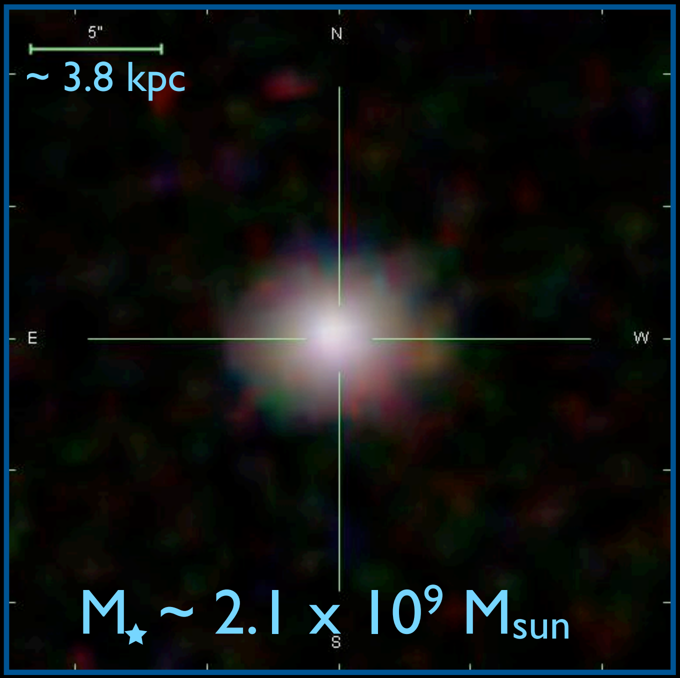

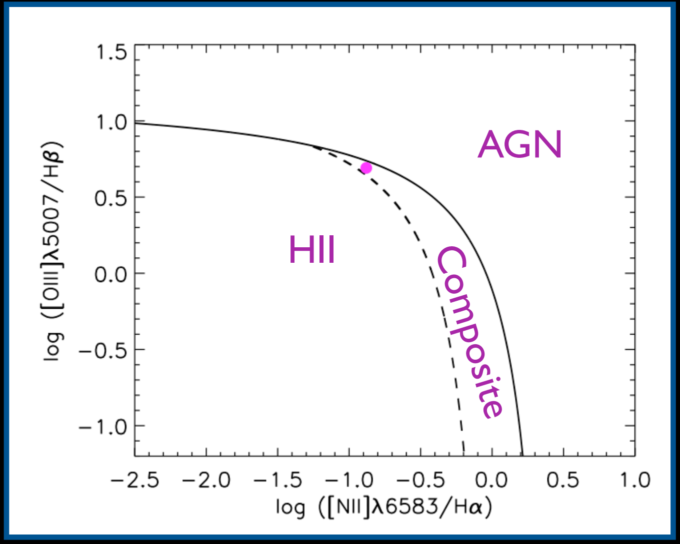

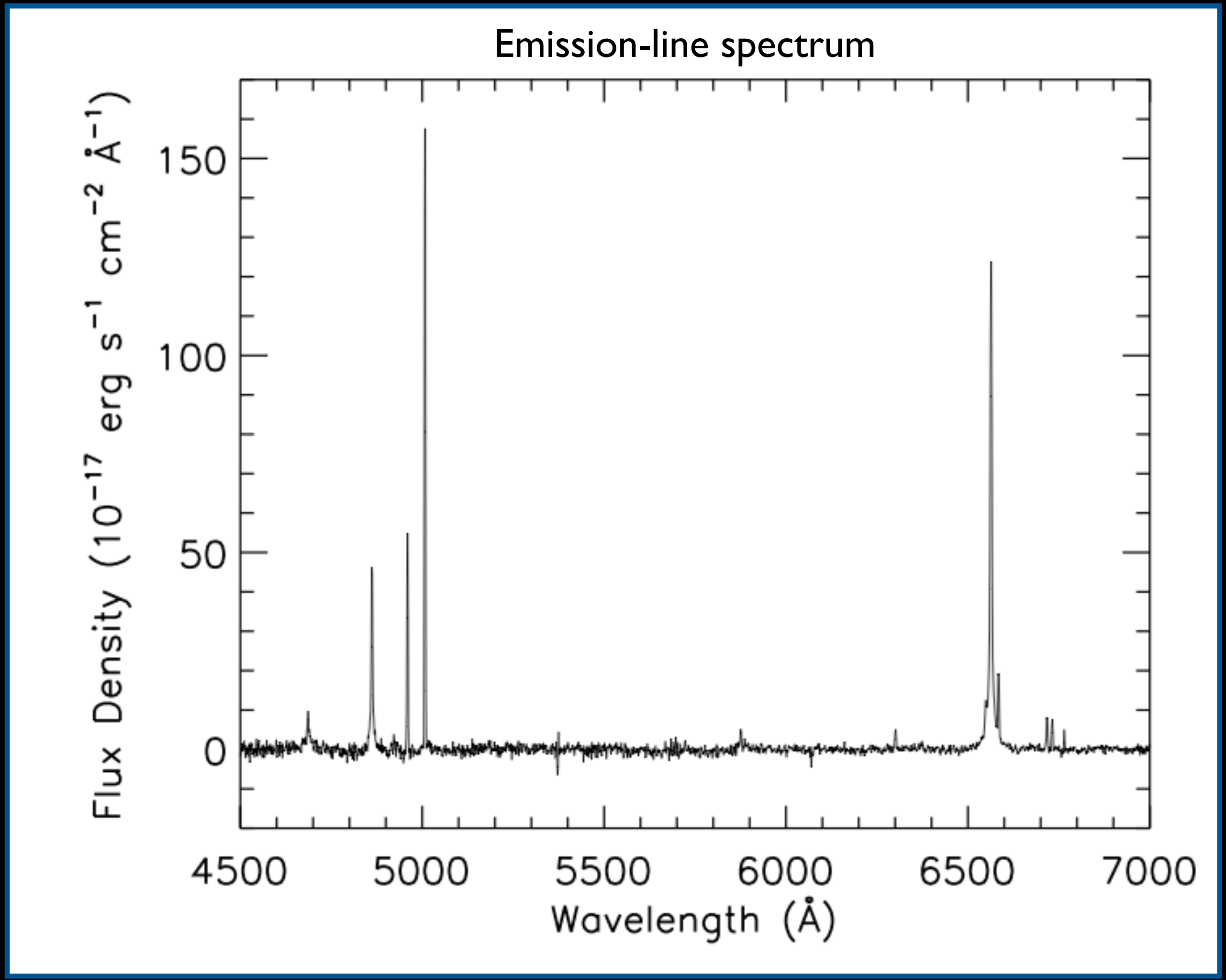

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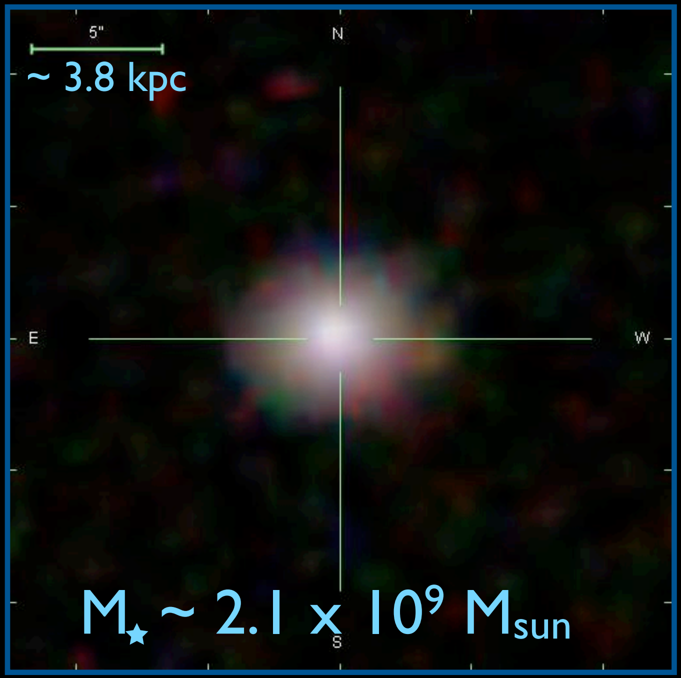
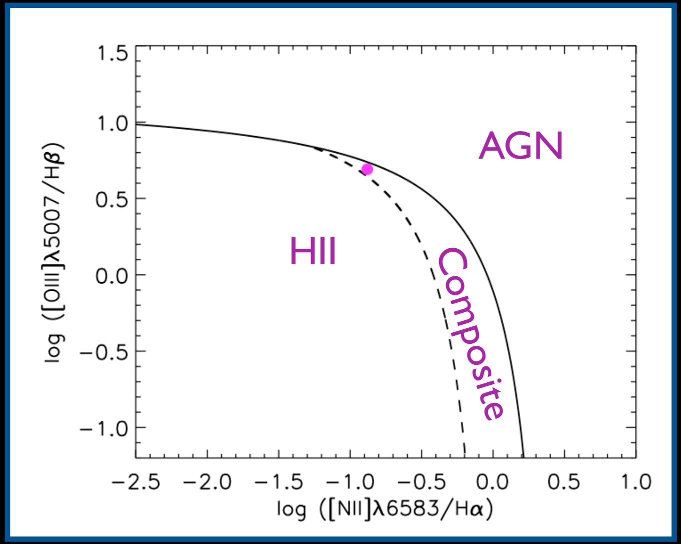
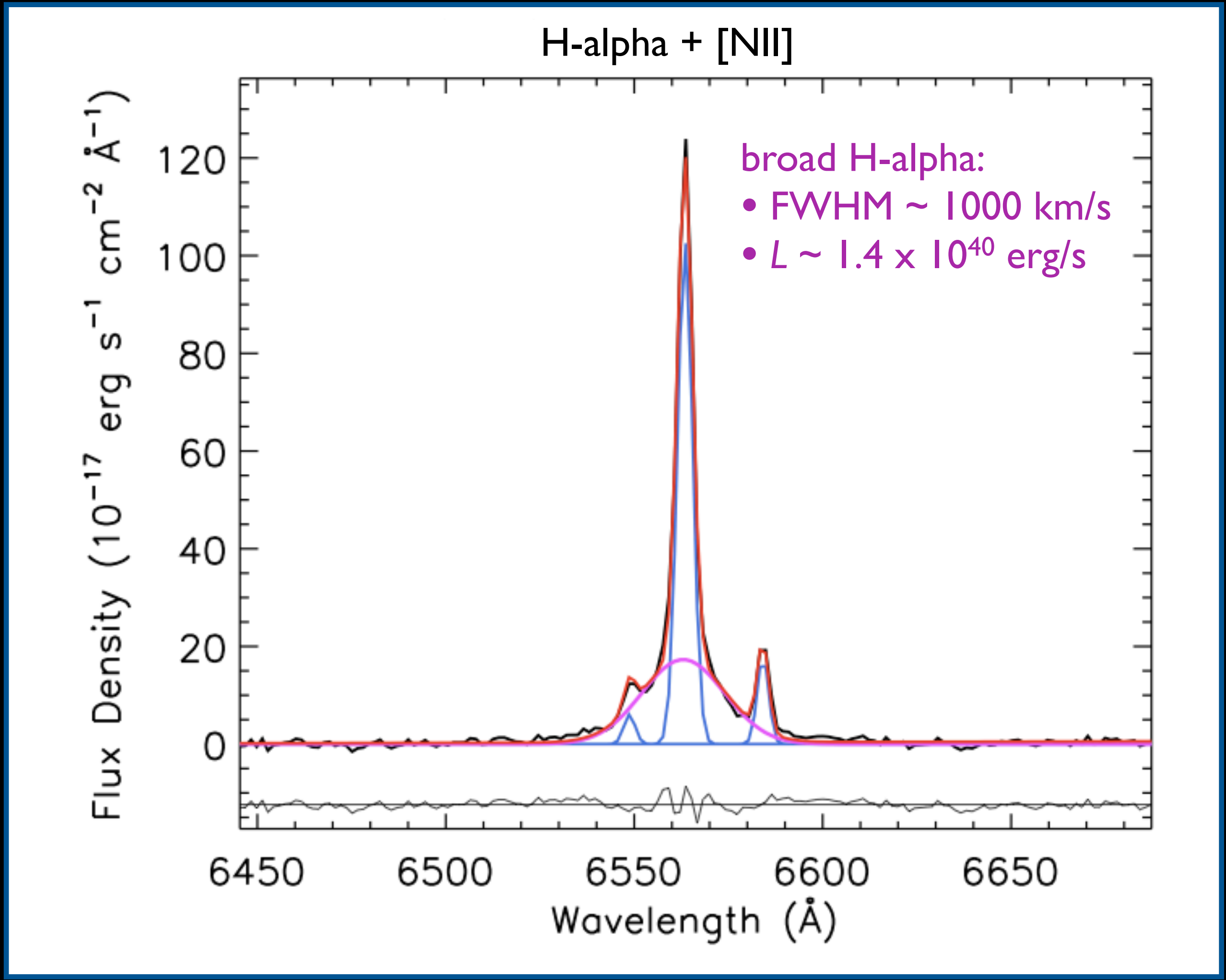


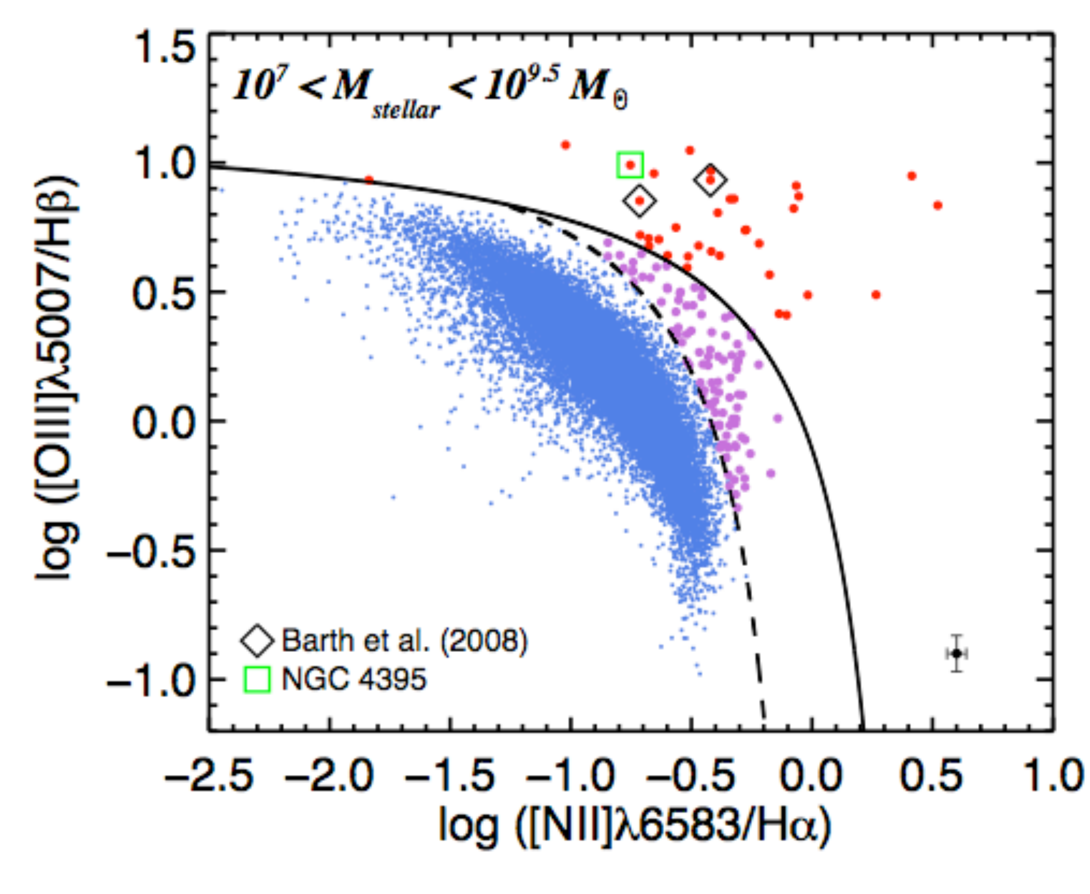




M_{BH} ~ 4 x 10^5 M_{sun}

Narrow-line BPT diagrams

All ~25,000 dwarf galaxies



35 AGN

101 Composites

Narrow-line BPT diagrams

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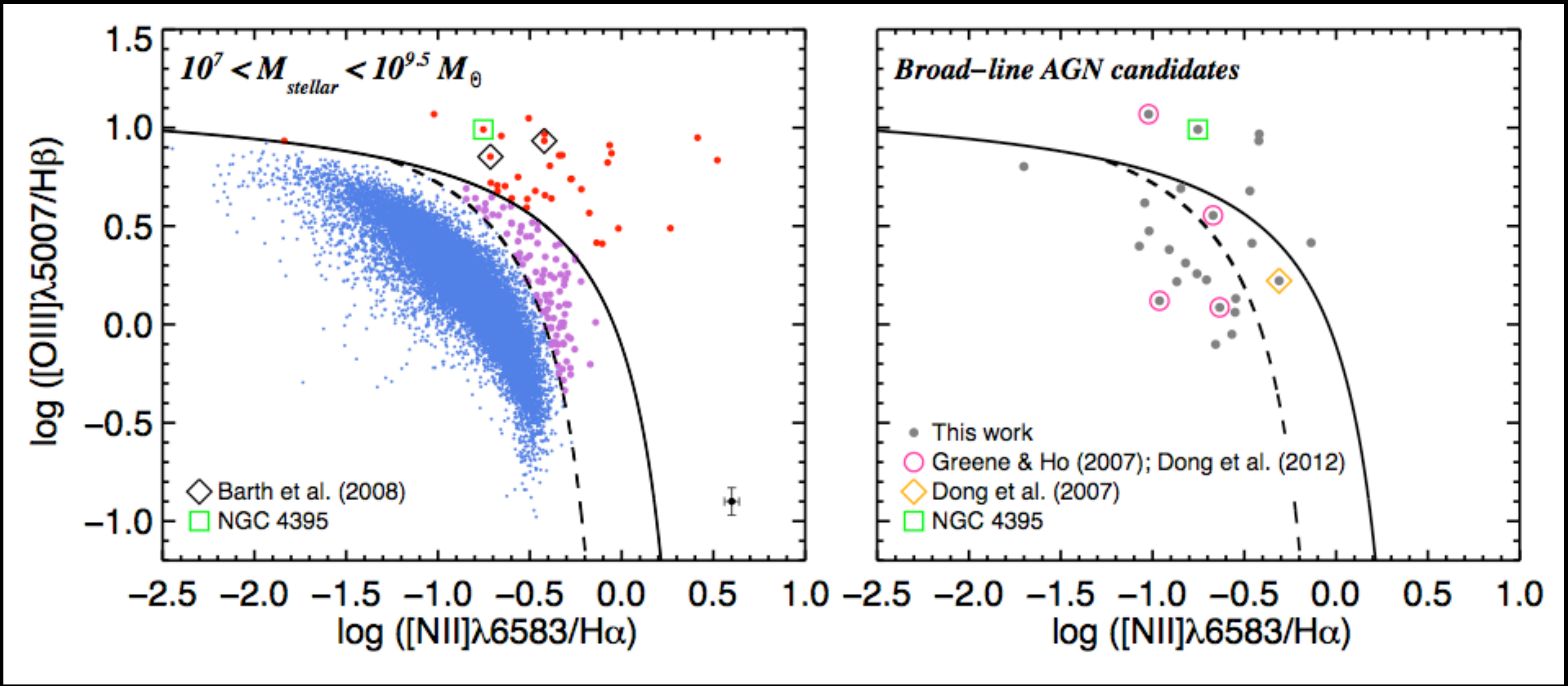
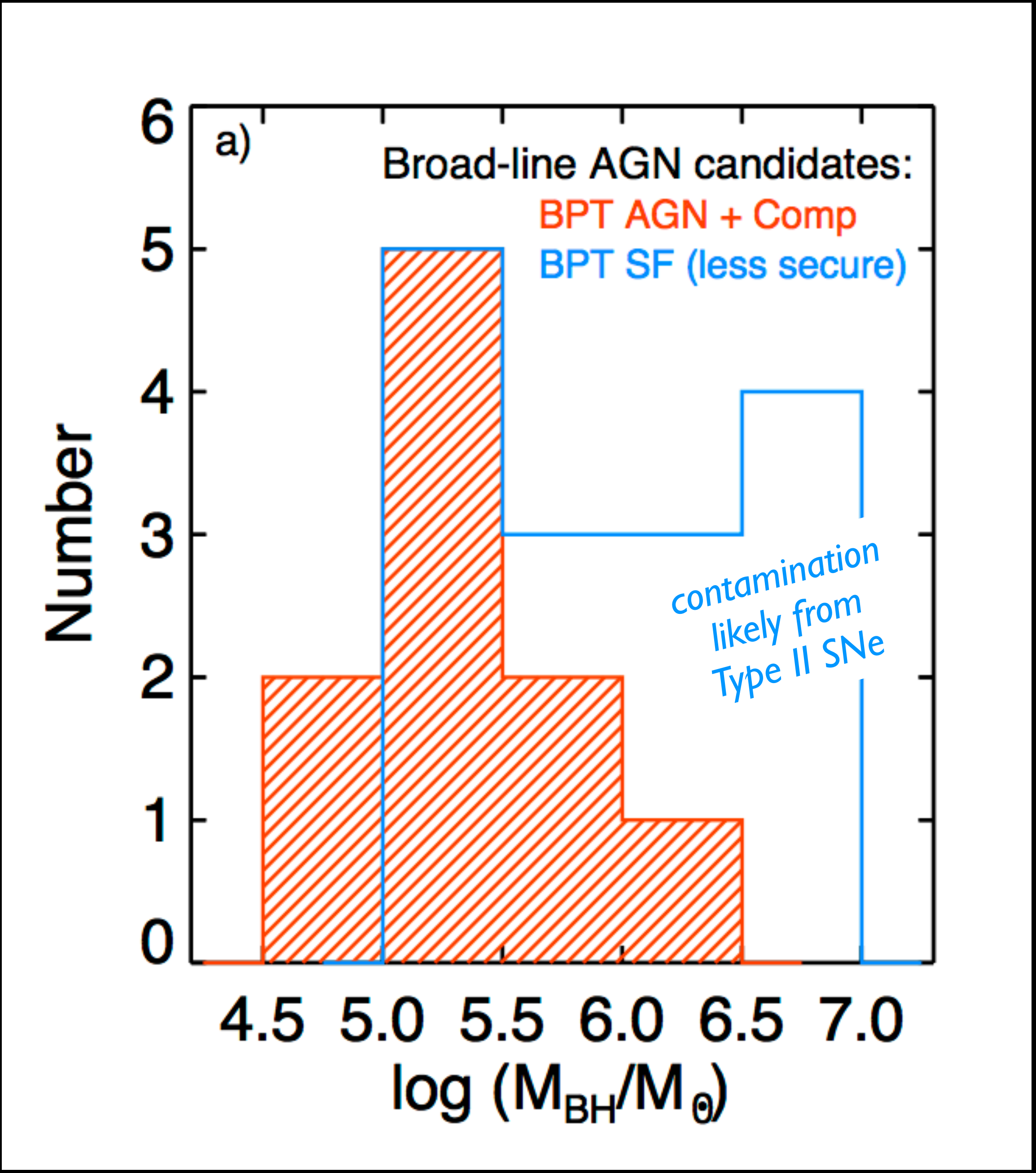


35 AGN
101 Composites

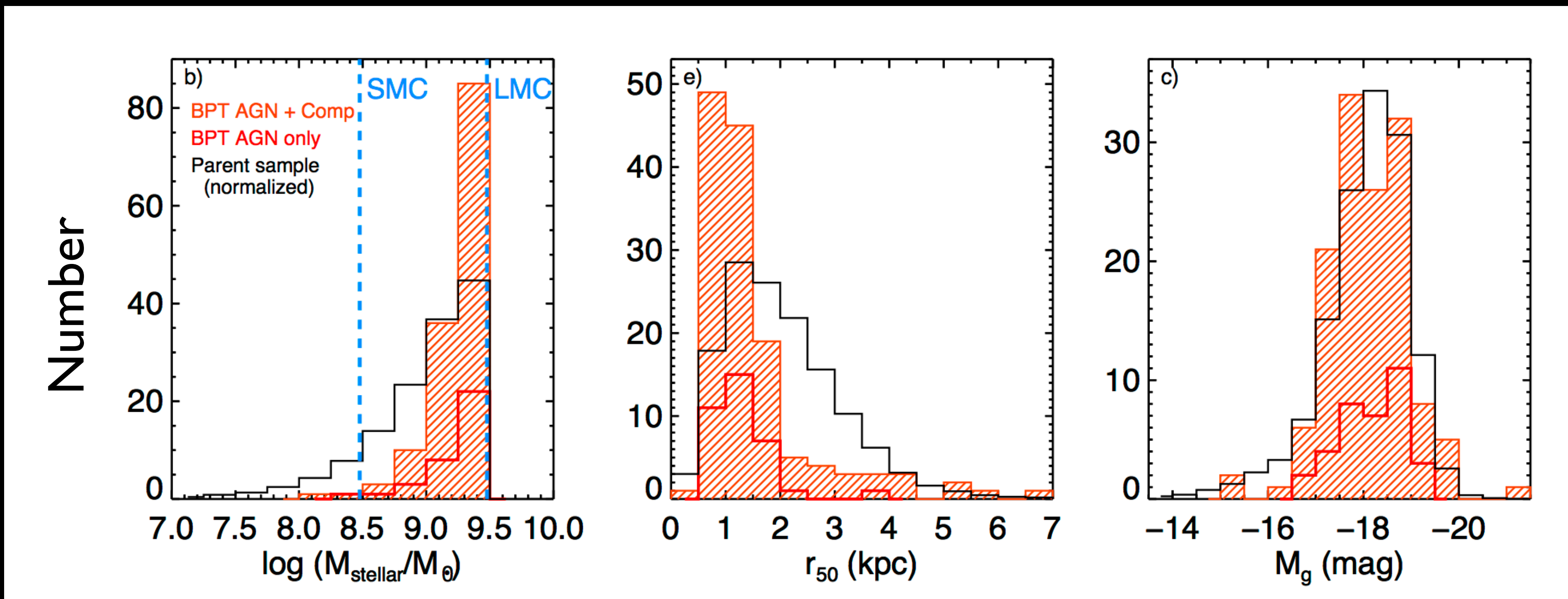
25 broad-line AGN candidates

(with virial BH mass estimates)

BH mass distribution for broad-line AGN candidates



Host Galaxies



stellar mass half-light radius *Mg*

Largest sample of dwarfs hosting massive BHs to date

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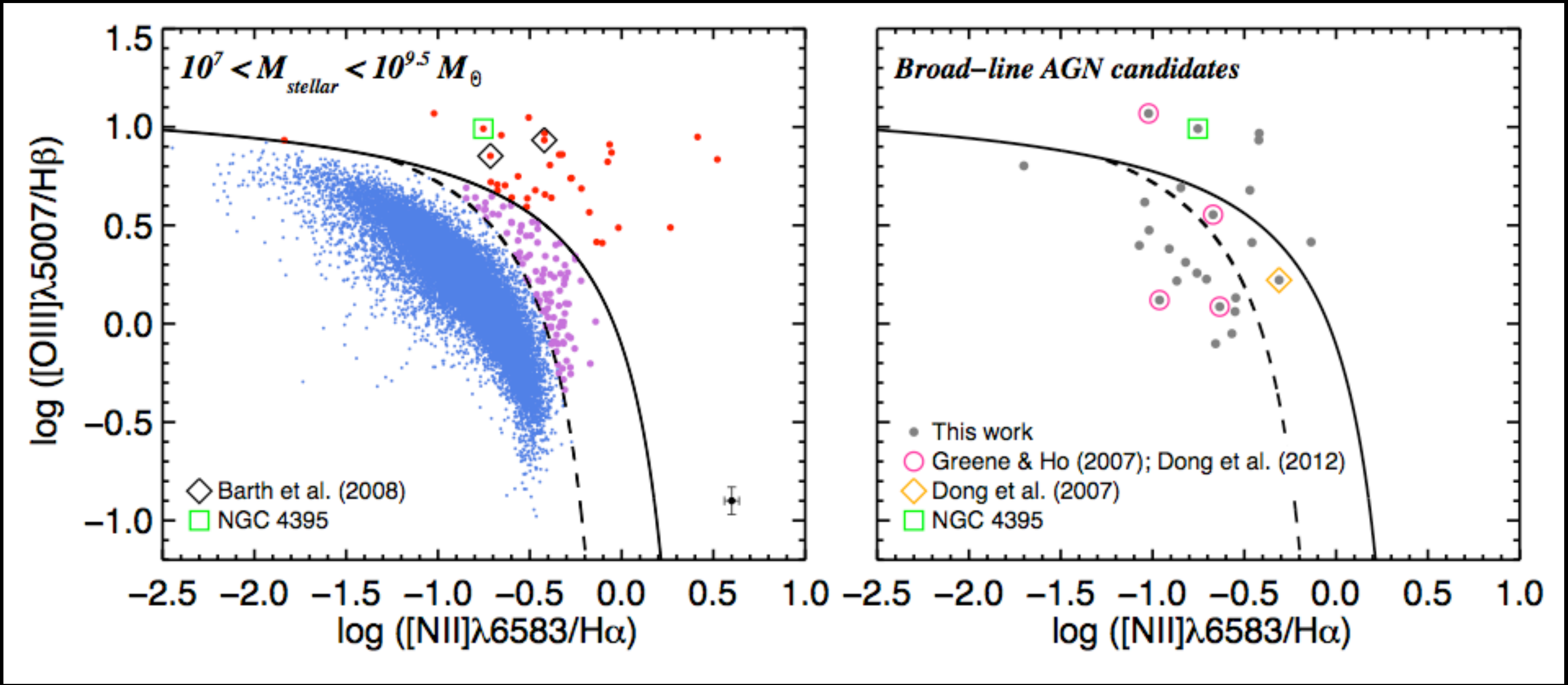

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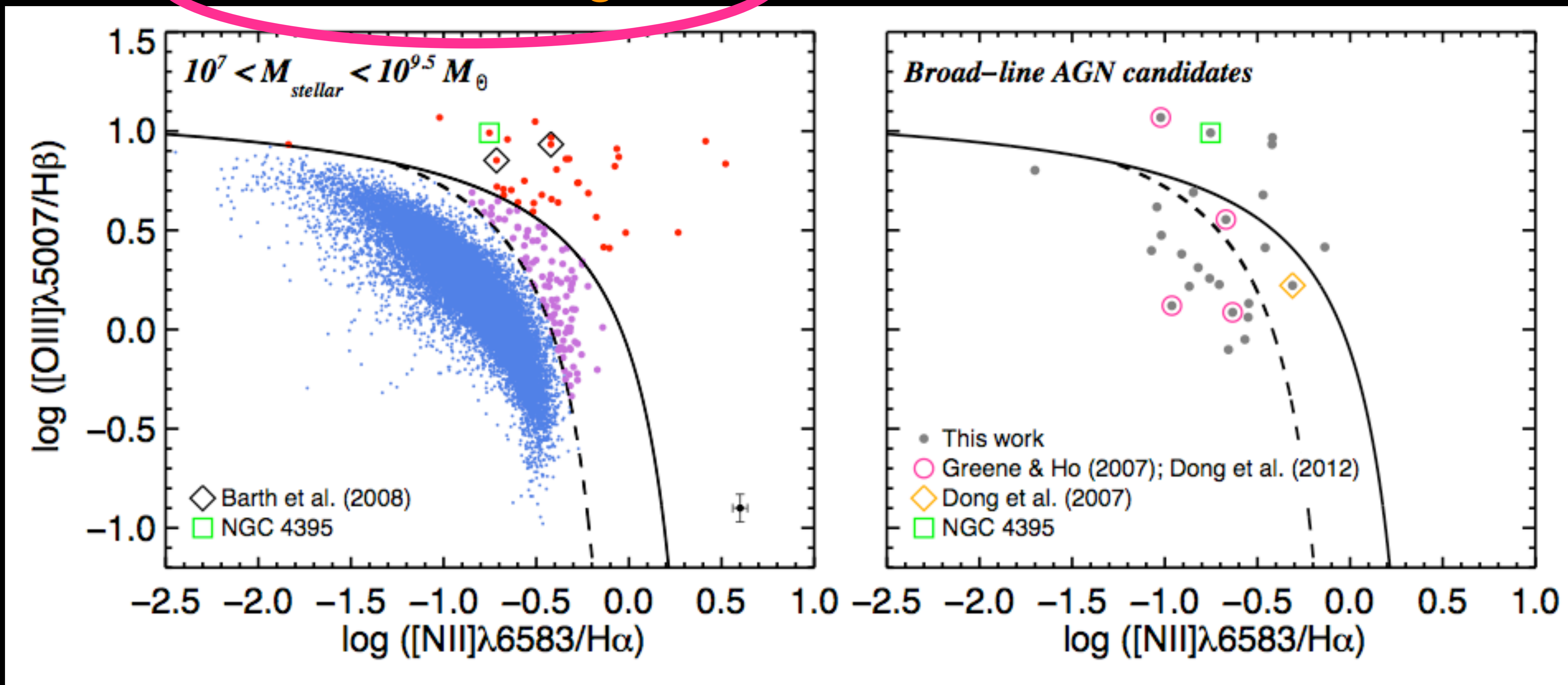

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~0.5% of dwarfs have *optical signatures* of accreting massive BHs

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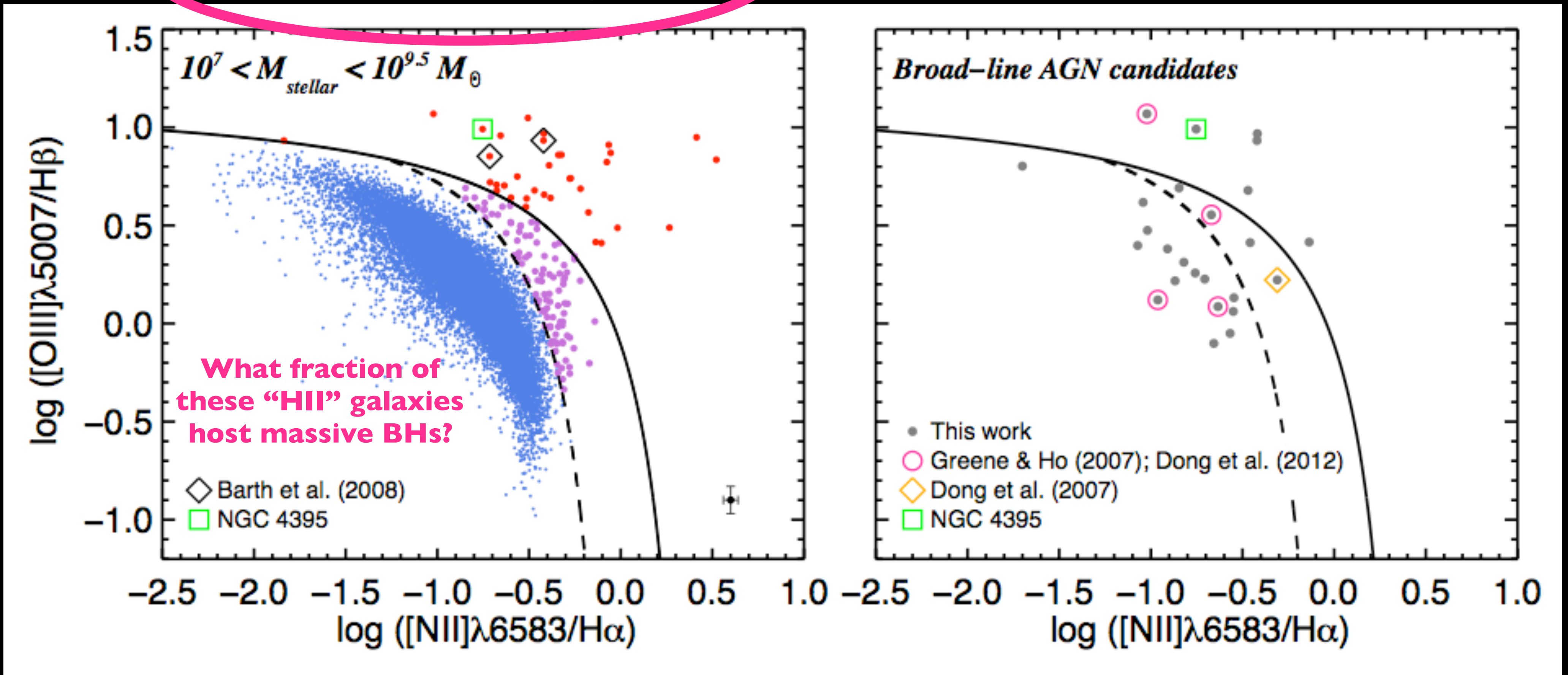

35 AGN

101 Composites

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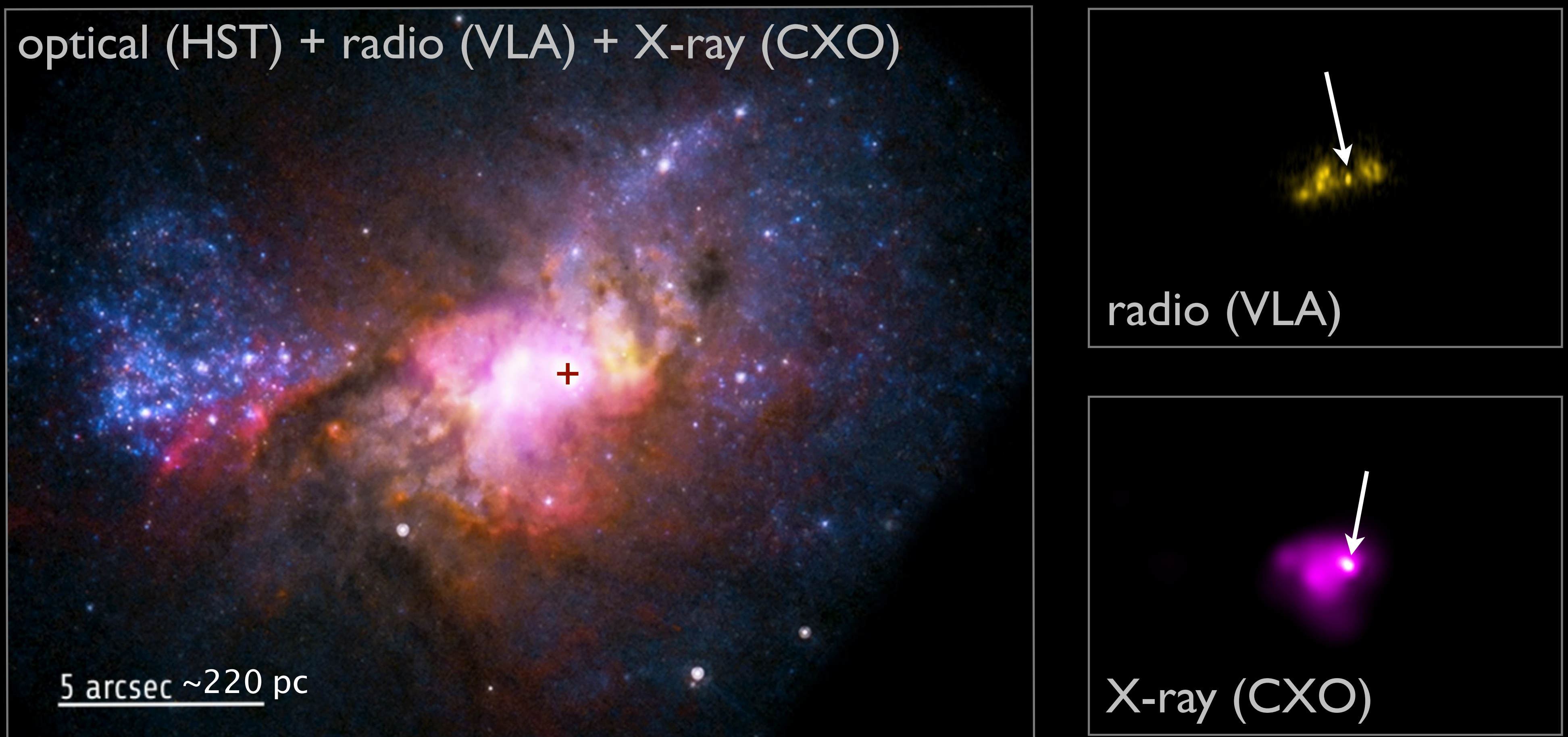
Need other diagnostics!

High-resolution radio + X-ray observations

- More sensitive to weakly accreting BHs
- Can pick out AGN in galaxies with lots of star formation

Need other diagnostics!

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

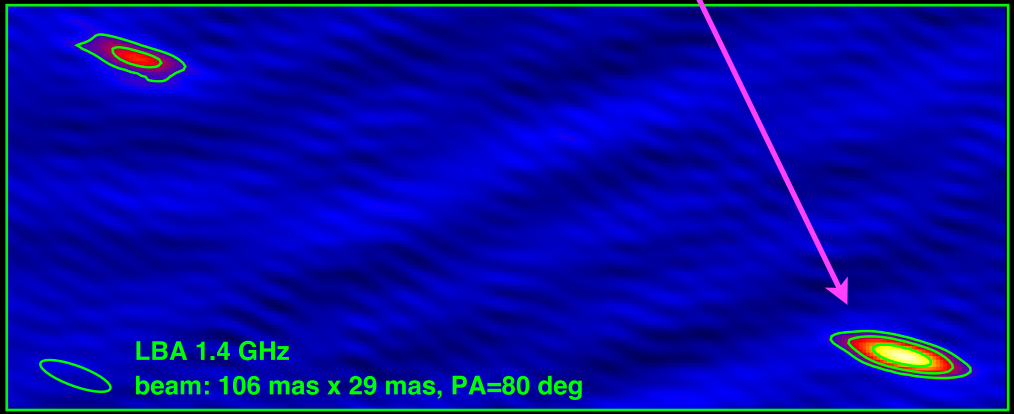


Reines et al. 2011, *Nature*

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

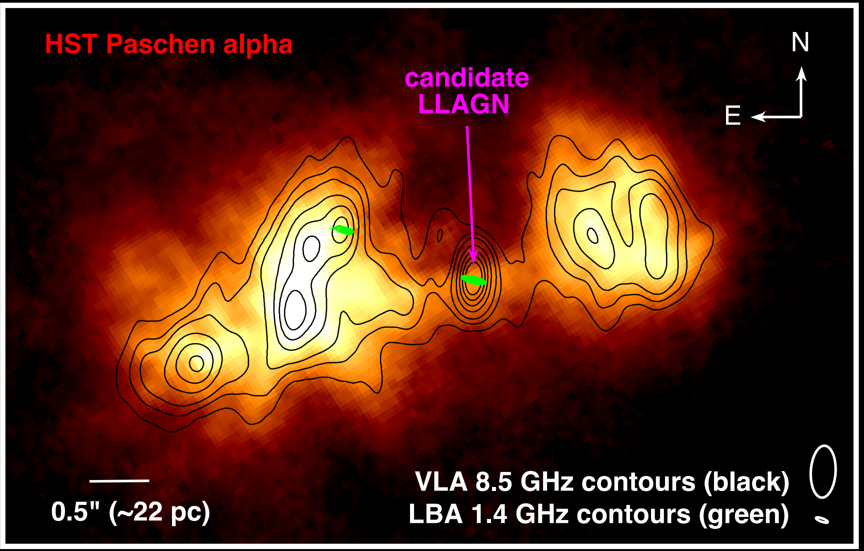
VLBI follow-up with the Long Baseline Array (LBA)

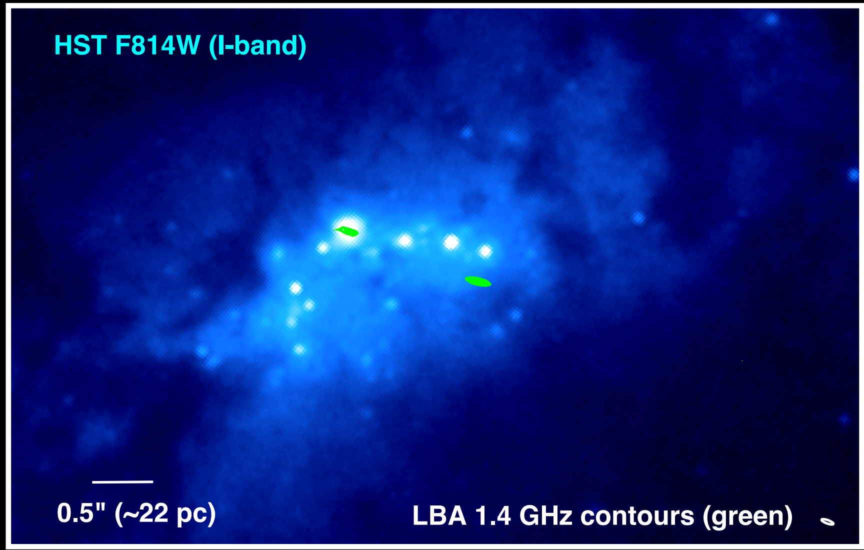
nuclear radio source:
$\lesssim$ 3 x 1 pc



Reines & Deller 2012

HST imaging of central ~ 250 pc





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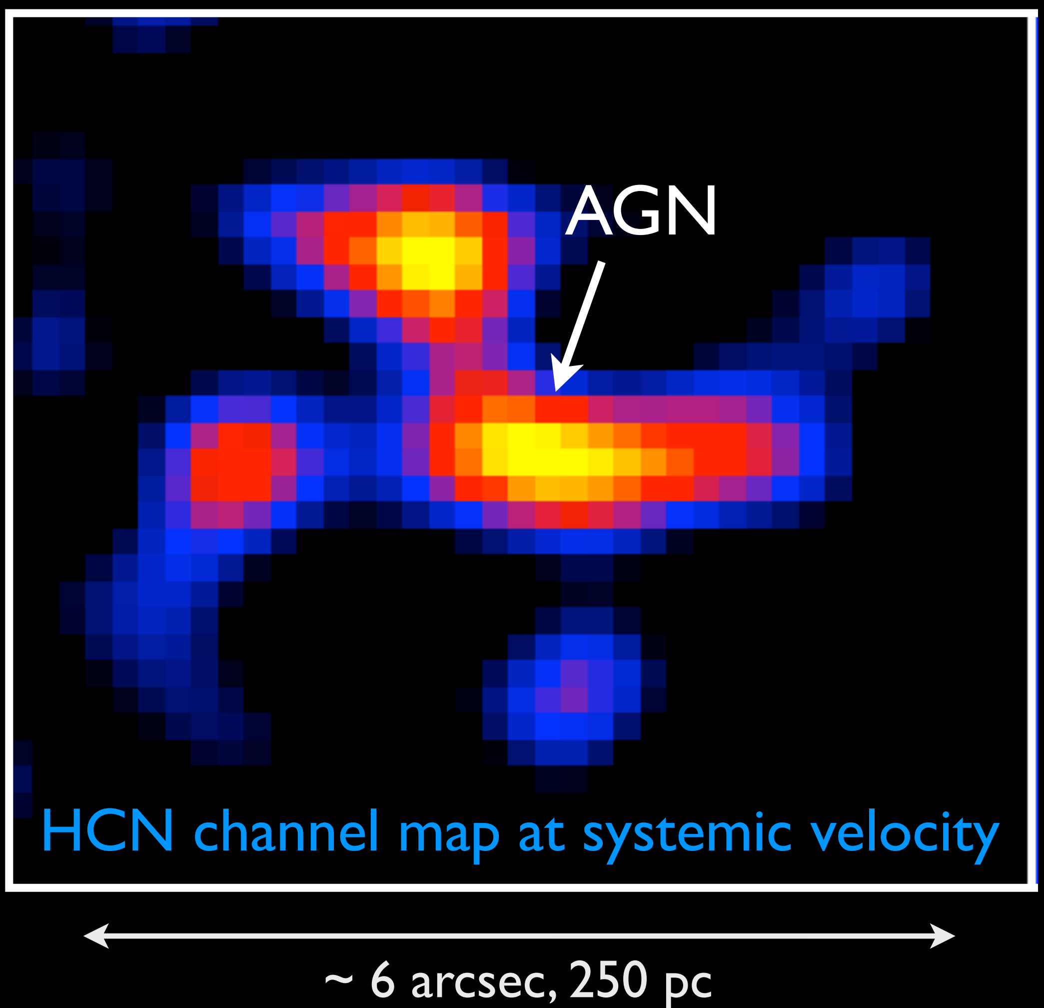
ALMA

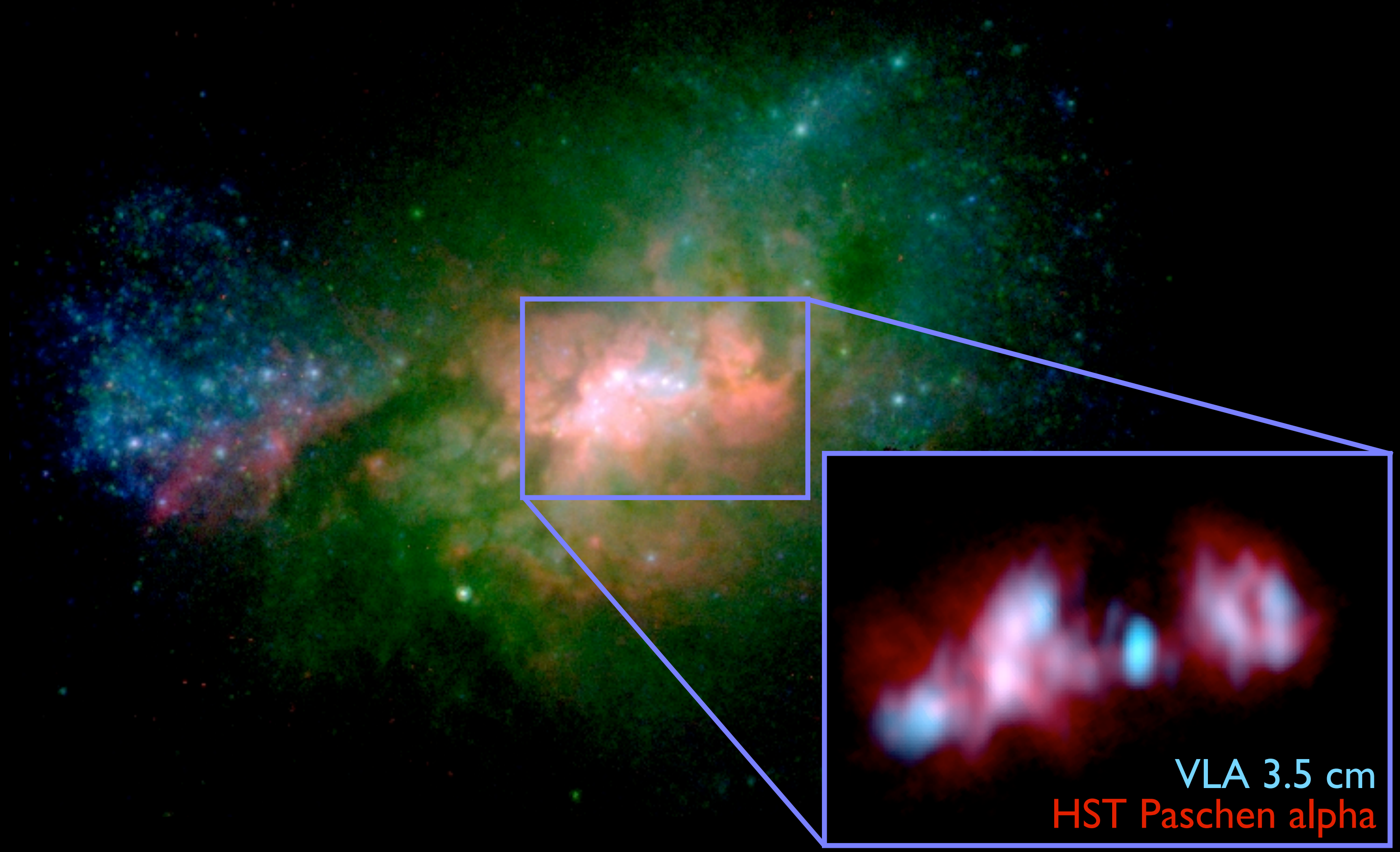


- HCN (dense molecular gas tracer)
- spatially coincident with VLA radio continuum source
- at systemic velocity (and presumably the dynamical center) of the galaxy

Reines, Johnson et al., in prep

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

- Black hole mass ~ $10^{5\text{-}7}$ M_{sun} from fundamental plane of black hole activity
- No discernible bulge or nuclear star cluster
- Irregular morphology without a well-defined nucleus, newly formed globular clusters



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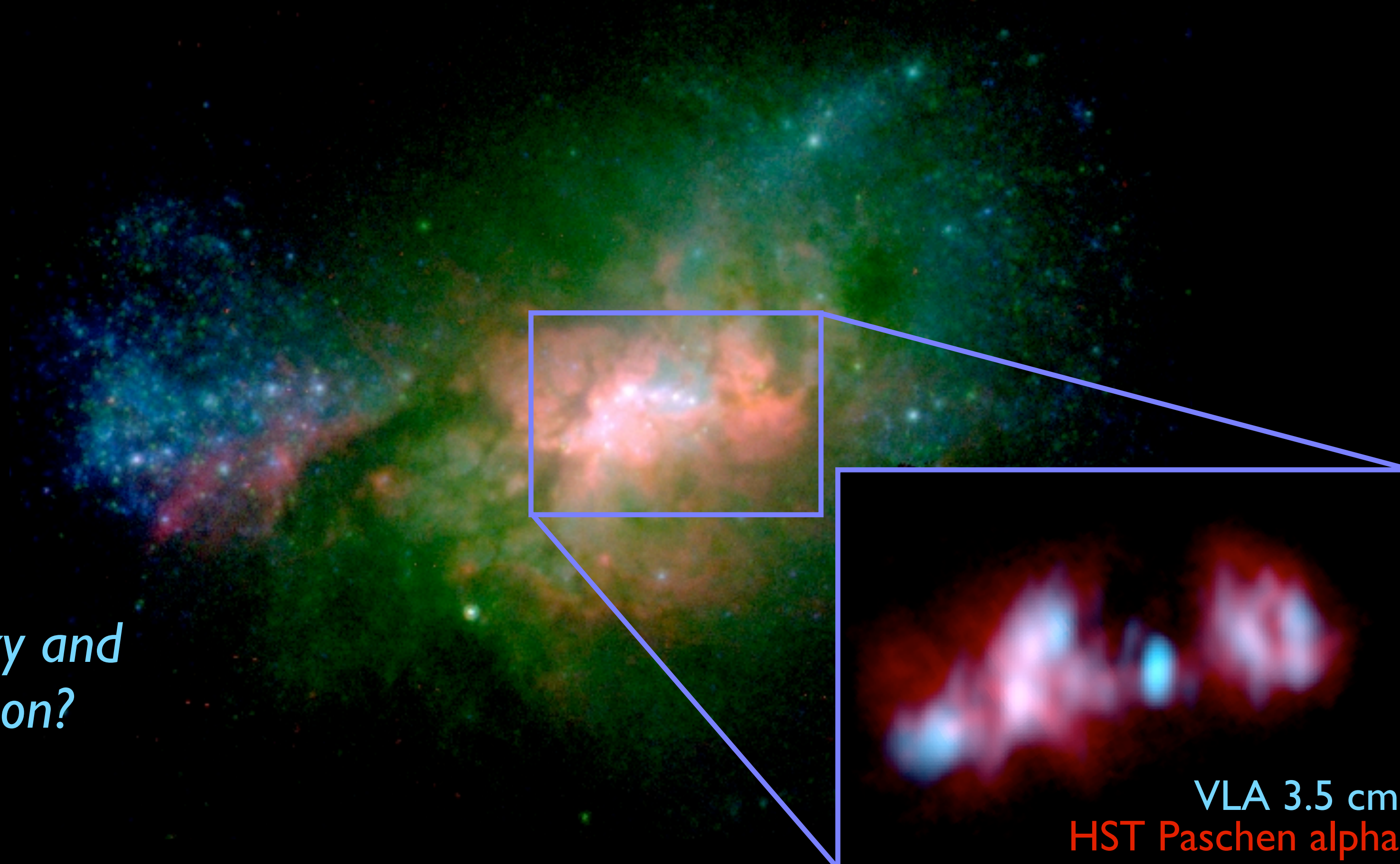
Early stage of galaxy and black hole evolution?



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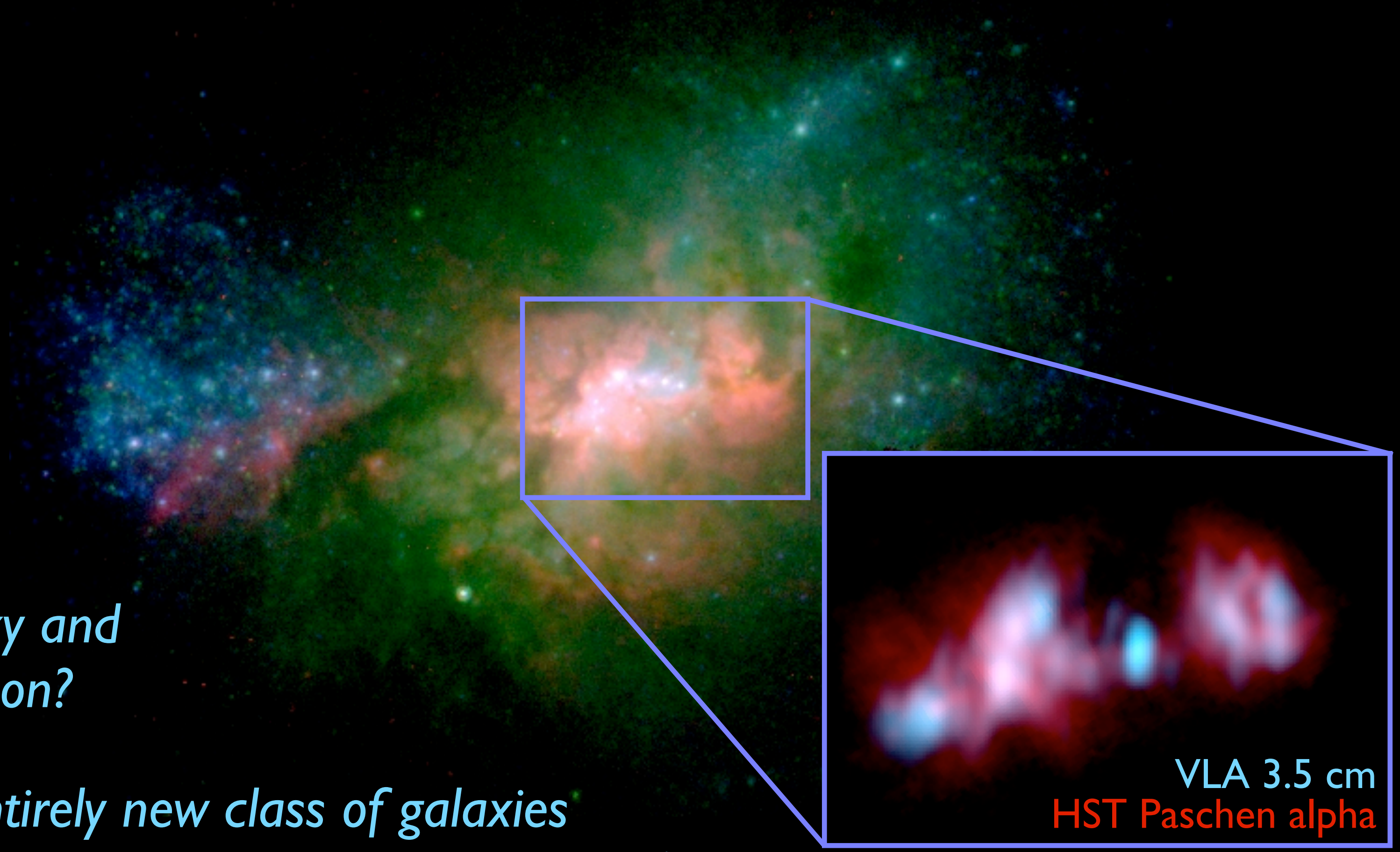
- No discernible bulge or nuclear star cluster
- Irregular morphology without a well-defined nucleus, newly formed globular clusters



Early stage of galaxy and black hole evolution?

Opens up an entirely new class of galaxies in which to search for the least-massive black holes!

Summary

- Dwarf galaxies can help reveal the origin of supermassive BH seeds

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

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

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