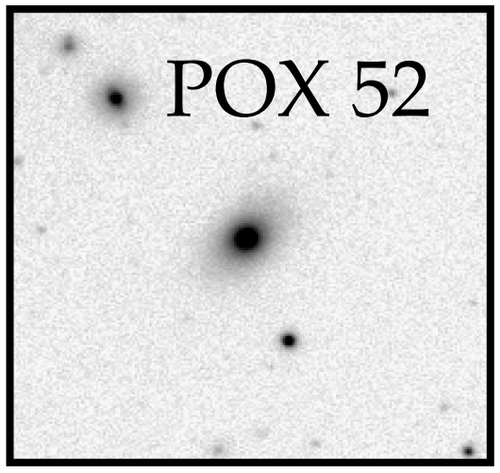
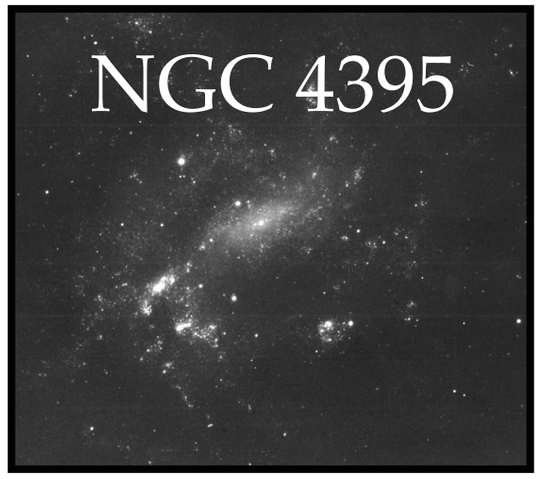




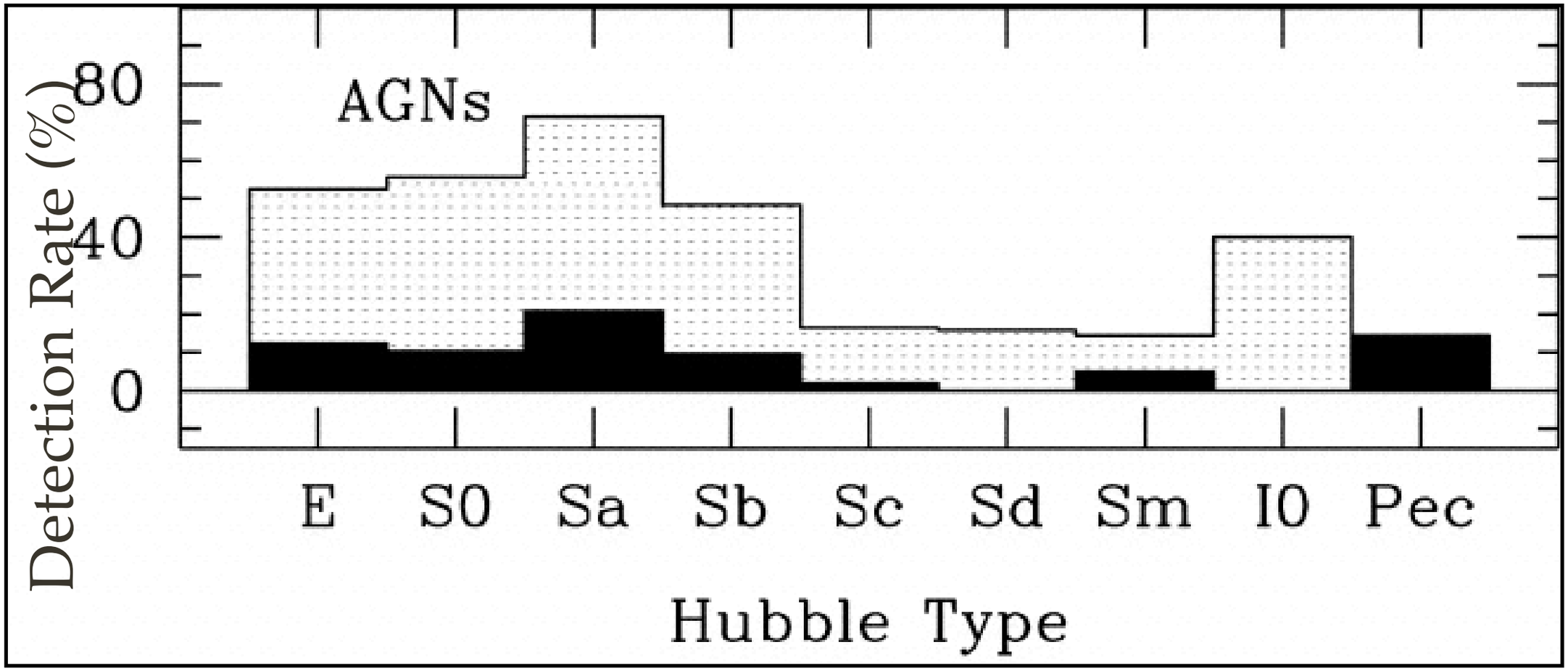
Low-mass Black Holes in Galaxy Centers

Jenny Greene (Princeton)

Luis Ho (Carnegie), Aaron Barth (UC Irvine), Carol Thornton (UC Irvine), Jim Ulvestad (NSF), Joan Wrobel (NRAO), Ting Xiao (UC Irvine), Yanfei Jiang (Princeton), Cheng-Yu Kuo (UVa)

BH Demographics

Ho, Filippenko, & Sargent 1997



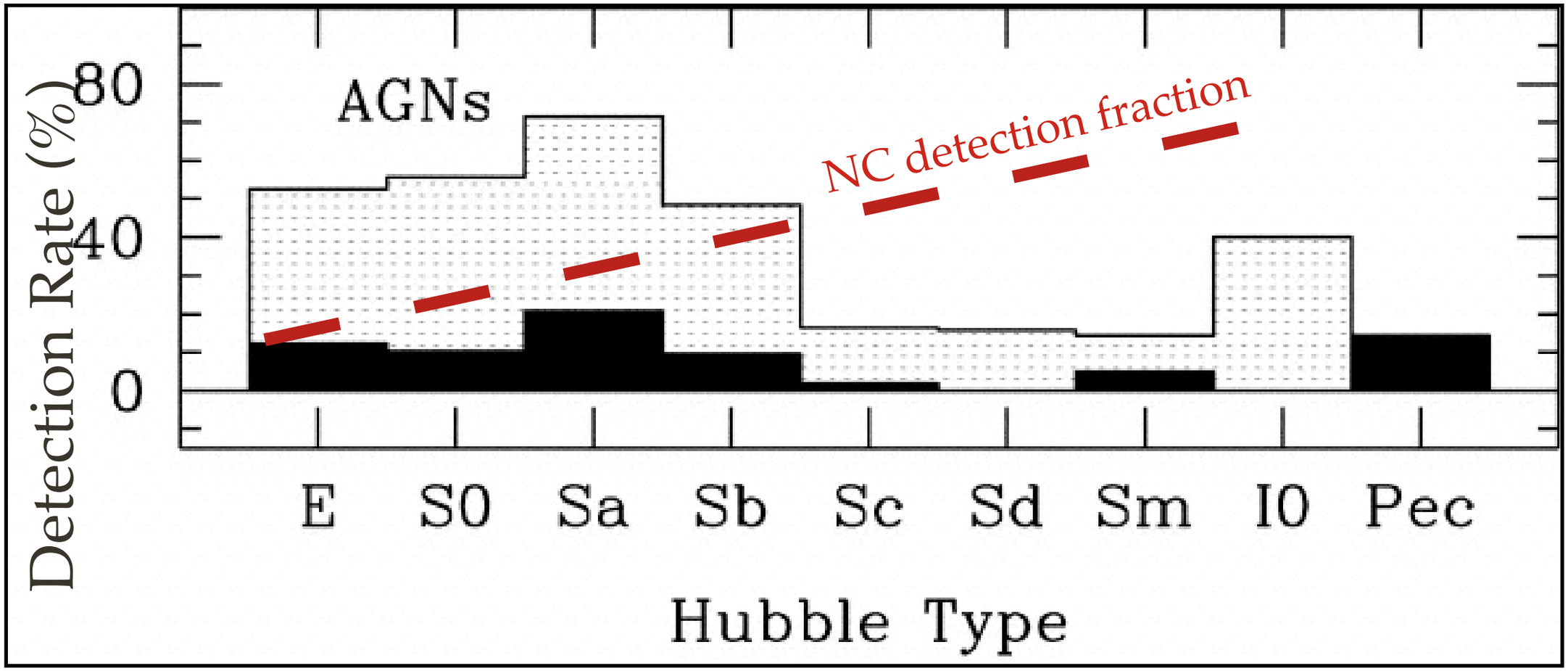
- AGNs in 60% of galaxies earlier than Sbc:

BHs are ubiquitous in early-type galaxies

- Reverse is true for nuclear star clusters

BH Demographics

Ho, Filippenko, & Sargent 1997



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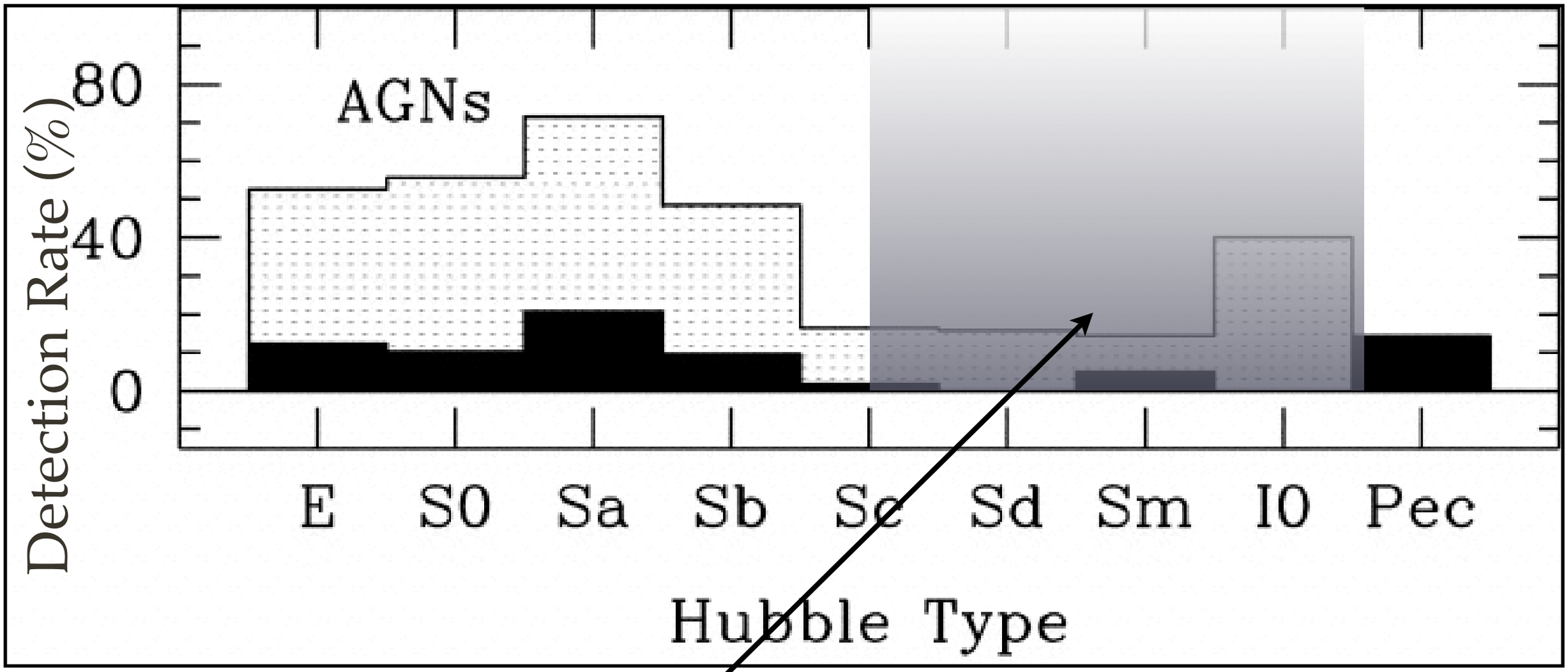


Optical spectroscopic searches plagued with incompleteness due to star formation, dust, and flux limits

When do NCs and BHs coexist? Are they physically related?

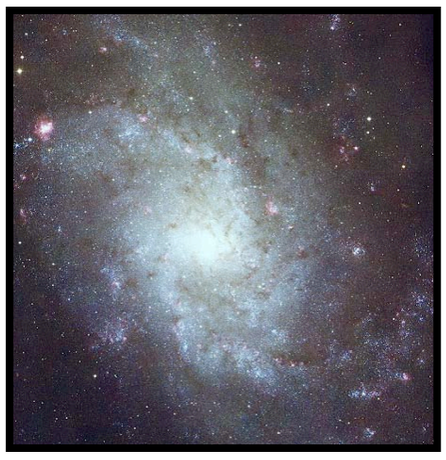
1. A solid handle on BH demographics in late-type galaxies and at low BH mass
2. Do BH masses scale with galaxy (or NC?) properties at low mass?

We do not (yet) know the space density or occupation fractions of low-mass BHs.

Search Techniques ($10^5\ M_\odot$ BHs)

- Dynamical methods: *inactive or active BHs, limited to a few Mpc*
- Optical spectroscopy: *nuclear activity required, sensitive to dust and star formation*
- MIR spectroscopy: *nuclear activity required*
- X-ray spectroscopy: *nuclear activity required*
- tidal disruptions, gravitational radiation, high-resolution radio imaging, optical variability

Dynamics (I)

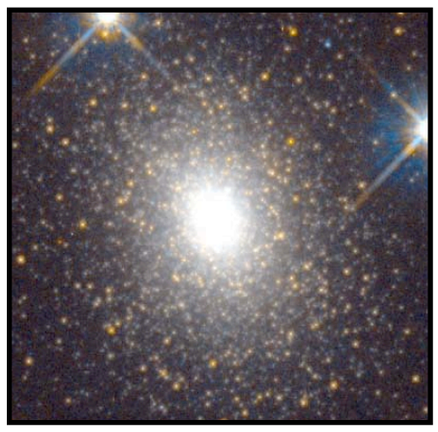


M33: Nuclear BH $< 1500\ M_\odot$

(Gebhardt et al. 2001)

NGC 205: Nuclear BH $< 20{,}000\ M_\odot$

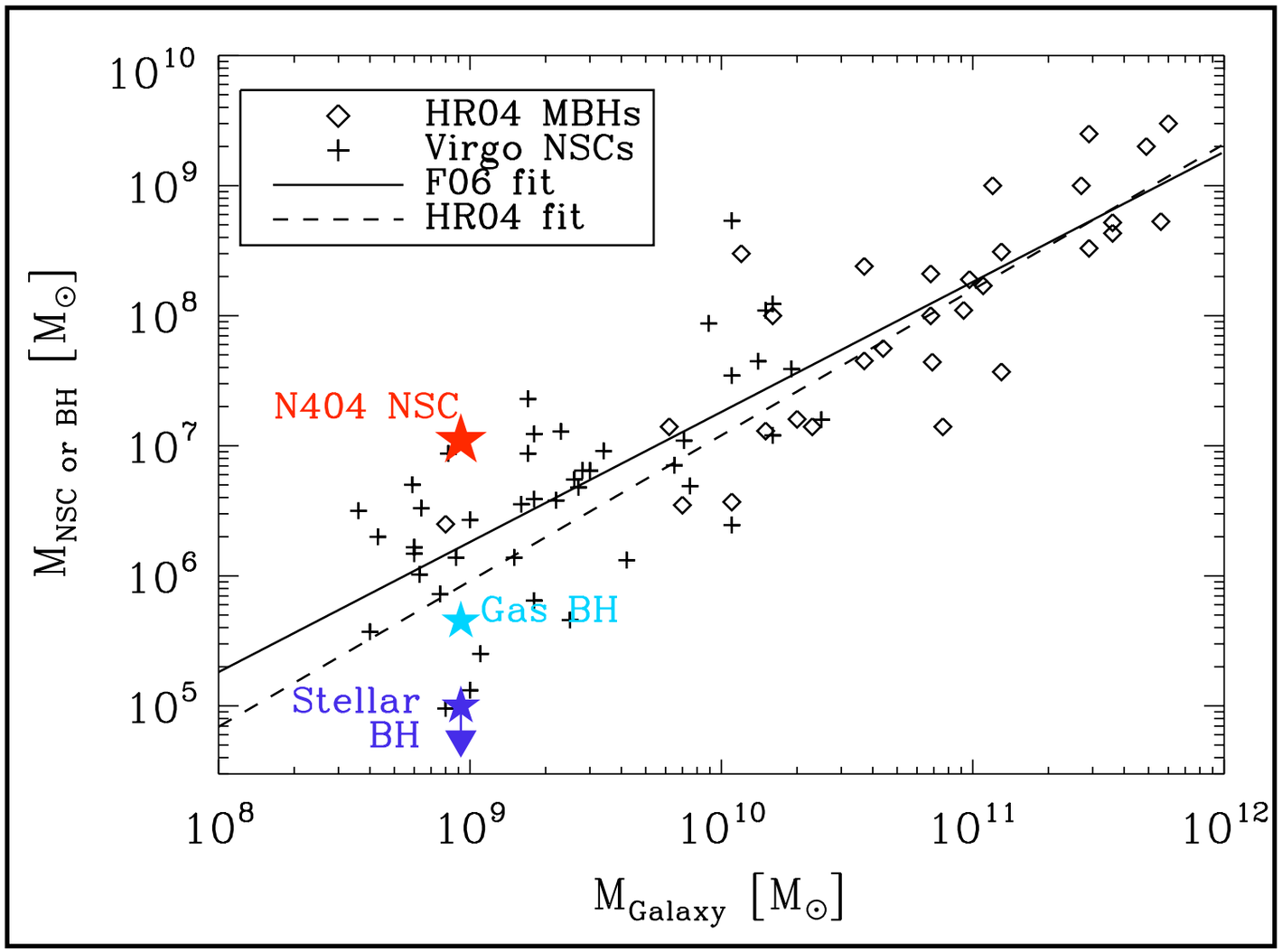
(Valluri et al. 2004)



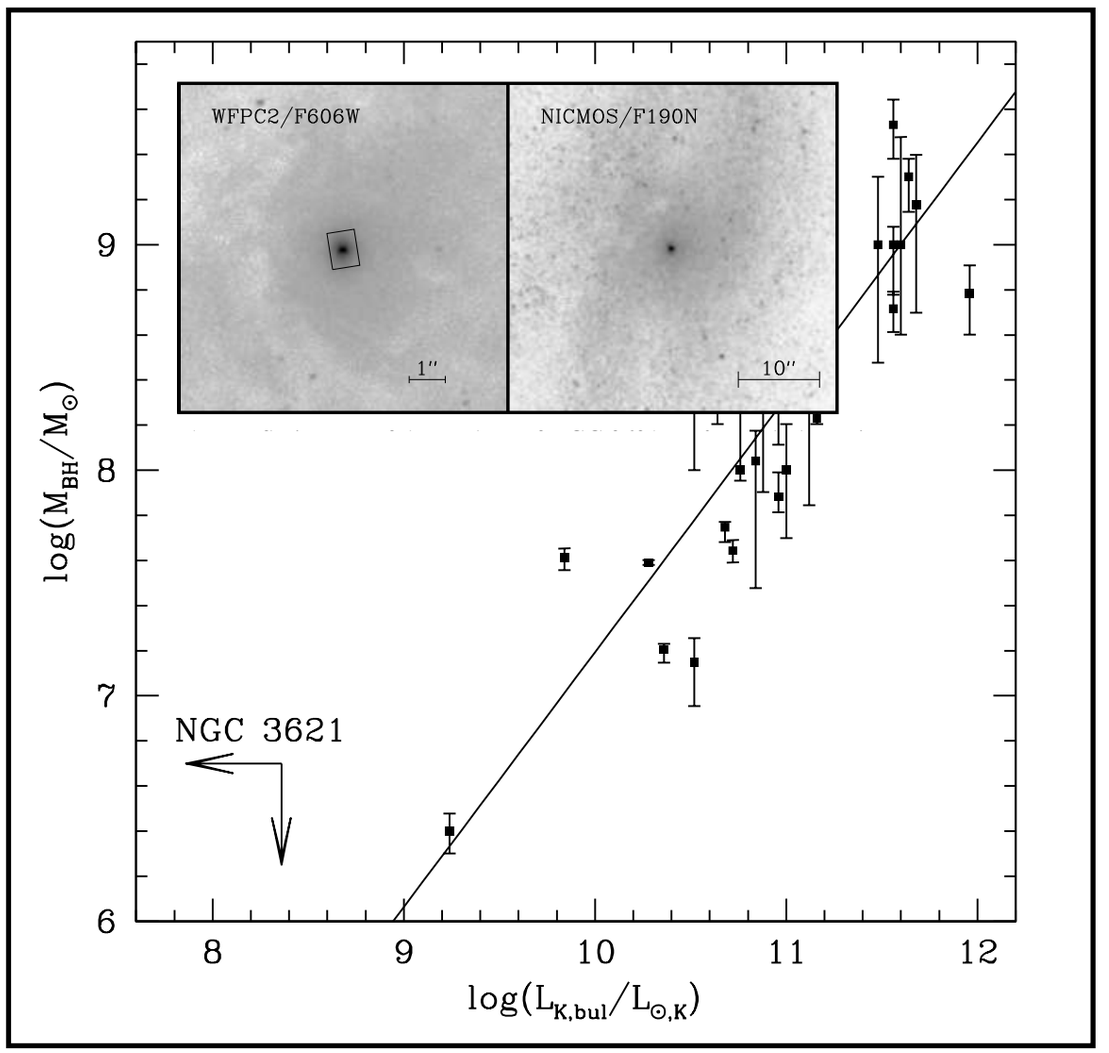
G1, Omega Cen, (other globular clusters?)

(Gebhardt et al. 2002, 2005; Noyola et al.)

Dynamics (II)

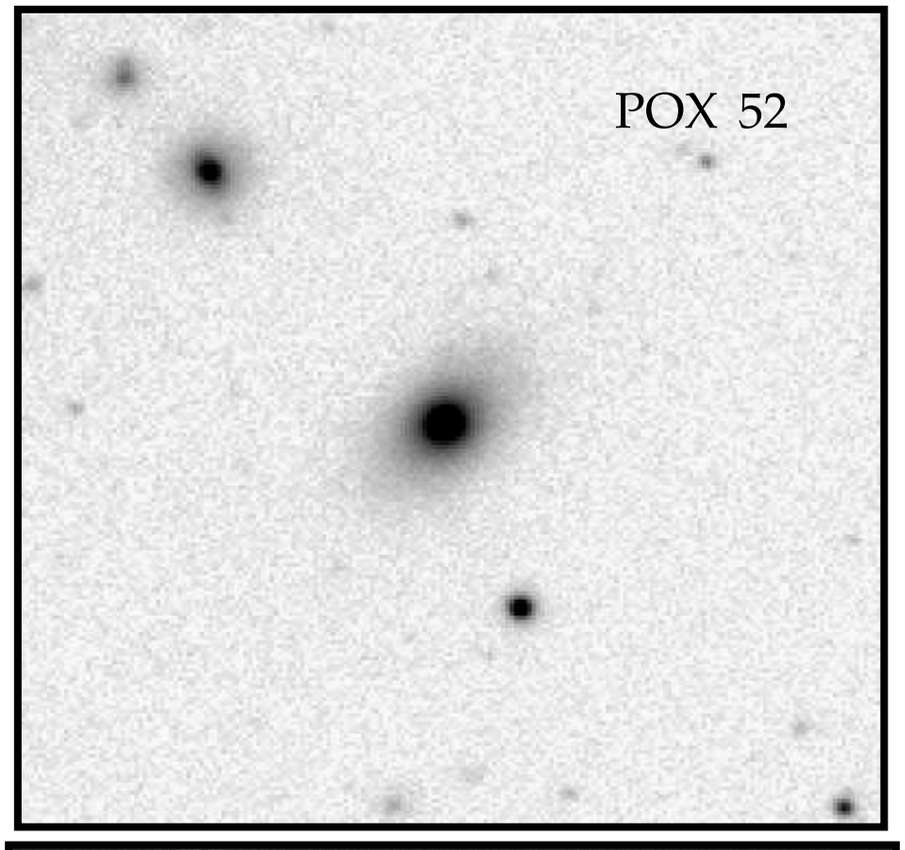


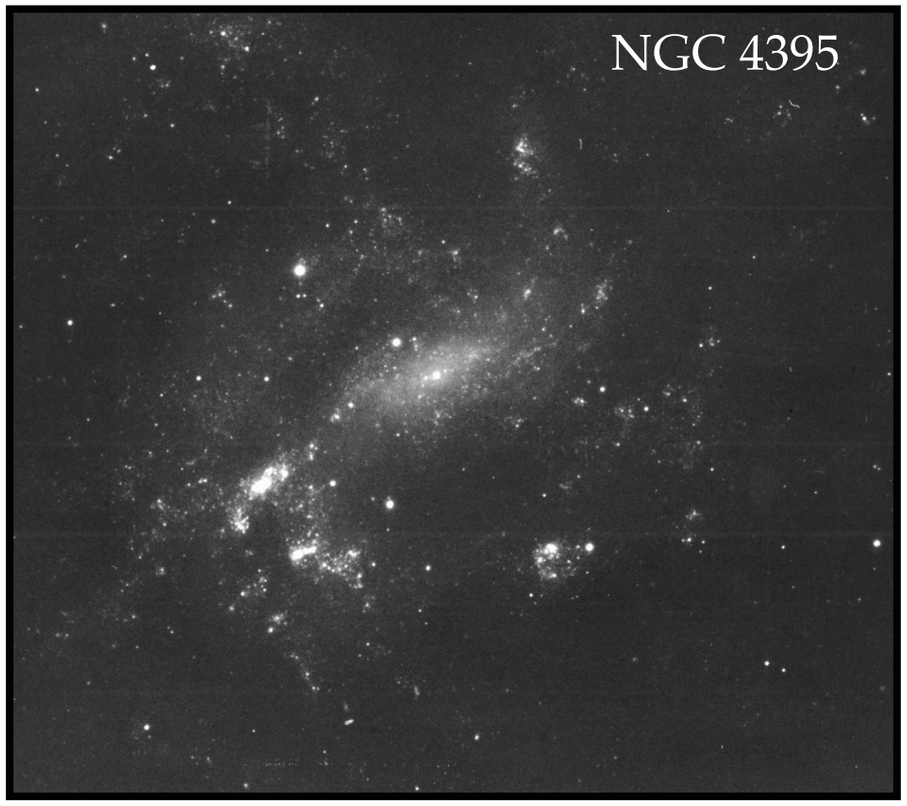
Seth et al. 2010



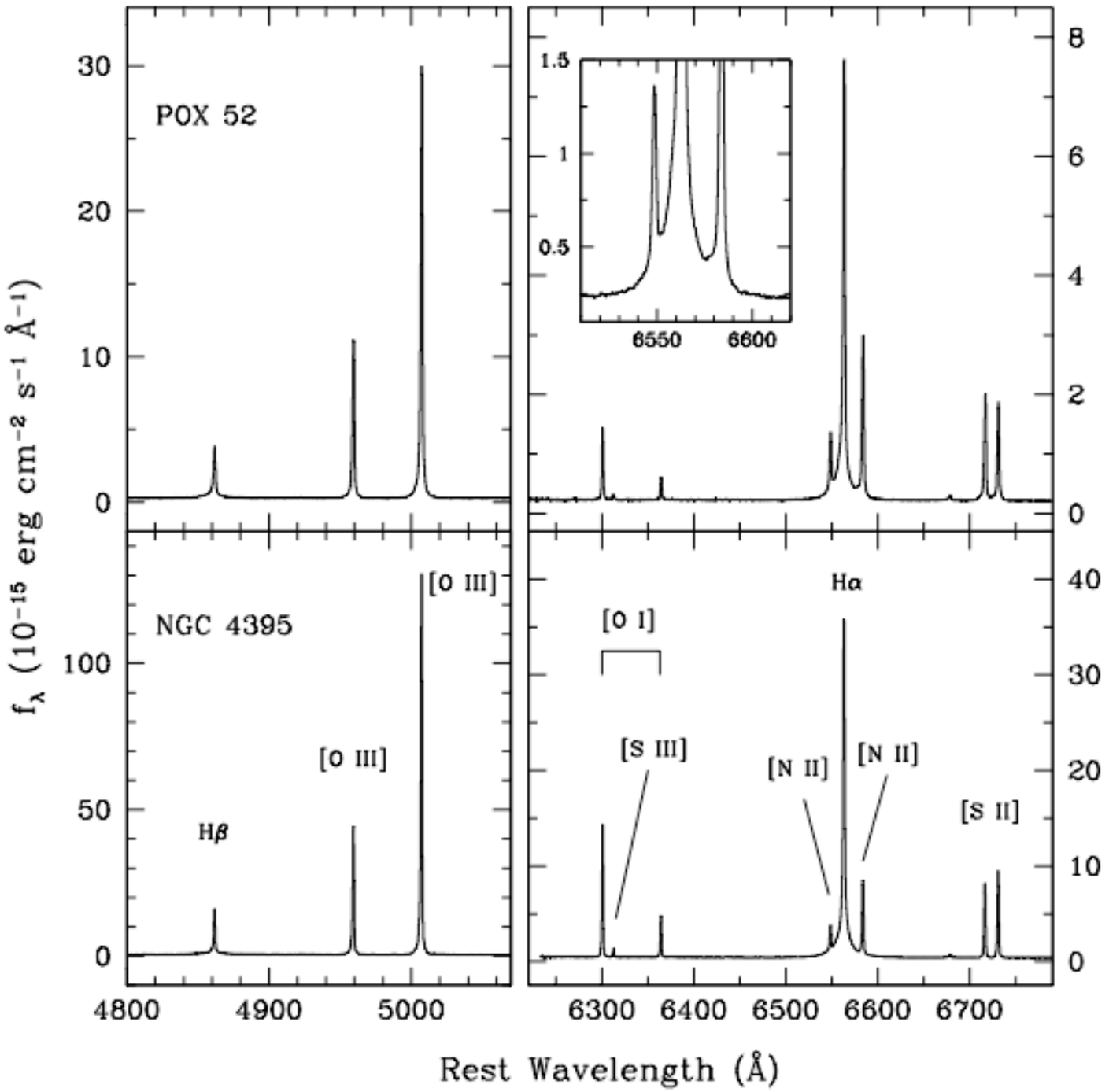
Barth et al. 2008

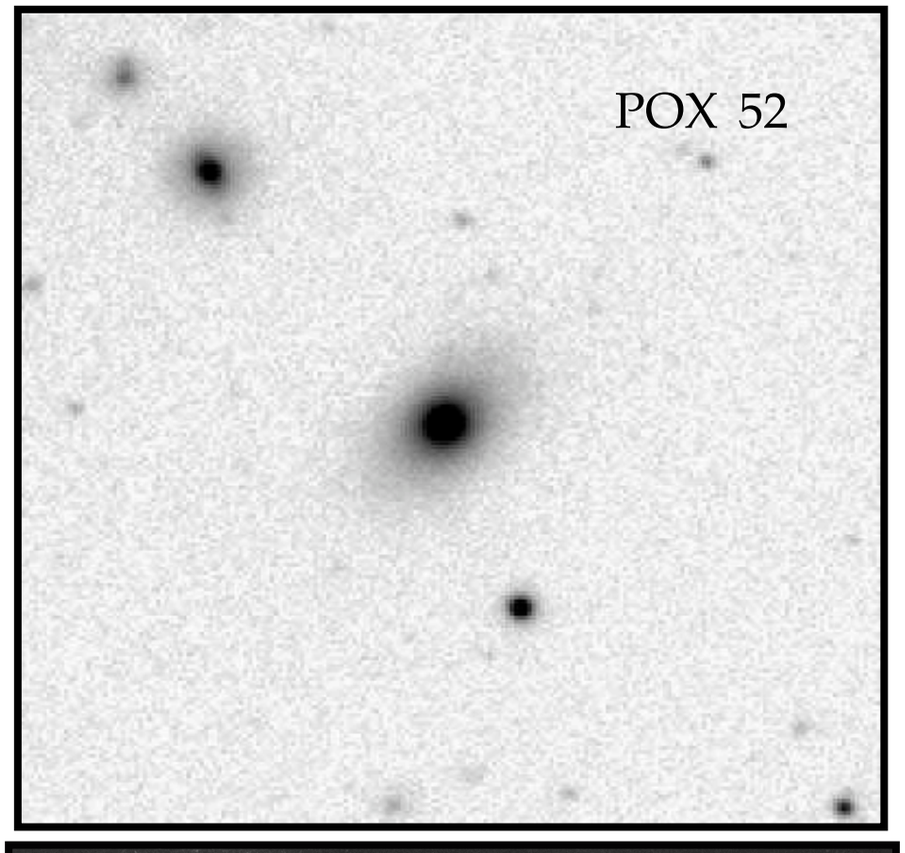
Optical Spectroscopy

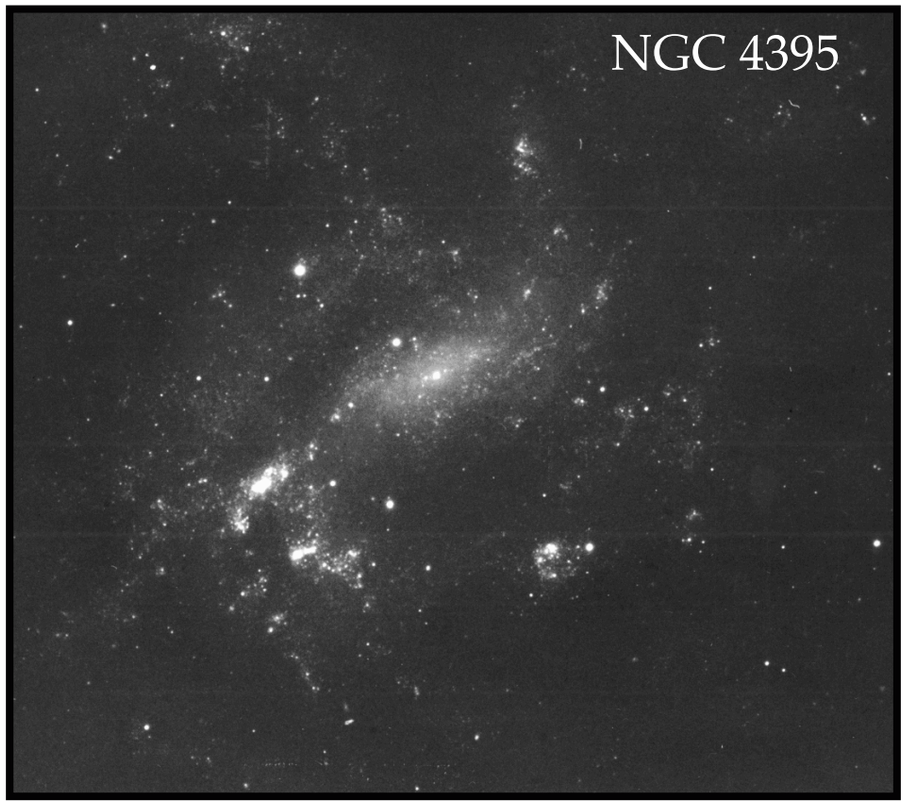




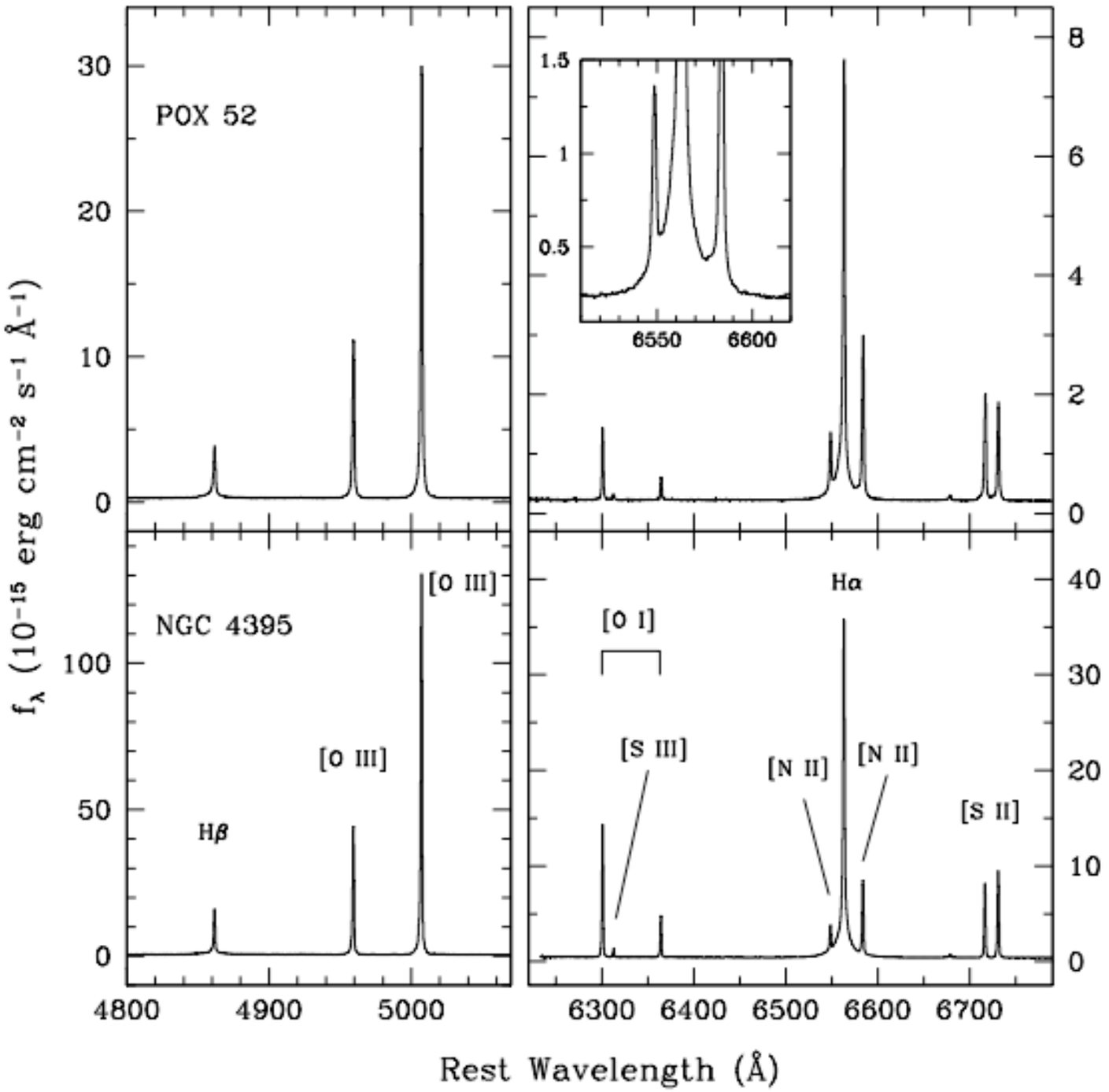
Barth et al. 2004







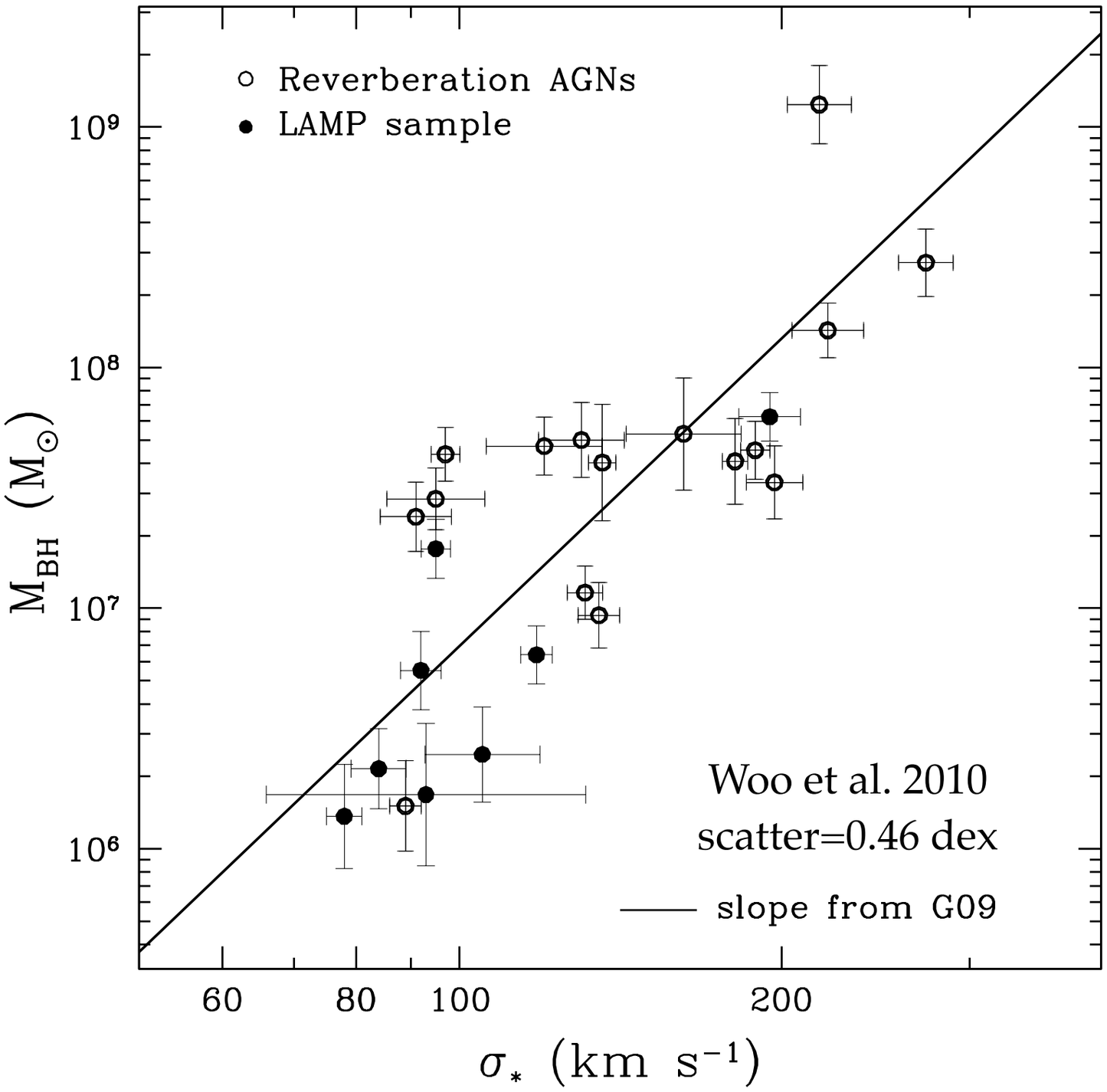
Barth et al. 2004



Both objects have $M_{BH} \sim 10^5\ M_\odot$

Neither have classical bulges.

BH Masses from AGNs



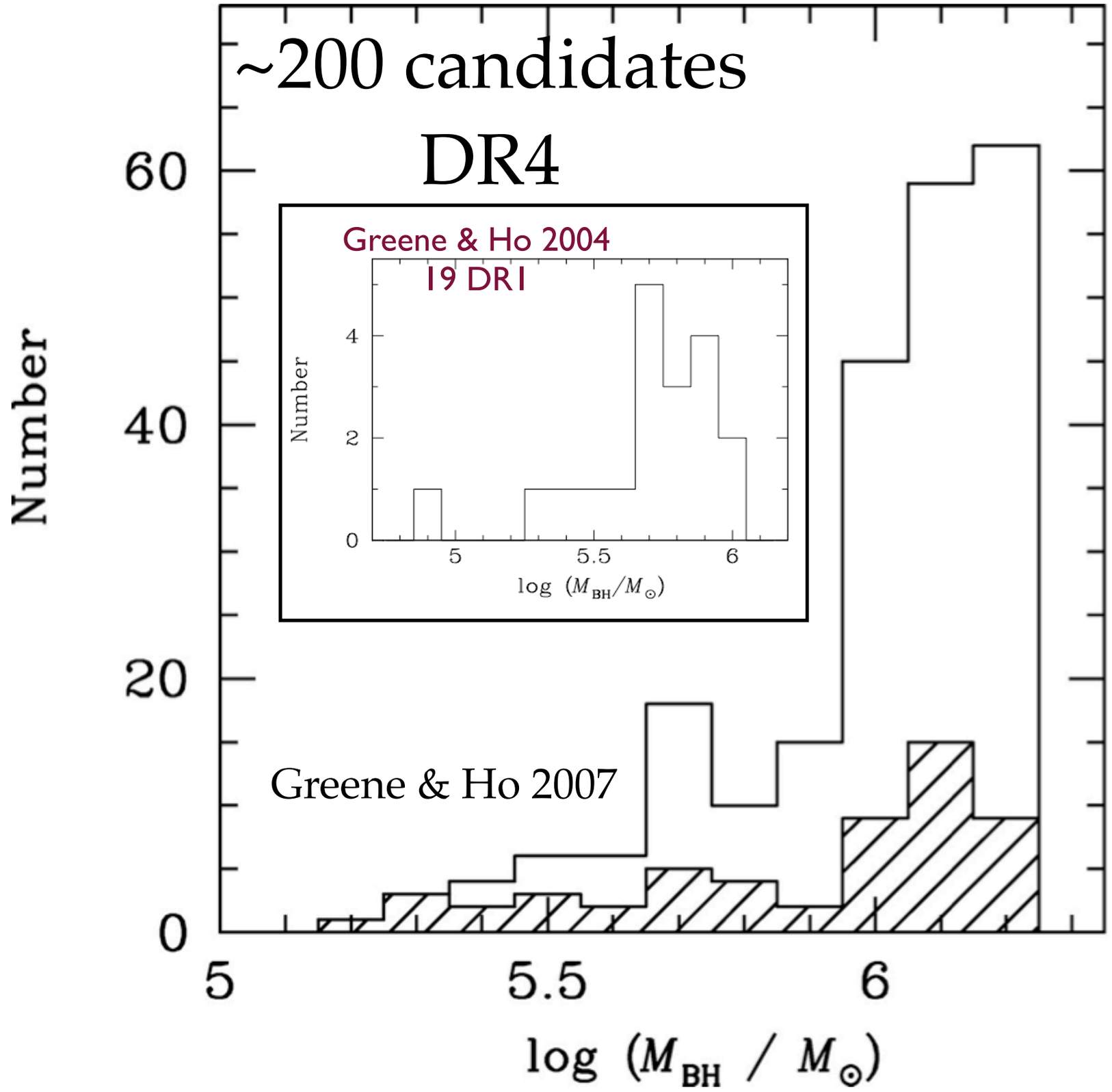
Broad-line region gas as dynamical tracer

Velocity from line-width

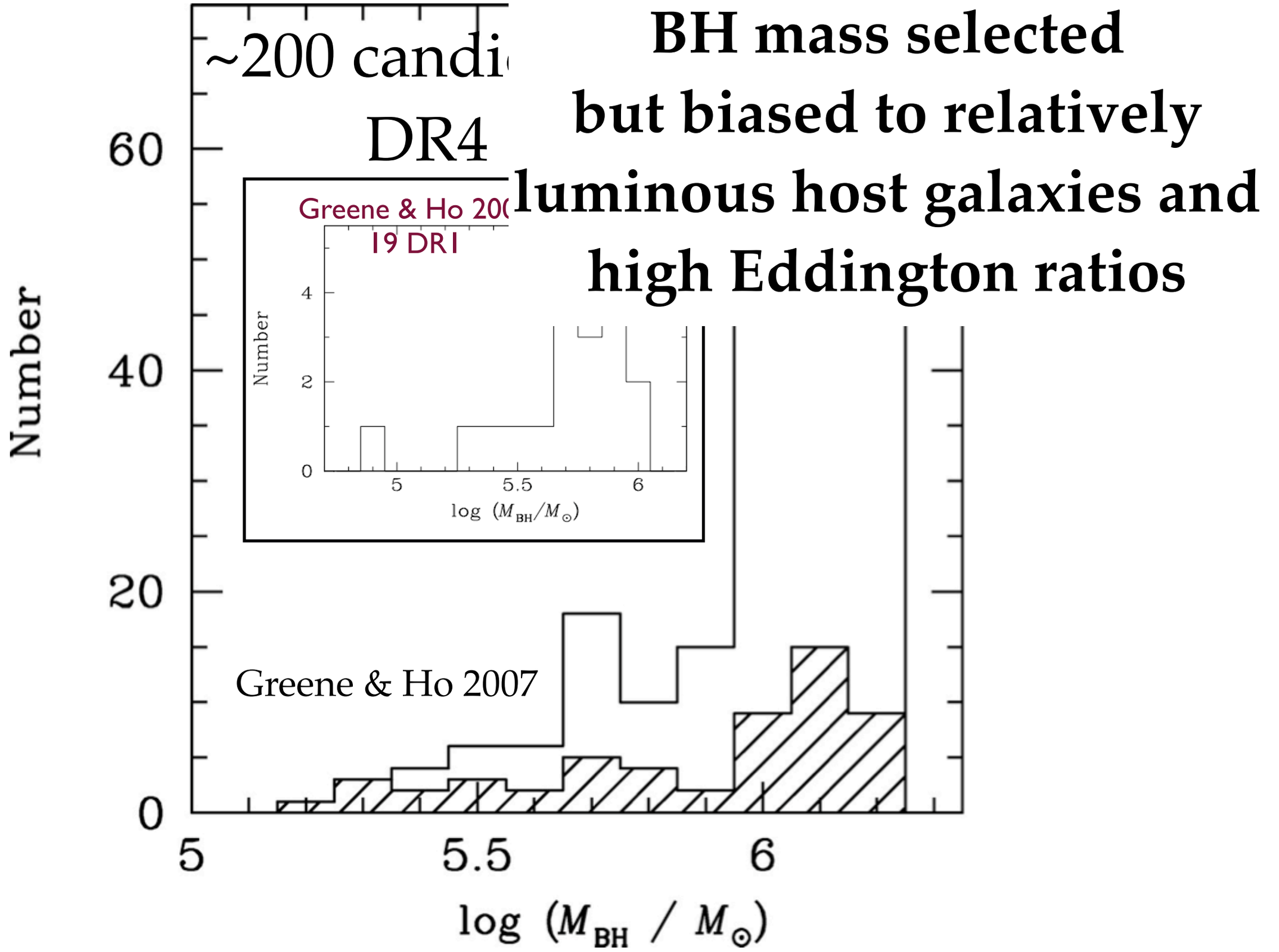
Radius from standard relations between AGN luminosity and BLR radius

Masses calibrated by comparison with M_{BH}-$\sigma_\star$

See also Onken et al. 2004, Greene & Ho 2006, Shen et al. 2008



See also Dong et al. for an alternate search technique

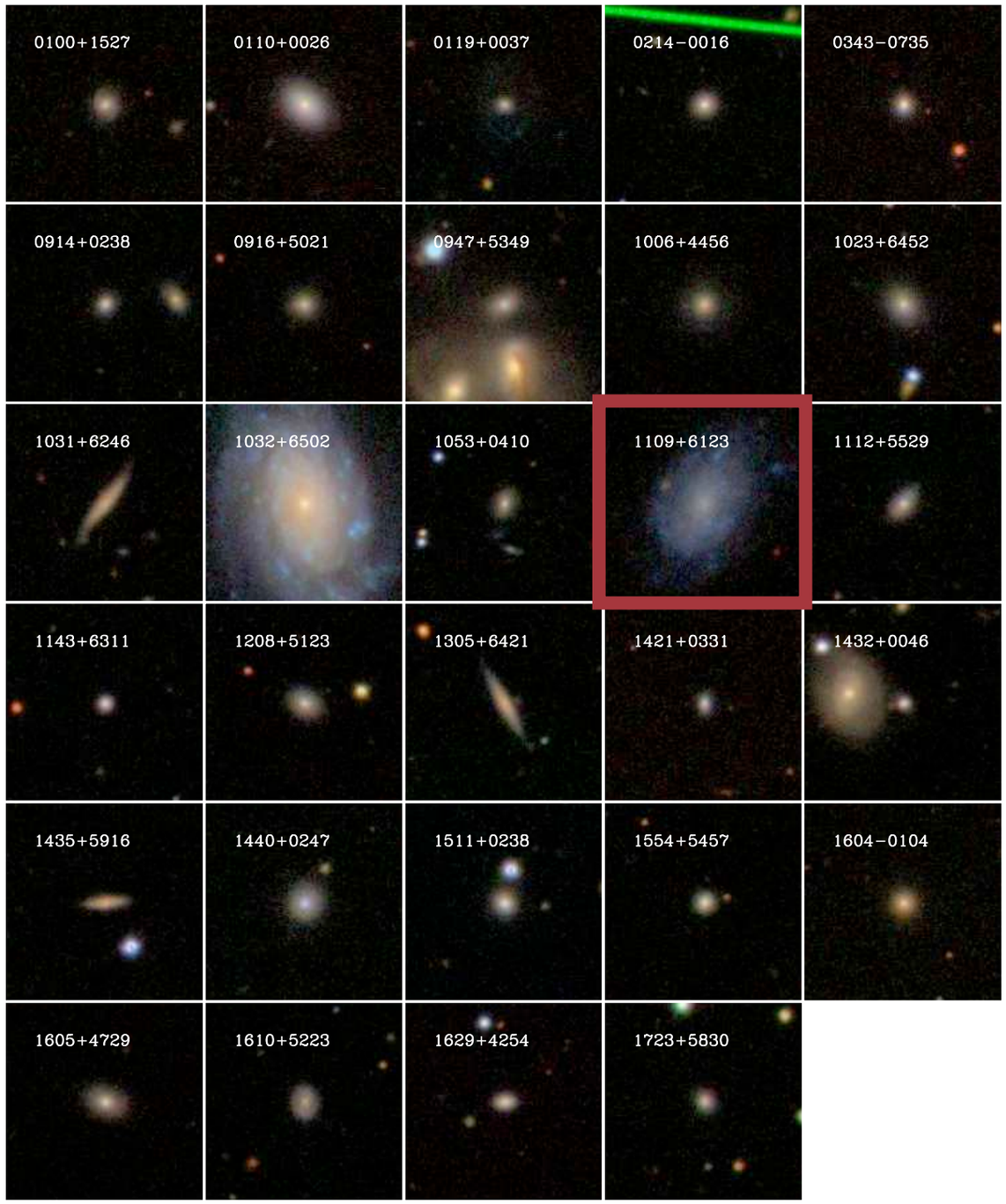


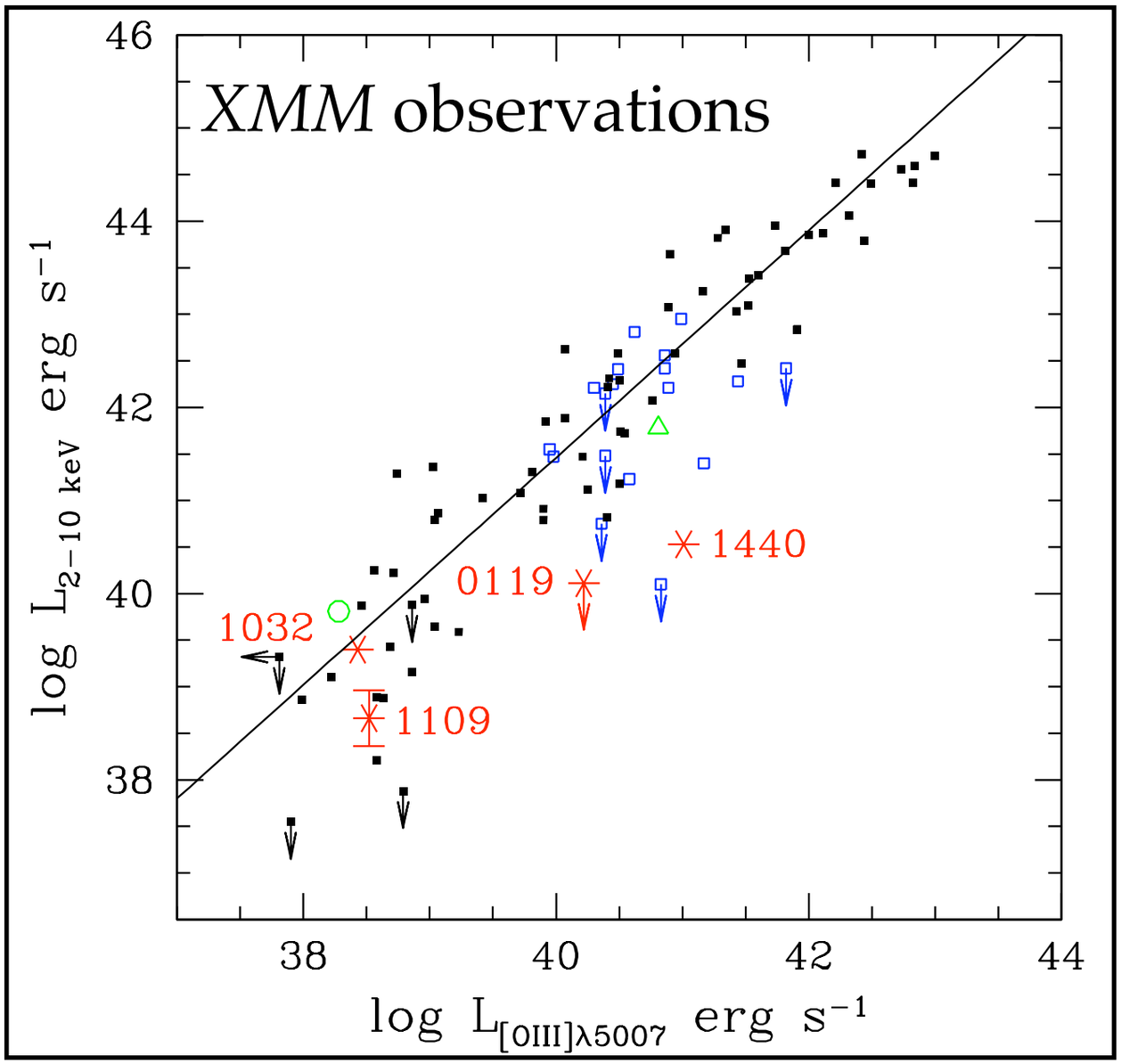
BH mass selected but biased to relatively luminous host galaxies and high Eddington ratios

See also Dong et al. for an alternate search technique

Narrow-line Counterparts From SDSS

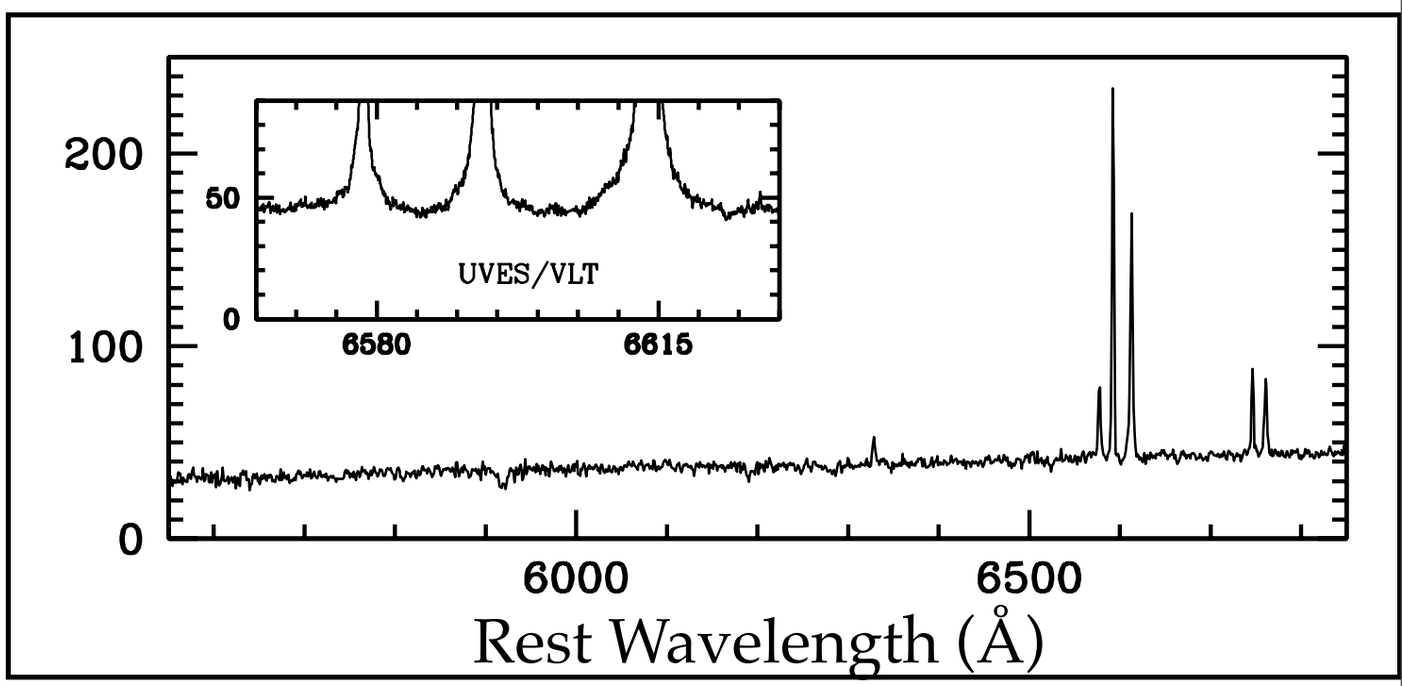
Barth, Greene, & Ho 2008





Thornton, Barth, Ho, & Greene 2009

NGC 1042
Optical Spectrum

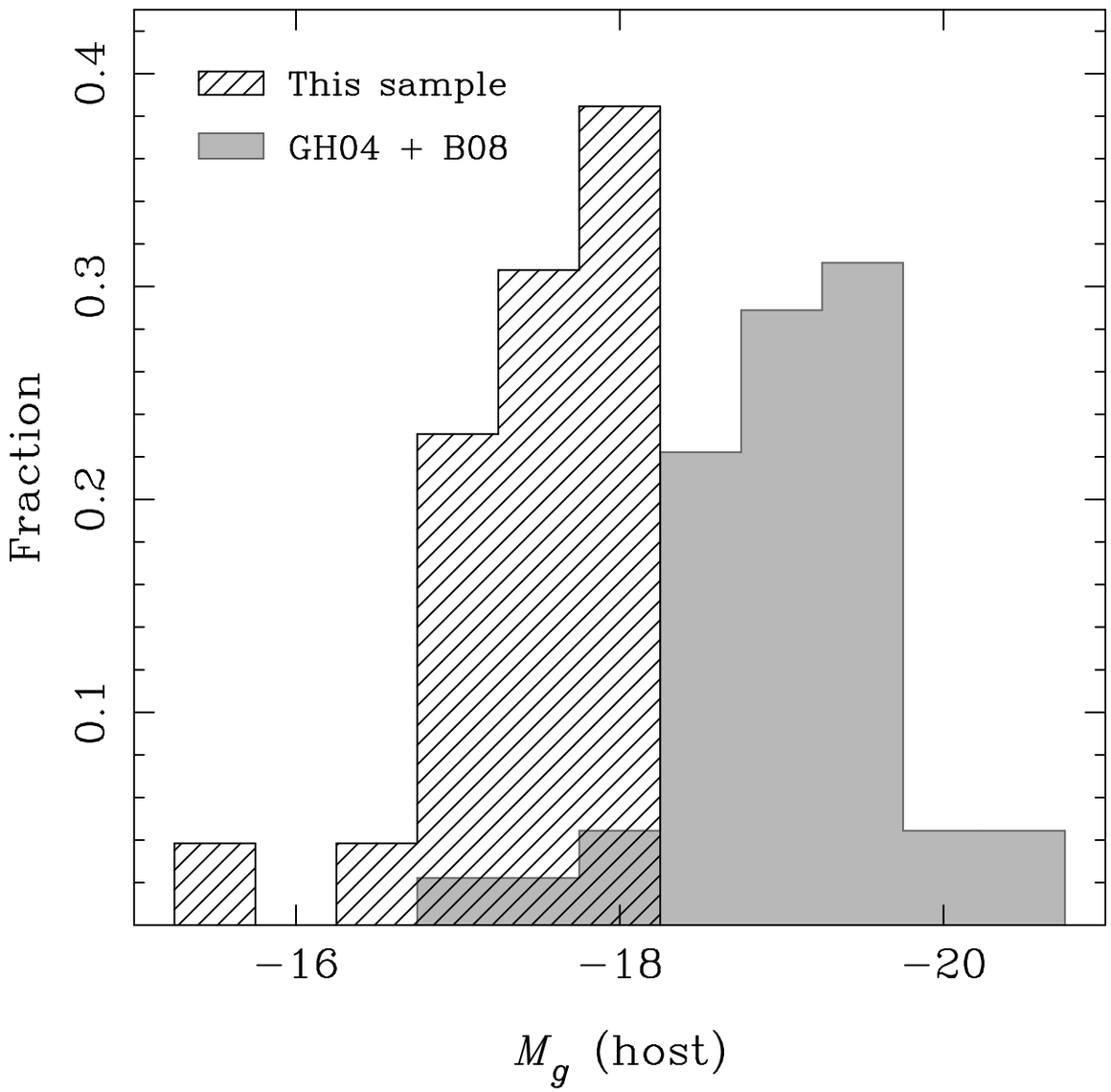


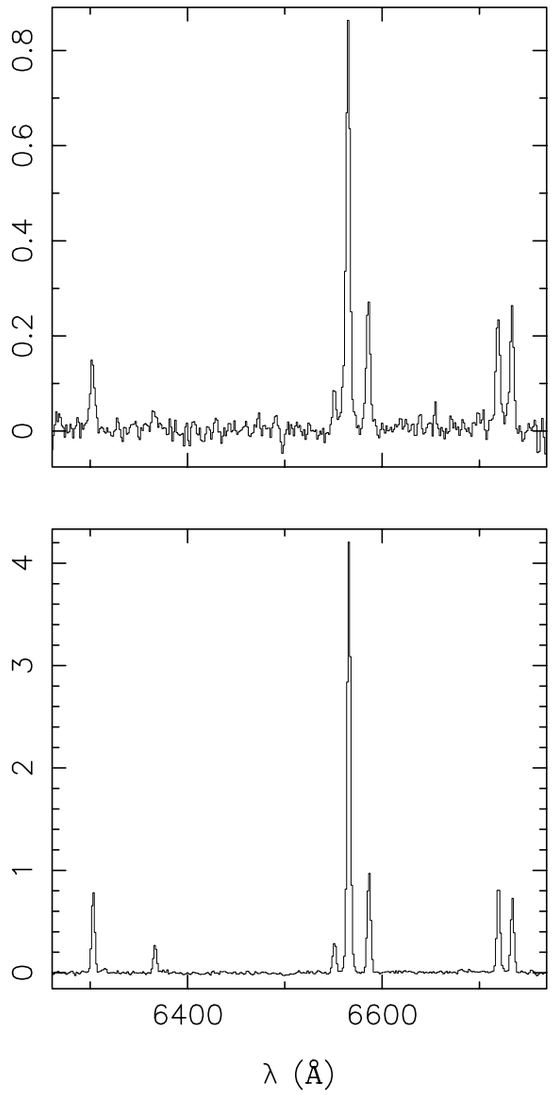
Shields et al. 2008

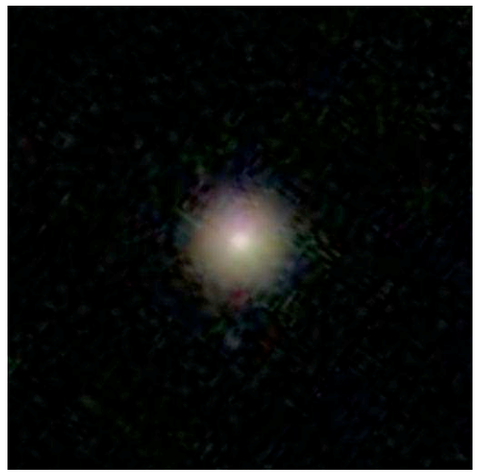
A New Volume-Limited Survey

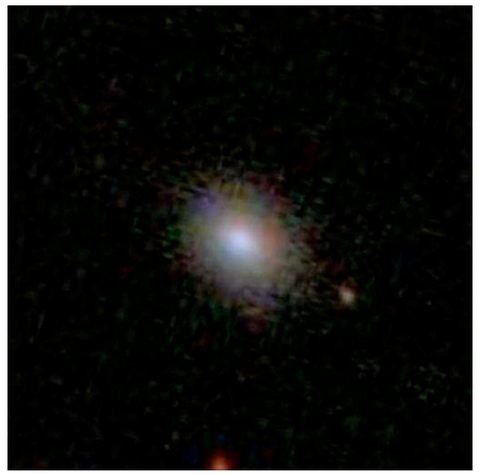
- PI: E. Moran
- Starts with all galaxies with M_g < -14 within 80 Mpc and redshifts in SDSS, ALFALFA, or NED
- Has spectra for all targets (either with SDSS or a large number of ground-based facilities)
- 24 new AGNs, no broad-line objects

Volume-limited Search



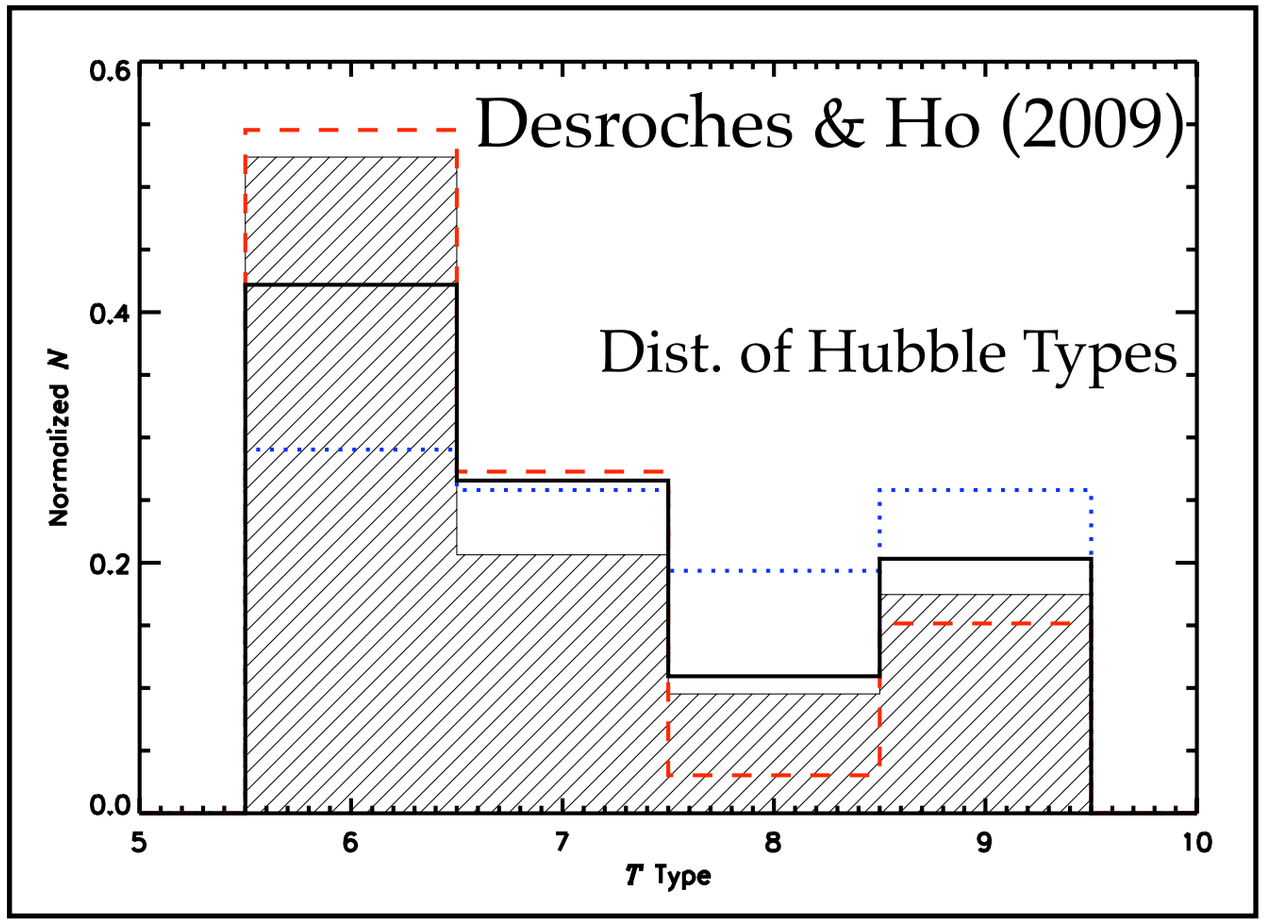






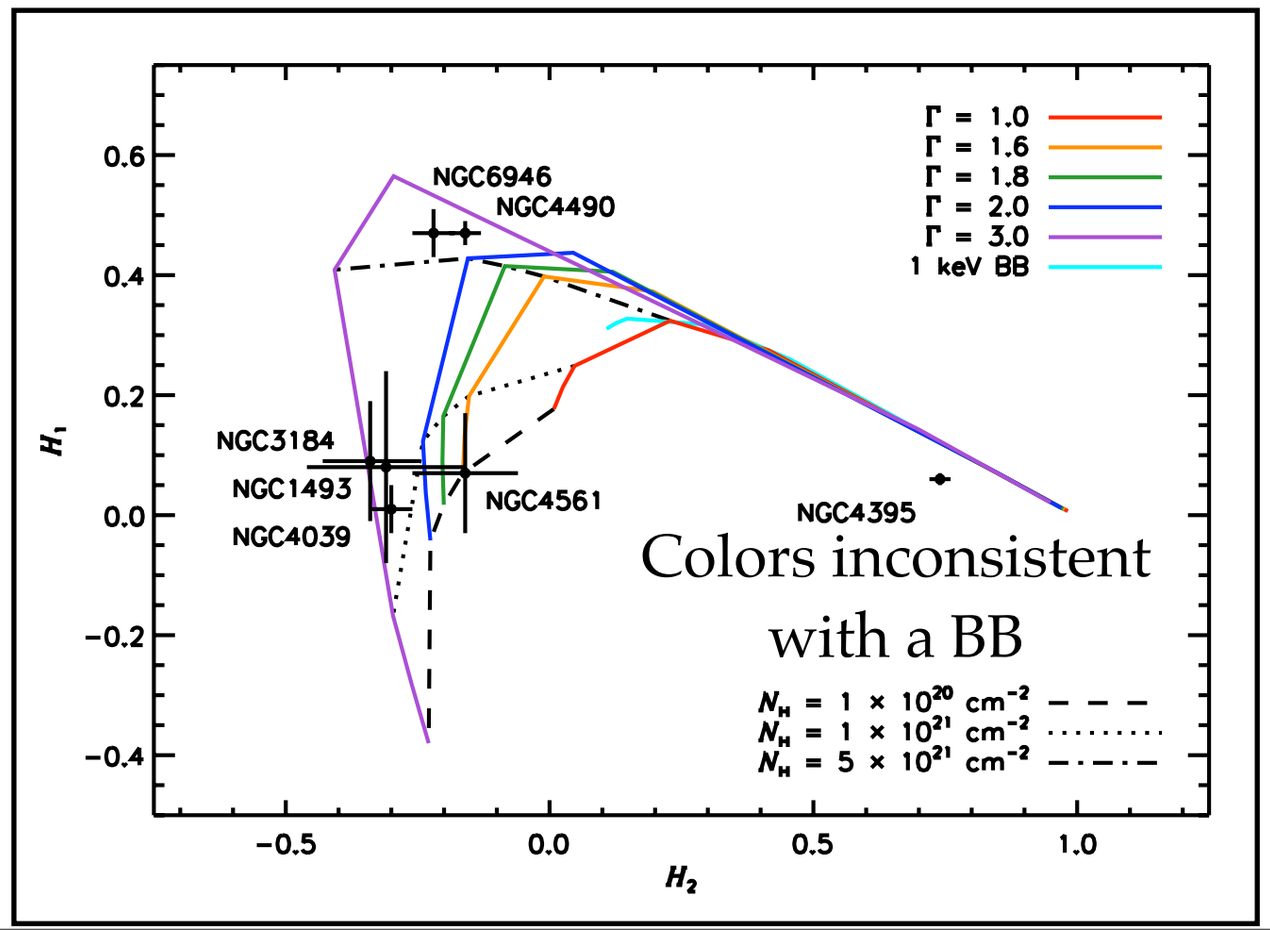
Moran et al. in prep

Multiwavelength Searches

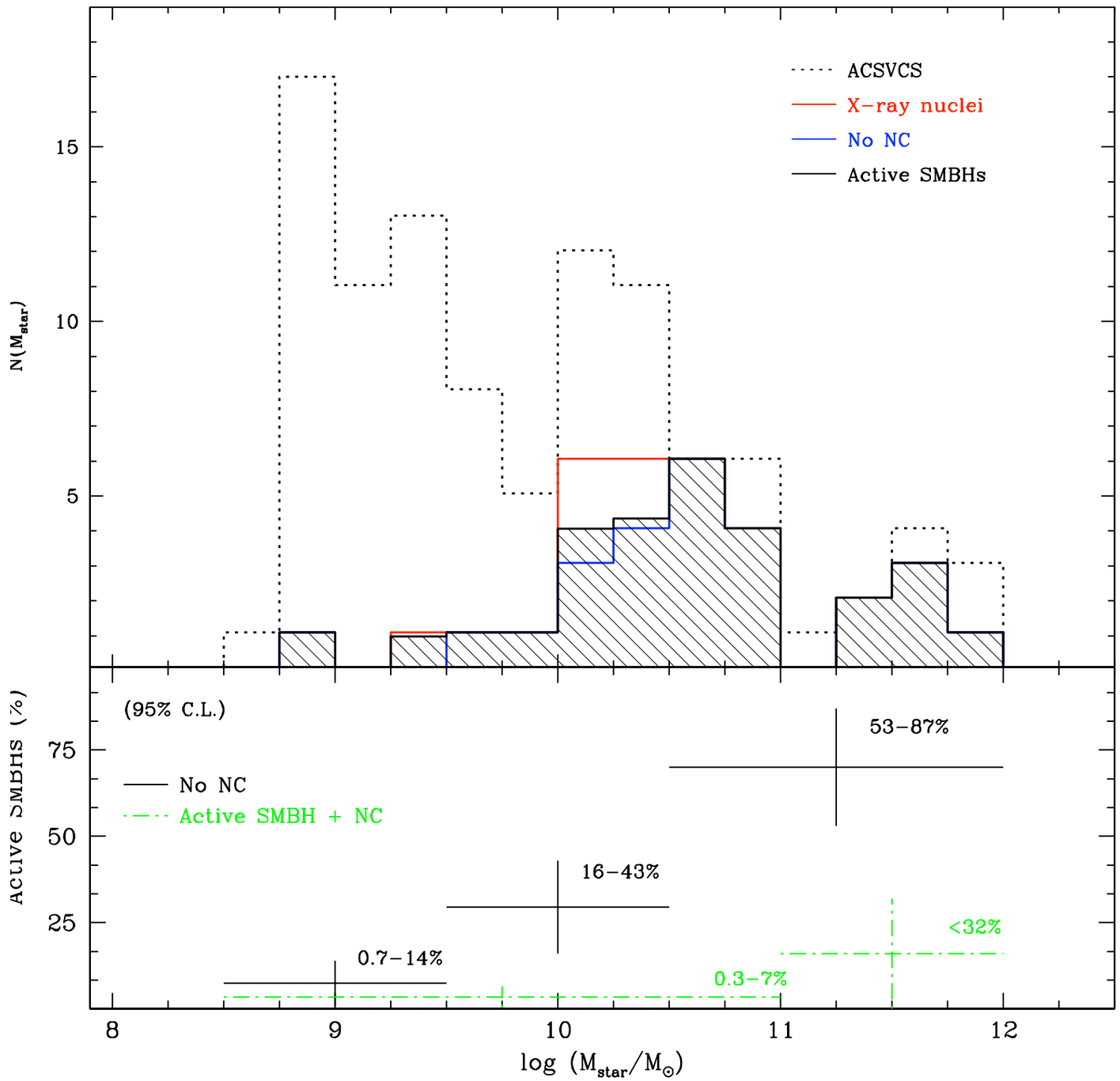


X-ray

- Also starts with Palomar survey
- Statistical detection rate ~18-25%, higher than optical surveys
- see also Ghosh et al.

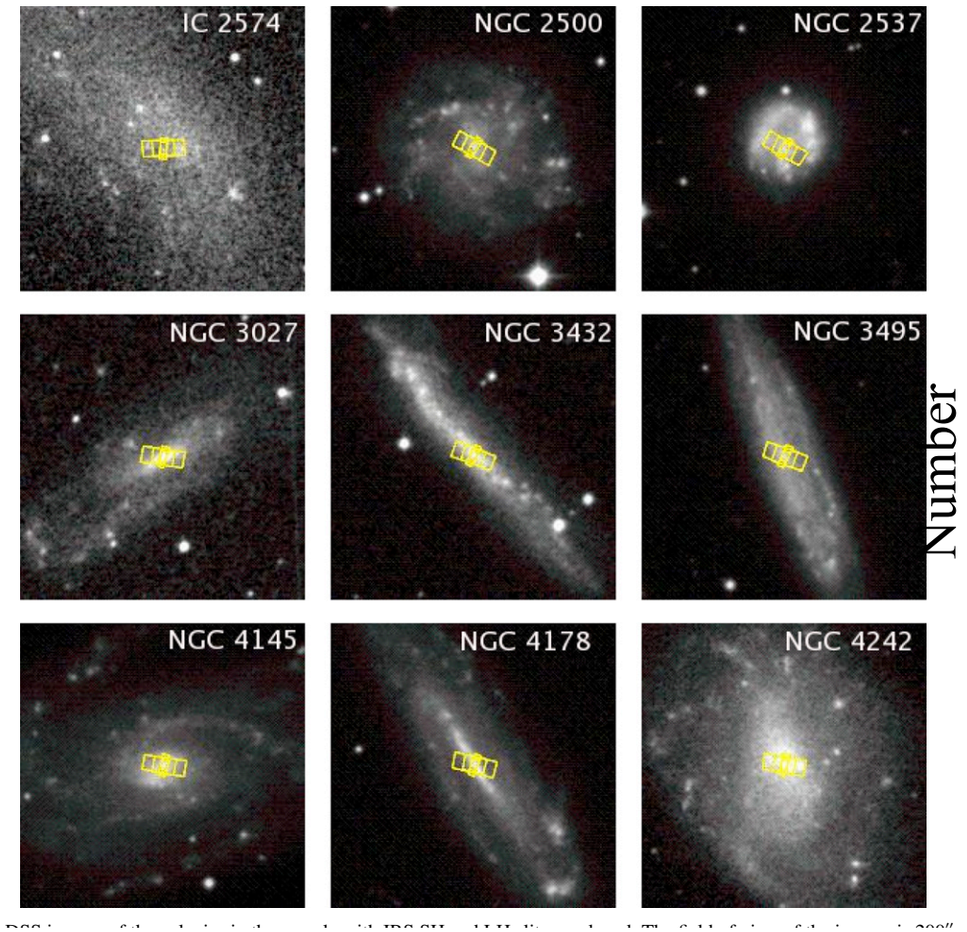


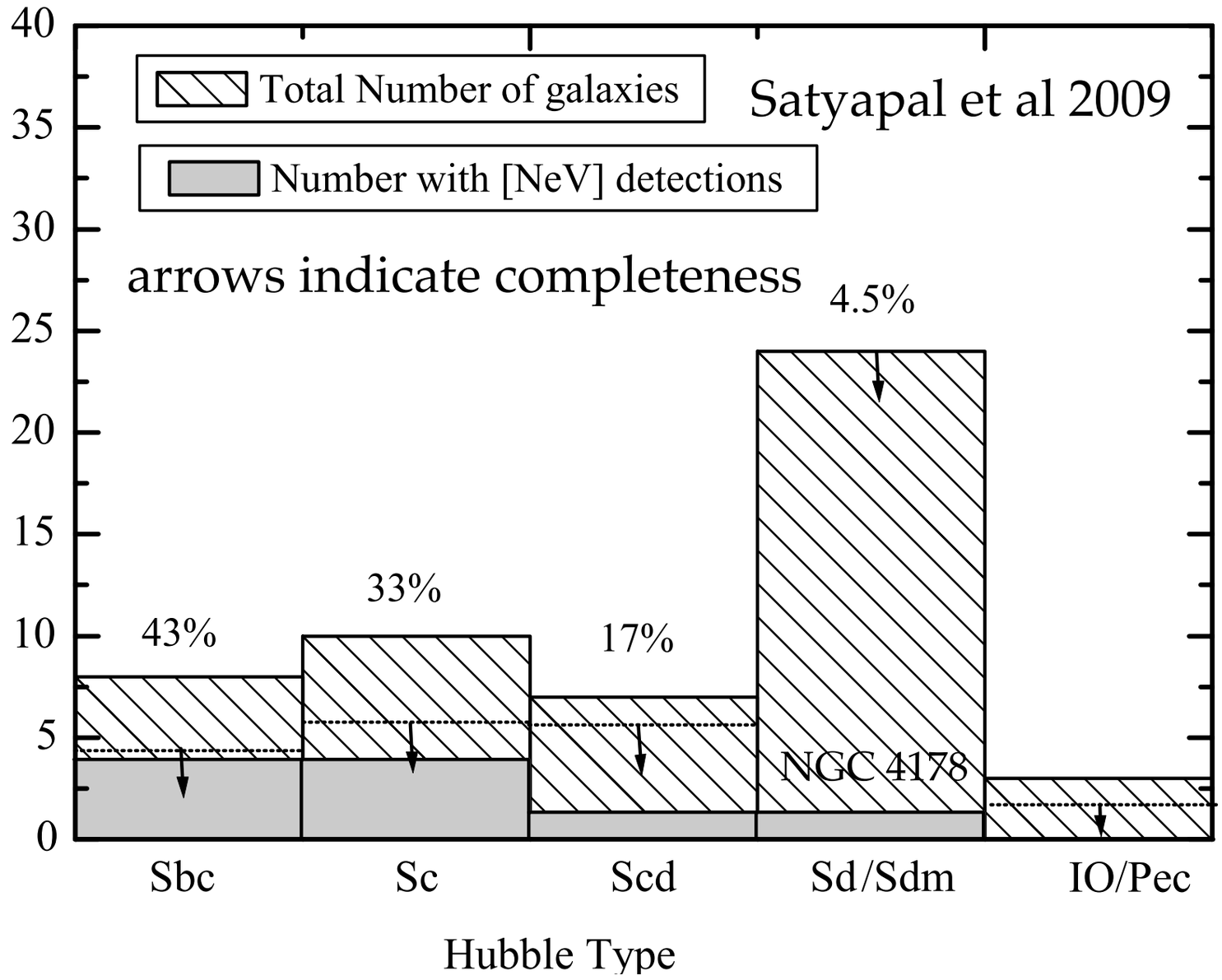
AMUSE: X-ray survey of Virgo



Gallo et al. 2008, 2010

MIR Spectroscopy





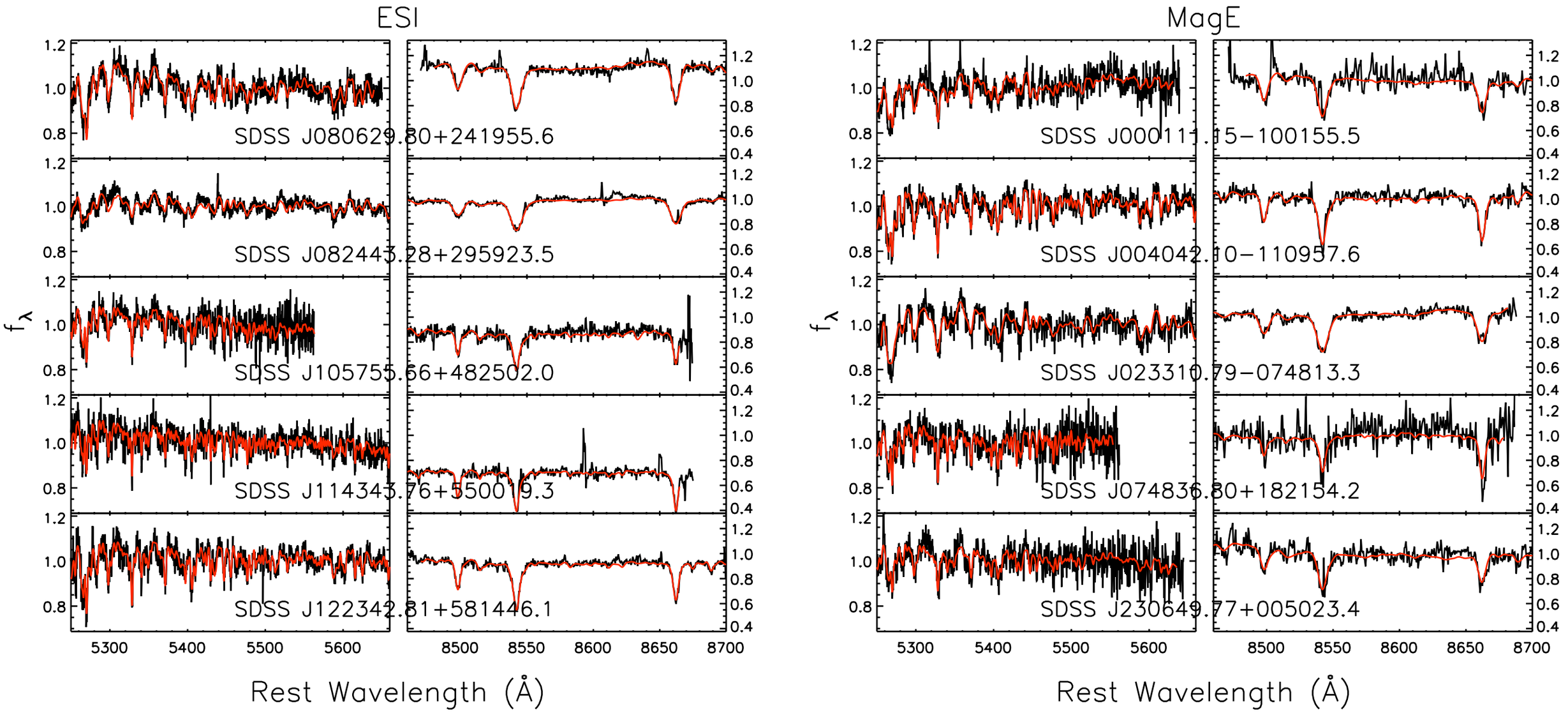
Shows evidence that the occupation fraction really drops in the latest Hubble types

Are NCs required to host BH? Based on 3 objects.

Space Densities

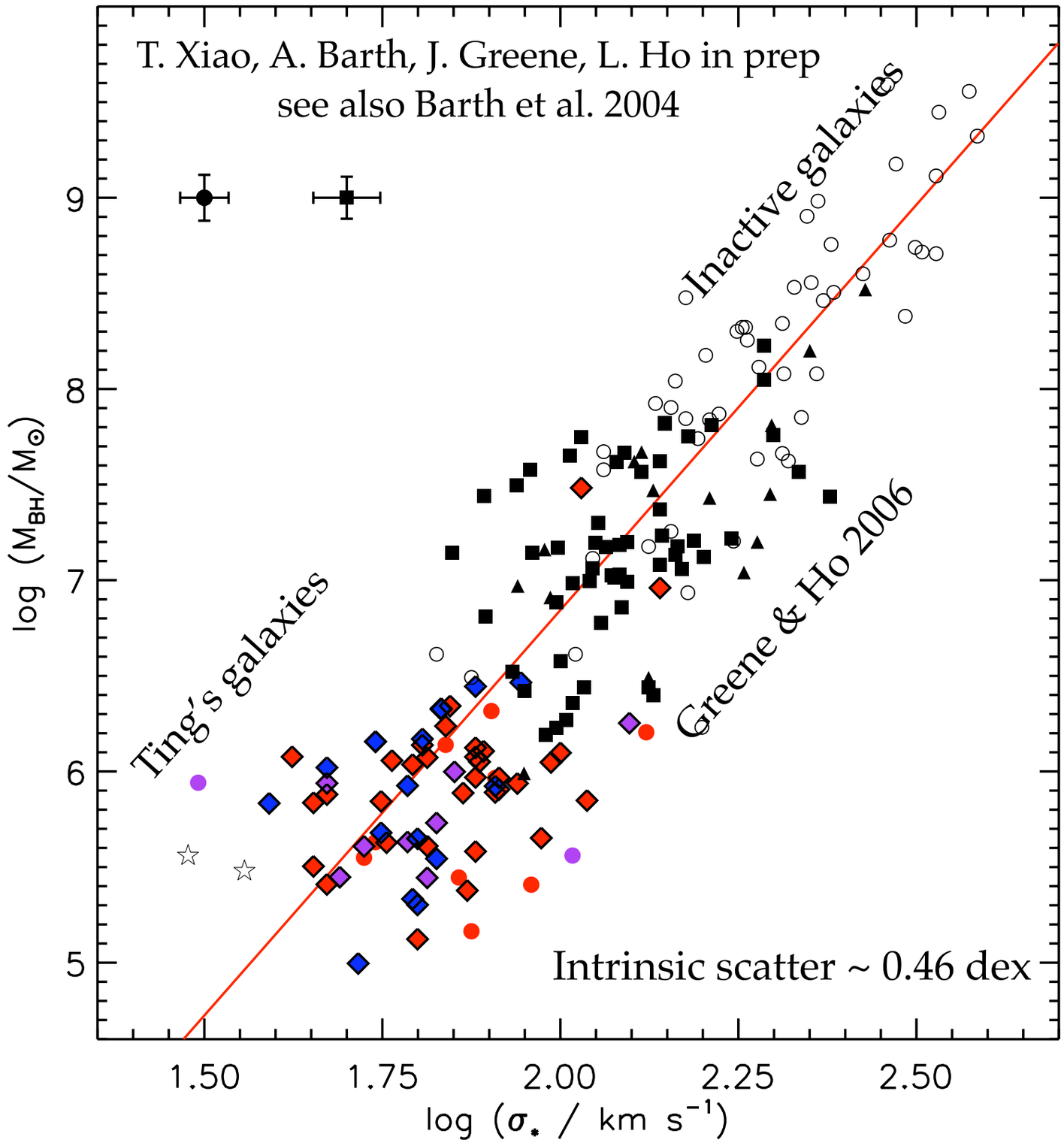
- SDSS sample alone too biased by selection effects
- Combination of Moran+Satyapal studies should yield real constraints
- Hints that space density really is falling in Sd galaxies
- Searches using tidal disruptions, dynamical measurements, gravitational radiation(?) all upcoming

Scaling Relations

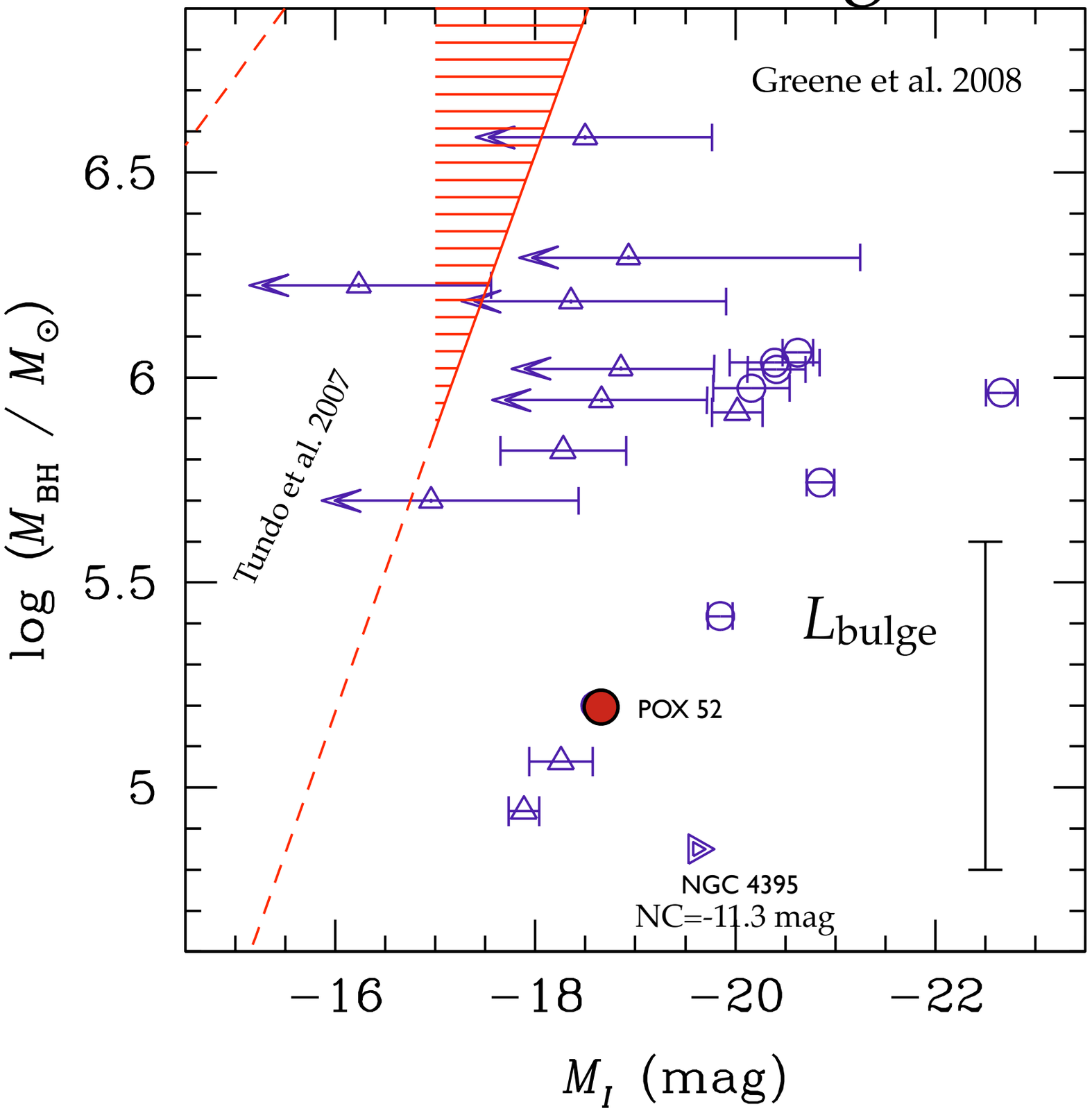


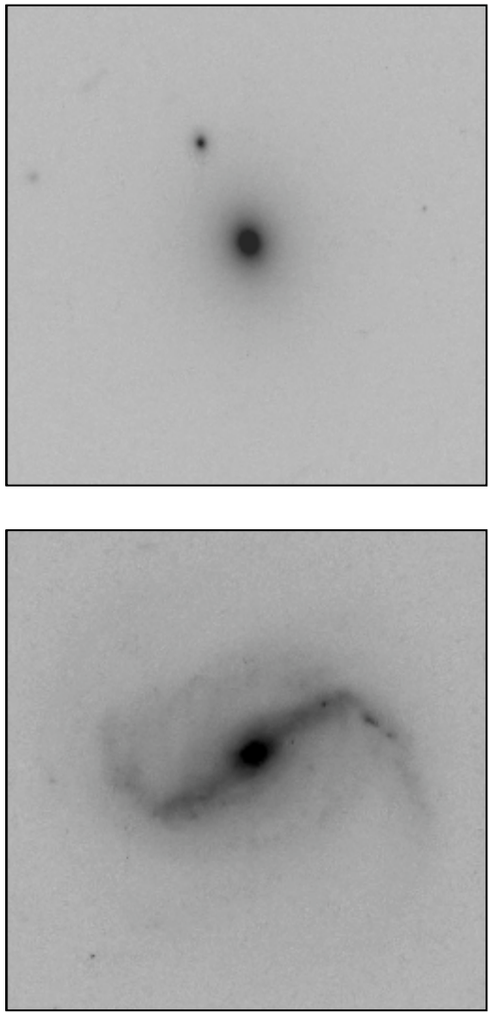
Ting Xiao, graduate student with Aaron Barth, has analyzed 80 more Keck and MagE spectra for the SDSS broad-line sample

M_{BH}-$\sigma_\star$ continuous (?)



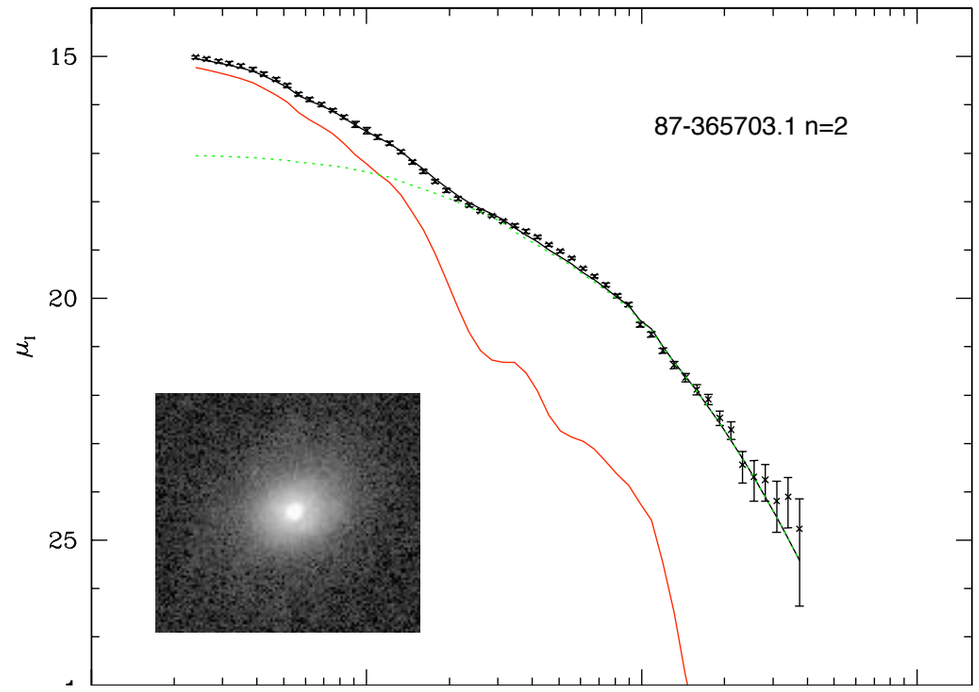
M_{BH}-M_{bulge} (?)





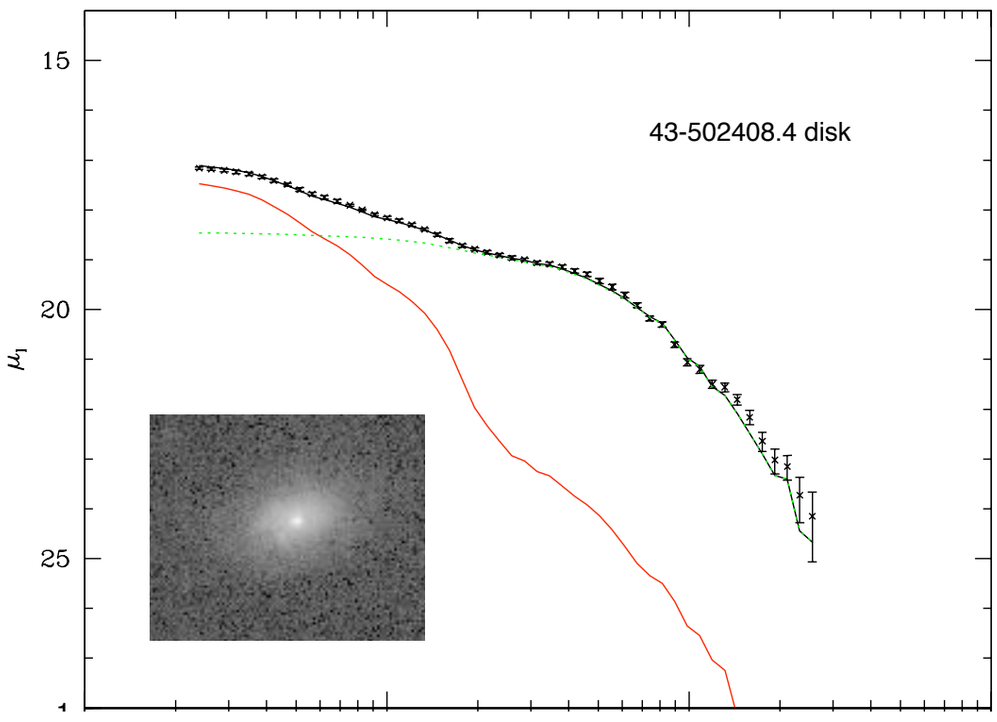
HST / ACS imaging
1 orbit / galaxy, *BI*

Yanfei Jiang, graduate student at Princeton, has plowed through all ~170 *HST*/WFPC2 images!



Jiang, Greene, Barth, Ho in prep

Pure ‘bulge’ galaxies ~40%



Pure ‘disk’ galaxies ~10%

Scaling Relations from Megamasers

Chien Y. Peng (Herzberg Institute)
the Megamaser Cosmology Project:
James Braatz, Cheng-Yu Kuo, Fred Lo, Jim Condon (NRAO), Mark Reid, Lincoln Greenhill

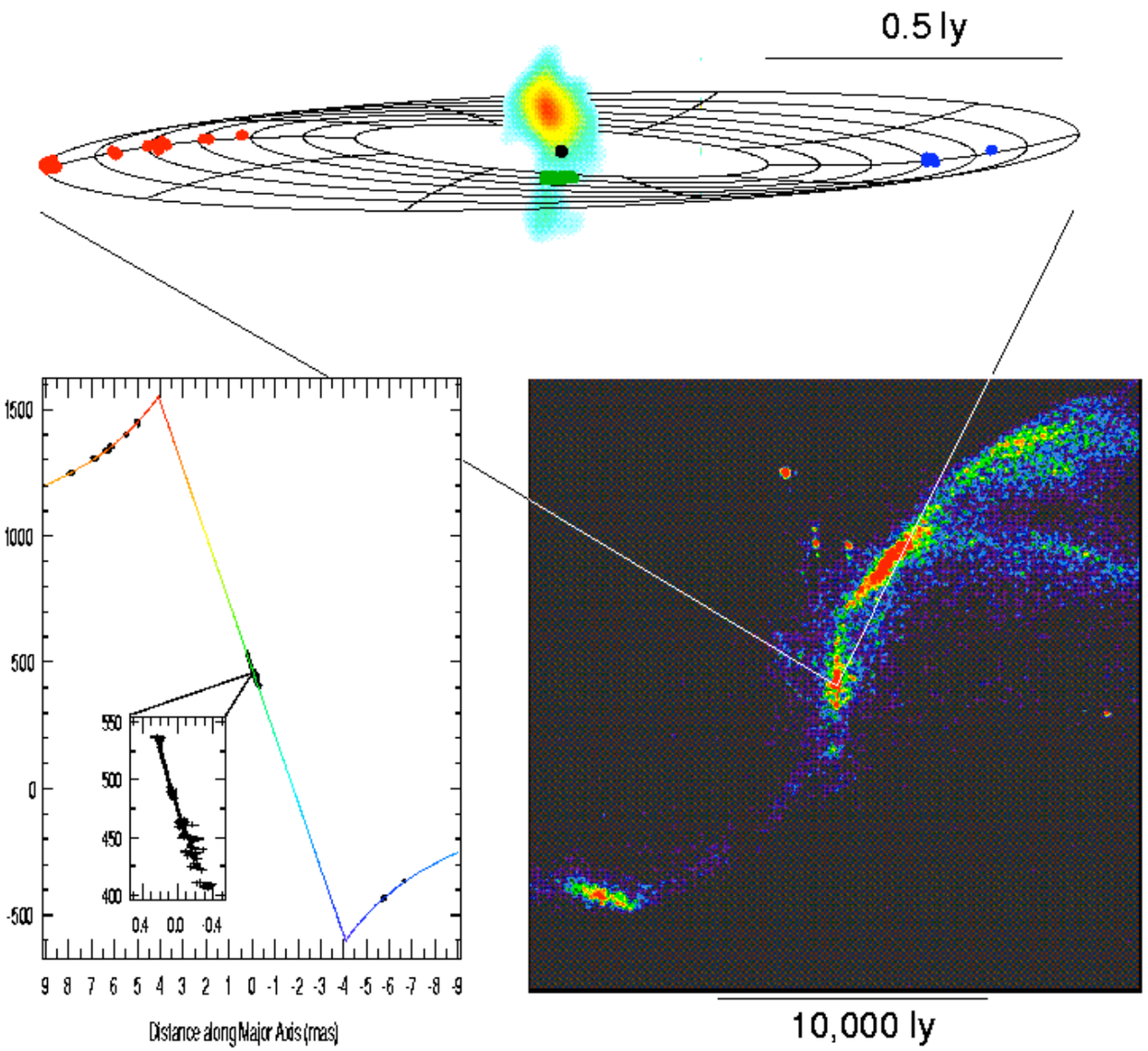
NGC 4258

- H_20 megamasers (microwave amplification by stimulated emission; 10^2-10^4 $L_\odot$) as dynamical tracers

- Very precise BH mass (3.9 ±0.1 x 10^7 $M_\odot$), relatively free of systematic bias

- With accelerations, also measure an independent distance

- Along with MW, best case to rule out astrophysical alternatives to SMBH (e.g., Maoz et al. 1995, 1998)



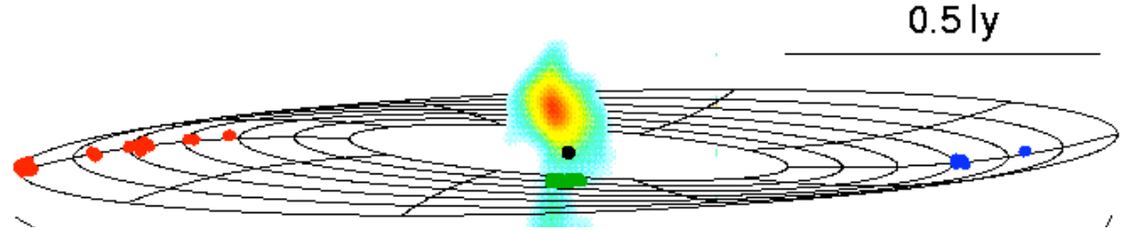
Miyoshi et al., Herrnstein et al., Greenhill, Humphreys, Moran
galaxy is ~7 Mpc away

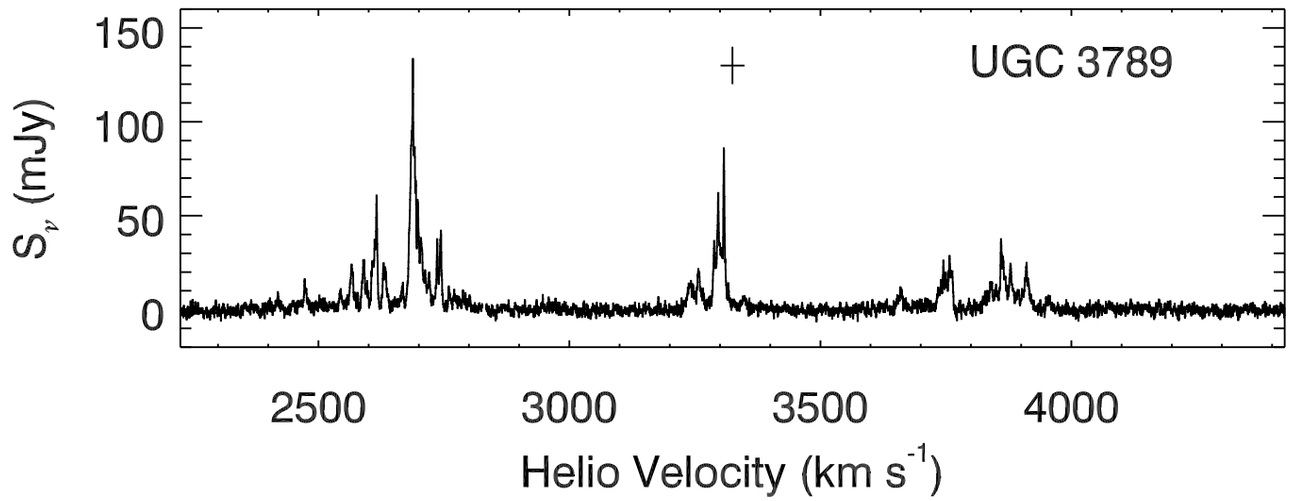
Step 1: Single-Dish Search

- Advent of Green Bank Telescope - doubled the number of maser galaxies

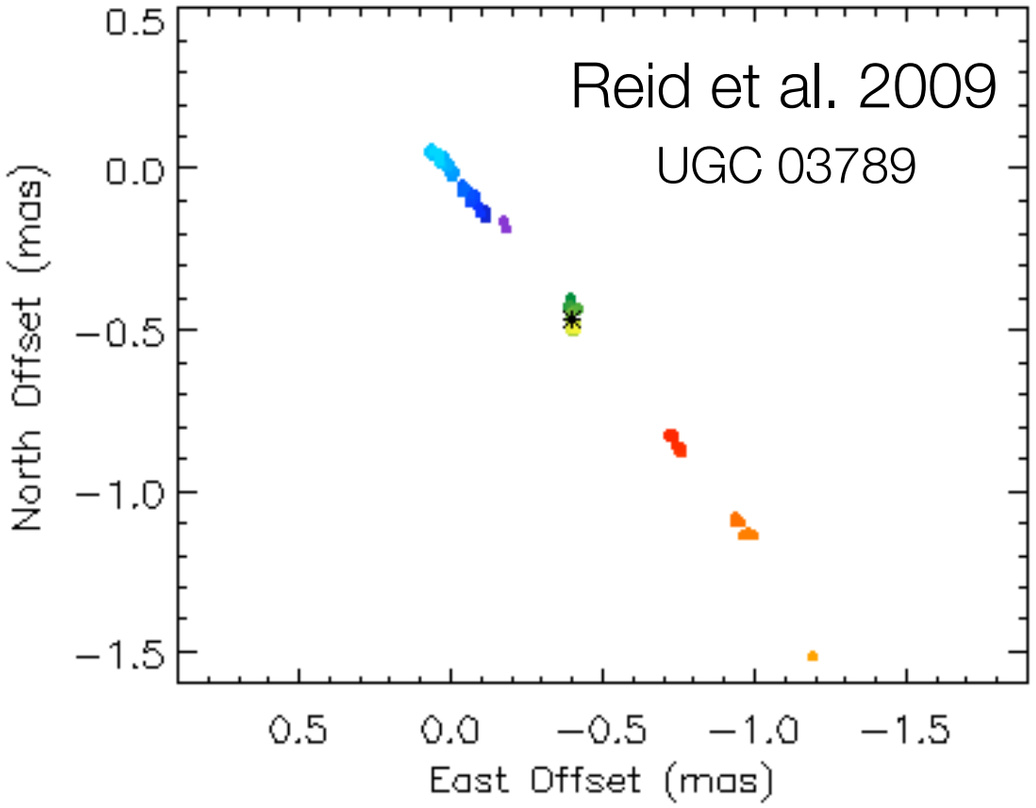
- So far searches have focused on obscured active galaxies from optical spectroscopic surveys; one volume-limited survey. ~1/3 of obscured AGNs detected.

- ~40-60% of maser galaxies have the systemic+high-velocity features indicative of maser disks



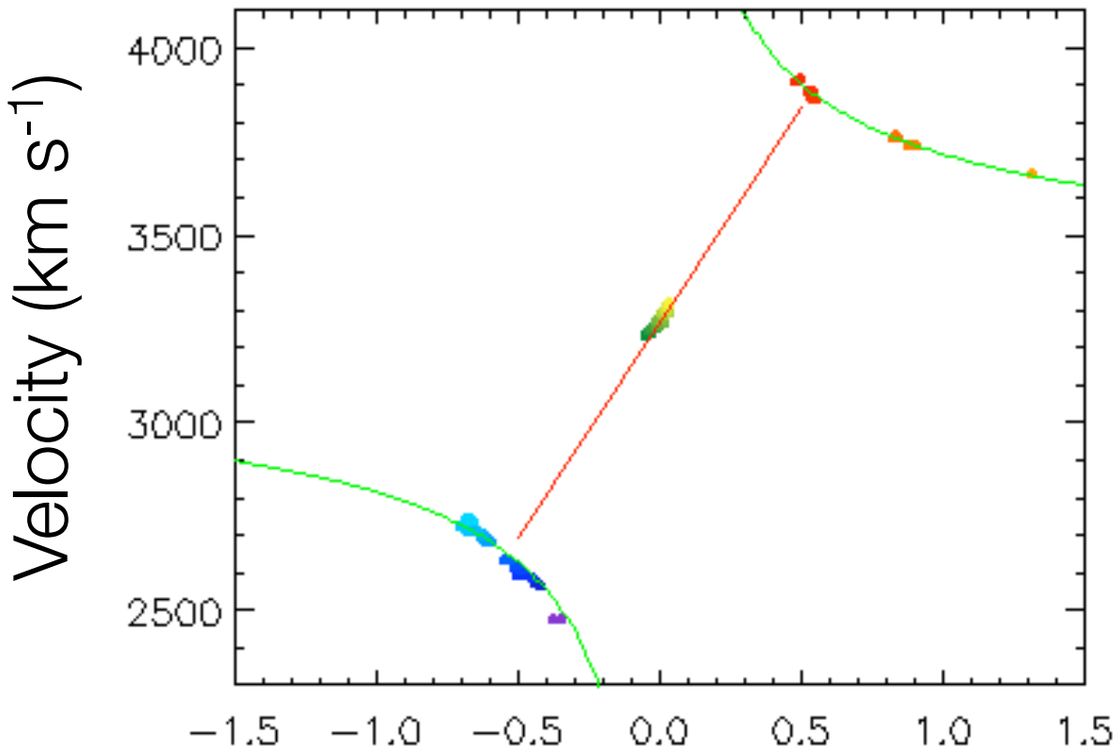


Step 2: VLBI



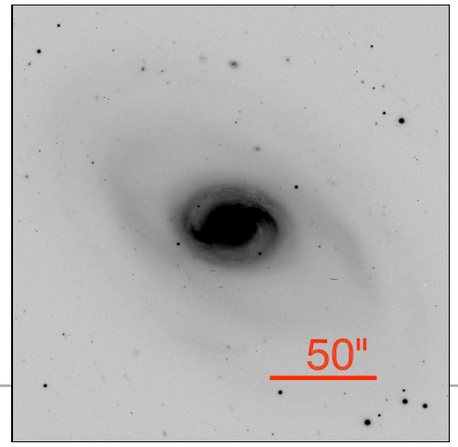
Spatial distribution on the sky reveals an edge-on disk

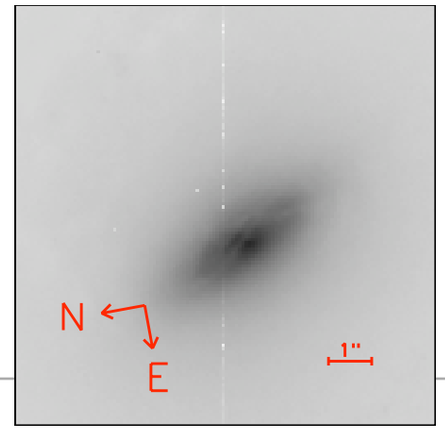
Rotation curves reveal Keplerian rotation around a (very) compact object

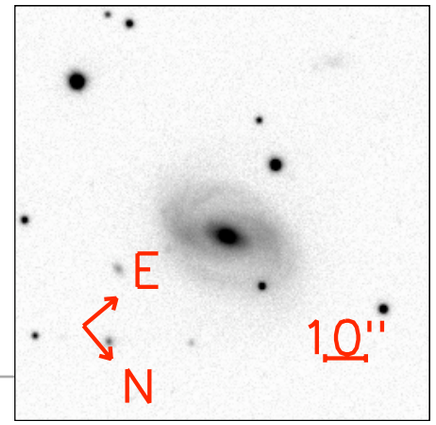


This case allows to rule out virtually all astrophysically plausible alternatives to SMBH

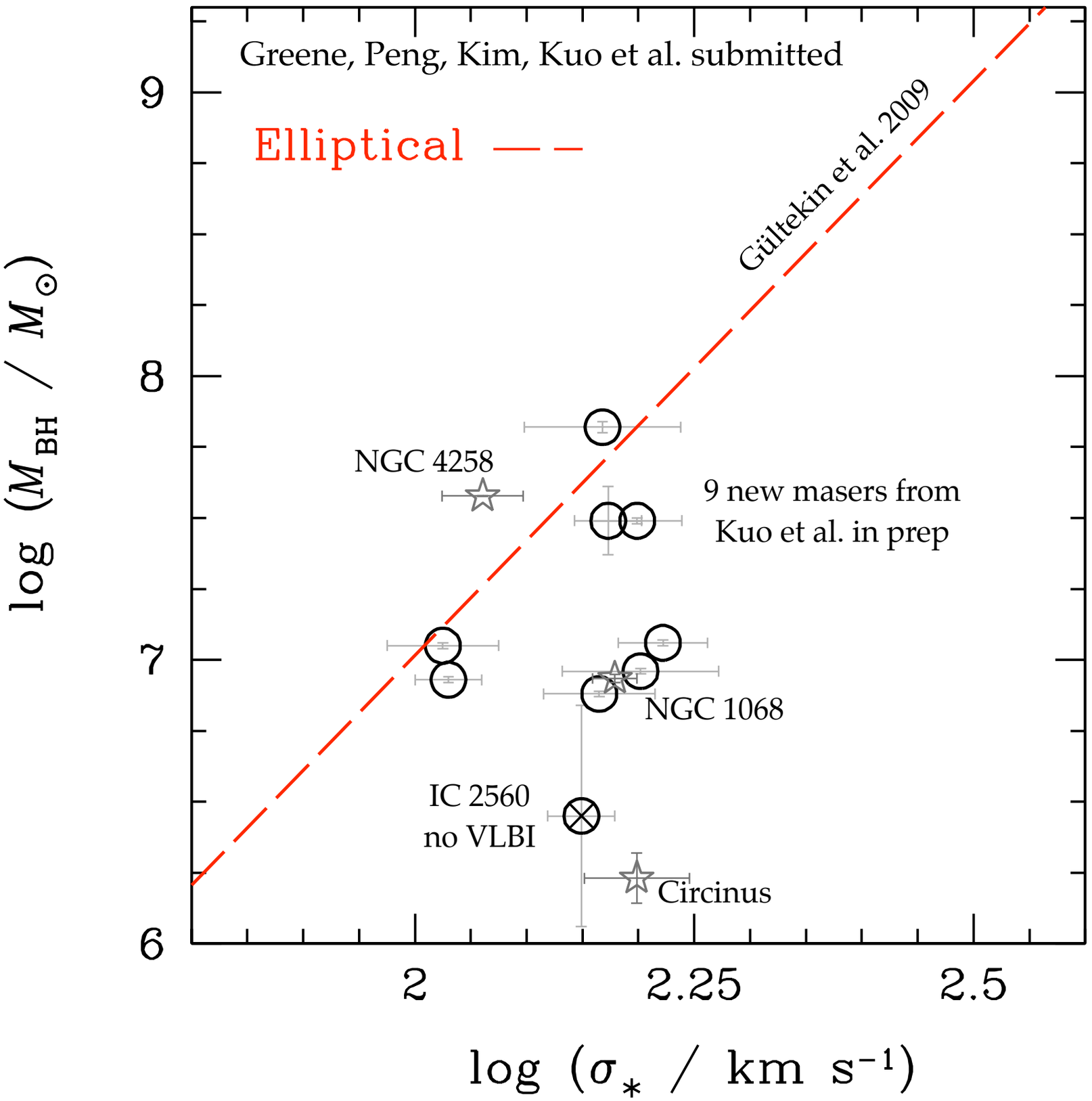
New Maser Systems



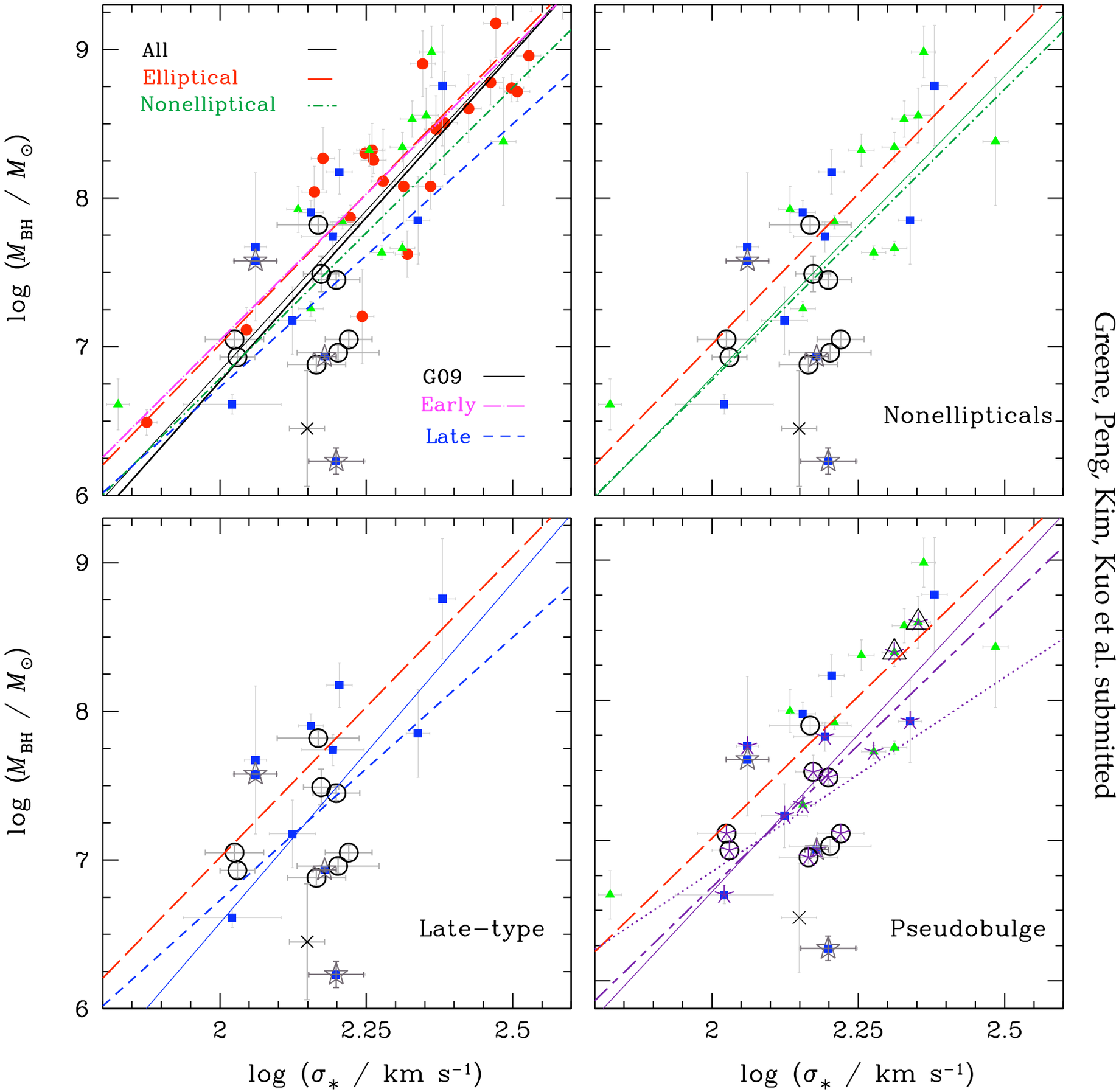




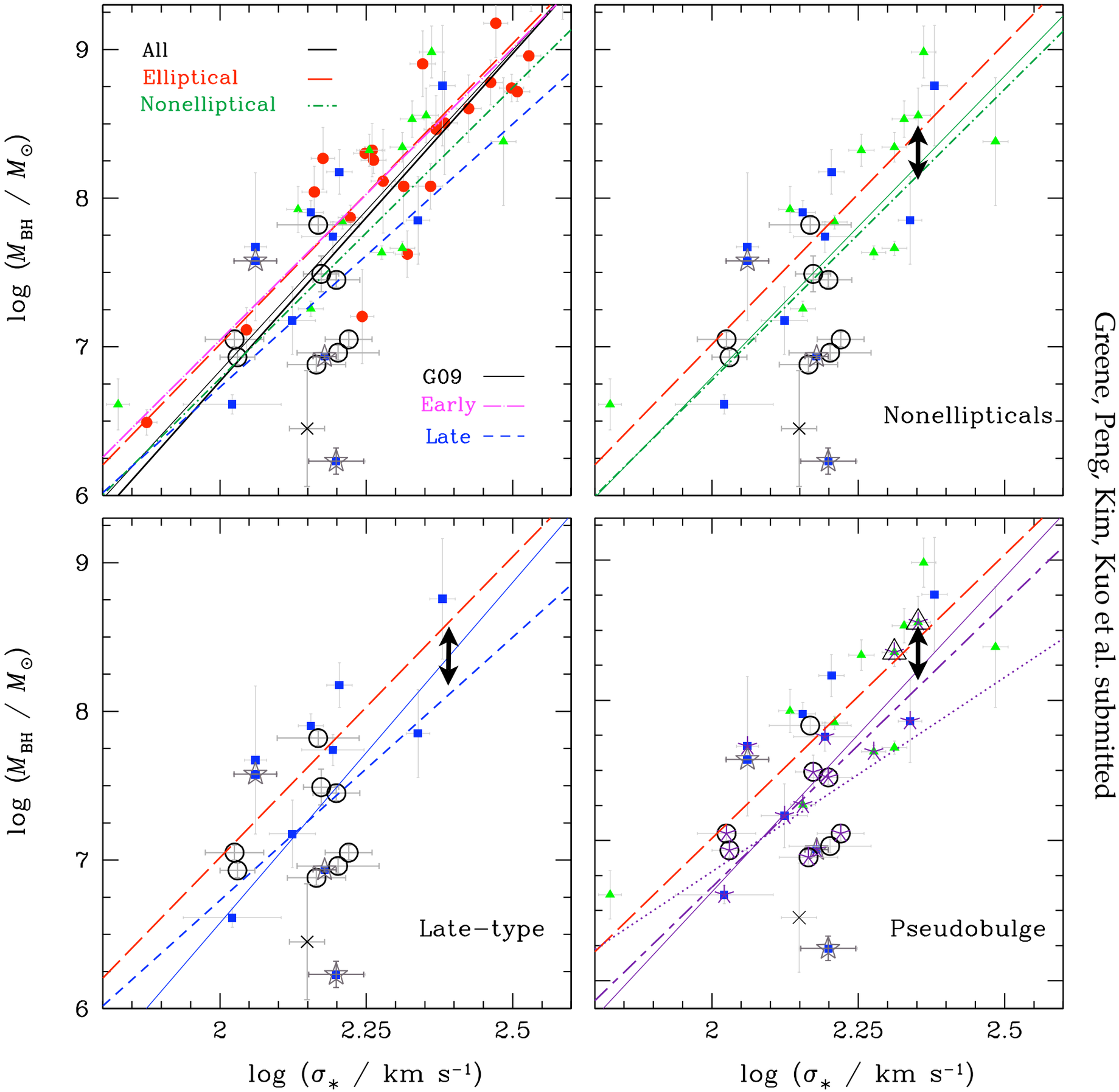
- 10-20 new megamaser disks, ~6 good enough for distances: Megamaser Cosmology Project
- Masses are all within ~x3 of 10^7 $\boldsymbol{M}_\odot$ (with ~15% uncertainties)
- Galaxies are all spirals (S0-Sb), with >60% barred. 15 < D < 150 Mpc.
- These are obscured active galaxies, many are Compton thick. Eddington ratios are ~10%.
- Interestingly, not all edge-on galaxies
- BH masses will be reported by Kuo et al. in prep.



BH-bulge scaling relations are not universal



Greene, Peng, Kim, Kuo et al. submitted



Greene, Peng, Kim, Kuo et al. submitted

- Maser galaxies are offset to lower $\sigma_\star$. See also Hu, Gadotti, Erwin. Major caveat: are there small classical bulges that we don't measure with our ground-based slit spectra?
- Some galaxies do not grow their BHs effectively; perhaps because evolutionary history is more passive?
- How do we understand both the active and maser galaxies?
- We do not know BH mass function $<10^7\ M_{\odot}$.
- We cannot use $M_{\rm BH}$-$\sigma_\star$ to calibrate AGN masses.

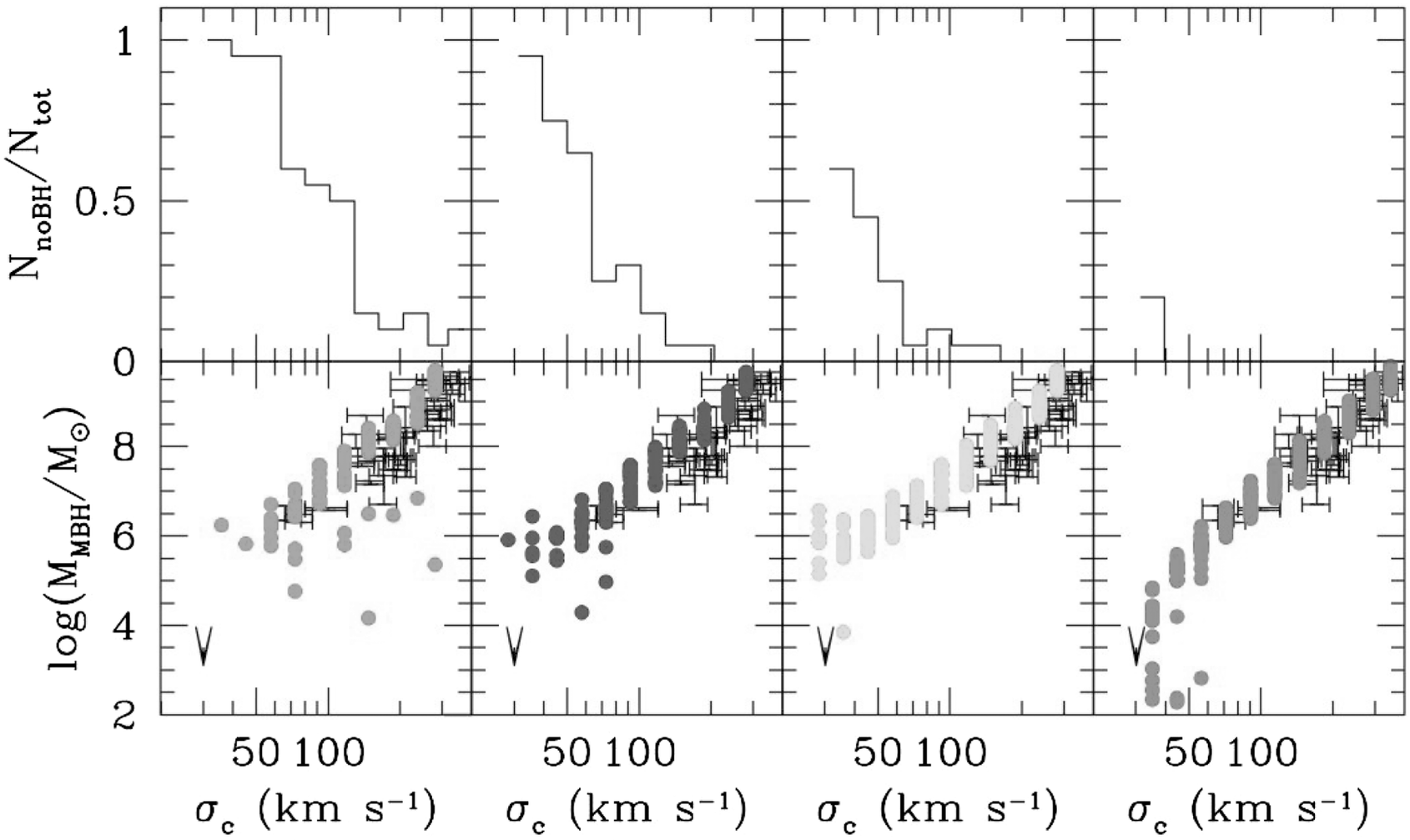
Summary

- There are ~10^5 $M_\odot$ BHs in low-mass (bulgeless) galaxies
- They are probably rare
- Dynamical modeling, X-ray and radio surveys, and tidal disruption detections should provide new insights
- BH scaling relations are not universal; story at low-mass is confusing at best

Hard Questions

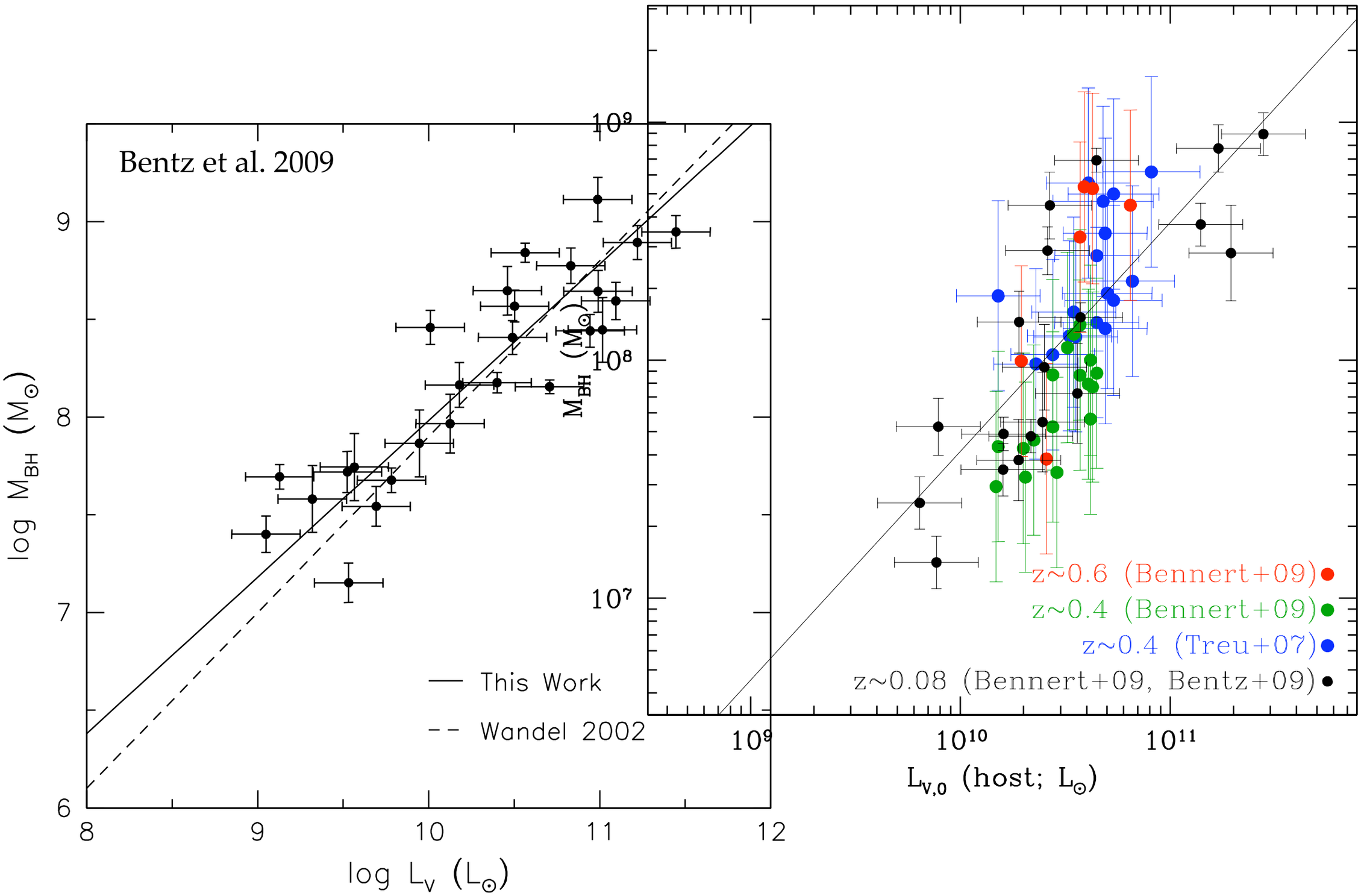
- Why does NGC 4395 have a BH, but not M33?
- Is there any evolutionary connection between NCs and BHs?
- Are the formation mechanisms for the low- and high-mass BHs different (e.g., cluster vs. gas disk)?
- Can we use observed scaling relations and mass limits to constrain seed formation models?

Volonteri et al. 2008



Direct gas collapse

Pop III remnants

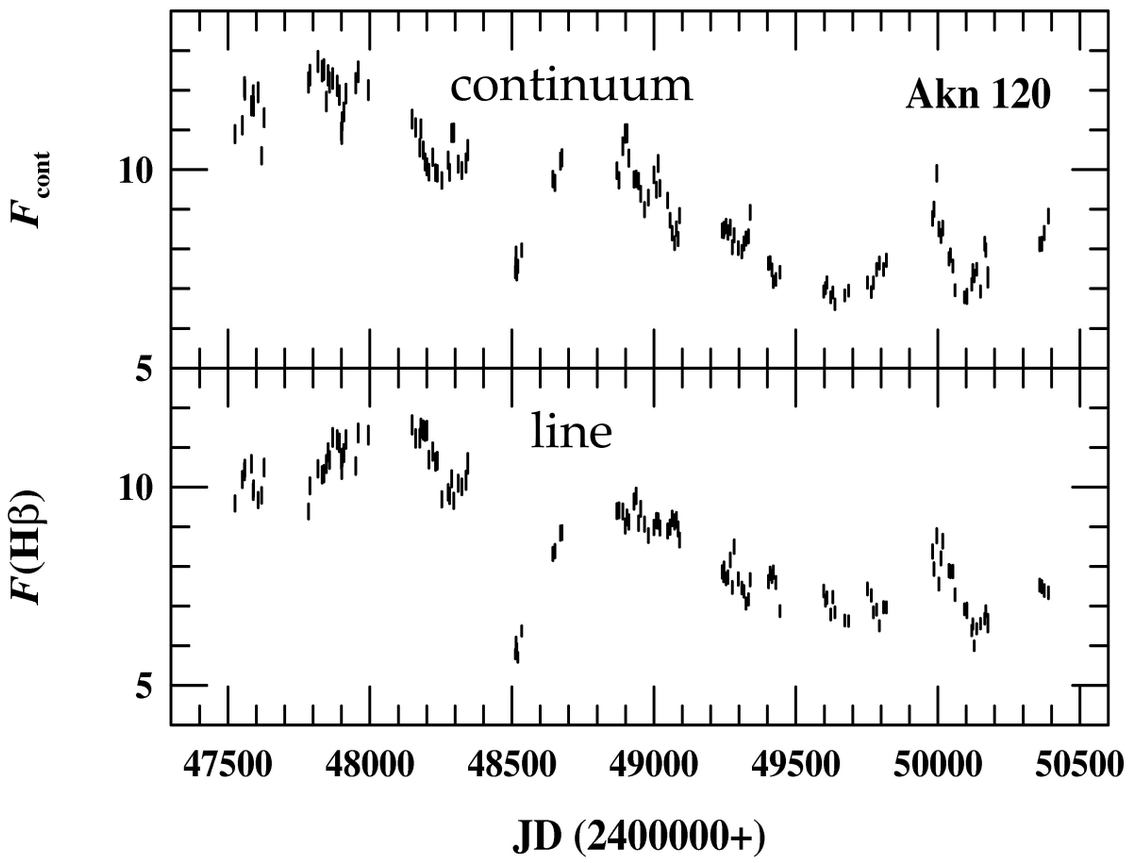


Shallower slope than inactive galaxies

scatter=0.38 dex

BH Masses in AGNs

Reverberation Mapping



Radius-Luminosity Relation

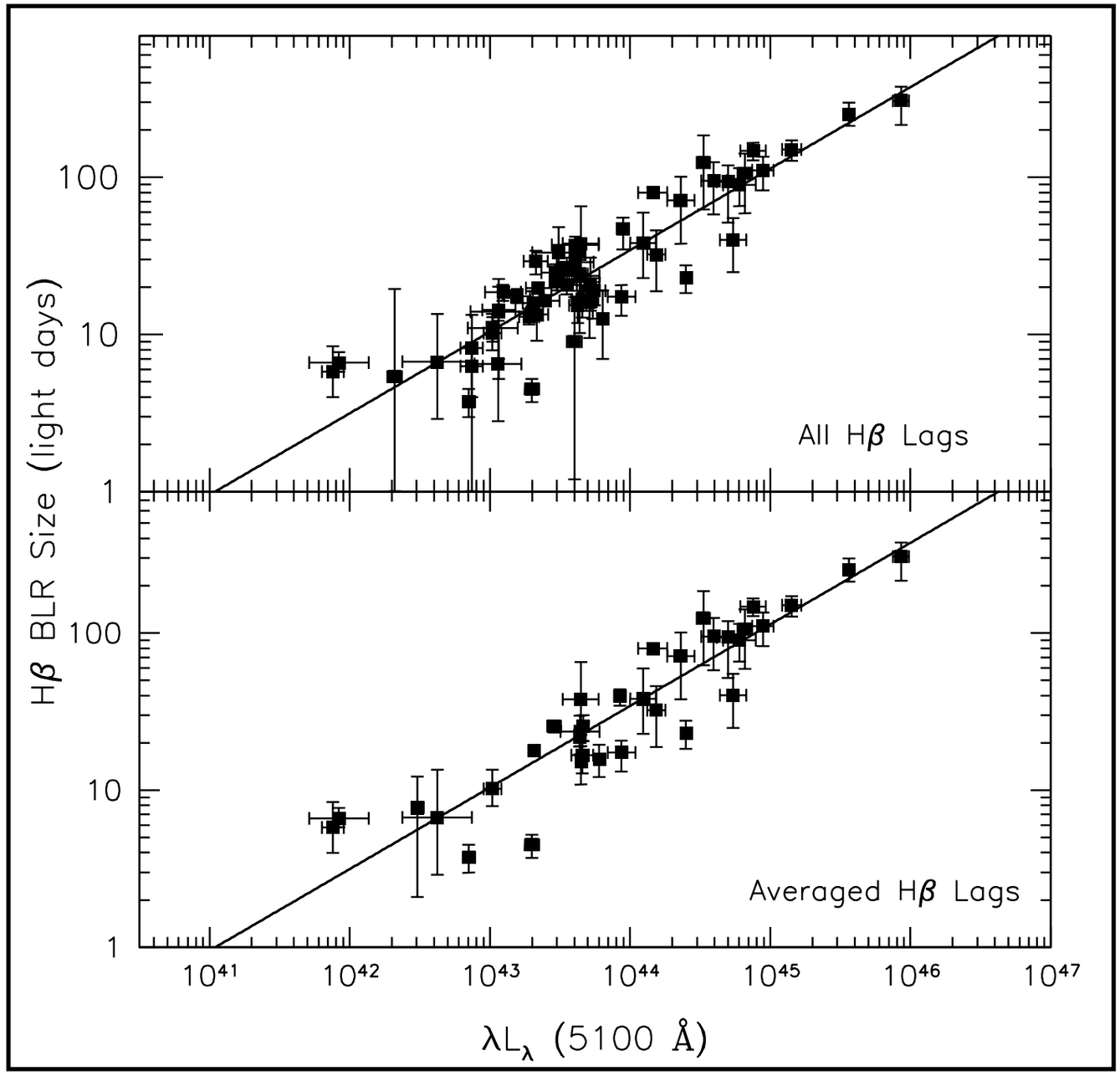
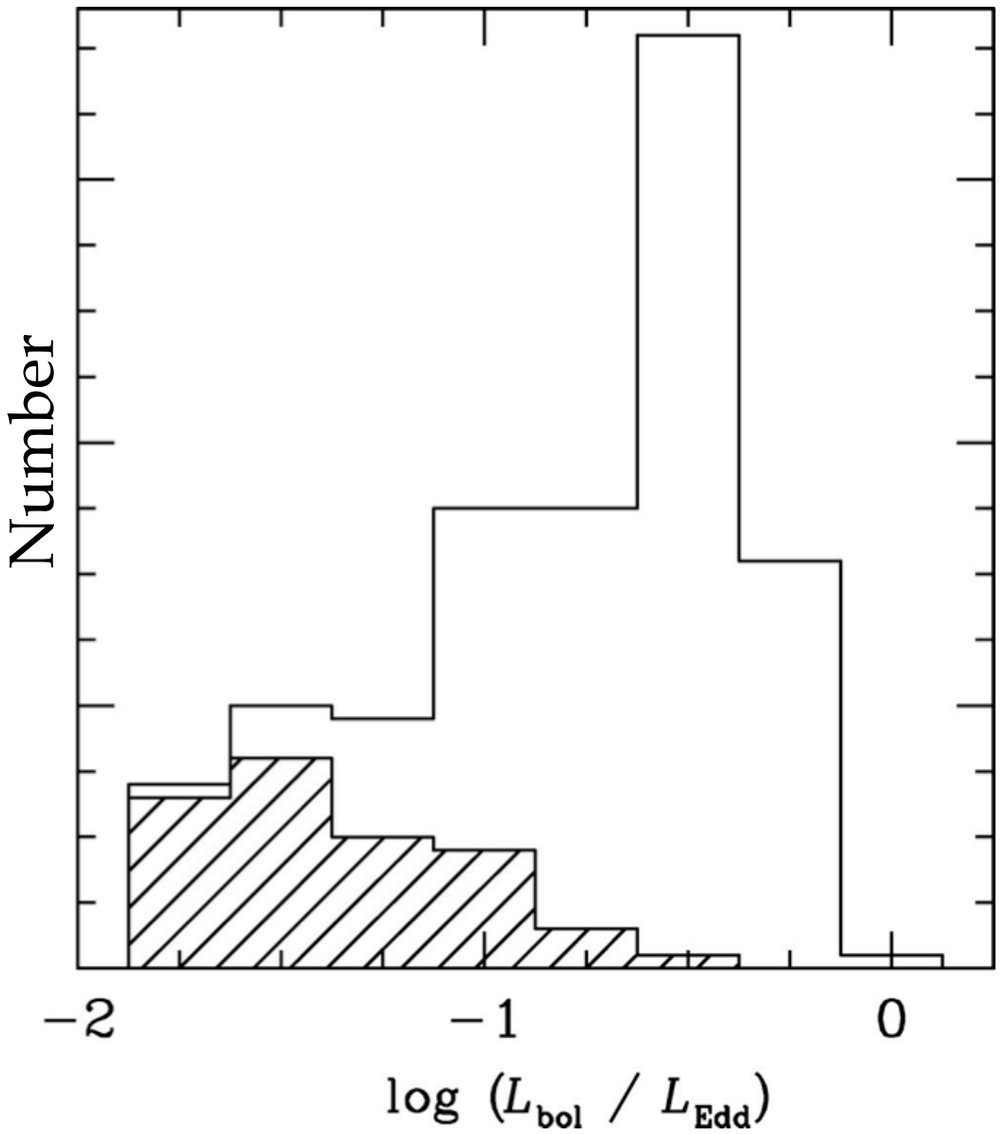


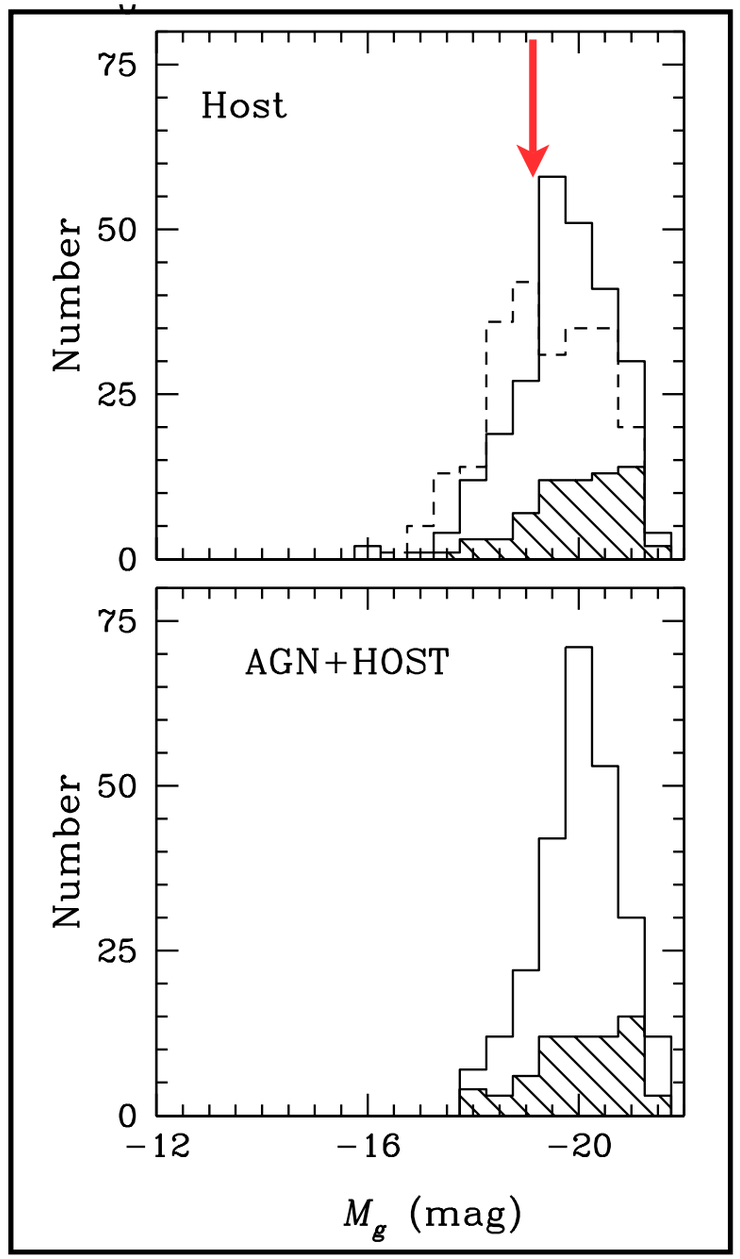
FIG. 5.— The Hβ R_{BLR}–L relationship after correcting the AGN luminosities for the contribution from host-galaxy starlight. The top panel shows each s measurement as a single data point, and the bottom panel shows the weighted mean of multiple measurements for any individual object. The solid lines best fit to the relationship (listed in bold face in Table 9), which has a slope of $\alpha = 0.519^{+0.063}_{-0.066}$.

Bentz et al. 2008

From SDSS

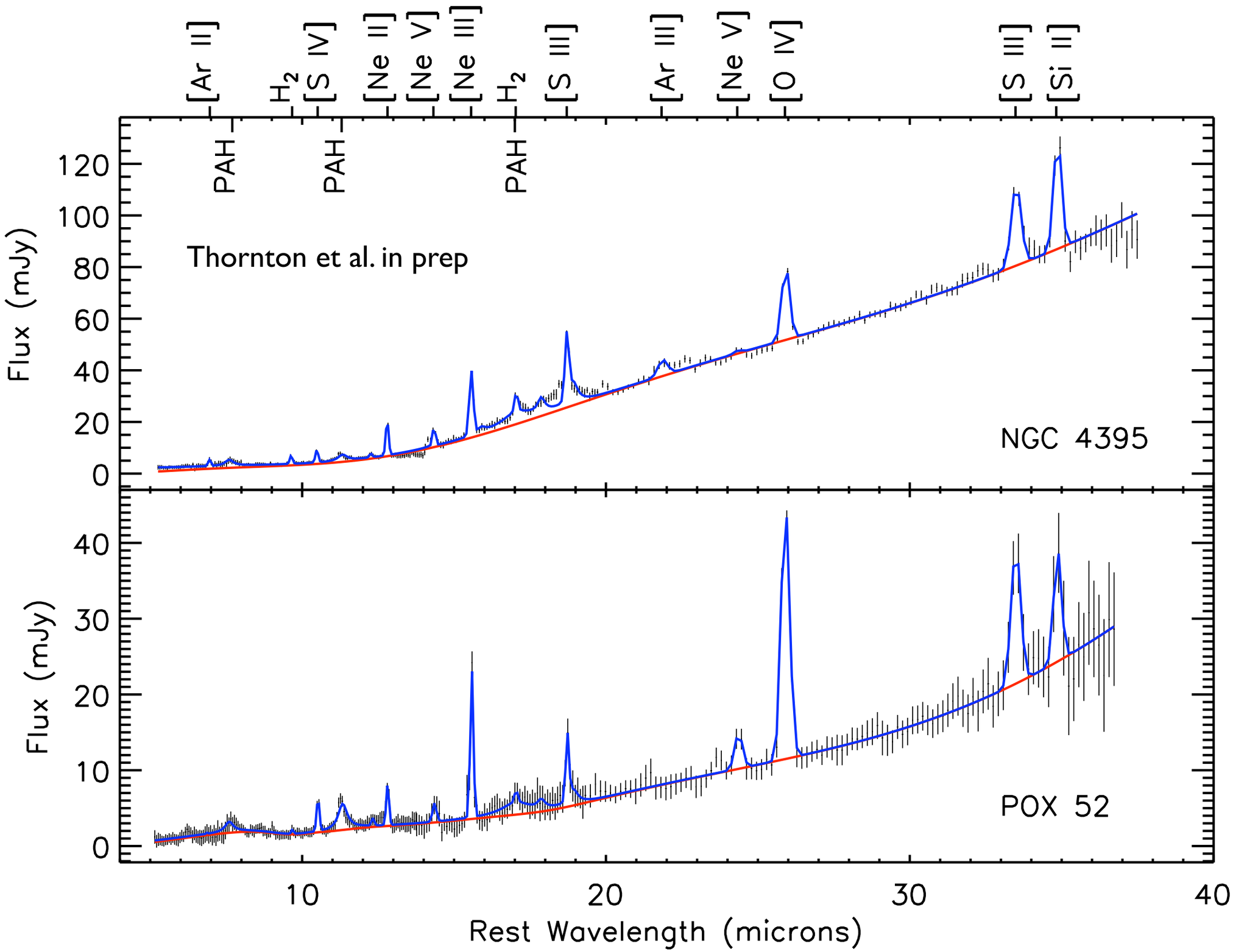


High fraction of Eddington luminosity

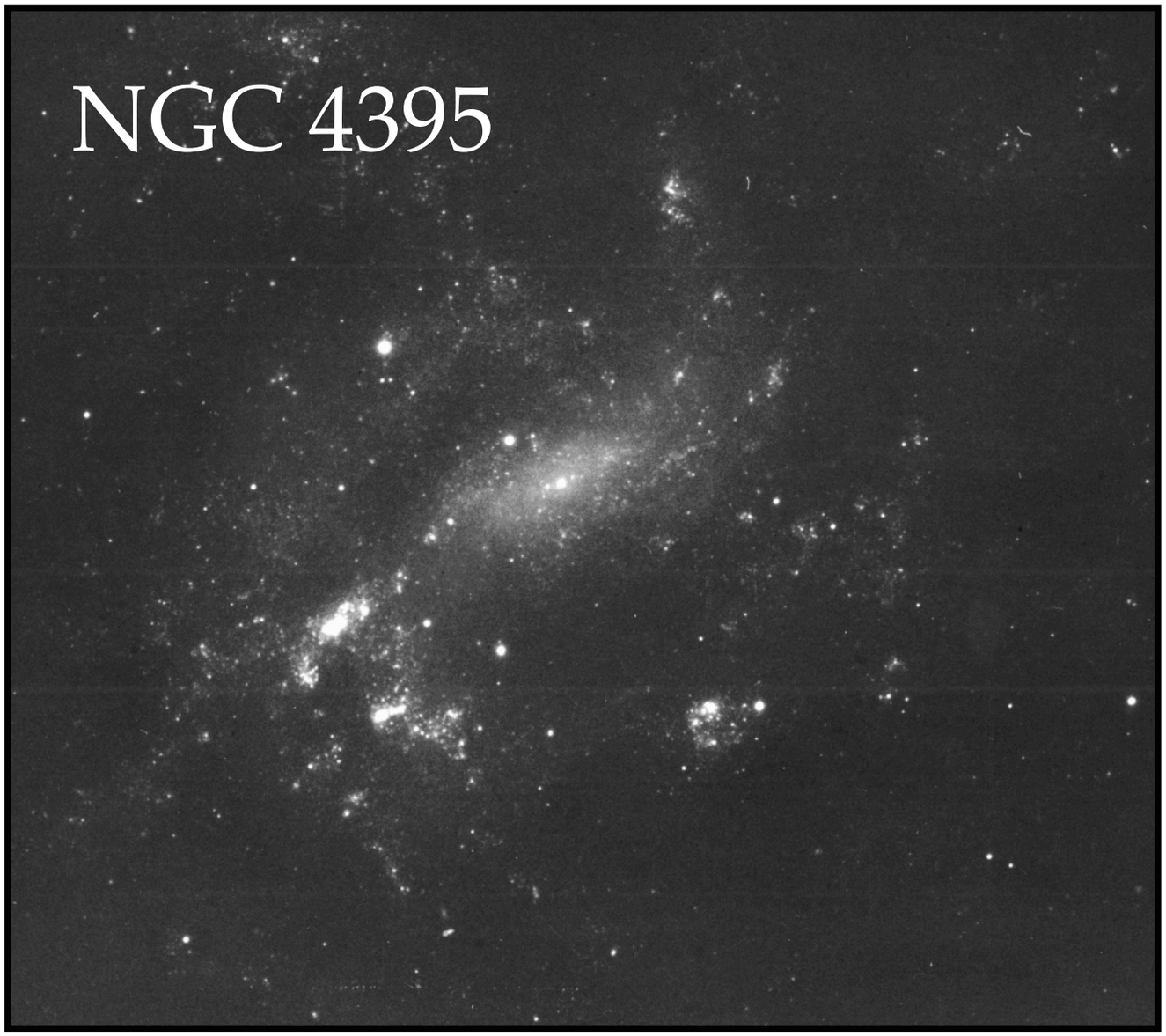


Hosts are faint (1 mag > L^*)

Spitzer

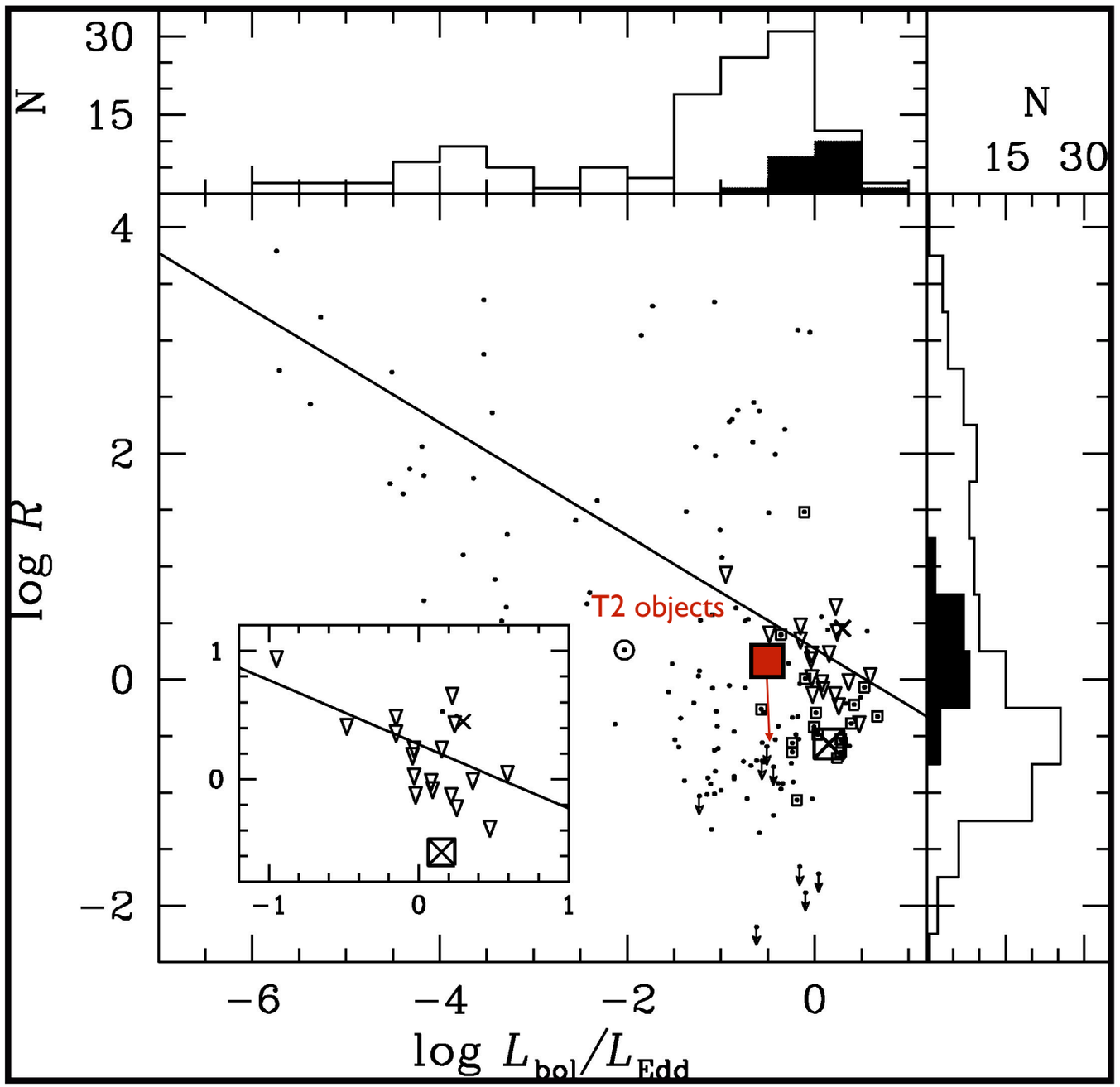

[Ar II]
H2
[S IV]
[Ne II]
[Ne V]
[Ne III]
H2
[S III]
[Ar III]
[Ne V]
[O IV]
[S III]
[Si II]
PAH
PAH
PAH
Thornton et al. in prep
Flux (mJy)
120
100
80
60
40
20
0
NGC 4395
Flux (mJy)
40
30
20
10
0
POX 52
10
20
30
40
Rest Wavelength (microns)

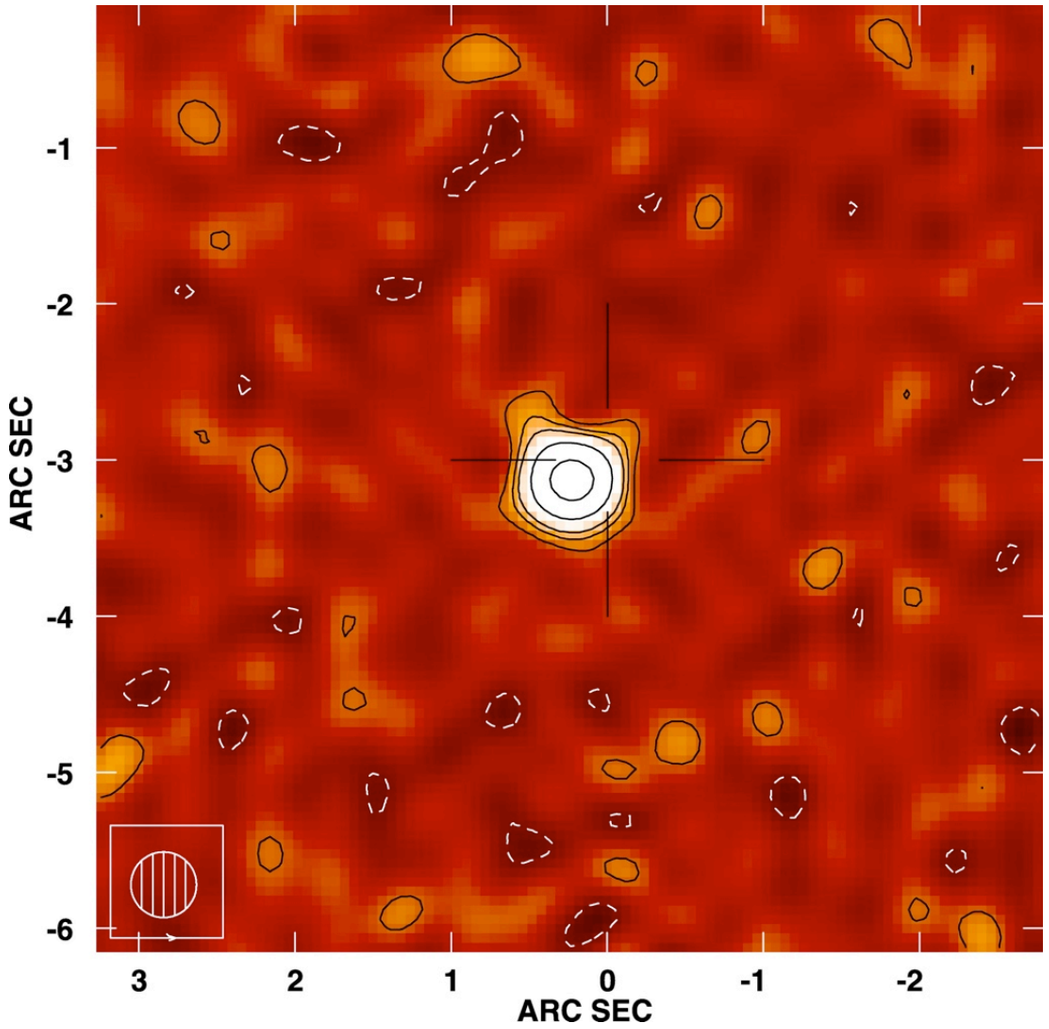
Optical Spectroscopy



Filippenko & Sargent 1989

- Sdm galaxy, 4 Mpc away
- Broad-line AGN, compact radio core, violently variable X-rays
- Unambiguous BH in a late-type spiral. Can we find more?

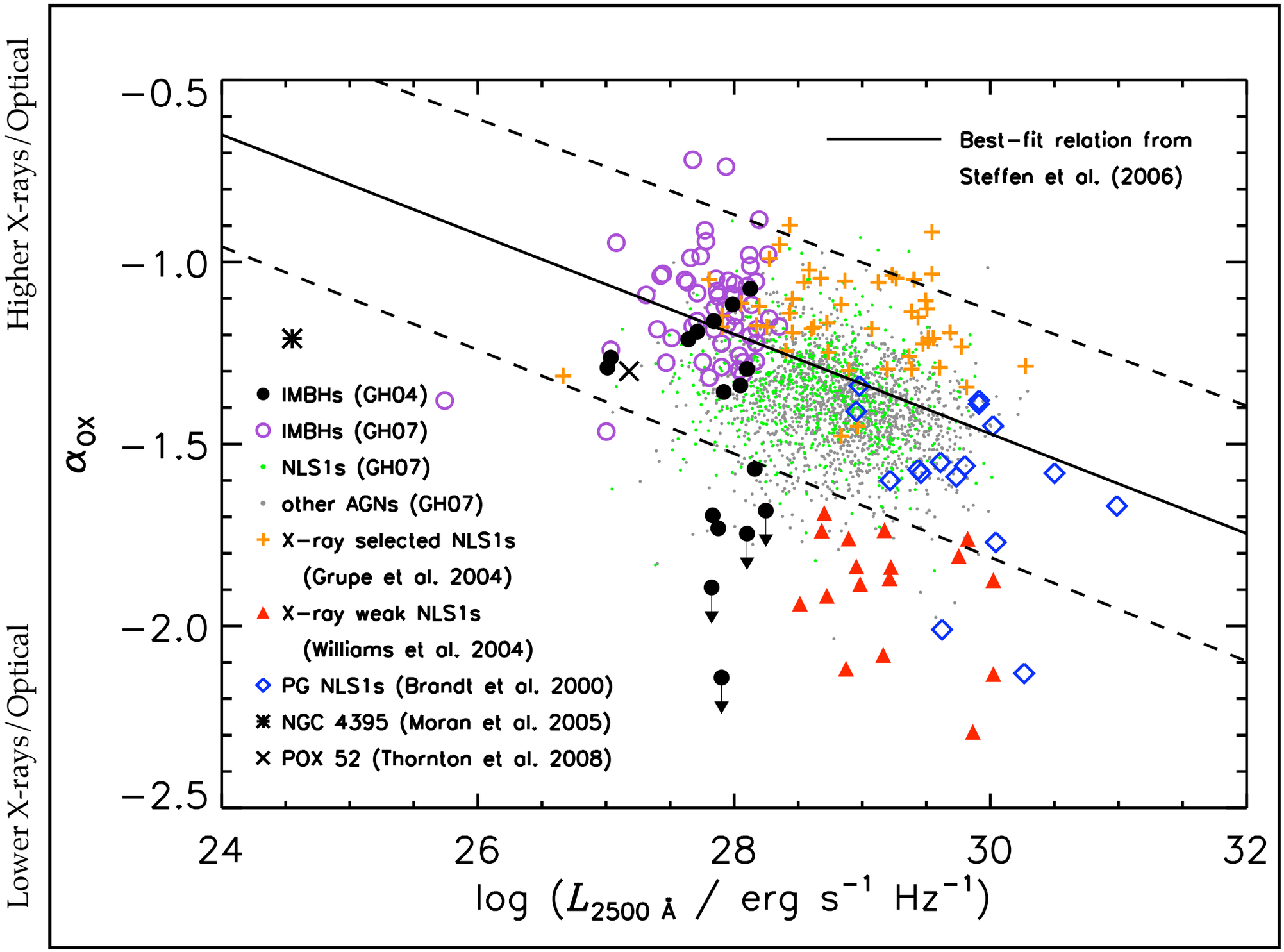




GH10: Wrobel, Greene, Ho, & Ulvestad 2008

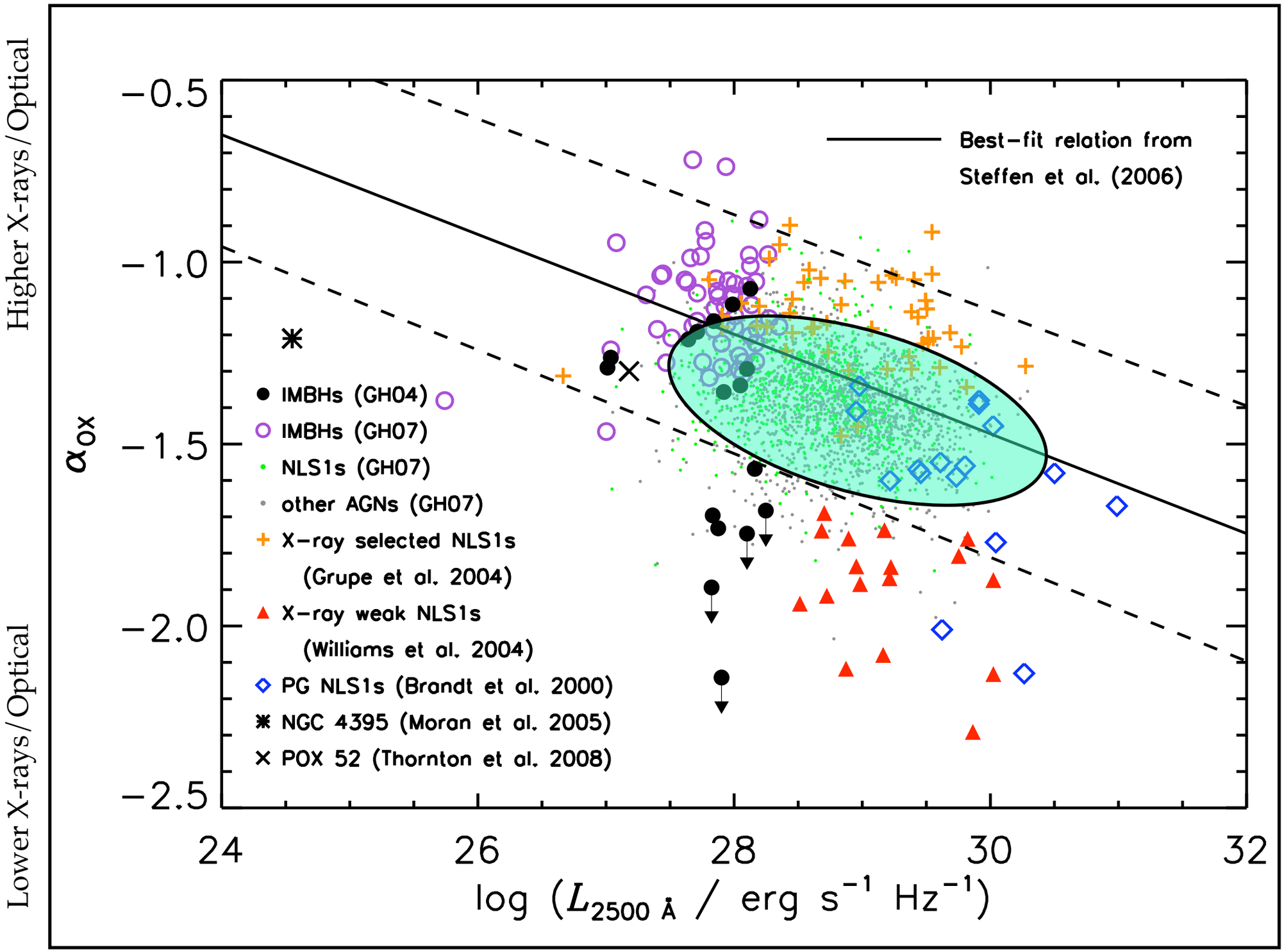
non-detection in the radio (VLA)

Greene, Ho, & Ulvestad 2006



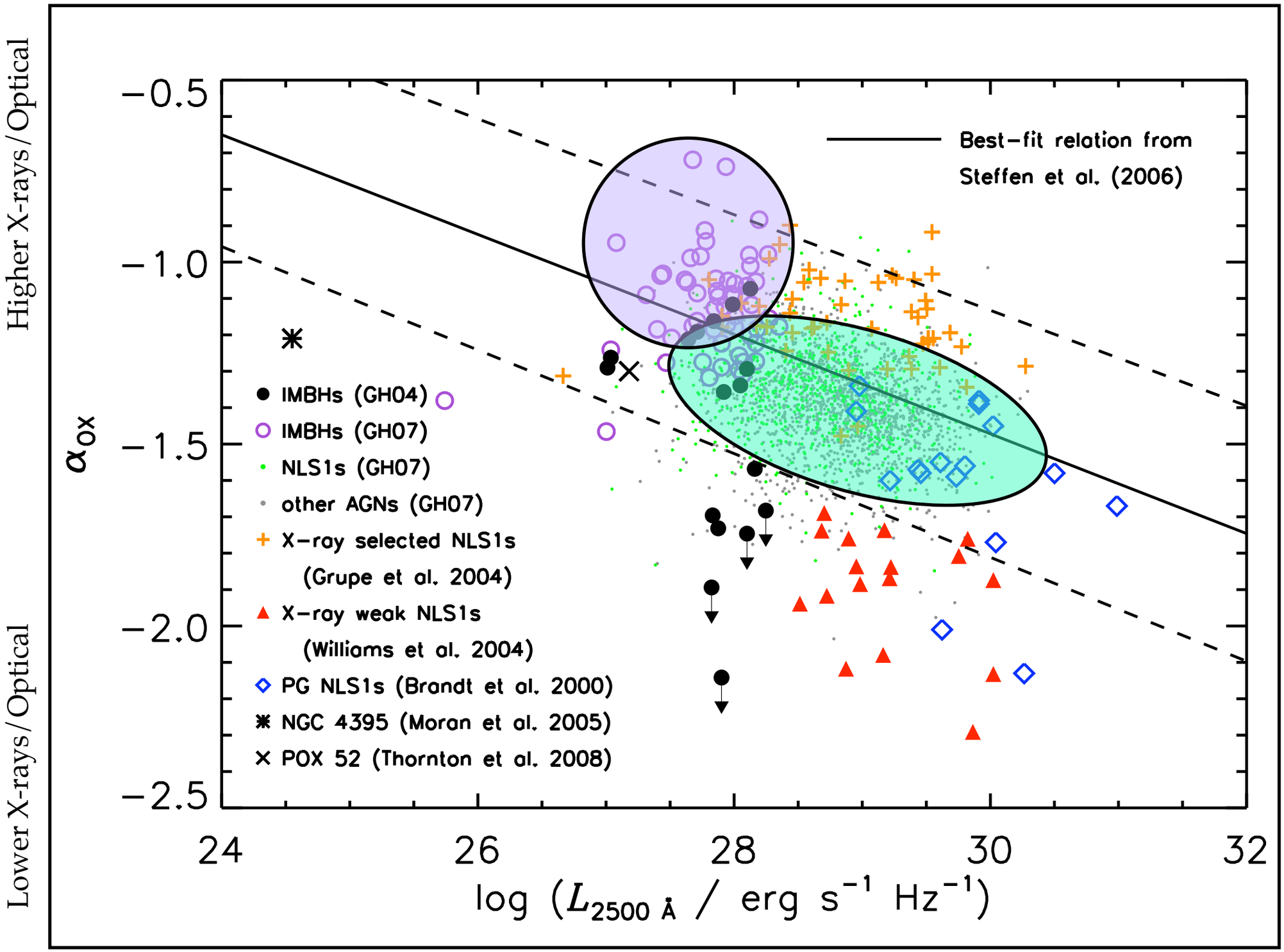
Desroches, Greene, & Ho 2009

Greene & Ho 2007



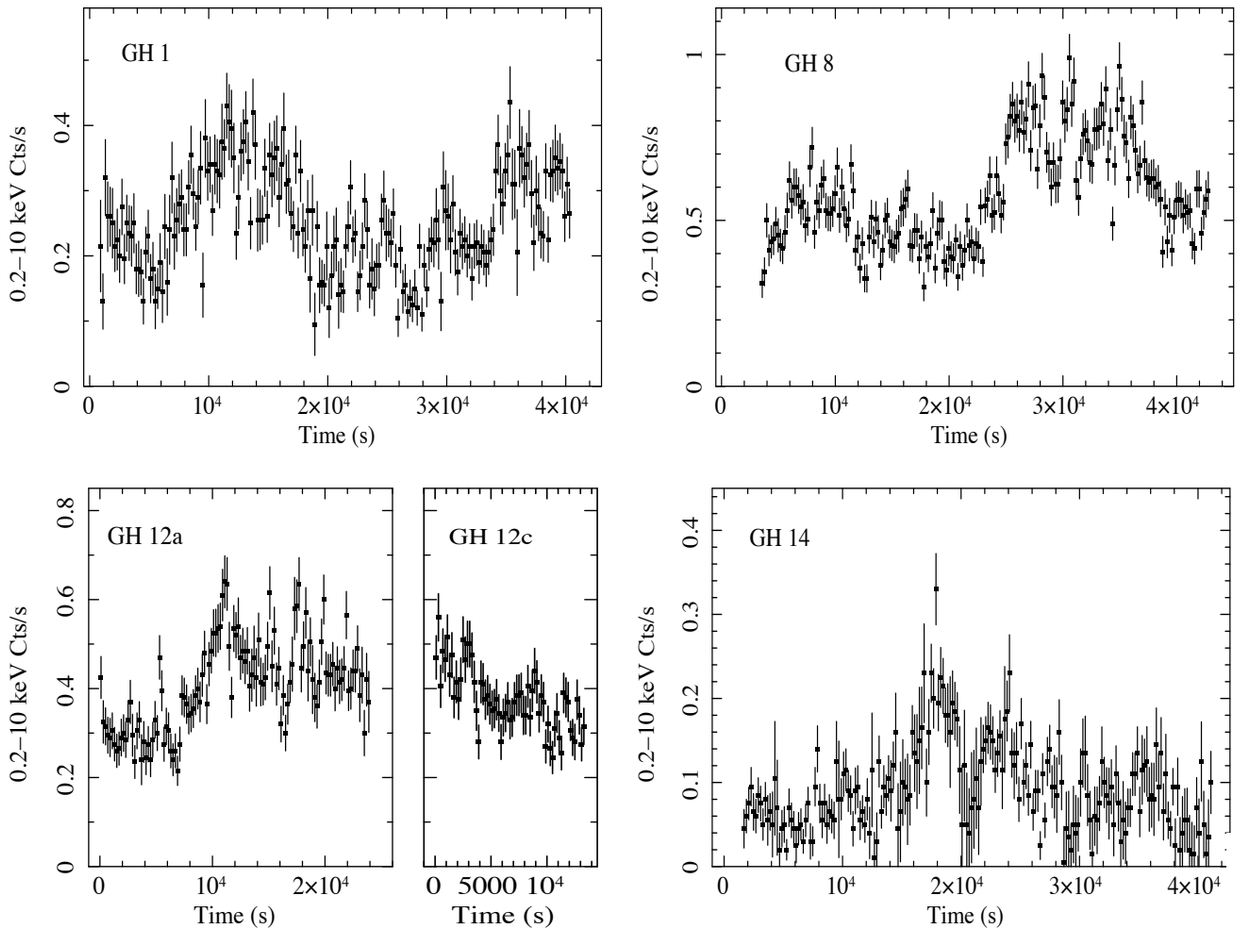
Desroches, Greene, & Ho 2009

Greene & Ho 2007



Desroches, Greene, & Ho 2009

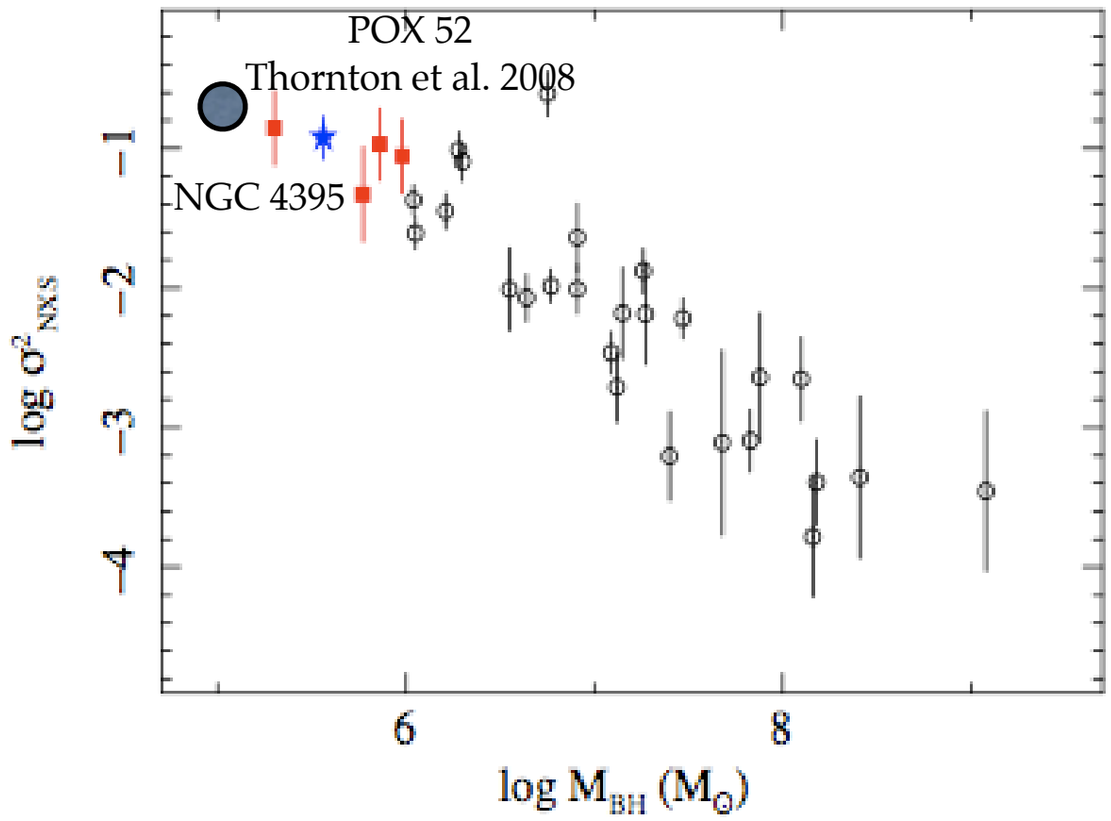
Greene & Ho 2007



40 ks *XMM* observations

σ_{NXS} is the integral of the power spectrum above the break

σ_{NXS} correlated with BH mass



Miniutti et al. 2008