Nearby Galaxies and their Black Holes

- Black Holes and Dark Matter
- Black Holes and Disks, Bars & Pseudo-Bulges
- Black Holes and Classical Bulges & Ellipticals
- Which Black Hole Correlation is the Tightest?

Ralf Bender and John Kormendy,
and the SINFONI-BH team:
Peter Erwin, Max Fabricius, Felix Klein, Nina Nowak,
Stefanie Rusli, Roberto Saglia, Jens Thomas

Do Black Holes Correlate With Dark Matter Halos?

BEYOND THE BULGE: A FUNDAMENTAL RELATION BETWEEN SUPERMASSIVE BLACK HOLES AND DARK MATTER HALOS

LAURA FERRARESE
Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854; lff@physics.rutgers.edu
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ABSTRACT

The possibility that the masses M_{BH} of supermassive black holes (SBHs) correlate with the total gravitational mass of their host galaxy, or the mass M_{DM} of the dark matter halo in which they presumably formed, is investigated using a sample of 16 spiral and 20 elliptical galaxies. The bulge velocity dispersion σ_c, typically defined within an aperture of size $R \lesssim 0.5$ kpc, is found to correlate tightly with the galaxy's circular velocity v_c, the latter measured at distances from the Galactic center at which the rotation curve is flat, $R \sim 20$–80 kpc. By using the well-known M_{BH}-σ_c relation for SBHs and a prescription to relate v_c to the mass of the dark matter halo M_{DM} in a standard ΛCDM cosmology, the correlation between σ_c and v_c is equivalent to one between M_{BH} and M_{DM}. Such a correlation is found to be nonlinear, with the ratio M_{BH}/M_{DM} decreasing from 2×10^{-4} for $M_{DM} \sim 10^{14}\ M_\odot$ to 10^{-5} for $M_{DM} \sim 10^{12}\ M_\odot$. Preliminary evidence suggests that halos of mass smaller than $\sim 5 \times 10^{11}\ M_\odot$ are increasingly less efficient at forming SBHs—perhaps even unable to form them.

$v_c \approx 150$ km s^{-1}

see also Volonteri et al. 2011, astro-ph 1103.1644

Do Black Holes Correlate With Dark Matter Halos?

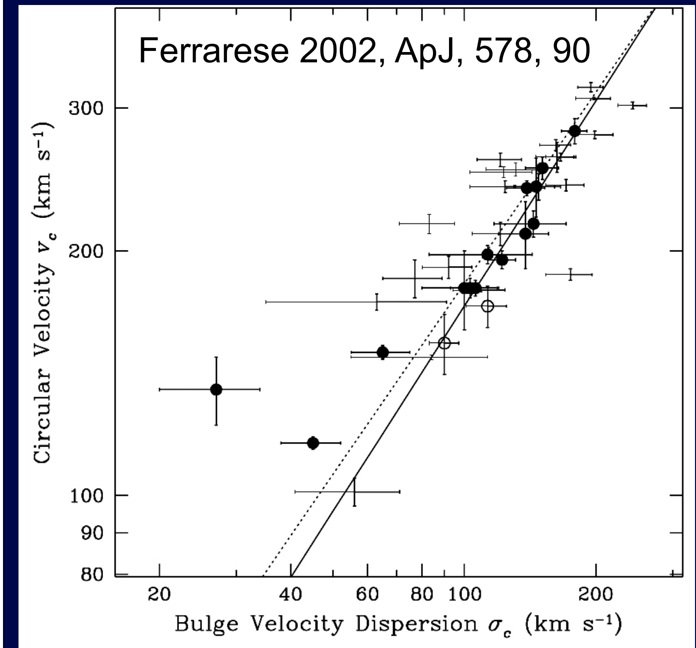


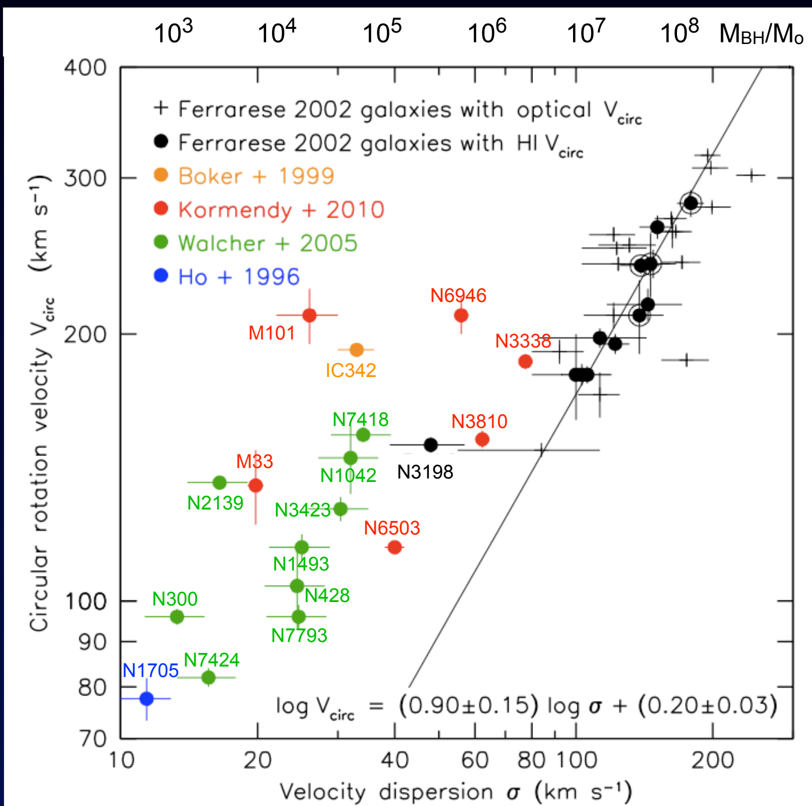
FIG. 1.—Correlation between bulge velocity dispersion σ_c and disk circular velocity v_c for a sample of 37 galaxies with either optical (*open circles*) or H I (*filled circles*) rotation curves. Points marked by error bars only correspond to galaxies for which the rotation curves does not extend beyond R_{25}. The galaxy to the far left, with the smallest value of σ_c, is NGC 598. The solid line corresponds to a fit to all galaxies with $\sigma_c > 70$ km s^{-1} and $R(v_c)/R_{25} > 1.0$. The dotted line corresponds to the fit to all galaxies, with the only exclusion of NGC 598.

The suggested M_{BH} - M_{DM} correlation is based on this correlation between outer disk rotation velocity and bulge velocity dispersion.

Almost all black objects at $V_{circ} \geq 150$ km/s contain bulges ! the bulges take part in the halo-disk-bulge conspiracy and thus V_{circ} and σ are correlated.

Best test to check whether bulges or dark matter drive this relation are Scd galaxies (with nuclei) but no bulges or pseudo-bulges.

Do Black Holes Correlate With Dark Matter Halos?



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

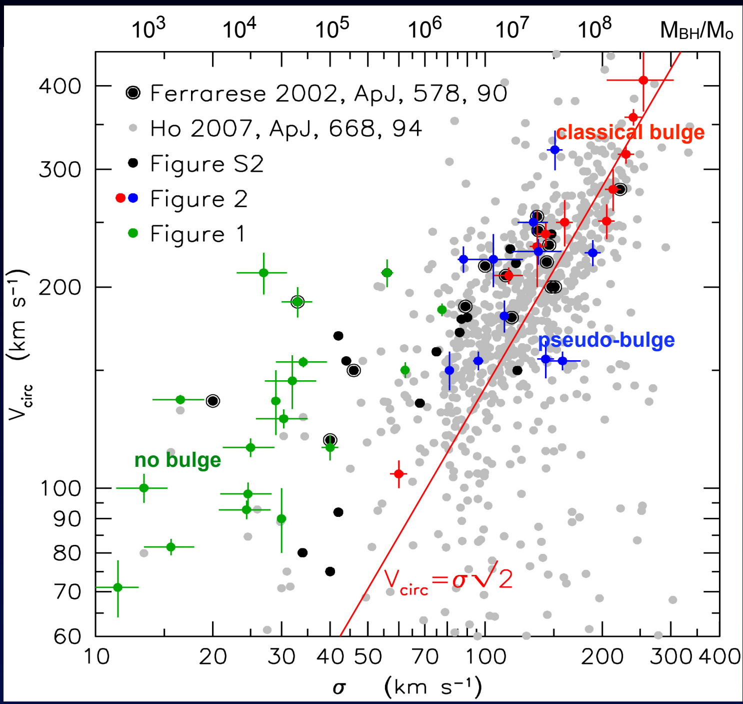
almost all black objects at $V_{circ} \geq 150$ km/s contain bulges ! the bulges take part in the halo-disk-bulge conspiracy and thus V_{circ} and σ are correlated.

(circled points are classical bulges)

Kormendy & Bender, Nature, Jan. 2011

Note: IC 342 velocity dispersion of Ferrarese (77 km/s) replaced by correct value of Boker et al. (33 km/s); likewise, M33 corrected from 27 km/s to 20 km/s.

Black Holes do **NOT** correlate with dark matter halos!



$M_\bullet - \sigma_{bulge}$ correlation is different for galaxies with and without bulges:

For pure-disk galaxies,

if $\sigma_{nucleus}$ is surrogate for $M_\bullet$, then $M_\bullet$ does not correlate with disk V_c;

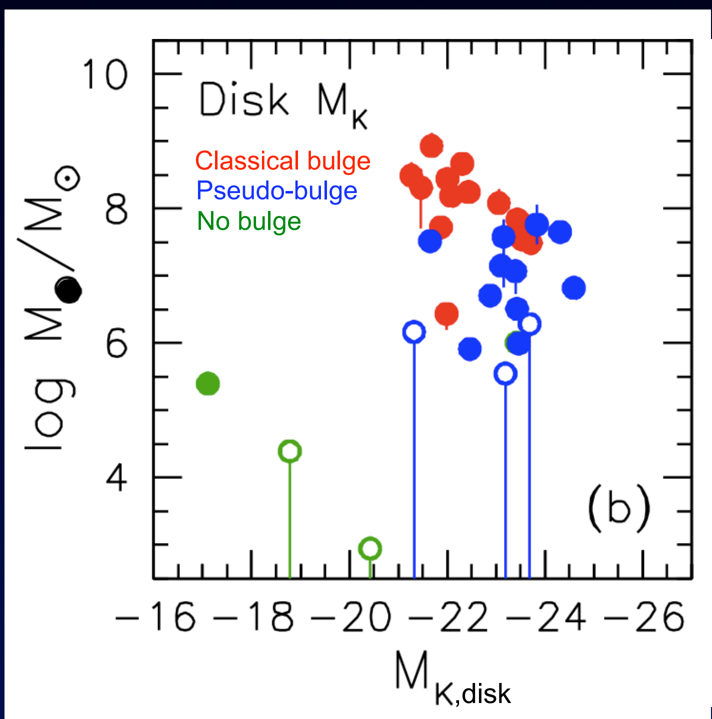
if $\sigma_{nucleus}$ is not surrogate for $M_\bullet$, then $M_\bullet$ demographics are different for that reason.

Kormendy & Bender, Nature, Jan. 2011

Modern data ⇒ the V_{circ} - σ correlation is anyway not tight enough to imply co-evolution of black holes and dark matter.

Supermassive Black Holes do not correlate with galaxy disks.

Kormendy & Gebhardt, Texas Symp. 2001 .... Kormendy, Bender & Cornell, Nature 2011



Disks and Dark Matter halos
do not correlate with black holes,

while classical bulges and ellipticals do.
(more on that later ...)

What about pseudo-bulges and bars?
How are they correlated with black holes?

Note: pseudo-bulges are high-density, disky central components in S+S0 galaxies that were grown out of the disk by “bar”-driven secular evolution, not by major mergers (Kormendy & Kennicutt, ARAA 2004).

Thus, one may expect that barred galaxies and pseudo-bulge galaxies show similar behaviour in the black hole-galaxy correlations. However, note that barred galaxies and pseudo-bulge galaxies are not identical!

Do barred galaxies and pseudo-bulges fall below the M_{BH}-σ relation?

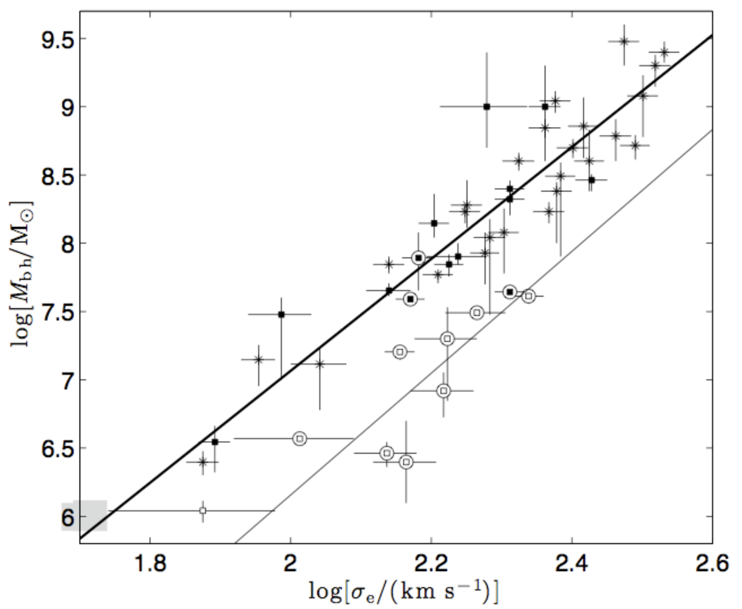


Figure 4. Comparison of the $M_{\rm bh}$-σ_e relation for elliptical galaxies (stars), classical bulges (filled squares), and pseudobulges (open squares). The barred disk galaxies are marked by circles. The thick and thin solid lines are the best fit results for the early-type bulges and the pseudobulges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

J. Hu (2008) concludes that barred galaxies and pseudo-bulges fall below the M_{BH}-σ relation....

Greene, Ho & Barth (2008) similarly find that M_{BH}-σ is different for Es and pseudo-bulges.

small caveat: could velocity dispersions for bulges be over-estimated due to the presence of a bar?

(Note: pseudo-bulges and bars are not the same!)

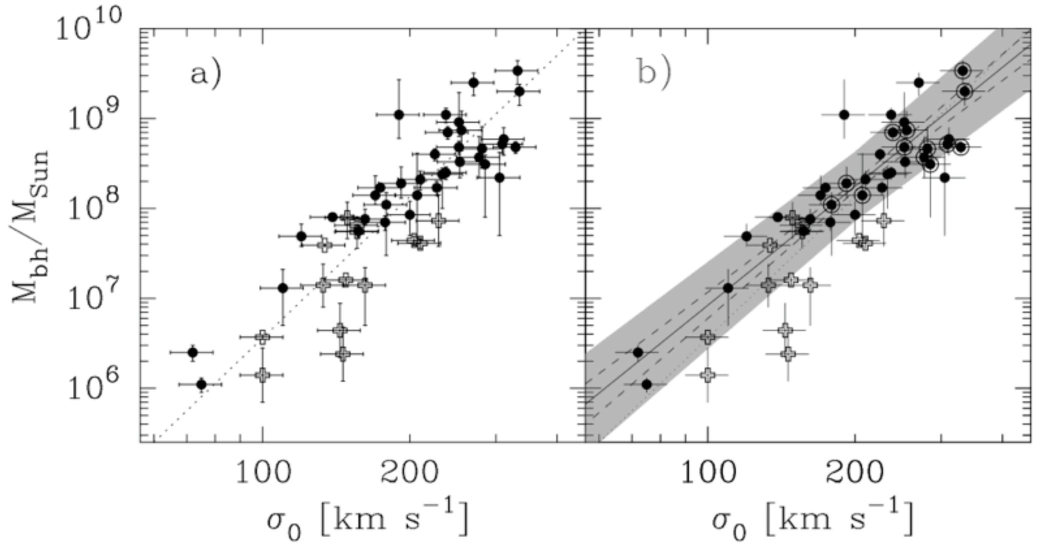


Figure 1: 50 galaxies in the M_{bh}-σ_0 diagram (see Table 1). The 14 barred galaxies are denoted by the crosses. Known "core galaxies" have been circled in panel b). The solid line is the optimal linear regression to the non-barred galaxies, as given by Eq. 1, while the dashed lines delineate the 1σ 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.

Graham (2008, 2009) also finds that barred galaxies fall below the M_{BH}-σ relation of bulges and ellipticals.

Beifiori et al. (2009) challenge this result using a sample of 105 galaxies with M_{BH} estimated from HST STIS emission line-width (Sarzi et al. 2002 method).

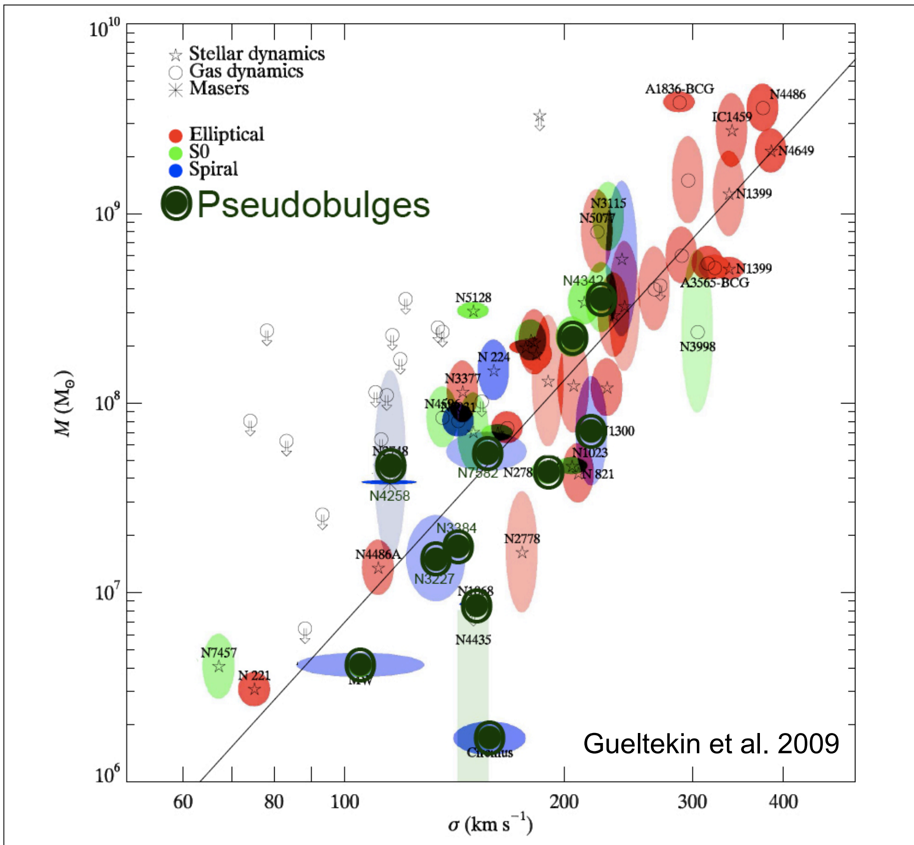
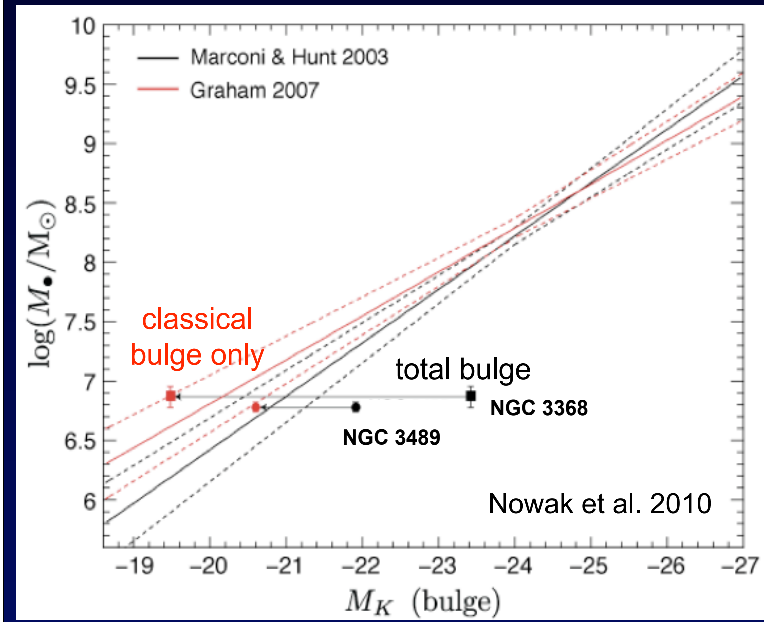


FIG. 1.— The M–σ relation for galaxies with dynamical measurements. The symbol indicates the method of BH mass measurement: stellar dynamical (*pentagrams*), gas dynamical (*circles*), masers (*asterisks*). Arrows indicate $3\sigma_{68}$ upper limits to BH mass. If the $3\sigma_{68}$ limit is not available, we plot it at 3 times the $1\sigma_{68}$ or at 1.5 times the $2\sigma_{68}$ limits. For clarity, we only plot error boxes for upper limits that are close to or below the best-fit relation. The color of the error ellipse indicates the Hubble type of the host galaxy: elliptical (*red*), S0 (*green*), and spiral (*blue*). The saturation of the colors in the error ellipses or boxes is inversely proportional to the area of the ellipse or box. Squares are galaxies that we do not include in our fit. The line is the best fit relation to the full sample: $M_{BH} = 10^{8.12}\ M_\odot(\sigma/200\ \text{km s}^{-1})^{4.24}$.

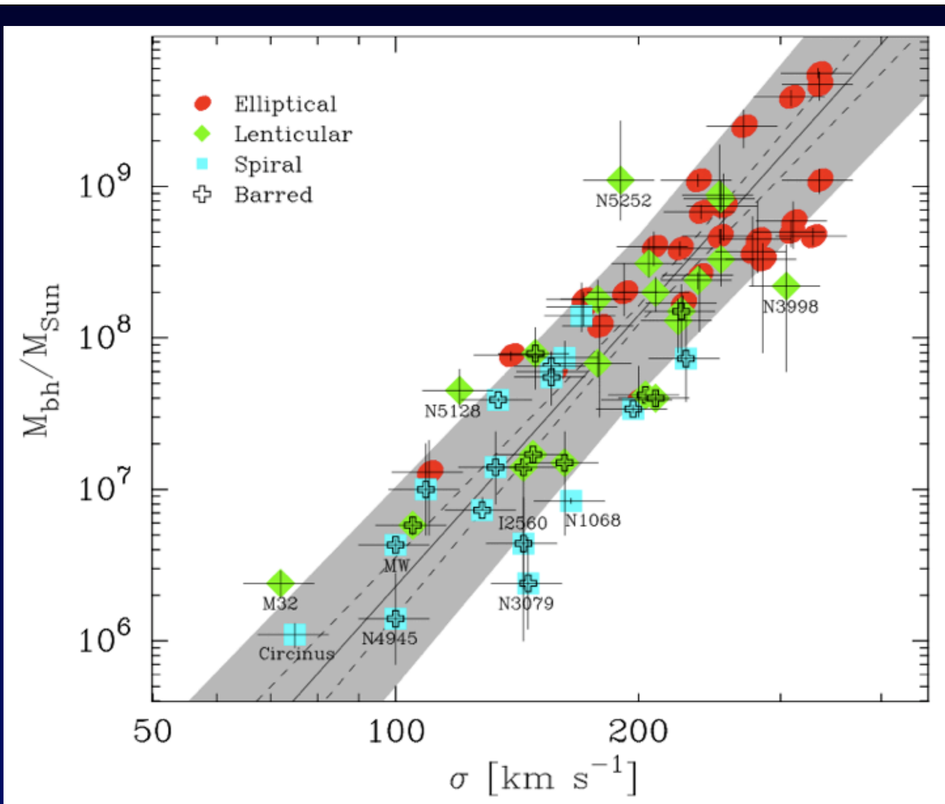
Gueltekin et al. (2009) found an only small offset of pseudo-bulges from classical bulges.

Caveats were that the sample was small, not all bulges were yet classified, and some bulge classifications were uncertain.

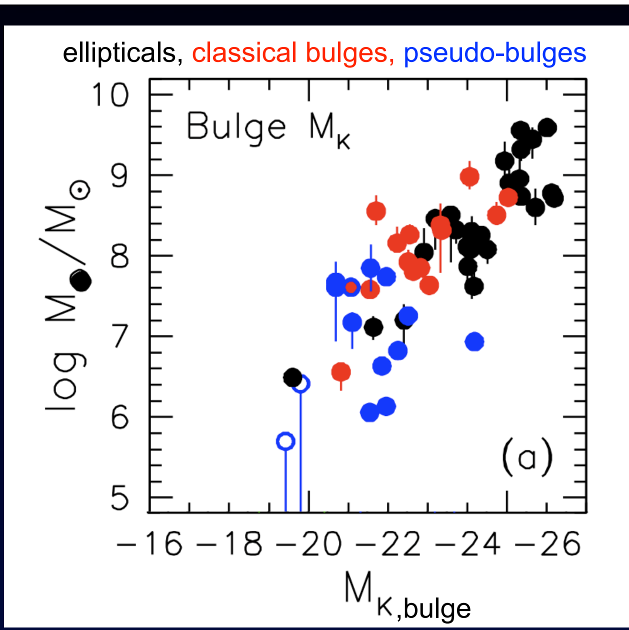
However, no offset is found either with the complete bulge classification for all Gueltekin objects by Kormendy & Bender (2011)



Nowak et al. (2010) find evidence that in two-component bulges, black hole mass may be better correlated with just classical bulge mass, not the total bulge mass including the pseudo-bulge component.



Graham et al 2011: M_{BH} and σ correlate in barred galaxies, but there seems to exist a (small) offset to M_{BH}-σ of classical bulges. The offset depends on the adopted slope of M_{BH}-σ.

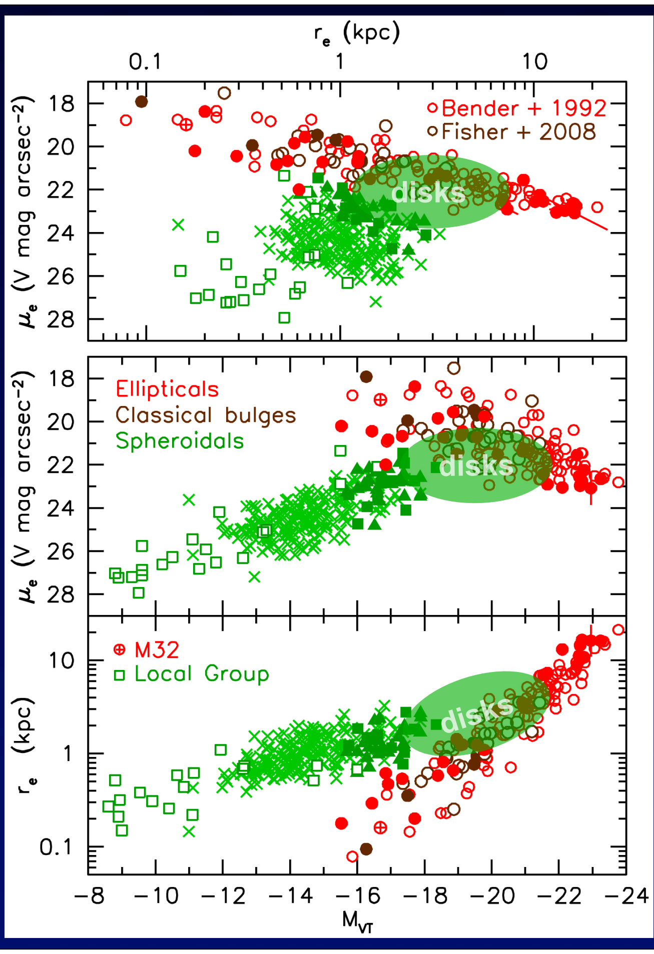


Kormendy, Bender & Cornell (2011) find that Black Holes do not correlate with pseudo-bulges. Even after a careful decomposition the scatter remains large. They suggest that there exist two modes of black hole growth related to different objects:

=> rapid merger driven BH growth leads to coevolution of Es and classical bulges

=> secular, slow growth of BH leads to NO co-evolution with pseudo-bulges/disks

see also Hopkins et al. (2006), Greene, Ho & Barth (2008), Orban de Xivry (2011), ...



In the bulge-elliptical sequence of Wirth & Gallagher (1984), Kormendy (1985, 1987), and Sandage et al. (1985), which corresponds to the merger or gas-stellar sequence of Bender, Burstein & Faber (1992), merger-driven coevolution of bulges/Es and black holes takes place.

In the spheroidal-irregular-disk sequence major mergers are not important (but other processes like Sn-driven winds, stripping etc) and black holes do not co-evolve with galaxy properties, their growth is determined by secular, local processes leading to lower black hole masses and larger scatter.

Kormendy, Fisher, Cornell & Bender 2009,

see also John Kormendy's talk here

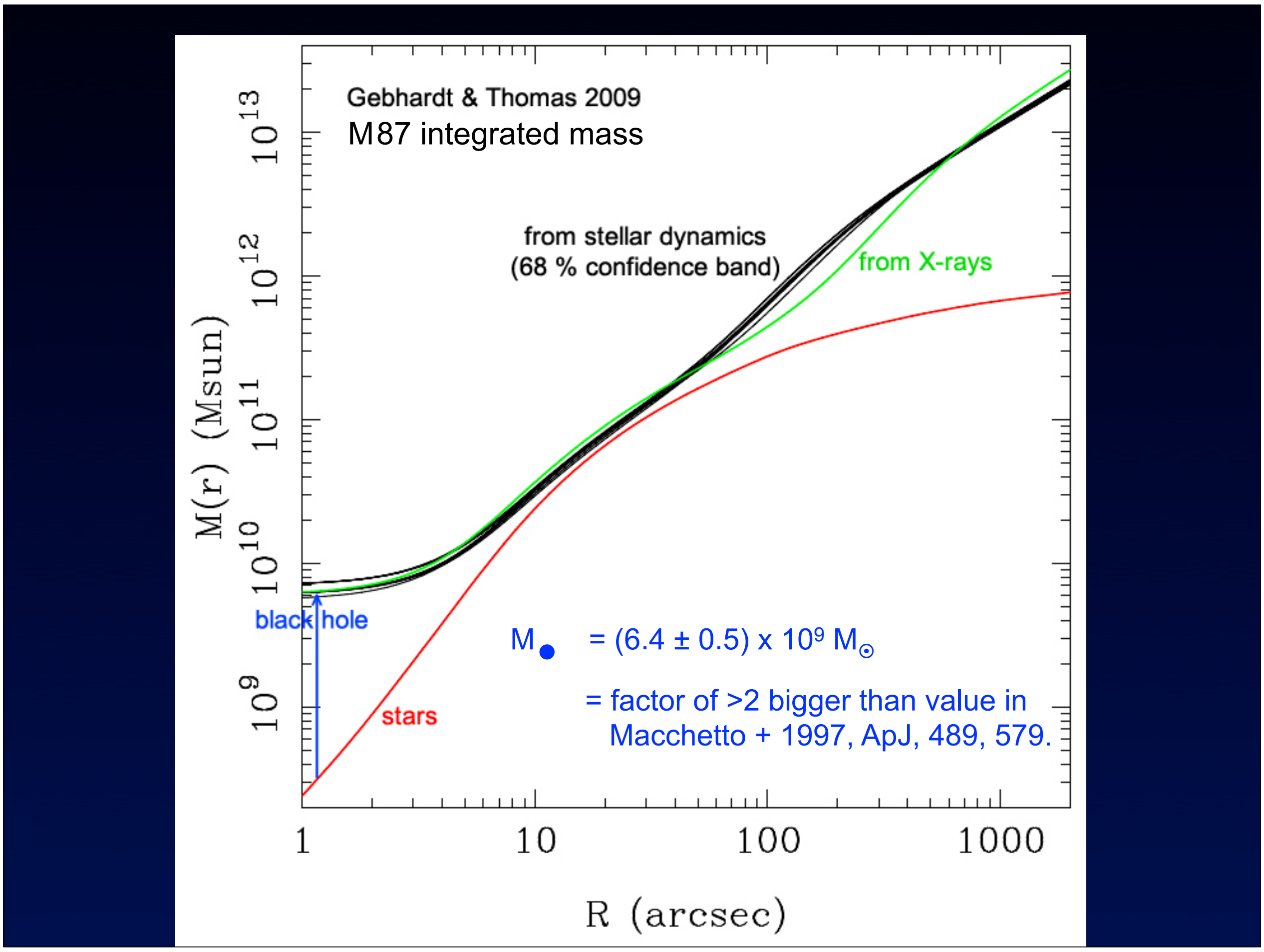
Classical bulges and ellipticals

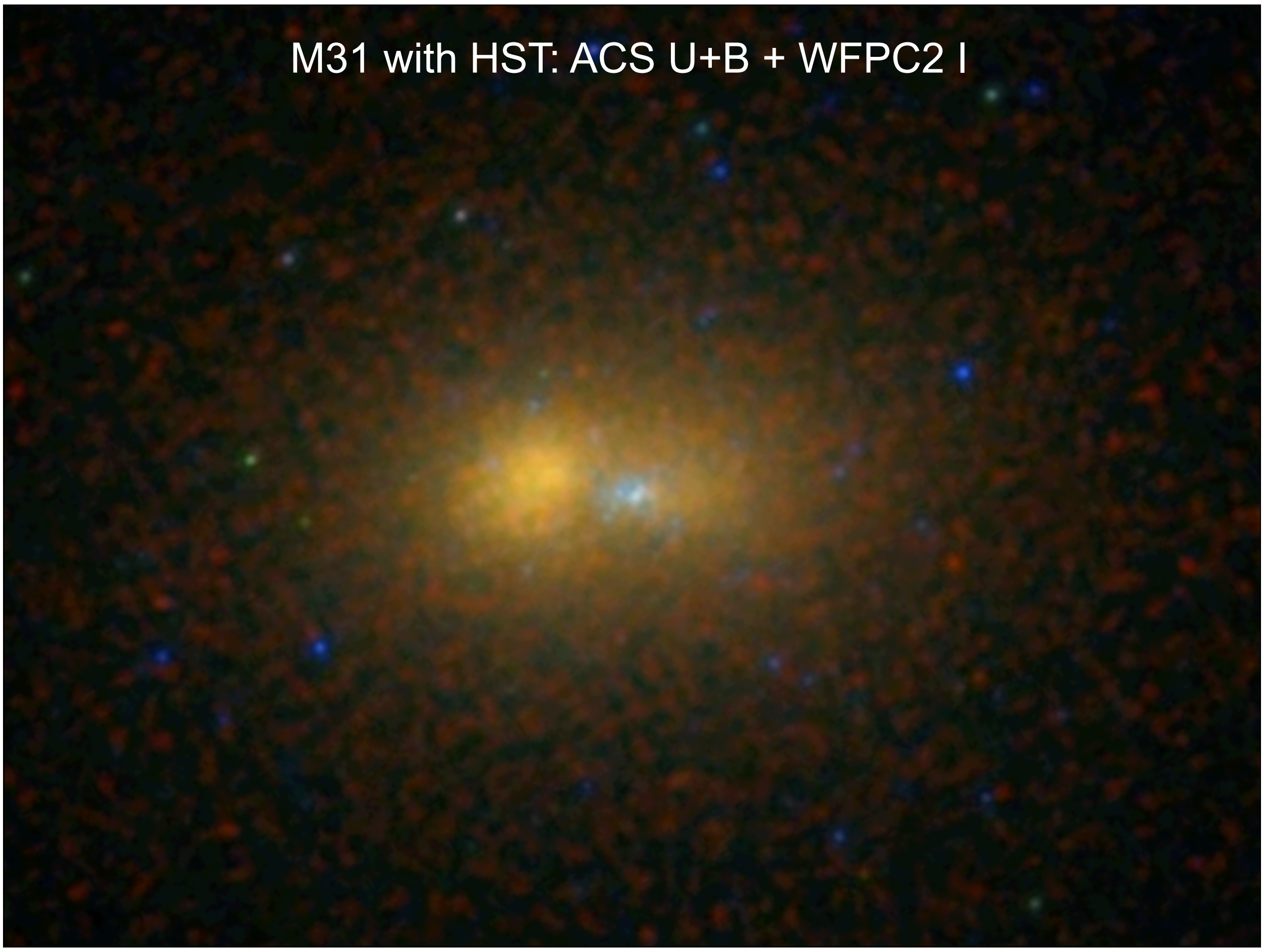
Which parameter correlates best with black hole mass?
(i.e. produces the smallest scatter in BH predictions)

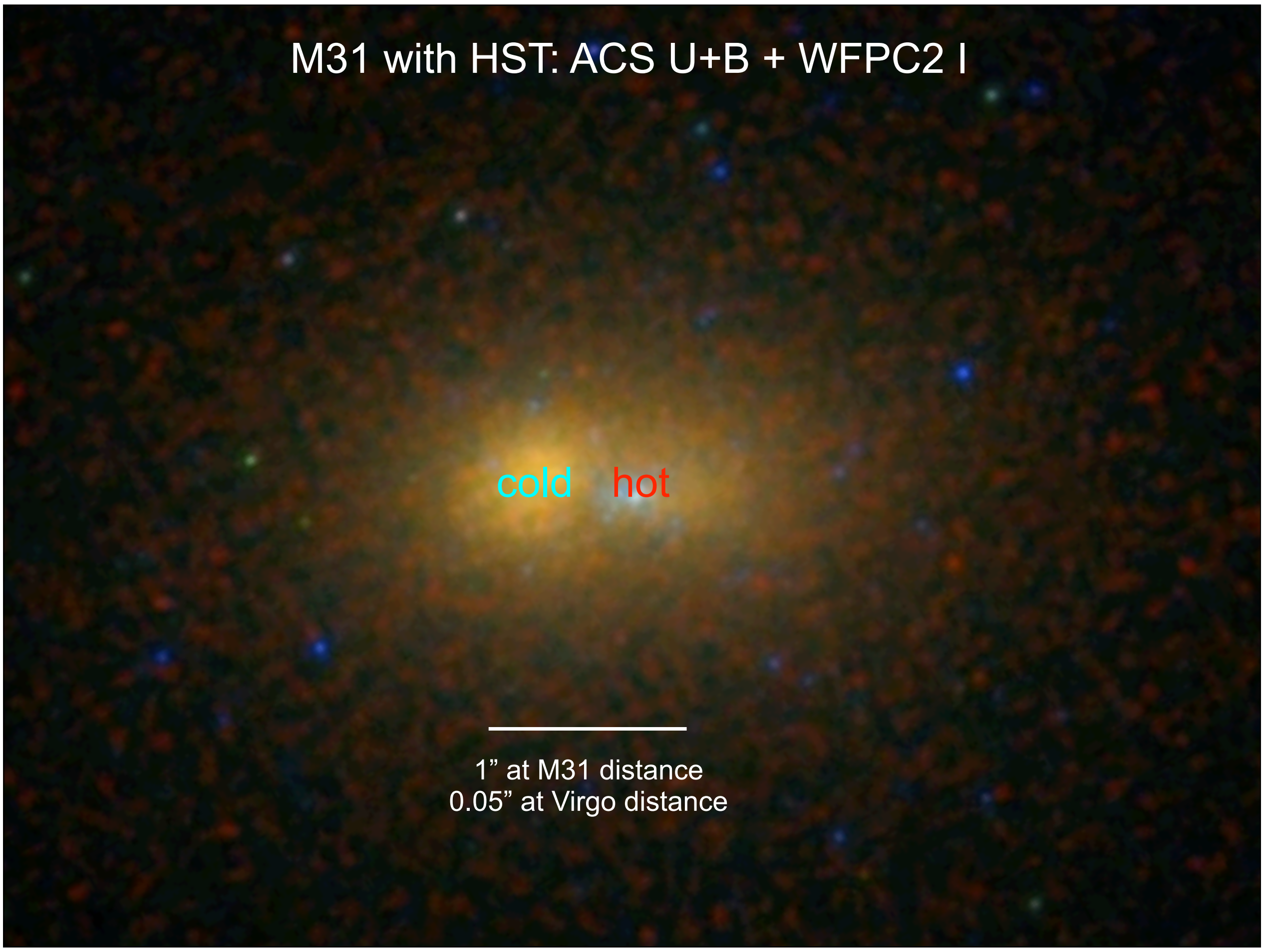
When analysing the various correlations, one needs to keep in mind the following potential limitations:

- technical issues, e.g. LOSVD extraction (R. Houghton's thesis), IFU vs longslit (e.g. Cappellari et al 2010), ...
- triaxiality and/or dynamically too restricted models (van den Bosch & de Zeeuw 2010: M_{BH} of NGC 3379 doubles with triaxial model)
- 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: M_{BH} = 3.7e9 ➜ 6.7e9 (Thomas+Gebhardt 2009); more objects in Schulze & Gebhardt 2010 and 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.
- ...

Thus, because of these systematic effects, it won't be easy to achieve a scatter below ~ 0.3 dex ... 0.2 dex.


Gebhardt & Thomas 2009
M87 integrated mass
from stellar dynamics
(68 % confidence band)
from X-rays
black hole
stars
M● = (6.4 ± 0.5) x 10⁹ M☉
= factor of >2 bigger than value in
Macchetto + 1997, ApJ, 489, 579.
M(r) (Msun)
R (arcsec)
1
10
100
1000


M31 with HST: ACS U+B + WFPC2 I



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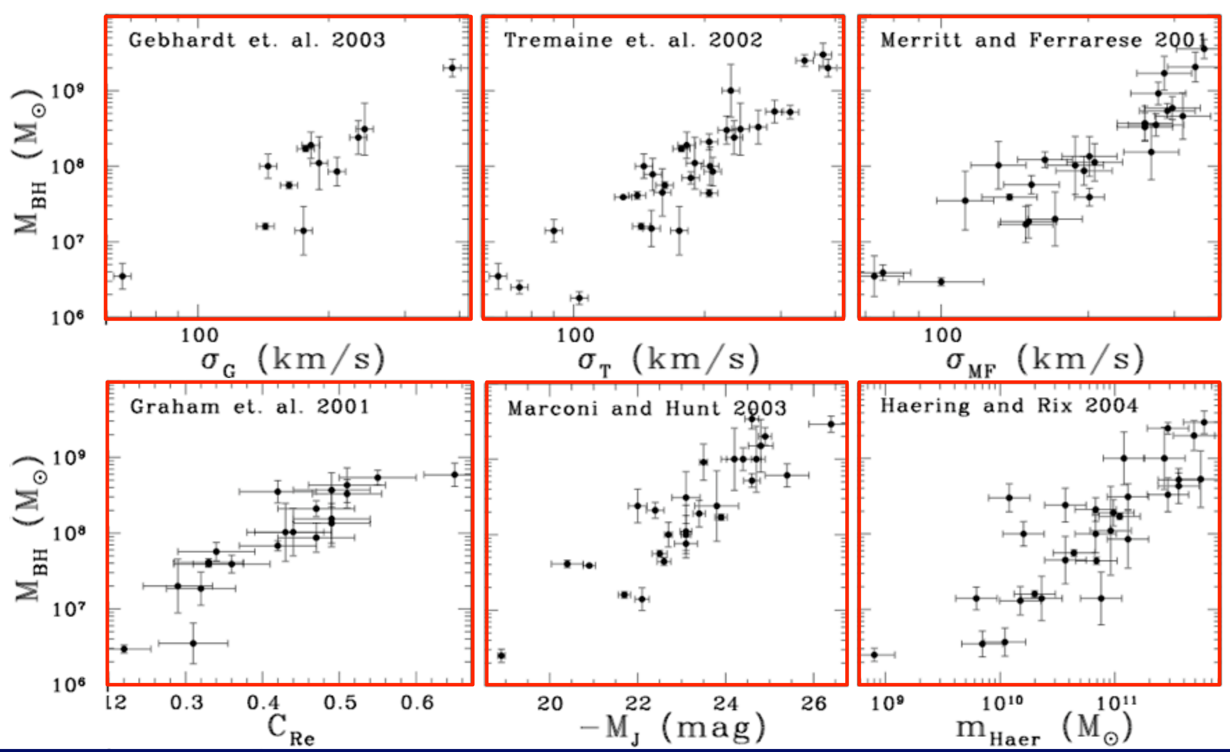
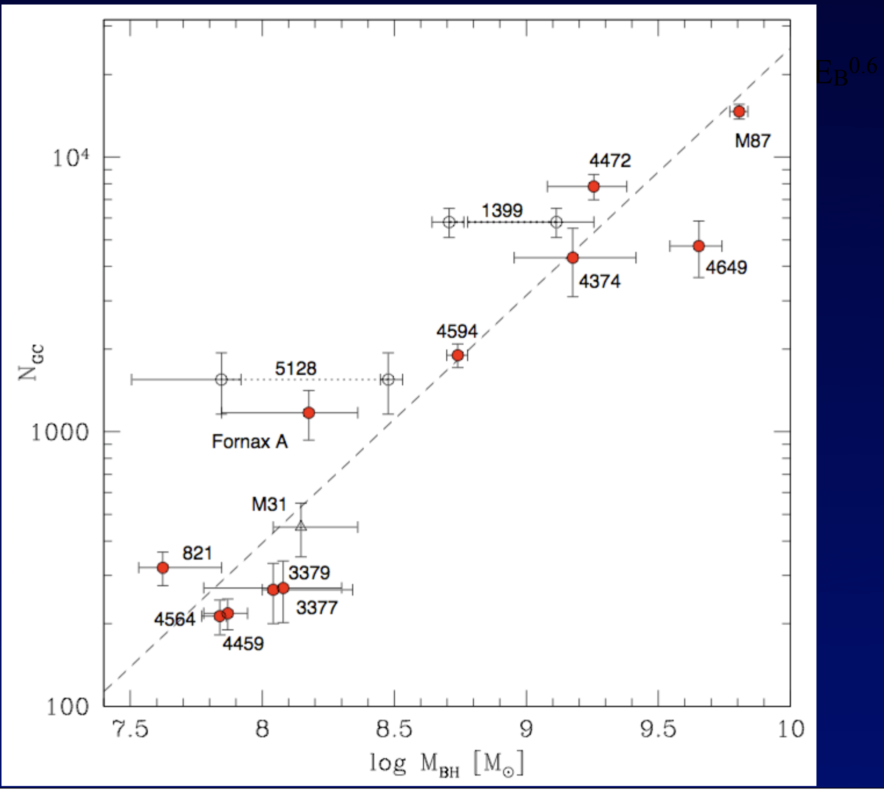
Which bulge parameter is the best M_{BH} predictor?

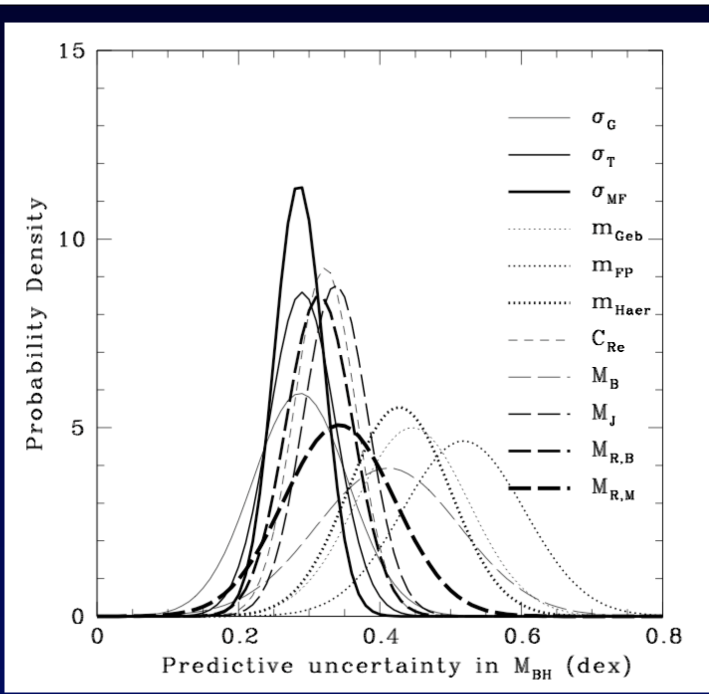


correlation of black hole mass with velocity dispersion and bulge luminosity, bulge mass and concentration parameter for various samples (Novak, Faber & Dekel, 2006)

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, see also Harris & Harris (2011)

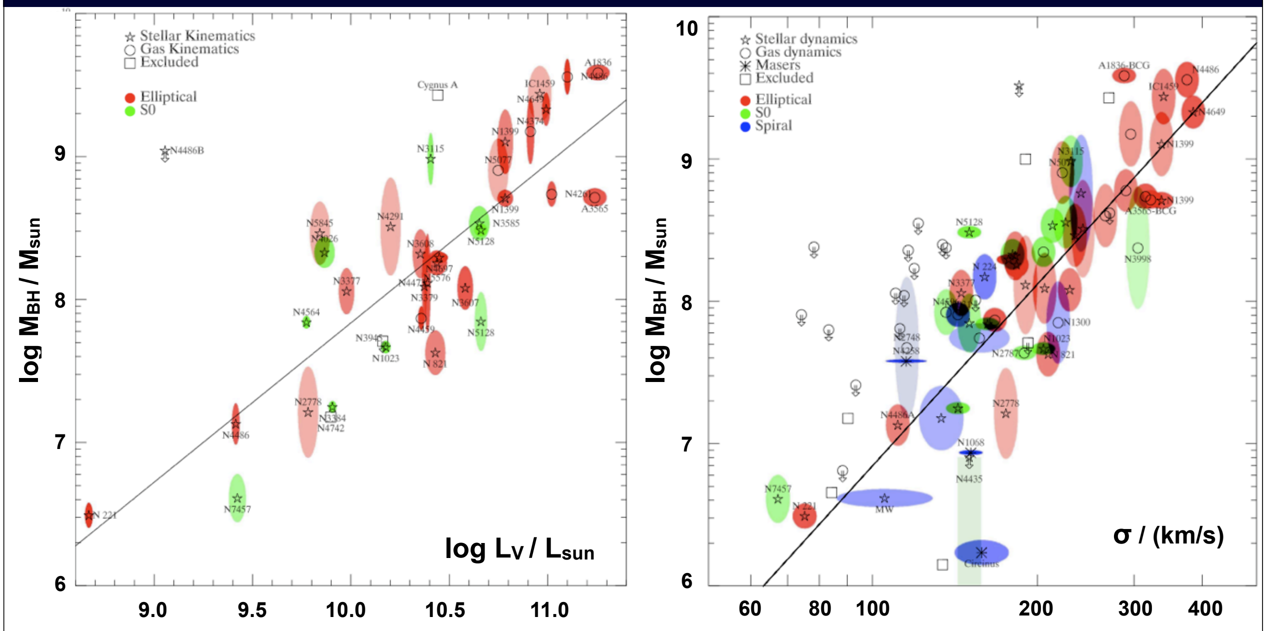




Predictive power of an observable X for M_{BH}. Except for the relations between M_{BH} and σ_{MF} or C_{Re}, which are dominated by measurement errors, all other relations show significant intrinsic scatter.

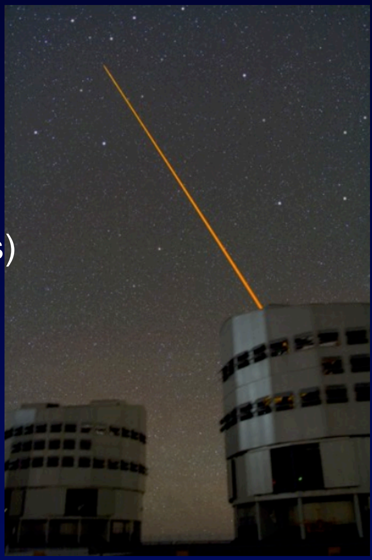
None of the the predictor variables X can predict BH masses to better than 0.3 dex or within a factor 2 (Novak, Faber, Dekel 2006). This is still true today.

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 spiral bulges (but the spiral sub-sample is small and pseudo-bulges are included).
- The scatter in M_{BH}-L_V is 0.38 for ellipticals.
- Graham et al. (2011) reach similar conclusions for M_{BH}-σ with a larger sample.

The VLT-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 objects (e.g. compacts, mergers)
- Find constraints on BH formation/evolution models
- Estimate what is the best M_{BH} predictor: K-luminosity, mass, velocity dispersion or ?

Method:

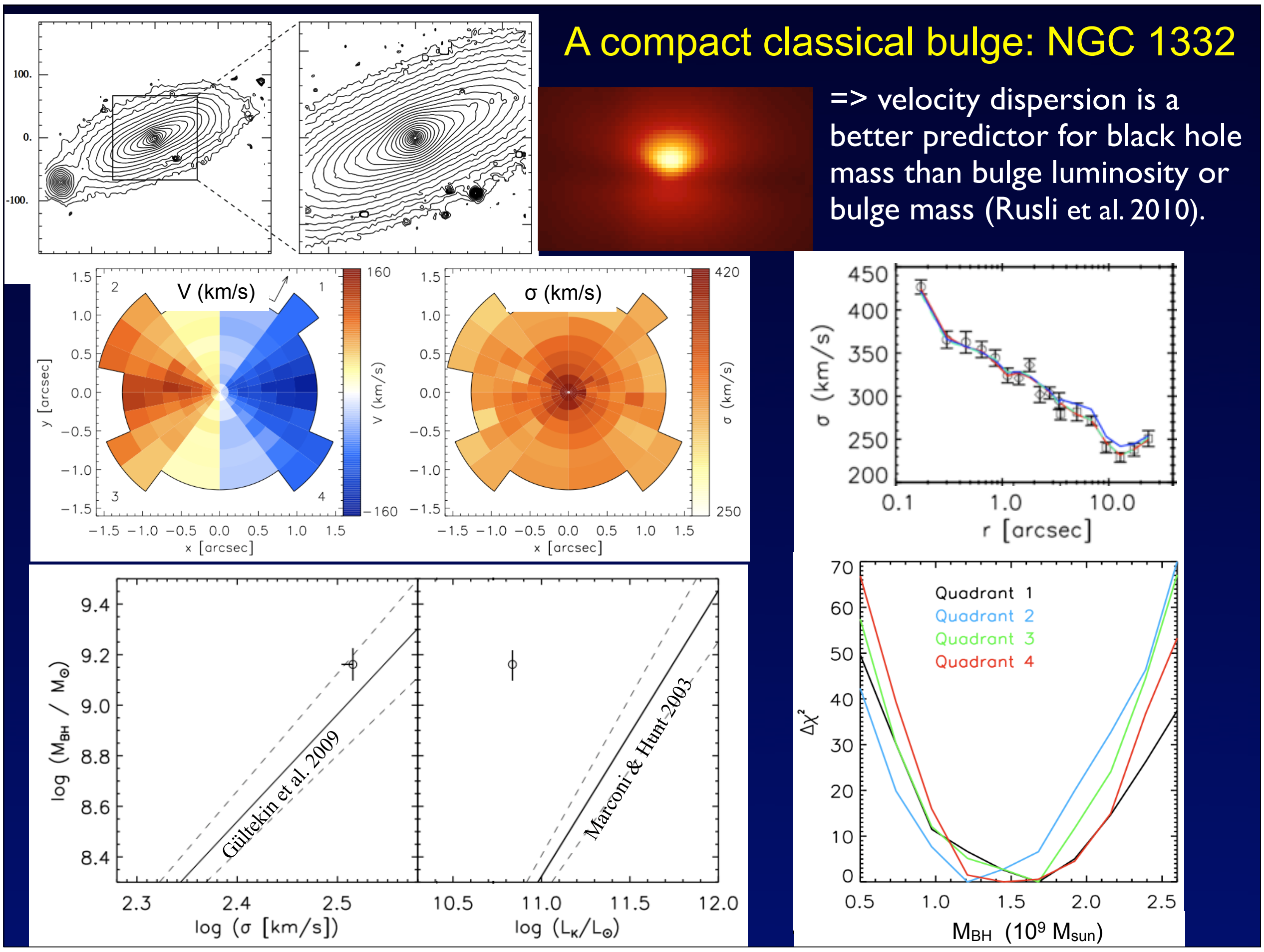
- Use stellar kinematics in NIR (less dust-affected)
- use AO-assisted SINFONI@VLT (more light-collecting power than HST, FWHM~0.1" achievable)
- combine with longslit or 2D (e.g.SAURON) kinematics
- model with axisymmetric Schwarzschild-method

The SINFONI Black Hole Sample

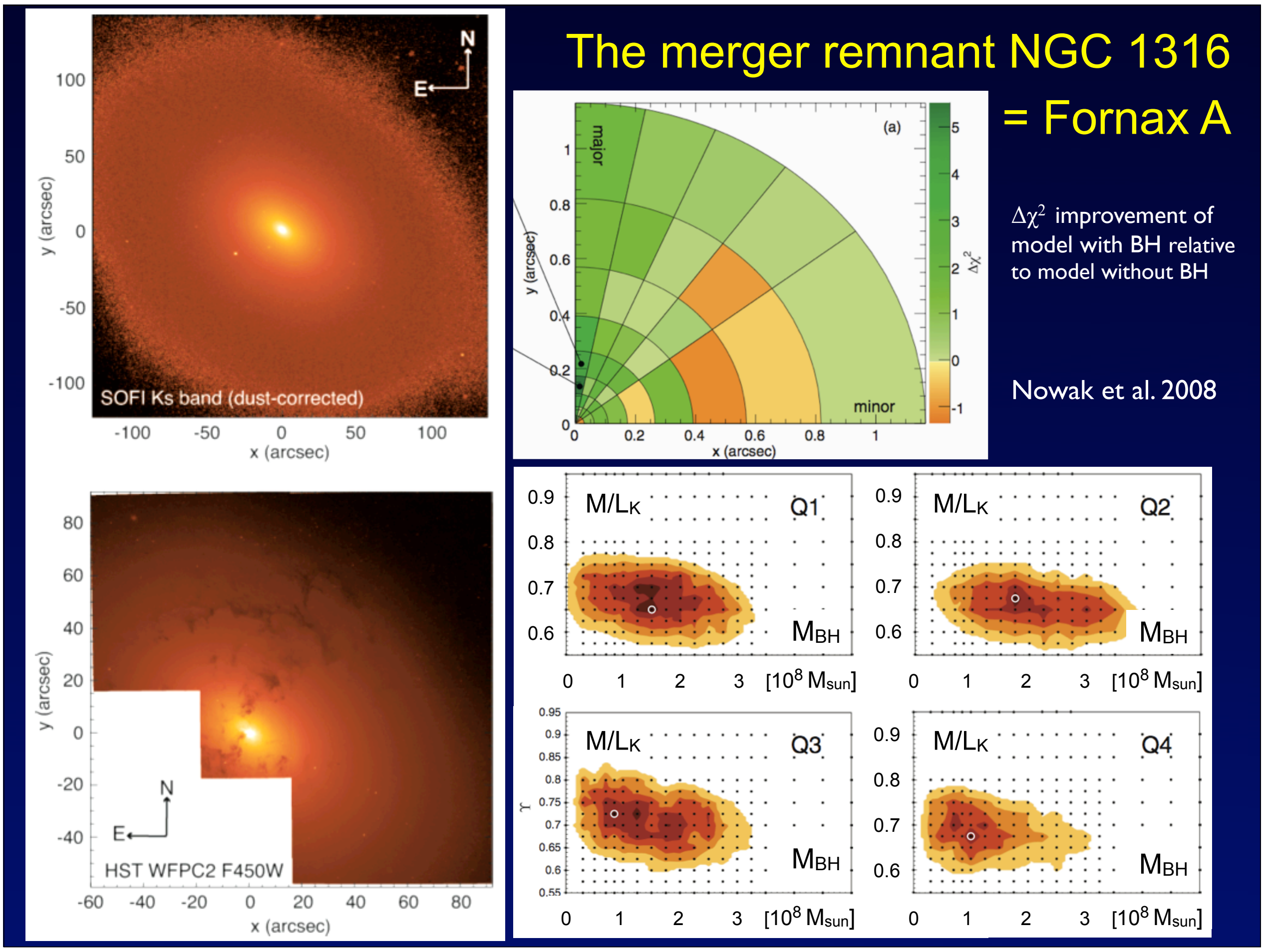
Galaxy	*FWHM (")*
NGC 307	0.20
NGC 1316	0.085
NGC 1332	0.15
NGC 1374	0.13
NGC 1398	0.14
NGC 1407	0.20
NGC 1550	0.17
NGC 3091	0.13
NGC 3137	0.10
NGC 3351	0.18
NGC 3368	0.17
NGC 3412	0.15
NGC 3489	0.08
NGC 3627	0.09
NGC 3923	0.33
NGC 4371	0.14
NGC 4472	0.33

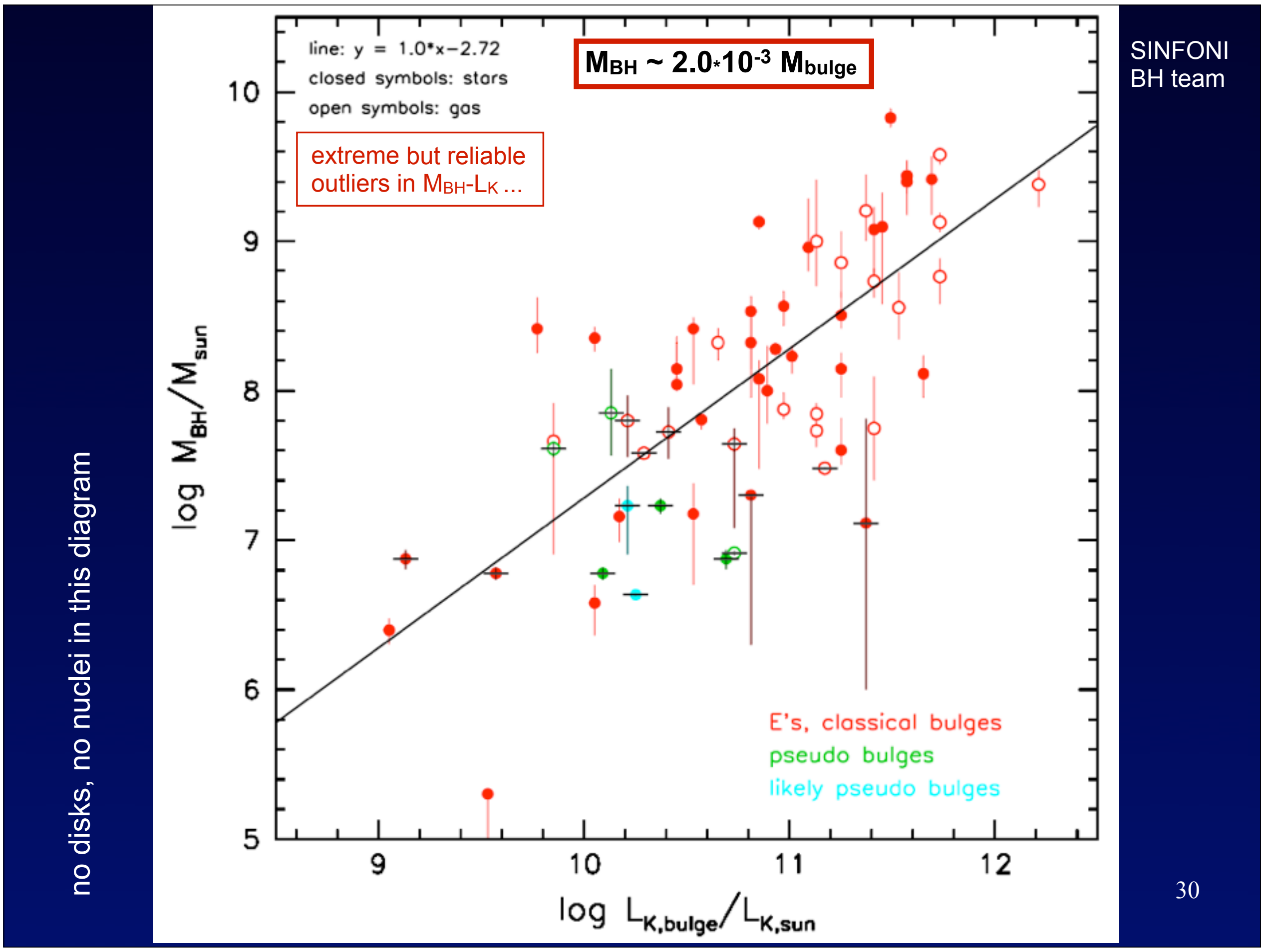
Galaxy	*FWHM (")*
NGC 4486a	0.10
NGC 4486b	0.16
NGC 4501	0.15
NGC 4536	0.18
NGC 4569	0.16
NGC 4579	0.23
NGC 4699	0.10
NGC 4751	0.15
NGC 4762	0.14
NGC 5018	0.15
NGC 5102	0.08
NGC 5328	0.12
NGC 5419	0.19
NGC 5516	0.14
NGC 7619	0.17
ESO 138-5	0.36

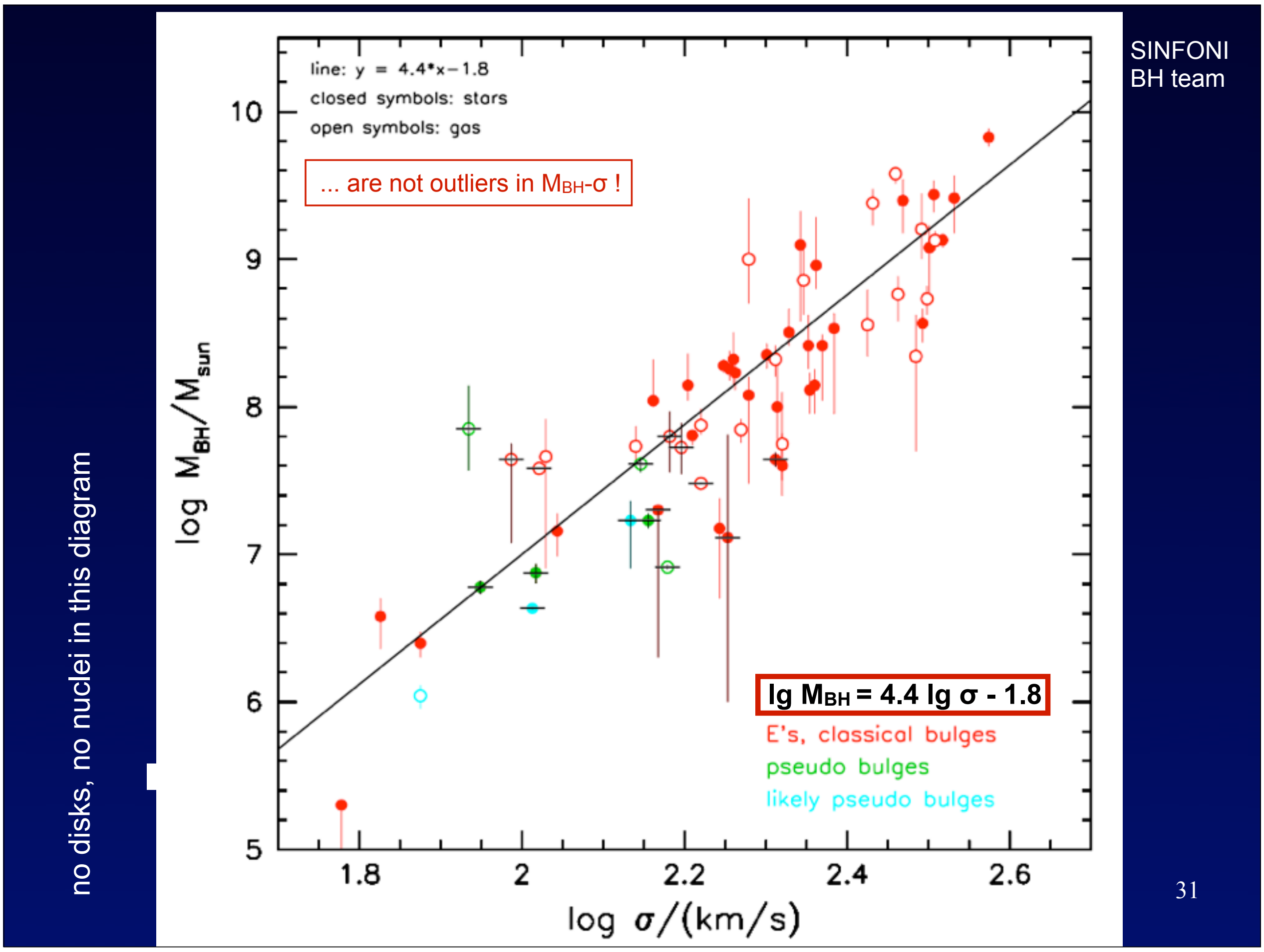
Up to now, good black masses exist for only 50+ galaxies.
We add another ~30 exploring dusty and extreme objects.


A compact classical bulge: NGC 1332
=> velocity dispersion is a better predictor for black hole mass than bulge luminosity or bulge mass (Rusli et al. 2010).
V (km/s)
σ (km/s)
x [arcsec]
y [arcsec]
σ (km/s)
r [arcsec]
Quadrant 1
Quadrant 2
Quadrant 3
Quadrant 4
Δχ²
M_BH (10⁹ M_sun)
log (M_BH / M_⊙)
Gültekin et al. 2009
Marconi & Hunt 2003
log (σ [km/s])
log (L_K/L_⊙)


NGC 1316
wikisky


The merger remnant NGC 1316
= Fornax A
$\Delta\chi^2$ improvement of model with BH relative to model without BH
Nowak et al. 2008
SOFI Ks band (dust-corrected)
HST WFPC2 F450W
y (arcsec)
x (arcsec)
major
minor
M/LK
MBH
Q1
Q2
Q3
Q4
[10^8 Msun]


no disks, no nuclei in this diagram
line: y = 1.0*x−2.72
closed symbols: stars
open symbols: gas
MBH ~ 2.0*10^-3 Mbulge
extreme but reliable outliers in MBH-LK ...
SINFONI BH team
log MBH/Msun
log LK,bulge/LK,sun
E's, classical bulges
pseudo bulges
likely pseudo bulges
30



Conclusions

- Black Holes do not correlate with Dark Halo circular velocity.
- Black Holes do not correlate with disk luminosity or disk mass.
- Black Holes correlate only weakly or not at all with pseudo-bulges.
- The evidence that barred galaxies fall below M_{BH}-σ is contradictory.
- Black Holes correlate best with classical bulges and ellipticals.
- These observations indicate that black hole formation/growth is driven by baryonic physics and is most efficient in violent mergers.
- It is suggested that there exist two modes of BH growth:
  (Kormendy, Bender & Cornell 2011, see also Greene, Ho & Barth 2008, Orban de Xivry 2011...)
  => rapid BH growth in global mergers, likely accompanied by Quasar-like activity, leads to coevolution of bulges and BHs.
  => secular (and intrinsically) driven BH growth in disk galaxies, likely accompanied by Seyfert-type activity, does not lead to co-evolution.
- The scatter of the M_{BH}-$L_{K,bulge}$ (and M_{BH}-M_{bulge}) relation is larger than of the M_{BH}-σ relation, which is about 0.3 dex.
- *In general,* M_{BH}-σ still seems to be the most *useful* predictor for M_{BH}.