Low-mass Black Holes in Active Galaxies

jenny greene

Yanfei Jiang, Aaron Barth, Ting Xiao, Luis Ho
Malte Schramm, John Silverman
Chien Y. Peng
the Megamaser Cosmology Project:
James Braatz, Cheng-Yu Kuo, Fred Lo, Jim Condon, Mark Reid, Lincoln Greenhill

What is a “low-mass” black hole?

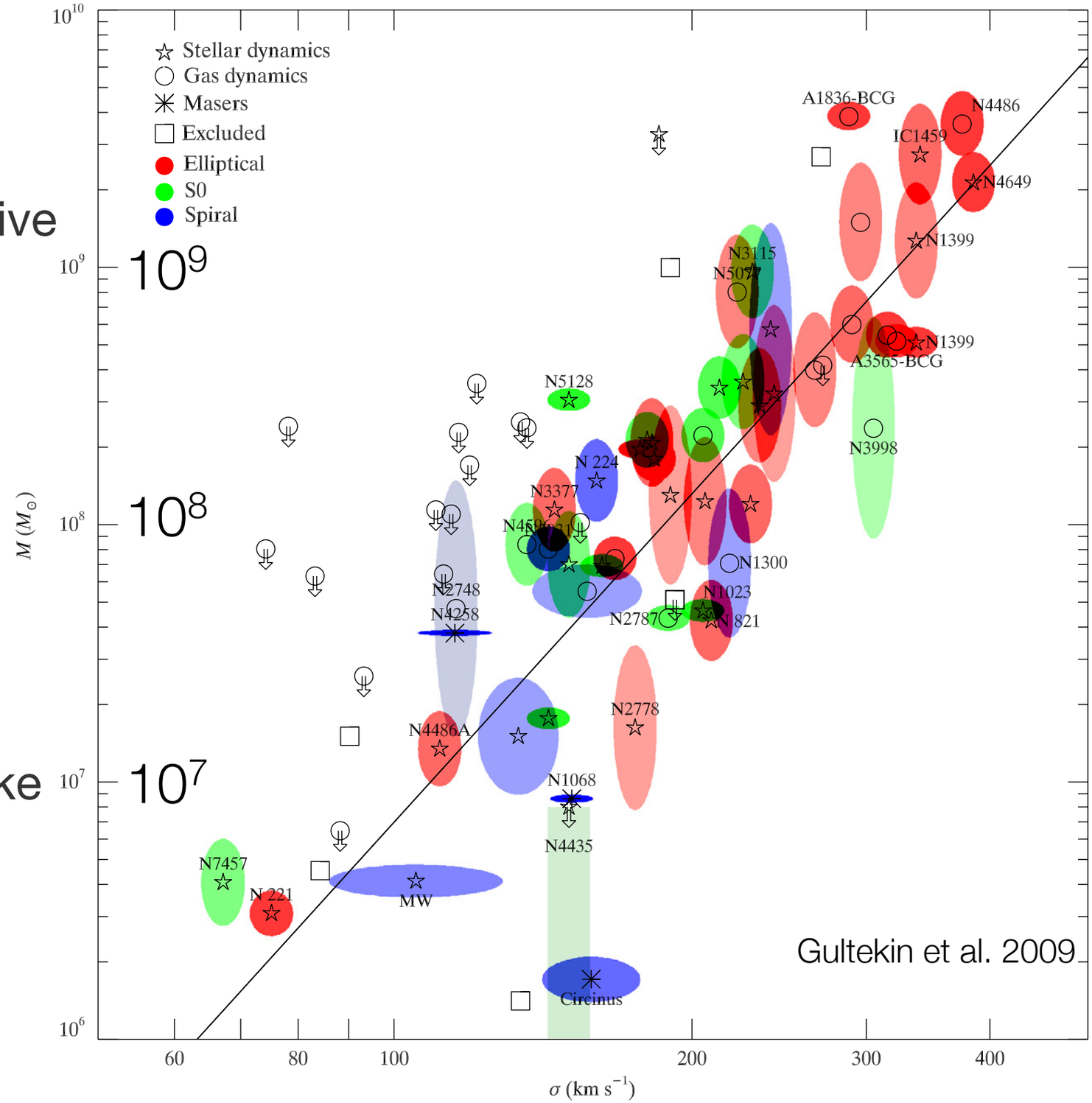
$<10^6\ M_\odot$ (< than the MW)

What are the smallest supermassive BHs?

Is a bulge required to host a BH?

What are the formation mechanisms of seed BHs?

What might we see with a LISA-like gravity wave experiment?



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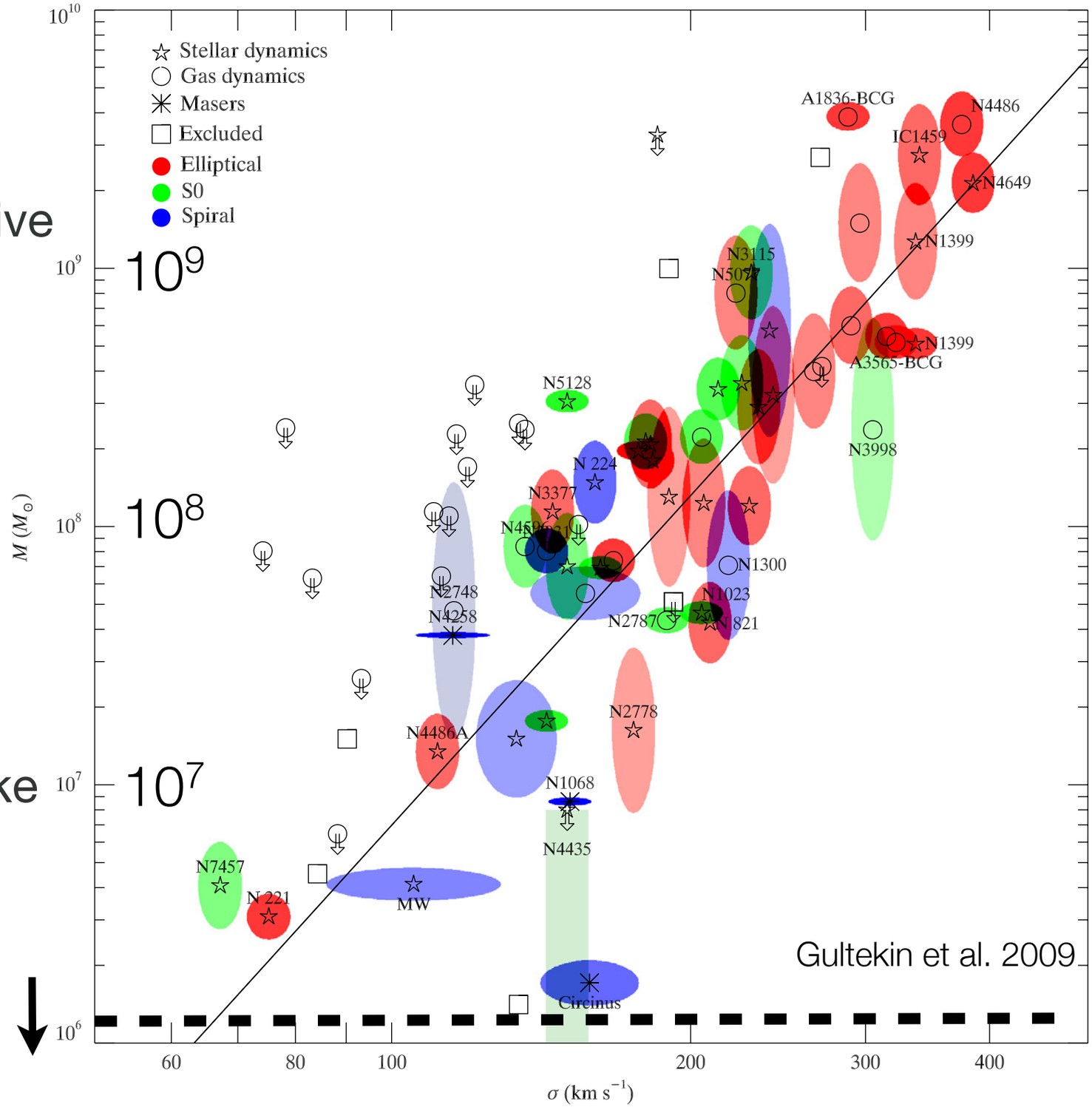
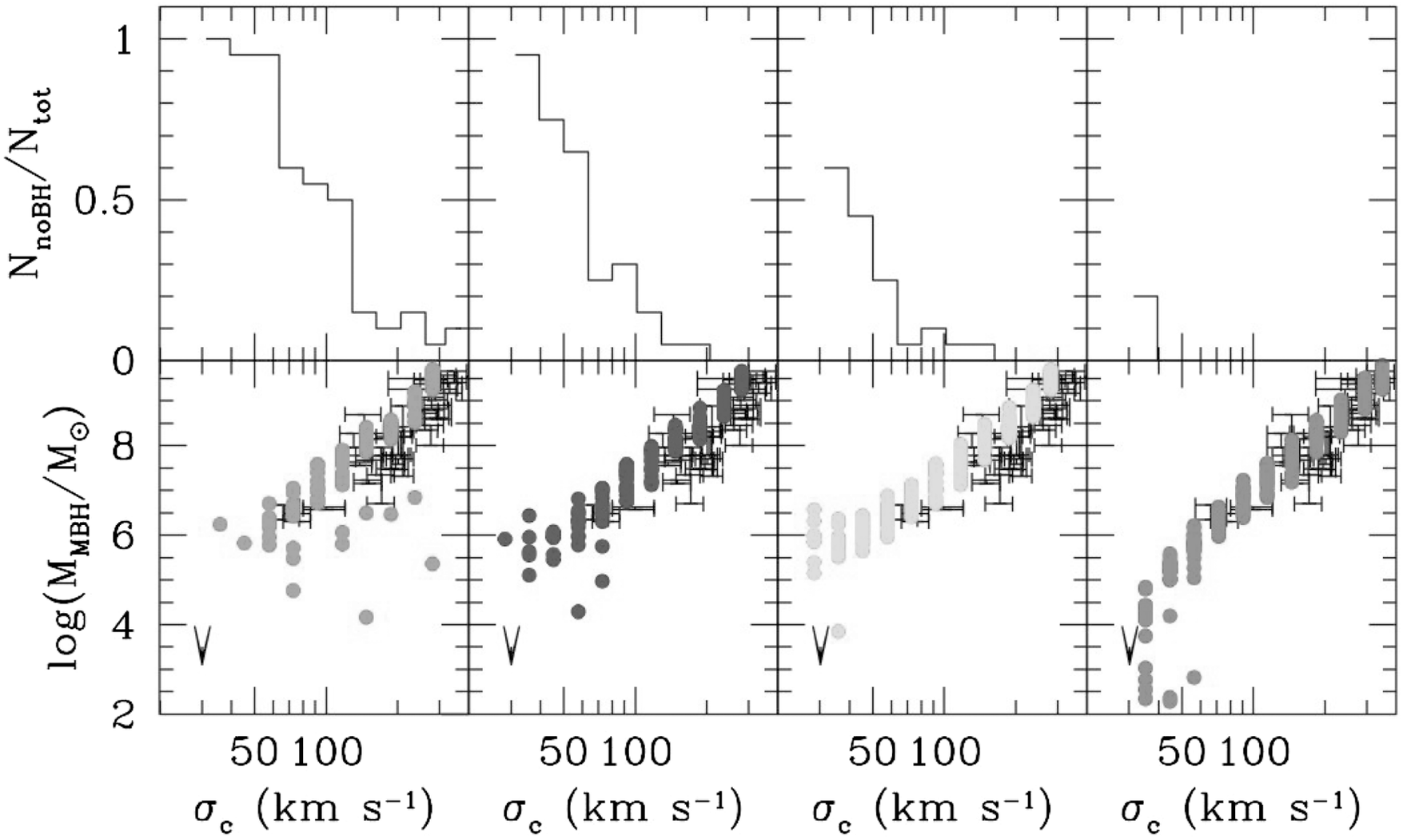


What do we want to know?

Volonteri et al. 2008



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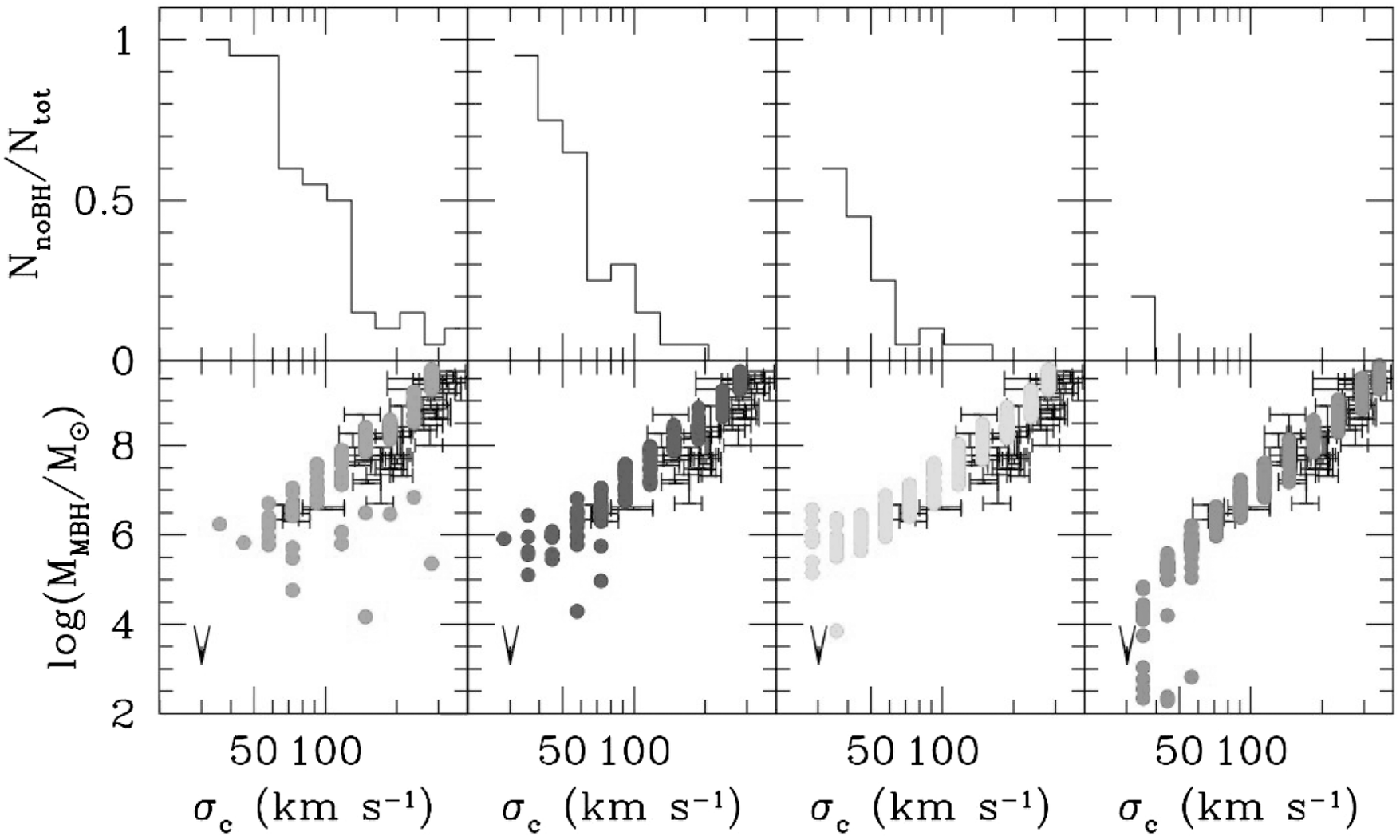


Space densities

Number of off-nuclear BHs

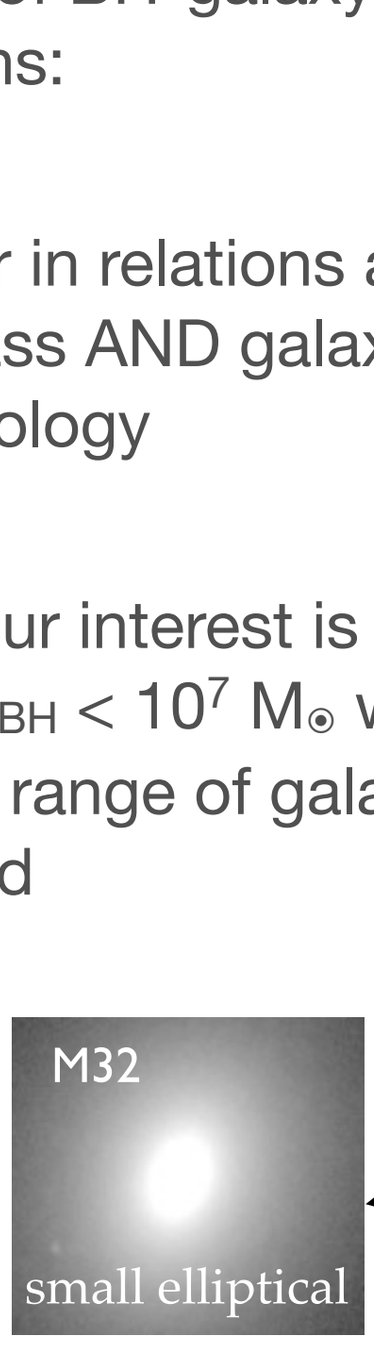
Scaling relations

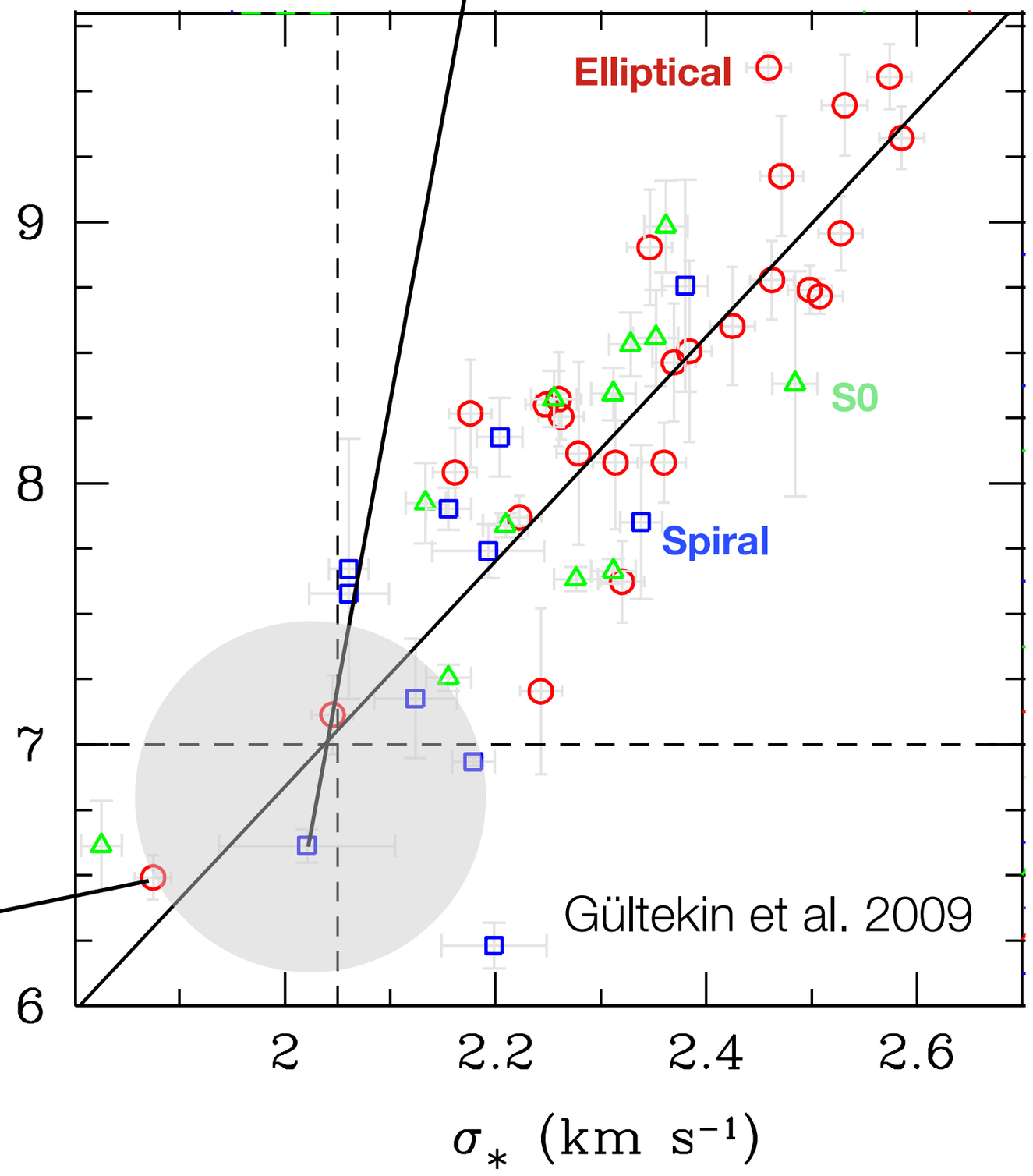
What is a “low-mass” black hole?

Origin of BH-galaxy scaling relations:

Scatter in relations as function of BH mass AND galaxy morphology

Then our interest is in all systems with $M_{BH} < 10^7\ M_\odot$ where the widest range of galaxy morphology is found





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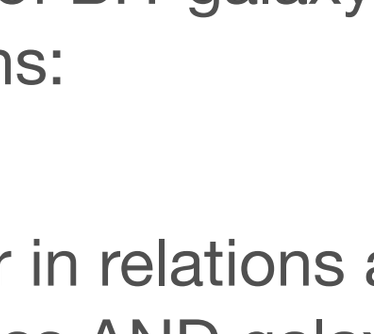
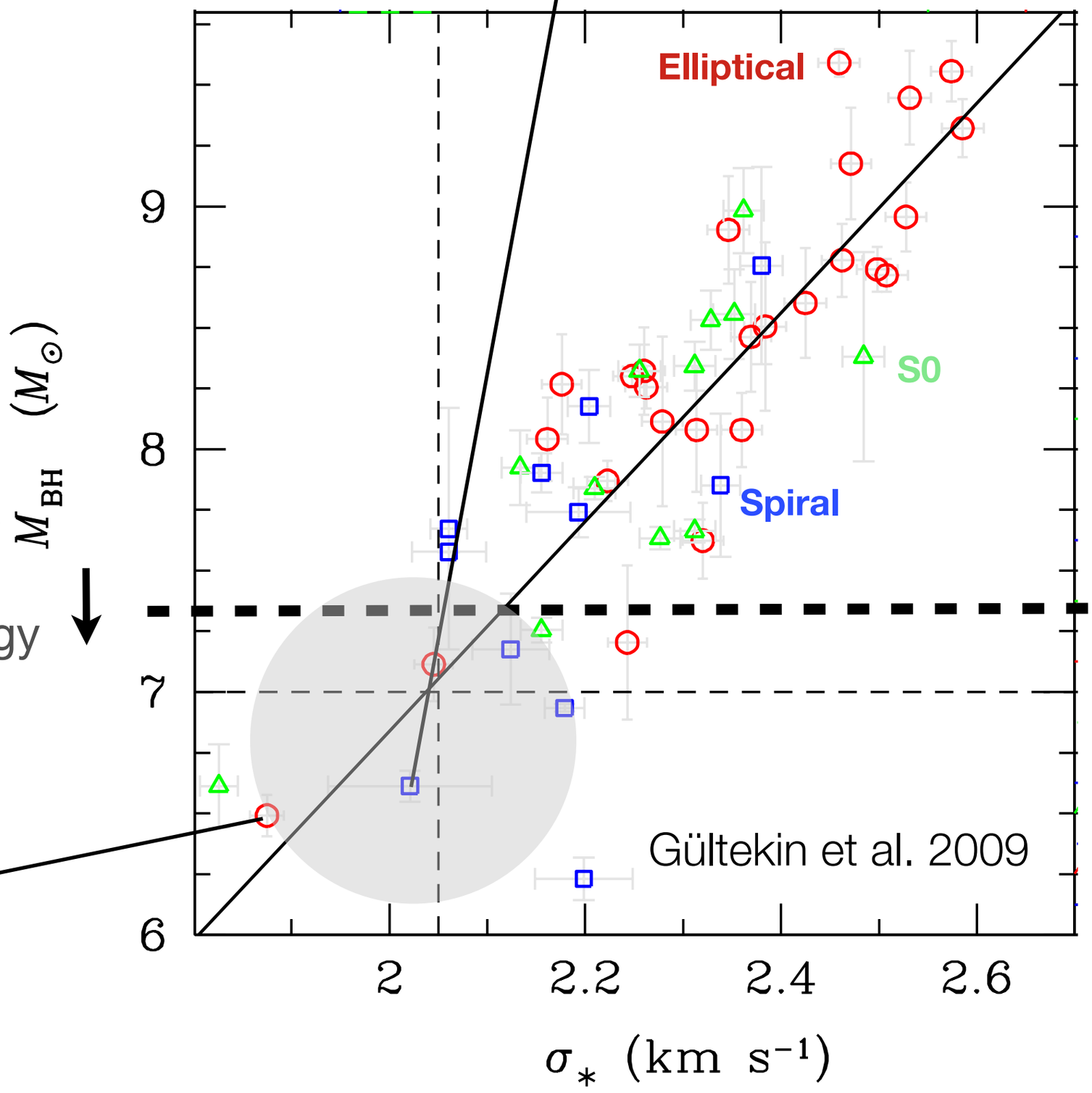
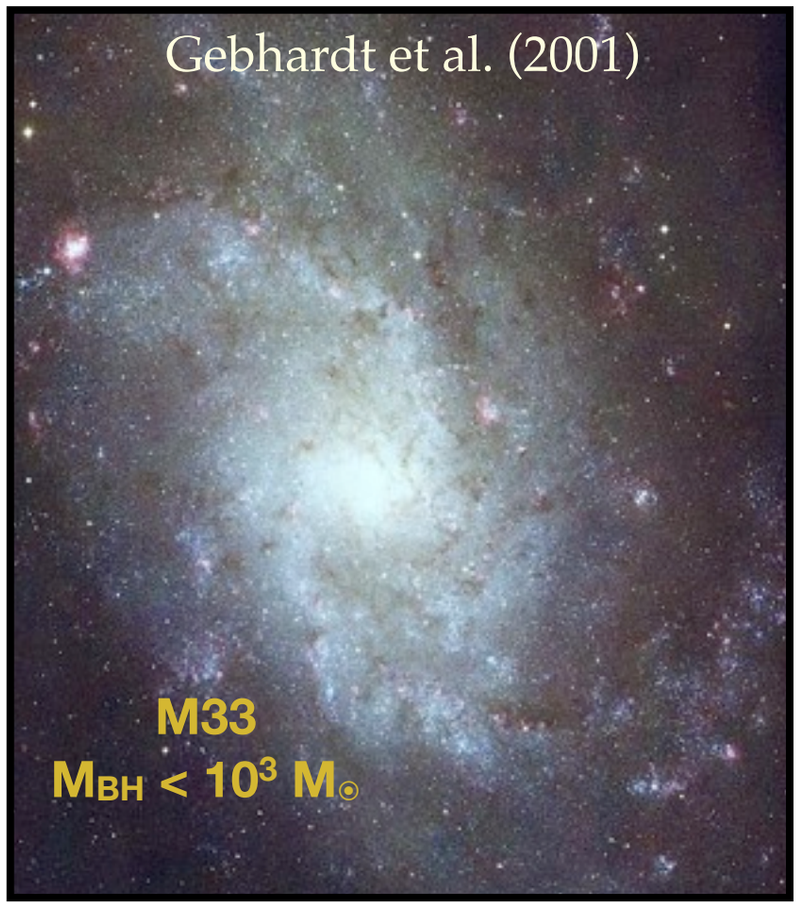
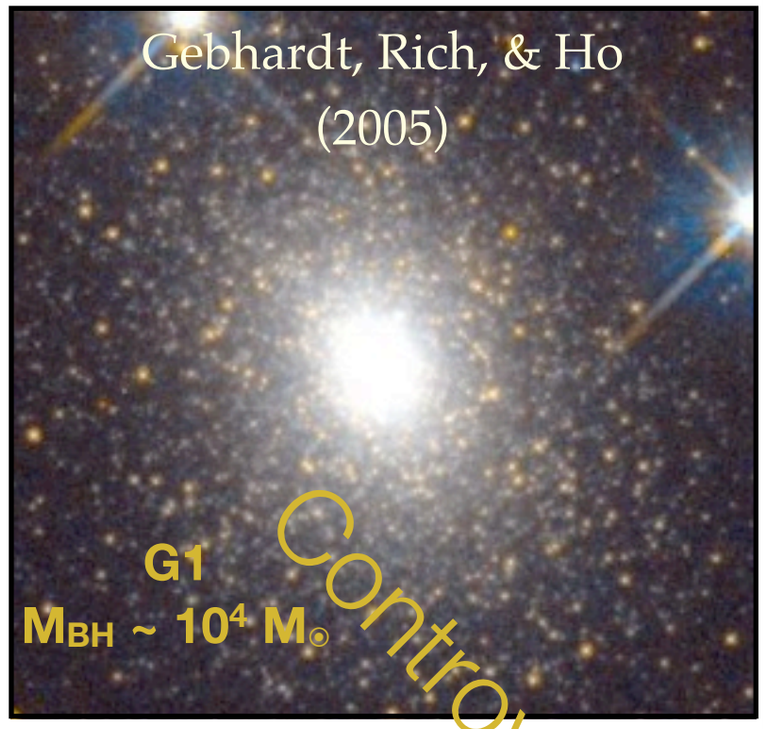


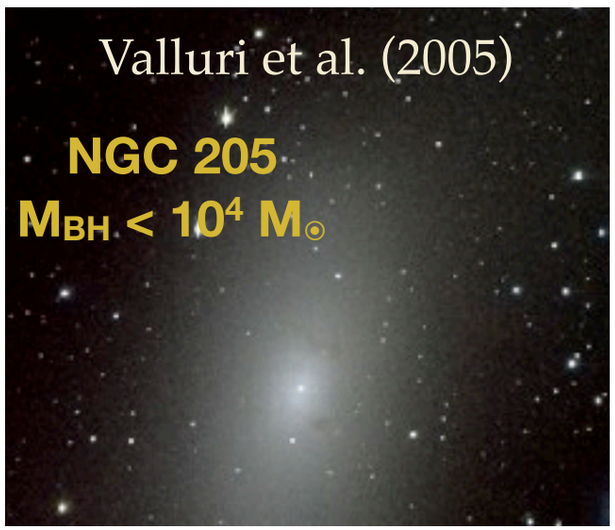


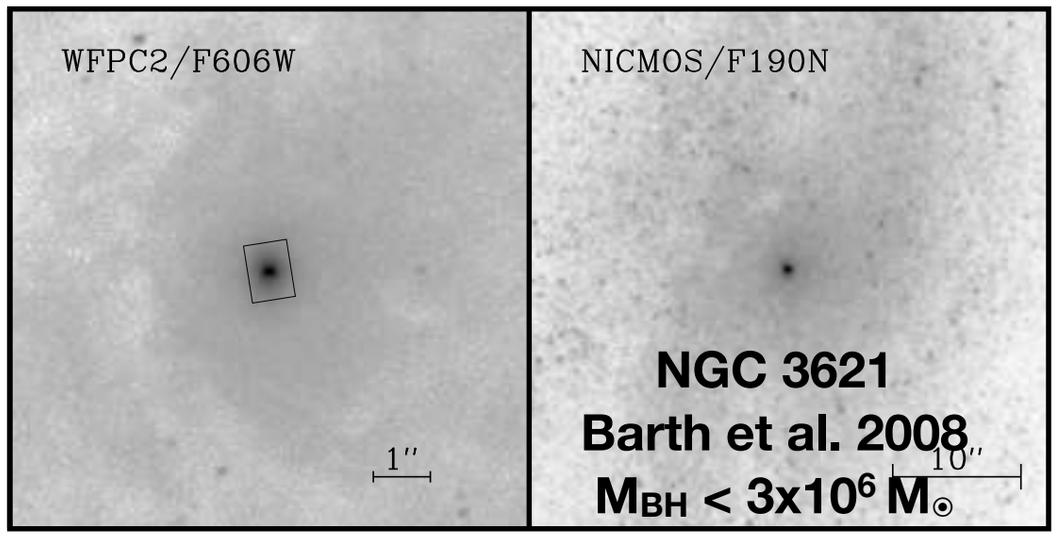
How do we find BHs with $M_{BH} < 10^6\ M_\odot$?

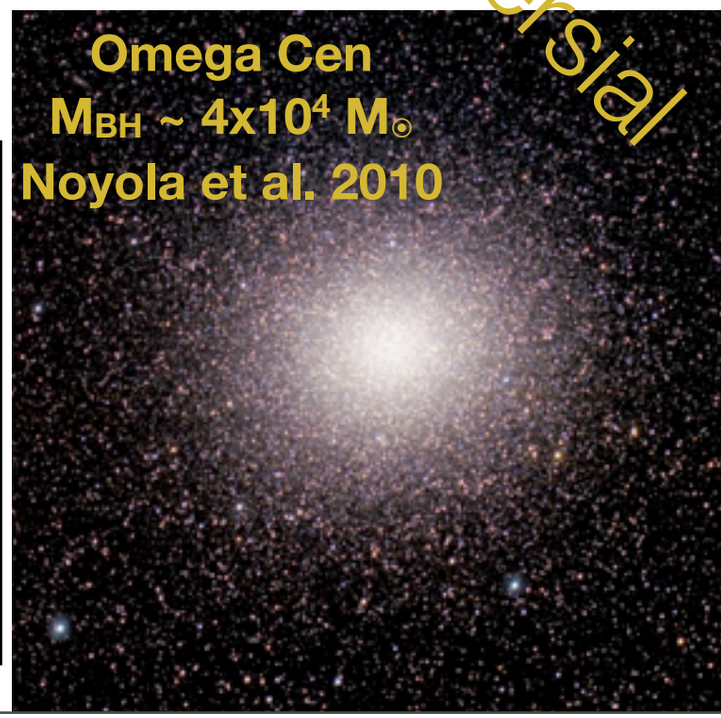
Dynamical BH masses for $<10^6$ $M_\odot$ BHs only possible within a few Mpc





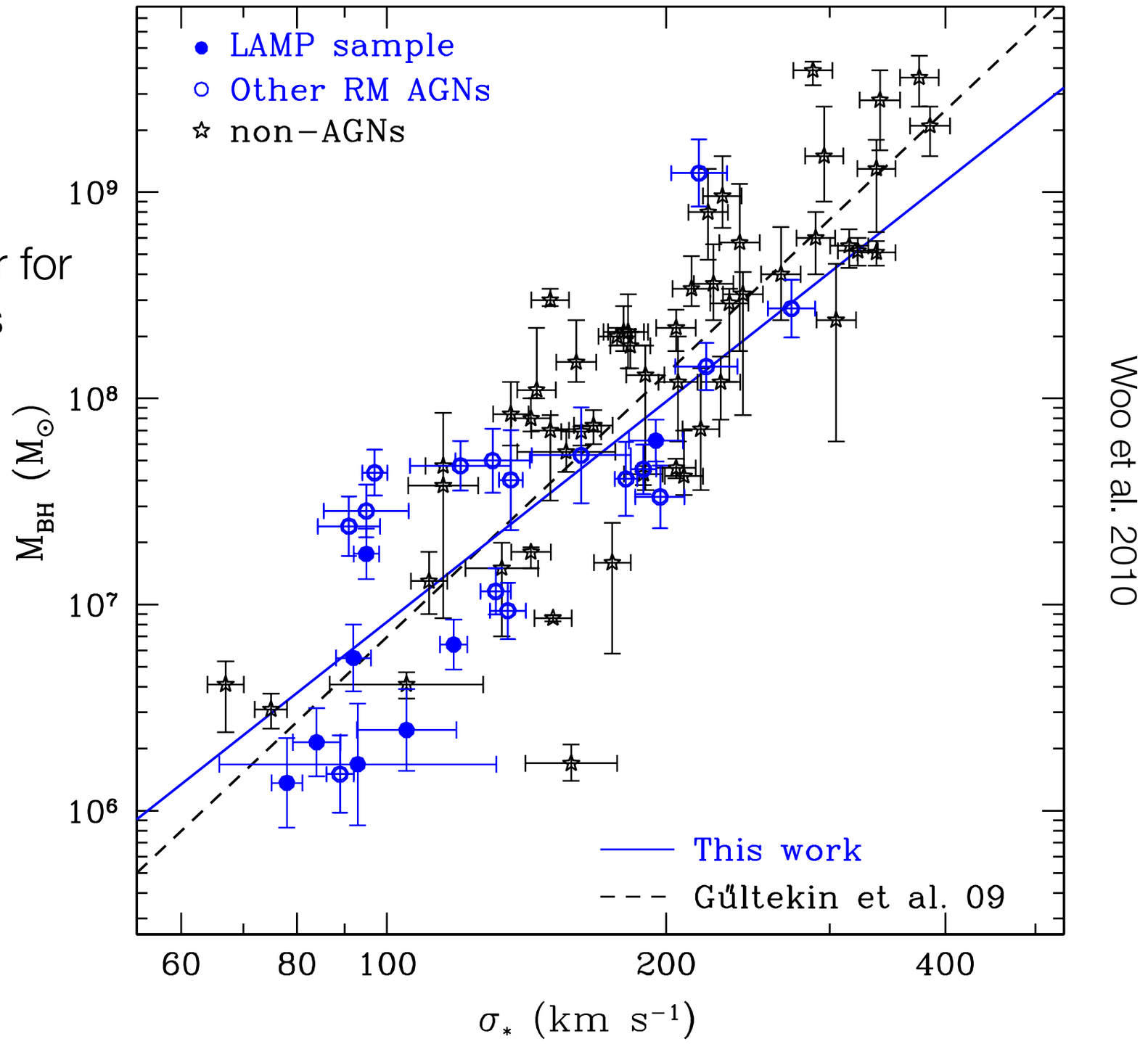






Reverberation Mapping...Hasn't quite reached such low masses yet (except for NGC 4395)

see Aaron's poster for LAMP II results



Otherwise must rely on signatures of nuclear activity

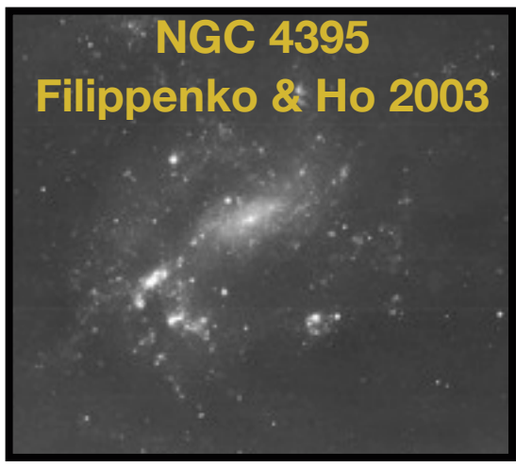
Optical line emission, broad or narrow: SDSS (Greene & Ho; Dong et al., Barth et al., Moran et al.); nearby objects (e.g., Filippenko & Ho; Barth et al., Shields et al.)

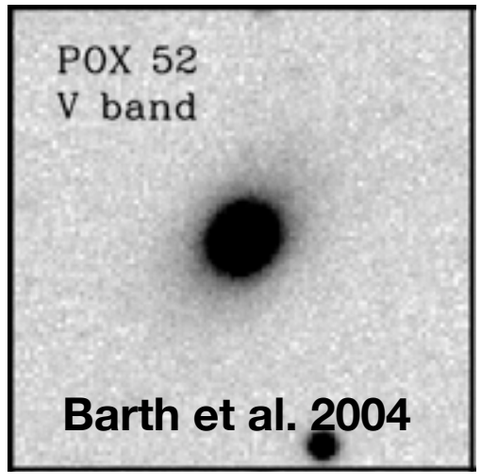
X-ray (+radio): Desroches & Ho; Ghosh et al.; Gallo et al.; Reines et al.; Schramm et al.

MIR (mostly via spectroscopy): Satyapal et al.; Goulding et al.

10^7 10^8 10^9 10^{10}

Stellar Mass ($M_\odot$) ⟶





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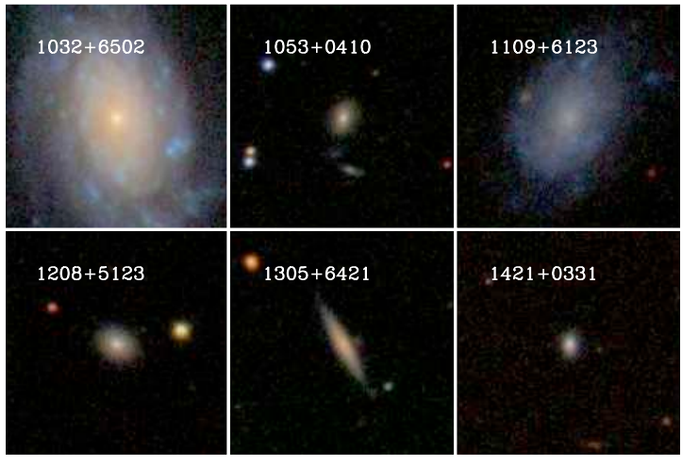
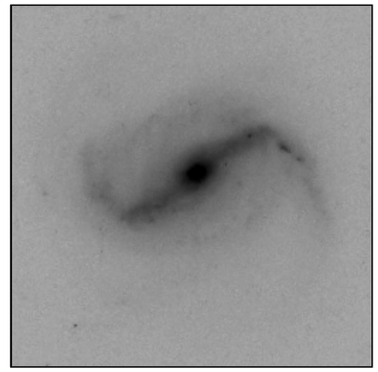


Narrow-line AGNs from SDSS

Greene & Ho (2004, 2007)



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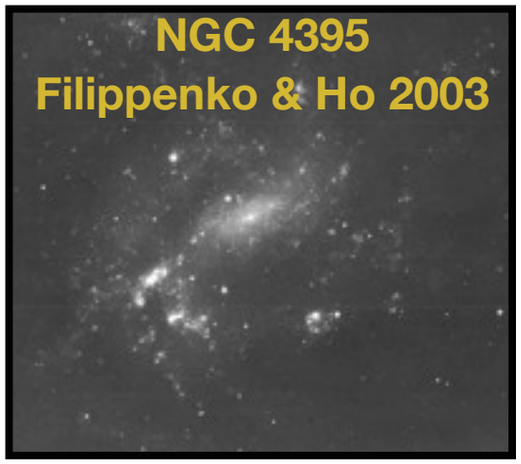

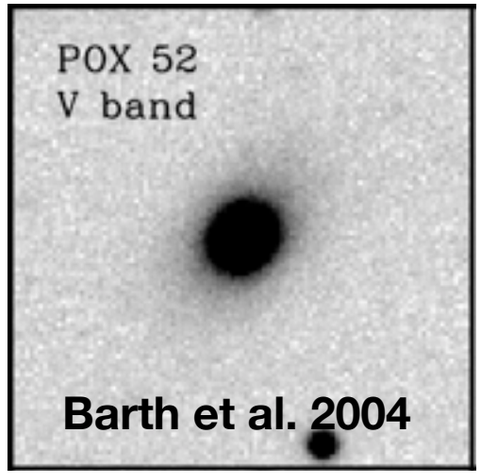

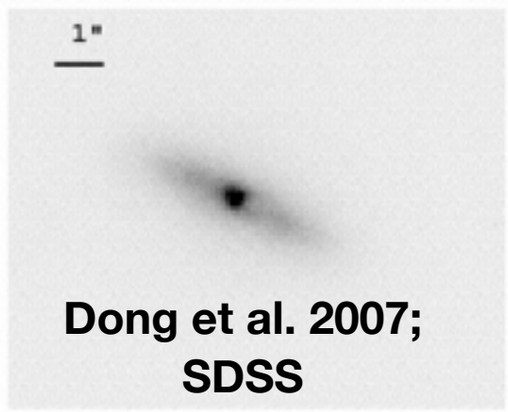

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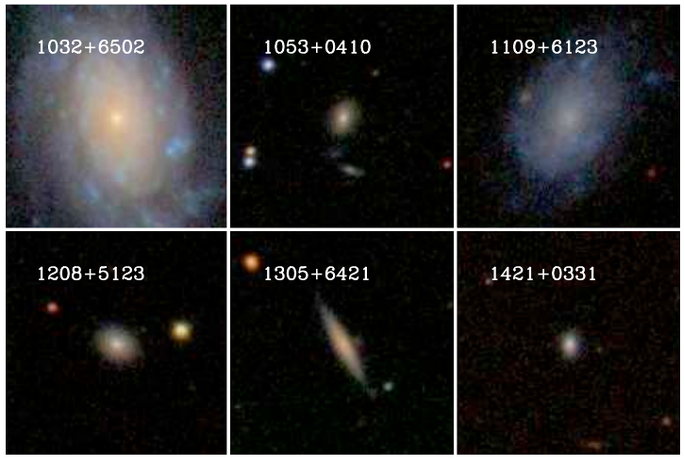

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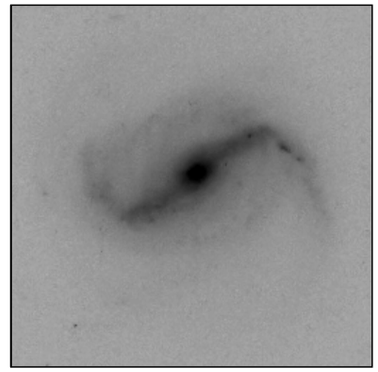

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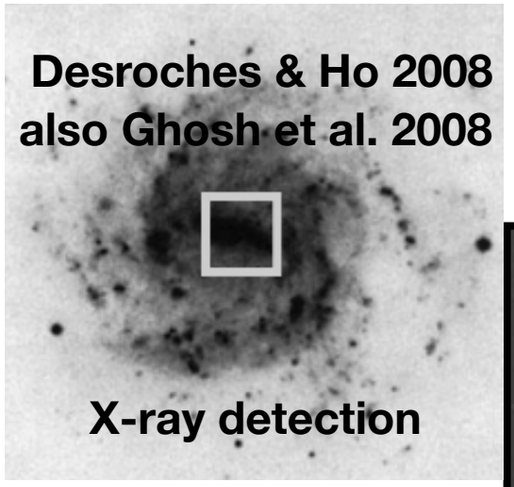

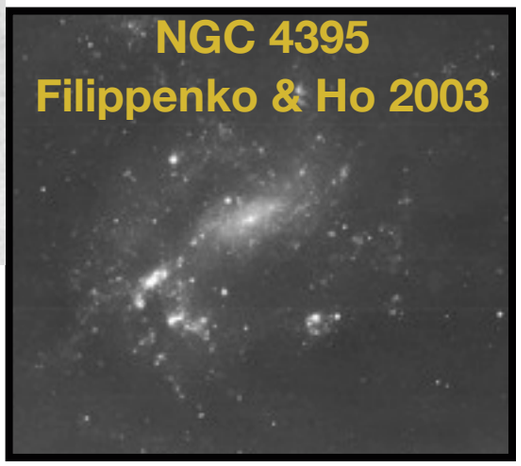

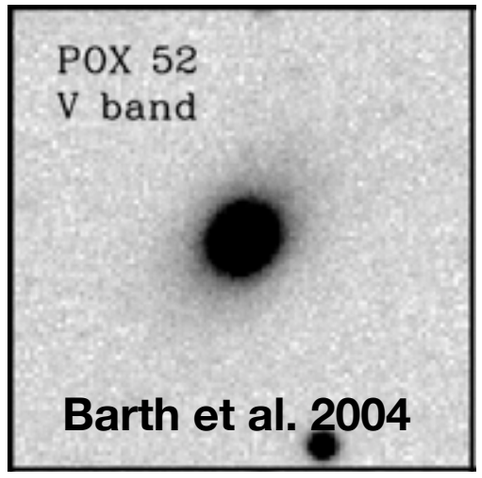

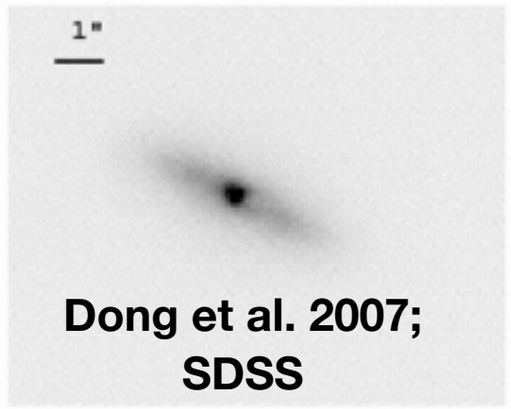

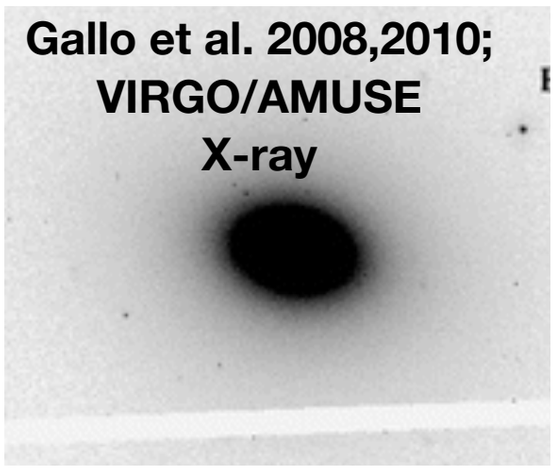

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Moran et al.

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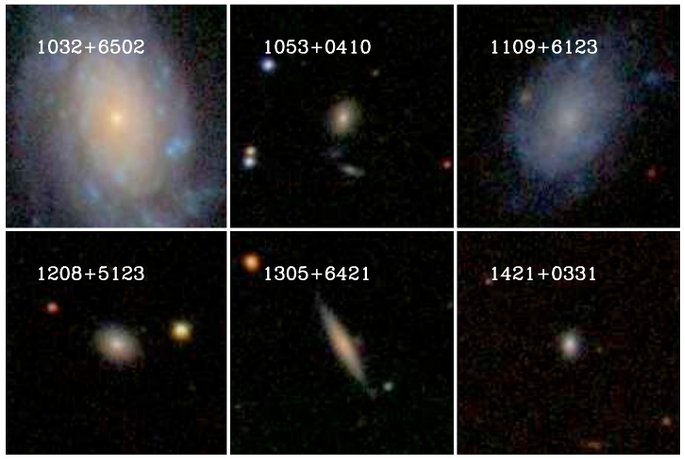

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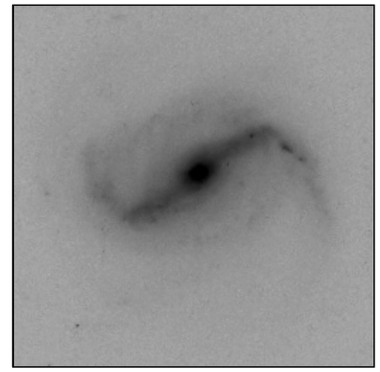

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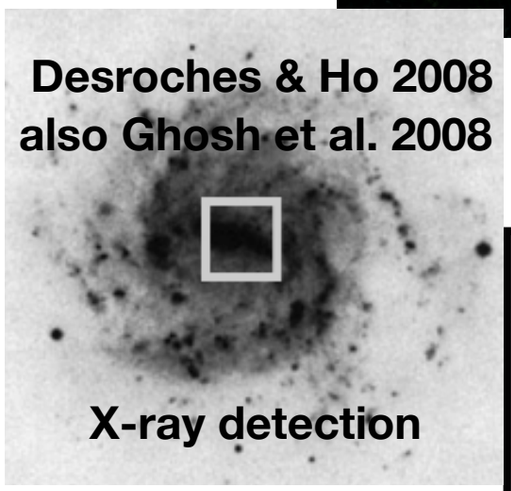

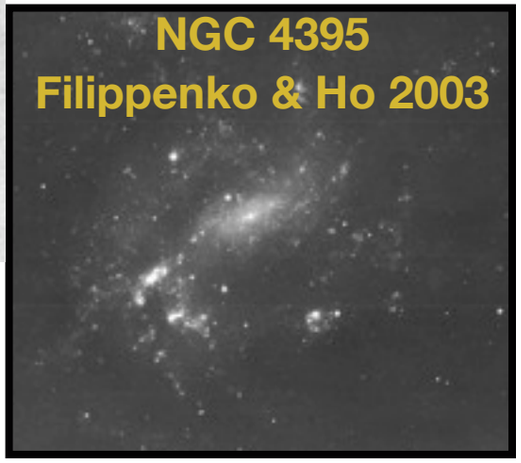

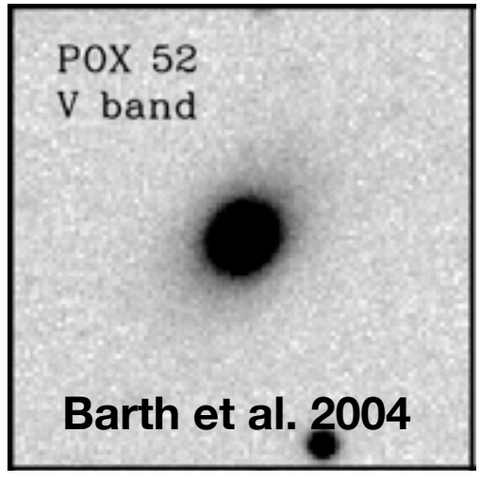

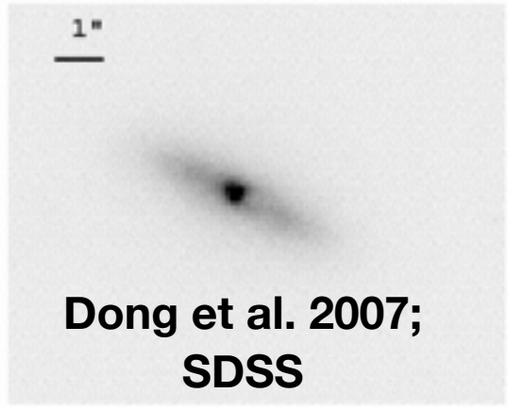

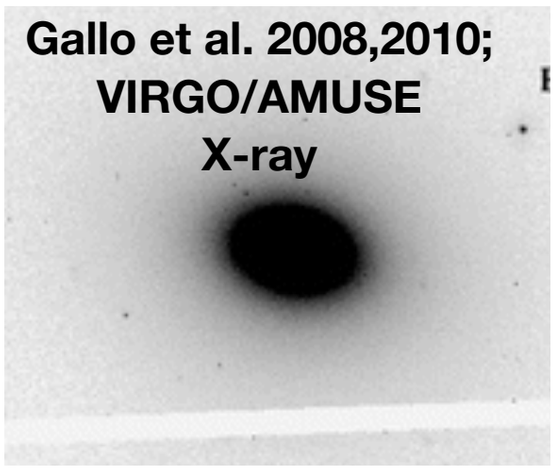

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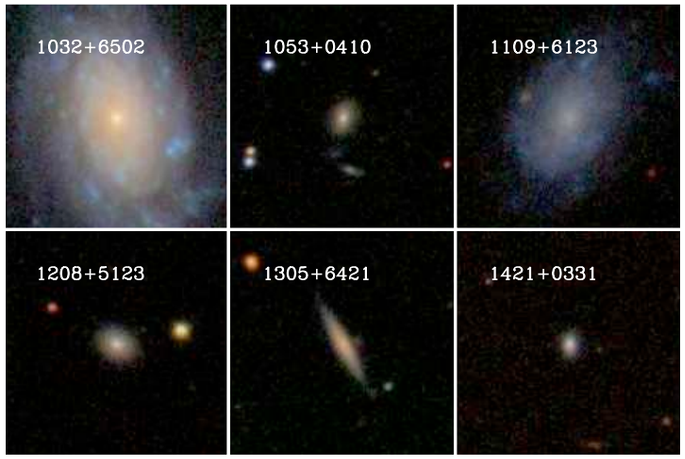

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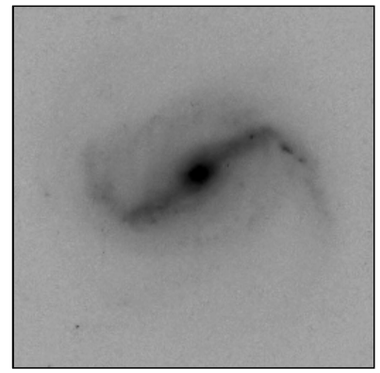

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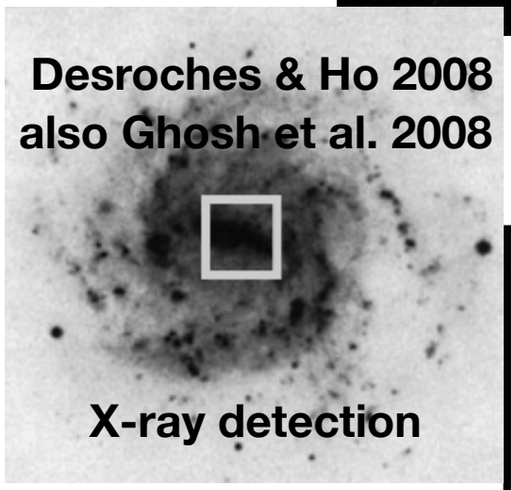

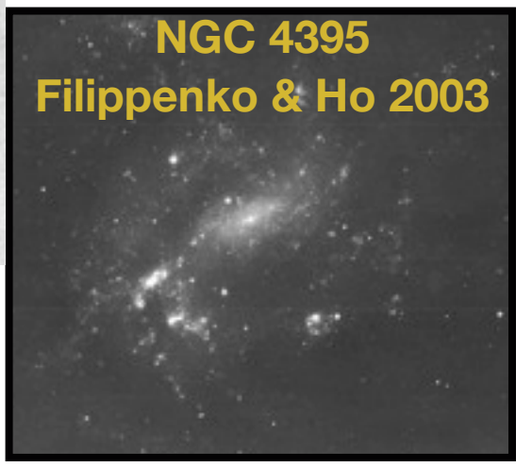

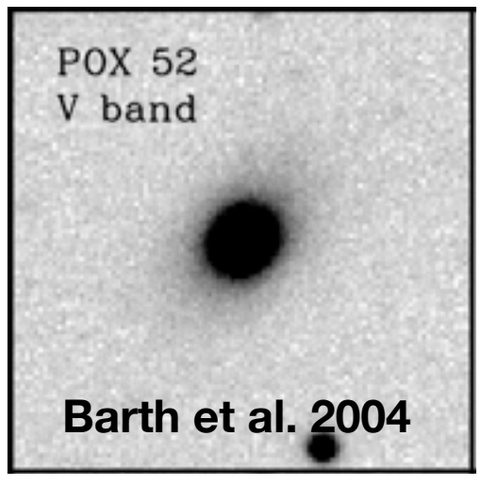

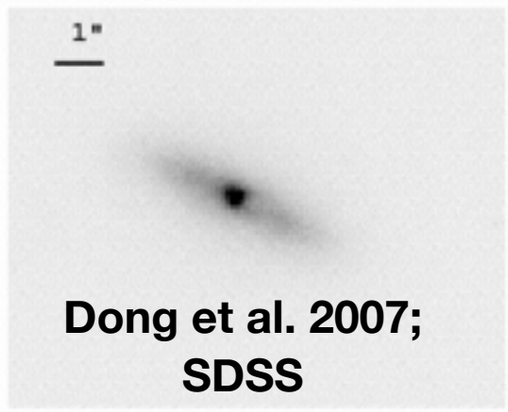

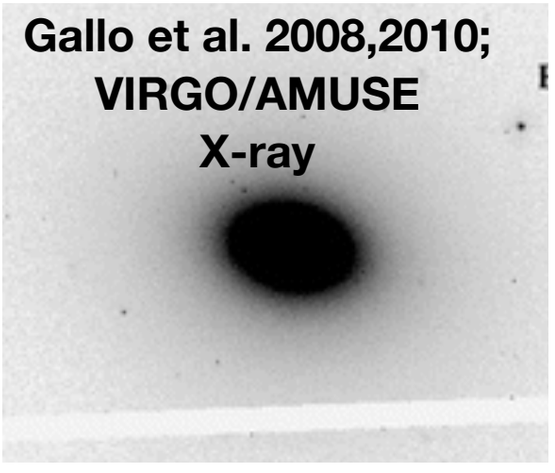

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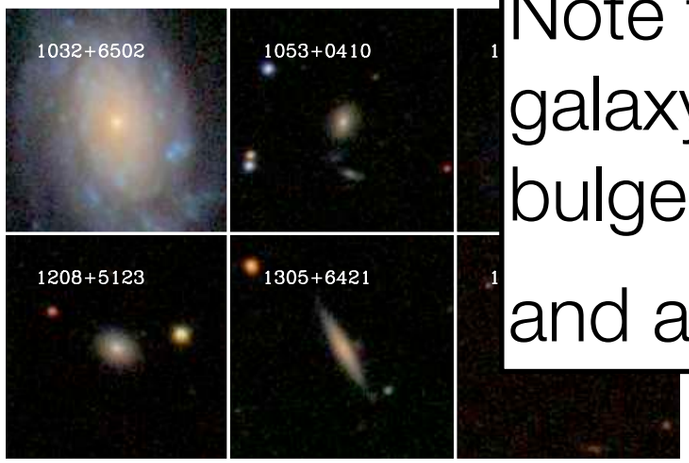

Narrow-line AGNs from SDSS

Note the wide array of galaxy morphologies: bulgeless spirals, spheroidals, and a dwarf starburst…

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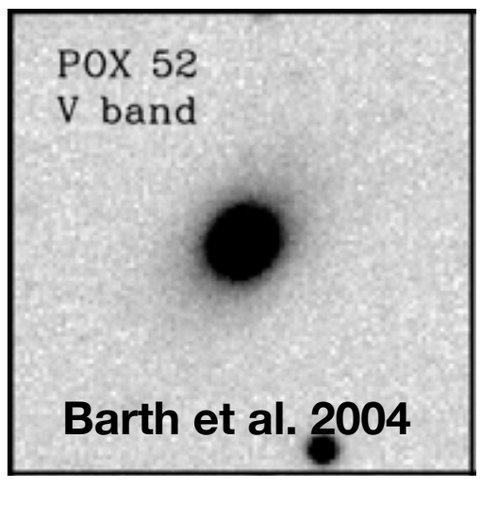
Desroches & Ho 2008
also Ghosh et al. 2008

X-ray detection

NGC 4395
Filippenko & Ho 2003



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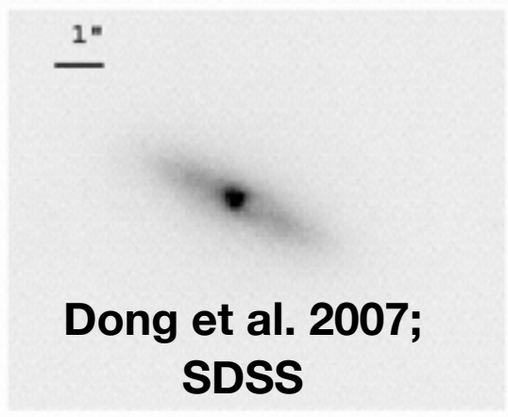

Dong et al. 2007;
SDSS

Henize 2-10;
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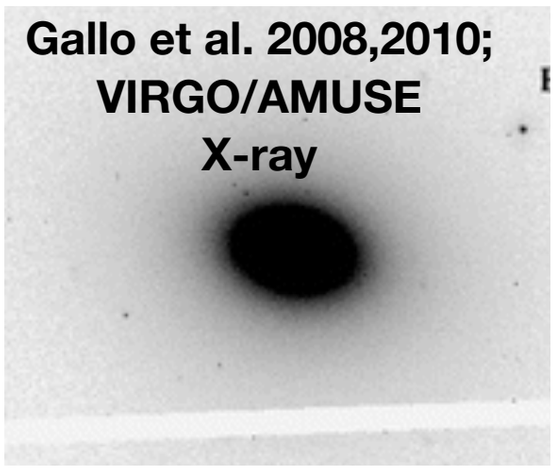

Gallo et al. 2008,2010;
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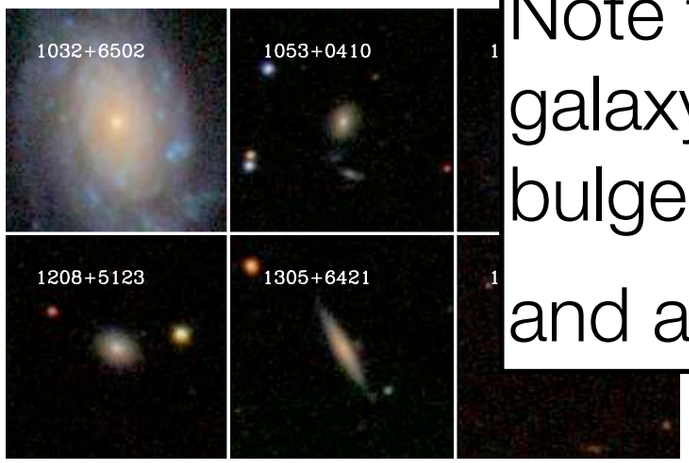

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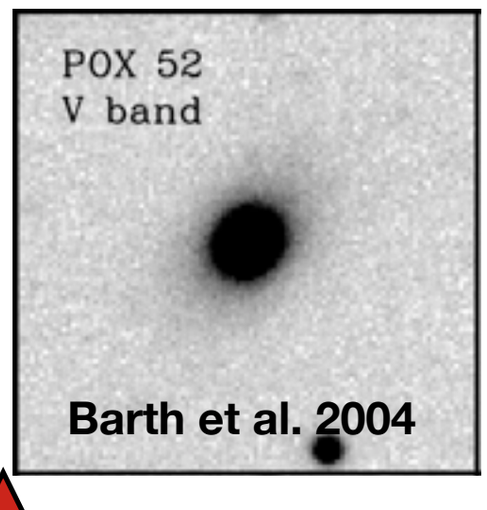

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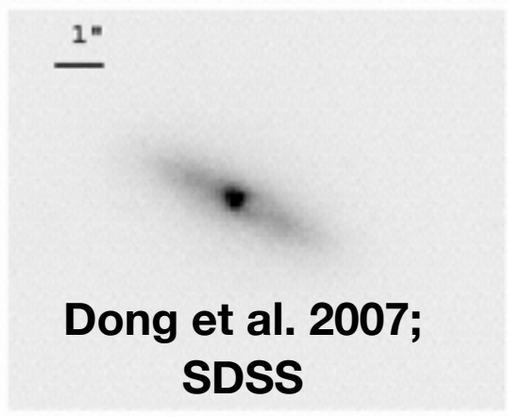

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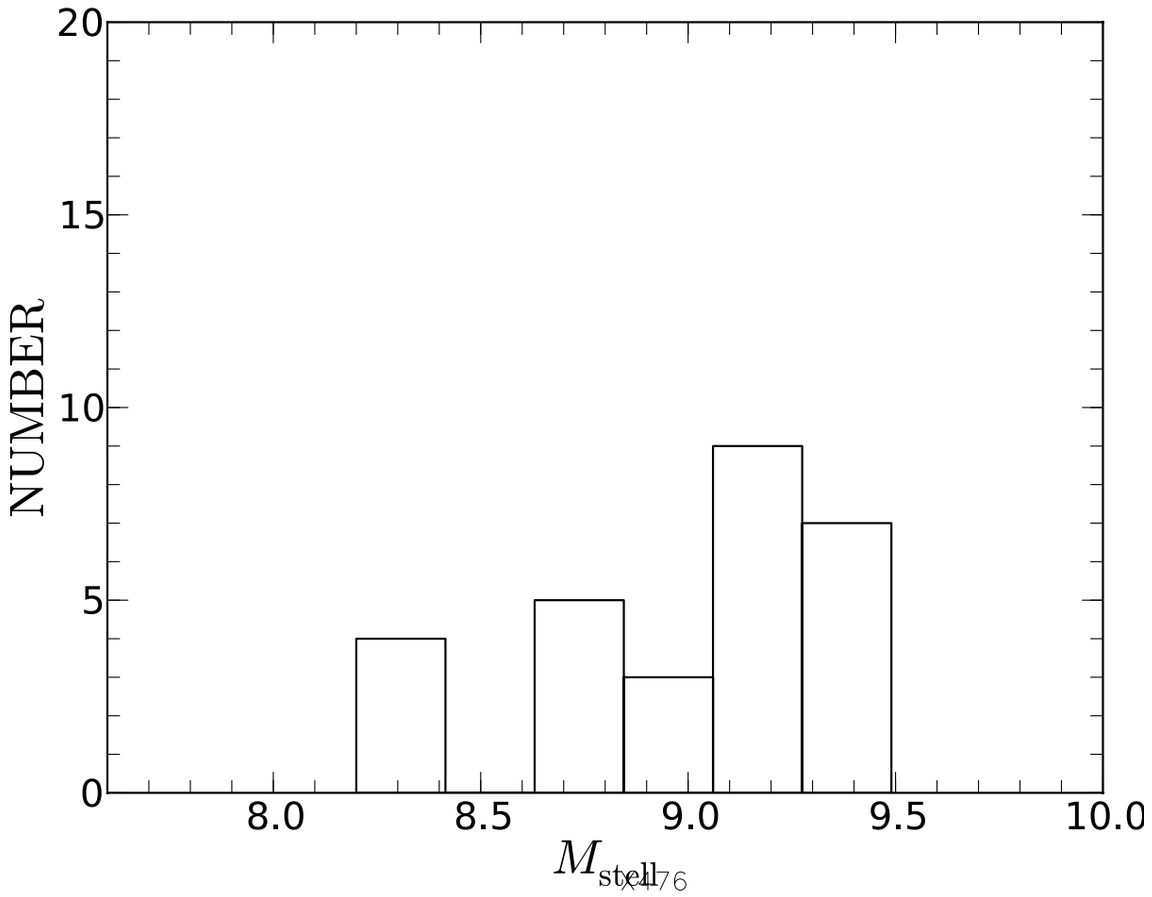
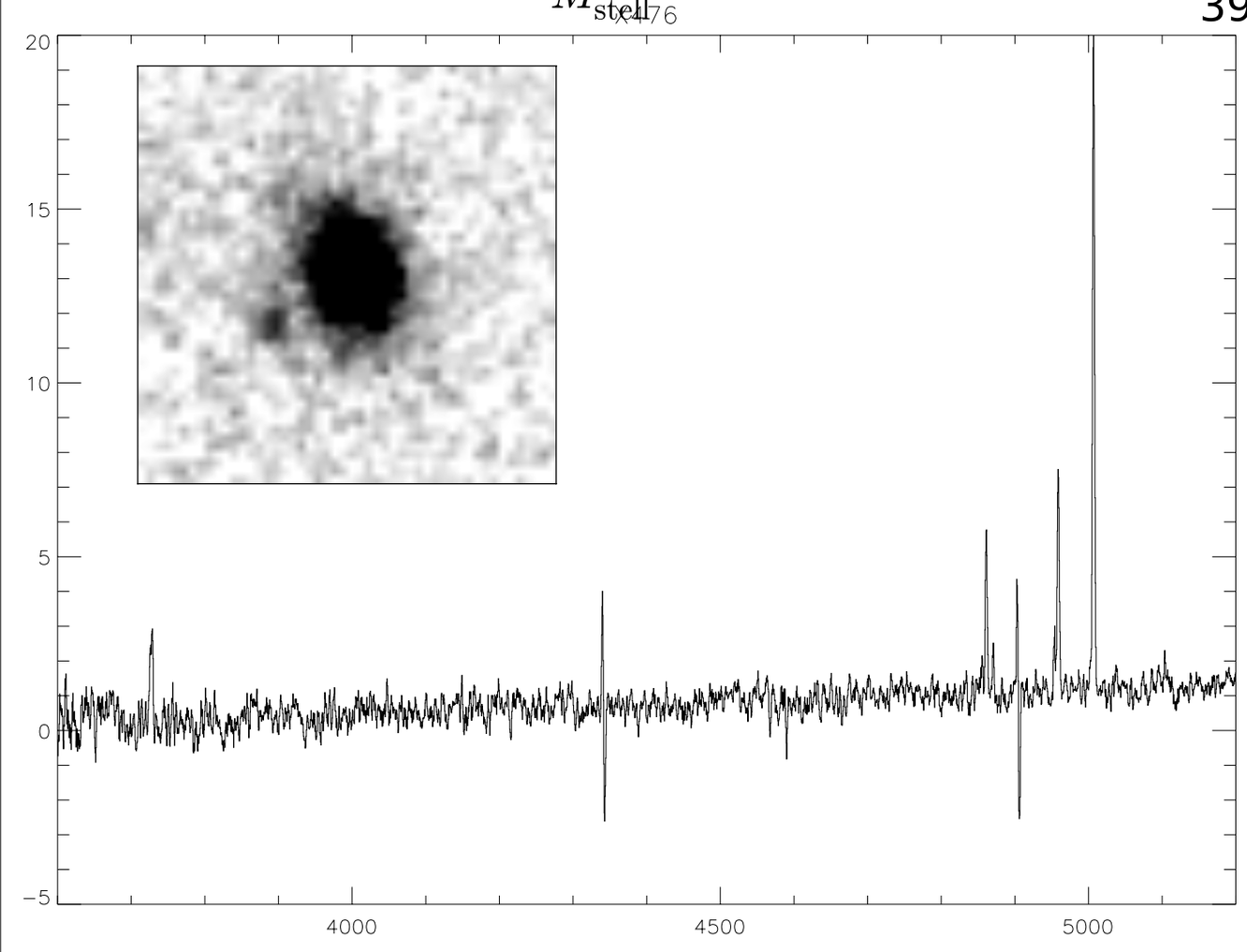
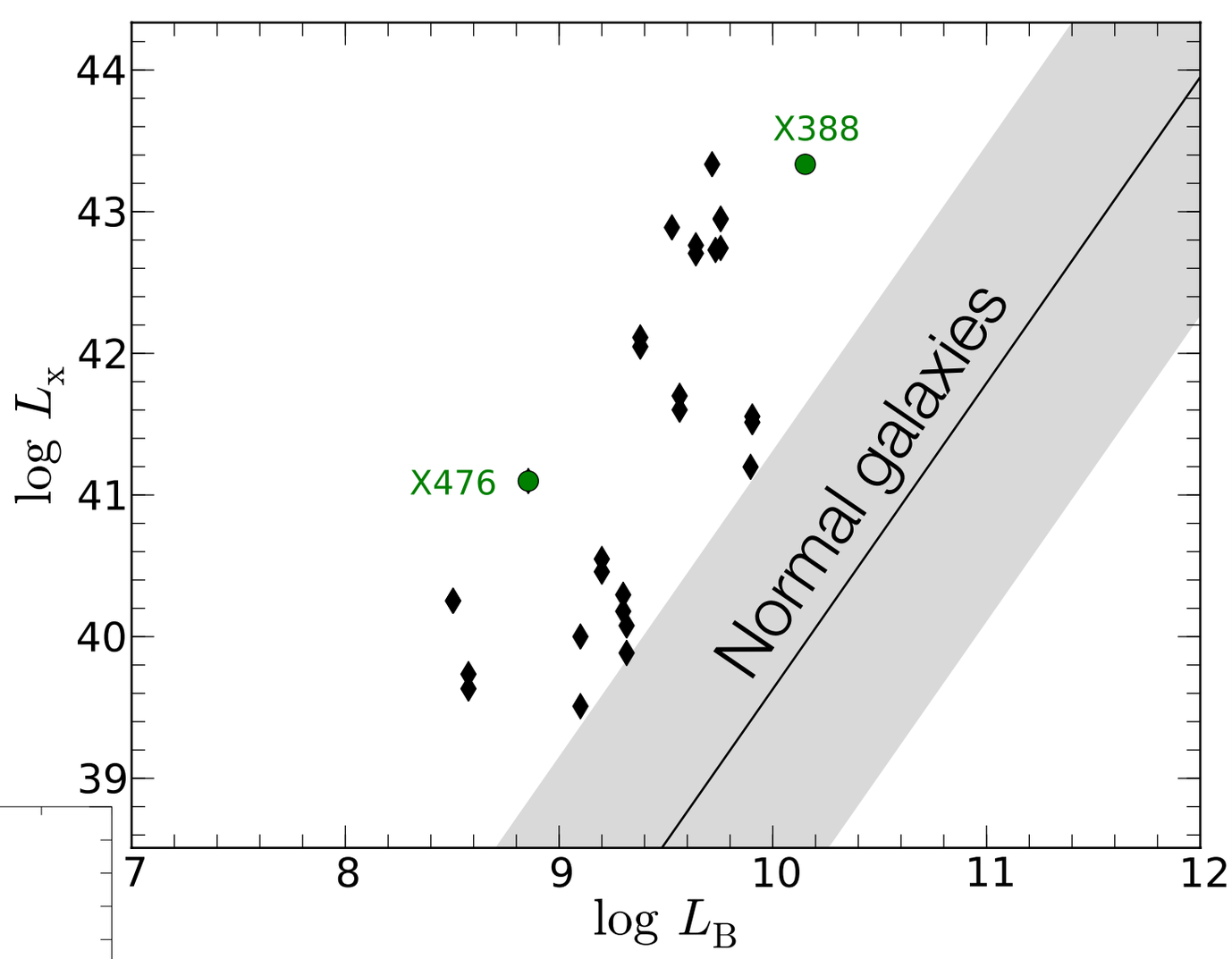
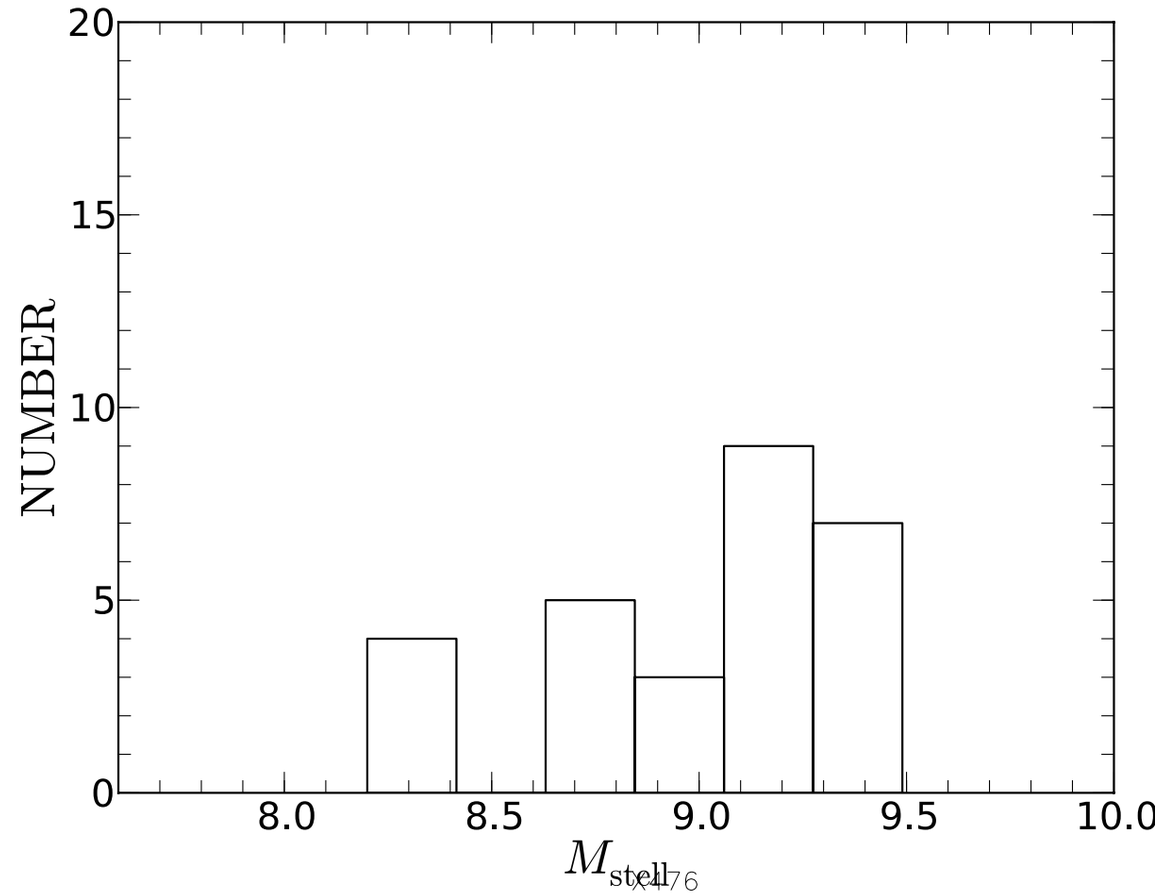
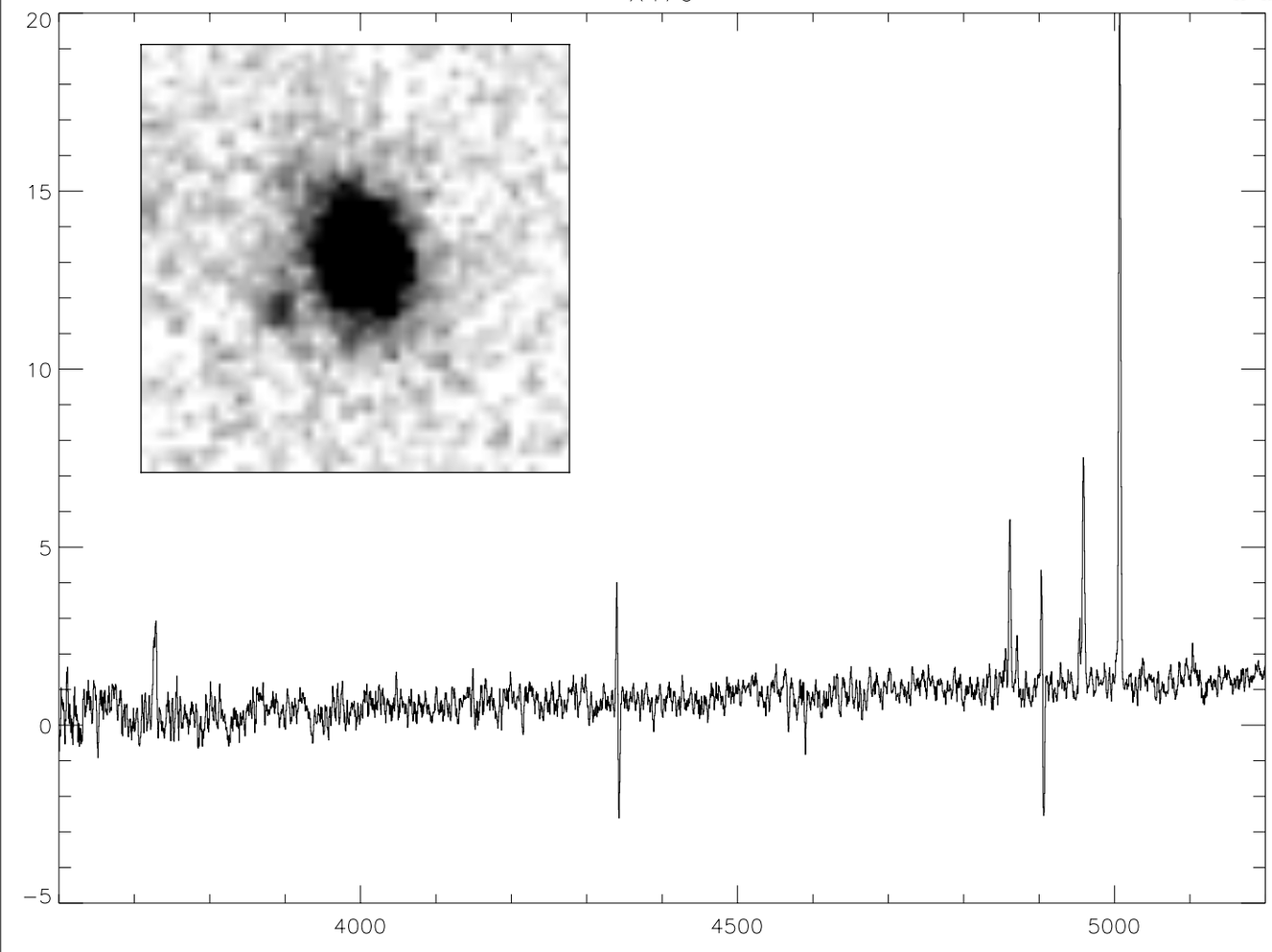


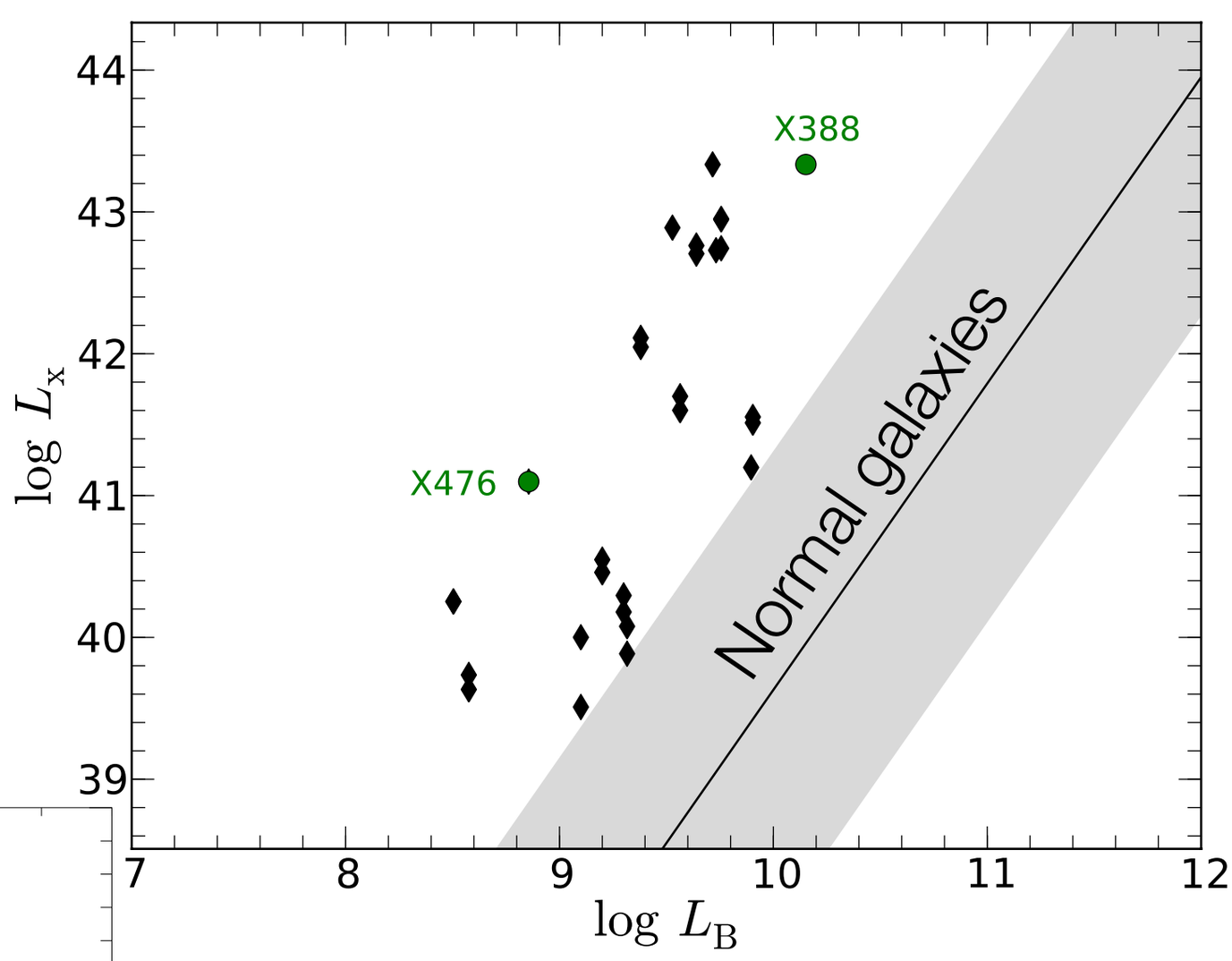


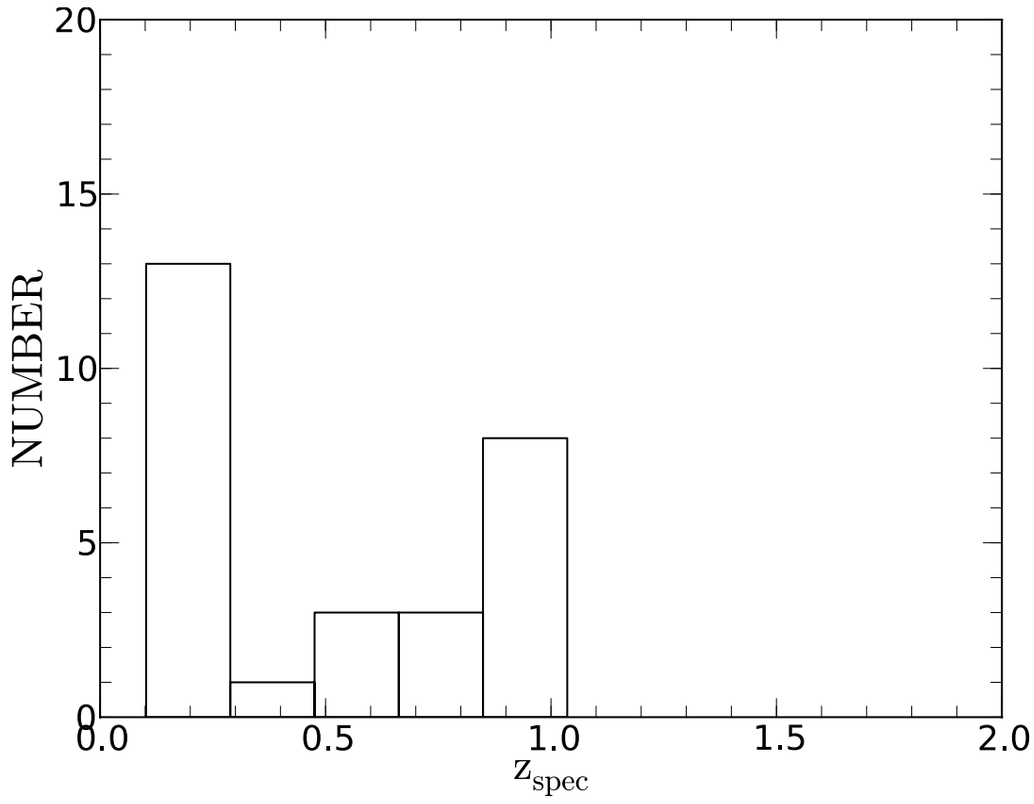


New sample from M. Schramm and J. Silverman using the 4Ms CDFS. These are selected to have $M^* < 10^{9.5}\ M_\odot$ and all have high L_X/L_B.


NUMBER
$M_{\rm stell}$


X476


X388
X476
Normal galaxies
log $L_{\rm x}$
log $L_{\rm B}$


NUMBER
$z_{\rm spec}$

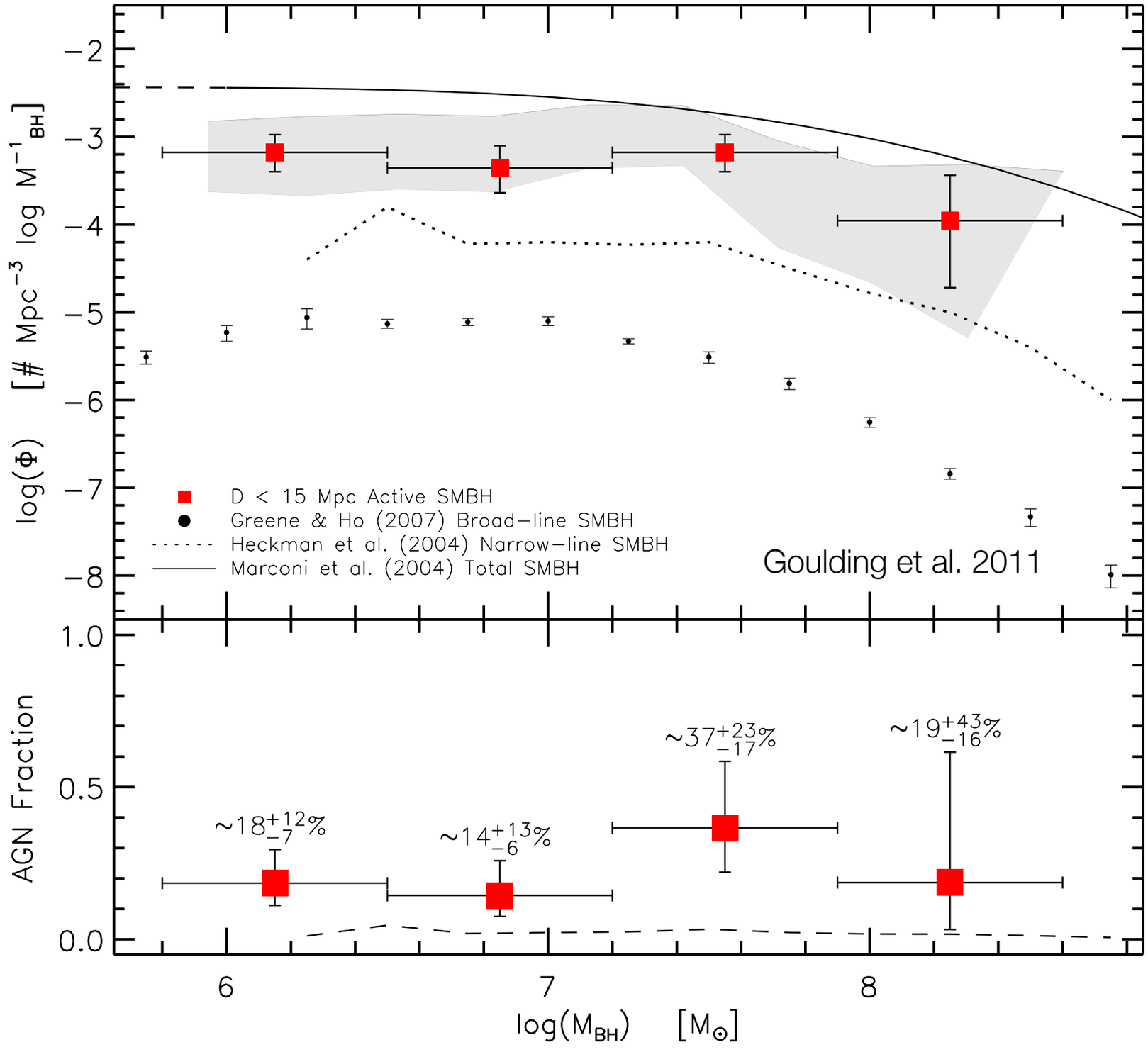
N
J
T
N

nd
.
$L_{\rm B}$.

Space Densities Still Uncertain

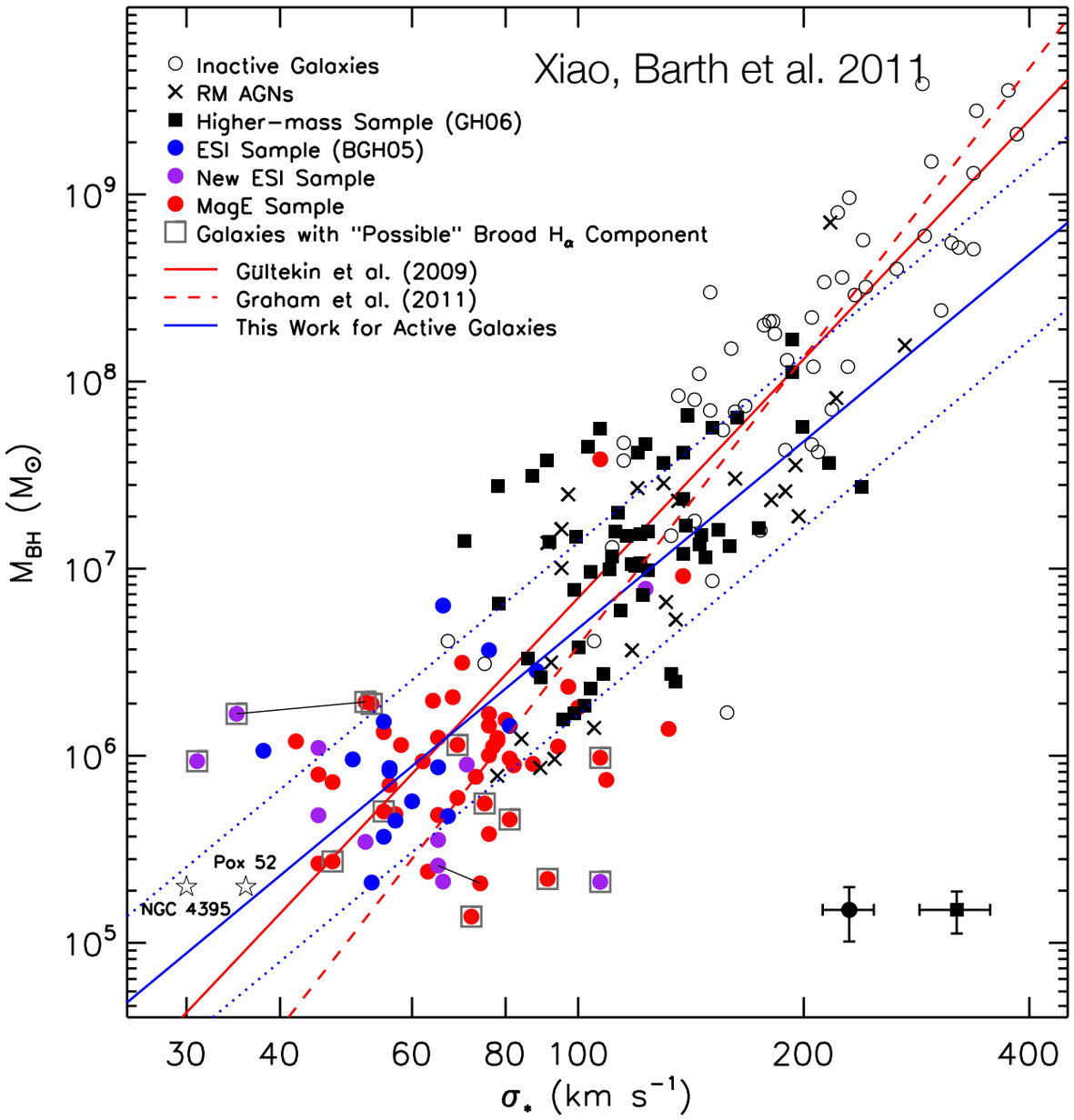
Goulding et al. used MIR selection. See also the recent paper by Schulze et al based on the Hamburg ESO survey

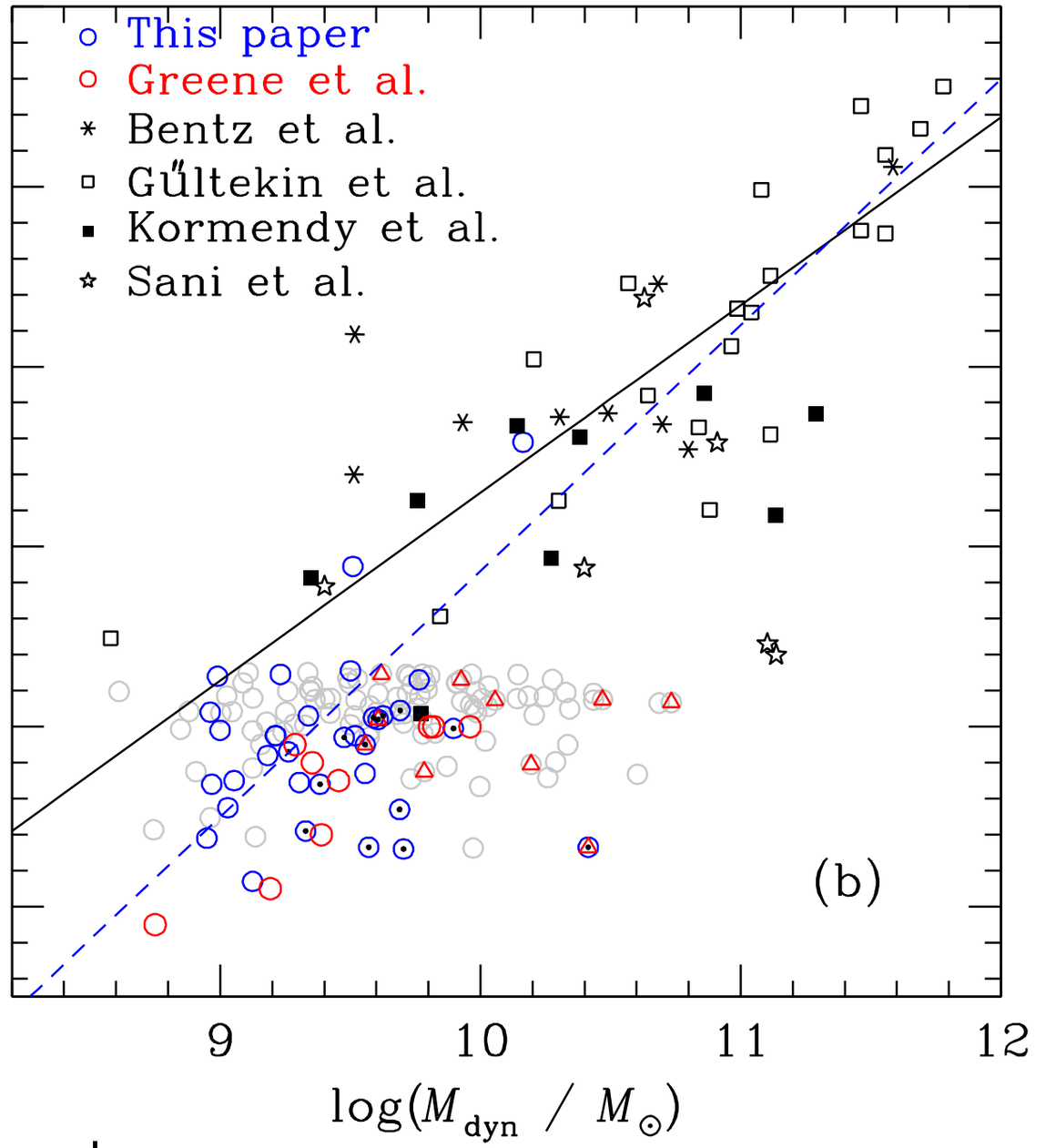
Reines and Moran will discuss promising new search strategies



Scaling Relations Still Uncertain

Broad-line AGN sample (SDSS)





Stellar velocity dispersions measured from stars

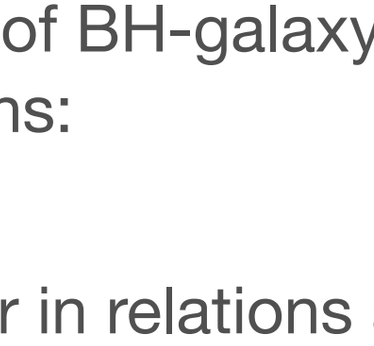
Jiang et al. 2011

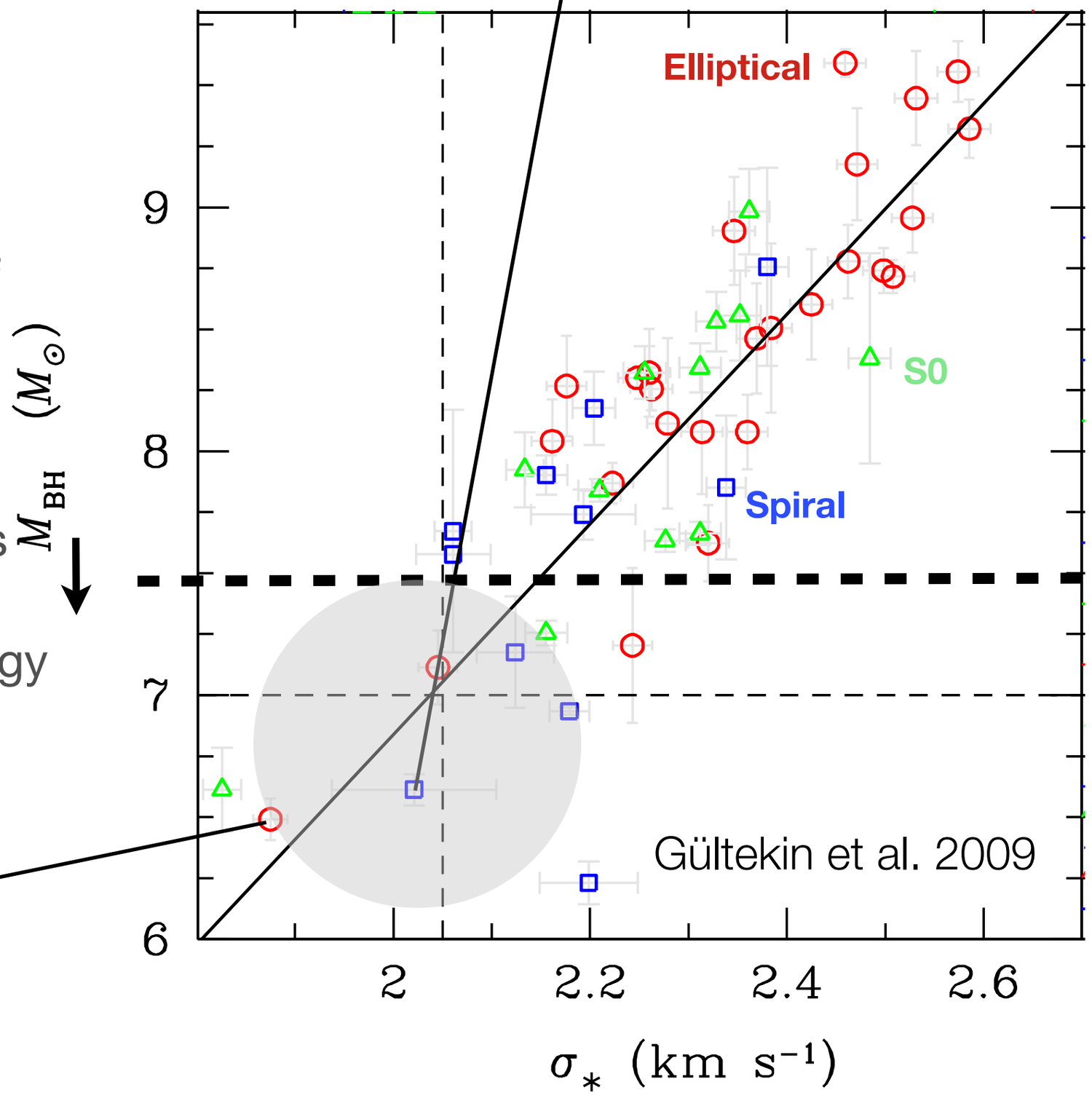
What is a “low-mass” black hole?

Origin of BH-galaxy scaling relations:

Scatter in relations as function of BH mass AND galaxy morphology

Then our interest is in all systems with $M_{BH} < 10^7\ M_\odot$ where the widest range of galaxy morphology is found





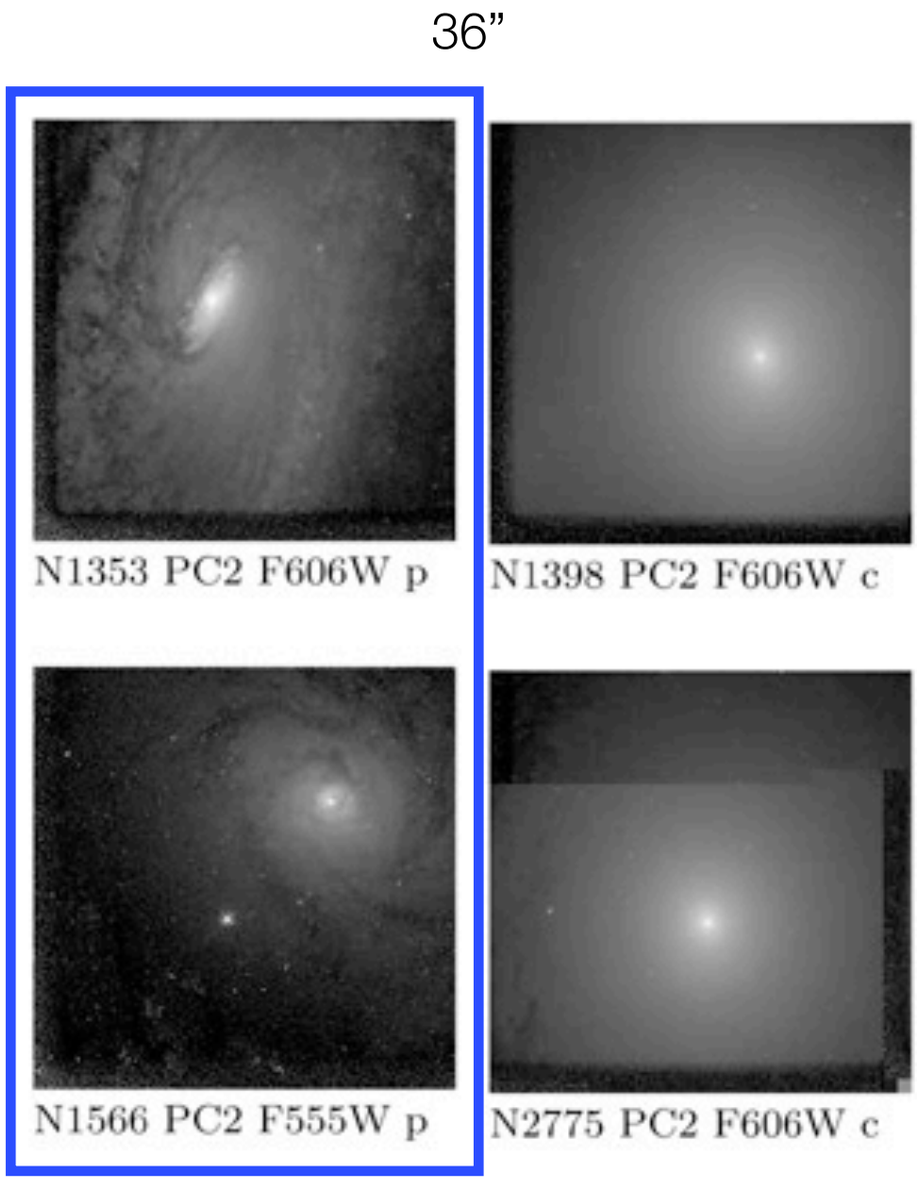
Pseudobulges

Two types of bulges (central, luminous component)

Elliptical galaxies inside disks (Sombrero), disky bulges (see right)

Rotationally supported, bars, ovals, rings, nuclear spirals, ongoing star formation, low dispersions in the center

These bulges built secularly (Kormendy & Kennicutt 2004)



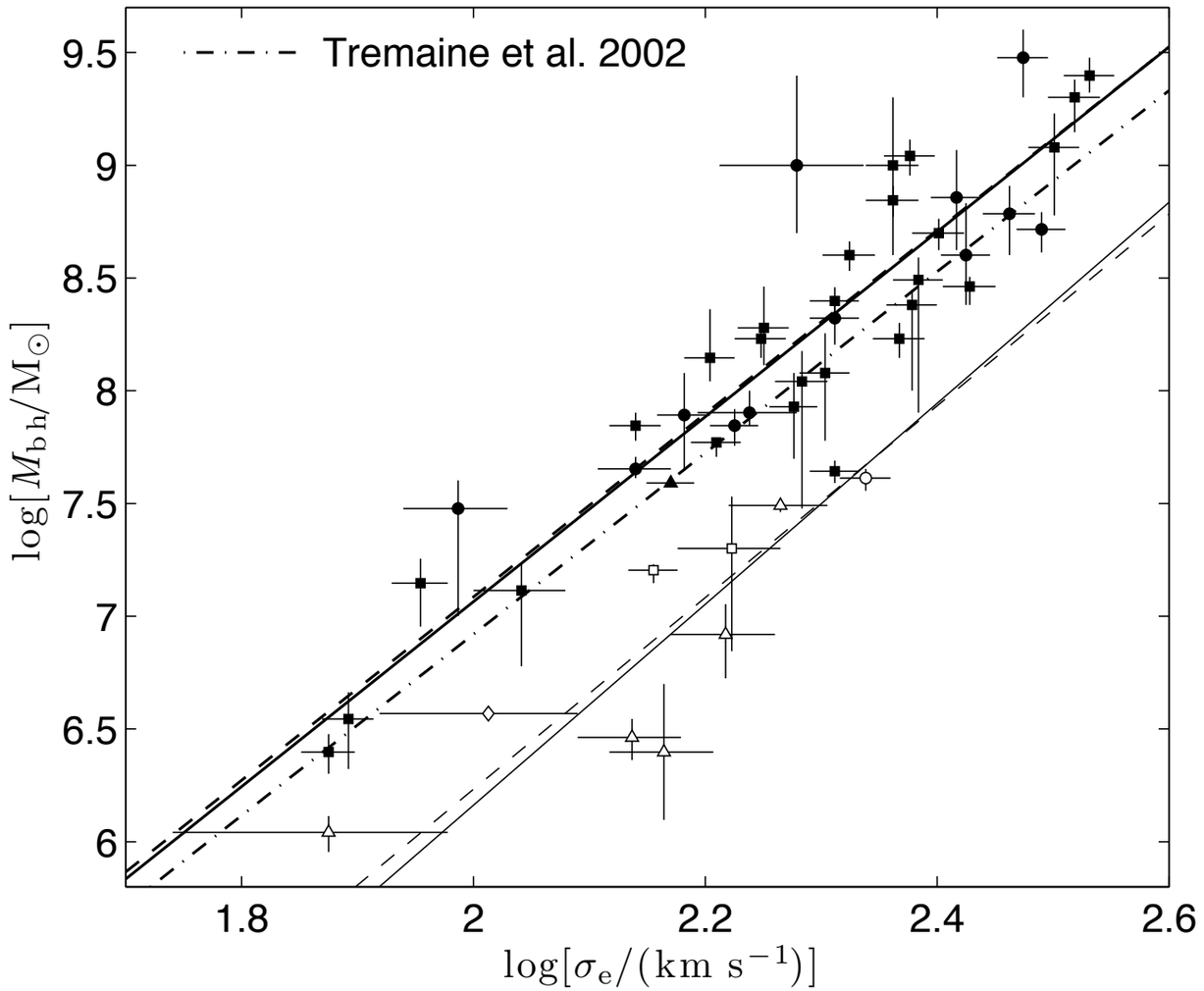
Fisher et al. 2009

Black Hole-Pseudobulge relations?

Gültekin et al. 2009 see no differences in M_{BH}-$\sigma_\star$ relation while

Hu 2008, Gadotti & Kauffmann 2009 report differences; see also Greene, Ho, & Barth 2008

Some concensus that pseudobulges have higher $\sigma_\star$ at fixed BH mass



Hu 2008

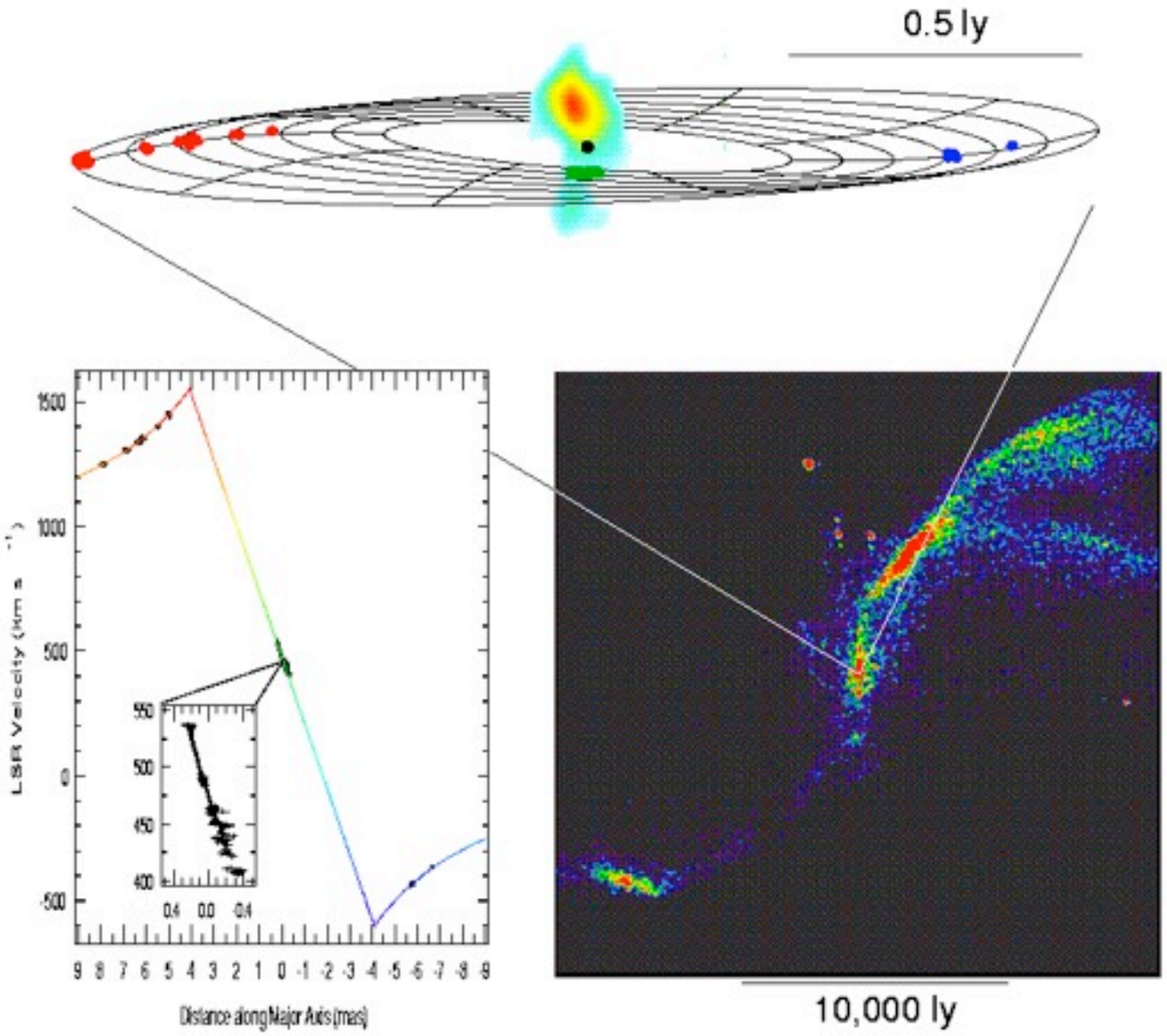
NGC 4258

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

- Very precise BH mass ($3.9\pm0.1 \times 10^7$ $M_\odot$), 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

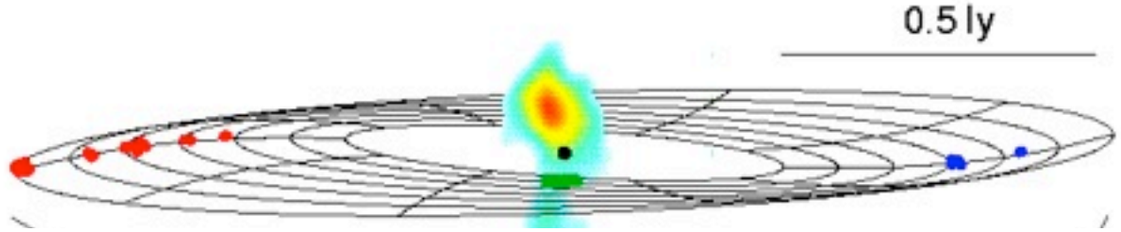
galaxy is ~7 Mpc away

Step 1: Single-Dish Search

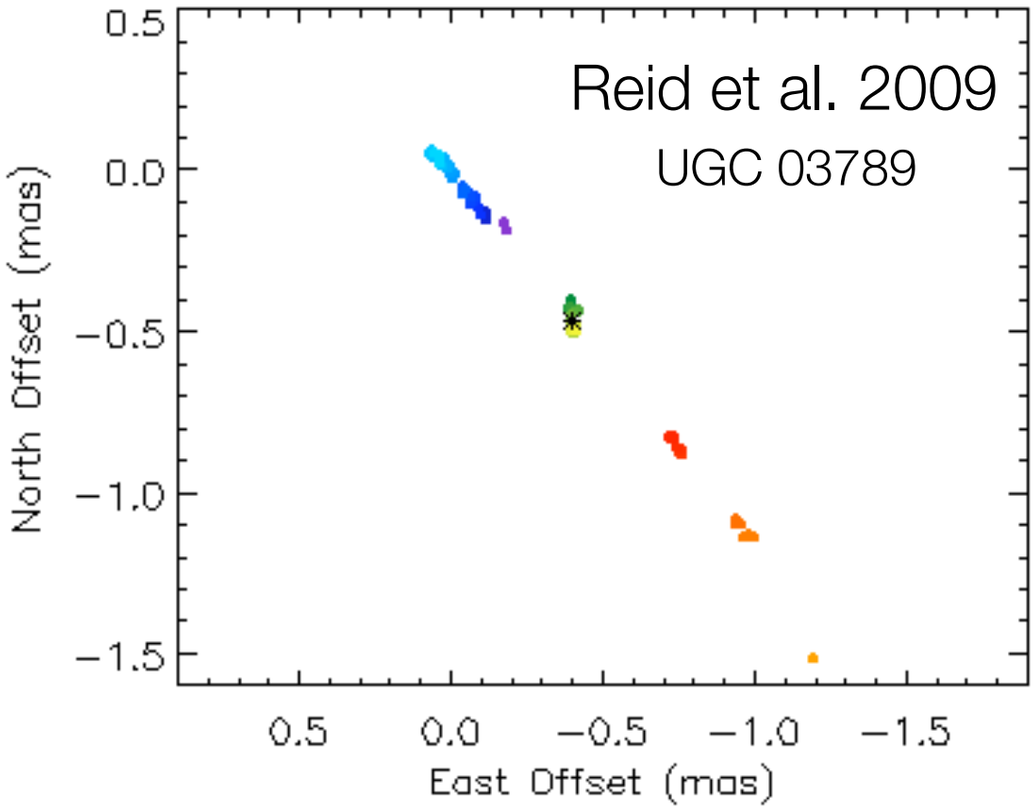
- Advent of Green Bank Telescope - doubled the number of maser galaxies

- 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

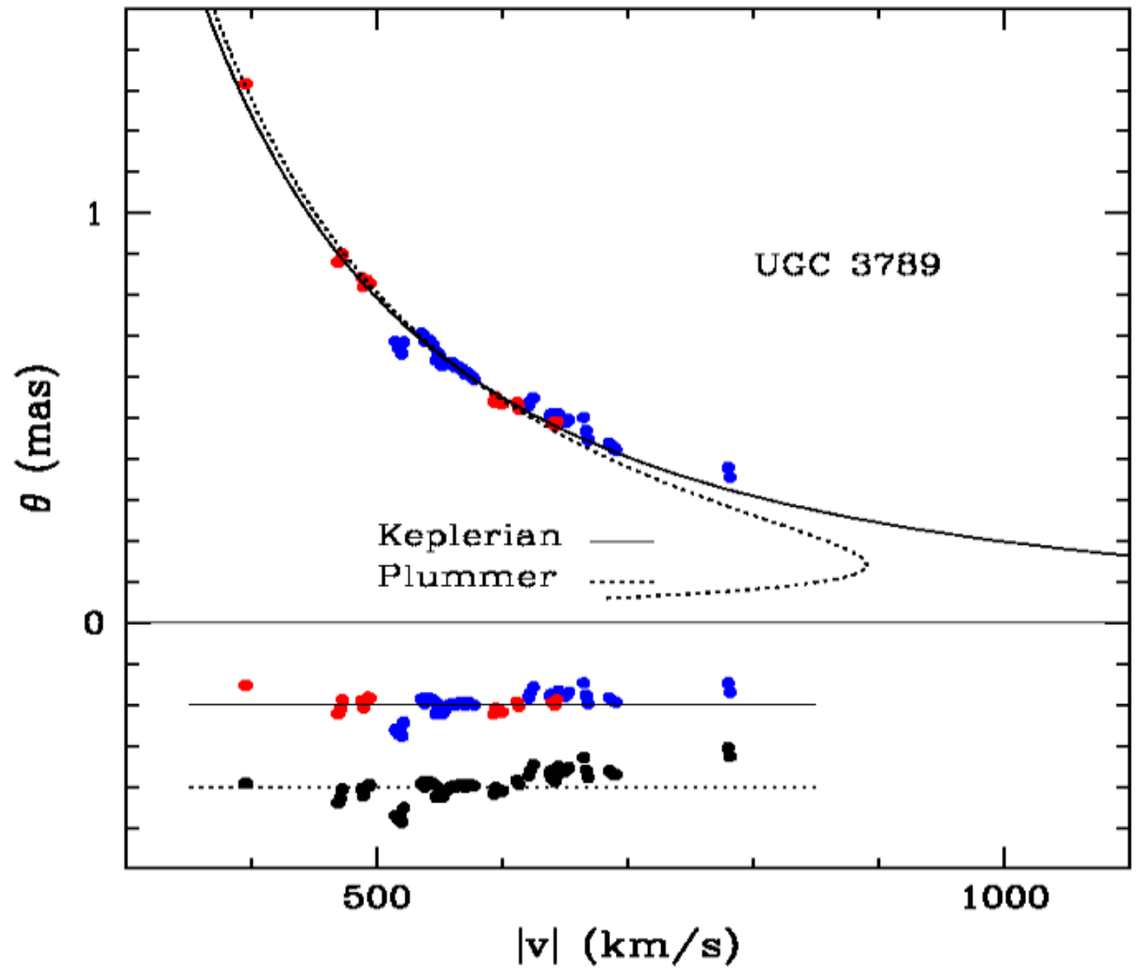


Step 2: VLBI

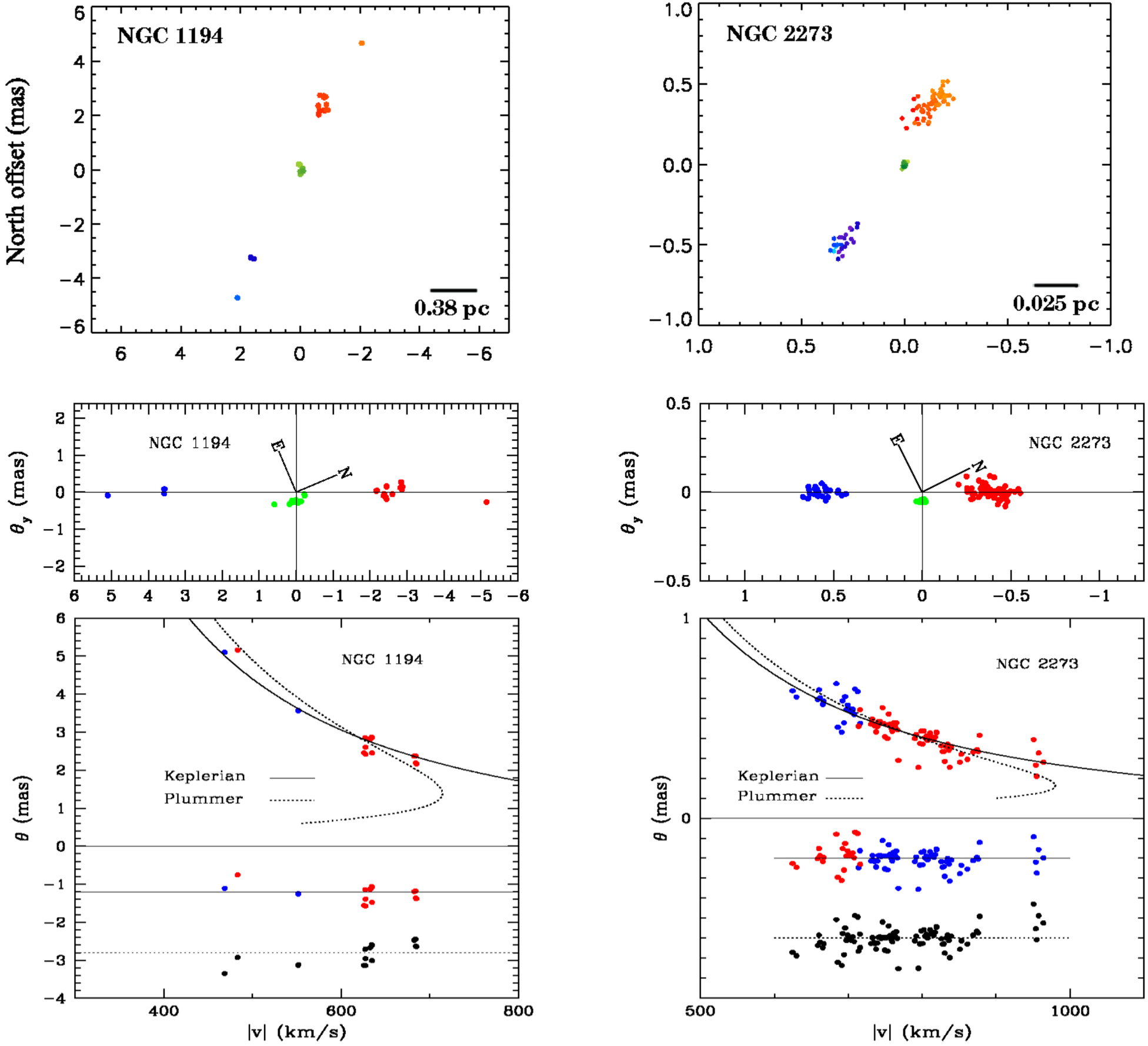


Spatial distribution on the sky reveals an edge-on disk

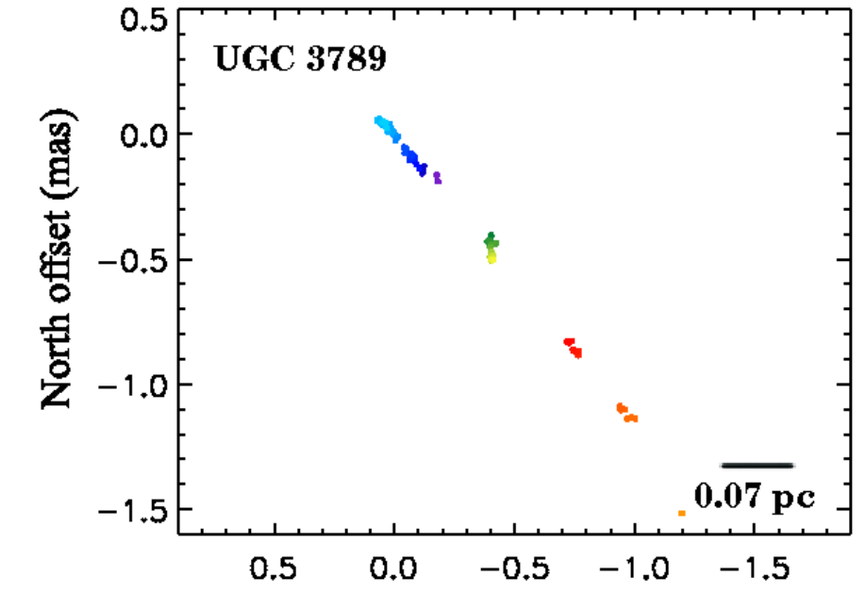
Rotation curves reveal Keplerian rotation around a (very) compact object

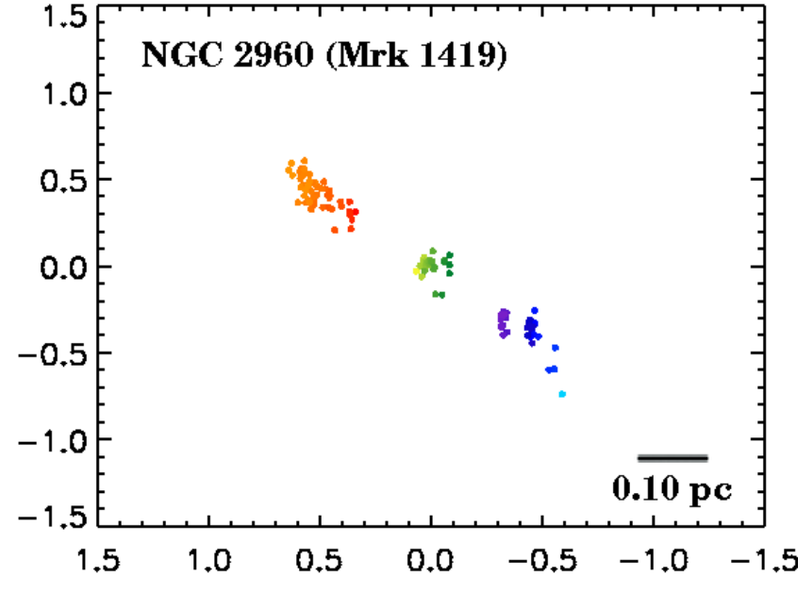


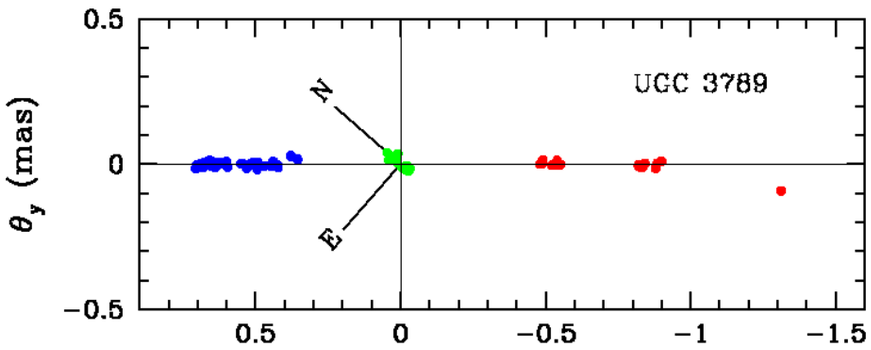
Kuo et al. 2011 presents 7 new BH masses.

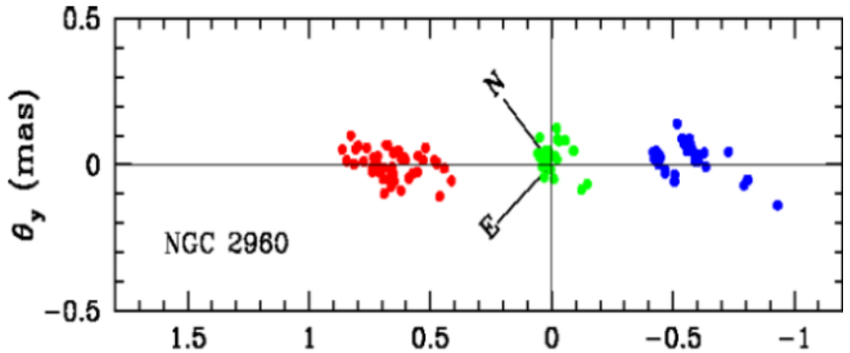


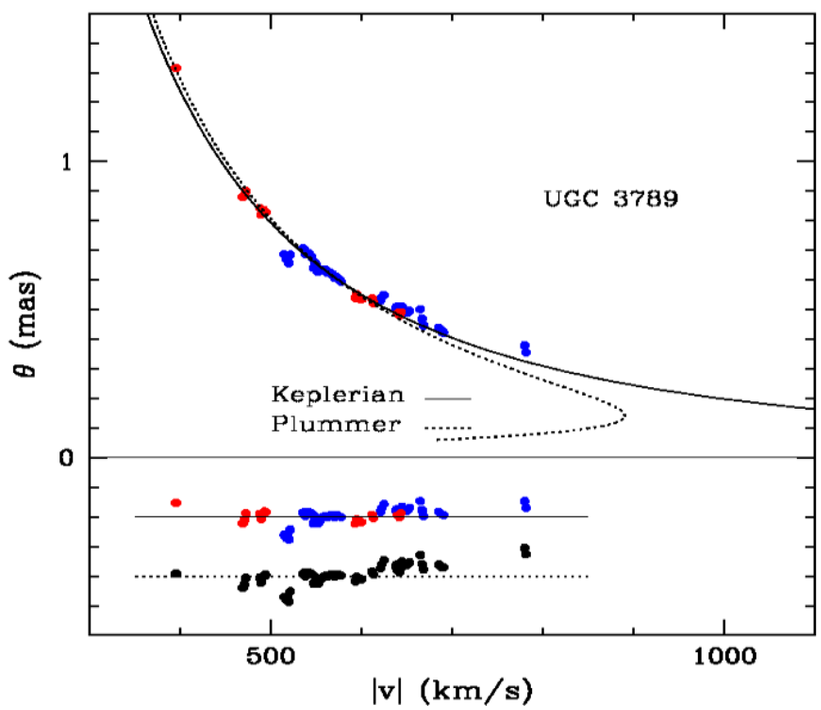
Kuo et al. 2010 (astroph/1008.2046)

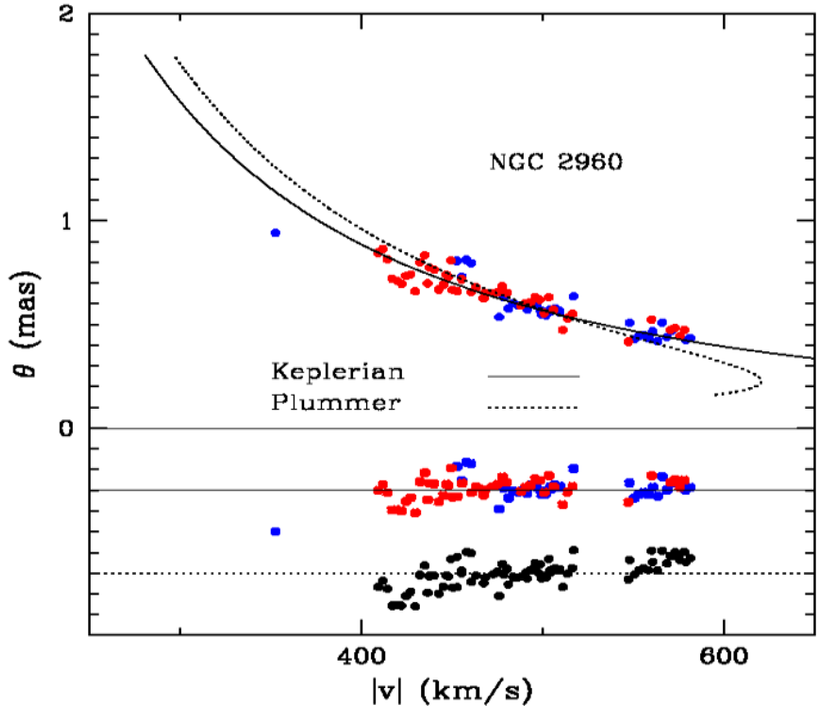








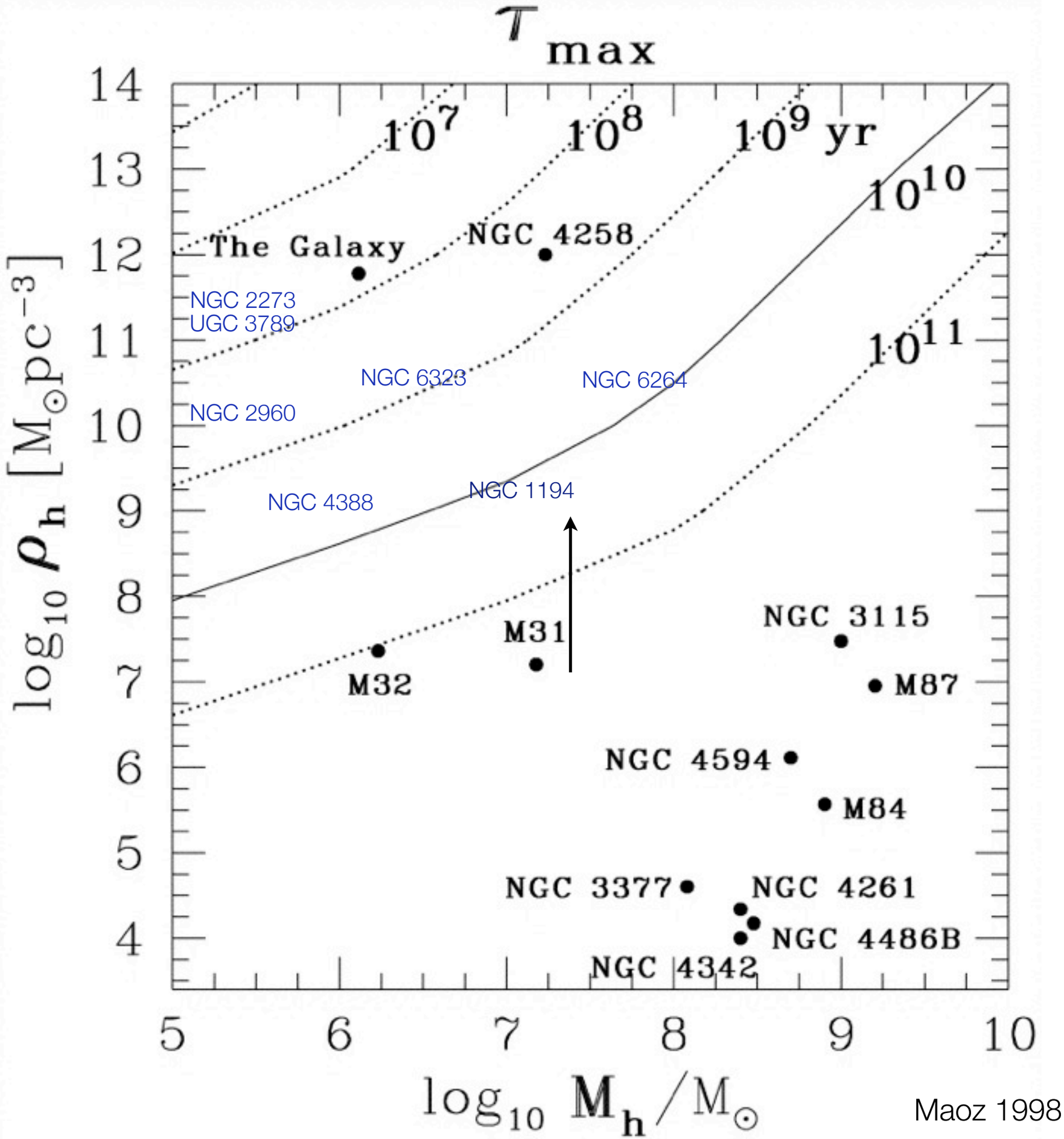




Kuo et al. 2011

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 ~10% 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 reported in Kuo et al. 2011; scaling relations in Greene et al. 2010.


τ_{max}
10^7
10^8
10^9 yr
10^{10}
10^{11}
The Galaxy
NGC 4258
NGC 2273
UGC 3789
NGC 6323
NGC 6264
NGC 2960
NGC 4388
NGC 1194
M31
M32
NGC 3115
M87
NGC 4594
M84
NGC 3377
NGC 4261
NGC 4486B
NGC 4342
$\log_{10} \rho_h$ [$M_\odot pc^{-3}$]
$\log_{10} M_h / M_\odot$
14
13
12
11
10
9
8
7
6
5
4
5
6
7
8
9
10

Maoz 1998

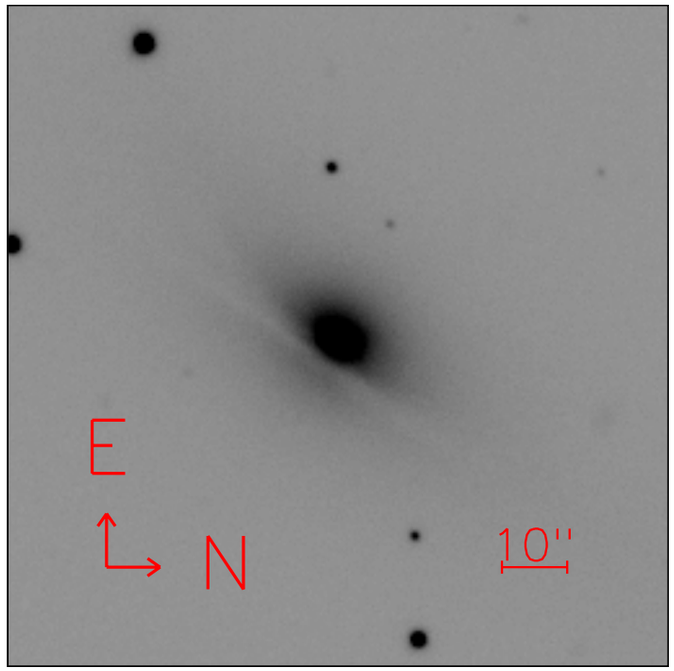
Cross Comparisons

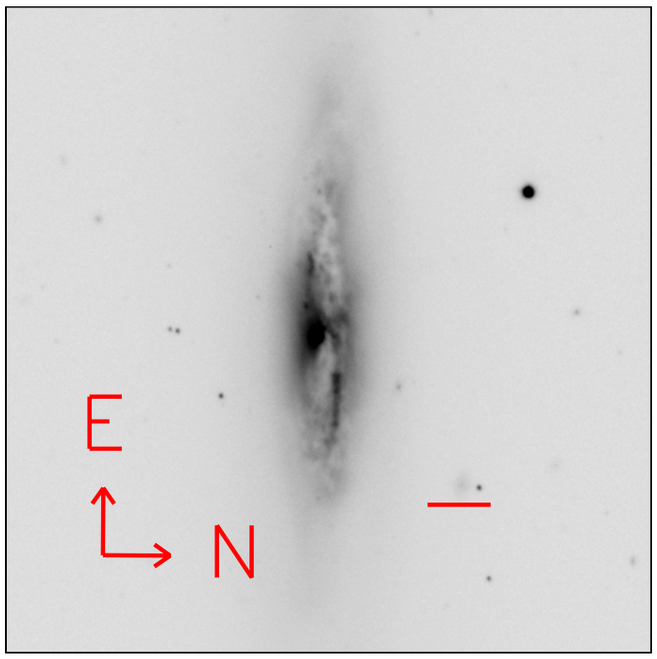
So far, only NGC 4258 has megamaser+stellar dynamical masses (Siopis et al. 2009

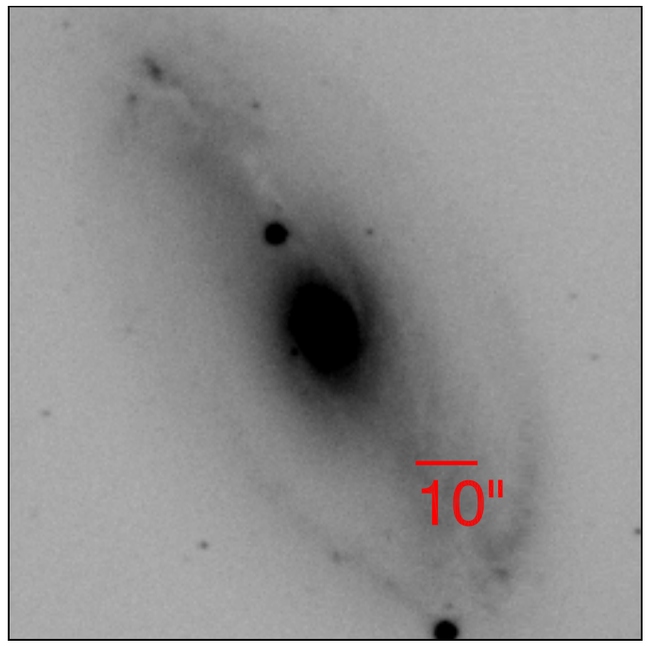
We (van de Venn; Remco; Jonelle; Anil; Gebhardt...) will get data for NGC 1194...still waiting for data for NGC 4388

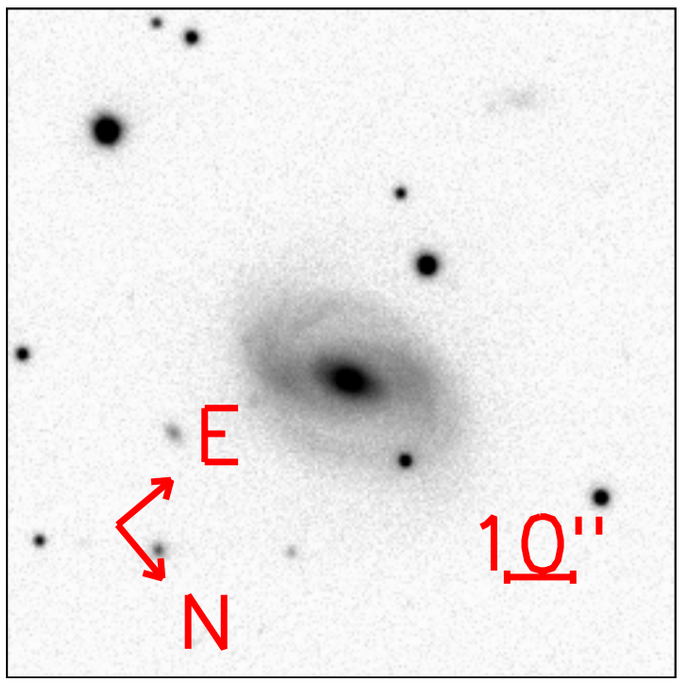
Can’t obviously do RM for these, they are obscured (possible in NIR??)

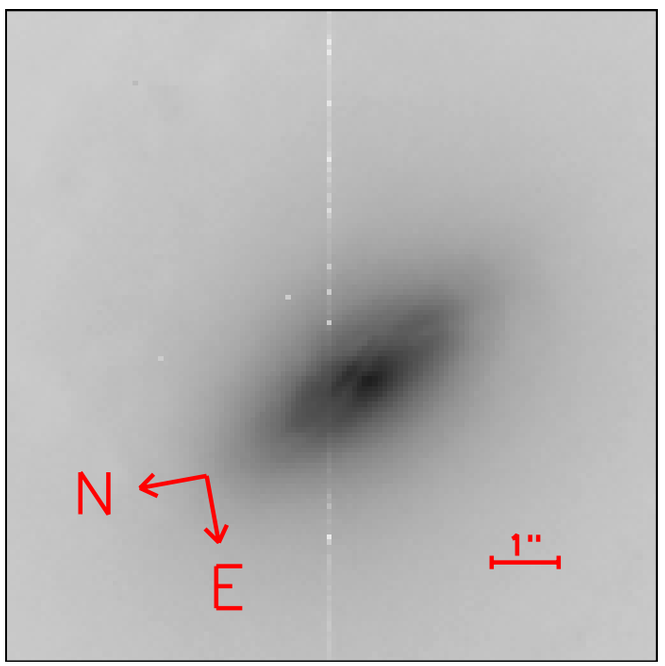
X-ray masses

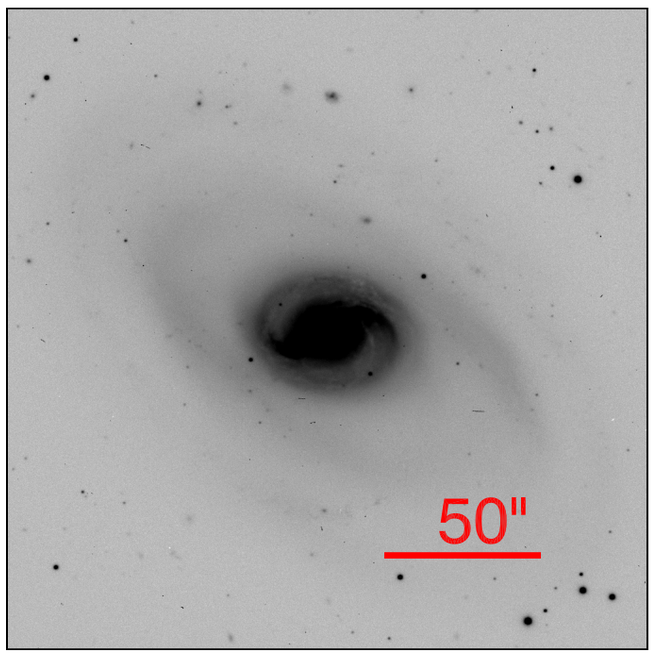




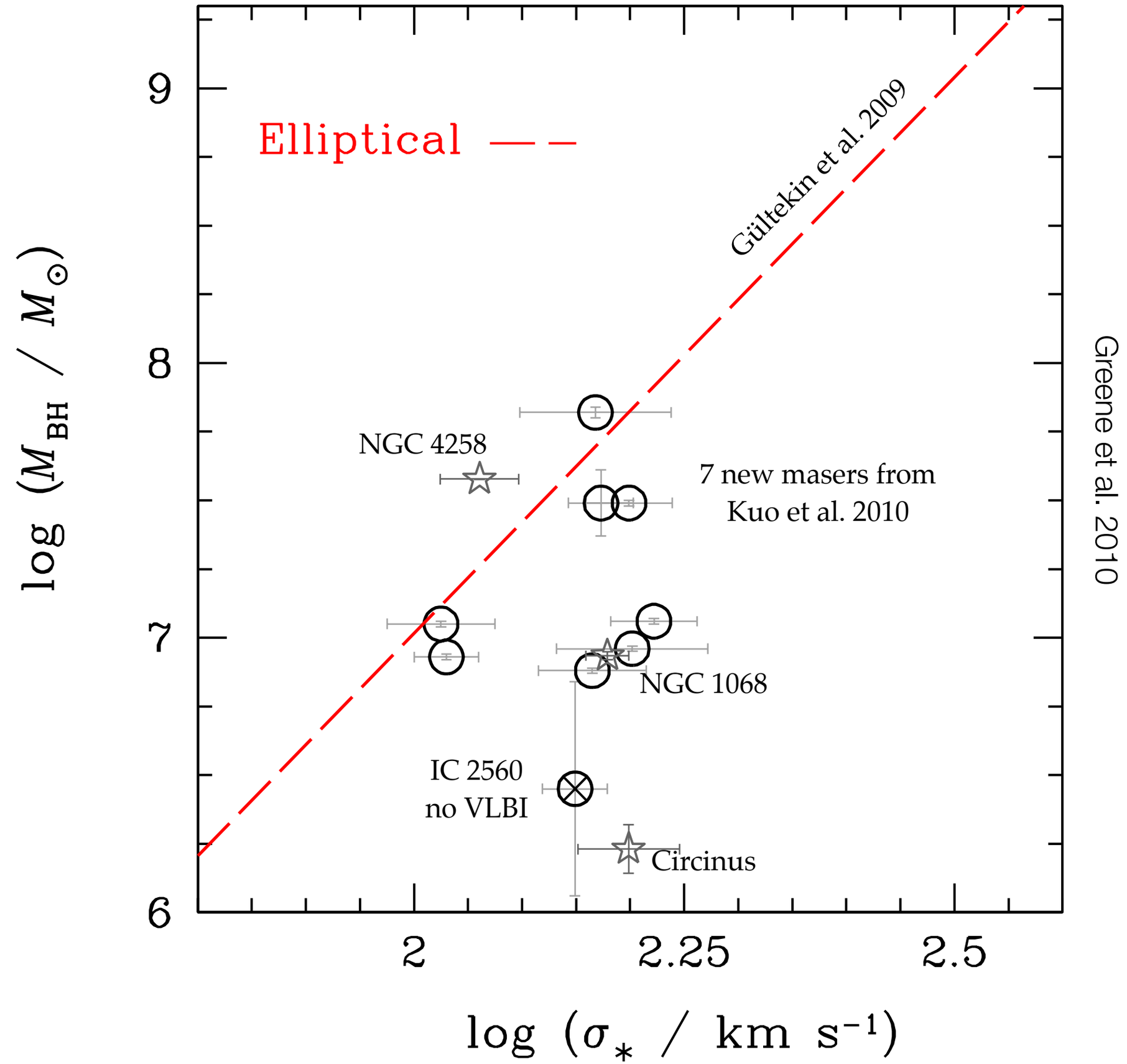


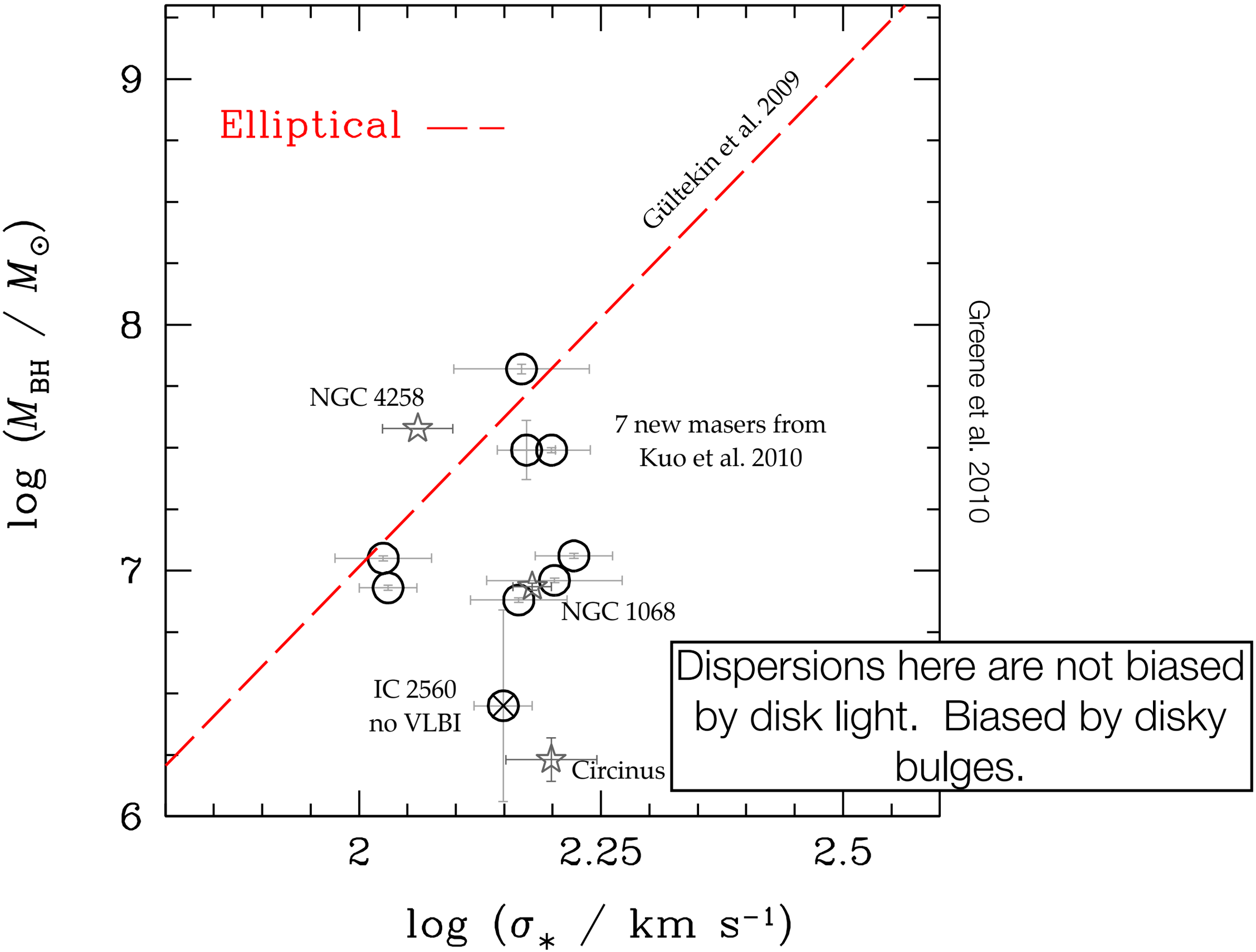


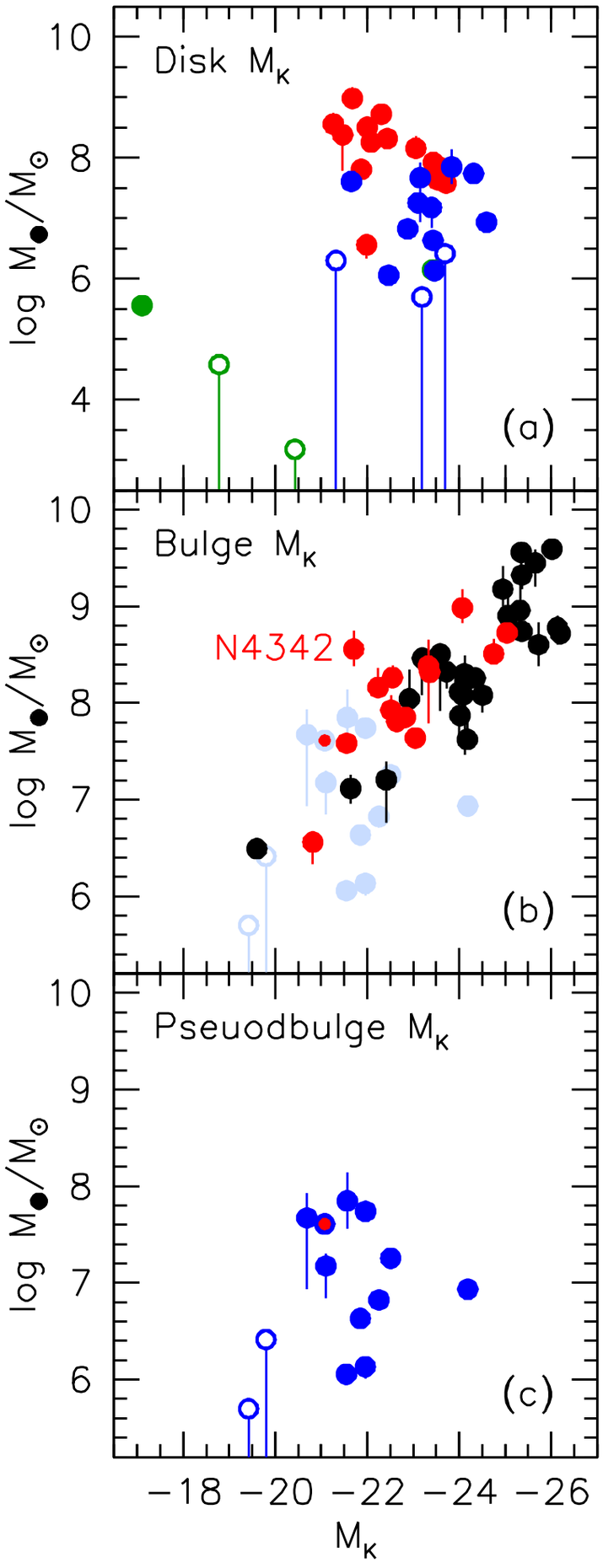




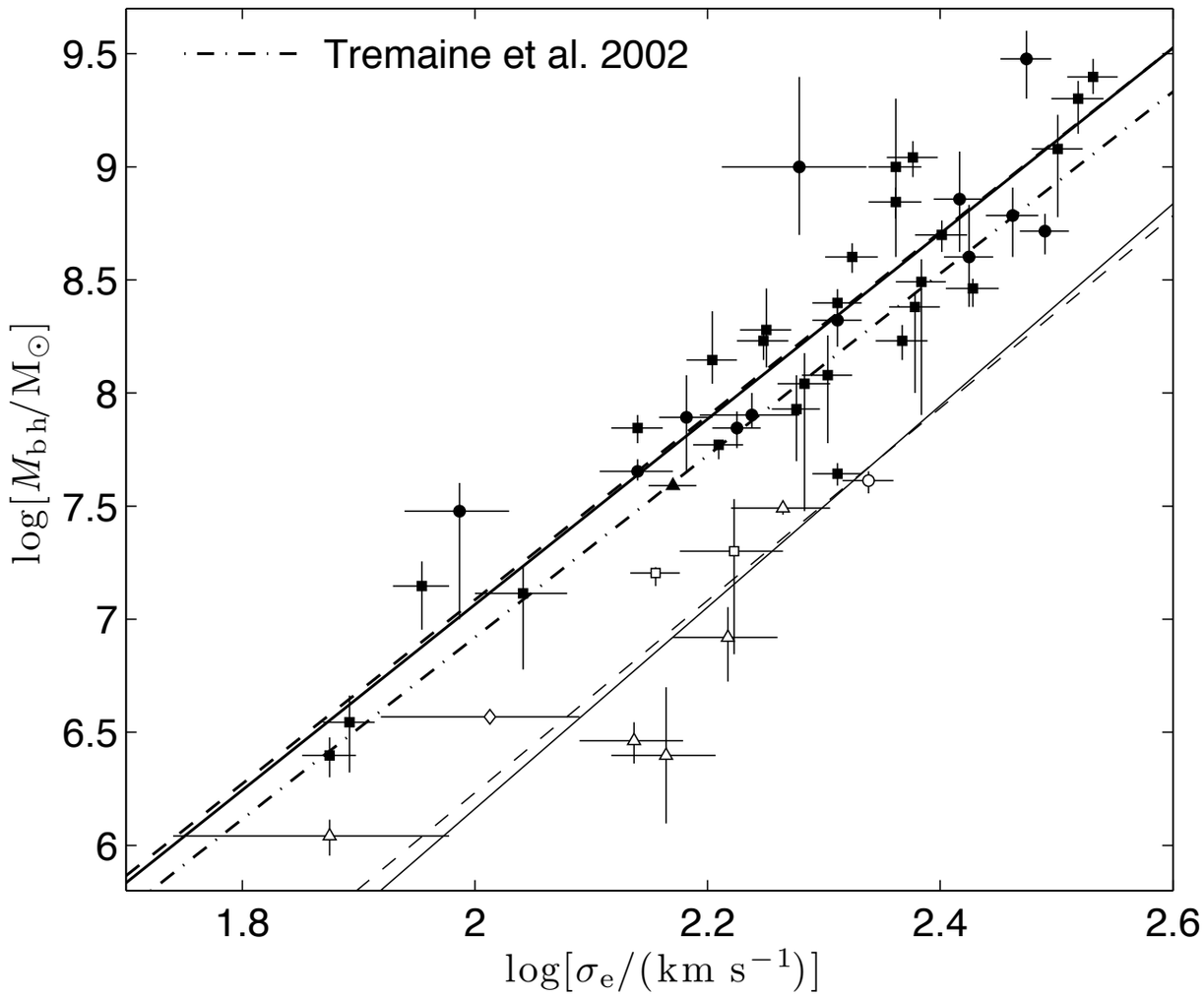
Based on morphology and color, the sample is dominated by pseudobulges


Elliptical
Gültekin et al. 2009
Greene et al. 2010
NGC 4258
7 new masers from
Kuo et al. 2010
NGC 1068
IC 2560
no VLBI
Circinus
9
8
7
6
2
2.25
2.5
log (M_BH / M_⊙)
log (σ_* / km s^-1)


Elliptical
Gültekin et al. 2009
Greene et al. 2010
NGC 4258
7 new masers from
Kuo et al. 2010
NGC 1068
IC 2560
no VLBI
Circinus
Dispersions here are not biased by disk light. Biased by disky bulges.
log (M_{BH} / $M_\odot$)
log (σ_* / km s^{-1})
9
8
7
6
2
2.25
2.5



Kormendy et al. 2011



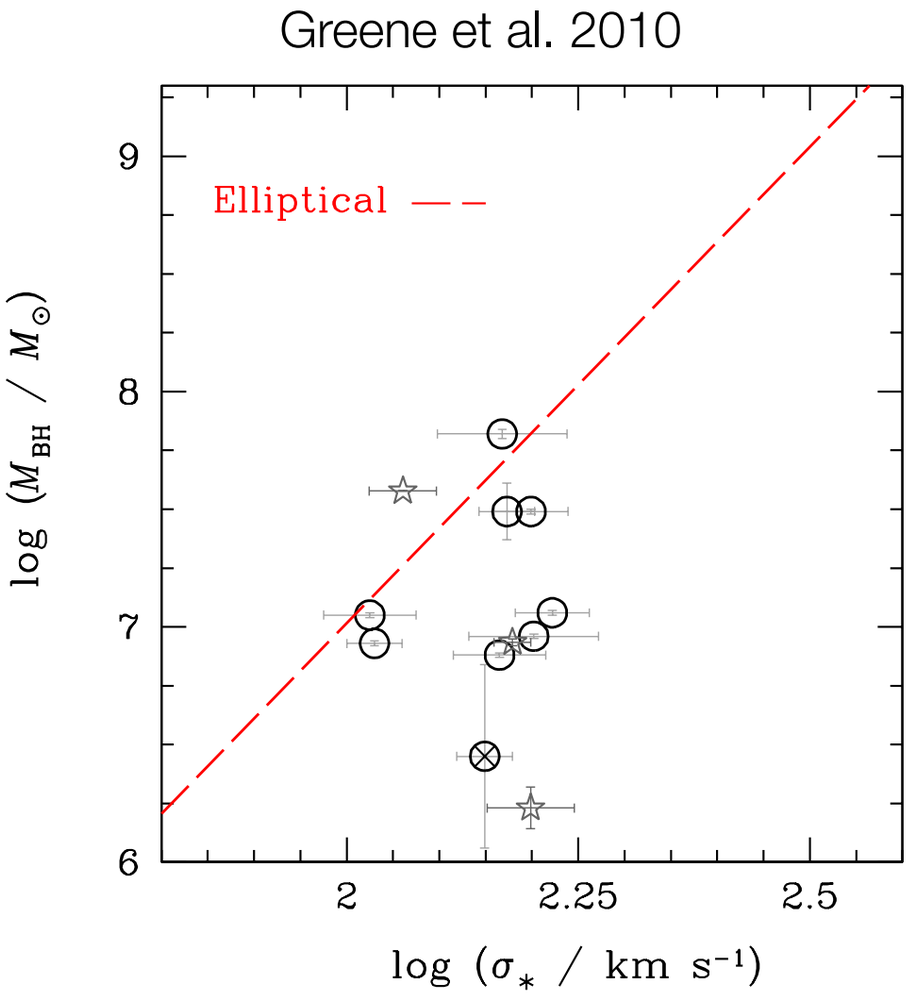
Hu 2008;
also Gadotti & Kauffmann, Greene et al. 2008; Hu 2009; etc.

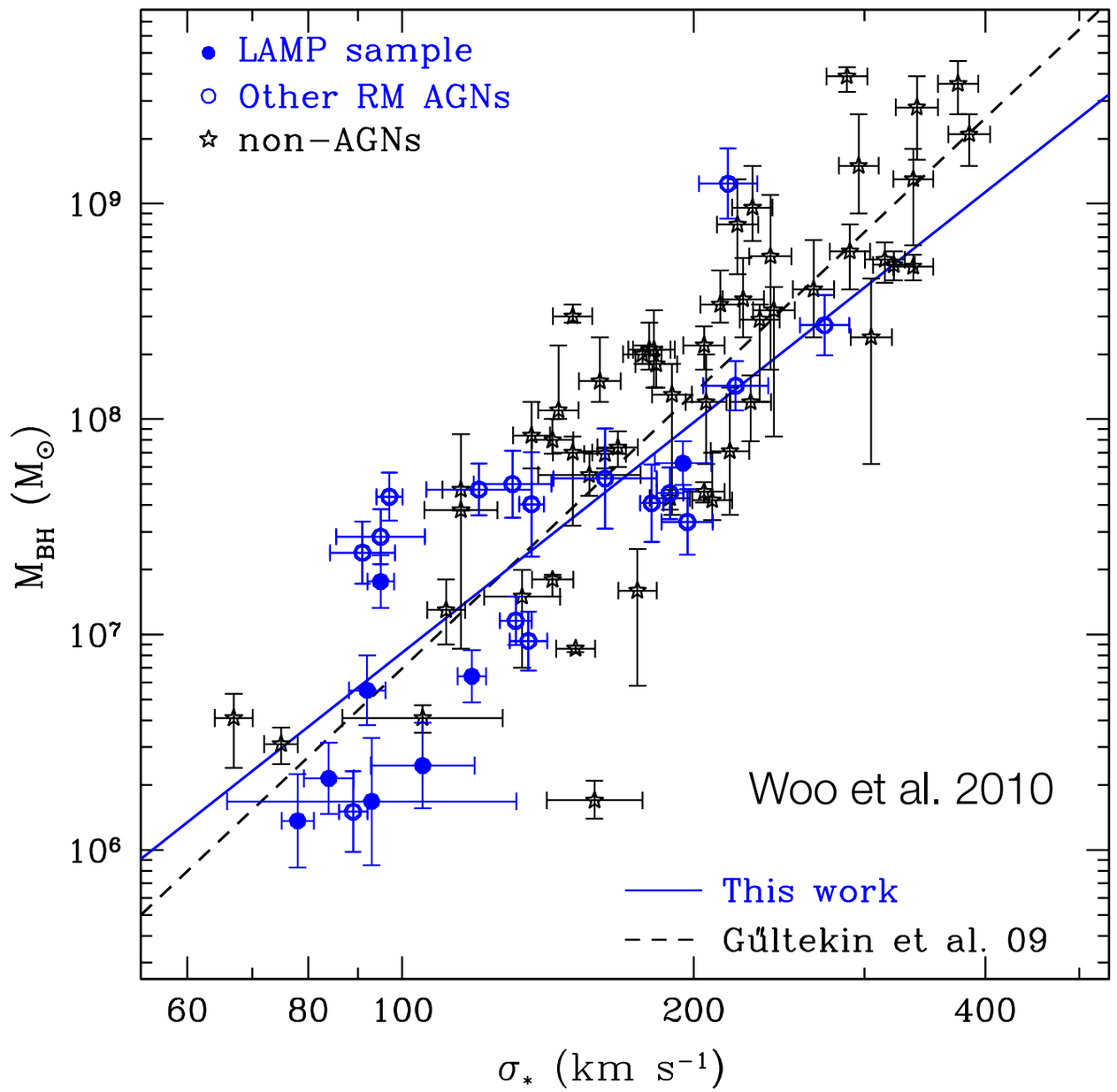
Is this primarily a *morphology* effect? So there is no correlation between BH mass and pseudobulge mass?

If yes, then the interpretation is that BH-bulge scaling relations are established in the making of classical bulges (e.g., merging/BH feedback).

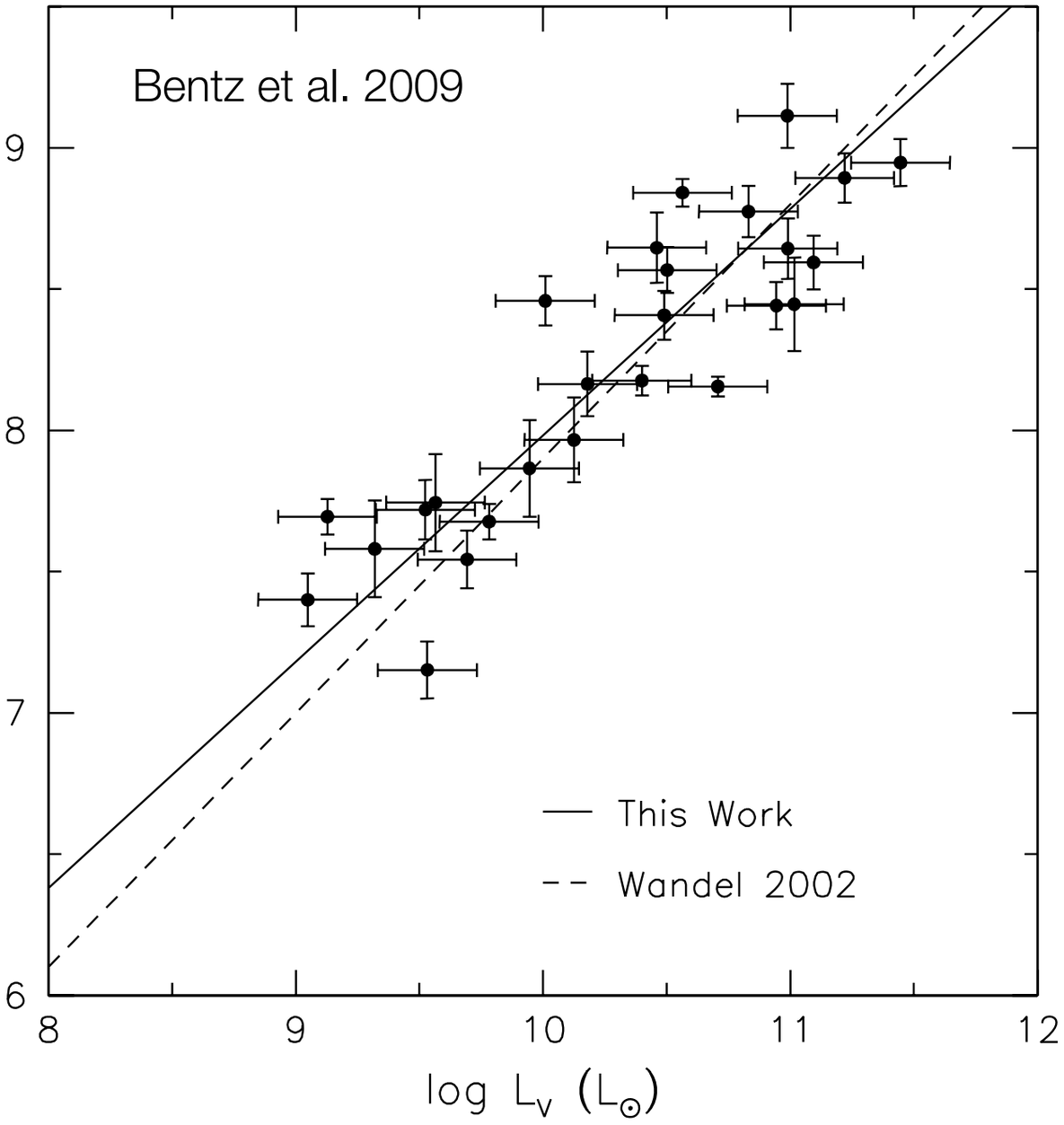
But the data are also consistent with a BH mass dependent change in scaling relations.

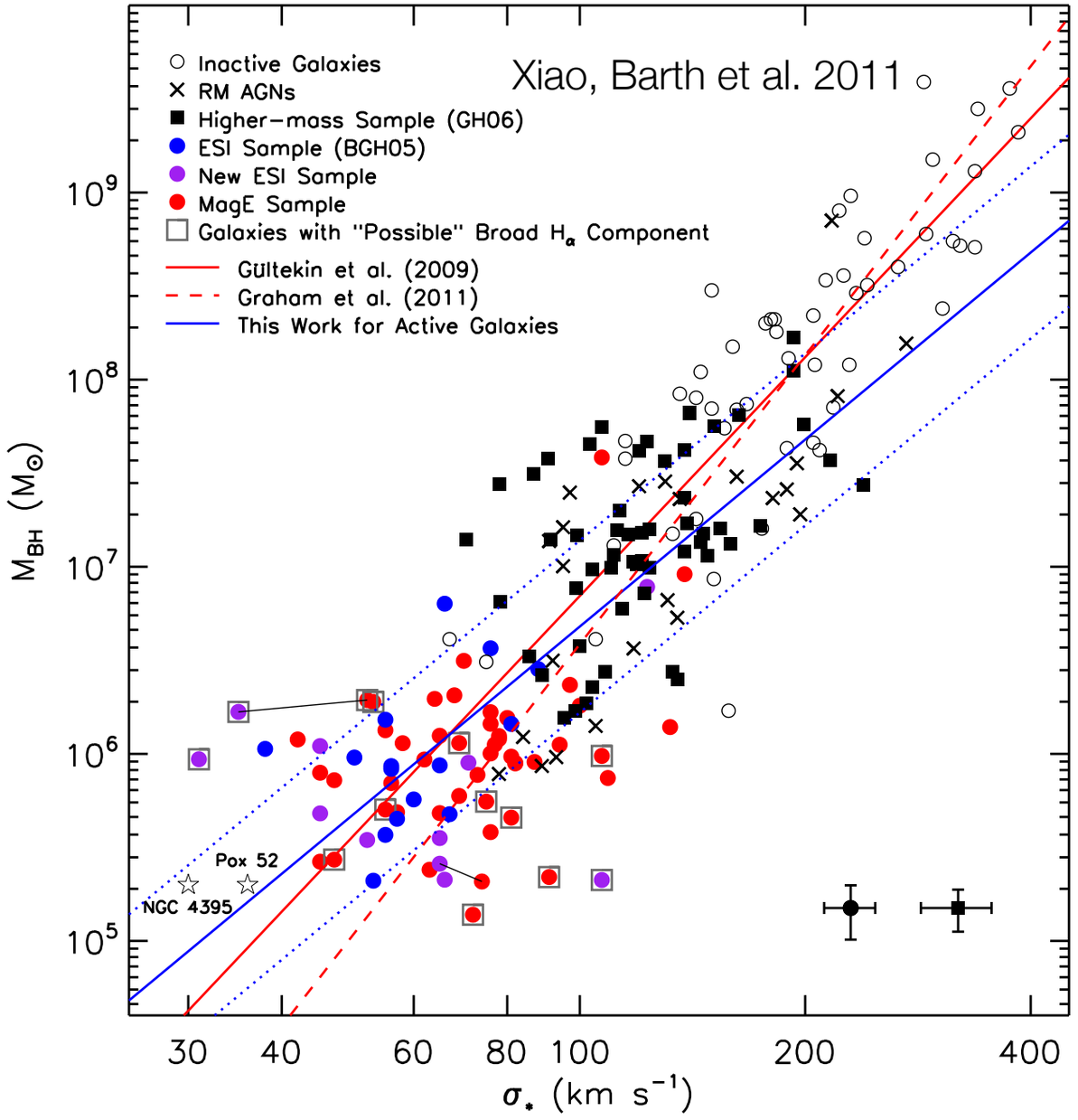
In which case, the interpretation is less clear. Perhaps provides support for a picture in which BH-bulge scaling relations are just a side effect of many mergers in high mass galaxies (e.g., Peng 2007; Jahnke & Maccio 2010).





What is the difference? Why is the scatter the same as the inactive galaxies?


Bentz et al. 2009
log M_{BH} ($M_\odot$)
log L_V ($L_\odot$)
This Work
Wandel 2002
9
8
7
6
8
9
10
11
12


Xiao, Barth et al. 2011
Inactive Galaxies
RM AGNs
Higher−mass Sample (GH06)
ESI Sample (BGH05)
New ESI Sample
MagE Sample
Galaxies with "Possible" Broad H_α Component
Gültekin et al. (2009)
Graham et al. (2011)
This Work for Active Galaxies
Pox 52
NGC 4395
M_{BH} ($M_\odot$)
σ_* (km s^{-1})
10^9
10^8
10^7
10^6
10^5
30
40
60
80
100
200
400

Population of galaxies are the same: Sa-Sc spirals.

Population of BHs are the same -- both masers and low-mass RM objects have similar BH masses and Eddington ratios

Brad Peterson would say the RM masses are just better...

How we measure f? Selection effects...?

Open Questions (?)

What are the space densities of BHs with $M_{BH} < 10^6\ M_\odot$?

Does the scatter in BH-bulge scaling relations depend on morphology or BH mass or both?

small question: Why do we get different answers about BH-galaxy scaling relations from RM and dynamical samples?