Multi-wavelength Searches for Local Relics of Black Hole Seeds in Dwarf Galaxies

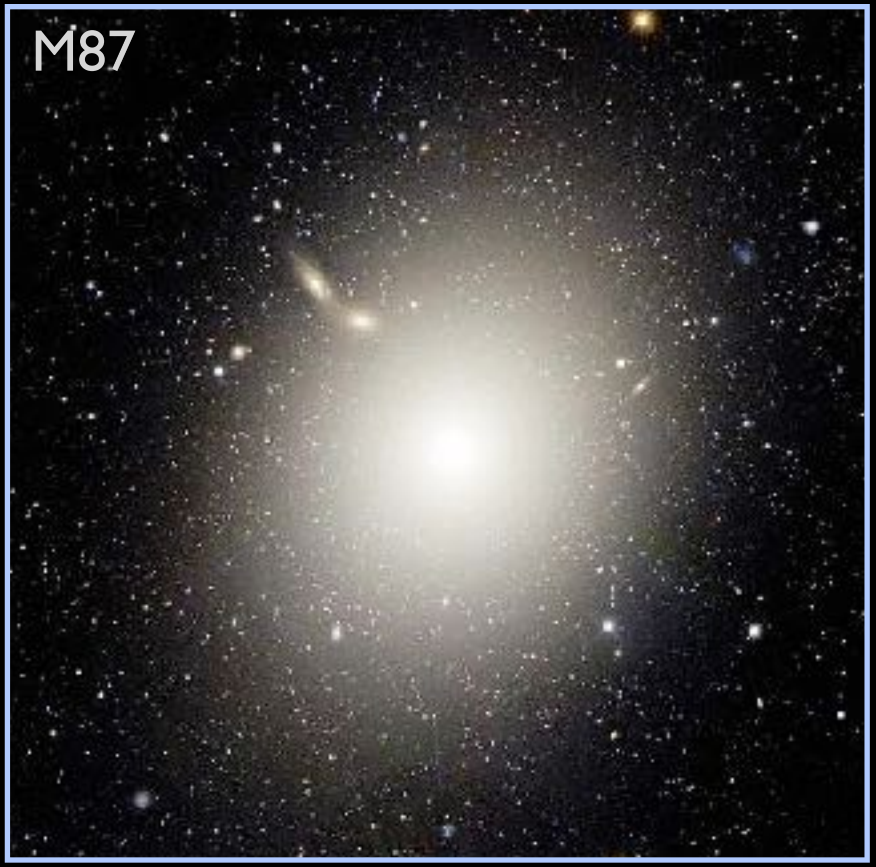
AMY REINES

HUBBLE FELLOW, NOAO

(joining the faculty at Montana State University in August)

The Importance of Massive Black Holes

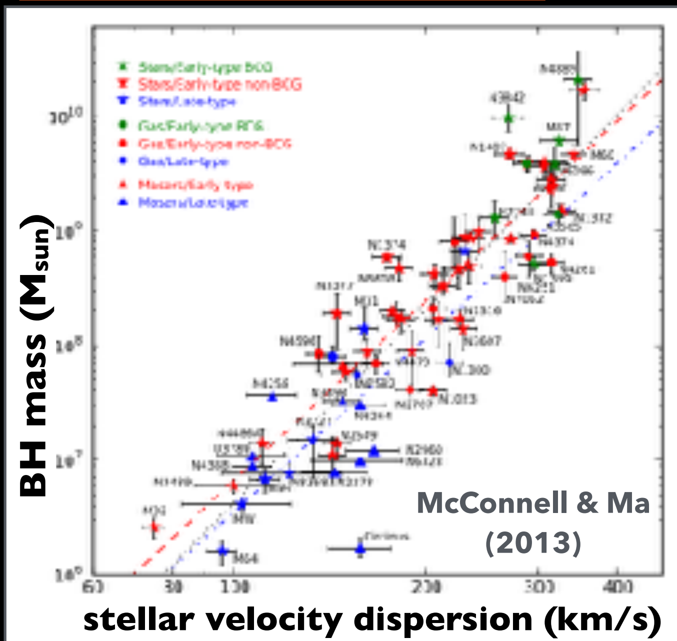
$M_{BH} \sim 1.4 \times 10^8\ M_{sun}$ (Bender et al. 2005)

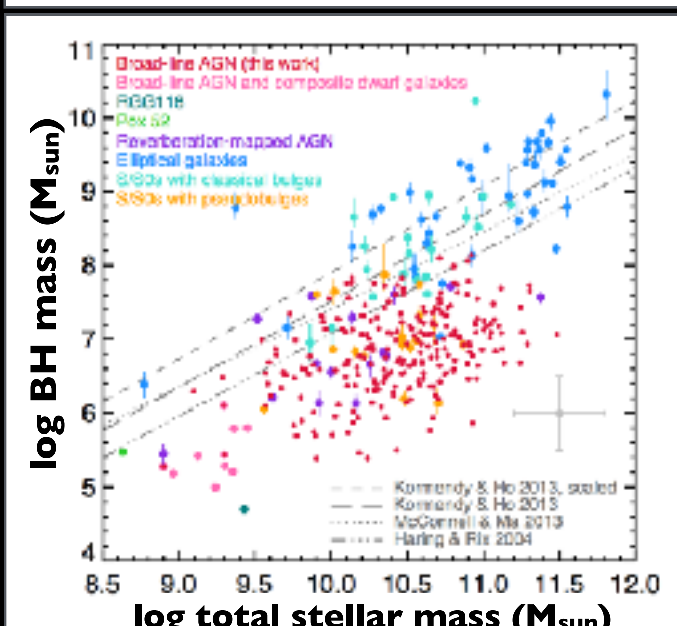


$M_{BH} \sim 6.6 \times 10^9\ M_{sun}$ (Gebhardt et al. 2011)

The Importance of Massive Black Holes

BH and galaxy evolution





Reines & Volonteri (2015)

The Importance of Massive Black Holes

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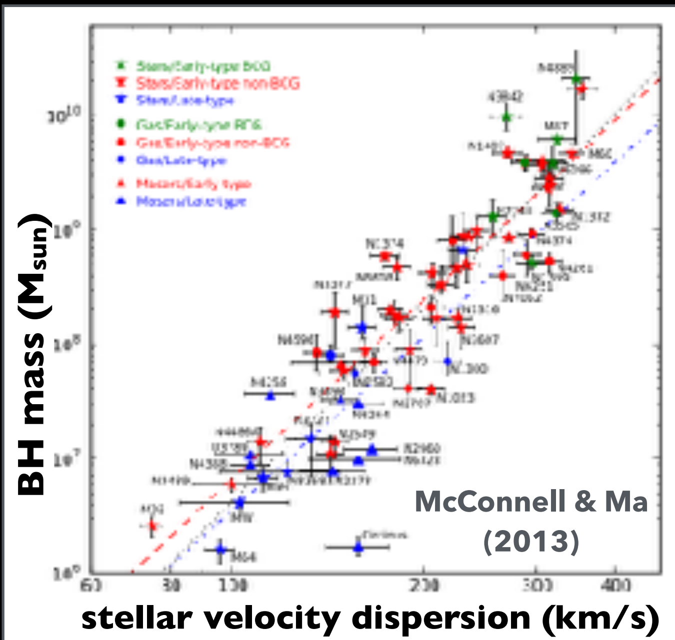

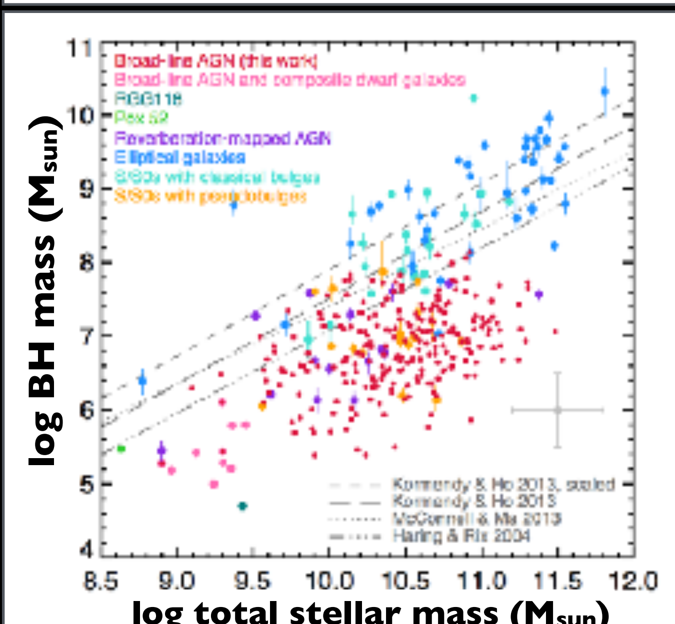

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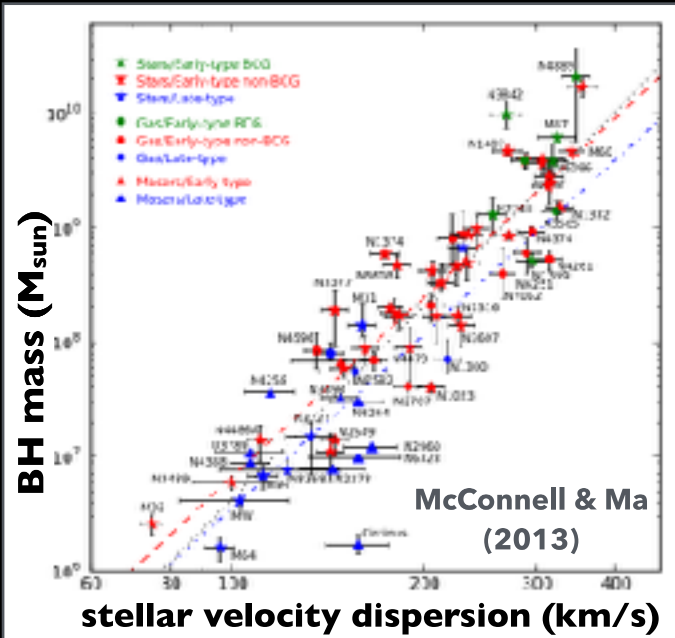

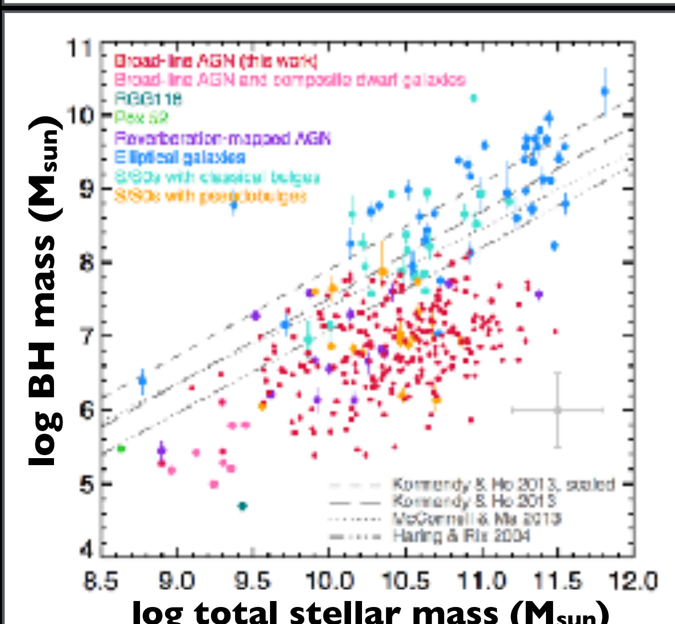

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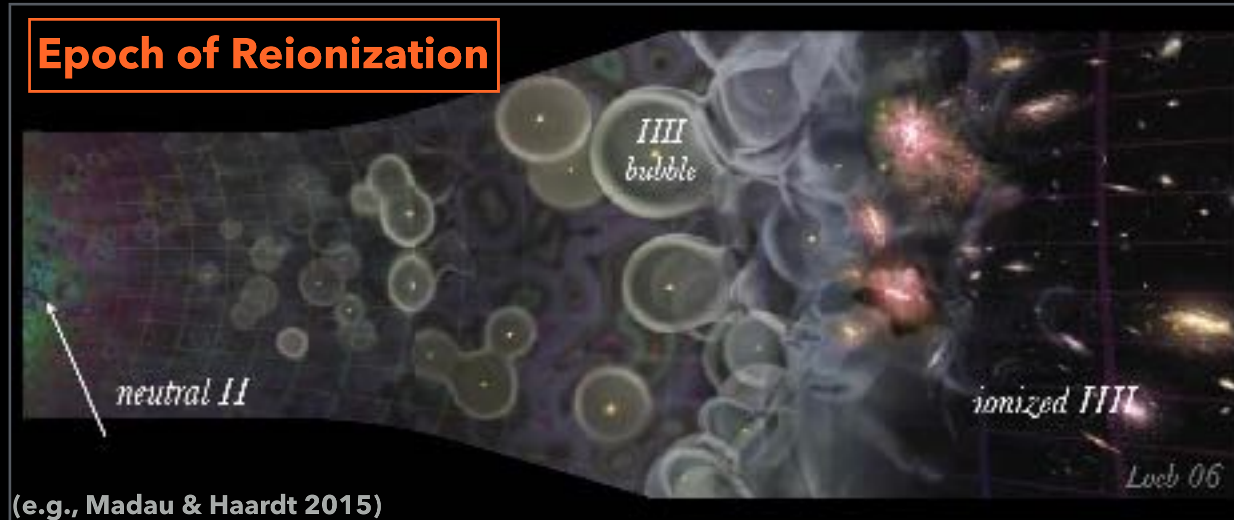

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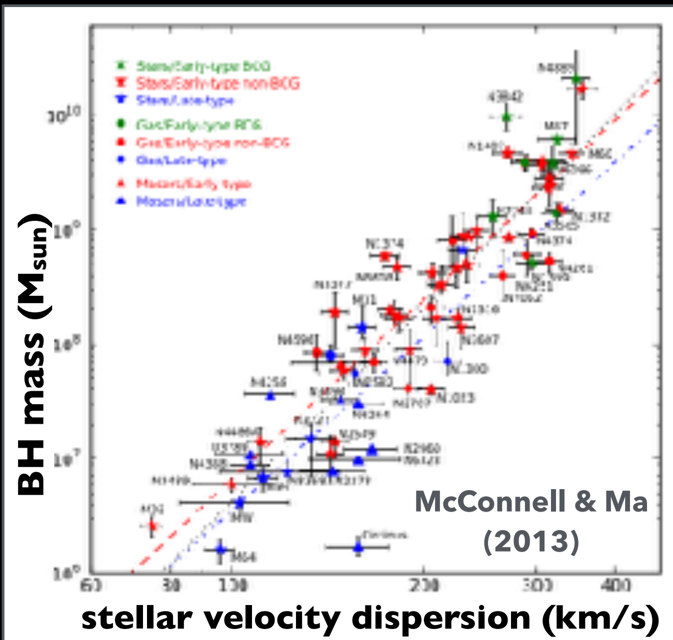
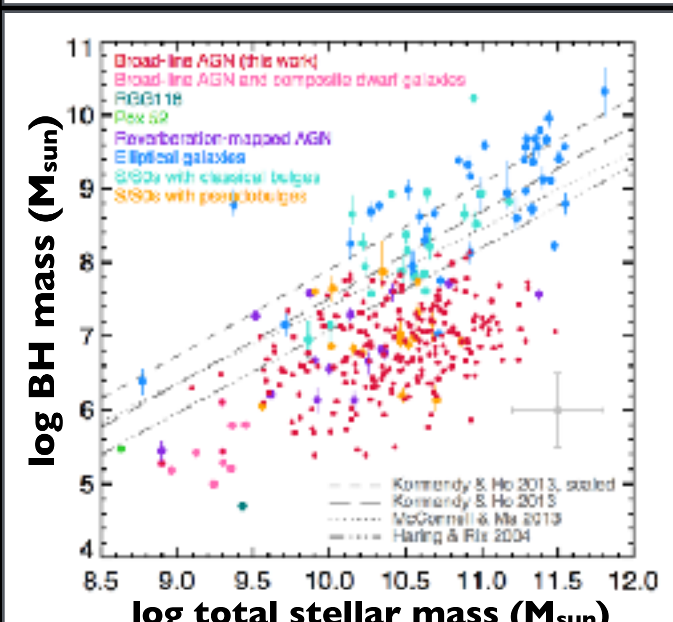
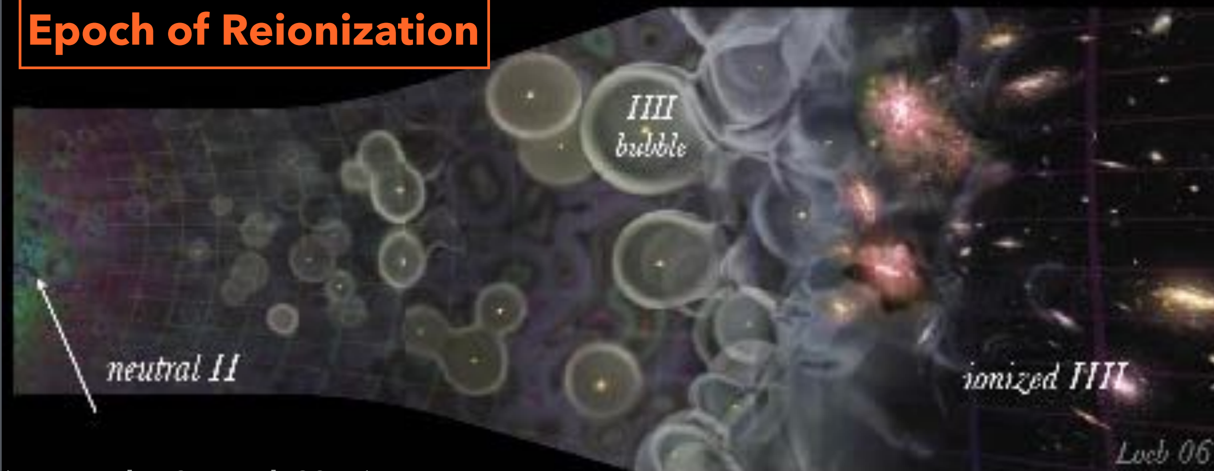




Reines & Volonteri (2015)

Epoch of Reionization



(e.g., Madau & Haardt 2015)

AGNs

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

Tidal Disruption Events

Guillochon et al. (2014)

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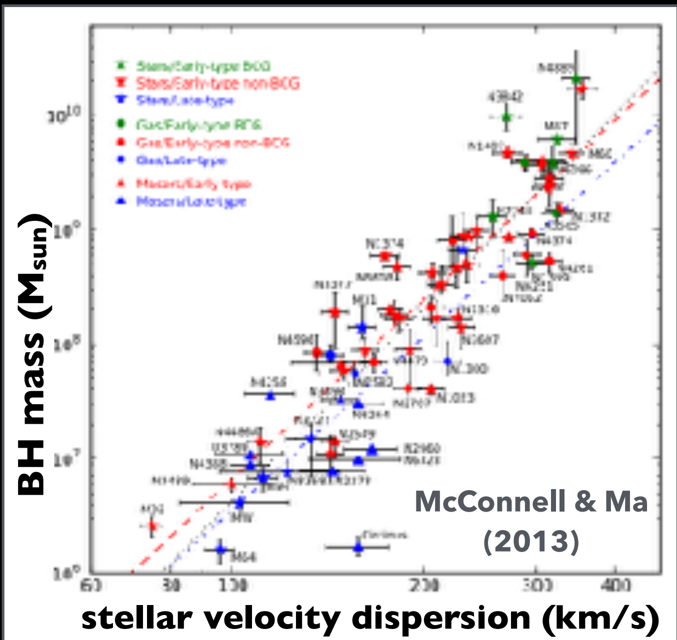

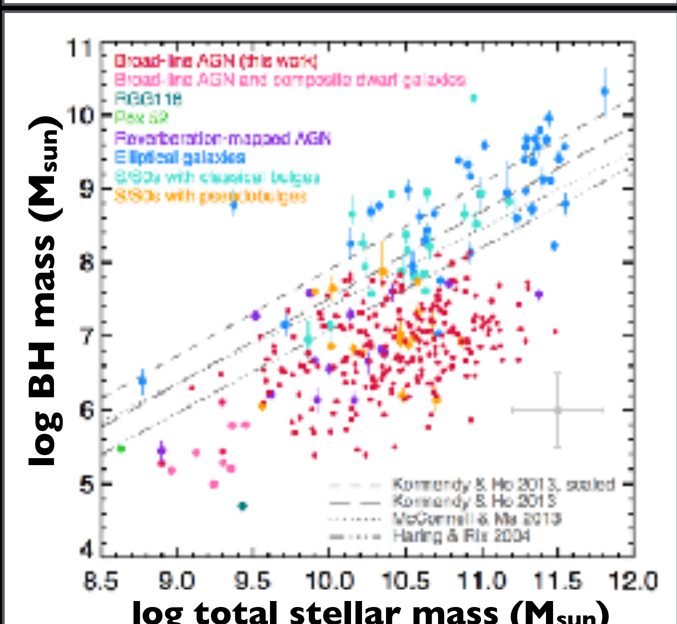

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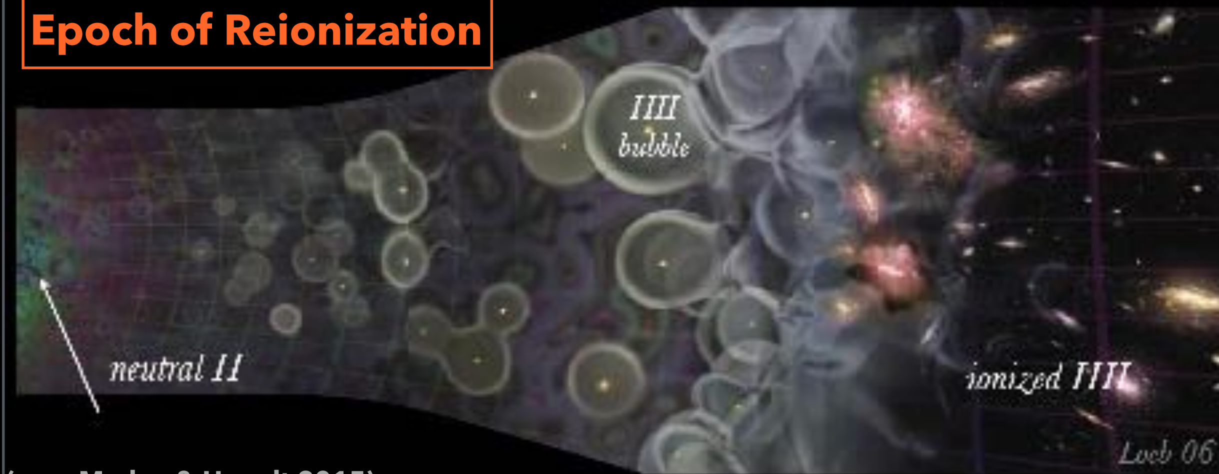

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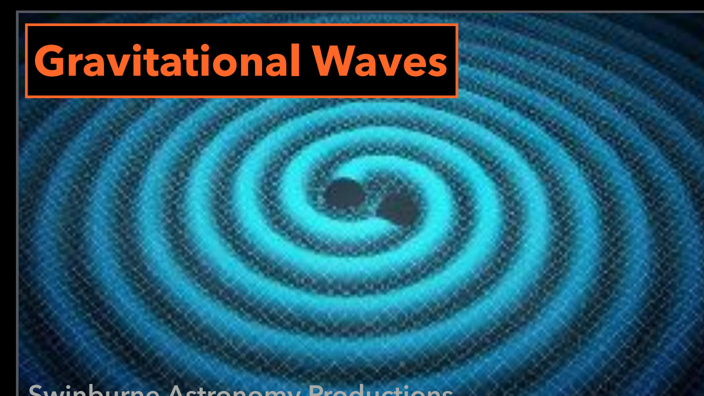
Gravitational Waves

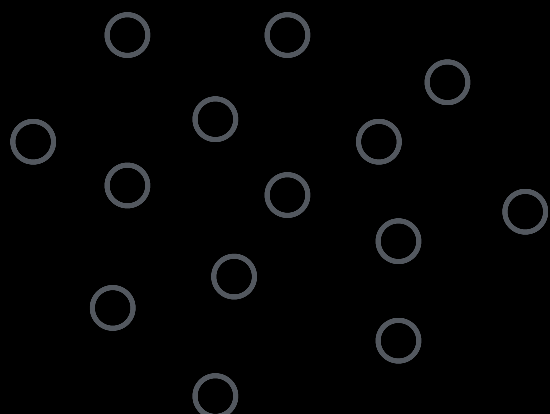


Swinburne Astronomy Productions

The origin of the first “seed” BHs is largely unknown

Theory: Possible BH seed formation mechanisms

Remnants from first generation of massive stars



- $M_{BH} \sim 100\ M_{sun}$
- abundant

Direct collapse of dense gas

- $M_{BH} \sim 10^5 - 10^6\ M_{sun}$
- rare

for reviews, see e.g., Volonteri (2010); Natarajan (2014); Johnson & Haardt (2016); Latif & Ferrara (2016)

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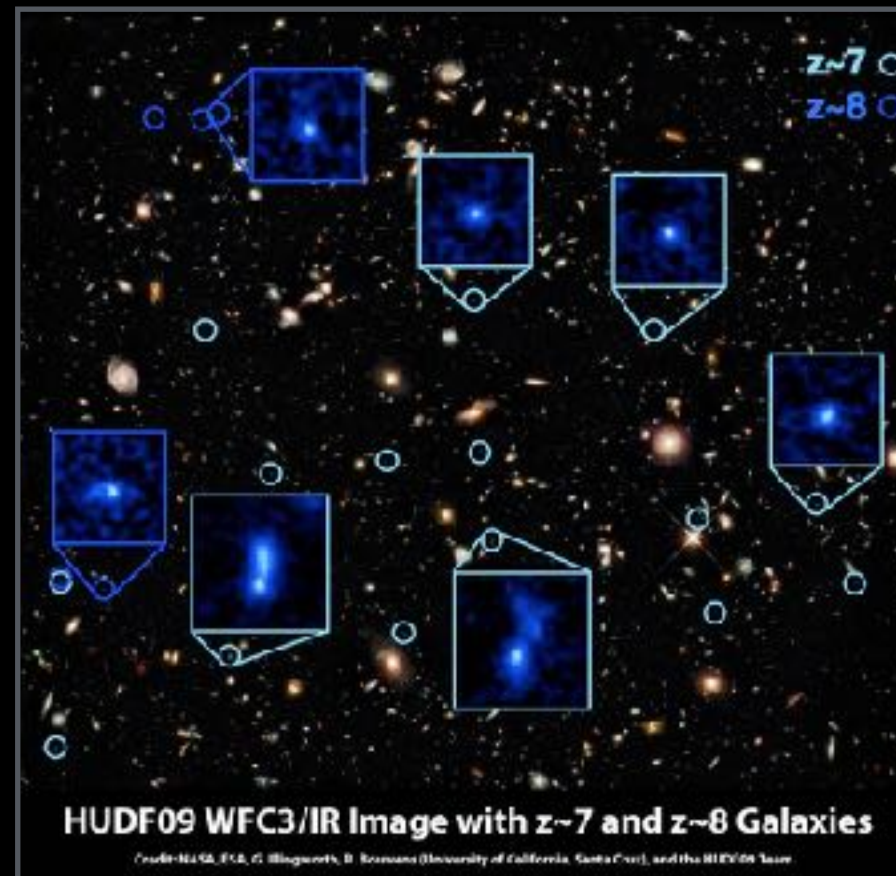
Observations: Detecting seed BHs at high-z is not currently feasible



- *Our knowledge of BHs in the high-z Universe is limited to luminous quasars with hefty BHs ($M_{BH} > 10^8$-10^9 M_{sun})*

- *AGN signatures in z>6 galaxies have remained elusive*

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Observations: Nearby dwarf galaxies contain local relics of BH seeds

(can tell us about the masses, host galaxies and formation mechanism of the first BHs)

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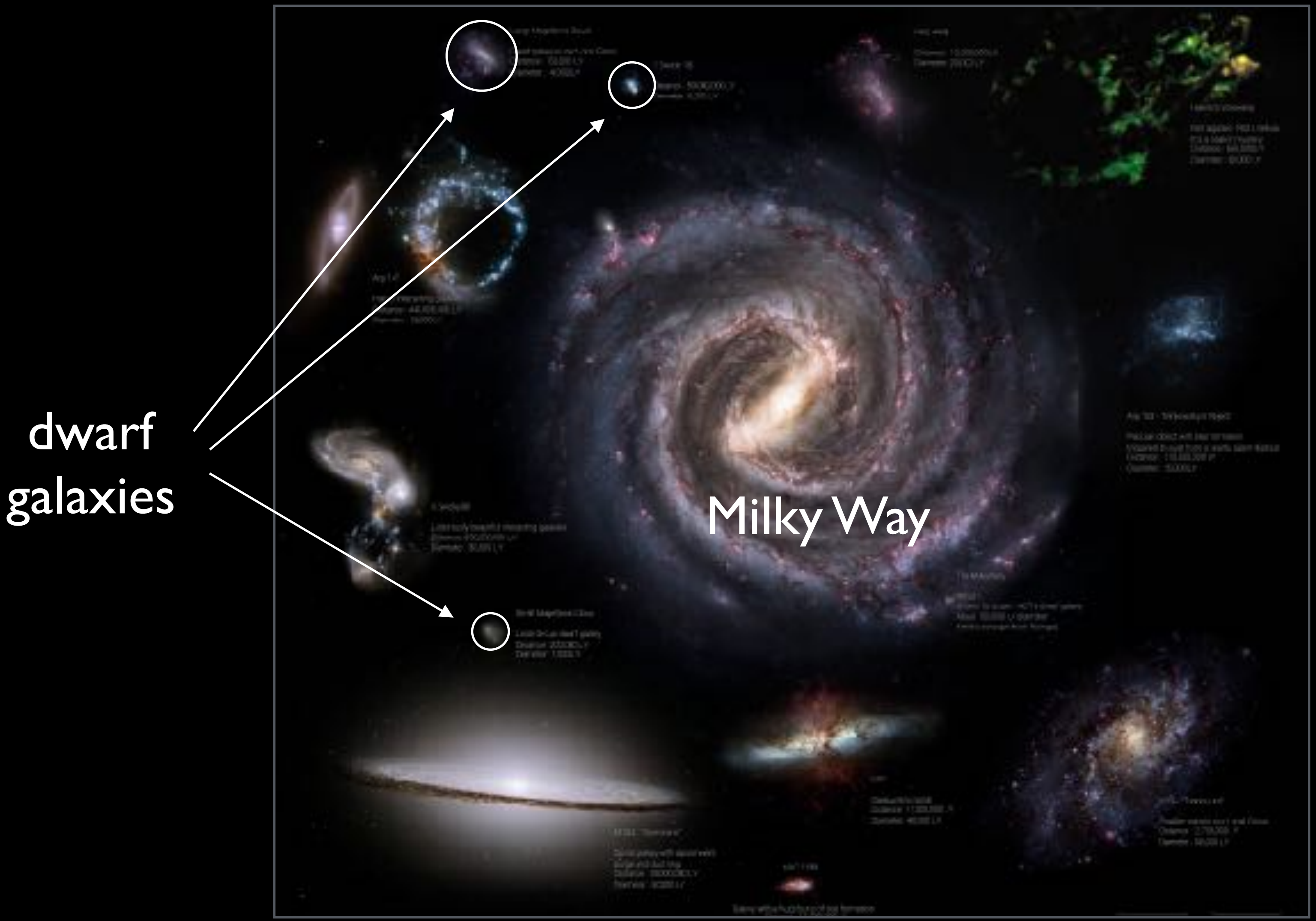

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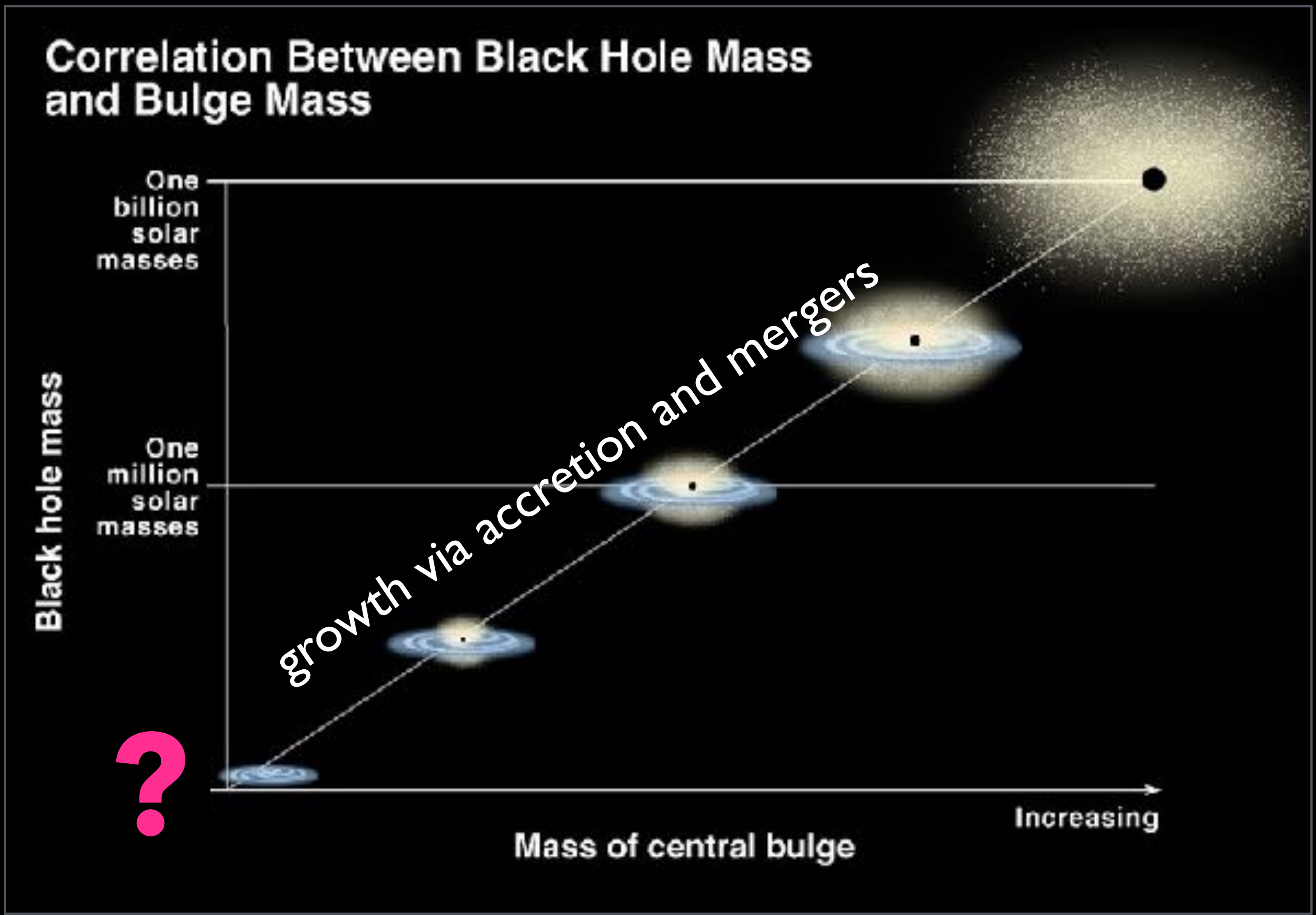
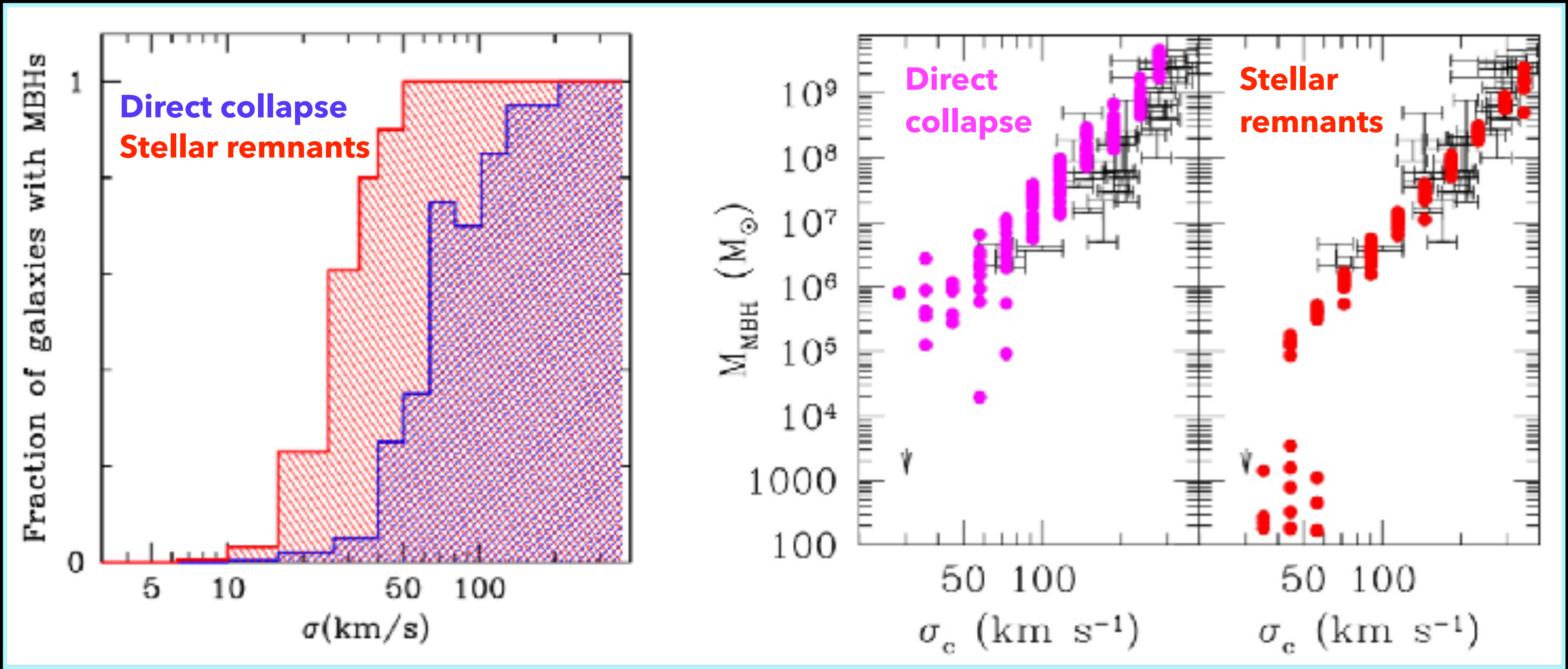


K. Cordes, S. Brown (STScI)

Models of BH growth in a cosmological context predict that the observational signatures indicative of seed formation are strongest in dwarf galaxies

predictions at z=0



BH occupation fraction

M_{BH}-host galaxy relations

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

We can learn about the origin of massive BHs from *observations* of nearby dwarf galaxies

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Dynamical BH detections/limits in nearby dwarfs

Table 2. BH masses and upper limits in nearby dwarf galaxies based on stellar and gas dynamics.

Galaxy	Description	M_{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 (2016) review

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

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

AGNs in Dwarf Galaxies are Elusive AGNs

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- AGNs in dwarf galaxies are powered by smaller BHs than typical AGNs
- These AGNs are less luminous (at a given Eddington fraction)

Eddington (maximum) luminosity is proportional to BH mass

$$L_{\rm Edd} = 1.3 \times 10^{38} (M_{\rm BH}/M_{\odot})\ {\rm erg\ s^{-1}}$$

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- Need to lower threshold for what might be an AGN
- Need to be aware of possible contamination from star-formation related emission

Optical spectroscopy has produced the largest sample of dwarf galaxies hosting massive black holes

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

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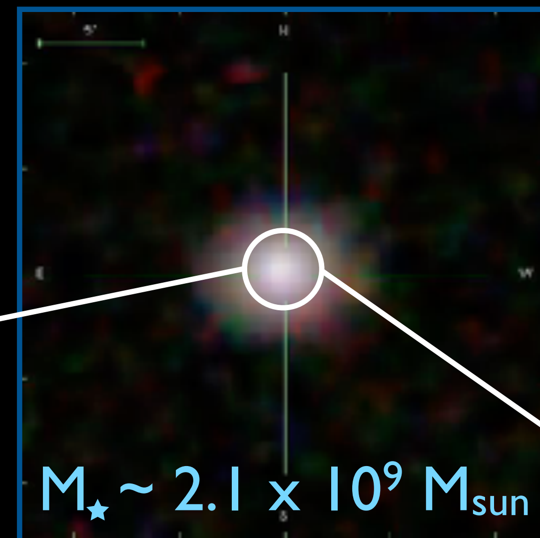

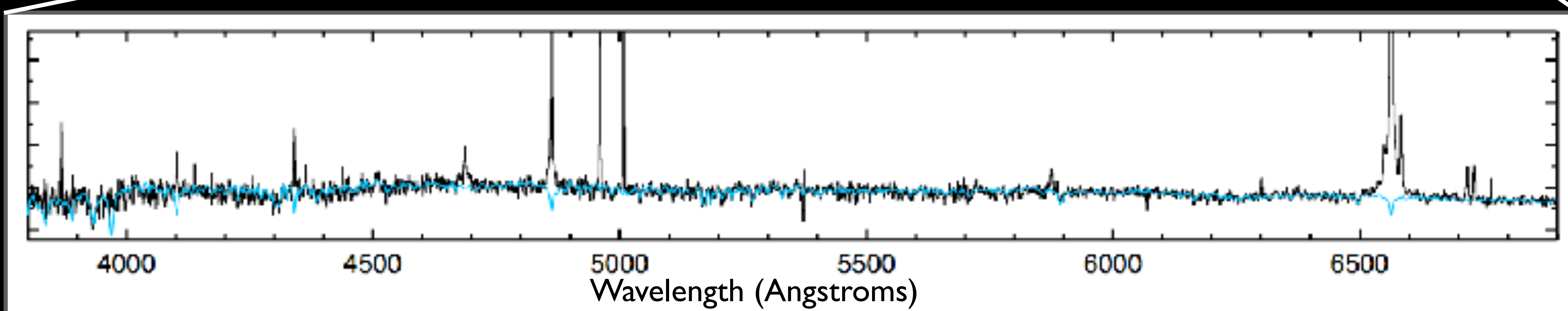

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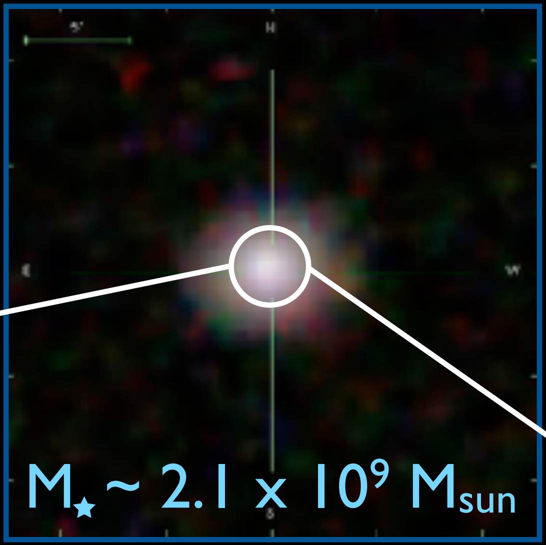

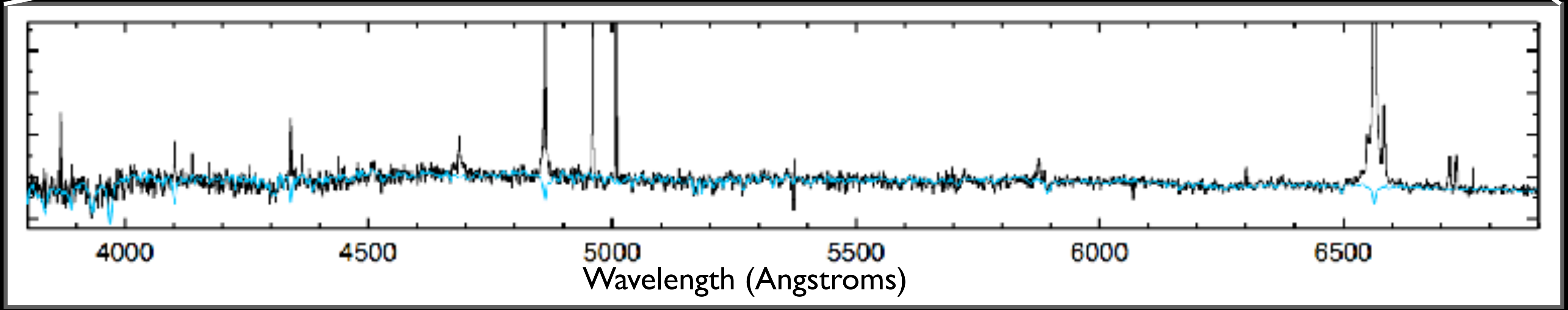

>100 dwarf galaxies with massive BHs

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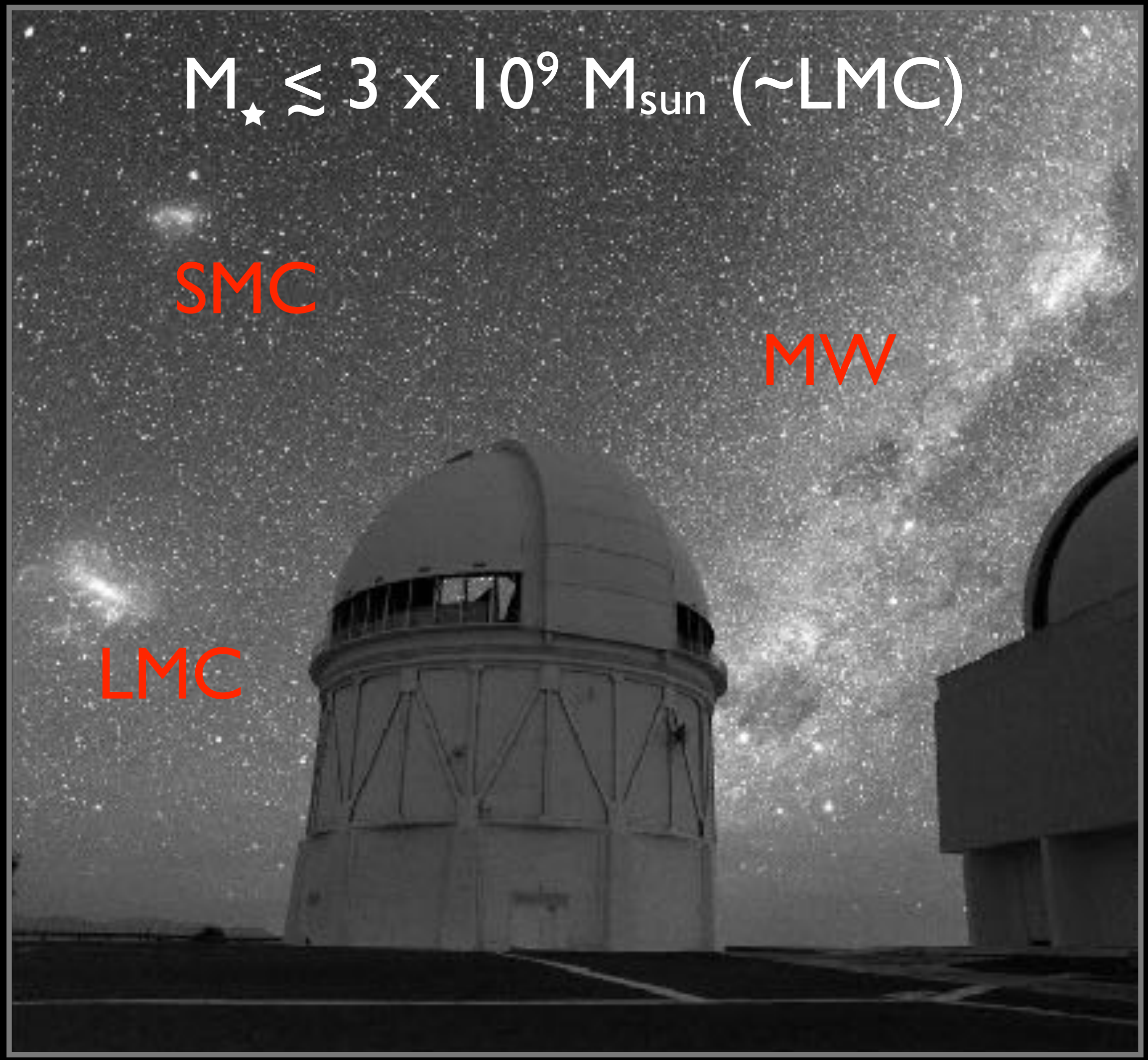

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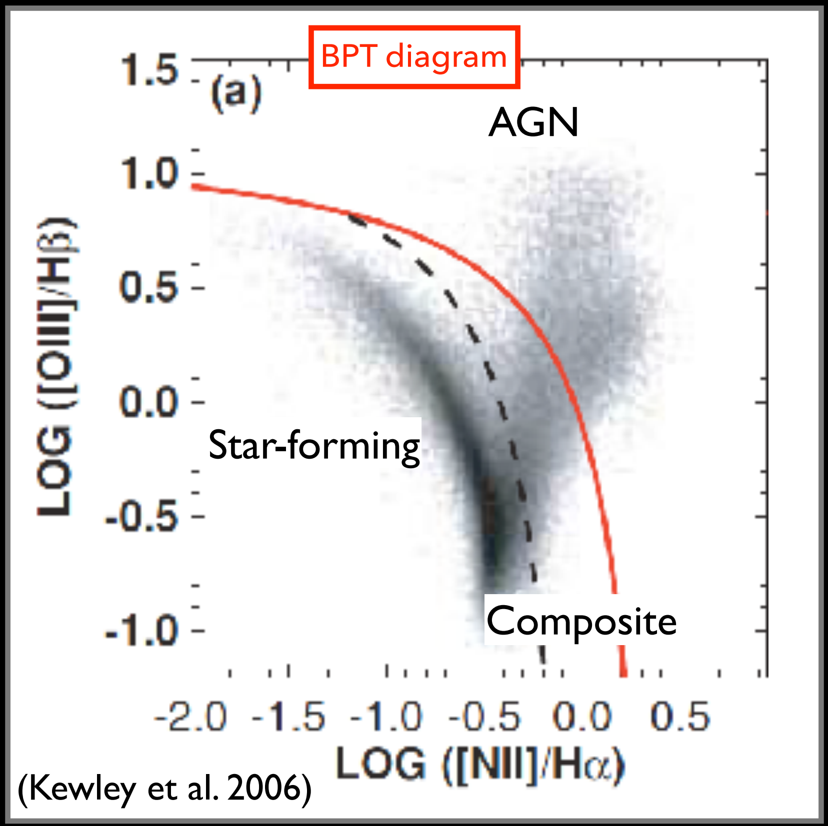

narrow-line AGN

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

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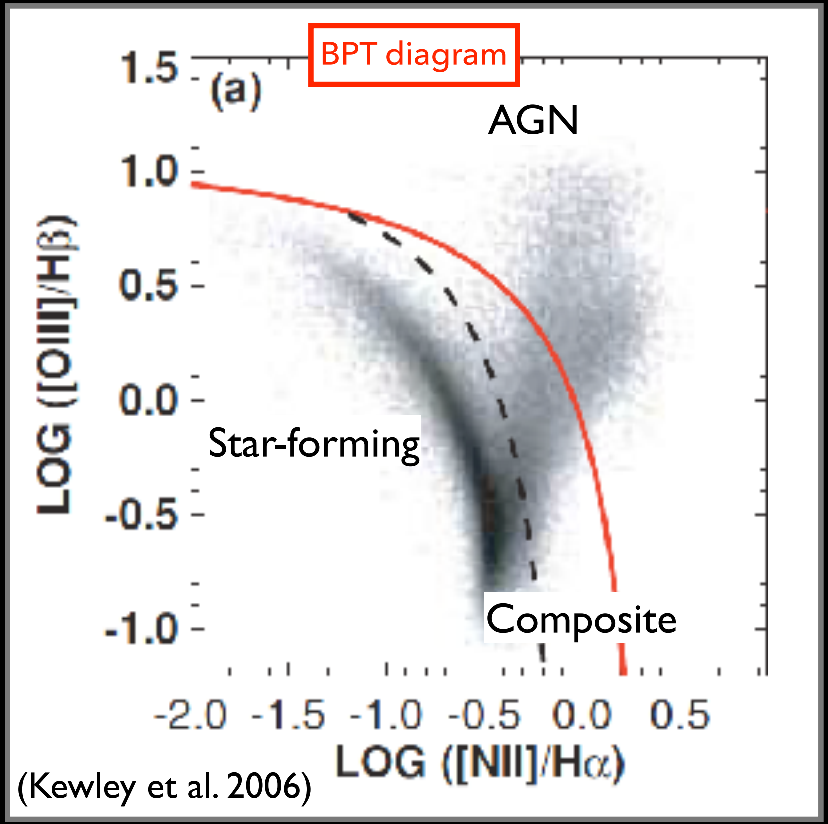

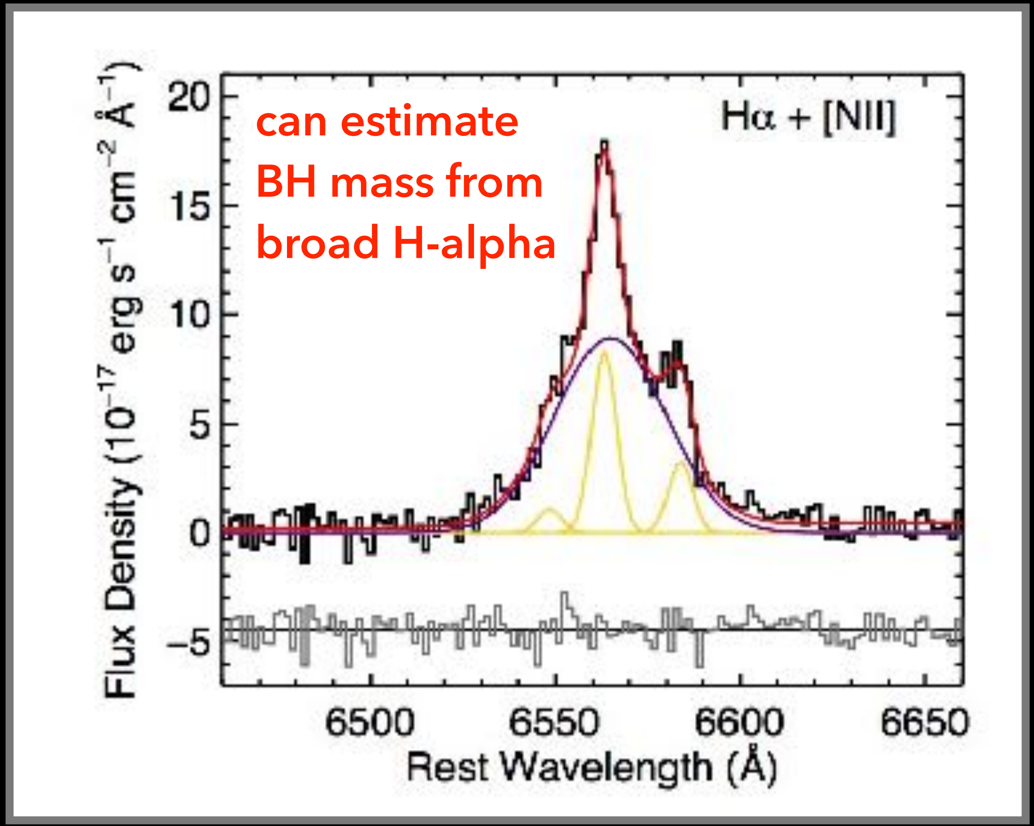

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* search for broad H-alpha emission that can signify dense gas orbiting a BH

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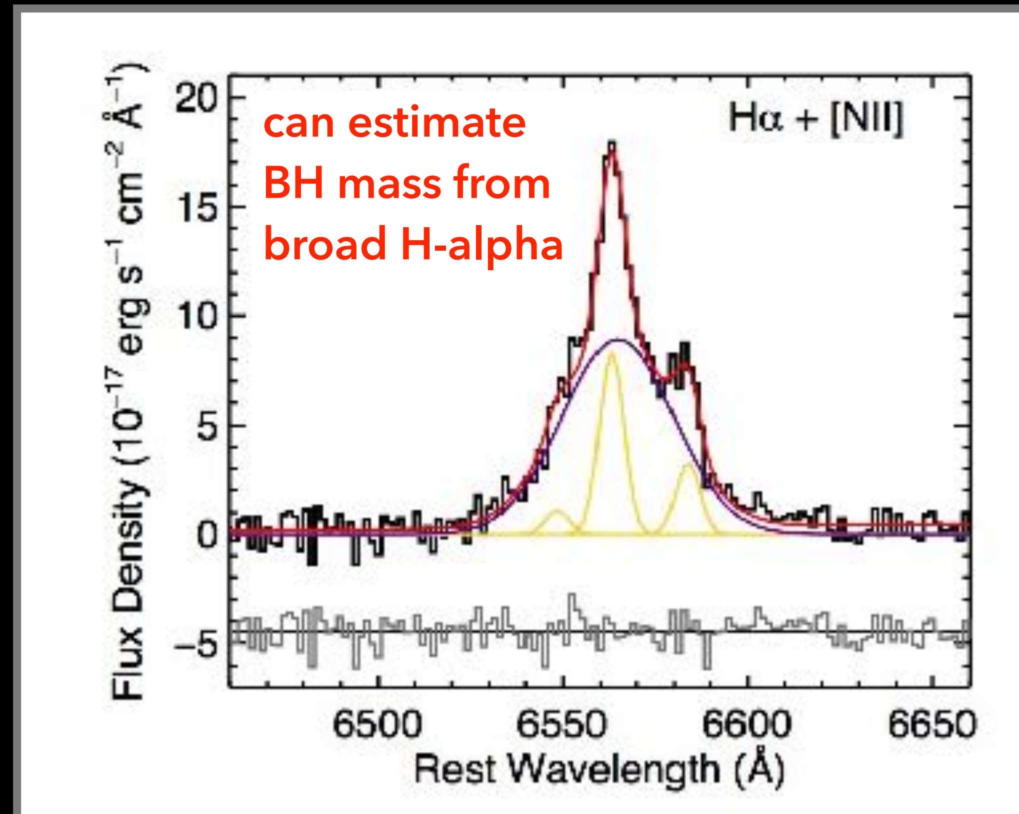
$$M_{BH} \sim R\,V^2 / G$$

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



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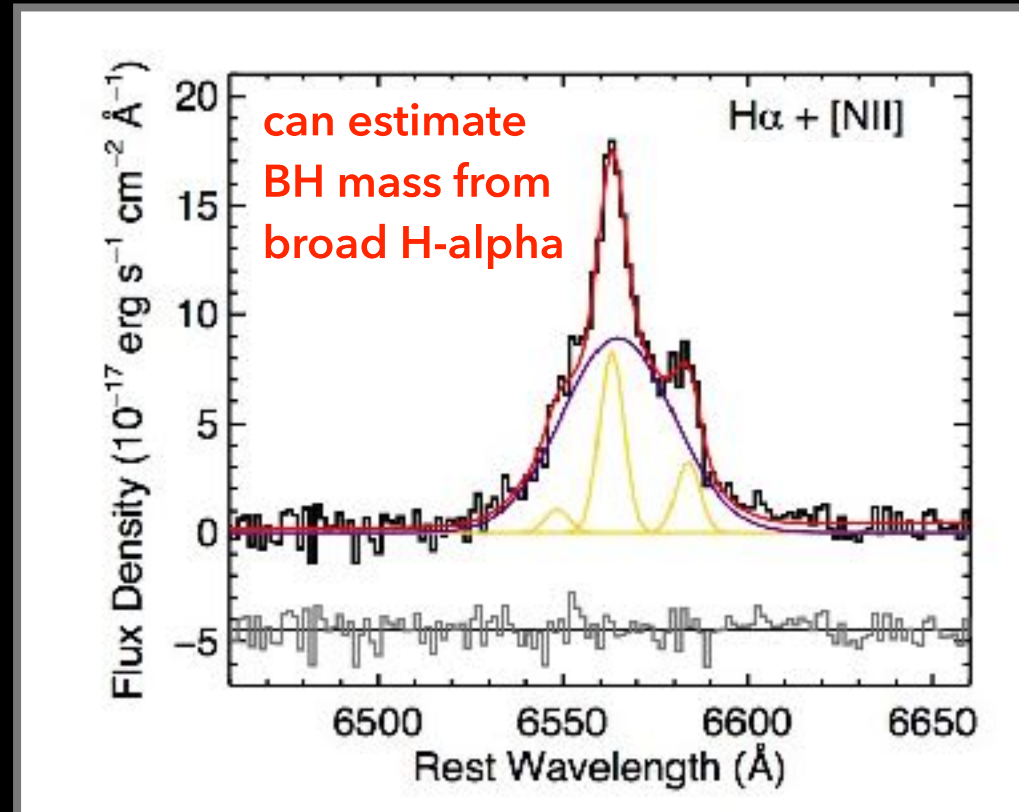

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use ***R* - *L*** **relationship from reverberation-mapped AGN**

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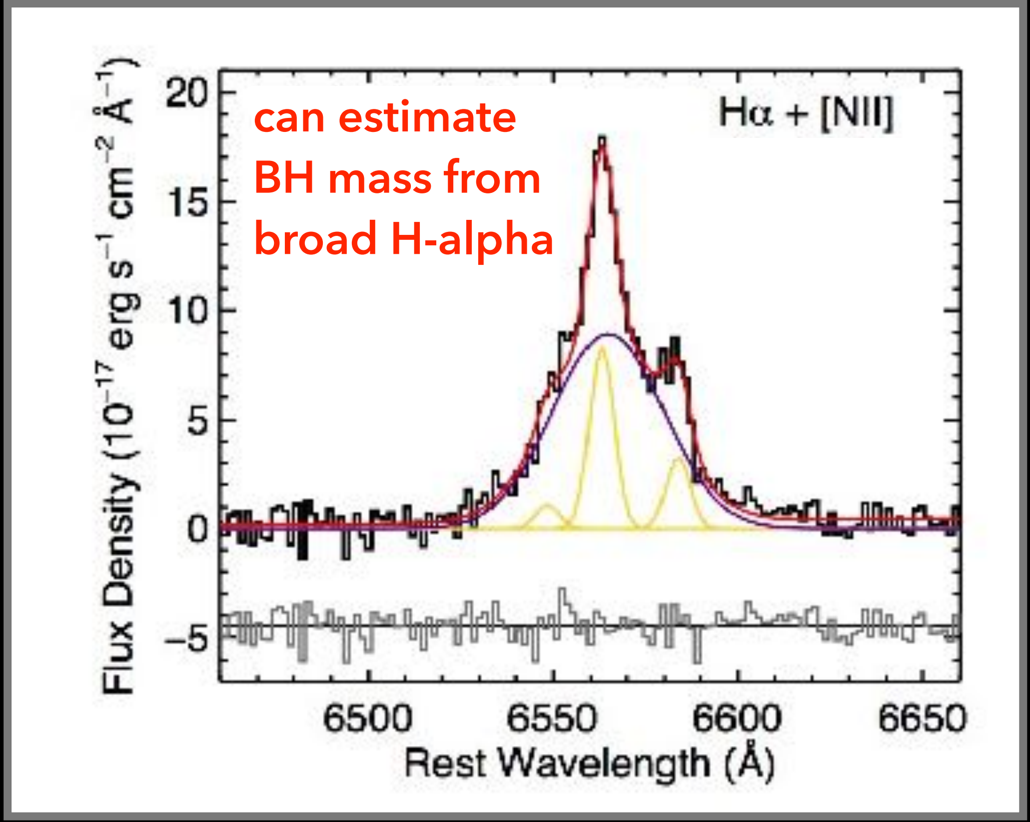

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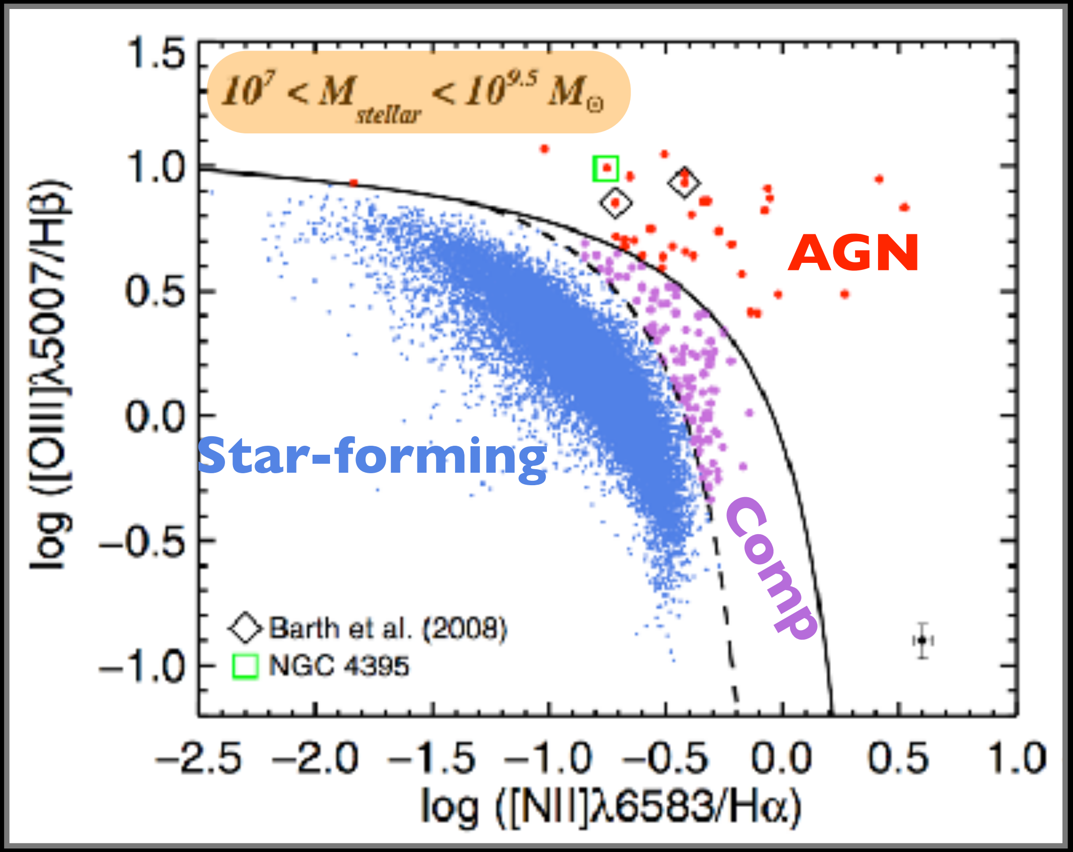

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101 Composites

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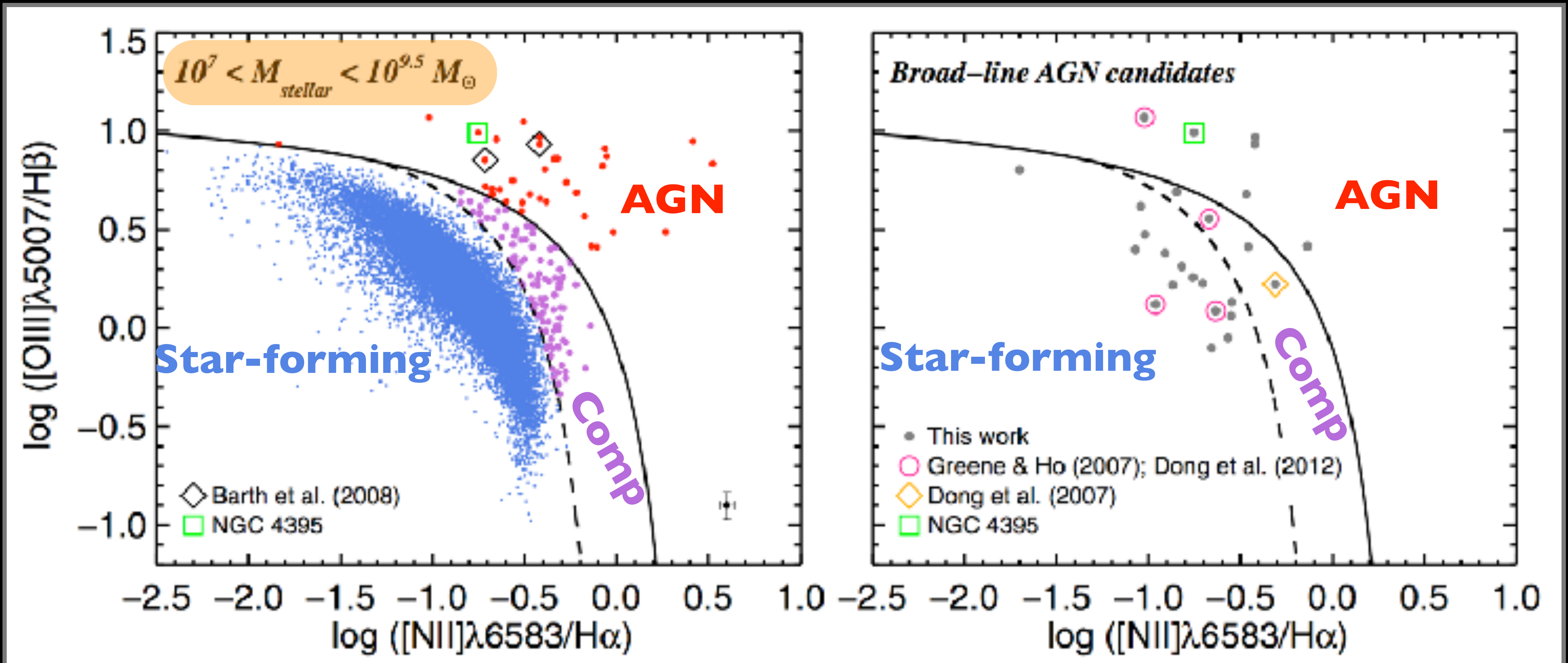

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(with BH mass estimates)

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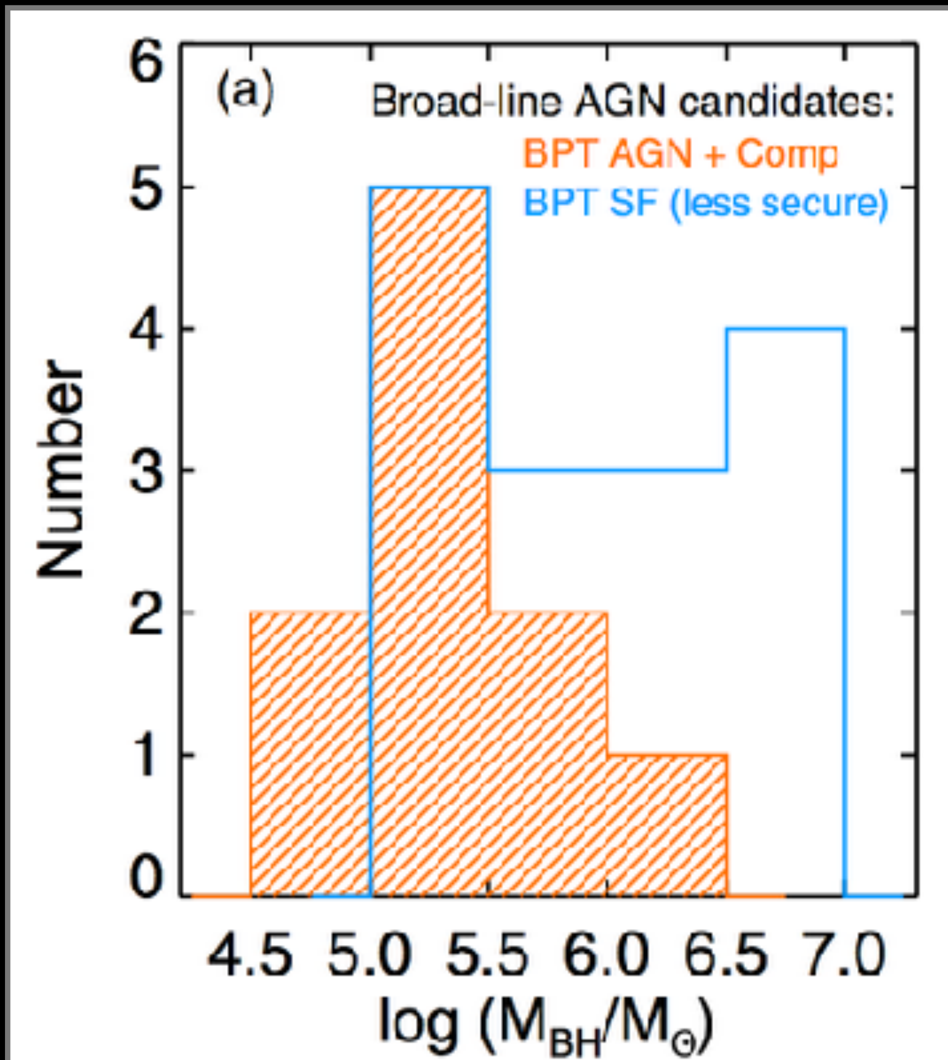

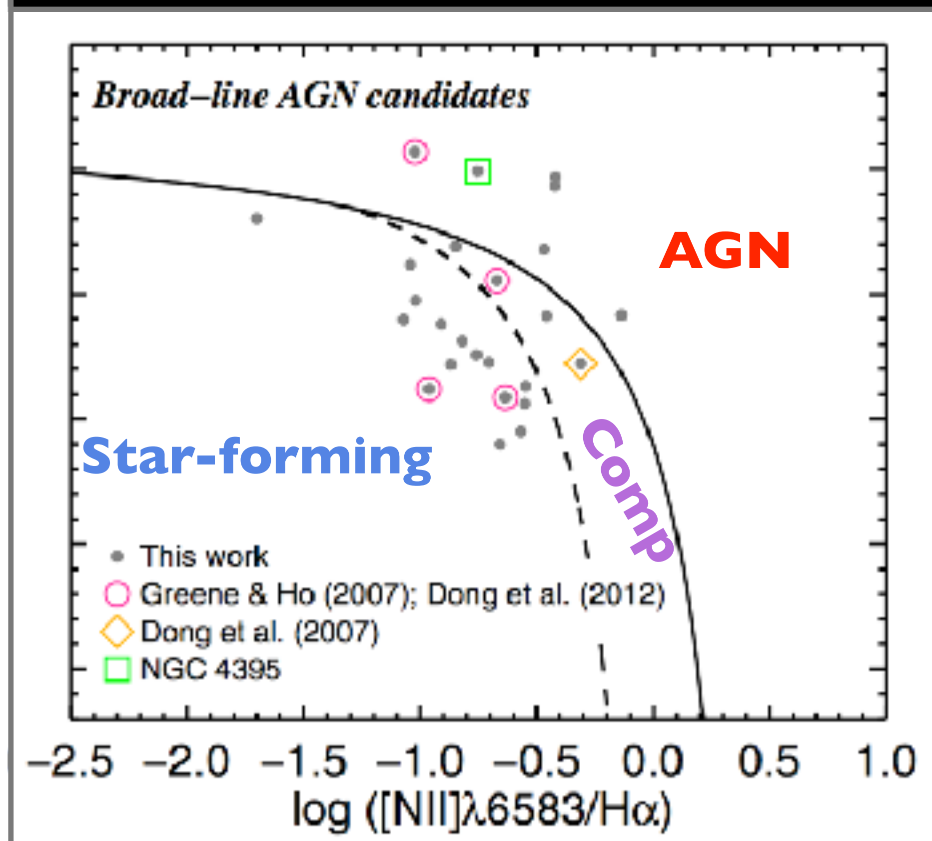

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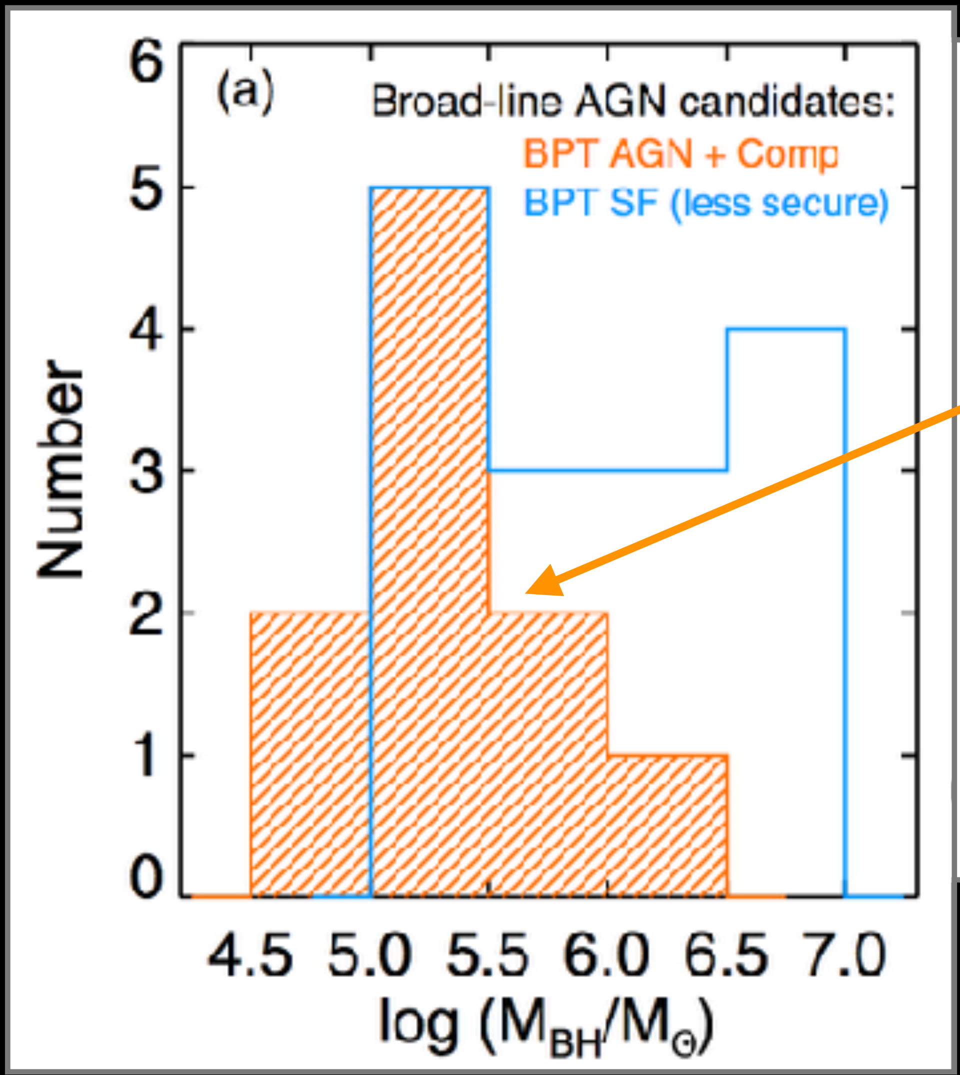

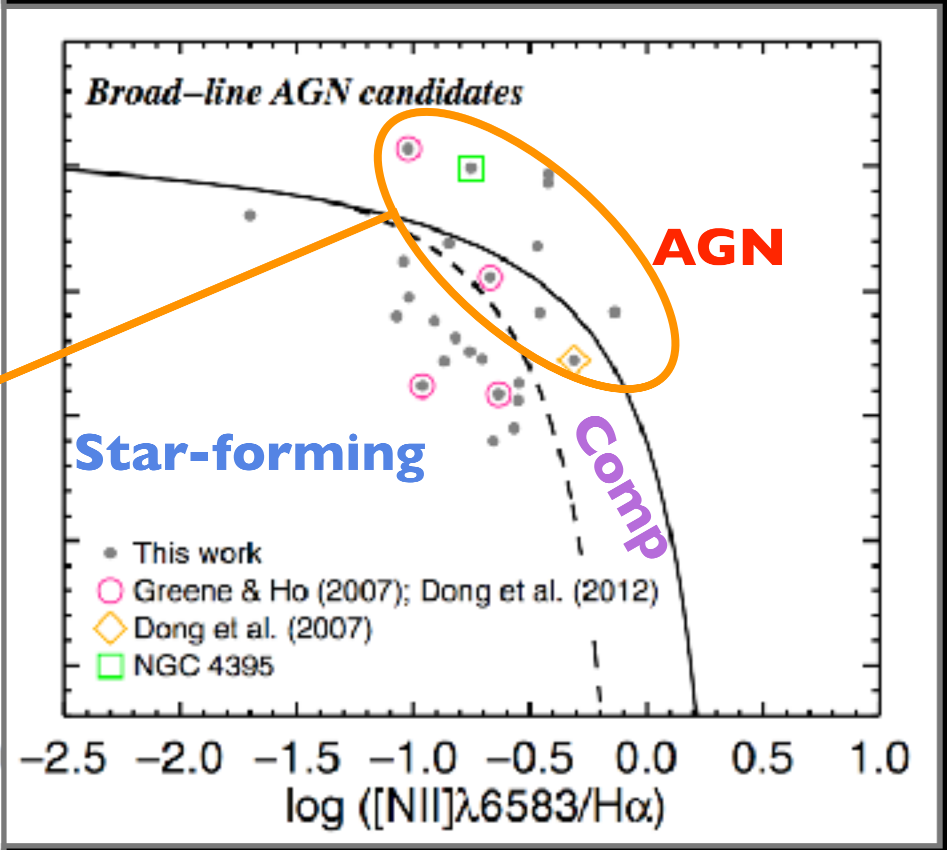

Least-massive black holes known

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

(also see RGG 118; Baldassare, Reines et al. 2015)

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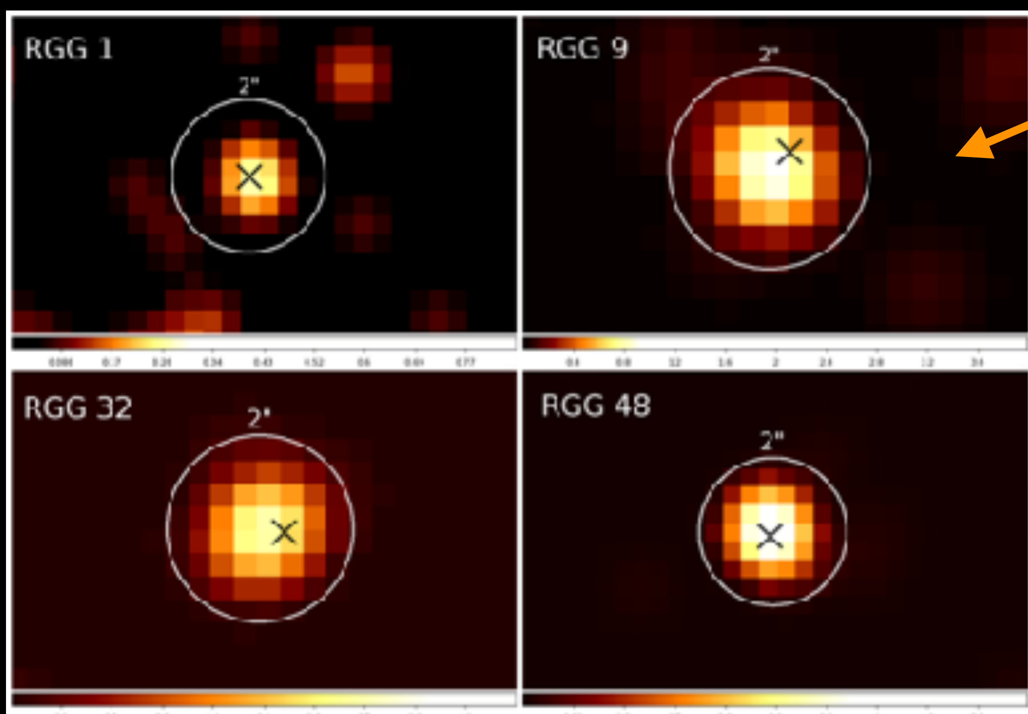
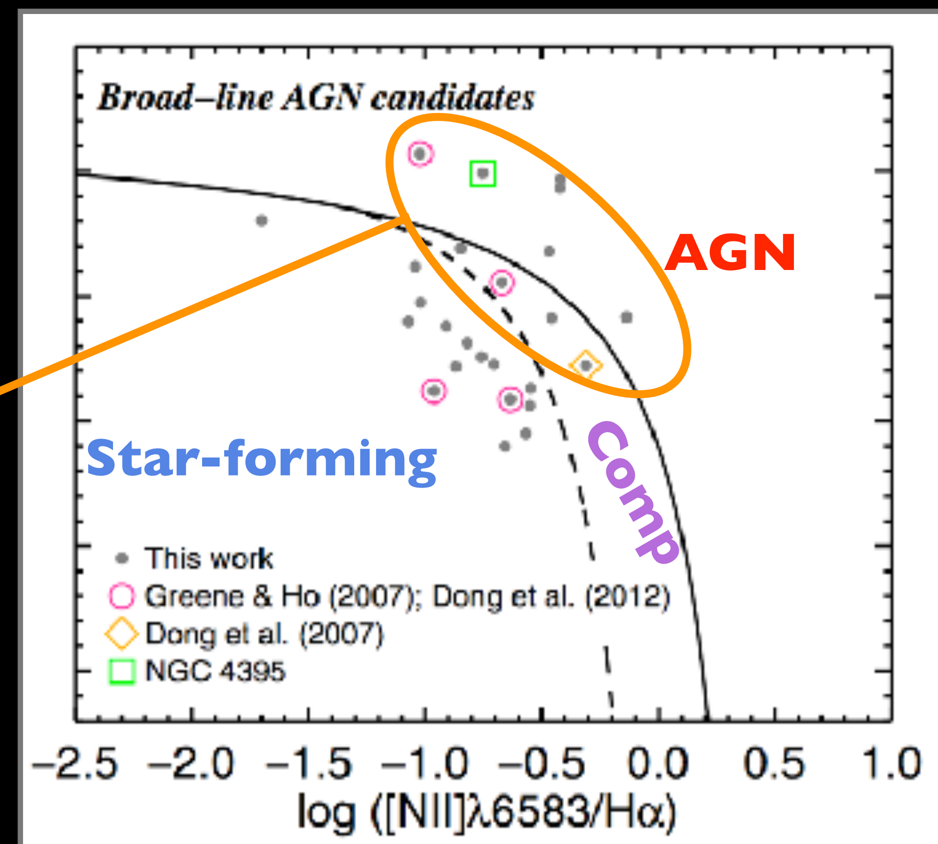
First systematic search for AGN in dwarf galaxies (Reines et al. 2013)

X-ray observations confirm active massive BHs

(Baldassare, Reines et al. 2017)





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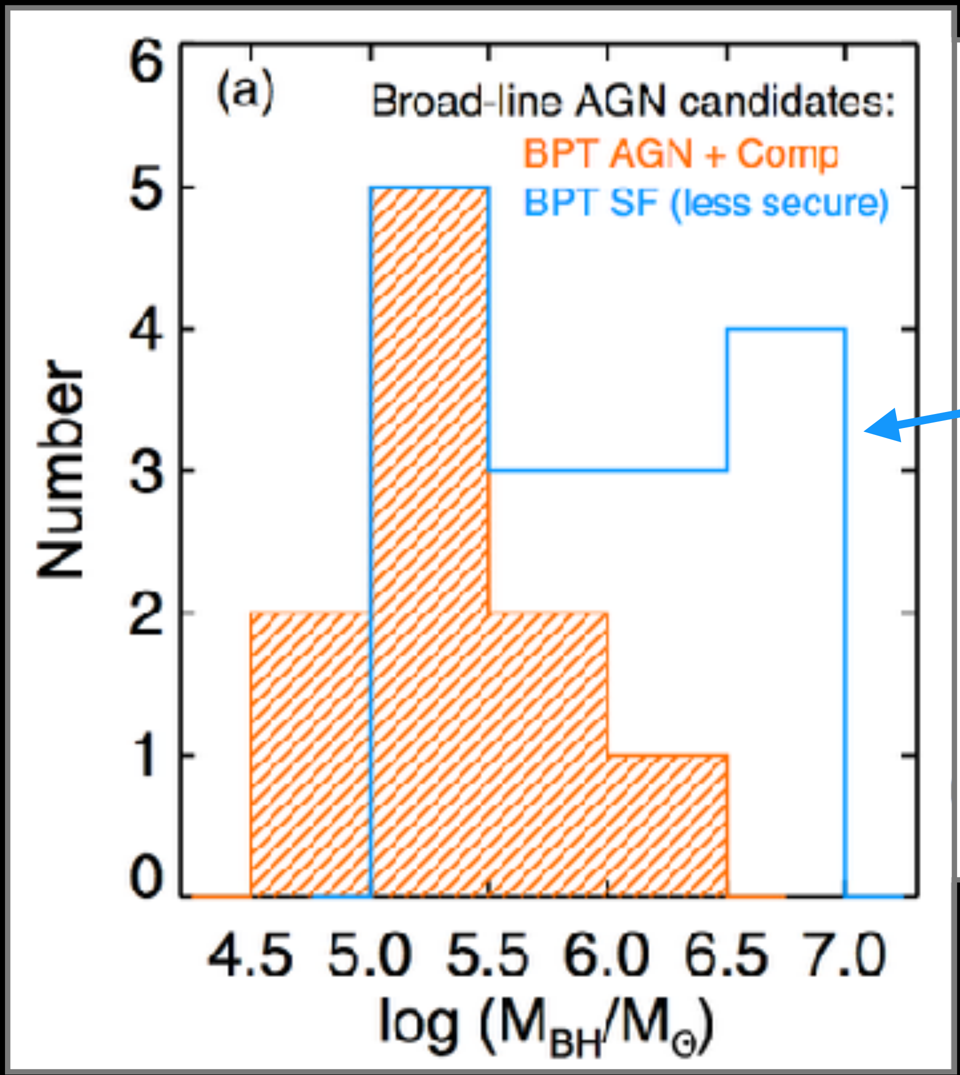

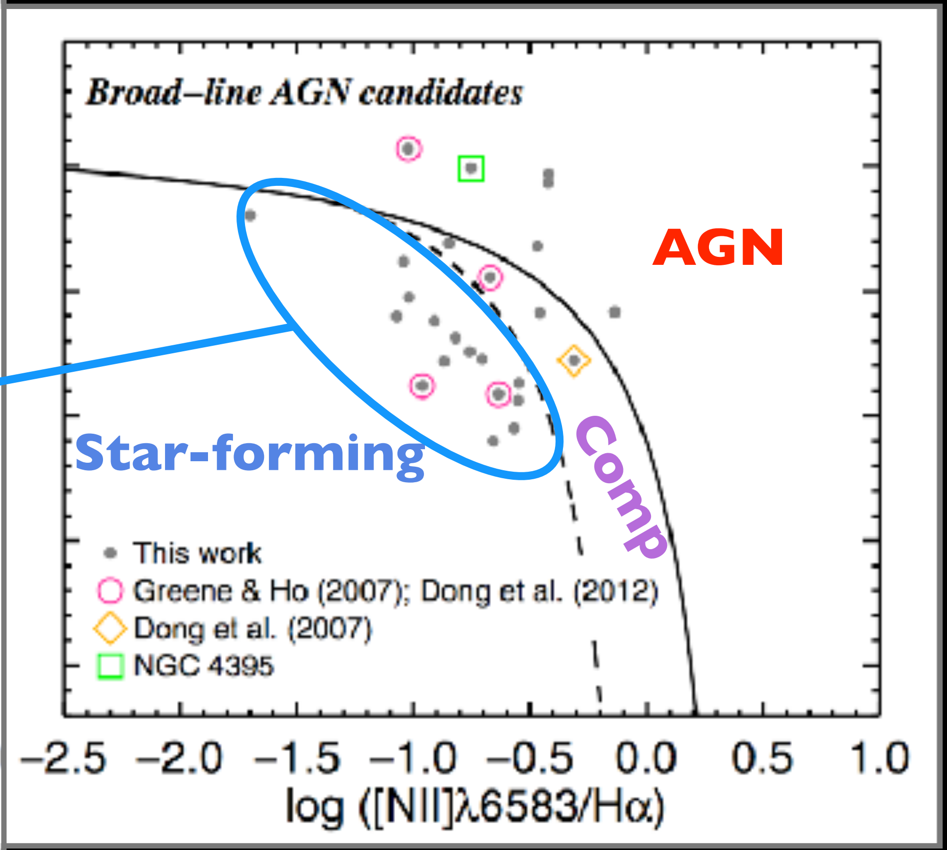

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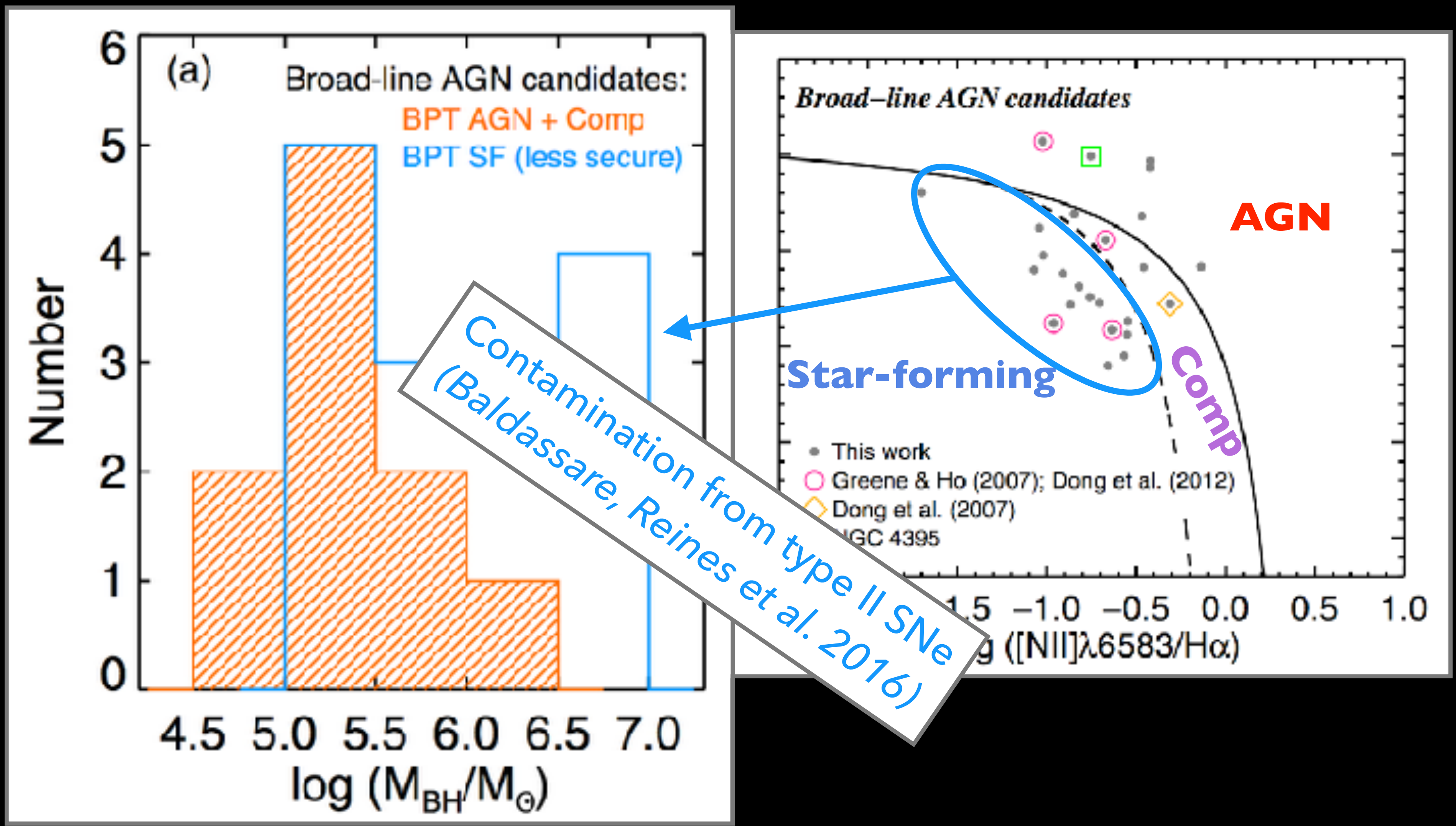

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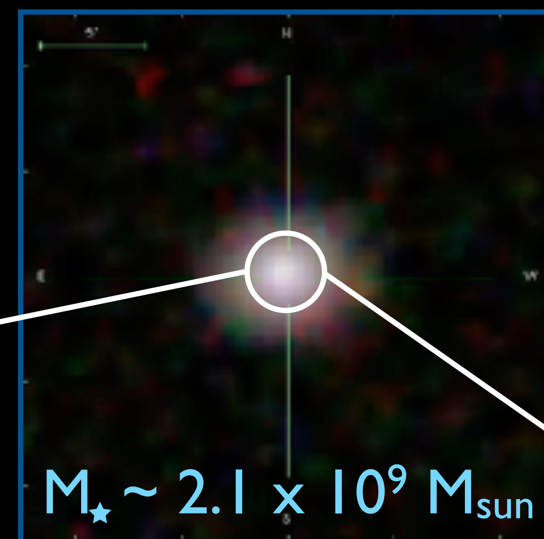
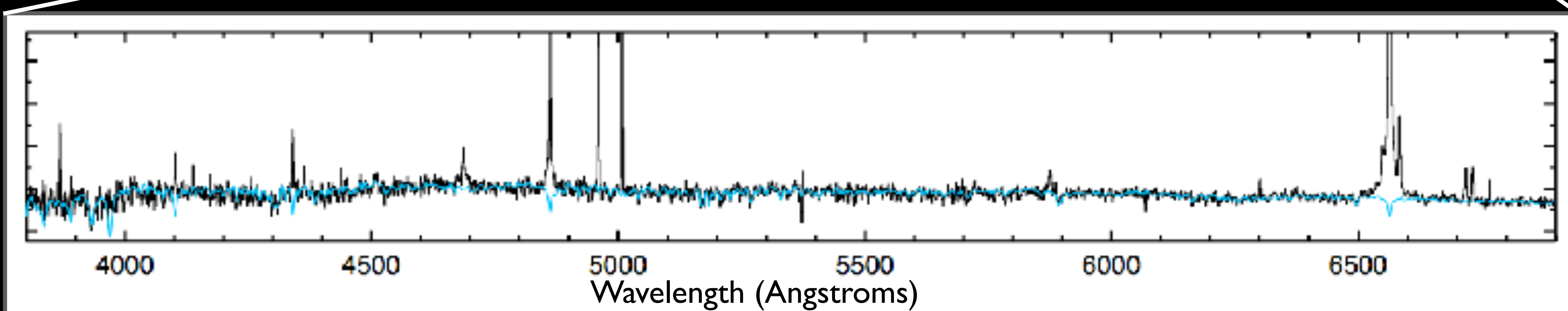
... however, only sensitive to the most actively accreting BHs in galaxies with low star formation

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





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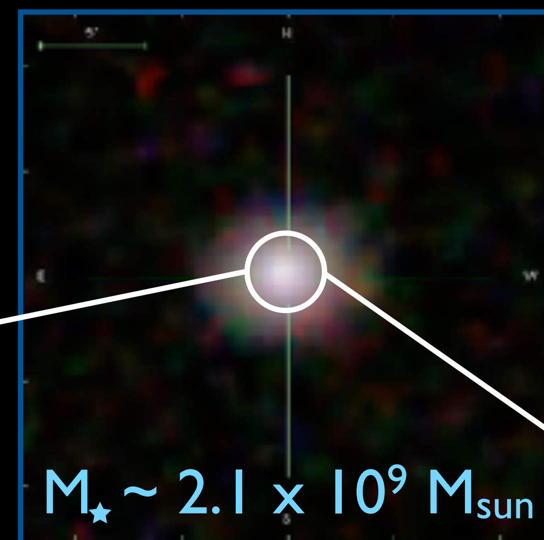
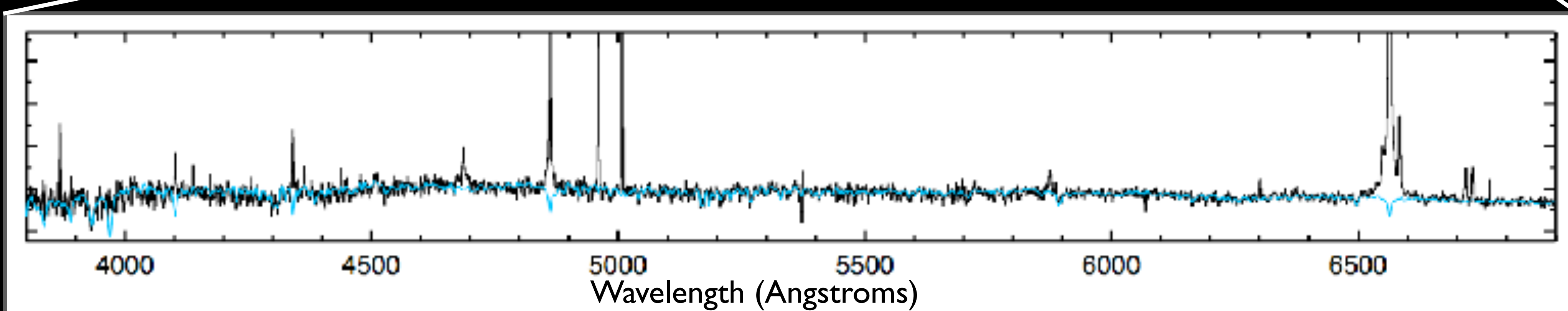
Need other diagnostics!

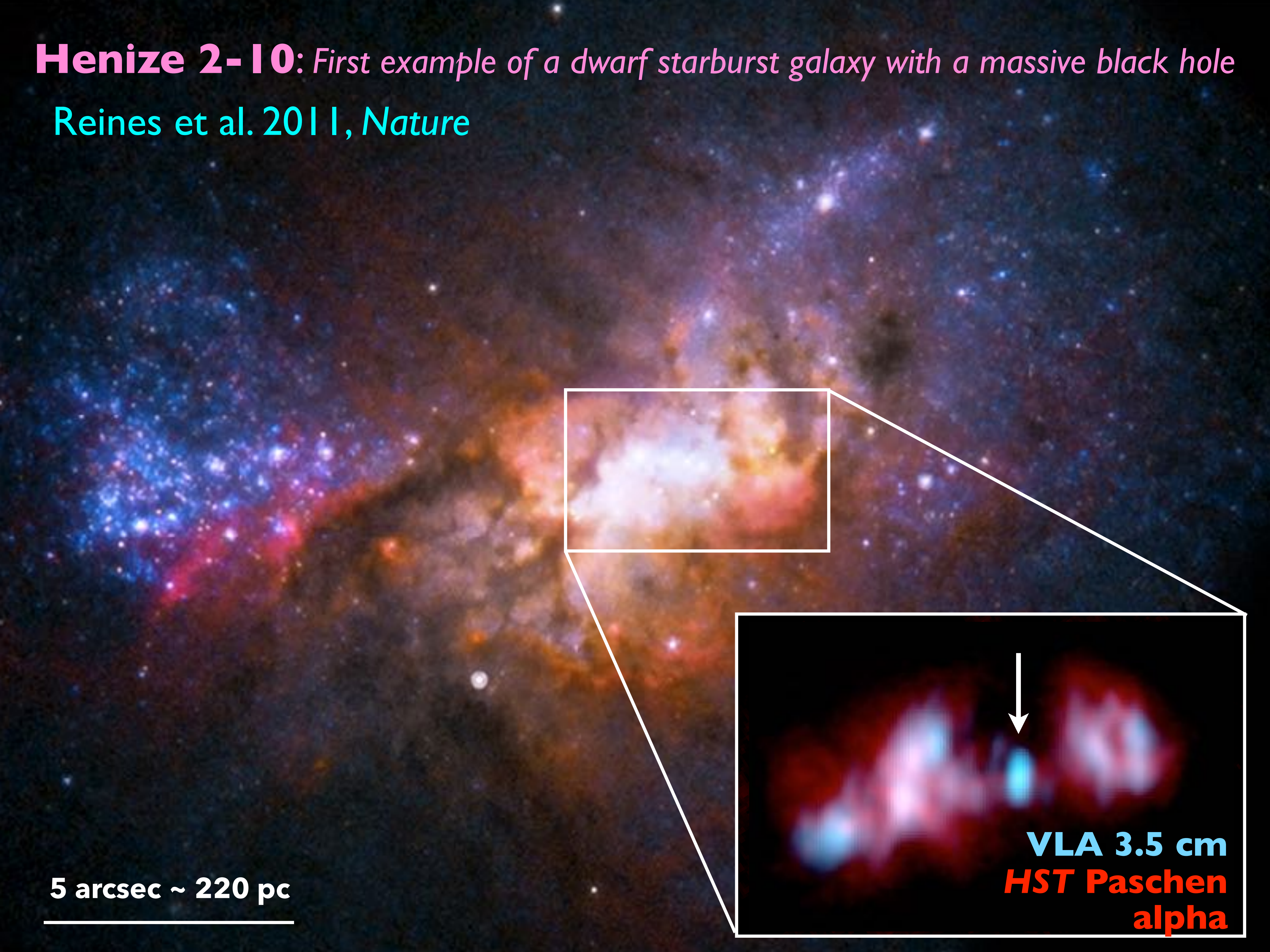




High-resolution radio + X-ray observations can reveal massive BHs in dwarf galaxies missed at optical wavelengths

- Improve our understanding of the demographics of BHs in dwarf galaxies
- Probes a different parameter space (e.g., lower BH accretion rates, star-forming host galaxies)
- Beware of X-ray binaries and supernova remnants

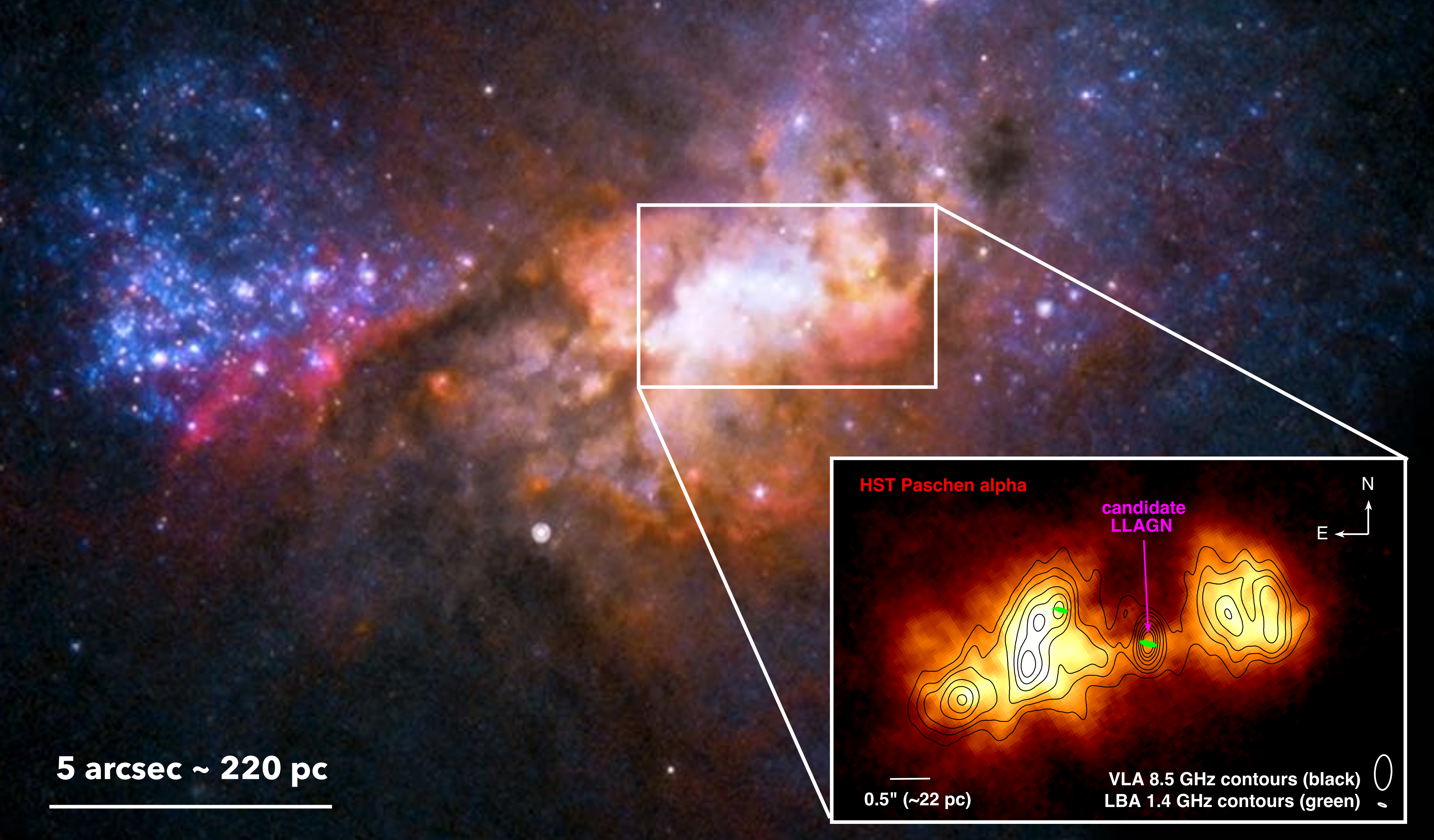

Henize 2-10: *First example of a dwarf starburst galaxy with a massive black hole*
Reines et al. 2011, *Nature*
5 arcsec ~ 220 pc
Optical - *HST*
Image from CXC press release

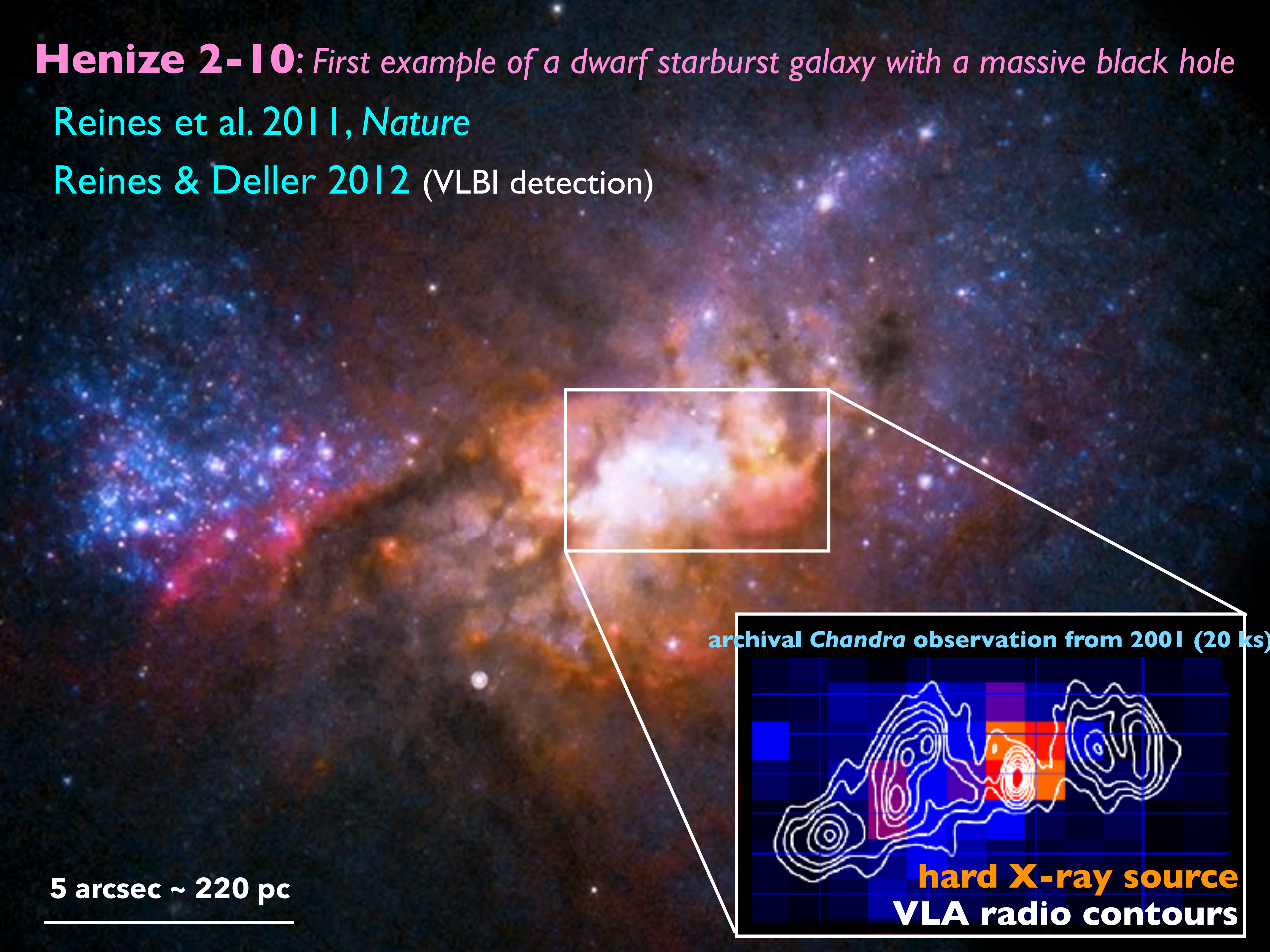

Henize 2-10: First example of a dwarf starburst galaxy with a massive black hole
Reines et al. 2011, Nature
VLA 3.5 cm
HST Paschen alpha
5 arcsec ~ 220 pc

Henize 2-10: *First example of a dwarf starburst galaxy with a massive black hole*

Reines et al. 2011, *Nature*

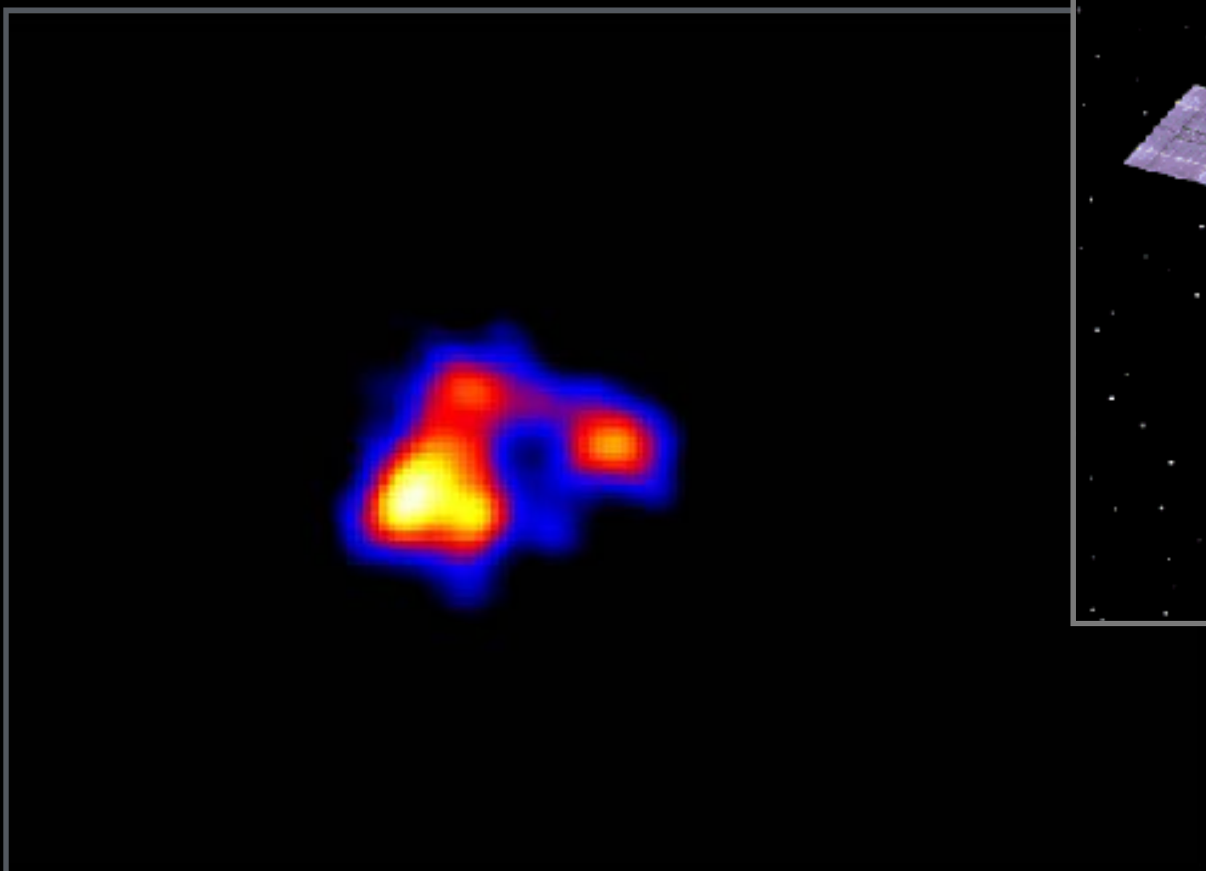
Reines & Deller 2012 (VLBI detection)




Henize 2-10: First example of a dwarf starburst galaxy with a massive black hole
Reines et al. 2011, Nature
Reines & Deller 2012 (VLBI detection)
archival Chandra observation from 2001 (20 ks)
hard X-ray source
VLA radio contours
5 arcsec ~ 220 pc

X-rays from the massive black hole in Henize 2-10

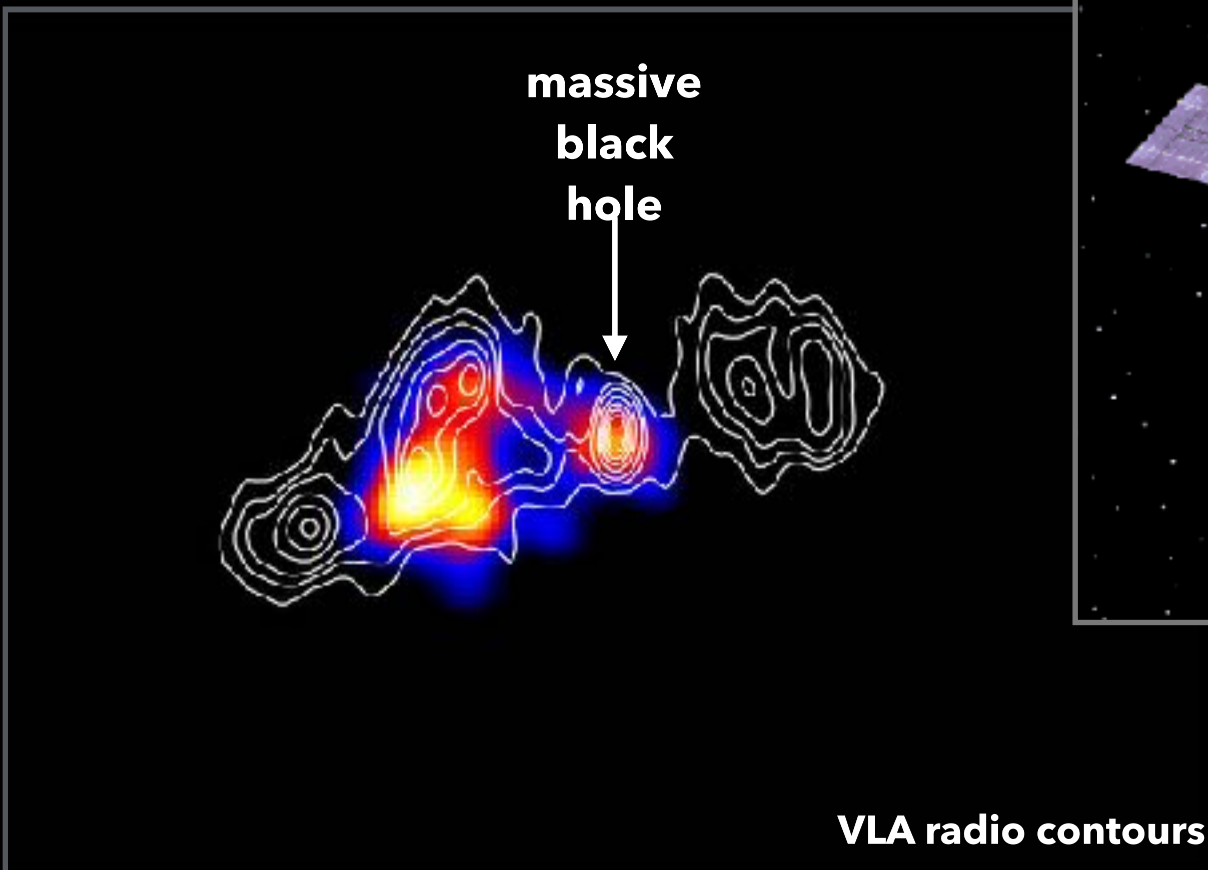
New *Chandra* observations (200 ks)



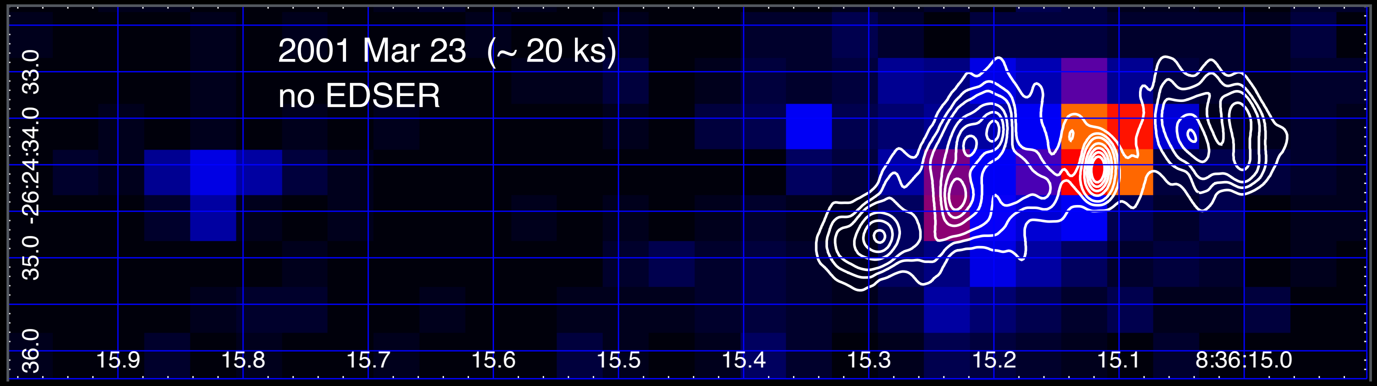
Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

New *Chandra* observations (200 ks)



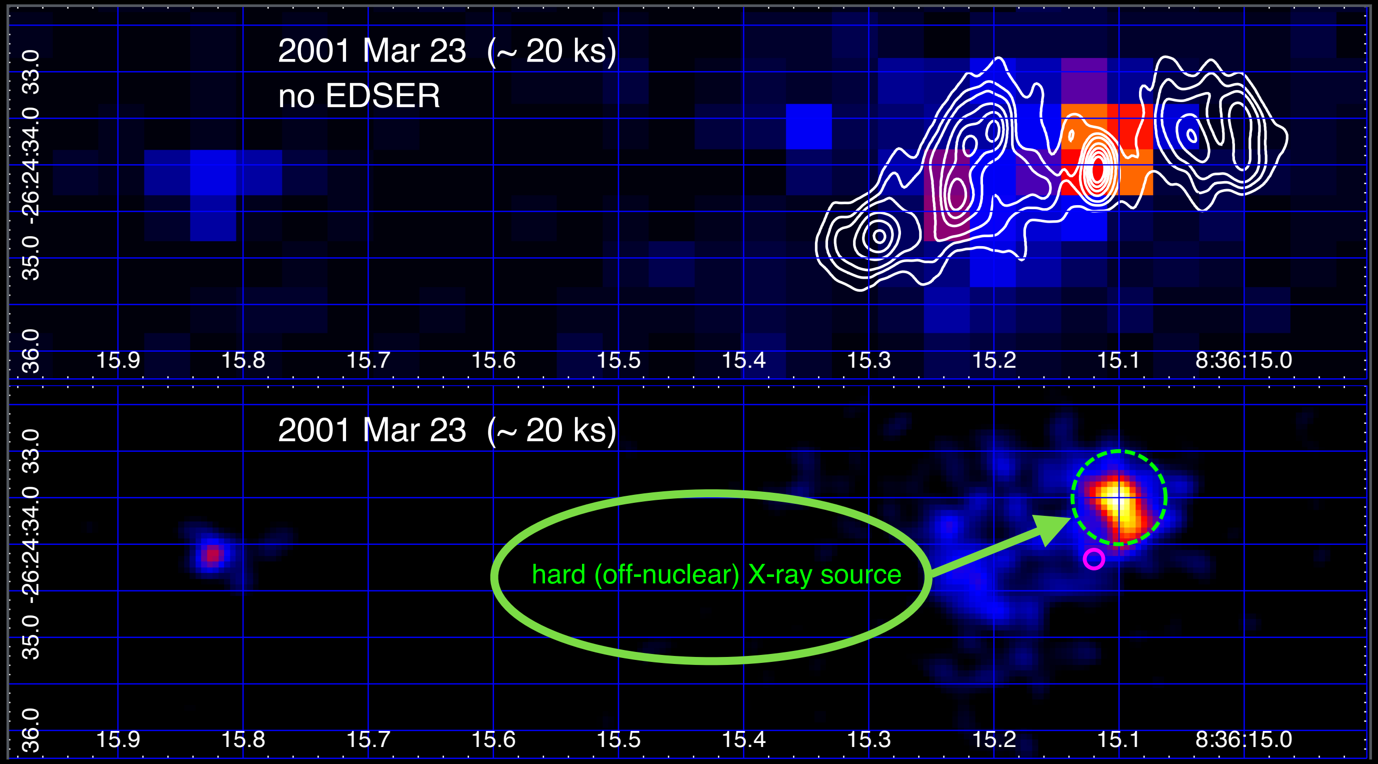
Reines, Reynolds et al. 2016
ApJ Letters, 830, 35



Chandra observations of Henize 2-10

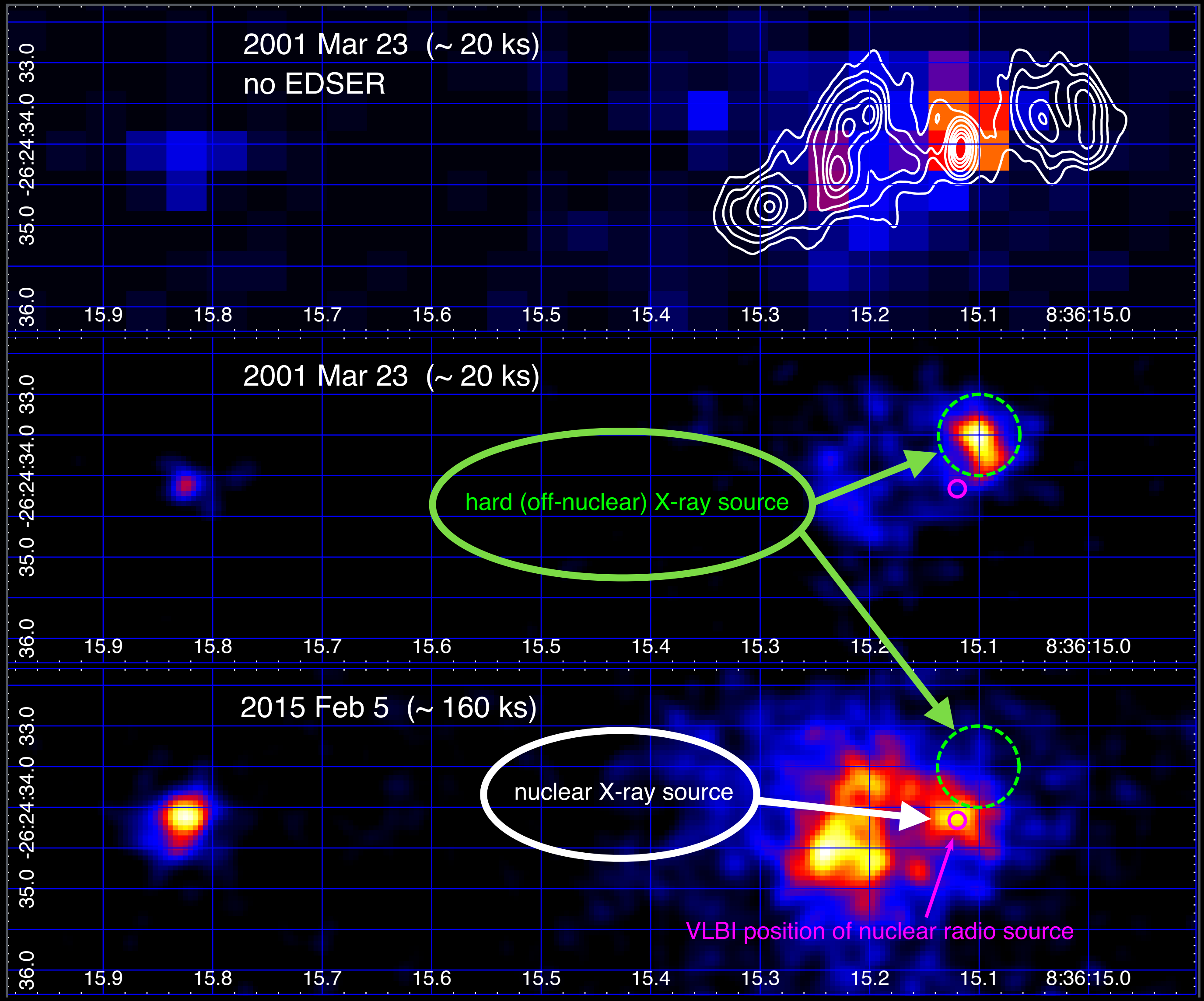
Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

Chandra observations of Henize 2-10



Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

Chandra observations of Henize 2-10

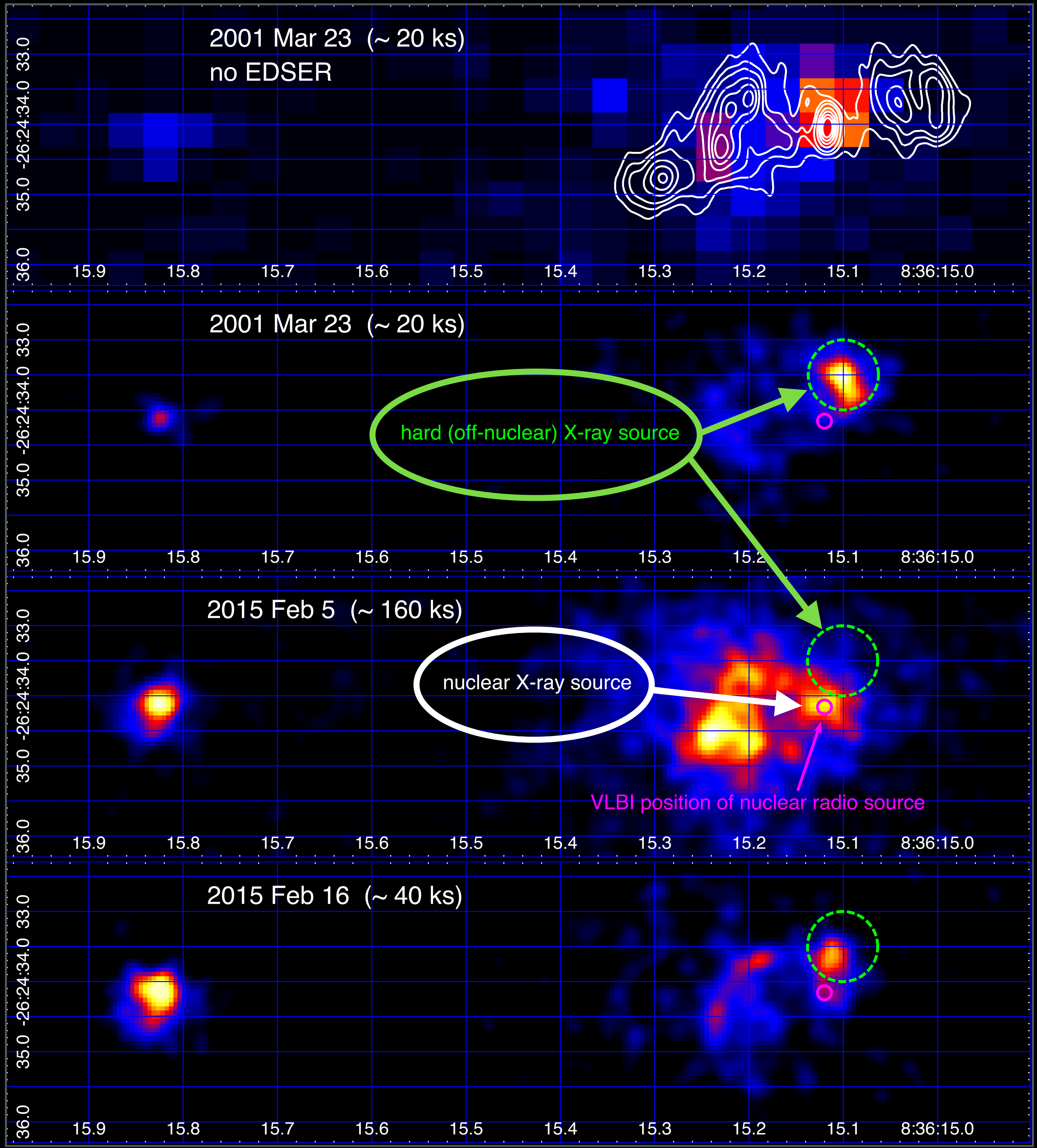


(not on the same count rate scale)

Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

Chandra observations of Henize 2-10

(not on the same count rate scale)



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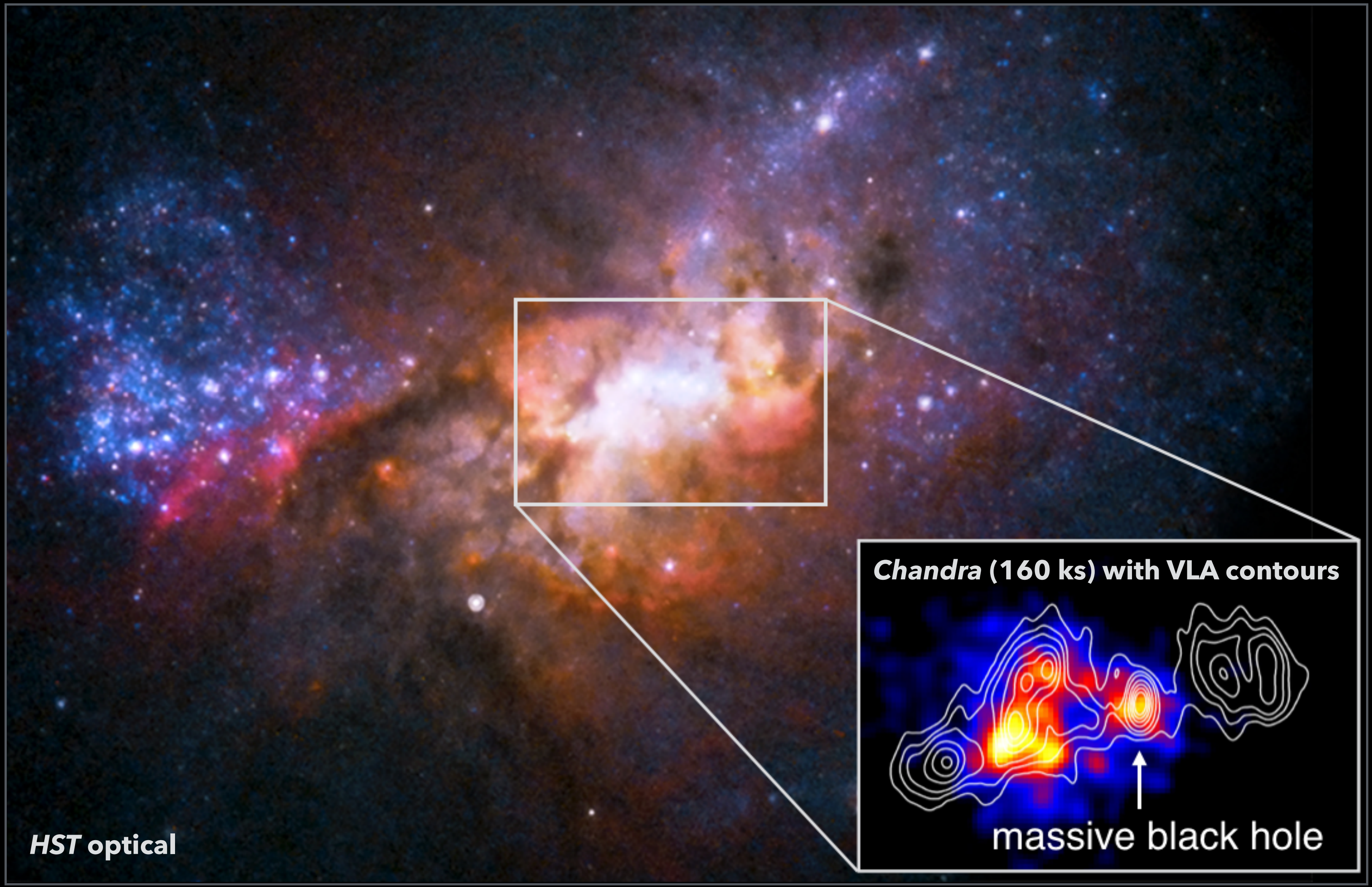
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10



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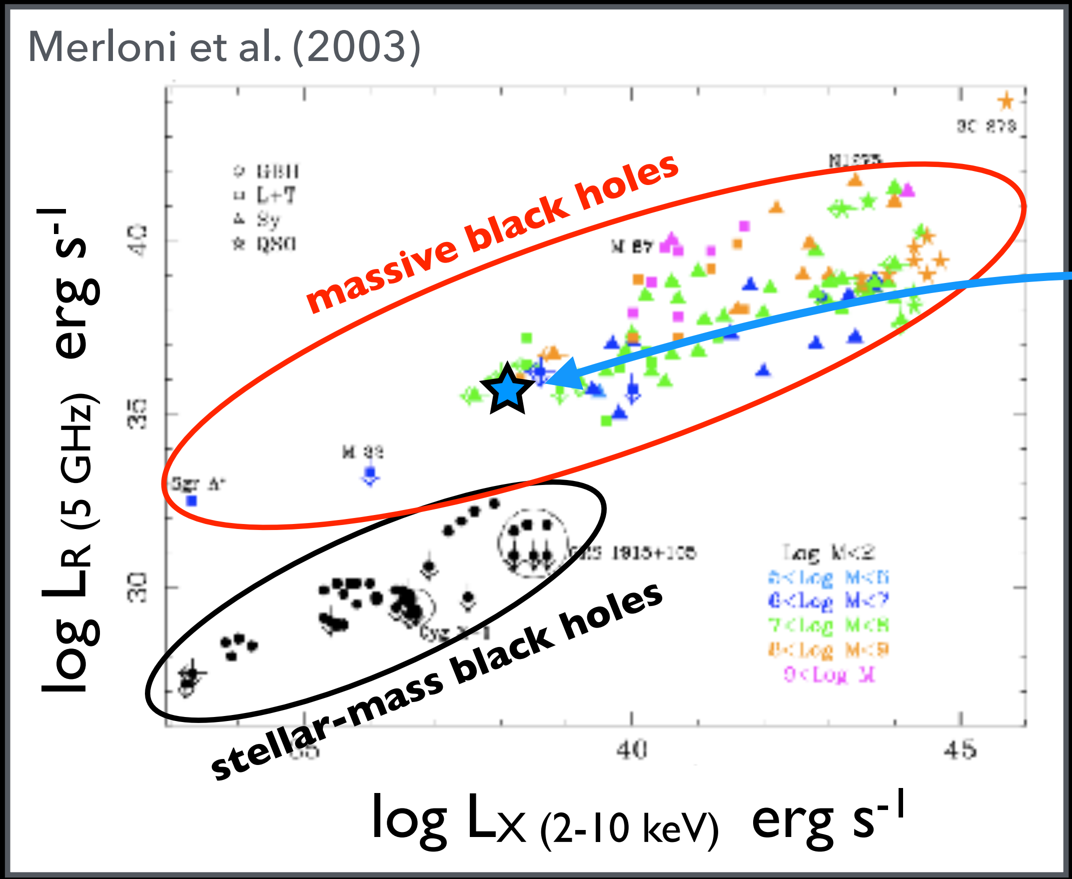
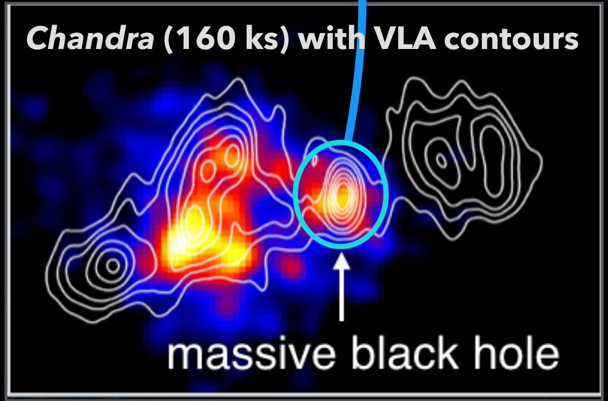
X-rays from the massive black hole in Henize 2-10



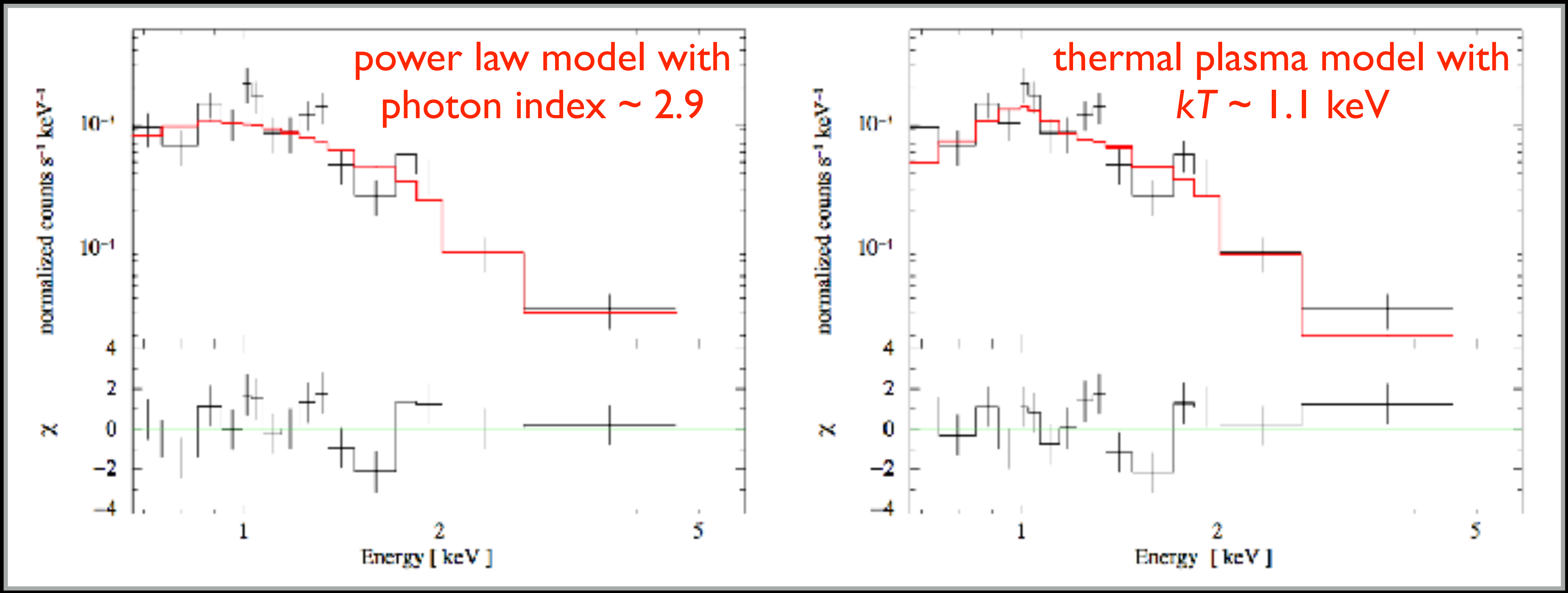


- $L_R \sim 4 \times 10^{35}$ erg s^{-1}
- $L_X \sim 10^{38}$ erg s^{-1}

Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

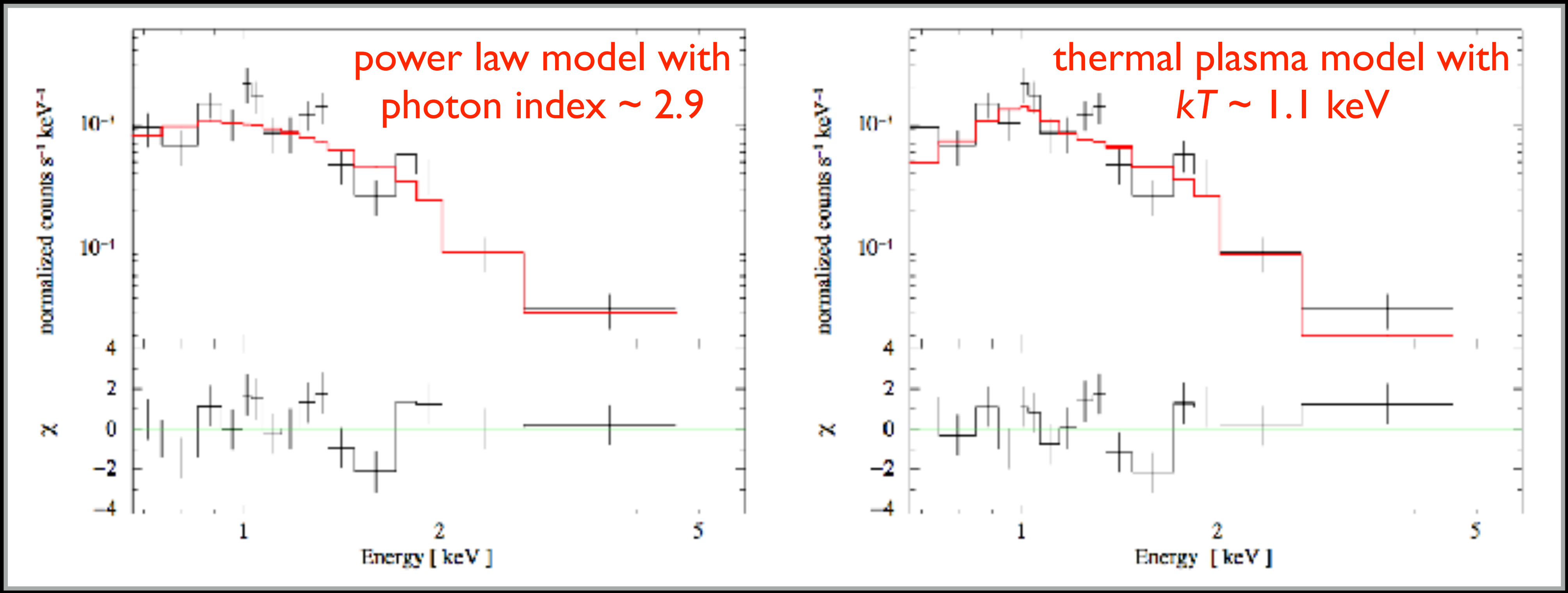
X-ray spectrum of the nucleus



Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

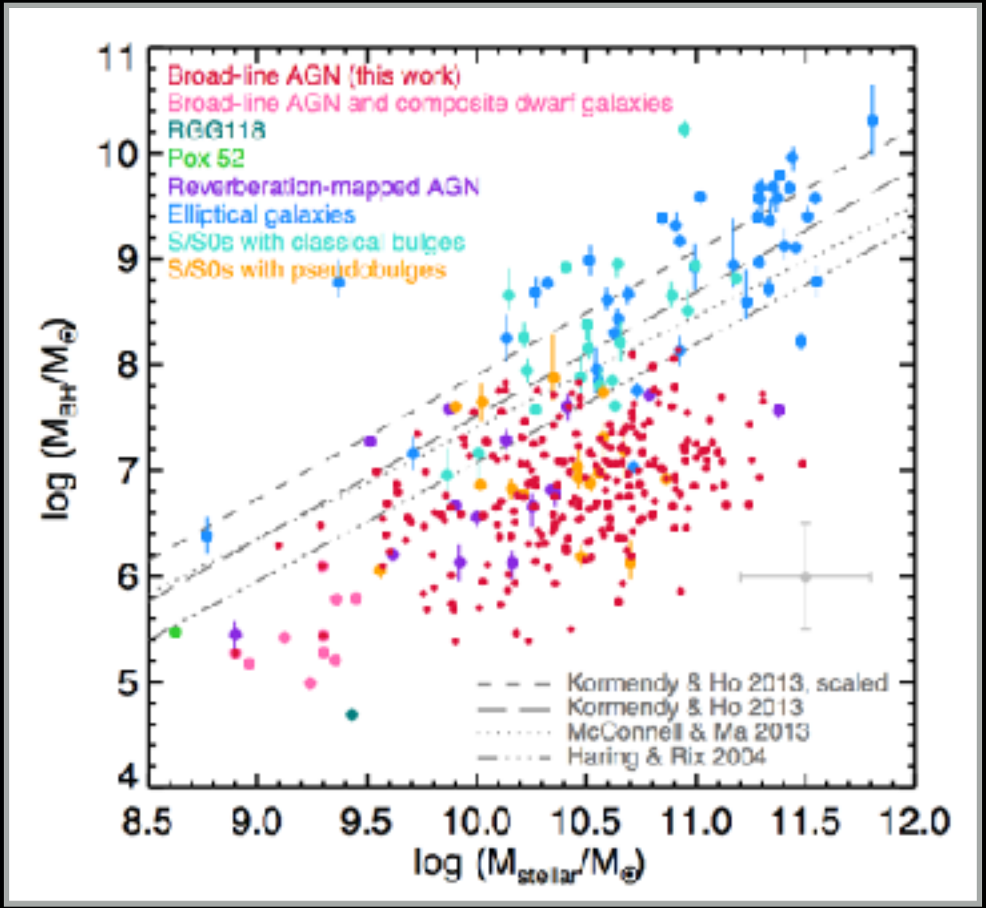
X-ray spectrum of the nucleus



- $L_{0.3\text{-}10\ \mathrm{keV}} \sim 10^{38}$ erg s^{-1}
- BH is radiating significantly below its Eddington luminosity

Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10



Reines & Volonteri (2015)

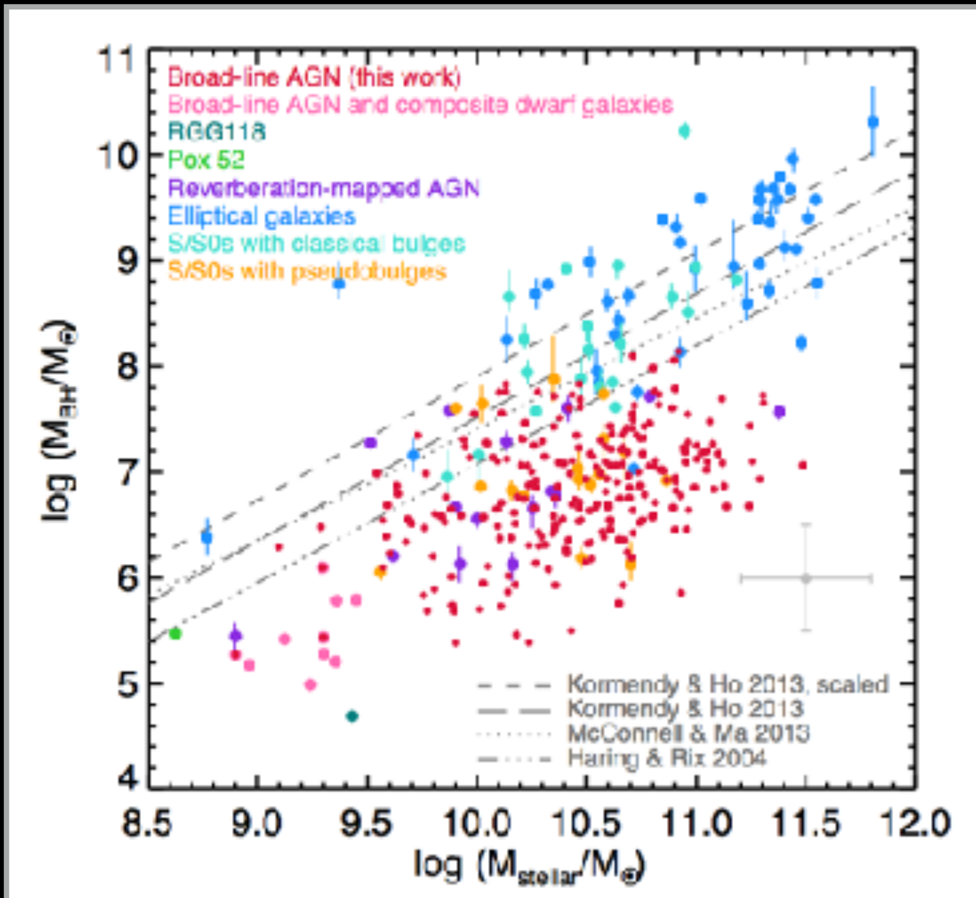
Scaling between BH mass and galaxy total stellar mass

⟶ $\mathbf{M_{BH} \sim 3 \times 10^6\ M_{sun}}$

- $L_{0.3\text{-}10\ \mathrm{keV}} \sim 10^{38}$ erg s^{-1}
- BH is radiating significantly below its Eddington luminosity

Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10



Reines & Volonteri (2015)

Scaling between BH mass and galaxy total stellar mass

→ **M_{BH} ~ 3 x10^6 M_{sun}**

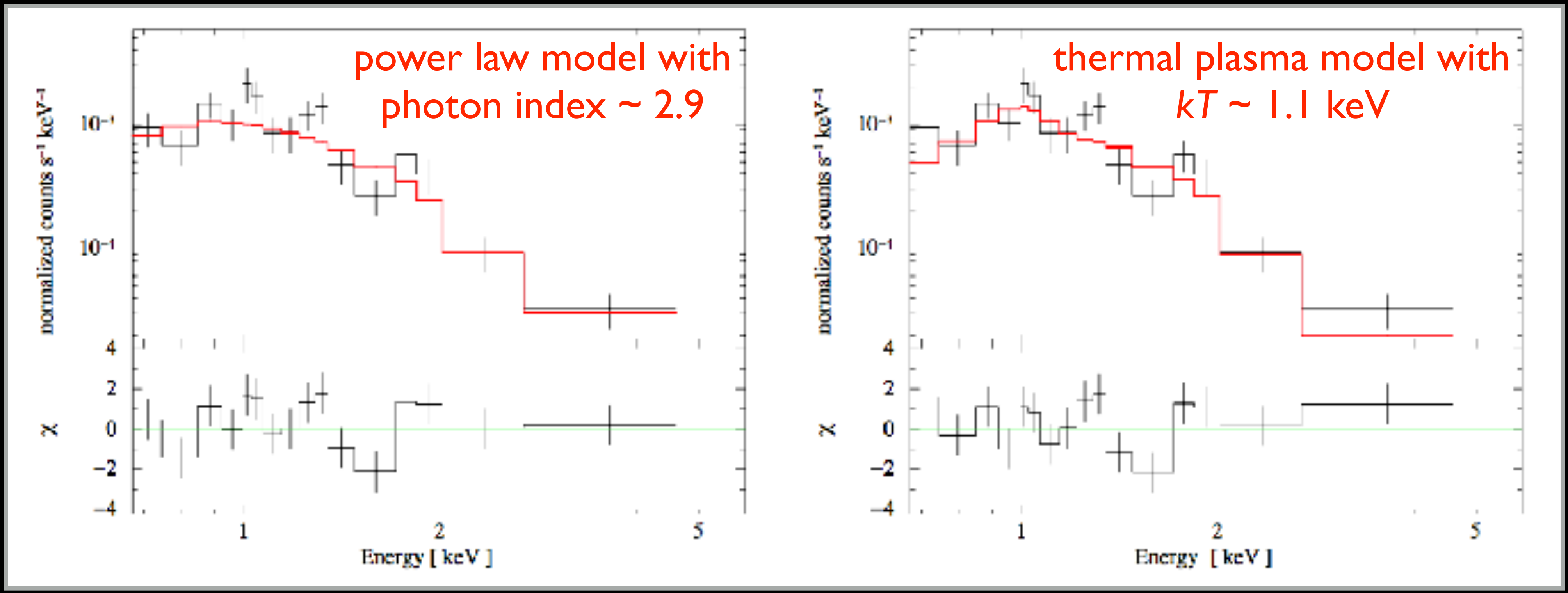
→ **L_{BH}~10^{-6} L_{Edd}**

- $L_{0.3\text{-}10\ keV}$ ~ 10^{38} erg s^{-1}
- BH is radiating significantly below its Eddington luminosity

Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

Soft spectrum resembles other weakly accreting massive BHs, including Sagittarius A* (e.g., Baganoff et al. 2003; Constantin et al. 2009, Gultekin et al. 2012)

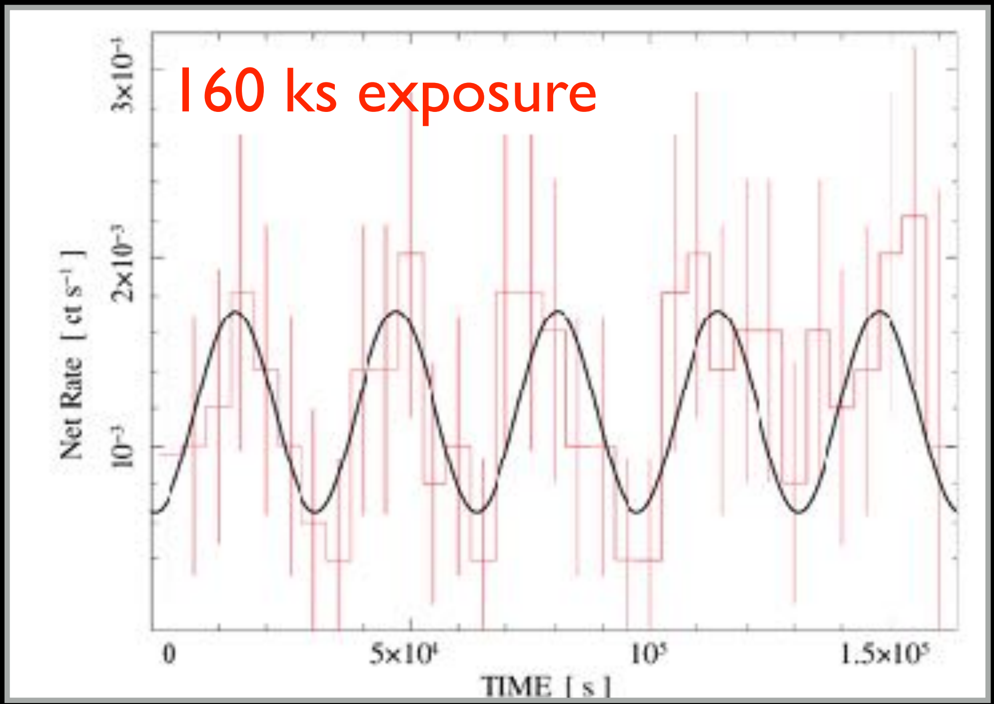


- $L_{0.3\text{-}10\ \mathrm{keV}} \sim 10^{38}$ erg s^{-1}
- BH is radiating significantly below its Eddington luminosity

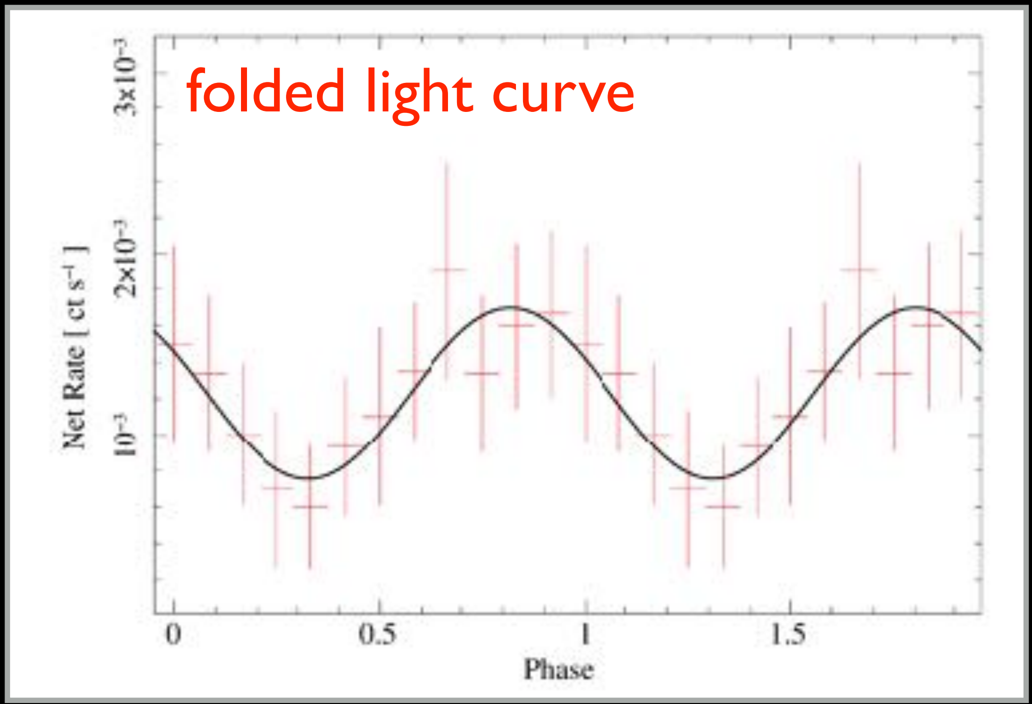
Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

Variability on hour-long timescales



Light curve with
best-fit sine model
(P = 33.5 ks = 9.3 hrs)



Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

Variability on hour-long timescales

Possible origins for a ~9-hr periodicity:

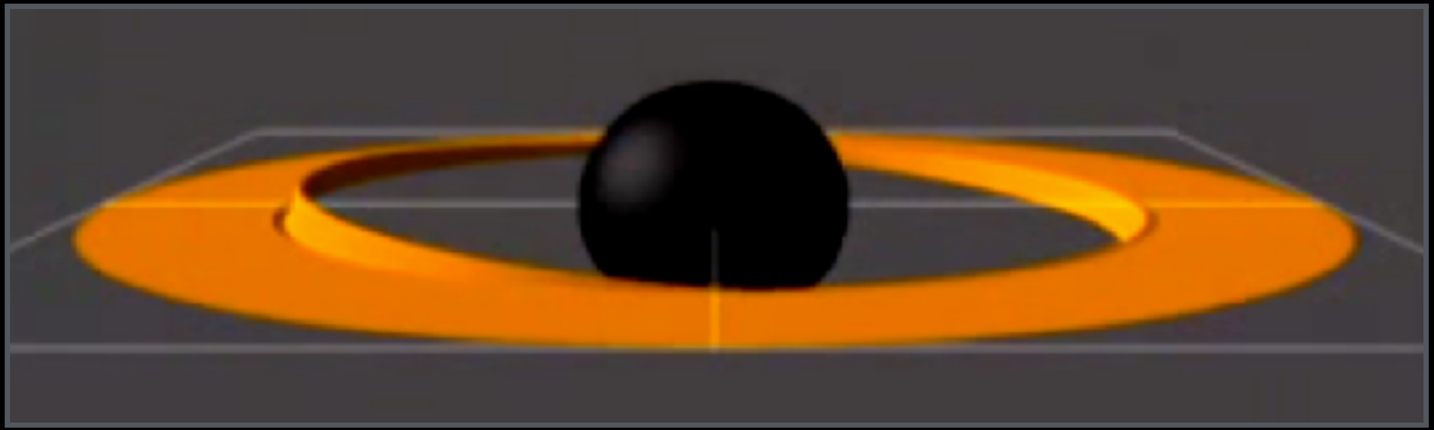
Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

Variability on hour-long timescales

Possible origins for a ~9-hr periodicity:

- **Most likely origin is a *low-frequency QPO* in the accretion flow**



Lense-Thirring precession - vertical wobbling due to frame dragging

Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

X-rays from the massive black hole in Henize 2-10

Variability on hour-long timescales

Possible origins for a ~9-hr periodicity:

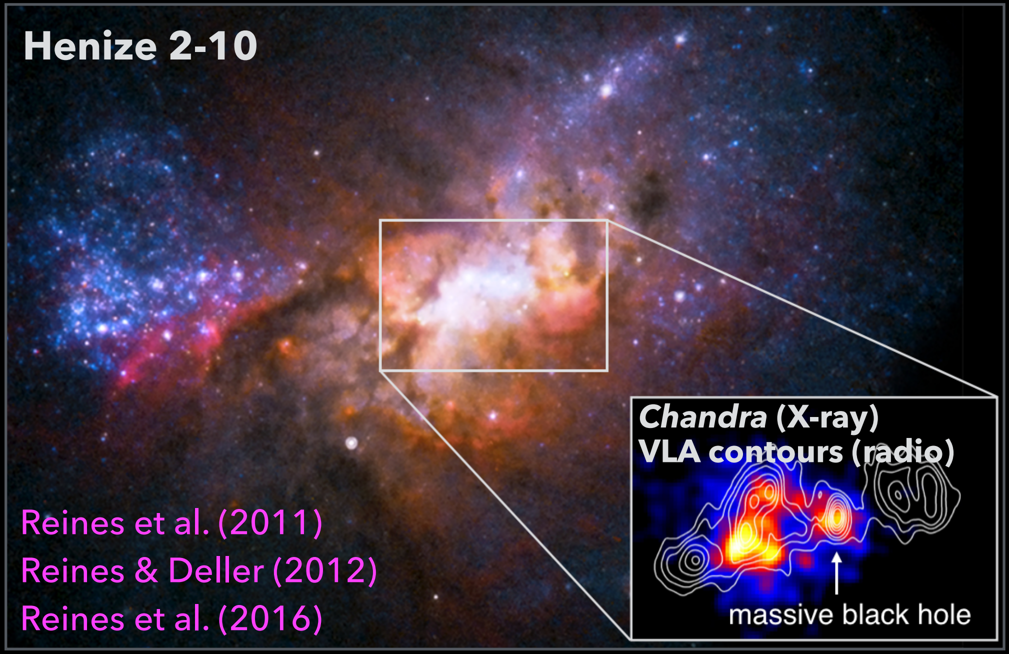
- **Most likely origin is a *low-frequency QPO* in the accretion flow**

- *High-frequency QPO*:
  unlikely given the BH mass implied by the observed frequency (~10^8 Msun)

- *Massive BH binary:*
  unlikely given the extremely short timescale until coalescence implied by the observed frequency (< 5 years)

Reines, Reynolds et al. 2016
ApJ Letters, 830, 35

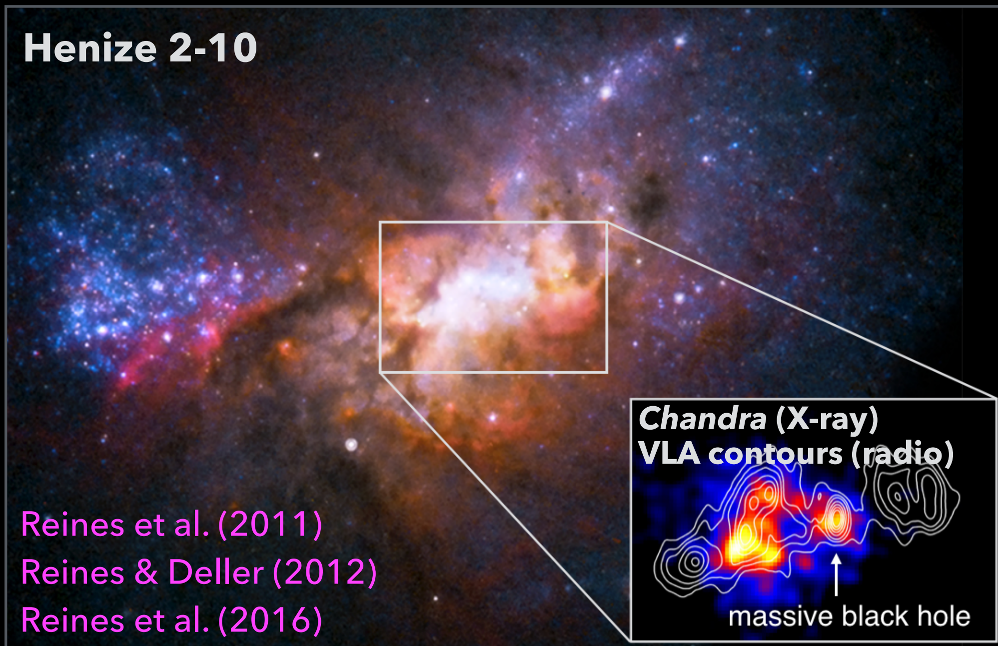
High-resolution radio + X-ray observations can reveal massive BHs in dwarf galaxies missed at optical wavelengths



Evidence for a massive black hole in Henize 2-10:

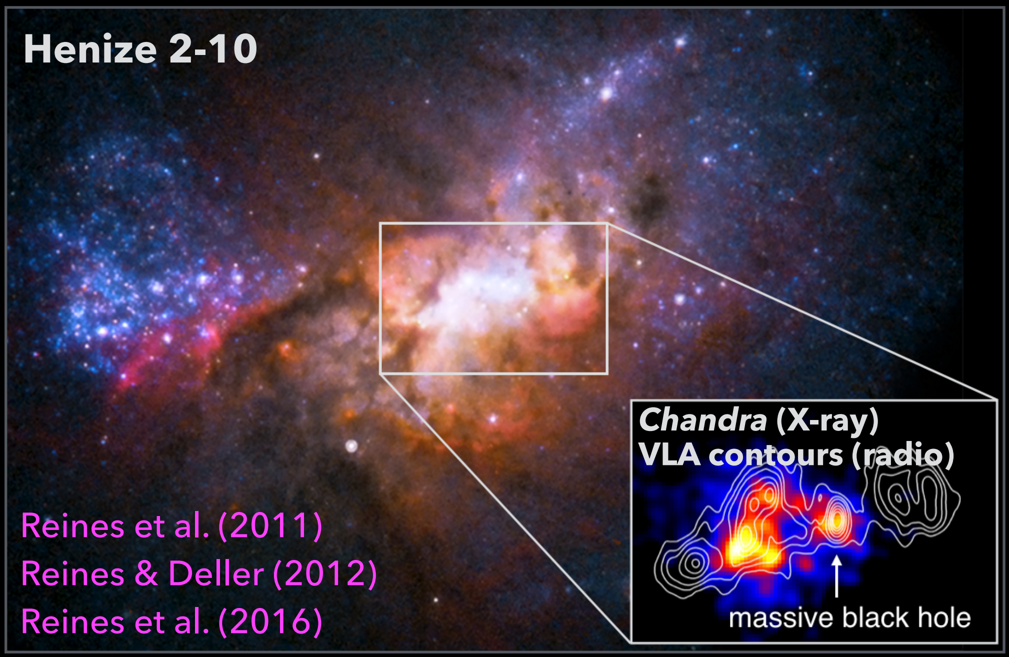
- Parsec-scale non-thermal radio core with spatially coincident X-ray source
- At center of a ~250 pc-long rotating ionized gas structure
- Much too luminous in the radio to be an X-ray binary
- X-ray variability on hour-long timescales rules out a supernova remnant

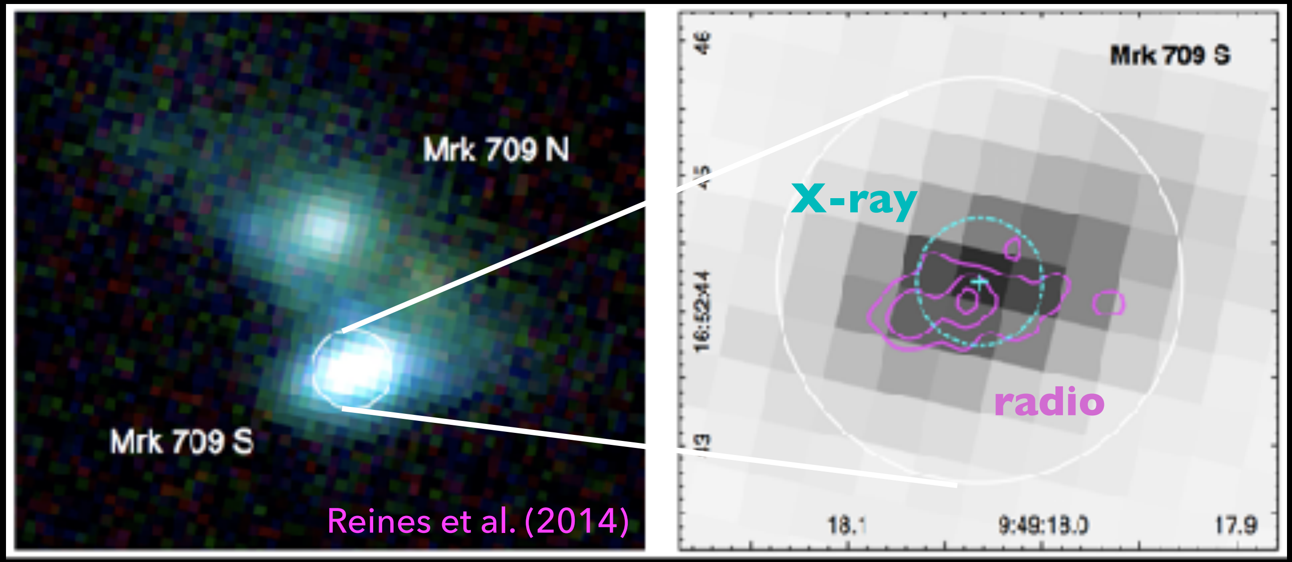
High-resolution radio + X-ray observations can reveal massive BHs in dwarf galaxies missed at optical wavelengths



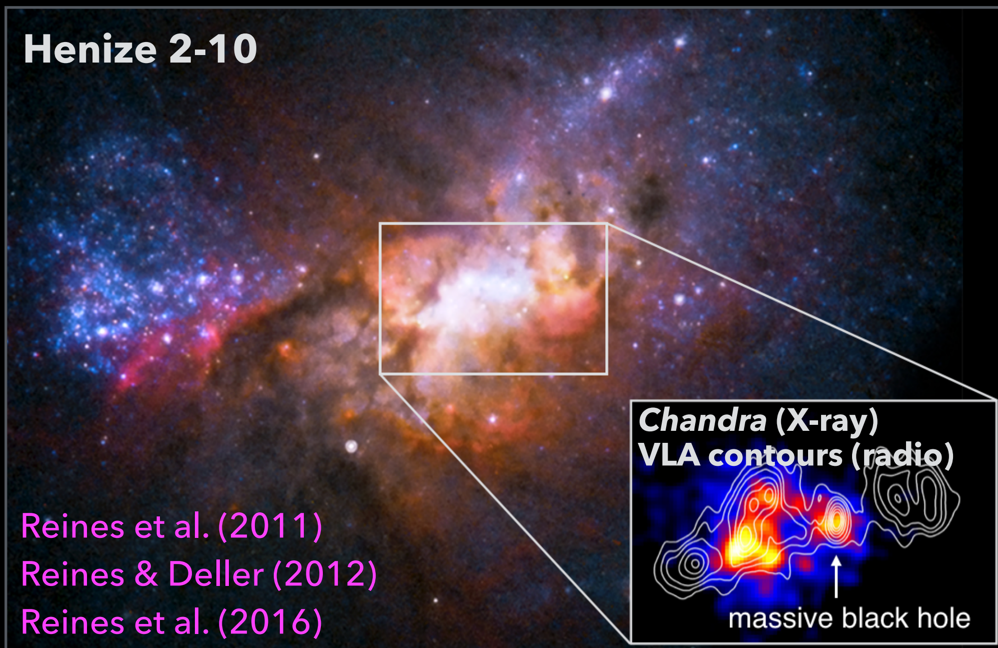
Motivation to search for additional examples of massive BHs in dwarf galaxies using high-resolution radio and X-ray observations

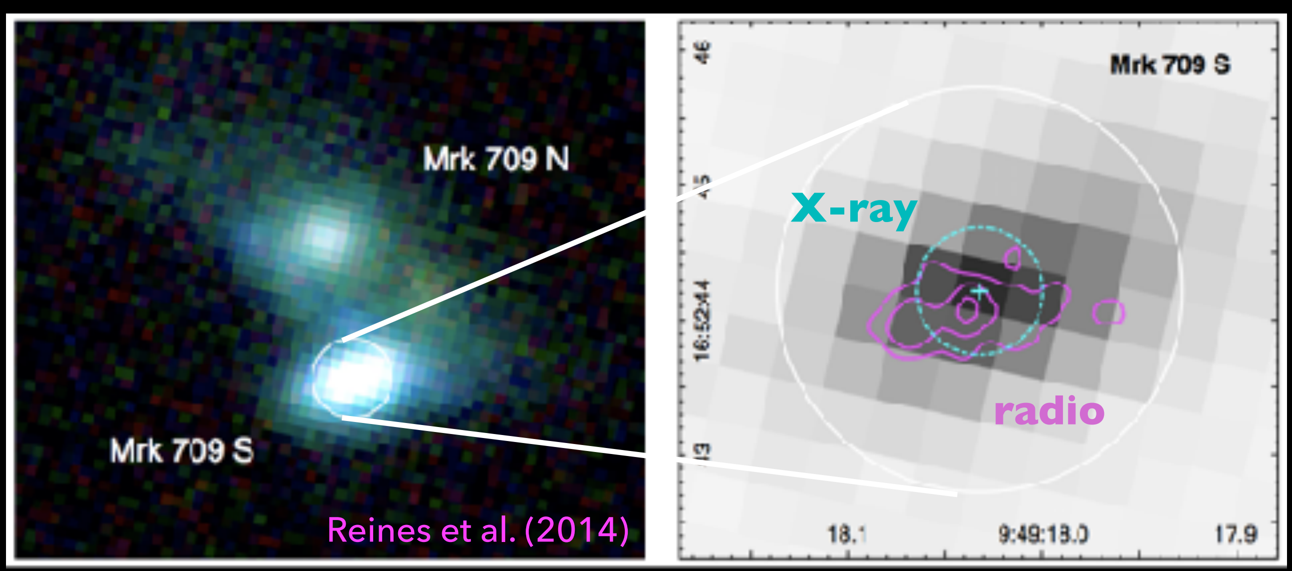
High-resolution radio + X-ray observations can reveal massive BHs in dwarf galaxies missed at optical wavelengths





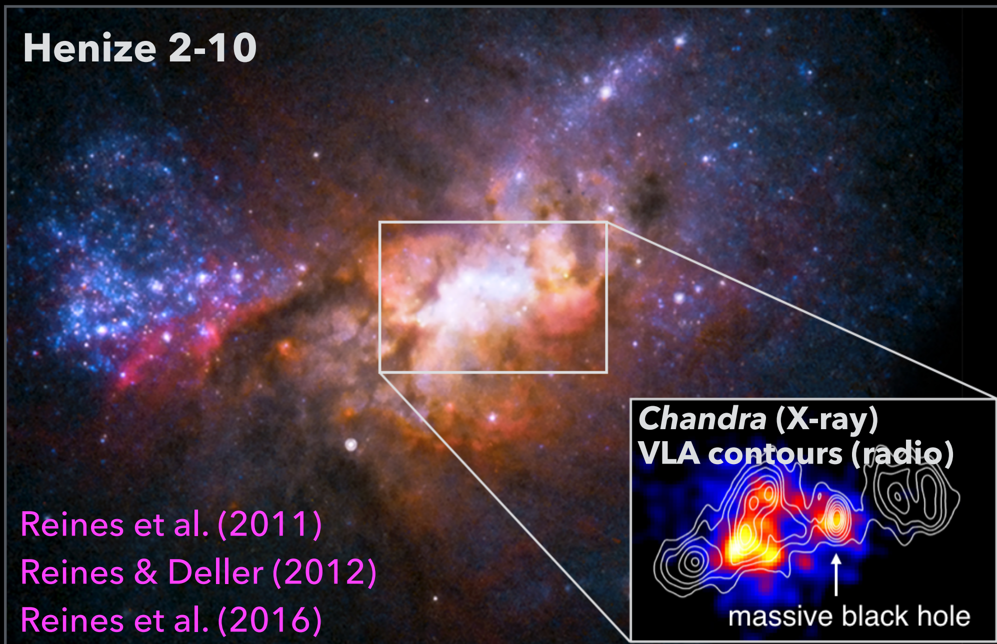
High-resolution radio + X-ray observations can reveal massive BHs in dwarf galaxies missed at optical wavelengths

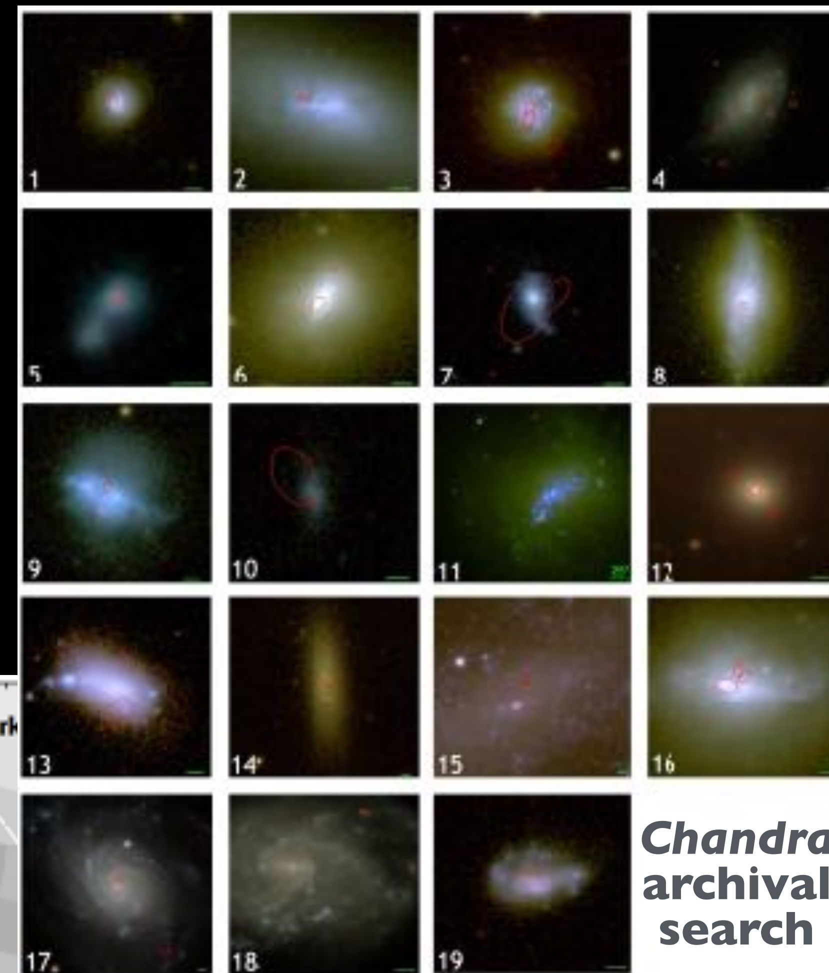




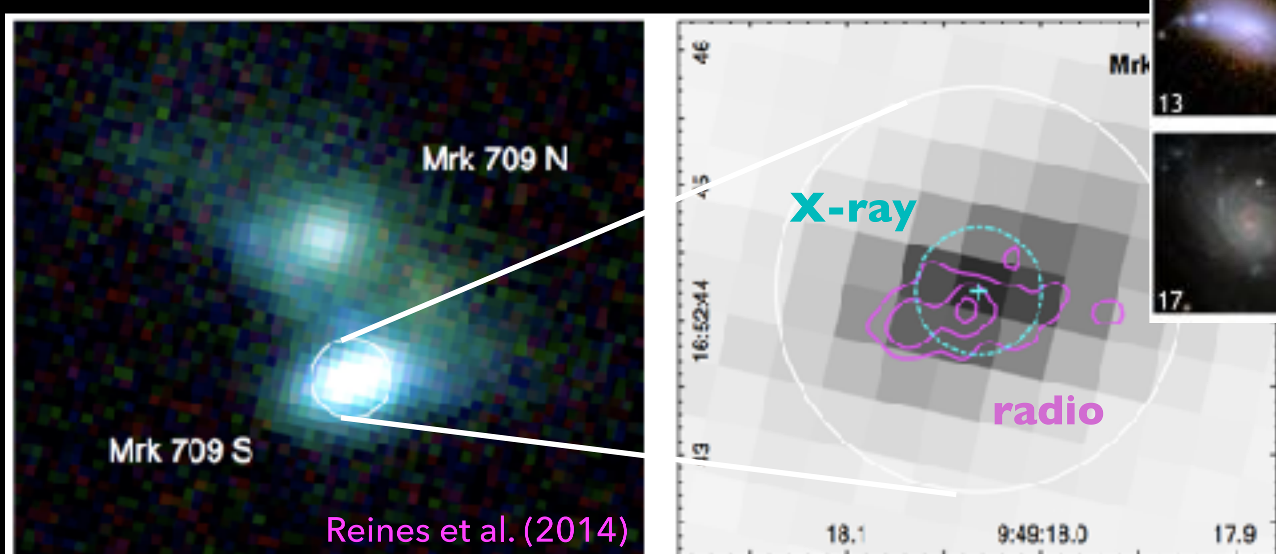
Large survey underway

High-resolution radio + X-ray observations can reveal massive BHs in dwarf galaxies missed at optical wavelengths



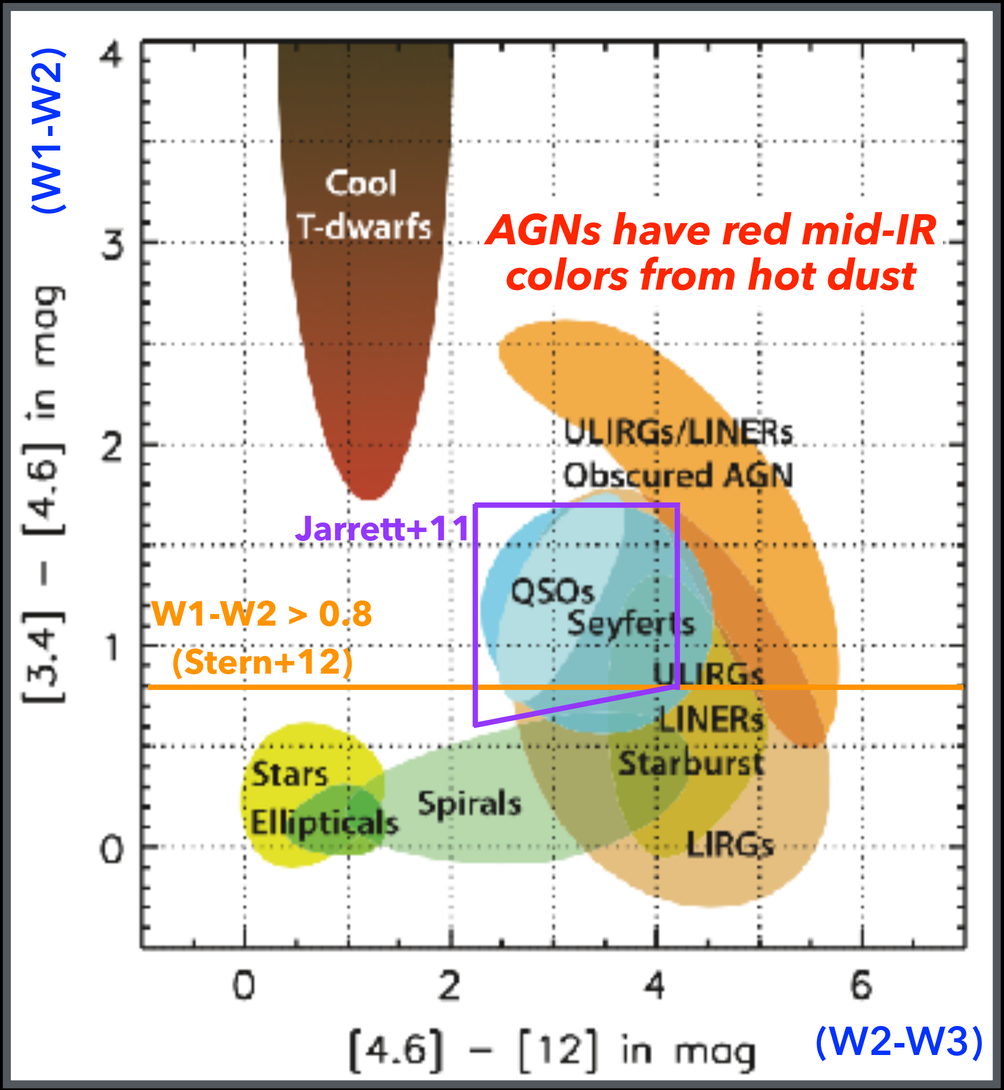


Lemons, Reines et al. (2015)



Large survey underway

Mid-IR selection of AGN candidates in dwarf galaxies



WISE color-color diagram
(Wright et al. 2010)

Wide-field Infrared Survey Explorer (WISE)

Mid-IR selection of AGN candidates in dwarf galaxies

The Astrophysical Journal, 784:113 (8pp), 2014 April 1 doi:10.1088/0004-63

DISCOVERY OF A POPULATION OF BULGELESS GALAXIES WITH EXTREMELY RED MID-IR COLORS: OBSCURED AGN ACTIVITY IN THE LOW-MASS REGIME?

S. Satyapal[1], N. J. Secrest[1], W. McAlpine[1], S. L. Ellison[2], J. Fischer[3], and J. L. Rosenberg[1]

Mon. Not. R. Astron. Soc. 000, 000–000 (2014) Printed 20 November 2014 (MN LaTeX style file v2.2)

Infrared Signature of Active Massive Black Holes in Nearby Dwarf Galaxies

Francine R. Marleau, Dominic Clancy, Matteo Bianconi and Rebecca Habas
Institute of Astro and Particle Physics, University of Innsbruck, 6020 Innsbruck, Austria

MNRAS 454, 3722–3742 (2015) doi:10.1093/mnras

The search for active black holes in nearby low-mass galaxies using optical and mid-IR data

Lia F. Sartori,[1★] Kevin Schawinski,[1★] Ezequiel Treister,[2] Benny Trakhtenbrot,[1†] Michael Koss,[1‡] Maryam Shirazi[1] and Kyuseok Oh[1,3]
[1]*Institute for Astronomy, Department of Physics, ETH Zürich, Wolfgang Pauli Strasse 27, CH 8093 Zürich, Switzerland*
[2]*Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile*
[3]*Department of Astronomy, Yonsei University, Seoul 120-749, Republic of Korea*

Mid-IR selection of AGN candidates in dwarf galaxies

Beware of contamination from dwarf starburst galaxies

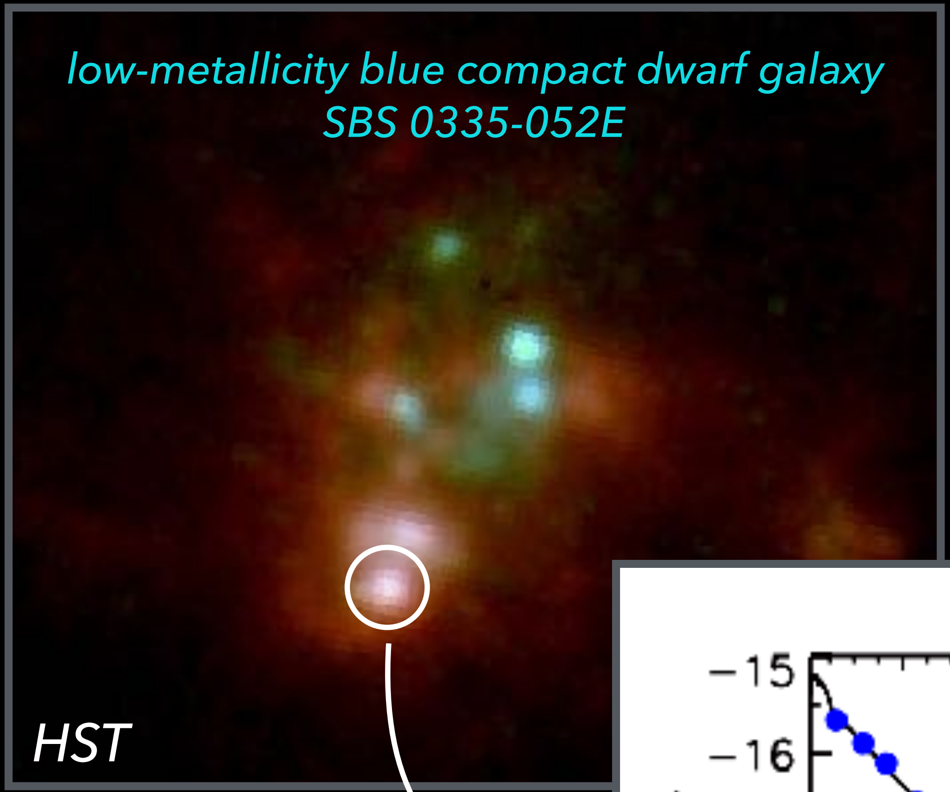
Mid-IR selection of AGN candidates in dwarf galaxies

Beware of contamination from dwarf starburst galaxies

Reines et al. 2008b

Mid-IR selection of AGN candidates in dwarf galaxies

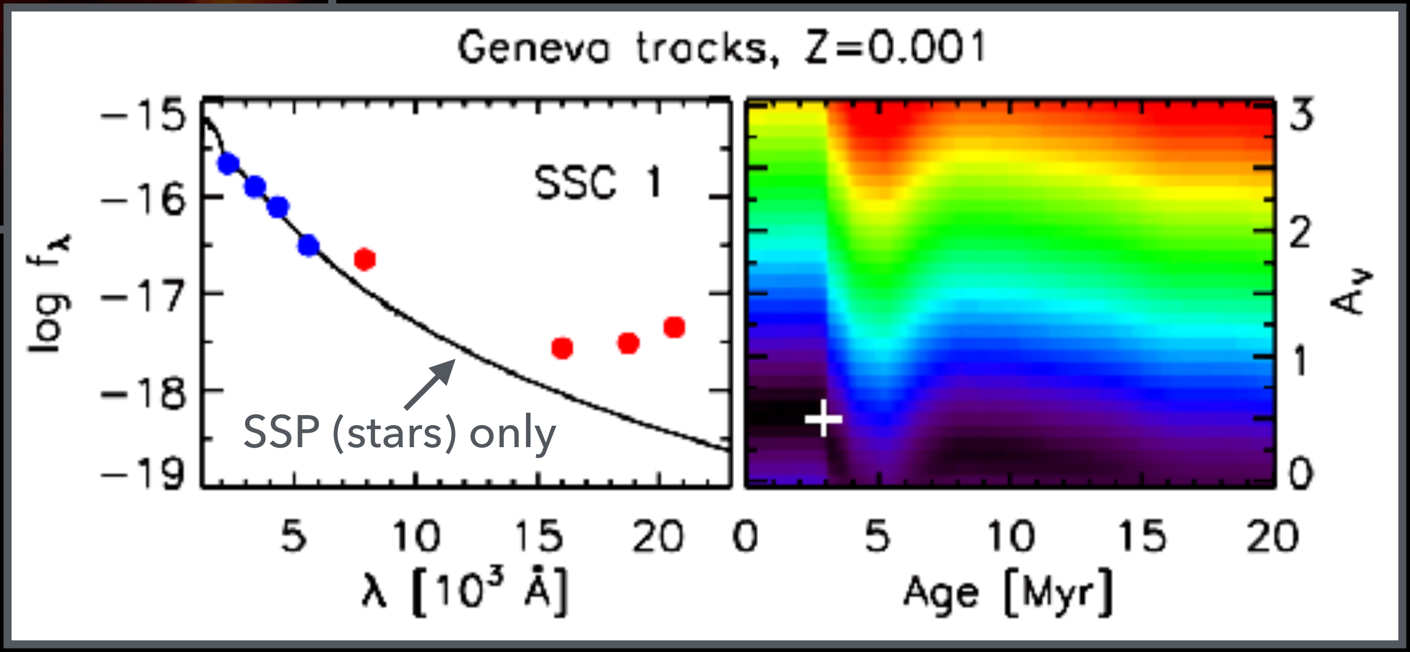
Beware of contamination from dwarf starburst galaxies



spectral energy distribution

↓

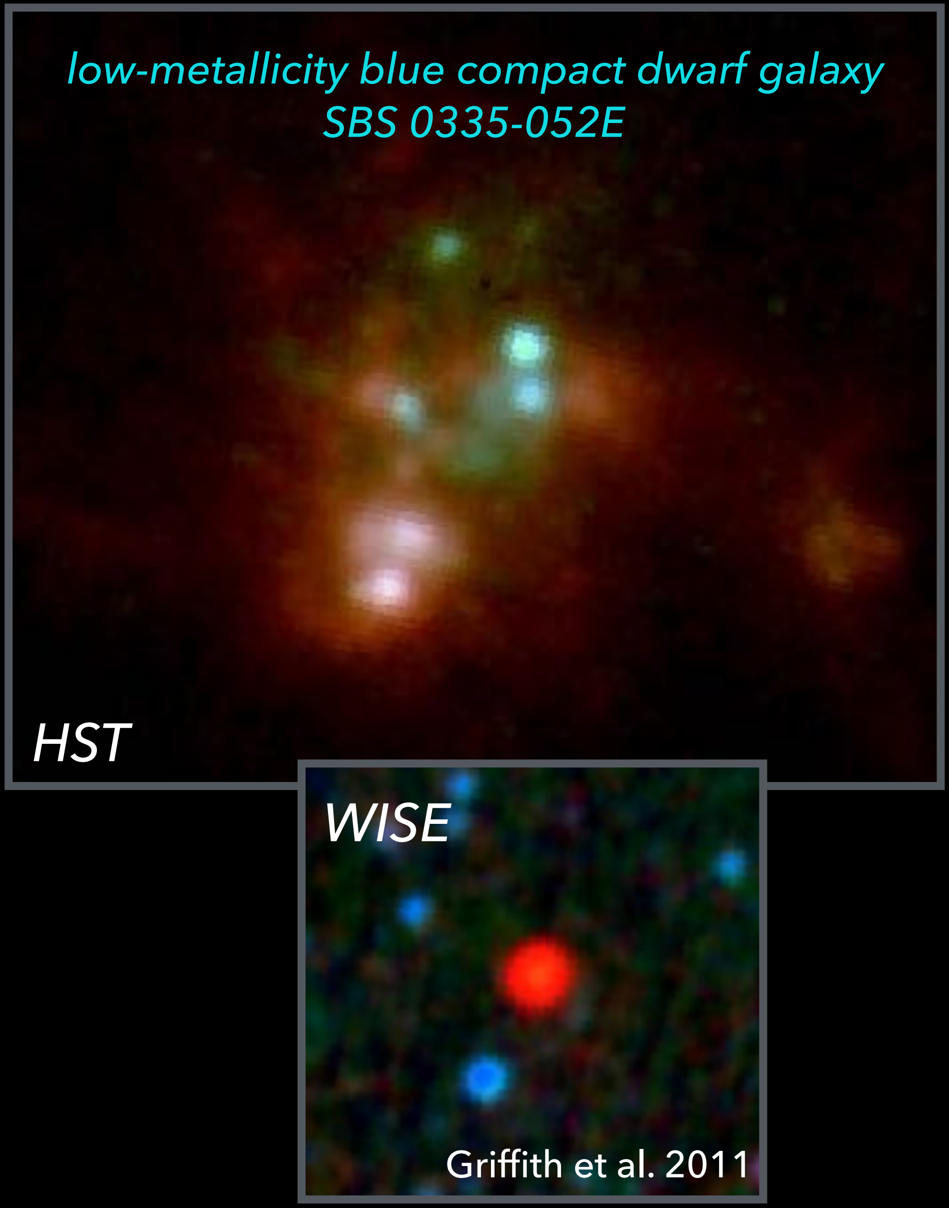
infrared excess from hot dust



Reines et al. 2008b

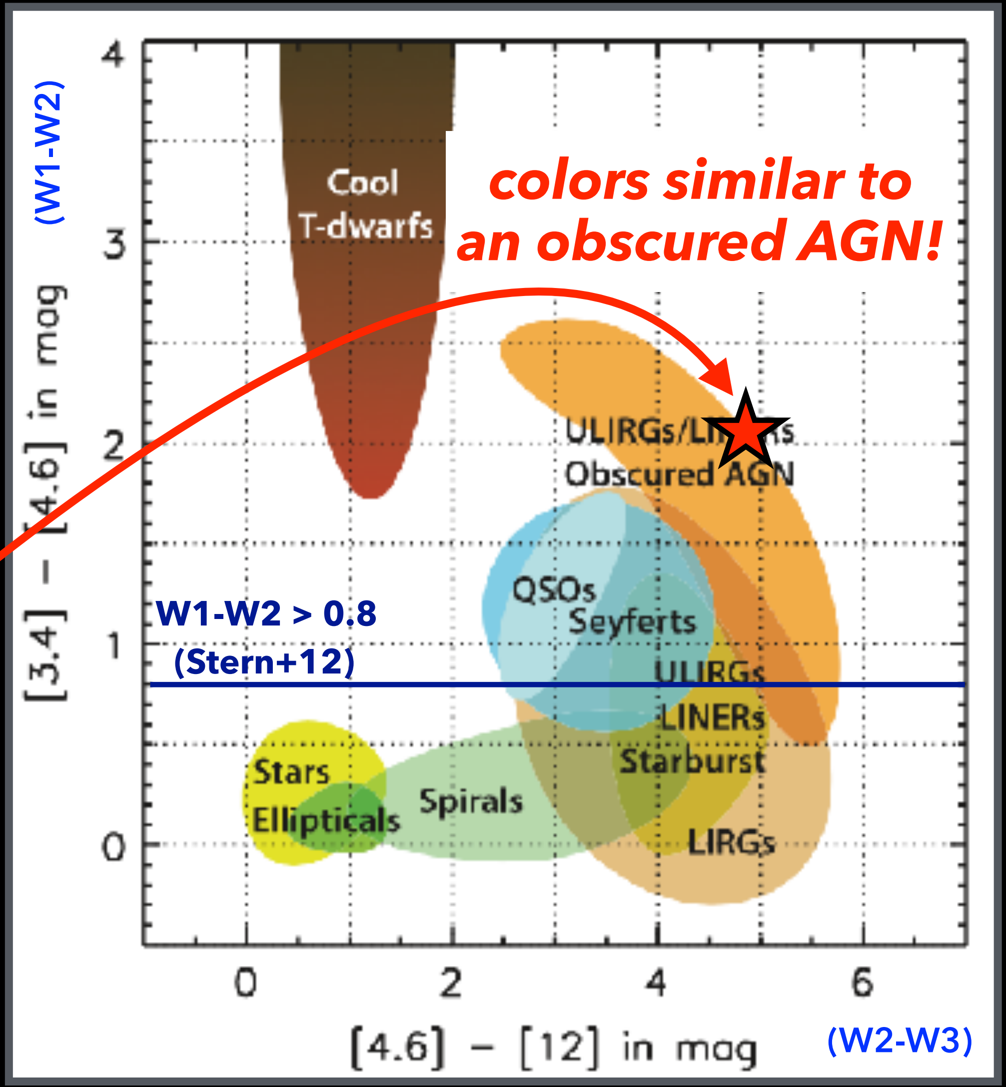
Mid-IR selection of AGN candidates in dwarf galaxies

Beware of contamination from dwarf starburst galaxies



Mid-IR selection of AGN candidates in dwarf galaxies

Beware of contamination from dwarf starburst galaxies

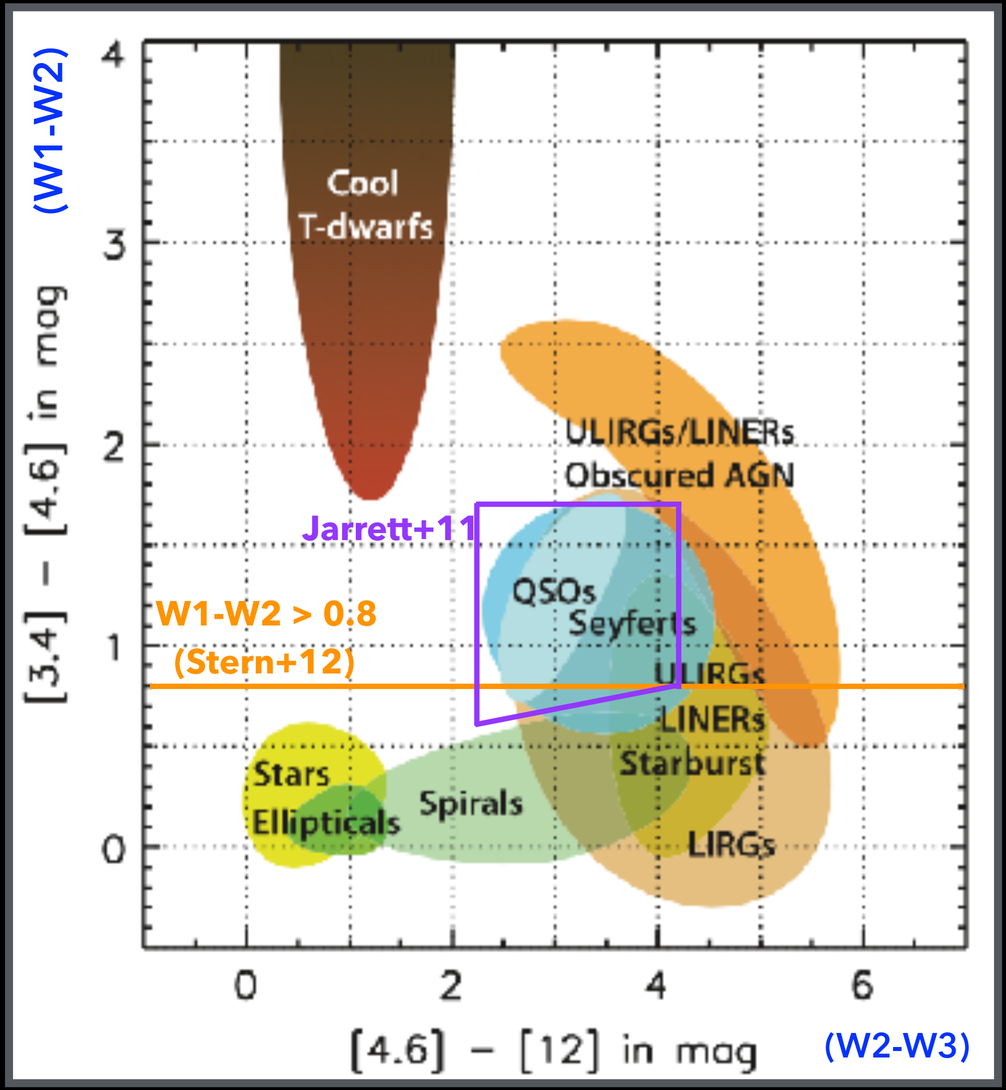


WISE color-color diagram
(Wright et al. 2010)

Mid-IR colors of dwarf galaxies: Young starbursts mimicking AGNs

Hainline, Reines et al. 2016* *(*postdoc at the University of Arizona/Steward Observatory)*

Kevin Hainline



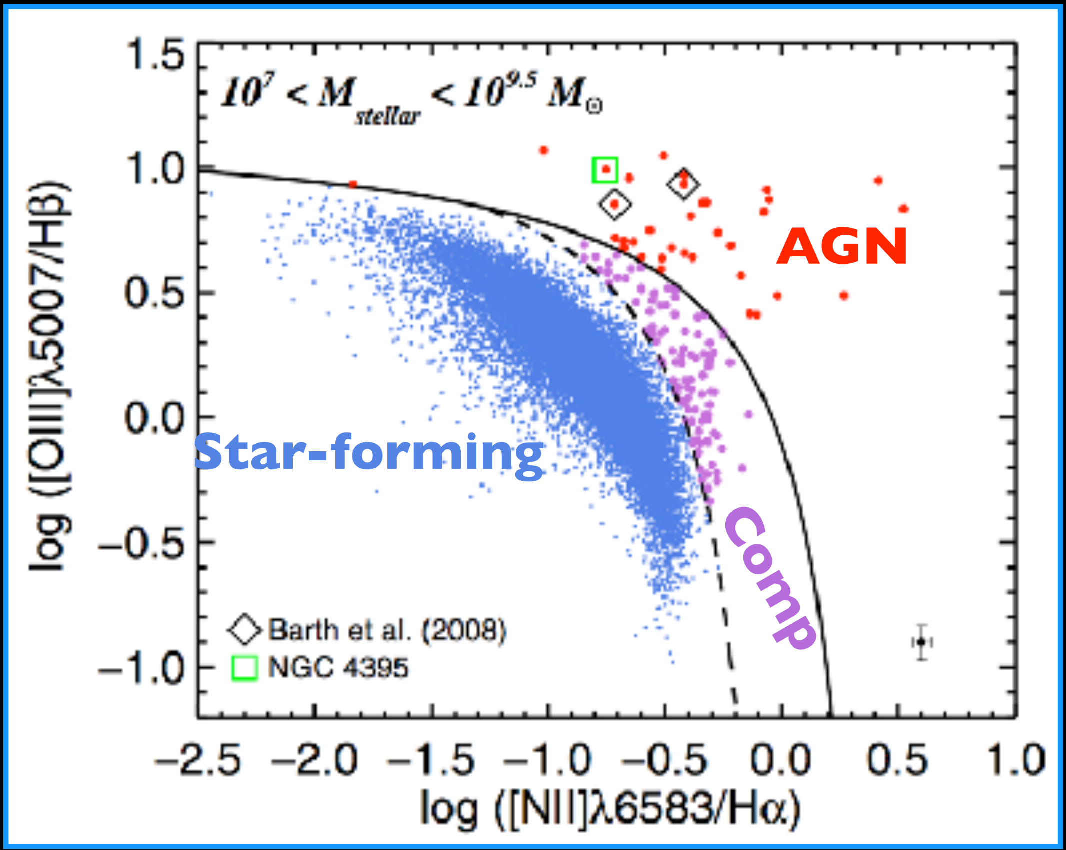
WISE color-color diagram
(Wright et al. 2010)

(also see O'Connor et al. 2016)

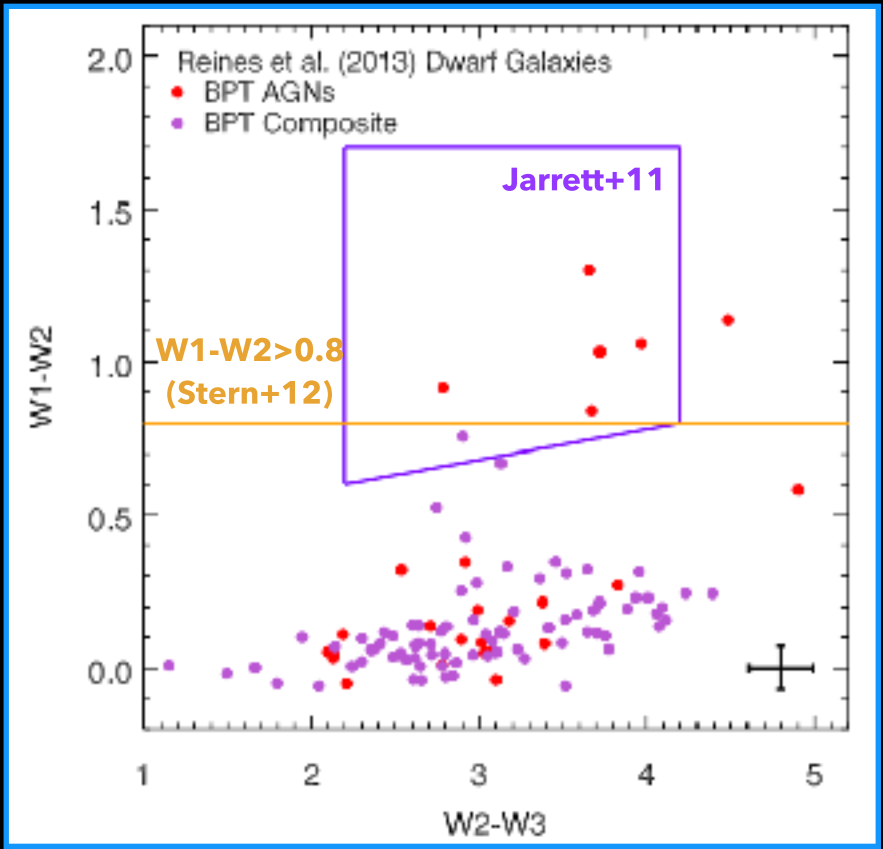
Mid-IR colors of dwarf galaxies: Young starbursts mimicking AGNs

Hainline, Reines et al. 2016 (*postdoc at the University of Arizona/Steward Observatory)*

Reines et al. (2013)



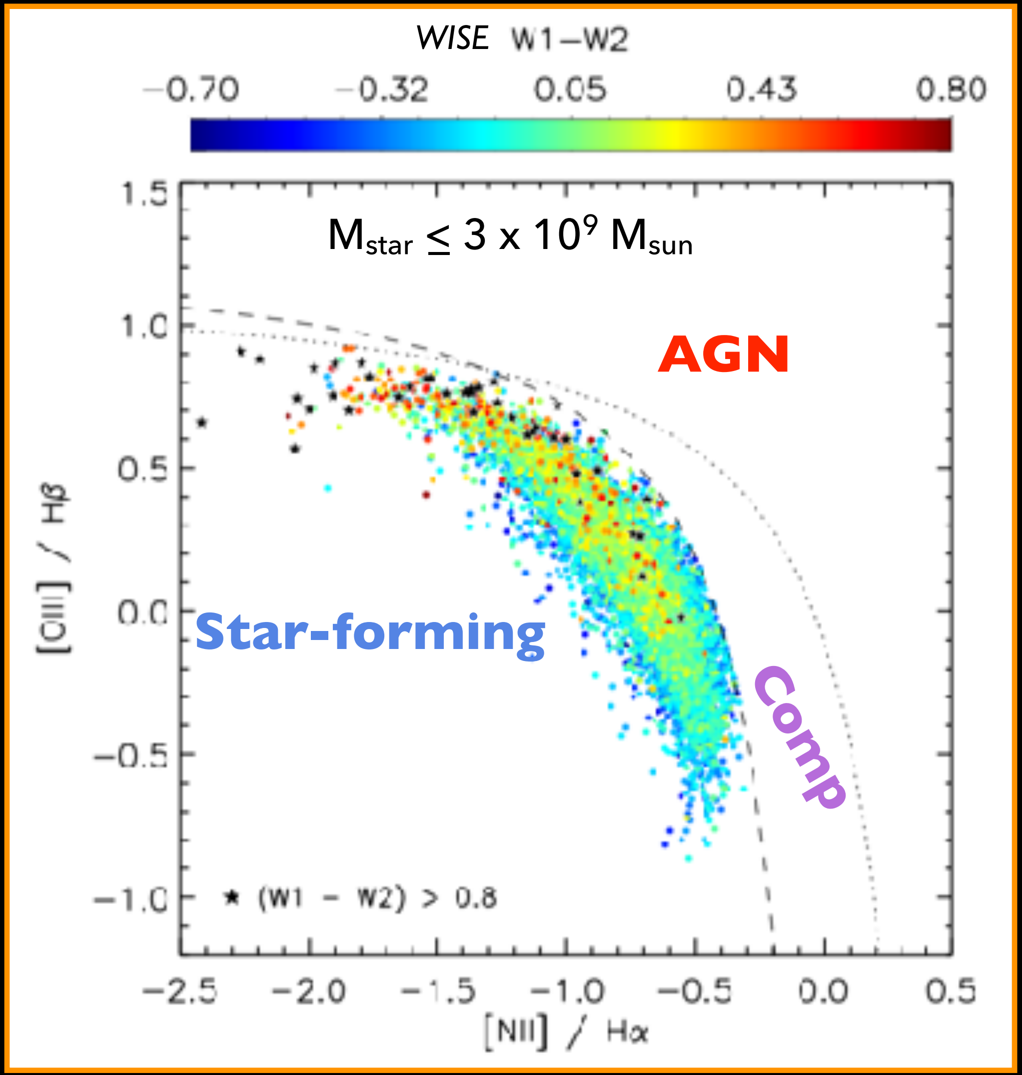
Optically selected AGNs/Composites in WISE color space



The majority of optically selected AGNs/Composites in dwarf galaxies have mid-IR emission dominated by host galaxies (at WISE resolution).

Mid-IR colors of dwarf galaxies: Young starbursts mimicking AGNs

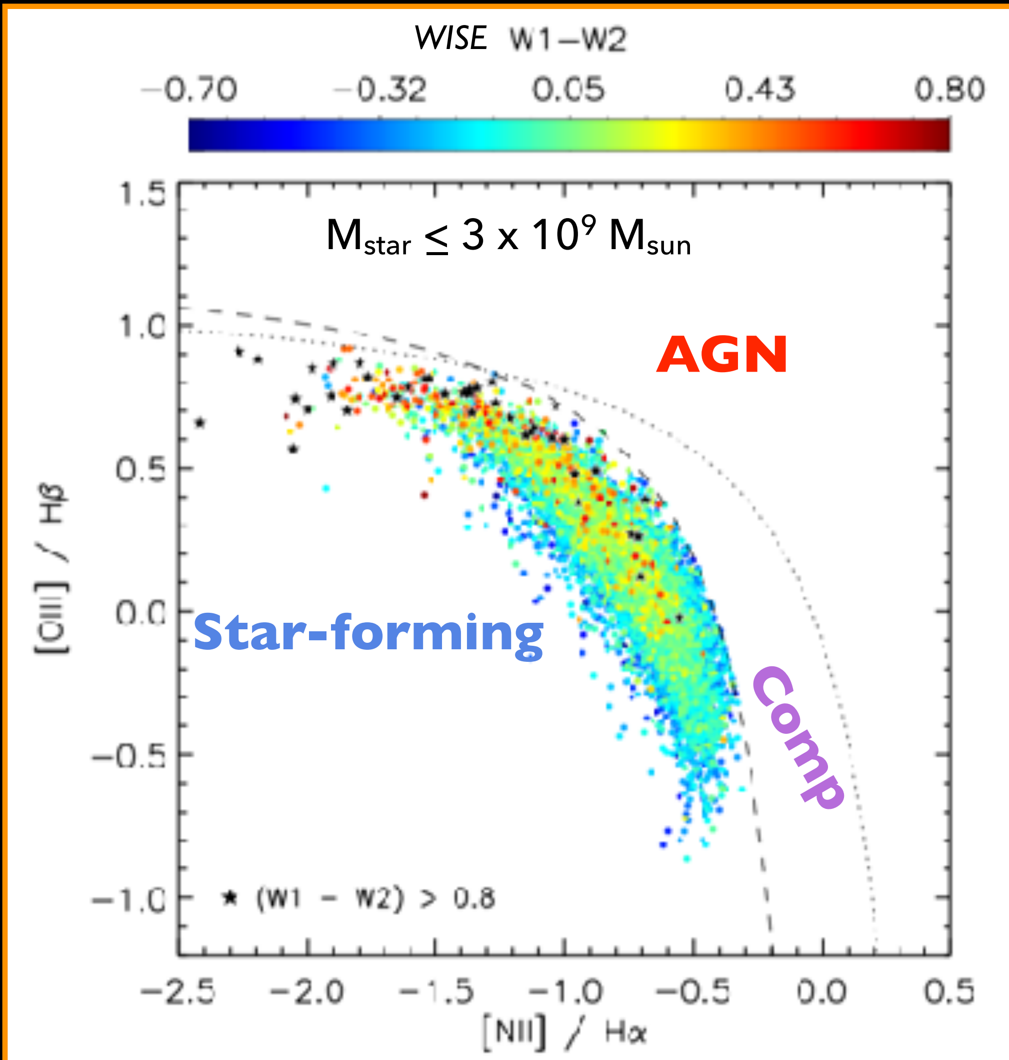
Hainline, Reines et al. 2016 (*postdoc at the University of Arizona/Steward Observatory)*



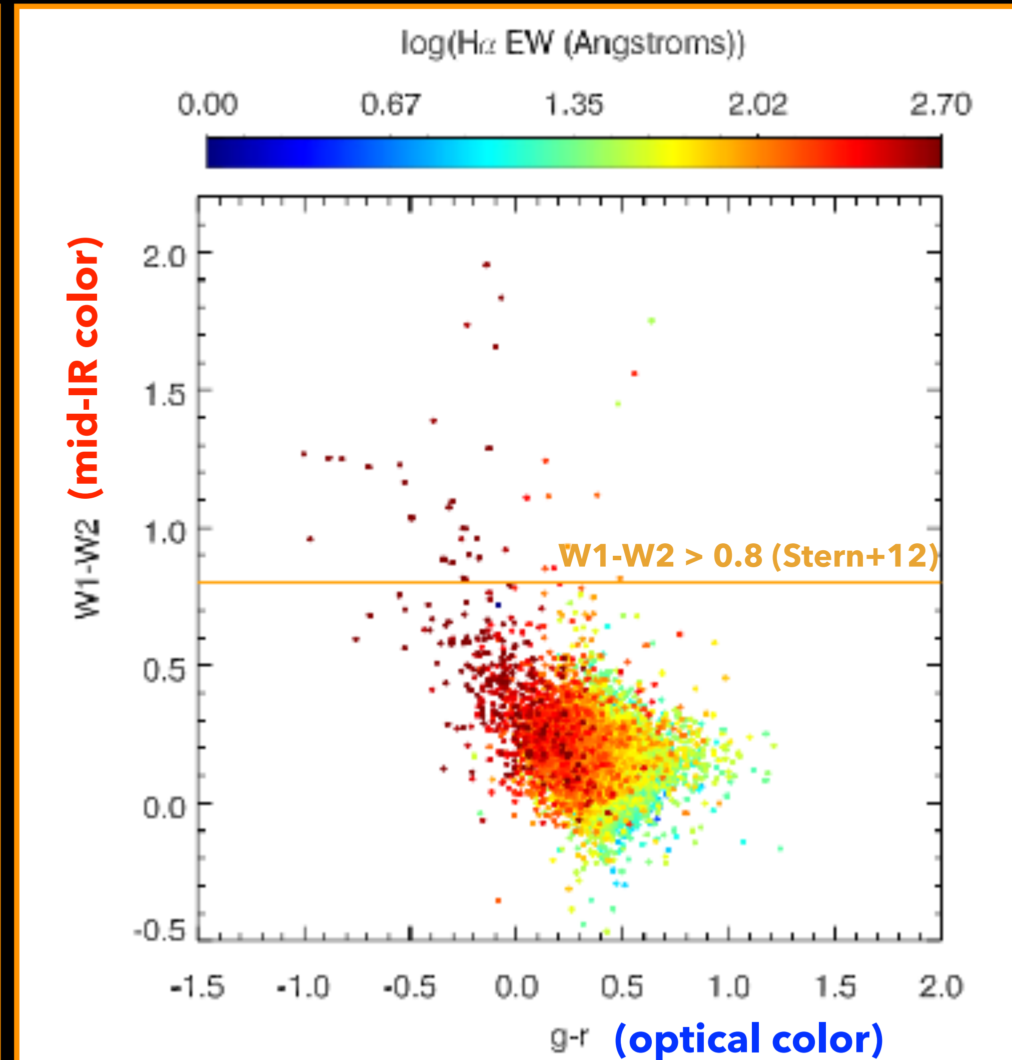
BPT diagram (optical classification)

Mid-IR colors of dwarf galaxies: Young starbursts mimicking AGNs

Hainline, Reines et al. 2016 (*postdoc at the University of Arizona/Steward Observatory)*



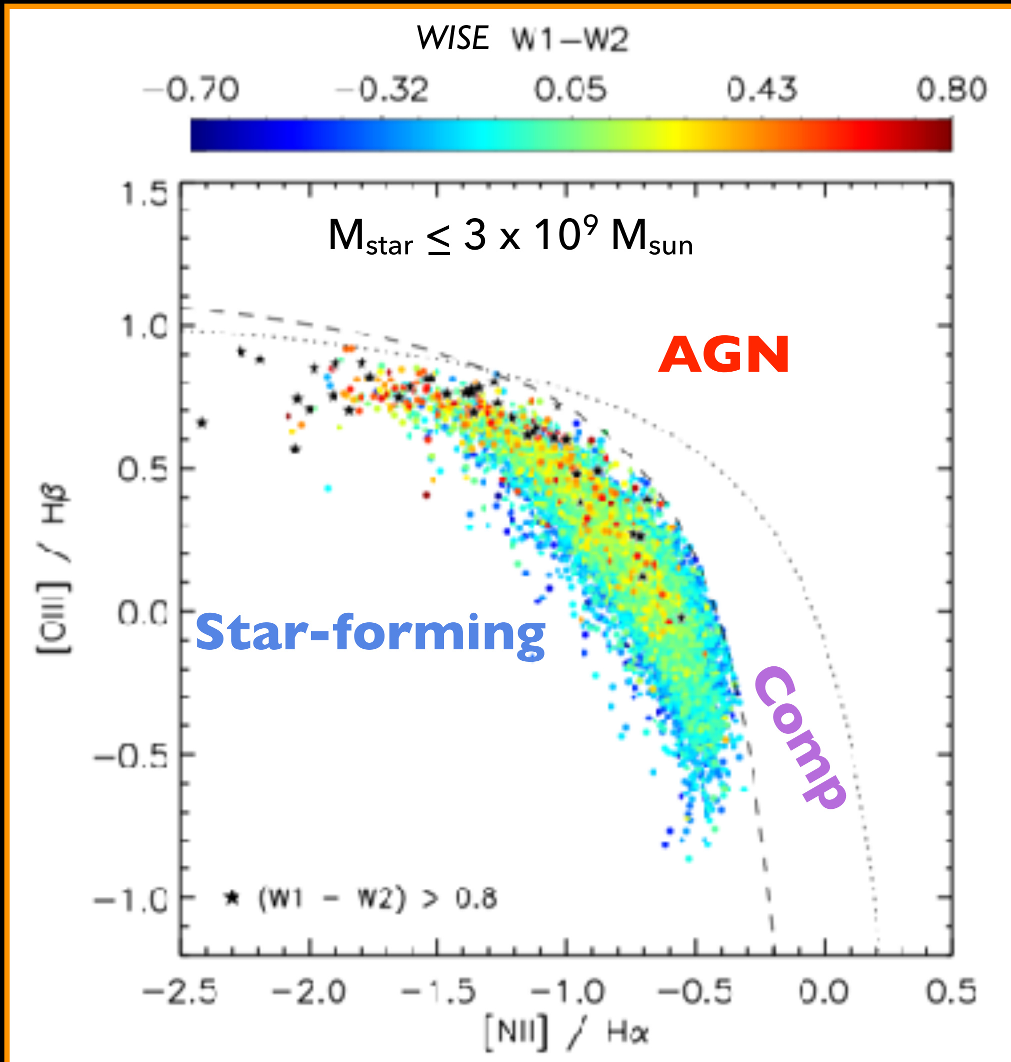
BPT diagram (optical classification)



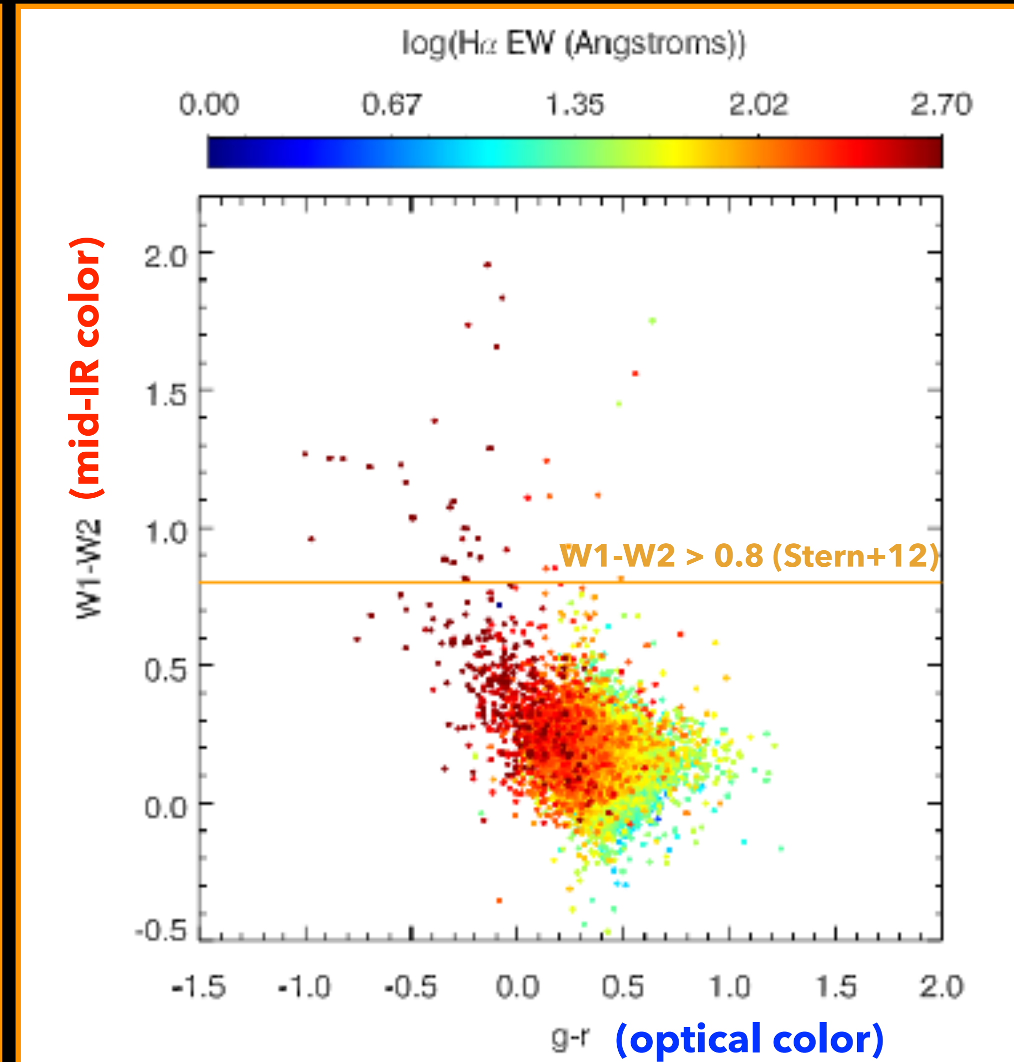
Star-forming dwarf galaxies

Mid-IR colors of dwarf galaxies: Young starbursts mimicking AGNs

Hainline, Reines et al. 2016 (*postdoc at the University of Arizona/Steward Observatory)*



BPT diagram (optical classification)



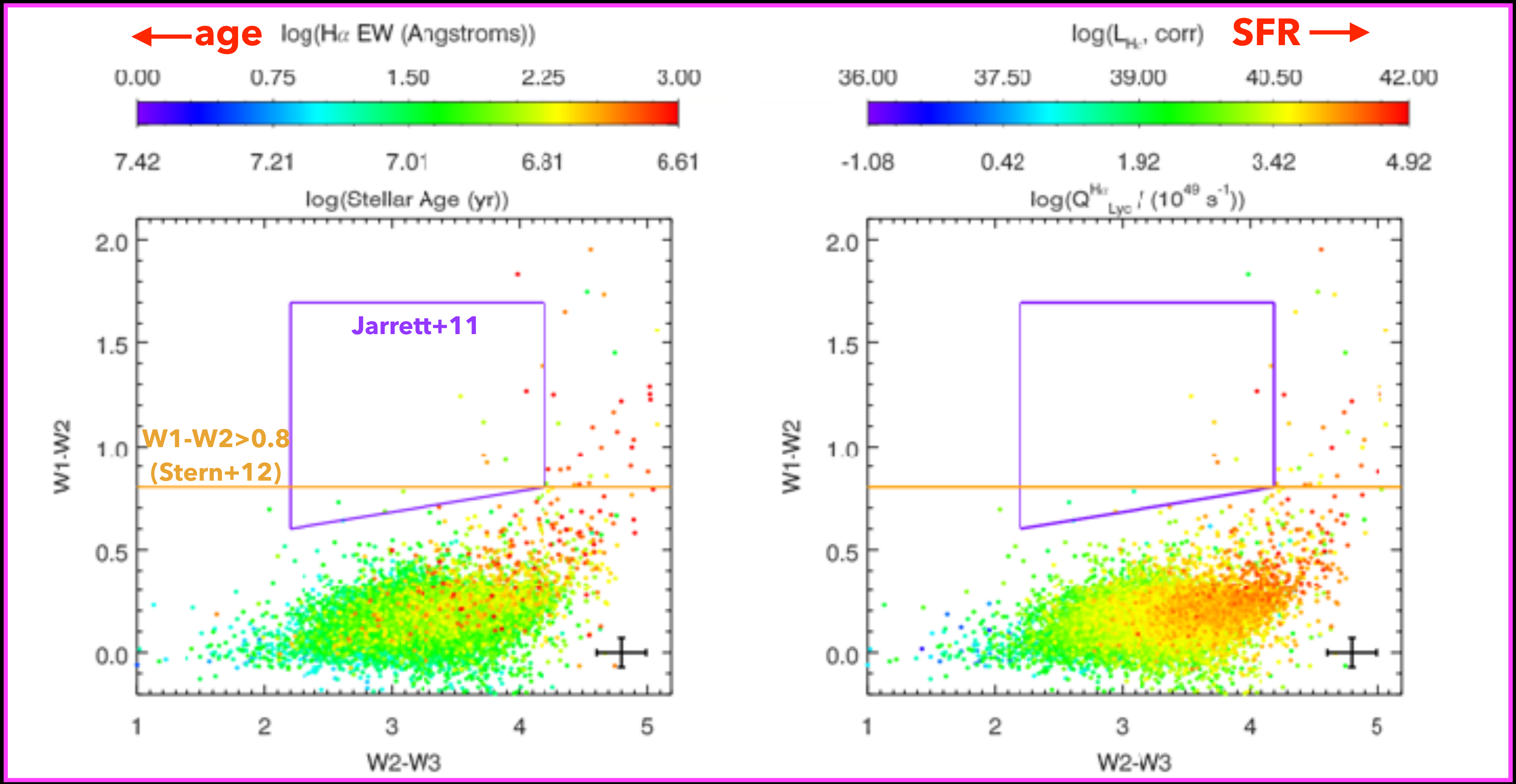
Star-forming dwarf galaxies

Star-forming dwarf galaxies with the bluest optical colors and youngest ages have the reddest mid-IR colors.

Mid-IR colors of dwarf galaxies: Young starbursts mimicking AGNs

Hainline, Reines et al. 2016 (*postdoc at the University of Arizona/Steward Observatory)*

Optically selected star-forming dwarf galaxies

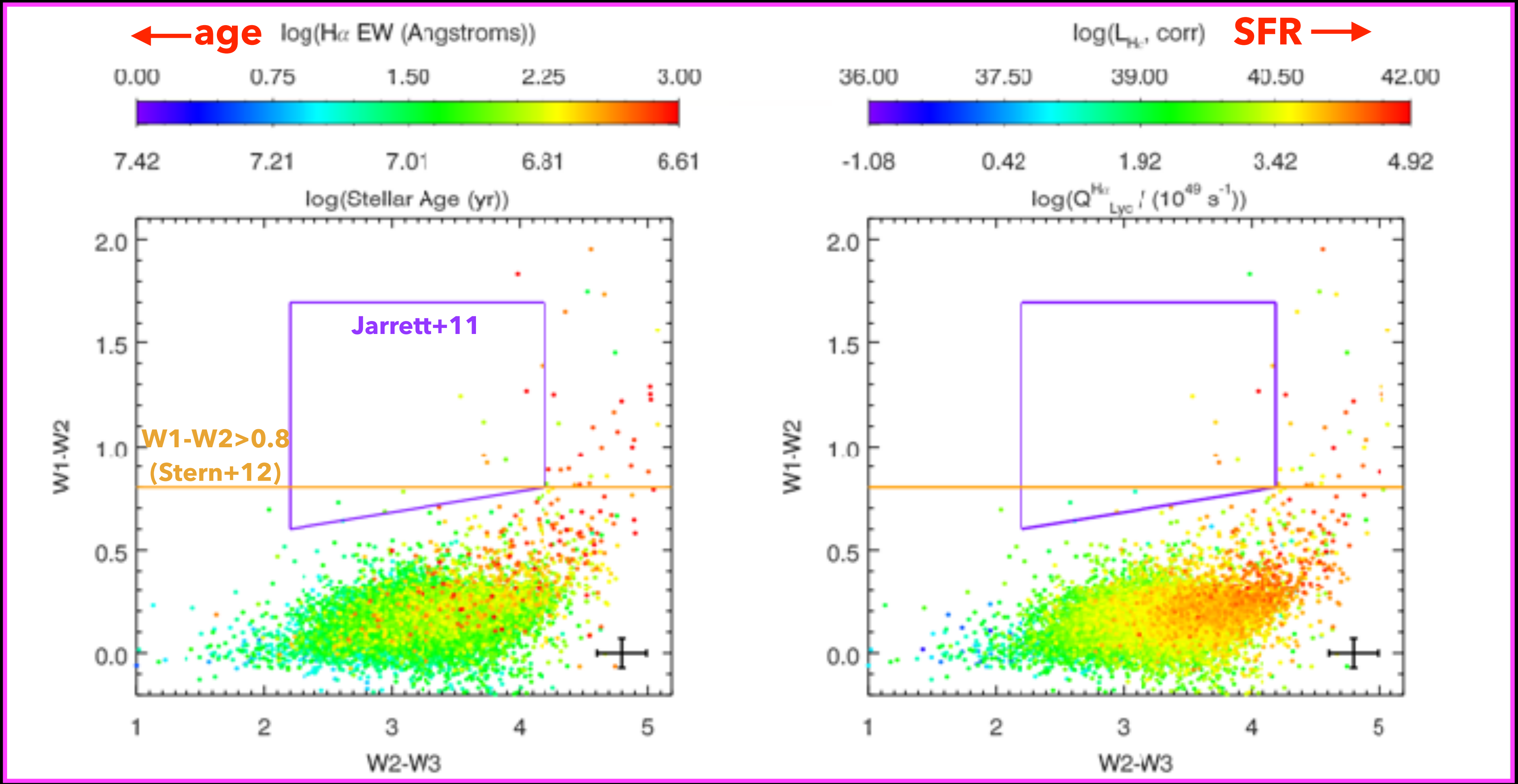


Star-forming dwarf galaxies with the youngest ages and highest SFRs have the reddest mid-IR colors.

Mid-IR colors of dwarf galaxies: Young starbursts mimicking AGNs

Hainline, Reines et al. 2016 (*postdoc at the University of Arizona/Steward Observatory)*

Optically selected star-forming dwarf galaxies



Systematic trend between star forming properties and mid-IR colors indicates the mid-IR emission is unlikely to be powered by AGNs

Review paper:

Publications of the Astronomical Society of Australia (PASA), Vol. 33, e054, 20 pages (2016).

doi:10.1017/pasa.2016.46

Observational Signatures of High-Redshift Quasars and Local Relics of Black Hole Seeds

Amy E. Reines[1,3*] and Andrea Comastri[2]

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[2]INAF - Osservatorio Astronomico di Bologna, via Ranzani 1, 40127, Bologna, Italy
[3]Email: reines@noao.edu

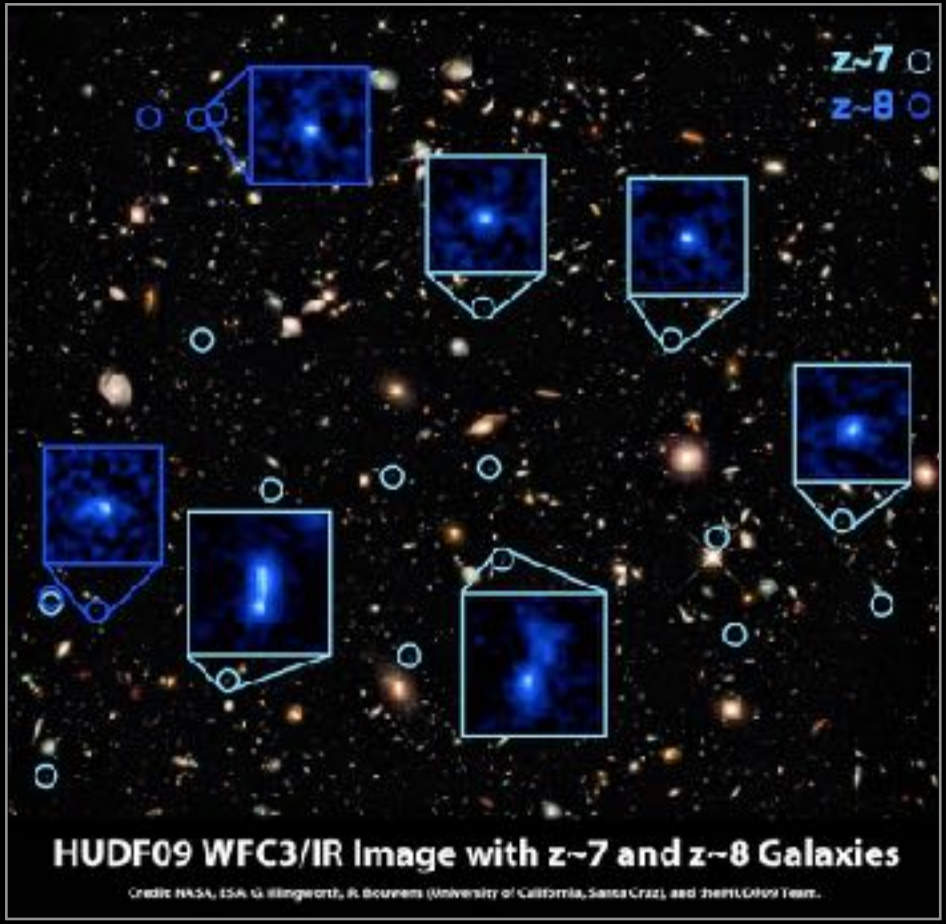
(Received April 29, 2016; Accepted September 2, 2016)

Abstract

Observational constraints on the birth and early evolution of massive black holes come from two extreme regimes. At high redshift, quasars signal the rapid growth of billion-solar-mass black holes and indicate that these objects began remarkably heavy and/or accreted mass at rates above the Eddington limit. At low redshift, the smallest nuclear black holes known are found in dwarf galaxies and provide the most concrete limits on the mass of black hole seeds. Here, we review current observational work in these fields that together are critical for our understanding of the origin of massive black holes in the Universe.

Connections to the high-redshift Universe

- stellar masses similar to the dwarfs that I'm studying locally
- expect that they would have already been seeded with a BH

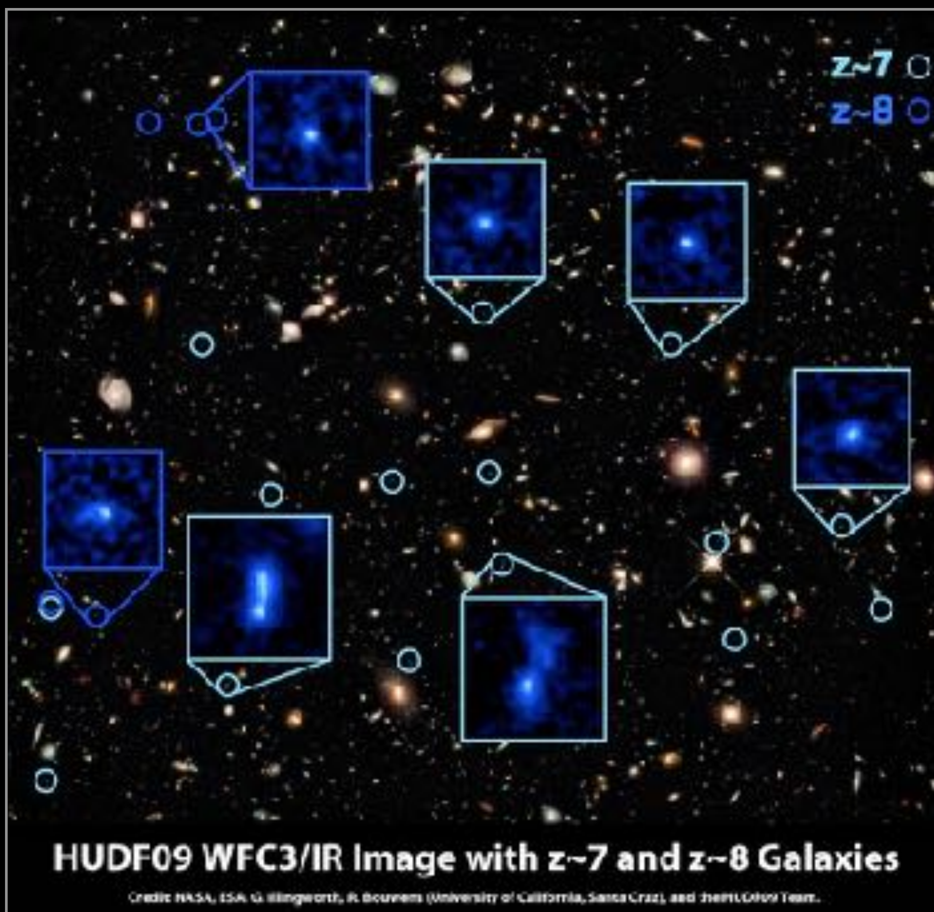


- blue, compact galaxies 600-800 Myr after the Big Bang (Bouwens+10)
- intrinsic sizes $\lesssim$ 1 kpc (Oesch+10)
- masses ~ 10^9-10^{10} M_{sun} (Labbé+10)

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; Vito et al. 2016)



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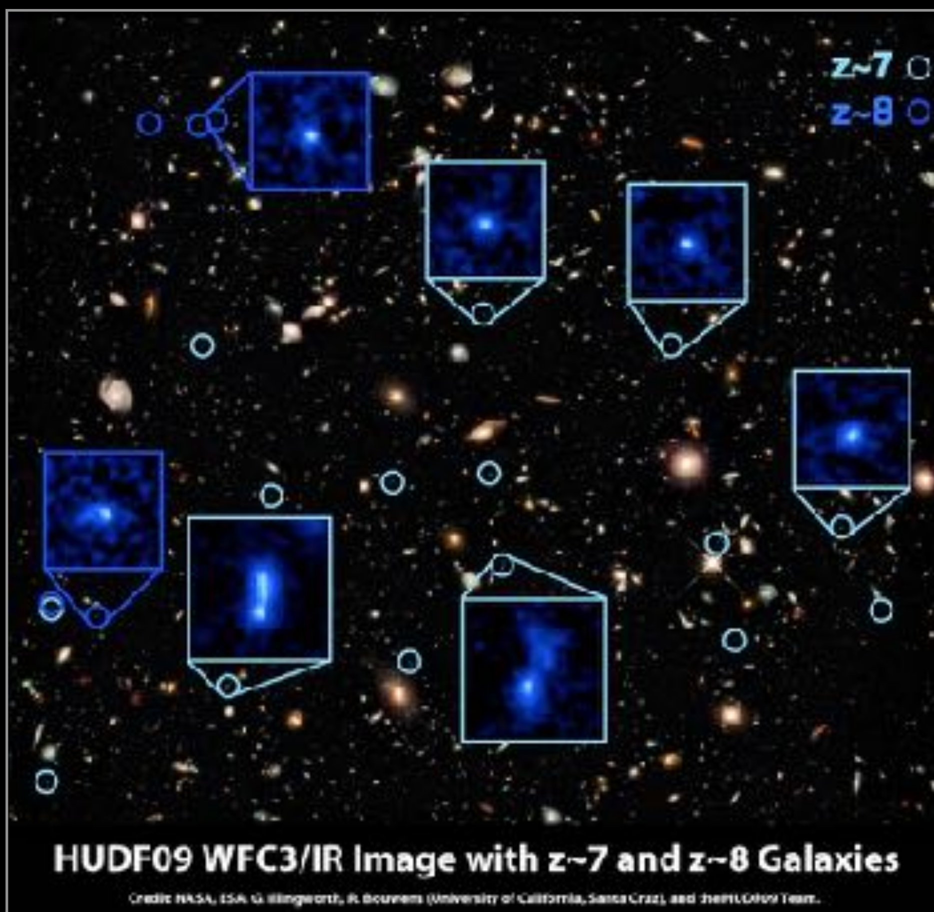

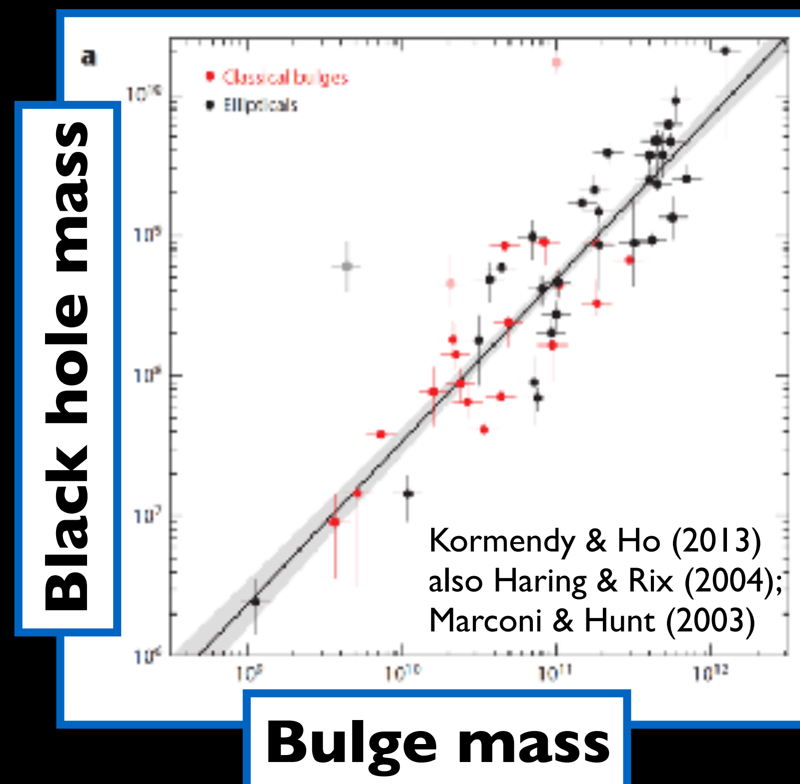

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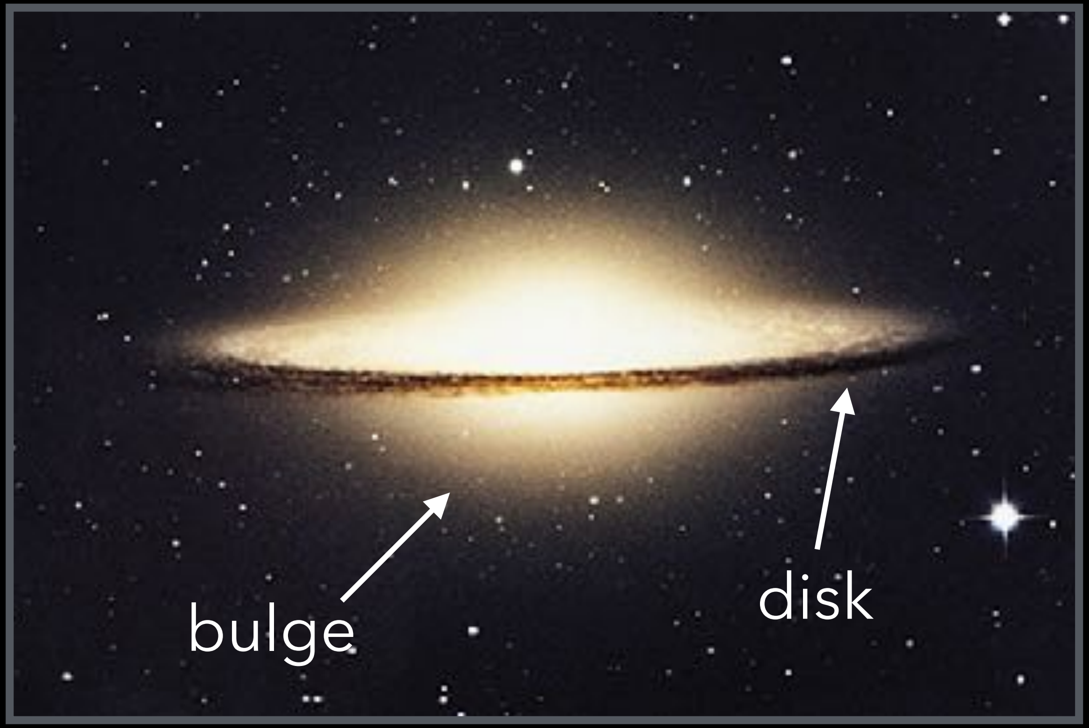

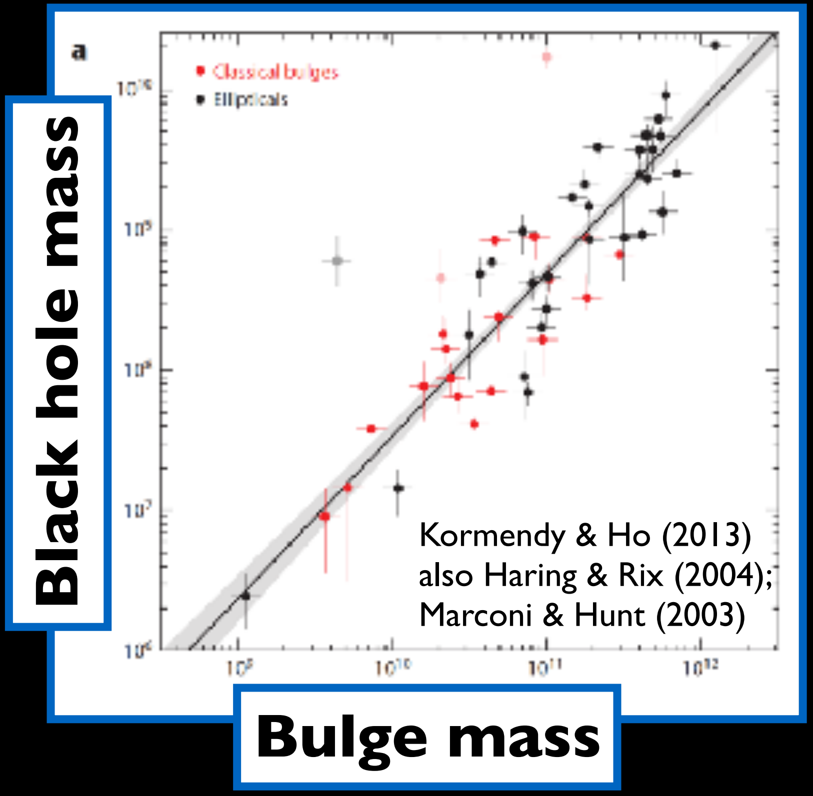

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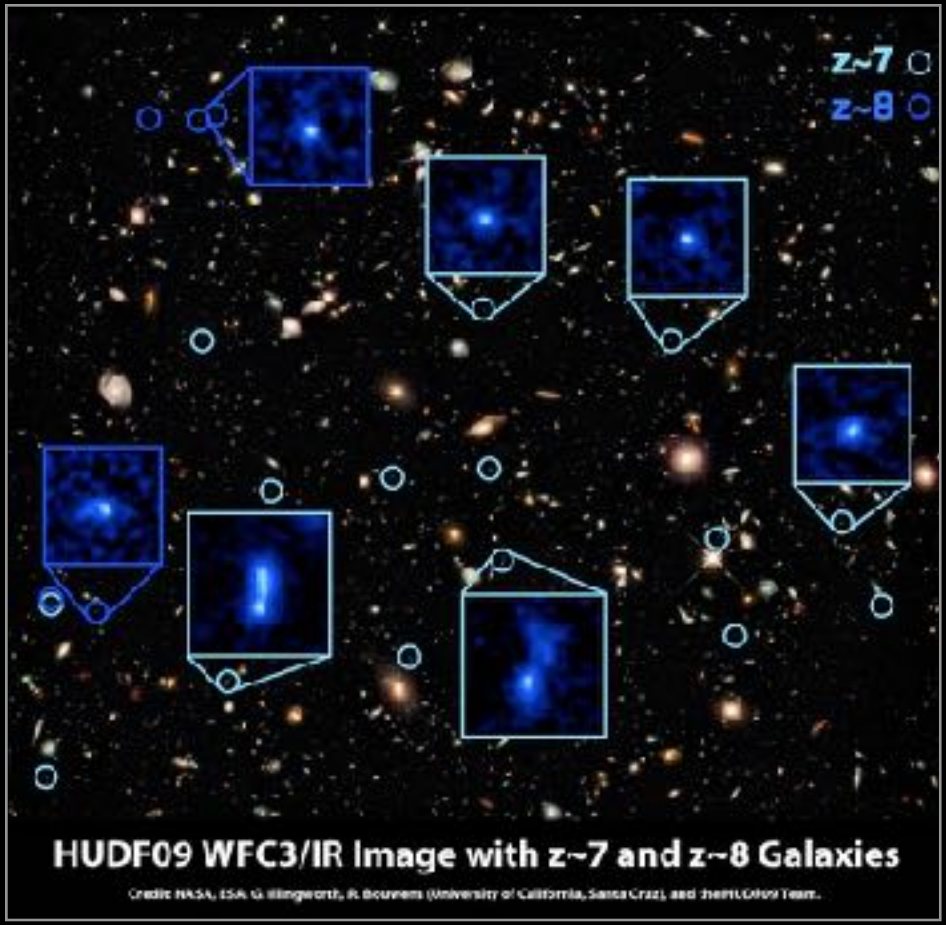
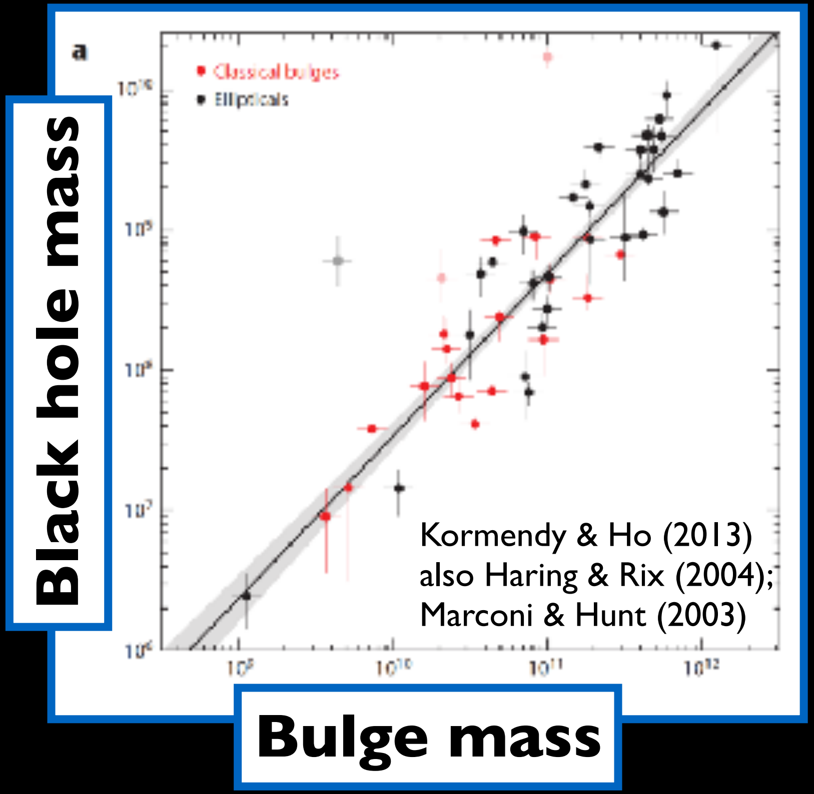




Expect M_{BH} ~10^6 M_{sun}

Connections to the high-redshift Universe

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

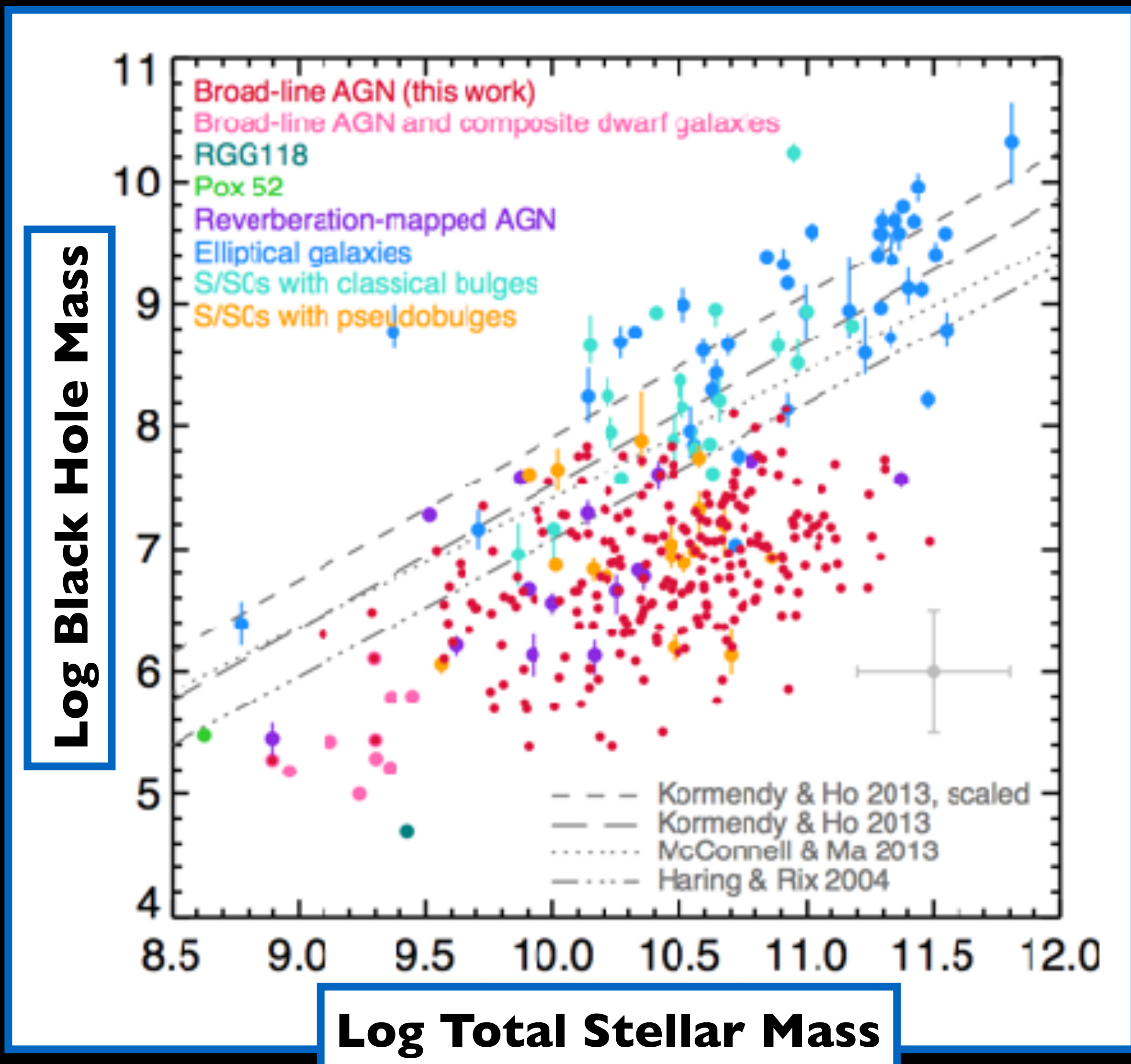
Reines & Volonteri 2015

"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

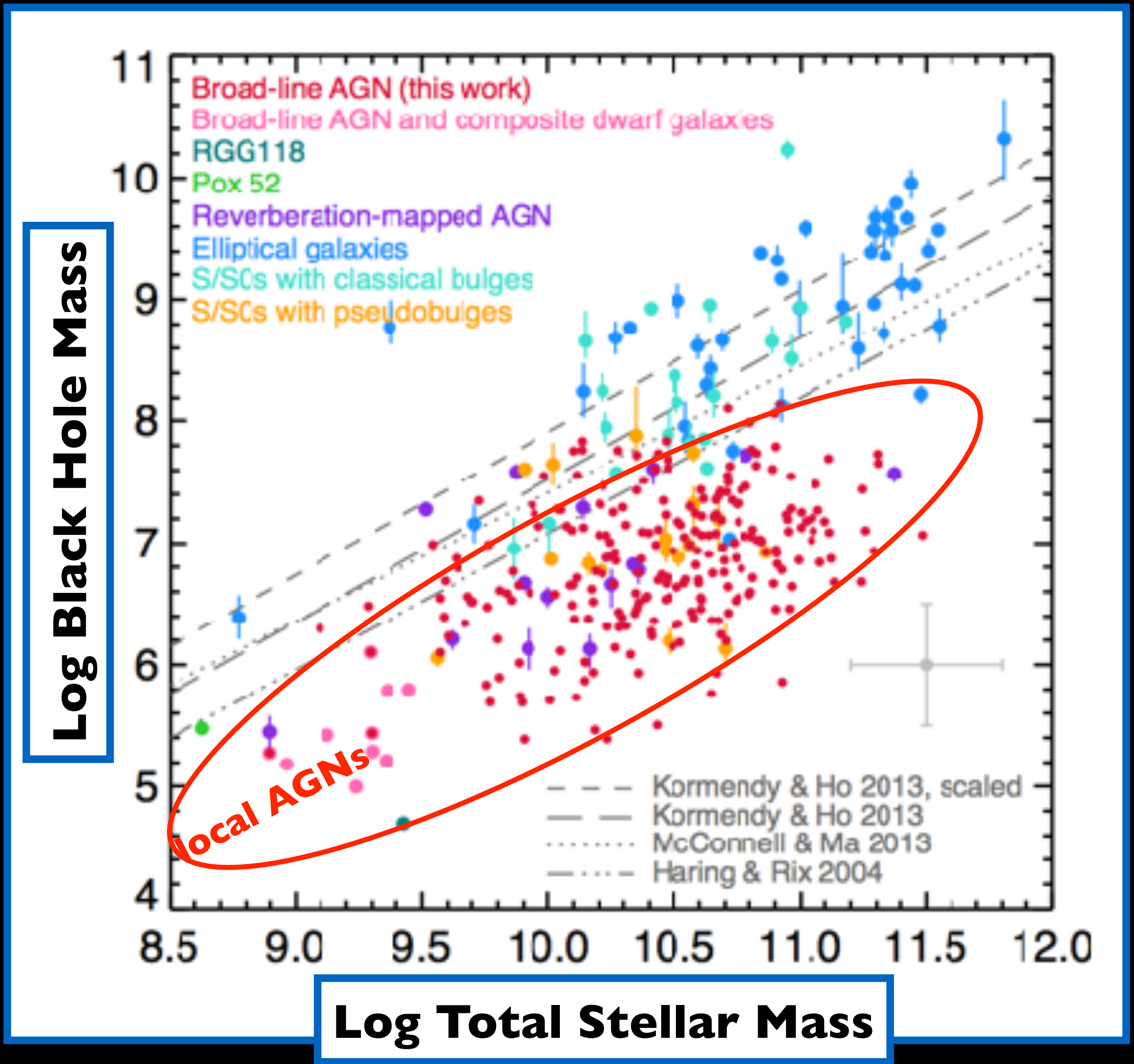
vs.

total galaxy stellar mass

(341 nearby galaxies)

Connections to the high-redshift Universe

Reines & Volonteri 2015



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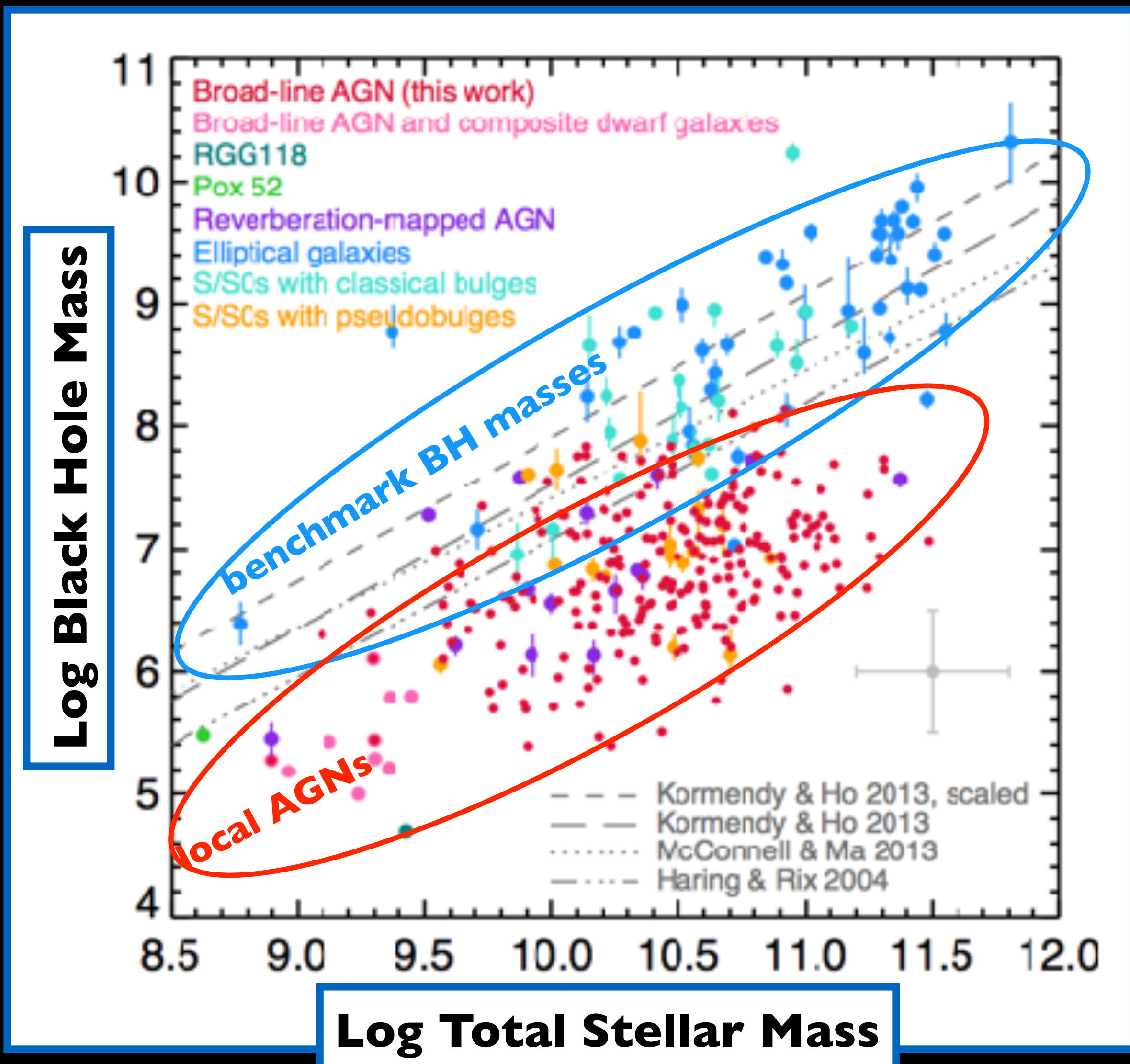

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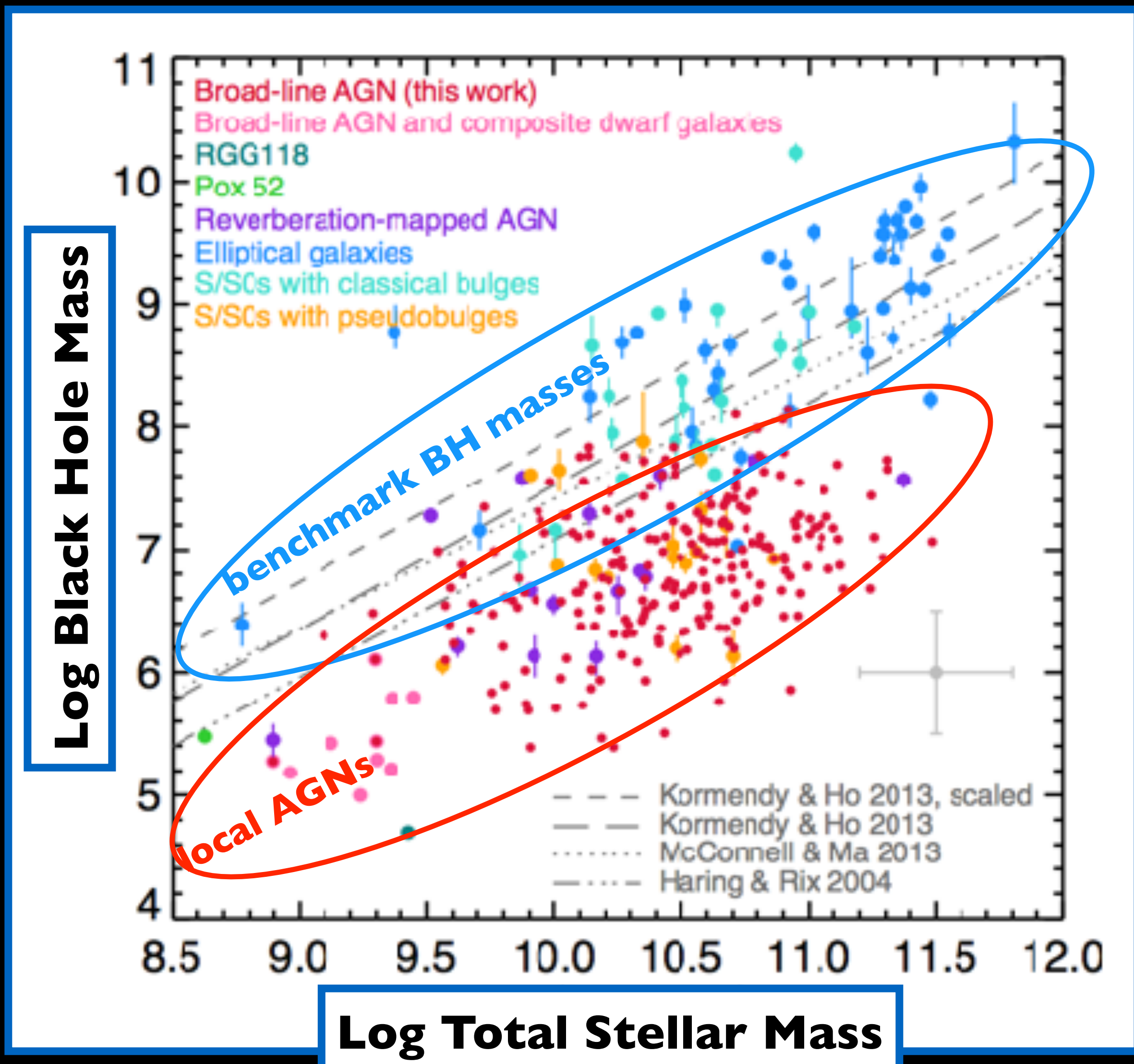
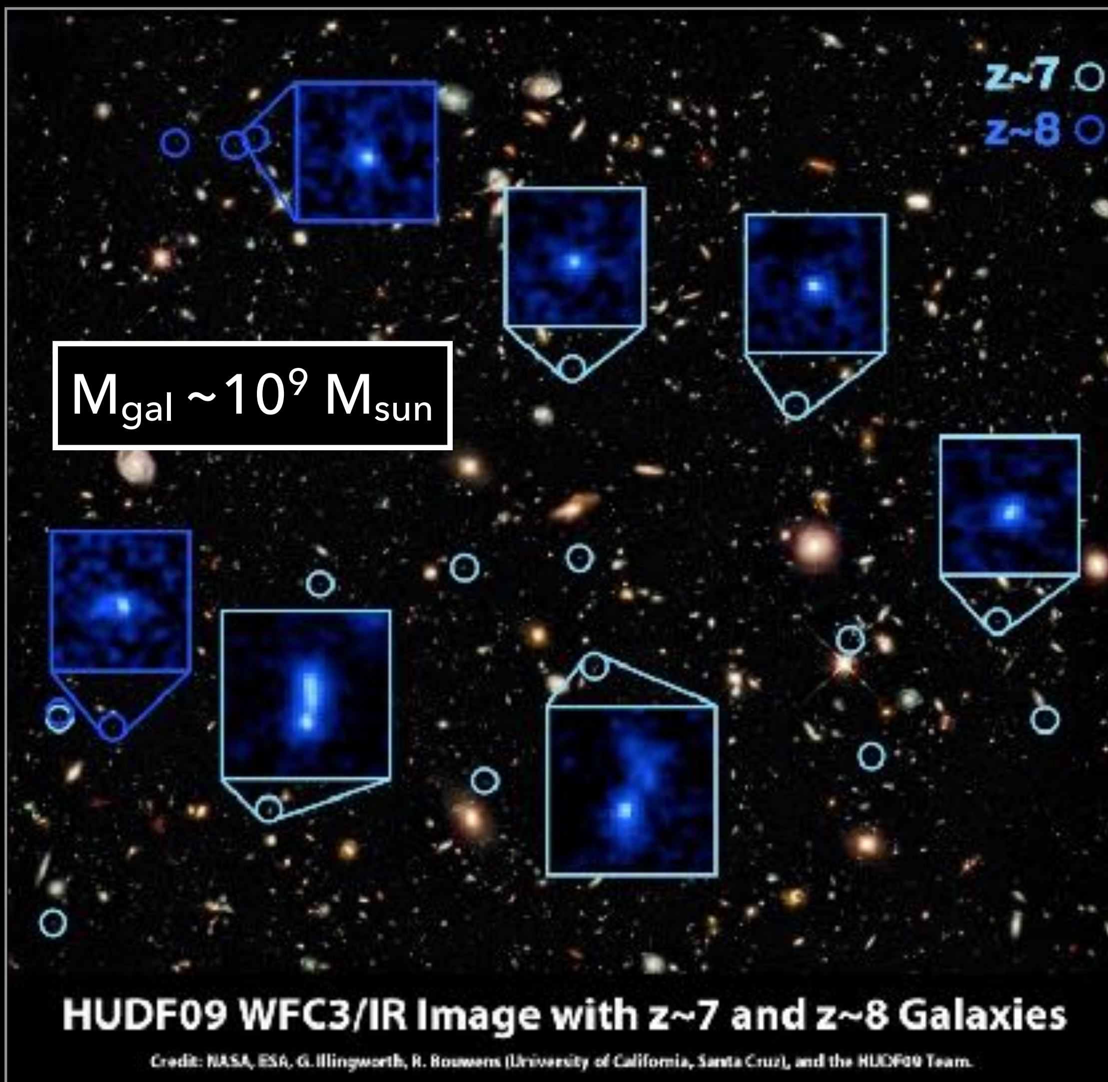


$M_{BH} \sim 10^{-3}\ M_{gal}$

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

Connections to the high-redshift Universe



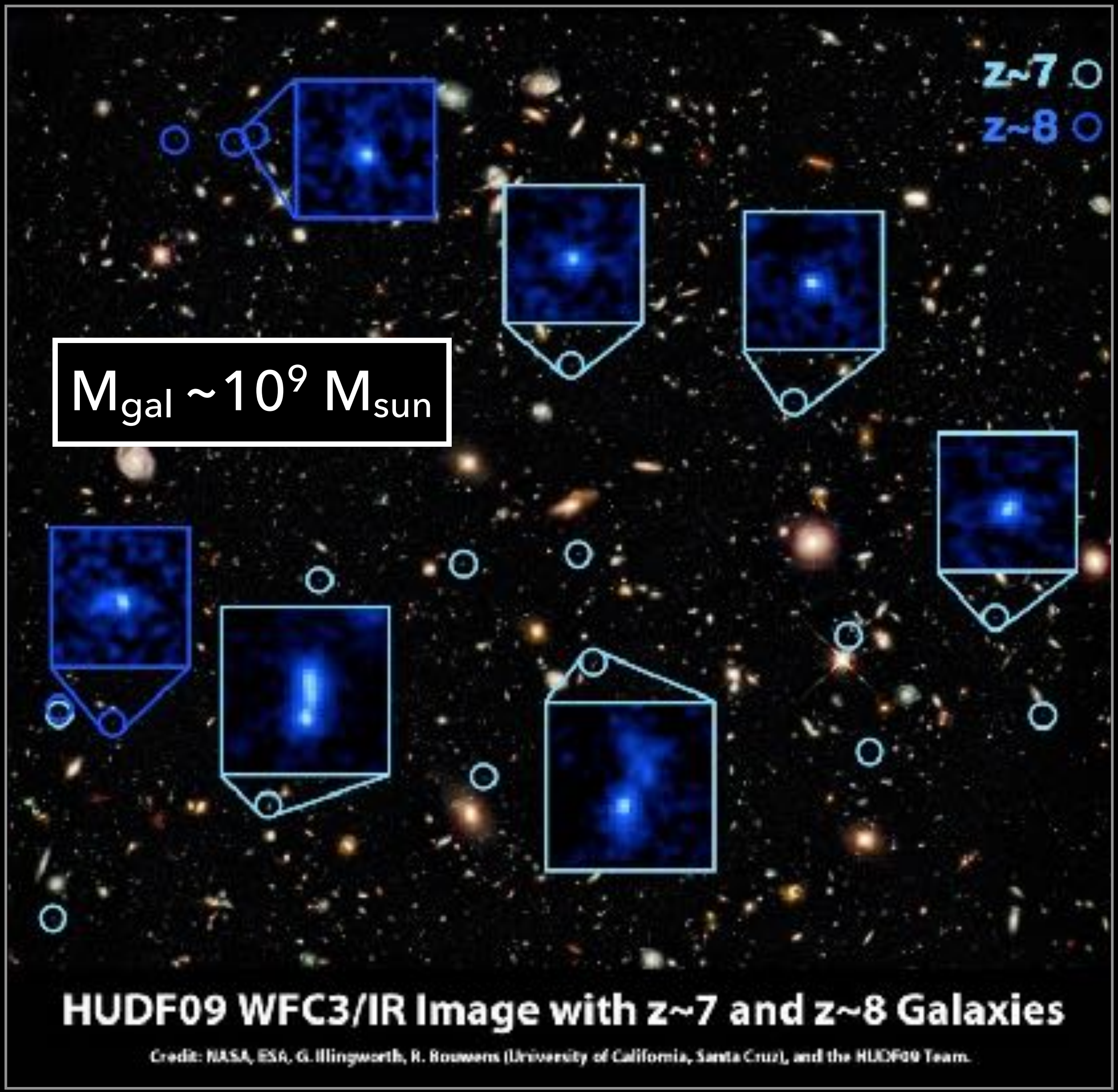
$M_{BH} \sim 10^{-3}\ M_{gal}$

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

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

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

Connections to the high-redshift Universe



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

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

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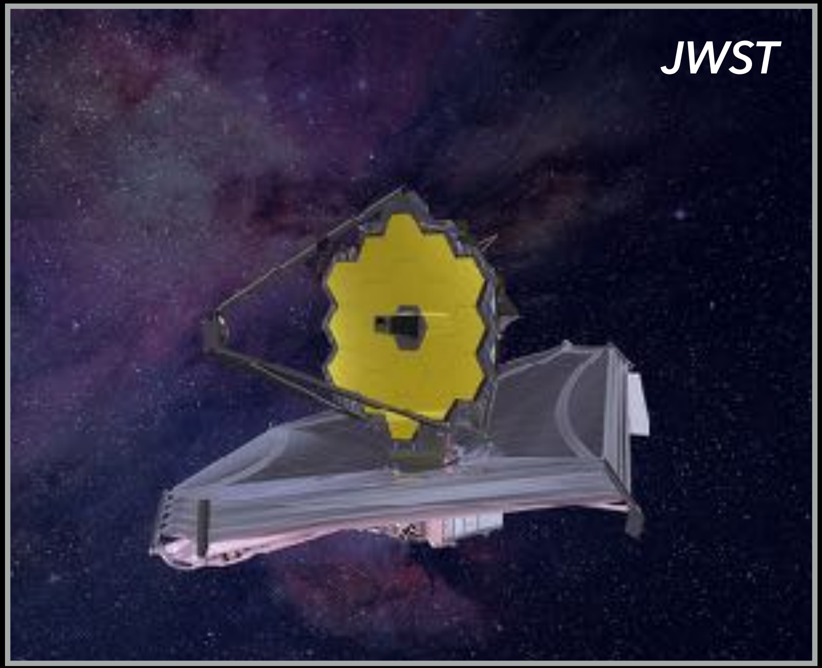
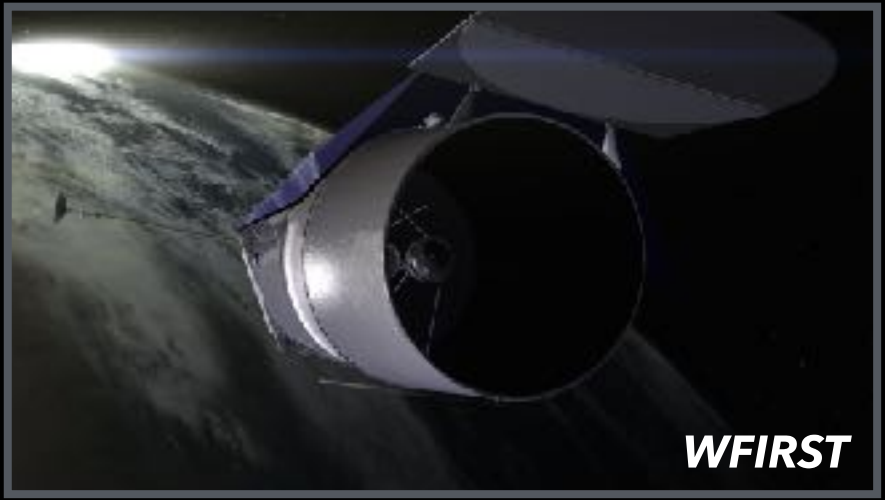
$\longrightarrow M_{BH} \sim 10^5 M_{sun}$

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

Volonteri & Reines 2016

Elusive AGN in the Next Era

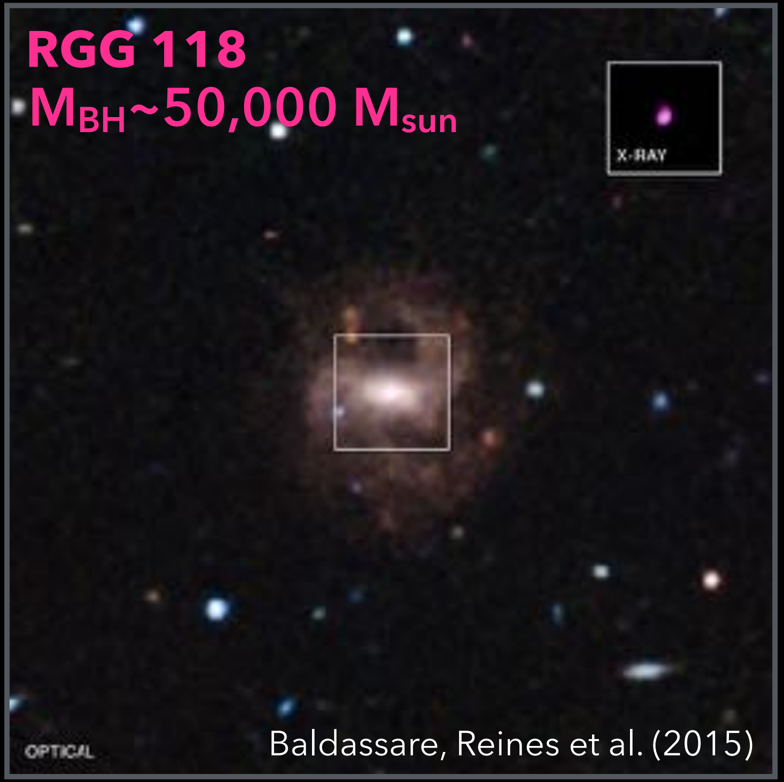




Elusive AGN in the Next Era

Observational constraints on the origin of BH seeds come from two extreme regimes:

High-z quasars with giant BHs pose a challenge for models of BH formation and growth



Dwarf galaxies at z~0 provide the most concrete limits on the masses of BH seeds

Samples will continue to grow in the next era

Summary

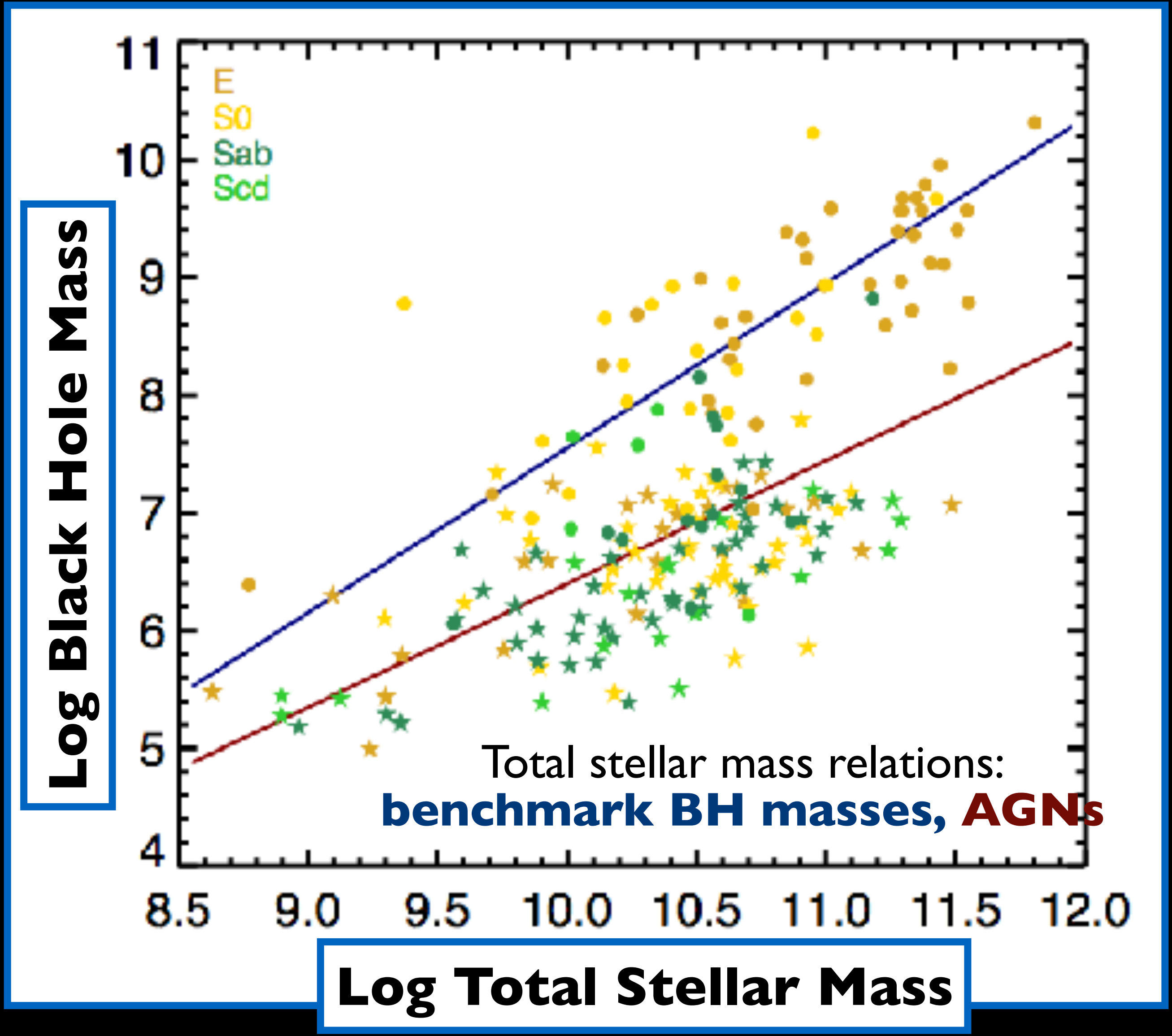
- Contrary to conventional wisdom, dwarf galaxies can host massive BHs.
- Dwarf galaxies hold clues to the formation of the first seed BHs.
- We are finding the smallest BHs known in galaxy nuclei ($\sim 10^4$-10^5 M_{sun}).
- Identifying BHs in dwarf galaxies is challenging. Beware of contamination from stellar processes (starbursts, SNe, SNRs, XRBs)!
- The scaling between BH mass and total stellar mass in local AGN host galaxies can explain current lack of AGN detections in high-redshift, low-mass galaxies.
- With upcoming telescopes and surveys, we will start to reveal more of these elusive AGNs.

extra slides…

LOCAL BH-TO-TOTAL STELLAR MASS RELATIONS

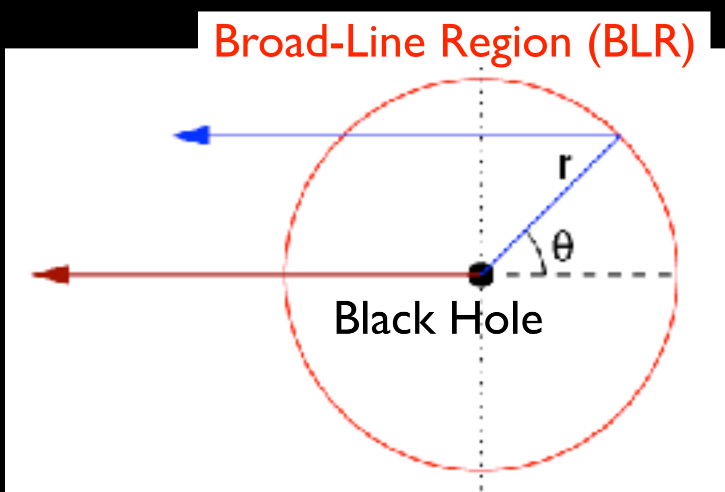
(REINES & VOLONTERI 2015)

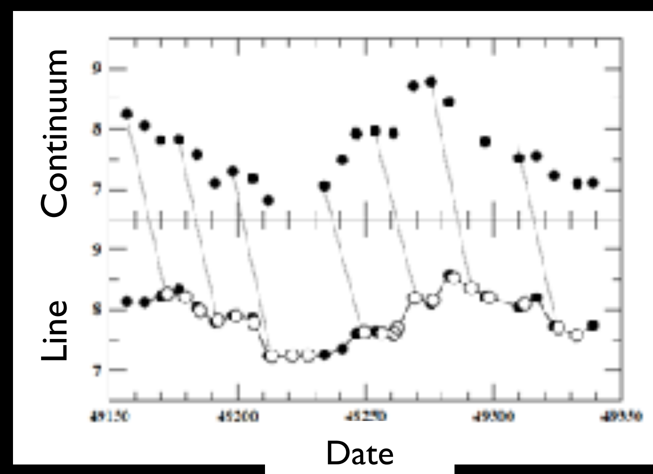
Approximate morphological types:

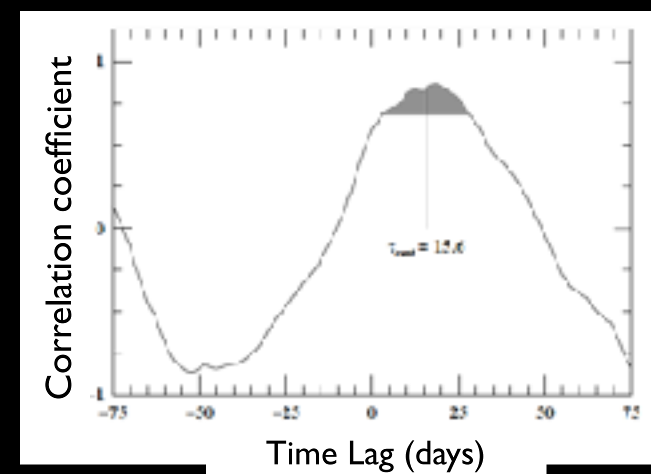


Estimating black hole masses for AGN with broad H-alpha

- Assume motion of broad-line emitting gas is dominated by gravity of BH: $M_{BH} \sim R V^2 / G$
- Need velocity (from line width) and radius (more complicated...)
- Radius of broad-line region measured for ~50 AGN using reverberation mapping
- For reverberation-mapped AGN, correlation between radius and luminosity
- For other AGN, we use the luminosity of broad H-alpha as a proxy for radius



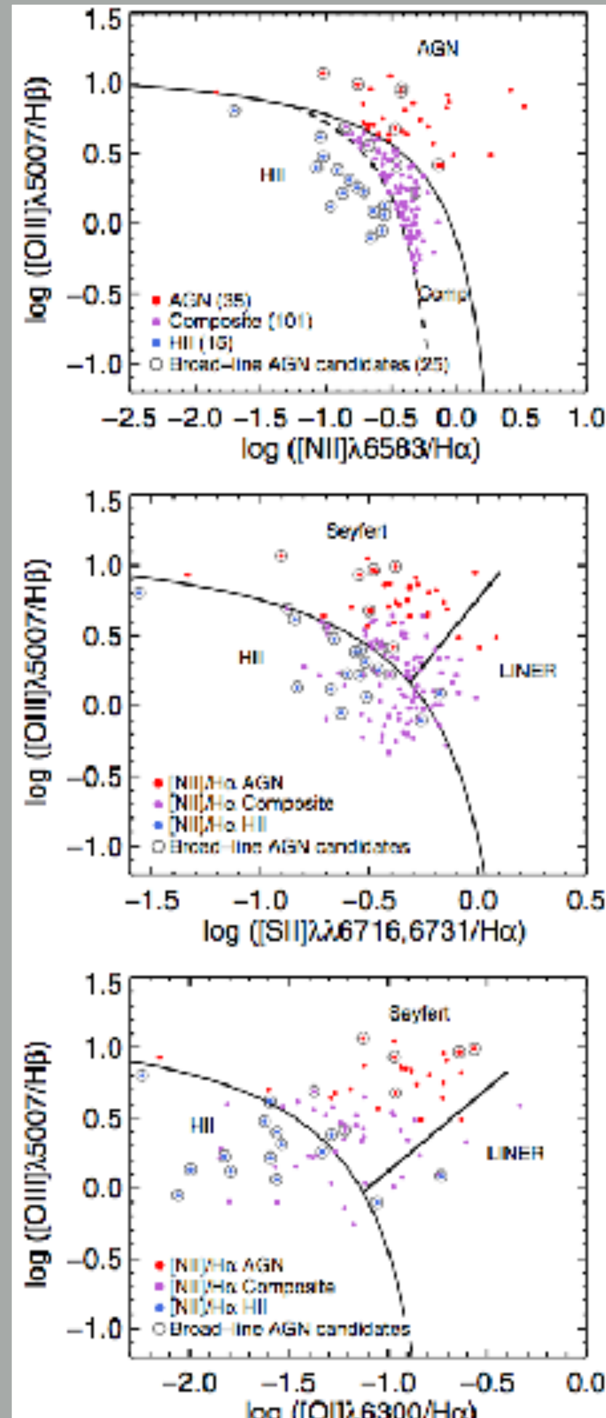




(Peterson 2001)

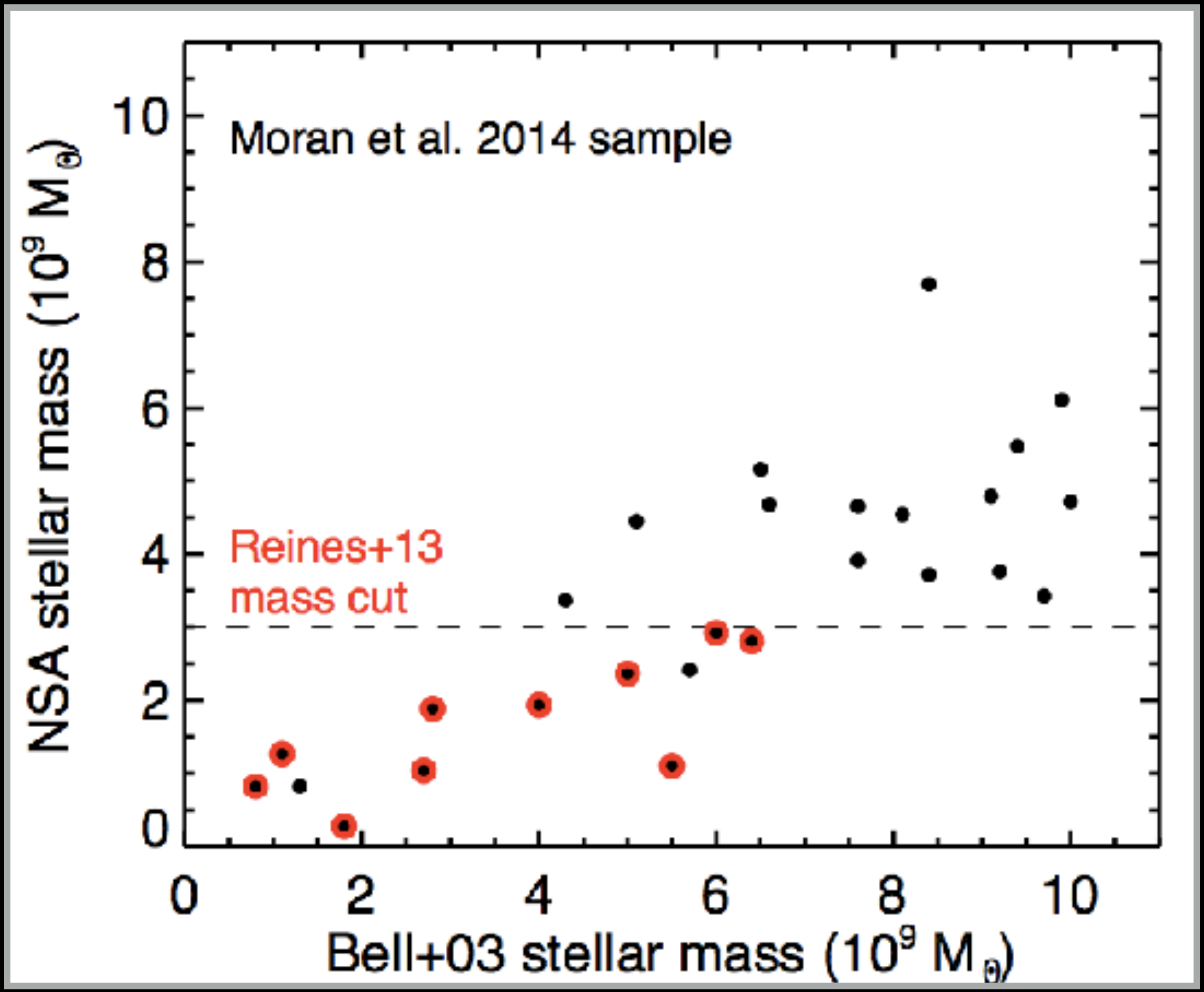
$$\log\left(\frac{M_{BH}}{M_\odot}\right) = \log \epsilon + 6.57 + 0.47 \log\left(\frac{L_{H\alpha}}{10^{42}\ \mathrm{erg\ s^{-1}}}\right) + 2.06 \log\left(\frac{\mathrm{FWHM}_{H\alpha}}{10^{3}\ \mathrm{km\ s^{-1}}}\right)$$

(Reines et al. 2013, equation 5)



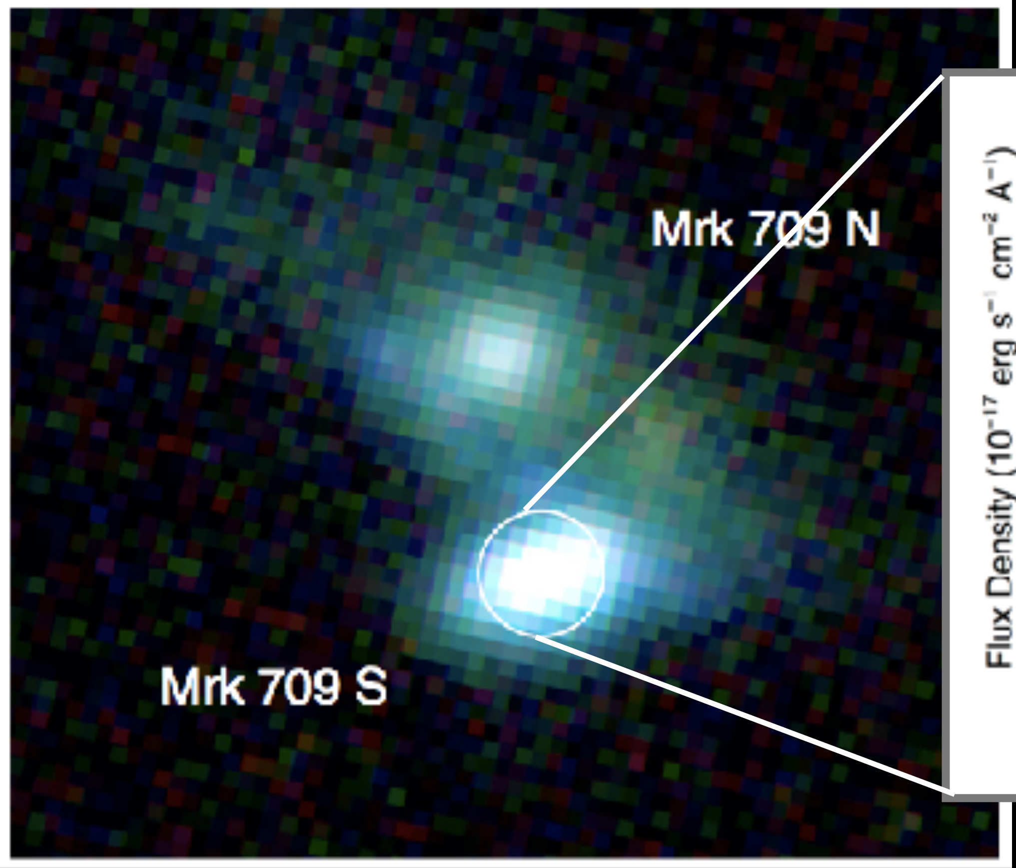
AGN
HII
Comp
AGN (35)
Composite (101)
HII (16)
Broad-line AGN candidates (25)
log ([OIII]λ5007/Hβ)
log ([NII]λ6583/Hα)
Seyfert
LINER
[NII]/Hα AGN
[NII]/Hα Composite
[NII]/Hα HII
log ([SII]λλ6716,6731/Hα)
log ([OI]λ6300/Hα)

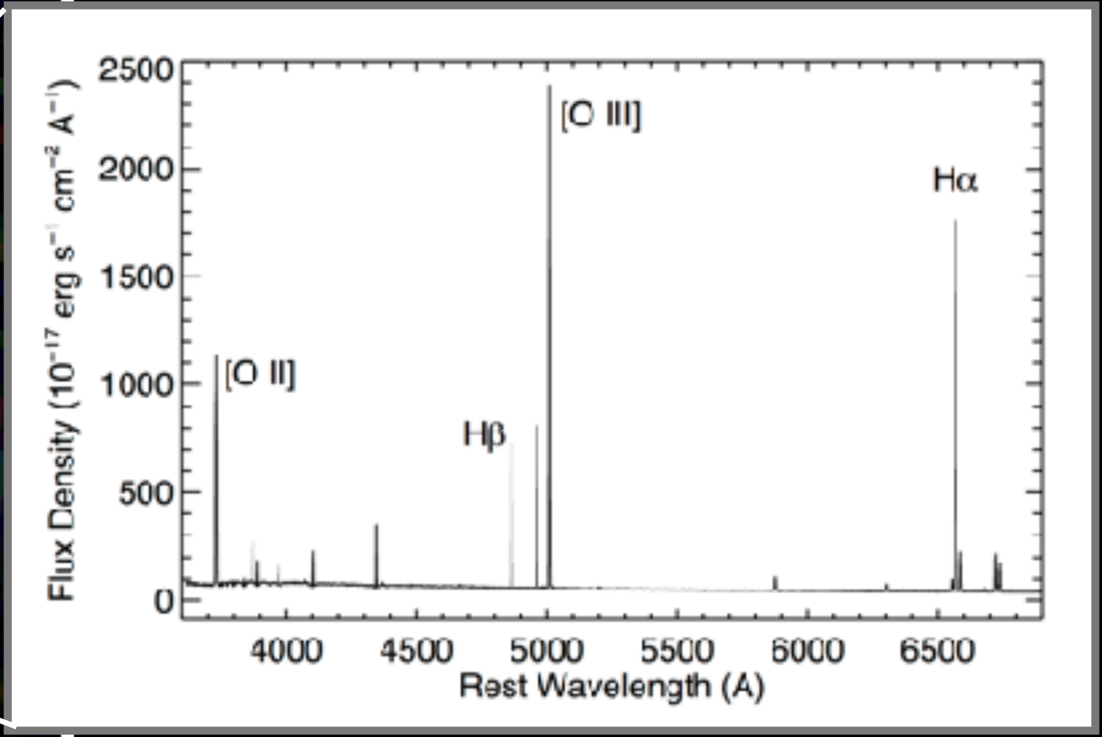
Dwarf galaxies with optical signatures of active massive BHs



Reines+13	Moran+14
M < 3e9 Msun (from NSA)	M < 1e10 Msun (from Bell+03)
D < 225 Mpc	D < 80 Mpc
35 AGN + 101 Comp.	28 AGN

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





SDSS spectrum

Reines et al. 2014

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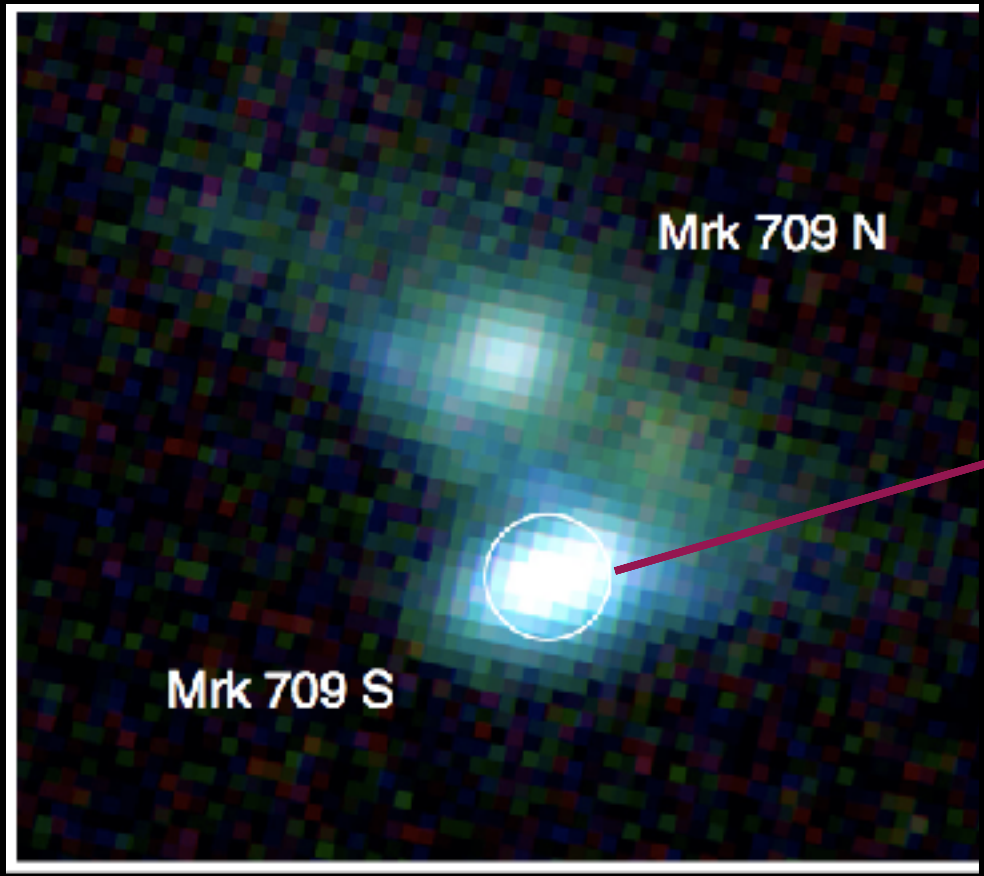

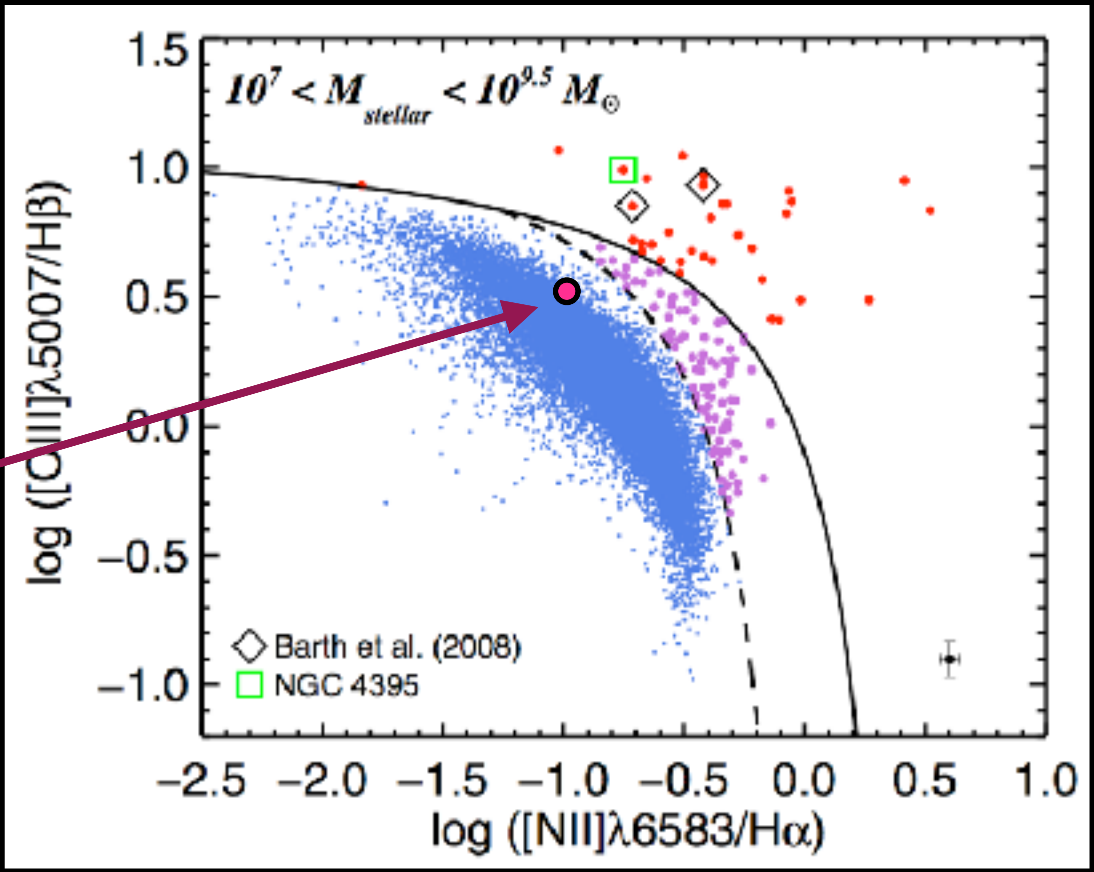

diagnostic diagram from Reines et al. 2013

Reines et al. 2014