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

Amy Reines
Einstein Fellow
NRAO Charlottesville

Motivation: The origin of supermassive BH seeds

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- SMBHs are fundamental components of today's massive galaxies

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

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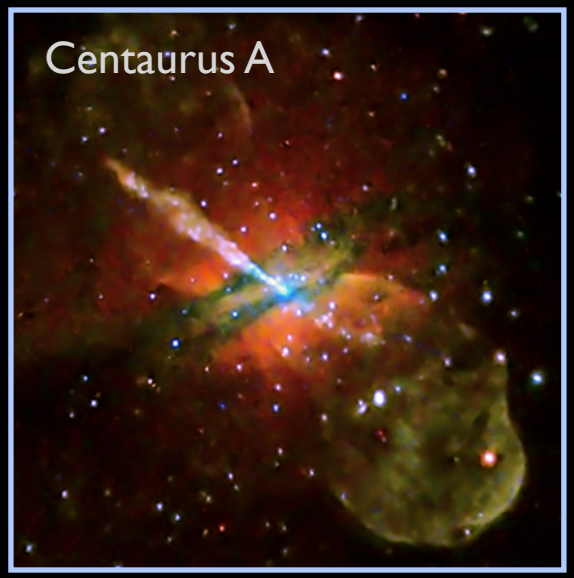

NASA/CXC/CfA/R.Kraft et al.

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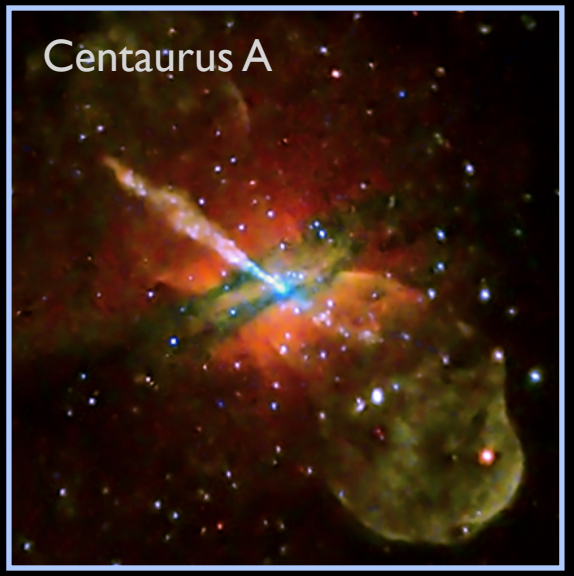

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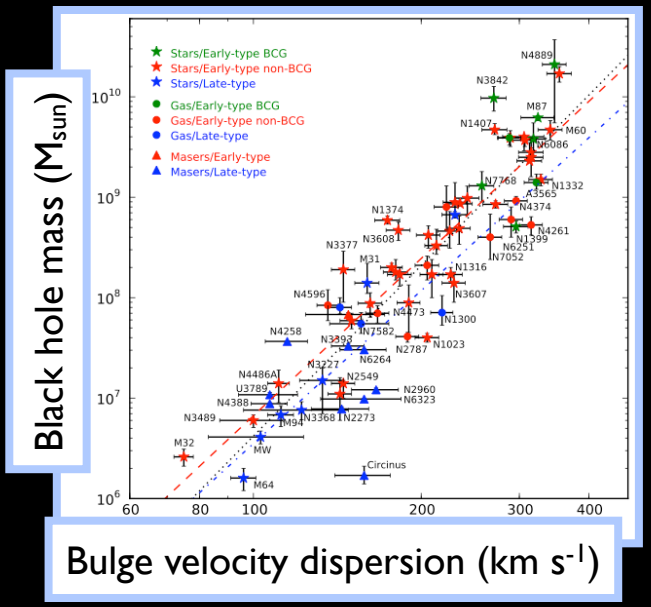

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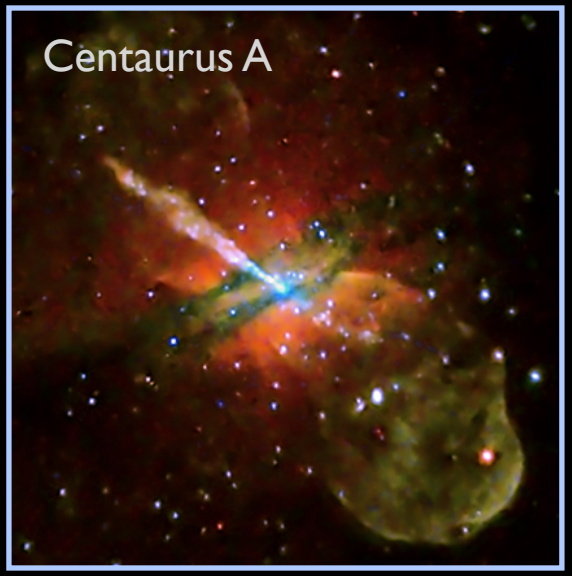

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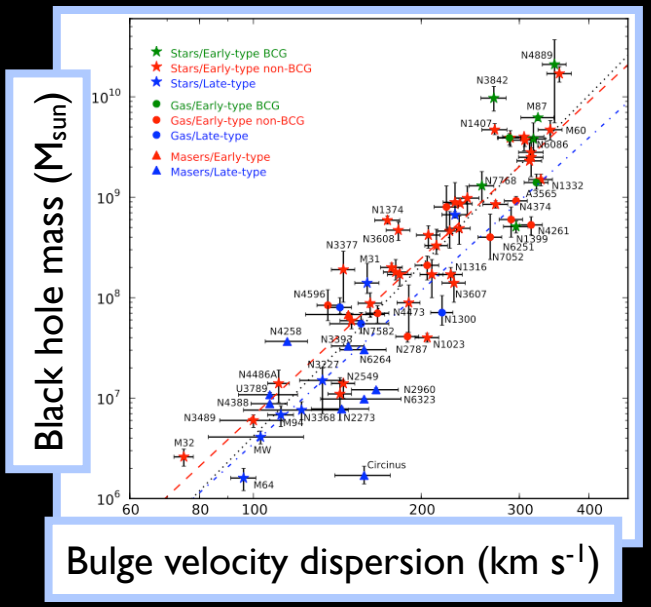

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We don't know how these SMBHs get started in the first place

Motivation: The origin of supermassive BH seeds

Some questions:

- How did the "seeds" of supermassive black holes form in the early universe and how massive were they initially?

- What types of galaxies did the seeds form in?

- Did galaxies and nuclear black holes grow synchronously? If not, which developed first?

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

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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)

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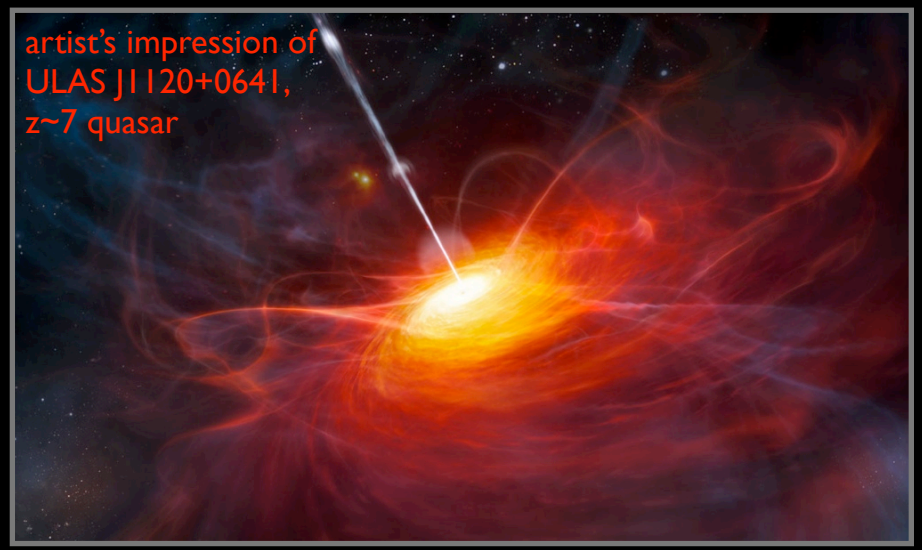

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★*Low-redshift dwarf galaxies*

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

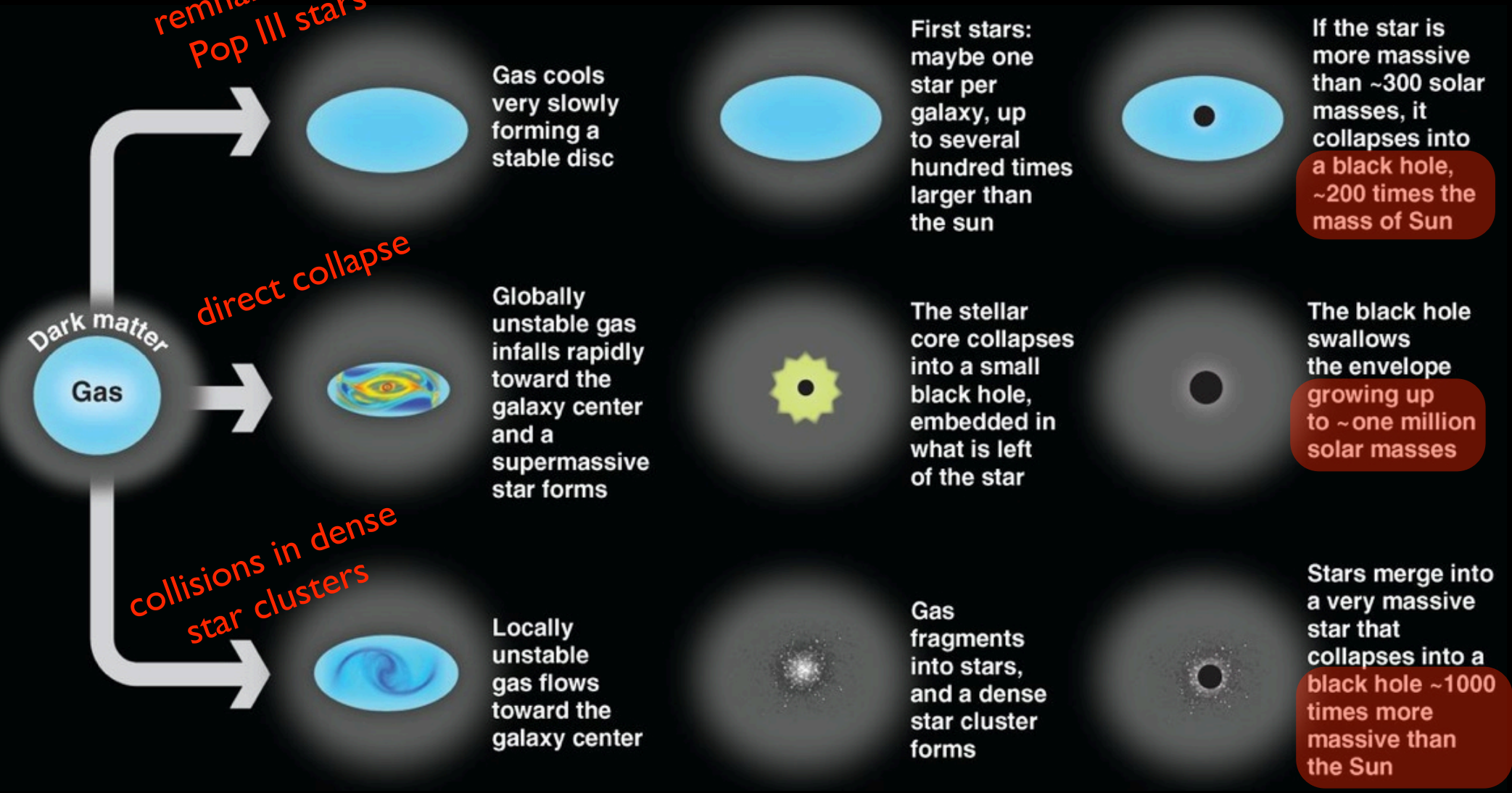
  e.g. Filippenko & Ho (2003); Barth et al. (2004); Reines et al. (2011)

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

  e.g. Volonteri 2010 and references therein

Motivation: The origin of supermassive BH seeds

Possible formation mechanisms:

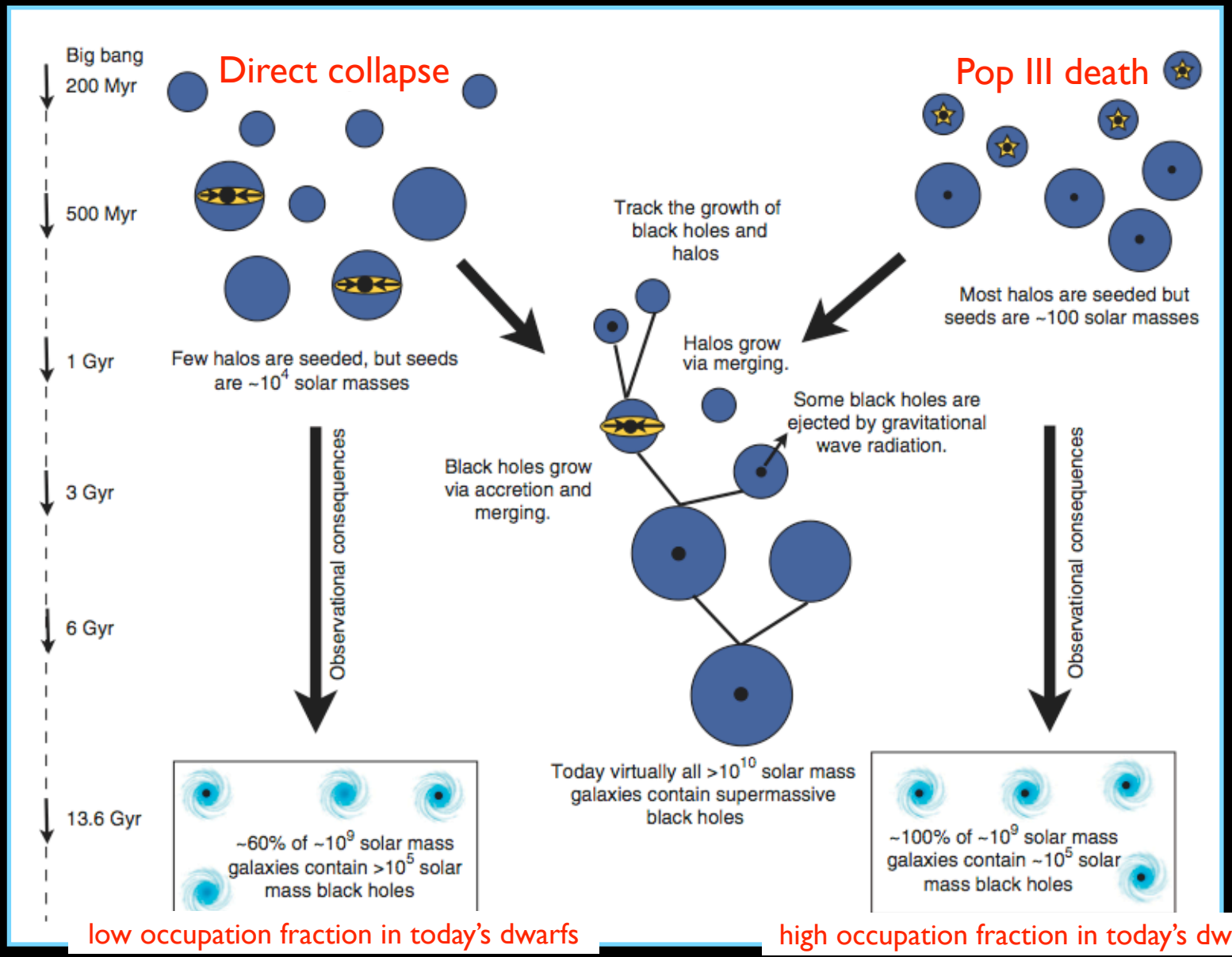


Volonteri 2012, *Science*

Motivation: The origin of supermassive BH seeds

Evolution of seed BHs

time



low occupation fraction in today's dwarfs

high occupation fraction in today's dwarfs

Greene 2012, *Nature Communications*

Observations in the low-mass regime

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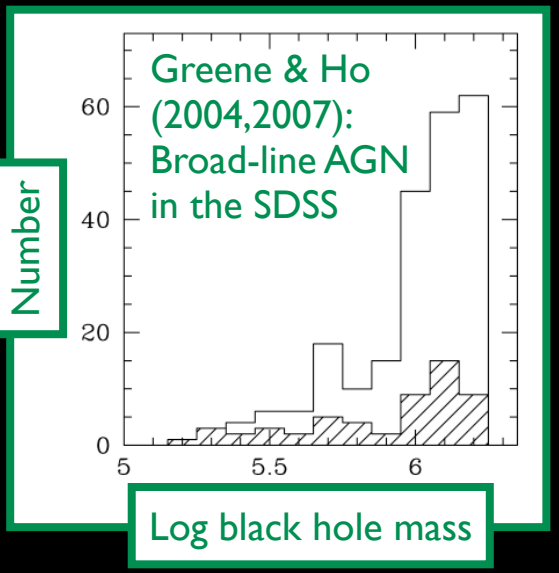

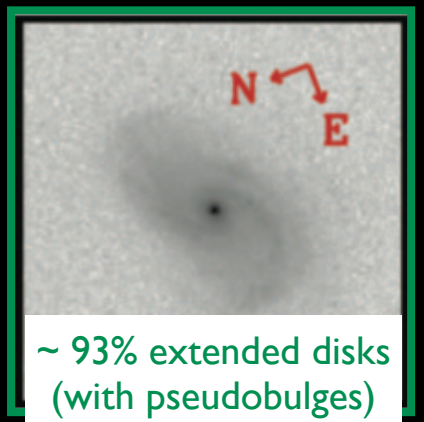

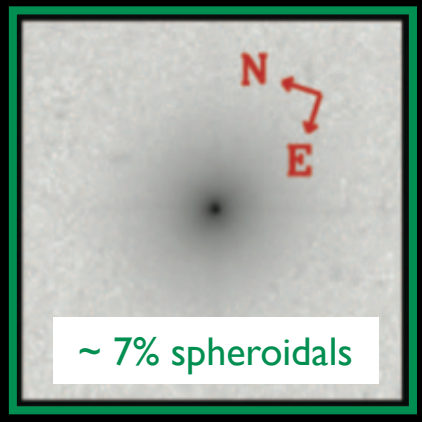

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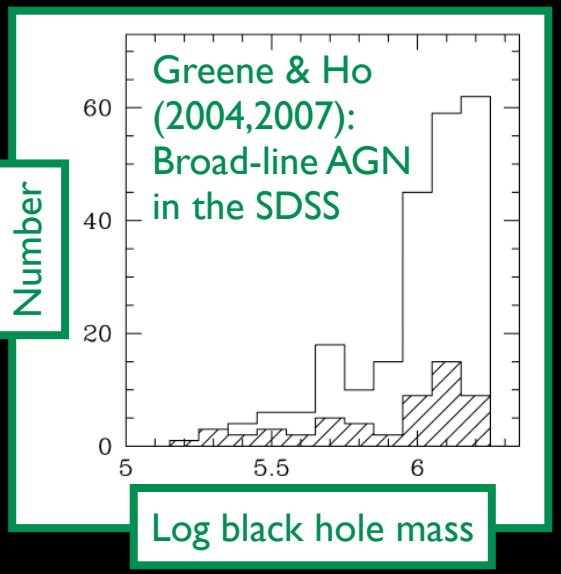

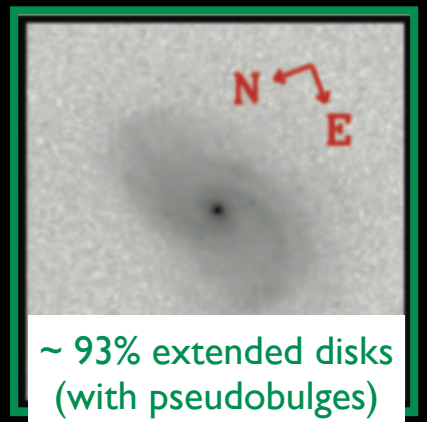

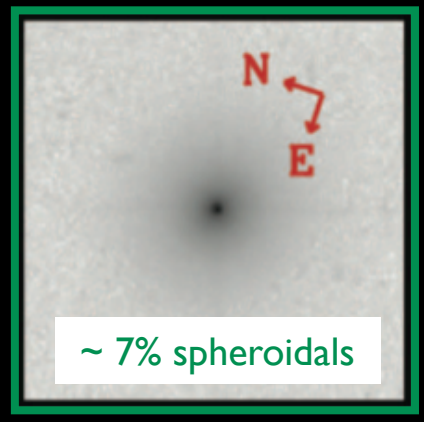

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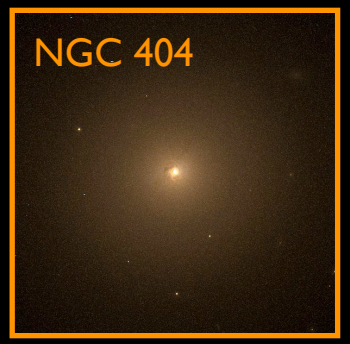

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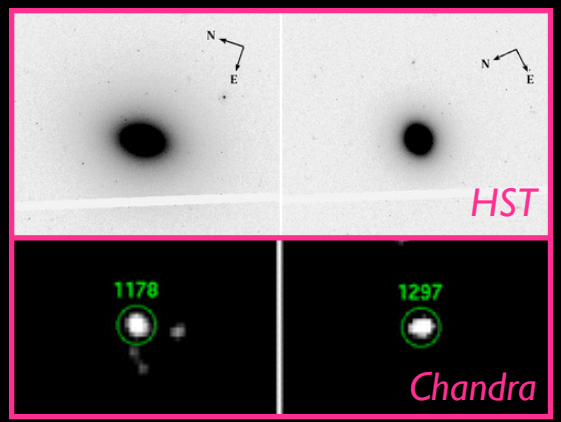

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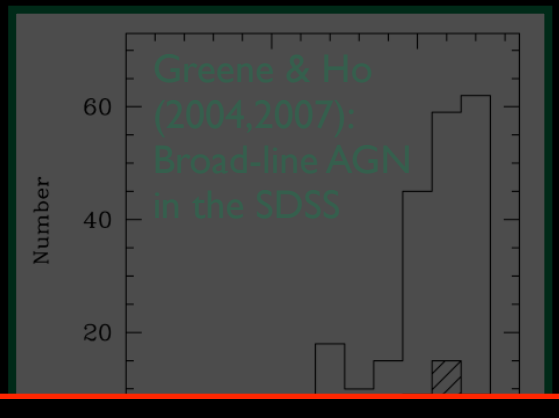

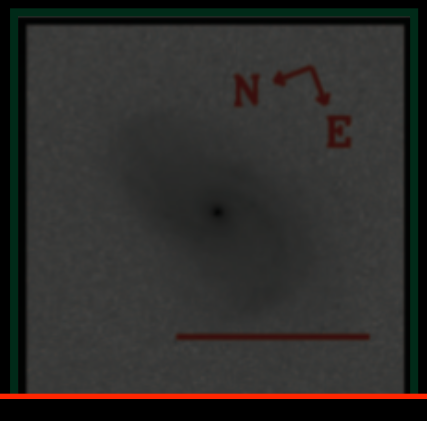

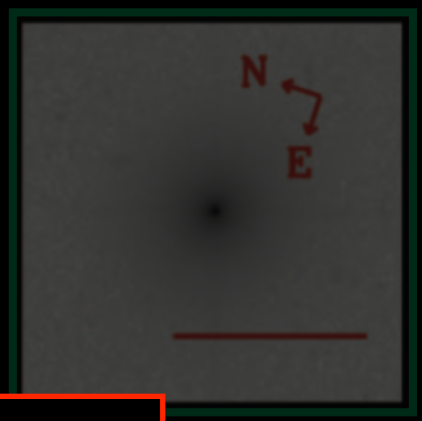

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Need larger samples of dwarf galaxies hosting massive BHs

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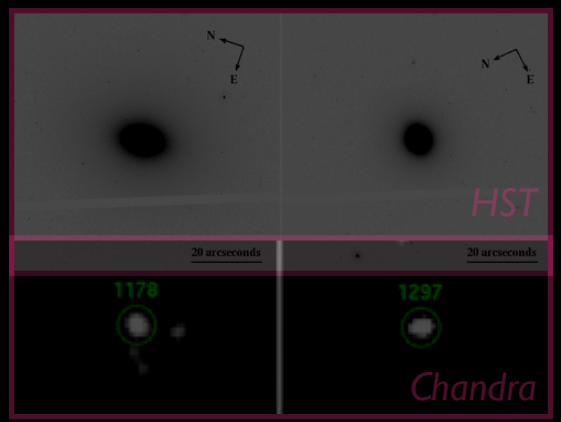

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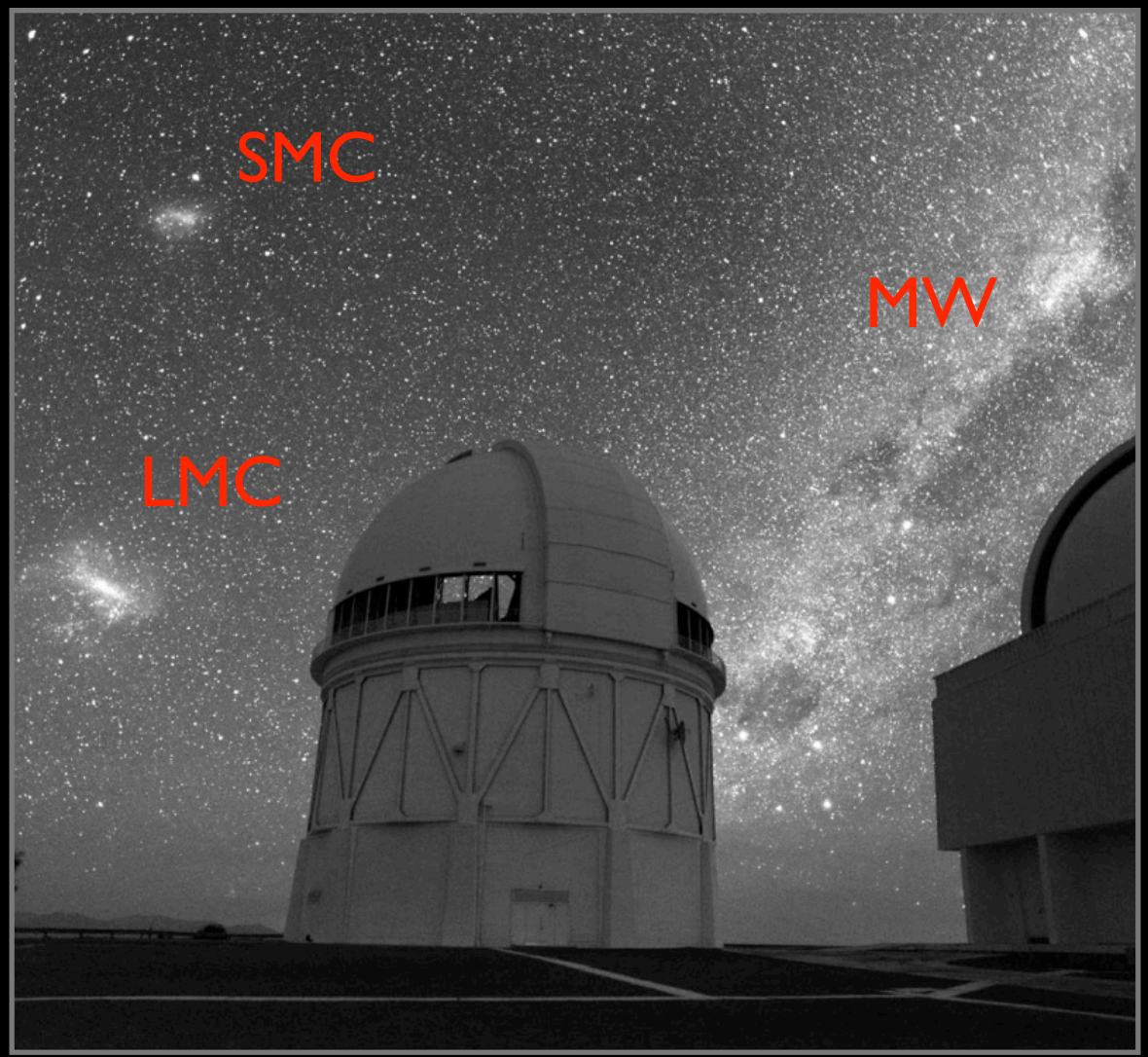
Dwarf galaxies with optical signatures of active massive BHs

(Reines, Greene & Geha, in preparation)

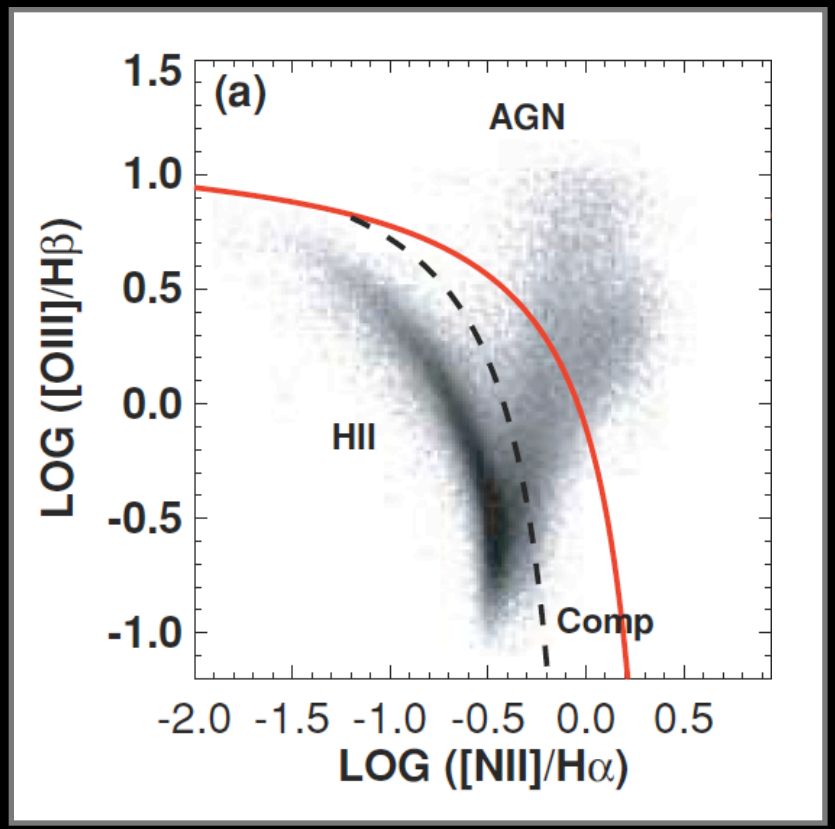
Dwarf galaxies with optical signatures of active massive BHs

~26,000 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 diagram)



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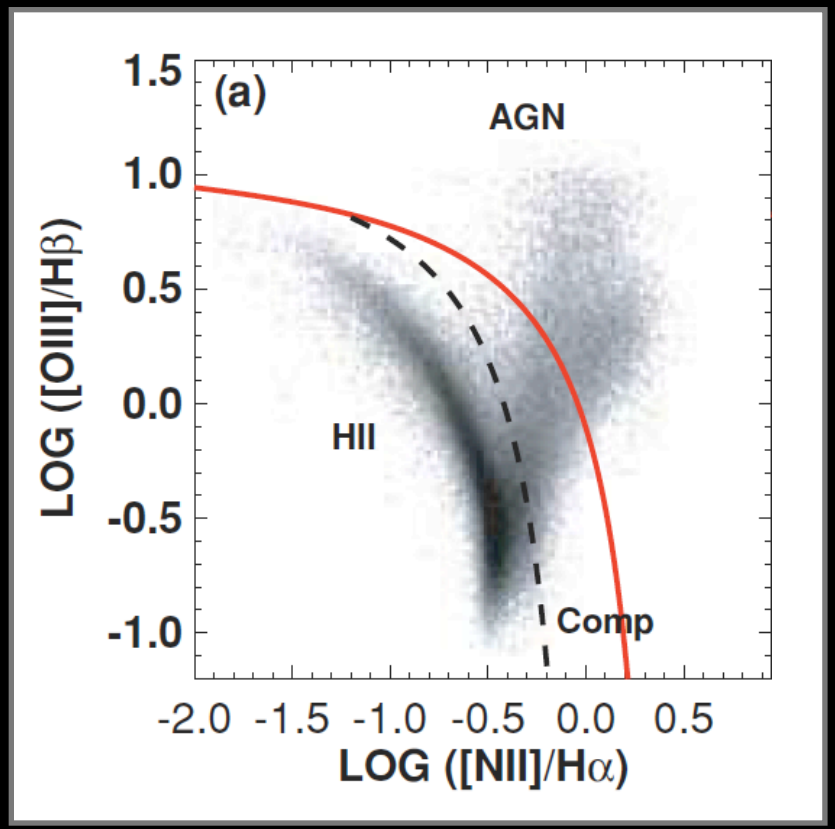

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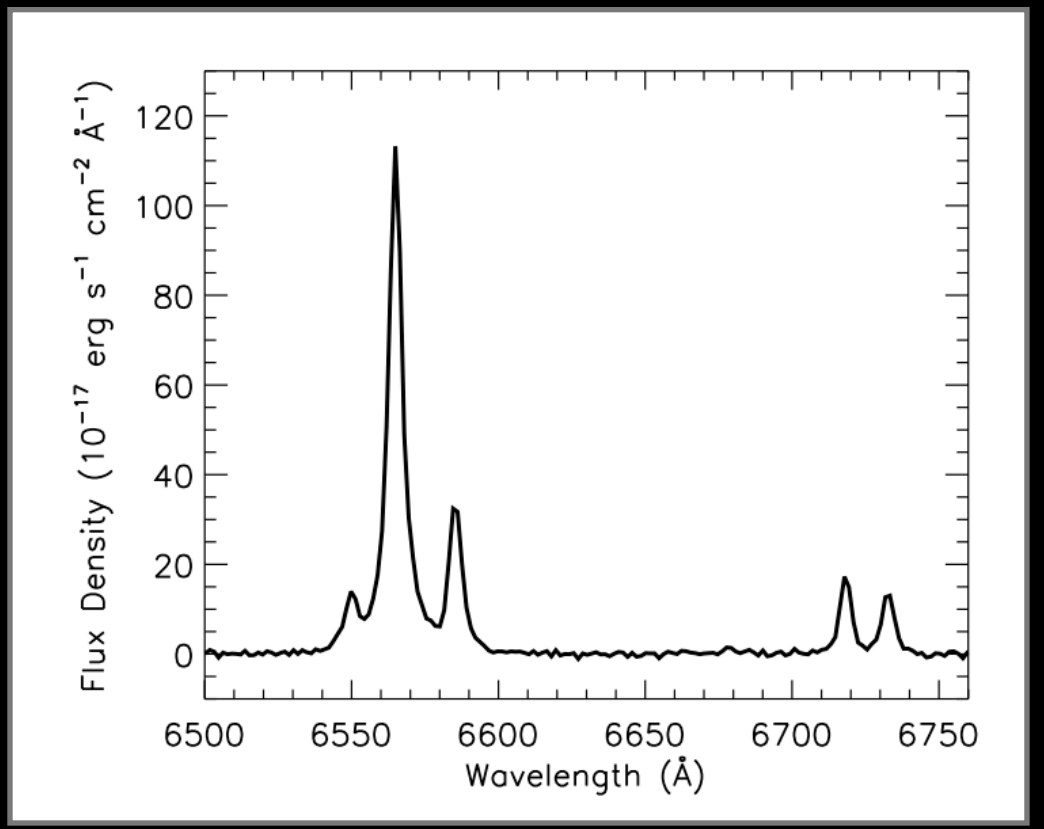
Broad H-alpha



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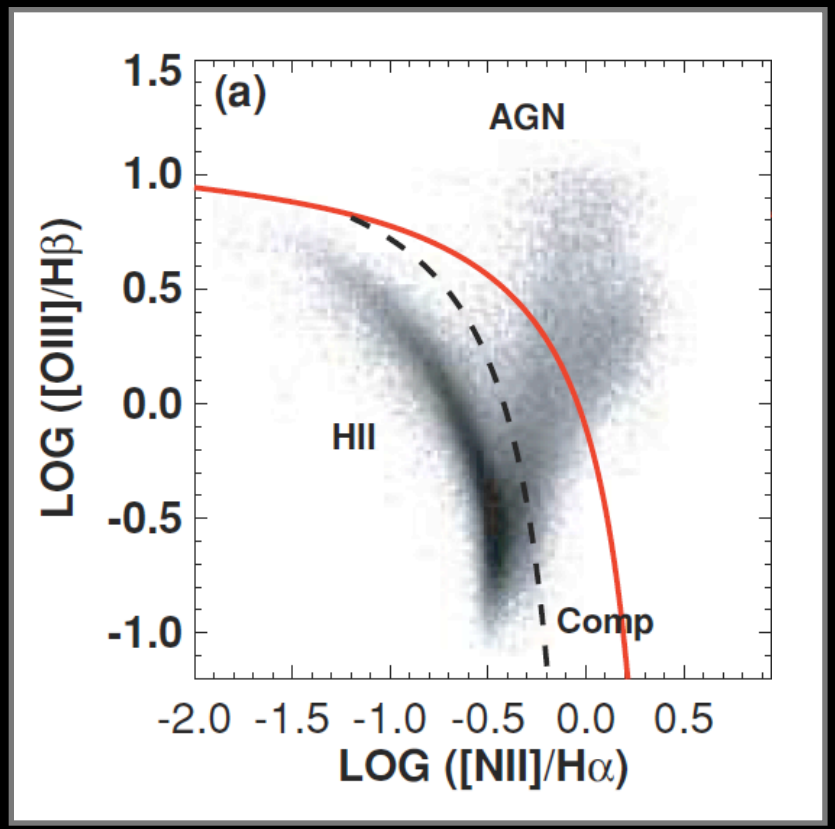

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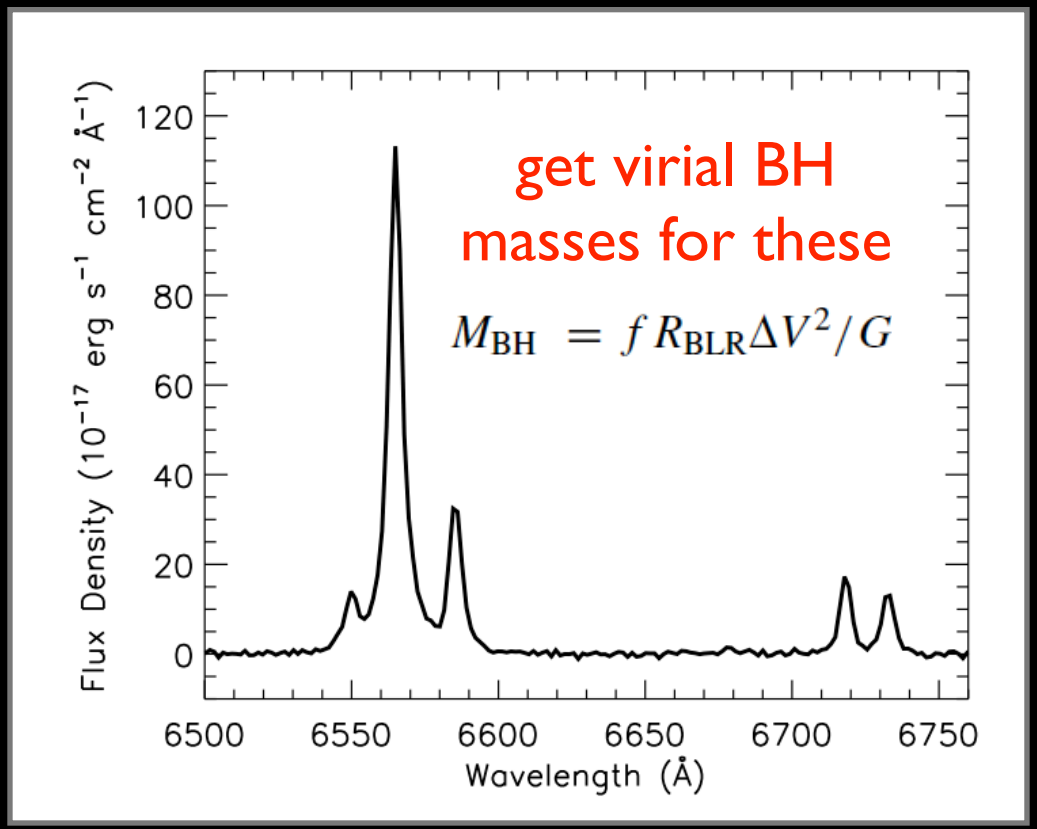

(method from Greene & Ho 2005)

Overview of the method

1. Select dwarf emission line galaxies and get SDSS spectra

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

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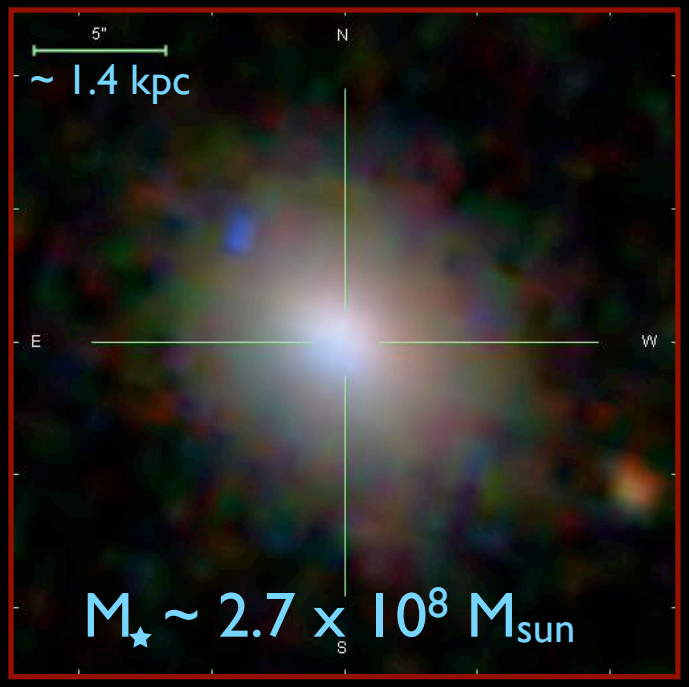
4. Calculate virial black hole masses from broad H-alpha

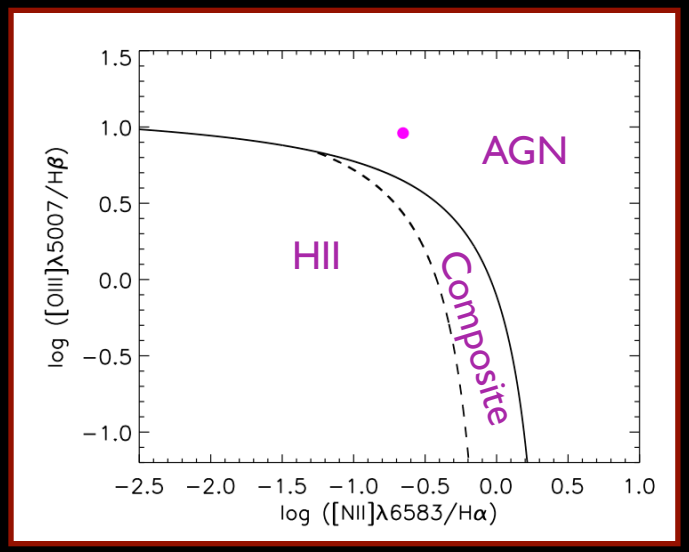
$$M_{\rm BH} = f\, R_{\rm BLR} \Delta V^2 / G$$

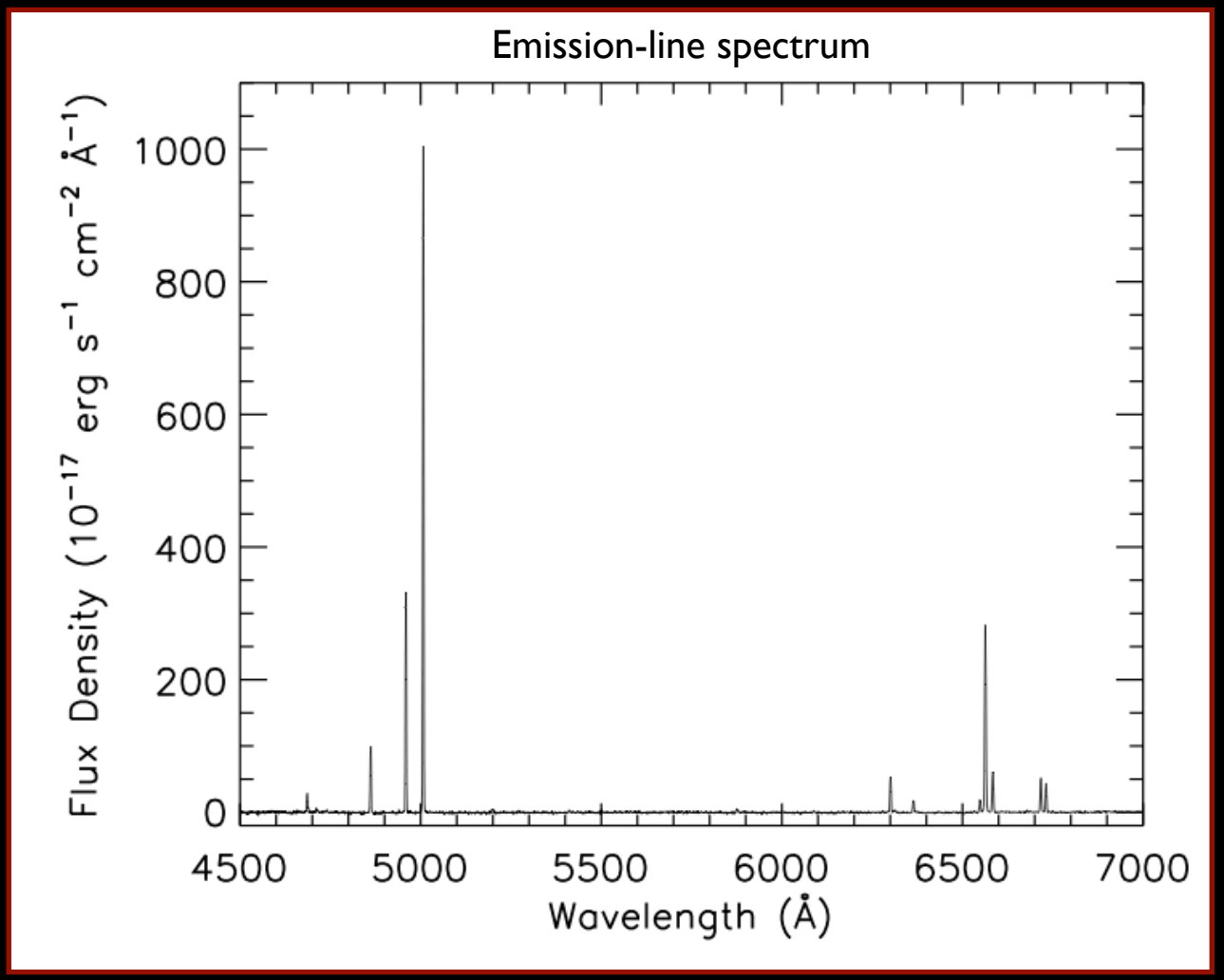
$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = 6.40^{+0.09}_{-0.07} + (0.45 \pm 0.05)\log\left(\frac{L_{\rm H\alpha}}{10^{42}\ {\rm erg\ s^{-1}}}\right) + (2.06 \pm 0.06)\log\left(\frac{\rm FWHM(H\alpha)}{10^3\ {\rm km\ s^{-1}}}\right)$$

(method from Greene & Ho 2005)

Example 1: Narrow-line AGN







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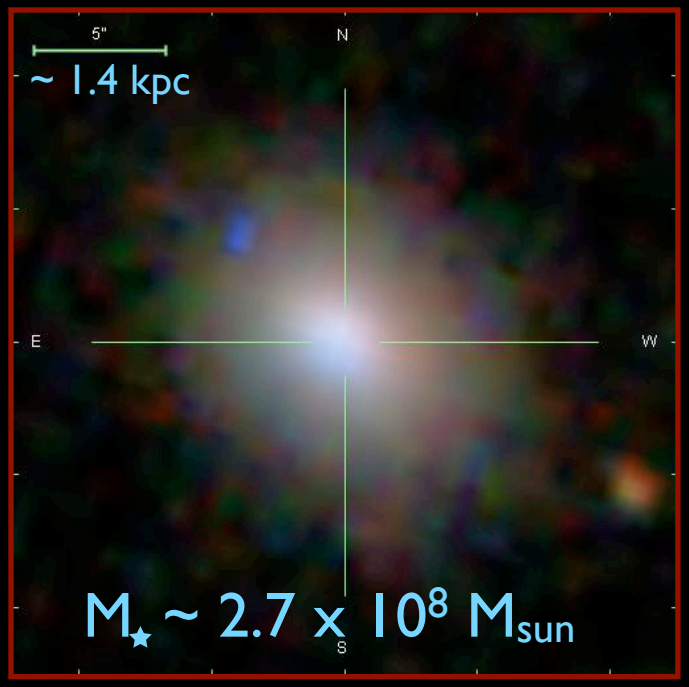

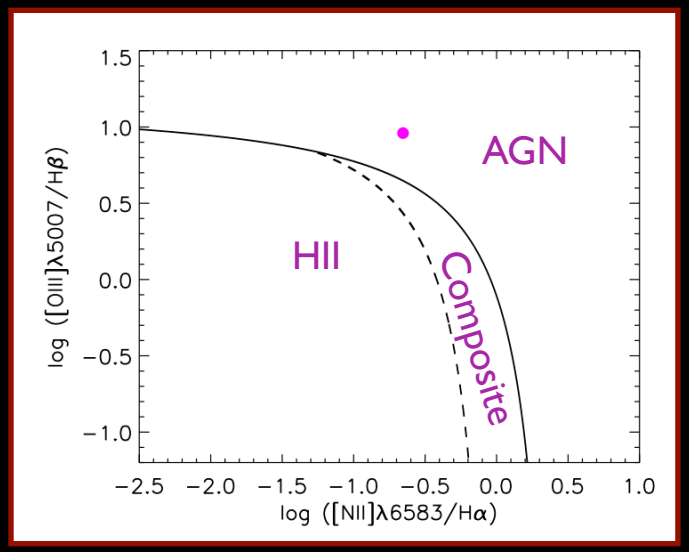

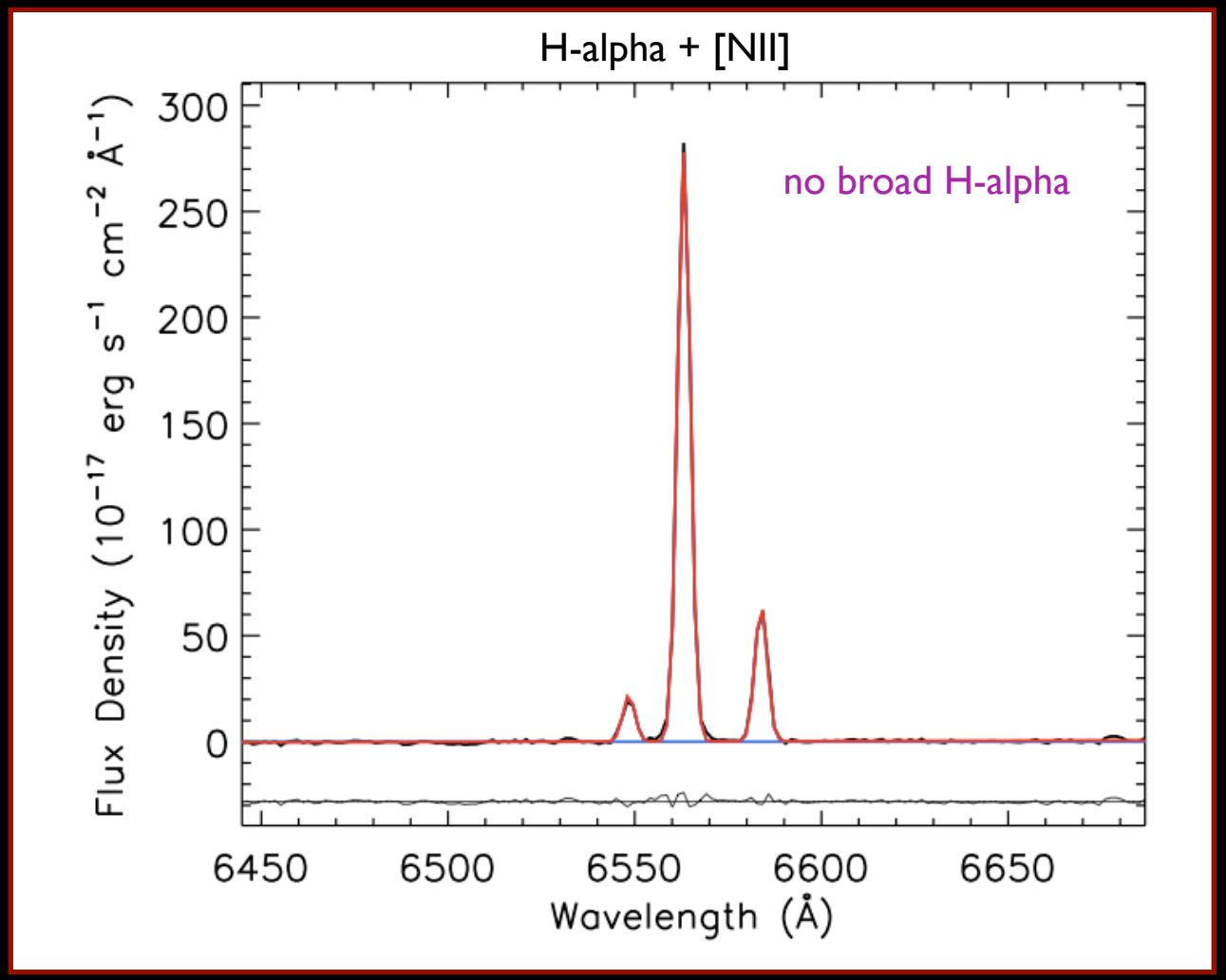

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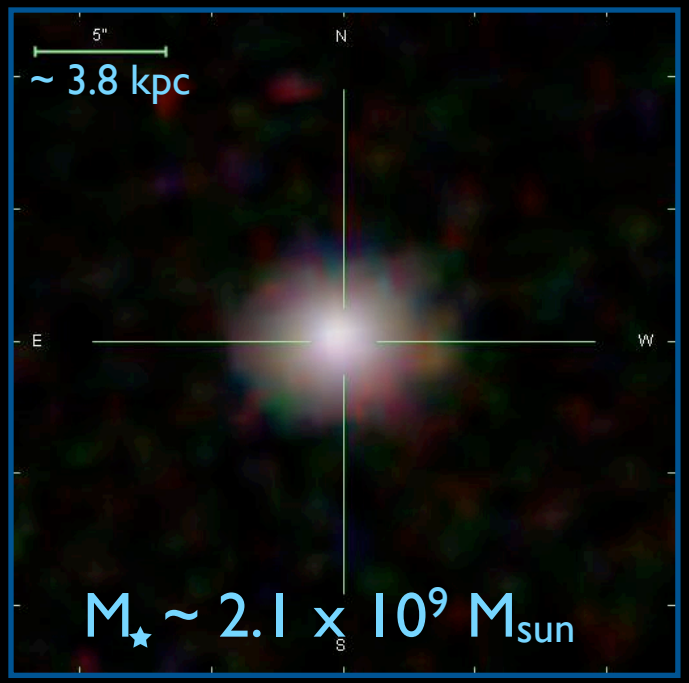

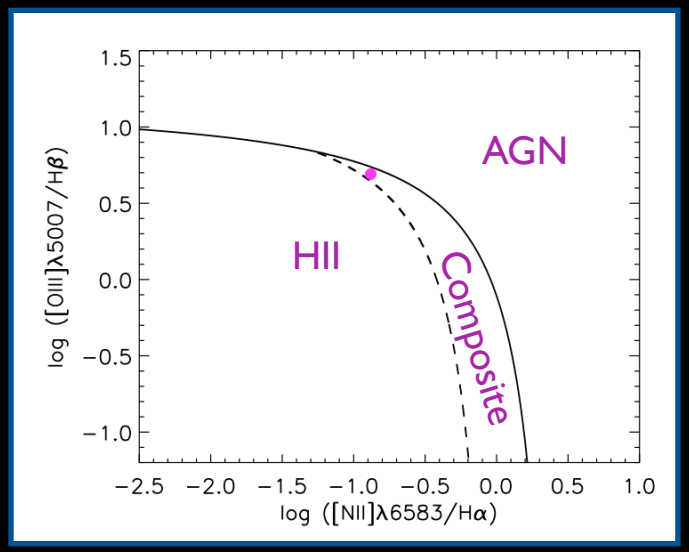

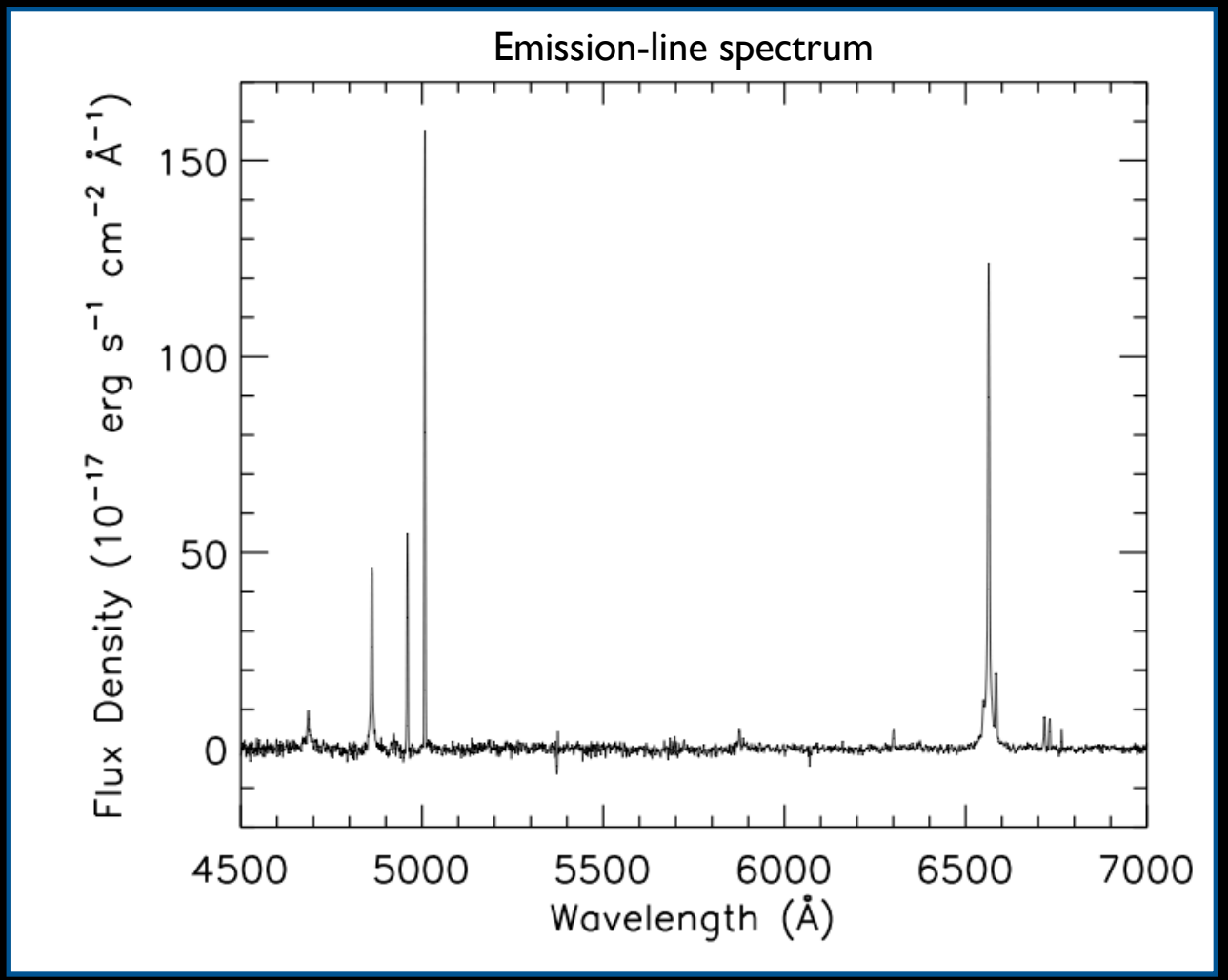

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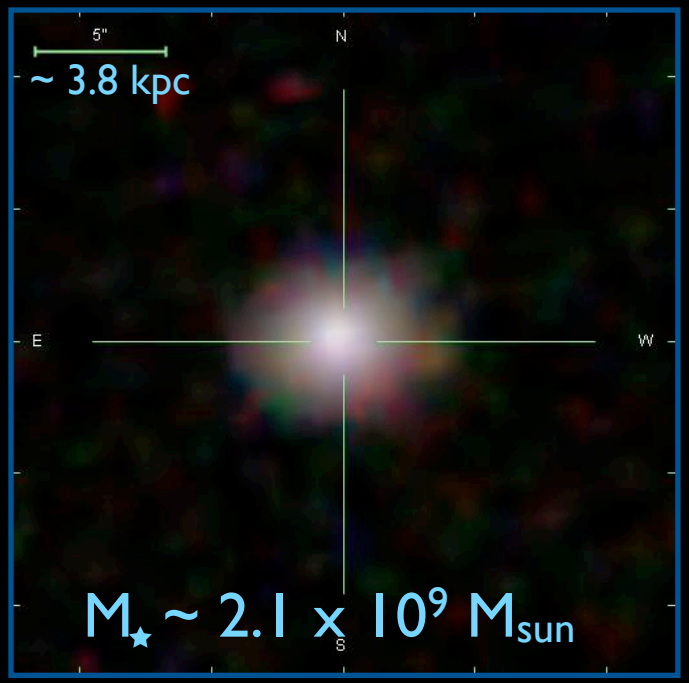
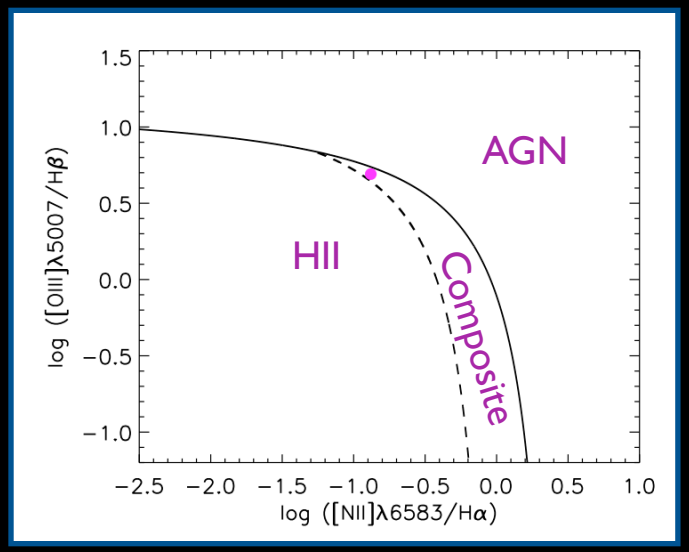
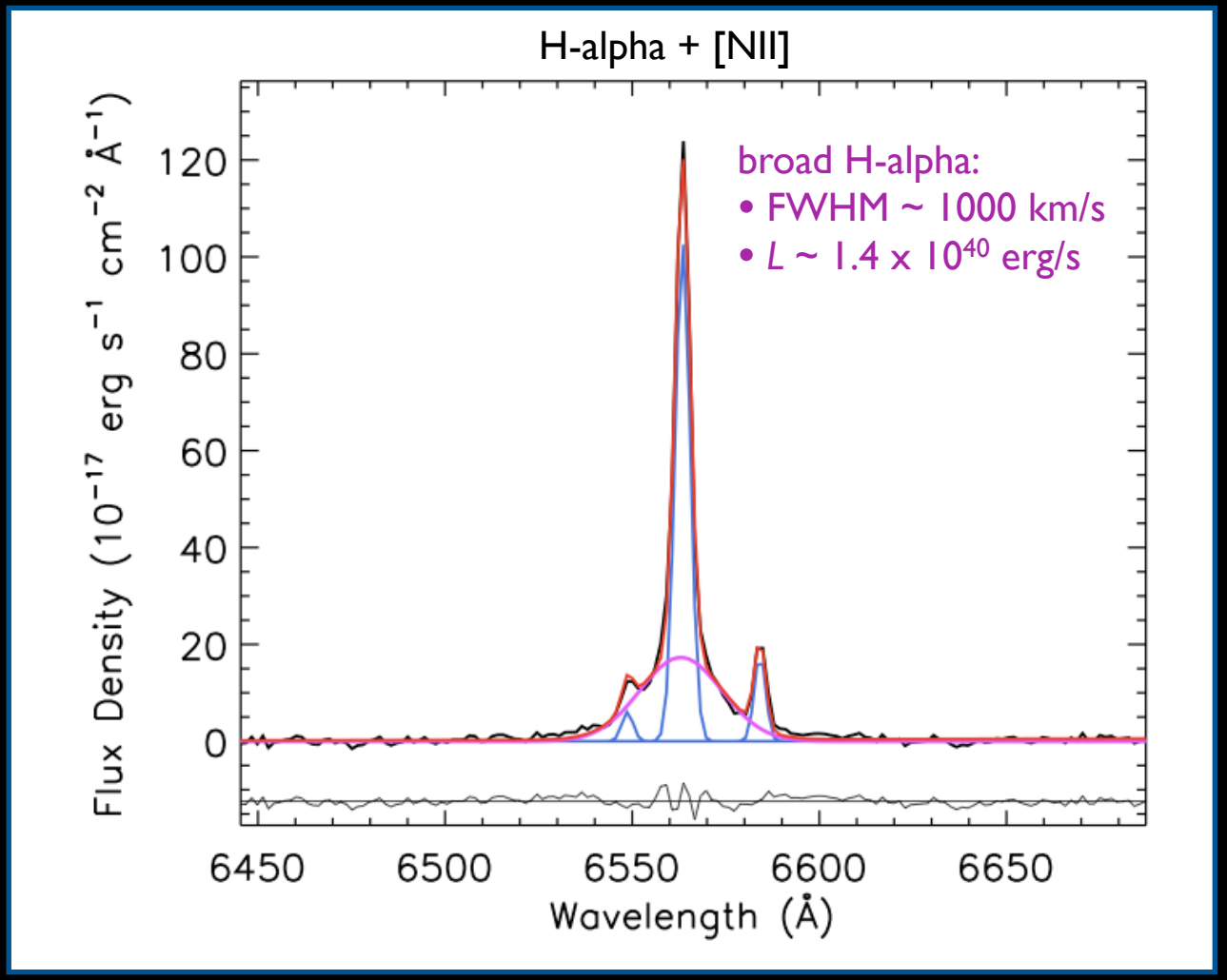


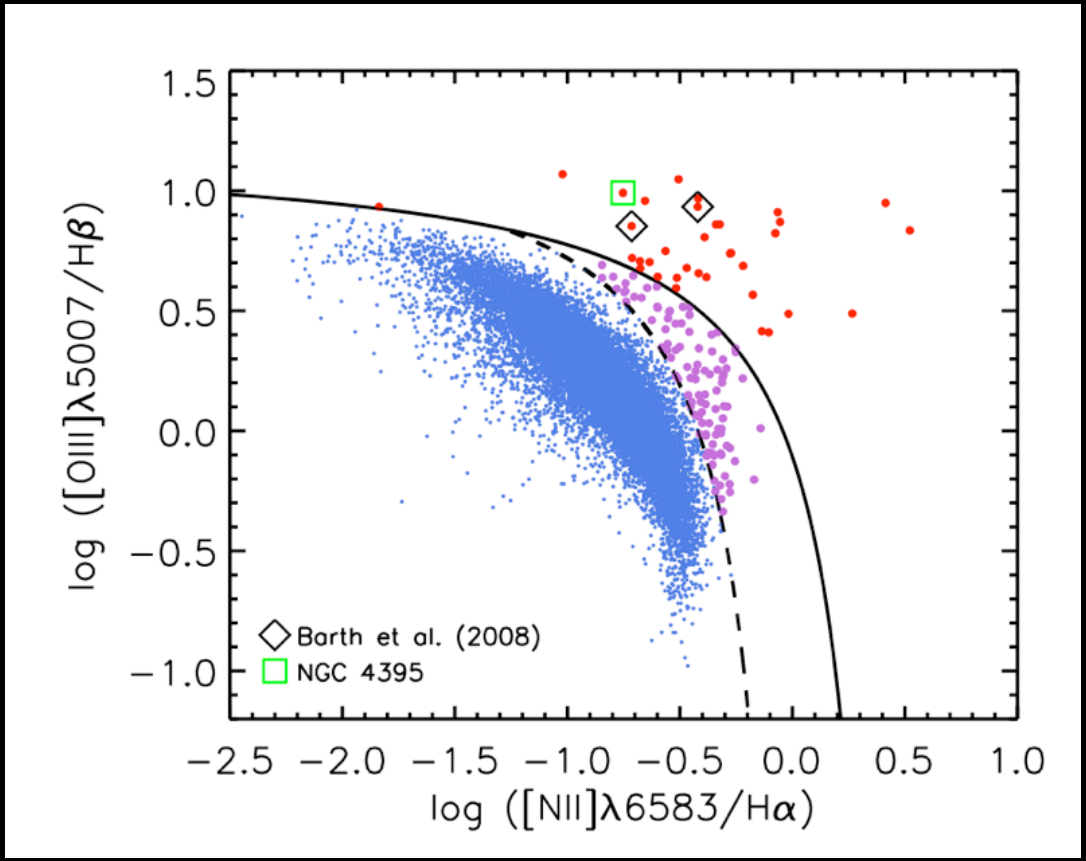




$M_{BH} \sim 4 \times 10^5 M_{sun}$

BPT diagrams

All ~26,000 dwarf galaxies



35 AGN

101 Composites

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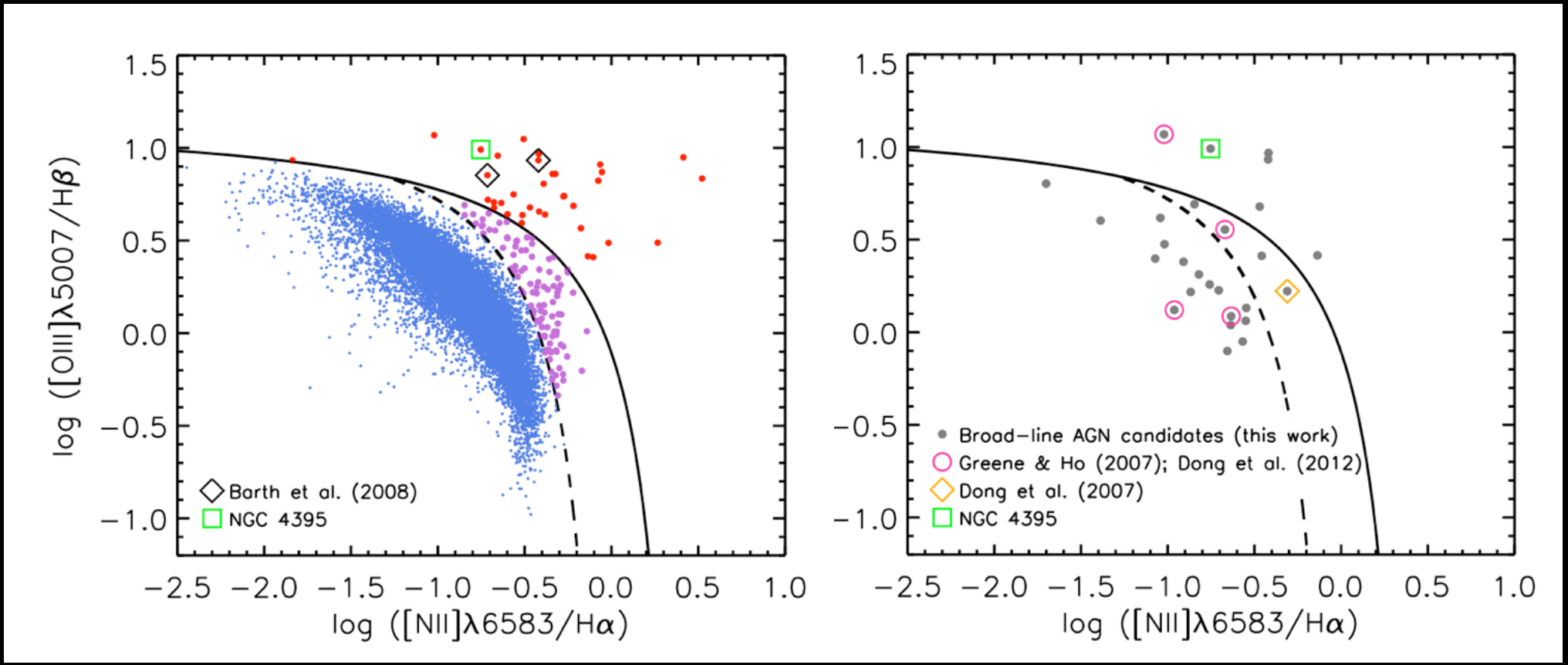
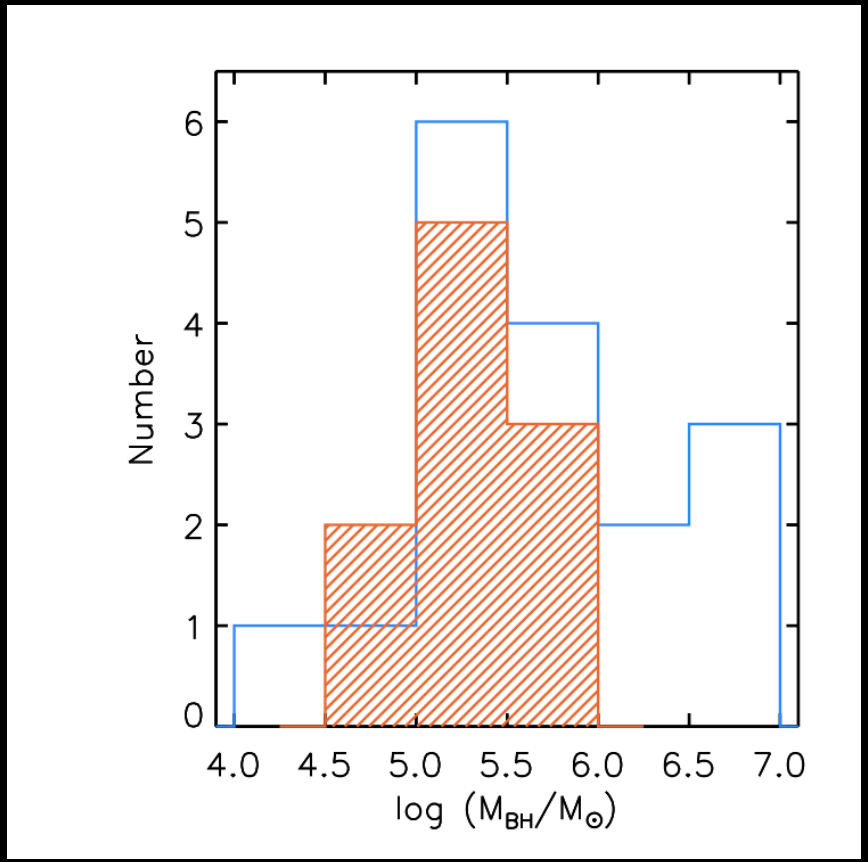
Broad-line AGN candidates



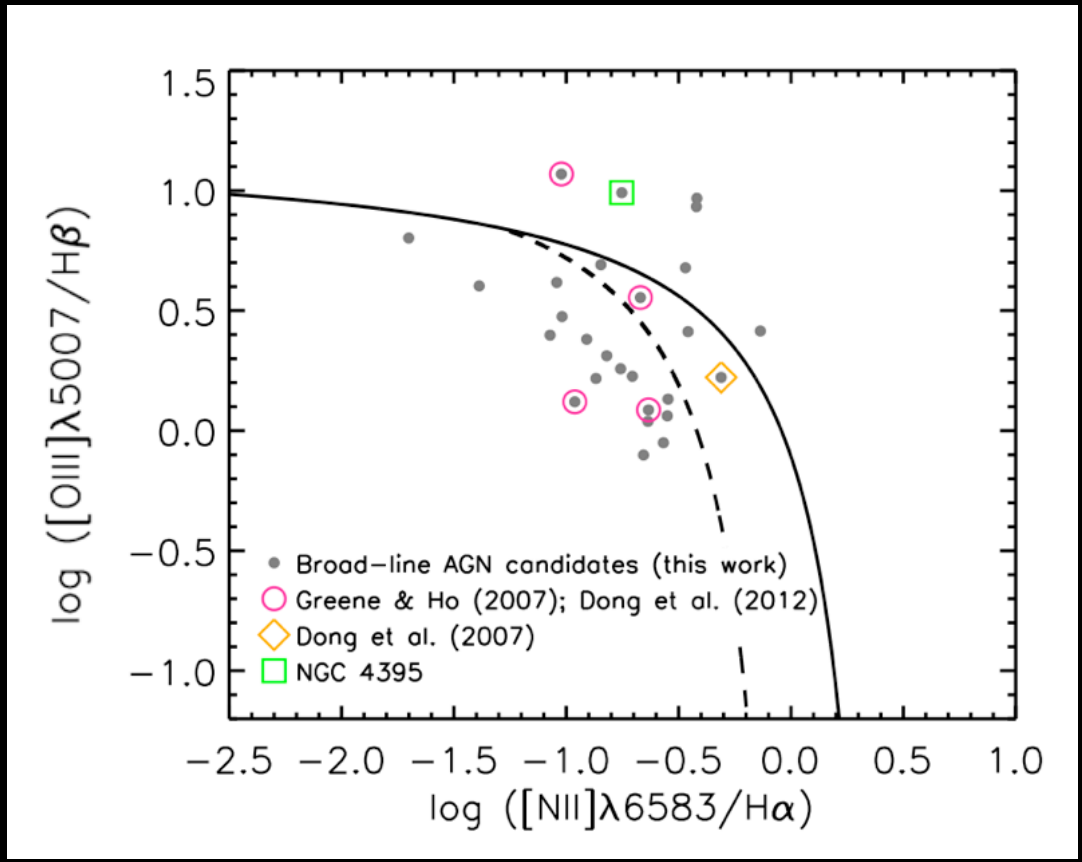
35 AGN
101 Composites

27 broad-line AGN candidates
(with virial BH mass estimates)

BH mass distribution for broad-line AGN candidates



black hole mass



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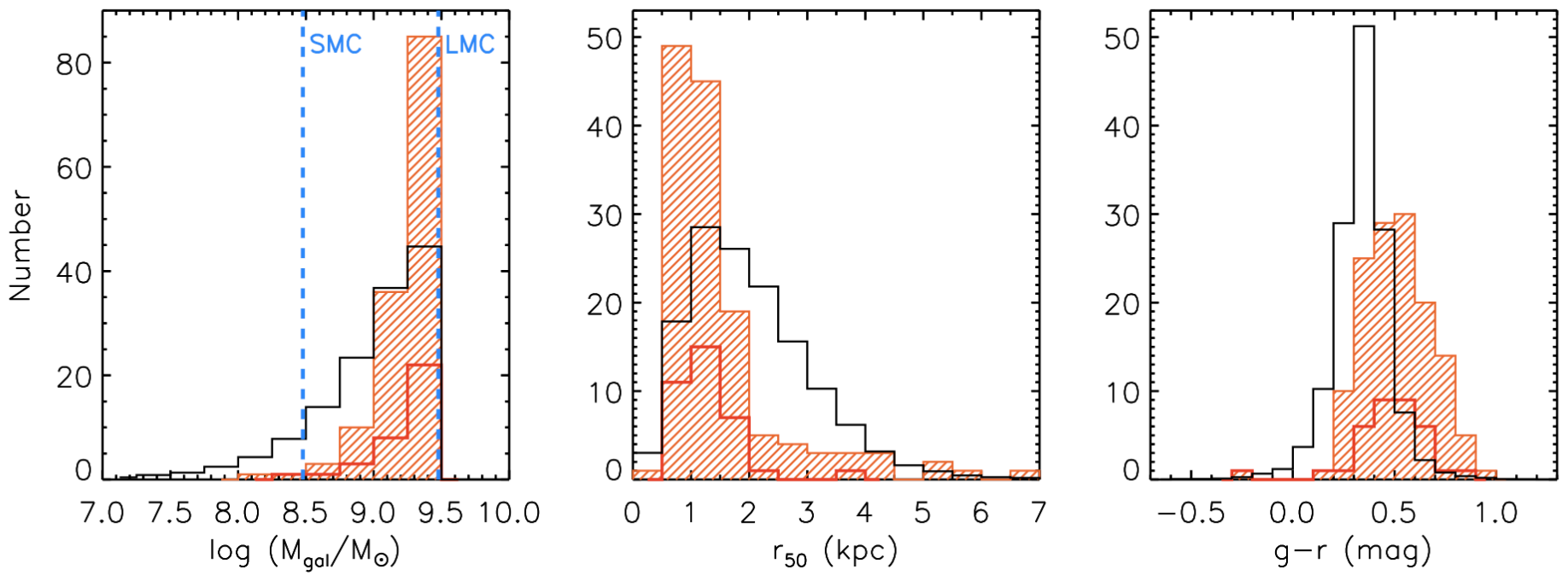
Galaxy properties

(BPT AGN+composites in orange, normalized parent sample in black)



stellar mass

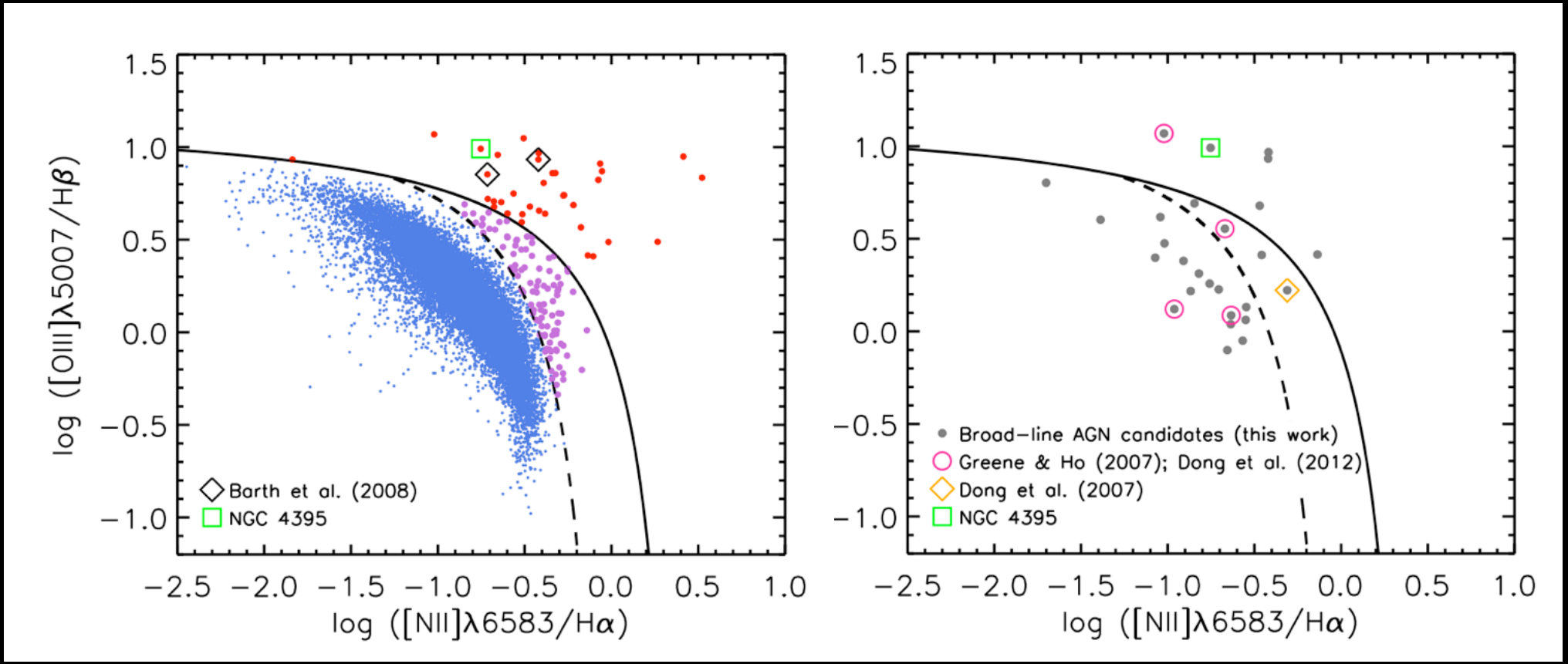
half-light radius

g-r color

Largest sample of dwarfs hosting massive BHs to date (>100)

All ~26,000 dwarf galaxies

Broad-line AGN candidates



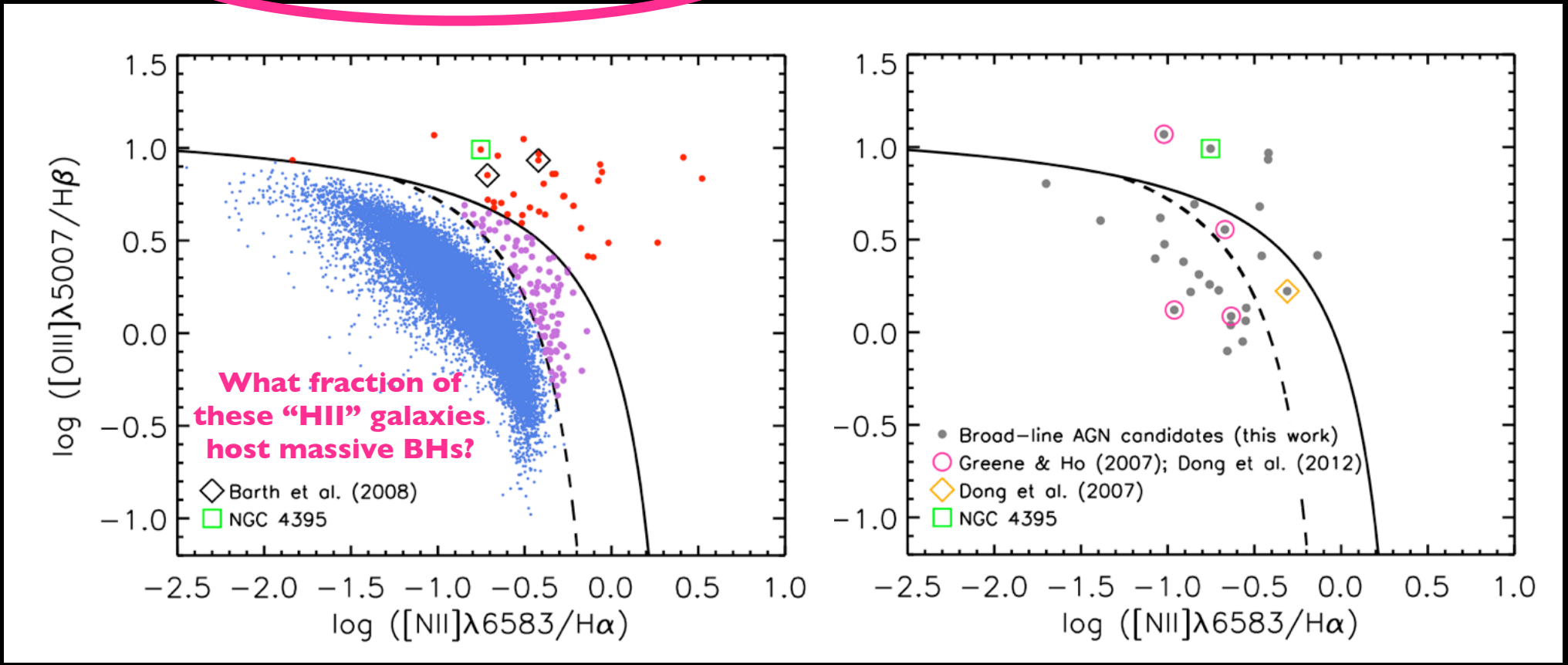
35 AGN
101 Composites

27 broad-line AGN candidates

Largest sample of dwarfs hosting massive BHs to date (>100)

All ~26,000 dwarf galaxies

Broad-line AGN candidates



35 AGN
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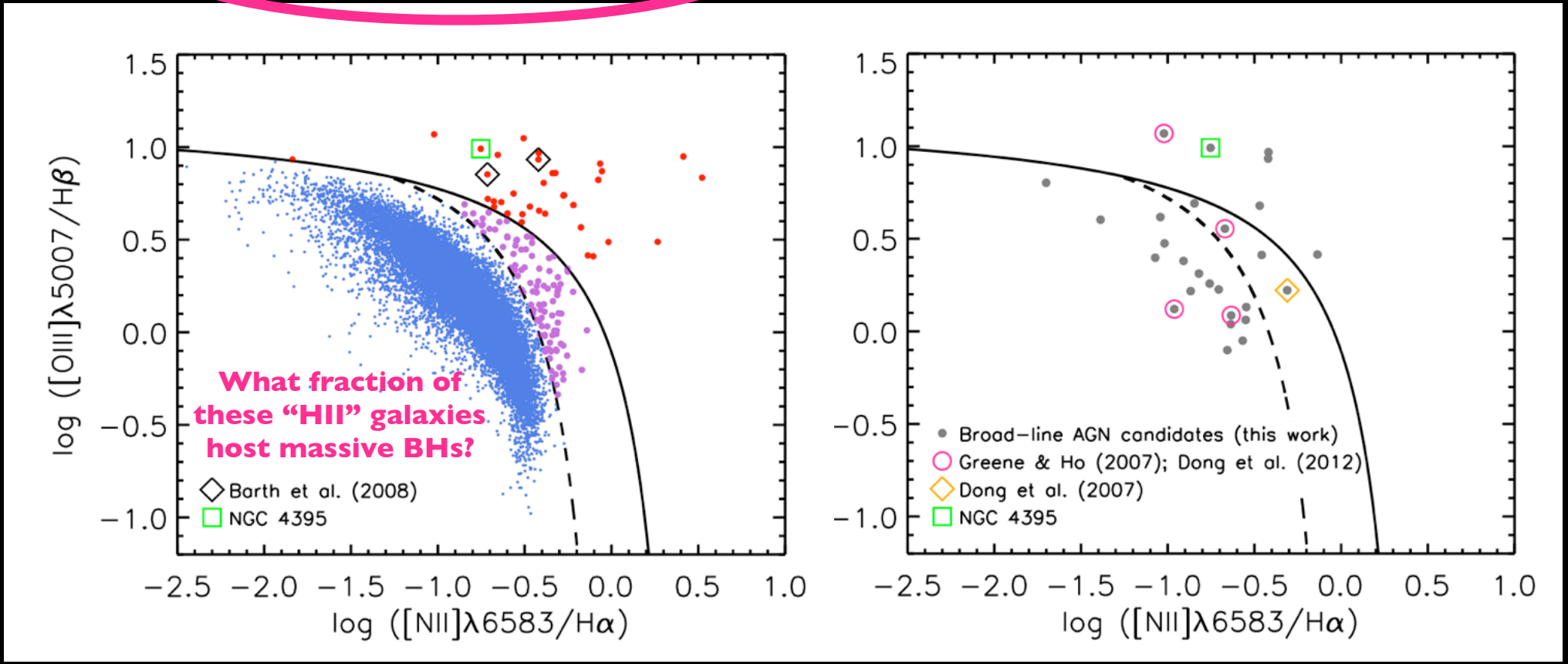
< 1% of dwarfs have *optical signatures* of accreting massive BHs

Largest sample of dwarfs hosting massive BHs to date (>100)

All ~26,000 dwarf galaxies

Broad-line AGN candidates

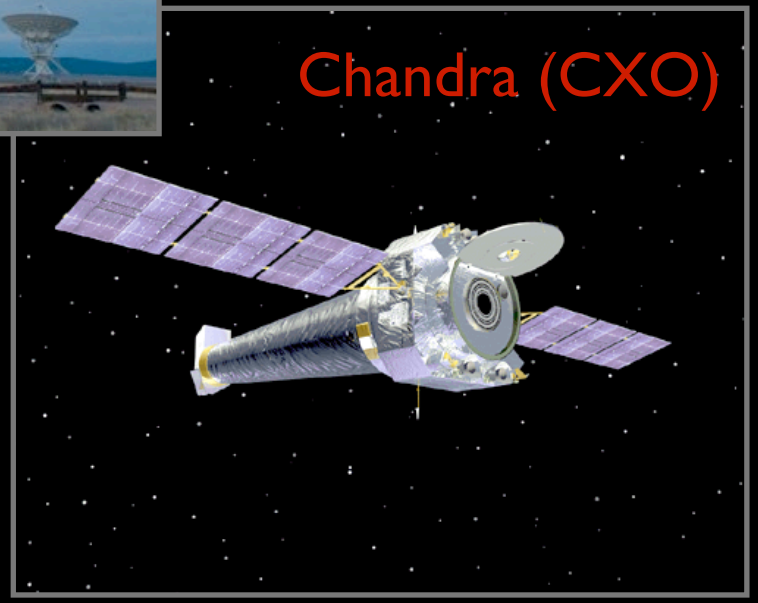


35 AGN
101 Composites

27 broad-line AGN candidates

Need other diagnostics!

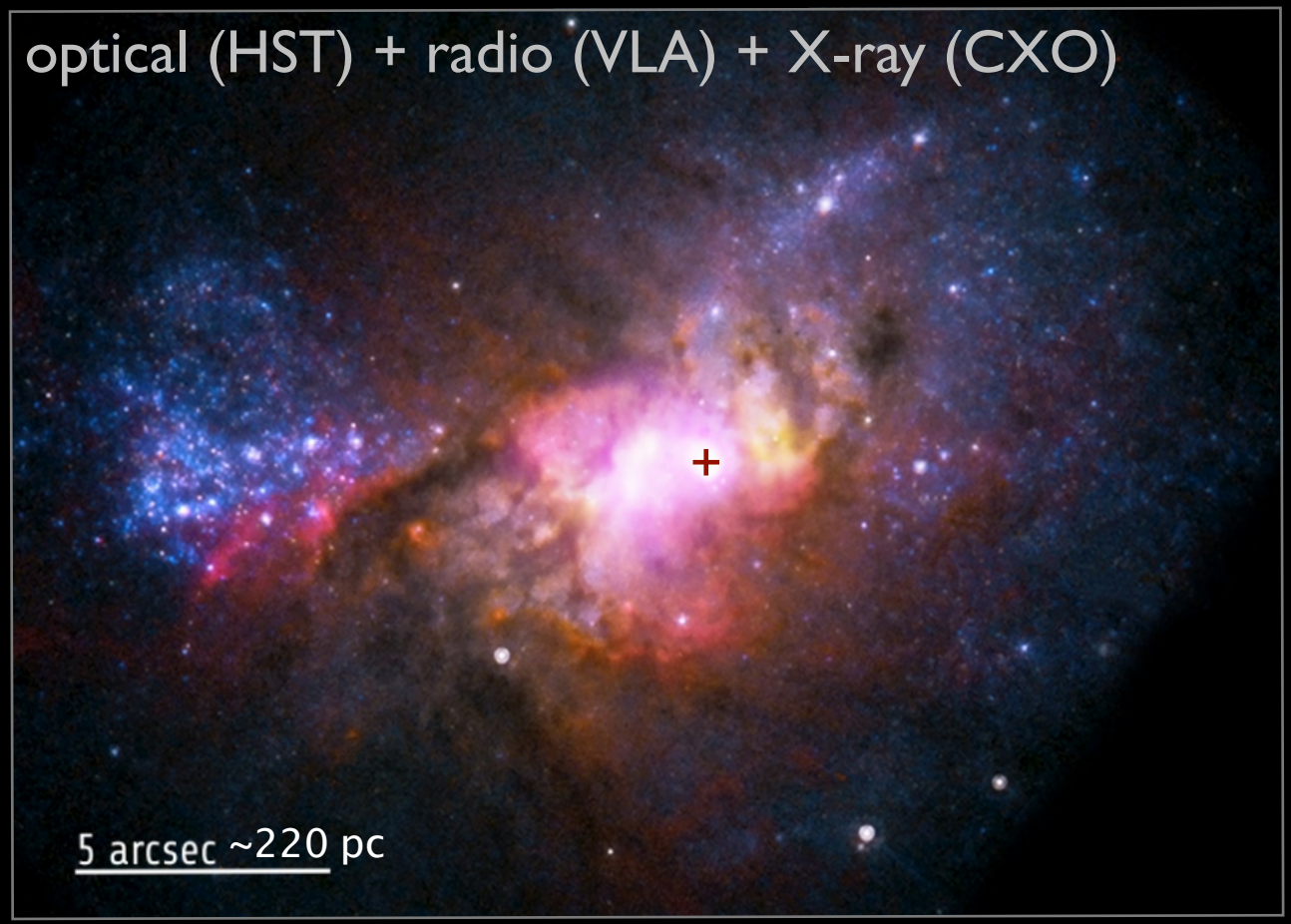
High-resolution radio + X-ray observations

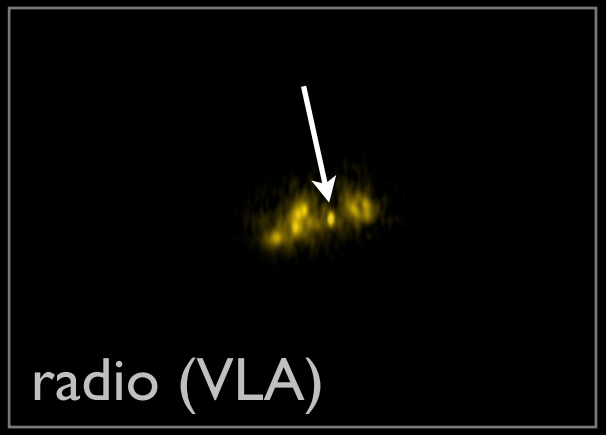


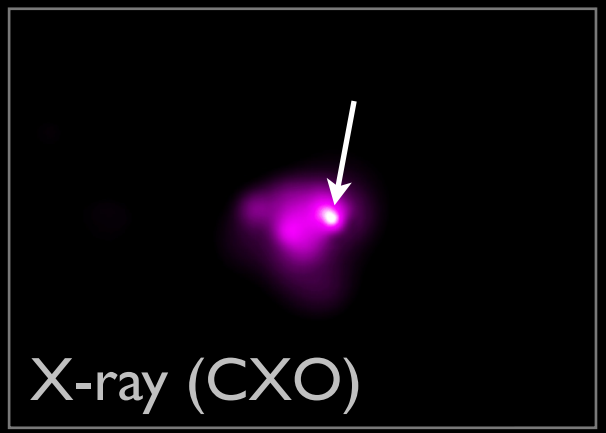
- More sensitive to weakly accreting BHs
- Can pick out AGN in galaxies with lots of star formation

Need other diagnostics!

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





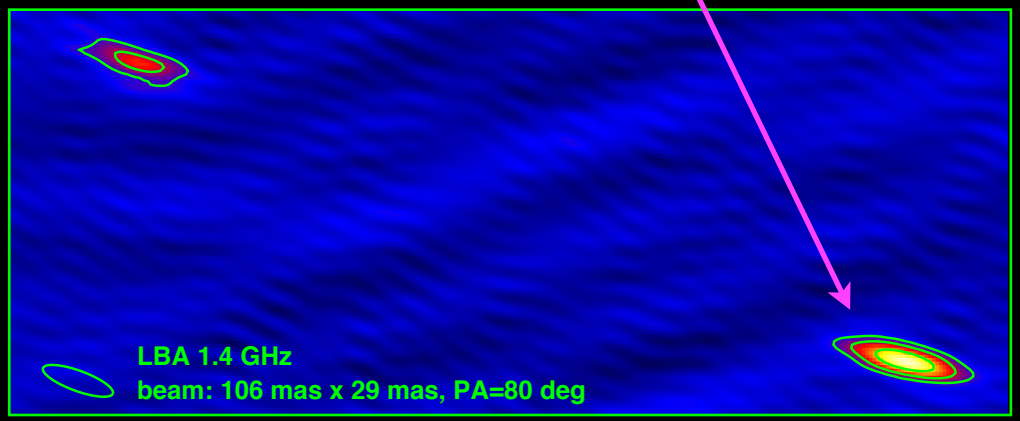


Reines et al. 2011, *Nature*

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

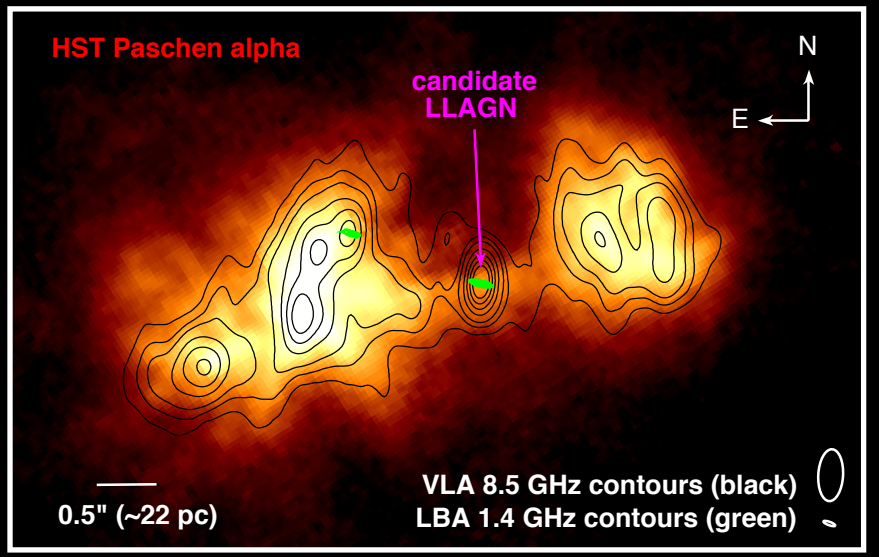
VLBI follow-up with the Long Baseline Array (LBA)

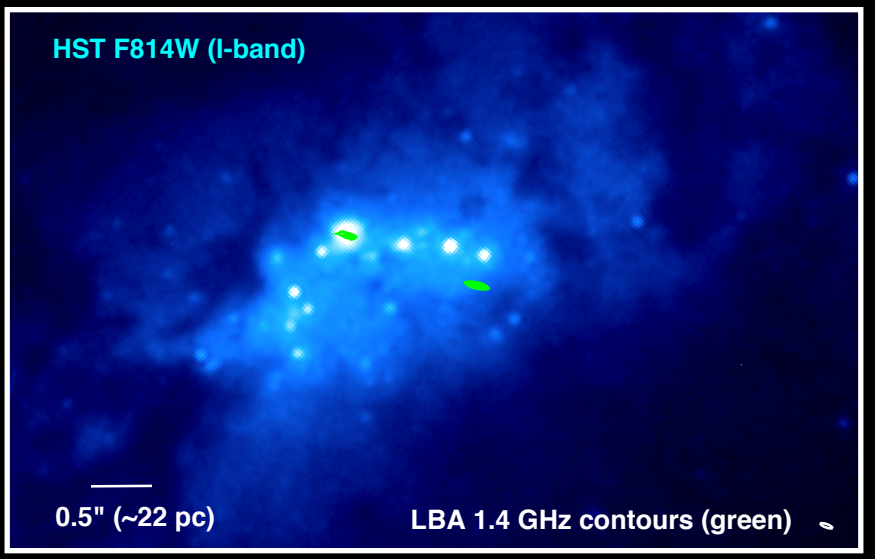
nuclear radio source:
≲ 3 x 1 pc



Reines & Deller (2012)

HST imaging of central ~ 250 pc





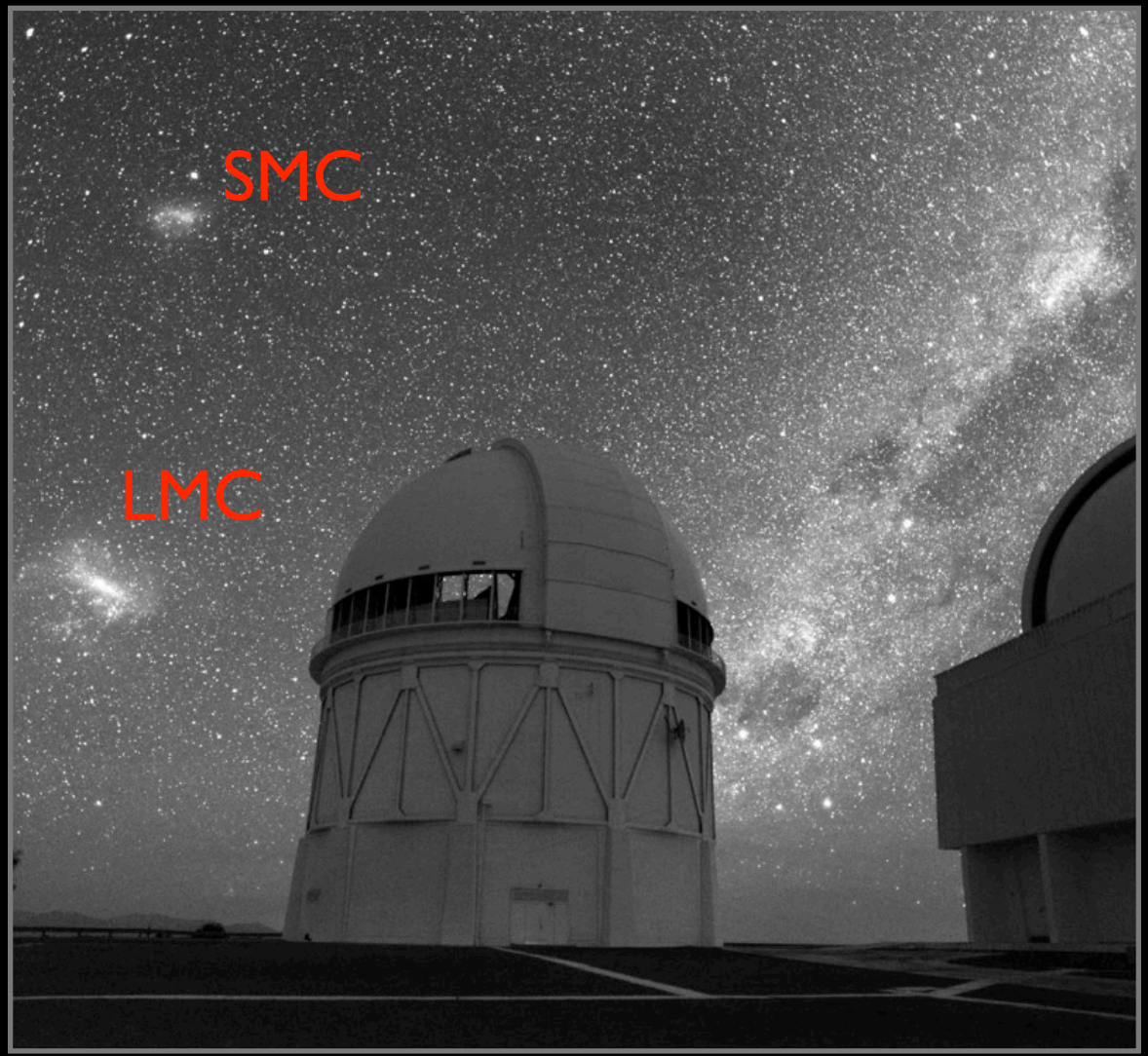
A massive BH in the dwarf starburst galaxy Henize 2-10

~ 1 kpc

$M_\star \sim 3 \times 10^9 M_{sun}$

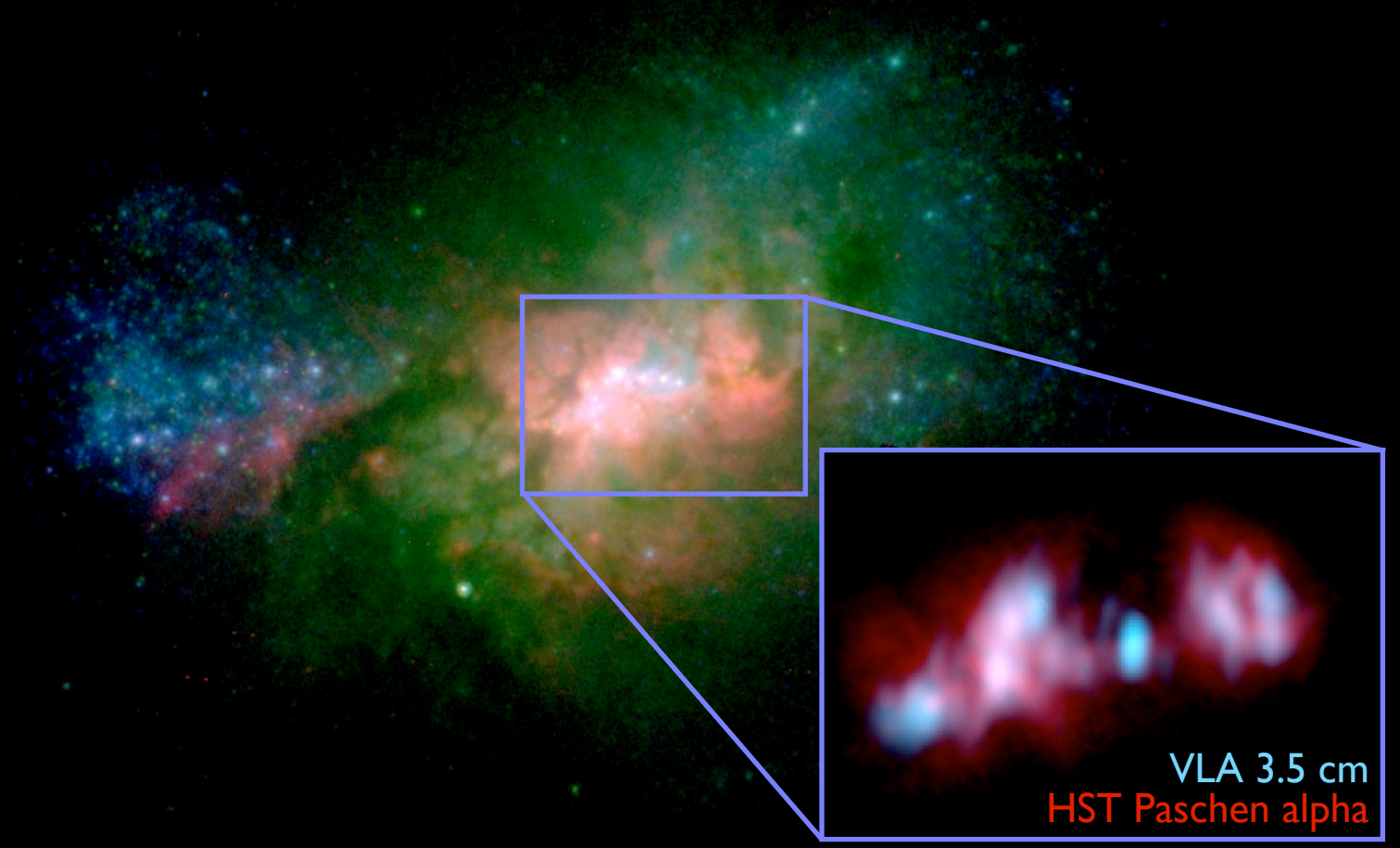
$SFR \sim 2 M_{sun}/yr$

familiar dwarf galaxies - the Magellanic Clouds



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

- Black hole mass ~ 10^6 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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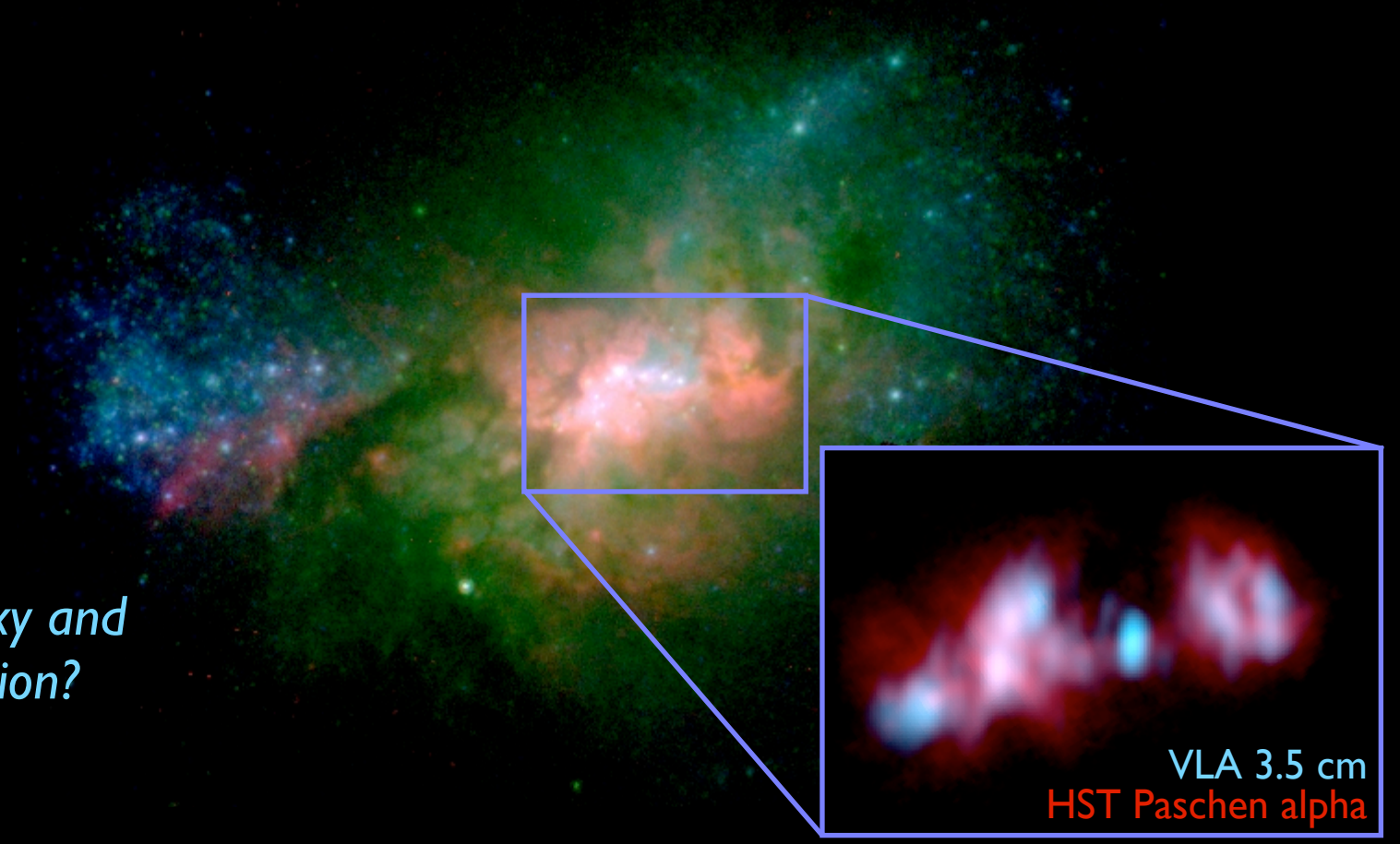

Early stage of galaxy and black hole evolution?

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

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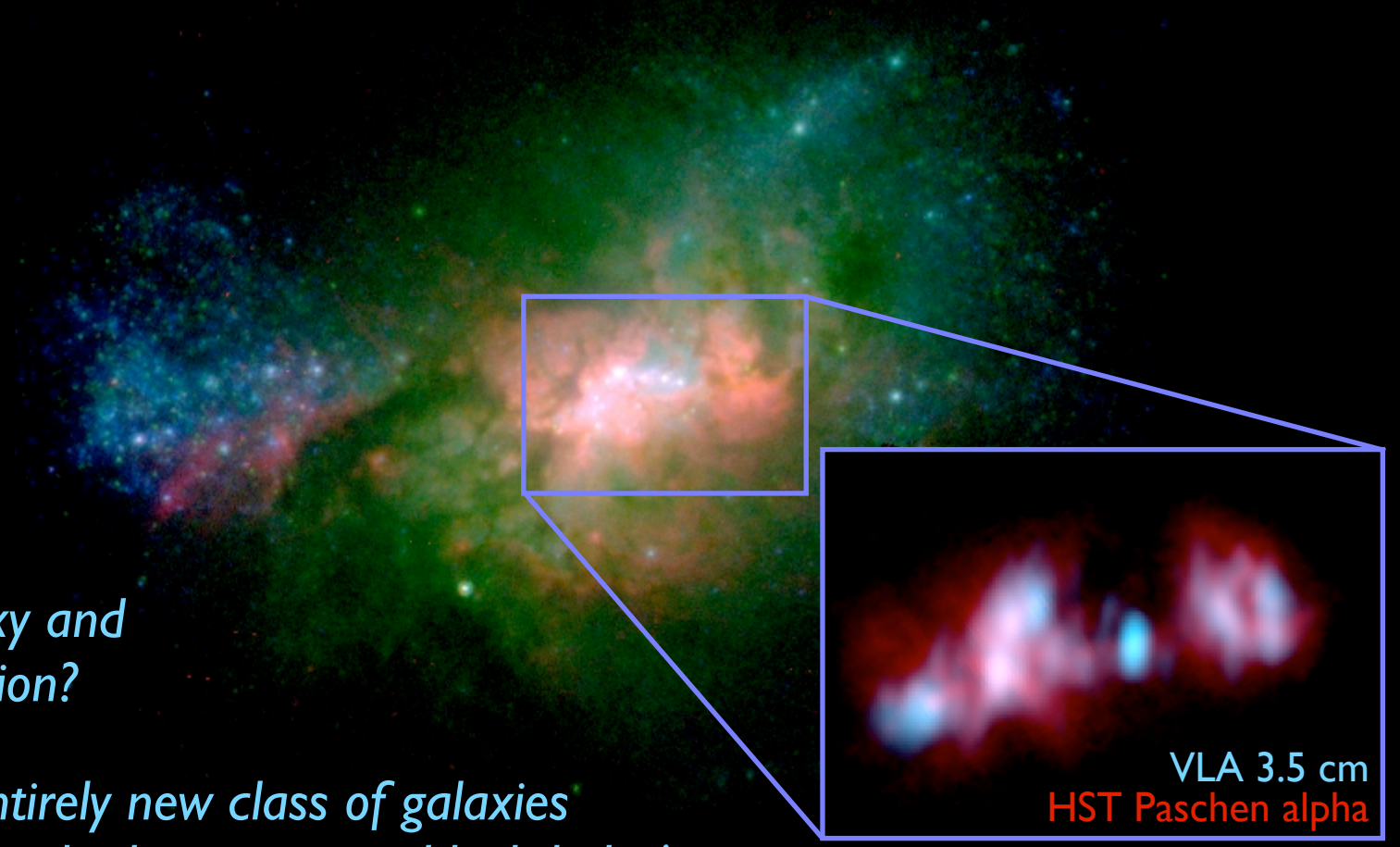

Early stage of galaxy and black hole evolution?

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

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

ALMA

***Cycle 0*:** Band 3 observations, 1.8" resolution (P.I. Johnson)

***Cycle 1*:** Band 6 observations, 0.22" resolution (P.I. Reines)

Summary

- Dwarf galaxies can help reveal the origin of supermassive BH seeds
- Found largest sample (>100) of massive BHs in dwarf galaxies to date using optical diagnostics
- Multiwavelength evidence for a BH in the dwarf starburst galaxy Henize 2-10
- Planning large-scale VLA survey to find candidate BHs in dwarf galaxies
- Host galaxies have stellar masses comparable to the Magellanic Clouds, a mass regime where very few massive BHs have been found