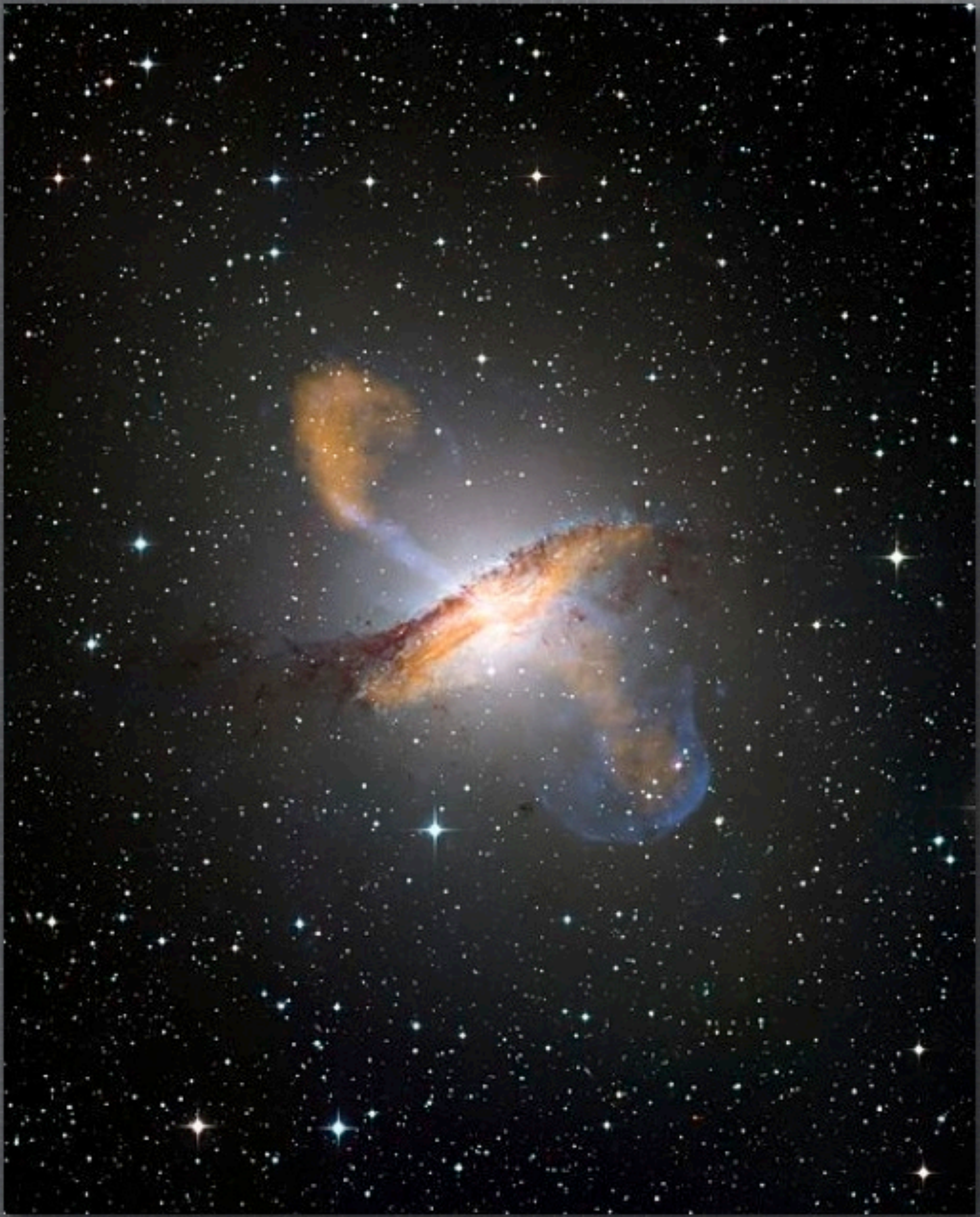
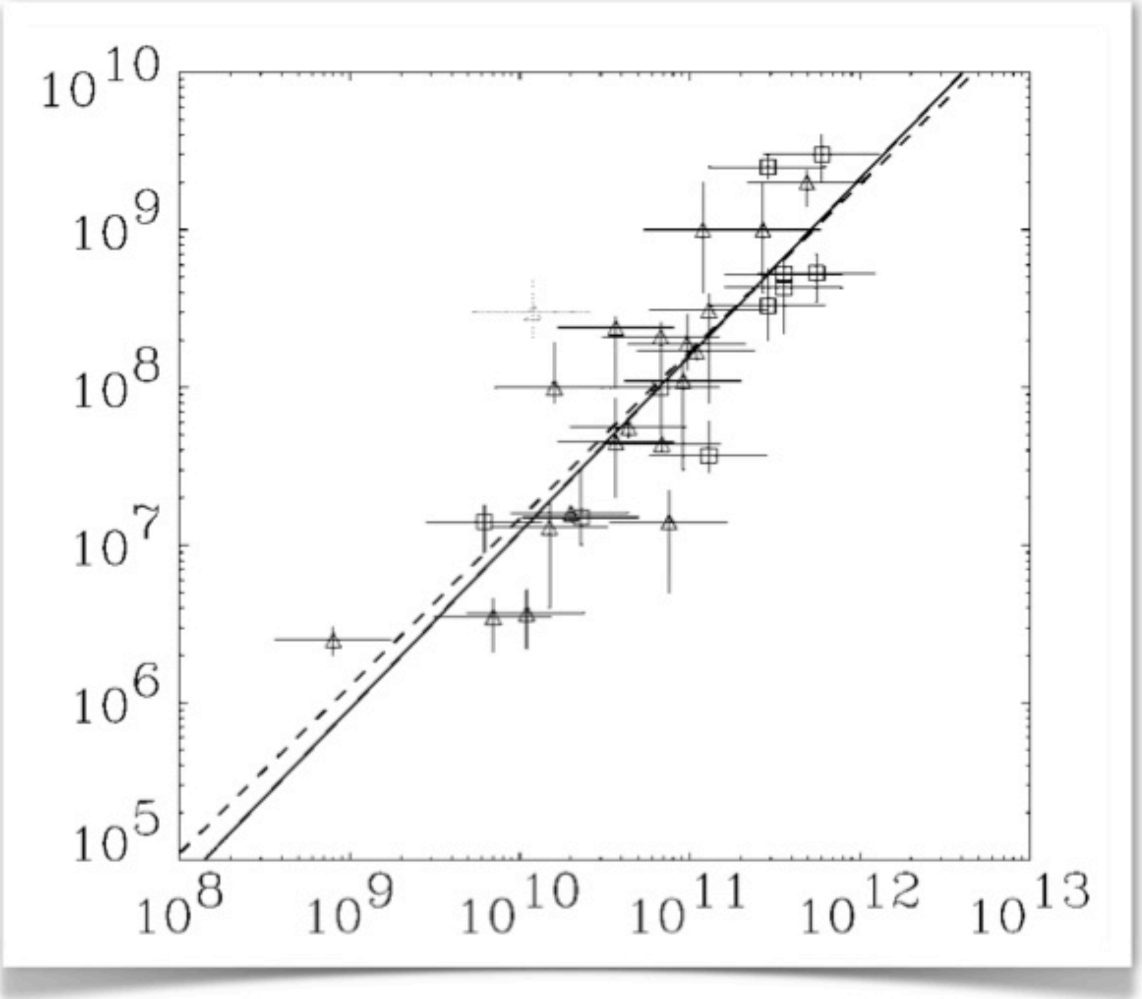


Remco van den Bosch
MPIA

2013 KITP Santa Barbara

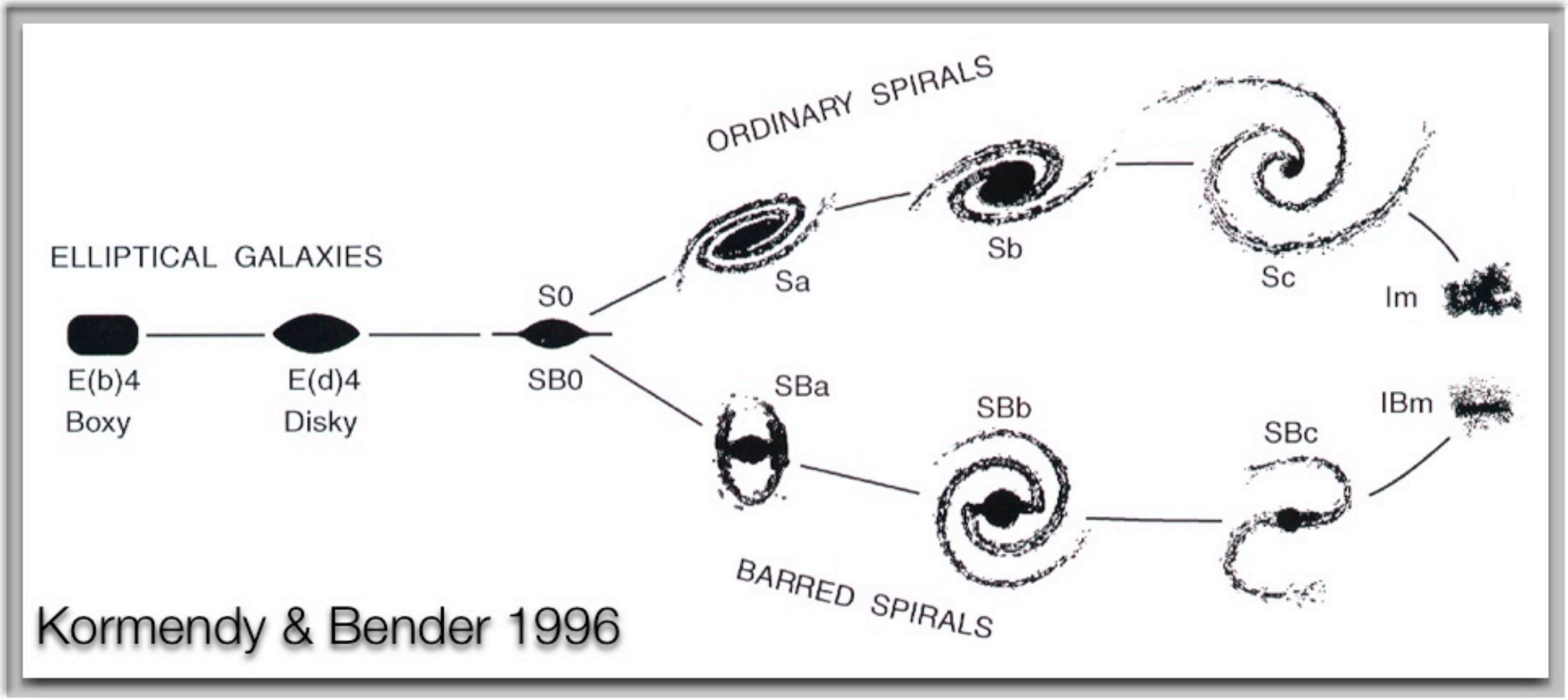
BH-BULGE RELATION



Black Hole Mass
[10^5 - 10^{10} M⬟]

Bulge Mass
[10^8 - 10^{12} M★]

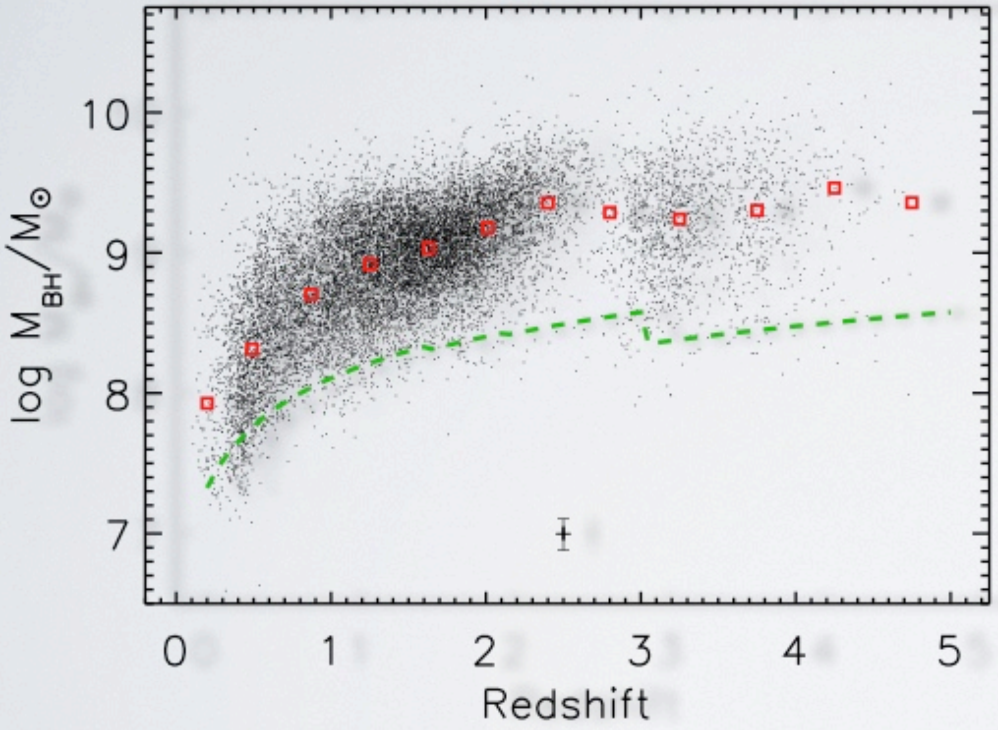
Haering, N & Rix, H.-W.
(2004):
On The Black Hole Mass-Bulge Mass Relation.



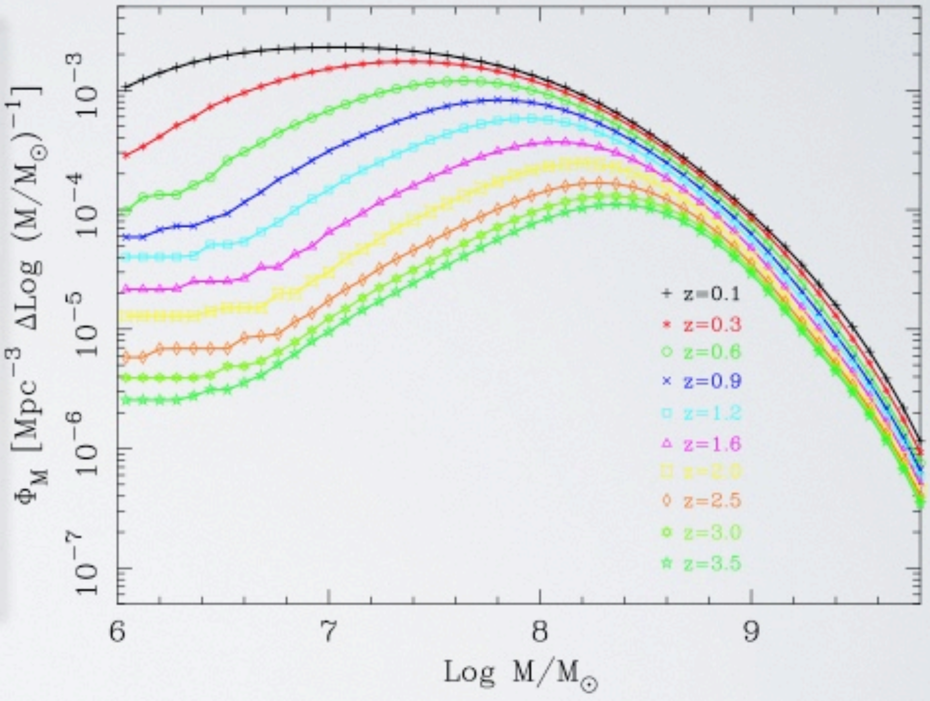
Kormendy & Bender 1996

BH EVOLUTION

Vestergaard+ 2008



Merloni 2004



THEORIES...

Several explanations have been proposed for the existence of these empirical relationships

- direct feedback between the black hole and its host galaxy (Silk & Rees, Fabian, King & Pringle)
- galaxy-galaxy merging and the subsequent violent relaxation and dissipation (Kormendy, Hopkins)
- non-causal, statistical process of galaxy-galaxy merging (Peng 2007, Jahnke & Maccio 2010)

$$M_\bullet \propto \sigma^4$$

The distribution of black hole masses is an indicator of their formation

THEORIES...

Several explanations have been proposed for the existence of these empirical relationships

- direct feedback between the black hole and its host galaxy (Silk & Rees, Fabian, King & Pringle)
- galaxy-galaxy merging and the subsequent violent relaxation and dissipation (Kormendy, Hopkins)
- non-causal, statistical process of galaxy-galaxy merging (Peng 2007, Jahnke & Maccio 2010)

The distribution of black hole masses is an indicator of their formation

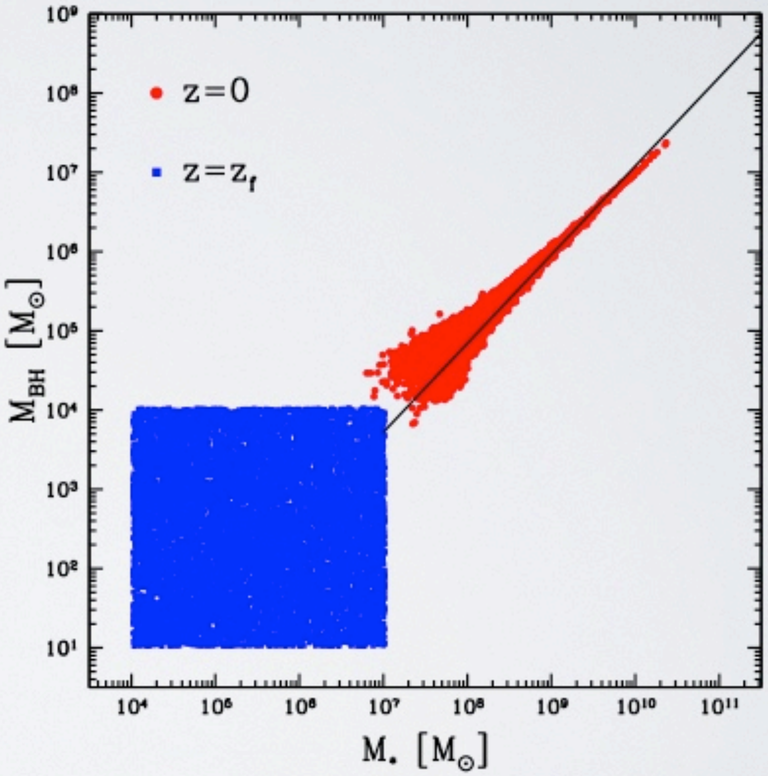
Di Matteo et al (2005)

THEORIES...

Several explanations have been proposed for the existence of these empirical relationships

- direct feedback between the black hole and its host galaxy (Silk & Rees, Fabian, King & Pringle)
- galaxy-galaxy merging and the subsequent violent relaxation and dissipation (Kormendy, Hopkins)
- non-causal, statistical process of galaxy-galaxy merging (Peng 2007, Jahnke & Maccio 2010)

The distribution of black hole masses is an indicator of their formation



THEORIES...

Several explanations have been proposed for the existence of these empirical relationships

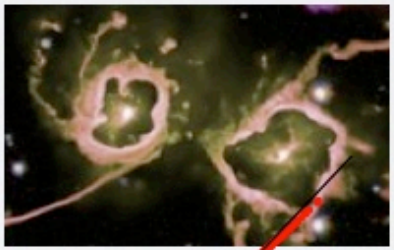
Prediction:

- direct feedback between the black hole and its host galaxy (Silk & Rees, Fabian, King & Pringle)

$M_\bullet \propto \sigma^4$

No scatter

- galaxy-galaxy merging and the subsequent violent relaxation and dissipation (Kormendy, Hopkins)



BH linked to galaxy bulge

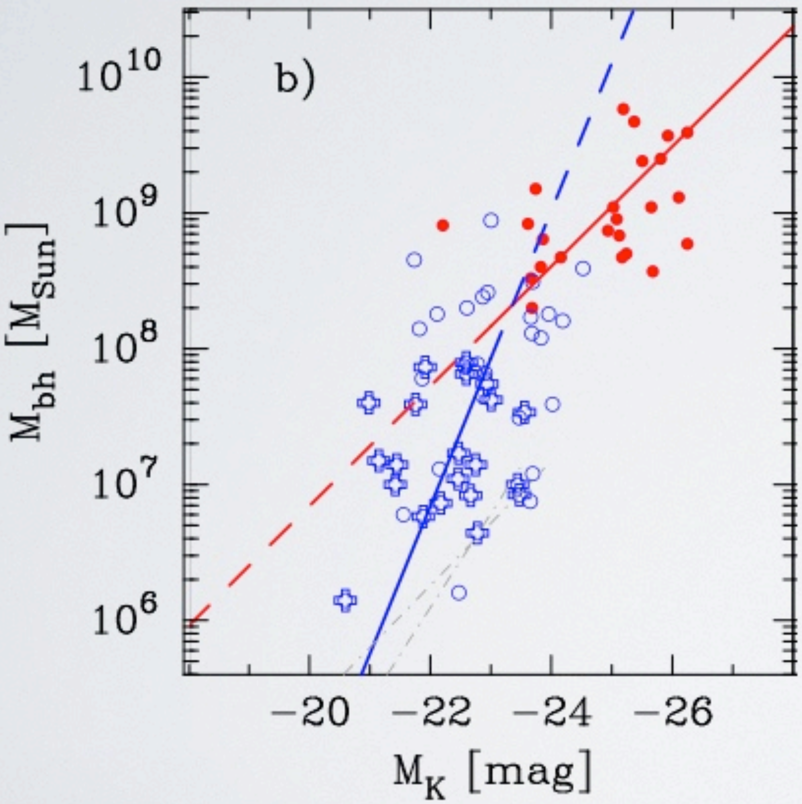
- non-causal, statistical process of galaxy-galaxy merging (Peng 2007, Jahnke & Maccio 2010)

Scatter decreases with # mergers

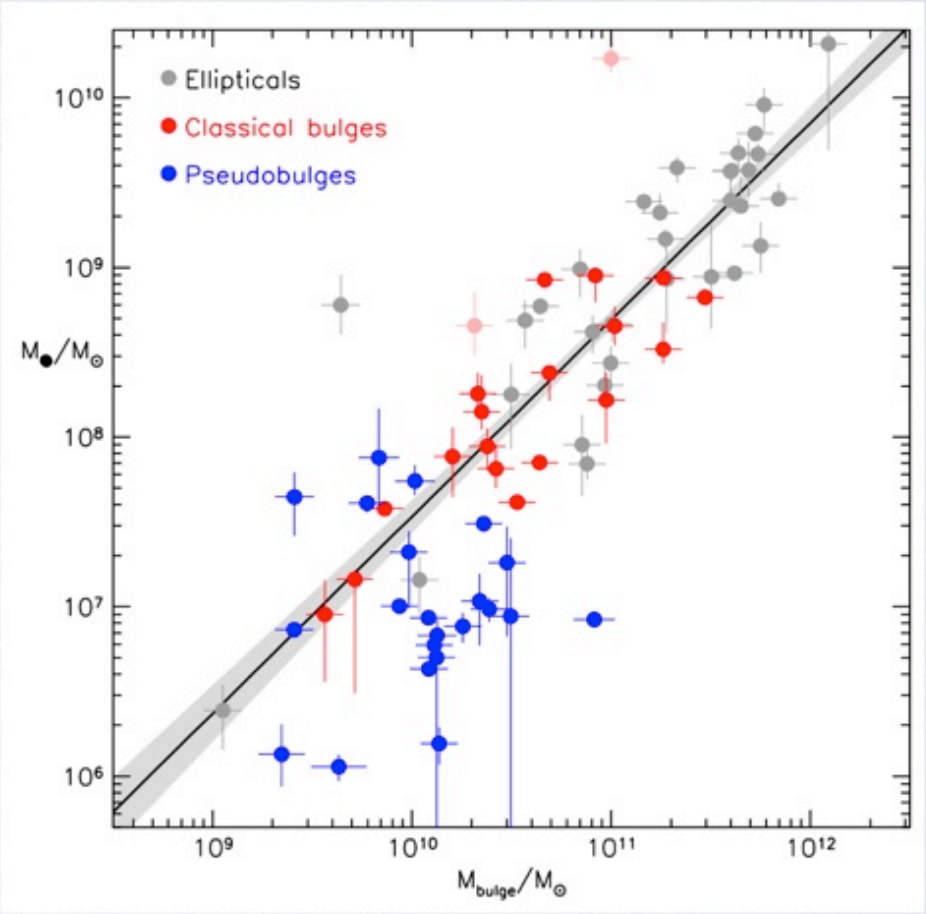
The distribution of black hole masses is an indicator of their formation

BH-BULGE IN 2013

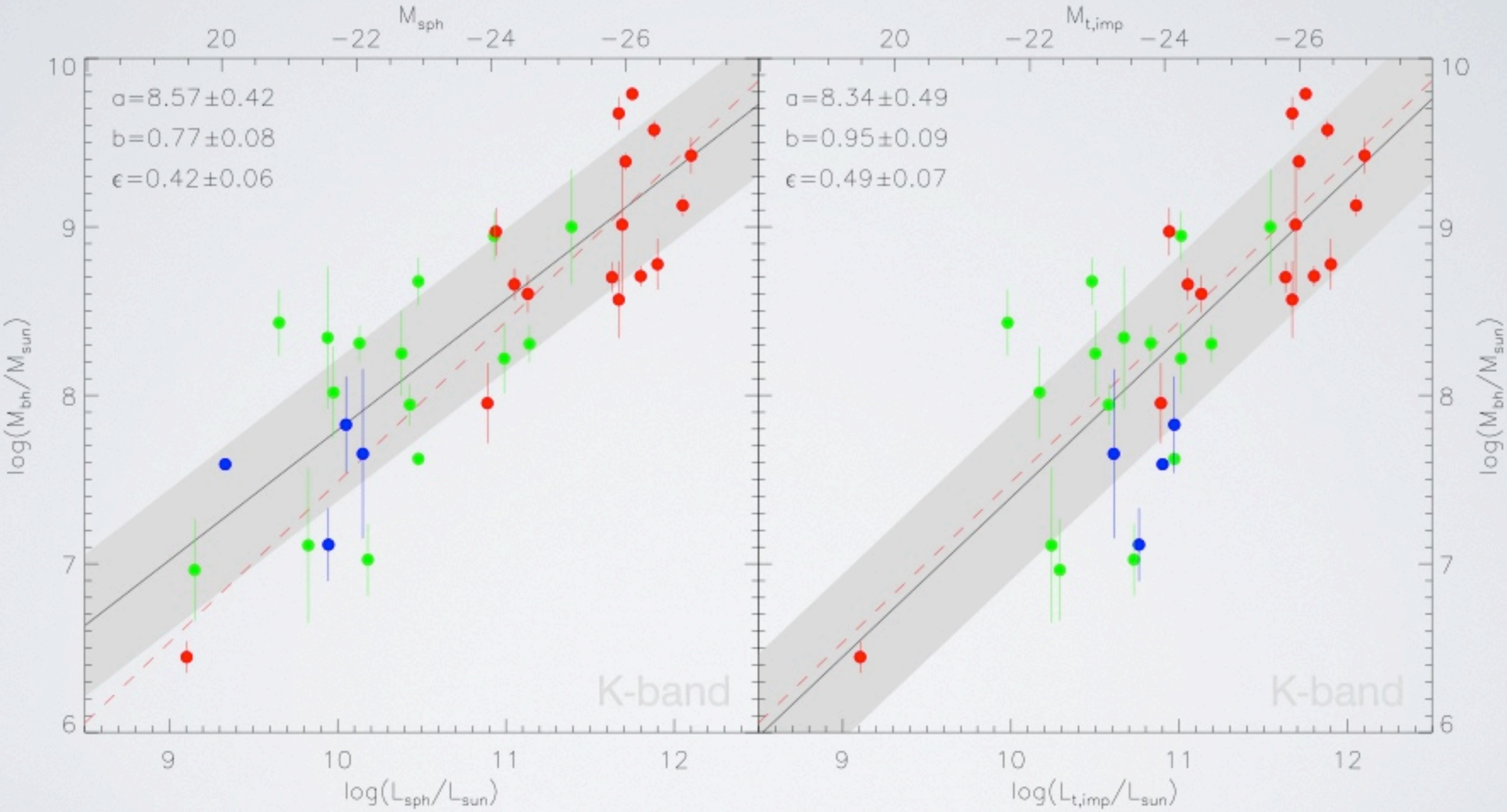
Graham & Scott



Kormendy & Ho



BH-BULGE IN 2013

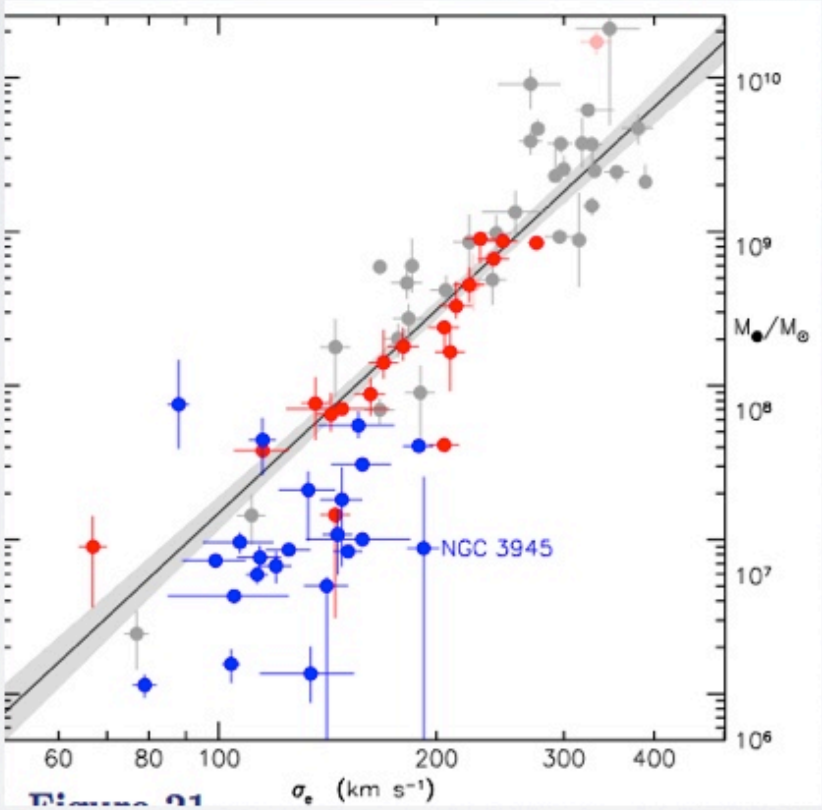


Läsker et al 2013 submitted

Remco van den Bosch

M-σ SCALING RELATION

Kormendy & Ho

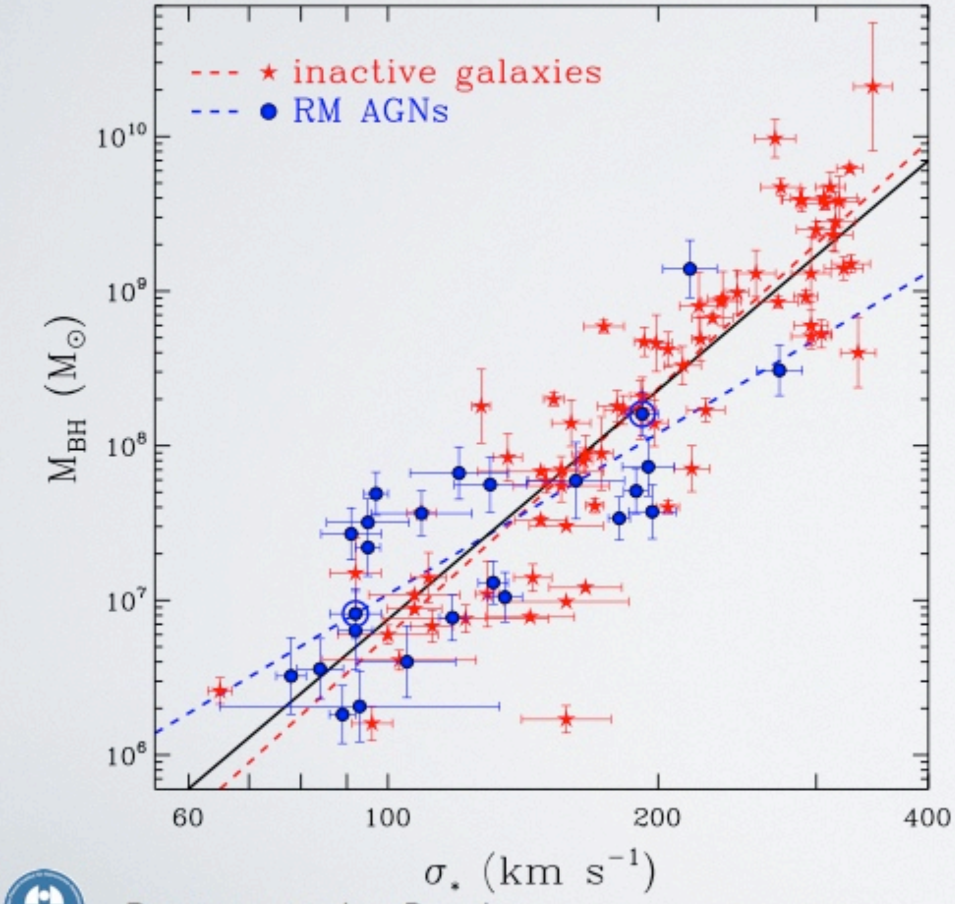


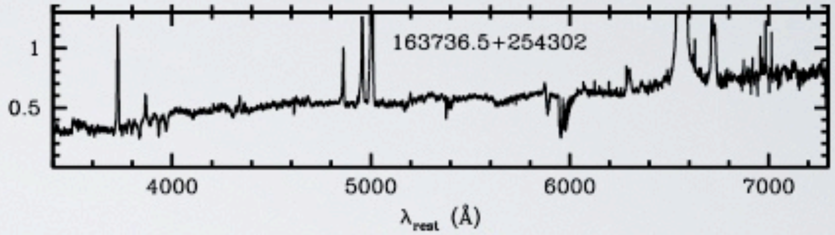
Black hole mase (Msun)

σ (km/s)

M-σ RELATION IS CALIBRATOR FOR AGNS

Woo et al. 2010, 2013





$$M_{\rm BH} = f\,\frac{(\Delta V)^2 R_{\rm BLR}}{G}$$

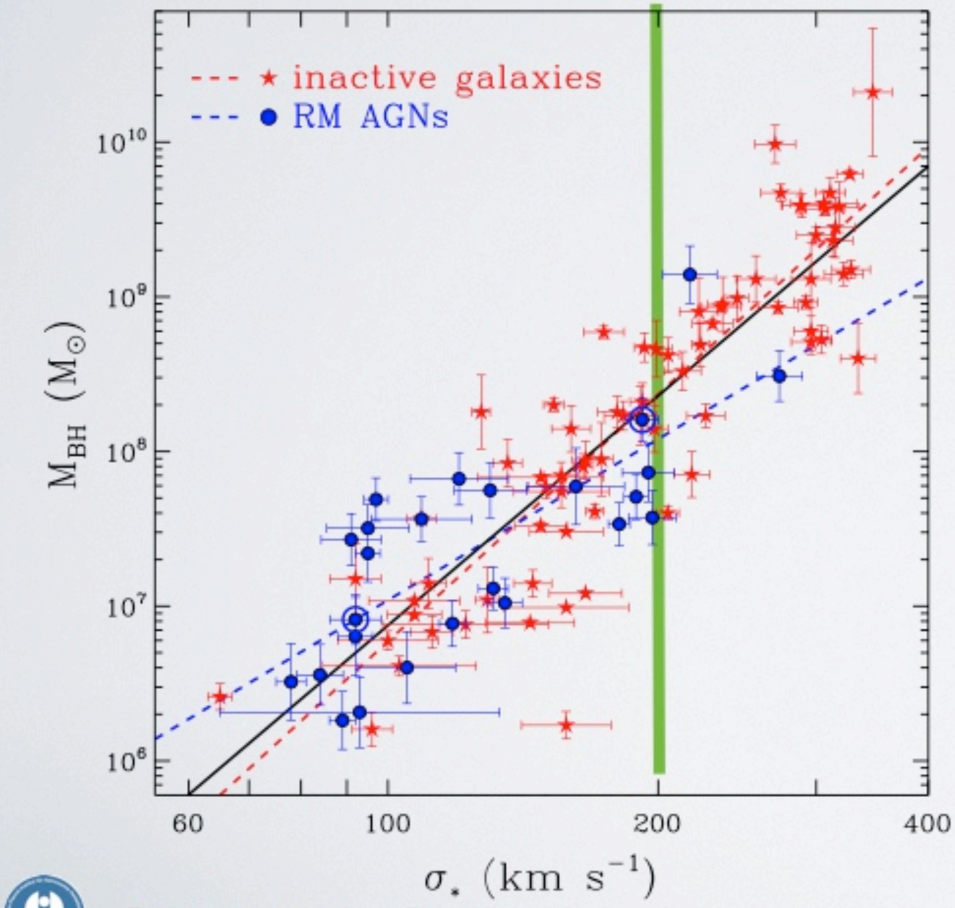
Relation is the basis for all other line width AGNS black hole masses.

The local non-agn bhmasses are mostly early-type galaxies

The AGNs are almost all disks.

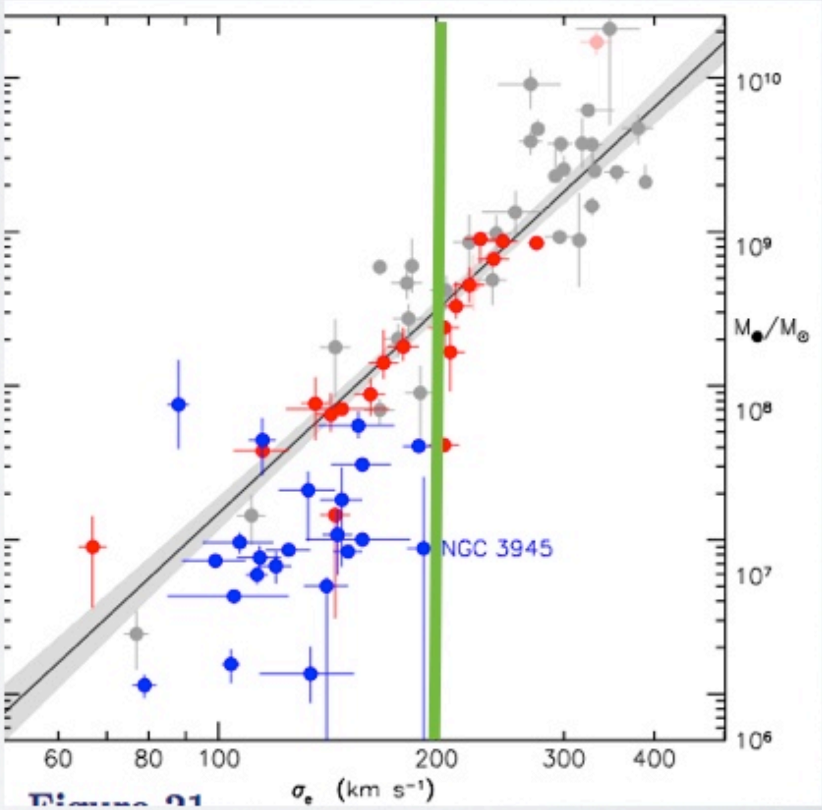
M-σ RELATION IS CALIBRATOR FOR AGNS

Woo et al. 2010, 2013



Kormendy & Ho

Black hole mase (Msun)



σ (km/s)

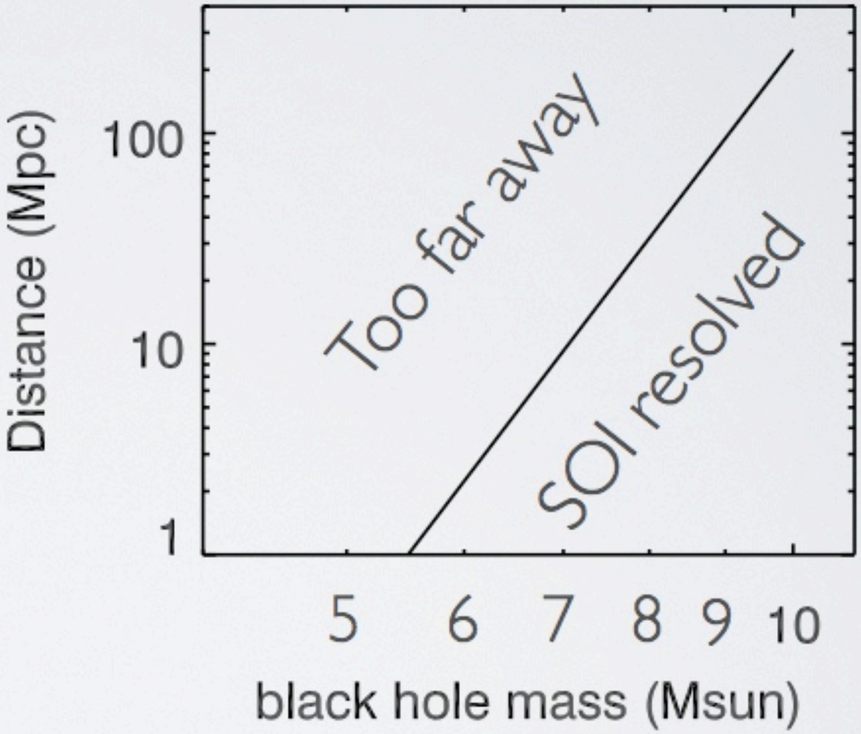
WHY ARE THERE FEW BLACK HOLE MASS MEASUREMENTS AT Z=0?

- **MANY REQUIREMENTS FOR DYNAMICAL ESTIMATES:**
- Resolve the Sphere-of-influence

$$R_{soi} = \frac{GM_\bullet}{D\sigma^2} \propto \frac{\sigma^{2.2}}{D}$$

Thus HST/STIS or AO. And few available targets

- Spatially resolved kinematics
- High resolution photometry for stellar mass model



HET OBSERVATIONS

- Long slit spectra with the Marcario Low Resolution Spectrograph
- 4200-7400 AA, 180km/s resolution, 1''x2.5' slit
- 1000 galaxies observed to date
- Distances less then ~140 Mpc
- Effectively probing the most massive nearby galaxies

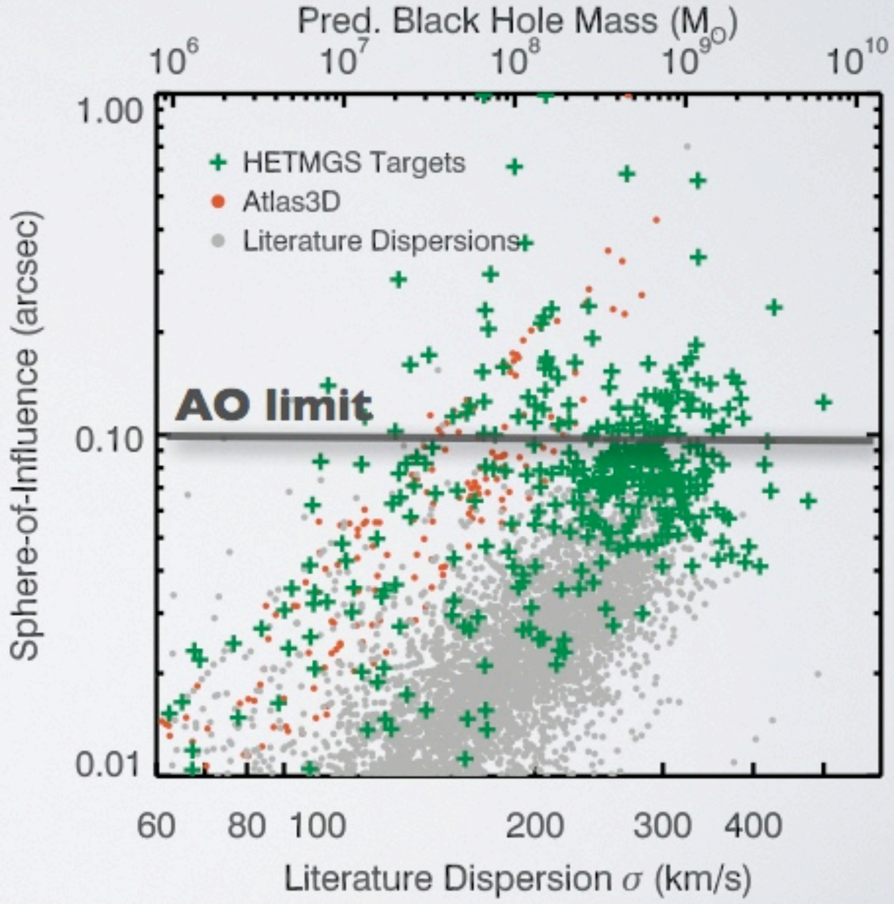
HET NEARBY MASSIVE GALAXIES SURVEY

- **Select candidate galaxies using literature velocity dispersion from Hyperleda database**

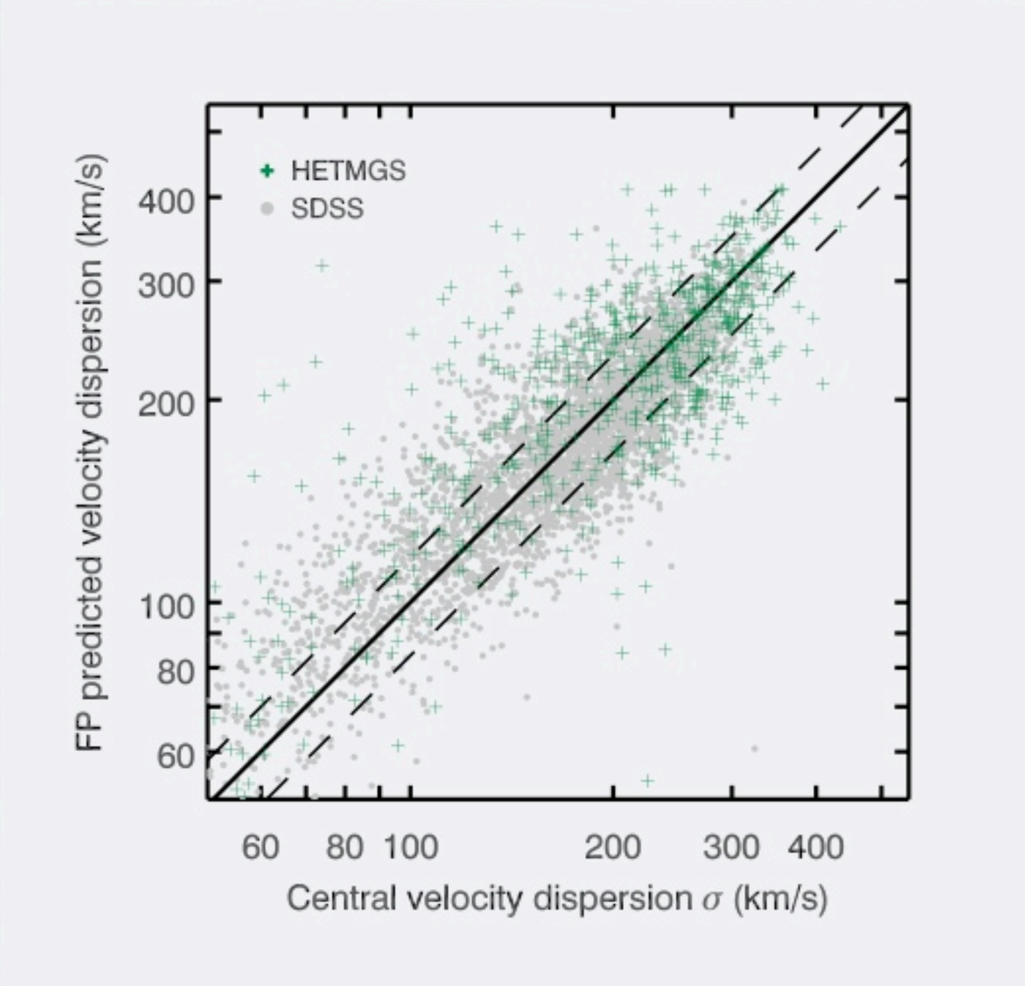
- predict black hole mass using M-sigma

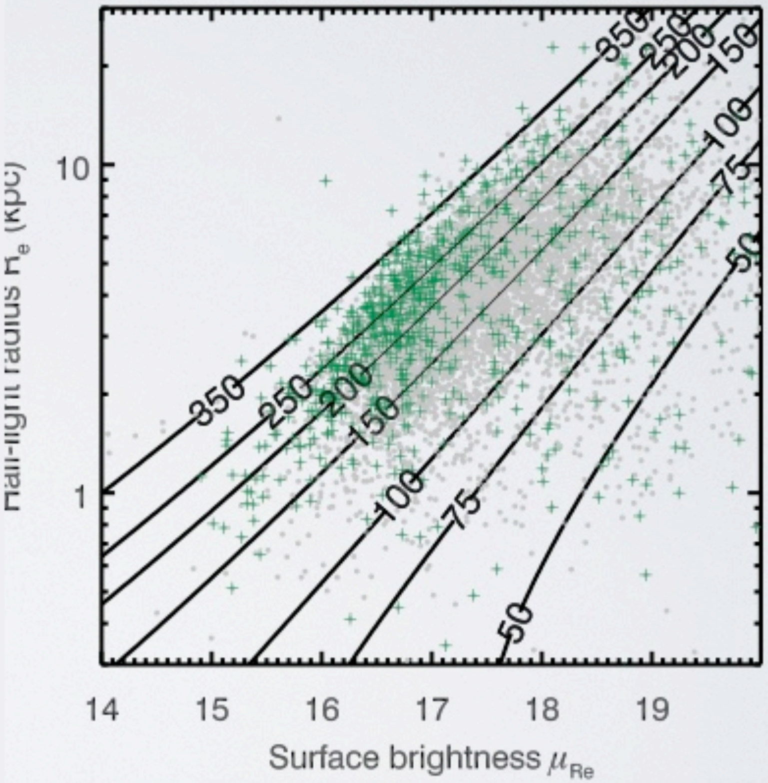
- few targets with SOI>0.1"

- Most nearby galaxies are not in SDSS



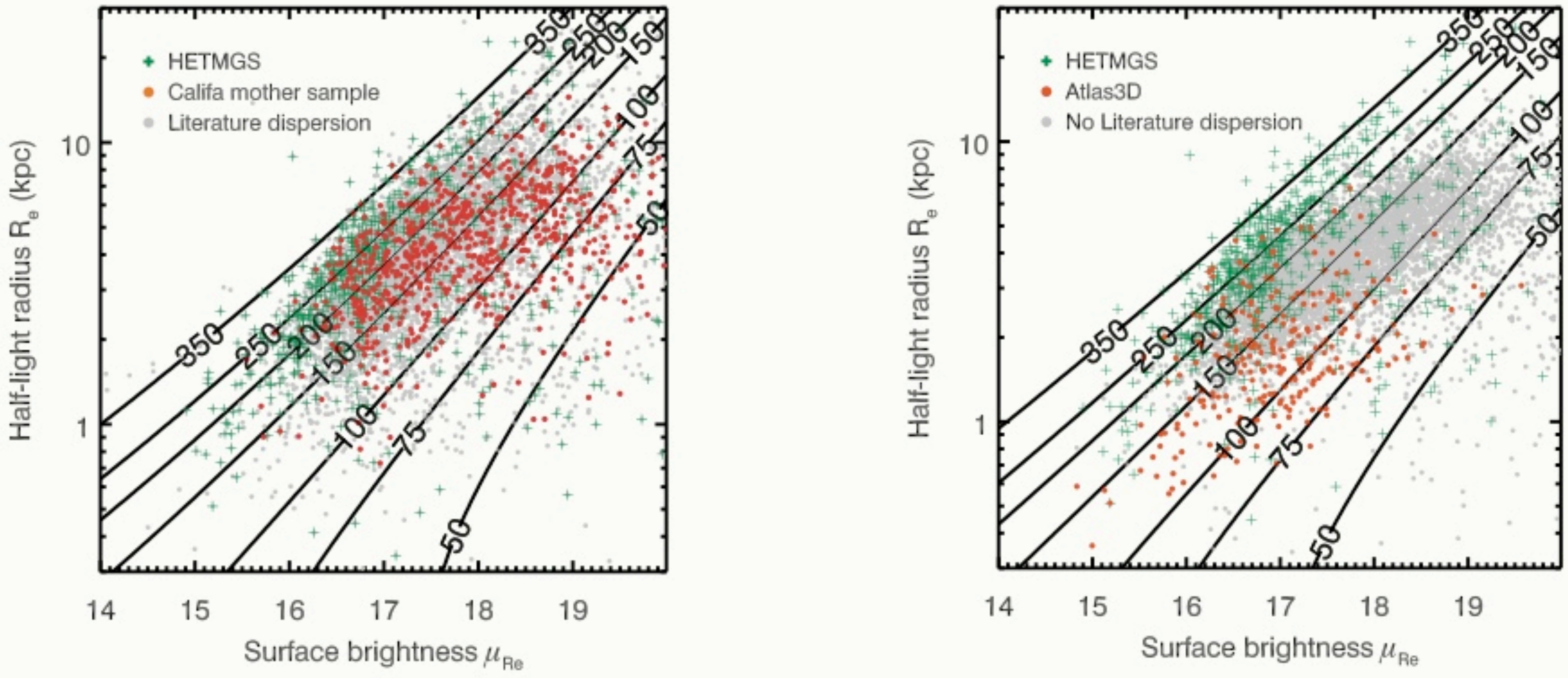
2MASS FUNDAMENTAL PLANE



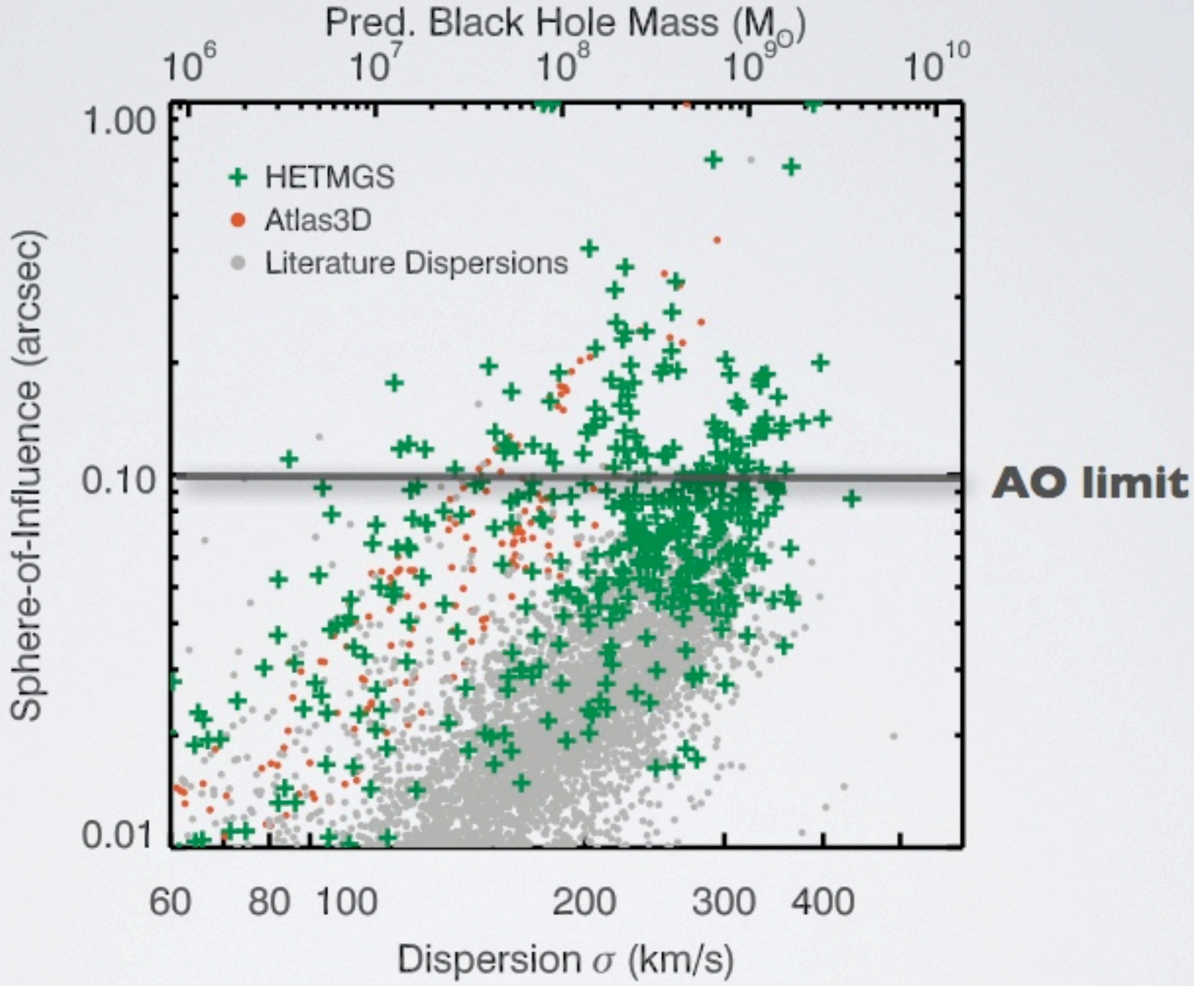


- **The fundamental plane (Virial Theorem) defines the relation between galaxy mass, size and velocity dispersion.**

GATEWAY TO MORE BLACK HOLE MASSES

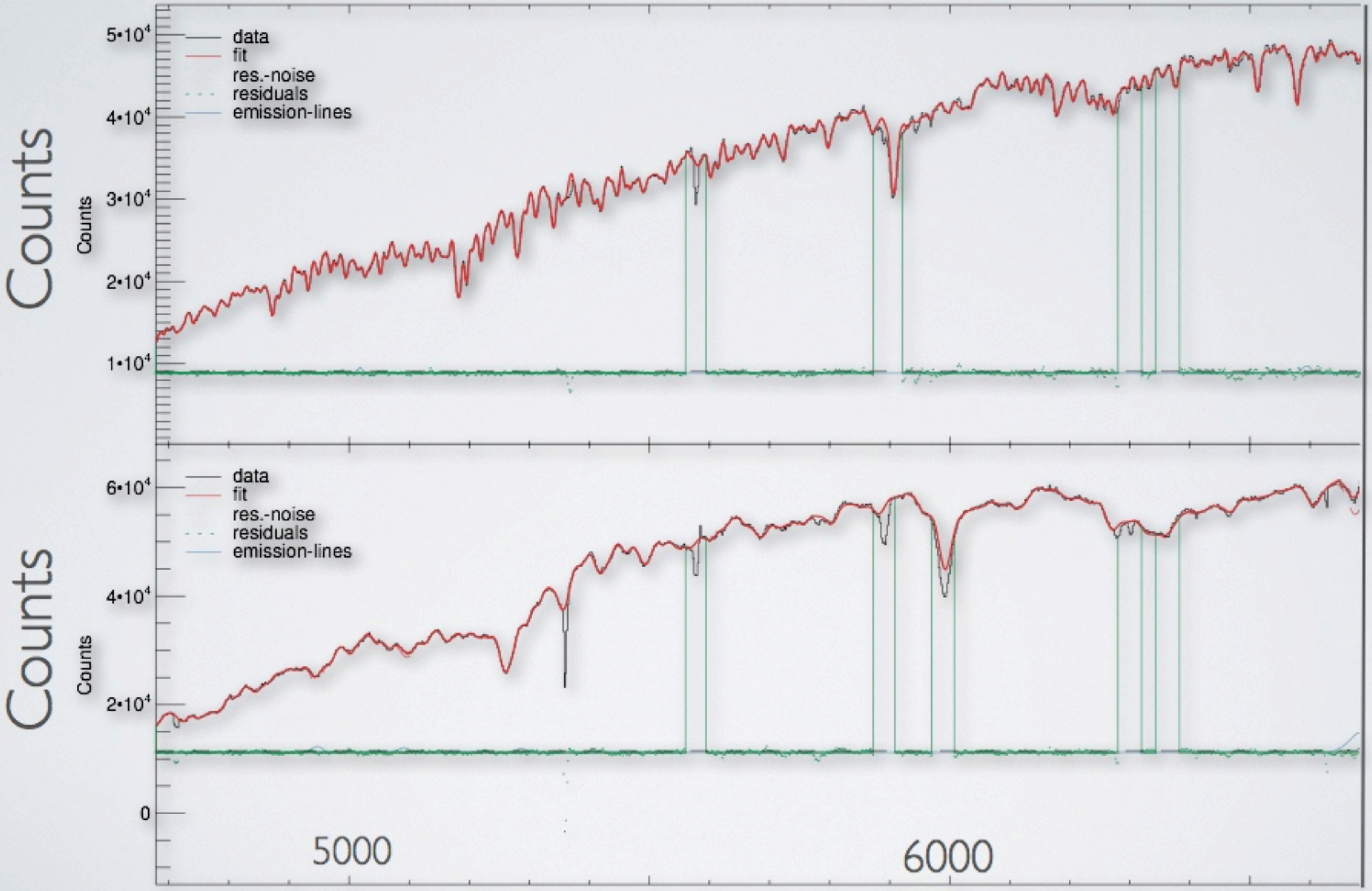


GATEWAY TO MORE BLACK HOLE MASSES



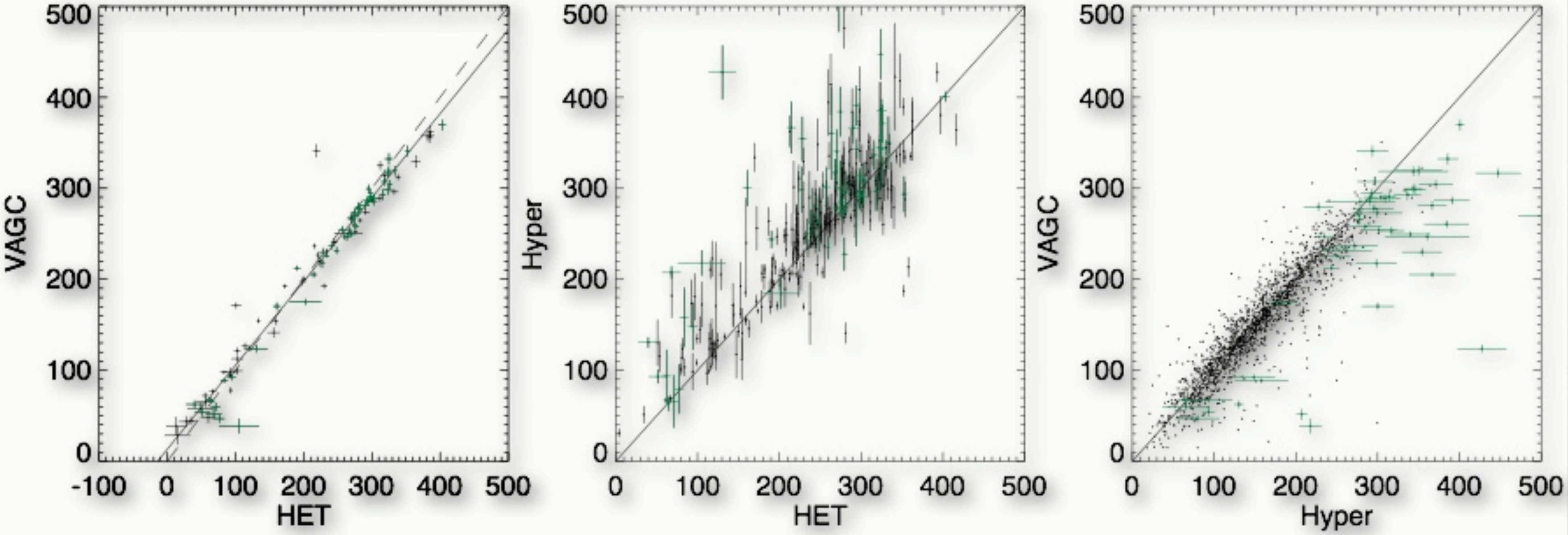
Remco van den Bosch

HOW TO MEASURE STELLAR KINEMATICS



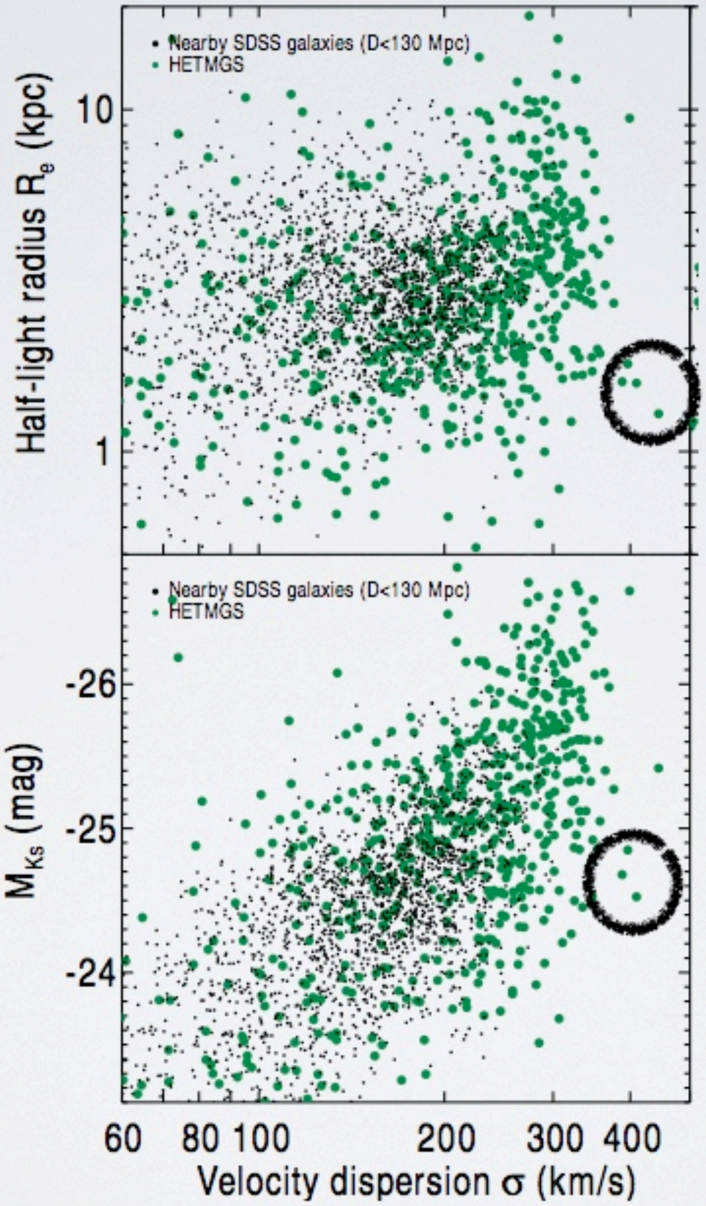
Remco van den Bosch

DISPERSION COMPARISON



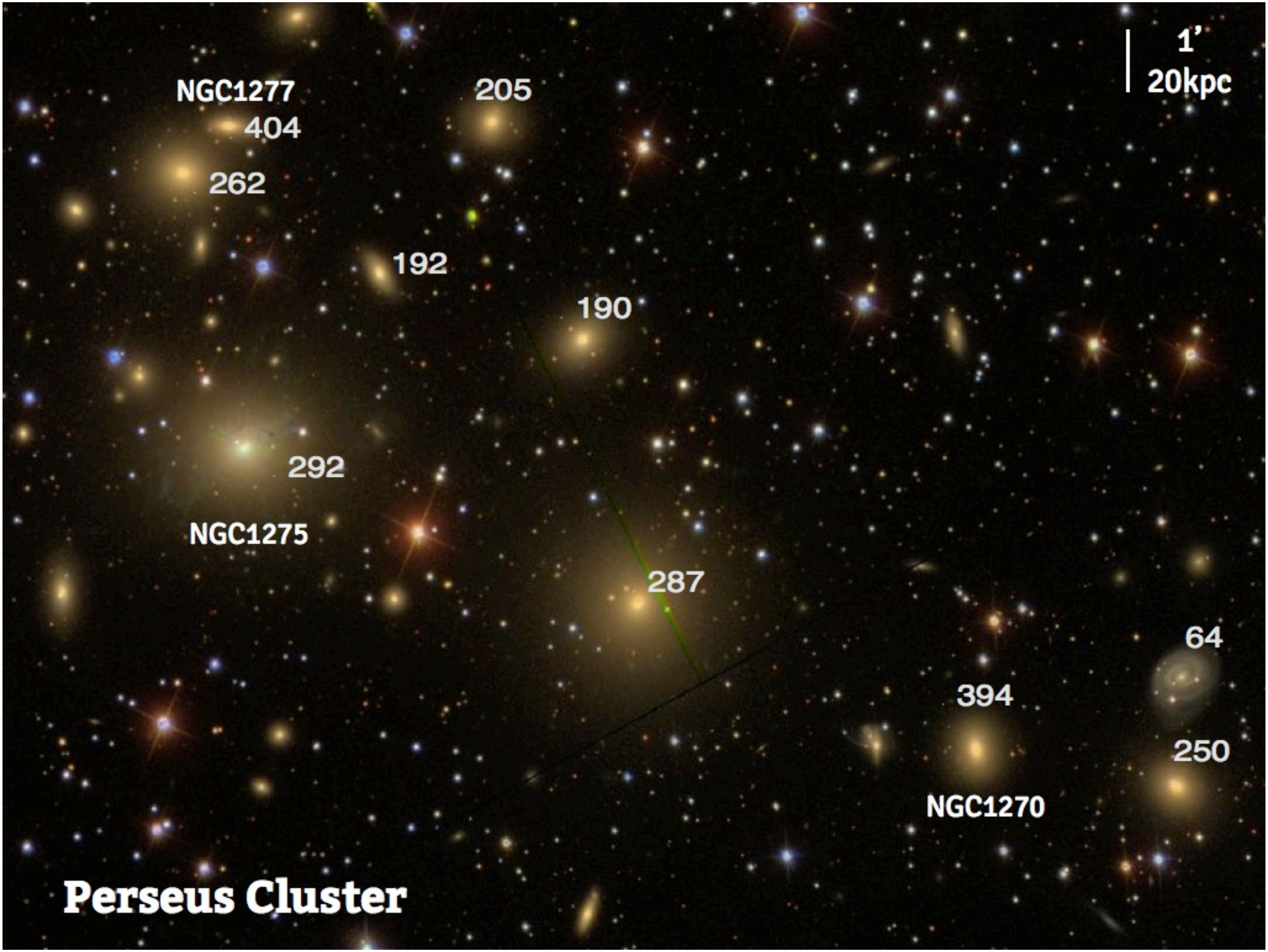
- Hyperleda dispersions unreliable

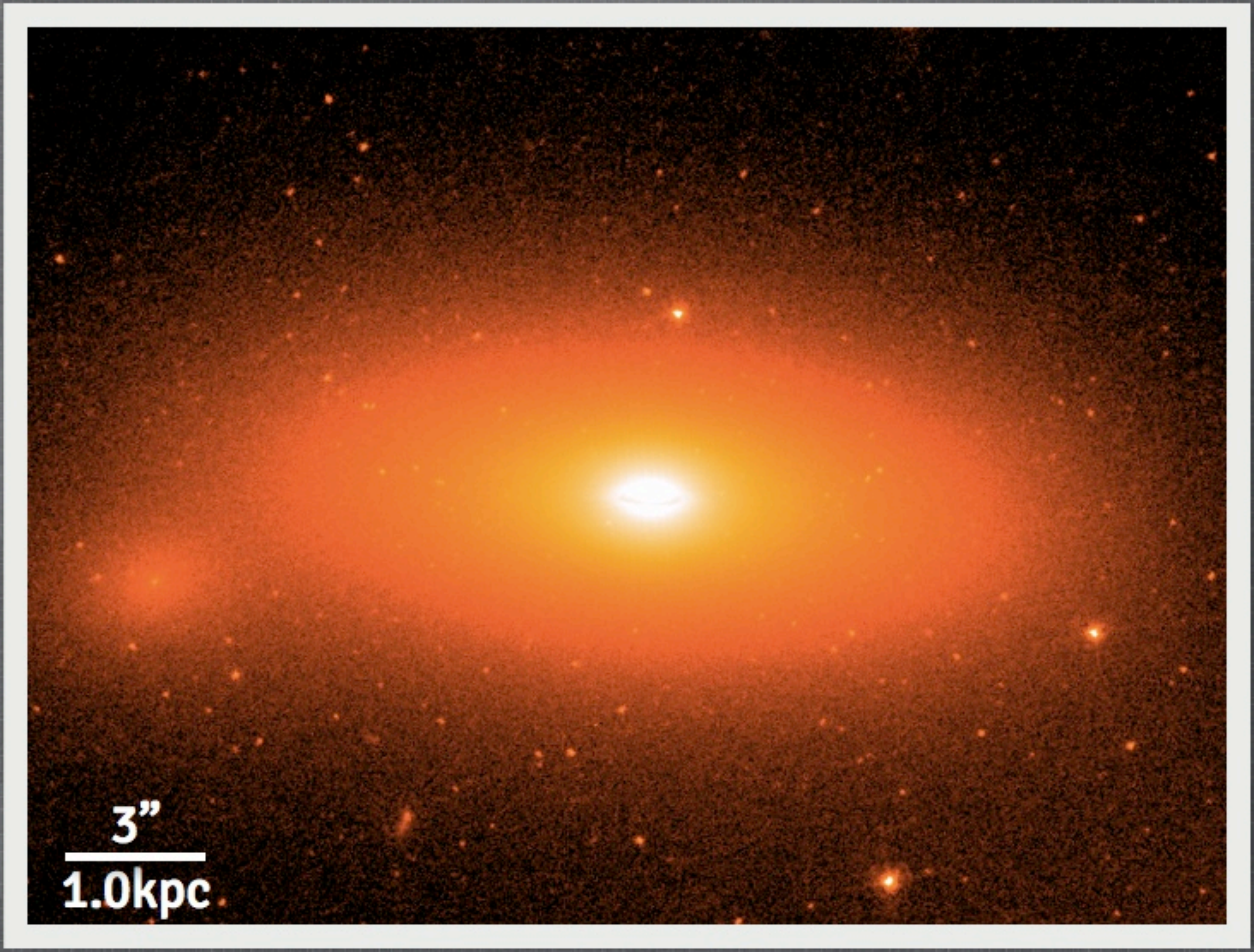
GALAXY PROPERTIES



Remco van den Bosch

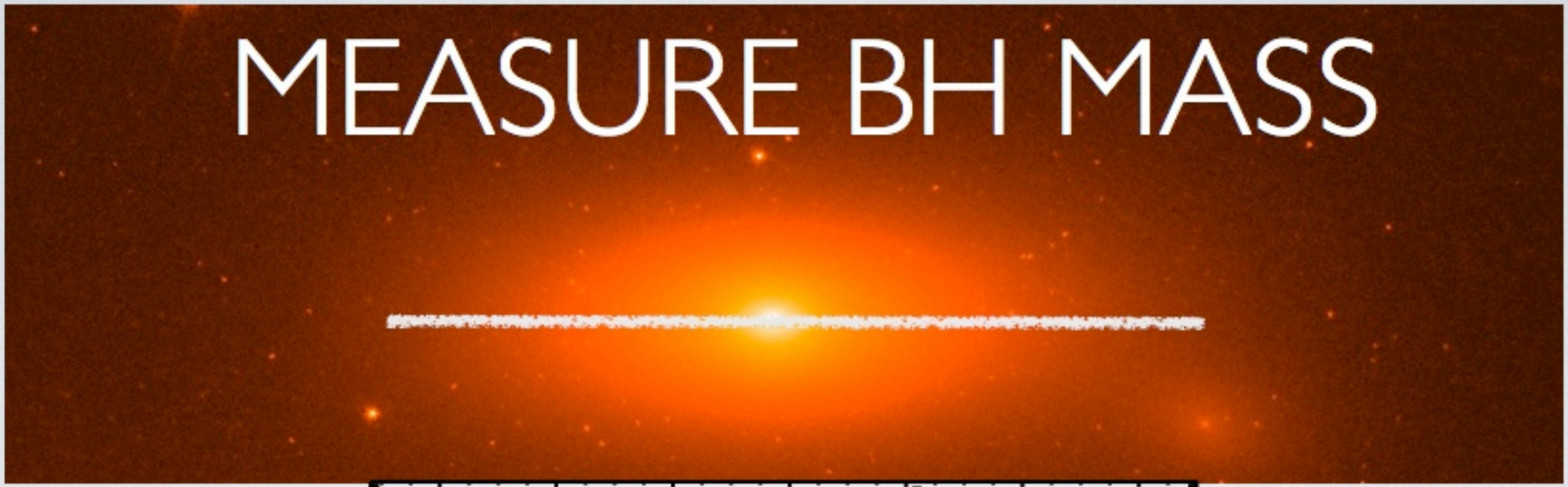
Perseus Cluster

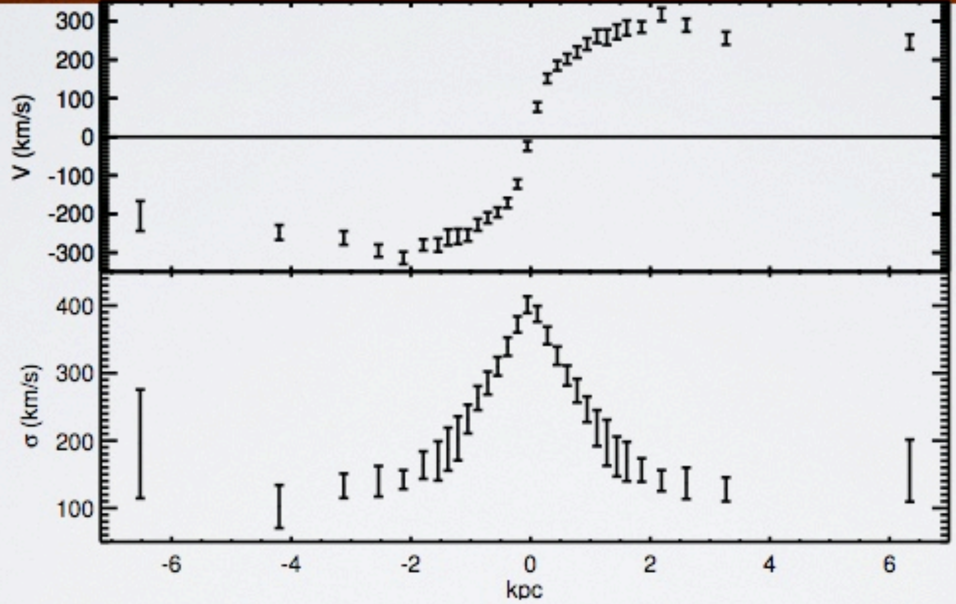

NGC1277
205
404
262
192
190
292
NGC1275
287
64
394
250
NGC1270
1’
20kpc
Perseus Cluster



HST ACS/F550M OF NGC1277

MEASURE BH MASS



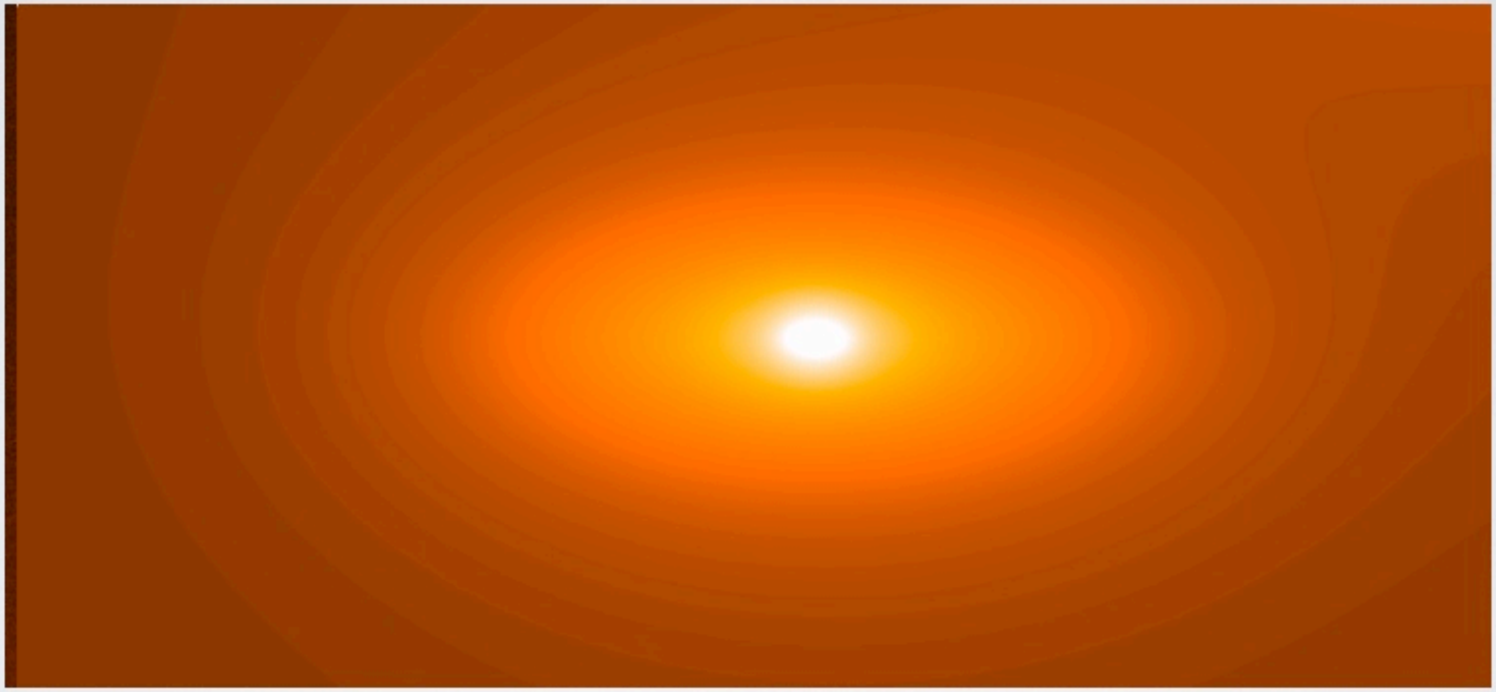


Use orbit-based models to measure the mass distribution:

- Construct a trial potential, including stars, black hole, dark matter
- Compute all possible orbits in trial potential
- Reconstruct the galaxy from orbits and at the same time fit the observed stellar kinematics
- Search over trial potentials to find optimal models

TRIAL POTENTIAL

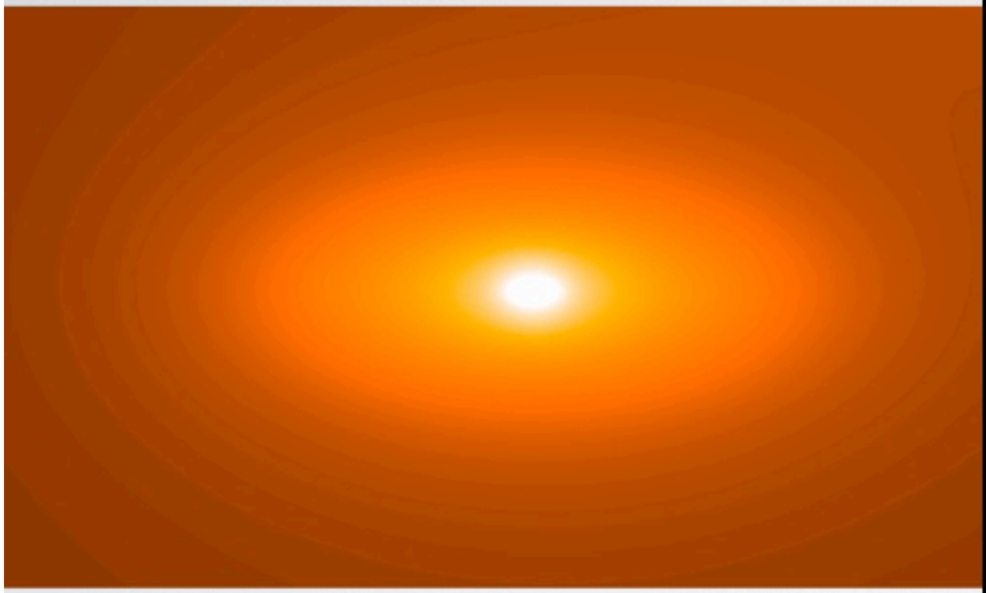
Construct an analytical prescription consisting of 2D Gaussians, which then gets de-projected into 3D

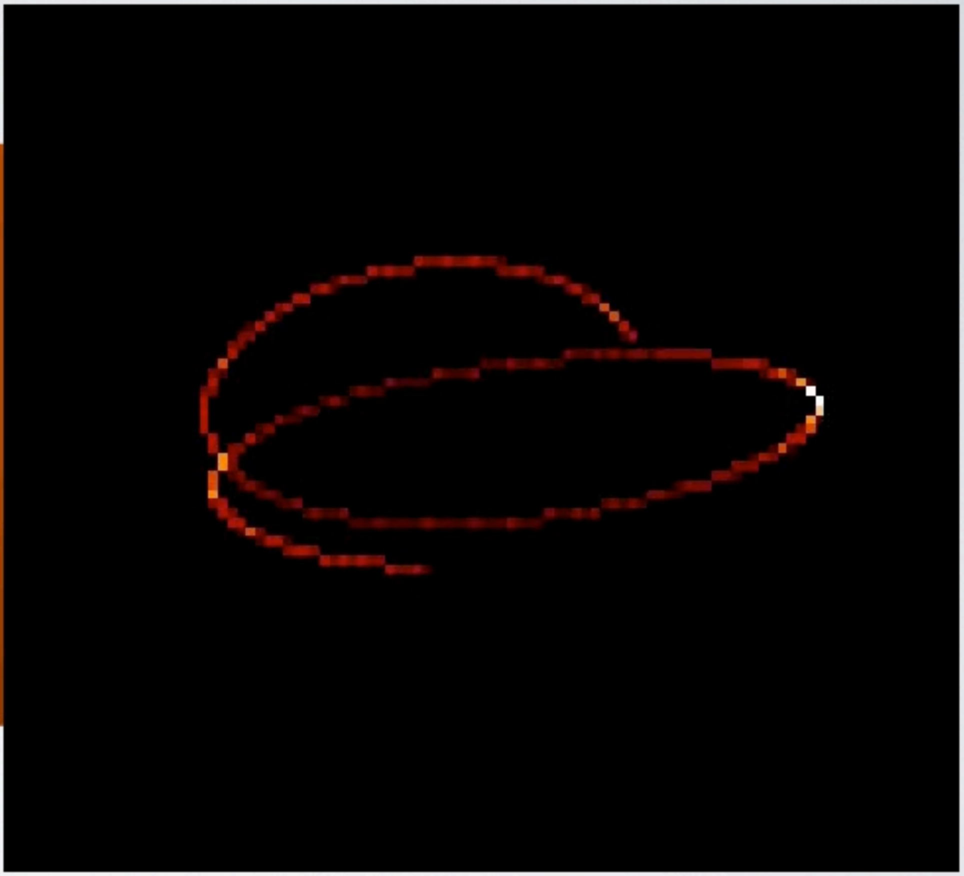


Use orbit-based models to measure the mass distribution:

- *Construct a trial potential, **including stars**, black hole, dark matter*
- Integrate all types of orbits in trial potential
- Reconstruct the galaxy from orbits and at the same time fit the observed stellar kinematics
- Search over trial potentials to find optimal models

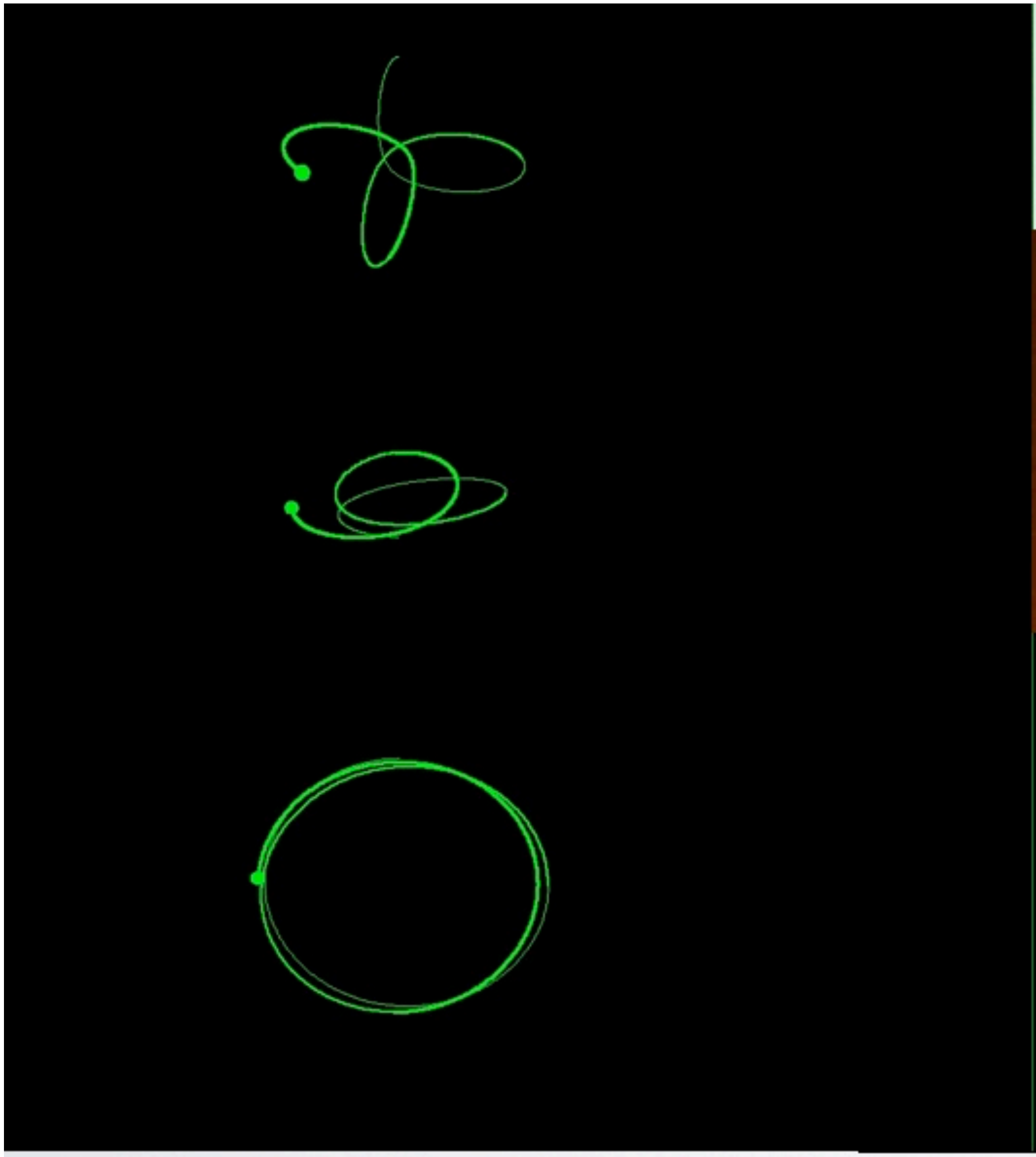
INTEGRATE ORBITS

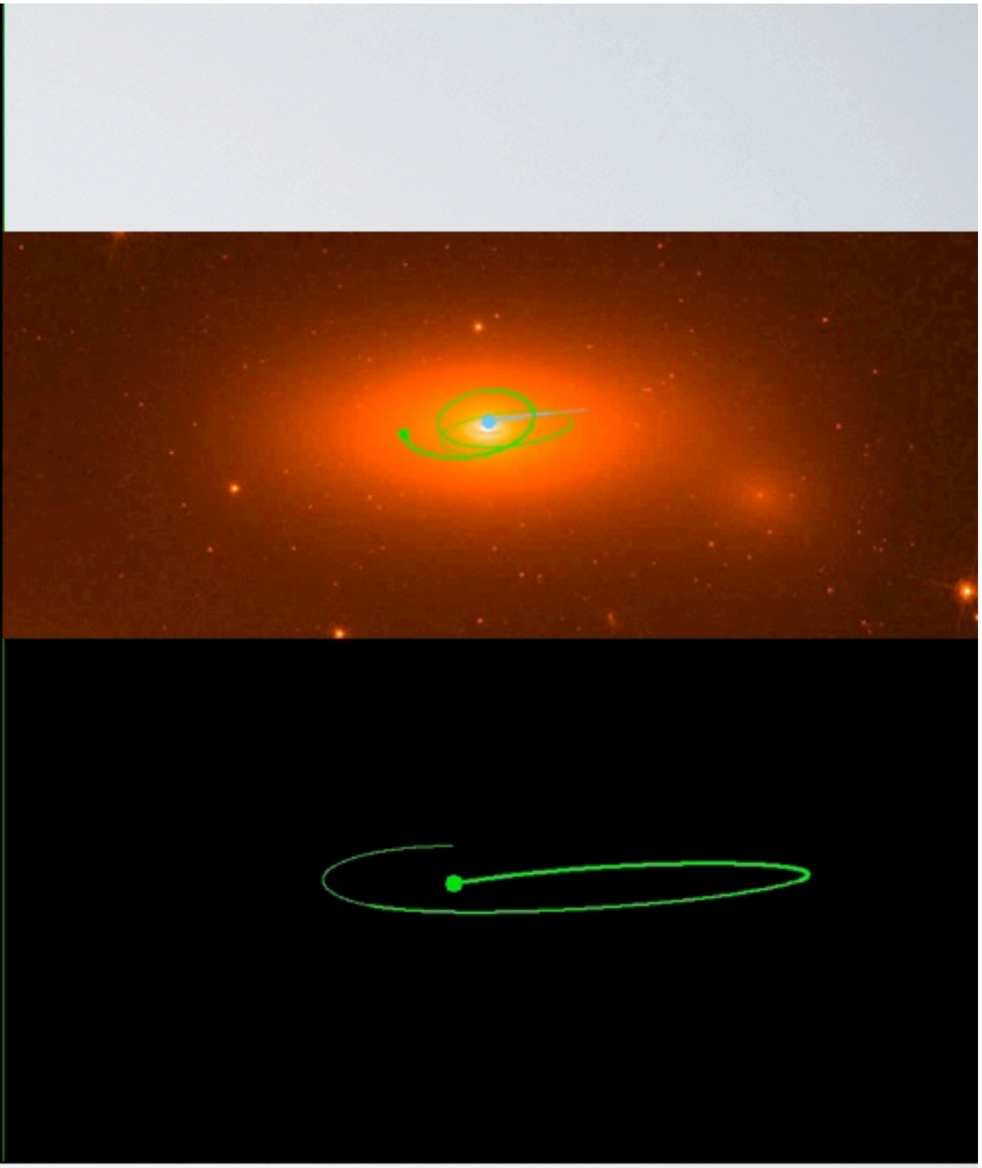




Use orbit-based models to measure the mass distribution:

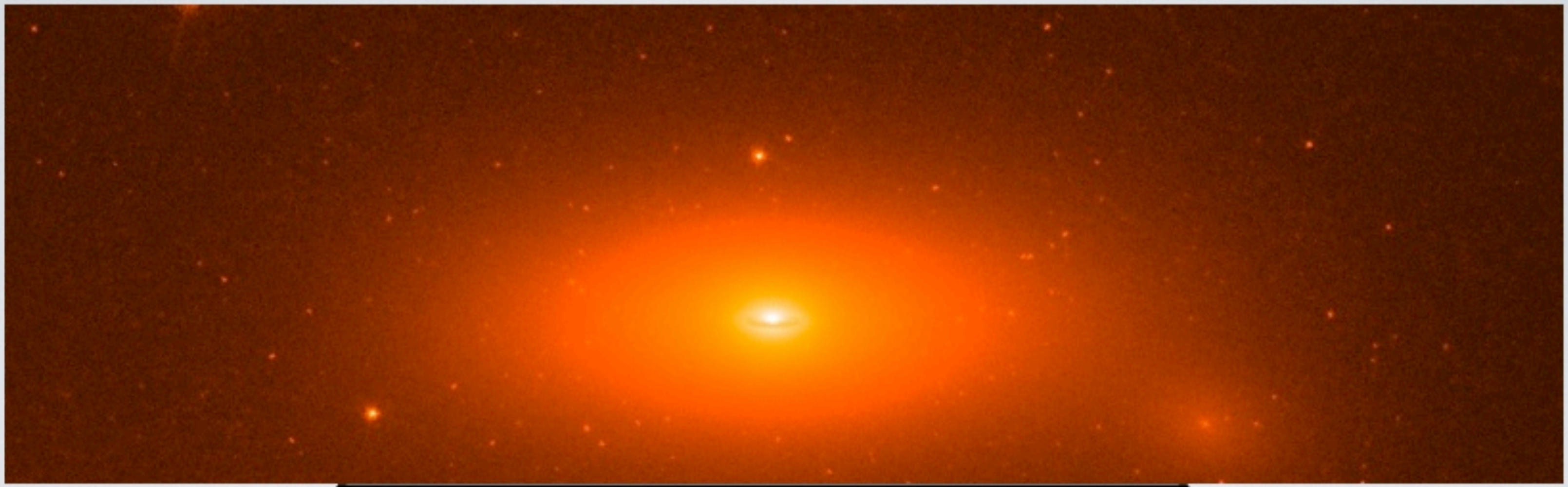
- Construct a trial potential, including stars, black hole, dark matter
- *Integrate all types of orbits in trial potential*
- Reconstruct the galaxy from orbits and at the same time fit the observed stellar kinematics
- Search over trial potentials to find optimal models

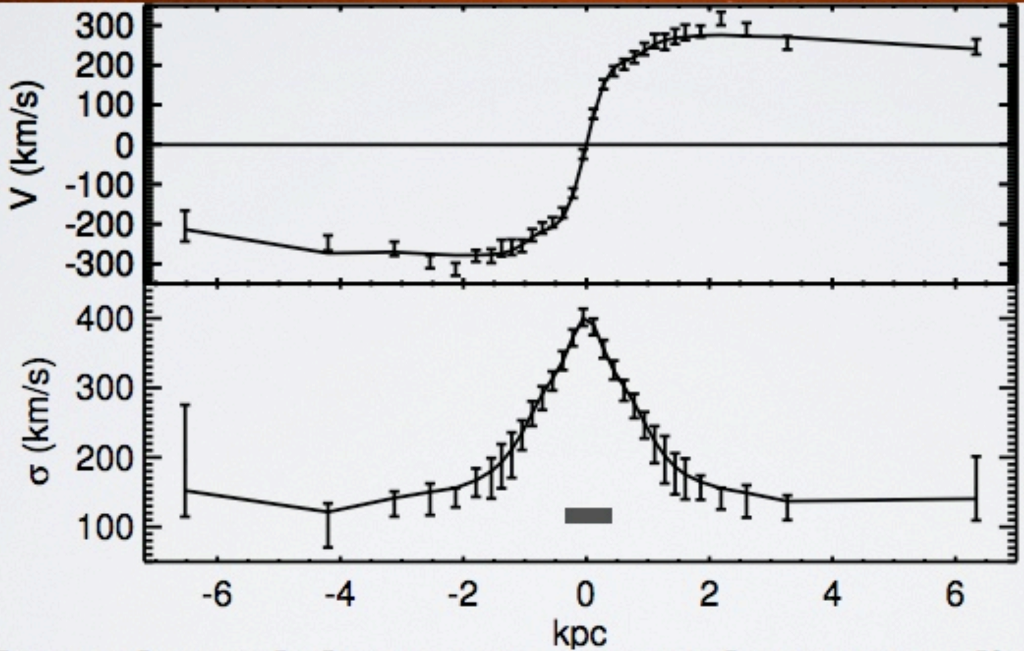




Use orbit-based models to measure the mass distribution:

- *Construct a trial potential, **including stars**, black hole, dark matter*
- Integrate all types of orbits in trial potential
- *Reconstruct the galaxy from orbits and at the same time fit the observed stellar kinematics*
- Search over trial potentials to find optimal models

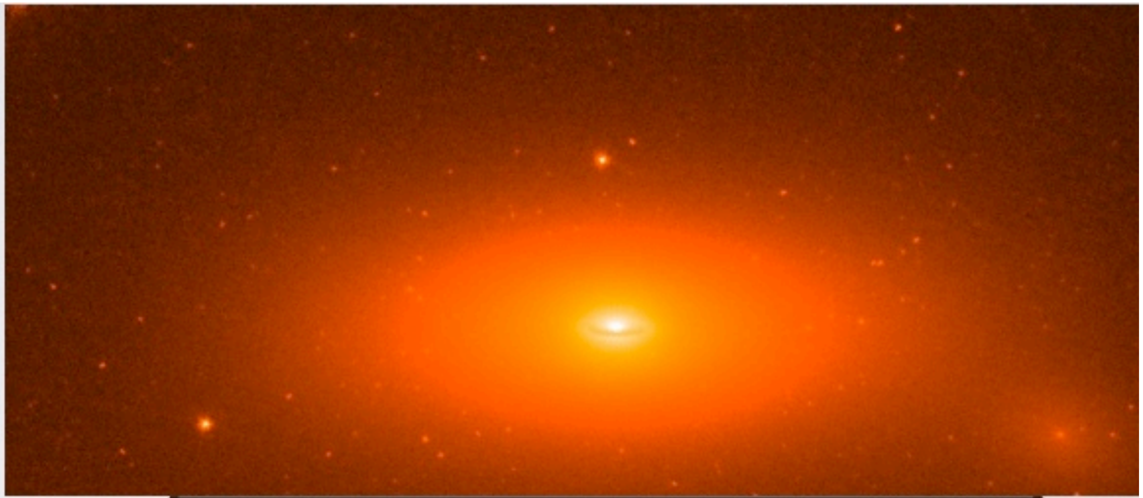


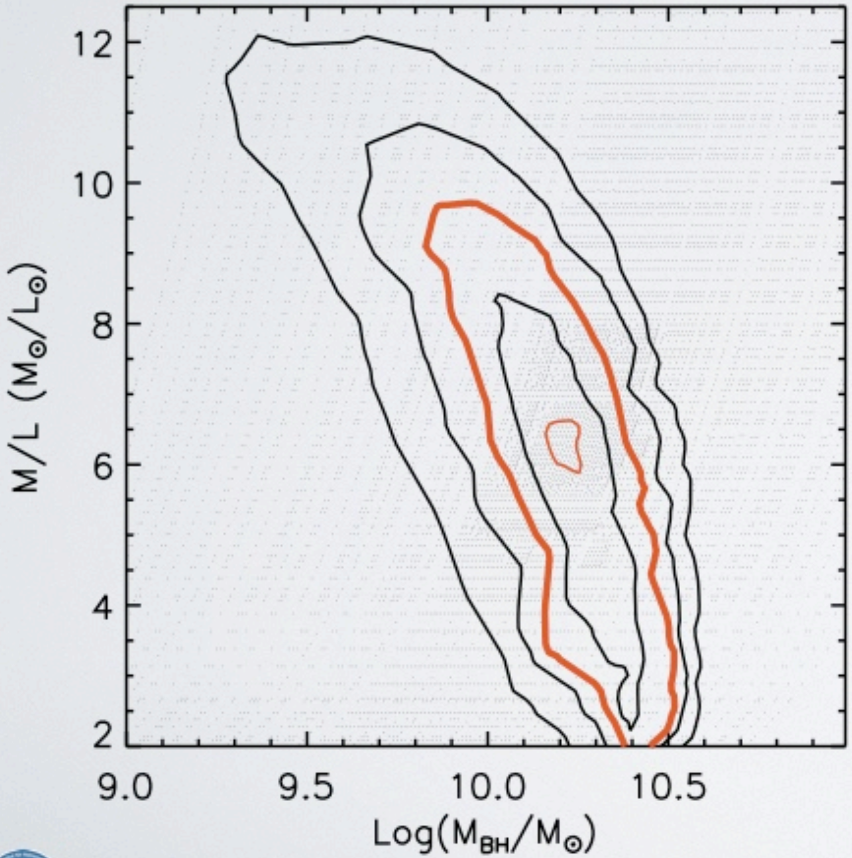


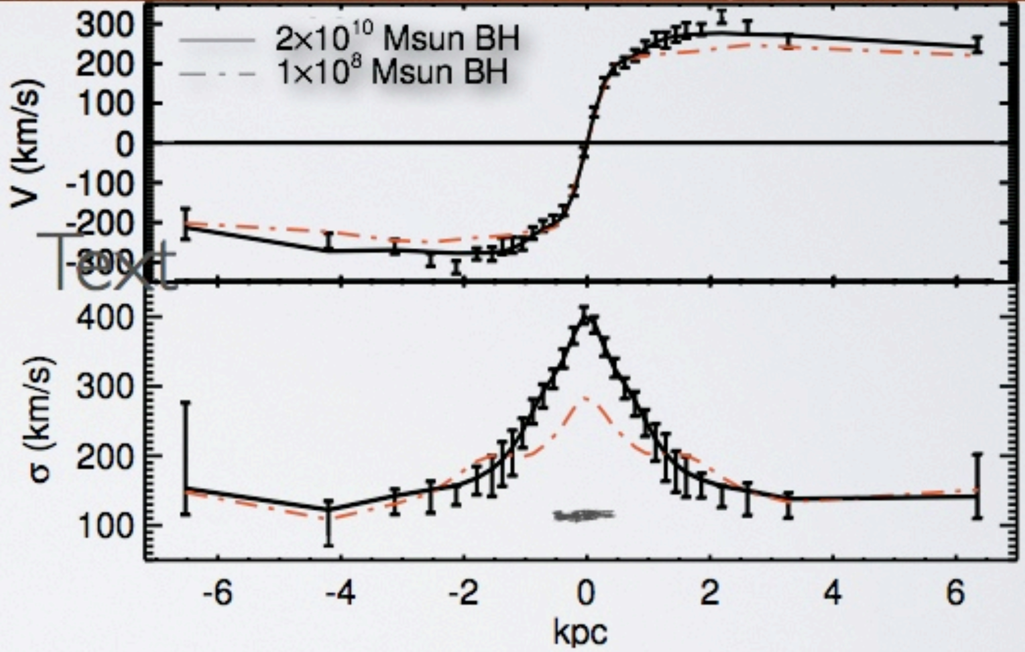
Use orbit-based models to measure the mass distribution:

- Construct a trial potential, including stars, black hole, dark matter
- Integrate all types of orbits in trial potential
- Reconstruct the galaxy from orbits and at the same time fit the observed stellar kinematics
- *Search over trial potentials to find optimal models*

A BIG BLACK HOLE IN A SMALL GALAXY



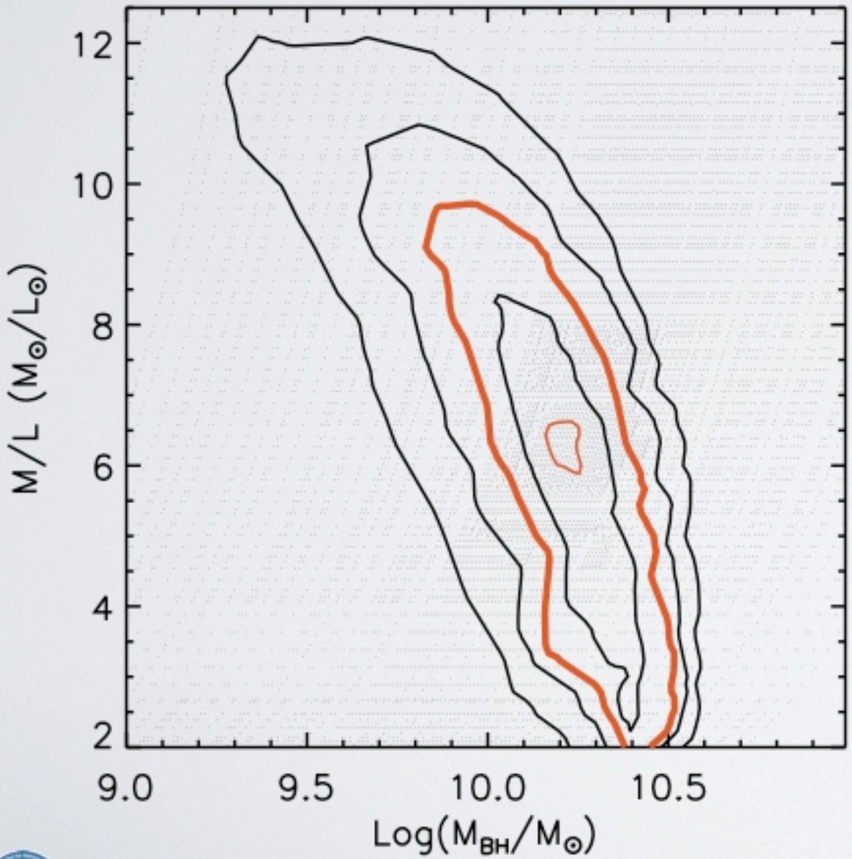


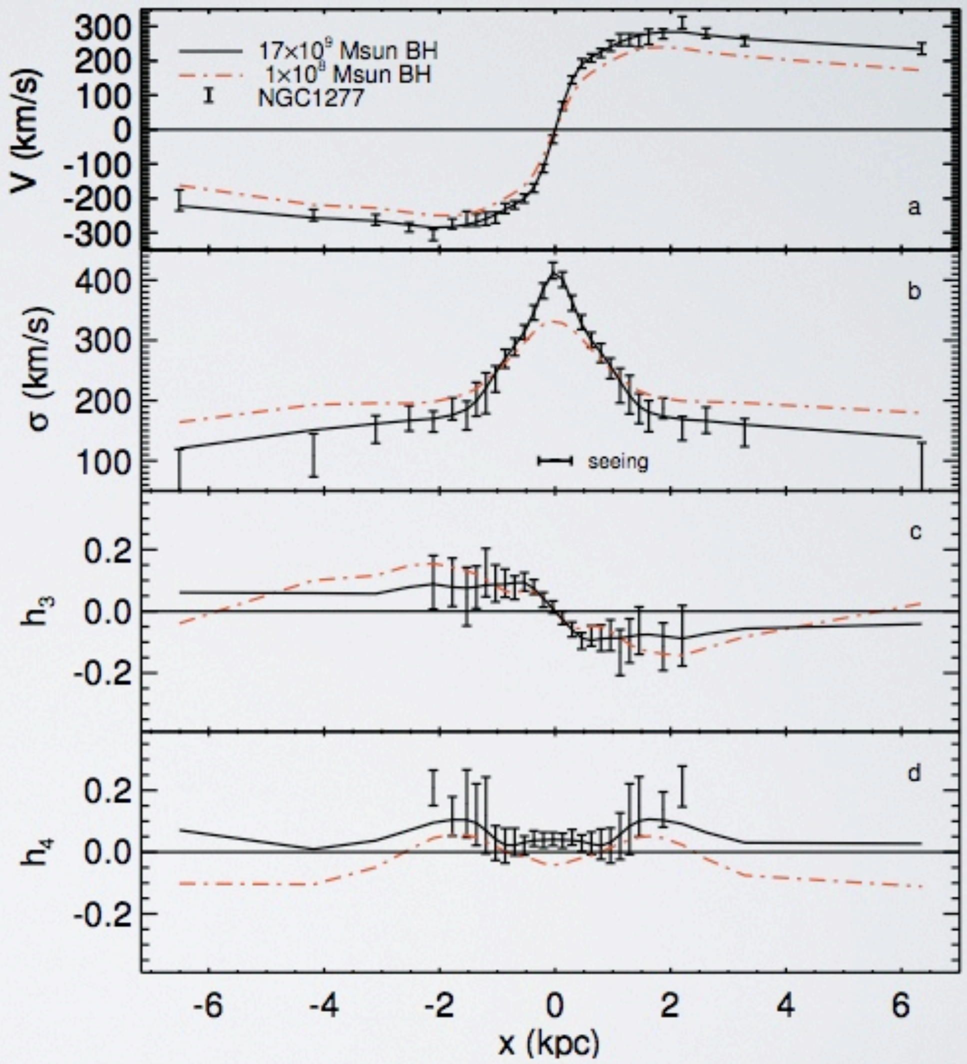


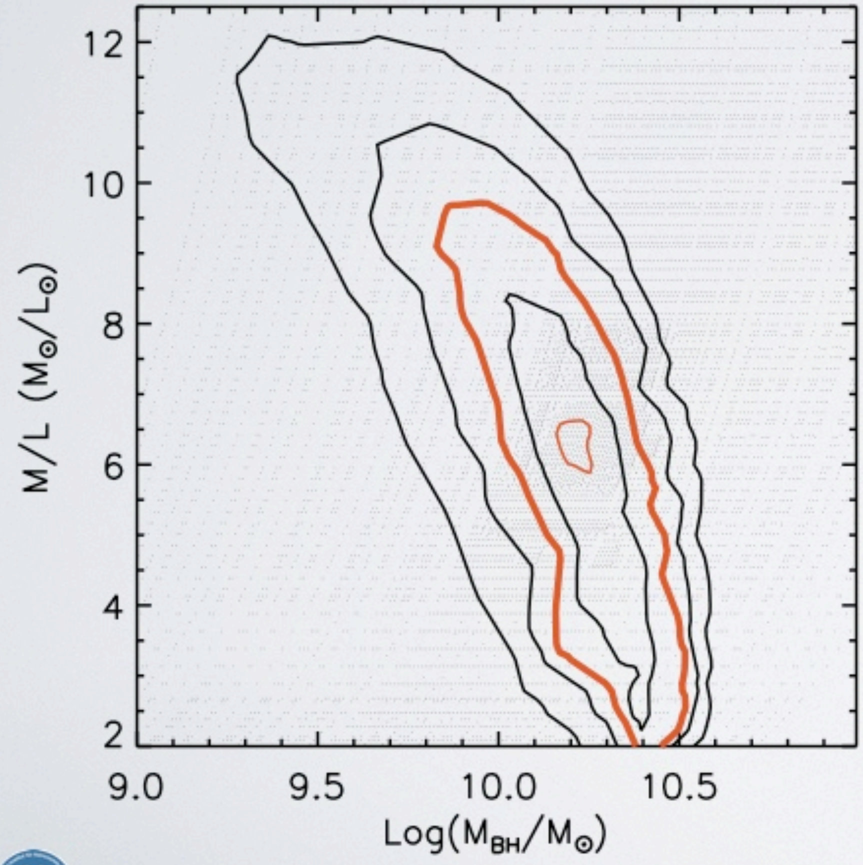
$$M_\bullet = \quad 17 \pm 3 \times 10^9\,\mathrm{M}_\odot$$

$$M_\star = \quad 1.2 \times 10^{11}\,\mathrm{M}_\odot$$

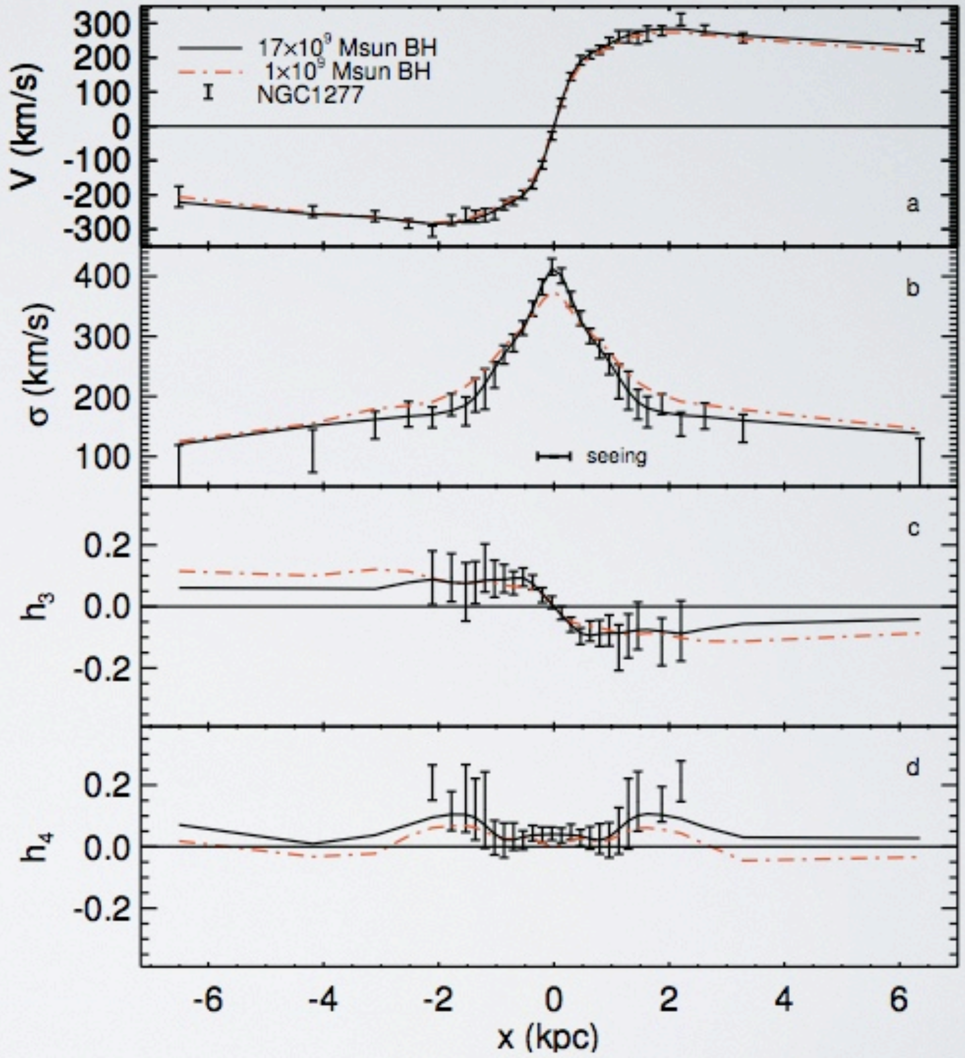
$$\sigma_e = \quad 230 - 360\,\mathrm{kms}^{-1}$$


12
10
8
6
4
2
M/L (M⊙/L⊙)
9.0
9.5
10.0
10.5
Log(M_BH/M⊙)


17×10^9 Msun BH
1×10^8 Msun BH
NGC1277
V (km/s)
300
200
100
0
-100
-200
-300
a
σ (km/s)
400
300
200
100
seeing
b
h3
0.2
0.0
-0.2
c
h4
0.2
0.0
-0.2
d
-6
-4
-2
0
2
4
6
x (kpc)



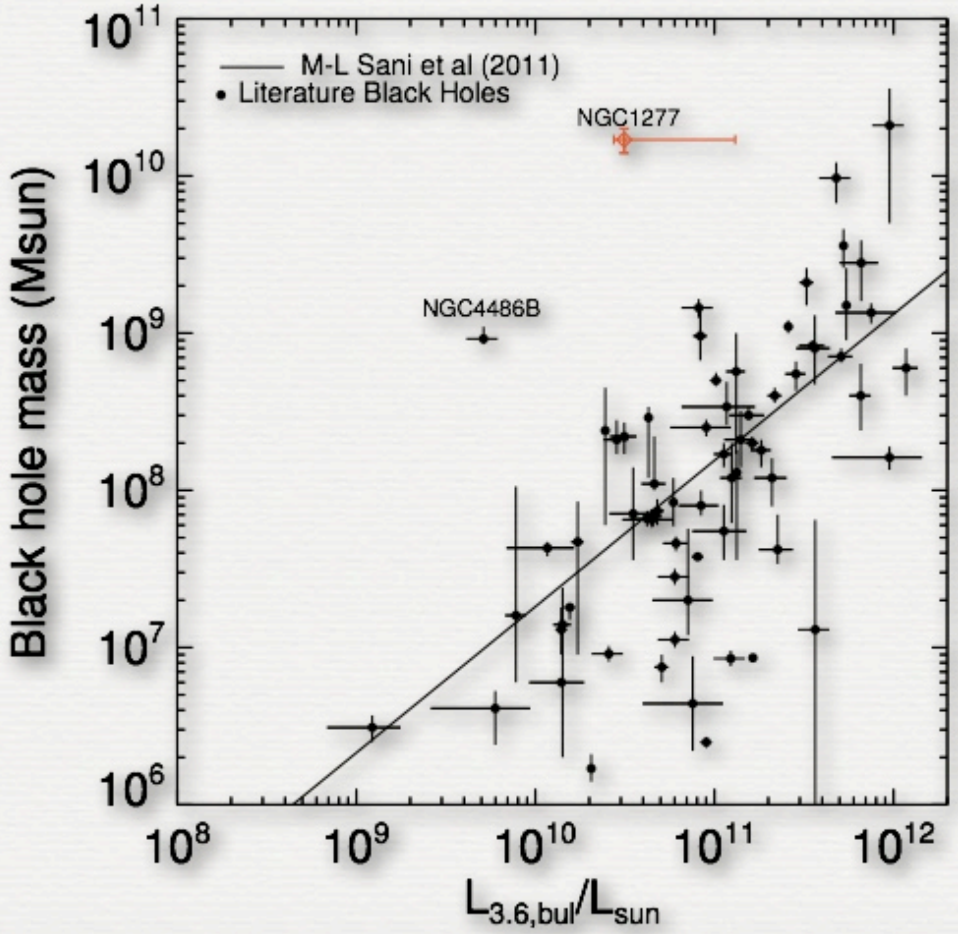
12
10
8
6
4
2
M/L $(M_\odot/L_\odot)$
9.0
9.5
10.0
10.5
$\mathrm{Log}(M_{BH}/M_\odot)$



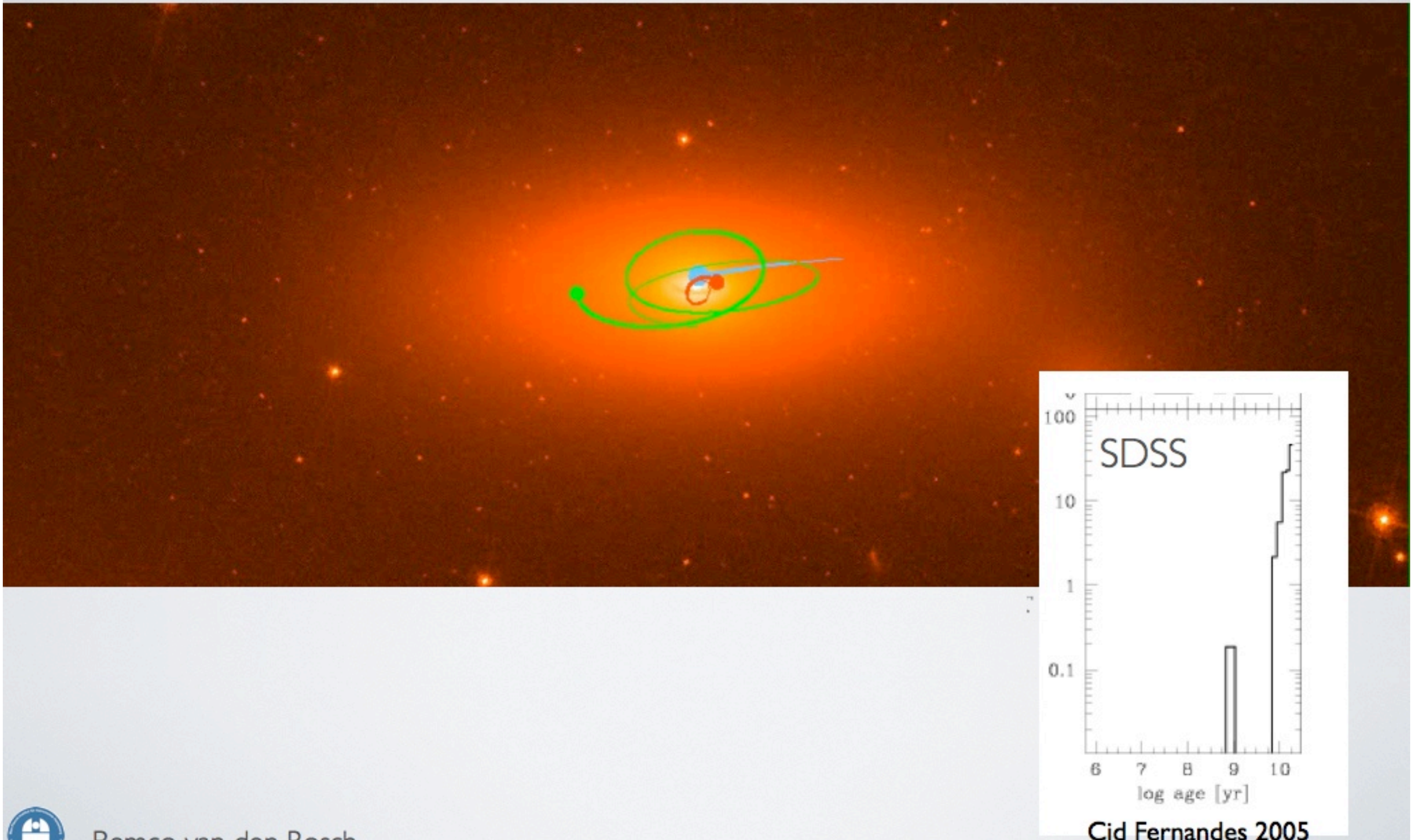
17×10^9 Msun BH
1×10^9 Msun BH
NGC1277
V (km/s)
300
200
100
0
-100
-200
-300
a
σ (km/s)
400
300
200
100
seeing
b
h_3
0.2
0.0
-0.2
c
h_4
0.2
0.0
-0.2
d
-6
-4
-2
0
2
4
6
x (kpc)

BLACK HOLE - BULGE RELATION

Sani et al. 2011, Kuo et al. 2010, Rusli et al. 2010, McConnel 2011a,b, Gültekin 2011

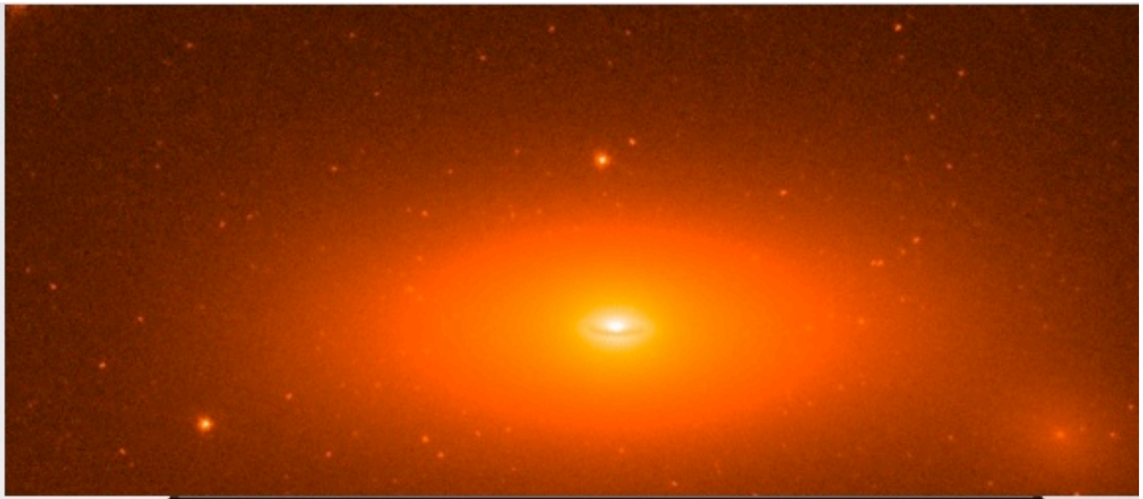


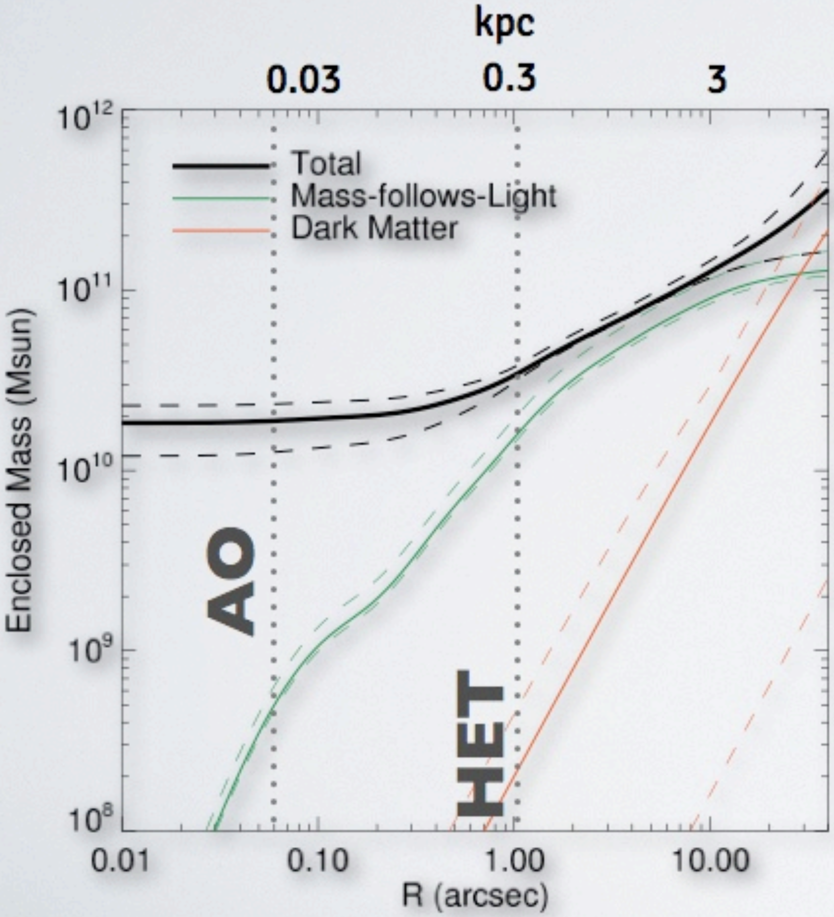
NGC1277 IS AN OLD DISK GALAXY

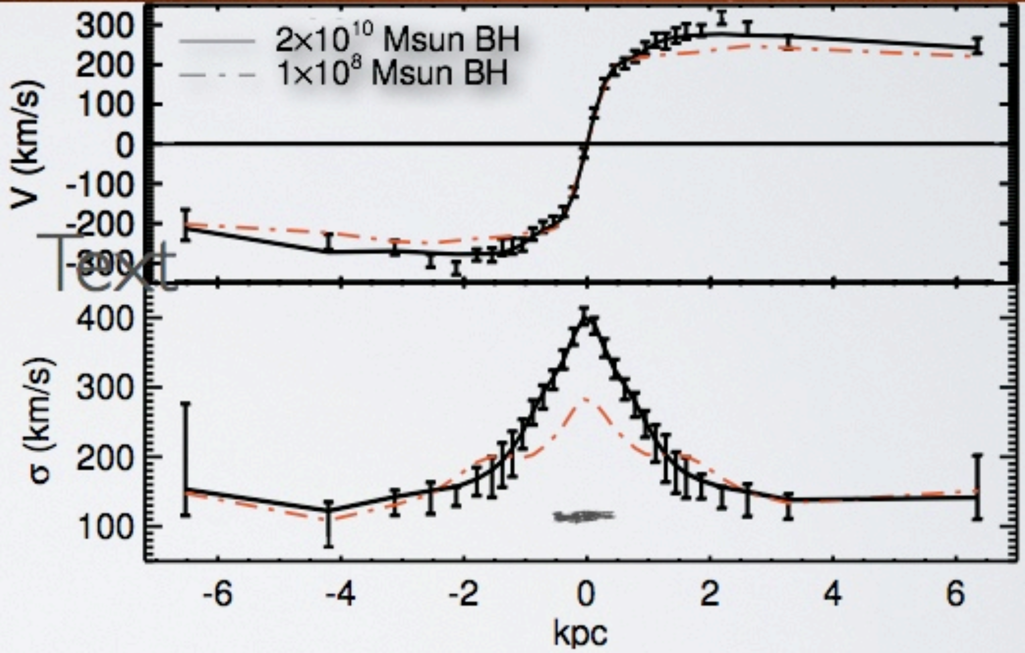


Cid Fernandes 2005

ULTIMATE PROOF REQUIRES AO







Text

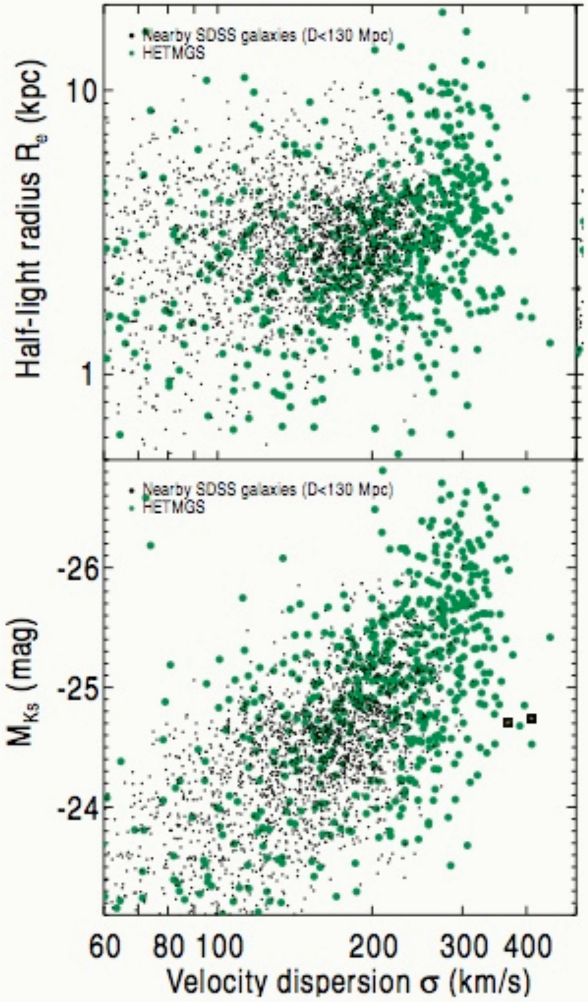
$$M_\bullet = \quad 17 \pm 3 \times 10^9 \, \mathrm{M}_\odot$$

$$M_\star = \quad 1.2 \times 10^{11} \, \mathrm{M}_\odot$$

$$\sigma_e = \quad 230 - 360 \, \mathrm{kms}^{-1}$$

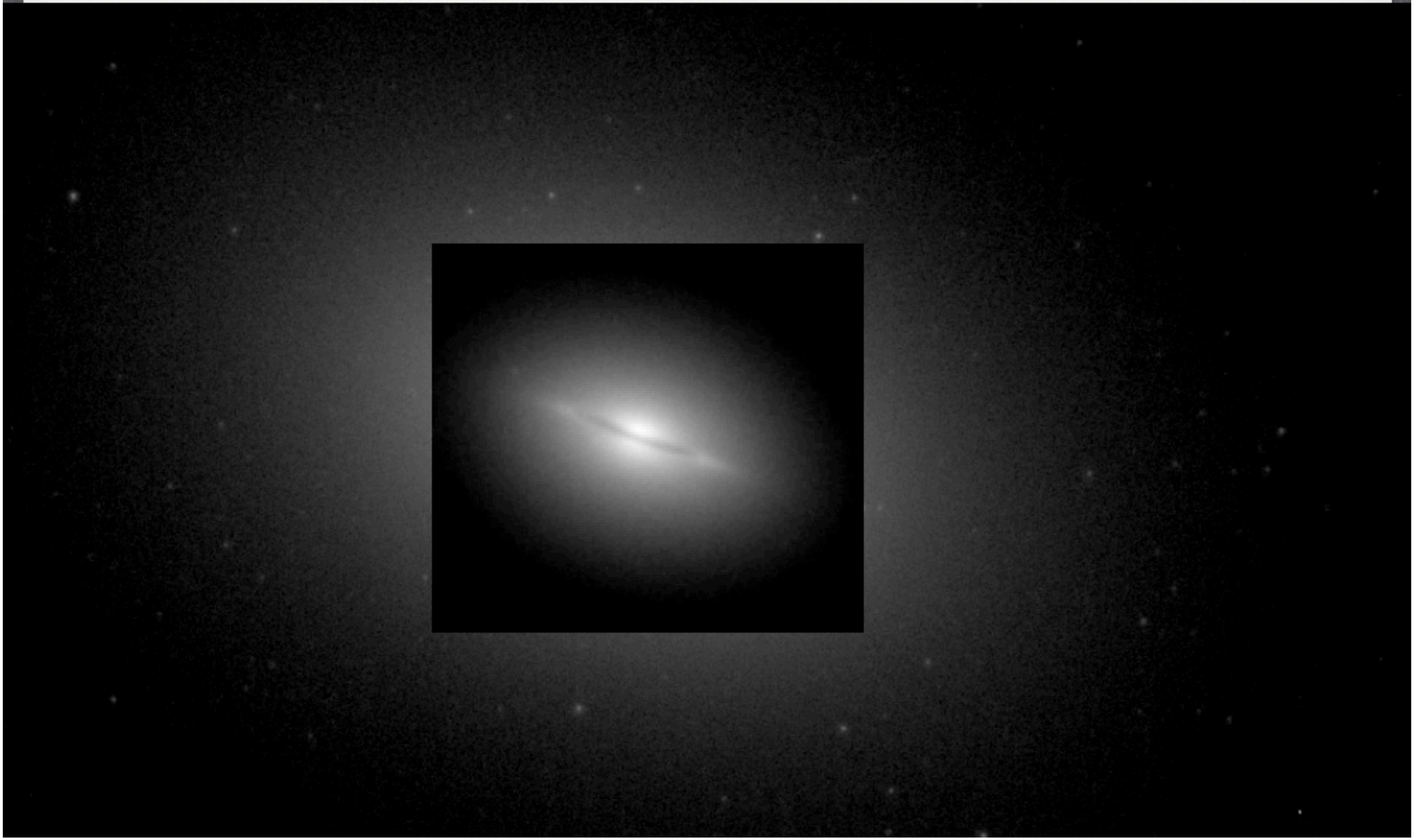
Remco van den Bosch

N1277 IS NOT ALONE

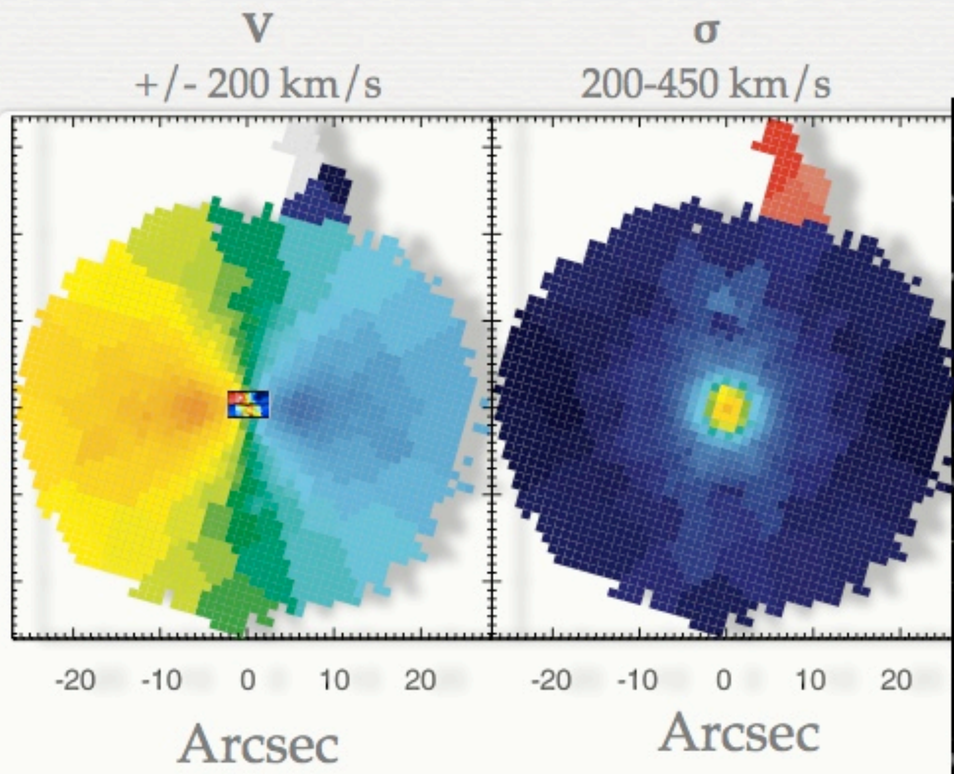


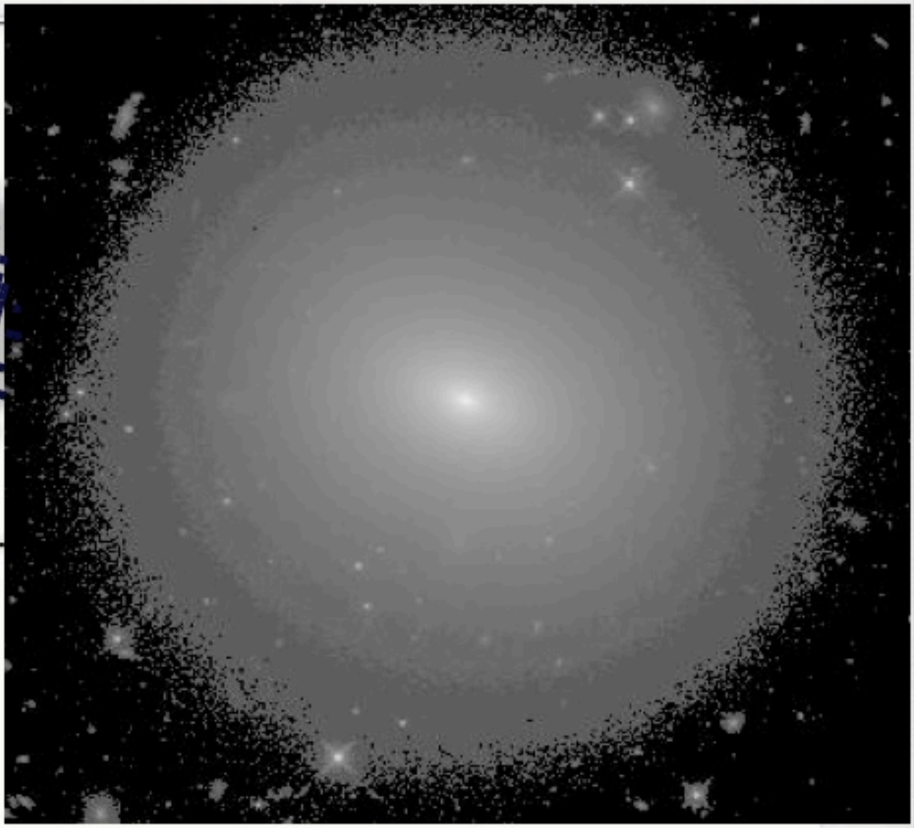
NGC1270

40″ or 13 kpc



PPAK IFU KINEMATICS

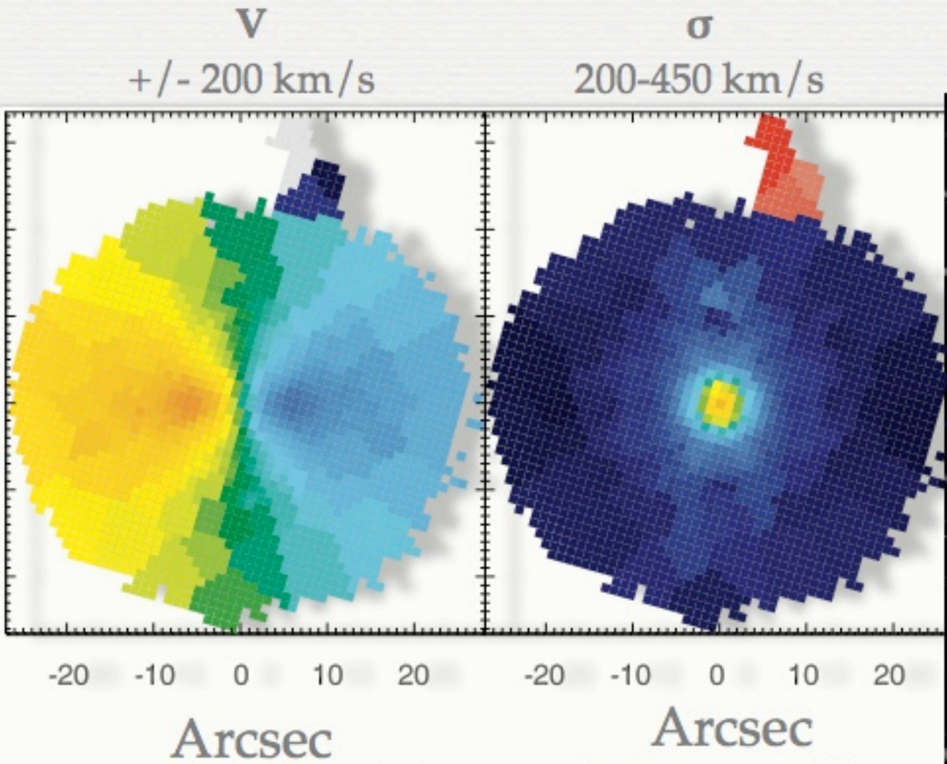


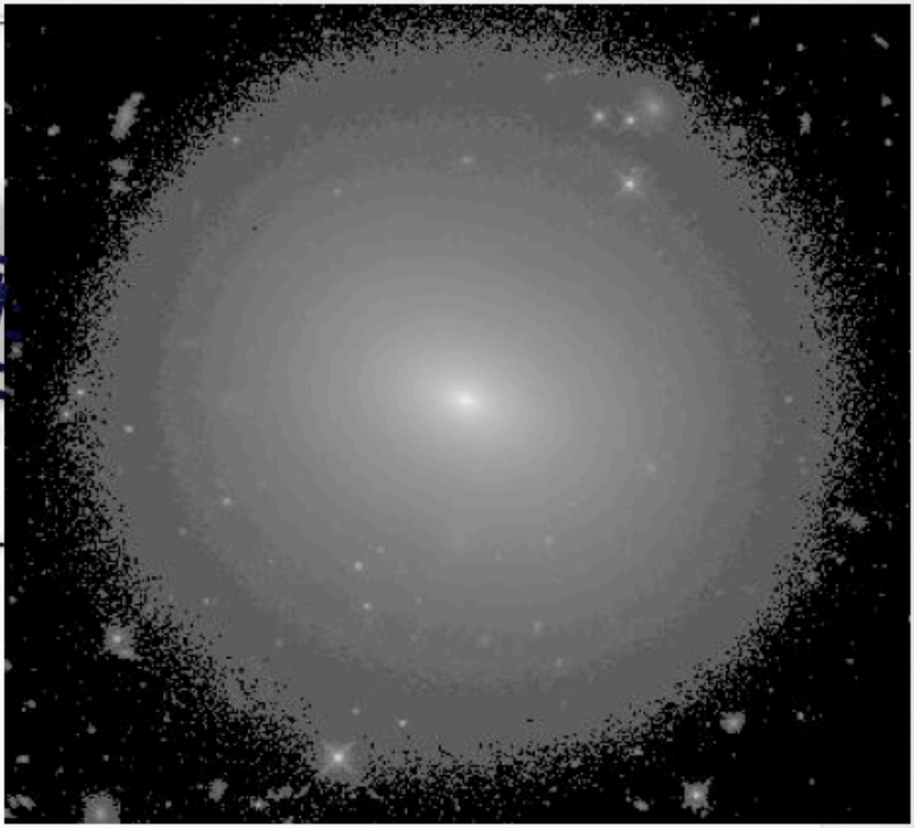


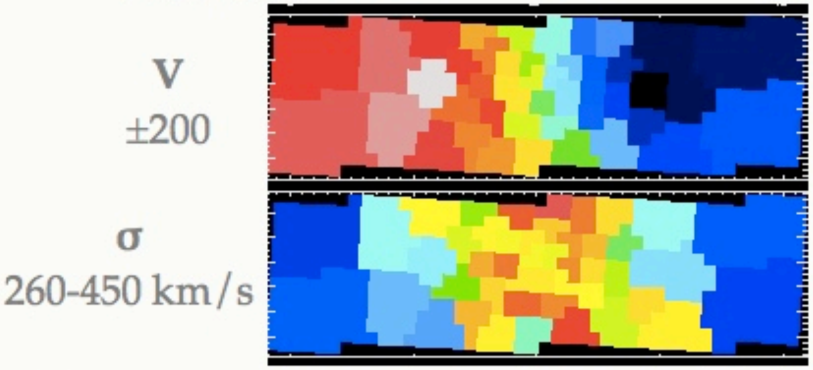
- Deep IFU observations with 3" fibers out to 5 half-light radii.

PPAK Observations by Akin Yildirim

PPAK IFU KINEMATICS

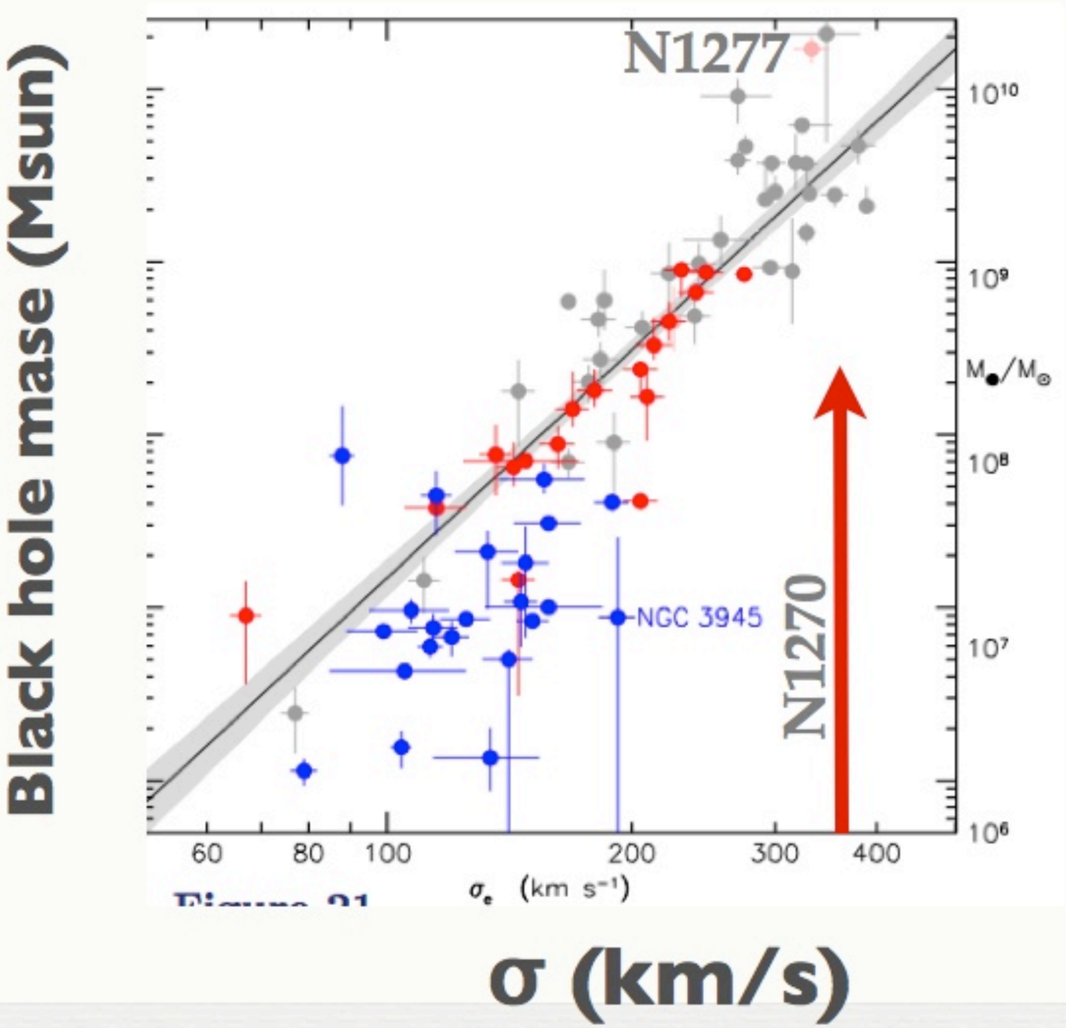






Osiris Observations by Jonelle Walsh

N1270 ON M-SIGMA



BLACK HOLES IN BULGE-LESS GALAXIES

- 5e4 Msun BH in N4395: Seyfert 1 (Edri +2012)
- The galaxies still forming (stars) today are disks and some have AGN. These thus have an SMBH, but no bulge. (e.g. Greene +08, Simmons+2012)

Figure 31

The Sd – Sm galaxy NGC 4395 (SDSS *gri* image from NED). The low surface brightness, the lack of a bulge, and the presence of a nuclear star cluster are characteristic of dwarf, late-type galaxies. M 33 and M 101 are more luminous and higher-surface-brightness analogs (Kormendy et al. 2010).

LARGE DIFFERENCE IN METHODS, PEOPLE AND INSTRUMENTS.

EVEN WITHIN PAPERS (E.G. RUSLI+13)

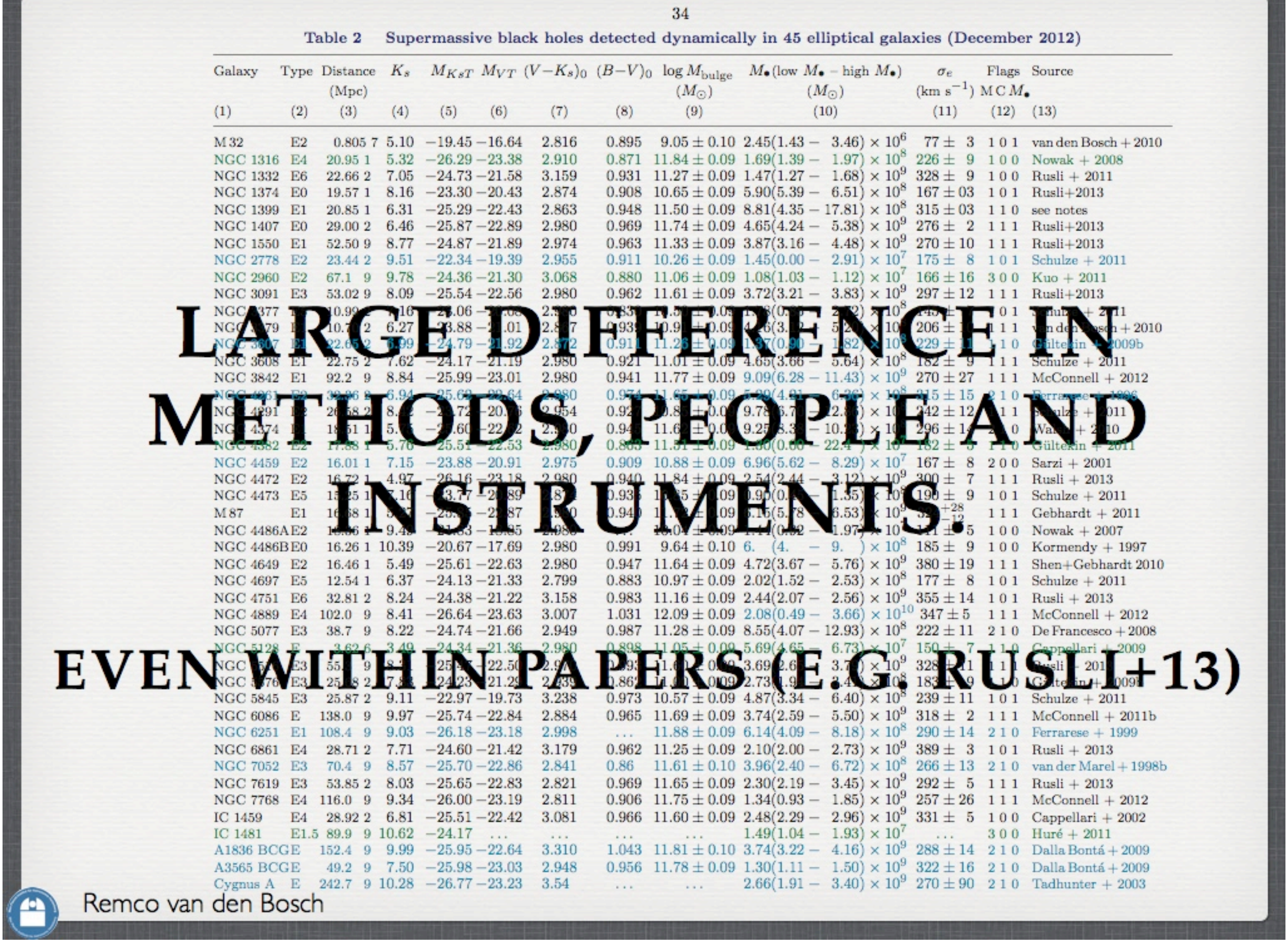
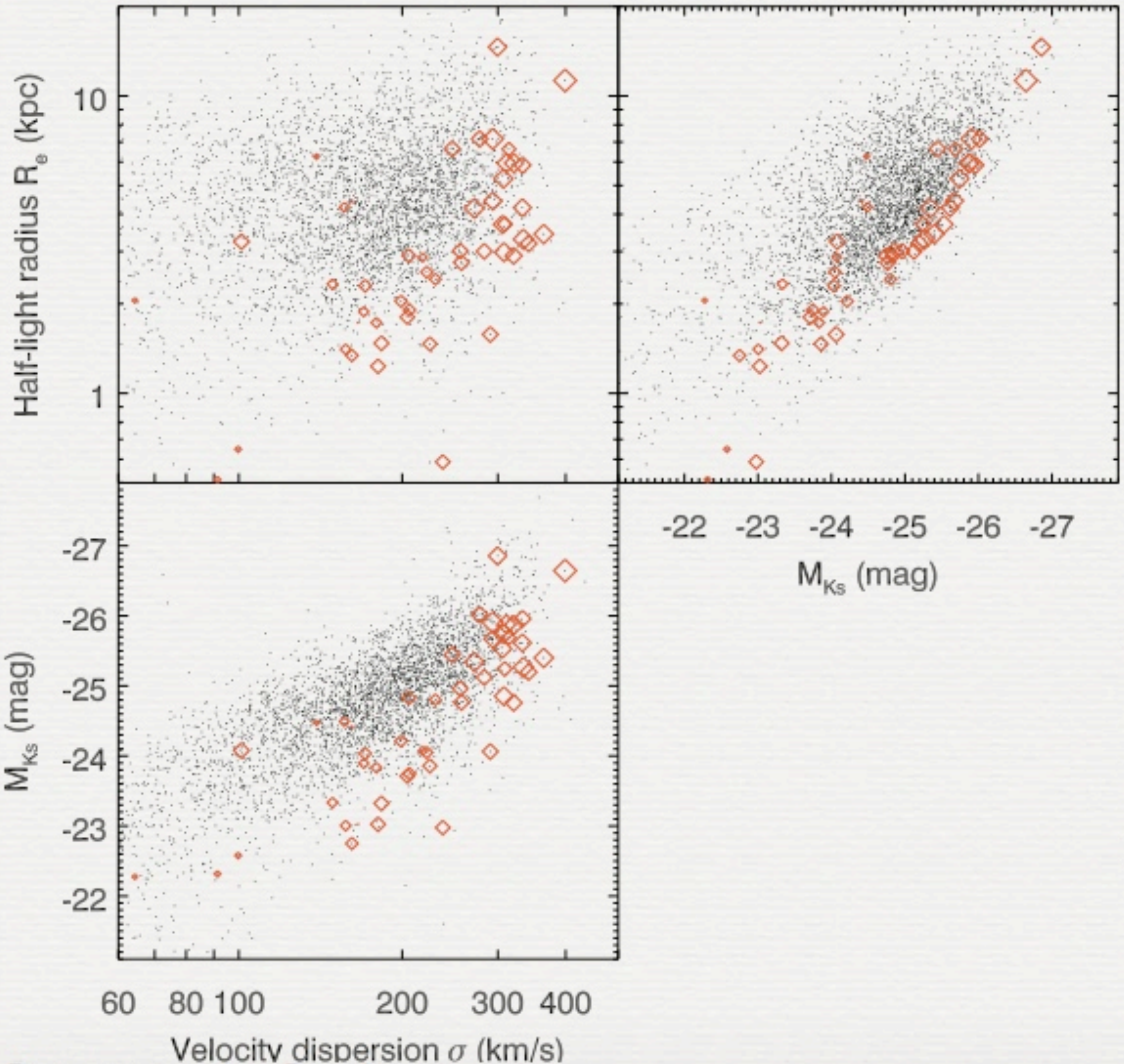


Table 2 Supermassive black holes detected dynamically in 45 elliptical galaxies (December 2012)

Galaxy (1)	Type (2)	Distance (Mpc) (3)	K_s (4)	M_{K_sT} (5)	M_{VT} (6)	$(V-K_s)_0$ (7)	$(B-V)_0$ (8)	$\log M_{\rm bulge}$ $(M_\odot)$ (9)	$M_\bullet$ (low $M_\bullet$ – high $M_\bullet$) $(M_\odot)$ (10)	σ_e (km s^{-1}) (11)	Flags M C $M_\bullet$ (12)	Source (13)
M 32	E2	0.805 7	5.10	−19.45	−16.64	2.816	0.895	9.05 ± 0.10	$2.45(1.43 - 3.46) \times 10^6$	77 ± 3	1 0 1	van den Bosch + 2010
NGC 1316	E4	20.95 1	5.32	−26.29	−23.38	2.910	0.871	11.84 ± 0.09	$1.69(1.39 - 1.97) \times 10^8$	226 ± 9	1 0 0	Nowak + 2008
NGC 1332	E6	22.66 2	7.05	−24.73	−21.58	3.159	0.931	11.27 ± 0.09	$1.47(1.27 - 1.68) \times 10^9$	328 ± 9	1 0 0	Rusli + 2011
NGC 1374	E0	19.57 1	8.16	−23.30	−20.43	2.874	0.908	10.65 ± 0.09	$5.90(5.39 - 6.51) \times 10^8$	167 ± 03	1 0 1	Rusli+2013
NGC 1399	E1	20.85 1	6.31	−25.29	−22.43	2.863	0.948	11.50 ± 0.09	$8.81(4.35 - 17.81) \times 10^8$	315 ± 03	1 1 0	see notes
NGC 1407	E0	29.00 2	6.46	−25.87	−22.89	2.980	0.969	11.74 ± 0.09	$4.65(4.24 - 5.38) \times 10^9$	276 ± 2	1 1 1	Rusli+2013
NGC 1550	E1	52.50 9	8.77	−24.87	−21.89	2.974	0.963	11.33 ± 0.09	$3.87(3.16 - 4.48) \times 10^9$	270 ± 10	1 1 1	Rusli+2013
NGC 2778	E2	23.44 2	9.51	−22.34	−19.39	2.955	0.911	10.26 ± 0.09	$1.45(0.00 - 2.91) \times 10^7$	175 ± 8	1 0 1	Schulze + 2011
NGC 2960	E2	67.1 9	9.78	−24.36	−21.30	3.068	0.880	11.06 ± 0.09	$1.08(1.03 - 1.12) \times 10^7$	166 ± 16	3 0 0	Kuo + 2011
NGC 3091	E3	53.02 9	8.09	−25.54	−22.56	2.980	0.962	11.61 ± 0.09	$3.72(3.21 - 3.83) \times 10^9$	297 ± 12	1 1 1	Rusli+2013
NGC [illegible]377	[illegible]	10.99 2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $\times 10^8$	[illegible]	[illegible] 0 1	[illegible] + 2[illegible]11
NGC [illegible]79	[illegible]	10.7[illegible] 2	6.27	−[illegible]3.88	−[illegible].01	2.8[illegible]7	[illegible]939	[illegible]0.9[illegible] ± 0.09	4.[illegible]6(3.[illegible] − 5.[illegible]) × 10[illegible]	206 ± [illegible]	[illegible] 1 1	van den [illegible]sch + 2010
NGC 3607	E1	22.65 2	6.99	−24.79	−21.92	2.872	0.911	11.26 ± 0.09	$1.37(0.90 - 1.82) \times 10^8$	229 ± 11	[illegible] 1 0	Gültekin + 2009b
NGC 3608	E1	22.75 2	7.62	−24.17	−21.19	2.980	0.921	11.01 ± 0.09	$4.65(3.66 - 5.64) \times 10^8$	182 ± 9	1 1 1	Schulze + 2011
NGC 3842	E1	92.2 9	8.84	−25.99	−23.01	2.980	0.941	11.77 ± 0.09	$9.09(6.28 - 11.43) \times 10^9$	270 ± 27	1 1 1	McConnell + 2012
NGC 4261	E2	[illegible]	6.94	−25.6[illegible]	−22.64	2.980	0.974	11.65 ± 0.09	[illegible](4.[illegible] − 6.36) × 10^8	315 ± 15	2 1 0	Ferrarese + [illegible]
NGC [illegible]291	[illegible]	26.[illegible]8 2	8.[illegible]	−[illegible].72	−20.[illegible]	2.954	0.92[illegible]	[illegible]0.8[illegible] ± 0.0[illegible]	9.78(6.7[illegible] − [illegible]2.[illegible]) × 10[illegible]	242 ± 12	[illegible] 1 1	[illegible]ulze + [illegible]011
NGC [illegible]374	[illegible]	18.[illegible]1 1	5.[illegible]	−[illegible].60	−22.[illegible]2	2.[illegible]0	0.94[illegible]	11.6[illegible] ± 0.0[illegible]	9.25([illegible].3[illegible] − 10.2[illegible]) × 10[illegible]	296 ± 1[illegible]	[illegible] 0	Wa[illegible] + 2[illegible]10
NGC [illegible]382	E2	17.88 1	5.76	−25.51	−22.53	2.980	0.8[illegible]3	11.5[illegible] ± 0.09	[illegible](0.[illegible] − 22.4) × 10^7	182 ± [illegible]	[illegible] 1 0	Gültekin + 2011
NGC 4459	E2	16.01 1	7.15	−23.88	−20.91	2.975	0.909	10.88 ± 0.09	$6.96(5.62 - 8.29) \times 10^7$	167 ± 8	2 0 0	Sarzi + 2001
NGC 4472	E2	16.72 1	4.97	−26.16	−23.18	2.980	0.940	11.84 ± 0.09	$2.54(2.44 - 3.12) \times 10^9$	300 ± 7	1 1 1	Rusli + 2013
NGC 4473	E5	15.[illegible]5 1	[illegible].16	−[illegible]3.77	−20.[illegible]9	2.87[illegible]	0.93[illegible]	1[illegible]5 ± 0.09	0.9[illegible](0.[illegible] − 1.35) × 10[illegible]	19[illegible] ± 9	1 0 1	Schulze + 2011
M 87	E1	16.[illegible]8 1	[illegible]	−[illegible]	−2[illegible].87	2.[illegible]0	0.94[illegible]	1[illegible] ± 0.09	[illegible].15(5.78 − [illegible].53) × 10^9	[illegible]$^{+28}_{-12}$	1 1 1	Gebhardt + 2011
NGC 4486A	E2	[illegible] 1	9.4[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ± 0.09	[illegible](0.[illegible] − 1.97) × 10[illegible]	[illegible] ± 5	1 0 0	Nowak + 2007
NGC 4486B	E0	16.26 1	10.39	−20.67	−17.69	2.980	0.991	9.64 ± 0.10	$6.\ (4. - 9.\ ) \times 10^8$	185 ± 9	1 0 0	Kormendy + 1997
NGC 4649	E2	16.46 1	5.49	−25.61	−22.63	2.980	0.947	11.64 ± 0.09	$4.72(3.67 - 5.76) \times 10^9$	380 ± 19	1 1 1	Shen+Gebhardt 2010
NGC 4697	E5	12.54 1	6.37	−24.13	−21.33	2.799	0.883	10.97 ± 0.09	$2.02(1.52 - 2.53) \times 10^8$	177 ± 8	1 0 1	Schulze + 2011
NGC 4751	E6	32.81 2	8.24	−24.38	−21.22	3.158	0.983	11.16 ± 0.09	$2.44(2.07 - 2.56) \times 10^9$	355 ± 14	1 0 1	Rusli + 2013
NGC 4889	E4	102.0 9	8.41	−26.64	−23.63	3.007	1.031	12.09 ± 0.09	$2.08(0.49 - 3.66) \times 10^{10}$	347 ± 5	1 1 1	McConnell + 2012
NGC 5077	E3	38.7 9	8.22	−24.74	−21.66	2.949	0.987	11.28 ± 0.09	$8.55(4.07 - 12.93) \times 10^8$	222 ± 11	2 1 0	De Francesco + 2008
NGC 5128	E	3.62 6	3.49	−24.34	−21.36	2.980	0.898	11.05 ± 0.09	$5.69(4.65 - 6.73) \times 10^7$	150 ± 7	1 1 0	Cappellari + 2009
NGC [illegible]	E3	55.[illegible] 9	8.[illegible]	−25.[illegible]	−22.50	2.9[illegible]	[illegible]93	[illegible]1.6[illegible] ± 0.[illegible]	3.69([illegible]2.6[illegible] − 3.7[illegible]) × 10^9	328 ± [illegible]1	1 1 1	[illegible]usli + 201[illegible]
NGC [illegible]76	E3	25.[illegible]8 2	7.[illegible]	−24.23	−21.2[illegible]	2.[illegible]39	0.86[illegible]	1[illegible] ± 0.09	2.73([illegible]1.9[illegible] − [illegible]3.4[illegible]) × 10[illegible]	183 ± [illegible]9	1 1 0	G[illegible]te[illegible]in + [illegible]009[illegible]
NGC 5845	E3	25.87 2	9.11	−22.97	−19.73	3.238	0.973	10.57 ± 0.09	$4.87(3.34 - 6.40) \times 10^8$	239 ± 11	1 0 1	Schulze + 2011
NGC 6086	E	138.0 9	9.97	−25.74	−22.84	2.884	0.965	11.69 ± 0.09	$3.74(2.59 - 5.50) \times 10^9$	318 ± 2	1 1 1	McConnell + 2011b
NGC 6251	E1	108.4 9	9.03	−26.18	−23.18	2.998	…	11.88 ± 0.09	$6.14(4.09 - 8.18) \times 10^8$	290 ± 14	2 1 0	Ferrarese + 1999
NGC 6861	E4	28.71 2	7.71	−24.60	−21.42	3.179	0.962	11.25 ± 0.09	$2.10(2.00 - 2.73) \times 10^9$	389 ± 3	1 0 1	Rusli + 2013
NGC 7052	E3	70.4 9	8.57	−25.70	−22.86	2.841	0.86	11.61 ± 0.10	$3.96(2.40 - 6.72) \times 10^8$	266 ± 13	2 1 0	van der Marel + 1998b
NGC 7619	E3	53.85 2	8.03	−25.65	−22.83	2.821	0.969	11.65 ± 0.09	$2.30(2.19 - 3.45) \times 10^9$	292 ± 5	1 1 1	Rusli + 2013
NGC 7768	E4	116.0 9	9.34	−26.00	−23.19	2.811	0.906	11.75 ± 0.09	$1.34(0.93 - 1.85) \times 10^9$	257 ± 26	1 1 1	McConnell + 2012
IC 1459	E4	28.92 2	6.81	−25.51	−22.42	3.081	0.966	11.60 ± 0.09	$2.48(2.29 - 2.96) \times 10^9$	331 ± 5	1 0 0	Cappellari + 2002
IC 1481	E1.5	89.9 9	10.62	−24.17	…	…	…	…	$1.49(1.04 - 1.93) \times 10^7$	…	3 0 0	Huré + 2011
A1836 BCGE		152.4 9	9.99	−25.95	−22.64	3.310	1.043	11.81 ± 0.10	$3.74(3.22 - 4.16) \times 10^9$	288 ± 14	2 1 0	Dalla Bontá + 2009
A3565 BCGE		49.2 9	7.50	−25.98	−23.03	2.948	0.956	11.78 ± 0.09	$1.30(1.11 - 1.50) \times 10^9$	322 ± 16	2 1 0	Dalla Bontá + 2009
Cygnus A	E	242.7 9	10.28	−26.77	−23.23	3.54	…	…	$2.66(1.91 - 3.40) \times 10^9$	270 ± 90	2 1 0	Tadhunter + 2003

Remco van den Bosch

STRONG BIAS ON THE SCALING RELATIONS



Future:

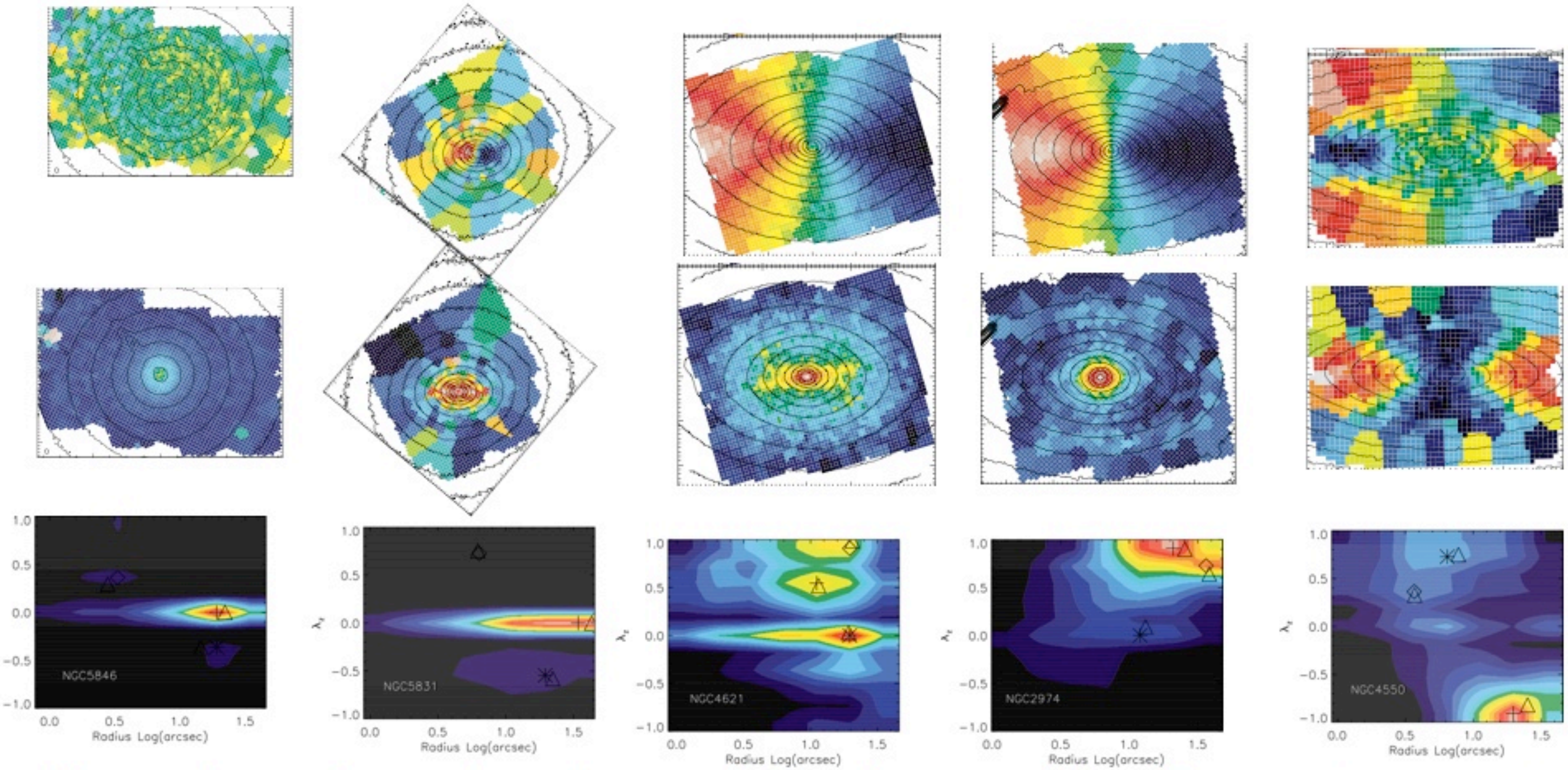
- Sample all kinds of host galaxies
- Uniform data on host galaxies
- AO IFU spectroscopy of the nuclear region
- Uniform BH mass analysis.

Remco van den Bosch

Orbit-based Dynamical Decomposition

Pseudo-bulges and classical bulges

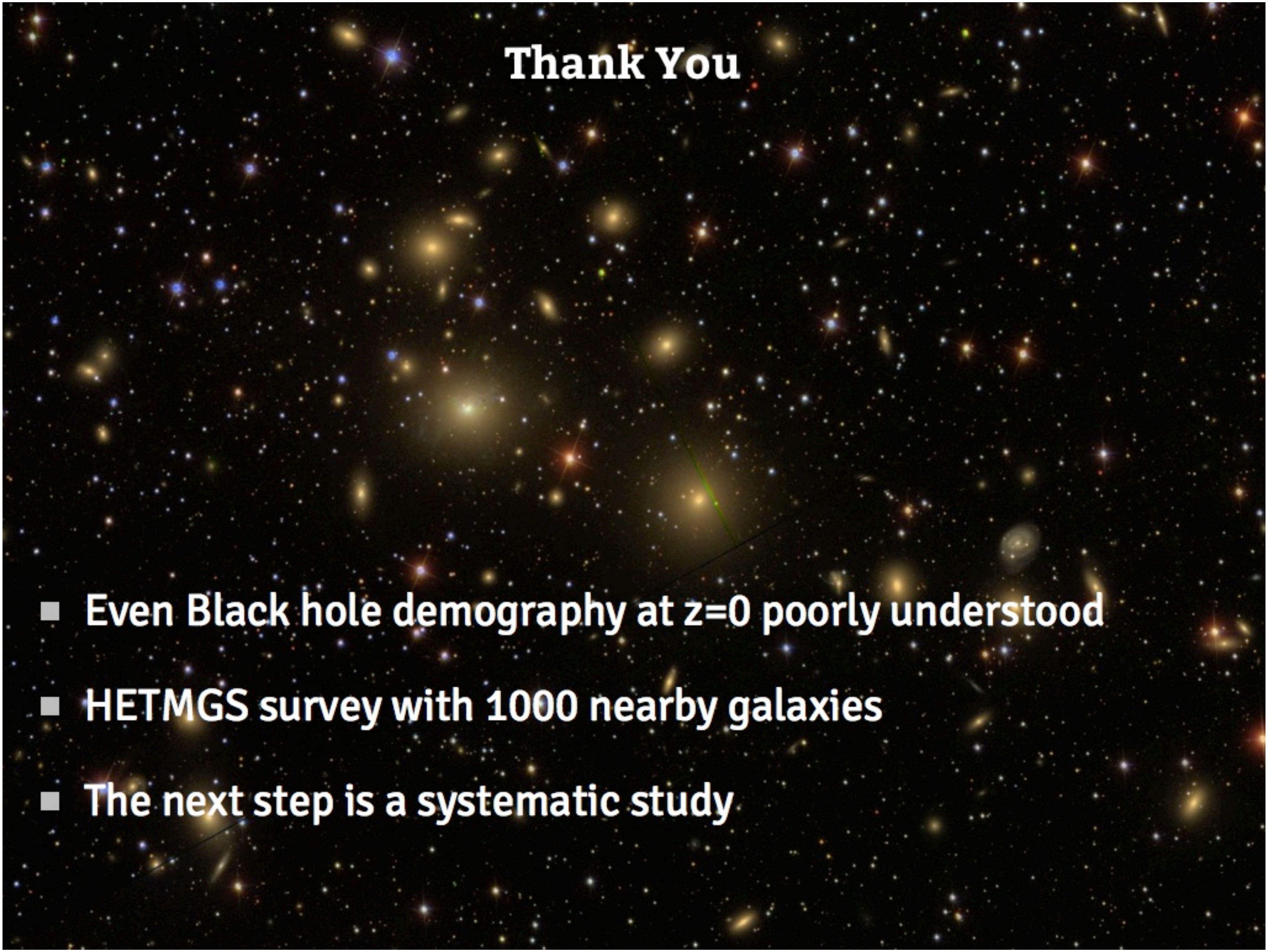
NR NGC4486 | **SR/KDC** NGC5831 | **FR** NGC4621 | **FR** NGC2974 | **2σ** NGC4550



All stars on low spin orbits (bulge) | few stars in rotating component (kdc) | (B/T>0.5) Dominant bulge | (B/T<0.5) Dominant Disk | Counter-rotating disks and small bulge

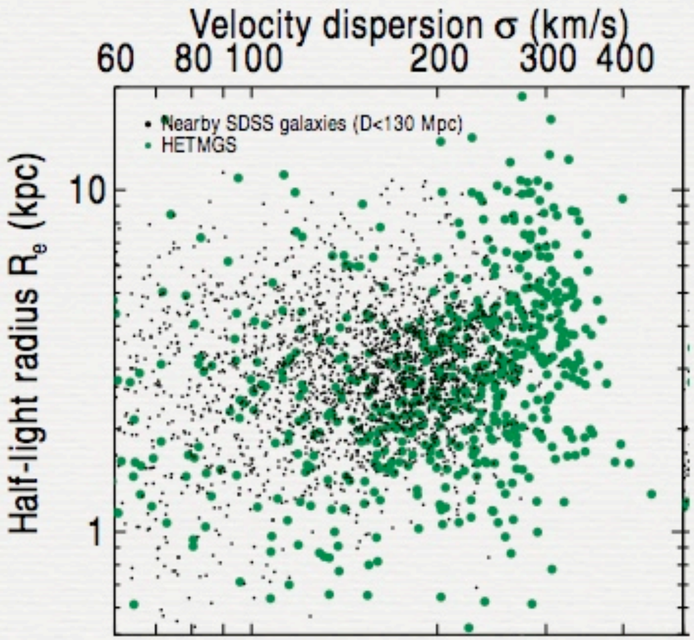
Increasing Spin

Thank You

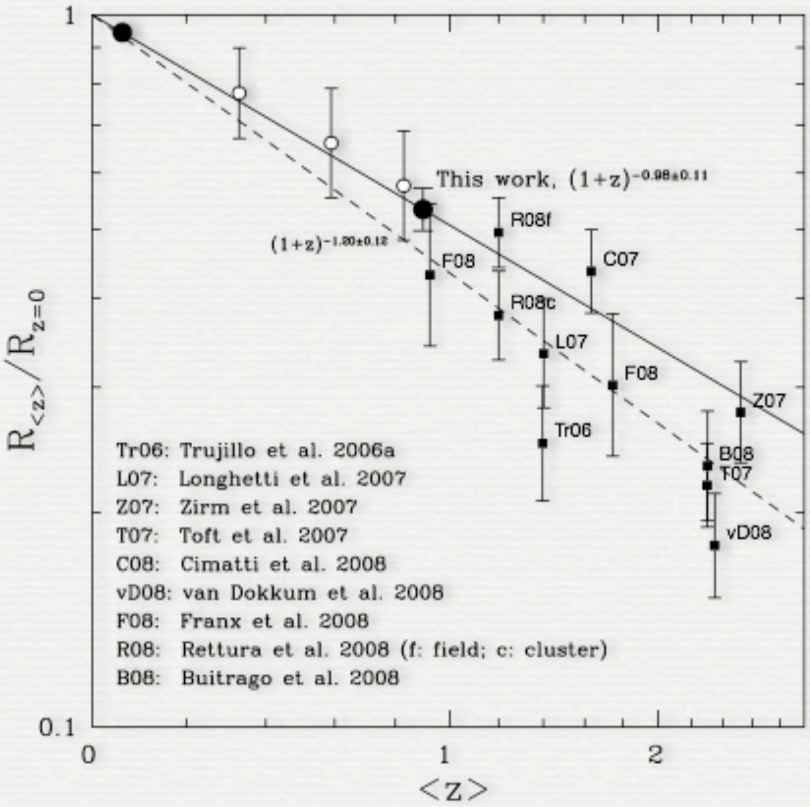


- Even Black hole demography at z=0 poorly understood
- HETMGS survey with 1000 nearby galaxies
- The next step is a systematic study

GALAXY SIZE EVOLUTION

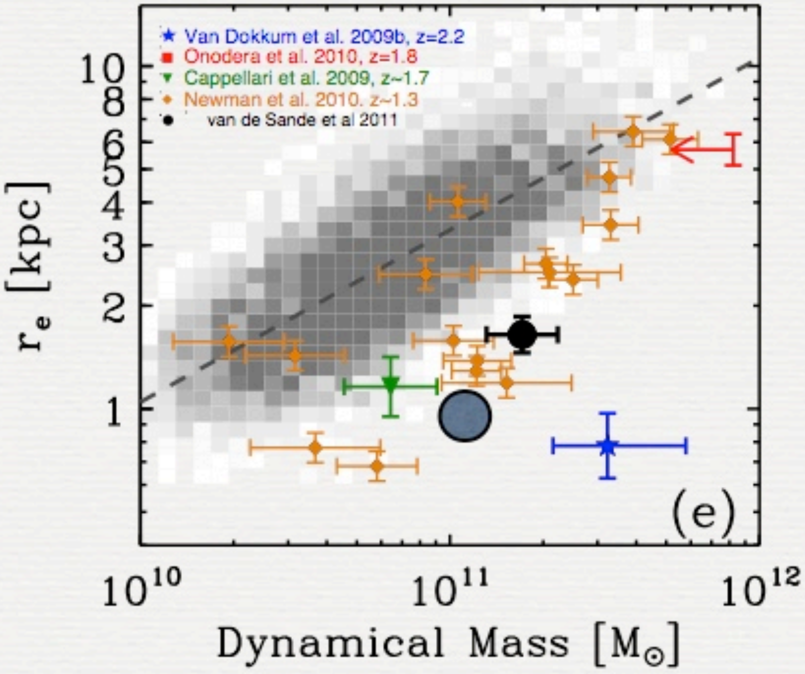


van der Wel+2008

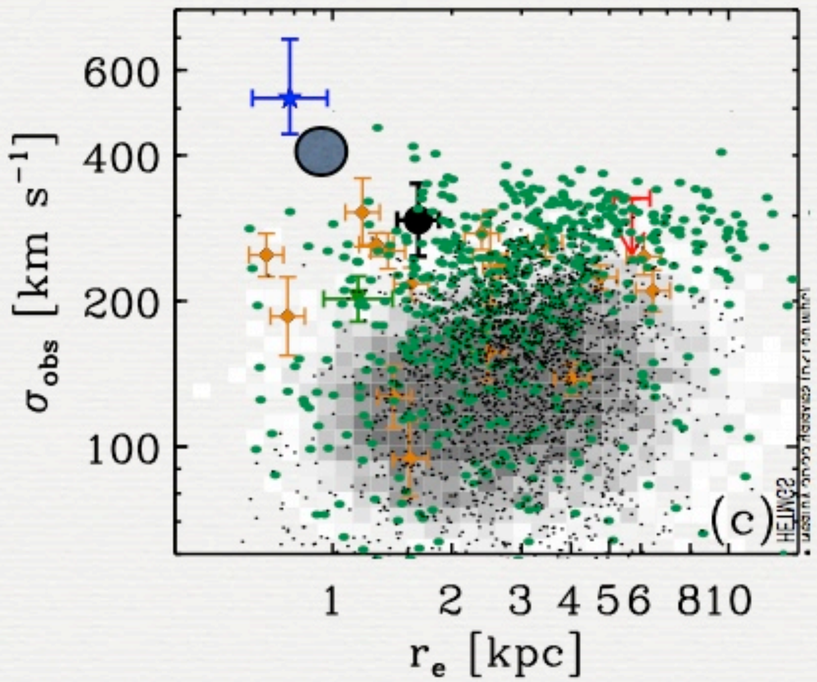


Remco van den Bosch

GALAXY SIZE EVOLUTION

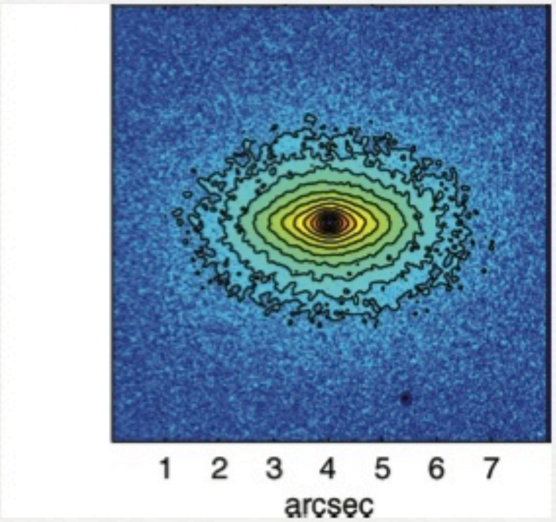


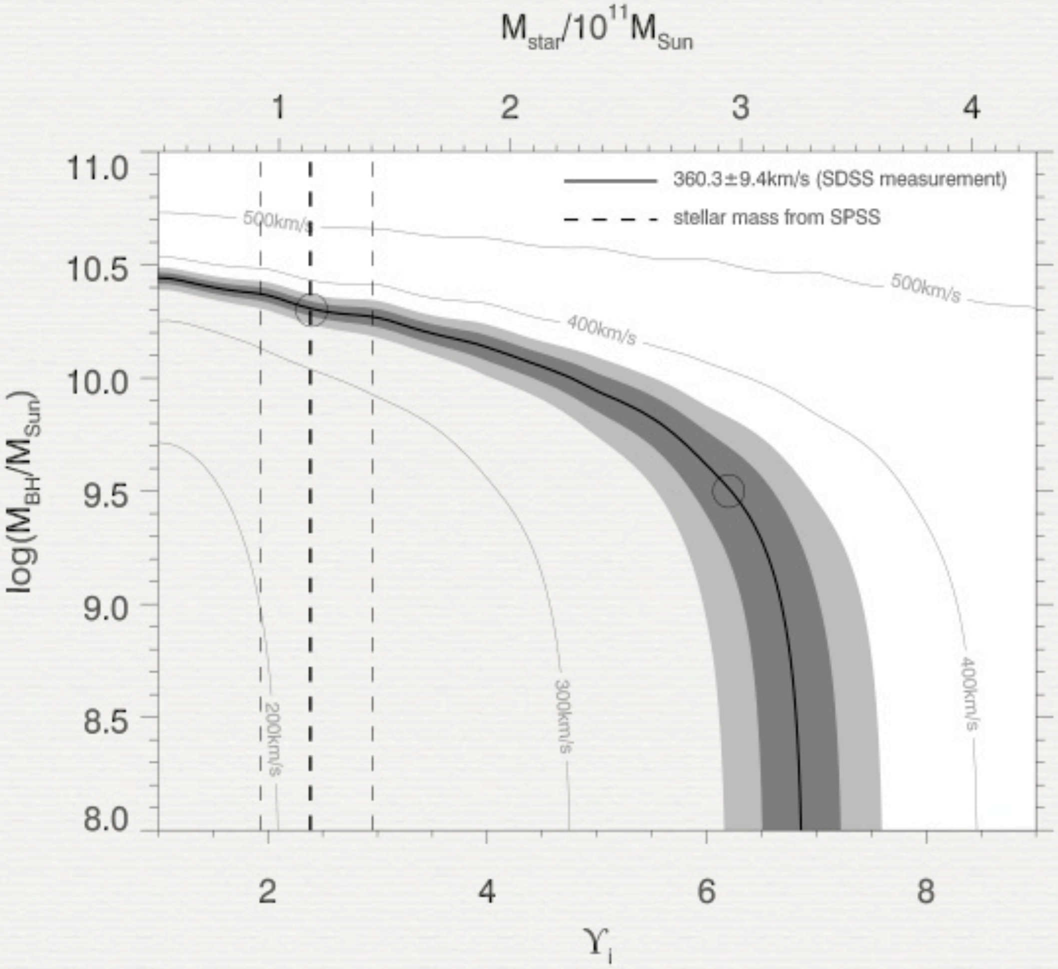
van de Sande et al 2011



THESE GALAXIES EXIST IN SDSS TOO

BERNARDI ET AL. 2007





Ronald Läsker