Massive Black Holes in Nearby Dwarf Galaxies

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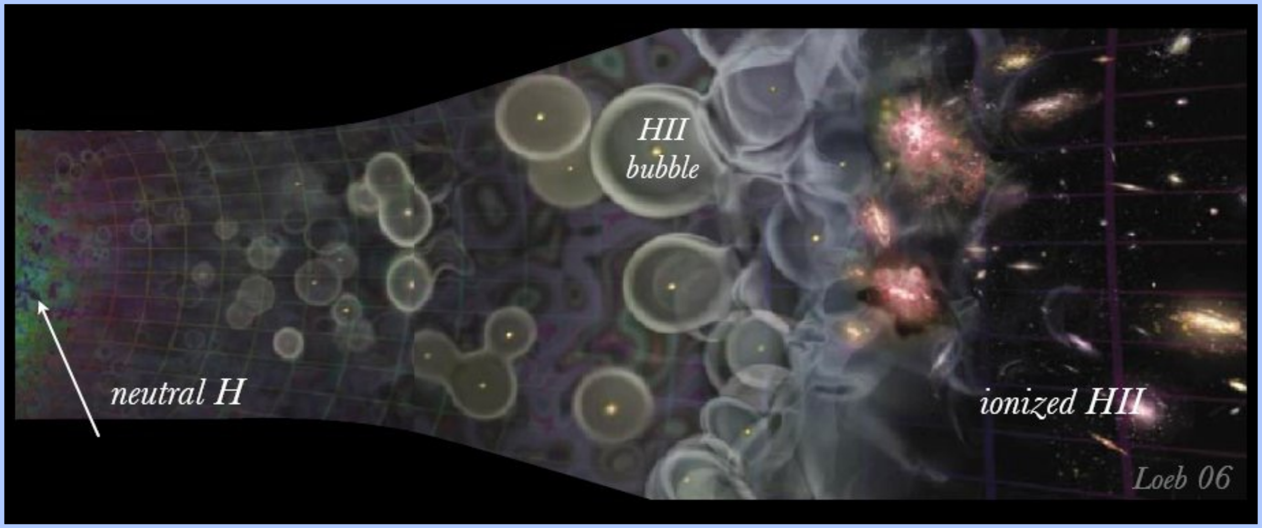
Motivation: The origin of massive black holes (BHs)

- Massive BHs are fundamental components of today's massive galaxies
- Massive BHs are thought to play an important role in the evolution of galaxies
- Active massive BHs in the early universe likely contributed to reionization



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

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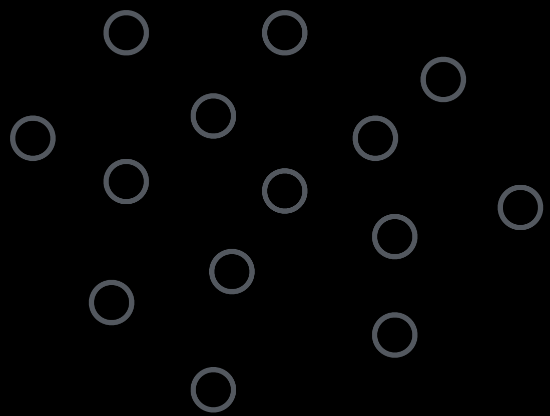
Present-day dwarf galaxies can help reveal the origin of massive black holes

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

Theory: possible seed formation mechanisms

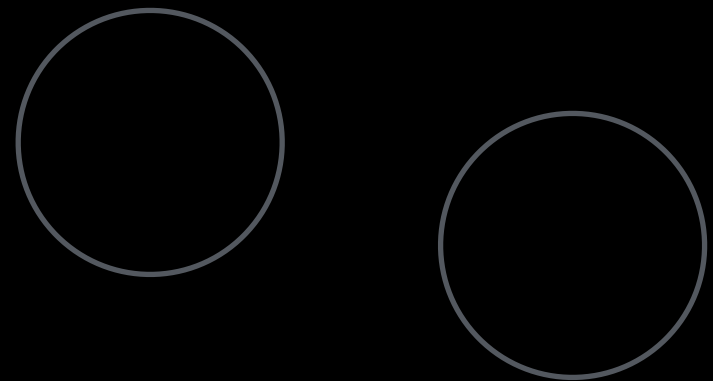
Pop III remnants



- light seeds
- $M_{BH} \sim 100\ M_{sun}$
- abundant
  (high occupation fraction)

e.g., Madau & Rees 2001;
Haiman & Loeb 2001;
Madau et al. 2014

Direct collapse

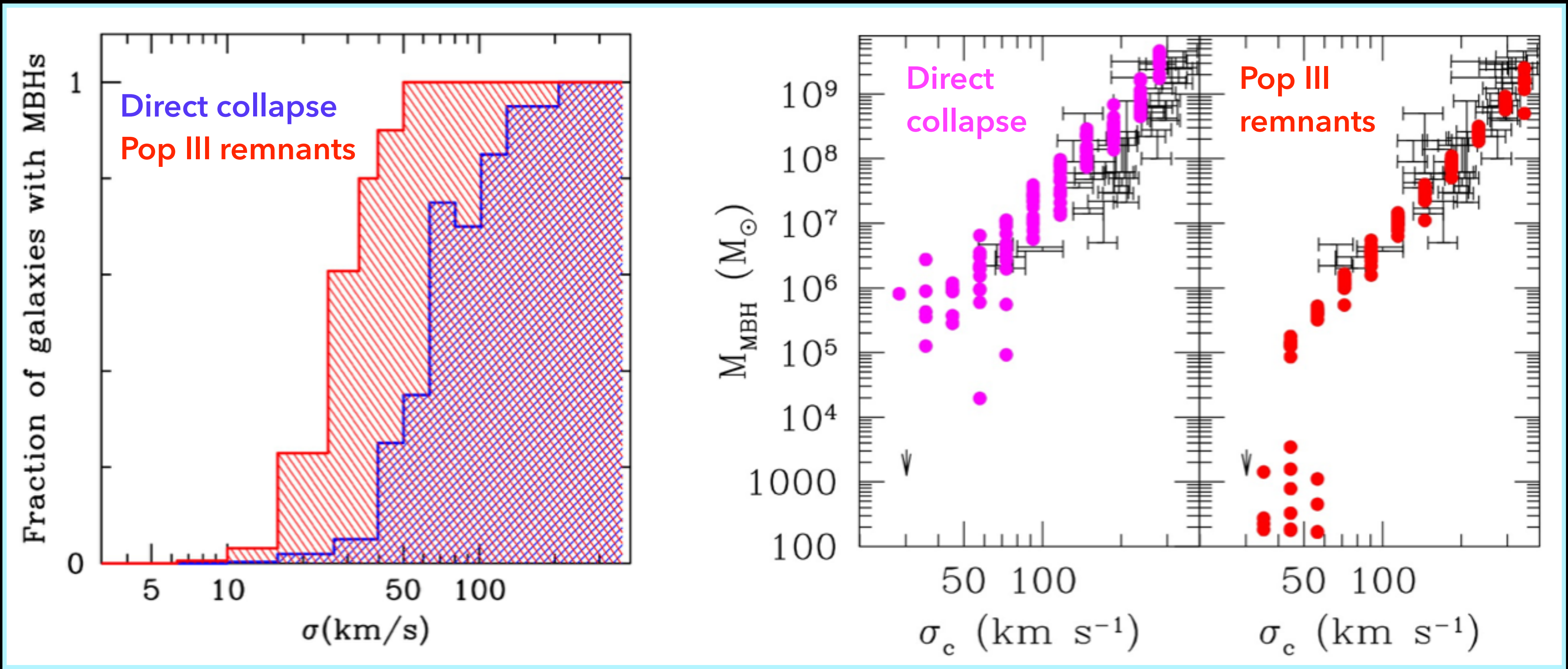


- heavy seeds
- $M_{BH} \sim 10^5\ M_{sun}$
- rare
  (low occupation fraction)

e.g., Loeb & Rasio 1994;
Begelman et al. 2006;
Lodato & Natarajan 2006

Models of BH growth in a cosmological context indicate that present-day dwarfs can distinguish between seed formation mechanisms

predictions at z=0

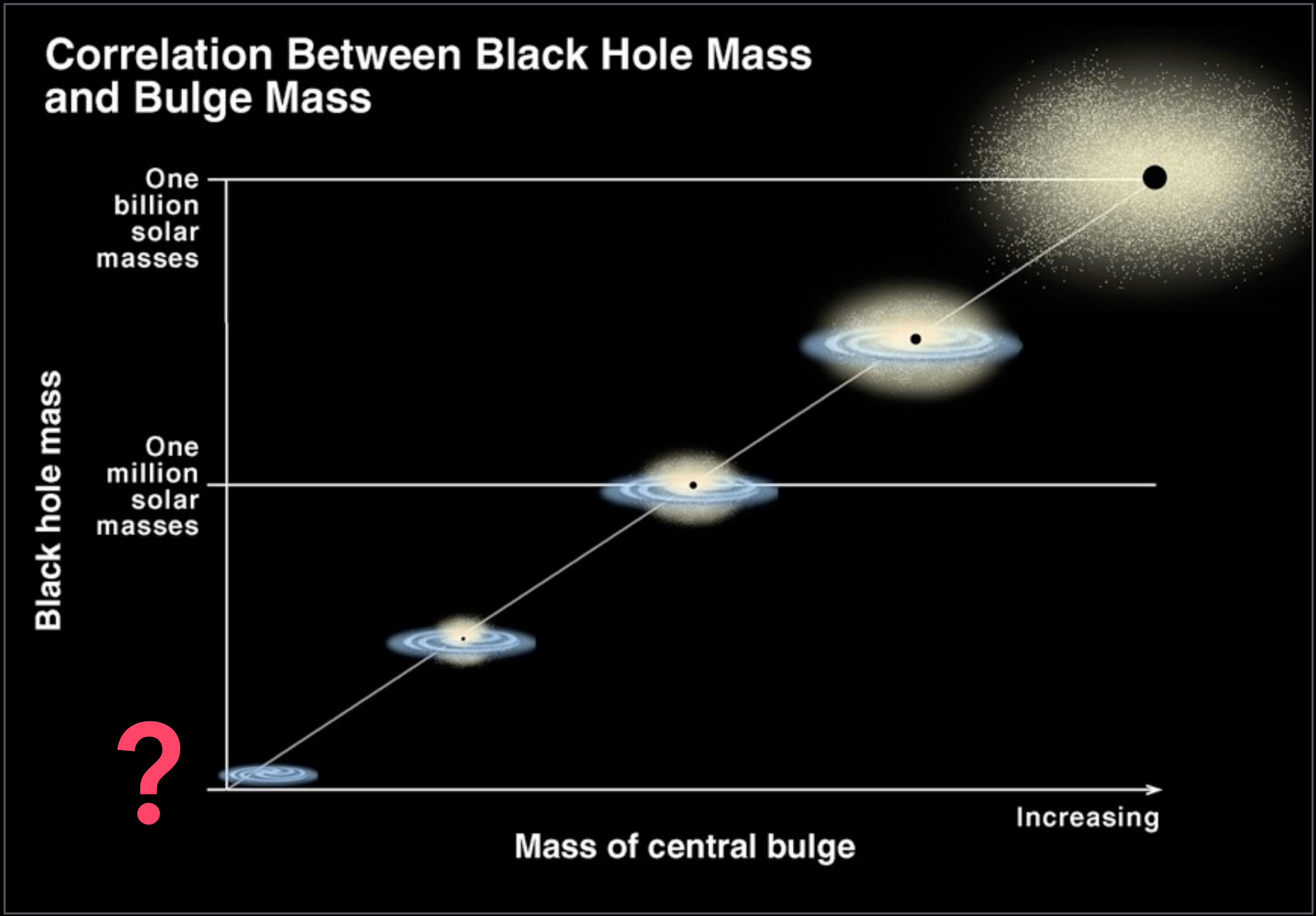


BH occupation fraction

M_{BH}-sigma relation

Volonteri et al. (2008); Van Wassenhove et al. (2010)

…smallest black holes in dwarf galaxies



adapted from K. Cordes, S. Brown (STScI)

Until recently, very few dwarf galaxies were known to host massive black holes

Dynamical BH detections/limits in nearby dwarfs

Table 1 BH masses and upper limits in nearby dwarf galaxies based on stellar and gas dynamics.

Galaxy	Description	$M_{\rm BH}$	Reference
M32	elliptical, M31 satellite	$(2.4 \pm 1.0) \times 10^6$	van den Bosch & de Zeeuw (2010)[a]
NGC 404	S0, $d \sim 3.06$ Mpc	$4.5^{+3.5}_{-2.0} \times 10^5$	Seth et al. (2010)
NGC 4395	Sd, $d \sim 4.4$ Mpc	$4^{+8}_{-3} \times 10^5$	den Brok et al. (2015)
NGC 205	elliptical, M31 satellite	$\leq 2.2 \times 10^4$	Valluri et al. (2005)
Fornax	spheroidal, MW satellite	$\leq 3.2 \times 10^4$	Jardel & Gebhardt (2012)
Ursa Minor	spheroidal, MW satellite	$\leq (2-3) \times 10^4$	Lora et al. (2009)

[a] Also see e.g., Dressler & Richstone (1988); van der Marel et al. (1998); Joseph et al. (2001); Verolme et al. (2002); Kormendy (2004).

Reines & Comastri review, submitted

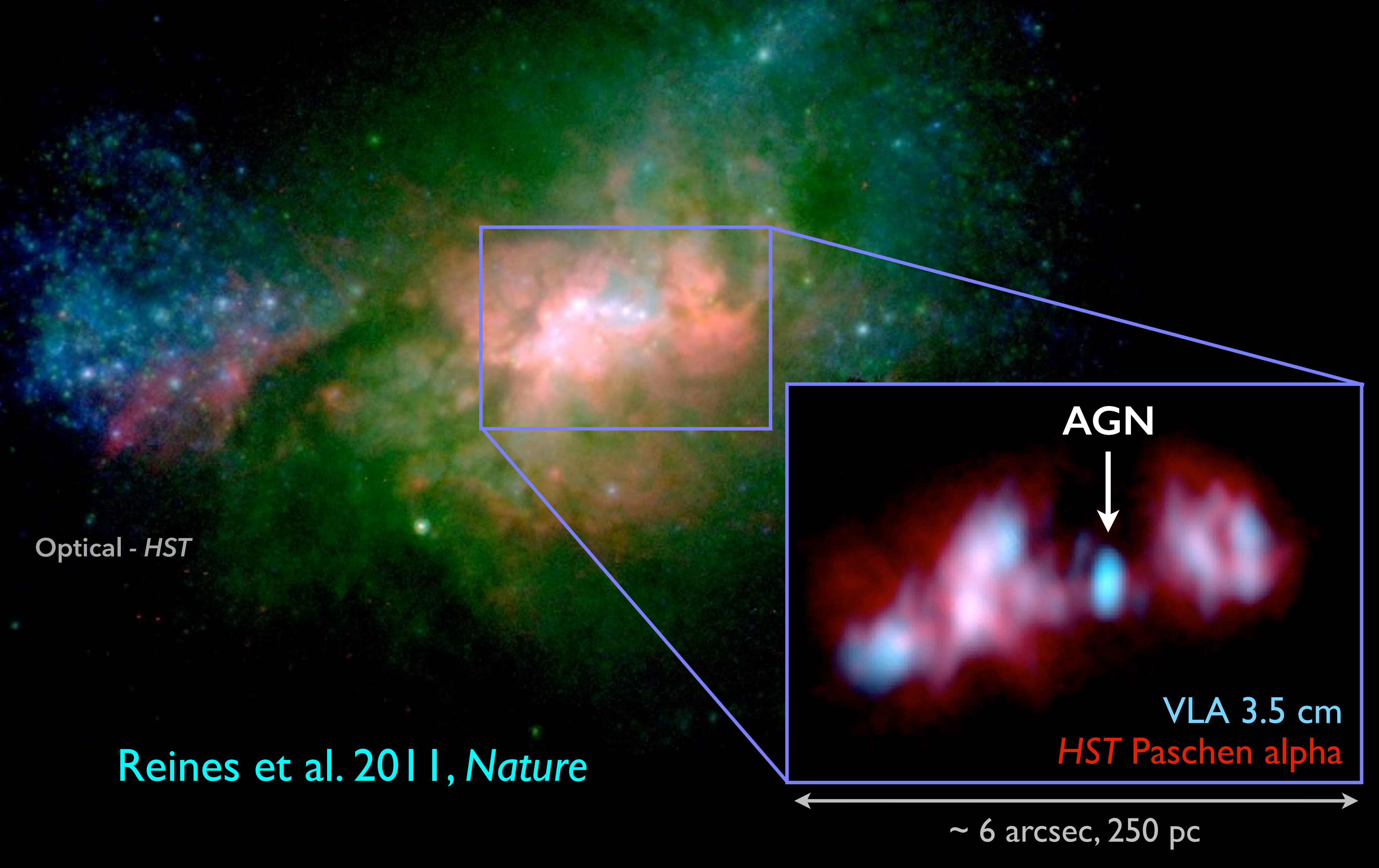
Gravitational sphere of influence cannot be resolved for low-mass BHs in small galaxies much beyond the Local Group

⟶ *Need to look for *active* BHs in more distant dwarfs*

High-resolution radio + X-ray observations

A massive black hole in the dwarf starburst galaxy Henize 2-10

First example of a dwarf starburst galaxy with a massive black hole



Reines et al. 2011, *Nature*

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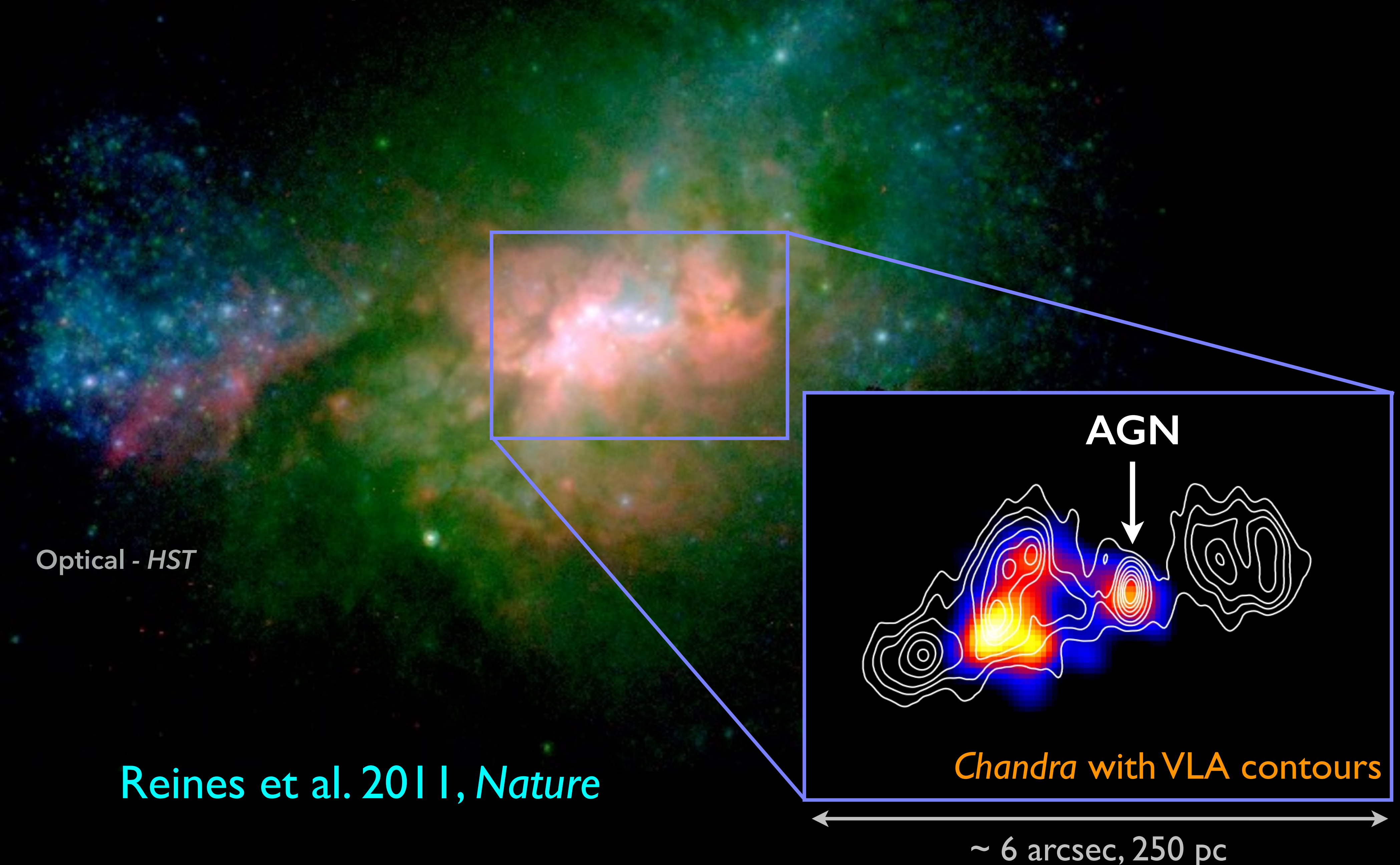


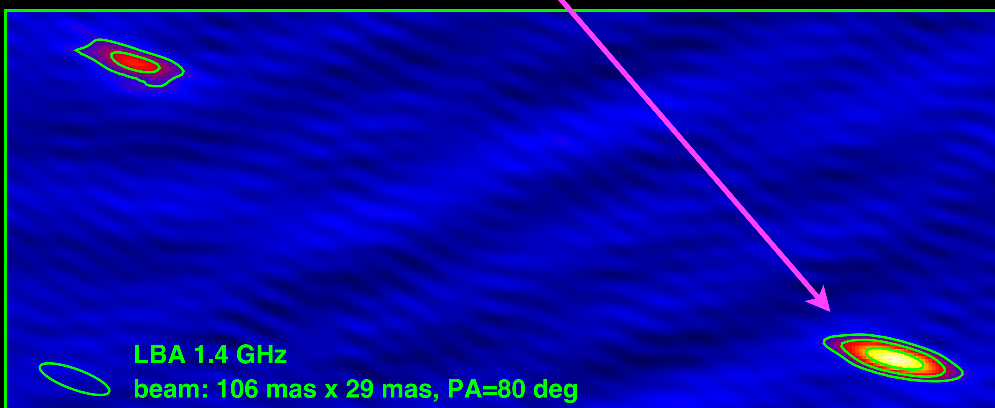
Reines et al. 2011, *Nature*

A massive black hole in the dwarf starburst galaxy Henize 2-10

Follow-up VLBI observations reveal a non-thermal, parsec-scale, radio core

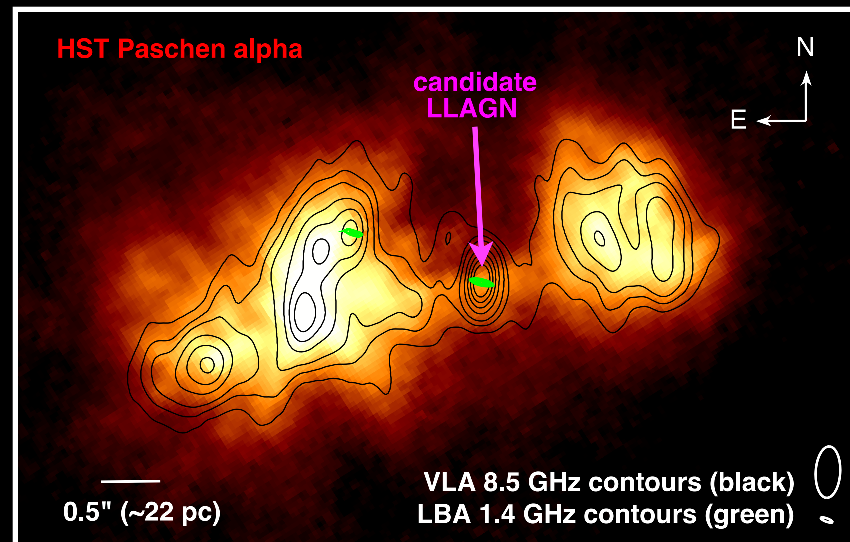
VLBI detection:

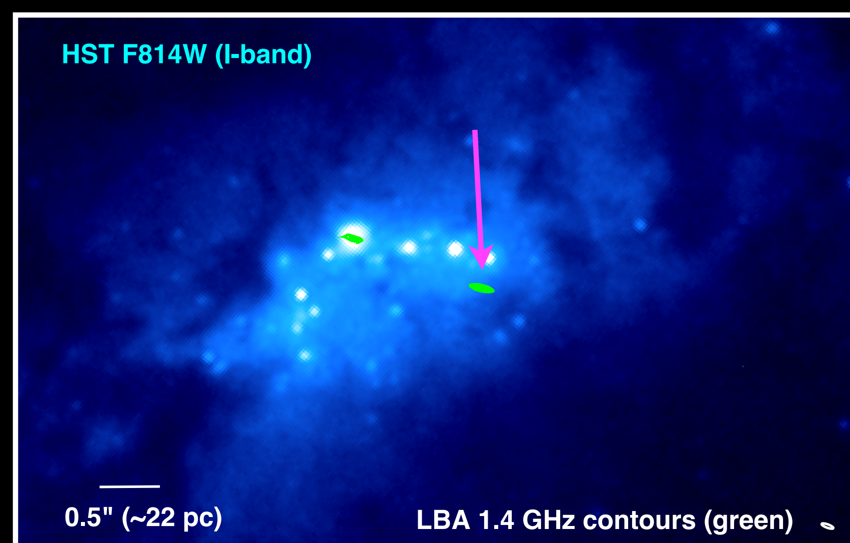
nuclear radio source $\lesssim 3 \times 1$ pc



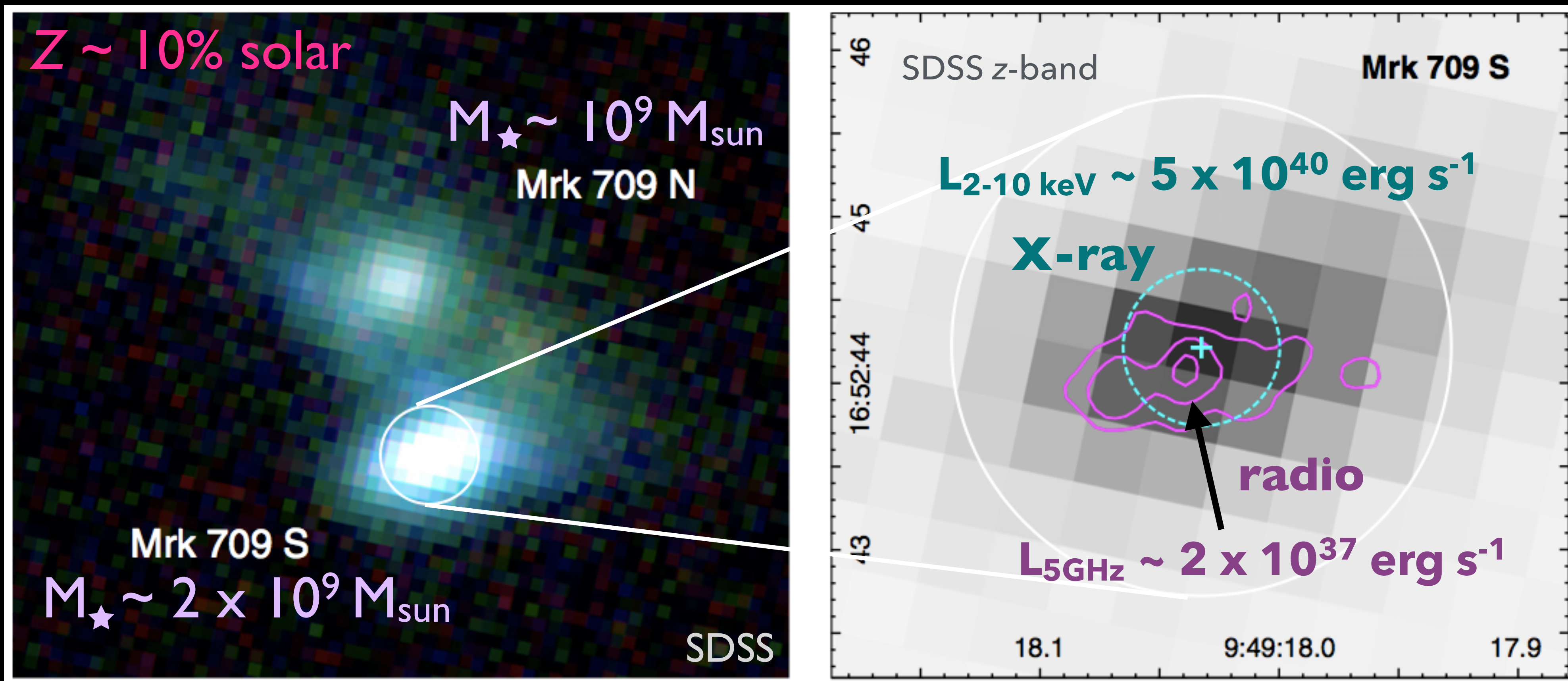
Reines & Deller 2012

HST imaging of central ~ 250 pc





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
- Among the most metal-poor galaxies with evidence for an AGN, and also in an interacting pair (high-z analog?)

Reines et al. (2014)

An X-ray Selected Sample of Candidate BHs in Dwarf Galaxies

Lemons, Reines et al. 2015 (*undergrad at the University of Michigan)*

(Mining the Chandra archive)

* cross match ~44,000 dwarf galaxies with the Chandra Source Catalog

* analyze archival Chandra observations for 31 dwarf galaxies (664 ks)

* find point-like hard X-ray sources

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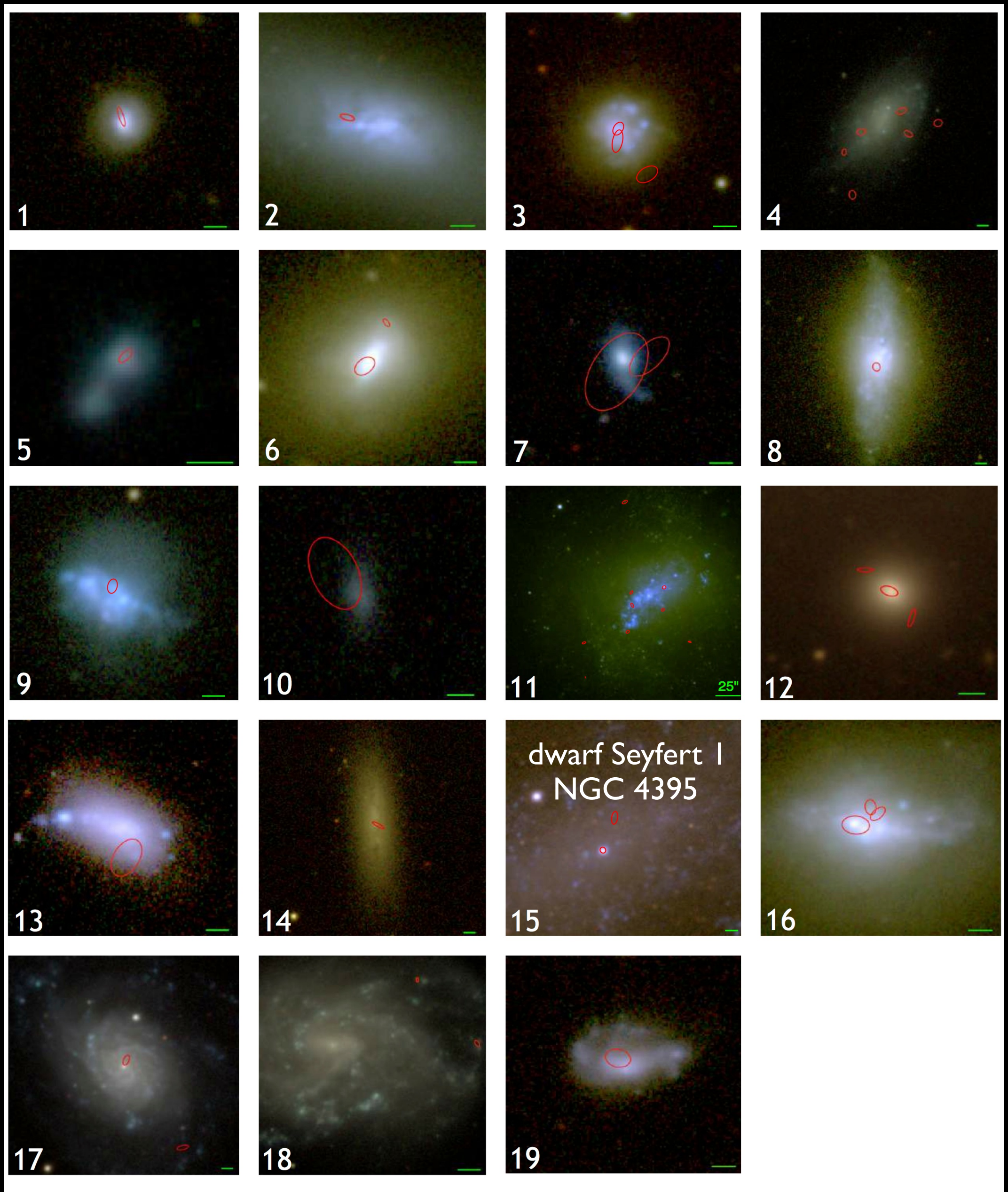


19 dwarf galaxies with a total of 43 hard X-ray sources ($L_{2\text{-}10\ keV} \sim 10^{37}\text{-}10^{40}$ erg/s)

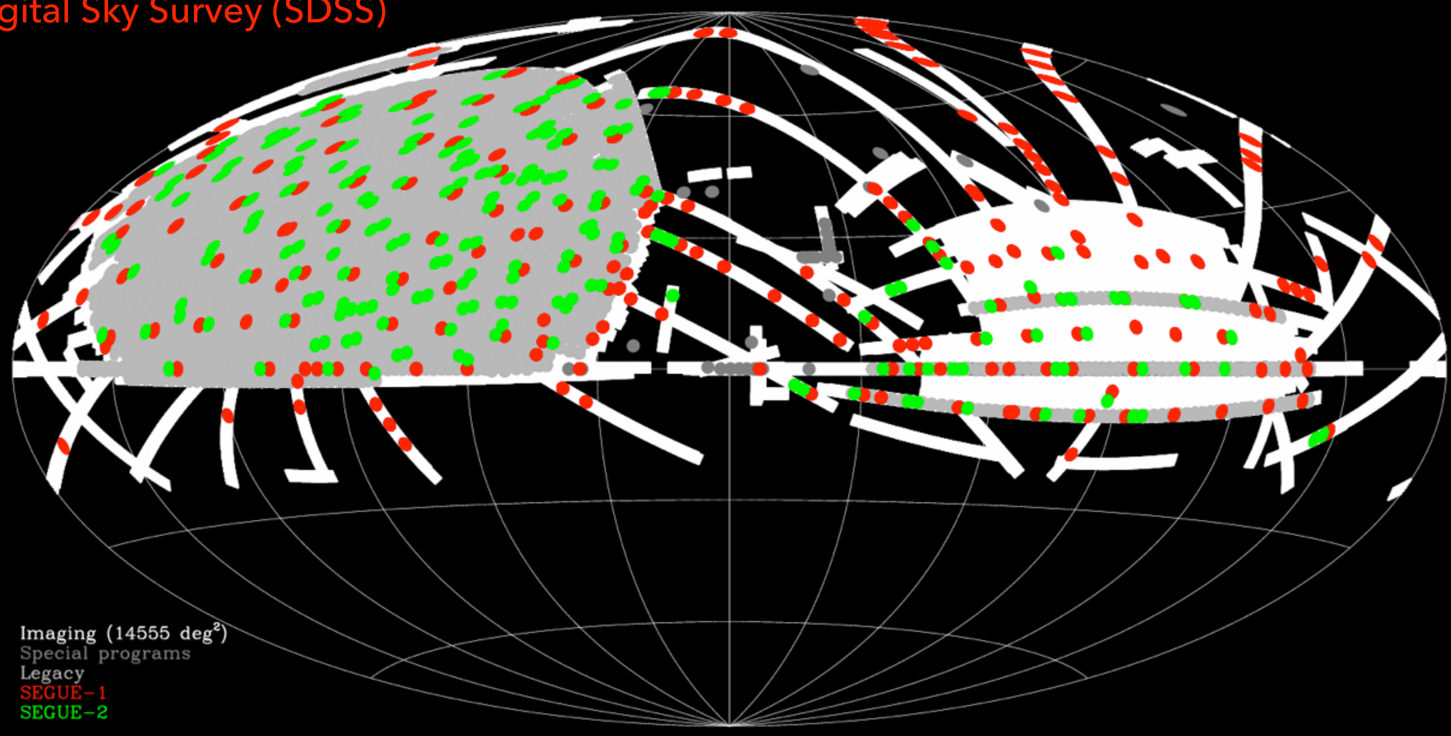
most sources are likely luminous stellar-mass XRBs

some could be massive BHs radiating at low Eddington ratios

Dwarf galaxies with optical signatures of active massive BHs

First systematic search for AGN in dwarf galaxies (Reines et al. 2013)

Sloan Digital Sky Survey (SDSS)



>100 dwarf galaxies with massive BHs!

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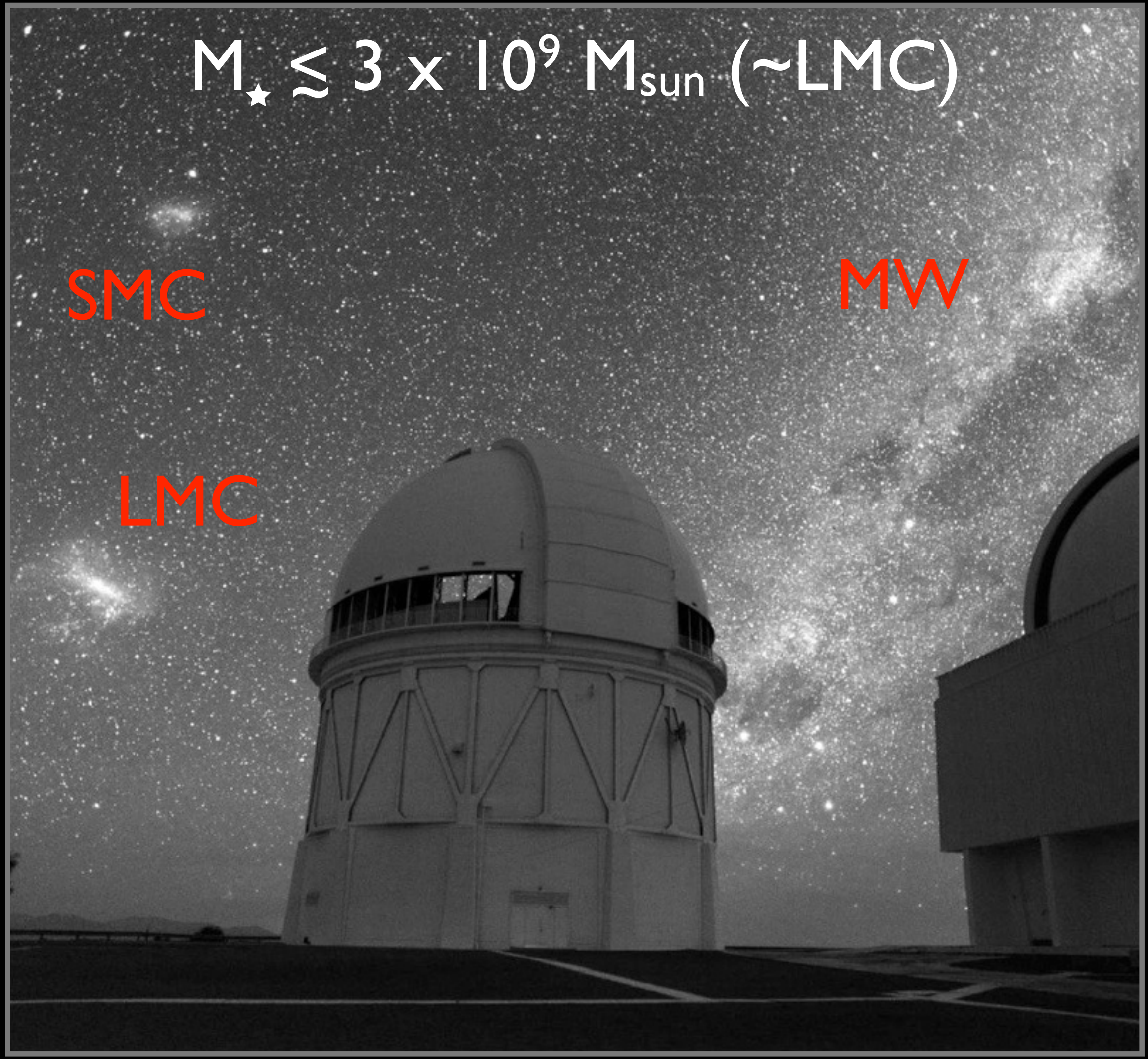

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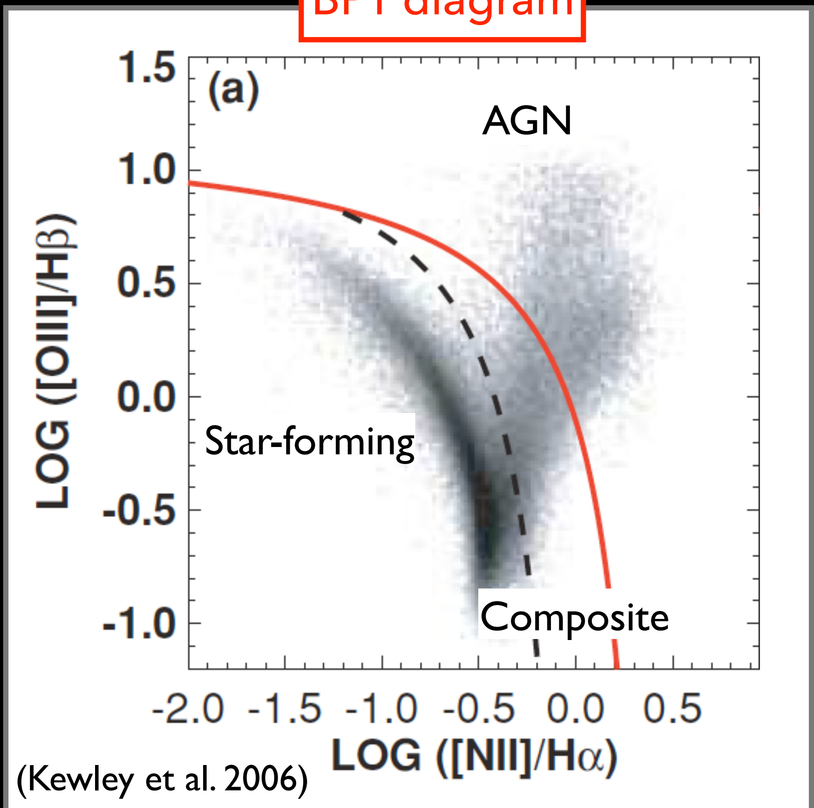
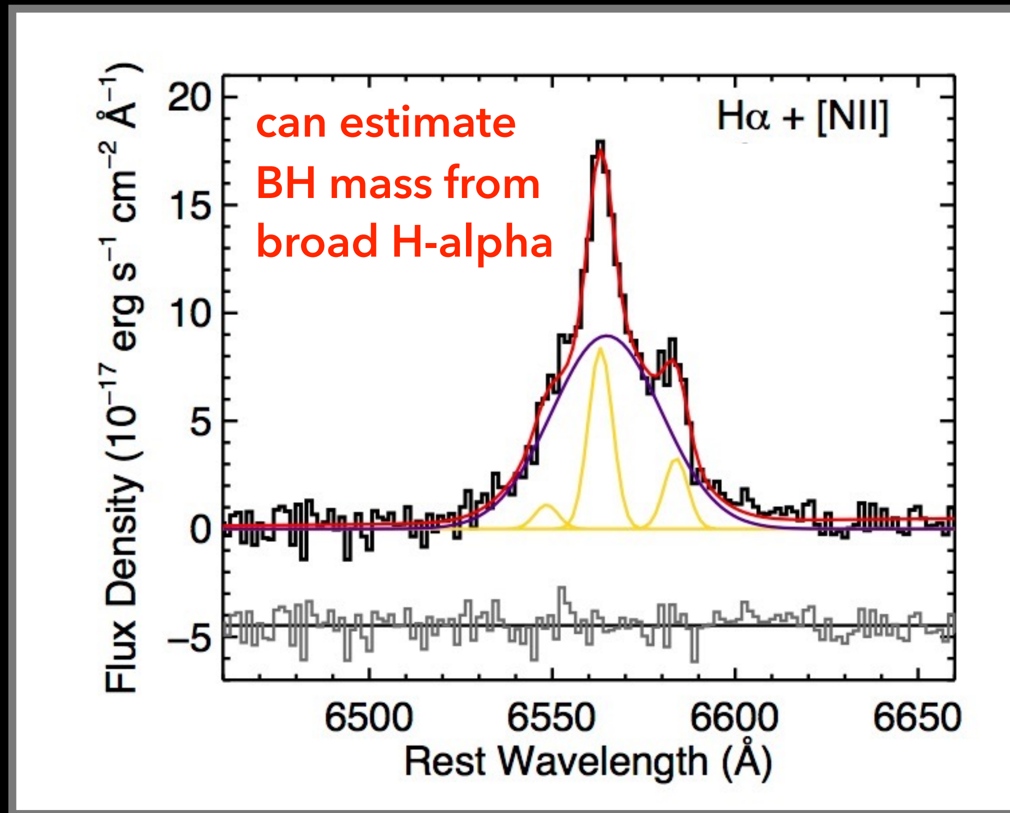
BPT diagram



(Kewley et al. 2006)



narrow-line AGN

broad-line AGN

* use emission-line diagnostic diagrams to look for photoionization signatures (AGN + composites)

* search for broad H-alpha emission that can signify dense gas orbiting a BH

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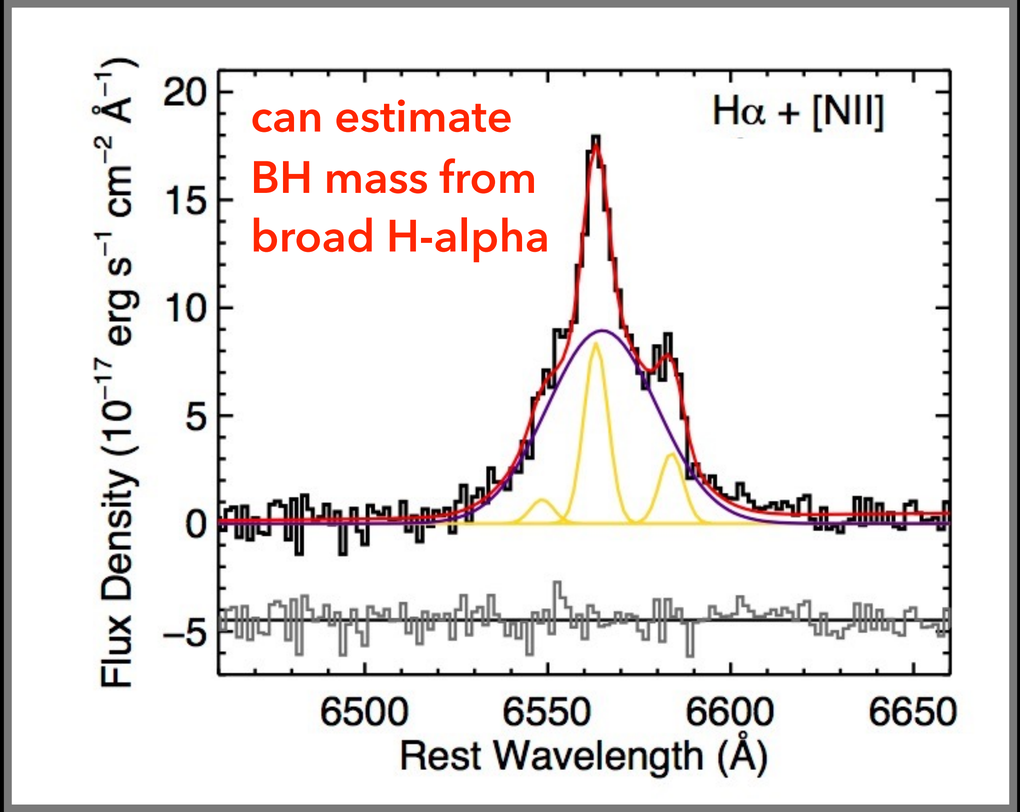
$M_{BH} \sim R\,V^2 / G$

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

(Reines et al. 2013, eqn. 5; and references therein)



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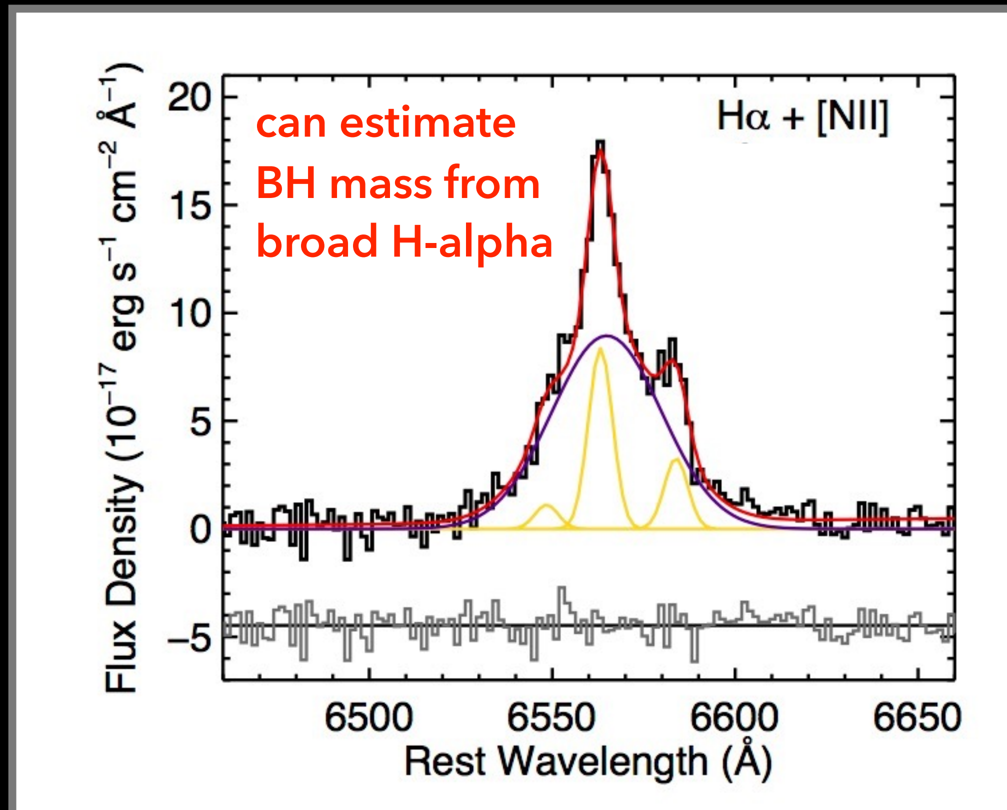

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use *R* - *L* relationship
from reverberation-mapped AGN

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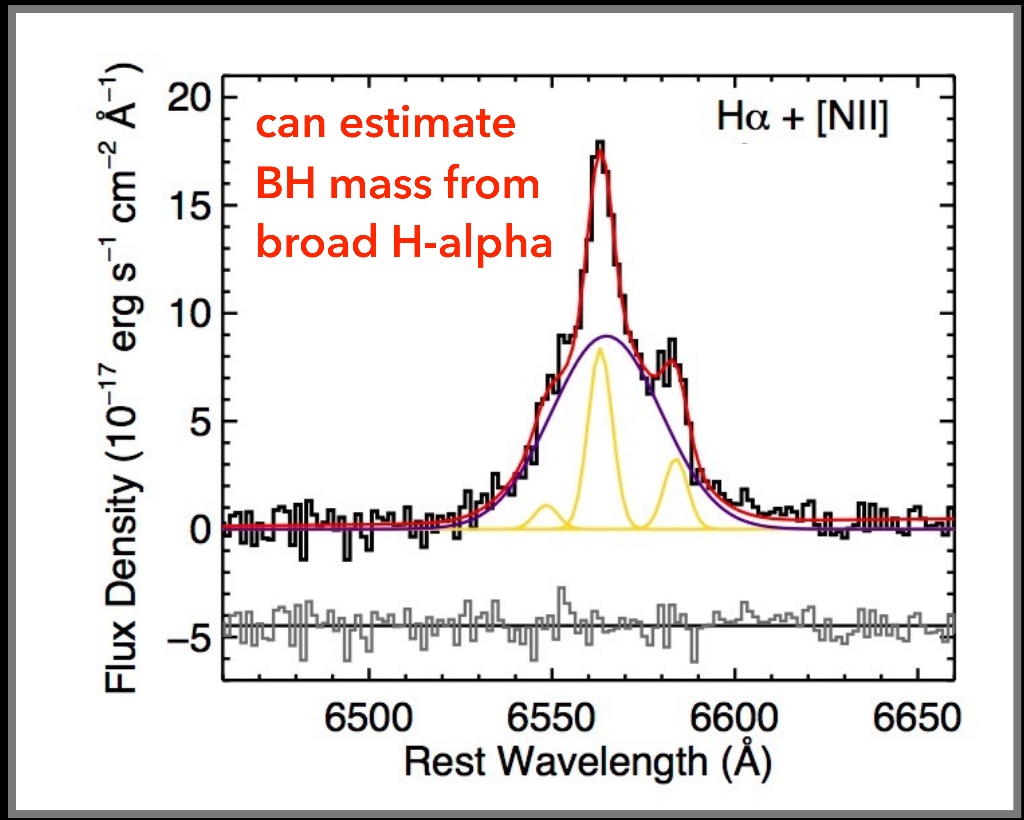

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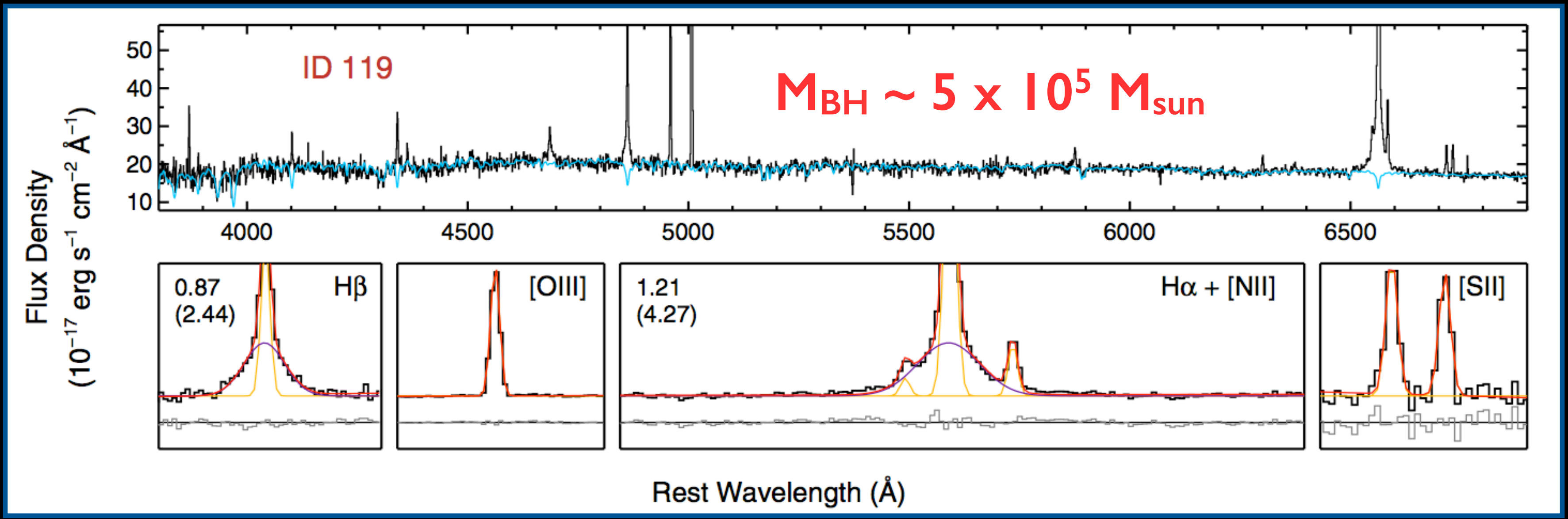

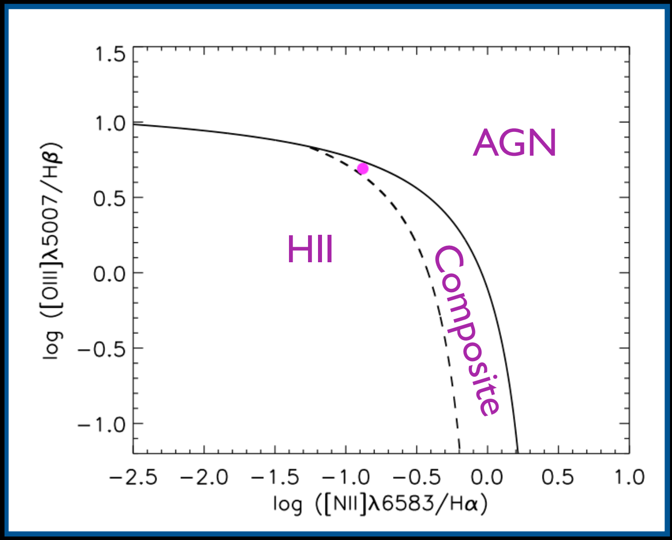

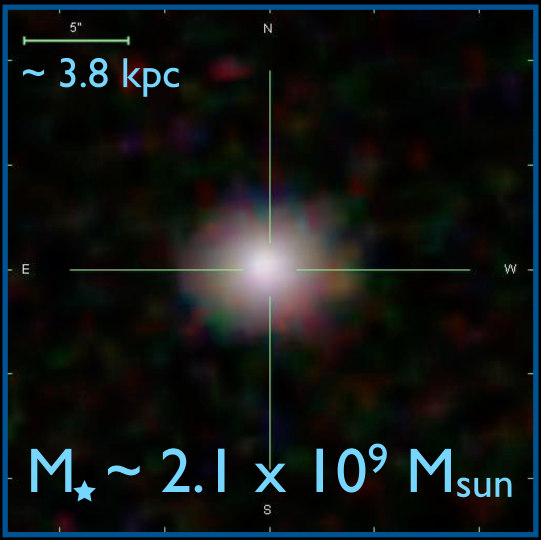

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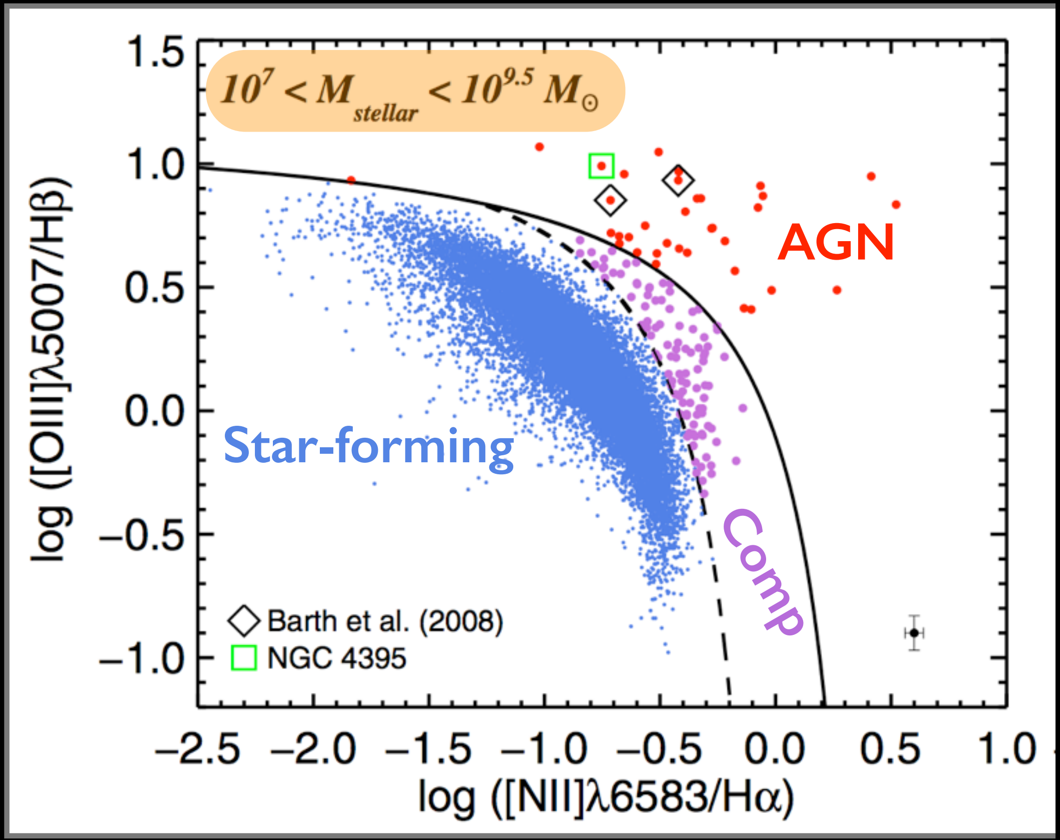


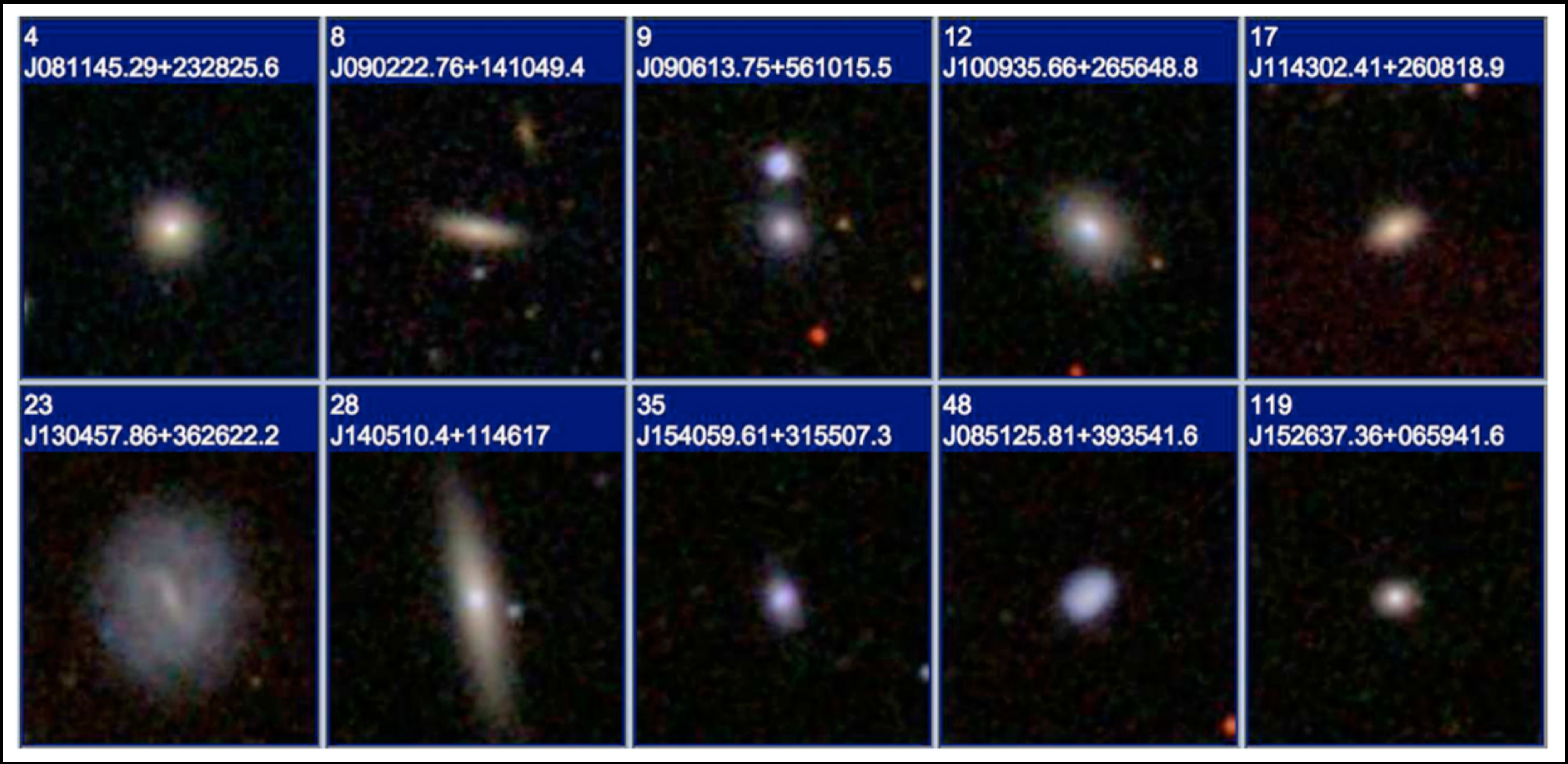
35 AGN
101 Composites

> order of magnitude increase in the number of known dwarfs with massive BHs

Dwarf galaxies with optical signatures of active massive BHs

First systematic search for AGN in dwarf galaxies (Reines et al. 2013)

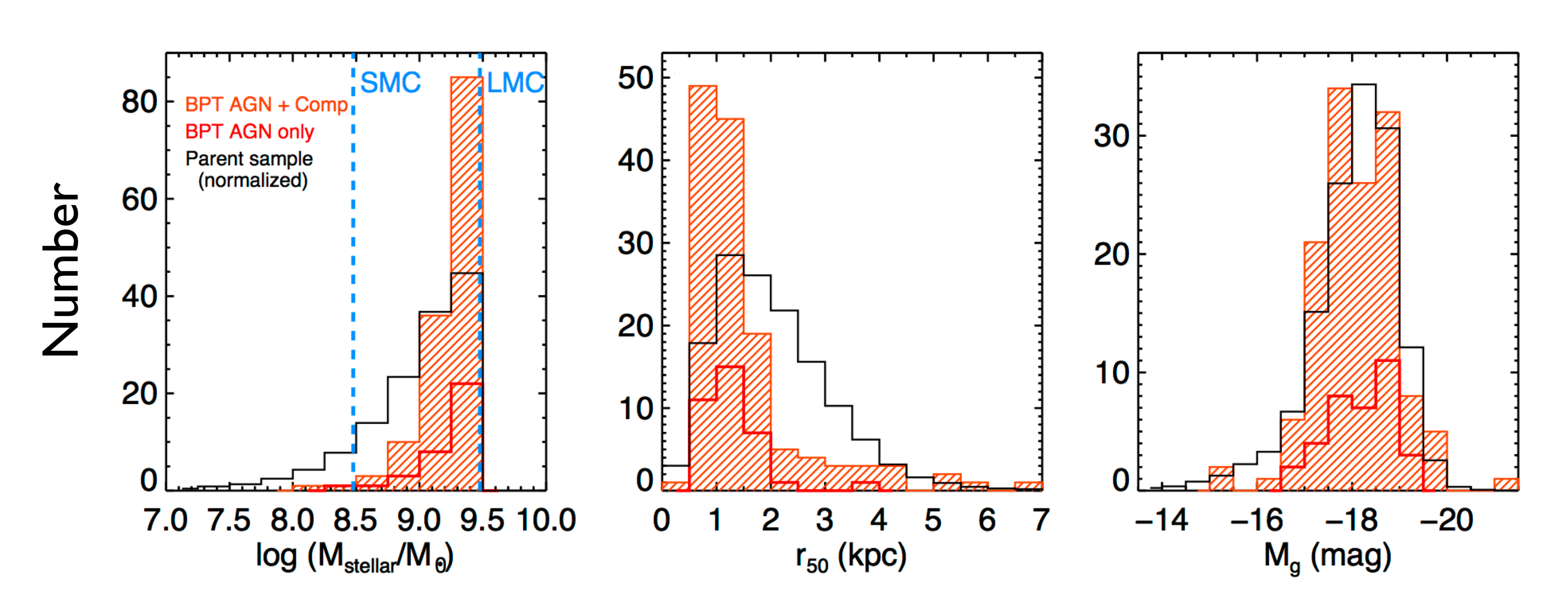
Examples of host galaxies



Dwarf galaxies with optical signatures of active massive BHs

First systematic search for AGN in dwarf galaxies (Reines et al. 2013)

Smallest and least-massive galaxies known to host massive BHs



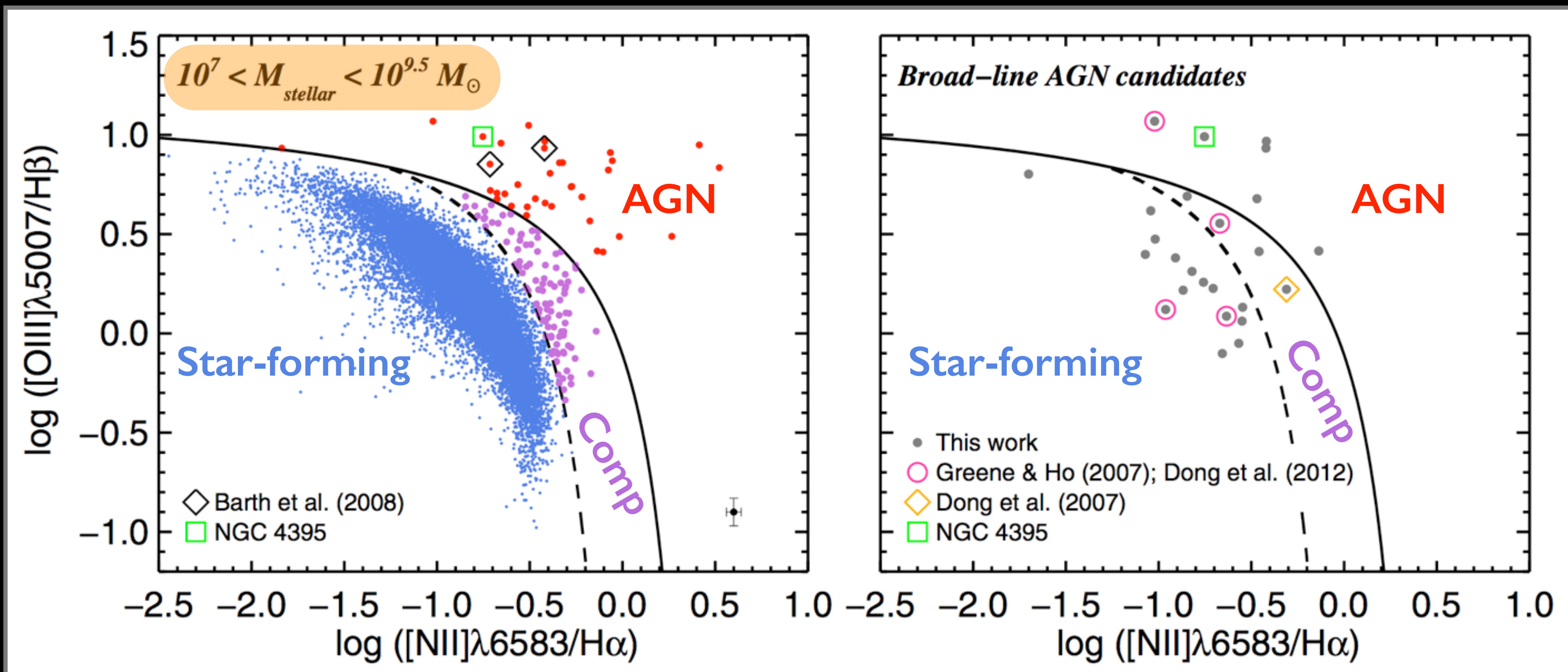
stellar mass

half-light radius

Mg

Dwarf galaxies with optical signatures of active massive BHs

First systematic search for AGN in dwarf galaxies (Reines et al. 2013)



35 AGN
101 Composites

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

Dwarf galaxies with optical signatures of active massive BHs

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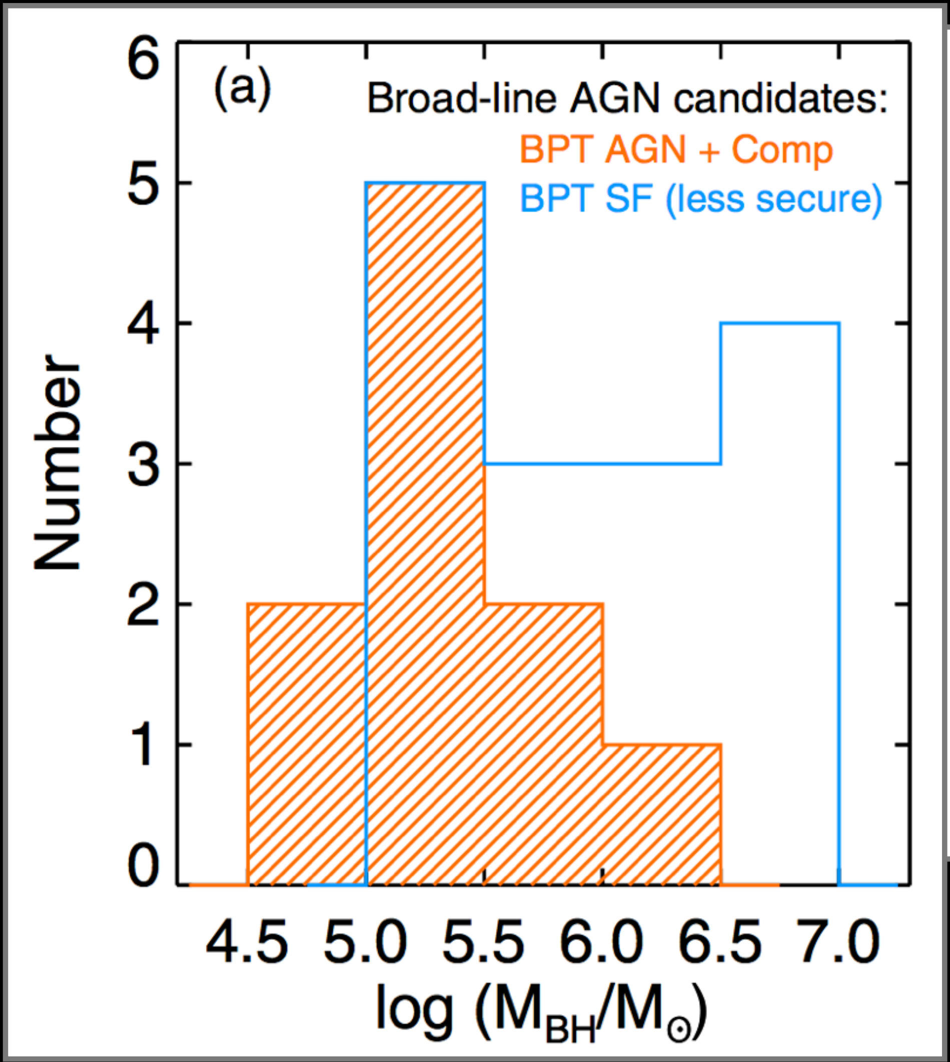

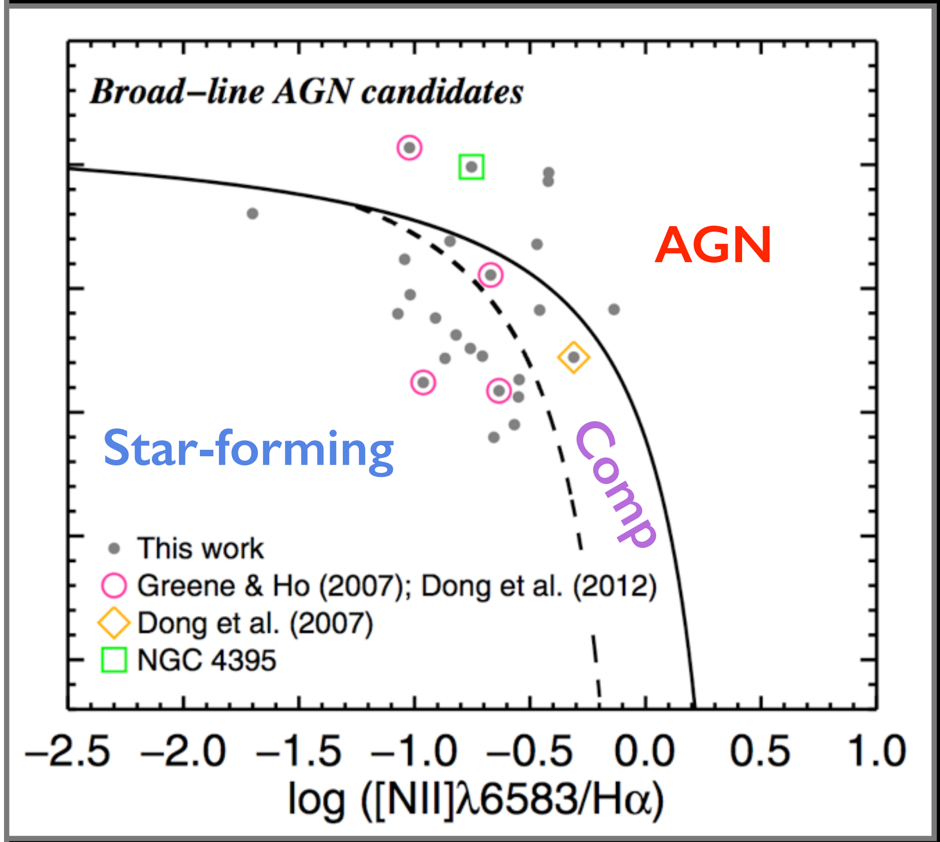

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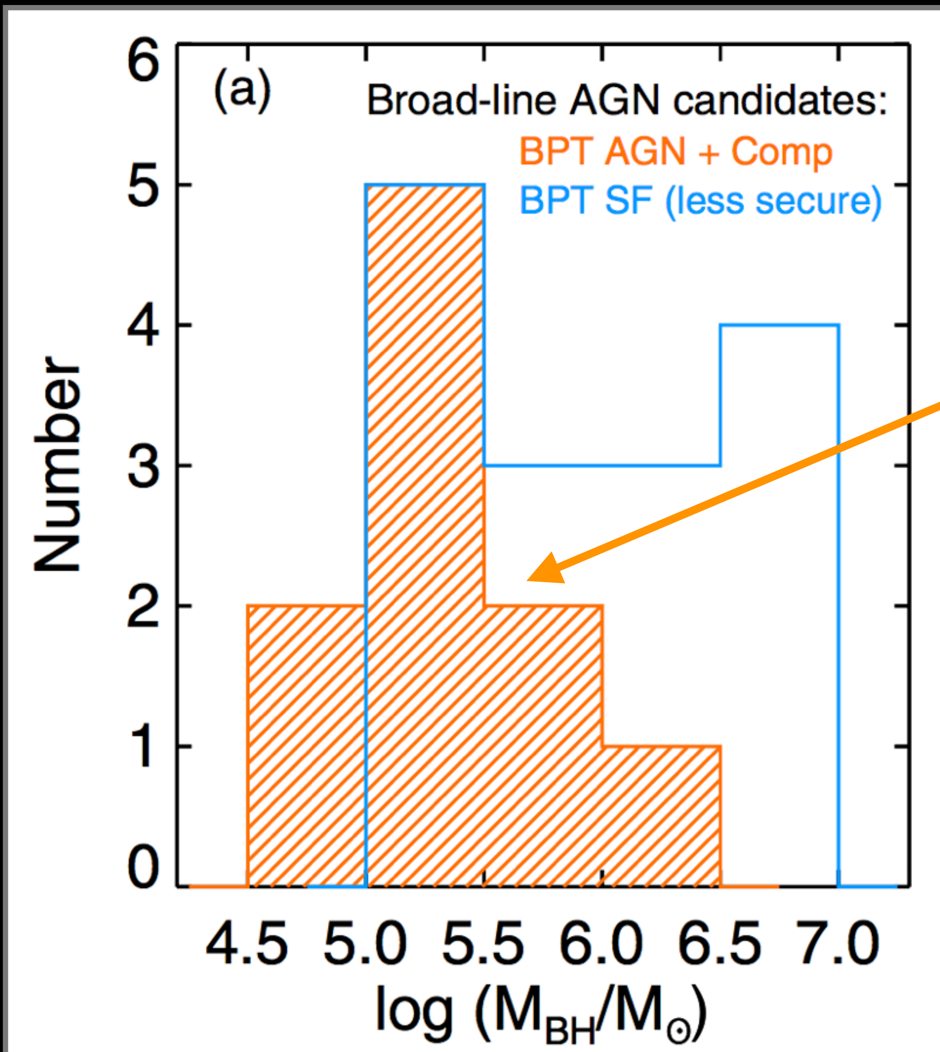
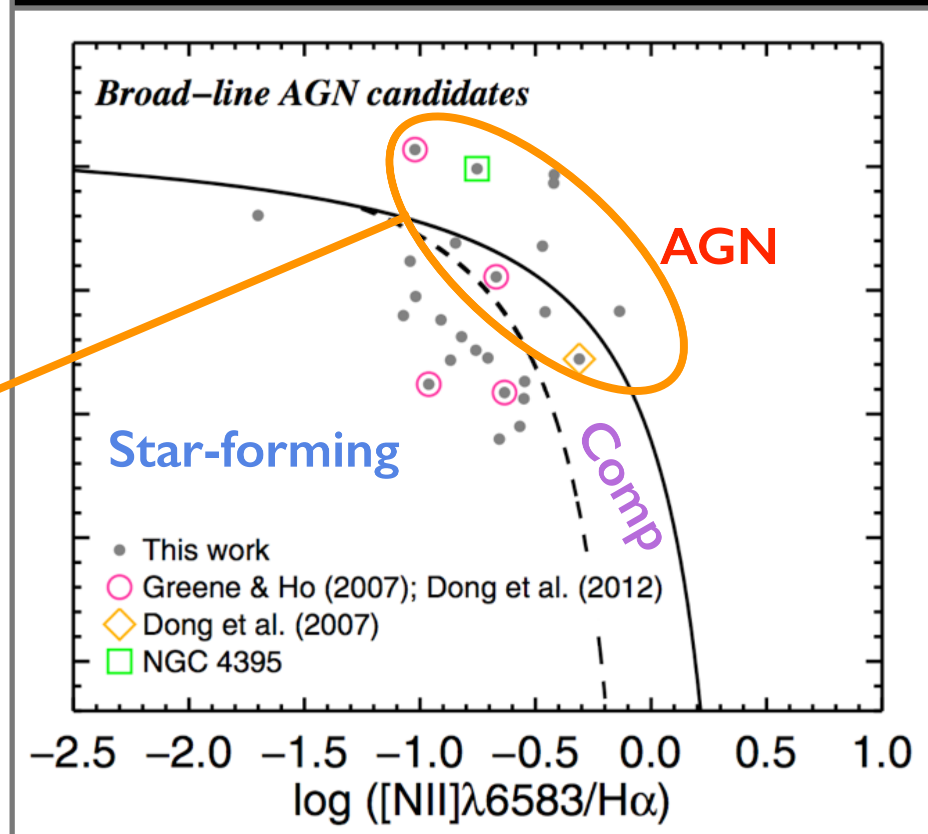


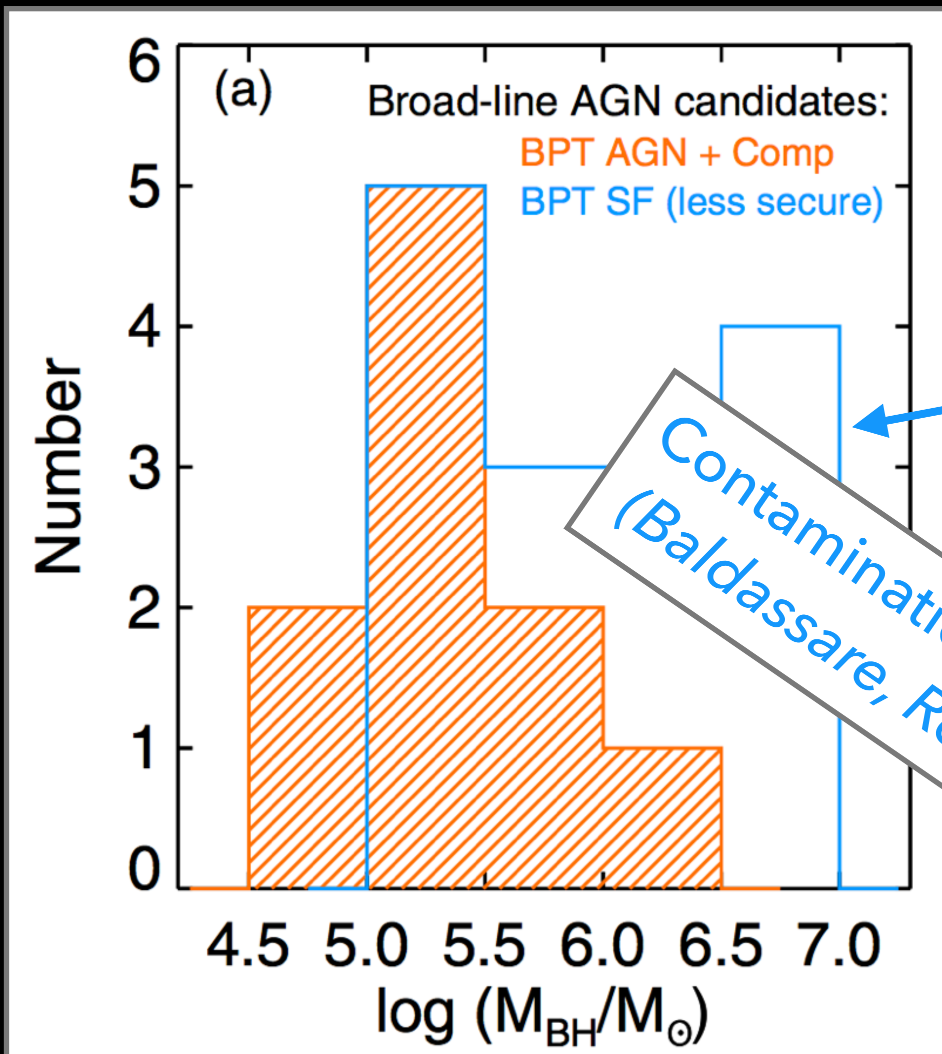


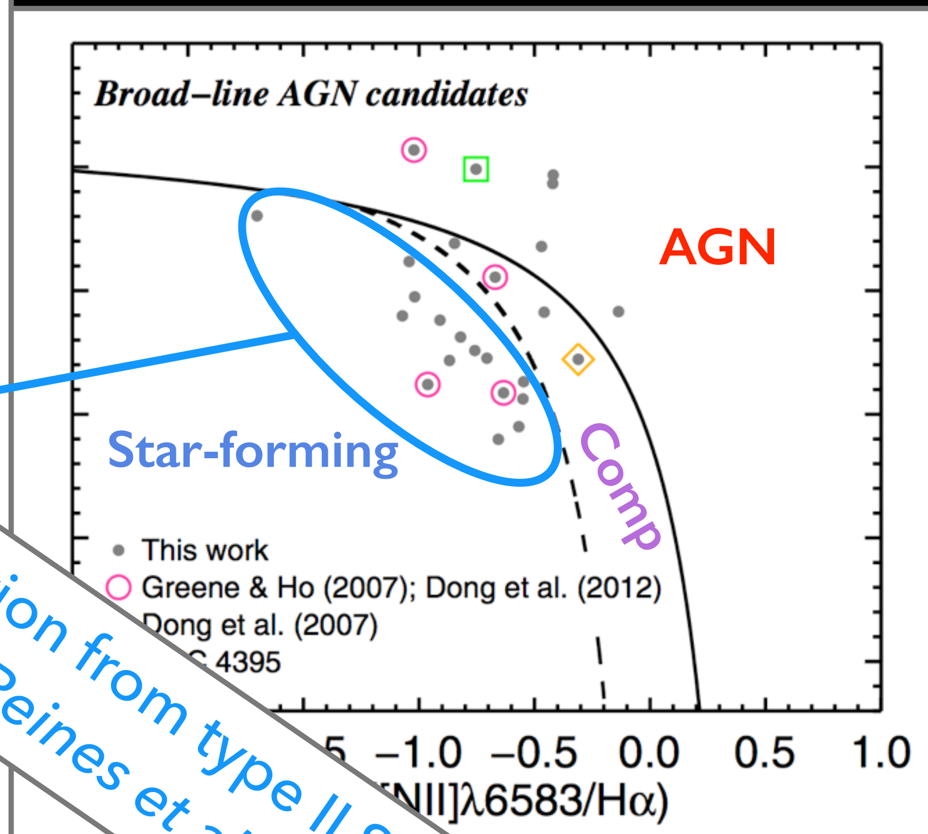
Least-massive black holes known

(median $M_{BH} \sim 2 \times 10^5\ M_{sun}$)

Dwarf galaxies with optical signatures of active massive BHs

First systematic search for AGN in dwarf galaxies (Reines et al. 2013)



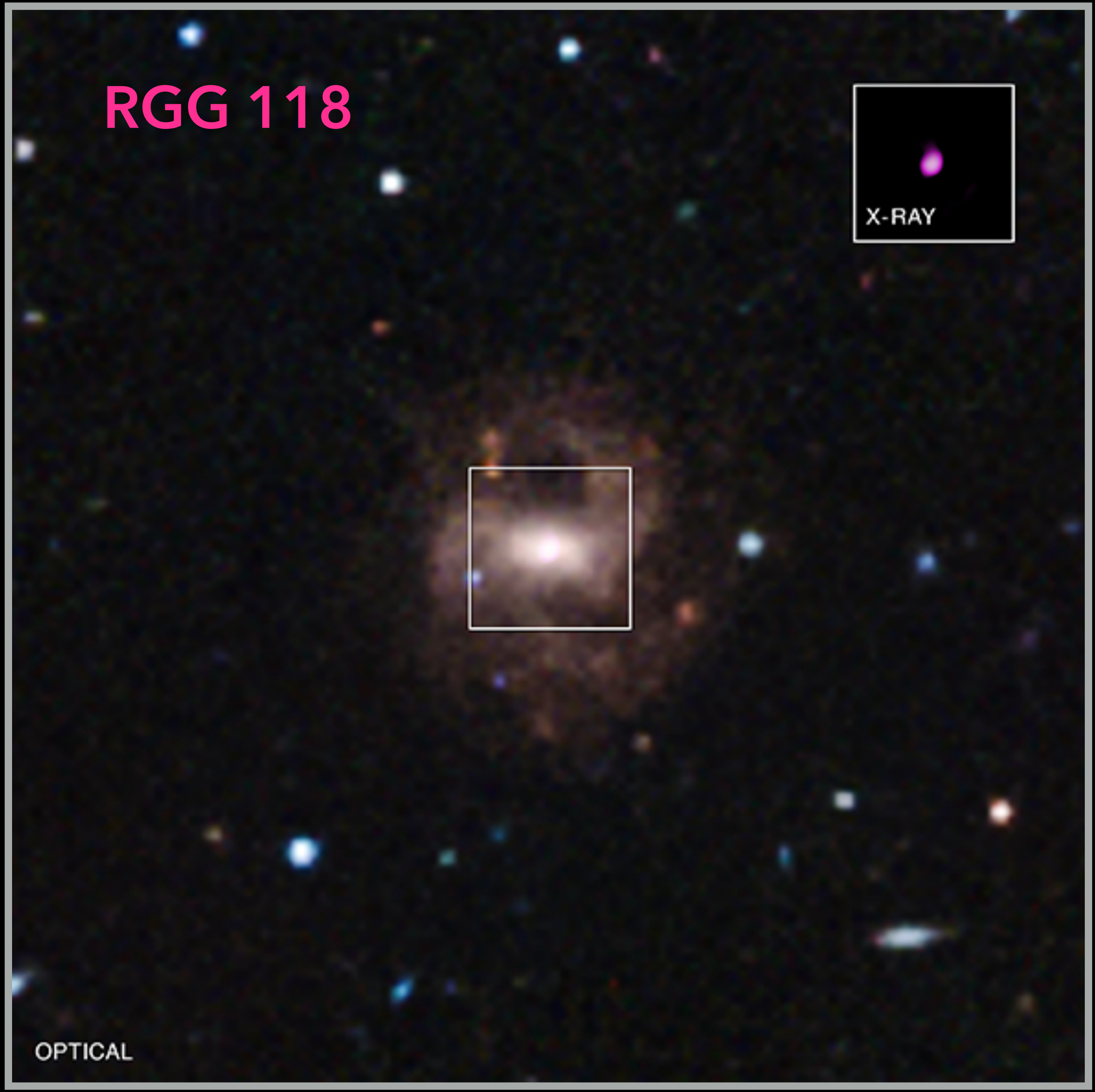


Contamination from type II SNe (Baldassare, Reines et al. 2016)

A ~50,000 M_{sun} black hole in the nucleus of RGG 118

Baldassare, Reines et al. 2015 (*grad student at the University of Michigan)*

Vivienne Baldassare



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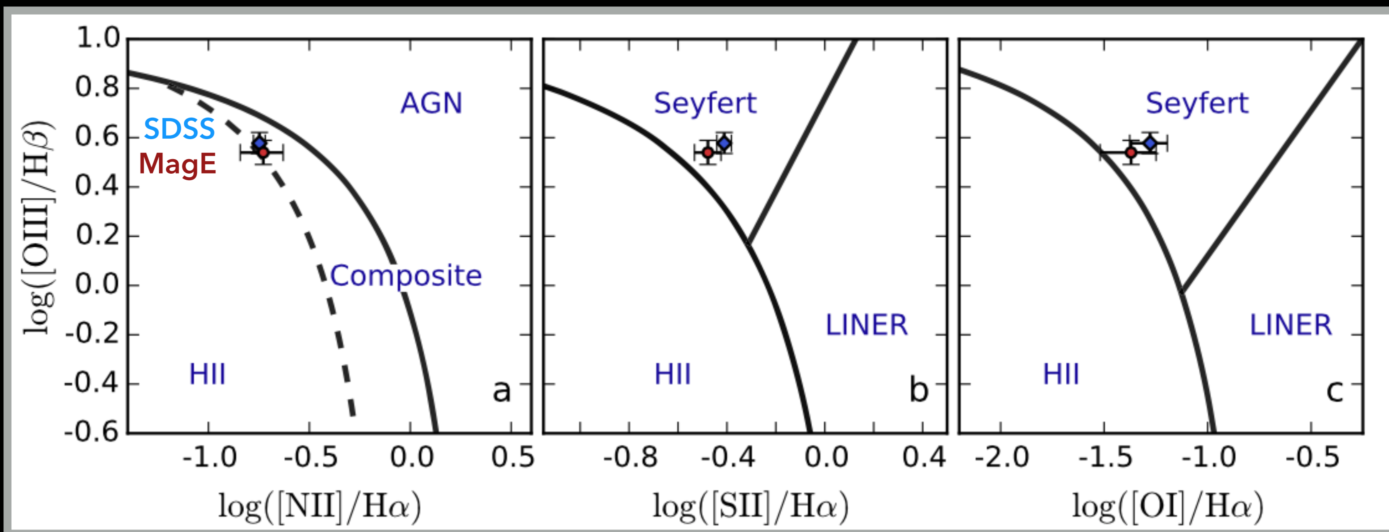


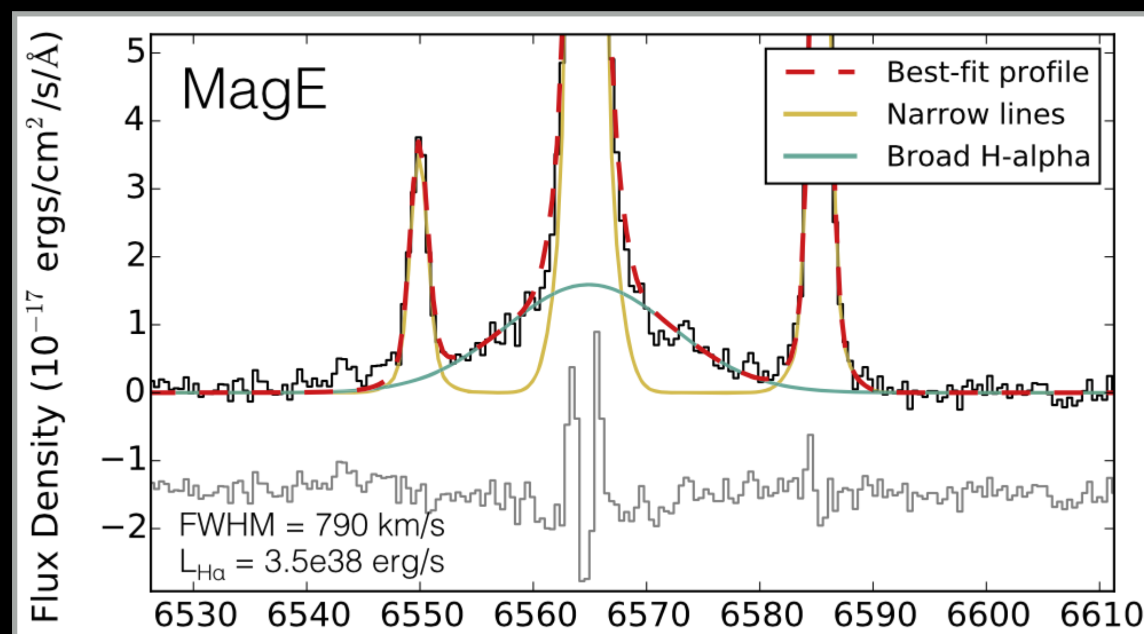
narrow emission line ratios indicate an AGN

Broad H-alpha detected

↓

tiny BH!

M_{BH}~50,000 M_{sun}



A ~50,000 M_{sun} black hole in the nucleus of RGG 118

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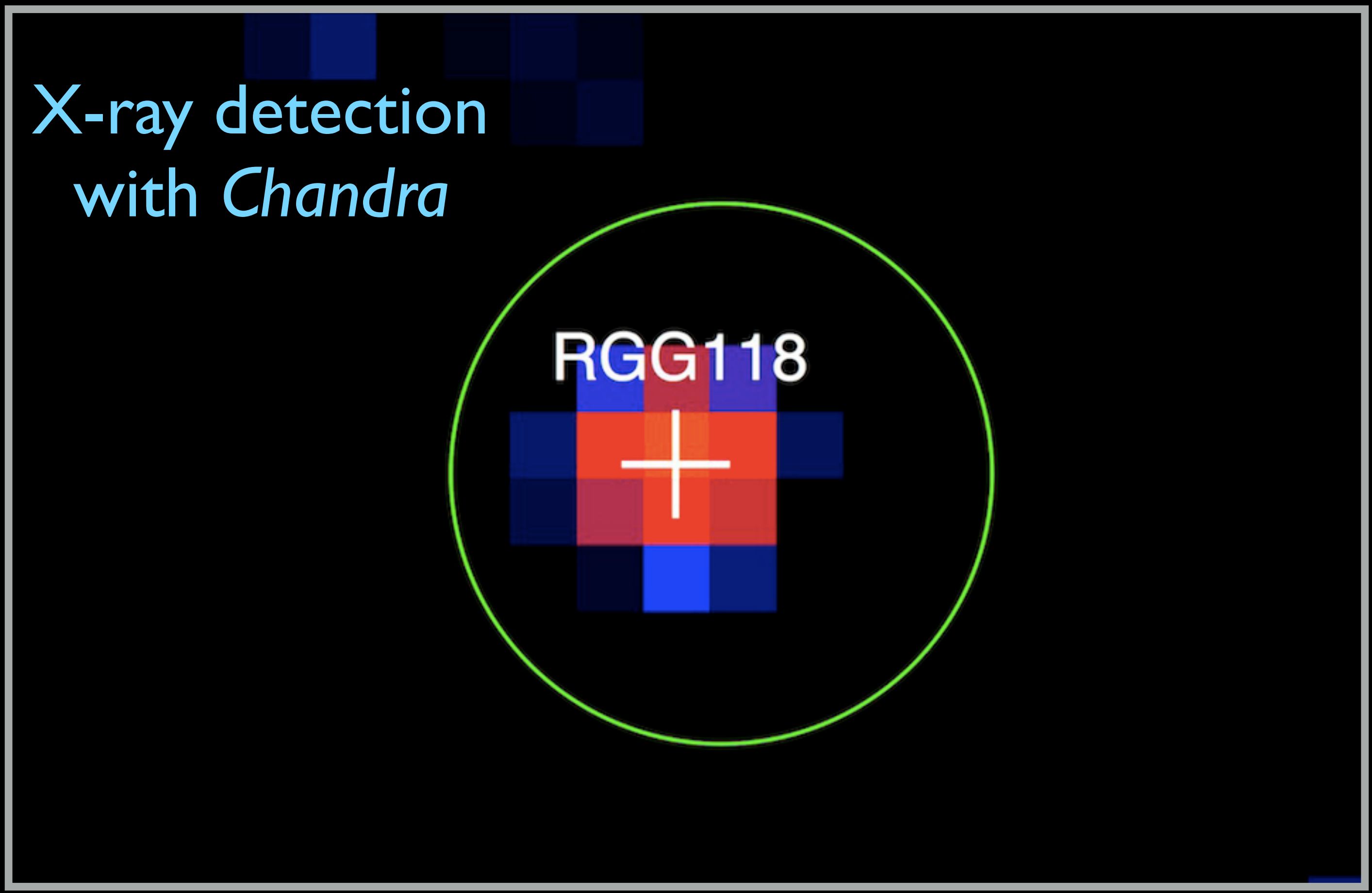
Accretion powered luminosity of ~ 4 x10^{40} erg/s, Eddington ratio ~1%



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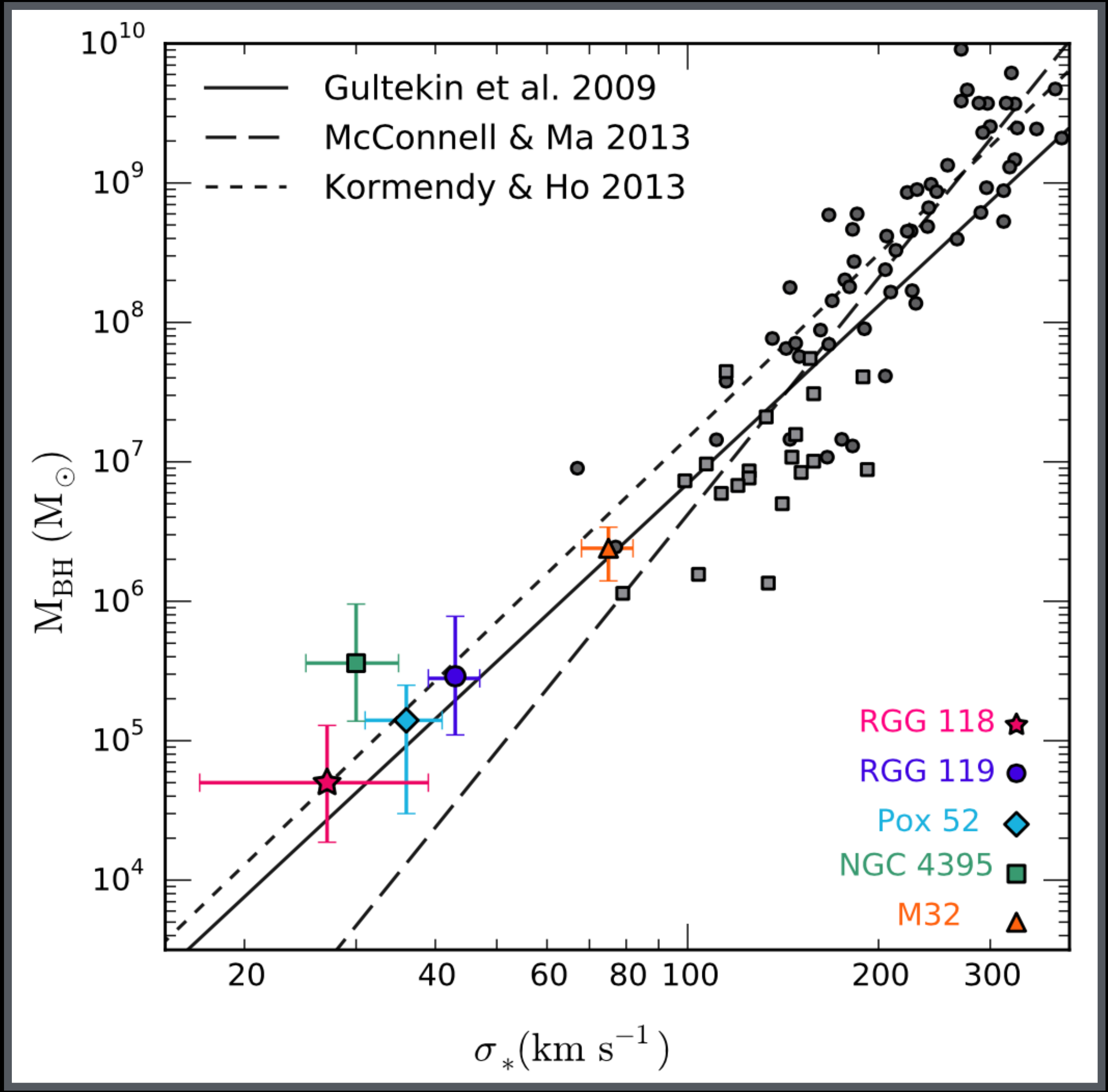


Figure from Baldassare et al. (2016)

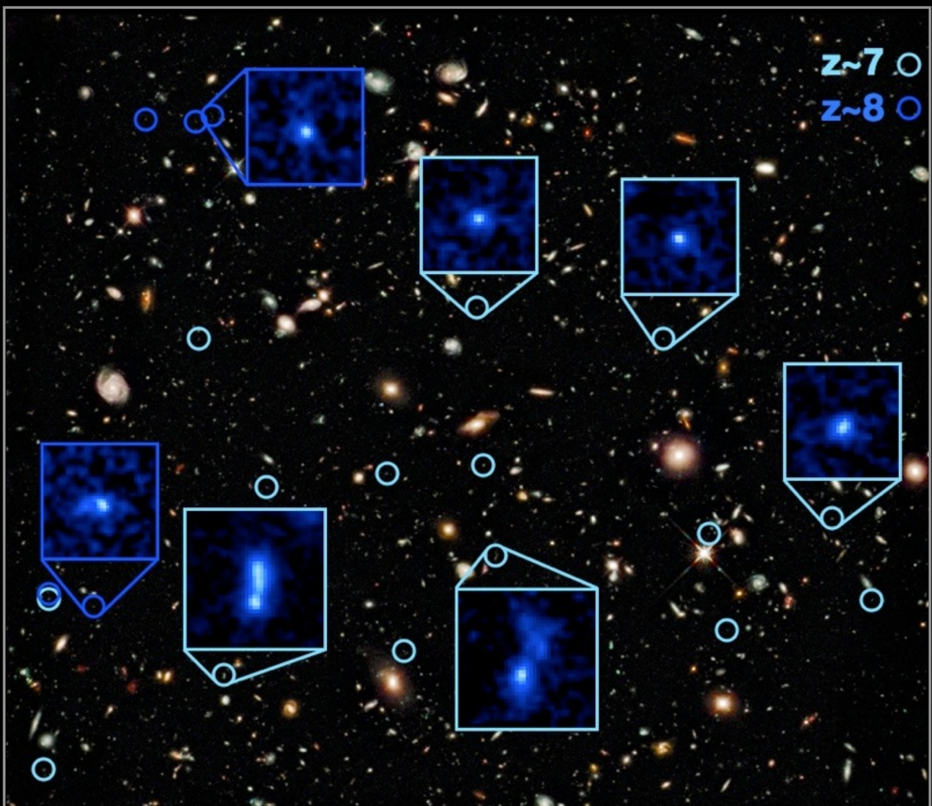
Massive black holes in nearby dwarf galaxies are much more common than previously thought.

What about black holes in high-redshift (low-mass) galaxies?

Connections to the high-redshift Universe

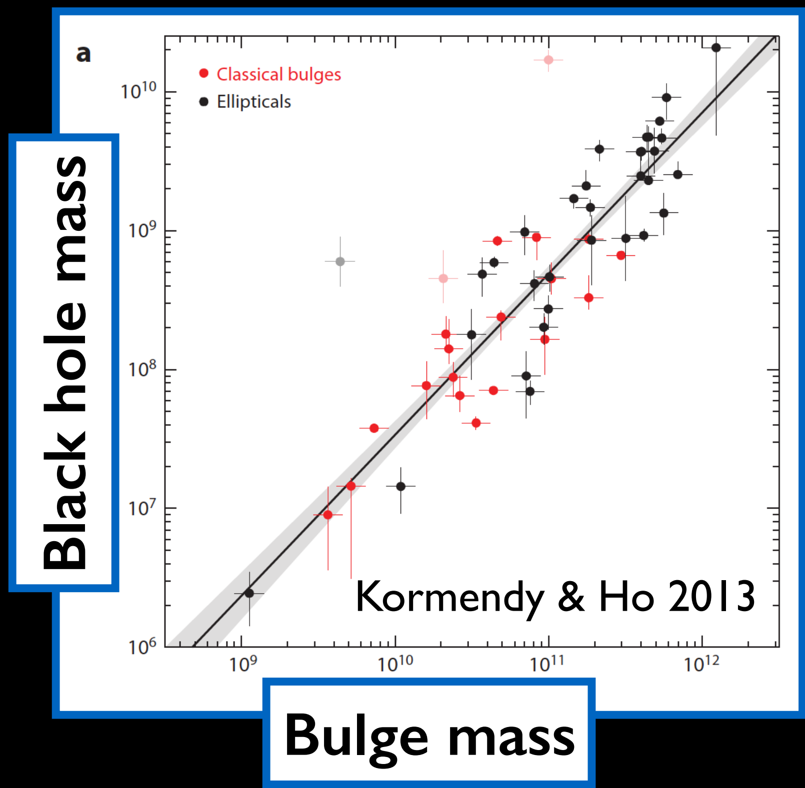
Searches for AGN in galaxies with stellar masses ~10^9 M_{sun} at z > 6 have found very few, if any, black holes

(Willott 2011; Fiore et al. 2012; Cowie et al. 2012; Treister 2013; Giallongo et al. 2015; Weigel et al. 2015)



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.



Expect M_{BH} ~10^6 M_{sun}

Connections to the high-redshift Universe

"Relations between central black hole mass and total galaxy stellar mass in the local Universe"

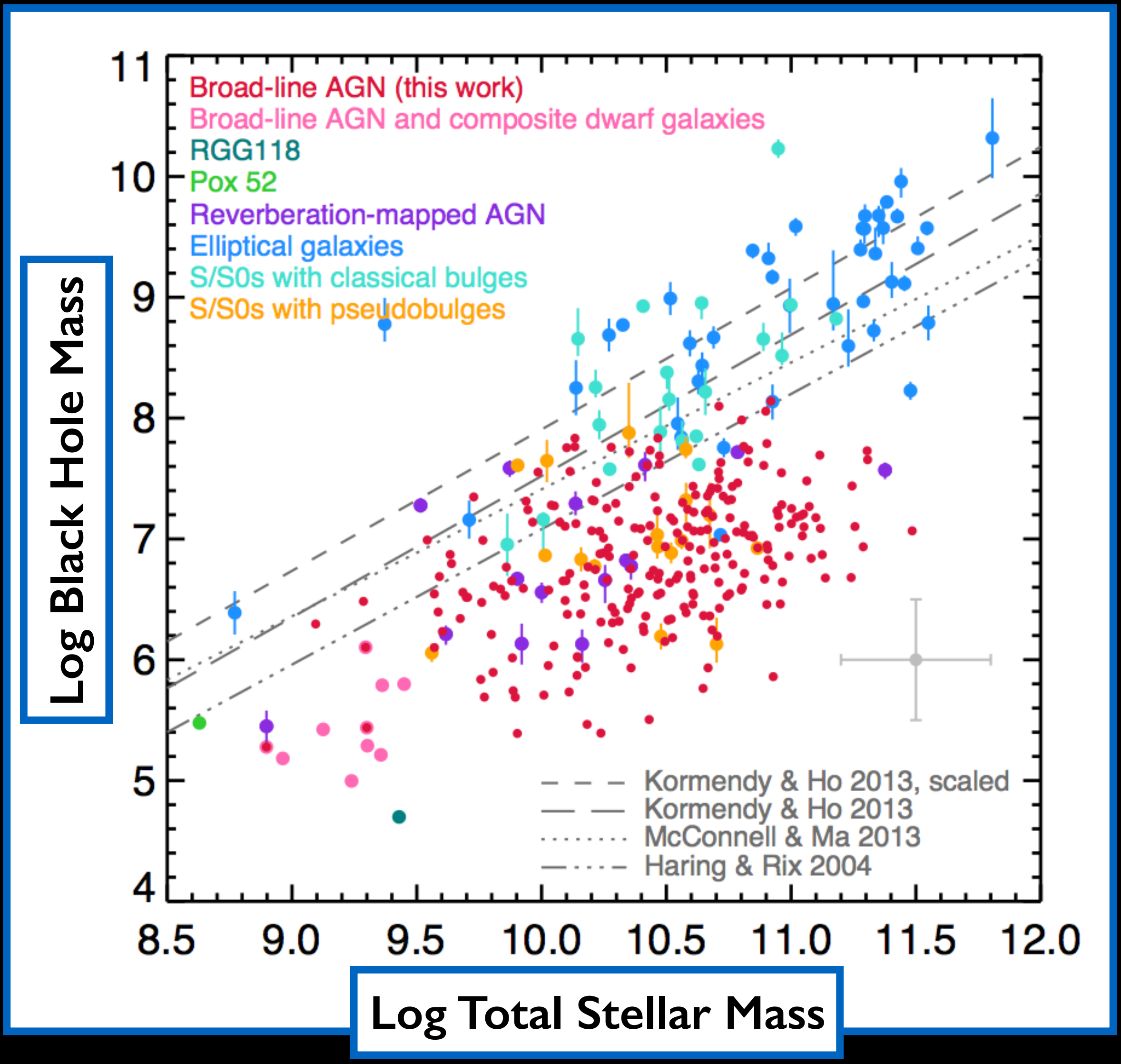
Reines & Volonteri 2015

"Inferences on the relations between central black hole mass and total galaxy stellar mass in the high-redshift Universe"

Volonteri & Reines 2016

Connections to the high-redshift Universe

Reines & Volonteri 2015



BH mass

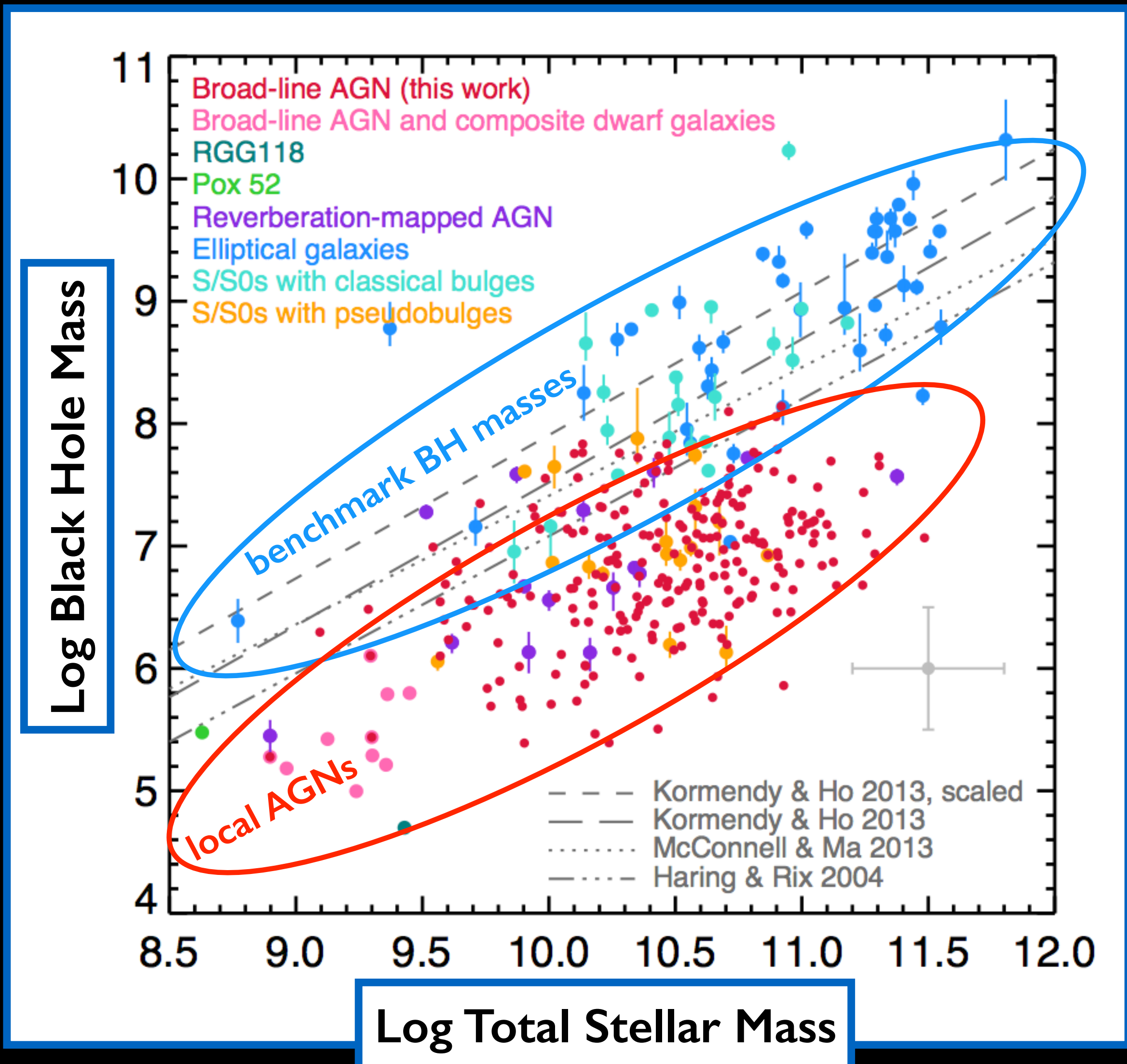
vs.

total galaxy stellar mass

(341 nearby galaxies)

Connections to the high-redshift Universe

Reines & Volonteri 2015



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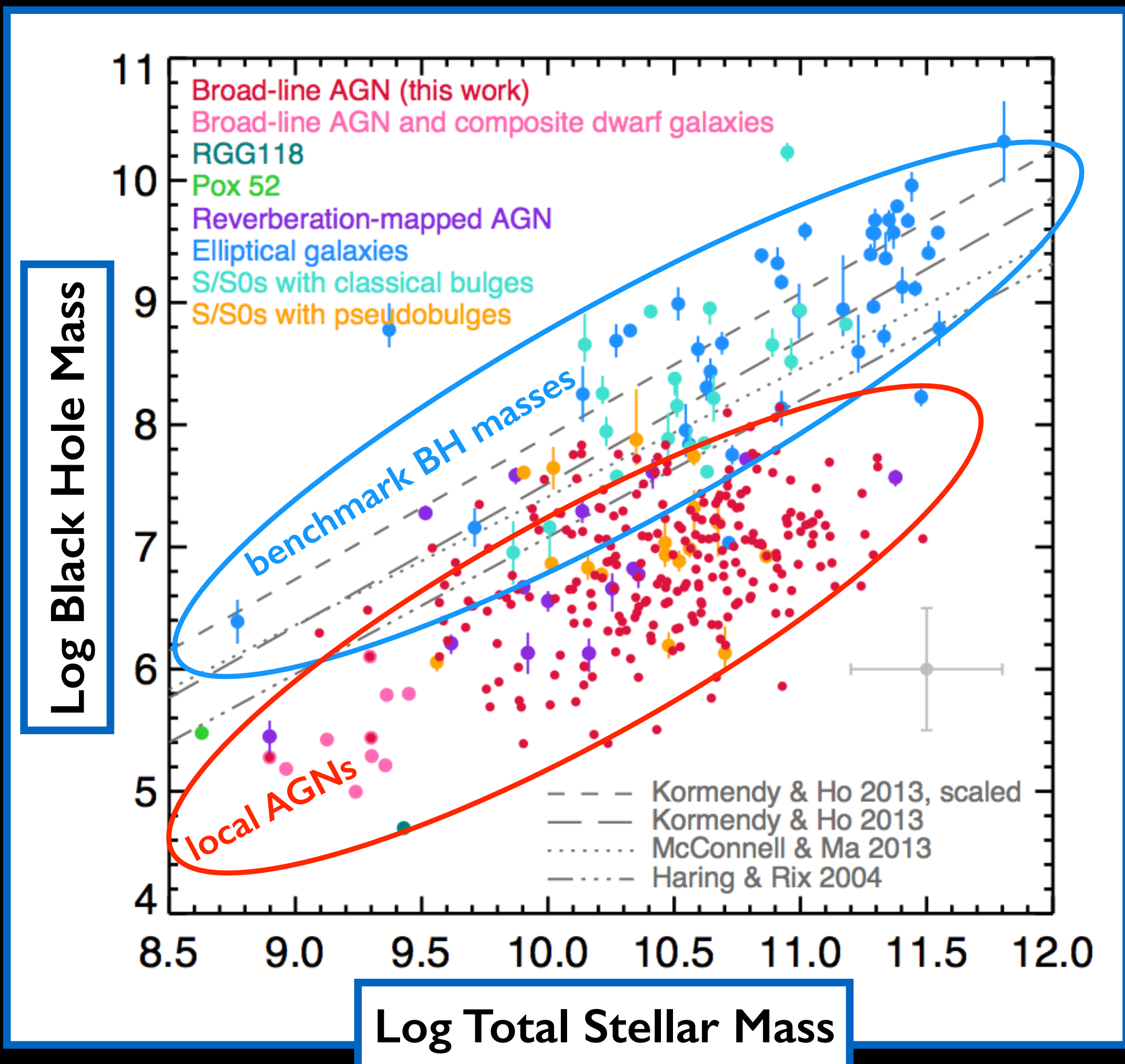
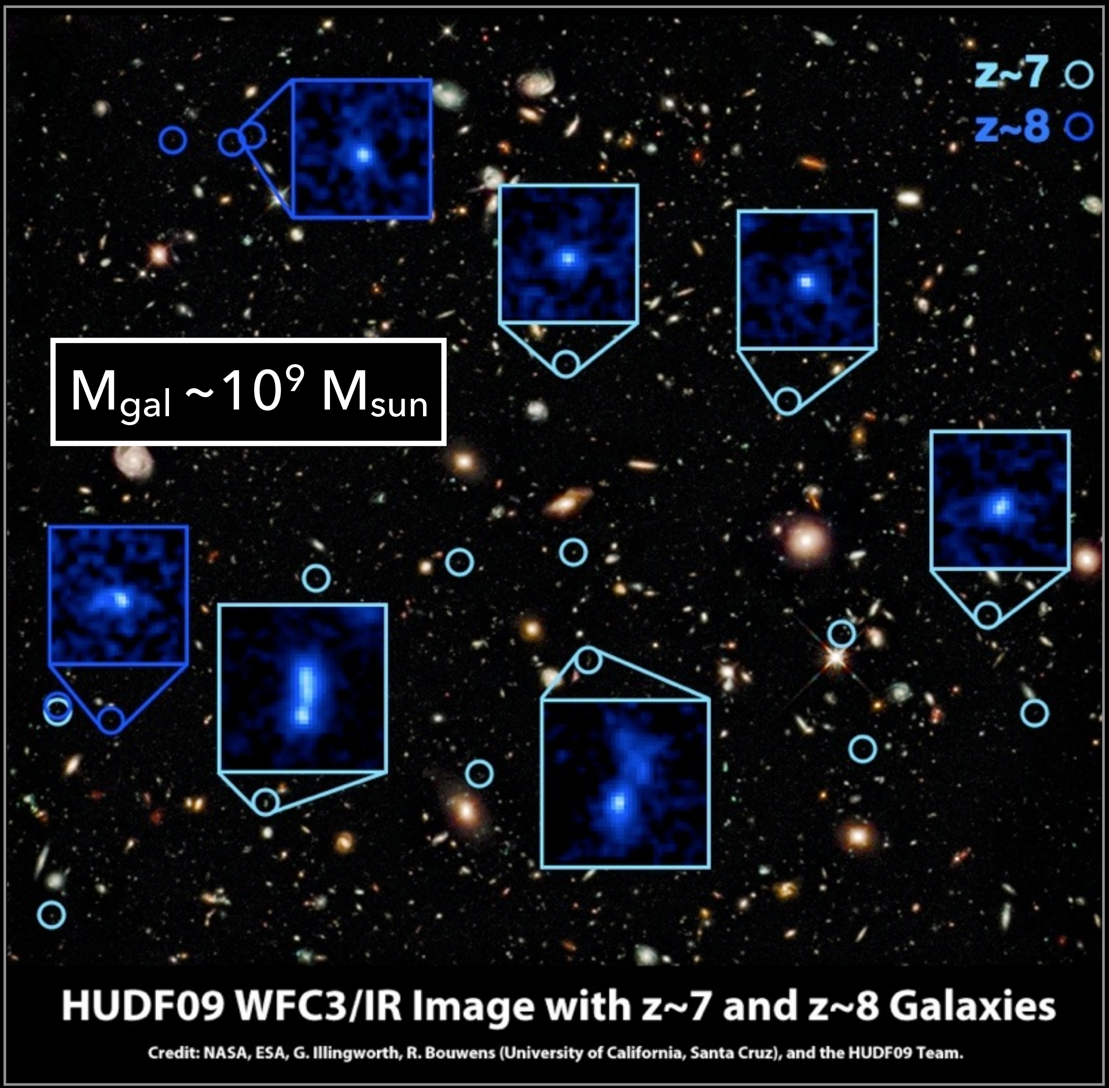


$M_{BH} \sim 10^{-3}\ M_{gal}$

$M_{BH} \sim 10^{-4}\ M_{gal}$

Connections to the high-redshift Universe



$M_{BH} \sim 10^{-3}\ M_{gal}$

$\longrightarrow M_{BH} \sim 10^{6}\ M_{sun}$

$M_{BH} \sim 10^{-4}\ M_{gal}$

$\longrightarrow M_{BH} \sim 10^{5}\ M_{sun}$

- AGNs expected to be less luminous
- Consistent with non-detections

Volonteri & Reines 2016

Summary

- Searching for and studying the smallest BHs in dwarf galaxies is currently our best observational probe of the origin of massive BHs

- Recently increased the number of dwarf galaxies known to host massive BHs by more than an order of magnitude (Reines+11; Reines+13; Reines+14)

- Finding the smallest BHs known in galaxy nuclei (~10^4-10^5 M_{sun}) (Reines+13; Baldassare+15)

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

- Scaling between BH mass and total stellar mass in local AGN host galaxies can explain lack of AGN detections in high-redshift, low-mass galaxies (Reines & Volonteri 2015; Volonteri & Reines 2016)