UNIVERSITÀ DEGLI STUDI FIRENZE

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

The relation between supermassive black holes and their host galaxies

AGN13

BEAUTY and the BEAST

Alessandro Marconi

Dipartimento di Fisica e Astronomia, Università di Firenze

INAF - Osservatorio Astrofisico di Arcetri

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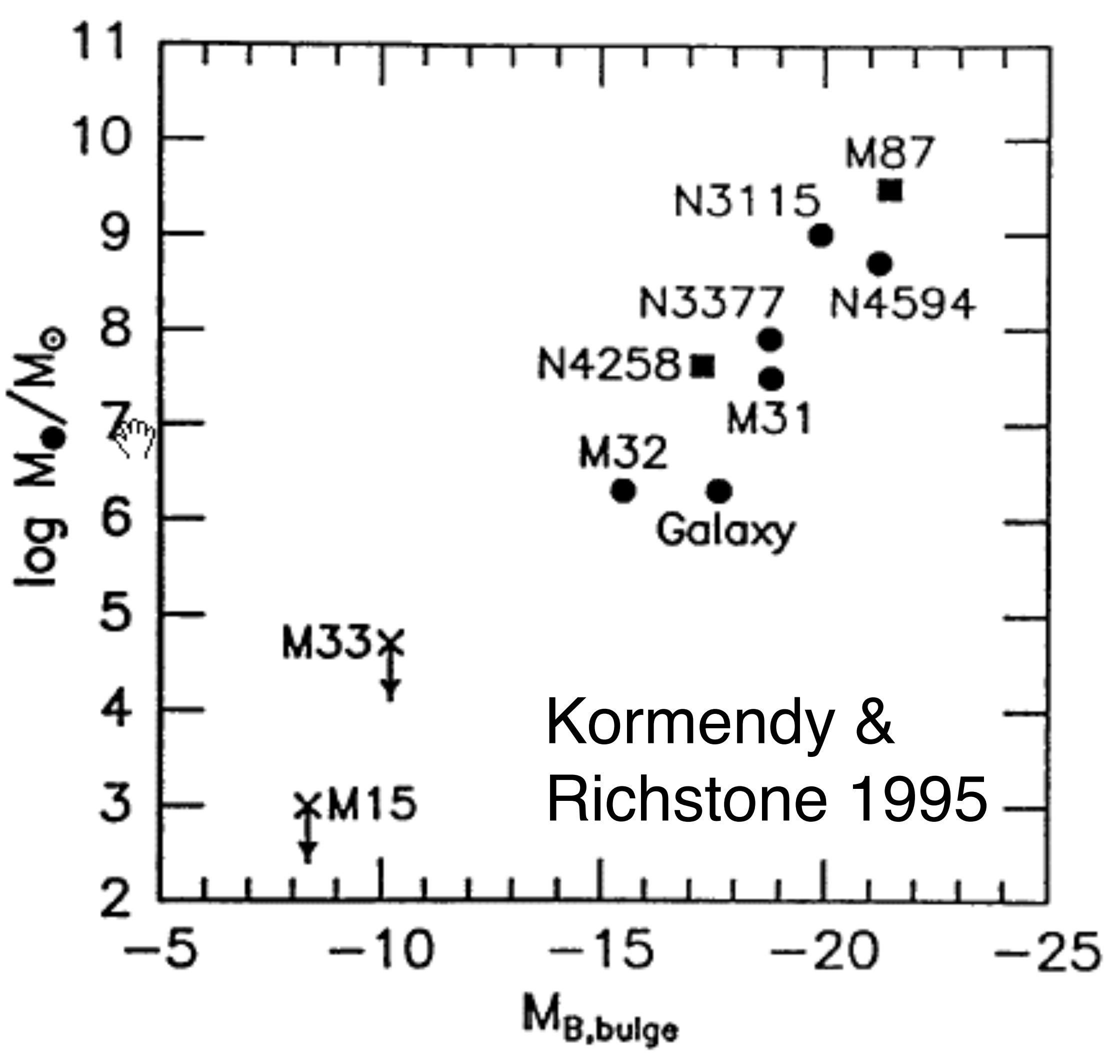
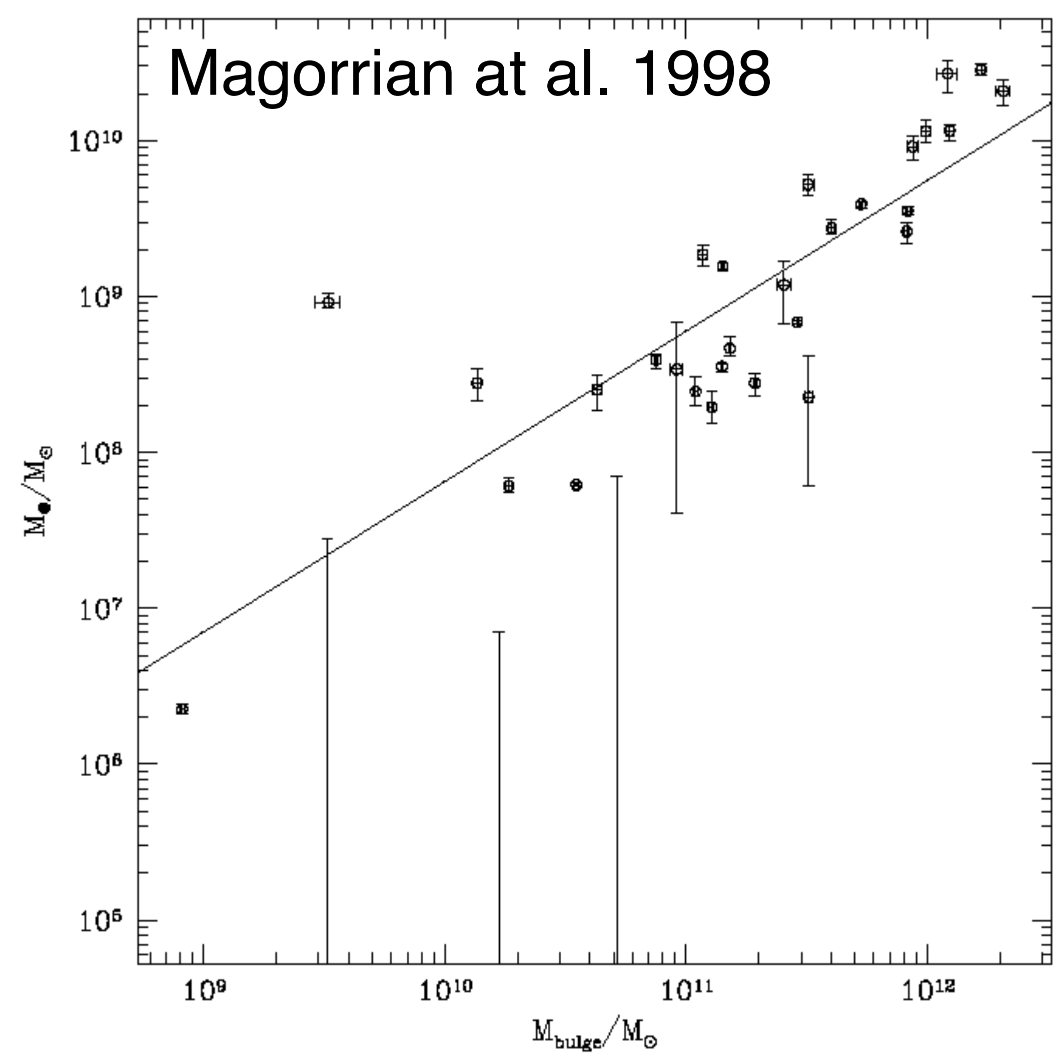
When it all started

Correlations BH - host spheroid

- ⭐ Kormendy & Richstone (1995) suggest M_{BH} vs $L_{B,spher}$
- ⭐ Magorrian at al. (1998) find M_{BH} and M_{spher} (“Magorrian” relation)
  - Low resolution ground based data
  - Most mass estimates overestimated (2-I models)

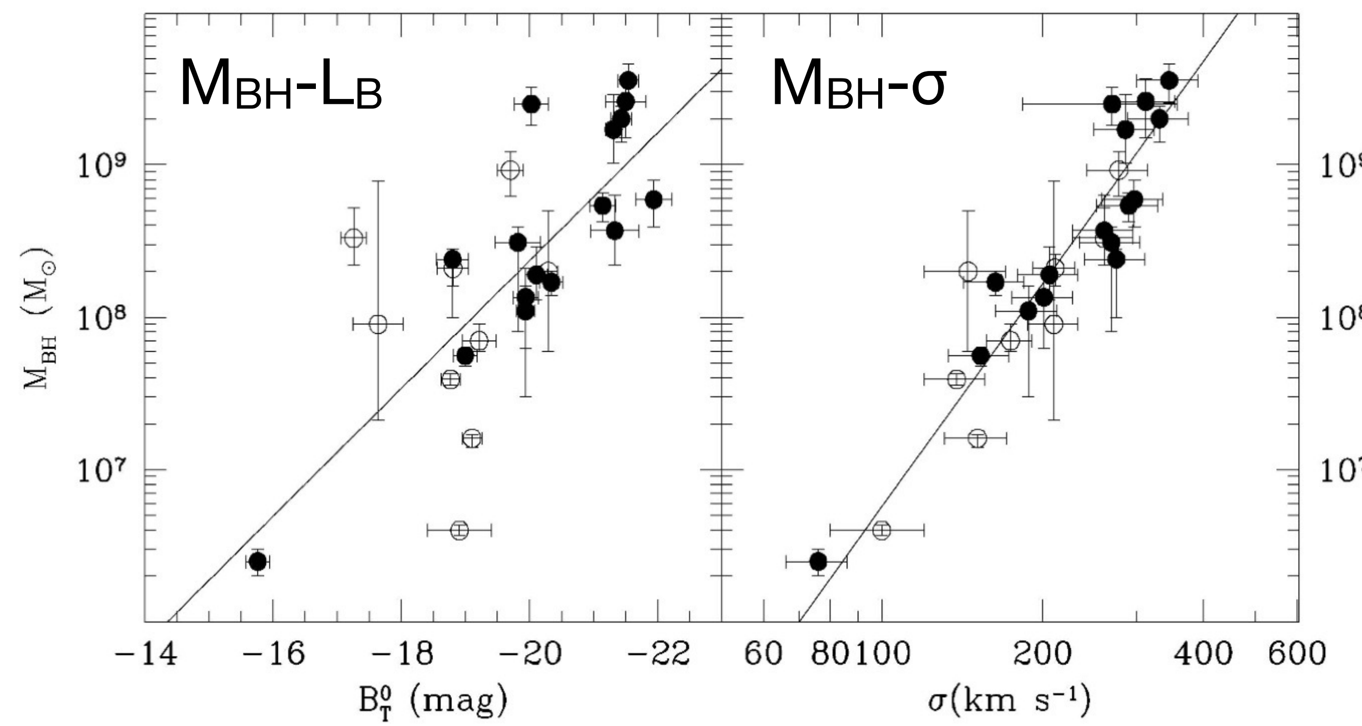




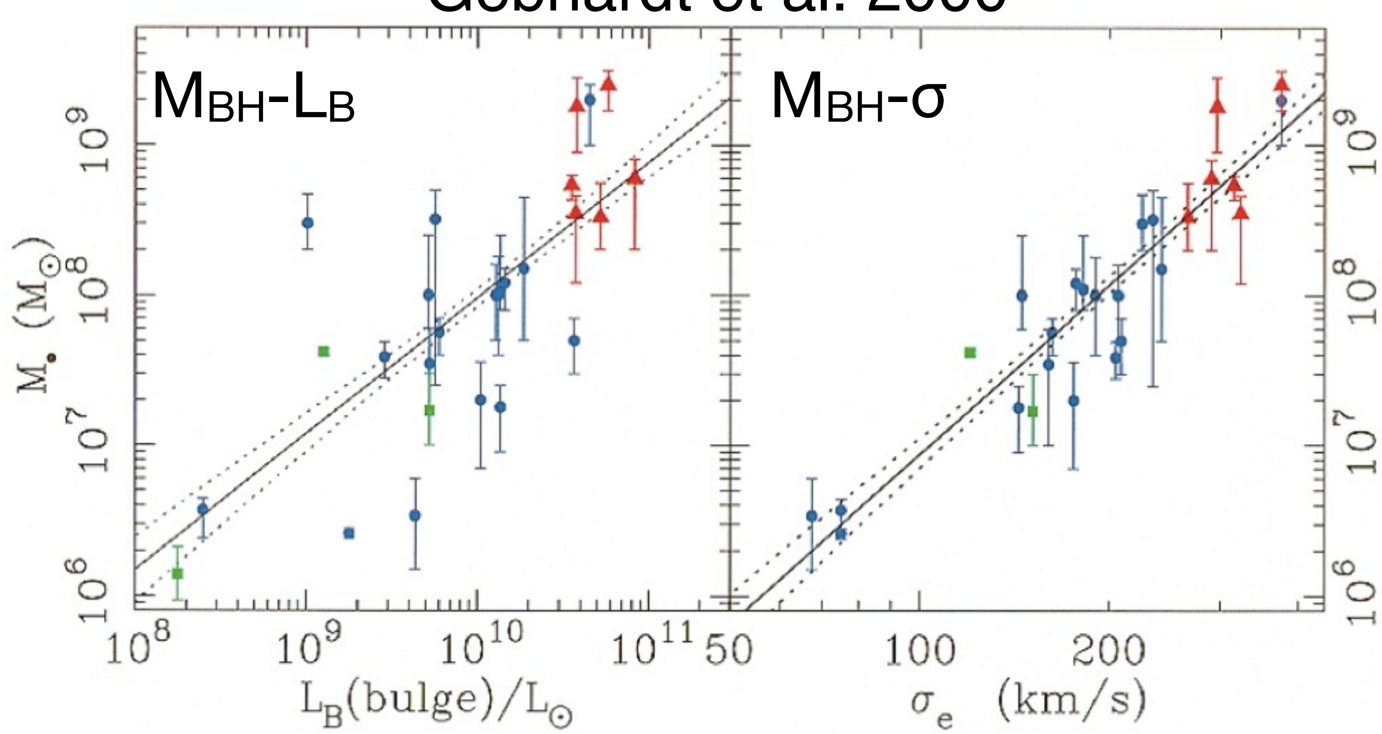
When it boomed

- Two groups independently find tight relation M_{BH} vs σ
- Big and hot debate about the slope $M_{BH} \sim \sigma^5$ (FM00) and $M_{BH} \sim \sigma^4$ (G00)

Ferrarese & Merritt 2000

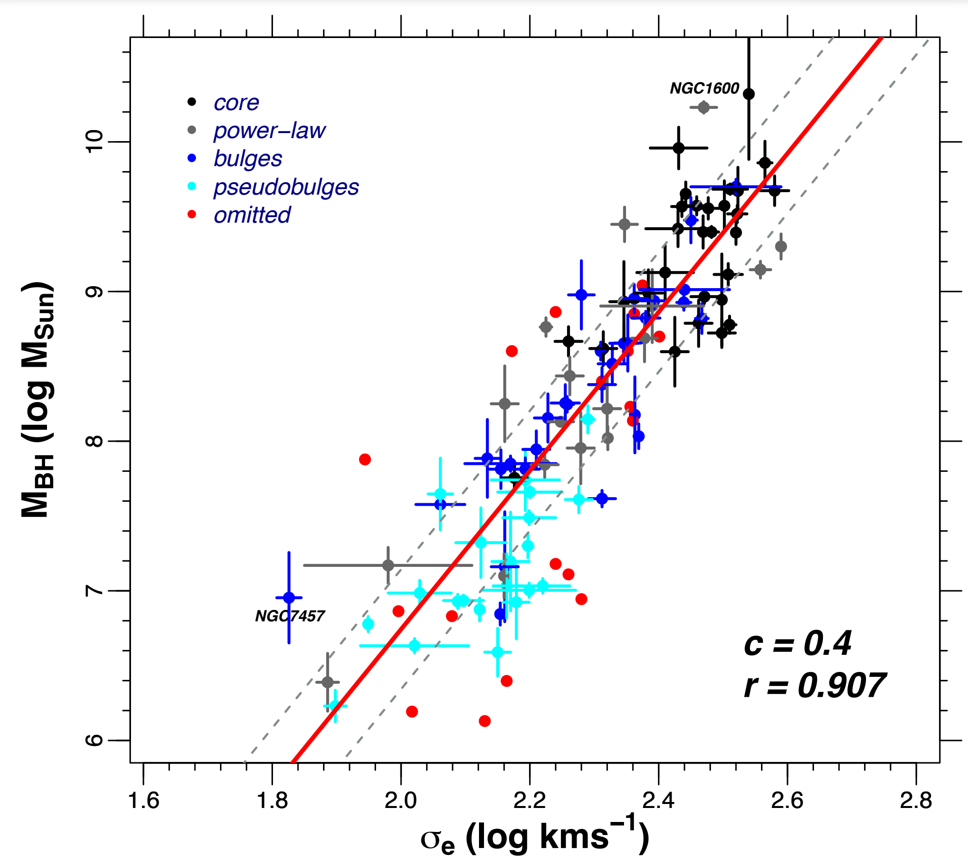


Gebhardt et al. 2000

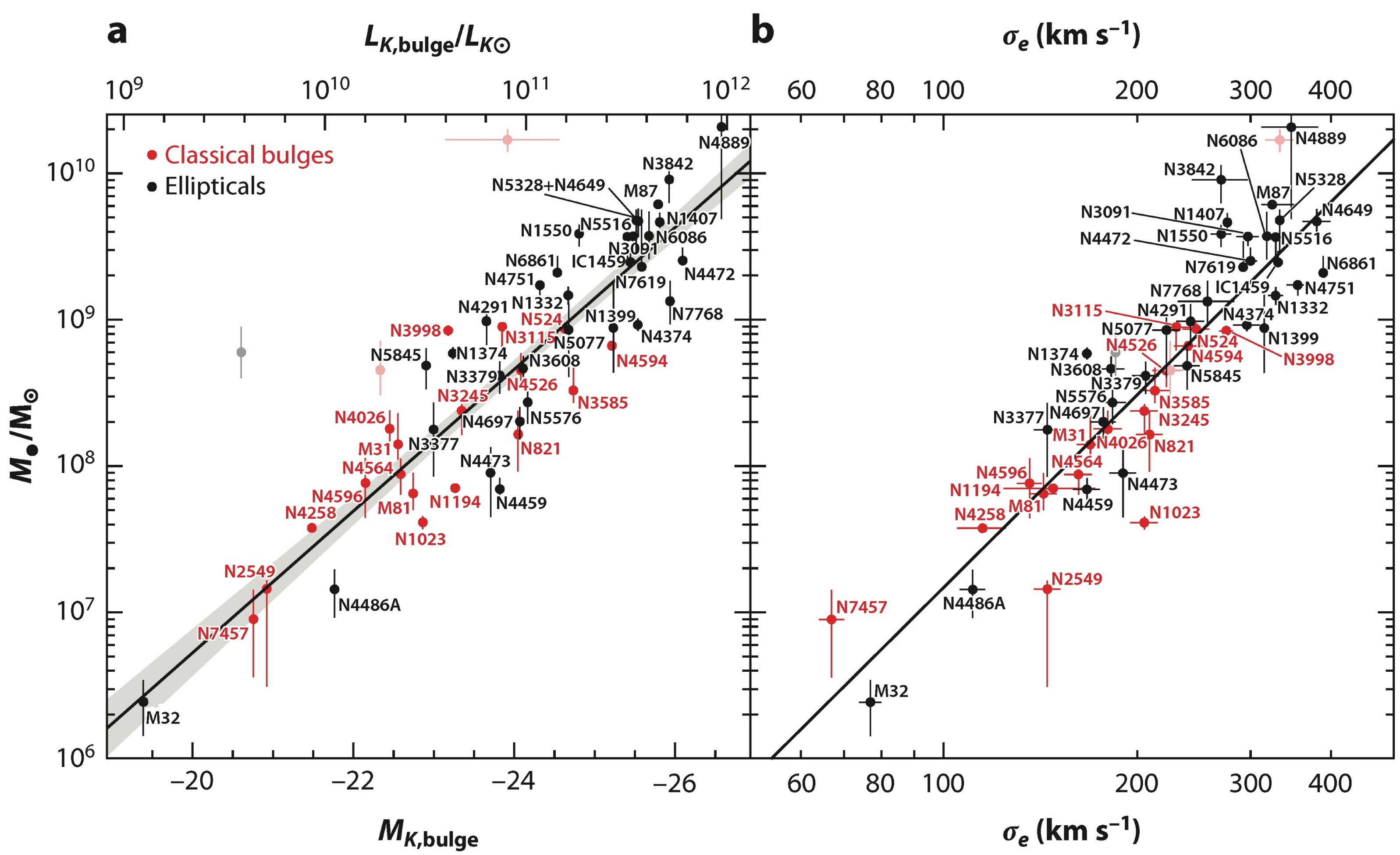


Where we are now …

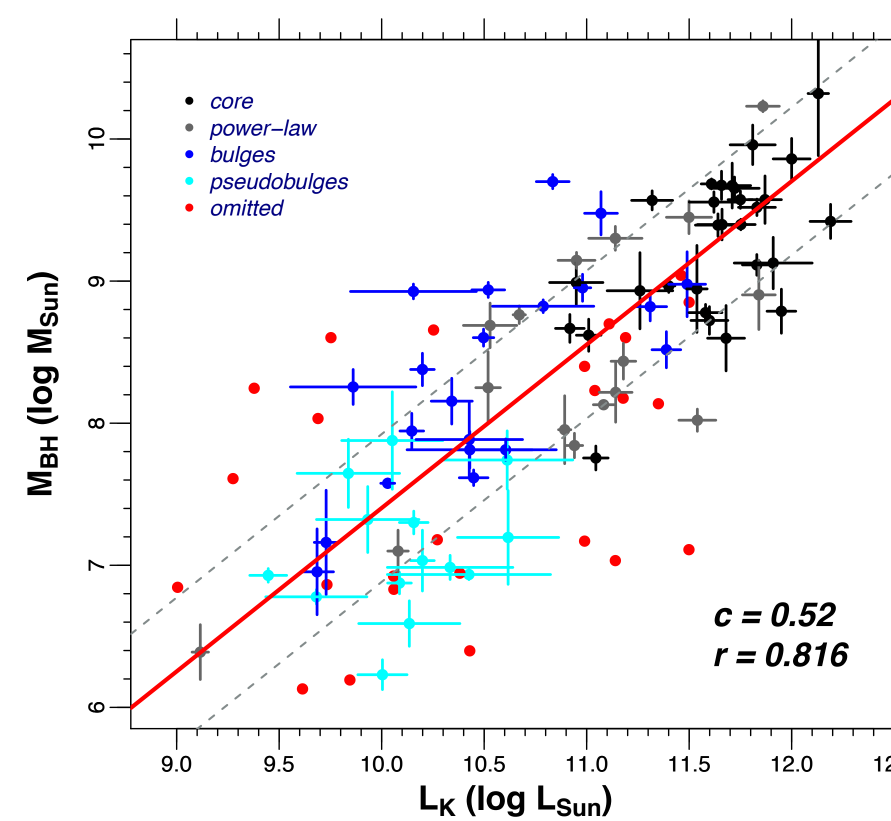
- Over 100 mass estimates (stars, gas, masers)
- Differences among galaxy types (early, spirals, pseudo bulges …)
- Many correlations of M_{BH} (vs σ, L, R, n, DM Halo, GCs …)



De Nicola, AM, Longo 2018



Review by Kormendy & Ho 2013



What's new since 2000?

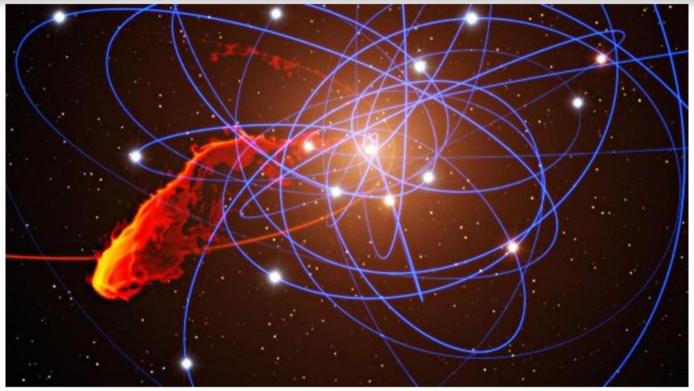
- BH mass measurements
  - How? Uncertainties? Open problems?
  - Are they really BHs?

- Which relations are real?
  - Real, observational effects or biases?
  - Physical meaning?
  - What about the Fundamental plane of spheroids?

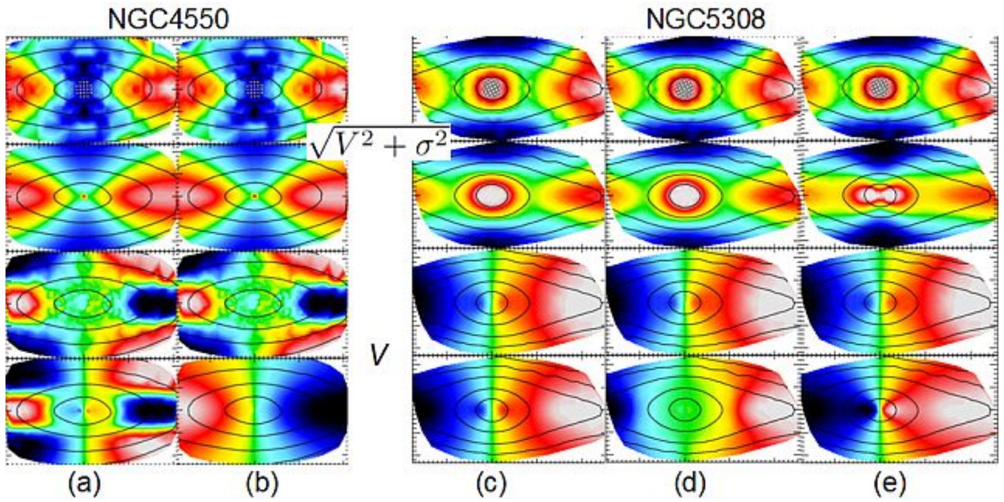
- Redshift evolution and origin of these relations?
  - problems in measuring BH masses (and galaxy properties) at high redshifts

BH Mass measurements

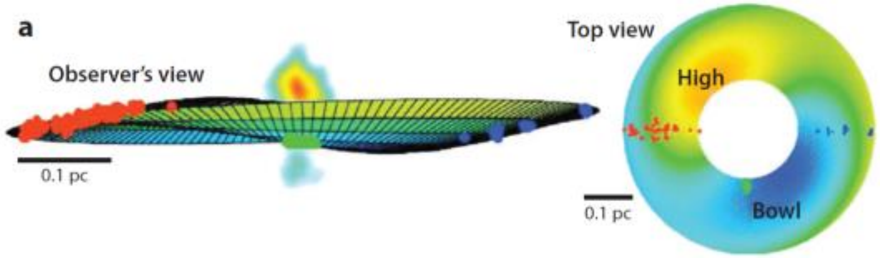
- Proper motions of stars
  - Only Milky Way Center



- Stellar kinematics
  - kinematics of stars and (complex) dynamical models



- Gas kinematics
  - kinematics of gas and simple kinematical models (rotating disks)
  - Masers (high spatial resolution from radio interferometry)
- Reverberation mapping & Virial Masses
  - Talk by Giorgio Calderone



- In all case need to resolve BH sphere of influence

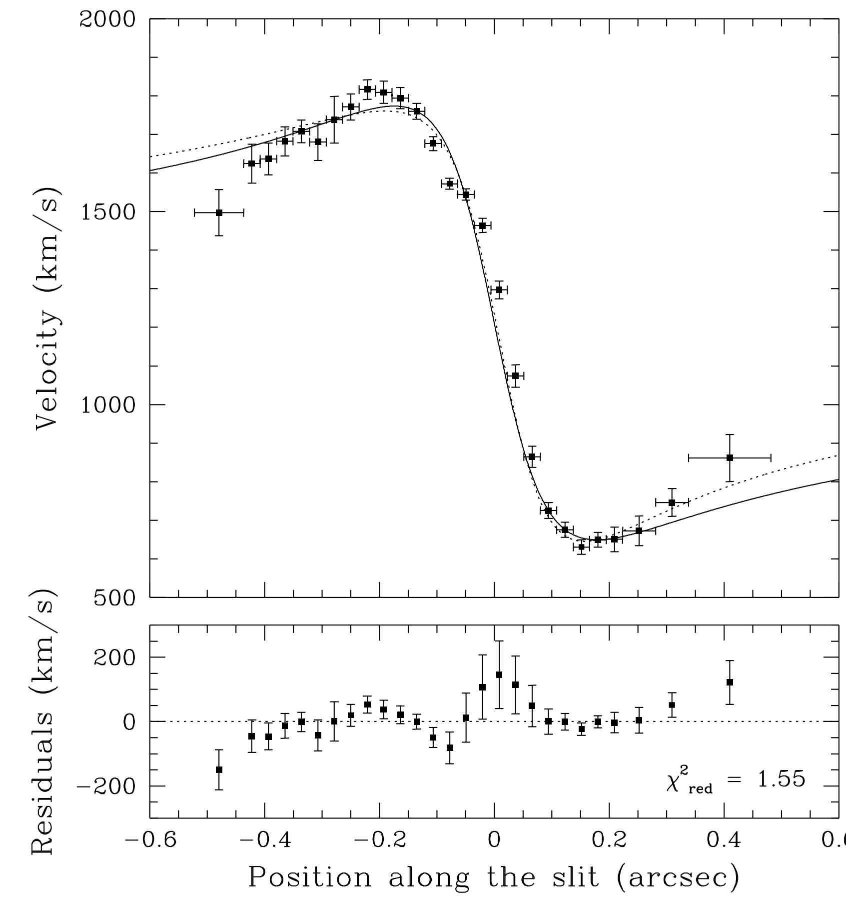
$$r_{BH} = \frac{G\,M_{BH}}{\sigma_\star^2} = 10.7\,\mathrm{pc}\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}$$

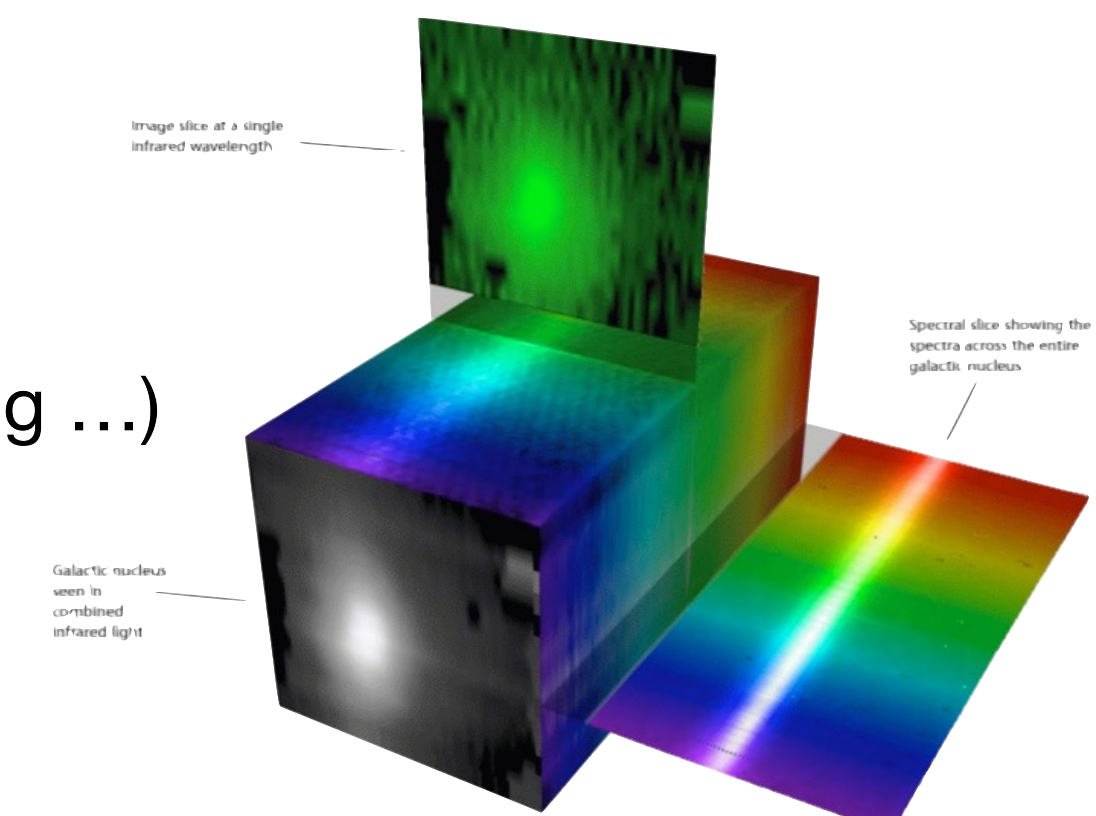
$$\theta_{BH} = 0.11''\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}\left(\frac{D}{20\,\mathrm{Mpc}}\right)^{-1}$$

Impact of AO & 3D spectroscopy

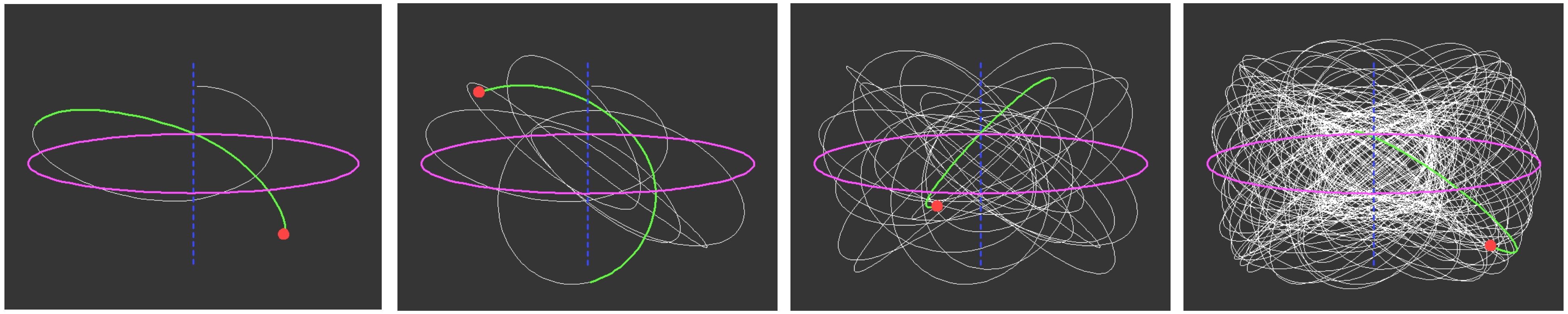
- Up to early 2000's
  - measurements with long list spectrographs
  - HST provided best spatial resolution
- Nowadays
  - use of integral field spectroscopy
  - high spatial resolution
    with AO @ 8m class telescopes
  - very high spatial resolution in submm
    with ALMA
- Future
  - Optical interferometry (very challenging …)
  - JWST (but little improvement…)
  - ELT and 30m class telescopes

M87 w/ HST, Macchetto, AM, +1997





Stellar dynamics: Schwarzschild models



t ⟶ Stellar orbit track

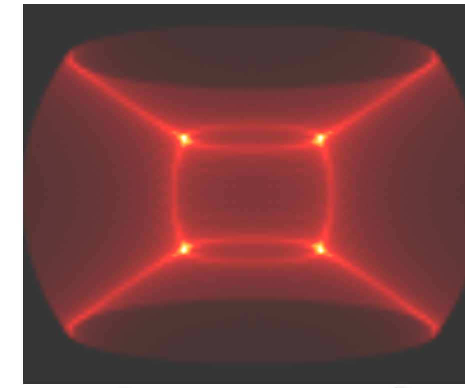
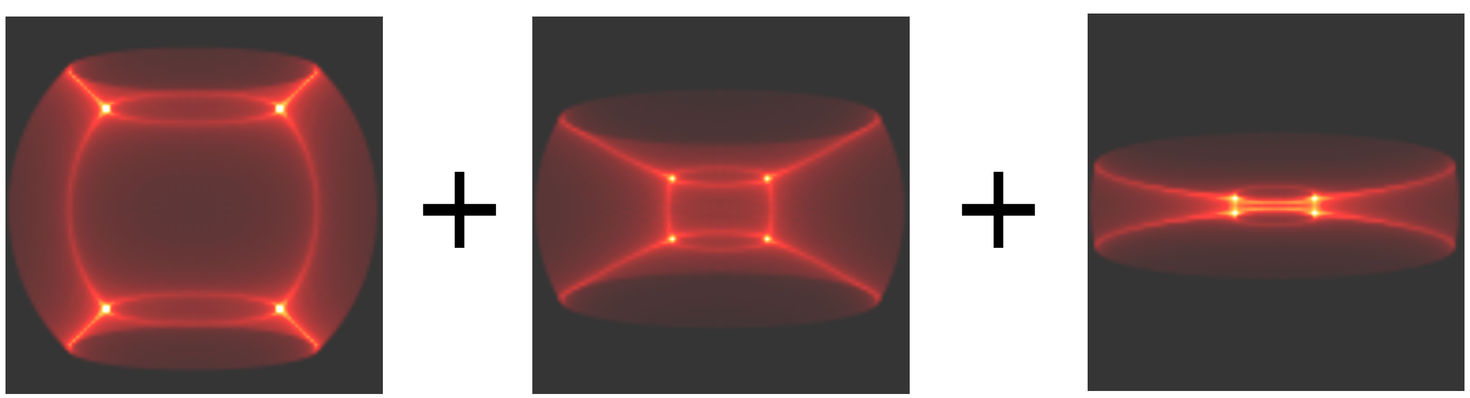


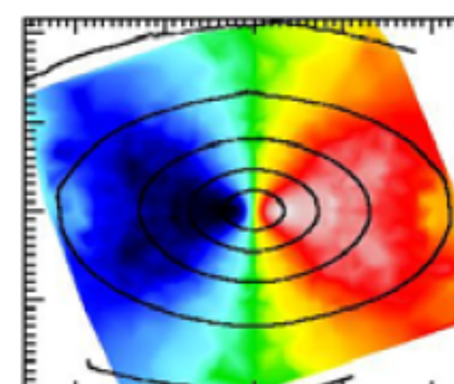
Image of orbit on sky

- ⭐ new thing: 3D data
- ⭐ 3-I models
- ⭐ inclusion of dark matter haloes (orbits from out to nuclear region)



images of model orbits (with weights) (Cappellari et al. 2004)

Observed galaxy image



Observed velocity field

M_{BH}, Y, orbital structure

[Courtesy of Michele Cappellari]

Stellar dynamics: the case of Centaurus A

Moments of LOSVD →

With AO (3” x 3” FOV)

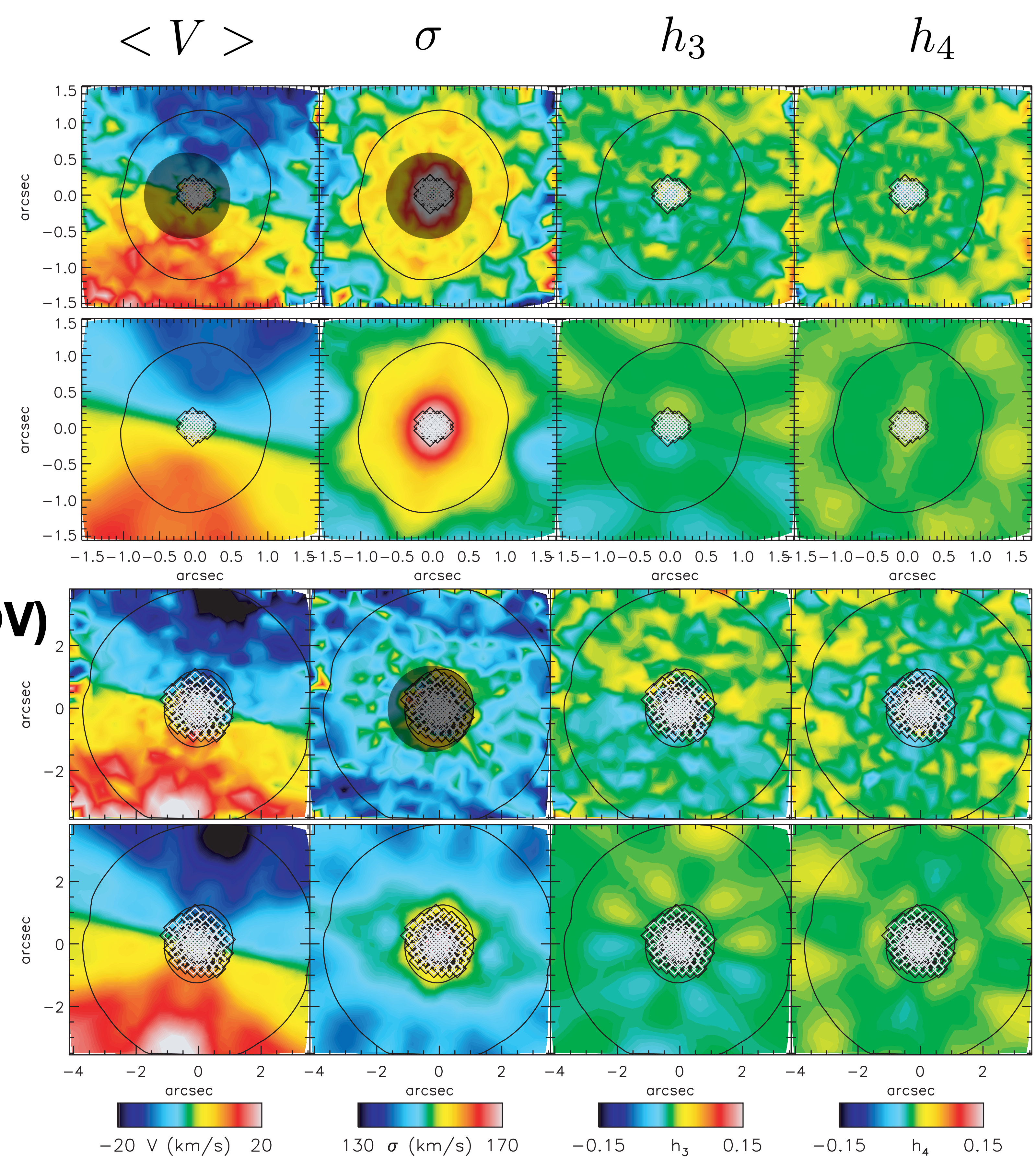
Data

Model

Seeing limited (8” x 8” FOV)

Data

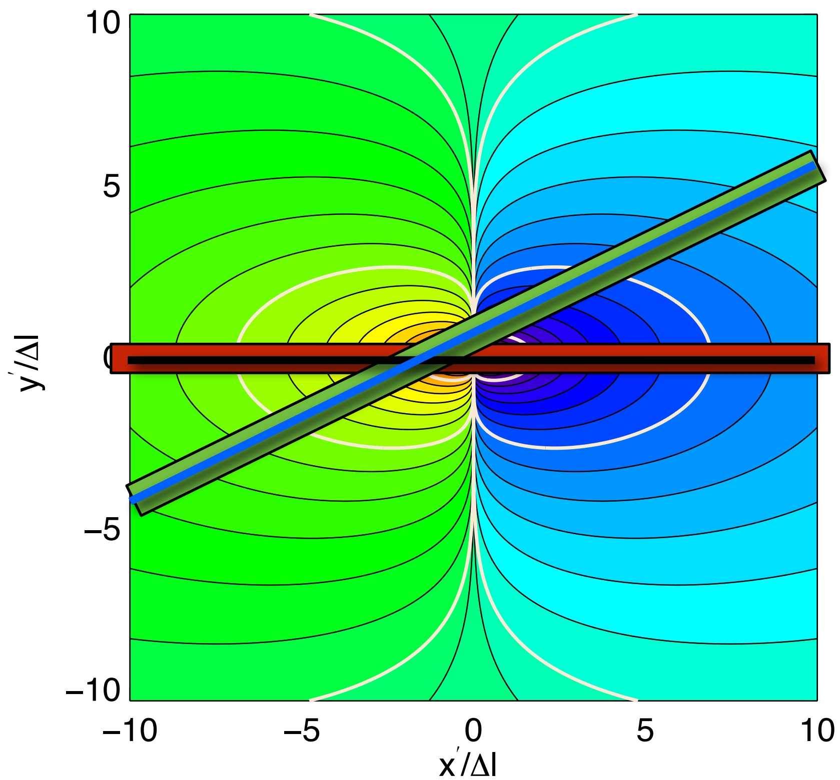
Model

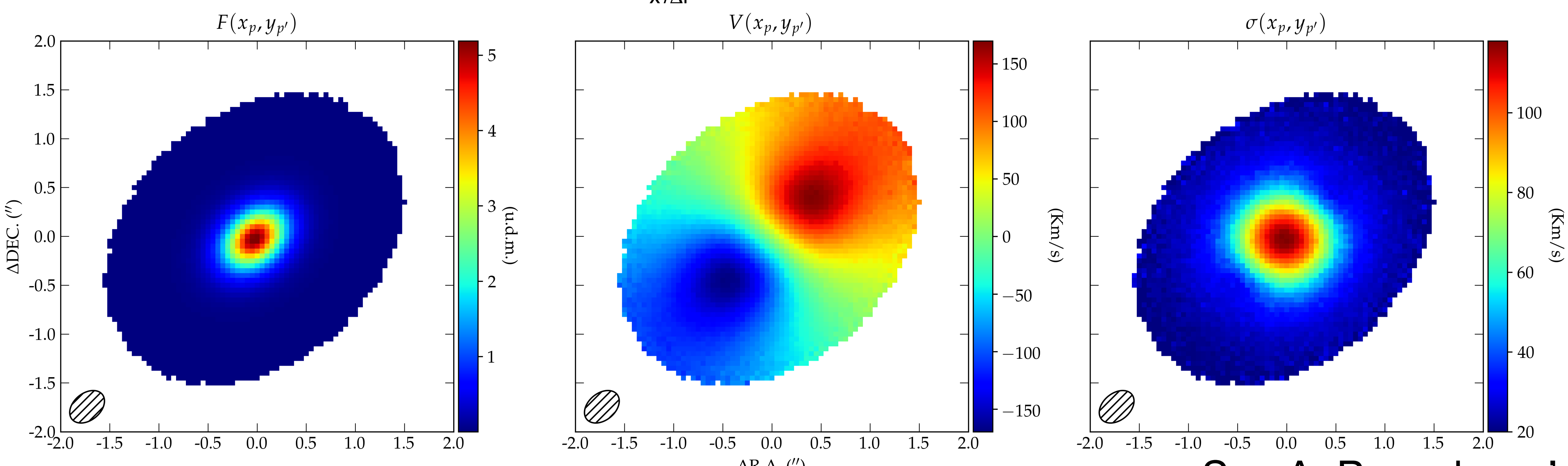


Cappellari et al. 2009

Gas kinematics

- Assume gas in circularly rotating disk
- Projected velocities and observational effects (e.g. beam smearing)





See A. Pensabene's Talk

Gas kinematics

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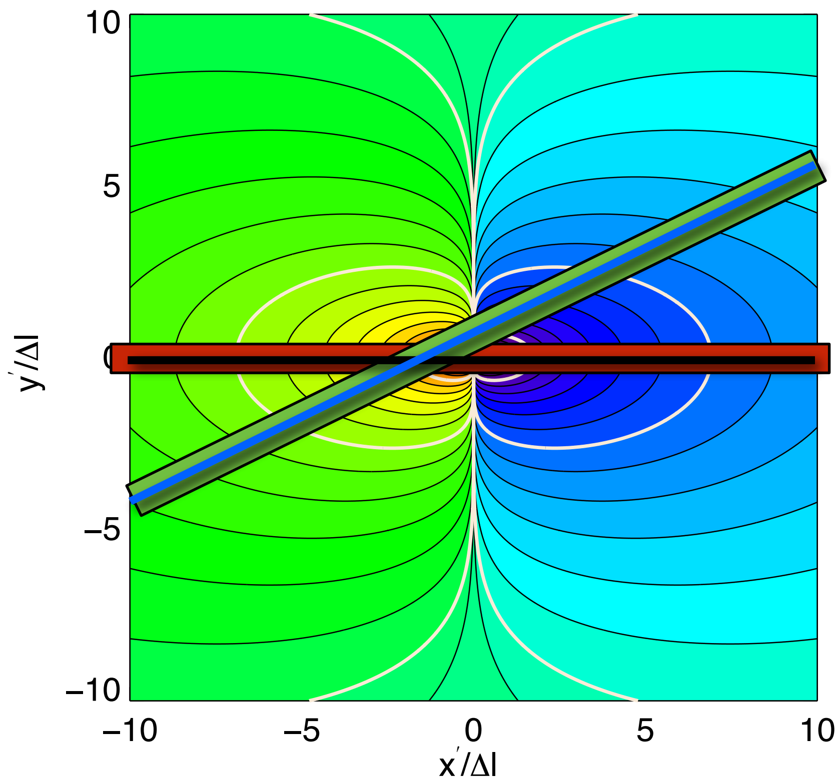
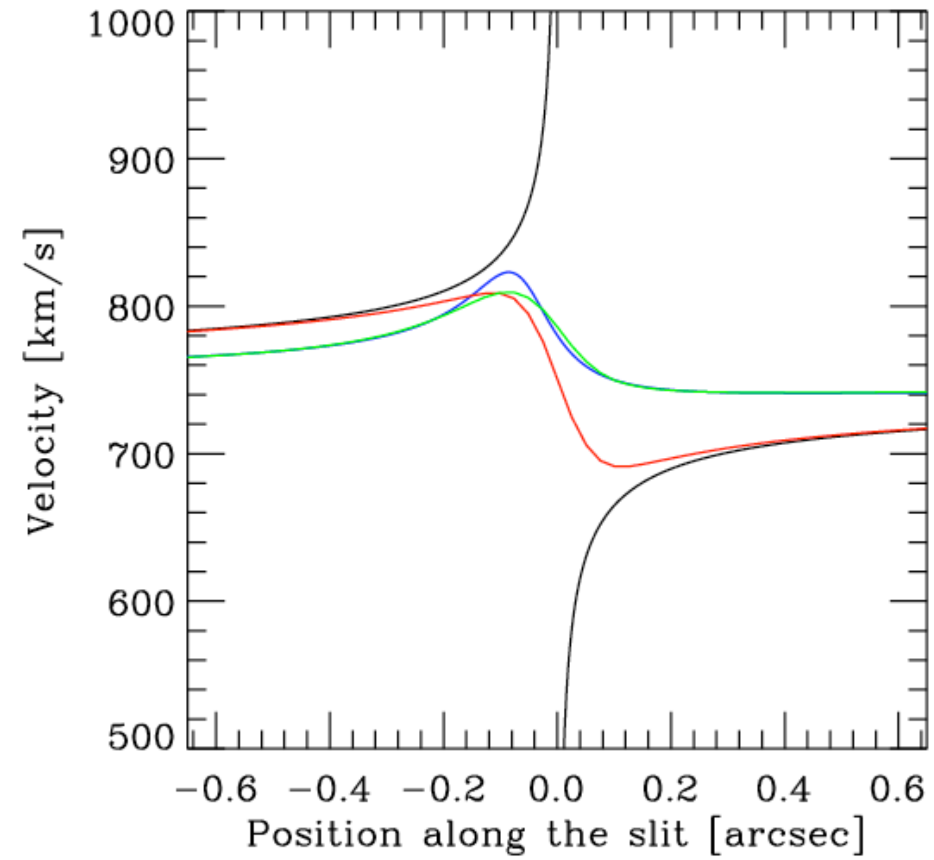
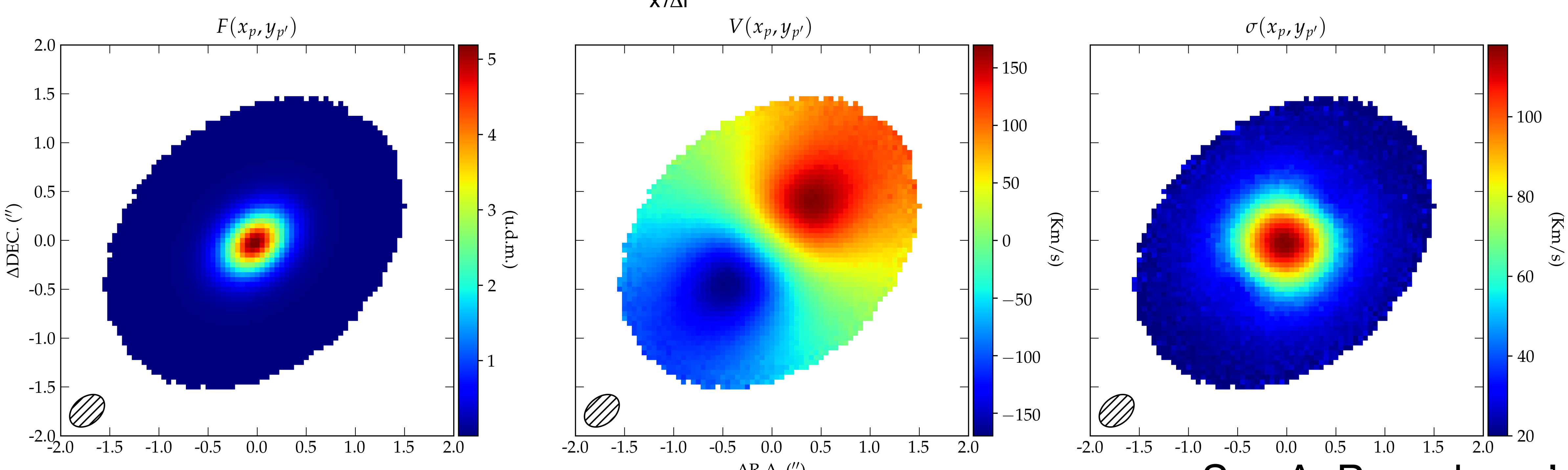




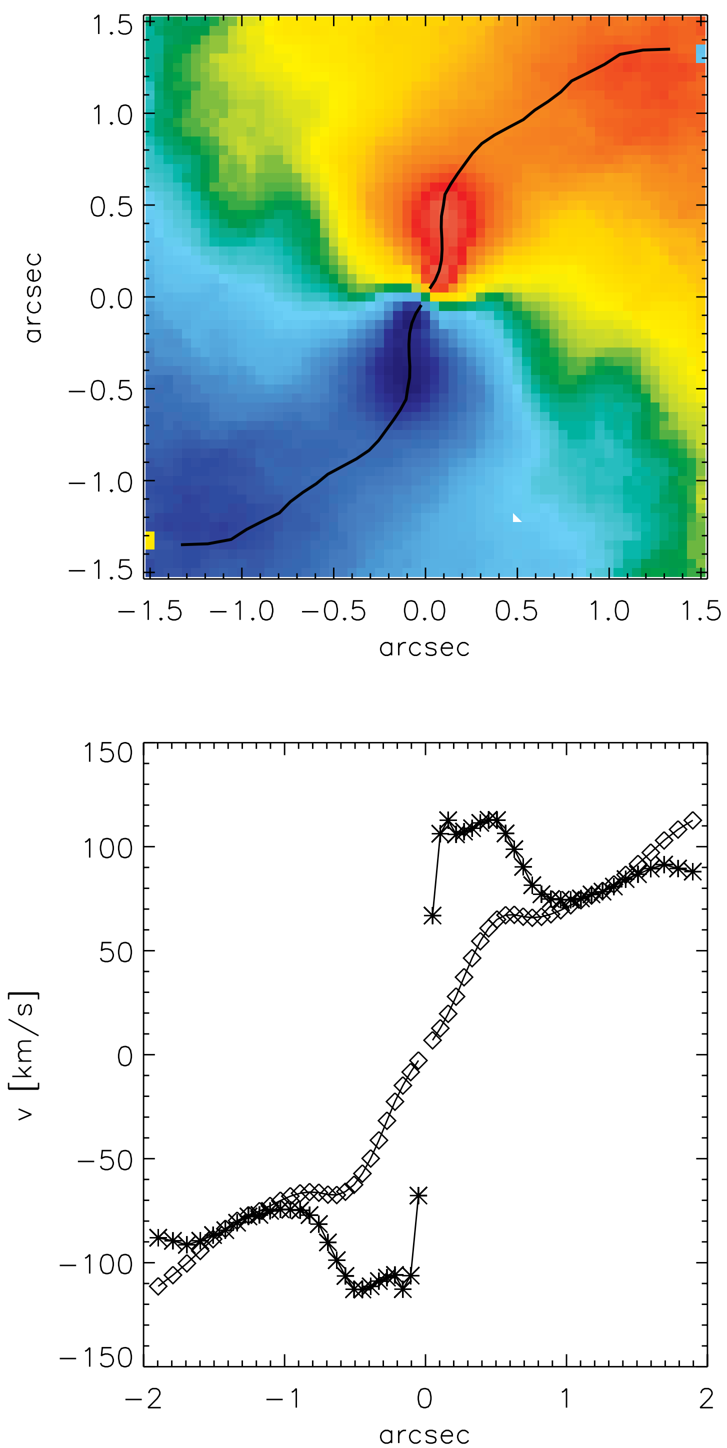


See A. Pensabene's Talk

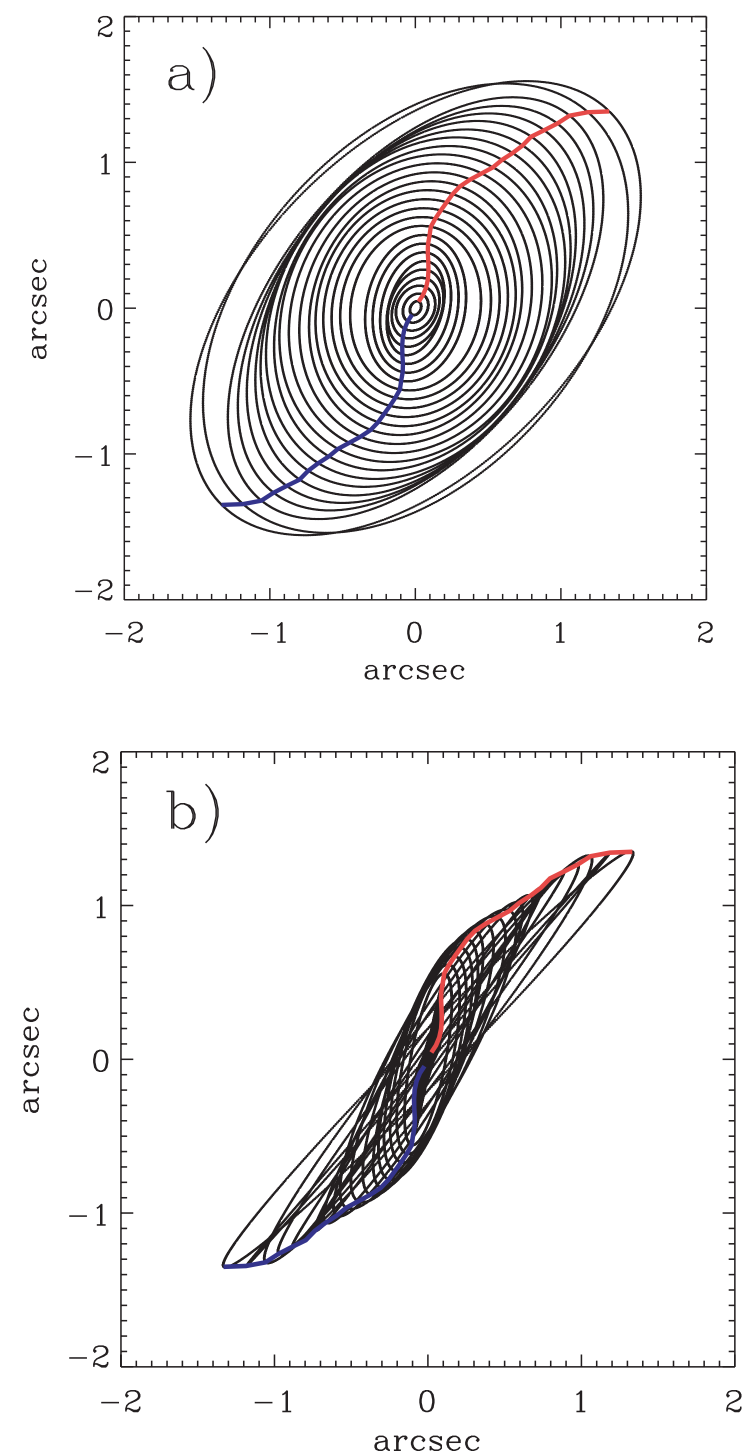
Gas kinematics: the case of Centaurus A

Velocity field from H_2 (2.12)

$M_{BH} = 4.5 \times 10^7 M_\odot$ $\qquad$ $M_{BH} = 0$



Warped disk model

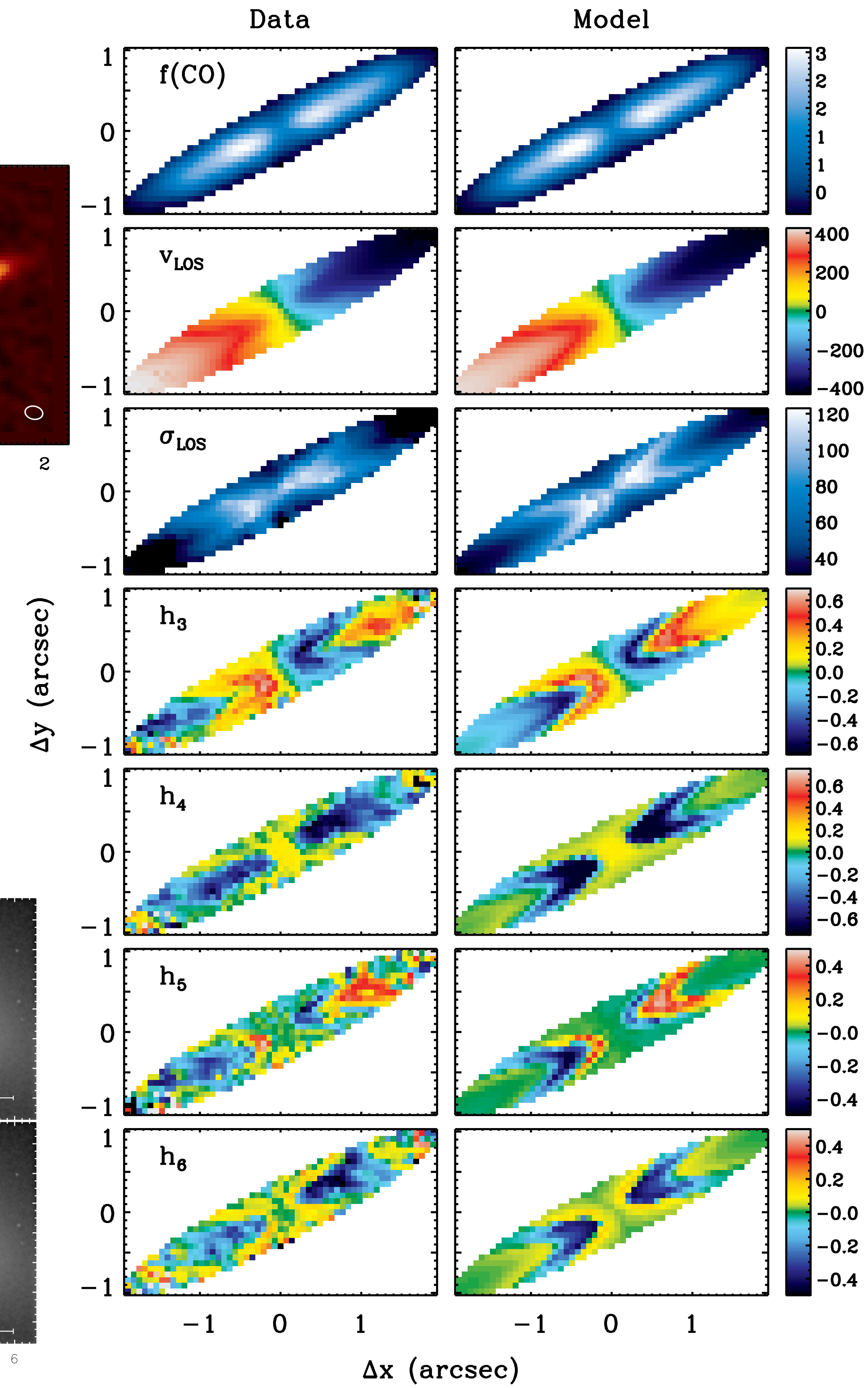


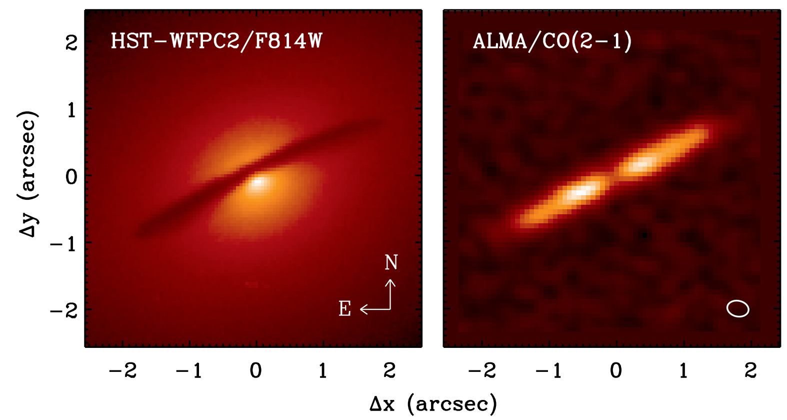
Neumayer et al. 2007

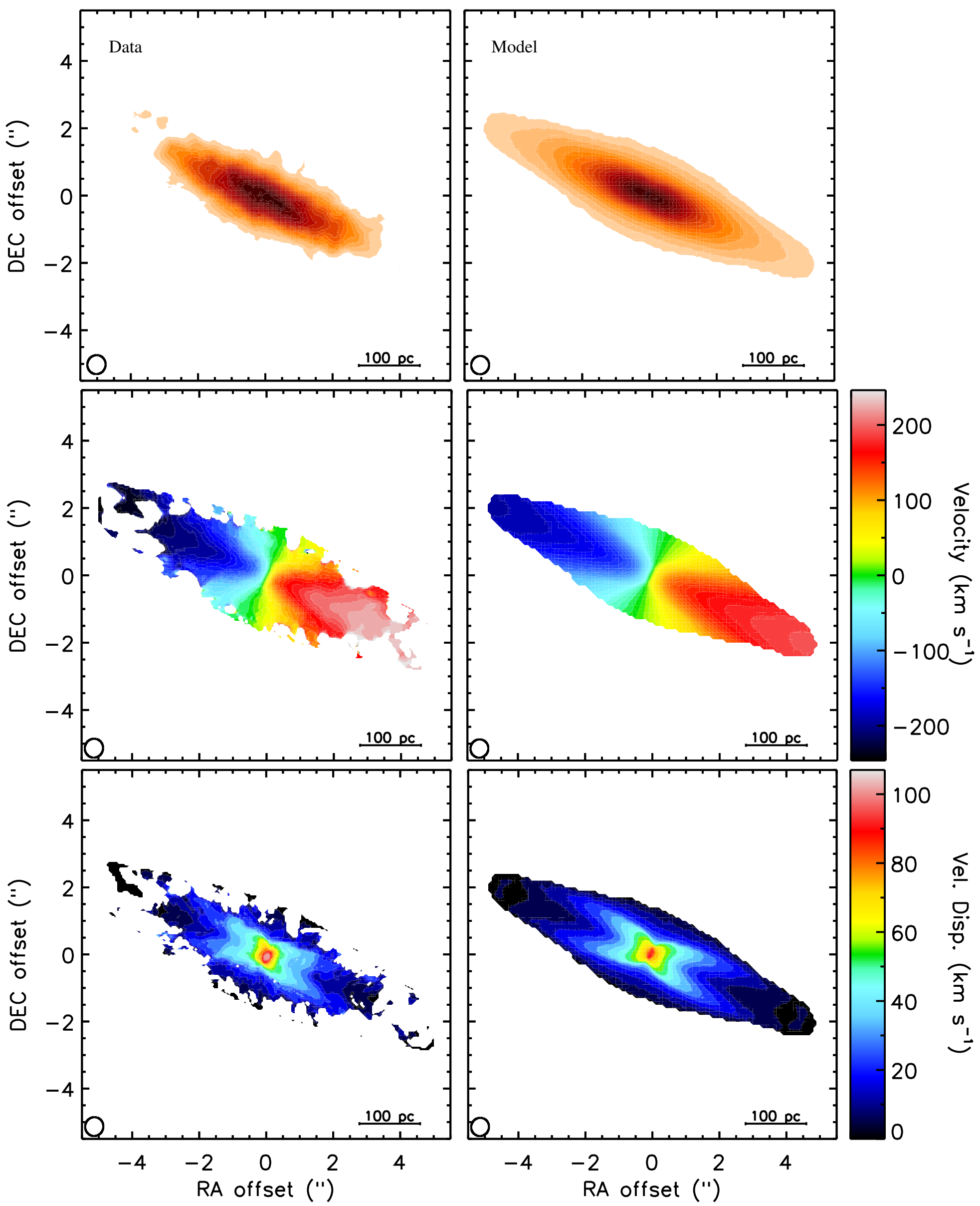
Gas kinematics: ALMA

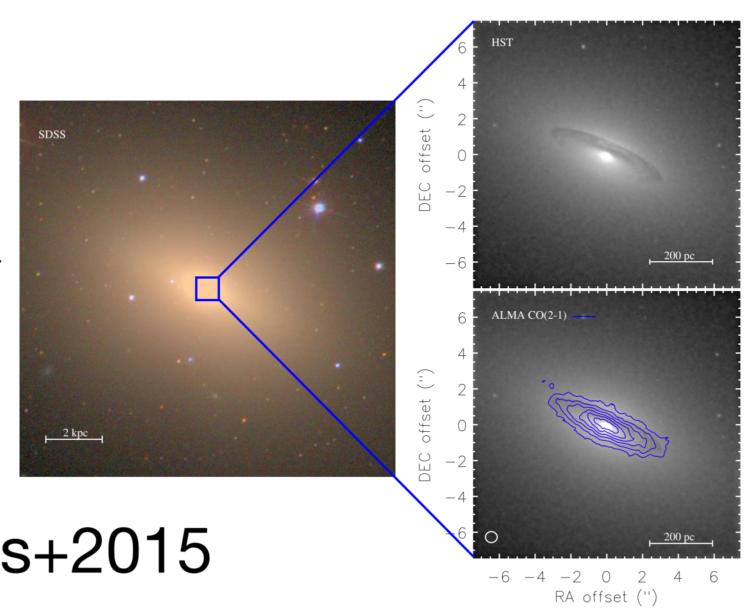
- CO lines in (mostly) spiral galaxies
- ALMA resolution (< 0.01-0.1”)
- Molecular gas less dynamically hot than ionised gas

NGC1332: Barth+2016





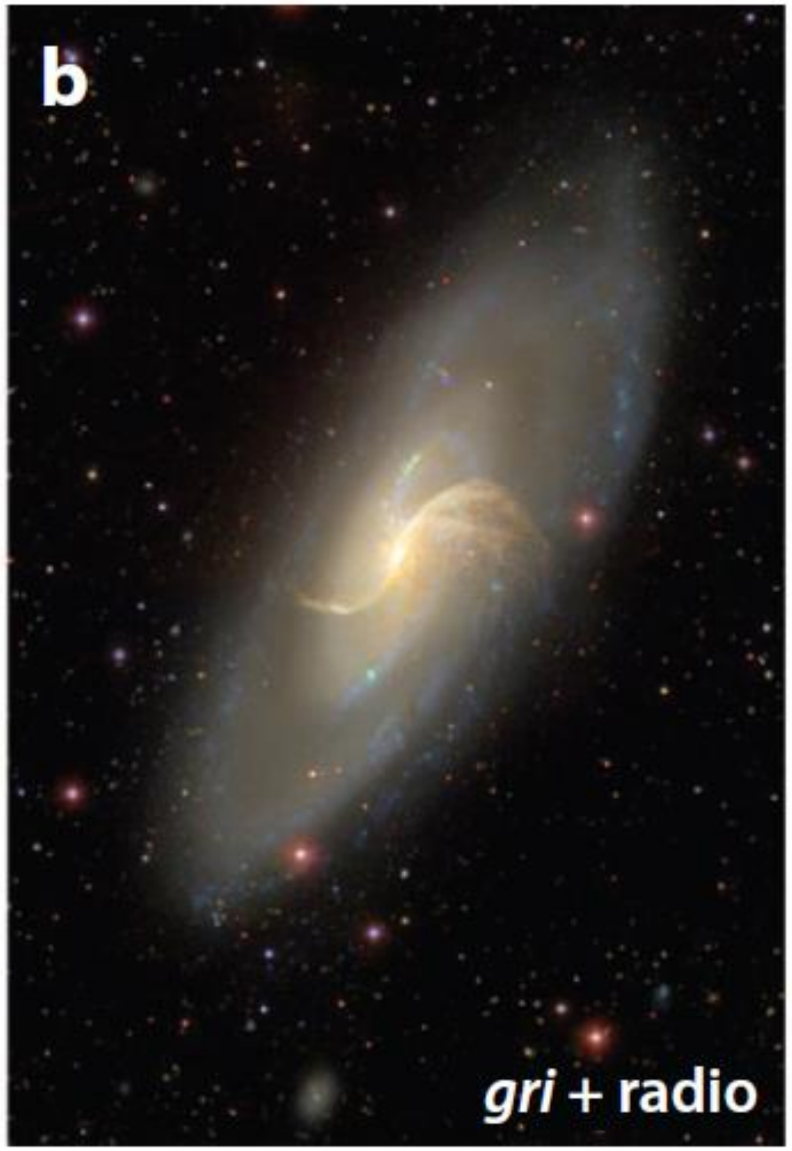


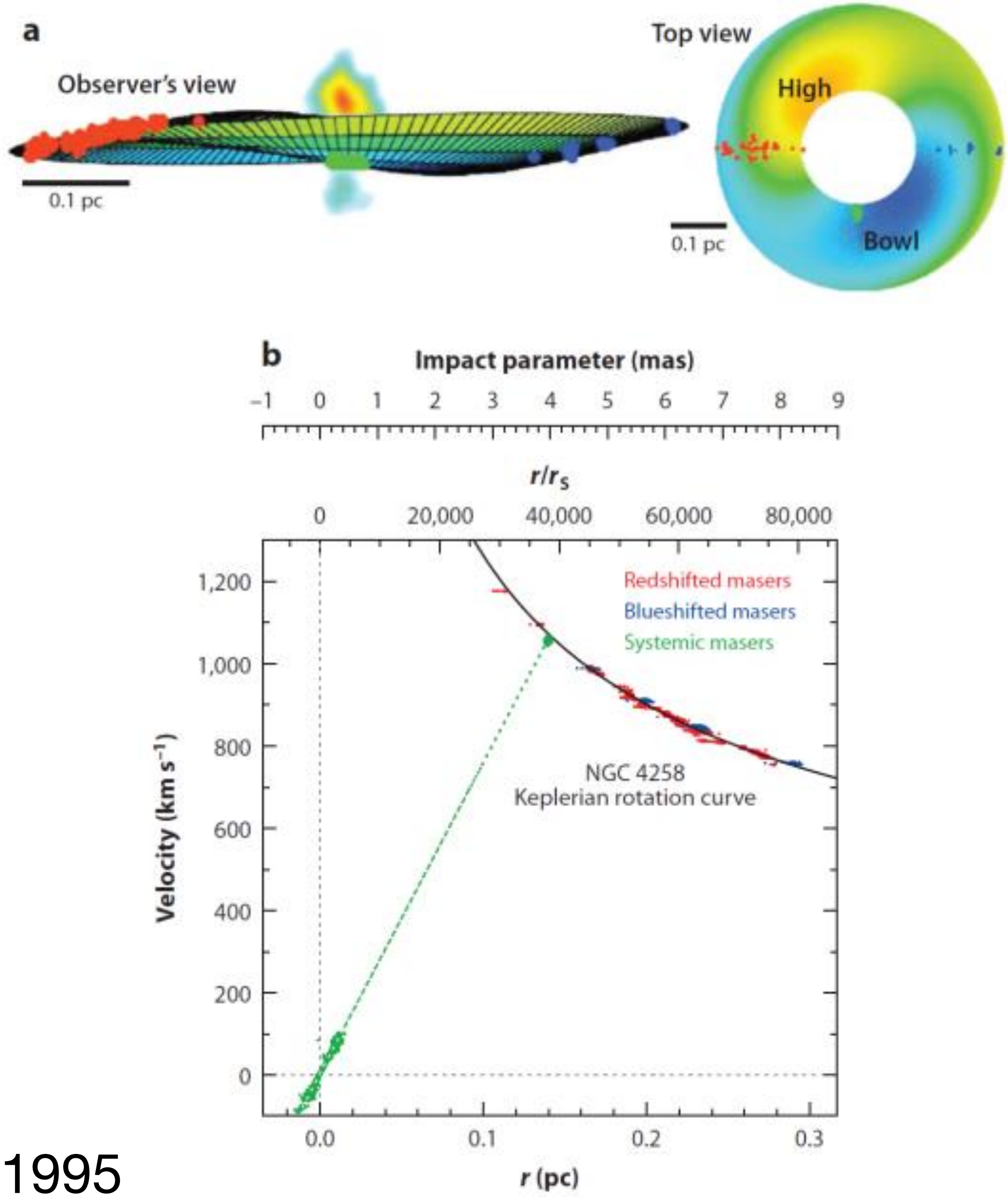


NGC4697: Davis+2015

Masers

- H$_2$O megamasers in galactic nuclei: “test particles”
- High spatial resolution of radio interferometers
- Possible to measure centripetal acceleration (Herrnstein+99): independent distance!

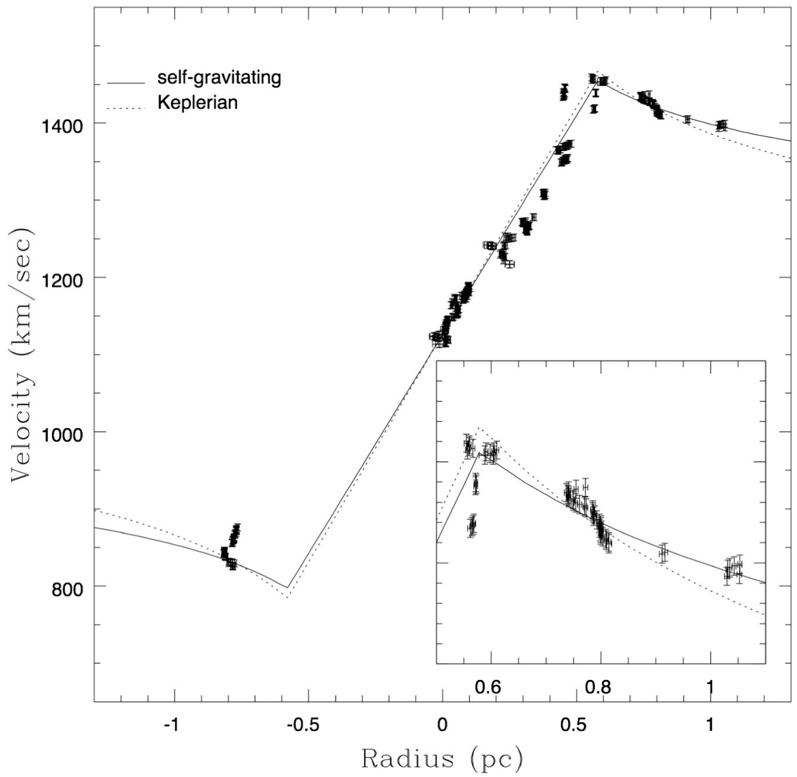




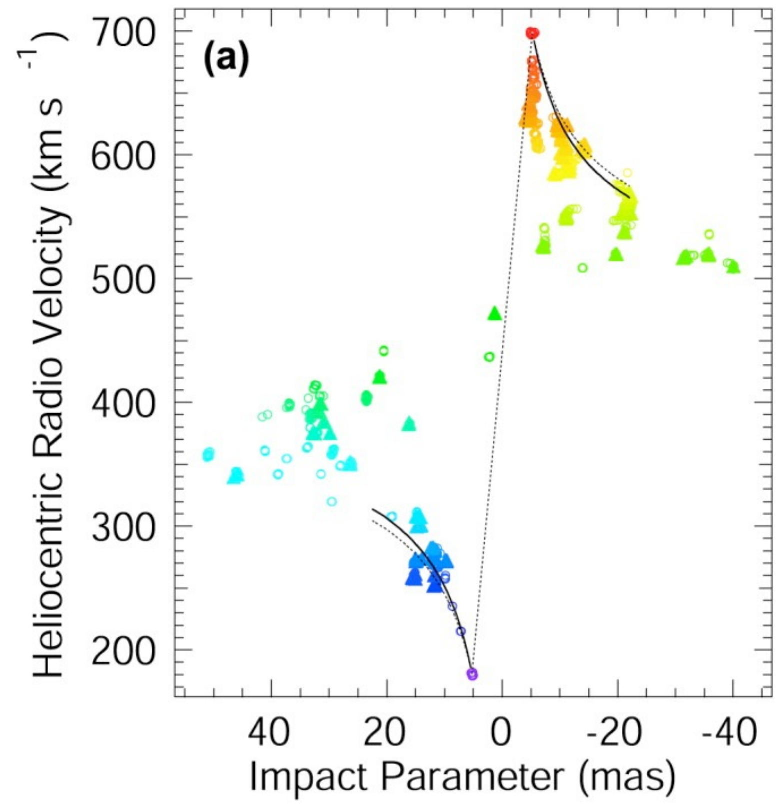
NGC 4258, Miyoshi+1995

Masers

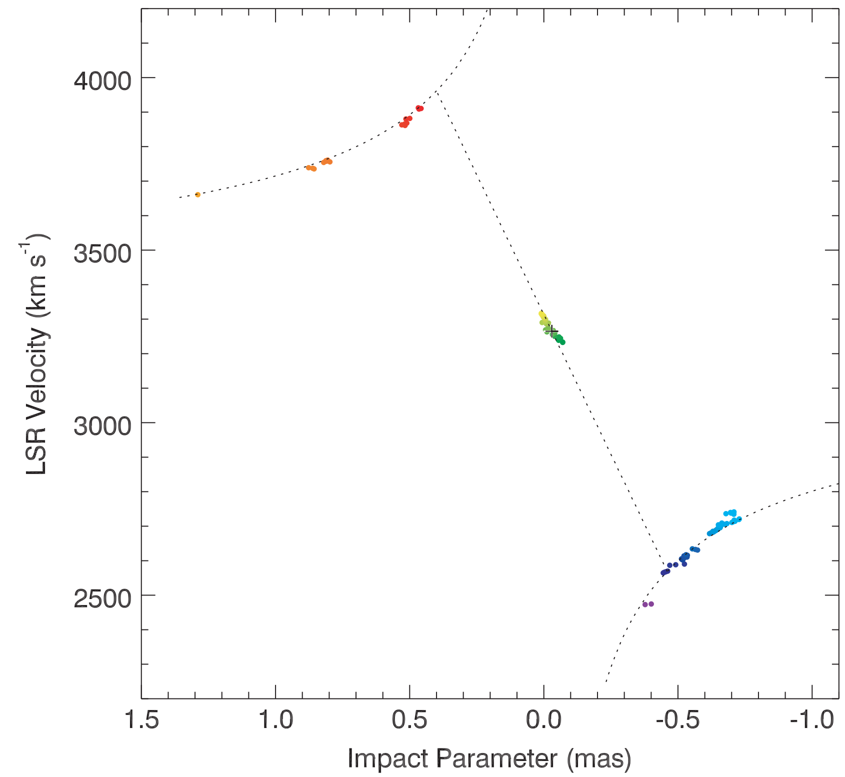
NGC1068: Greenhill+1996

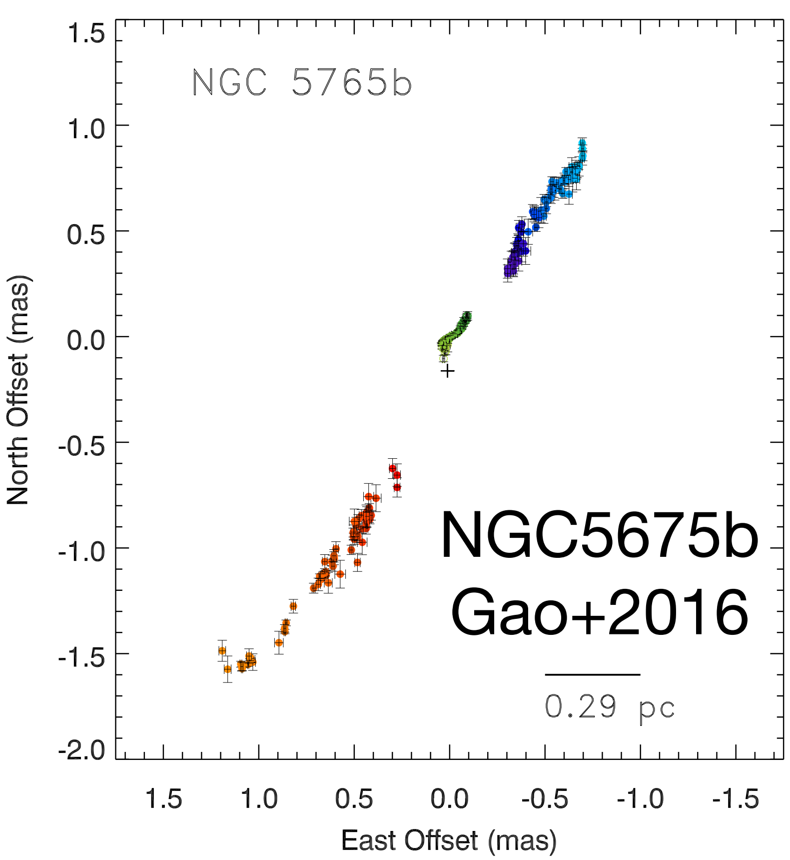


Circinus: Greenhill+2001

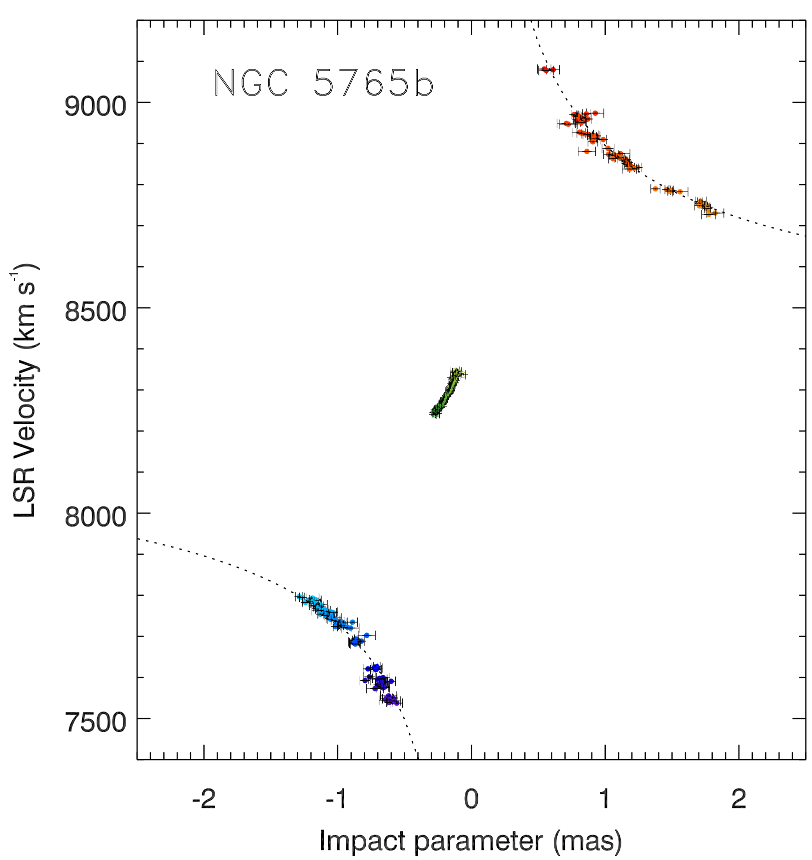


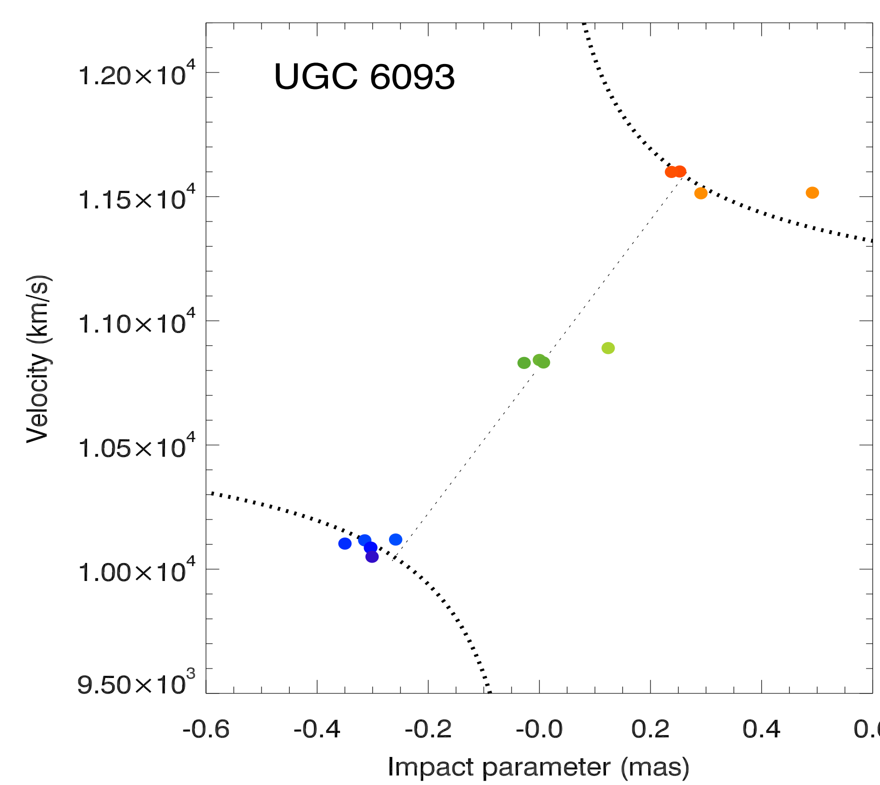
UGC3789: Reid+2009





NGC5675b
Gao+2016





UGC3789: Zhao+2018

Problems

Stellar dynamics

- Very complex models e.g. black boxes for “others”
- results depend on orbit library (e.g. number of stars)? (e.g. *Merritt*)
- results do depend on 2-I vs 3-I (e.g. *Gebhardt et al., Cappellari et al.*)
- results do depend on considering DM Halo (e.g. *Gebhardt et al.*)
- axisymmetric or triaxial galaxies?
- Jeans modelling reliable? (e.g. *Cappellari et al.*)

Gas kinematics

- Simple modelling but works only if gas is in circularly rotating thin disk
- Degeneracy M_{BH} - disk inclination
- Gas velocity dispersion: support against gravity and effects on BH mass?
- Effect of non gravitational motions (e.g. outflows)
- Masers: Effect of disk mass? Probably not (*Kuo+18*)
- Masers: only edge on disk observed (strong bias)

- **Both gas and stars:** errors underestimated?

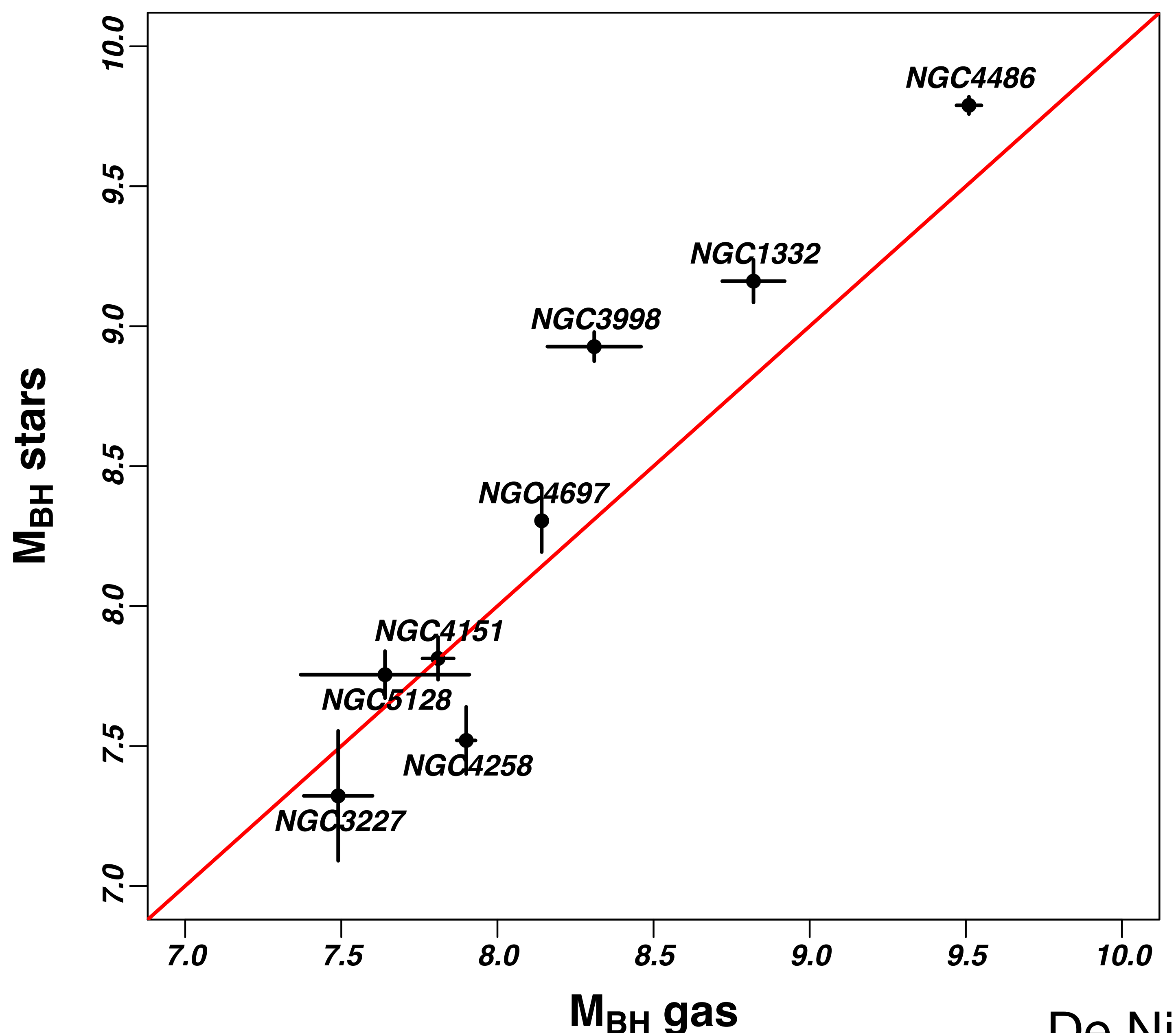
Stars vs gas comparison

Galaxies with independent M_{BH} measurements from stars and gas

Discrepancies ~0.2 dex, up to 0.5 dex

Systematic discrepancies at high mass end:

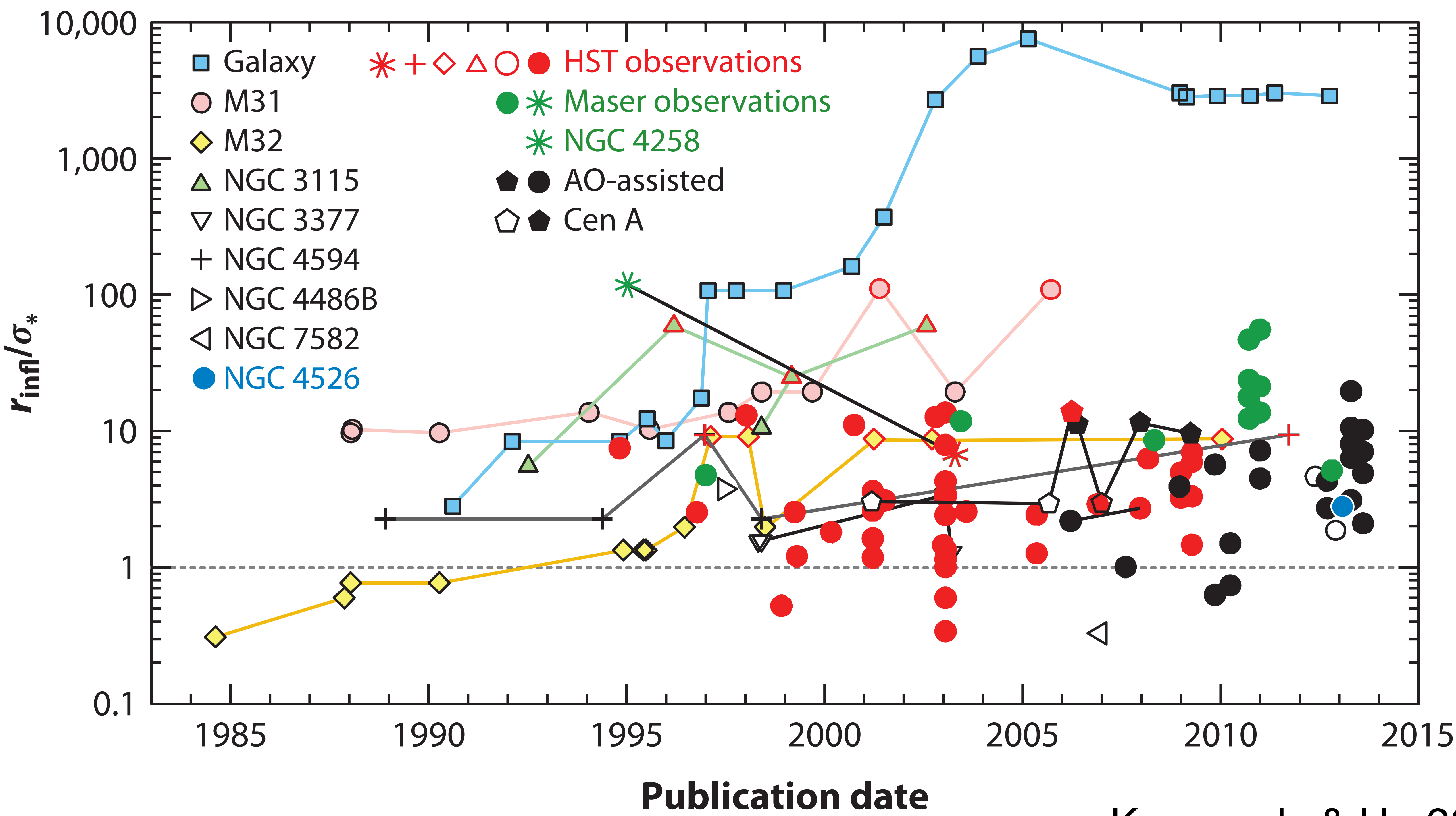
- ⭐ effect of DM Haloes and 3-I/axysimmetry in stars measures?
- ⭐ effect of gas velocity dispersion in gas measures?



De Nicola, AM, Longo 2018

Are they really BHs?

- Sometimes measurements "marginally" resolve BH sphere of influence
- Affects reliability of mass measurement



Kormendy & Ho 2013

Are they really BHs?

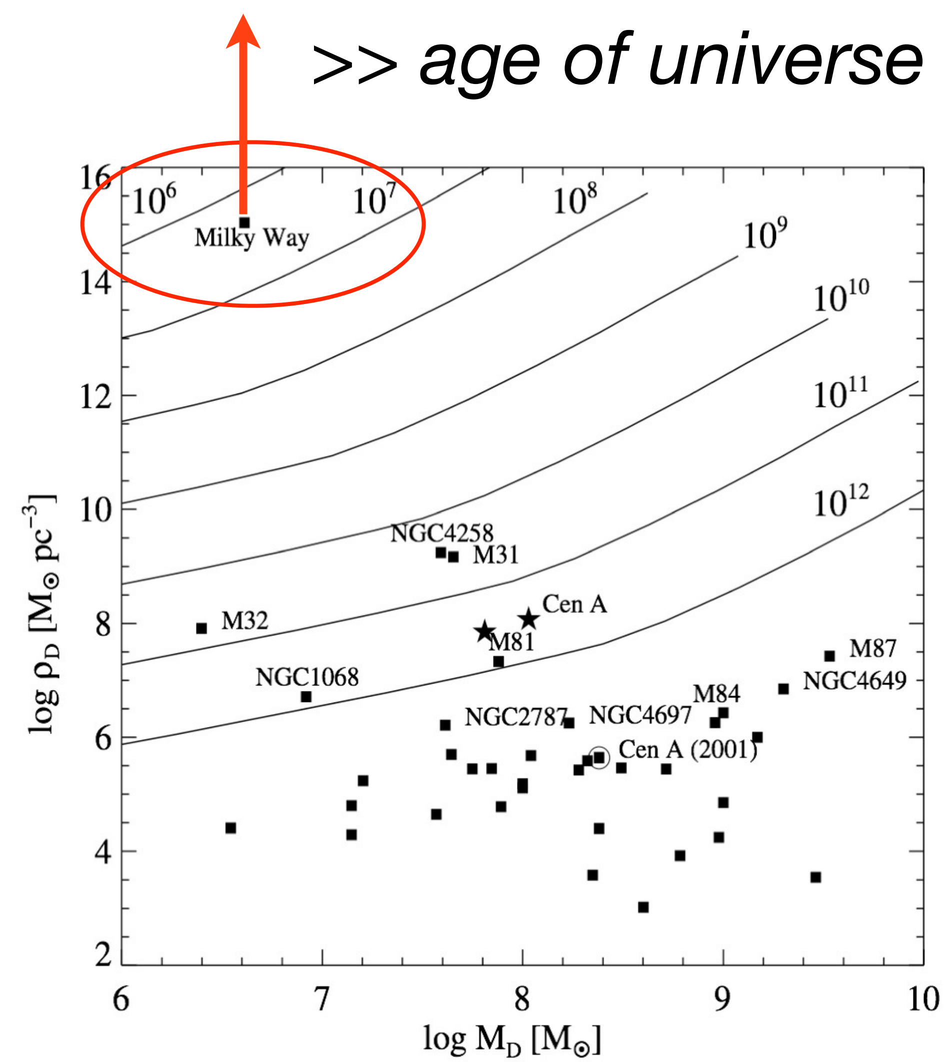
- *Observations find: dark mass confined within spatial resolution element*
- Unambiguous proof of BH: motions close to Schwarzschild radius
- At lower confidence: density of possible cluster so high that it must collapse to BH in short time (*Maoz+1998*)

In most cases survival time scales of clusters >> age of universe

Very far from R_{SCHW} scales

Method & Telescope	Scale (R_S)	No. of SBH Detections	$M_\bullet$ Range ($M_\odot$)	Typical Densities ($M_\odot$ pc^{-3})
Fe Kα line (XEUS, ConX)	3–10	0	N/A	N/A
Reverberation mapping (Ground based optical)	600	36	10^6–4×10^8	$\gtrsim 10^{10}$
Stellar proper motion (Keck, NTT, VLT)	1000	1	4×10^6	4×10^{16}
H_2O megamasers (VLBI)	10^4	1	4×10^7	4×10^9
Gas dynamics (optical) (Mostly *HST*)	10^6	11	7×10^7–4×10^9	$\sim 10^5$
Stellar dynamics (Mostly *HST*)	10^6	17	10^7–3×10^9	$\sim 10^5$

Ferrarese & Ford 2005



adapted from Maoz 1998

- Nuclear star clusters exist: are we overestimating BH masses?

BH Database as of “today”

- About 80 galaxies with “secure” BH masses
- Additional ~40 galaxies with less reliable measurements or upper limits
- Various galaxy morphological types

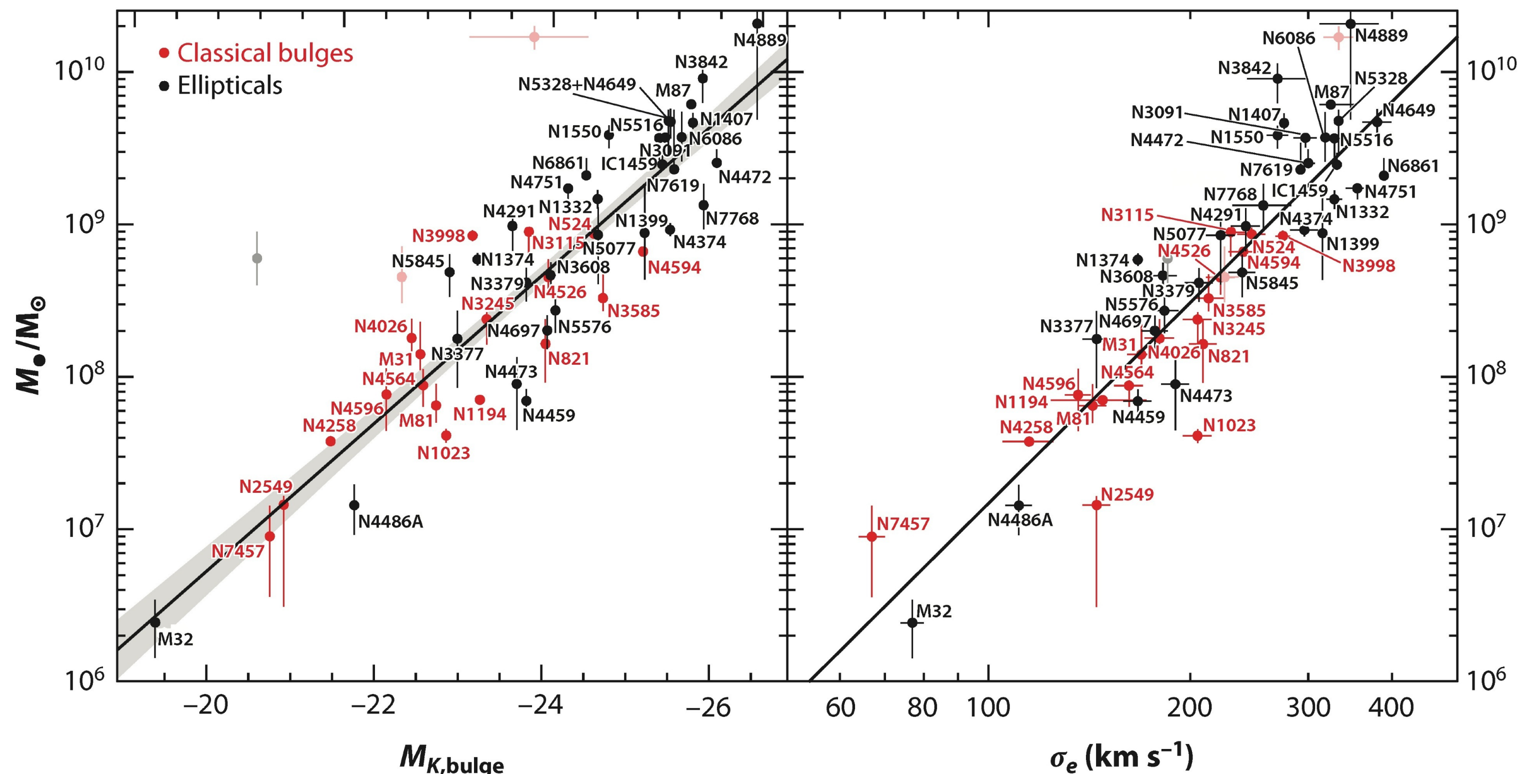
Galaxy	Morphology	A	Distance (Mpc)	M_{BH} (log $M_\odot$)	σ_e (log km/s)	L_K (log $L_\odot$)	R_e (log kpc)	B
Circinus	SABb:	3	2.82 ± 0.47	6.23 ± 0.10	1.90 ± 0.02	10 ± 0.12	-0.91 ± 0.07	1
A1836	BCGE	0	152.40 ± 8.43	9.57 ± 0.06	2.46 ± 0.02	11.75 ± 0.06	0.89 ± 0.02	0
IC1459	E4	0	28.92 ± 3.74	9.39 ± 0.08	2.52 ± 0.01	11.70 ± 0.06	0.90 ± 0.06	1
NGC524	S0	2	24.22 ± 2.23	8.94 ± 0.05	2.39 ± 0.02	10.52 ± 0.08	0.17 ± 0.07	1
NGC821	S0	1	23.44 ± 1.84	8.22 ± 0.21	2.32 ± 0.02	10.84 ± 0.31	0.33 ± 0.03	1
NGC1023	SB0	2	10.81 ± 0.80	7.62 ± 0.06	2.31 ± 0.02	10.45 ± 0.07	-0.41 ± 0.03	1
NGC1399	E1	0	20.85 ± 0.67	8.95 ± 0.31	2.498 ± 0.004	11.81 ± 0.06	1.53 ± 0.01	1
NGC2273	SBa	3	29.50 ± 1.90	6.93 ± 0.04	2.10 ± 0.03	10.43 ± 0.40	-0.57 ± 0.03	1
NGC2549	S0/	2	12.70 ± 1.64	7.16 ± 0.37	2.16 ± 0.02	9.73 ± 0.06	-0.72 ± 0.06	1
NGC3115	S0/	2	9.54 ± 0.4	8.95 ± 0.10	2.36 ± 0.02	10.93 ± 0.06	0.20 ± 0.06	1
NGC3227	SBa	3	23.75 ± 2.63	7.32 ± 0.23	2.12 ± 0.04	9.93 ± 0.25	-0.28 ± 0.05	1
NGC3245	S0	2	21.38 ± 1.97	8.38 ± 0.11	2.31 ± 0.02	10.20 ± 0.06	-0.60 ± 0.04	1
NGC3377	E5	1	10.99 ± 0.46	8.25 ± 0.25	2.16 ± 0.02	10.64 ± 0.25	0.52 ± 0.02	1
NGC3384	SB0	3	11.49 ± 0.74	7.03 ± 0.21	2.16 ± 0.02	10.20 ± 0.06	-0.51 ± 0.03	1
NGC3393	SABa	3	49.20 ± 8.19	7.20 ± 0.33	2.17 ± 0.03	10.62 ± 0.25	-0.48 ± 0.07	1
NGC3585	S0	2	20.51 ± 1.70	8.52 ± 0.13	2.33 ± 0.02	11.45 ± 0.25	0.93 ± 0.07	1
NGC3608	E1	0	22.75 ± 1.47	8.67 ± 0.10	2.26 ± 0.02	11.04 ± 0.25	0.68 ± 0.03	1
NGC3842	E1	0	92.20 ± 10.64	9.96 ± 0.14	2.43 ± 0.04	12.04 ± 0.06	1.52 ± 0.05	1
NGC3998	S0	2	14.30 ± 1.25	8.93 ± 0.05	2.44 ± 0.01	10.15 ± 0.31	-0.48 ± 0.04	1
NGC4026	S0	2	13.35 ± 1.73	8.26 ± 0.12	2.25 ± 0.02	9.86 ± 0.31	-0.39 ± 0.06	1
NGC4258	SABbc	2	7.27 ± 0.50	7.58 ± 0.03	2.06 ± 0.04	10.03 ± 0.03	-0.33 ± 0.03	1
NGC4261	E2	0	32.36 ± 2.84	8.72 ± 0.10	2.5 ± 0.02	11.53 ± 0.25	0.87 ± 0.04	1
NGC4291	E2	0	26.58 ± 3.93	8.99 ± 0.16	2.38 ± 0.02	10.86 ± 0.25	0.30 ± 0.06	1
NGC4459	E2	1	16.01 ± 0.52	7.84 ± 0.09	2.22 ± 0.02	10.64 ± 0.25	0.00 ± 0.01	1
NGC4473	E5	1	15.25 ± 0.49	7.95 ± 0.24	2.28 ± 0.02	10.80 ± 0.25	0.44 ± 0.01	1
NGC4564	S0	2	15.94 ± 0.51	7.95 ± 0.12	2.21 ± 0.02	10.15 ± 0.06	-0.41 ± 0.01	1
NGC4596	SB0	2	16.53 ± 6.23	7.88 ± 0.26	2.13 ± 0.02	10.34 ± 0.06	-0.14 ± 0.16	1
NGC4649	E2	0	16.46 ± 0.61	9.67 ± 0.10	2.58 ± 0.02	11.66 ± 0.06	0.90 ± 0.02	0
NGC4697	E5	1	12.54 ± 0.40	8.13 ± 0.01	2.25 ± 0.02	11.17 ± 0.31	0.64 ± 0.01	1
NGC4889	E4	0	102.00 ± 5.17	10.32 ± 0.44	2.54 ± 0.01	12.25 ± 0.06	1.47 ± 0.02	1
NGC5077	E3	0	38.70 ± 8.44	8.93 ± 0.27	2.35 ± 0.02	11.42 ± 0.06	0.64 ± 0.09	1
NGC5128	E	0	3.62 ± 0.20	7.75 ± 0.08	2.18 ± 0.02	10.80 ± 0.31	0.03 ± 0.02	1
NGC5576	E3	1	25.68 ± 1.66	8.44 ± 0.13	2.26 ± 0.02	11.02 ± 0.06	0.79 ± 0.03	1
NGC5845	E3	1	25.87 ± 4.07	8.69 ± 0.16	2.38 ± 0.02	10.43 ± 0.31	-0.41 ± 0.07	1
NGC6086	E	0	138.00 ± 11.45	9.57 ± 0.17	2.5 ± 0	11.87 ± 0.08	1.20 ± 0.04	0
NGC6251	E1	0	108.40 ± 9.00	8.79 ± 0.16	2.46 ± 0.02	11.94 ± 0.06	1.20 ± 0.04	1
NGC7052	E3	0	70.40 ± 8.45	8.60 ± 0.23	2.42 ± 0.02	11.77 ± 0.06	1.10 ± 0.05	1
NGC7582	SBab	3	22.30 ± 9.85	7.74 ± 0.20	2.19 ± 0.05	10.61 ± 0.32	-0.62 ± 0.19	0
NGC7768	E4	0	116.00 ± 27.50	9.13 ± 0.18	2.41 ± 0.04	12.00 ± 0.25	1.37 ± 0.10	1
UGC3789	SABab	3	49.90 ± 5.42	6.99 ± 0.08	2.03 ± 0.05	10.33 ± 0.31	-0.24 ± 0.05	1
NGC1332	S0	2	22.30 ± 1.85	8.82 ± 0.10	2.47 ± 0.01	11.20 ± 0.31	0.29 ± 0.06	1
NGC1374	E3	1	19.23 ± 0.66	8.76 ± 0.06	2.23 ± 0.01	10.72 ± 0.06	0.36 ± 0.01	1
NGC1407	E0	0	28.05 ± 3.37	9.65 ± 0.08	2.442 ± 0.003	11.72 ± 0.12	0.97 ± 0.05	0
NGC1550	SA0	0	51.57 ± 5.60	9.57 ± 0.07	2.44 ± 0.02	11.32 ± 0.10	0.66 ± 0.05	0
NGC3091	E3	0	51.25 ± 8.30	9.56 ± 0.07	2.48 ± 0.02	11.75 ± 0.06	1.10 ± 0.07	1
NGC3368	SABab	3	10.40 ± 0.96	6.88 ± 0.08	2.122 ± 0.003	10.09 ± 0.06	-0.57 ± 0.04	1
NGC3489	SAB0	3	12.10 ± 0.84	6.78 ± 0.05	1.949 ± 0.002	9.68 ± 0.25	-1.00 ± 0.03	1
NGC4751	E	1	26.92 ± 2.92	9.15 ± 0.06	2.56 ± 0.02	10.95 ± 0.09	0.52 ± 0.05	0
NGC5328	E	0	64.10 ± 6.96	9.67 ± 0.16	2.523 ± 0.002	11.71 ± 0.09	0.94 ± 0.05	0
NGC5516	E	0	58.44 ± 6.35	9.52 ± 0.06	2.52 ± 0.02	11.83 ± 0.09	1.30 ± 0.05	0
NGC6861	E	1	27.30 ± 4.55	9.30 ± 0.08	2.590 ± 0.003	11.14 ± 0.13	0.32 ± 0.07	0
NGC7619	E	0	51.52 ± 7.38	9.40 ± 0.11	2.47 ± 0.01	11.78 ± 0.25	1.16 ± 0.06	1
NGC2748	Sc	3	23.40 ± 8.24	7.65 ± 0.24	2.06 ± 0.02	9.84 ± 0.25	-0.39 ± 0.15	1
NGC4151	Sa	2	20.00 ± 2.77	7.81 ± 0.08	2.19 ± 0.02	10.61 ± 0.25	-0.18 ± 0.06	1
NGC7457	S0	2	12.53 ± 1.21	6.95 ± 0.30	1.83 ± 0.02	9.69 ± 0.08	-0.28 ± 0.04	1
NGC307	S0	2	52.80 ± 5.74	8.60 ± 0.06	2.31 ± 0.01	10.50 ± 0.05	-0.31 ± 0.05	0
NGC3627	SAB(s)b	3	10.05 ± 1.09	6.93 ± 0.05	2.088 ± 0.002	9.45 ± 0.09	-1.08 ± 0.05	0
NGC3923	E4	1	20.88 ± 2.70	9.45 ± 0.12	2.35 ± 0.02	11.50 ± 0.11	0.89 ± 0.06	0
NGC4486A	E2	1	16.00 ± 0.52	7.10 ± 0.15	2.16 ± 0.01	10.08 ± 0.05	-0.19 ± 0.01	0
NGC4501	SA(rs)b	3	16.50 ± 1.14	7.30 ± 0.08	2.20 ± 0.01	10.16 ± 0.07	-0.40 ± 0.03	0
NGC5018	E3	1	40.55 ± 4.87	8.02 ± 0.08	2.32 ± 0.01	11.54 ± 0.09	0.62 ± 0.05	0
NGC5419	E	0	56.20 ± 6.11	9.86 ± 0.14	2.56 ± 0.01	12.00 ± 0.09	1.26 ± 0.05	0
IC4296	BCGE	0	49.20 ± 3.63	9.11 ± 0.07	2.51 ± 0.02	11.78 ± 0.25	1.21 ± 0.03	1
NGC1277	S0/	2	73.00 ± 7.30	9.70 ± 0.05	2.52 ± 0.07	10.83 ± 0.08	0.09 ± 0.04	0
IC2560	SBbc	3	33.20 ± 3.32	6.59 ± 0.16	2.15 ± 0.02	10.13 ± 0.25	-0.14 ± 0.04	1

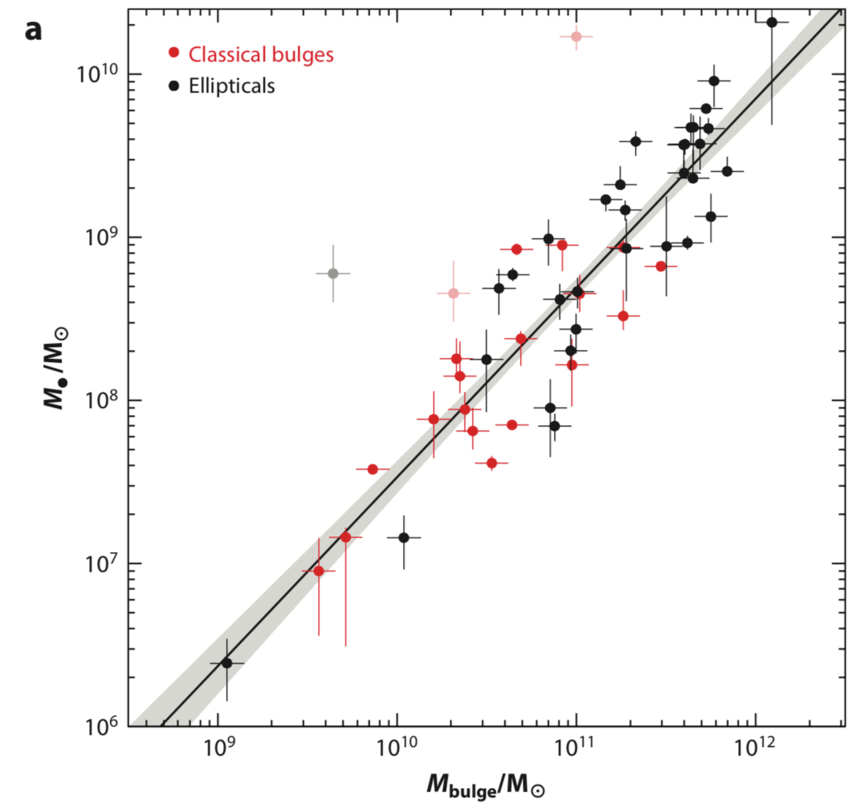
Galaxy	Morphology	A	Distance (Mpc)	M_{BH} (log $M_\odot$)	σ_e (log km/s)	L_K (log $L_\odot$)	R_e (log kpc)	B
NGC224	Sb	2	0.77 ± 0.03	8.15 ± 0.16	2.23 ± 0.02	10.34 ± 0.10	-0.19 ± 0.02	1
NGC4472	E2	0	17.14 ± 0.59	9.40 ± 0.04	2.48 ± 0.01	11.86 ± 0.06	1.05 ± 0.01	1
NGC3031	Sb	2	3.60 ± 0.13	7.81 ± 0.13	2.15 ± 0.02	10.43 ± 0.31	-0.24 ± 0.02	1
NGC4374	E1	0	18.51 ± 0.60	8.97 ± 0.05	2.47 ± 0.02	11.64 ± 0.25	1.07 ± 0.01	1
NGC4486	E1	0	16.68 ± 0.62	9.68 ± 0.04	2.51 ± 0.03	11.64 ± 0.25	0.85 ± 0.02	1
NGC4594	Sa	2	9.87 ± 0.82	8.82 ± 0.04	2.38 ± 0.02	10.79 ± 0.25	-0.03 ± 0.08	1
NGC3379	E1	0	10.70 ± 0.54	8.62 ± 0.11	2.31 ± 0.02	10.96 ± 0.25	0.42 ± 0.02	1
NGC221	E2	1	0.80 ± 0.03	6.39 ± 0.19	1.89 ± 0.02	9.12 ± 0.04	-0.90 ± 0.02	0
CygnusA	E	0	242.70 ± 24.27	9.42 ± 0.12	2.43 ± 0.05	12.19 ± 0.10	1.46 ± 0.04	0
NGC1271	SB0	2	80.00 ± 8.00	9.48 ± 0.15	2.45 ± 0.01	11.07 ± 0.08	0.34 ± 0.07	0
NGC1275	E	1	73.80 ± 7.38	8.90 ± 0.24	2.39 ± 0.08	11.84 ± 0.08	1.15 ± 0.04	0
NGC1600	E	0	64.00 ± 6.40	10.23 ± 0.04	2.47 ± 0.02	11.86 ± 0.08	1.08 ± 0.04	0
NGC3706	E	0	46.00 ± 4.60	8.78 ± 0.06	2.51 ± 0.01	11.58 ± 0.08	0.80 ± 0.04	0
NGC5252	S0	2	92.00 ± 9.20	8.98 ± 0.23	2.28 ± 0.02	11.49 ± 0.09	0.88 ± 0.06	0
NGC4339	E	1	16.00 ± 1.60	7.63 ± 0.36	1.98 ± 0.02	10.26 ± 0.25	0.37 ± 0.04	0
NGC4434	E	1	22.40 ± 2.24	7.85 ± 0.15	1.99 ± 0.02	10.28 ± 0.25	0.20 ± 0.04	0
NGC4578	E	1	16.30 ± 1.63	7.28 ± 0.22	2.03 ± 0.02	10.33 ± 0.25	0.49 ± 0.04	0
NGC4762	E	1	22.60 ± 2.26	7.36 ± 0.14	2.13 ± 0.02	11.05 ± 0.25	1.06 ± 0.04	0

De Nicola, AM, Longo 2018

Many BH-galaxy relations

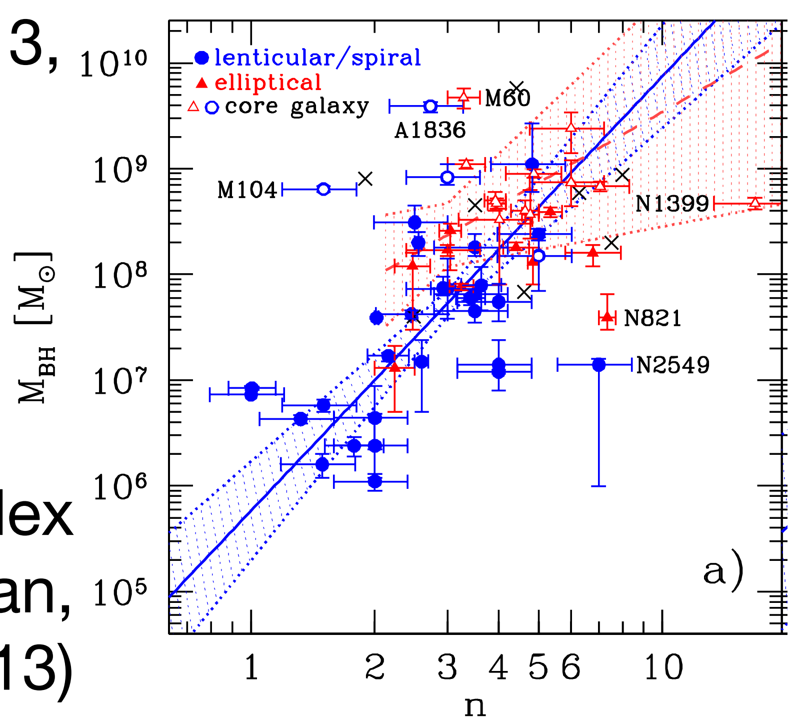
- BH masses correlate with almost every property of the *host spheroid*



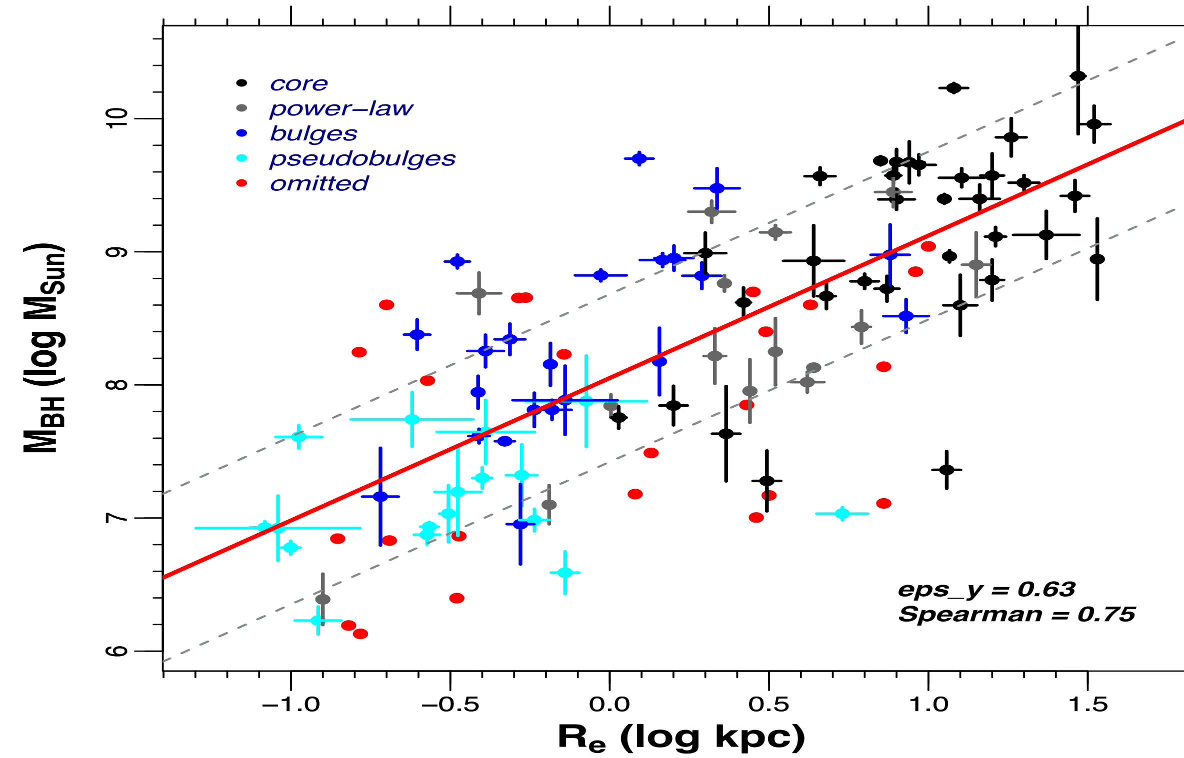


(Stellar) mass (e.g. Sani+11, K&H13, Reines & Volonteri 15)

L, σ (e.g. K&H 13, Mc Connell & Ma+13, Van Den Bosch 16)

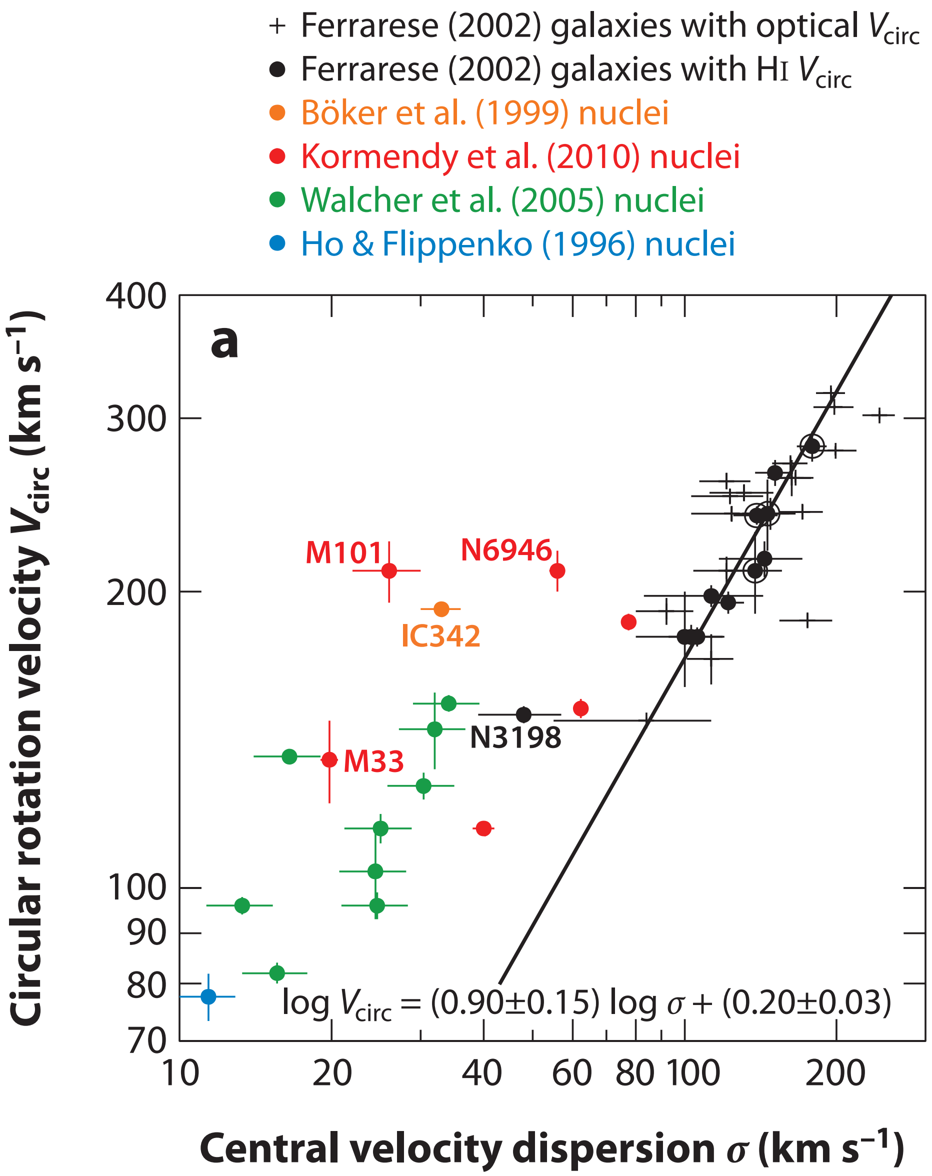


Sersic index (e.g. Savorgnan, Graham+13)

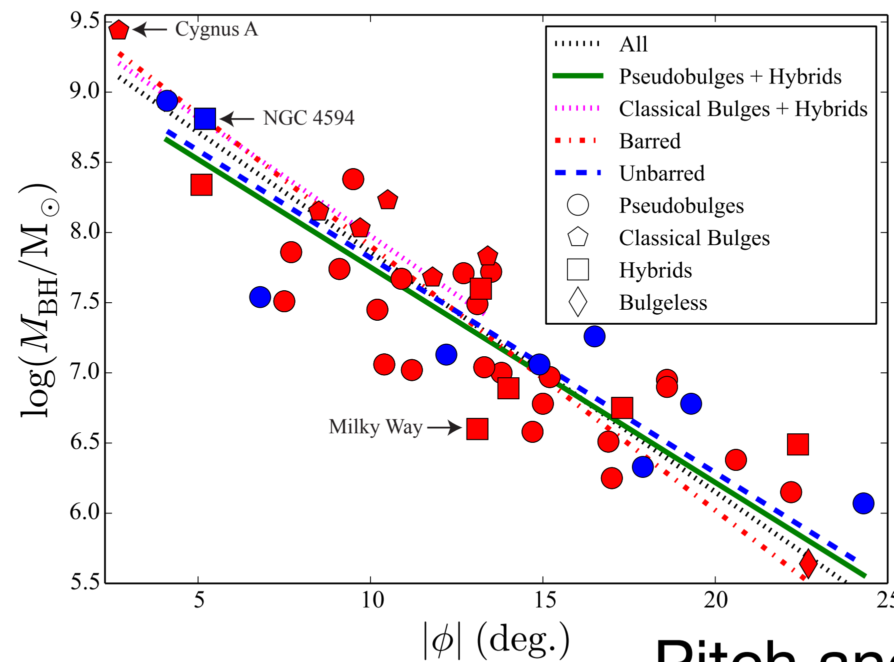


Effective radius (e.g. De Nicola+18)

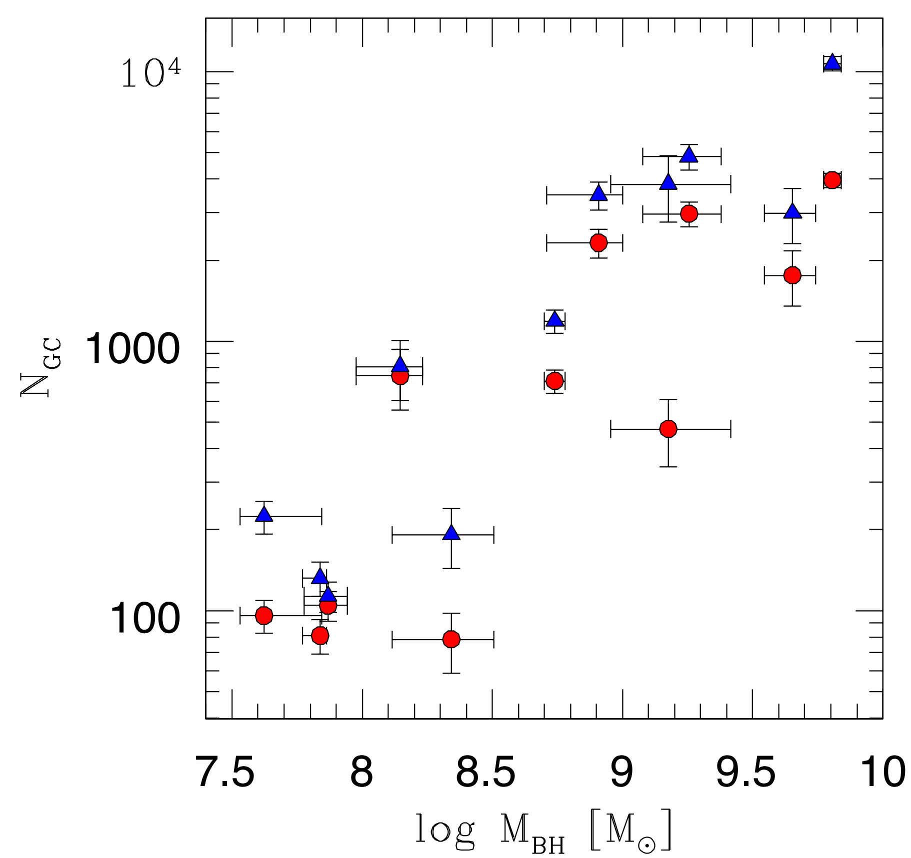
Many BH-galaxy relations



DM Halo mass
(see Kormendy & Ho 13)



Pitch angle of spiral arms (e.g. Davis+17)

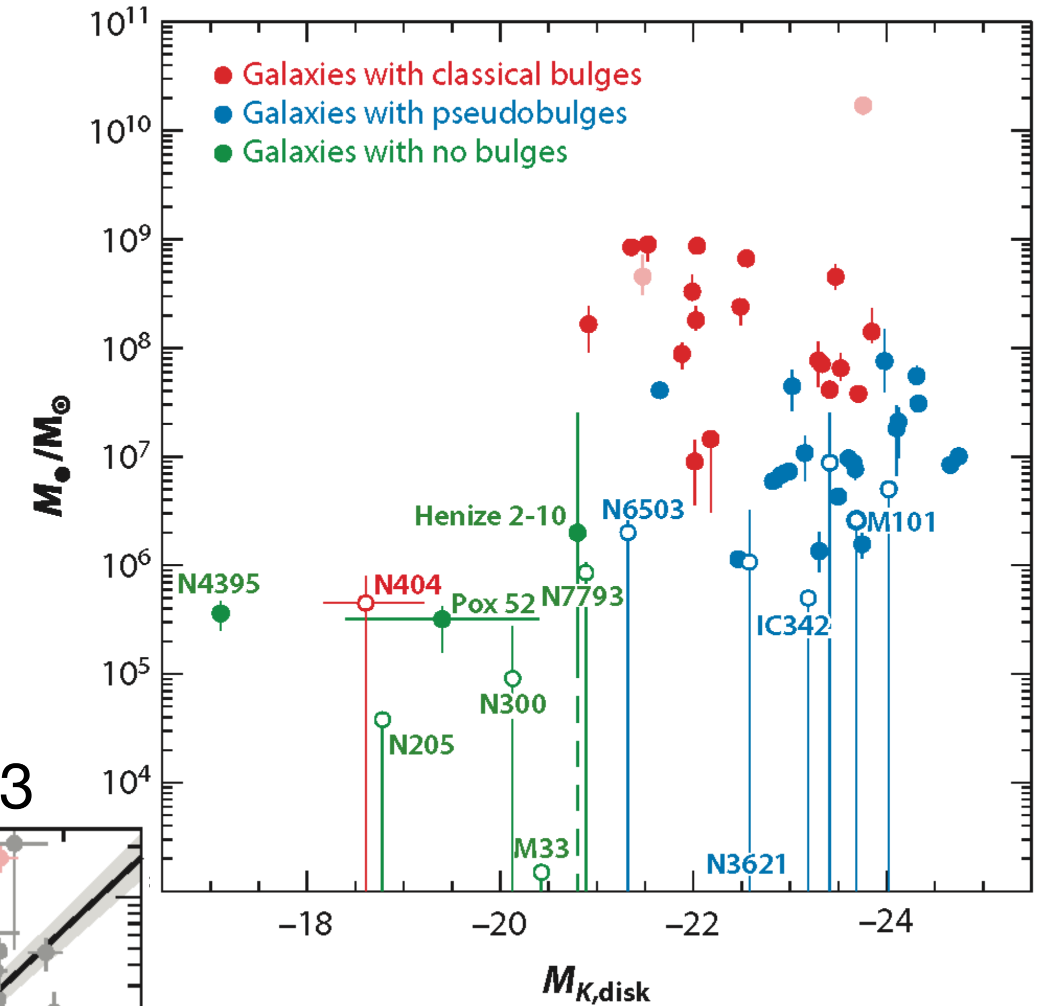


Number of globular clusters (Burkert & Tremaine 11)

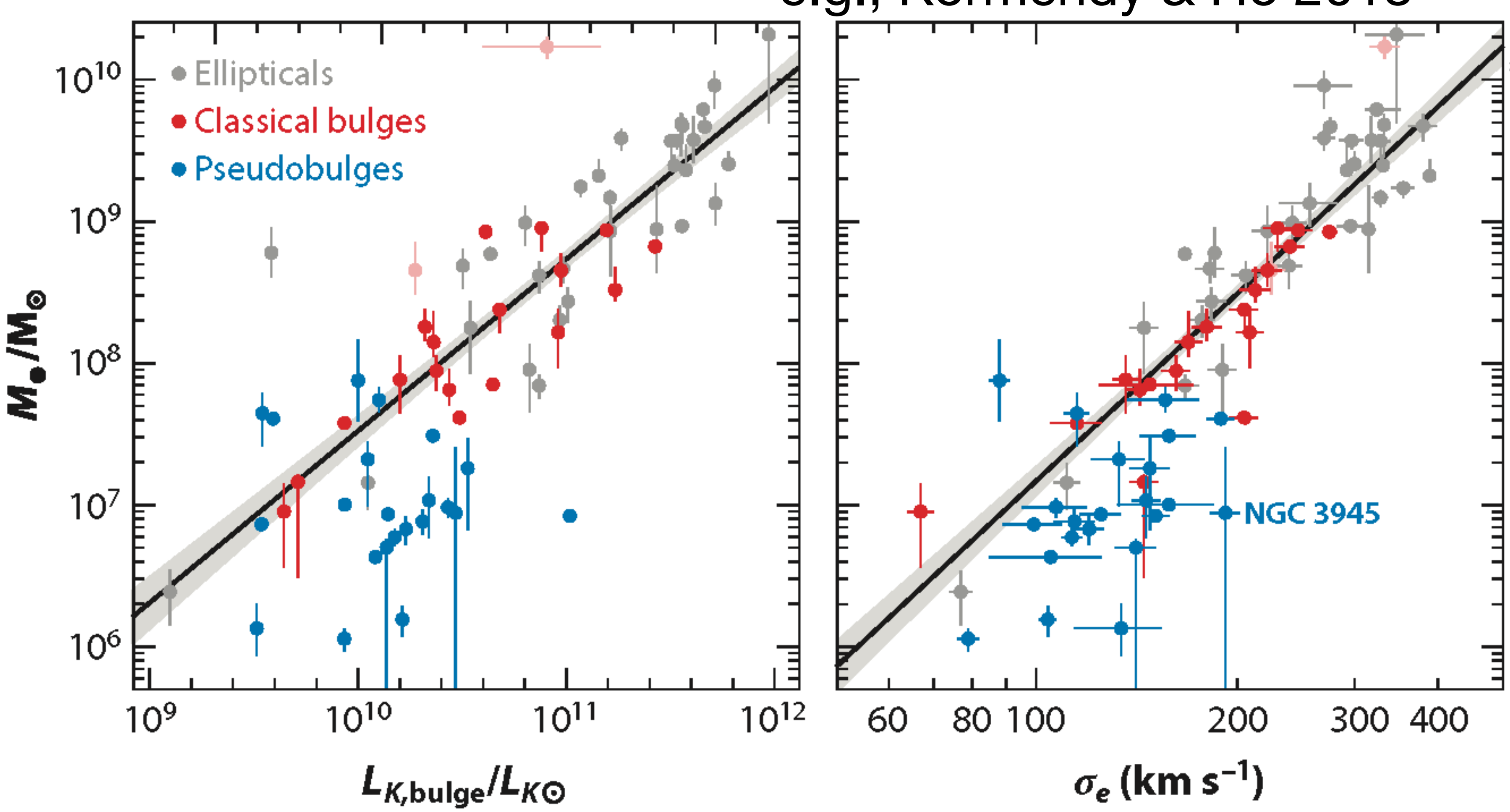
Bulges vs Pseudobulges and Disks

Our view has further changed in recent years

- different BH-galaxy relations for different "bulges", *disks do not correlate*
- classical bulges: form after merger events, feedback is important
- pseudo bulges: form by secular processes, no feedback required



e.g., Kormendy & Ho 2013

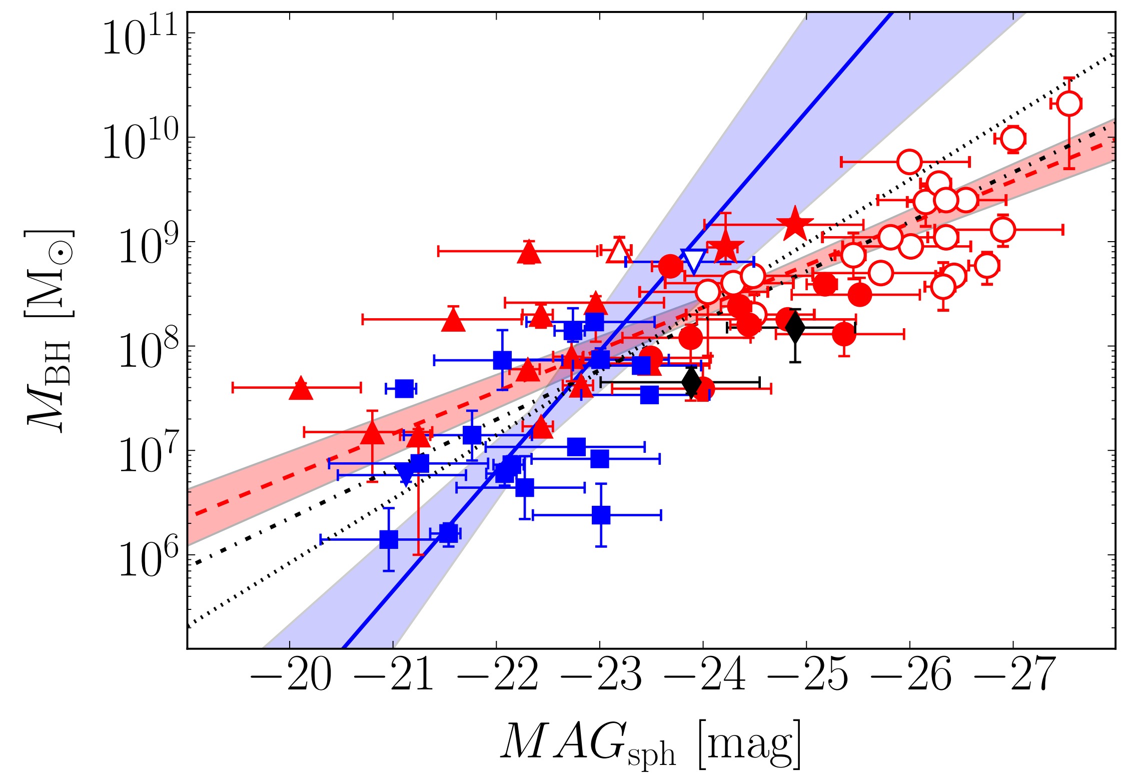


- but there are BHs in bulgeless galaxies …

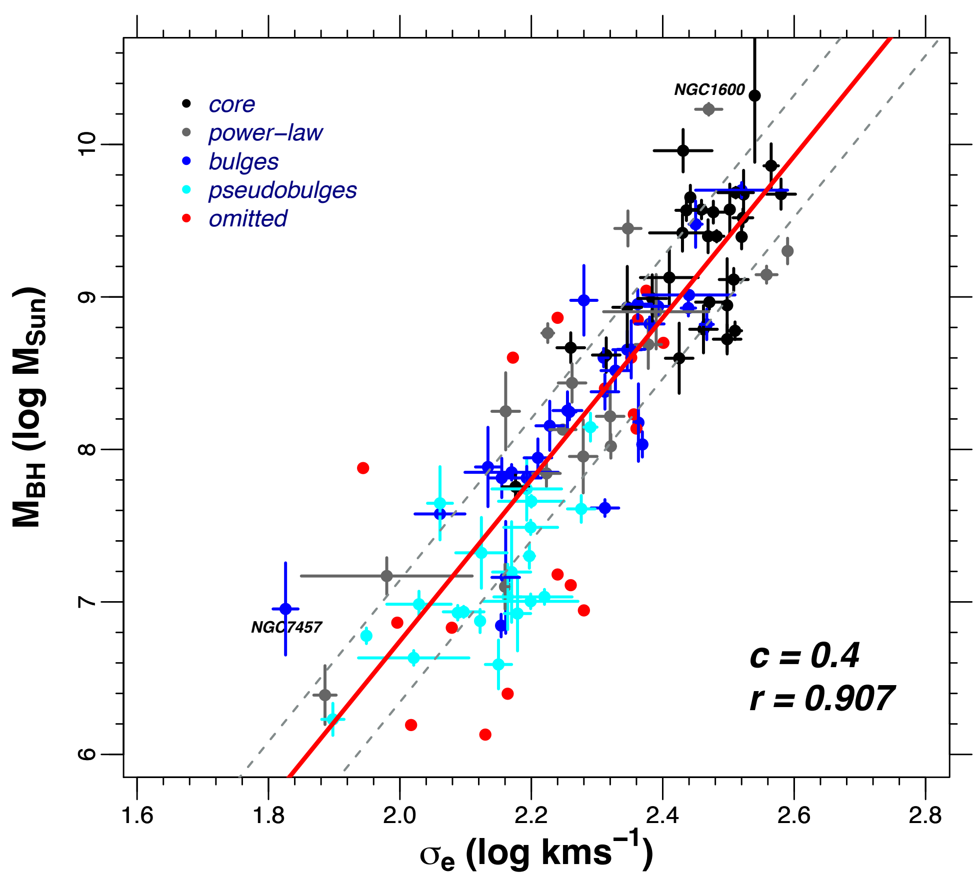
More complex than we previously thought …

Different relations for late & early types?

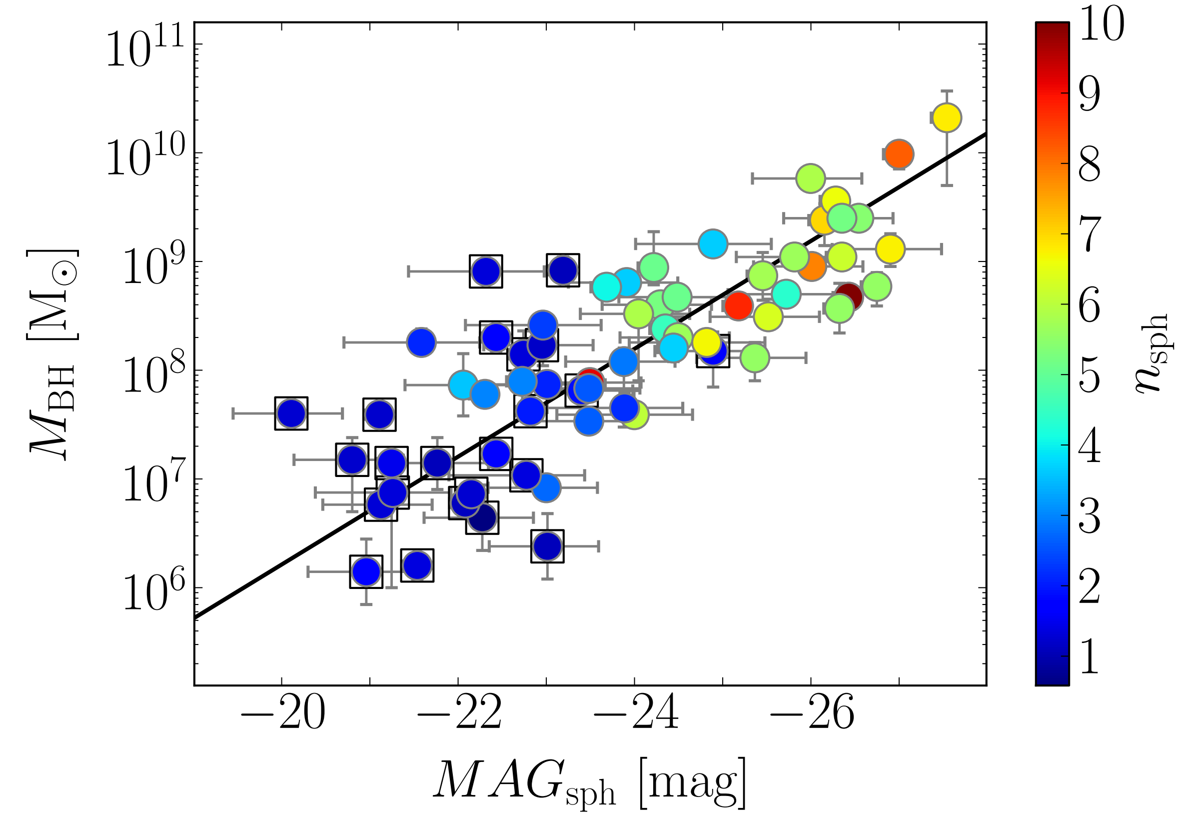
- Recent work with careful bulge/disk decomposition from 3.6 μm Spitzer images (Savorgnan & Graham 2015)
- Accurate BH-galaxy relations: no difference between bulges and pseudo-bulges, apparently due to different relations for early type galaxies spheroids (red sequence) and spiral galaxy bulges / spheroids (blue cloud)



Savorgnan, Graham, AM, Sani 2015



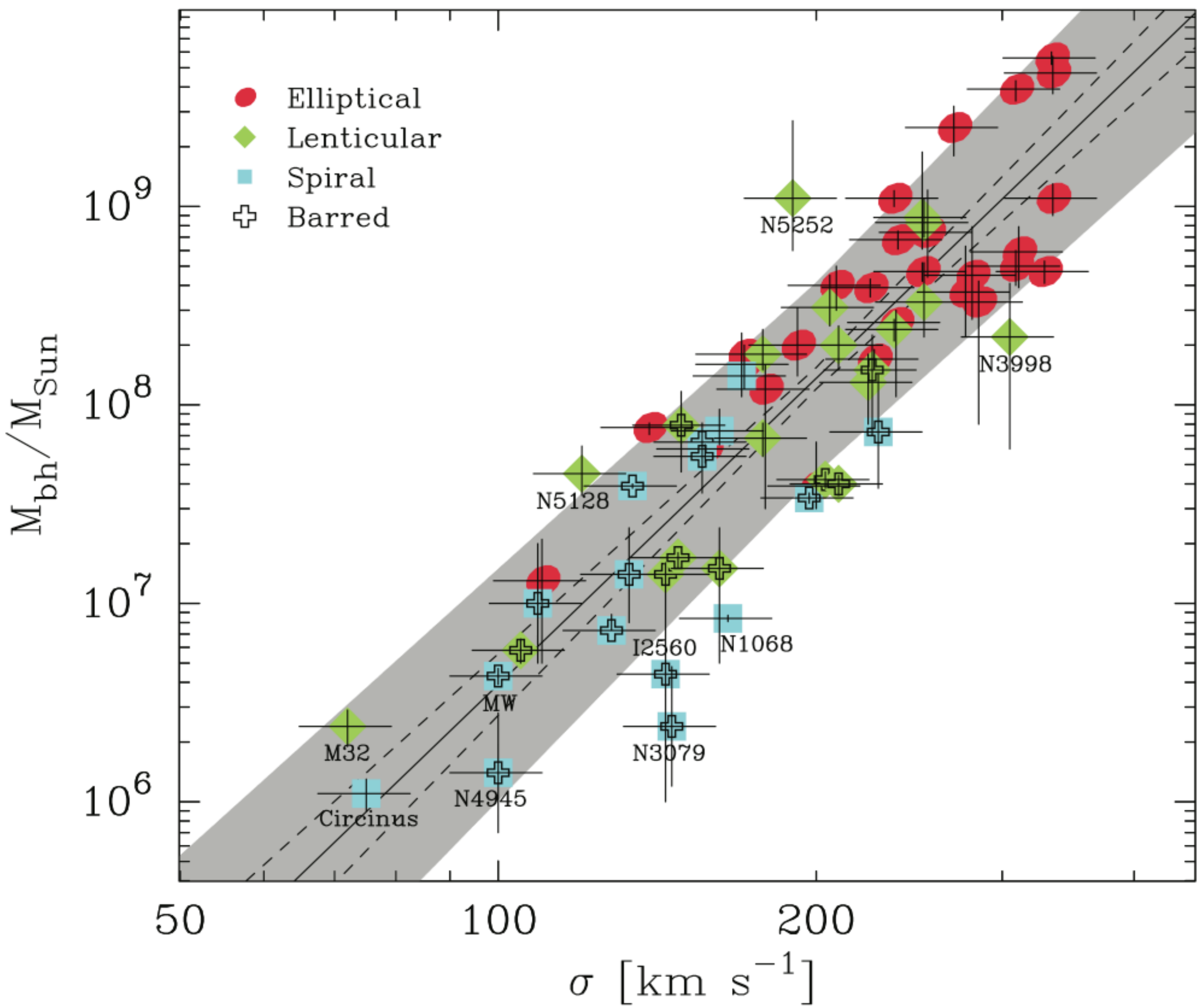
De Nicola, AM, Longo 18



An observational bias?

Maximum distance at which a BH can be detected (R_{BH} spatially resolved)

$$D = 22\,\mathrm{Mpc}\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}\left(\frac{\Delta\theta}{0.1''}\right)^{-1}$$



e.g. Batcheldor 2010 but see Gultekin+11

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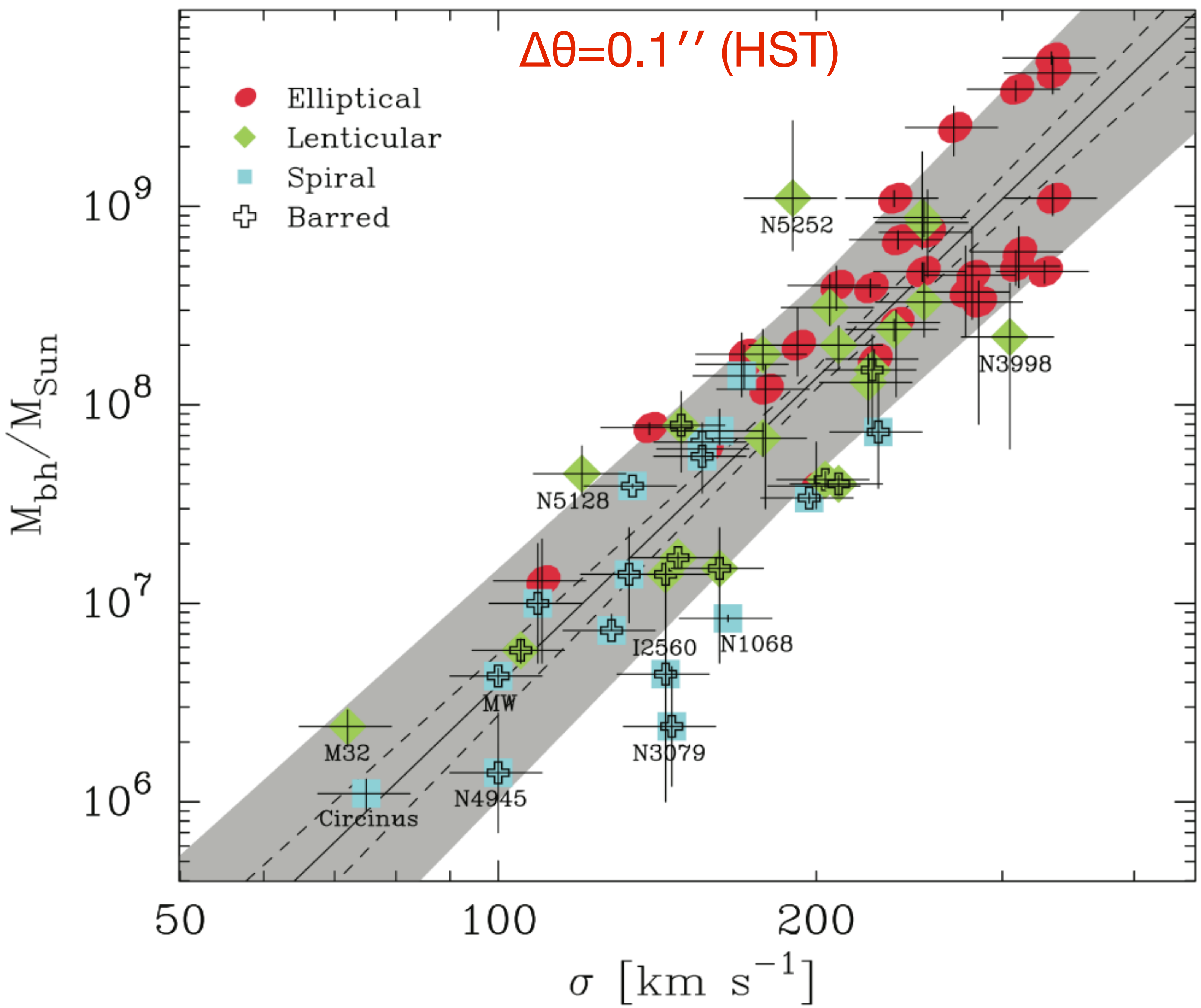

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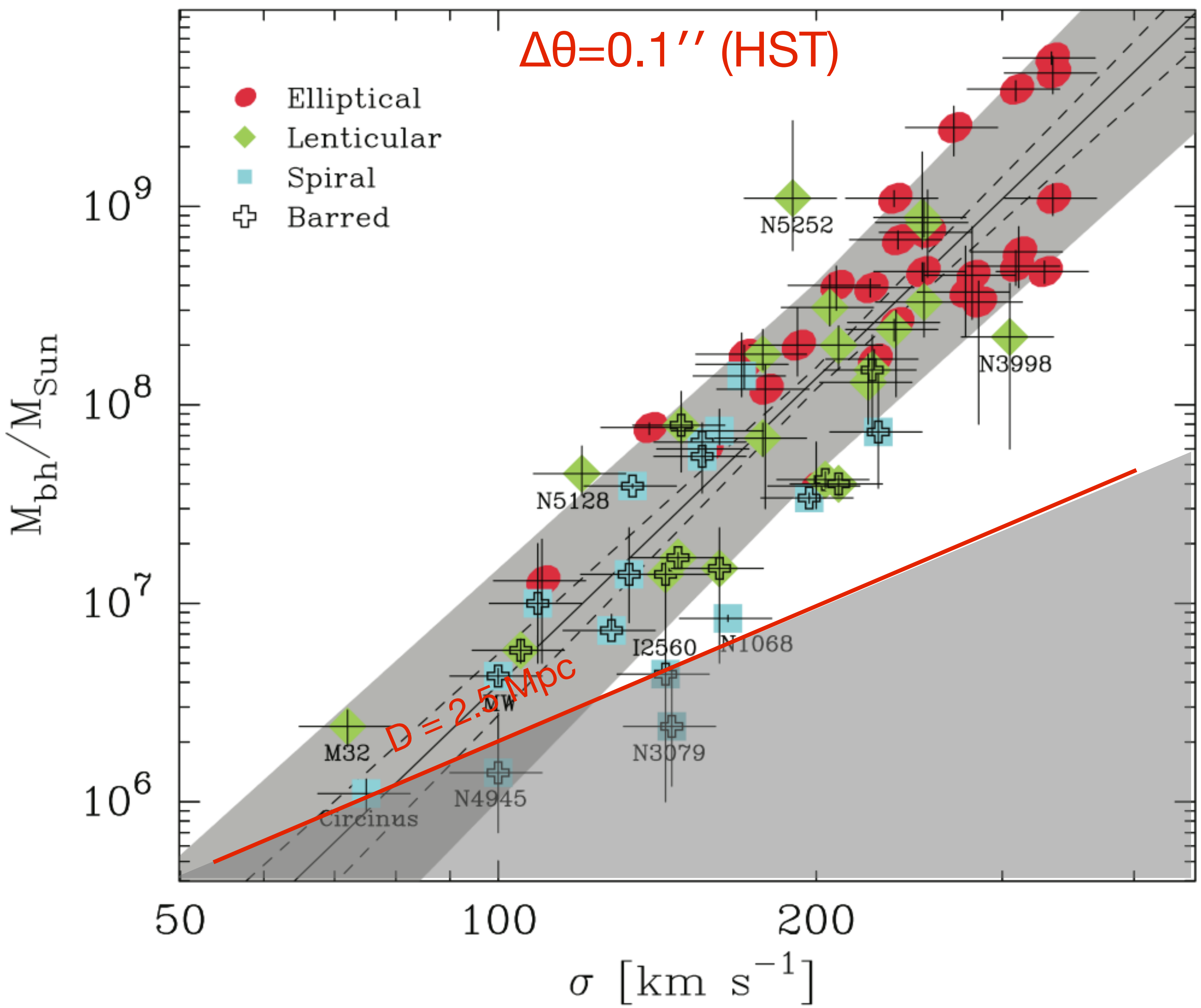

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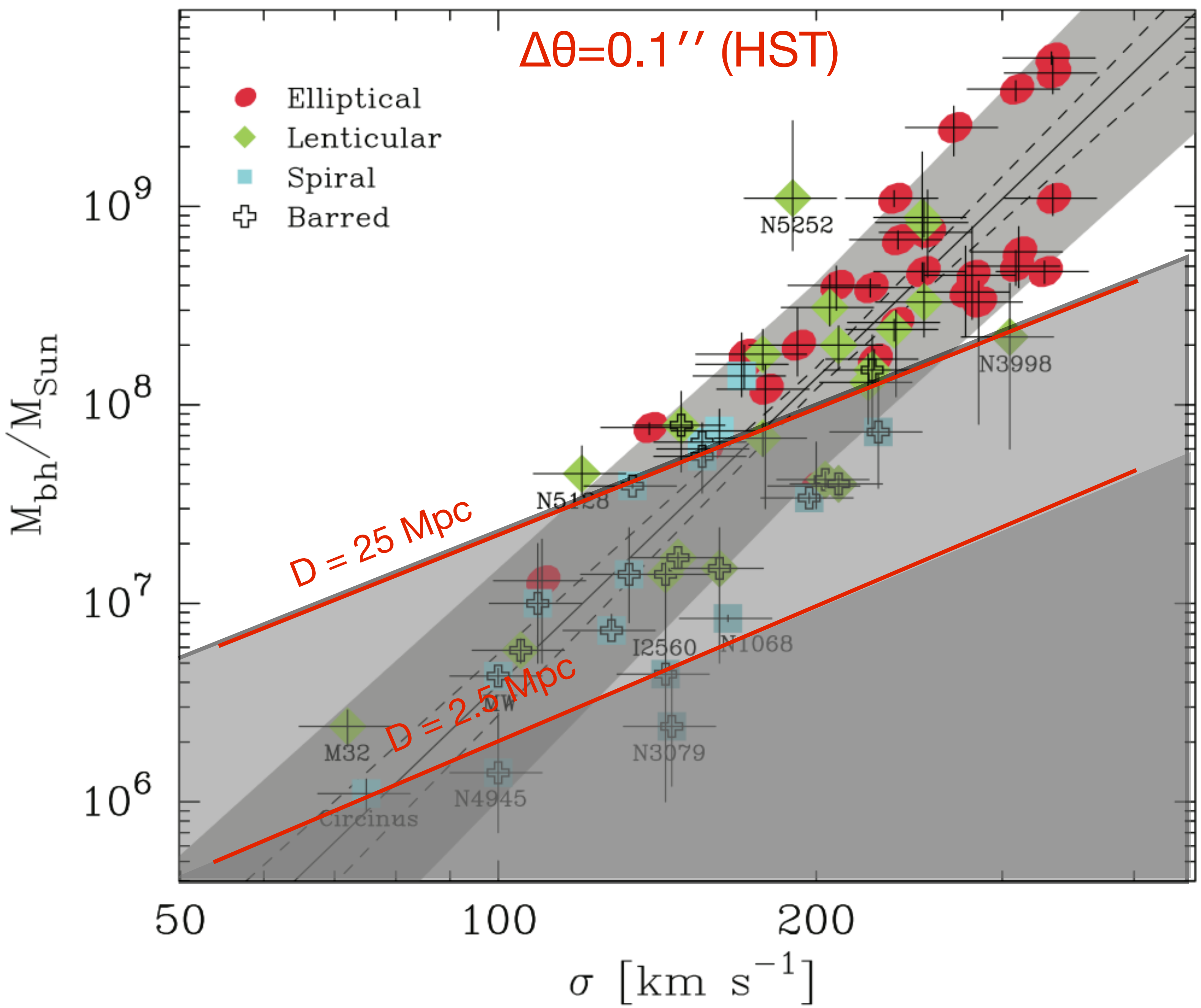

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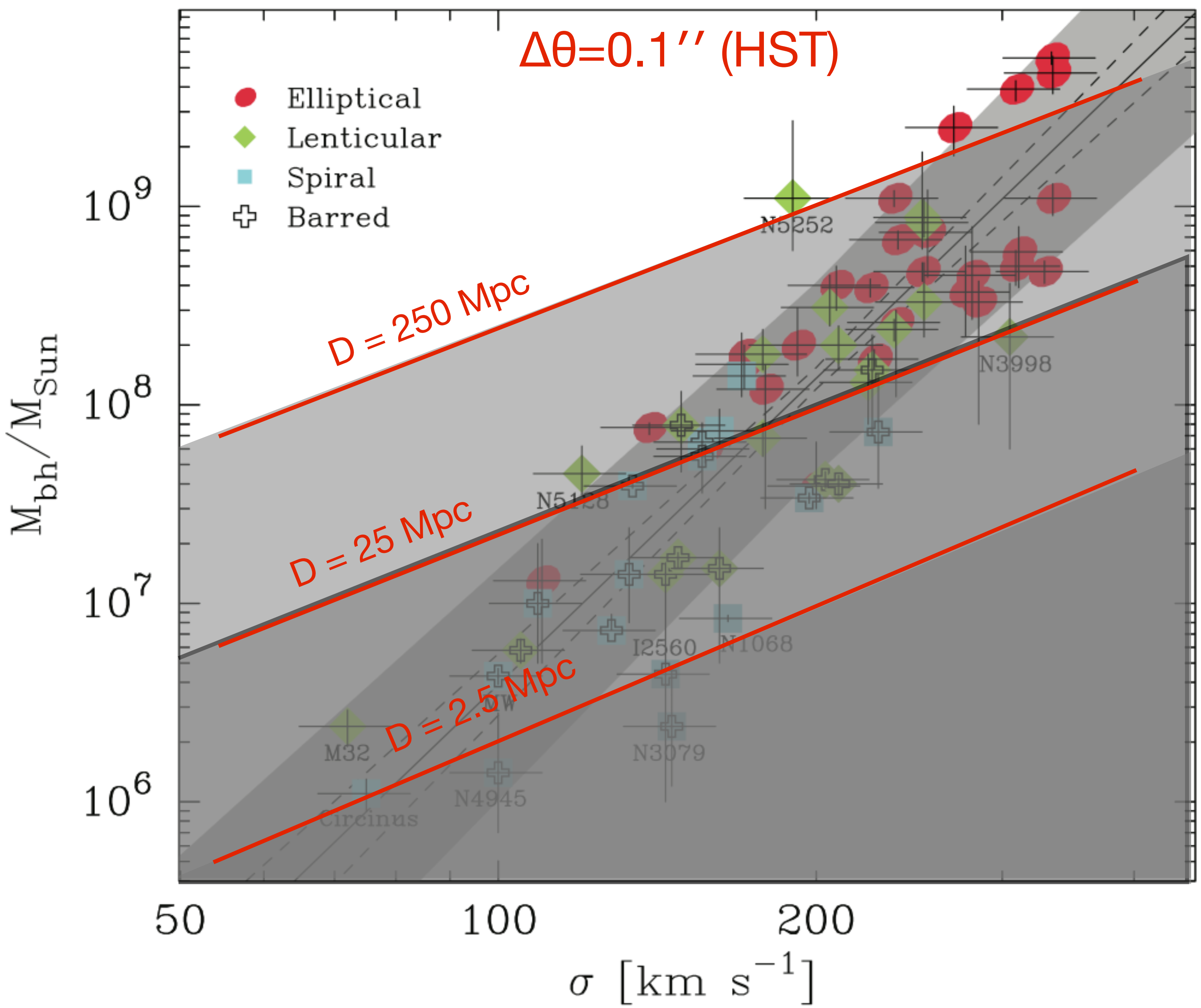

e.g. Batcheldor 2010 but see Gultekin+11

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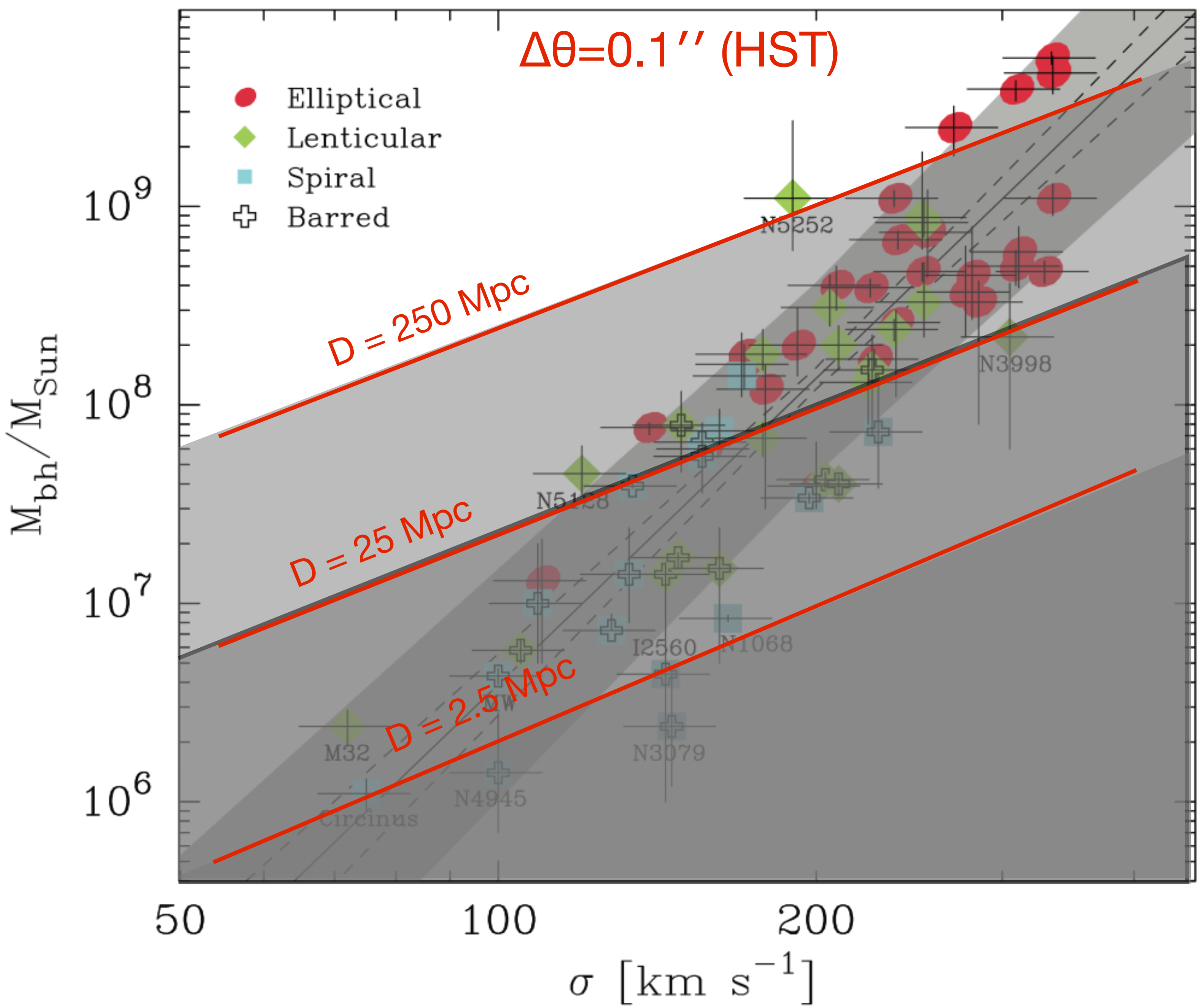


NO detection areas on M_{BH}-σ diagram for given Δθ, D:

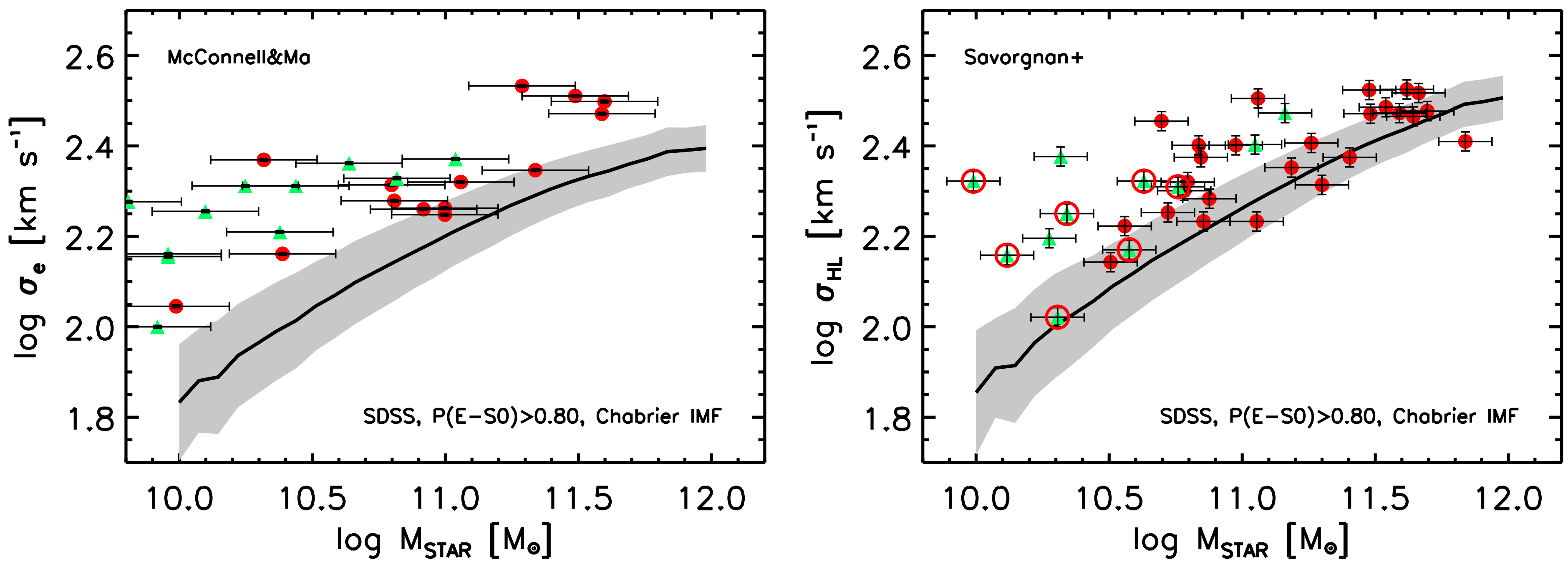
- Direct M_{BH} measures are limited to the local universe (D~250 Mpc)
- There are definitely no BHs above the correlation (big BHs in small galaxies)
- The area below the correlation is 'biased' and cannot be explored (small BHs in big galaxies?)

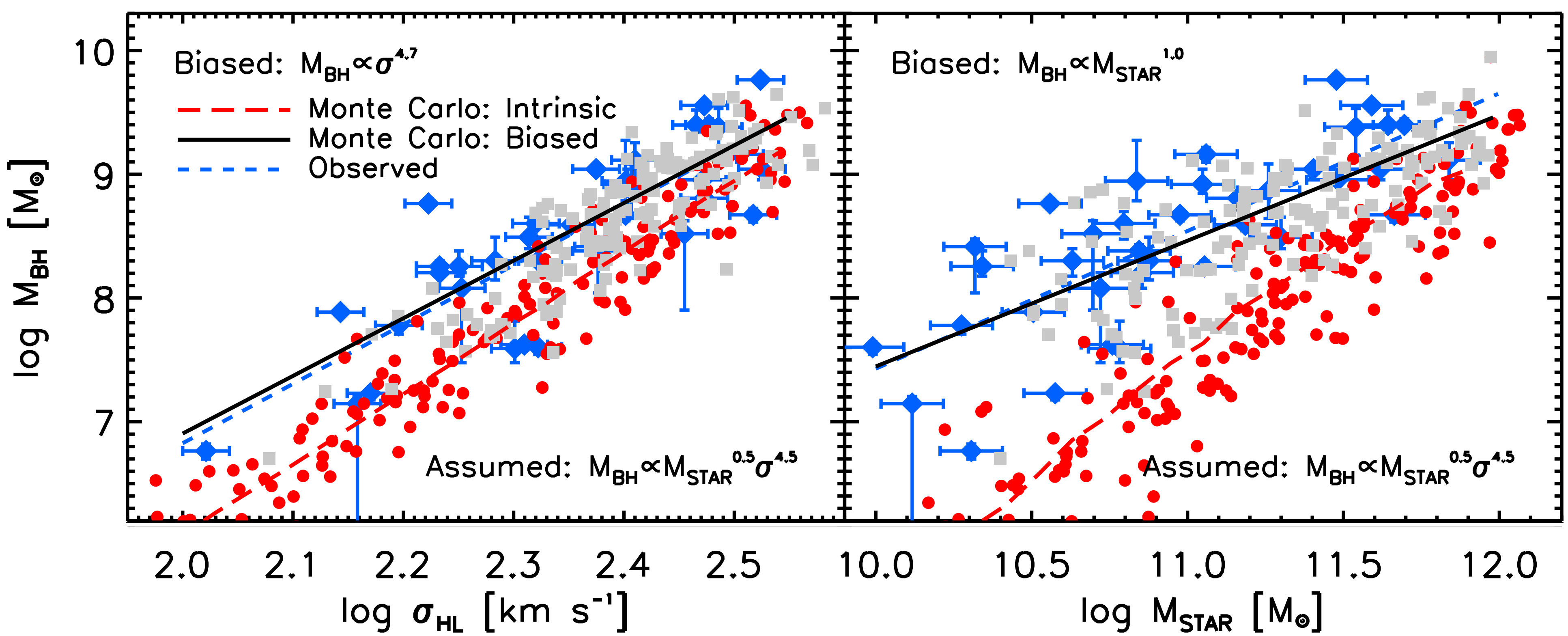
e.g. Batcheldor 2010 but see Gultekin+11

Mass Bias

Correlations are biased to higher Mass/Velocity dispersion galaxies

- *Normalization of M_{BH}-σ relation increased by factor ~3*





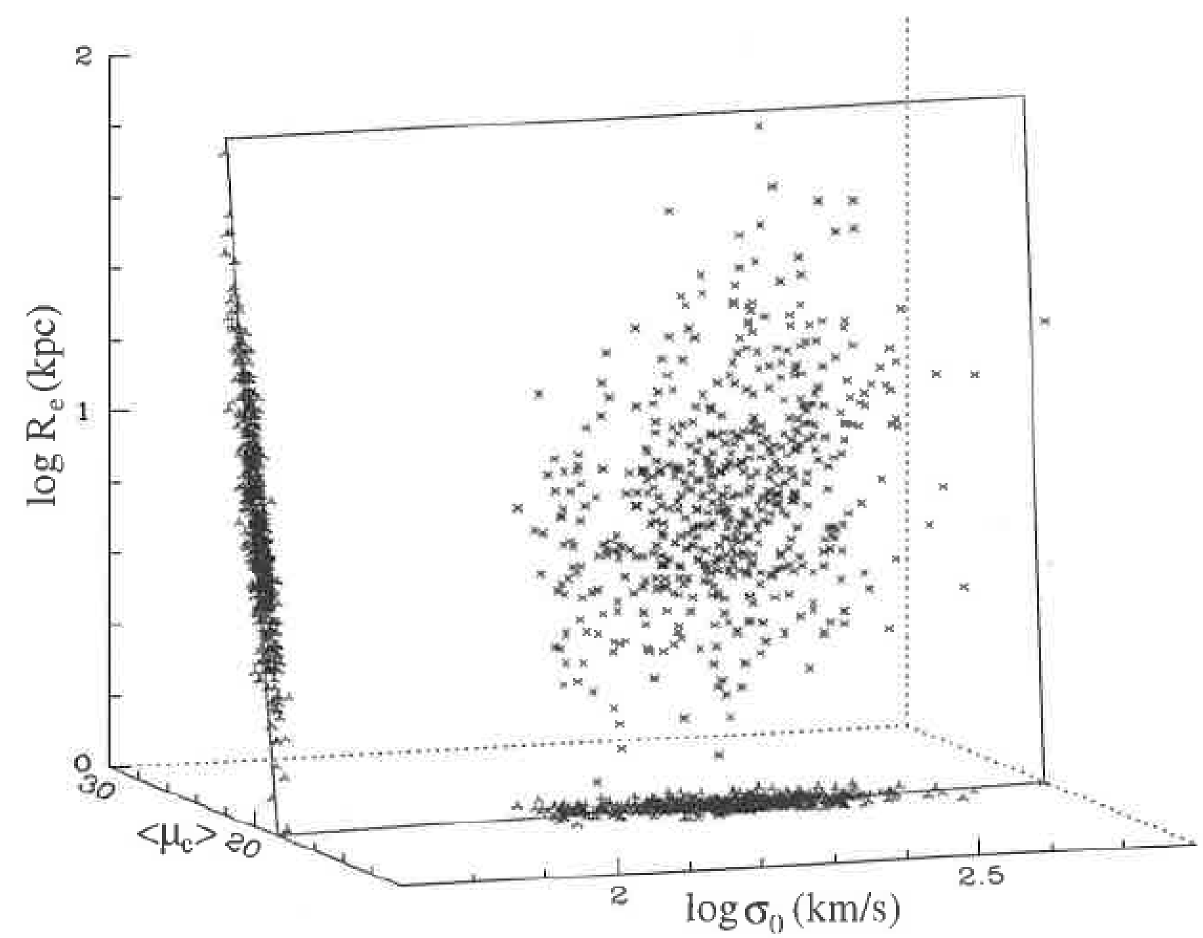
Shankar+16

Which is the “fundamental” relation?

- Relations with M, L, σ, R and other parameters suggest existence of “fundamental” BH-galaxy relation
- Proposal of BH “Fundamental plane” $M_{BH} \sim \sigma^{\alpha} R^{\beta}$ (e.g. Hopkins+2007)
  - Hopkins+ find $M_{BH} \sim \sigma^{3.0} R^{0.4}$ ($-E_{grav} \sim 2\ E_{kin} \sim \sigma^{4.0} R$)
- In general M_{BH}-σ considered “fundamental” because it has smaller intrinsic scatter

- What about the well-known fundamental plane of elliptical galaxies?
  - Almost never taken into account …

- Van den Bosch+16 finds $M_{BH} \sim (L_K/R_e)^{3.8}$ with same scatter as $M_{BH} \sim \sigma^{5.4}$ consistent with FP Projection
- M_{BH}-σ main relation, other relations are combination with FP



Data from Saglia+97, Wegner+99

BH Database as of “today”

- About 80 galaxies with “secure” BH masses
- Additional ~40 galaxies with less reliable measurements or upper limits
- Various galaxy morphological types

- De Nicola, AM, Longo (2018) combine “secure” BH masses with photometry from Spizter 3.6um or K band (good tracers of stellar mass)

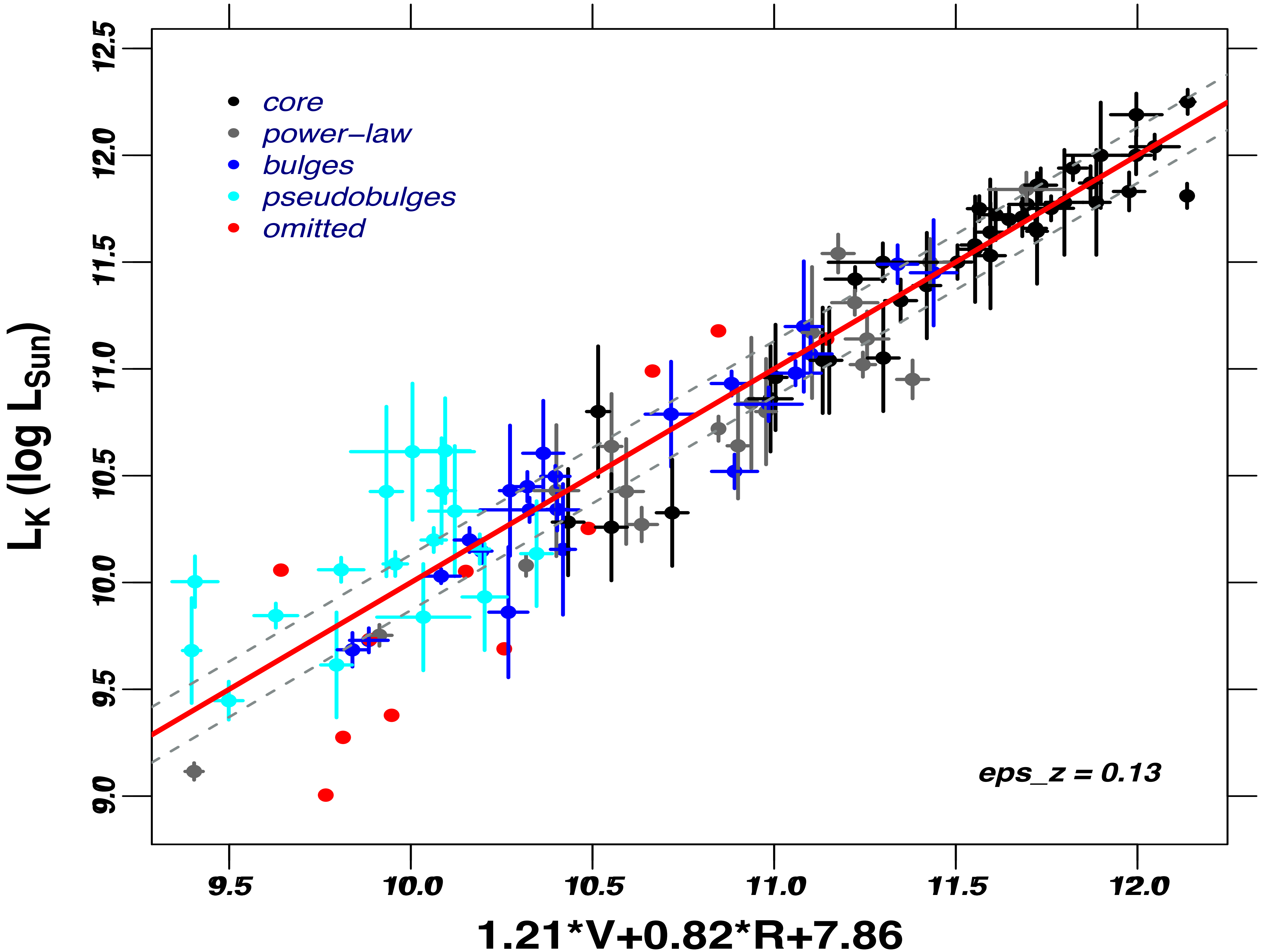
Galaxy	Morphology	A	Distance (Mpc)	M_{BH} (log $M_{\odot}$)	σ_e (log km/s)	L_K (log $L_{\odot}$)	R_e (log kpc)	B
Circinus	SABb:	3	2.82 ± 0.47	6.23 ± 0.10	1.90 ± 0.02	10 ± 0.12	-0.91 ± 0.07	1
A1836	BCGE	0	152.40 ± 8.43	9.57 ± 0.06	2.46 ± 0.02	11.75 ± 0.06	0.89 ± 0.02	0
IC1459	E4	0	28.92 ± 3.74	9.39 ± 0.08	2.52 ± 0.01	11.70 ± 0.06	0.90 ± 0.06	1
NGC524	S0	2	24.22 ± 2.23	8.94 ± 0.05	2.39 ± 0.02	10.52 ± 0.08	0.17 ± 0.07	1
NGC821	S0	1	23.44 ± 1.84	8.22 ± 0.21	2.32 ± 0.02	10.84 ± 0.31	0.33 ± 0.03	1
NGC1023	SB0	2	10.81 ± 0.80	7.62 ± 0.06	2.31 ± 0.02	10.45 ± 0.07	-0.41 ± 0.03	1
NGC1399	E1	0	20.85 ± 0.67	8.95 ± 0.31	2.498 ± 0.004	11.81 ± 0.06	1.53 ± 0.01	1
NGC2273	SBa	3	29.50 ± 1.90	6.93 ± 0.04	2.10 ± 0.03	10.43 ± 0.40	-0.57 ± 0.03	1
NGC2549	S0/	2	12.70 ± 1.64	7.16 ± 0.37	2.16 ± 0.02	9.73 ± 0.06	-0.72 ± 0.06	1
NGC3115	S0/	2	9.54 ± 0.4	8.95 ± 0.10	2.36 ± 0.02	10.93 ± 0.06	0.20 ± 0.06	1
NGC3227	SBa	3	23.75 ± 2.63	7.32 ± 0.23	2.12 ± 0.04	9.93 ± 0.25	-0.28 ± 0.05	1
NGC3245	S0	2	21.38 ± 1.97	8.38 ± 0.11	2.31 ± 0.02	10.20 ± 0.06	-0.60 ± 0.04	1
NGC3377	E5	1	10.99 ± 0.46	8.25 ± 0.25	2.16 ± 0.02	10.64 ± 0.25	0.52 ± 0.02	1
NGC3384	SB0	3	11.49 ± 0.74	7.03 ± 0.21	2.16 ± 0.02	10.20 ± 0.06	-0.51 ± 0.03	1
NGC3393	SABa	3	49.20 ± 8.19	7.20 ± 0.33	2.17 ± 0.03	10.62 ± 0.25	-0.48 ± 0.07	1
NGC3585	S0	2	20.51 ± 1.70	8.52 ± 0.13	2.33 ± 0.02	11.45 ± 0.25	0.93 ± 0.07	1
NGC3608	E1	0	22.75 ± 1.47	8.67 ± 0.10	2.26 ± 0.02	11.04 ± 0.25	0.68 ± 0.03	1
NGC3842	E1	0	92.20 ± 10.64	9.96 ± 0.14	2.43 ± 0.04	12.04 ± 0.06	1.52 ± 0.05	1
NGC3998	S0	2	14.30 ± 1.25	8.93 ± 0.05	2.44 ± 0.01	10.15 ± 0.31	-0.48 ± 0.04	1
NGC4026	S0	2	13.35 ± 1.73	8.26 ± 0.12	2.25 ± 0.02	9.86 ± 0.31	-0.39 ± 0.06	1
NGC4258	SABbc	2	7.27 ± 0.50	7.58 ± 0.03	2.06 ± 0.04	10.03 ± 0.03	-0.33 ± 0.03	1
NGC4261	E2	0	32.36 ± 2.84	8.72 ± 0.10	2.5 ± 0.02	11.53 ± 0.25	0.87 ± 0.04	1
NGC4291	E2	0	26.58 ± 3.93	8.99 ± 0.16	2.38 ± 0.02	10.86 ± 0.25	0.30 ± 0.06	1
NGC4459	E2	1	16.01 ± 0.52	7.84 ± 0.09	2.22 ± 0.02	10.64 ± 0.25	0.00 ± 0.01	1
NGC4473	E5	1	15.25 ± 0.49	7.95 ± 0.24	2.28 ± 0.02	10.80 ± 0.25	0.44 ± 0.01	1
NGC4564	S0	2	15.94 ± 0.51	7.95 ± 0.12	2.21 ± 0.02	10.15 ± 0.25	-0.41 ± 0.01	1
NGC4596	SB0	2	16.53 ± 6.23	7.88 ± 0.26	2.13 ± 0.02	10.34 ± 0.06	-0.14 ± 0.16	1
NGC4649	E2	0	16.46 ± 0.61	9.67 ± 0.10	2.58 ± 0.02	11.66 ± 0.06	0.90 ± 0.02	0
NGC4697	E5	1	12.54 ± 0.40	8.13 ± 0.01	2.25 ± 0.02	11.17 ± 0.31	0.64 ± 0.01	1
NGC4889	E4	0	102.00 ± 5.17	10.32 ± 0.44	2.54 ± 0.01	12.25 ± 0.06	1.47 ± 0.02	1
NGC5077	E3	0	38.70 ± 8.44	8.93 ± 0.27	2.35 ± 0.02	11.42 ± 0.06	0.64 ± 0.09	1
NGC5128	E	0	3.62 ± 0.20	7.75 ± 0.08	2.18 ± 0.02	10.80 ± 0.31	0.03 ± 0.02	1
NGC5576	E3	1	25.68 ± 1.66	8.44 ± 0.13	2.26 ± 0.02	11.02 ± 0.06	0.79 ± 0.03	1
NGC5845	E3	1	25.87 ± 4.07	8.69 ± 0.16	2.38 ± 0.02	10.43 ± 0.31	-0.41 ± 0.07	1
NGC6086	E	0	138.00 ± 11.45	9.57 ± 0.17	2.5 ± 0	11.87 ± 0.08	1.20 ± 0.04	0
NGC6251	E1	0	108.40 ± 9.00	8.79 ± 0.16	2.46 ± 0.02	11.94 ± 0.06	1.20 ± 0.04	1
NGC7052	E3	0	70.40 ± 8.45	8.60 ± 0.23	2.42 ± 0.02	11.77 ± 0.06	1.10 ± 0.05	1
NGC7582	SBab	3	22.30 ± 9.85	7.74 ± 0.20	2.19 ± 0.05	10.61 ± 0.32	-0.62 ± 0.19	0
NGC7768	E4	0	116.00 ± 27.50	9.13 ± 0.18	2.41 ± 0.04	12.00 ± 0.25	1.37 ± 0.10	1
UGC3789	SABab	3	49.90 ± 5.42	6.99 ± 0.08	2.03 ± 0.05	10.33 ± 0.31	-0.24 ± 0.05	1
NGC1332	S0	2	22.30 ± 1.85	8.82 ± 0.10	2.47 ± 0.01	11.20 ± 0.31	0.29 ± 0.06	1
NGC1374	E3	1	19.23 ± 0.66	8.76 ± 0.06	2.23 ± 0.01	10.72 ± 0.06	0.36 ± 0.01	1
NGC1407	E0	0	28.05 ± 3.37	9.65 ± 0.08	2.442 ± 0.003	11.72 ± 0.12	0.97 ± 0.05	0
NGC1550	SA0	0	51.57 ± 5.60	9.57 ± 0.07	2.44 ± 0.02	11.32 ± 0.10	0.66 ± 0.05	0
NGC3091	E3	0	51.25 ± 8.30	9.56 ± 0.07	2.48 ± 0.02	11.75 ± 0.06	1.10 ± 0.07	1
NGC3368	SABab	3	10.40 ± 0.96	6.88 ± 0.08	2.122 ± 0.003	10.09 ± 0.06	-0.57 ± 0.04	1
NGC3489	SAB0	3	12.10 ± 0.84	6.78 ± 0.05	1.949 ± 0.002	9.68 ± 0.25	-1.00 ± 0.03	1
NGC4751	E	1	26.92 ± 2.92	9.15 ± 0.06	2.56 ± 0.02	10.95 ± 0.09	0.52 ± 0.05	0
NGC5328	E	0	64.10 ± 6.96	9.67 ± 0.16	2.523 ± 0.002	11.71 ± 0.09	0.94 ± 0.05	0
NGC5516	E	0	58.44 ± 6.35	9.52 ± 0.06	2.52 ± 0.02	11.83 ± 0.09	1.30 ± 0.05	0
NGC6861	E	1	27.30 ± 4.55	9.30 ± 0.08	2.590 ± 0.003	11.14 ± 0.13	0.32 ± 0.07	0
NGC7619	E	0	51.52 ± 7.38	9.40 ± 0.11	2.47 ± 0.01	11.78 ± 0.25	1.16 ± 0.06	1
NGC2748	Sc	3	23.40 ± 8.24	7.65 ± 0.24	2.06 ± 0.02	9.84 ± 0.25	-0.39 ± 0.15	1
NGC4151	Sa	3	20.00 ± 2.77	7.81 ± 0.08	2.19 ± 0.02	10.61 ± 0.25	-0.18 ± 0.06	1
NGC7457	S0	2	12.53 ± 1.21	6.95 ± 0.30	1.83 ± 0.02	9.69 ± 0.08	-0.28 ± 0.04	1
NGC307	S0	2	52.80 ± 5.74	8.60 ± 0.06	2.31 ± 0.01	10.50 ± 0.05	-0.31 ± 0.05	0
NGC3627	SAB(s)b	3	10.05 ± 1.09	6.93 ± 0.05	2.088 ± 0.002	9.45 ± 0.09	-1.08 ± 0.05	0
NGC3923	E4	1	20.88 ± 2.70	9.45 ± 0.12	2.35 ± 0.02	11.50 ± 0.11	0.89 ± 0.06	0
NGC4486A	E2	1	16.00 ± 0.52	7.10 ± 0.15	2.16 ± 0.01	10.08 ± 0.05	-0.19 ± 0.01	0
NGC4501	SA(rs)b	3	16.50 ± 1.14	7.30 ± 0.08	2.20 ± 0.01	10.16 ± 0.07	-0.40 ± 0.03	0
NGC5018	E3	1	40.55 ± 4.87	8.02 ± 0.08	2.32 ± 0.01	11.54 ± 0.09	0.62 ± 0.05	0
NGC5419	E	0	56.20 ± 6.11	9.86 ± 0.14	2.56 ± 0.01	12.00 ± 0.09	1.26 ± 0.05	0
IC4296	BCGE	0	49.20 ± 3.63	9.11 ± 0.07	2.51 ± 0.02	11.78 ± 0.25	1.21 ± 0.03	1
NGC1277	S0/	2	73.00 ± 7.30	9.70 ± 0.05	2.52 ± 0.07	10.83 ± 0.08	0.09 ± 0.04	0
IC2560	SBbc	3	33.20 ± 3.32	6.59 ± 0.16	2.15 ± 0.02	10.13 ± 0.25	-0.14 ± 0.04	1

Galaxy	Morphology	A	Distance (Mpc)	M_{BH} (log $M_{\odot}$)	σ_e (log km/s)	L_K (log $L_{\odot}$)	R_e (log kpc)	B
NGC224	Sb	2	0.77 ± 0.03	8.15 ± 0.16	2.23 ± 0.02	10.34 ± 0.10	-0.19 ± 0.02	1
NGC4472	E2	0	17.14 ± 0.59	9.40 ± 0.04	2.48 ± 0.01	11.86 ± 0.06	1.05 ± 0.01	1
NGC3031	Sb	2	3.60 ± 0.13	7.81 ± 0.13	2.15 ± 0.02	10.43 ± 0.31	-0.24 ± 0.02	1
NGC4374	E1	0	18.51 ± 0.60	8.97 ± 0.05	2.47 ± 0.02	11.64 ± 0.25	1.07 ± 0.01	1
NGC4486	E1	0	16.68 ± 0.62	9.68 ± 0.04	2.51 ± 0.03	11.64 ± 0.25	0.85 ± 0.02	1
NGC4594	Sa	2	9.87 ± 0.82	8.82 ± 0.04	2.38 ± 0.02	10.79 ± 0.25	-0.03 ± 0.08	1
NGC3379	E1	0	10.70 ± 0.54	8.62 ± 0.11	2.31 ± 0.02	10.96 ± 0.25	0.42 ± 0.02	1
NGC221	E2	1	0.80 ± 0.03	6.39 ± 0.19	1.89 ± 0.02	9.12 ± 0.04	-0.90 ± 0.02	0
CygnusA	E	0	242.70 ± 24.27	9.42 ± 0.12	2.43 ± 0.05	12.19 ± 0.10	1.46 ± 0.04	0
NGC1271	SB0	2	80.00 ± 8.00	9.48 ± 0.15	2.45 ± 0.01	11.07 ± 0.08	0.34 ± 0.07	0
NGC1275	E	1	73.80 ± 7.38	8.90 ± 0.24	2.39 ± 0.08	11.84 ± 0.08	1.15 ± 0.04	0
NGC1600	E	0	64.00 ± 6.40	10.23 ± 0.04	2.47 ± 0.02	11.86 ± 0.08	1.08 ± 0.04	0
NGC3706	E	0	46.00 ± 4.60	8.78 ± 0.06	2.51 ± 0.01	11.58 ± 0.08	0.80 ± 0.04	0
NGC5252	S0	2	92.00 ± 9.20	8.98 ± 0.23	2.28 ± 0.02	11.49 ± 0.09	0.88 ± 0.06	0
NGC4339	E	1	16.00 ± 1.60	7.63 ± 0.36	1.98 ± 0.02	10.26 ± 0.25	0.37 ± 0.04	0
NGC4434	E	1	22.40 ± 2.24	7.85 ± 0.15	1.99 ± 0.02	10.28 ± 0.25	0.20 ± 0.04	0
NGC4578	E	1	16.30 ± 1.63	7.28 ± 0.22	2.03 ± 0.02	10.33 ± 0.25	0.49 ± 0.04	0
NGC4762	E	1	22.60 ± 2.26	7.36 ± 0.14	2.13 ± 0.02	11.05 ± 0.25	1.06 ± 0.04	0

De Nicola, AM, Longo 2018

FP of galaxies with BH Masses

- ⭐ All galaxies follow FP, also pseudo bulges seem to



De Nicola, AM, Longo 2018

A BH fundamental plane?

$$M_{BH} = (-0.21 \pm 0.33)L + (0.56 \pm 0.33)R + (4.10 \pm 0.39)V$$ *L, R, V,* logs

- Main dependence on $V = \log \sigma$, small dependence on $R = \log R_e$, no dependence on $L = \log L_{sph}$,
- Intrinsic scatter not decreased w.r.t. M_{BH}-σ

Hyperplane is not the fundamental relation!

To disentangle FP from M_{BH}-L,σ,R relations

- Assume BH fundamental relation
  $M_{BH} = \boldsymbol{\alpha} L + \boldsymbol{\beta} R + \gamma V + \boldsymbol{\Sigma}$ (Σ int. scatter)
- Model FP as a trivariate Gaussian distribution $\phi(L, R, V)$
- *Slopes and intrinsic scatters of all M_{BH}-L,σ,R can be computed analytically as a function of* $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, γ, $\boldsymbol{\Sigma}$

- We conclude that $M_{BH} \sim \sigma^{4.0} R^{0.4}$ is best relation (fundamental?)
  - This result takes into account FP

De Nicola, AM, Longo 2018

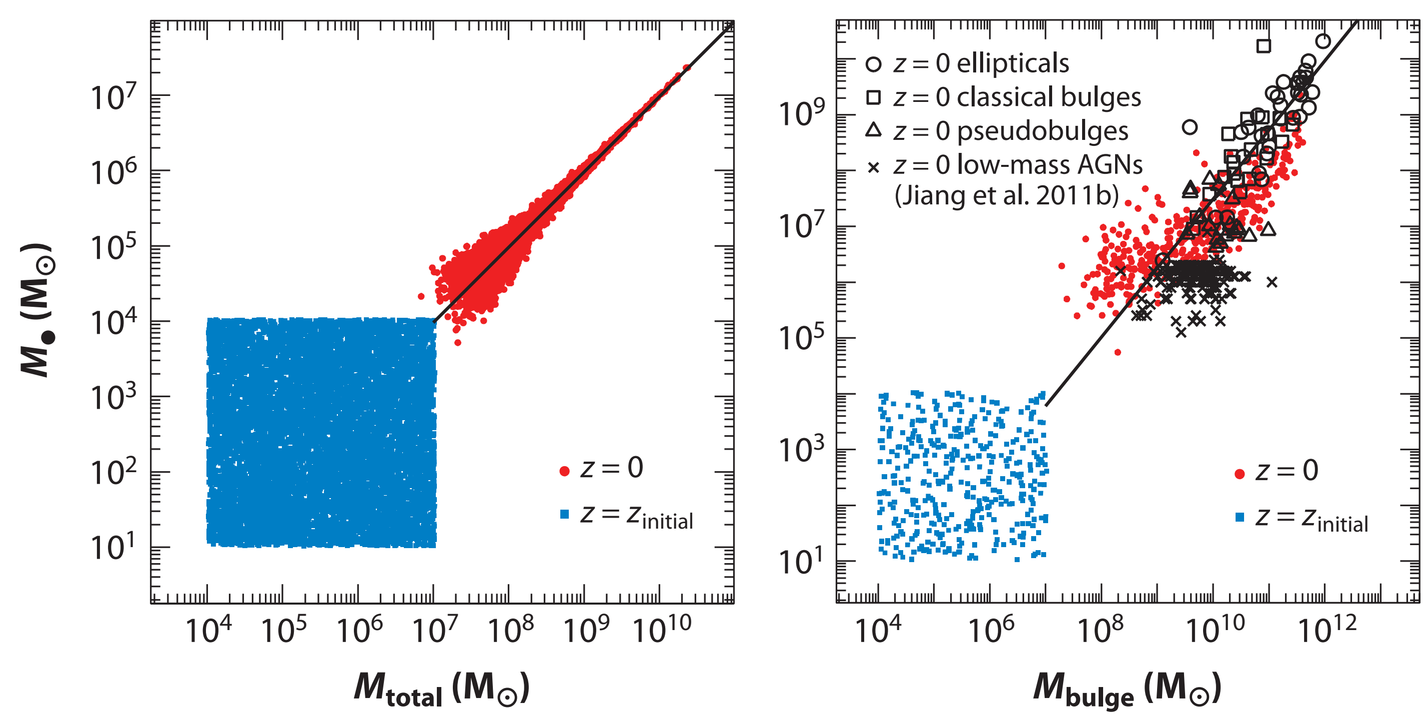
Physical meaning of BH-galaxy relations

Huge topic with hundreds/thousands of papers … a few key points:

- Relation M_{BH}-galaxy properties implies a physical link between BH and host galaxy (*Coevolution BH-galaxy*)
- BH sphere of influence very small: $V_{BH}/V_{gal} \sim 10^{-7}$ → no gravitational link
- Energy released to grow BH >> gravitational binding energy
  → **AGN feedback** (Talks by M. Brusa, R. Maiolino tomorrow)

Possibilities to establish M_{BH}-galaxy relations:

- AGN feedback on host galaxy (also needed to stop galaxy growth)
- BH self-regulation (i.e. feedback on small scales < 1 kpc)
- Random growth → central limit
  → big BHs in big galaxies
  - but scatter too large?

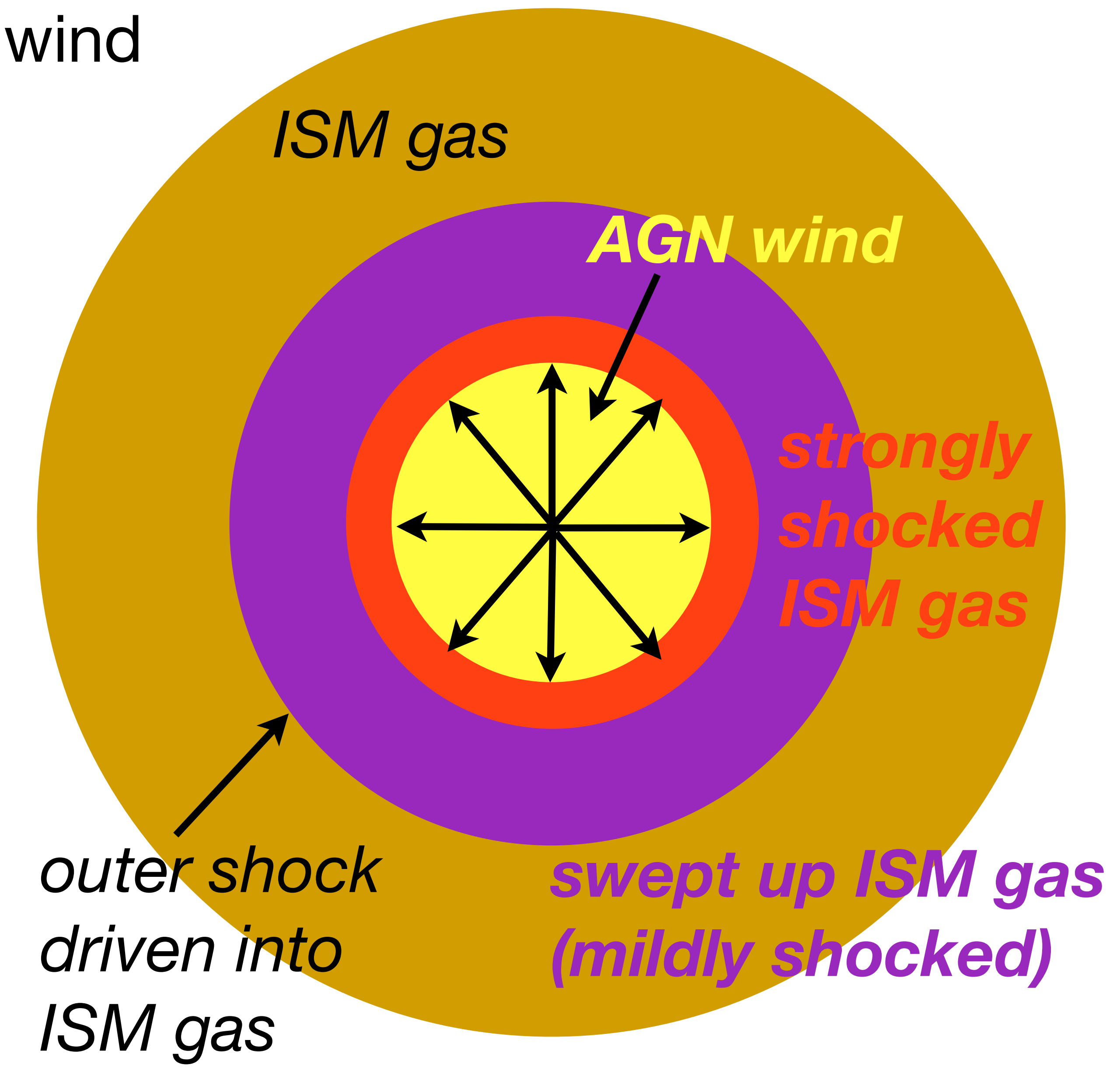


Jahnke & Macciò 11

A very simple model ...

Model by A. King and collaborators:

- for L/L_{Edd}~1 fast wind accelerated close to AGN
- wind creates a bubble which sweeps the gas in host galaxy ISM
- shock forms at the interface between wind and swept ISM
- post shock material is Compton-cooled by AGN up to ~kpc scales → wind is momentum driven
- wind falls back until $M_{BH} \sim M_{BH}(\sigma)$
- then expands beyond ~kpc scales, Compton-cooling no more effective → outflow becomes energy driven



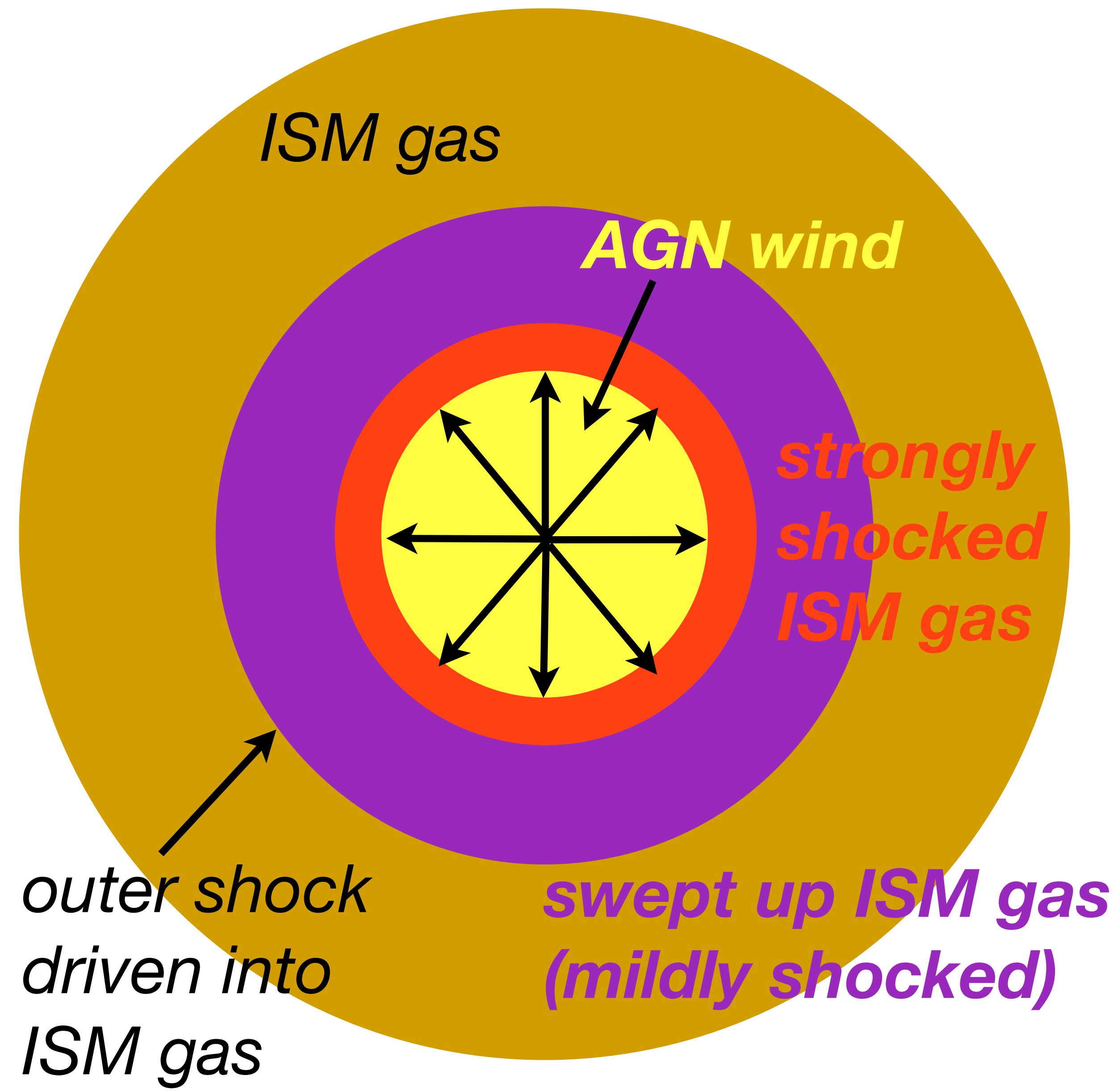
A very simple model …

- model prediction $$M_{\rm BH} = \frac{2 f_g \sigma_T}{\pi m_p G^2}\sigma^4 = 4.6 \times 10^8\,{\rm M}_\odot \left(\frac{\sigma}{200\,{\rm km}}\right)^4$$

- no free parameters, excellent agreement with observations!

- Extremely simple: spherical symmetry, ISM with uniform density, galaxy as isothermal sphere but …

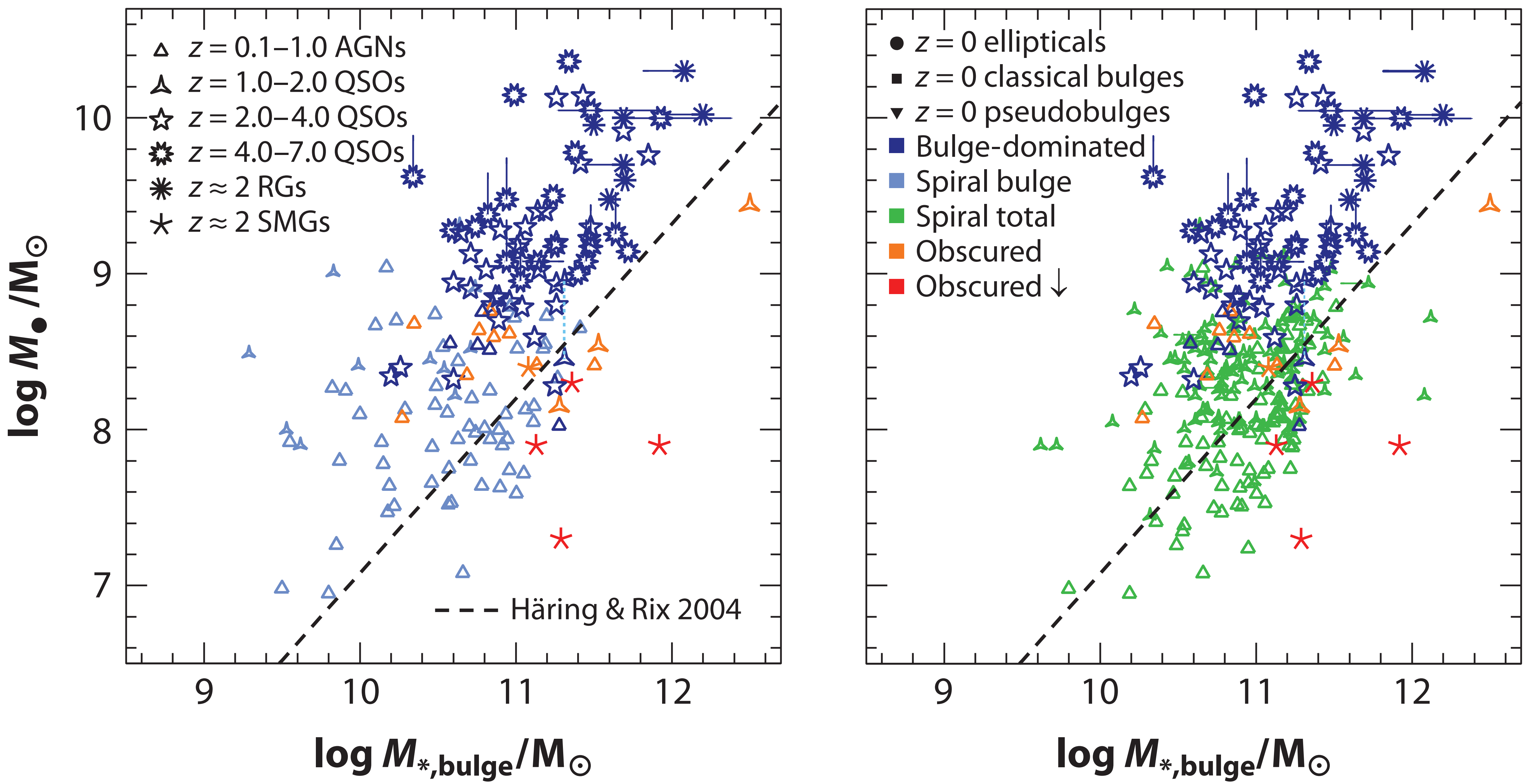
- agreement with observations tells us that the basic physics is probably there



M_{BH}-galaxy relations vs z

Review by Kormendy & Ho up to 2013

- Signs of evolution at z<2 disappear when whole galaxy is considered
- Increased M_{BH}/M_{Gal} weakens evidence for evolution at lower z



Kormendy & Ho 2013

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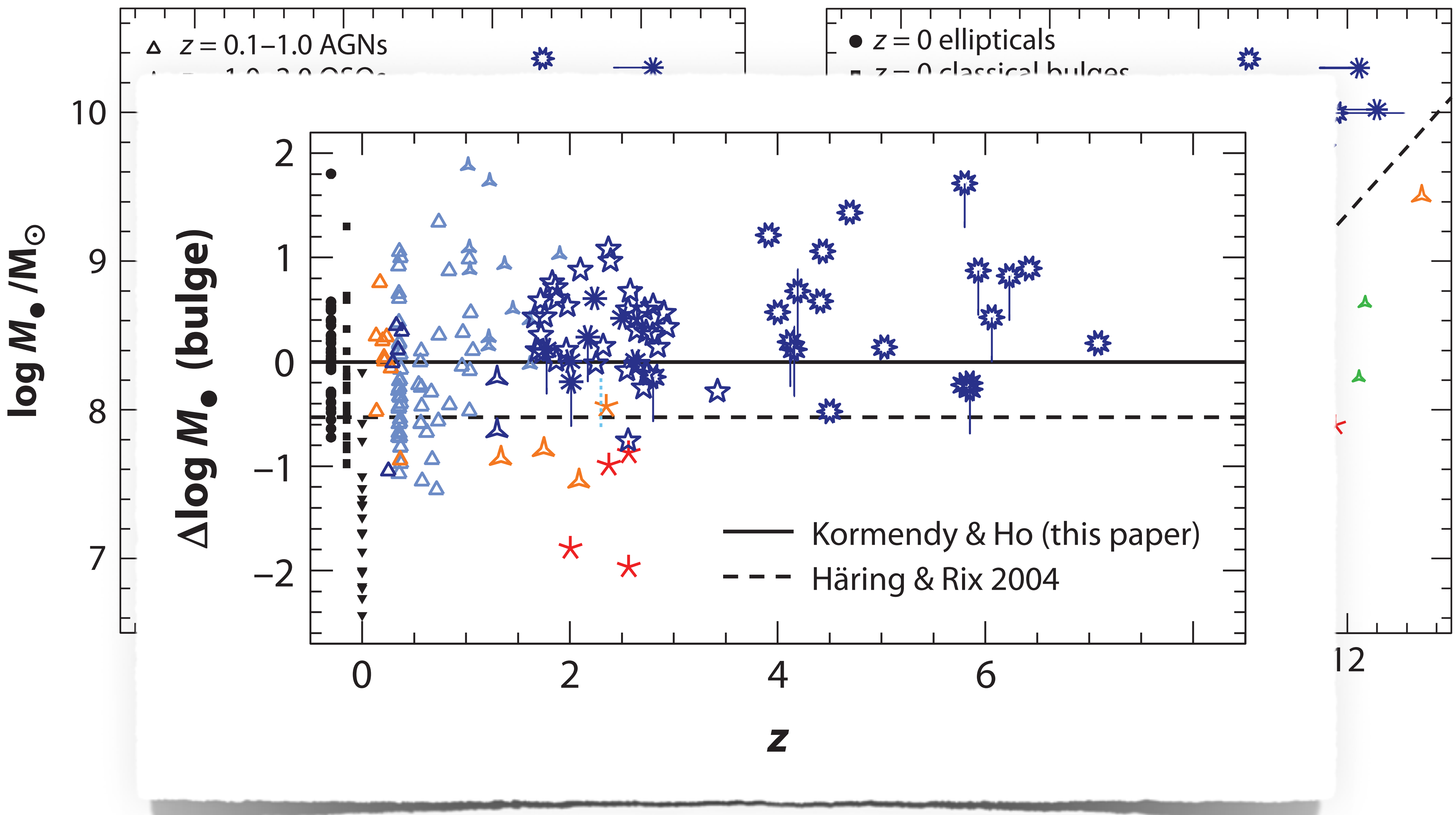
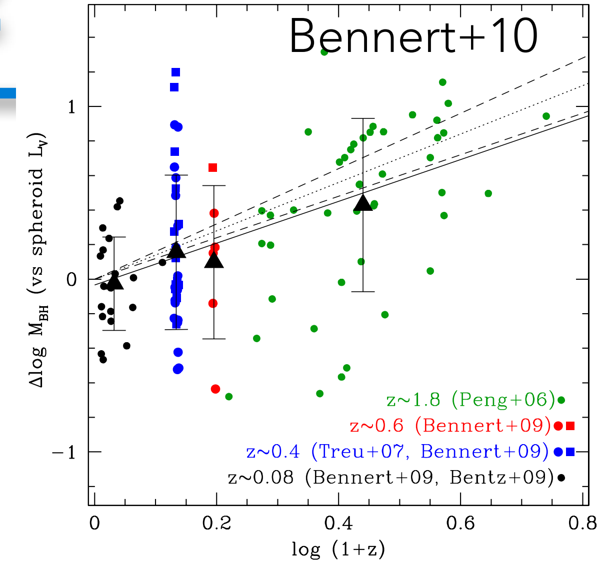
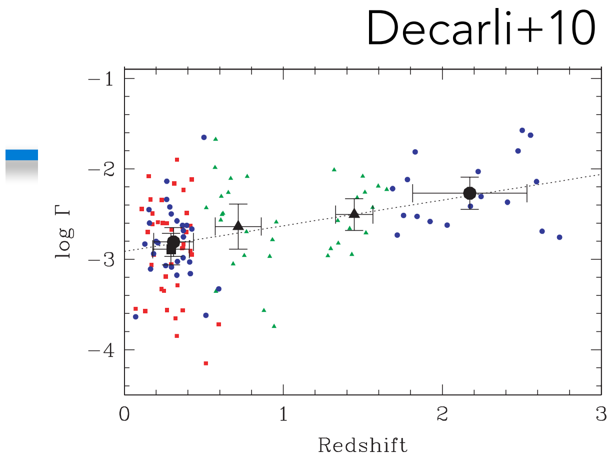


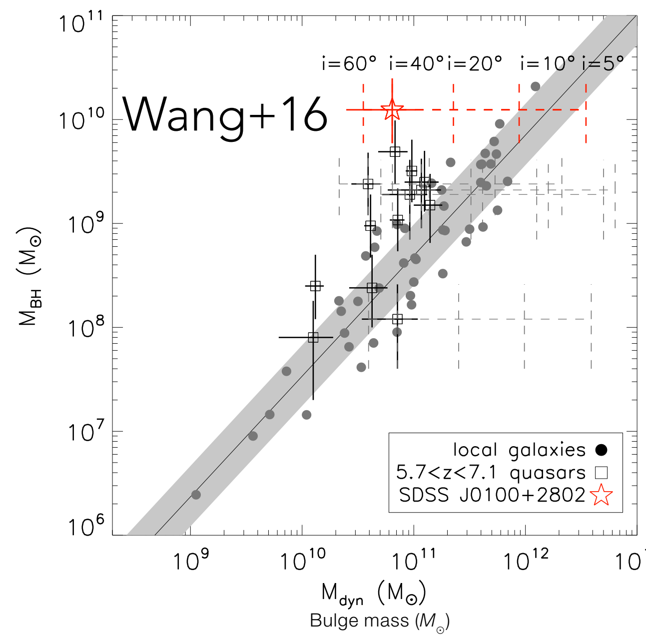
Kormendy & Ho 2013

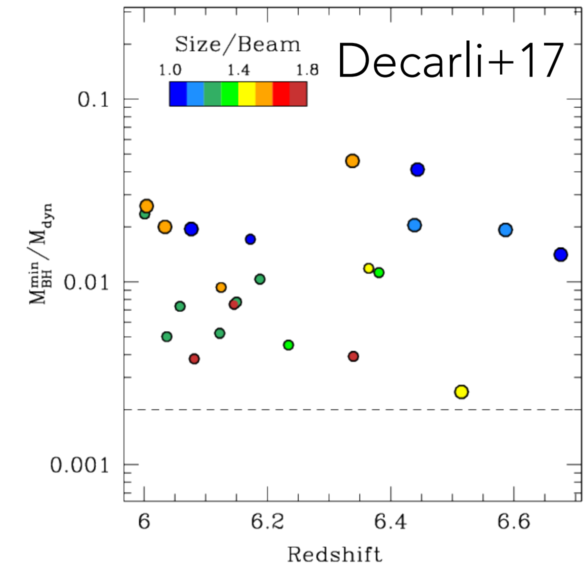
M_{BH}-galaxy relations vs z

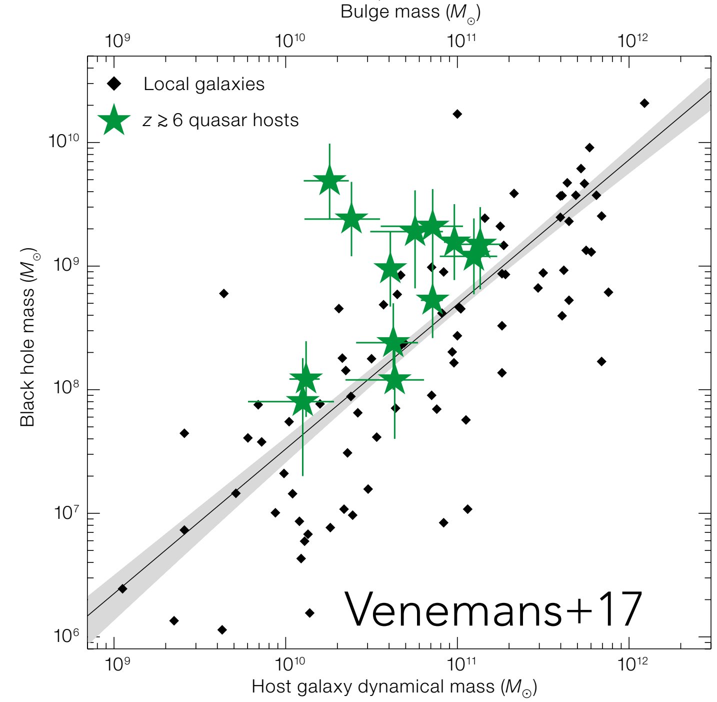
- Average M_{BH}/M_{gal} larger than in local universe at z <1-3 (Peng+06, Treu+04,07 , Woo+06,08, Bennert+10,11, Decarli+09,10, Alexander+09, Merloni+10)
- M_{BH}/M_{gal} increases at higher z (Wu+07, Ho+07, Maiolino+09, Walter+09): M_{BH} up to ~10% of M_{gal}!
- Large $M_{BH}/M_{gal(star)}$ might be due to selection effects (e.g. Lamastra+10) or biases (e.g. Lauer+07)
- The ALMA revolution: extension to very high redshift with "dynamical" M_{gal} (e.g. Maiolino+05, Walter+09, Wang+13, 16, Willott+13,15, Venemans+12,16,17, Banados+15, Decarli+17, Trakhtenbrot+17)

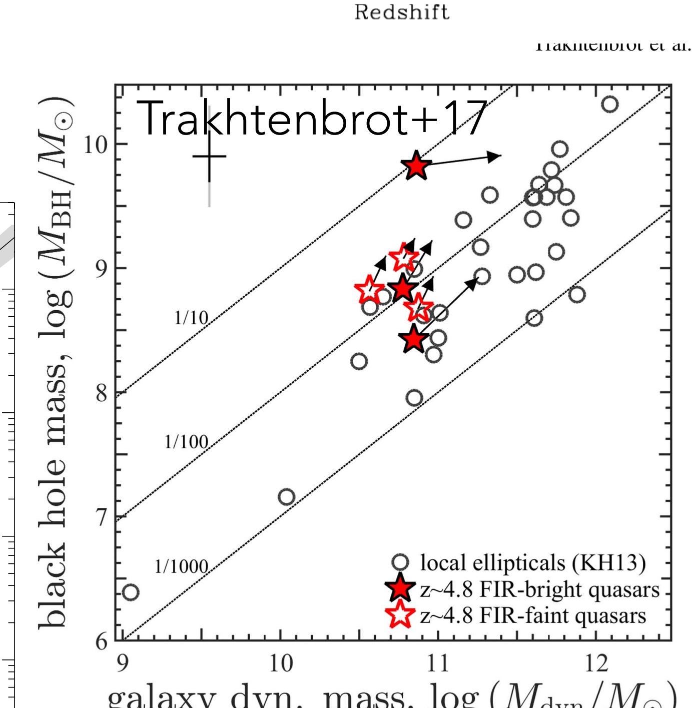












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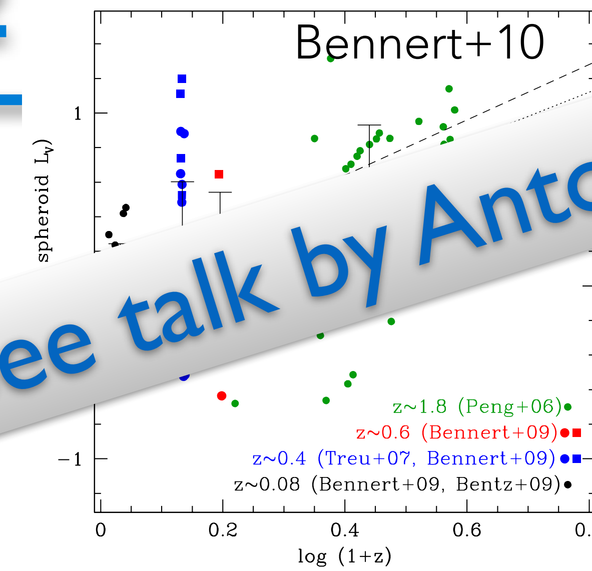
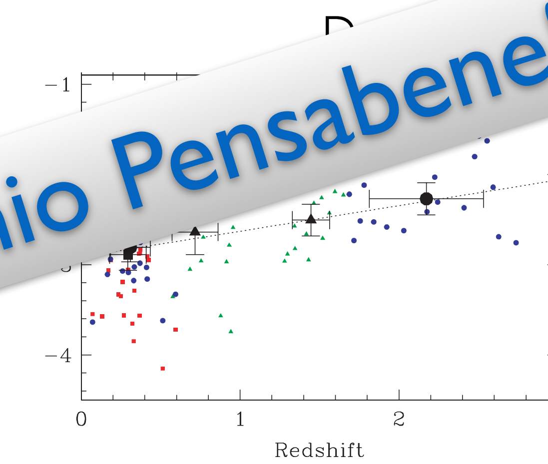
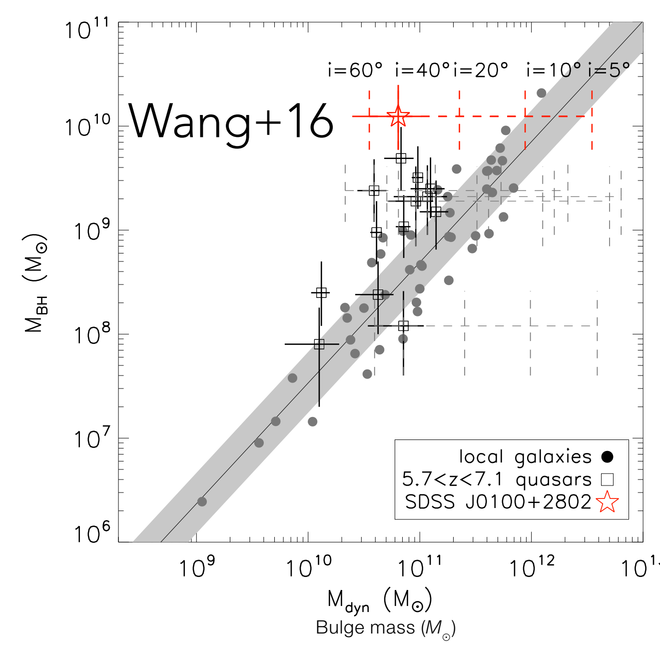
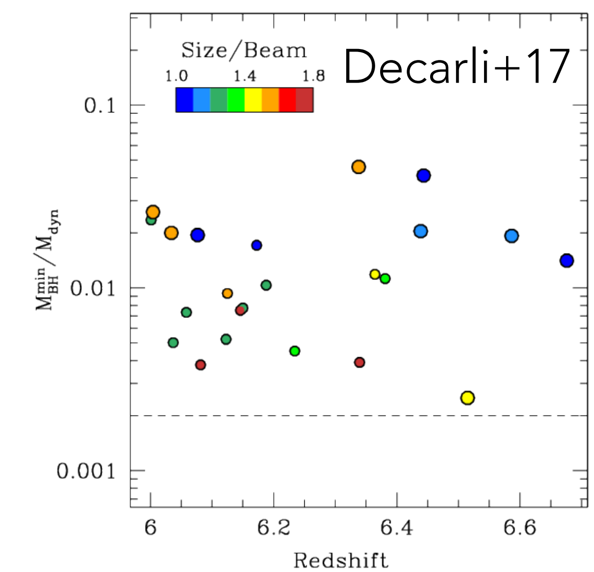
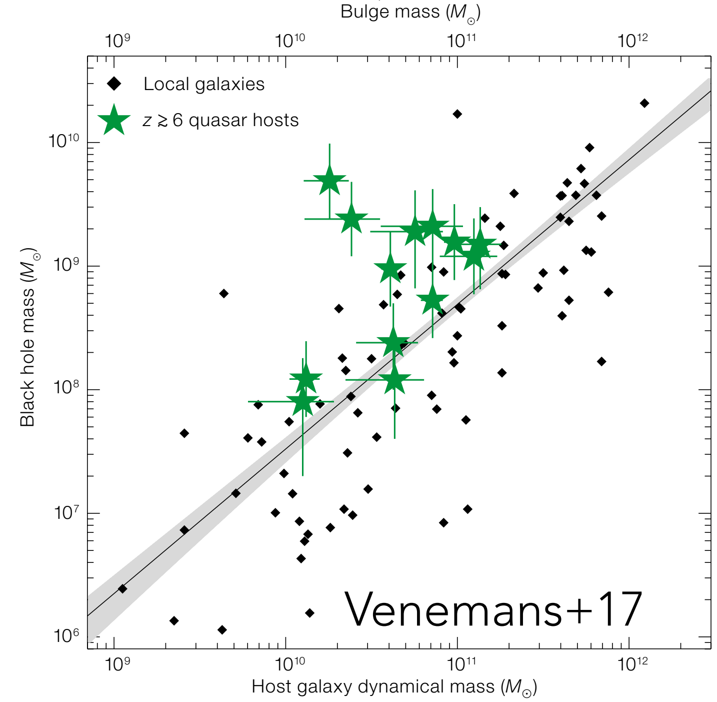
See talk by Antonio Pensabene!

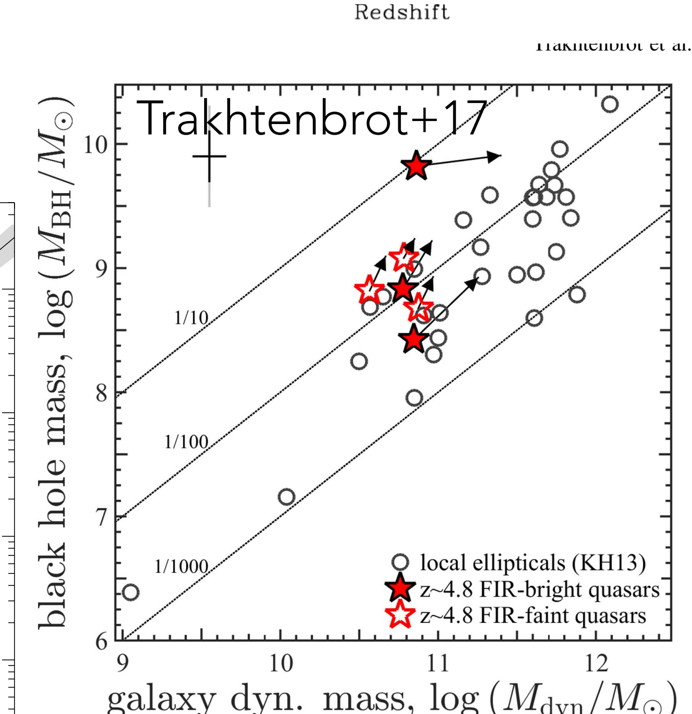








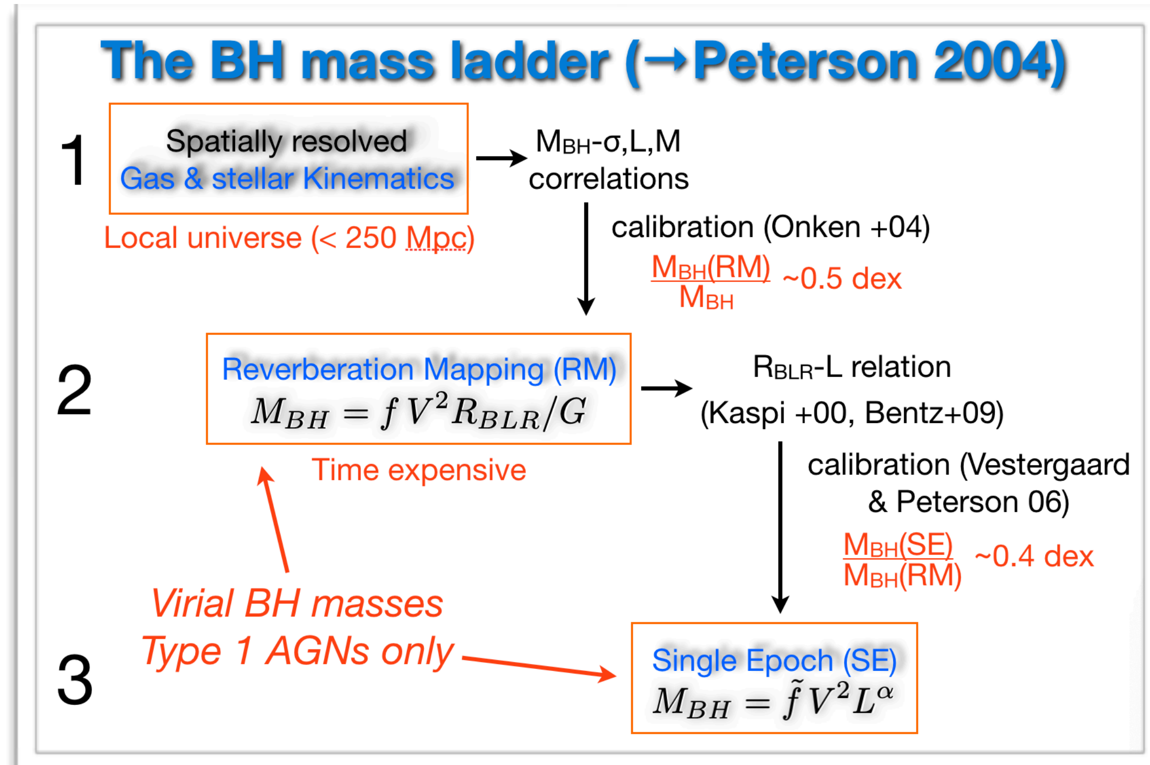


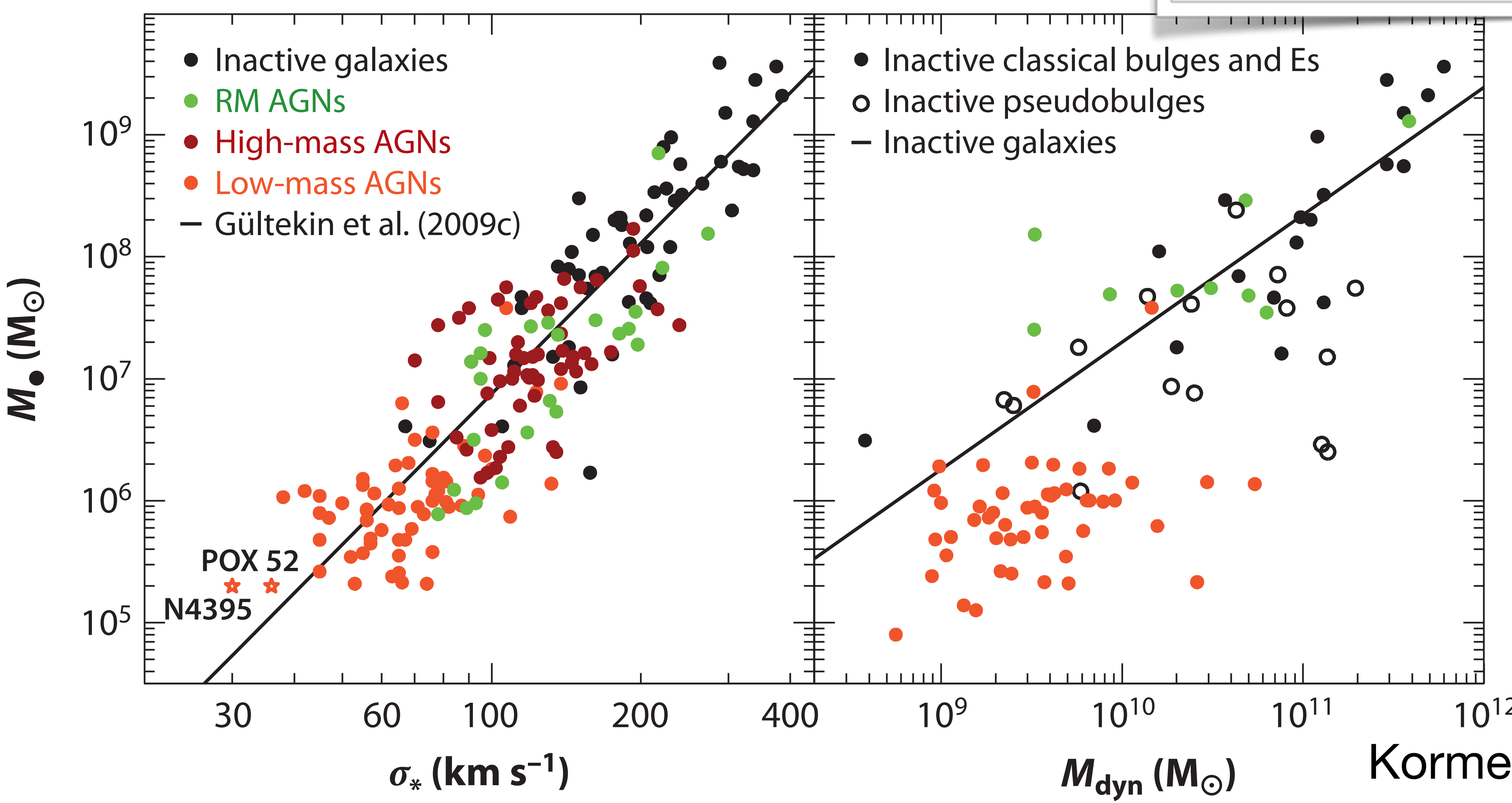


Redshift evolution: challenges on M_{BH}

Virial masses M_{BH} = **f** V^2 R /G

- **Only in type 1 AGN**
- Calibration i.e. **f**
  - based on assumption that AGN follow same relation as quiescent galaxies
  - what if BHs are under/overmassive?
  - inclination effect not considered



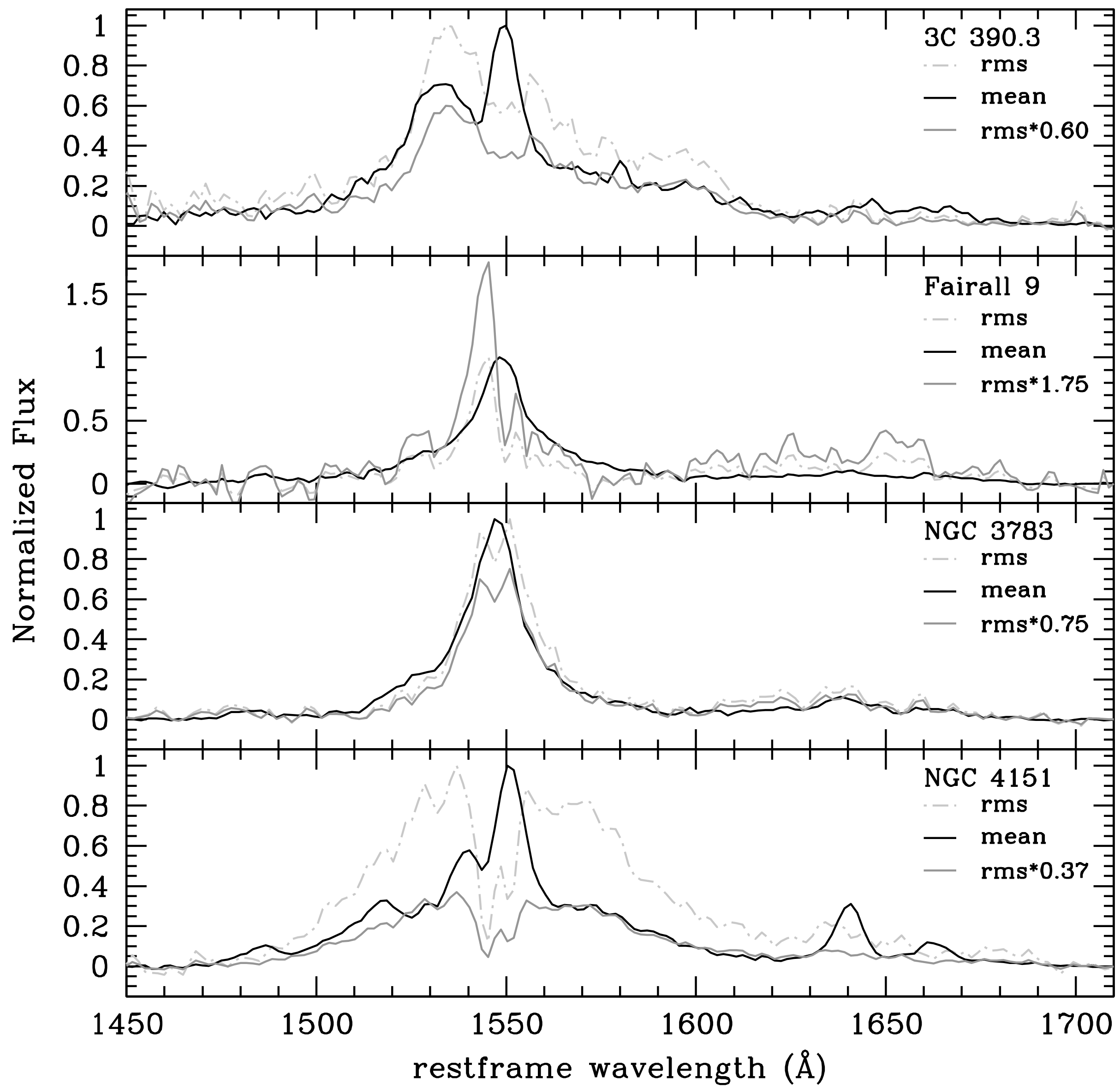


Kormendy & Ho 2013

Redshift evolution: challenges on M_{BH}

Virial masses $M_{BH} = \mathbf{f}\, V^2 R / G$

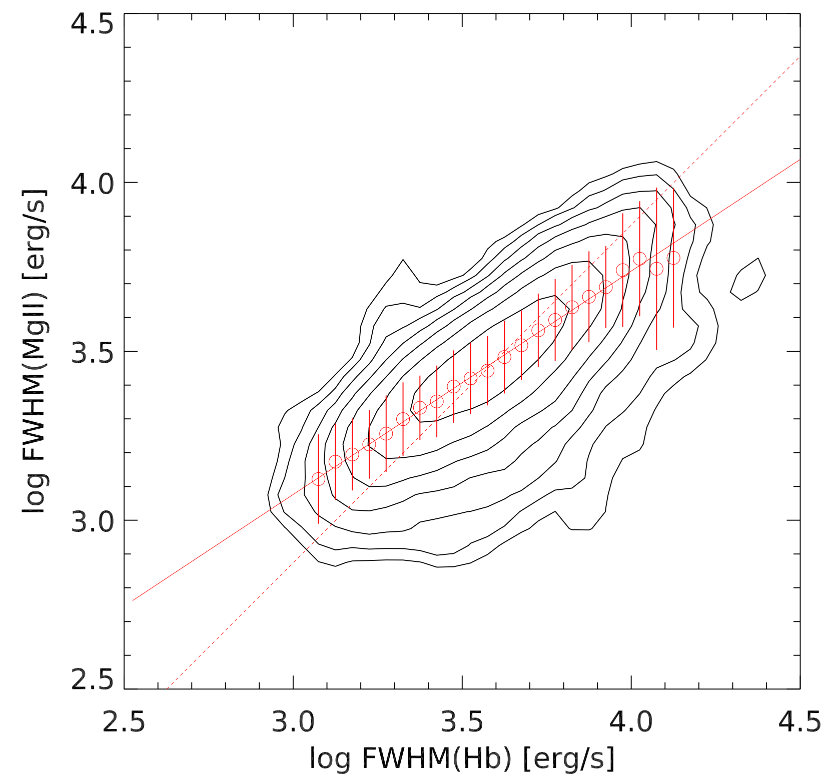
- CIV: used for very high redshift (with optical spectra) but reliability questioned by many authors
  - CIV probably affected by outflows
  - Denney 13 shows that CIV average line profile are different than *r.m.s.* ones: existence of non-BLR extended component (outflow?) strongly affects line width estimate



Denney 13

Redshift evolution: challenges on M_{BH}

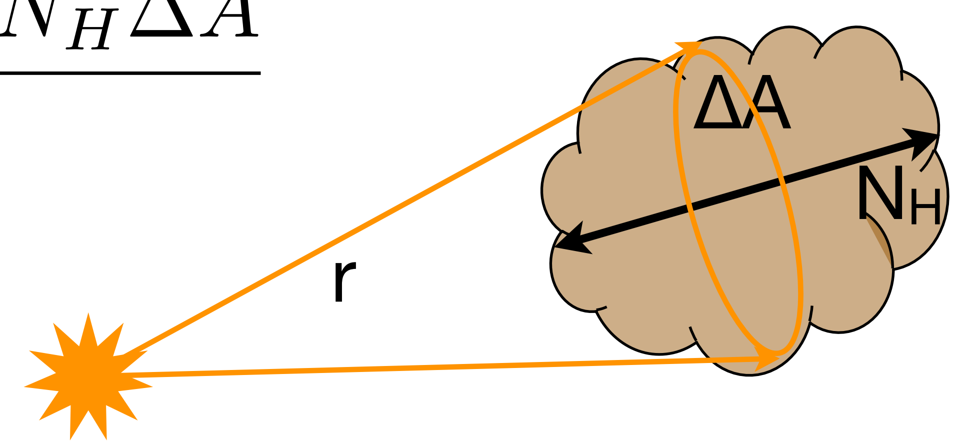
Virial masses M_{BH} = **f** V^2 R /G



- Radiation pressure
  - May affect BH mass estimates (partially cancel gravitational force; Marconi+08, +09)
  - Still an open issue
  - If all incident ionising photons absorbed by a BLR cloud (must be to have MgII emission …)

$$F = \frac{L_{ion}}{4\pi r^2 c}\Delta A \qquad F_{grav} = \frac{GM(r)m_p N_H \Delta A}{r^2}$$

$$\frac{F_{rad}}{F_{grav}} = \frac{L_{ion}}{4\pi G\, c\, m_p\, M(r)\, N_H} \simeq 5$$

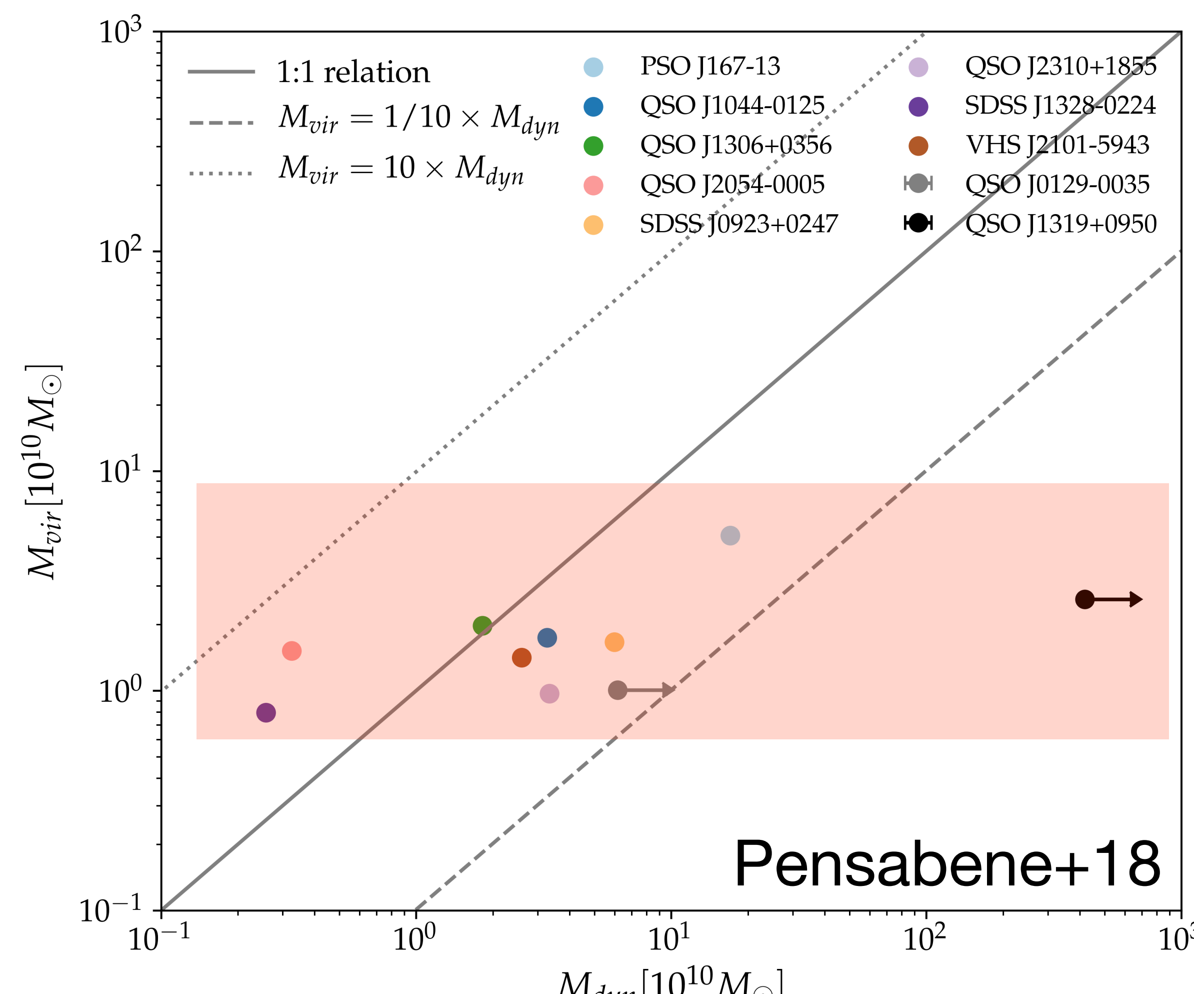


$$L_{ion} = 10^{13}L_\odot,\ M(r) = M_{BH} = 10^9 M_\odot,\ N_H = 10^{23} cm^{-2}$$

Redshift evolution: challenges on galaxy props.

Virial masses in (luminous) AGN

- Galaxy properties difficult to measure (galaxy difficult to "see" with AGN emission)
- Selection effects: sampling objects at specific time of their evolution (e.g. Lamastra+10)
- ALMA revolution: it is possible to measure dynamical galaxy masses up to high redshift
  - Same challenges as in BH mass measurement form gas (galaxy sizes at high z, similar to nuclear disk sizes i.e. < 1")
  - Usually galaxy masses are simple virial estimates
  - Dynamical masses are total masses within a few kpc



Conclusions

- BH mass measurements
  - There are open issues on gas and stellar kinematical measurements
  - We still not have the unambiguous proof that we detect BHs (except for Milky Way) but considering AGN they most likely are …

- Which relations are real?
  - We still need to probe the low BH in big bulge regime
  - Existence of correlations imply coevolution BH-galaxy
  - There is a fundamental correlation (e.g. M_{BH}-σ or M_{BH}-σ, R) the rest result from combination with galaxy structure (e.g. FP)

- Redshift evolution and origin of these relations?
  - At high redshift BH seem over massive compared to host galaxies
  - limited to type 1 AGN for virial BH masses
  - need to properly measure galaxy dynamical masses