Supermassive Black Holes in Nearby Galaxies

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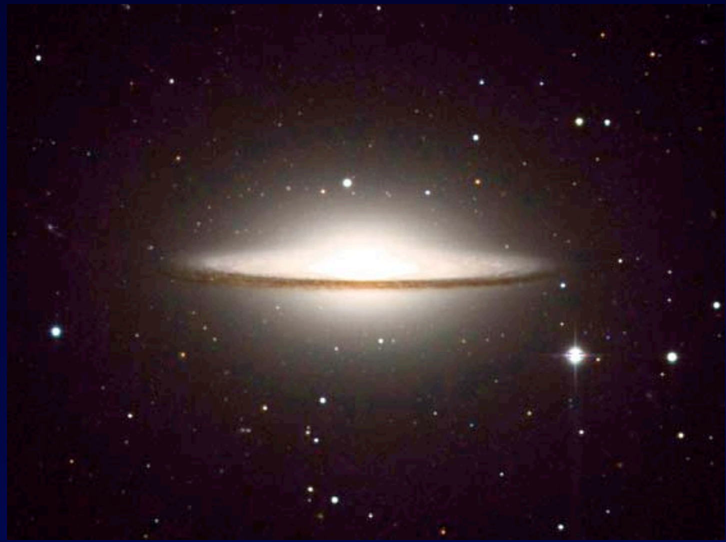
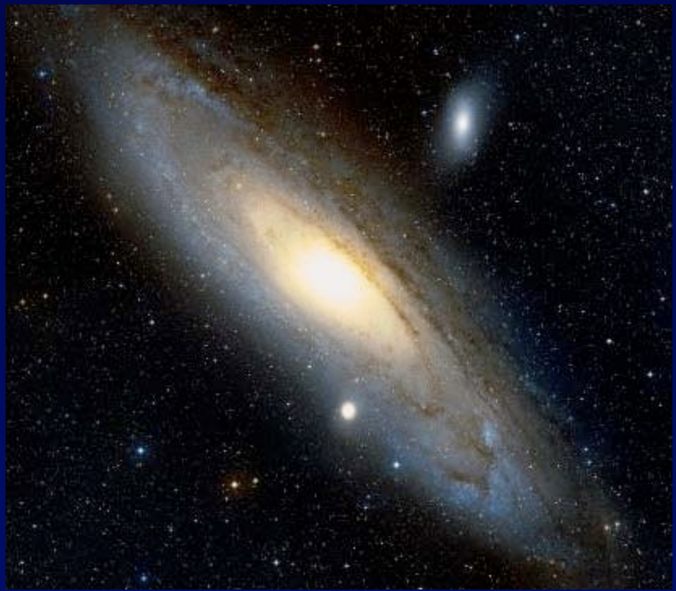
- Status of Black Hole - Host Galaxy Correlations
- Problems, Issues in Measuring Black Hole Masses and Sample Selection
- The VLT SINFONI Search Program for Supermassive Black Holes (S^3BH)
- First S^3BH Results on Classical Bulges, Pseudo-Bulges and Merger Remnants
- HET-HRS Search for Black Holes in Nuclei and Pseudo-Bulges of Sbc/Sc's?
- Black Holes better correlated with σ_{Bulge} or $L_{K,\ Bulge}$?

M 87: $M_{BH} \sim 6\ 10^9\ M_{sun}$



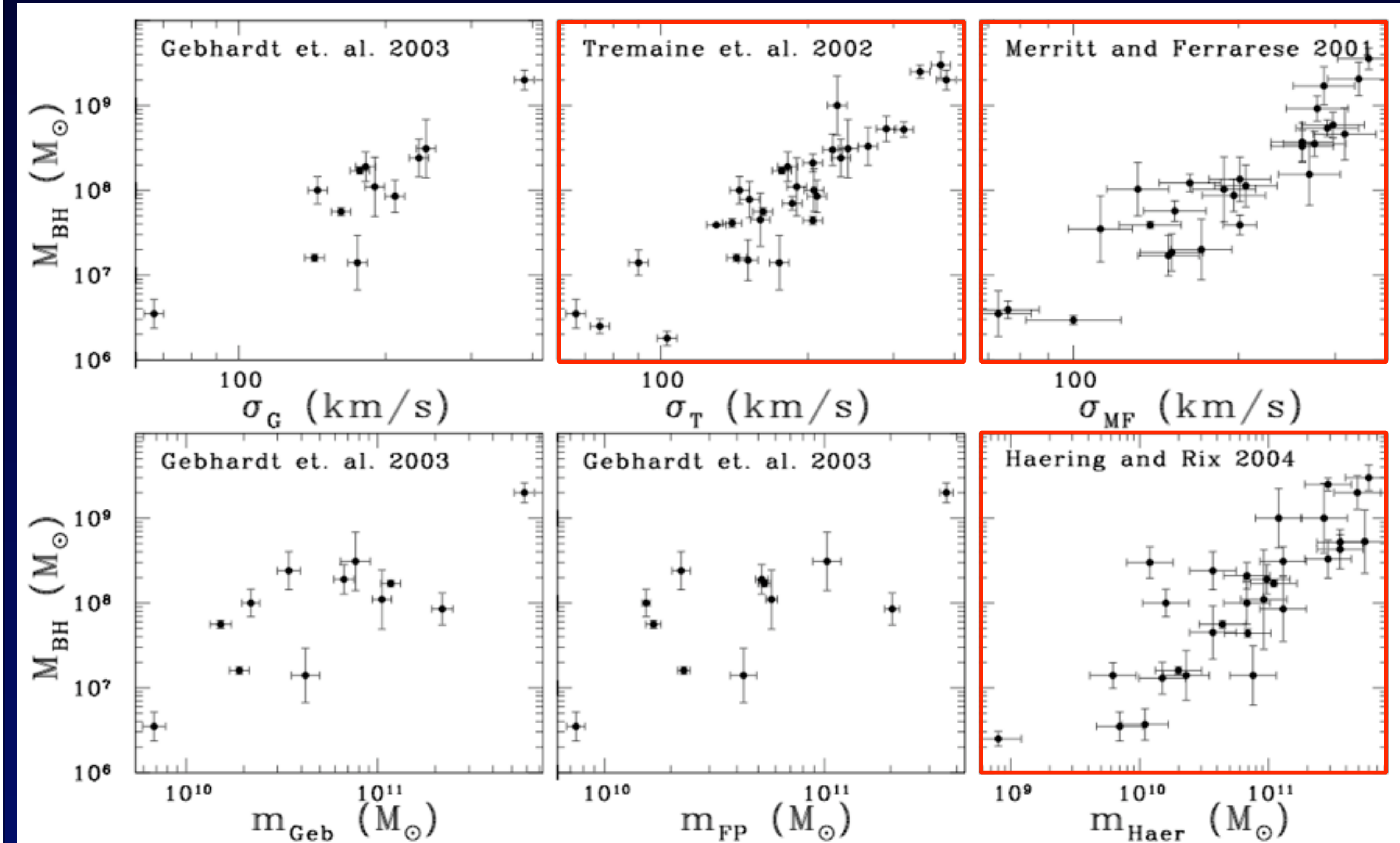
M 104: $M_{BH} \sim 5\ 10^8\ M_{sun}$



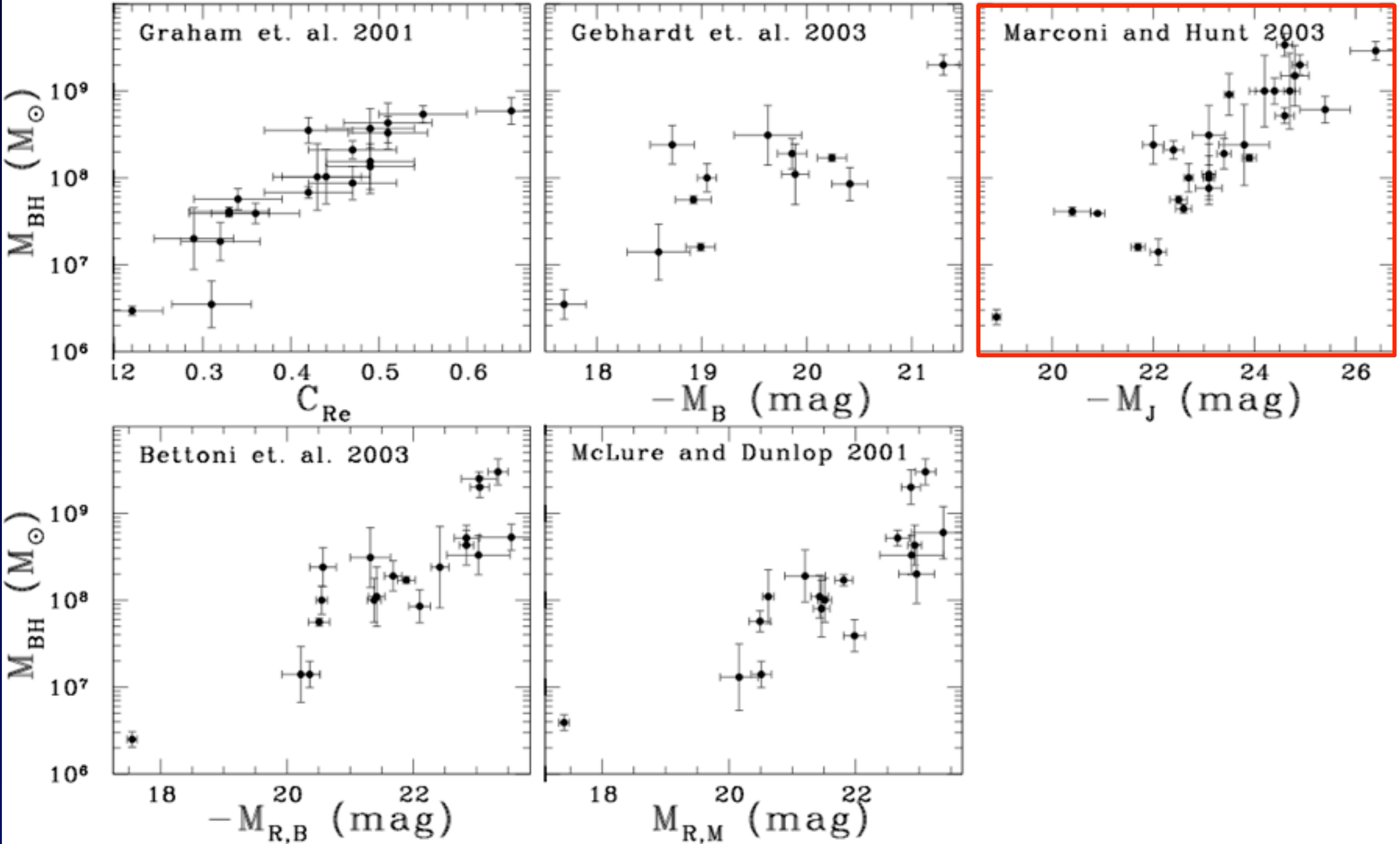
M 31: $M_{BH} \sim 1.4\ 10^8\ M_{sun}$
M 32: $M_{BH} \sim 3\ 10^6\ M_{sun}$

M 33: $M_{BH} < 1500\ M_{sun}$

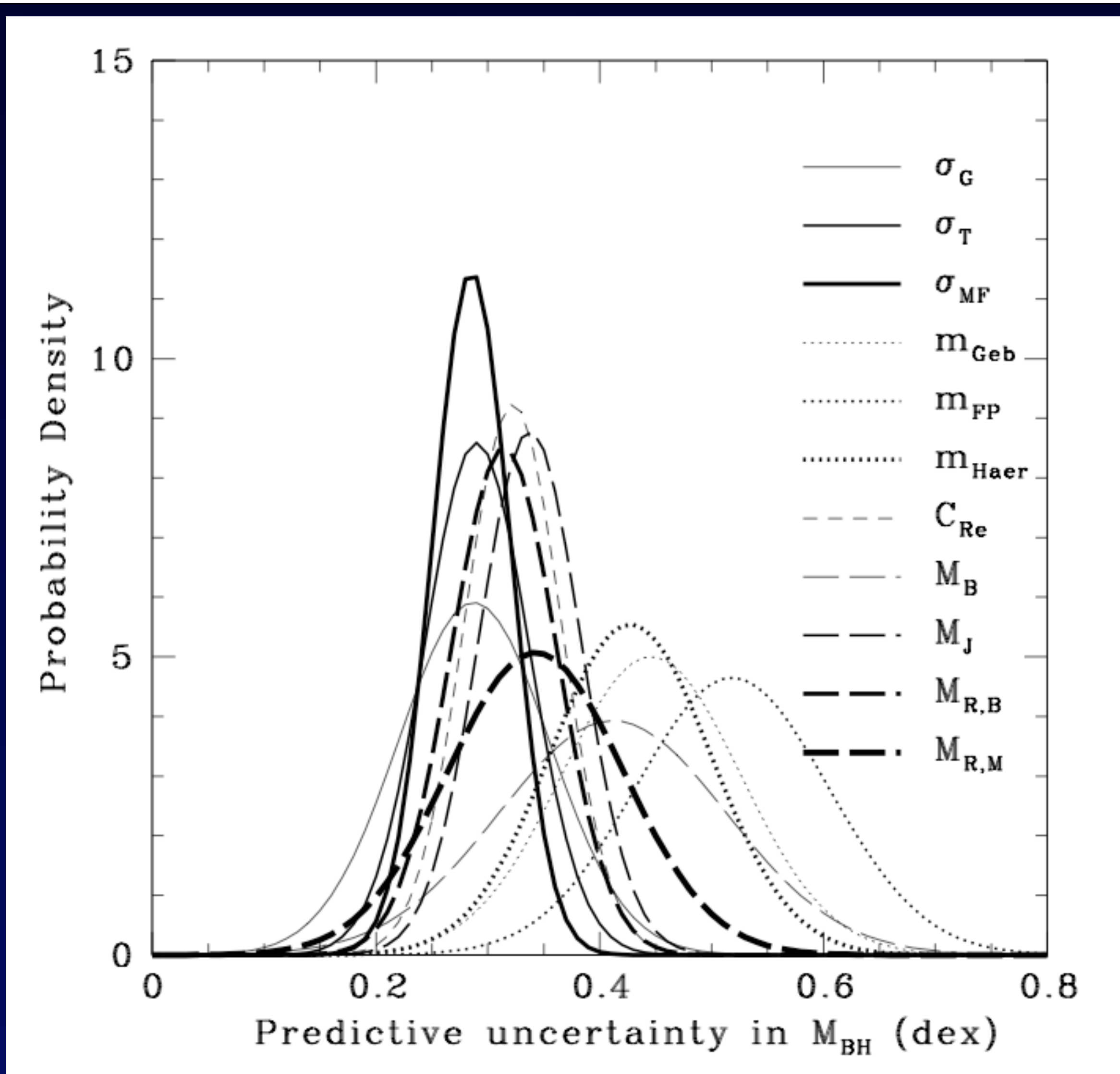
Which galaxy parameter is the best M_{BH} predictor? (AGN observer question)



correlation of black hole mass with velocity dispersion and bulge mass for various samples (Novak, Faber, Dekel, 2006)



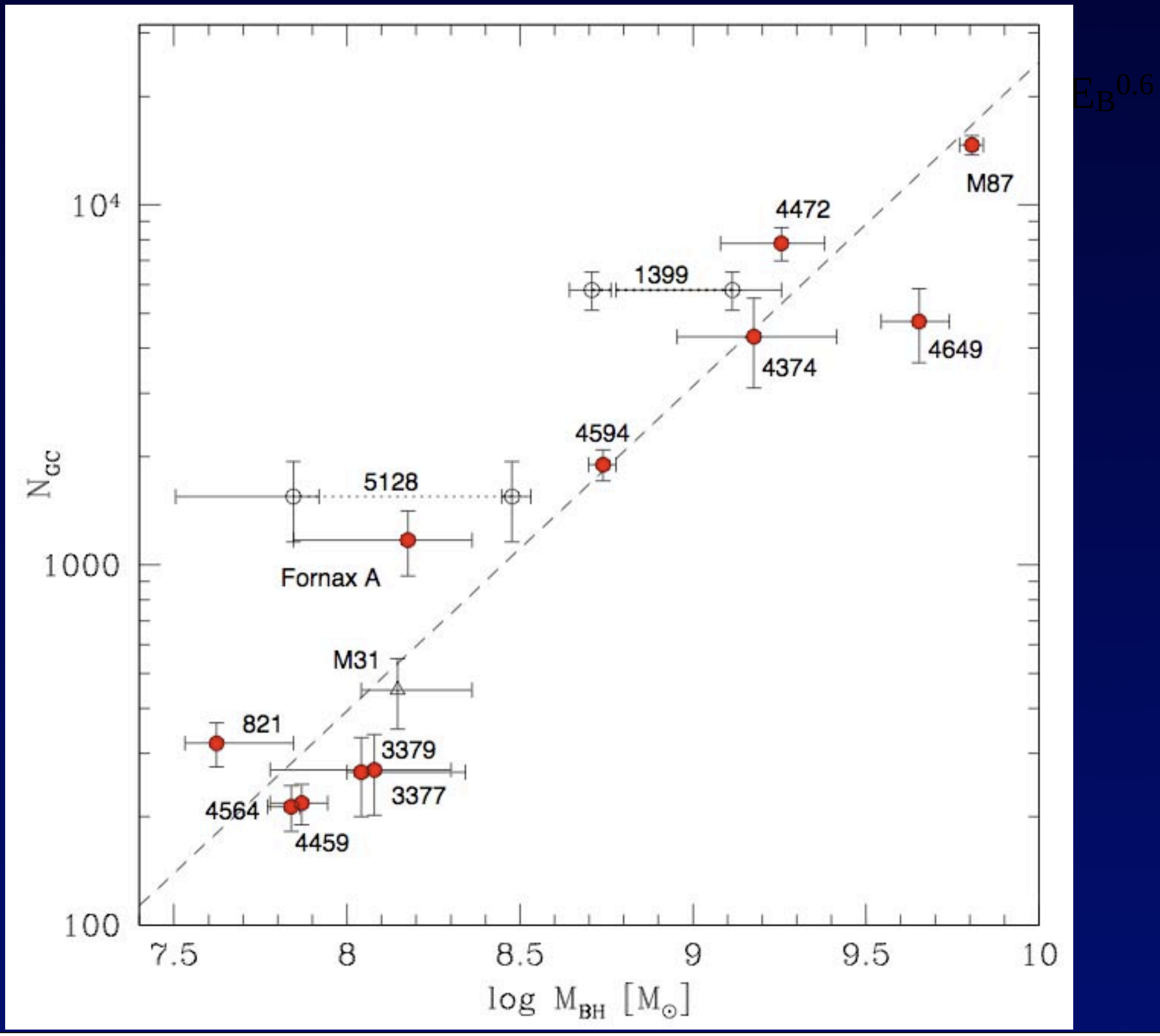
correlation of black hole mass with concentration parameter and luminosities for various samples (Novak, Faber, Dekel 2006)



Predictive power of an observable X for M_{BH}. Except for the relations between M_{BH} and σ_{MF} or C_{Re}, which are dominated by measurement errors, all other relations show significant intrinsic scatter.
None of the the predictor variables X can predict BH masses to better than 0.3 dex or within a factor 2 (Novak, Faber, Dekel 2006).

Burkert & Tremaine (2010) find that black hole mass correlates better with globular cluster number (scatter~0.2dex) than with velocity dispersion!

(but the sample is relatively small)



Deviations from M_{BH}-σ,L driven by structure and formation history?

(origin question)

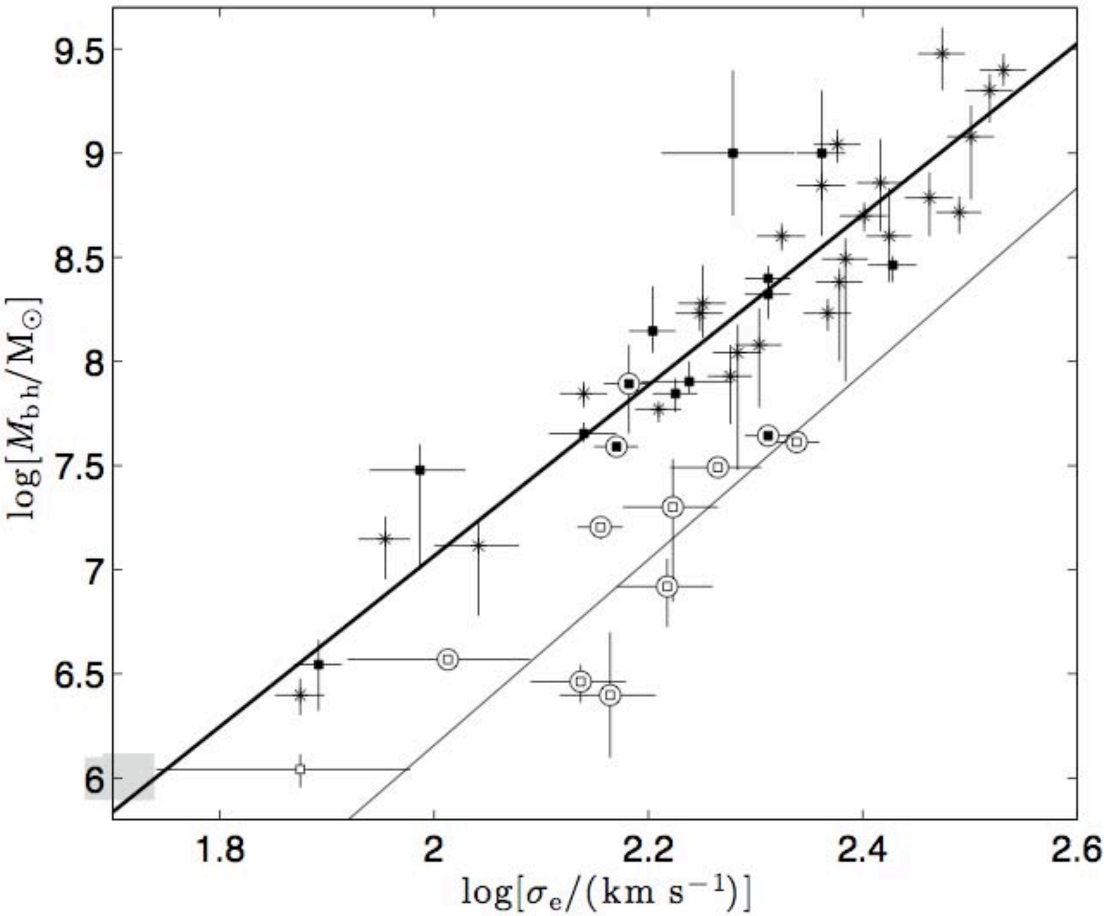


Figure 4. Comparison of the $M_{\rm bh}$-$\sigma_{\rm e}$ relation for elliptical galaxies (stars), classical bulges (filled squares), and pseudobulges (open squares). The barred disk galaxies are marked by circles. The thick and thin solid lines are the best fit results for the early-type bulges and the pseudobulges respectively.

Do pseudo-bulges
(= bulges grown from disk stars via secular evolution)
and barred galaxies
have lower black-hole masses at a given velocity dispersion than classical bulges?
J. Hu (2008)

caveat: variety of methods and sources for BH-masses and velocity dispersions

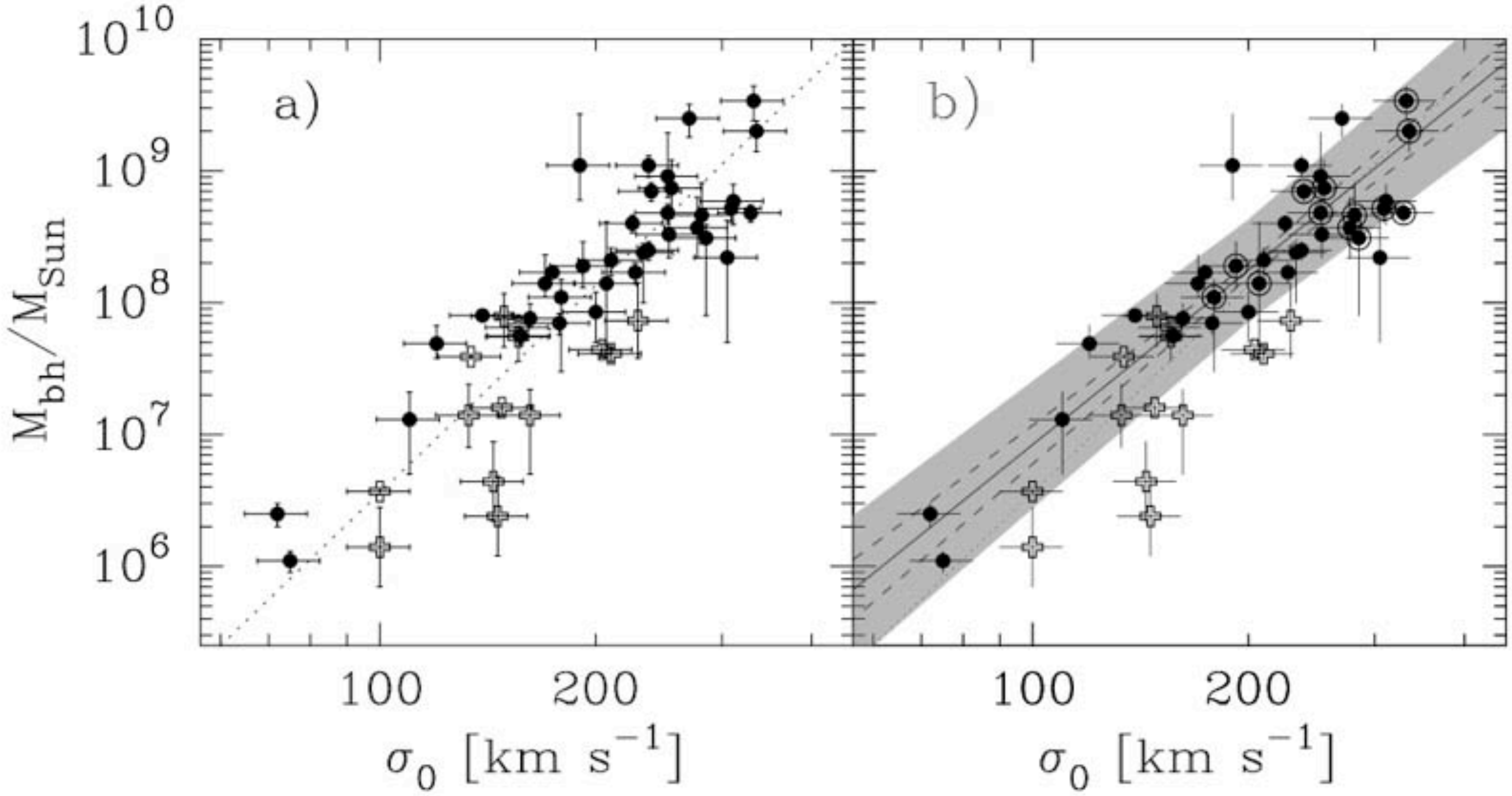


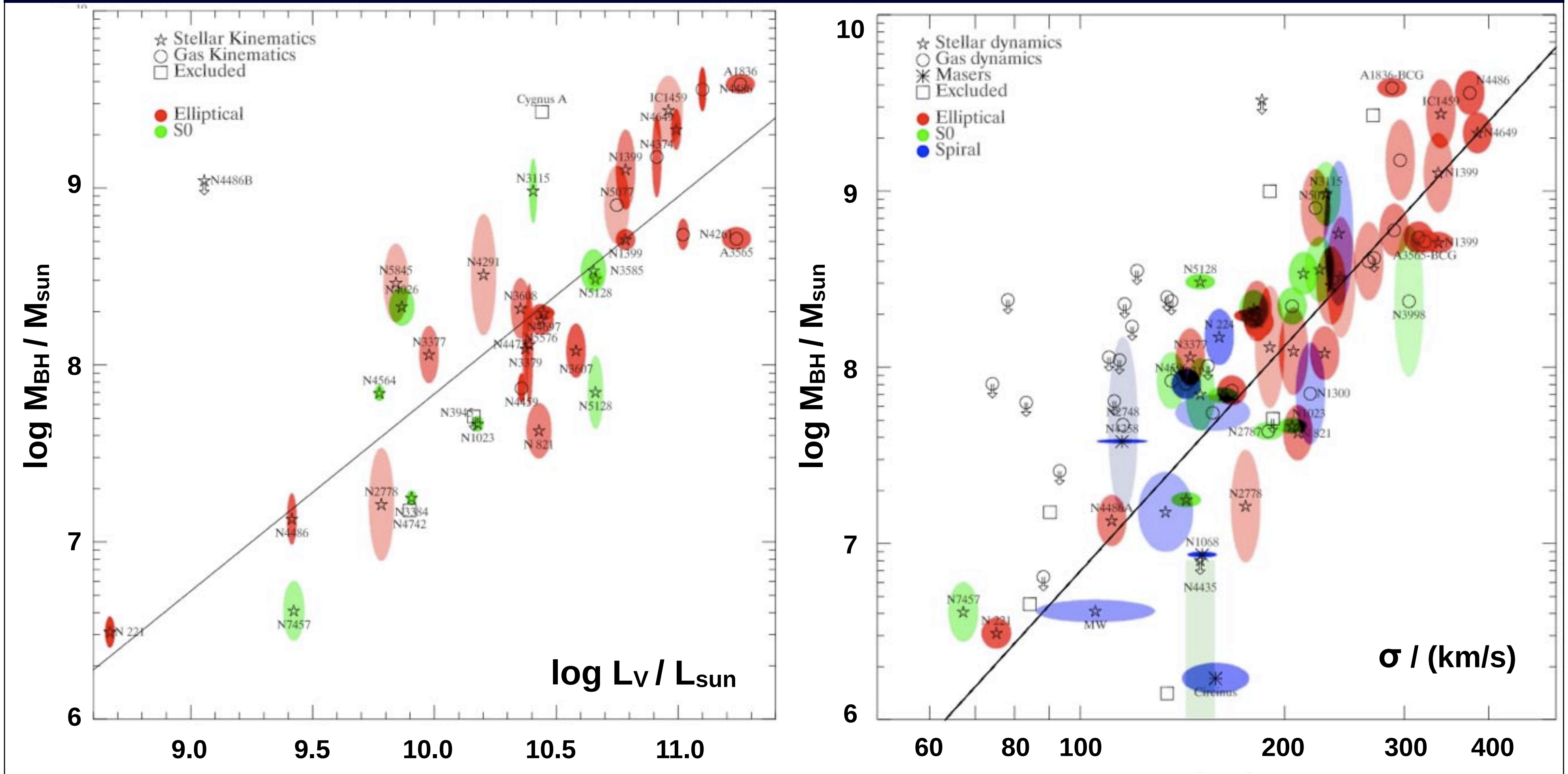
Figure 1: 50 galaxies in the M_{bh}-σ_0 diagram (see Table 1). The 14 barred galaxies are denoted by the crosses. Known "core galaxies" have been circled in panel b). The solid line is the optimal linear regression to the non-barred galaxies, as given by Eq. 1, while the dashed lines delineate the 1σ uncertainty for this relation. The shaded area extends this boundary by 0.33 dex in the log M_{bh} direction. The dotted line is the linear regression to all 50 data points.

Do barred galaxies have lower black hole masses? (Graham 2008)

Caveat: use of central velocity dispersions, which are more prone to dynamical structure than averaged dispersions, and may be affected by the black hole.

Beifiori et al. (2009) do not confirm this result using a sample of 105 galaxies with M_{BH} estimated from HST STIS emission line-width (Sarzi et al. 2002 method).

Intrinsic scatter of M_{BH}-σ and M_{BH}-L_V relations (Gültekin & Nukers 2009)



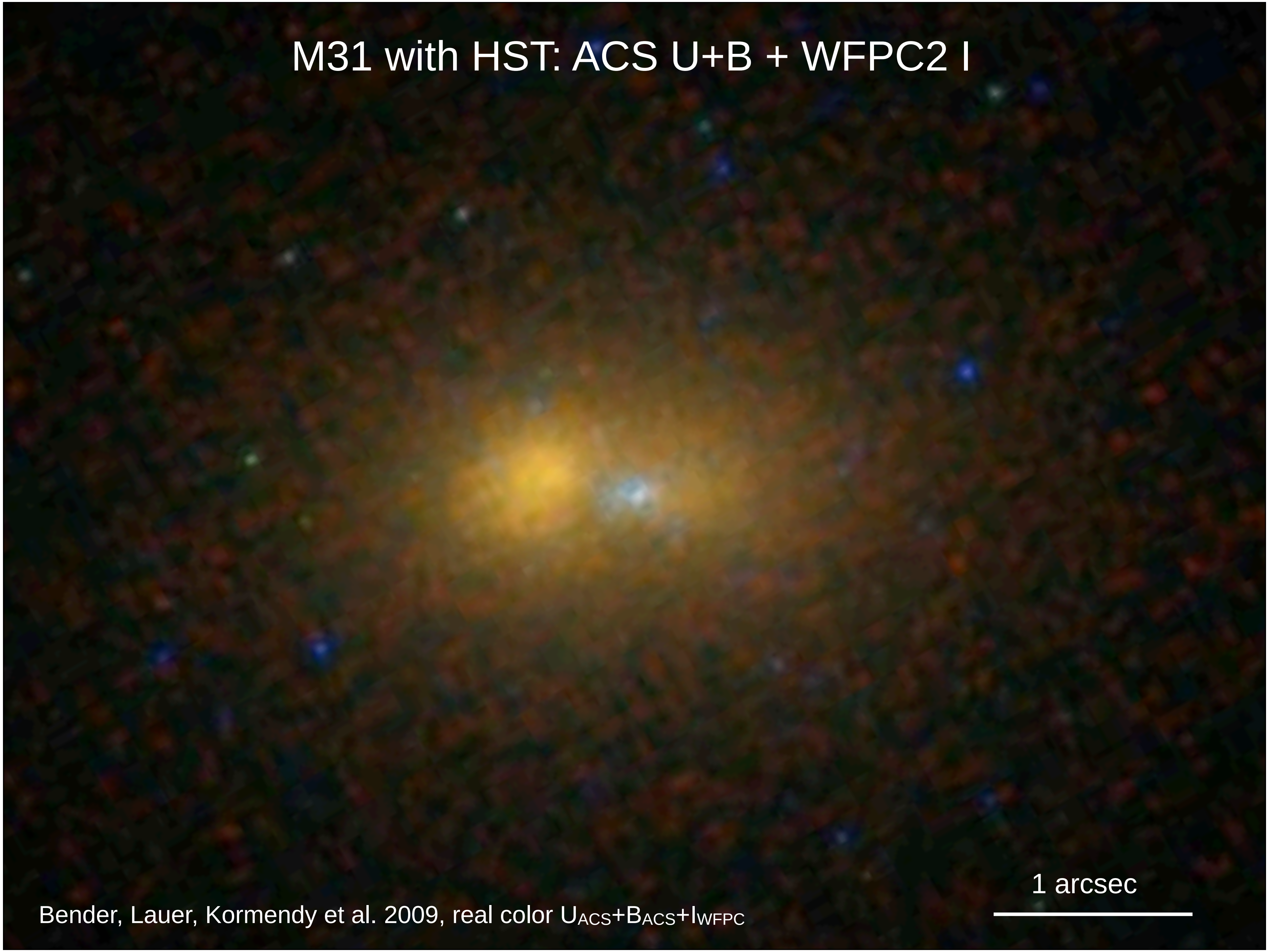
- The difference in fitting methodology is not the source of the difference in intrinsic scatter estimates, but it is the difference in the samples.
- The scatter in M_{BH}-σ is ~0.31 for ellipticals, ~0.44 for all galaxies and larger for spirals (but the spiral sub-sample probably IS too small... inclusion of Circinus makes a big difference!)
- The scatter in M_{BH}-L_V is 0.38 for ellipticals.
- There is no evidence for offsets of pseudo-bulges and barred galaxies (but the spiral sub-sample probably is too small...)

Besides problems with sample selection and homogenization, and with measuring σ, L, bulge-disk decompositon, M/L, dust etc,

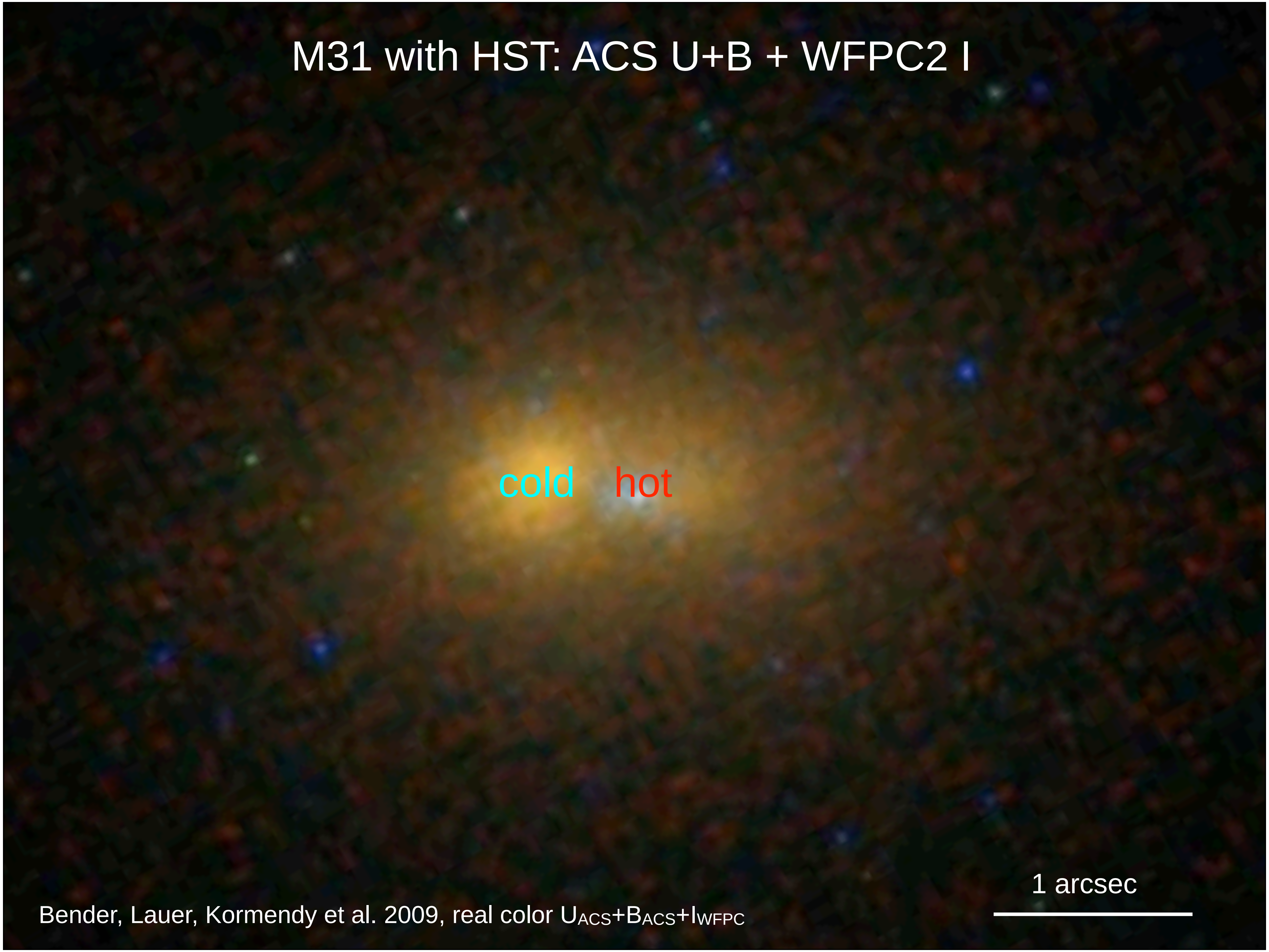
some of the observed scatter is very likely due to the difficulty in determining black hole masses accurately:

- technical issues (LOSVD extraction and characterization, e.g., R. Houghton's thesis)
- triaxiality and/or dynamically too restricted models
- M_{BH} too low if models do not include dark halo, in particular: larger BH masses to be expected for luminous low density galaxies. M87: 3.7e9 ➜ 6.7e9 (Thomas+Gebhardt 2009, Schulze+Gebhardt 2010, Rusli et al. 2011)
- Unknown and unusual (?) central structure can affect mass, e.g. M31: HST observations increased M_{BH} by a factor ~1.5 (Bender et al. 2005) ➜ only cure is high spatial resolution, or, possibly, superb S/N spectra which can show LOSVD peculiarities.
- ...

M31 with HST: ACS U+B + WFPC2 I



Bender, Lauer, Kormendy et al. 2009, real color $U_{ACS}+B_{ACS}+I_{WFPC}$


M31 with HST: ACS U+B + WFPC2 I
cold
hot
1 arcsec
Bender, Lauer, Kormendy et al. 2009, real color $U_{ACS}+B_{ACS}+I_{WFPC}$

A lesson: time evolution of the M 31 black hole mass

- $(0.05\text{-}1)\times10^{8}\ M_{\odot}$, ground-based kinematics (Kormendy 1988),
- $(3\text{-}7)\times10^{7}\ M_{\odot}$, ground-based kinematics (Dressler & Richstone 1988),
- $(4\text{-}5)\times10^{7}\ M_{\odot}$, ground-based kinematics (Richstone et al. 1990),
- $\sim7\times10^{7}\ M_{\odot}$, ground-based kinematics (Bacon et al. 1994),
- $(0.7\text{-}1)\times10^{8}\ M_{\odot}$, ground-based kinematics (Emsellem & Combes 1997)
- $(1.5\text{-}4.5)\times10^{7}\ M_{\odot}$, HST: BH offset from bulge center and center-of-mass argument for P1+BH (long shot) (Kormendy & Bender 1999)
- $\sim10^{8}\ M_{\odot}$, HST: eccentric disk model (Peiris and Tremaine 2003)
- $\sim1.4(+0.9,-0.3)\times10^{8}\ M_{\odot}$, HST: blue disk dynamics (Bender et al. 2005)

Physical scatter can only be measured and understood with well selected samples and reliably determined black hole masses. (avoid reverberation mapping, emission line widths for now... even though scatter in recent reverb-samples is smallish ~0.44, see Woo et al. 2010)

The MPE/USM group used SINFONI with Adaptive Optics at the VLT to measure black hole masses in 30+ hitherto non-observed galaxies.

The SINFONI Search for Supermassive Black Holes

Goals:

- Investigate extreme ends: high/low L,σ objects
- Black holes in pseudo-bulges vs classical bulges
- Black holes in very luminous/core ellipticals
- Black holes in odd guys (e.g. stripped Es, mergers)
- Find constraints on BH formation/evolution models
- Estimate what is the best M_{BH} predictor: K-luminosity, mass, velocity dispersion or ?

Method:

- Use stellar kinematics in NIR (less dust-affected)
- use AO-assisted SINFONI@VLT (more light-collecting power than HST, FWHM~0.1” achievable)
- combine with longslit or 2D (SAURON) kinematics
- model with axisymmetric Schwarzschild-method

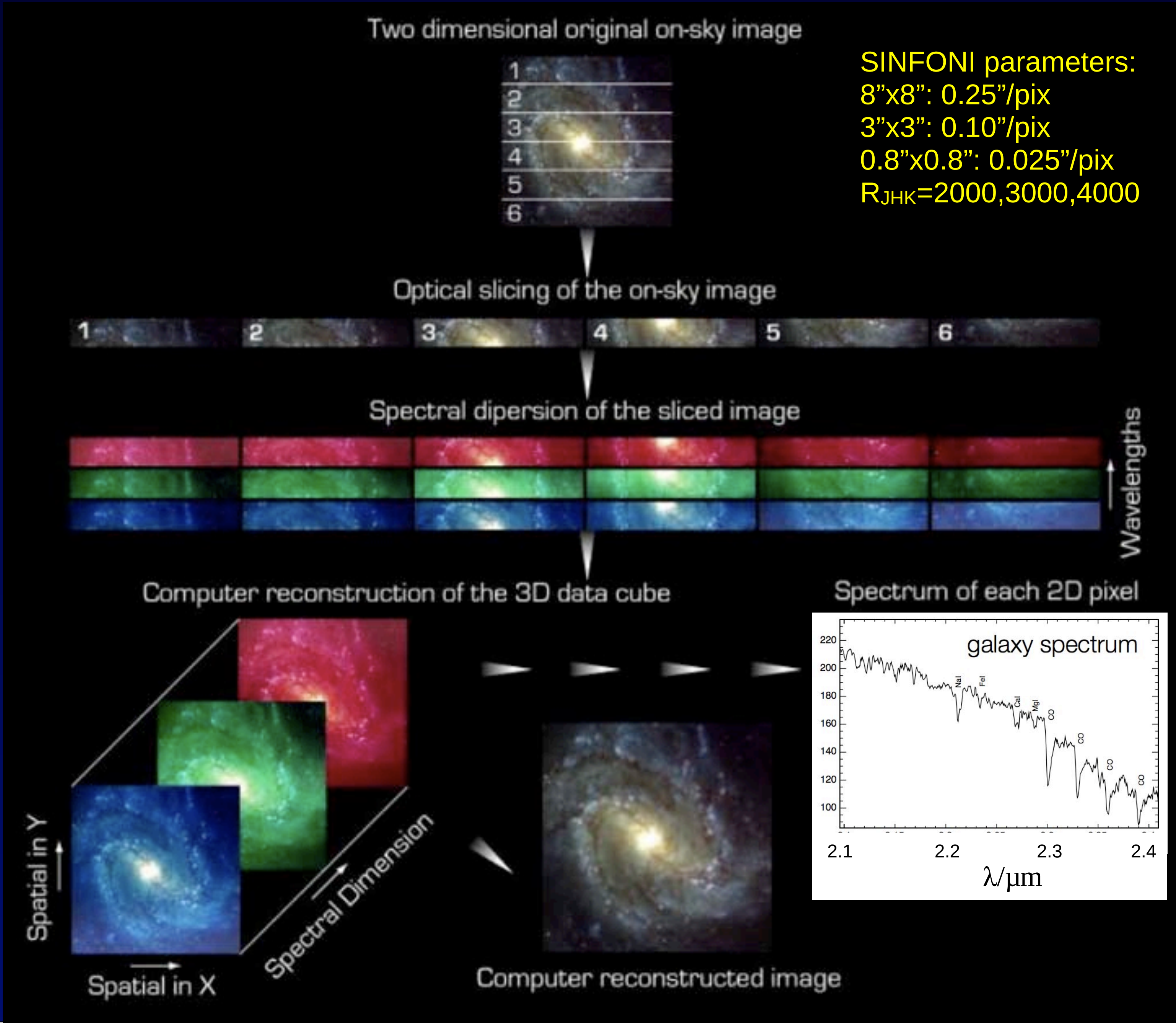
The SINFONI Black Hole Sample

Galaxy	*FWHM (")*
NGC 307	0.20
NGC 1316	0.085
NGC 1332	0.15
NGC 1374	0.13
NGC 1398	0.14
NGC 1407	0.20
NGC 1550	0.17
NGC 3091	0.13
NGC 3137	0.10
NGC 3351	0.18
NGC 3368	0.17
NGC 3412	0.15
NGC 3489	0.08
NGC 3627	0.09
NGC 3923	0.33
NGC 4371	0.14
NGC 4472	0.33

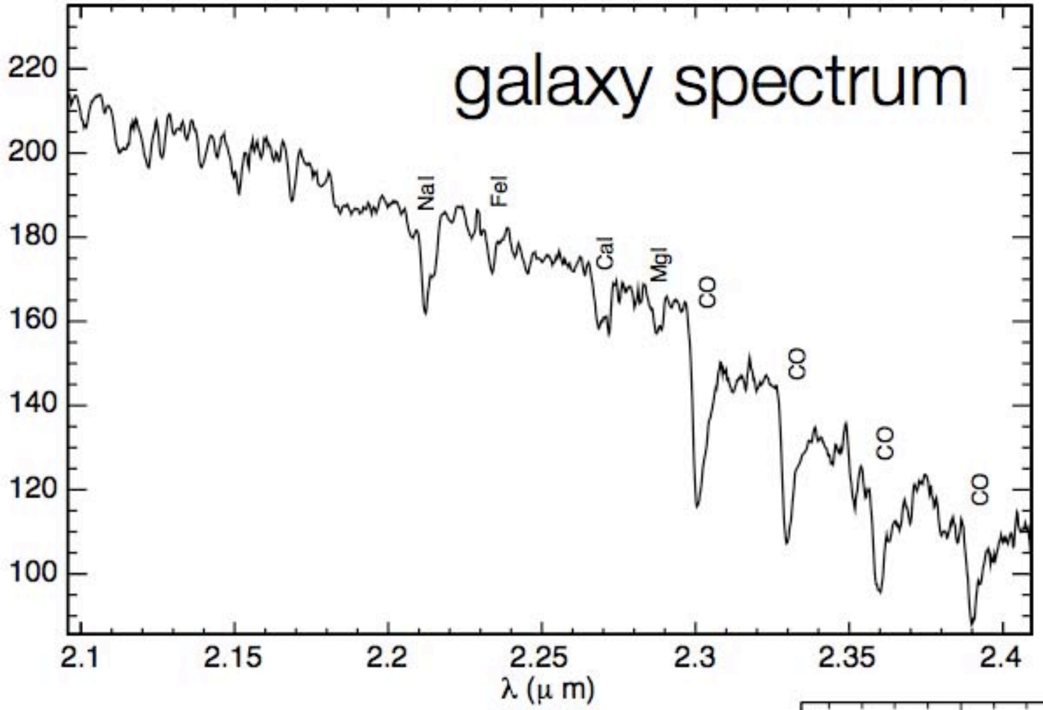
Galaxy	*FWHM (")*
NGC 4486a	0.10
NGC 4486b	0.16
NGC 4501	0.15
NGC 4536	0.18
NGC 4569	0.16
NGC 4579	0.23
NGC 4699	0.10
NGC 4751	0.15
NGC 4762	0.14
NGC 5018	0.15
NGC 5102	0.08
NGC 5328	0.12
NGC 5419	0.19
NGC 5516	0.14
NGC 7619	0.17
ESO 138-5	0.36

Up to now, good black masses exist for only ~50 galaxies.
We add another ~30 exploring dusty and extreme objects.

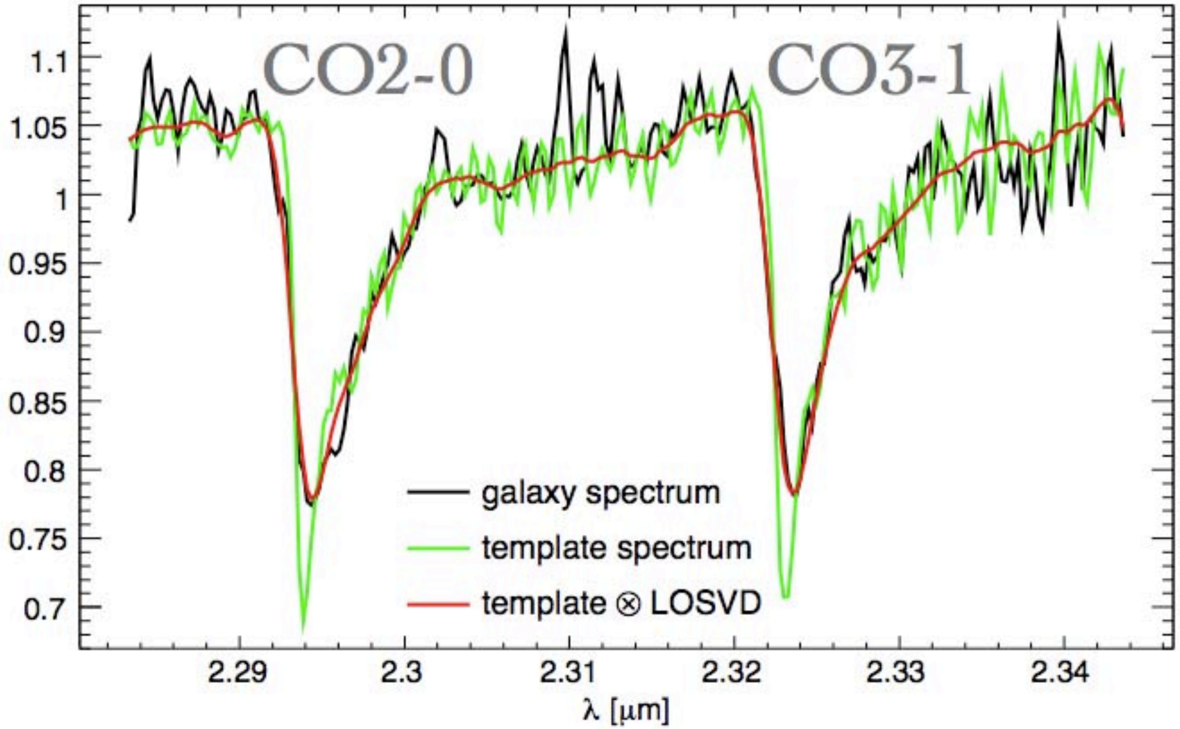
How SINFONI works:



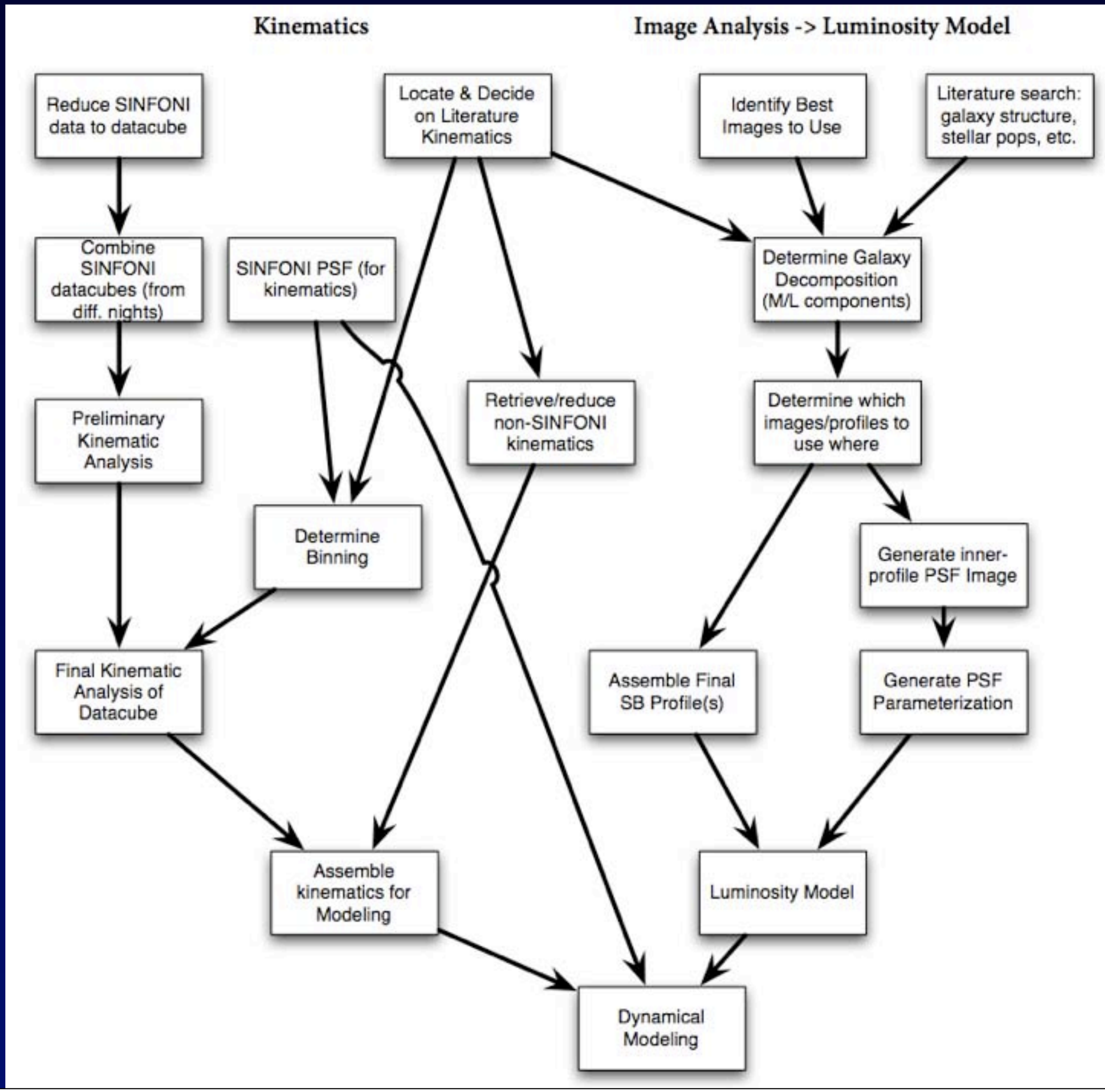
SINFONI parameters:
8”x8”: 0.25”/pix
3”x3”: 0.10”/pix
0.8”x0.8”: 0.025”/pix
R_{JHK}=2000,3000,4000



Spectral region of SINFONI data



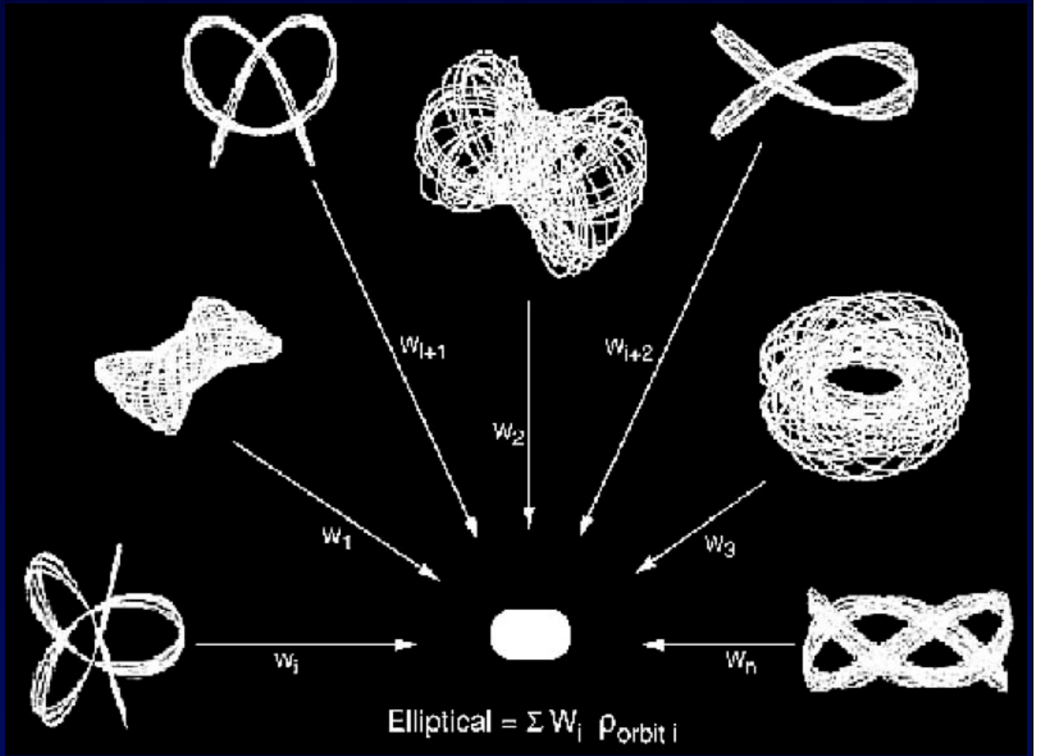
From Data to Dynamical Models:



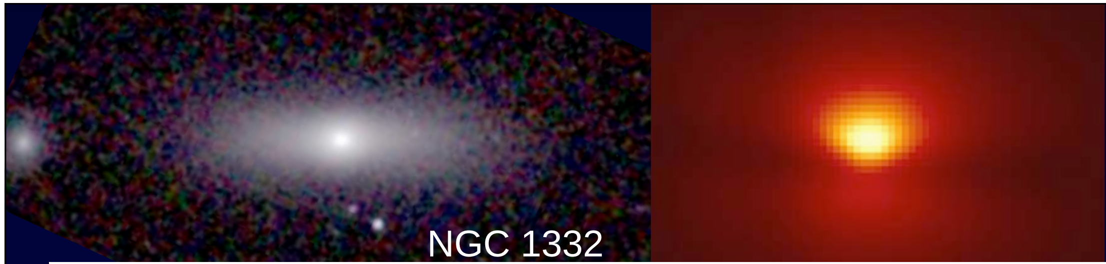
Modeling galaxy dynamics with Schwarzschild's method (1979):

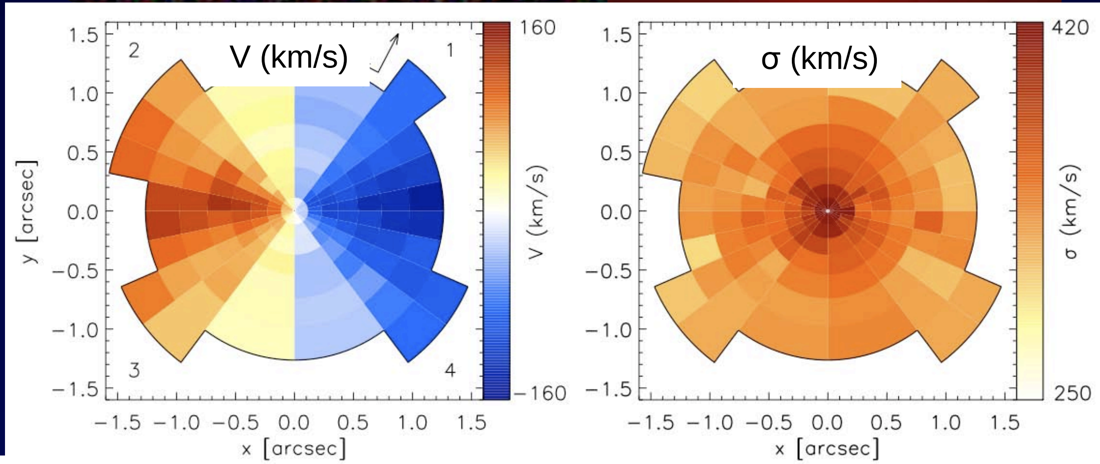
(Richstone&Tremaine 1988, van der Marel et al. 1998, Gebhardt et al. 2003, Thomas et al. 2004)

- deproject surface brightness profile to derive 3D axisymmetric density distribution of stars (assume inclination)
- choose an M/L ratio for the stars and derive the potential from Poisson's equation; add the potential of the BH
- calculate ~10^4 orbits with different energies, angular momenta and drop points and derive their time-averaged density distribution



- superimpose the orbits such that:
  (1) the surface brightness distribution is matched,
  (2) the velocity distribution (rotation, dispersion, higher moments) is matched
  (3) the phase space distribution is 'smooth' (e.g. by using an entropy constraint)
- repeat this procedure for a range of inclinations, stellar mass-to-light ratios and black hole masses, obtain confidence limits for M/L and M_{BH}.





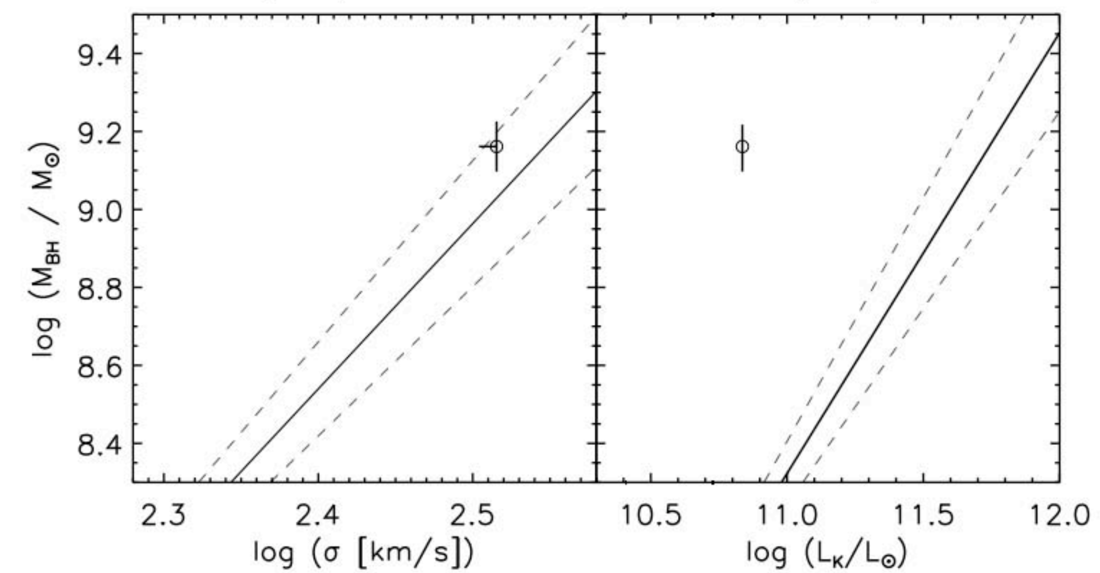
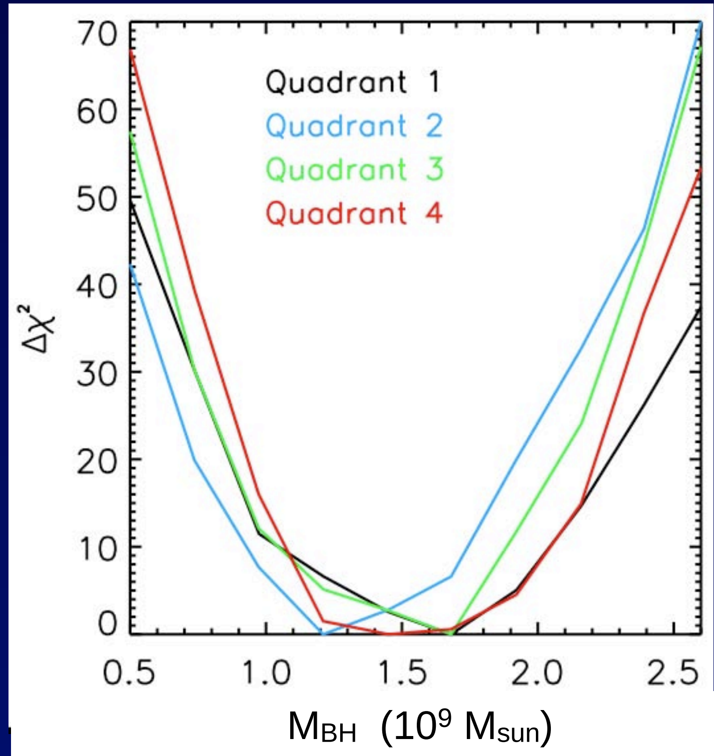
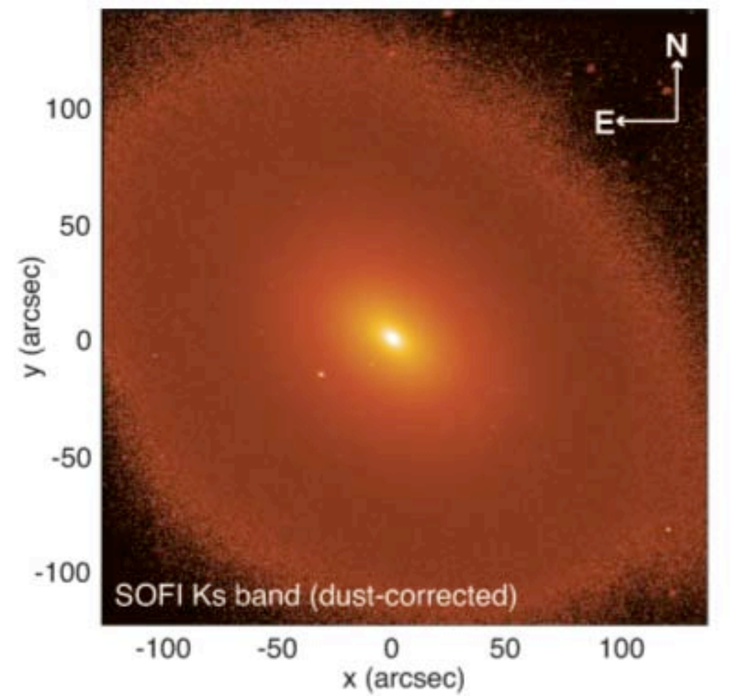


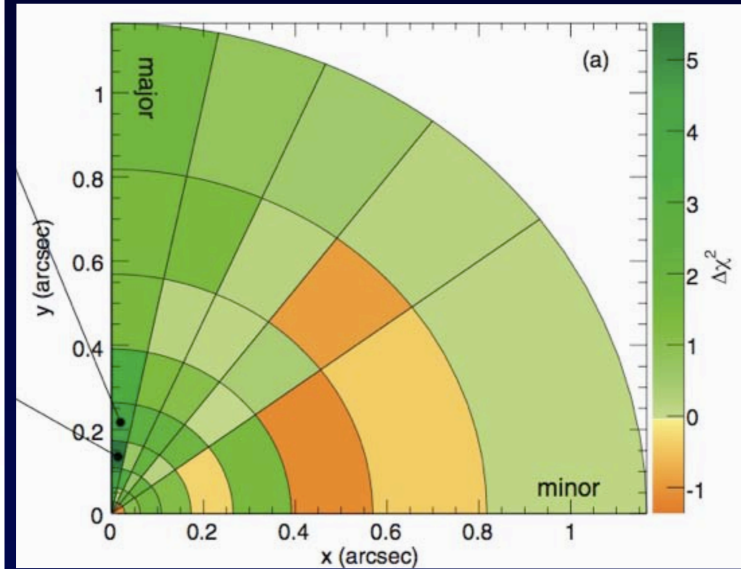
Figure 10. $M_{\rm BH}$-σ (left) and $M_{\rm BH}$-L (right) diagrams. NGC 1332 is plotted as a square in each panel along with the Gültekin et al. (2009) $M_{\rm BH}$-σ relation and Marconi&Hunt (2003) $M_{\rm BH}$-L_K relation.

For compact classical bulges like NGC 1332, velocity dispersion is a better predictor for black hole mass than bulge luminosity or mass (Rusli et al. 2010). Others: NGC 4342, NGC 4486B



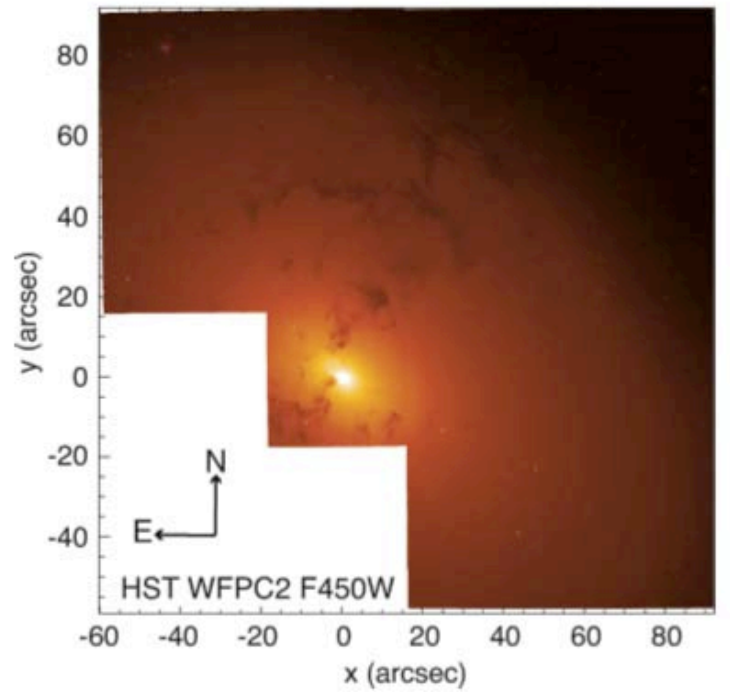
The merger remnant Fornax A

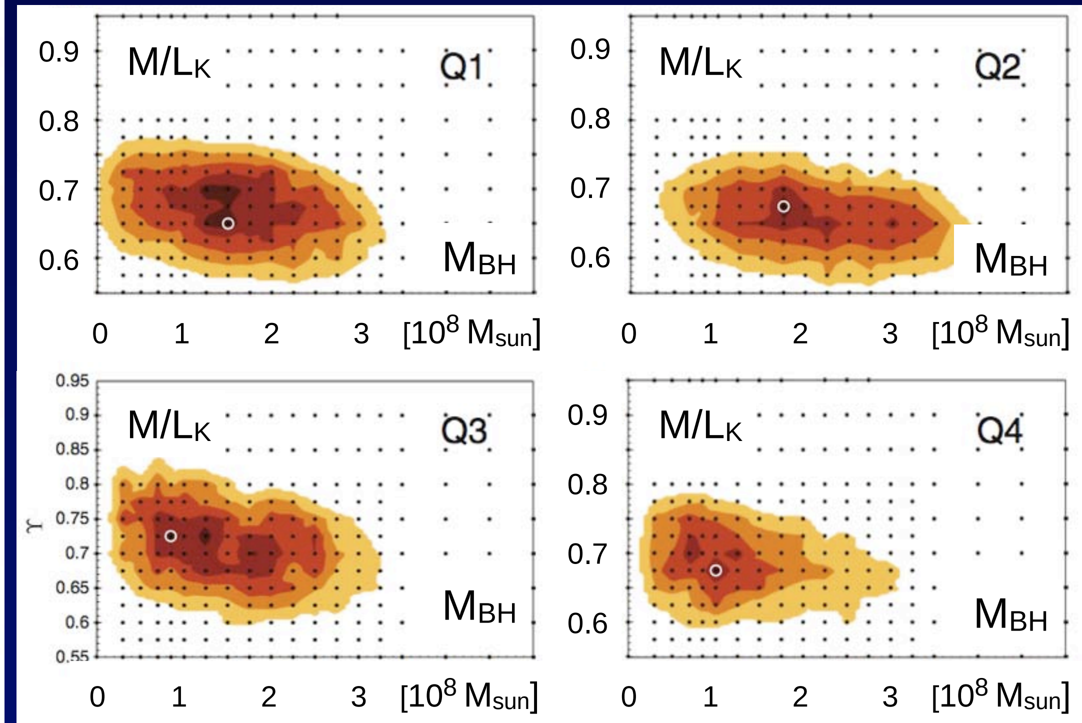




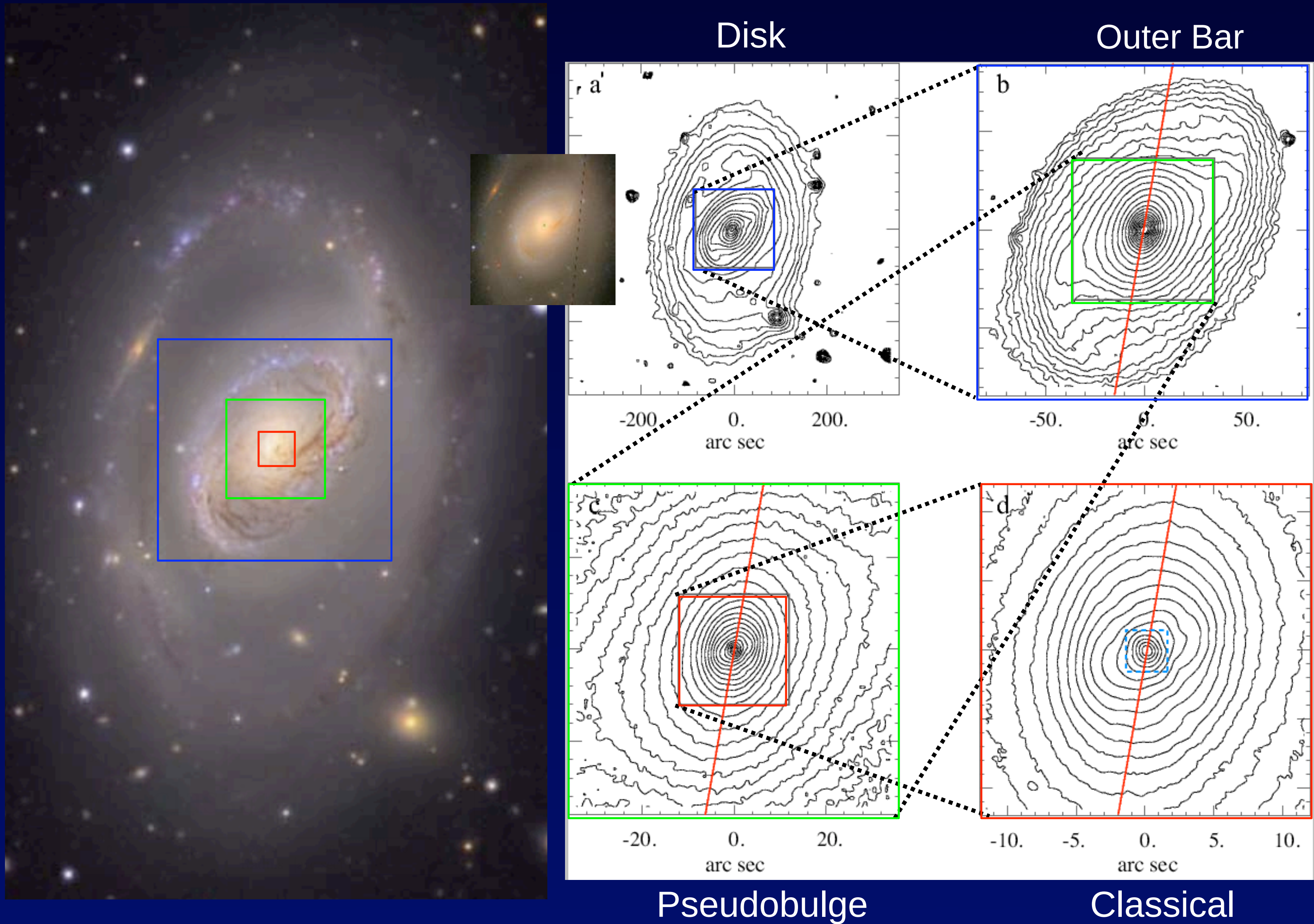
here, too, σ is a better predictor for M_{BH} than L_K.

$\Delta\chi^2$ improvement of model with BH relative to model without BH



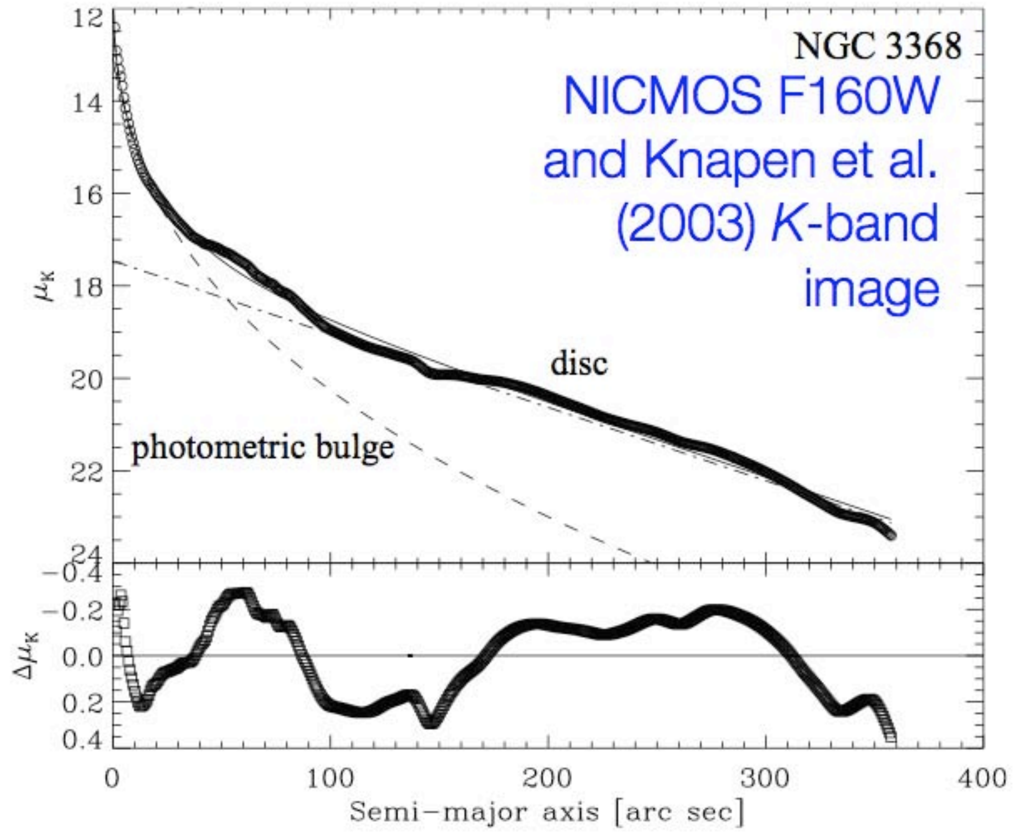


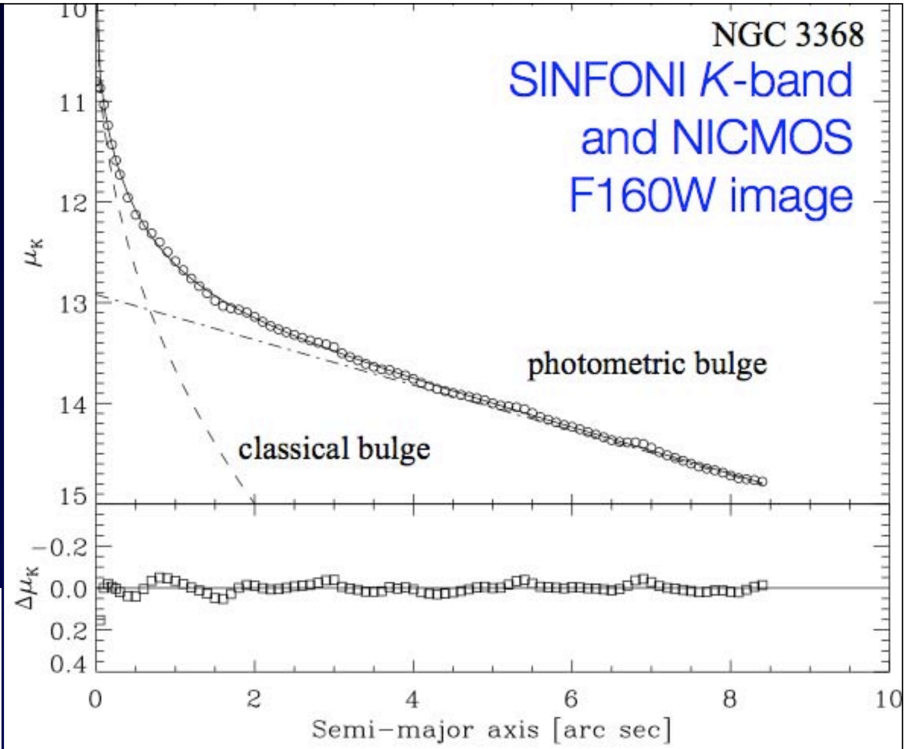
Black Holes and Pseudo-Bulges: NGC 3368

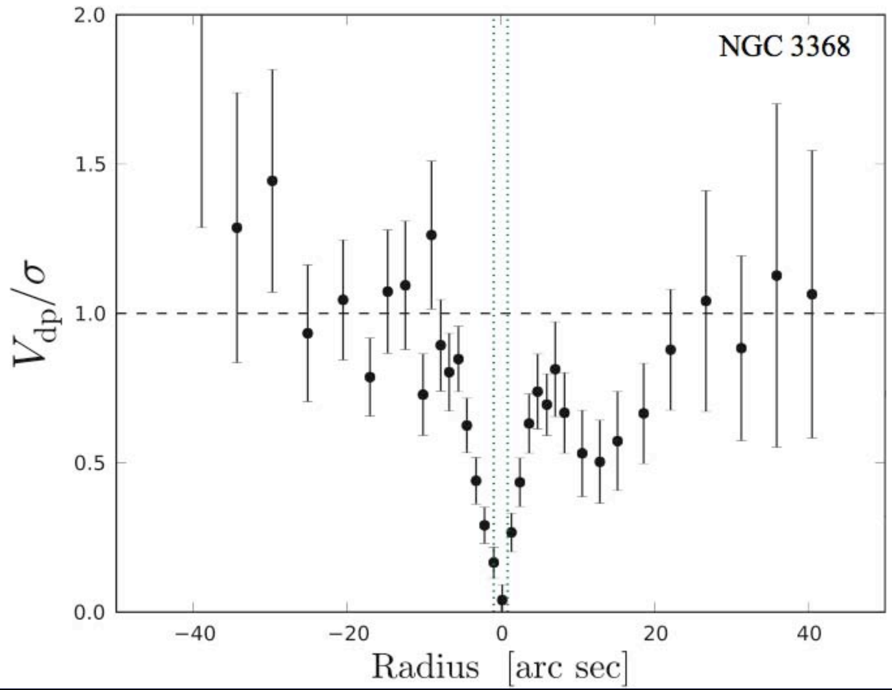


NGC 3368: decomposition in bulge and pseudo-bulge components based on photometric and kinematic data

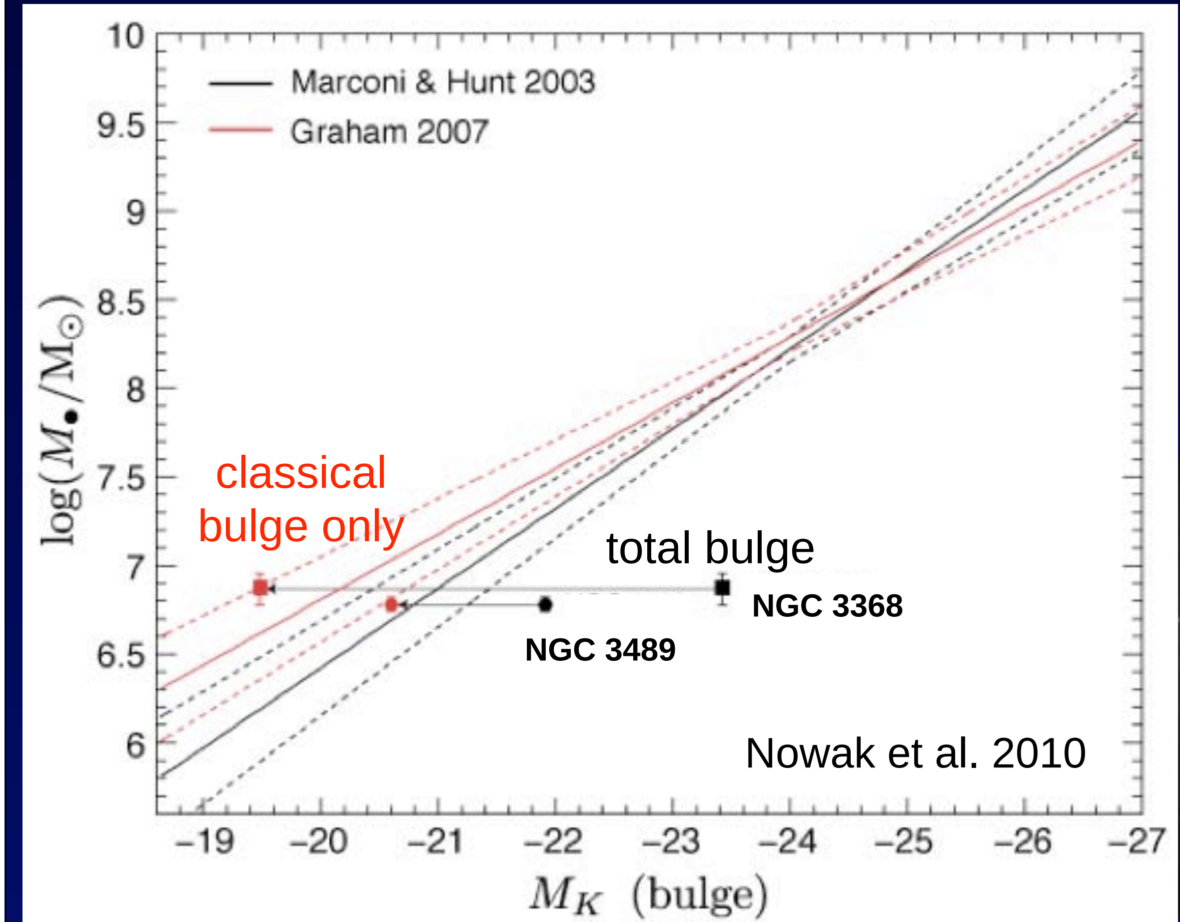
(Nowak et al. 2010, for pseudo-bulge criteria see Kormendy & Kennicutt 2004).





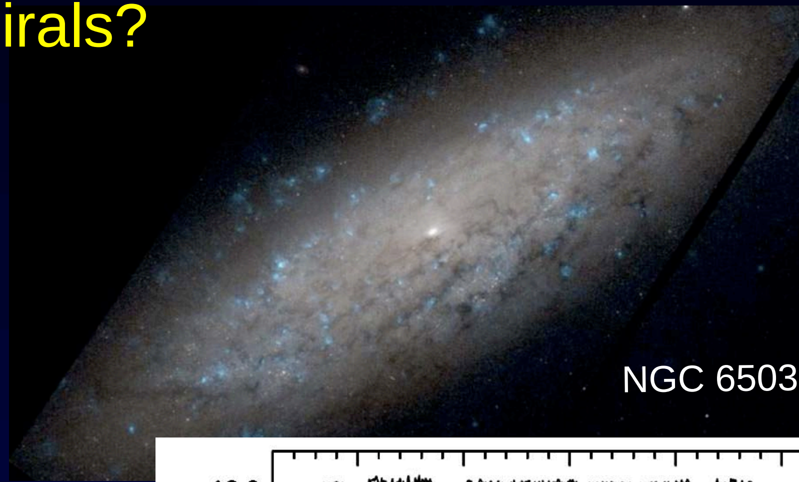


Black Holes seem to be better correlated with classical bulge mass, not the pseudo-bulge component (Nowak et al. 2010).

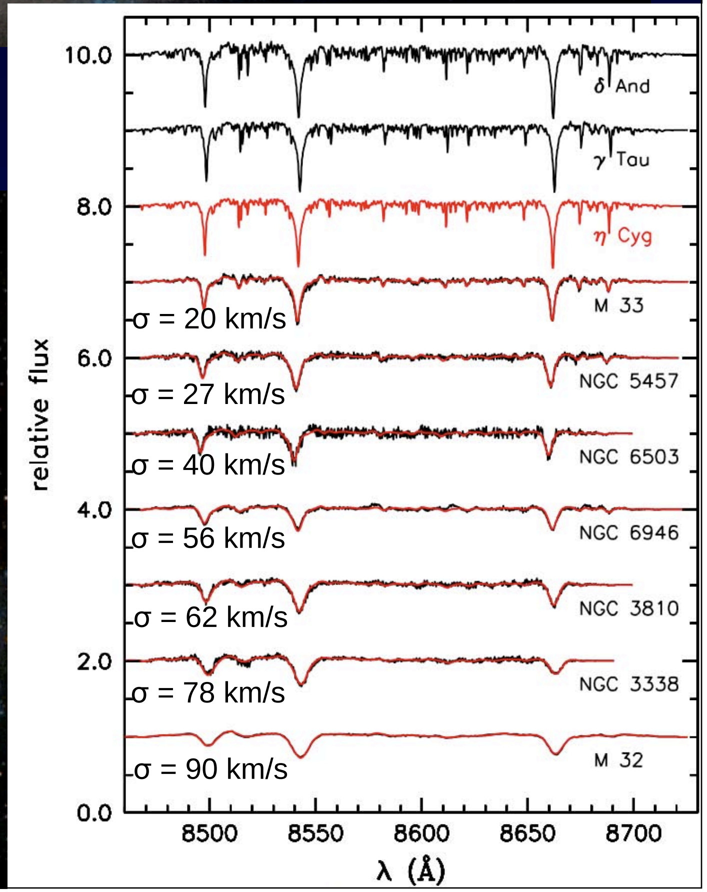


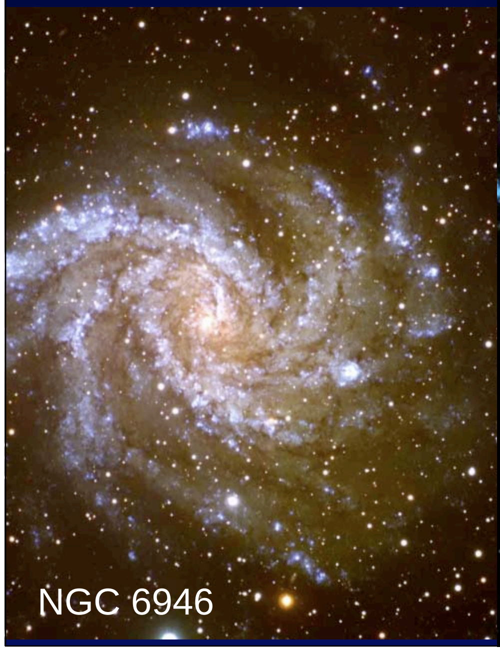
HET-program: Black Holes in Nuclei and Pseudo-Bulges of Late-Type Spirals?

Hobby-Eberly-Telescope-HRS, R = 15000, σ_{HRS} = 8 km/s

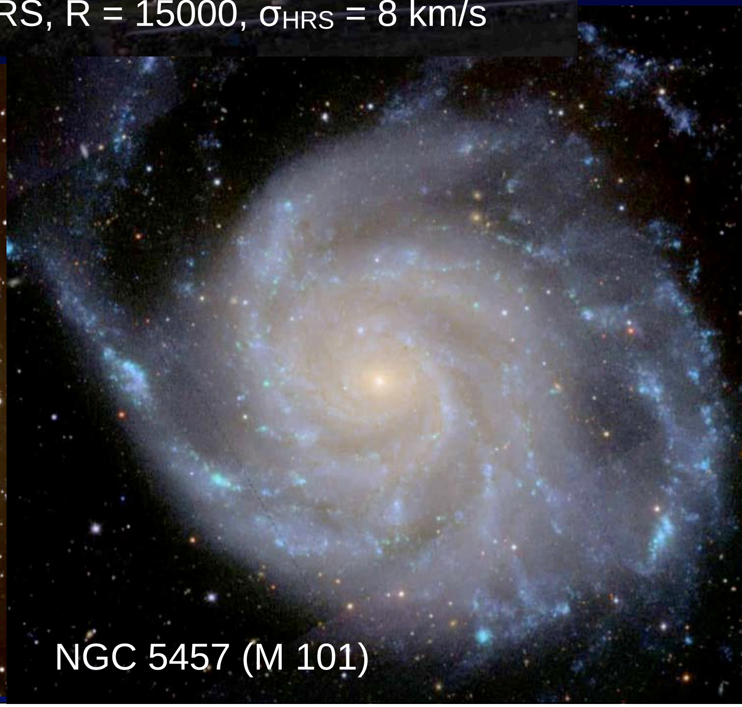


NGC 6503





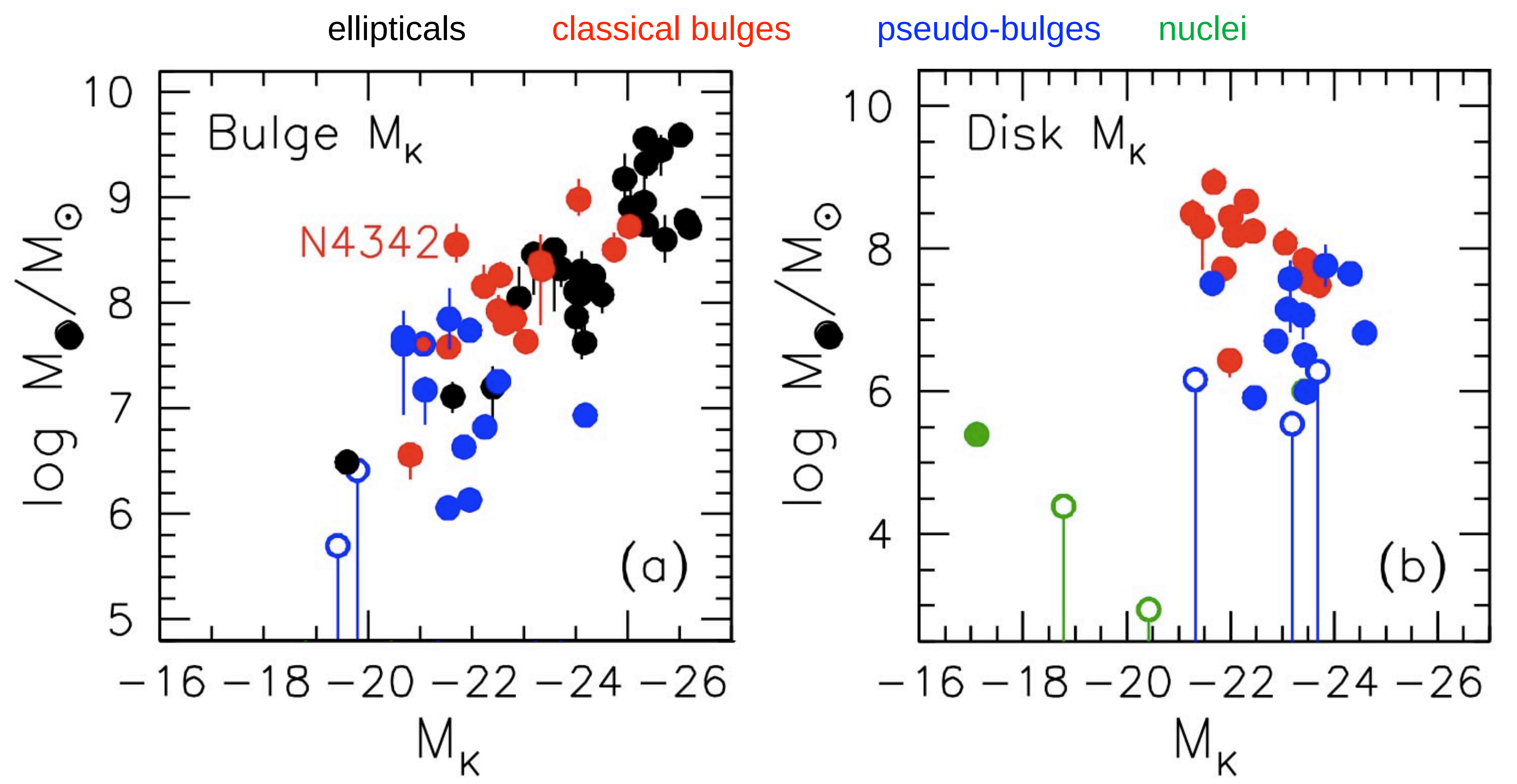
NGC 6946



NGC 5457 (M 101)

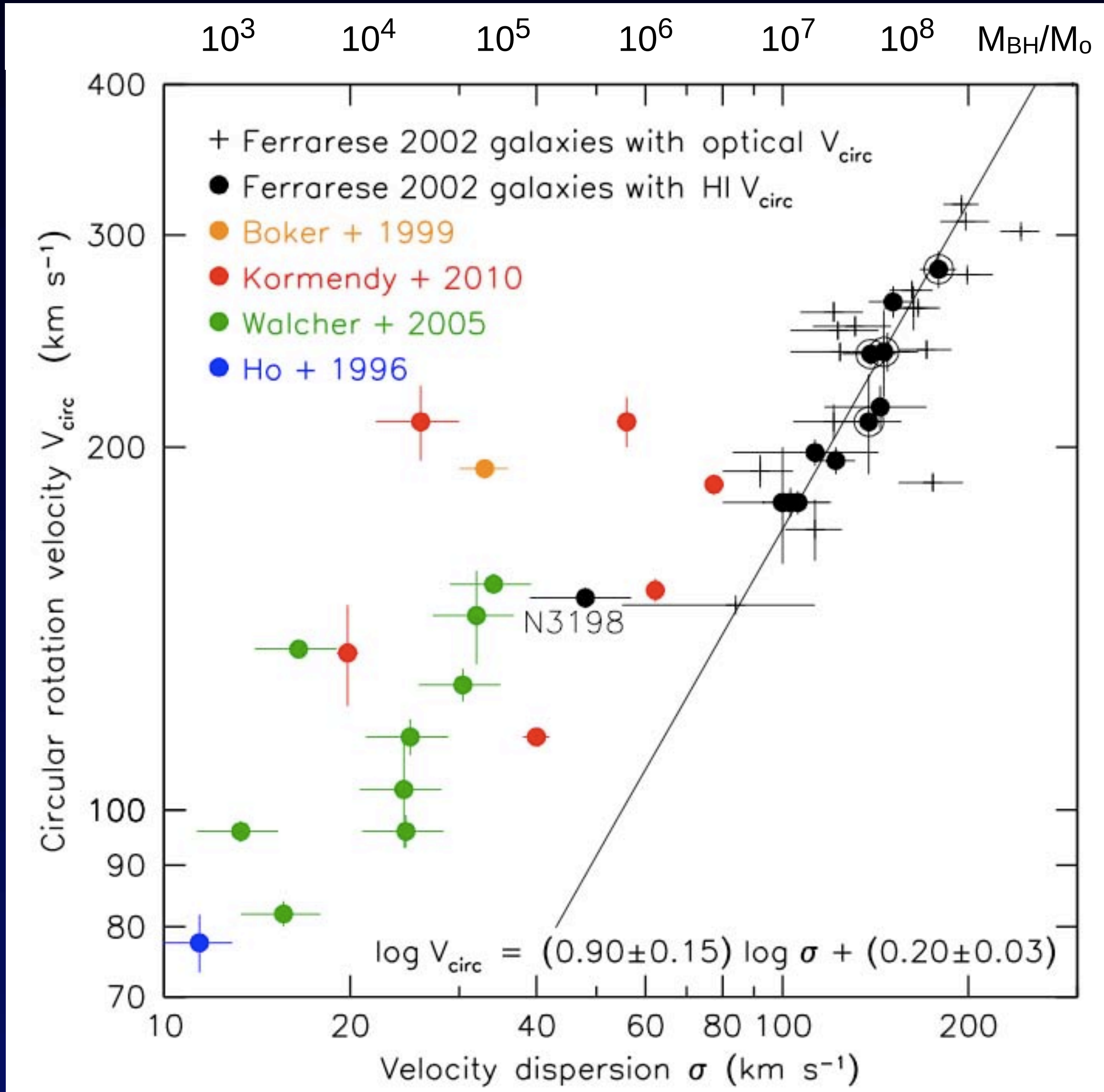
Supermassive Black Holes do not correlate with pseudo-bulges or galaxy disks

Kormendy, Bender & Cornell, Nature, Jan. 2011



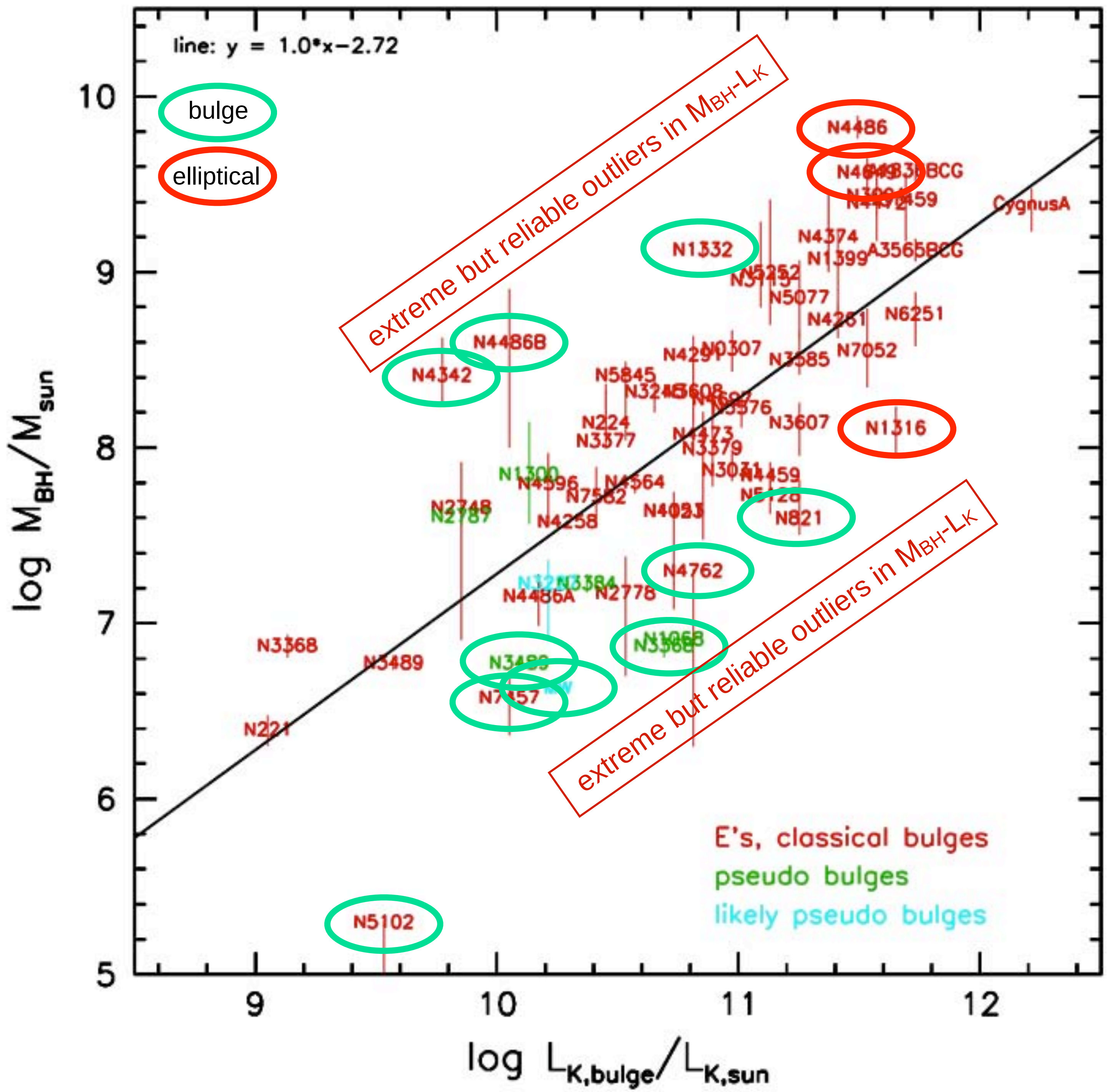
Supermassive Black Holes do not correlate with dark matter halos

Kormendy & Bender, Nature, Jan. 2011



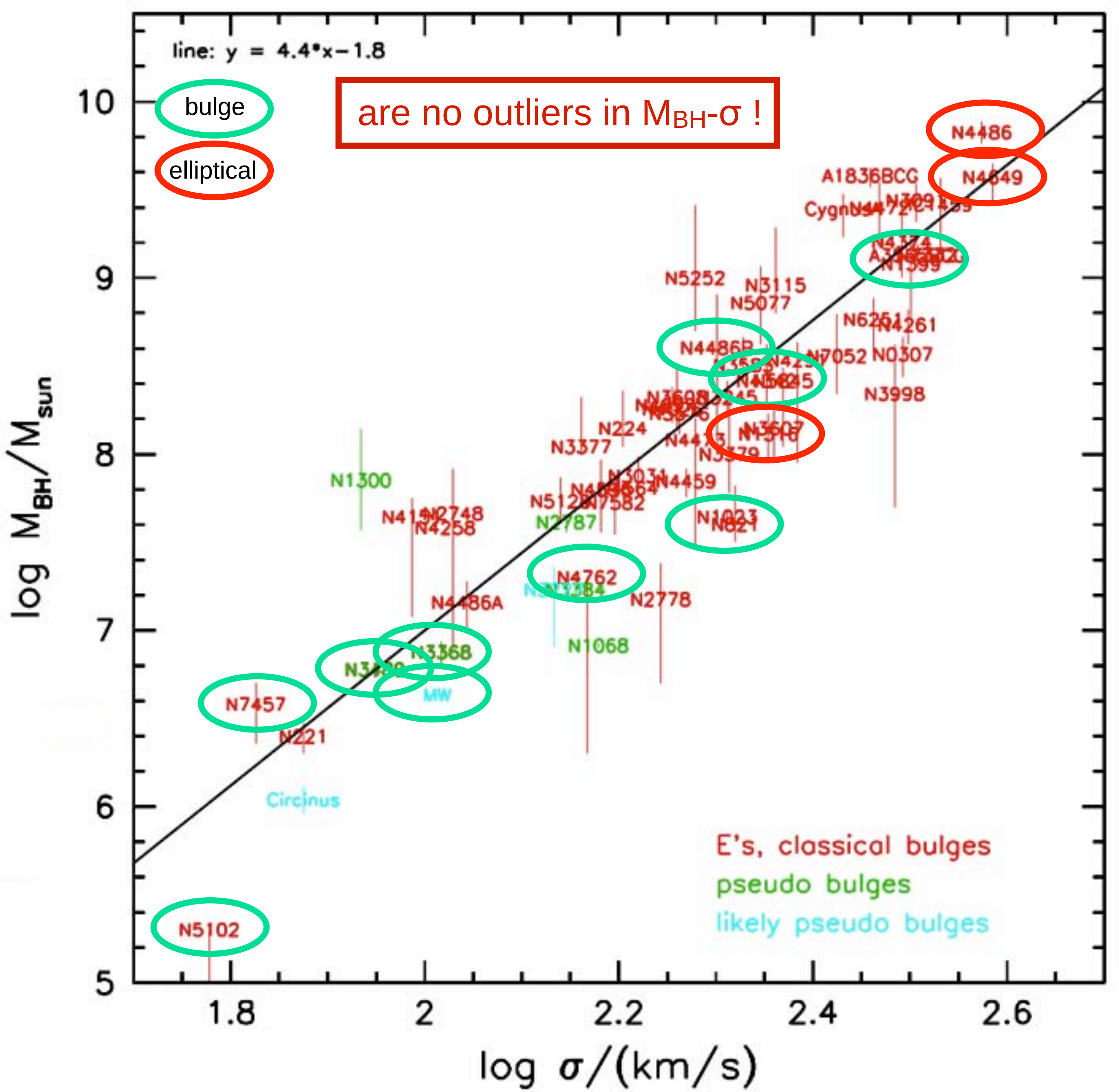
$M_{BH} \sim \sigma^{4.4}$

no disks, no nuclei in this diagram



Bender et al. 2011

no disks, no nuclei in this diagram



Bender
et al. 2011

Conclusions

- Black Holes do not correlate with disk luminosity
- Black Holes do not correlate with Dark Halo circular velocity
- Black Holes do not correlate with pseudo-bulge components,
a decomposition in a classical and a pseudo-bulge component moves objects closer to the M_{BH}-L relation: ➜ secular evolution may grow bulges outside the center and let their L_K grow more than M_{BH} (lack of gas implied?). Situation with respect to M_{BH}-σ relation is still unclear.
- The evidence that barred galaxies fall below M_{BH}-σ is contradictory.
- Black Holes correlate best with classical bulge/elliptical properties.
- The scatter in the M_{BH}-L_K (and M_{BH}-M_{gal}) relation is larger than in the M_{BH}-σ relation.
- Galaxies with higher spheroid density at a given L_K have larger M_{BH}.
- *In general,* M_{BH}-σ still seems to be the most *useful* predictor for M_{BH}.