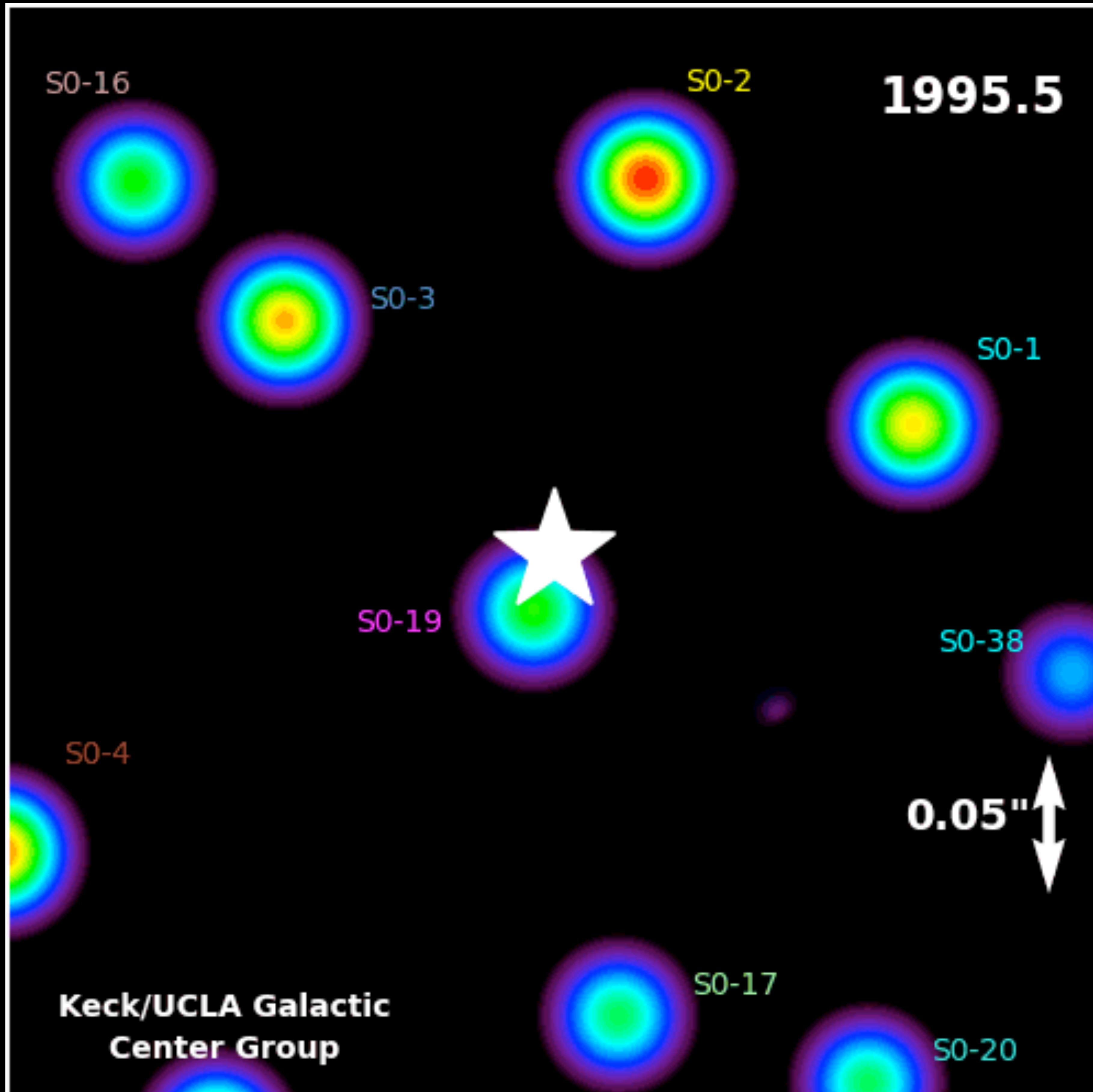
Black Holes, Big and Small

Impact on Galaxy Formation

Luis C. Ho（何子山）

Kavli Institute for Astronomy and Astrophysics (KIAA)

Peking University


S0-16
S0-2
1995.5
S0-3
S0-1
S0-19
S0-38
S0-4
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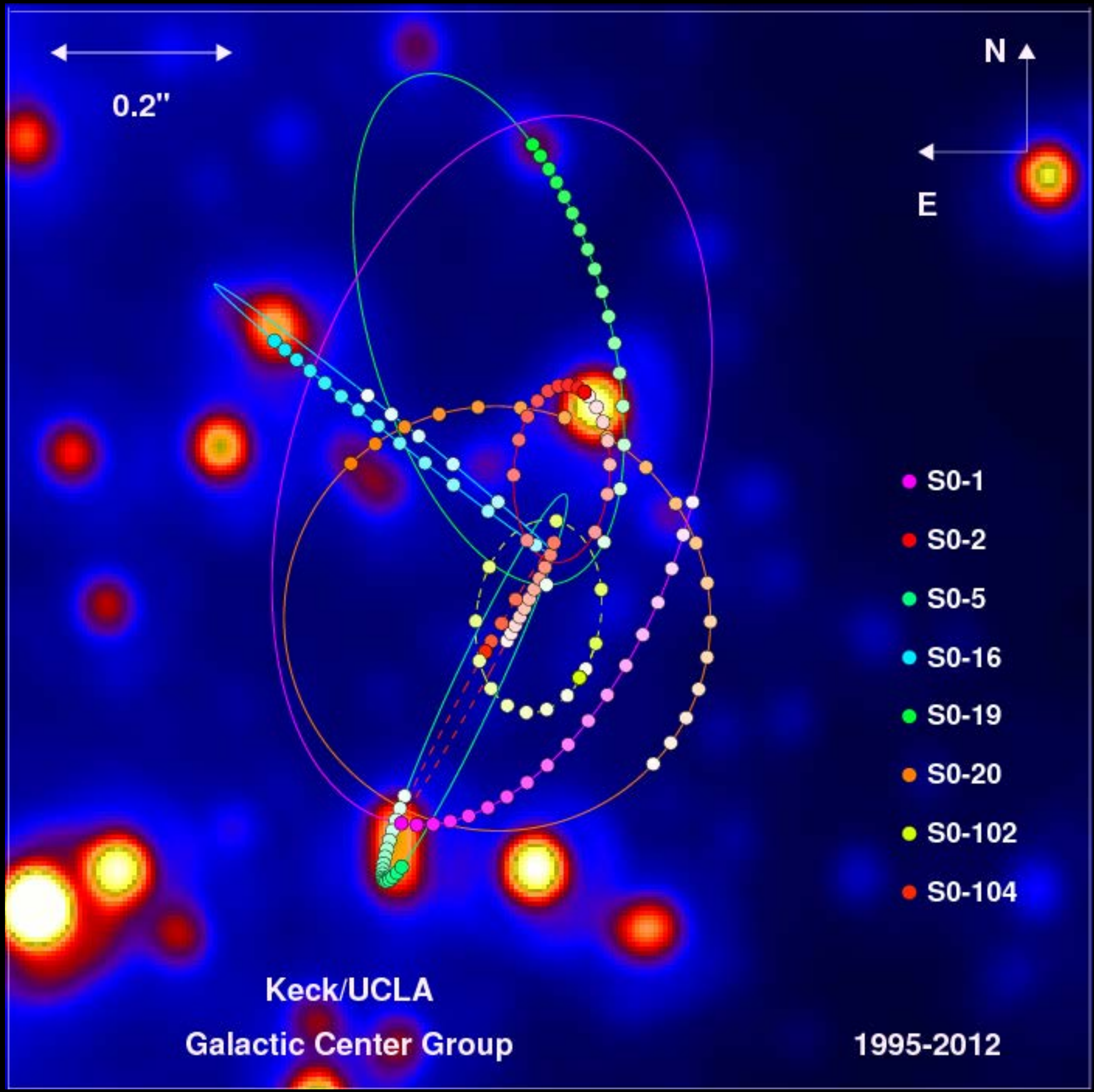
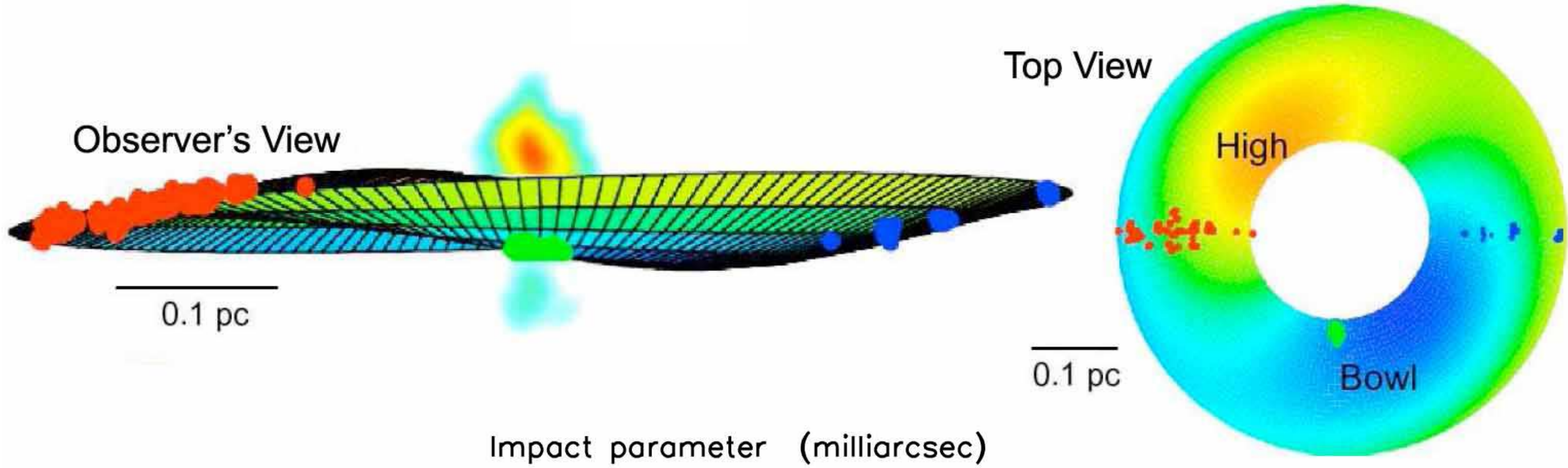
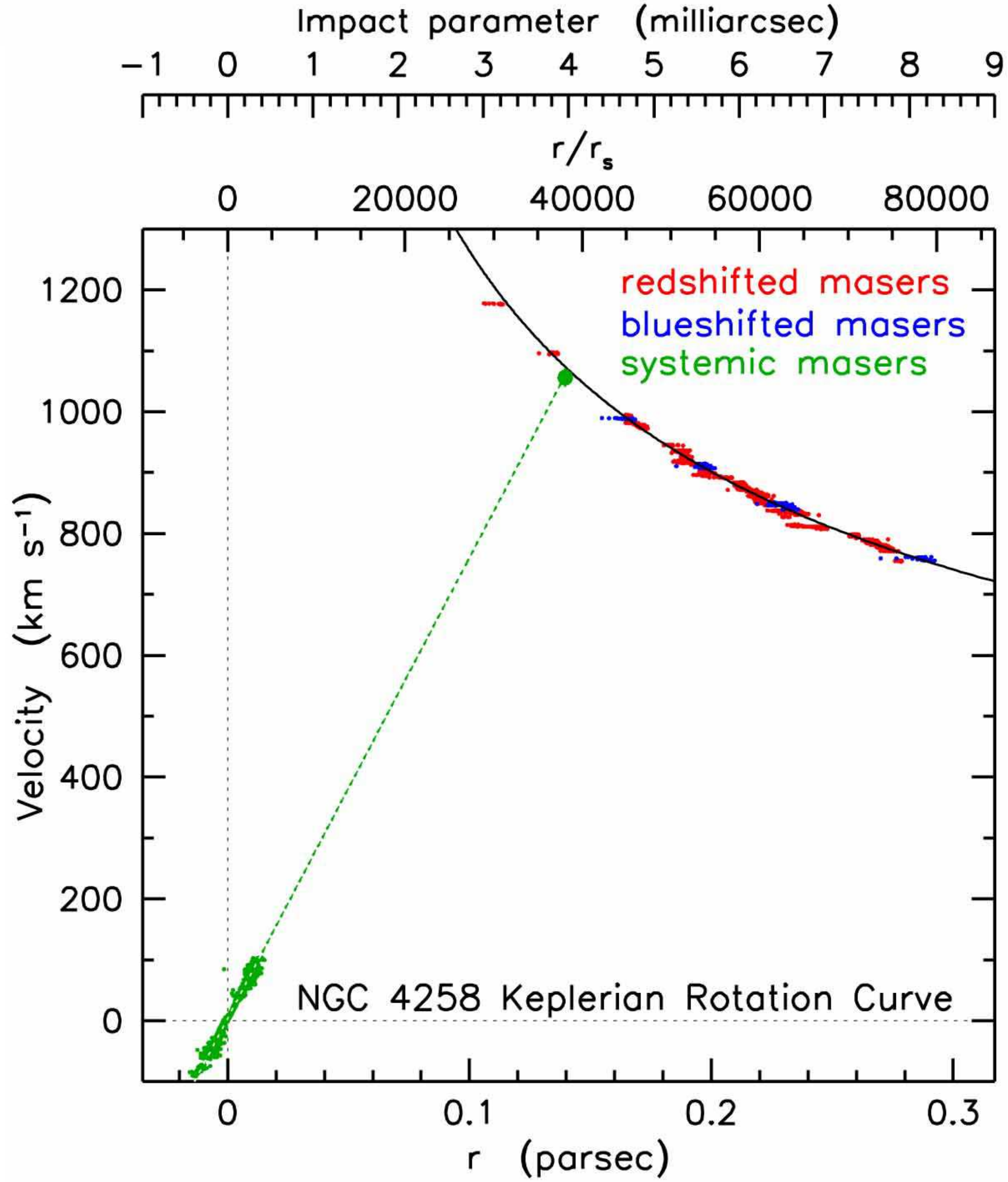
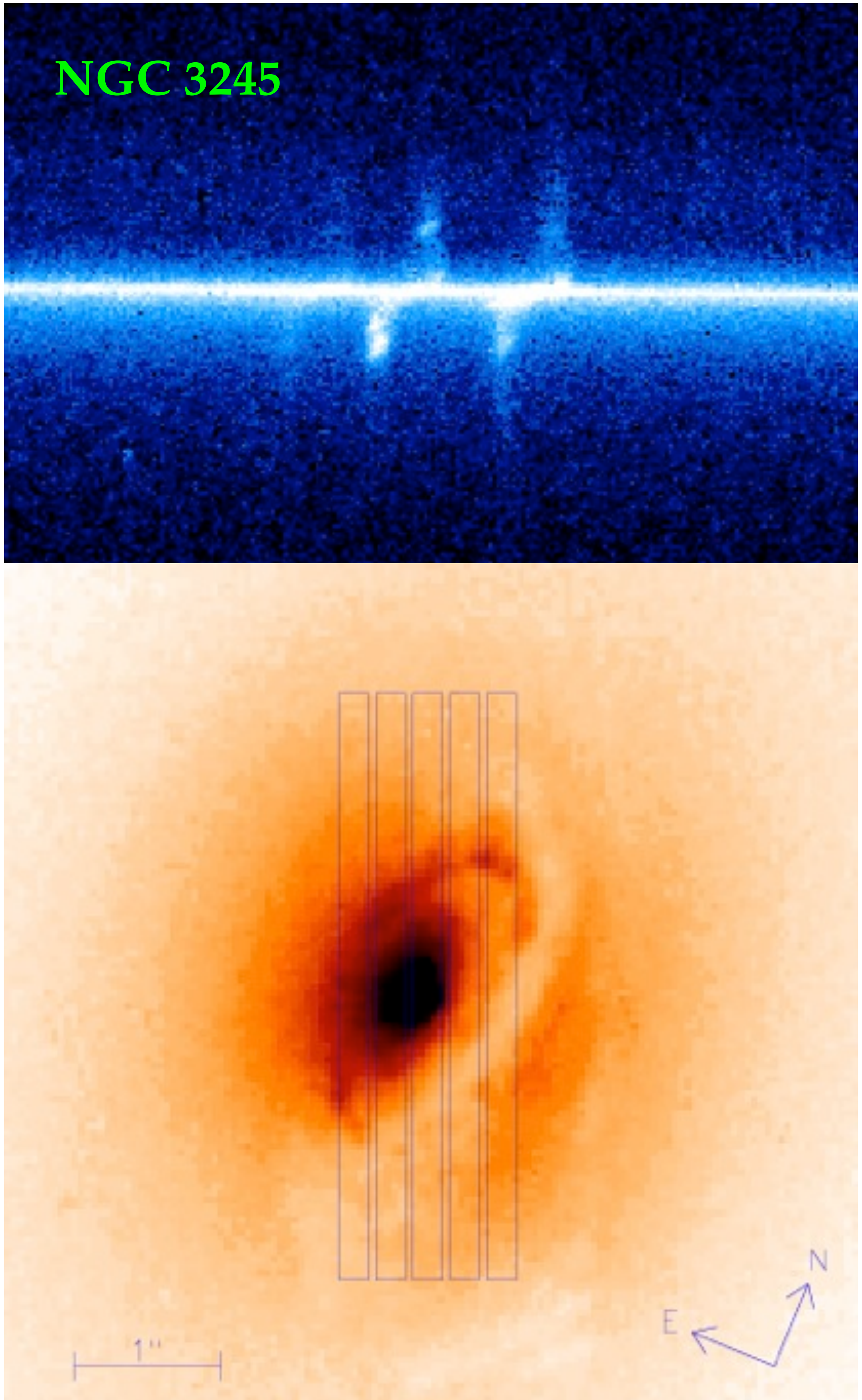
S0-17
Keck/UCLA Galactic
Center Group
S0-20

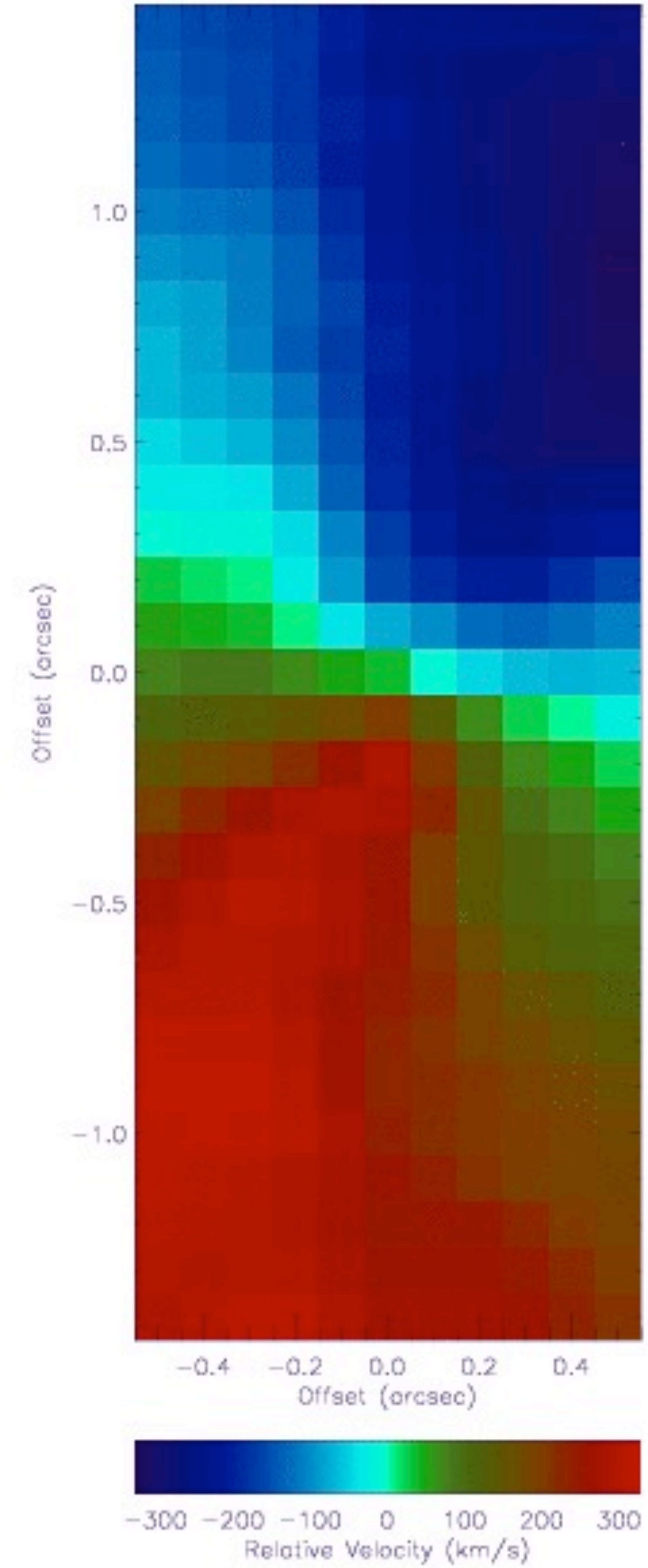

0.2"
N
E
S0-1
S0-2
S0-5
S0-16
S0-19
S0-20
S0-102
S0-104
Keck/UCLA
Galactic Center Group
1995-2012





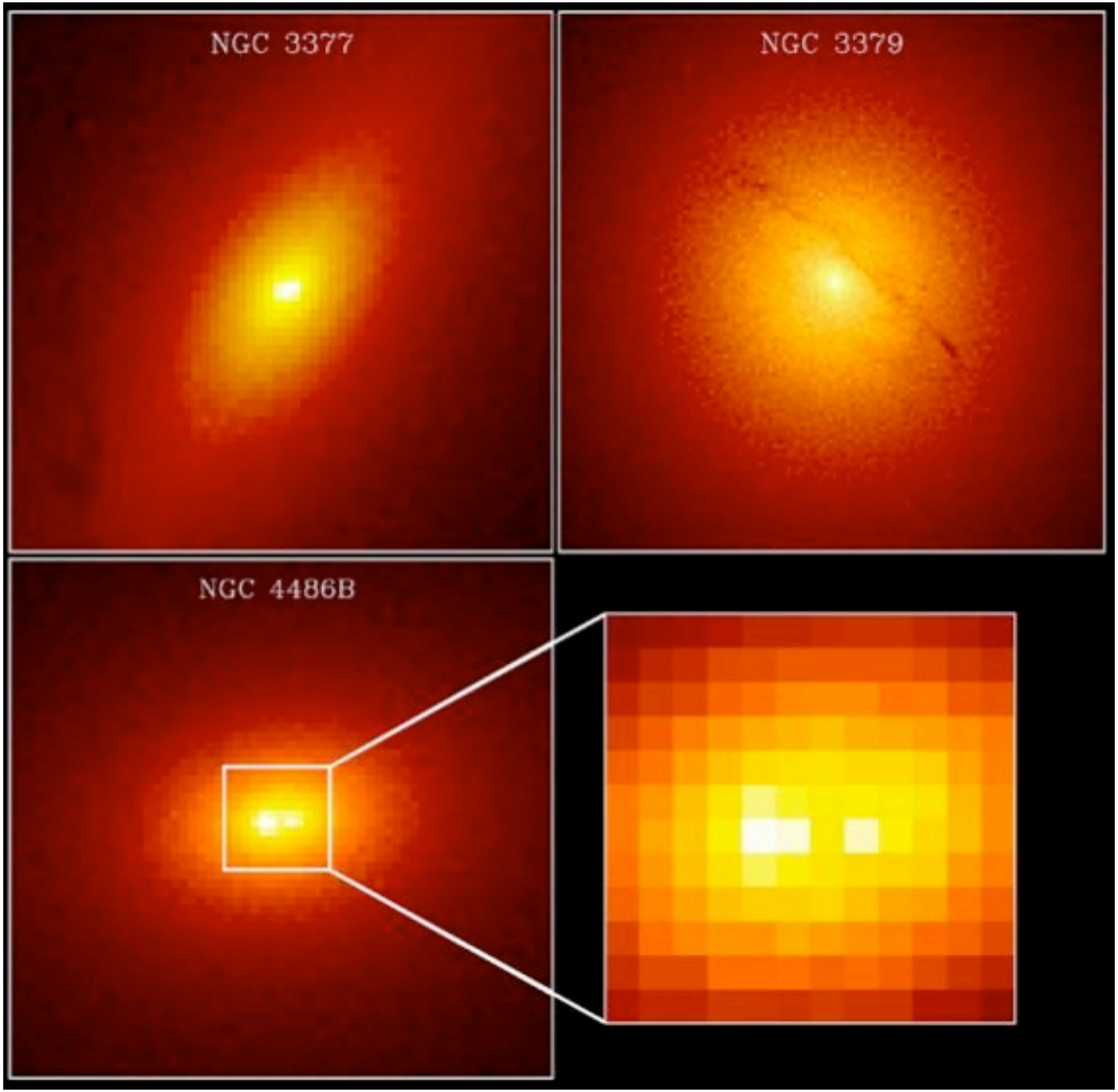
Miyoshi et al. (1995)
Herrnstein et al. (2005)

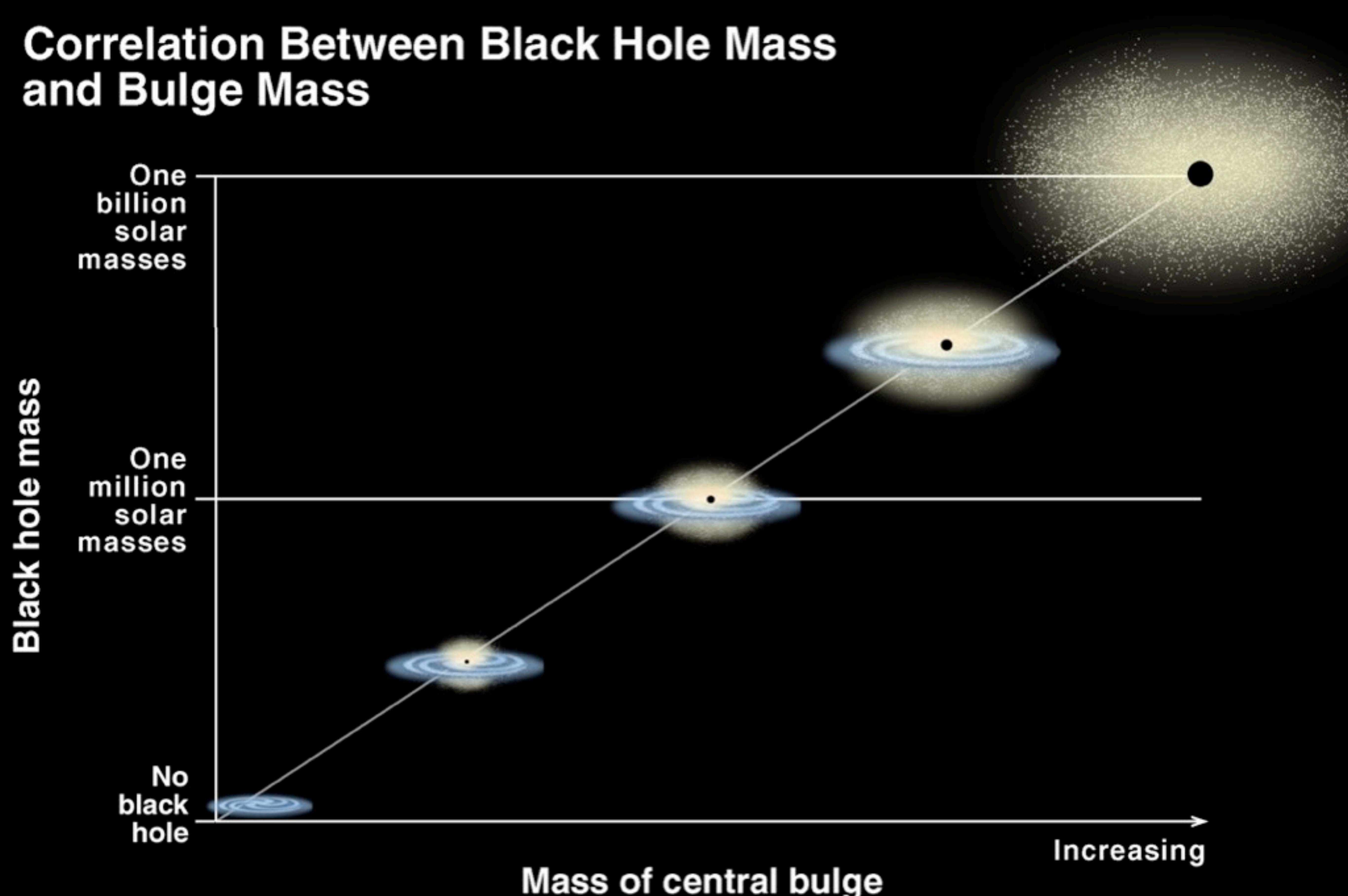




Barth, Ho et al. (2001)

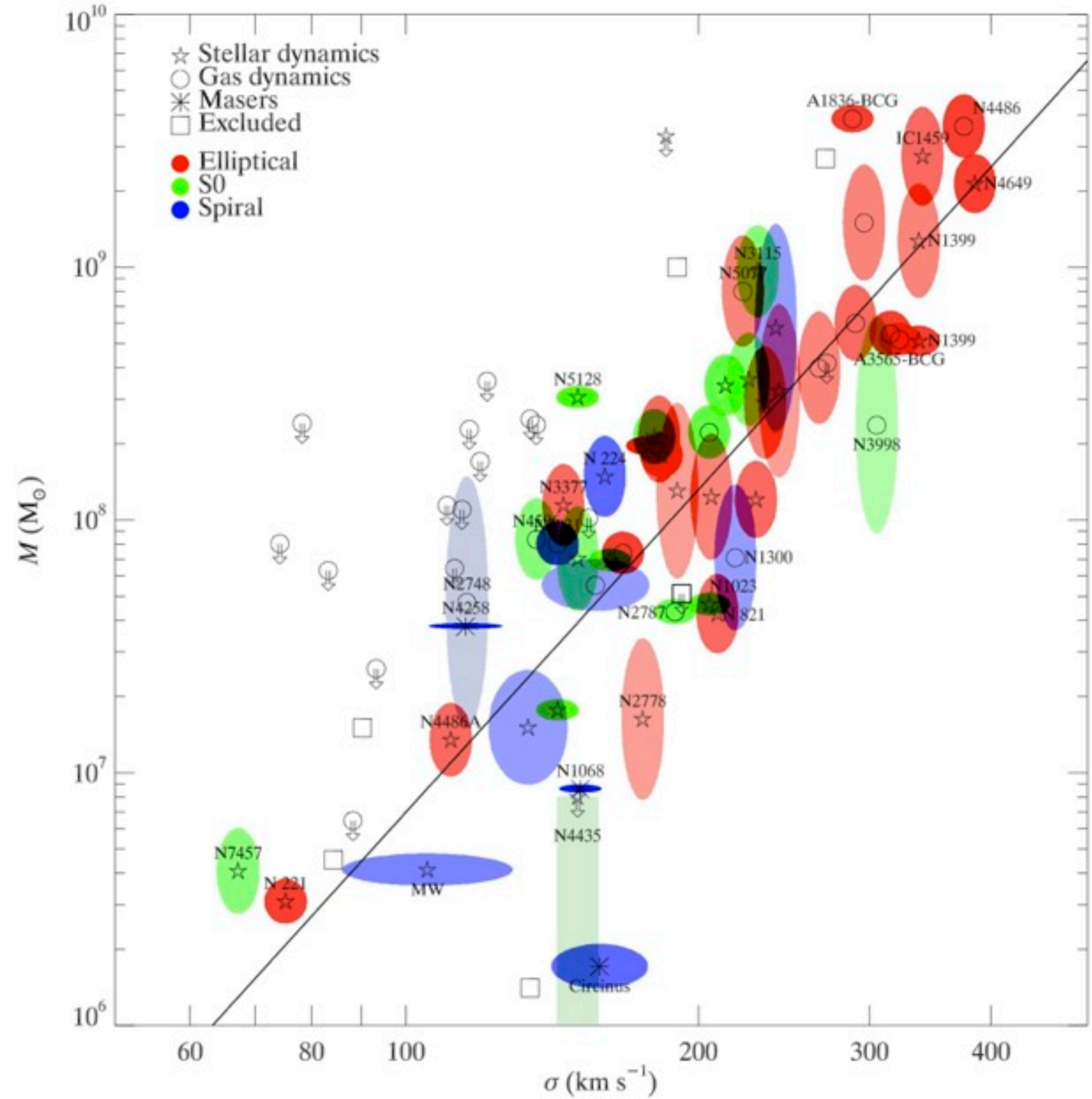
The “Nuker” Team





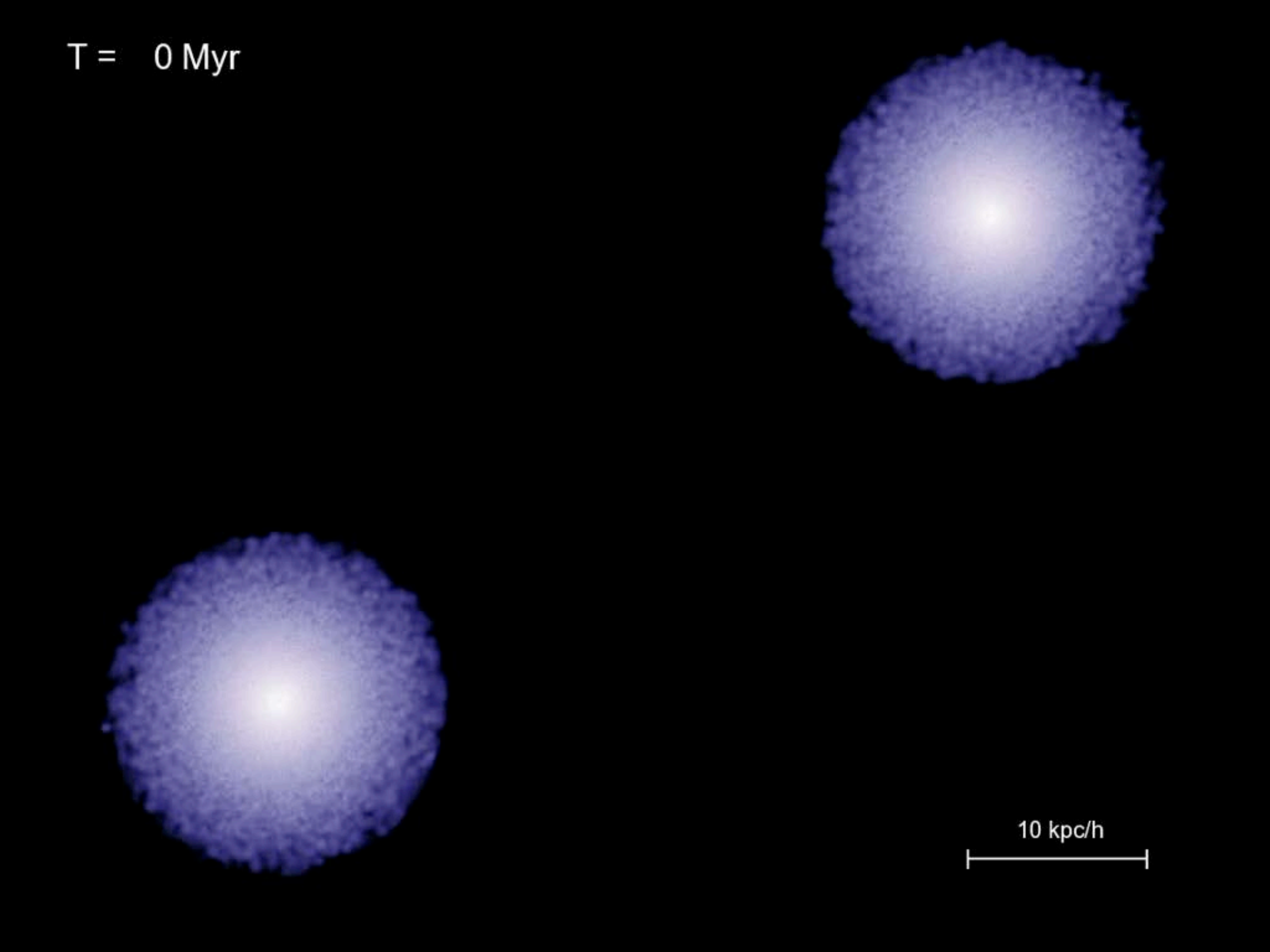
Magorrian et al. (1998)

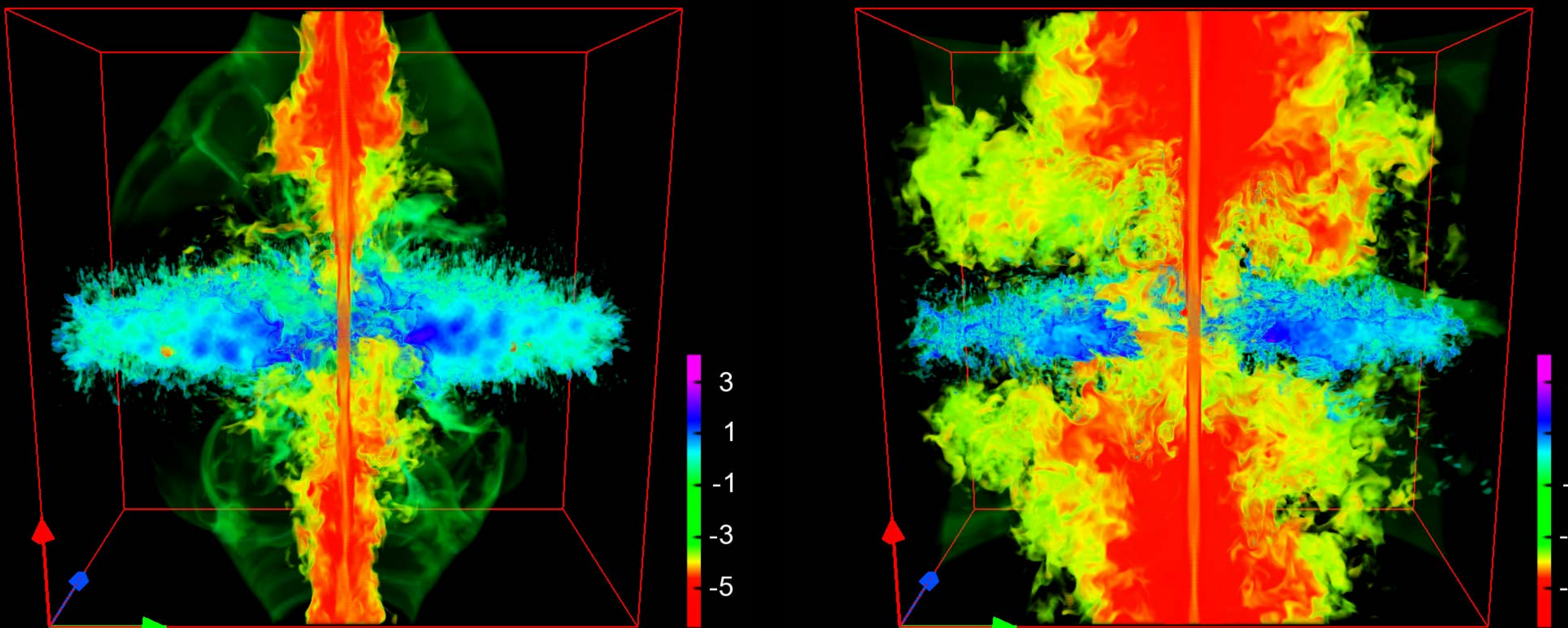
Gebhardt et al. (2000); Ferrarese & Merritt (2000); Gültekin et al. (2009)



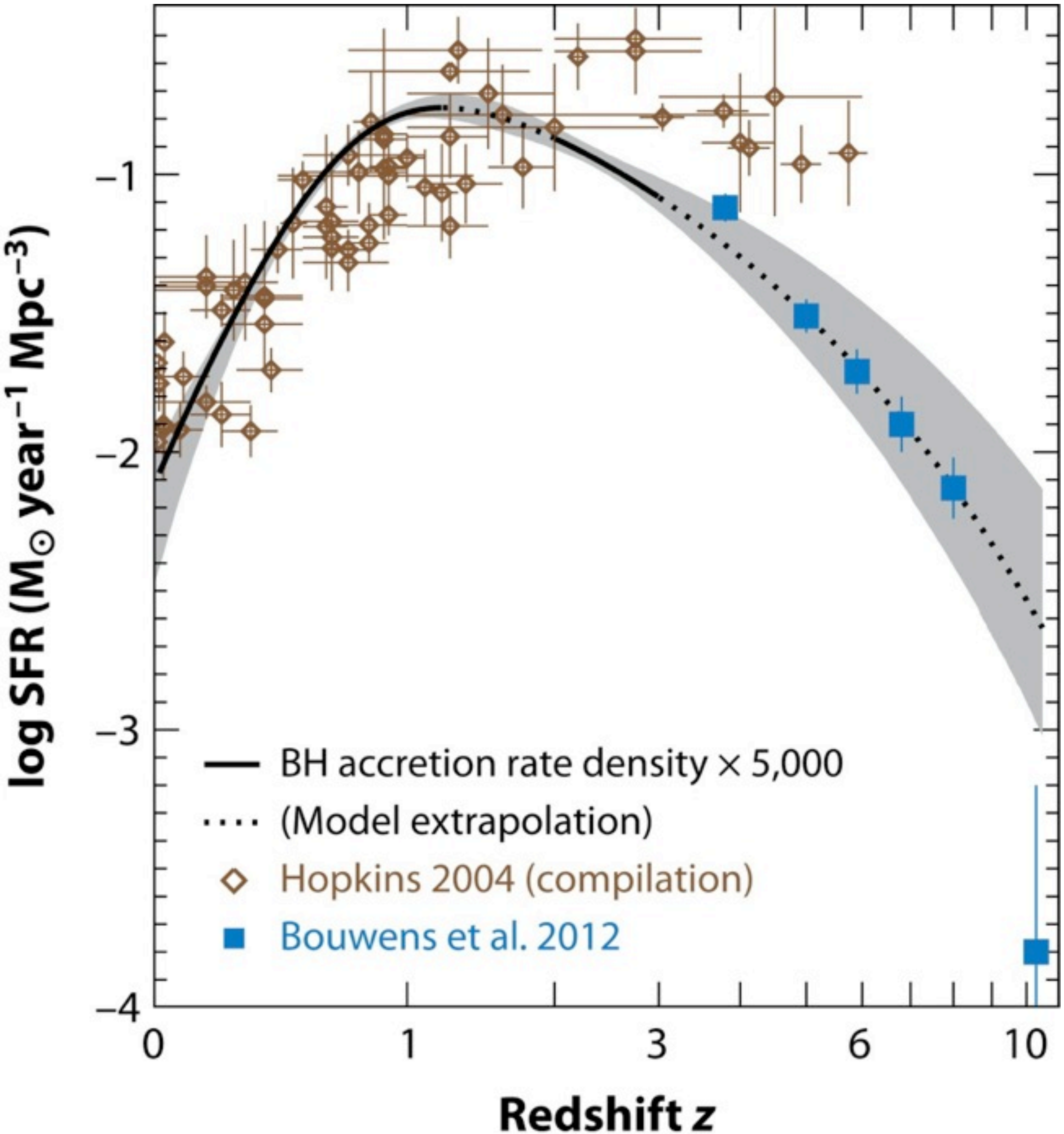
black hole mass →

bulge velocity dispersion →

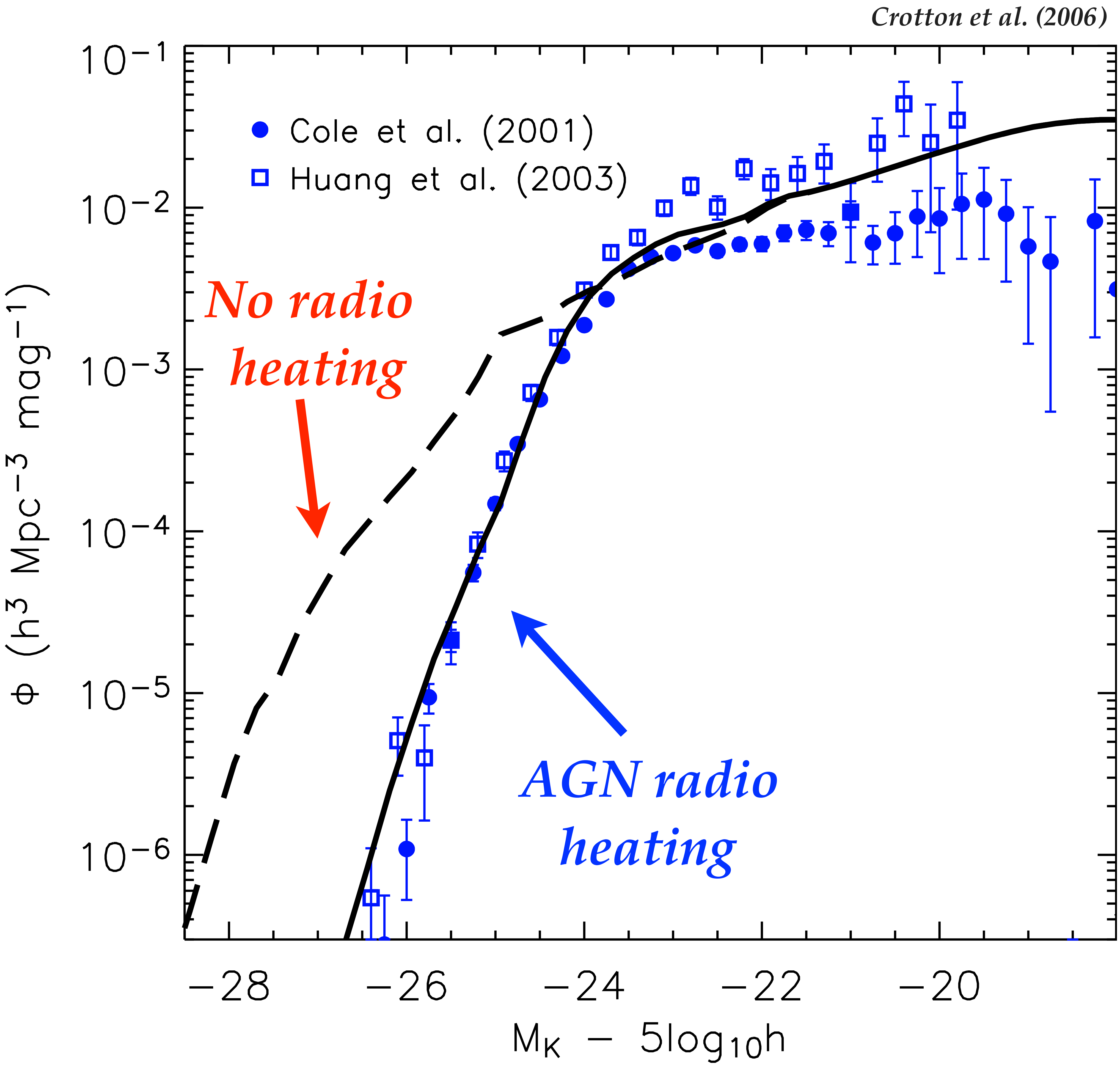

T = 0 Myr
10 kpc/h

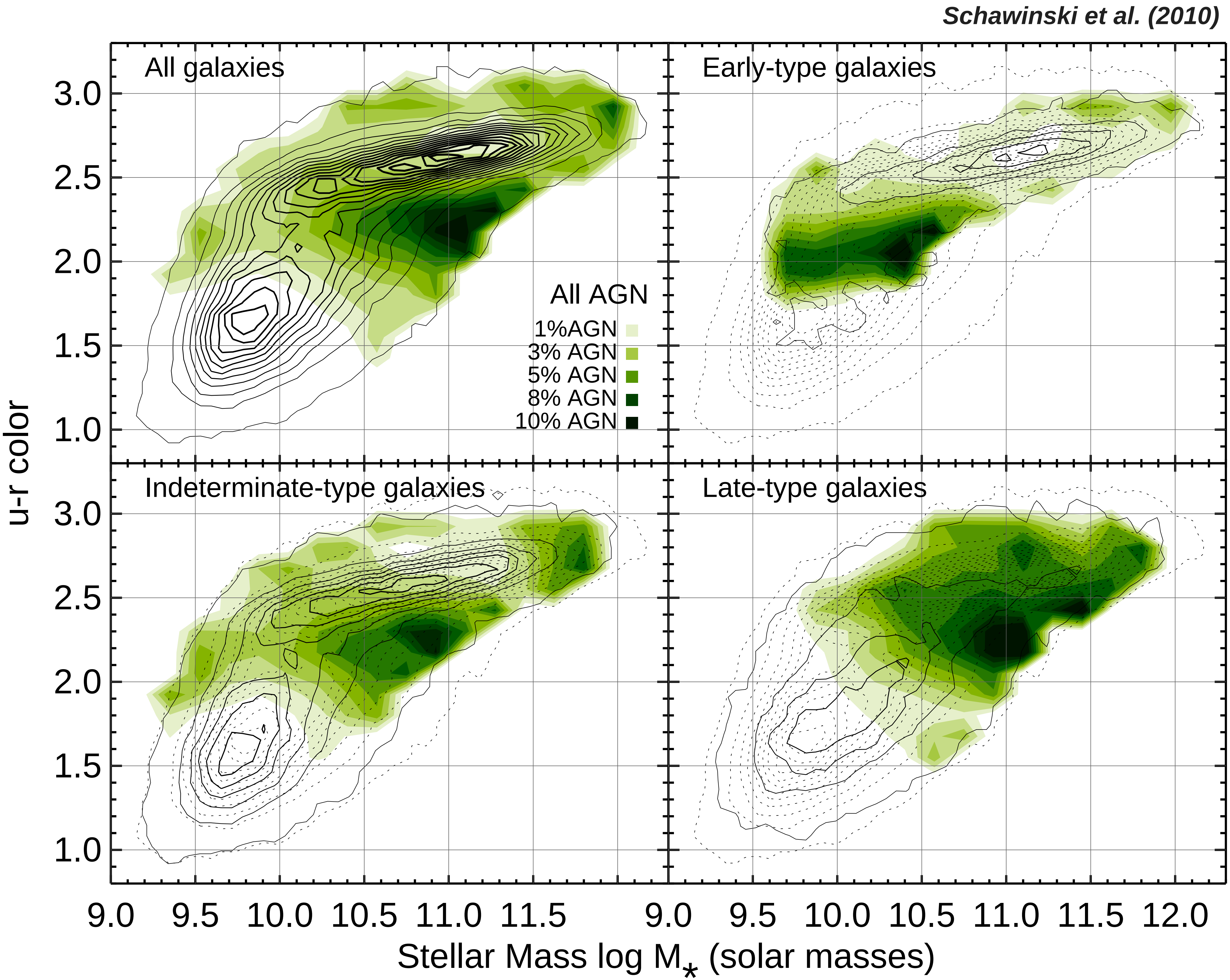


Gaiblier et al. (2012)



Kormendy & Ho (2013)


Crotton et al. (2006)
Cole et al. (2001)
Huang et al. (2003)
No radio heating
AGN radio heating
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Φ (h^3 Mpc^{-3} mag^{-1})
−28
−26
−24
−22
−20
$M_K - 5\log_{10}h$



Schawinski et al. (2010)
All galaxies
Early-type galaxies
Indeterminate-type galaxies
Late-type galaxies
All AGN
1%AGN
3% AGN
5% AGN
8% AGN
10% AGN
u-r color
3.0
2.5
2.0
1.5
1.0
9.0
9.5
10.0
10.5
11.0
11.5
12.0
Stellar Mass log M* (solar masses)

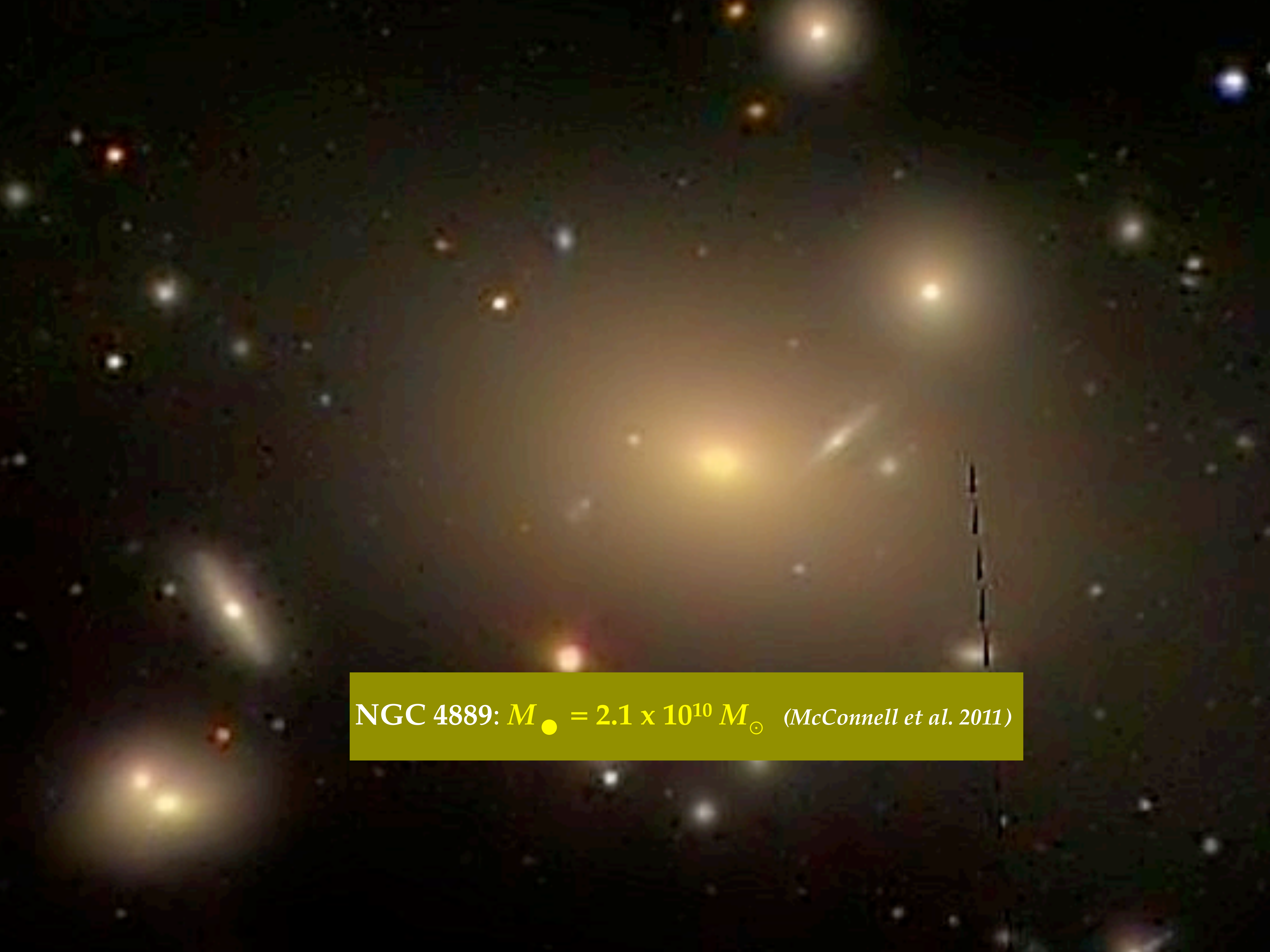
Standard "Paradigm"

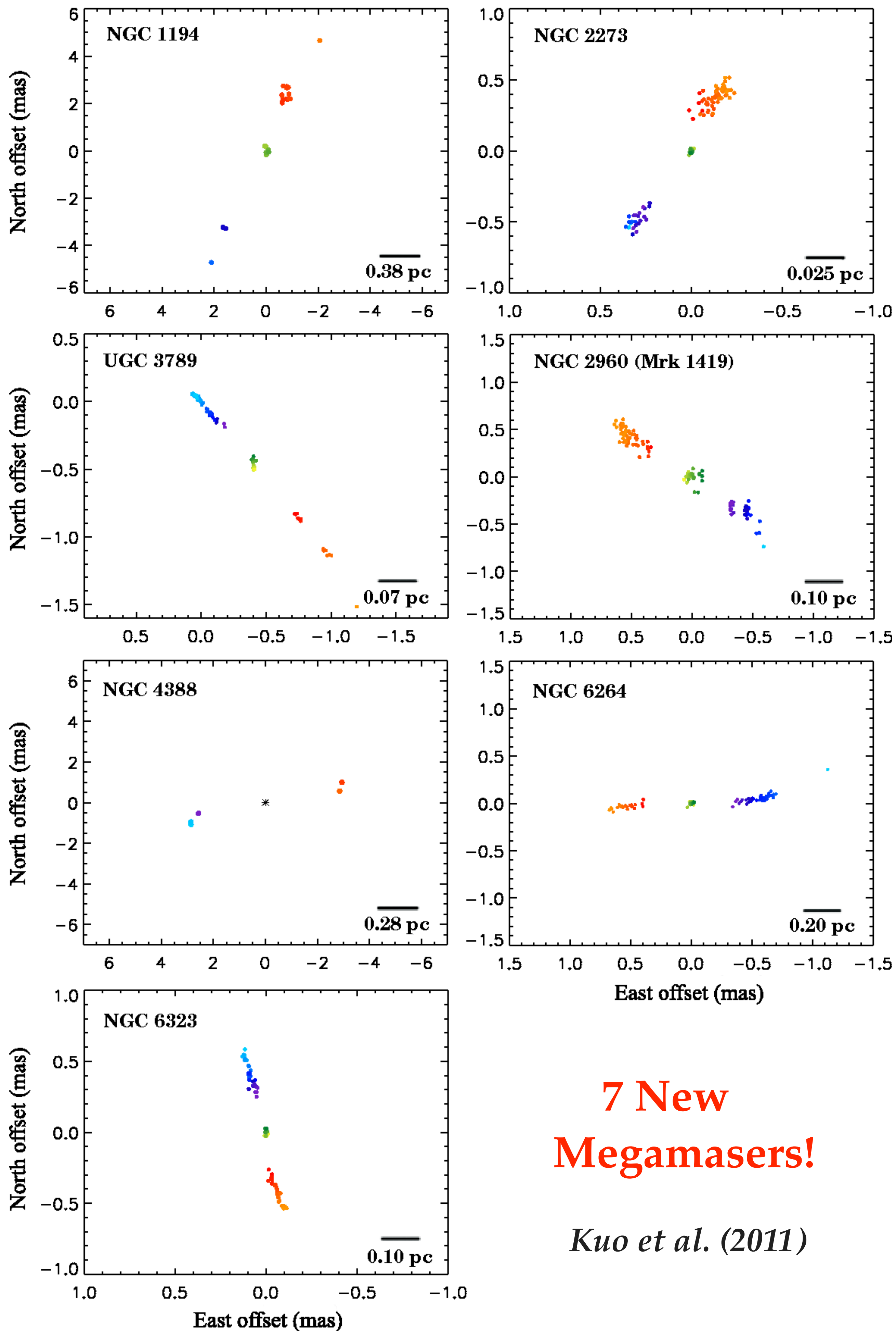
- All bulges contain BHs
- $M_\bullet \sim M_{\rm bulge}^{1.0}$ $\quad \langle M_\bullet / M_{\rm bulge} \rangle \sim 0.1\% - 0.2\%$
- $M_\bullet \propto \sigma^4$
- $M_\bullet - \sigma$ relation tighter than $M_\bullet - M_{\rm bulge}$ relation
- No strong dependence on galaxy mass or type
- Mild to strong evolution with redshift
- AGN feedback engineers BH-host correlations

Recent Developments

Kormendy & Ho (2013, ARA&A):

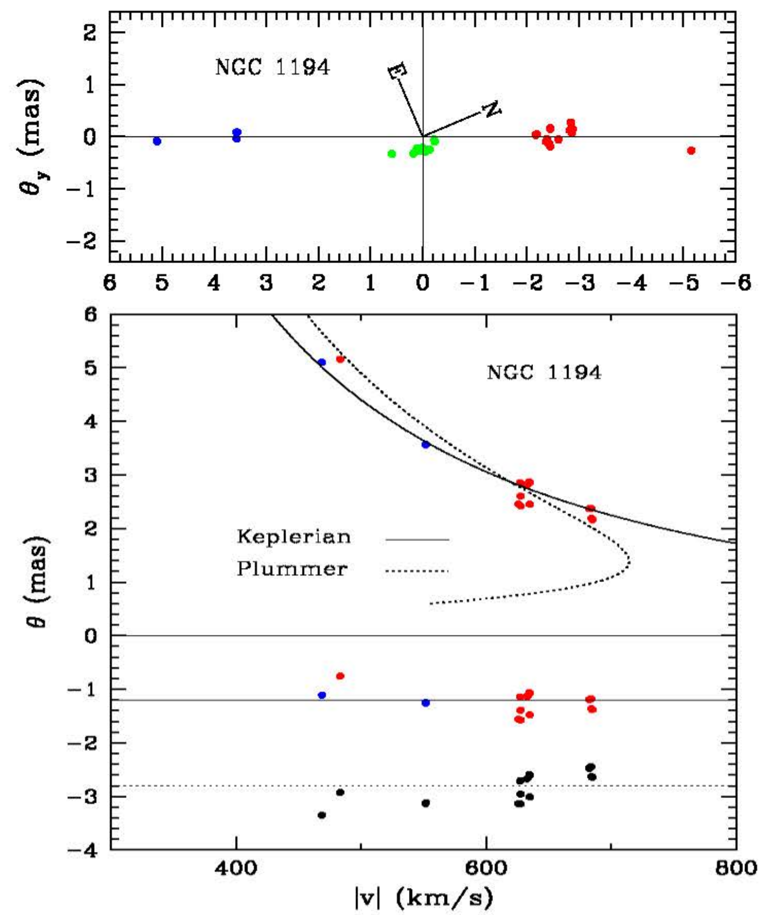
Coevolution (or Not) of Supermassive Black Holes and Galaxies

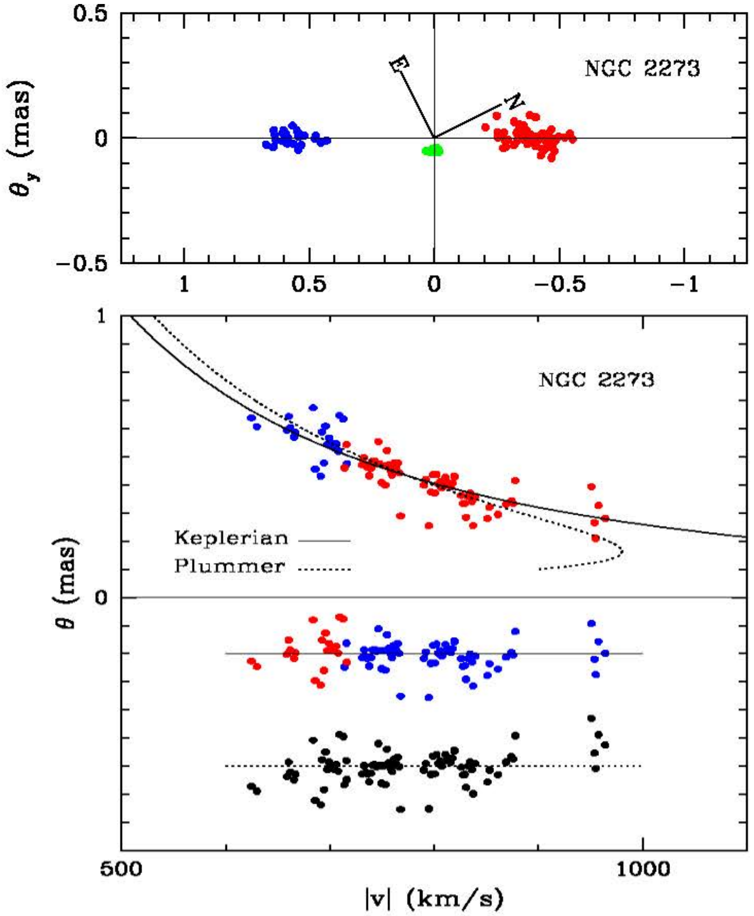

NGC 4889: $M_\bullet = 2.1 \times 10^{10}\, M_\odot$ *(McConnell et al. 2011)*

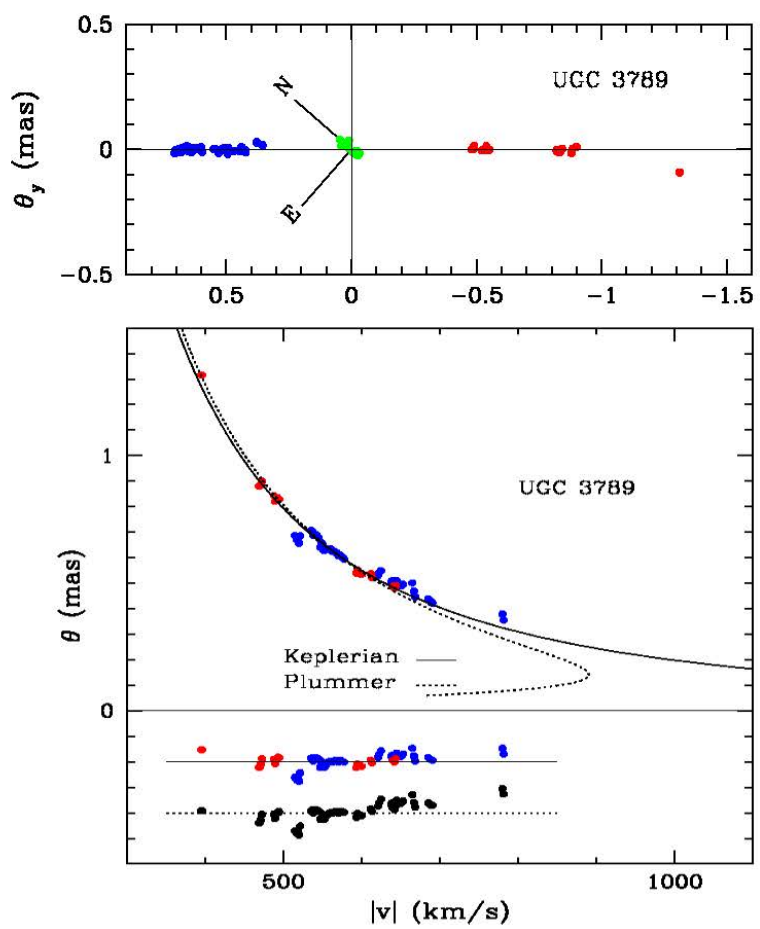


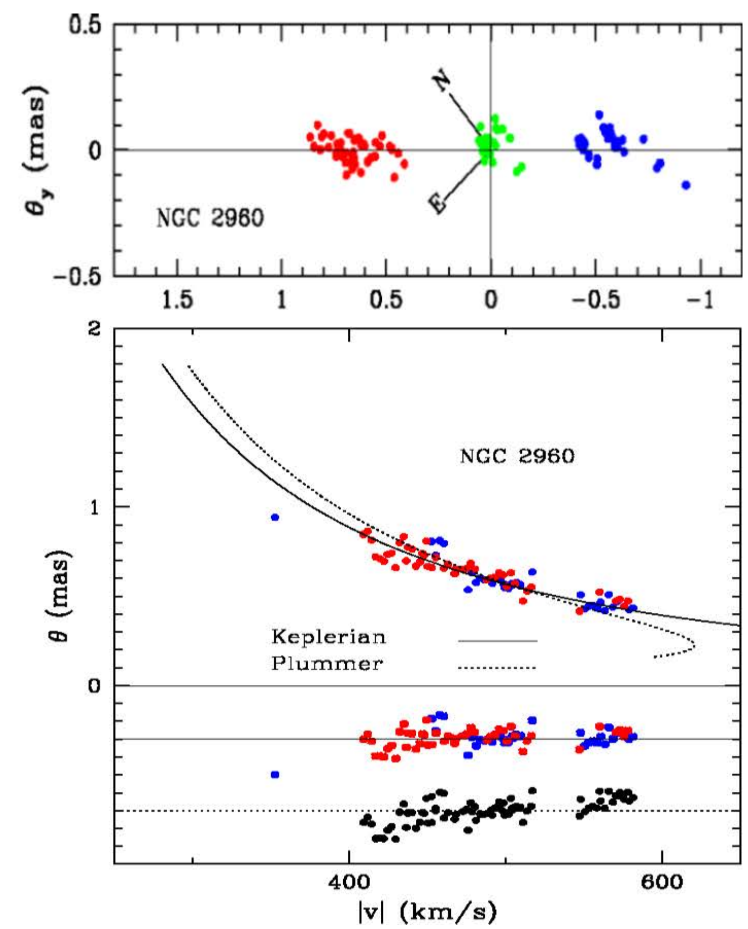
7 New Megamasers!

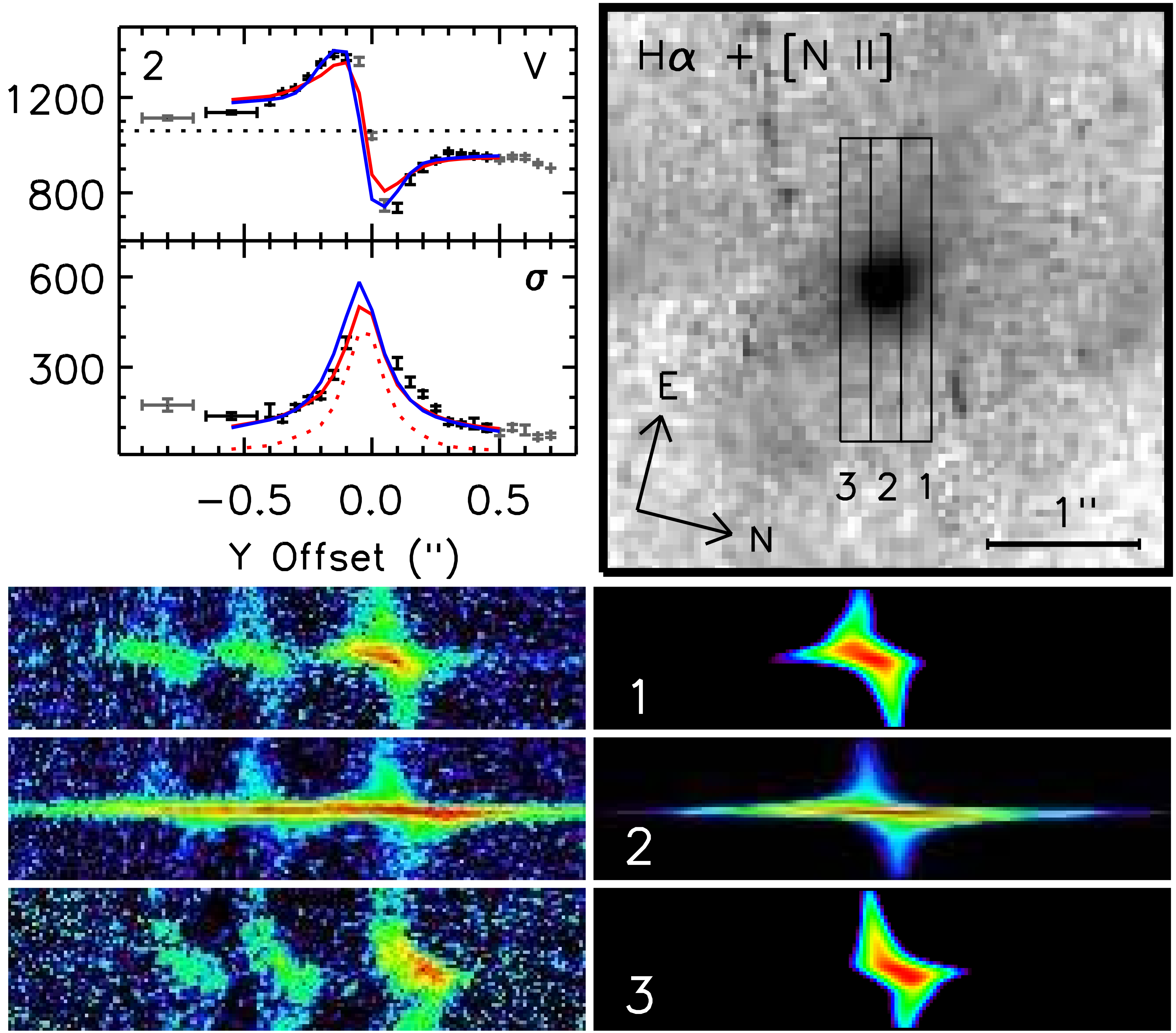
Kuo et al. (2011)


NGC 1194
E
N
θ_y (mas)
θ (mas)
Keplerian
Plummer
|v| (km/s)

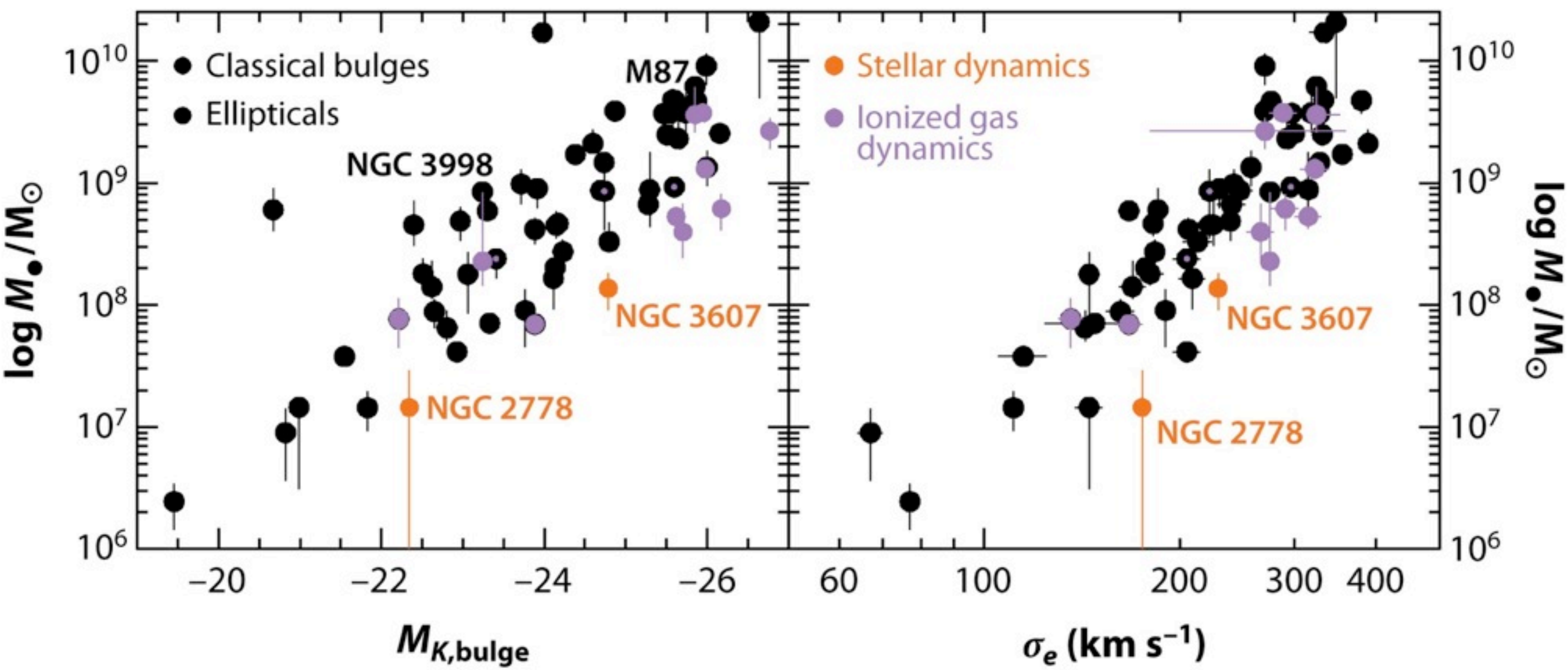

NGC 2273
E
N
θ_y (mas)
θ (mas)
Keplerian
Plummer
|v| (km/s)


UGC 3789
N
E
θ_y (mas)
θ (mas)
Keplerian
Plummer
|v| (km/s)

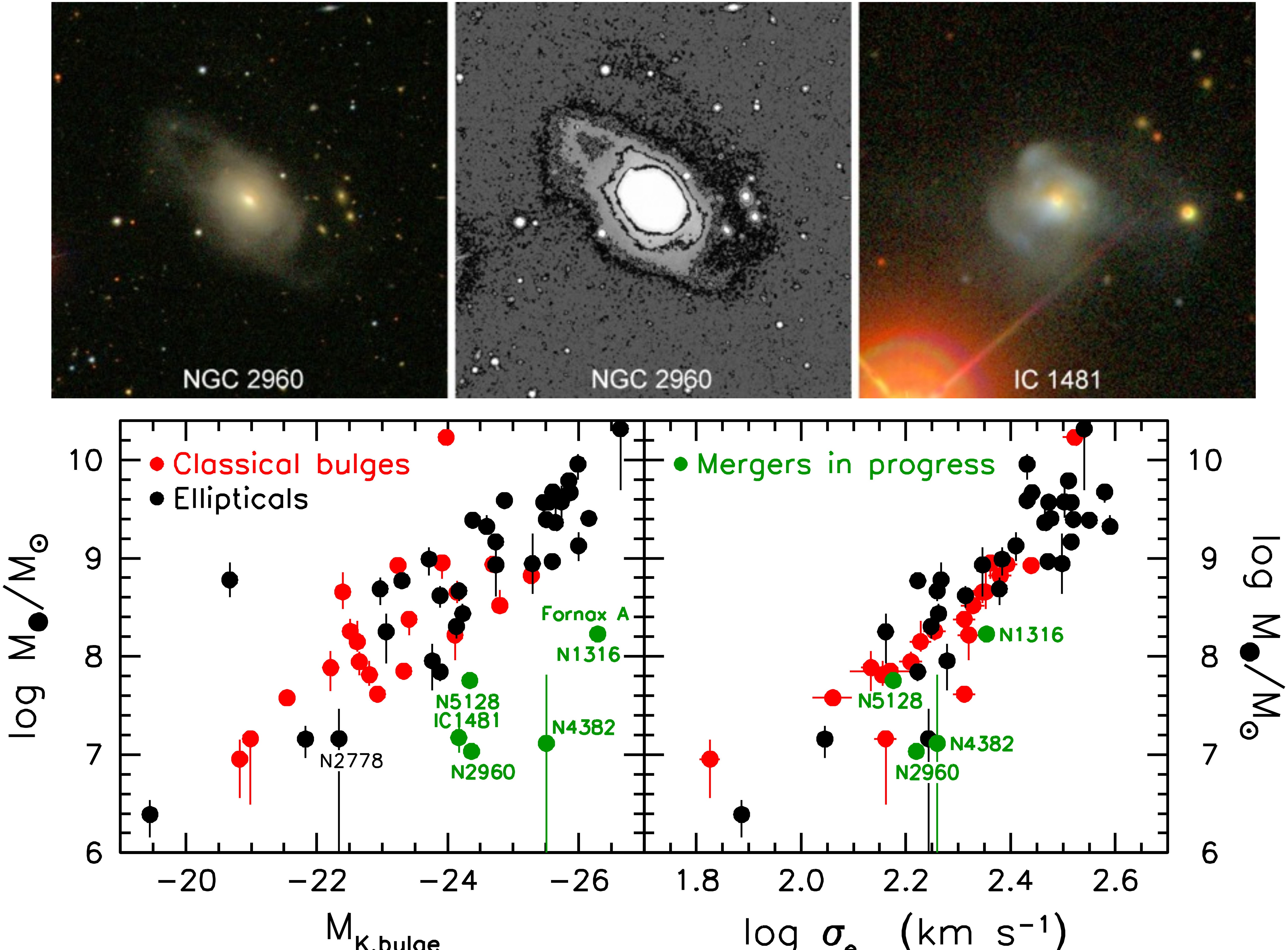

NGC 2960
N
E
θ_y (mas)
θ (mas)
Keplerian
Plummer
|v| (km/s)



2
V
1200
800
600
σ
300
−0.5
0.0
0.5
Y Offset ('')
Hα + [N II]
E
N
3 2 1
1''
1
2
3



Classical bulges
Ellipticals
M87
NGC 3998
NGC 3607
NGC 2778
Stellar dynamics
Ionized gas dynamics
log $M_\bullet/M_\odot$
10^{10}
10^9
10^8
10^7
10^6
−20
−22
−24
−26
$M_{K,\mathrm{bulge}}$
60
100
200
300
400
σ_e (km s^{-1})



NGC 2960
NGC 2960
IC 1481
Classical bulges
Ellipticals
Mergers in progress
log $M_\bullet/M_\odot$
$M_{K,\mathrm{bulge}}$
log σ_e (km s^{-1})
Fornax A
N1316
N5128
IC1481
N4382
N2960
N2778

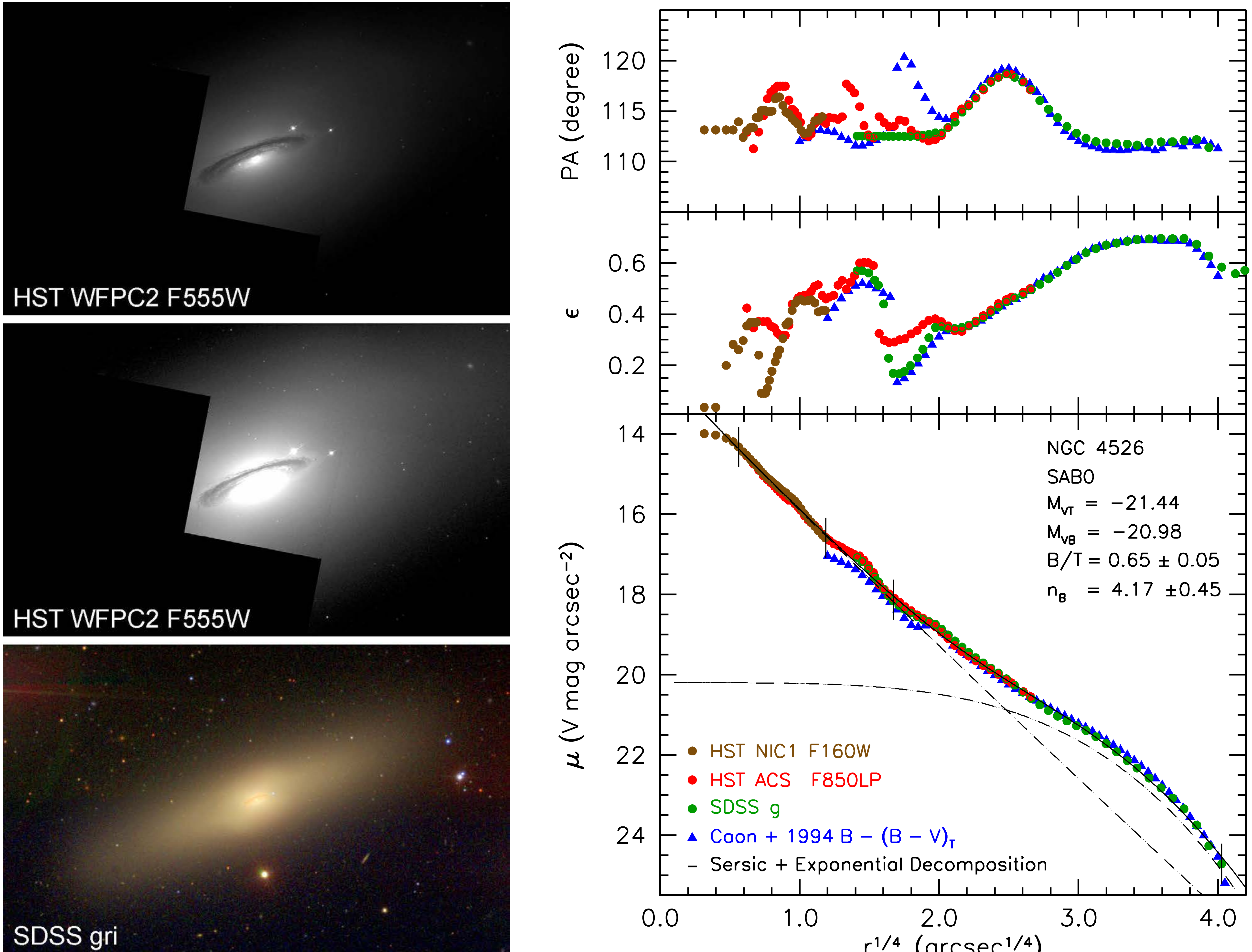

HST WFPC2 F555W
HST WFPC2 F555W
SDSS gri
PA (degree)
120
115
110
ϵ
0.6
0.4
0.2
μ (V mag arcsec^{-2})
14
16
18
20
22
24
NGC 4526
SAB0
M_{VT} = −21.44
M_{VB} = −20.98
B/T = 0.65 ± 0.05
n_B = 4.17 ±0.45
HST NIC1 F160W
HST ACS F850LP
SDSS g
Caon + 1994 B − (B − V)$_T$
Sersic + Exponential Decomposition
0.0
1.0
2.0
3.0
4.0
r$^{1/4}$ (arcsec$^{1/4}$)

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

Galaxy (1)	Type (2)	Distance (Mpc) (3)	K_s (4)	M_{KsT} (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 3377	E5	10.99 2	7.16	−23.06	−20.08	2.980	0.830	10.50 ± 0.09	$1.78(0.85 - 2.72) \times 10^8$	145 ± 7	1 0 1	Schulze + 2011
NGC 3379	E1	10.70 2	6.27	−23.88	−21.01	2.867	0.939	10.91 ± 0.09	$4.16(3.12 - 5.20) \times 10^8$	206 ± 10	1 1 1	van den Bosch + 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	1 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	32.36 2	6.94	−25.62	−22.64	2.980	0.974	11.65 ± 0.09	$5.29(4.21 - 6.36) \times 10^8$	315 ± 15	2 1 0	Ferrarese + 1996
NGC 4291	E2	26.58 2	8.42	−23.72	−20.76	2.954	0.927	10.85 ± 0.09	$9.78(6.70 - 12.86) \times 10^8$	242 ± 12	1 1 1	Schulze + 2011
NGC 4374	E1	18.51 1	5.75	−25.60	−22.62	2.980	0.945	11.62 ± 0.09	$9.25(8.38 - 10.23) \times 10^8$	296 ± 14	2 1 0	Walsh + 2010
NGC 4382	E2	17.88 1	5.76	−25.51	−22.53	2.980	0.863	11.51 ± 0.09	$1.30(0.00 - 22.4\ ) \times 10^7$	182 ± 5	1 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	15.25 1	7.16	−23.77	−20.89	2.874	0.935	10.85 ± 0.09	$0.90(0.45 - 1.35) \times 10^8$	190 ± 9	1 0 1	Schulze + 2011
M 87	E1	16.68 1	5.27	−25.85	−22.87	2.980	0.940	11.72 ± 0.09	$6.15(5.78 - 6.53) \times 10^9$	324^{+28}_{-12}	1 1 1	Gebhardt + 2011
NGC 4486A	E2	18.36 1	9.49	−21.83	−18.85	2.980	. . .	10.04 ± 0.09	$1.44(0.92 - 1.97) \times 10^7$	111 ± 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 + 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 5516	E3	55.3 9	8.31	−25.47	−22.50	2.970	0.993	11.60 ± 0.09	$3.69(2.65 - 3.79) \times 10^9$	328 ± 11	1 1 1	Rusli + 2013
NGC 5576	E3	25.68 2	7.83	−24.23	−21.29	2.939	0.862	11.00 ± 0.09	$2.73(1.94 - 3.41) \times 10^8$	183 ± 9	1 1 0	Gültekin + 2009b
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 + 1998
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 BCG	E	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 BCG	E	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

Table 3 Supermassive black holes detected dynamically in spiral and S0 galaxies galaxies (21 with classical bulges; 22 with pseudobulges; December 2012)

Object	Type	Distance (Mpc)	K_s	M_{KsT}	$M_{Ks,\mathrm{bulge}}$	$M_{Ks,\mathrm{disk}}$	B/T	PB/T	M_{VT}	$M_{V,\mathrm{bulge}}$	$M_{V,\mathrm{disk}}$	$(V-K_s)_0$	$(B-V)_0$	$\log M_{\mathrm{bulge}}$ $(M_\odot)$	$M_\bullet$(low $M_\bullet$ – high $M_\bullet$) $(M_\odot)$	σ_e (km s^{-1})	V_{circ} (km s^{-1})	Flags M $M_\bullet$	Source
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
M 31	Sb	0.774 8	0.573	−23.89	−22.62	−23.85	0.31	0.0	−21.14	−19.64	−20.83	2.746	0.865	10.35 ± 0.09	$1.43(1.12 - 2.34) \times 10^8$	169 ± 8	250 ± 20	1 0	Bender + 2005
M 81	Sb	3.604 8	3.831	−23.98	−22.81	−23.53	0.34	0.0	−21.06	−19.89	−20.61	2.913	0.879	10.42 ± 0.09	$6.5\ (5. - 9.\ ) \times 10^7$	143 ± 7	240 ± 10	1,2 0	see notes
NGC 524	S0	24.22 2	7.163	−24.78	−24.69	−22.04	0.92	0.0	−21.86	−21.77	−19.12	2.923	0.977	11.26 ± 0.09	$8.67(8.21 - 9.61) \times 10^8$	247 ± 12	...	1 0	Krajnović + 2009
NGC 821	S0	23.44 2	7.715	−24.17	−24.11	−20.92	0.95	0.0	−21.19	−21.13	−17.94	2.980	0.893	10.98 ± 0.09	$1.65(0.92 - 2.39) \times 10^8$	209 ± 10	...	1 1	Schulze + 2011
NGC 1023	SB0	10.81 2	6.238	−23.95	−22.95	−23.41	0.39	0.0	−20.99	−19.96	−20.45	2.964	0.946	10.53 ± 0.09	$4.13(3.71 - 4.56) \times 10^7$	205 ± 10	251 ± 15	1 0	Bower + 2001
NGC 1194	S0/	57.98 9	9.758	−24.08	−23.33	−23.33	0.5	0.0	−21.16	−20.40	−20.40	2.925	0.893	10.64 ± 0.09	$7.08(6.76 - 7.41) \times 10^7$	148 ± 24	203 ± 16	3 0	Kuo + 2011
NGC 1277	S0/	73. 10	9.813	−24.63	−23.98	−23.76	0.55	0.0	−21.31	−20.67	−20.45	3.313	0.985	11.00 ± 0.09	$1.7\ (1.4 - 2.0\ ) \times 10^{10}$	333 ± 17	...	1 1	van den Bosch + 2012
NGC 2549	S0/	12.70 2	8.046	−22.49	−20.99	−22.18	0.25	0.0	−19.55	−18.05	−19.24	2.942	0.912	9.71 ± 0.09	$1.45(0.31 - 1.65) \times 10^7$	145 ± 7	...	1 0	Krajnović + 2009
NGC 3115	S0/	9.54 2	5.883	−24.03	−23.91	−21.53	0.90	0.0	−21.13	−21.01	−18.63	2.901	0.928	10.92 ± 0.09	$8.97(6.20 - 9.54) \times 10^8$	230 ± 11	315 ± 20	1 1	Emsellem + 1999
NGC 3245	S0	21.38 2	7.862	−23.80	−23.41	−22.49	0.70	0.0	−20.88	−20.50	−19.58	2.914	0.888	10.69 ± 0.09	$2.39(1.63 - 2.66) \times 10^8$	205 ± 10	...	2 0	Barth + 2001
NGC 3585	S0	20.51 2	6.703	−24.88	−24.80	−21.99	0.93	0.0	−21.93	−21.85	−19.04	2.951	0.913	11.26 ± 0.09	$3.29(2.71 - 4.74) \times 10^8$	213 ± 11	280 ± 20	1 0	Gultekin + 2009a
NGC 3998	S0	14.30 2	7.365	−23.42	−23.24	−21.36	0.85	0.0	−20.63	−20.46	−18.57	2.786	0.936	10.67 ± 0.09	$8.45(7.79 - 9.15) \times 10^8$	275 ± 7	...	1 1	Walsh + 2012
NGC 3998	S0	14.30 2	7.365	−23.42	−23.24	−21.36	0.85	0.0	−20.63	−20.46	−18.57	2.786	0.936	10.67 ± 0.09	$2.27(1.43 - 3.28) \times 10^8$	275 ± 7	...	2 0	DeFrancesco + 2006
NGC 4026	S0	13.35 2	7.584	−23.05	−22.51	−22.03	0.61	0.0	−20.01	−19.47	−18.99	3.043	0.900	10.33 ± 0.09	$1.80(1.45 - 2.40) \times 10^8$	180 ± 9	300 ± 20	1 0	Gultekin + 2009a
NGC 4258	SABbc	7.27 6	5.464	−23.85	−21.55	−23.71	0.12	0.0	−20.94	−18.64	−20.80	2.907	0.676	9.86 ± 0.09	$3.78(3.74 - 3.82) \times 10^7$	115 ± 10	208 ± 6	3 0	Section 3.3
NGC 4342	S0	22.91 3	9.023	−22.78	−22.40	−21.48	0.70	0.01	−19.50	−19.11	−18.19	3.287	0.932	10.31 ± 0.09	$4.53(3.05 - 7.18) \times 10^8$	225 ± 11	...	1 0	Cretton + 1999b
NGC 4526	S0/	16.44 2	6.473	−24.61	−24.15	−23.47	0.65	0.0	−21.44	−20.98	−20.30	3.170	0.941	11.02 ± 0.09	$4.51(3.48 - 5.91) \times 10^8$	222 ± 11	290 ± 20	4 0	Davis + 2013
NGC 4564	S0	15.94 2	7.937	−23.09	−22.65	−21.88	0.67	0.0	−20.06	−19.62	−18.85	3.028	0.899	10.38 ± 0.09	$8.81(6.38 - 11.26) \times 10^7$	162 ± 8	...	1 1	Schulze + 2011
NGC 4594	Sa	9.87 2	4.625	−25.36	−25.28	−22.55	0.925	0.01	−22.38	−22.30	−19.57	2.980	0.934	11.47 ± 0.09	$6.65(6.24 - 7.05) \times 10^8$	240 ± 12	360 ± 10	1 1	Jardel + 2011
NGC 4596	SB0	16.53 4	7.463	−23.64	−22.21	−23.29	0.27	0.0	−20.72	−19.30	−20.38	2.913	0.920	10.20 ± 0.09	$7.67(4.43 - 11.41) \times 10^7$	136 ± 6	230 ± 30	2 0	Sarzi + 2001
NGC 7457	S0	12.53 2	8.179	−22.33	−20.82	−22.02	0.25	0.0	−19.45	−17.94	−19.14	2.880	0.844	9.56 ± 0.09	$0.90(0.36 - 1.43) \times 10^7$	67 ± 3	145 ± 6	1 1	Schulze + 2011
Galaxy	Sbc	0.00828	...	−23.7	−21.9	−23.5	0.0	0.19	−20.8	−18.9	−20.5	2.980	...	10.09 ± 0.10	$4.30(3.94 - 4.66) \times 10^6$	105 ± 20	220 ± 20	1 0	Genzel + 2010
Circinus	SABb:	2.82	4.71	−22.85	−21.55	−22.47	0.0	0.30	−19.80	−18.49	−19.41	3.052	0.410	9.63 ± 0.14	$1.14(0.94 - 1.34) \times 10^6$	79 ± 3	155 ± 5	3 0	Greenhill + 2003
NGC 1068	Sb	15.9 9	5.788	−25.23	−24.25	−24.66	0.0	0.41	−22.23	−20.92	−21.84	3.000	0.710	10.92 ± 0.10	$8.39(7.95 - 8.83) \times 10^6$	151 ± 7	283 ± 9	3 0	Lodato+2003, Huré+2002
NGC 1300	SBbc	21.5 9	7.564	−24.11	−21.71	−23.98	0.0	0.11	−21.32	−18.92	−21.19	2.791	0.653	9.84 ± 0.10	$7.55(3.89 - 14.75) \times 10^7$	88 ± 3	220 ± 10	2 0	Atkinson + 2005
NGC 2273	SBa	29.5 9	8.480	−23.89	−22.07	−23.67	0.0	0.19	−20.88	−19.06	−20.66	3.007	0.827	10.08 ± 0.09	$8.61(8.15 - 9.07) \times 10^6$	125 ± 9	220 ± 6	3 0	Kuo + 2011
NGC 2748	Sc	23.4 9	8.723	−23.13	−20.56	−23.02	0.0	0.094	−20.27	−17.70	−20.16	2.862	0.707	9.41 ± 0.10	$4.44(2.62 - 6.20) \times 10^7$	115 ± 5	150 ± 10	2 0	Atkinson + 2005
NGC 2787	SB0/a	7.45 2	7.263	−22.14	−21.06	−21.64	0.11	0.26	−19.10	−18.02	−18.60	3.038	0.944	9.78 ± 0.09	$4.07(3.55 - 4.47) \times 10^7$	189 ± 9	226 ± 10	2 0	Sarzi + 2001
NGC 3227	SBa	23.75 2	7.639	−24.25	−21.83	−24.12	0.0	0.108	−21.55	−19.13	−21.43	2.696	0.800	9.99 ± 0.09	$2.10(0.98 - 2.79) \times 10^7$	133 ± 12	250 ± 10	1 0	Davies + 2006
NGC 3368	SABab	10.62 2	6.320	−23.99	−22.48	−23.68	0.0	0.25	−21.14	−19.63	−20.82	2.854	0.838	10.26 ± 0.09	$7.66(6.13 - 9.19) \times 10^6$	125 ± 6	204 ± 5	1 0	Nowak + 2010
NGC 3384	SB0	11.49 2	6.750	−23.65	−22.56	−23.15	0.0	0.37	−20.55	−19.46	−20.05	3.105	0.906	10.34 ± 0.09	$1.08(0.59 - 1.57) \times 10^7$	146 ± 7	160 ± 10	1 1	Schulze + 2011
NGC 3393	SABa	49.2 9	9.059	−24.45	−23.03	−24.11	0.0	0.27	−21.48	−20.05	−21.14	2.968	0.813	10.48 ± 0.09	$1.57(0.58 - 2.55) \times 10^7$	148 ± 10	...	3 0	Kondratko+2008, Huré+2011
NGC 3489	SABa	11.98 2	7.370	−23.29	−22.15	−22.82	0.11	0.24	−20.17	−19.03	−19.70	3.120	0.815	10.11 ± 0.09	$5.94(5.11 - 6.78) \times 10^6$	113 ± 4	...	1 0	Nowak + 2010
NGC 3945	SB0	19.5 9	7.526	−23.93	−22.88	−23.41	0.04	0.34	−20.95	−19.90	−20.43	2.980	0.925	10.50 ± 0.09	$8.8\ (0.00 - 25.5\ ) \times 10^6$	192 ± 10	...	1 0	Gültekin + 2009b
NGC 4388	SBbc	16.53 4	8.004	−23.10	−20.55	−22.99	0.0	0.096	−20.14	−17.60	−20.03	2.955	0.711	9.41 ± 0.10	$7.31(7.13 - 7.48) \times 10^6$	99 ± 10	200 ± 10	3 0	Kuo + 2011
NGC 4736	Sab	5.00 2	5.106	−23.39	−22.29	−22.91	0.0	0.36	−20.68	−19.58	−20.20	2.710	0.735	10.13 ± 0.10	$6.77(5.21 - 8.33) \times 10^6$	120 ± 6	181 ± 10	1 0	Gebhardt + 2013
NGC 4826	Sab	7.27 2	5.330	−23.99	−22.24	−23.75	0.0	0.20	−20.98	−19.23	−20.74	3.009	0.803	10.14 ± 0.09	$1.56(1.17 - 1.95) \times 10^6$	104 ± 3	155 ± 5	1 0	Gebhardt + 2013
NGC 4945	Scd	3.58	4.438	−23.38	−20.50	−23.30	0.0	0.07	−20.58	−17.70	−20.50	2.801	1.20	9.35 ± 0.12	$1.35(0.87 - 2.03) \times 10^6$	134 ± 20	174 ± 10	3 0	Greenhill + 1997b
NGC 6264	SBb	147.6 9	11.407	−24.5	−22.6	−24.3	0.0	0.17	...	...	...	...	...	10.36 ± 0.09	$3.08(3.04 - 3.12) \times 10^7$	158 ± 15	...	3 0	Kuo + 2011
NGC 6323	SBab	113.4 9	10.530	−24.80	−21.55	−24.75	0.0	0.050	...	...	...	...	...	9.94 ± 0.09	$1.01(1.00 - 1.03) \times 10^7$	158 ± 26	...	3 0	Kuo + 2011
NGC 7582	SBab	22.3 9	7.316	−24.43	−21.96	−24.31	0.0	0.103	−21.78	−19.31	−21.66	2.649	0.738	10.02 ± 0.10	$5.51(4.56 - 6.81) \times 10^7$	156 ± 19	226 ± 10	2 0	Wold + 2006
IC 2560	SBbc	37.2 9	8.694	−24.19	−22.05	−24.02	0.0	0.14	−21.65	−19.51	−21.48	2.541	0.886	10.12 ± 0.09	$5.01(0.00 - 5.72) \times 10^6$	141 ± 10	196 ± 3	3 0	Yamauchi + 2012
UGC 3789	SABab	49.9	9.510	−24.03	−22.79	−23.61	0.0	0.32	−21.13	−19.89	−20.71	2.9	0.86	10.39 ± 0.09	$9.65(8.10 - 11.20) \times 10^6$	107 ± 12	273 ± 20	3 0	Kuo+2011, Huré+2011

Column 1 is the galaxy name. Rows are printed in red for galaxies with classical bulges; these are plotted with red symbols in BH correlation diagrams. Blue text and plot symbols are used for pseudobulges. The cyan $M_\bullet$ for NGC 3998 is plotted only in **Figure 12**. Otherwise, if $M_\bullet$ is shown in cyan, we accept the BH mass but do not include it in correlation fits (Sections 6.5, 6.6).
Column 2 is the galaxy Hubble type, mostly from RC3 with a few corrections from Kormendy & Bender (2013b).
Column 3 is the assumed distance (see notes to **Table 2**). For our Galaxy, Circinus, NGC 4945, and UGC 3789, see supplemental notes on individual galaxies.
Column 4 is the 2MASS K_s total magnitude. For three galaxies, it has been corrected as discussed in **Apparent Magnitude Corrections** in the table supplemental notes and in Supplemental Information. These corrections are generally negligible for disk galaxies,

Table 3 Supermassive black holes detected dynamically in spiral and S0 galaxies galaxies (21 with classical bulges; 22 with pseudobulges; December 2012)

Object	Type	Distance (Mpc)	K_s	M_{KsT}	$M_{Ks,\mathrm{bulge}}$	$M_{Ks,\mathrm{disk}}$	B/T	PB/T	M_{VT}	$M_{V,\mathrm{bulge}}$	$M_{V,\mathrm{disk}}$	$(V-K_s)_0$	$(B-V)_0$	$\log M_{\mathrm{bulge}}$ $(M_\odot)$	$M_\bullet$(low $M_\bullet$ – high $M_\bullet$) $(M_\odot)$	σ_e (km s^{-1})	V_{circ} (km s^{-1})	Flags M $M_\bullet$	Source
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
M 31																			
M 81																			
NGC																			
NGC																			
NGC 1																			
NGC 1																			
NGC 1																			
NGC 2																			
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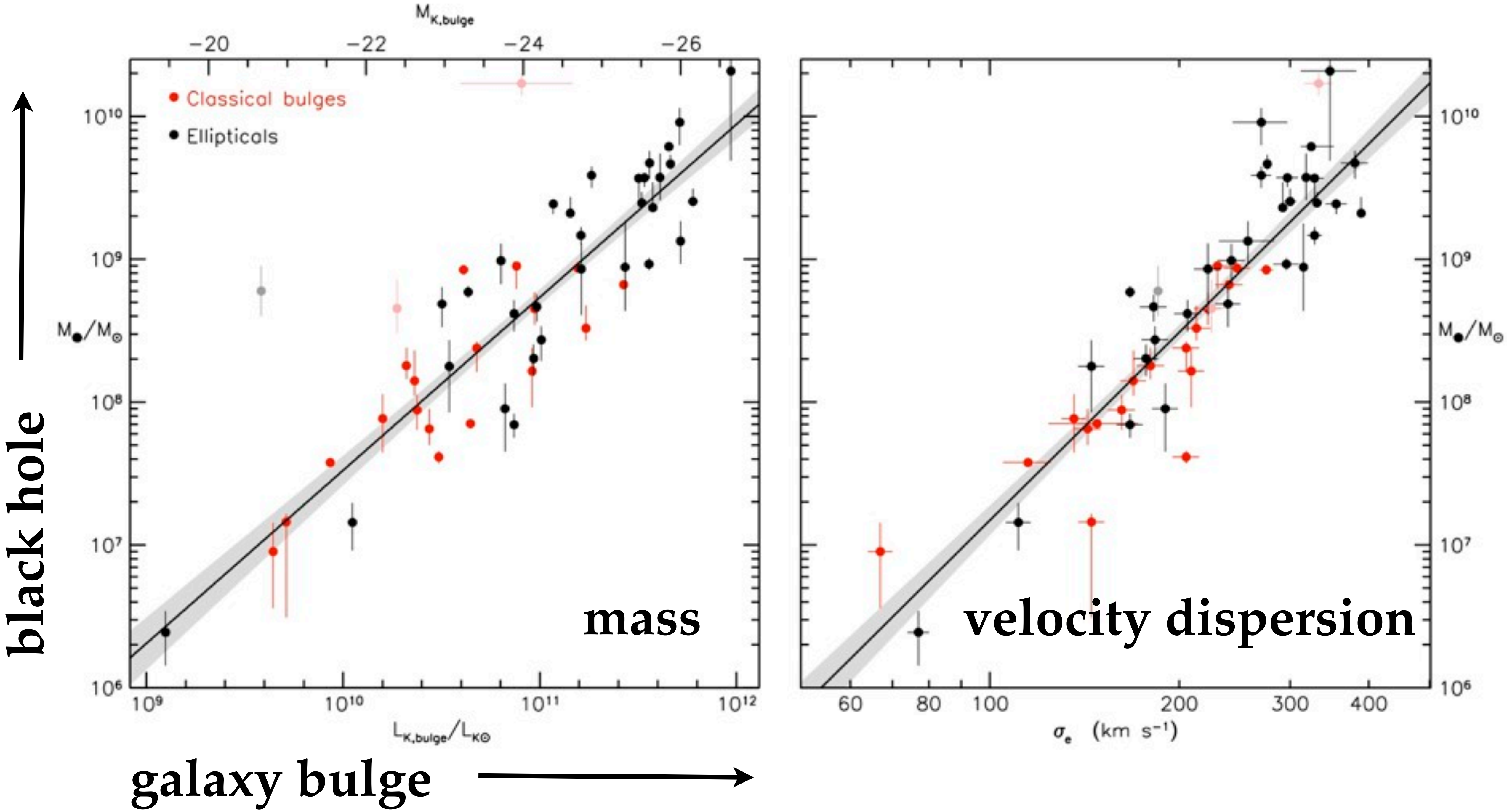
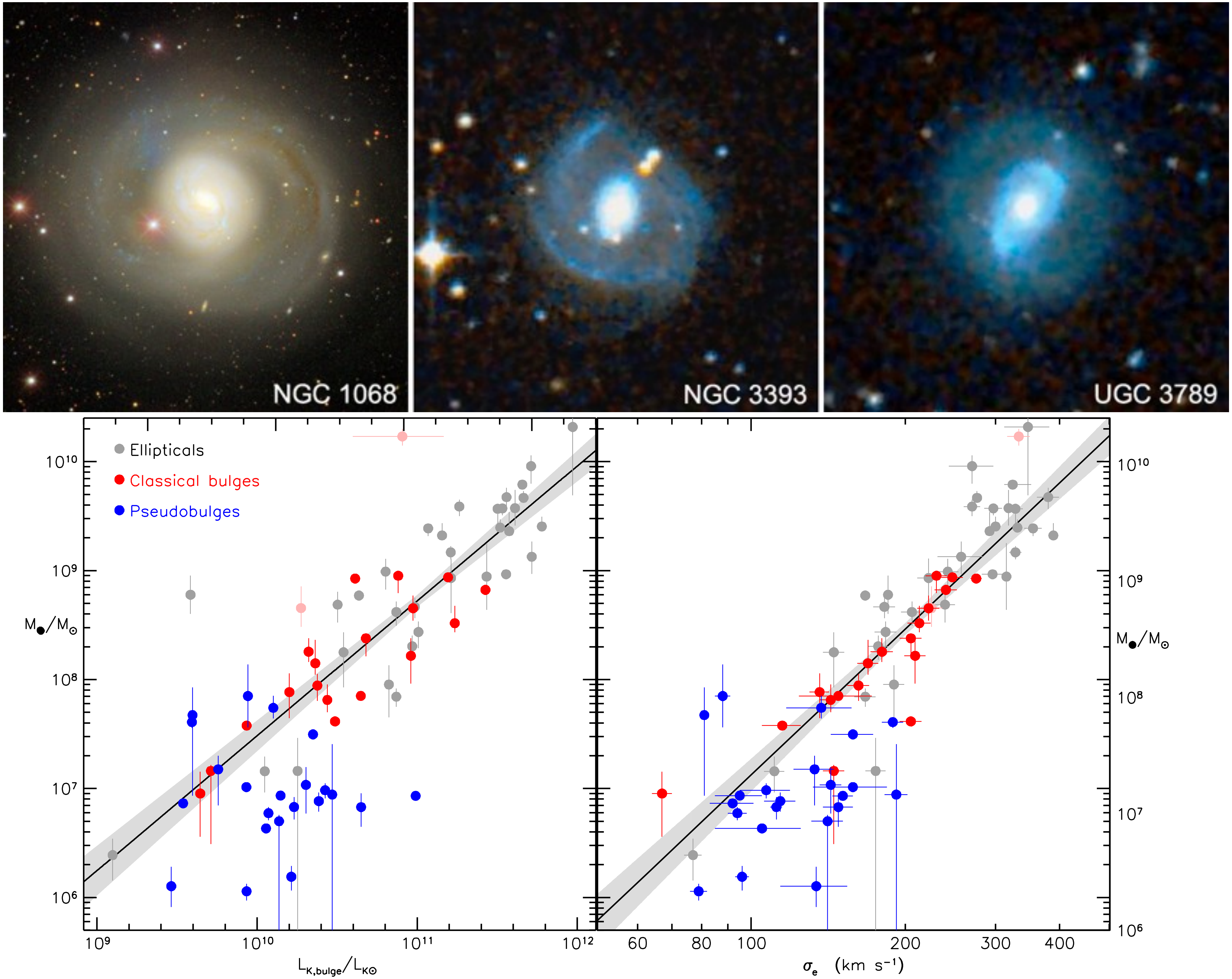
NGC 4																			
NGC 4																			
NGC 4																			
NGC 4																			
NGC 7																			
Galaxy	Sbc	0.00828	. . .	−23.7	−21.9	−23.5	0.0	0.19	−20.8	−18.9	−20.5	2.980	. . .	10.09 ± 0.10	$4.30(3.94 - 4.66) \times 10^6$	105 ± 20	220 ± 20	1 0	Genzel + 2010
Circinus	SABb:	2.82	4.71	−22.85	−21.55	−22.47	0.0	0.30	−19.80	−18.49	−19.41	3.052	0.410	9.63 ± 0.14	$1.14(0.94 - 1.34) \times 10^6$	79 ± 3	155 ± 5	3 0	Greenhill + 2003
NGC 1068	Sb	15.9 9	5.788	−25.23	−24.25	−24.66	0.0	0.41	−22.23	−20.92	−21.84	3.000	0.710	10.92 ± 0.10	$8.39(7.95 - 8.83) \times 10^6$	151 ± 7	283 ± 9	3 0	Lodato+2003, Huré+2002
NGC 1300	SBbc	21.5 9	7.564	−24.11	−21.71	−23.98	0.0	0.11	−21.32	−18.92	−21.19	2.791	0.653	9.84 ± 0.10	$7.55(3.89 - 14.75) \times 10^7$	88 ± 3	220 ± 10	2 0	Atkinson + 2005
NGC 2273	SBa	29.5 9	8.480	−23.89	−22.07	−23.67	0.0	0.19	−20.88	−19.06	−20.66	3.007	0.827	10.08 ± 0.09	$8.61(8.15 - 9.07) \times 10^6$	125 ± 9	220 ± 6	3 0	Kuo + 2011
NGC 2748	Sc	23.4 9	8.723	−23.13	−20.56	−23.02	0.0	0.094	−20.27	−17.70	−20.16	2.862	0.707	9.41 ± 0.10	$4.44(2.62 - 6.20) \times 10^7$	115 ± 5	150 ± 10	2 0	Atkinson + 2005
NGC 2787	SB0/a	7.45 2	7.263	−22.14	−21.06	−21.64	0.11	0.26	−19.10	−18.02	−18.60	3.038	0.944	9.78 ± 0.09	$4.07(3.55 - 4.47) \times 10^7$	189 ± 9	226 ± 10	2 0	Sarzi + 2001
NGC 3227	SBa	23.75 2	7.639	−24.25	−21.83	−24.12	0.0	0.108	−21.55	−19.13	−21.43	2.696	0.800	9.99 ± 0.09	$2.10(0.98 - 2.79) \times 10^7$	133 ± 12	250 ± 10	1 0	Davies + 2006
NGC 3368	SABab	10.62 2	6.320	−23.99	−22.48	−23.68	0.0	0.25	−21.14	−19.63	−20.82	2.854	0.838	10.26 ± 0.09	$7.66(6.13 - 9.19) \times 10^6$	125 ± 6	204 ± 5	1 0	Nowak + 2010
NGC 3384	SB0	11.49 2	6.750	−23.65	−22.56	−23.15	0.0	0.37	−20.55	−19.46	−20.05	3.105	0.906	10.34 ± 0.09	$1.08(0.59 - 1.57) \times 10^7$	146 ± 7	160 ± 10	1 1	Schulze + 2011
NGC 3393	SABa	49.2 9	9.059	−24.45	−23.03	−24.11	0.0	0.27	−21.48	−20.05	−21.14	2.968	0.813	10.48 ± 0.09	$1.57(0.58 - 2.55) \times 10^7$	148 ± 10	. . .	3 0	Kondratko+2008, Huré+2011
NGC 3489	SABa	11.98 2	7.370	−23.29	−22.15	−22.82	0.11	0.24	−20.17	−19.03	−19.70	3.120	0.815	10.11 ± 0.09	$5.94(5.11 - 6.78) \times 10^6$	113 ± 4	. . .	1 0	Nowak + 2010
NGC 3945	SB0	19.5 9	7.526	−23.93	−22.88	−23.41	0.04	0.34	−20.95	−19.90	−20.43	2.980	0.925	10.50 ± 0.09	$8.8\ (0.00 - 25.5\ ) \times 10^6$	192 ± 10	. . .	1 0	Gültekin + 2009b
NGC 4388	SBbc	16.53 4	8.004	−23.10	−20.55	−22.99	0.0	0.096	−20.14	−17.60	−20.03	2.955	0.711	9.41 ± 0.10	$7.31(7.13 - 7.48) \times 10^6$	99 ± 10	200 ± 10	3 0	Kuo + 2011
NGC 4736	Sab	5.00 2	5.106	−23.39	−22.29	−22.91	0.0	0.36	−20.68	−19.58	−20.20	2.710	0.735	10.13 ± 0.10	$6.77(5.21 - 8.33) \times 10^6$	120 ± 6	181 ± 10	1 0	Gebhardt + 2013
NGC 4826	Sab	7.27 2	5.330	−23.99	−22.24	−23.75	0.0	0.20	−20.98	−19.23	−20.74	3.009	0.803	10.14 ± 0.09	$1.56(1.17 - 1.95) \times 10^6$	104 ± 3	155 ± 5	1 0	Gebhardt + 2013
NGC 4945	Scd	3.58	4.438	−23.38	−20.50	−23.30	0.0	0.07	−20.58	−17.70	−20.50	2.801	1.20	9.35 ± 0.12	$1.35(0.87 - 2.03) \times 10^6$	134 ± 20	174 ± 10	3 0	Greenhill + 1997b
NGC 6264	SBb	147.6 9	11.407	−24.5	−22.6	−24.3	0.0	0.17	. . .	. . .	. . .	. . .	. . .	10.36 ± 0.09	$3.08(3.04 - 3.12) \times 10^7$	158 ± 15	. . .	3 0	Kuo + 2011
NGC 6323	SBab	113.4 9	10.530	−24.80	−21.55	−24.75	0.0	0.050	. . .	. . .	. . .	. . .	. . .	9.94 ± 0.09	$1.01(1.00 - 1.03) \times 10^7$	158 ± 26	. . .	3 0	Kuo + 2011
NGC 7582	SBab	22.3 9	7.316	−24.43	−21.96	−24.31	0.0	0.103	−21.78	−19.31	−21.66	2.649	0.738	10.02 ± 0.10	$5.51(4.56 - 6.81) \times 10^7$	156 ± 19	226 ± 10	2 0	Wold + 2006
IC 2560	SBbc	37.2 9	8.694	−24.19	−22.05	−24.02	0.0	0.14	−21.65	−19.51	−21.48	2.541	0.886	10.12 ± 0.09	$5.01(0.00 - 5.72) \times 10^6$	141 ± 10	196 ± 3	3 0	Yamauchi + 2012
UGC 3789	SABab	49.9	9.510	−24.03	−22.79	−23.61	0.0	0.32	−21.13	−19.89	−20.71	2.9	0.86	10.39 ± 0.09	$9.65(8.10 - 11.20) \times 10^6$	107 ± 12	273 ± 20	3 0	Kuo+2011, Huré+2011

−19.57	2.980	0.934	11.47 ± 0.09	$6.65(6.24 - 7.05) \times 10^8$	240 ± 12	360 ± 10
−20.38	2.913	0.920	10.20 ± 0.09	$7.67(4.43 - 11.41) \times 10^7$	136 ± 6	230 ± 30
−19.14	2.880	0.844	9.56 ± 0.09	$0.90(0.36 - 1.43) \times 10^7$	67 ± 3	145 ± 6
−20.5	2.980	. . .	10.09 ± 0.10	$4.30(3.94 - 4.66) \times 10^6$	105 ± 20	220 ± 20
−19.41	3.052	0.410	9.63 ± 0.14	$1.14(0.94 - 1.34) \times 10^6$	79 ± 3	155 ± 5
−21.84	3.000	0.710	10.92 ± 0.10	$8.39(7.95 - 8.83) \times 10^6$	151 ± 7	283 ± 9
−21.19	2.791	0.653	9.84 ± 0.10	$7.55(3.89 - 14.75) \times 10^7$	88 ± 3	220 ± 10

Column 1 is the galaxy name. Rows are printed in red for galaxies with classical bulges; these are plotted with red symbols in BH correlation diagrams. Blue text and plot symbols are used for pseudobulges. The cyan $M_\bullet$ for NGC 3998 is plotted only in **Figure 12**. Otherwise, if $M_\bullet$ is shown in cyan, we accept the BH mass but do not include it in correlation fits (Sections 6.5, 6.6).
Column 2 is the galaxy Hubble type, mostly from RC3 with a few corrections from Kormendy & Bender (2013b).
Column 3 is the assumed distance (see notes to **Table 2**). For our Galaxy, Circinus, NGC 4945, and UGC 3789, see supplemental notes on individual galaxies.
Column 4 is the 2MASS K_s total magnitude. For three galaxies, it has been corrected as discussed in **Apparent Magnitude Corrections** in the table supplemental notes and in Supplemental Information. These corrections are generally negligible for disk galaxies,



black hole
galaxy bulge
mass
velocity dispersion
Classical bulges
Ellipticals
M_K,bulge
−20
−22
−24
−26
M●/M⊙
L_K,bulge/L_K⊙
σ_e (km s⁻¹)
60
80
100
200
300
400


NGC 1068
NGC 3393
UGC 3789
Ellipticals
Classical bulges
Pseudobulges
$M_\bullet/M_\odot$
10^6
10^7
10^8
10^9
10^{10}
10^9
10^{10}
10^{11}
10^{12}
$L_{K,bulge}/L_{K\odot}$
60
80
100
200
300
400
σ_e (km s^{-1})

$M_\bullet - \sigma$ Relation

$M_\bullet - \sigma$ Relation

$$\frac{M_\bullet}{10^9\ M_\odot} = \left(0.309^{+0.037}_{-0.033}\right)\ \left(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}}\right)^{4.38\pm0.29} \quad \text{intrinsic scatter} = 0.28$$

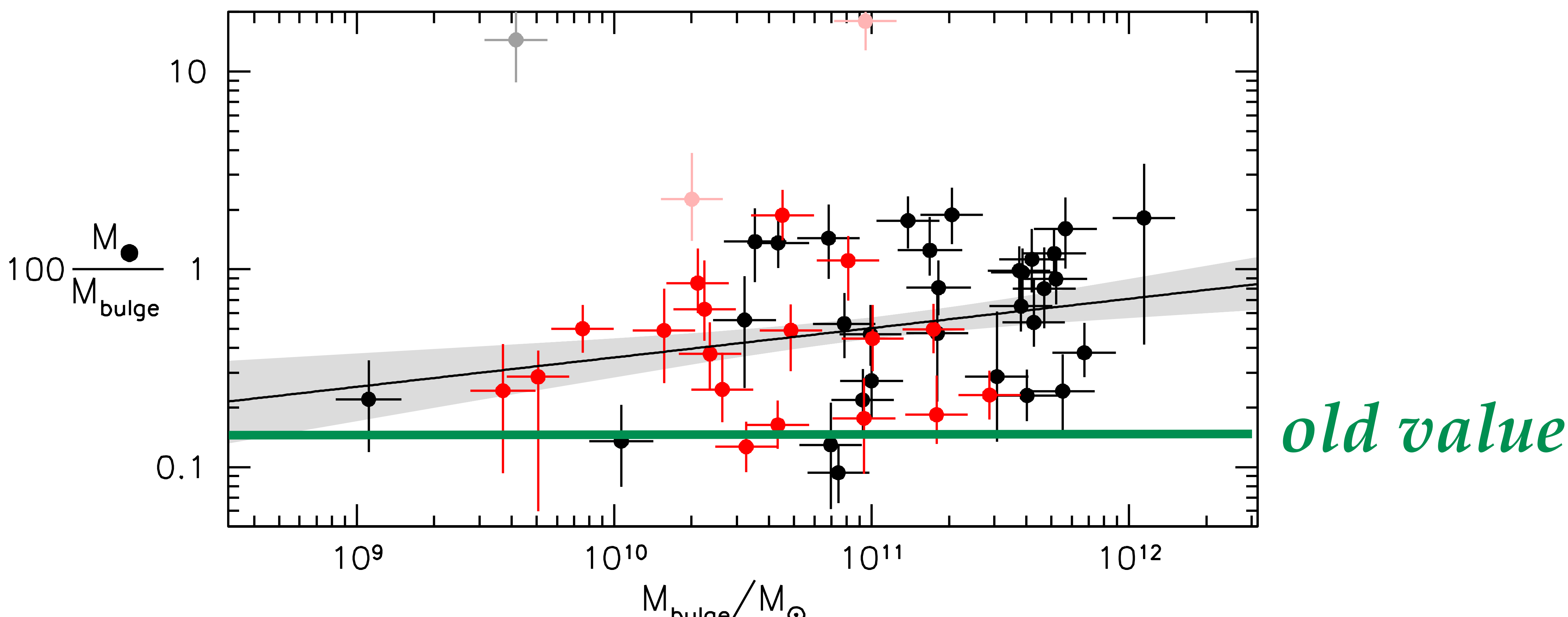
$M_\bullet - M_{\mathbf{bulge}}$ Relation

$M_\bullet - M_{\mathbf{bulge}}$ Relation

$$\frac{M_\bullet}{10^9\ M_\odot} = \left(0.49^{+0.06}_{-0.05}\right)\left(\frac{M_{\rm bulge}}{10^{11}\ M_\odot}\right)^{1.16\pm0.08} ;\ \text{intrinsic scatter} = 0.29\ \text{dex.}$$

$M_\bullet - M_{\mathrm{bulge}}$ Relation

$$\frac{M_\bullet}{10^9\ M_\odot} = \left(0.49^{+0.06}_{-0.05}\right)\left(\frac{M_{\mathrm{bulge}}}{10^{11}\ M_\odot}\right)^{1.16\pm0.08} \quad ; \text{ intrinsic scatter} = 0.29 \text{ dex.}$$



Virial BH Masses for Type 1 AGNs

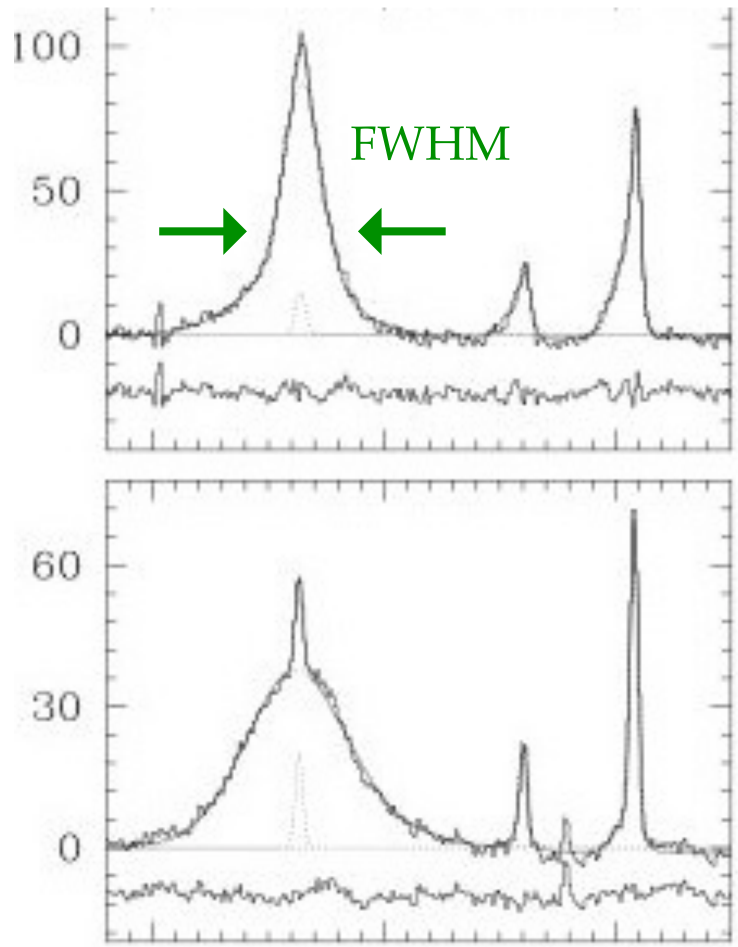
$$M_{\mathrm{virial}} = f\,RV^{2}/G$$

f geometric fudge factor

R BLR radius

V BLR velocity dispersion

Virial BH Masses for Type 1 AGNs



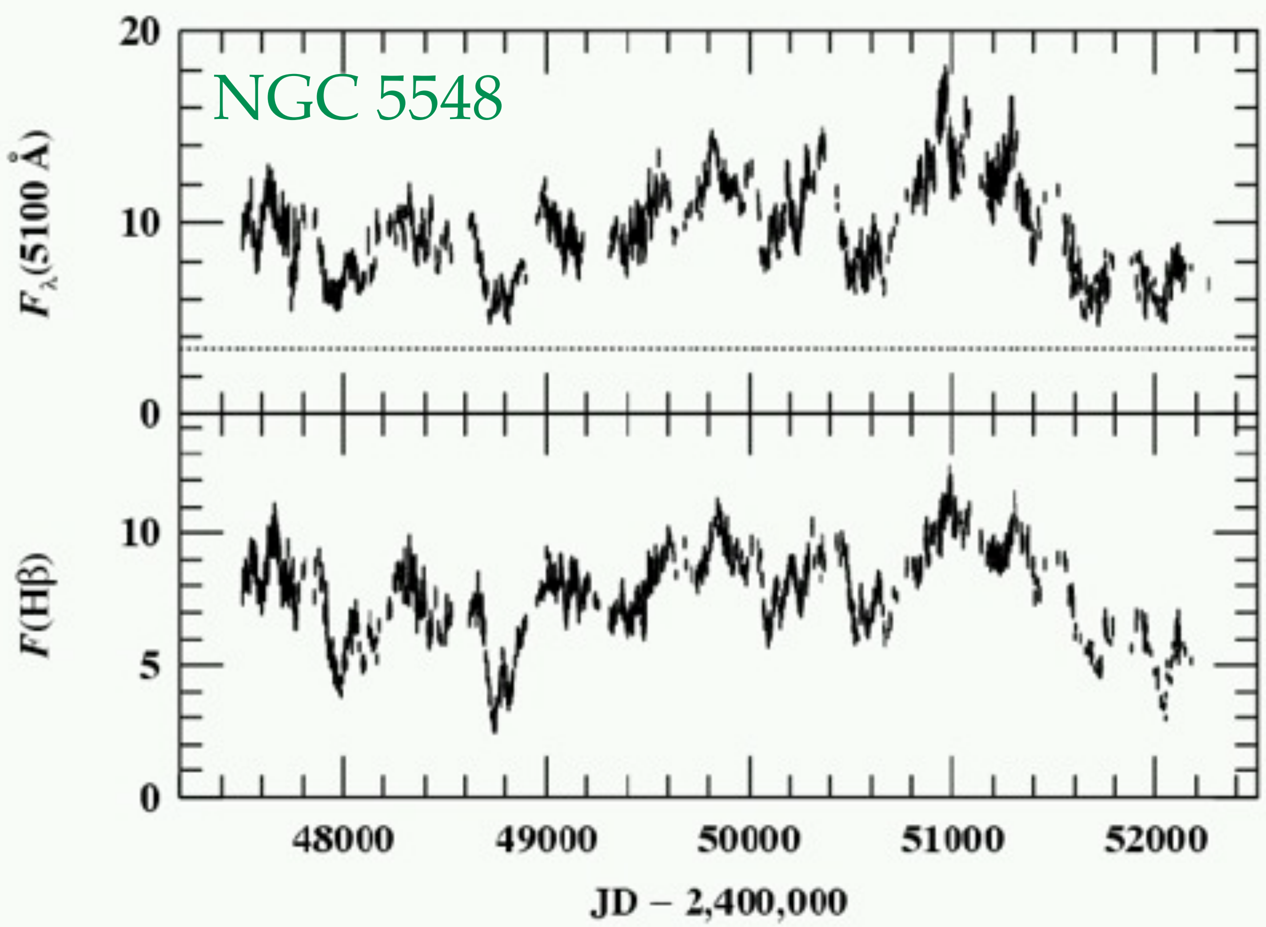
$$M_{\mathrm{virial}} = f\, R V^2 / G$$

f geometric fudge factor

R BLR radius

V BLR velocity dispersion

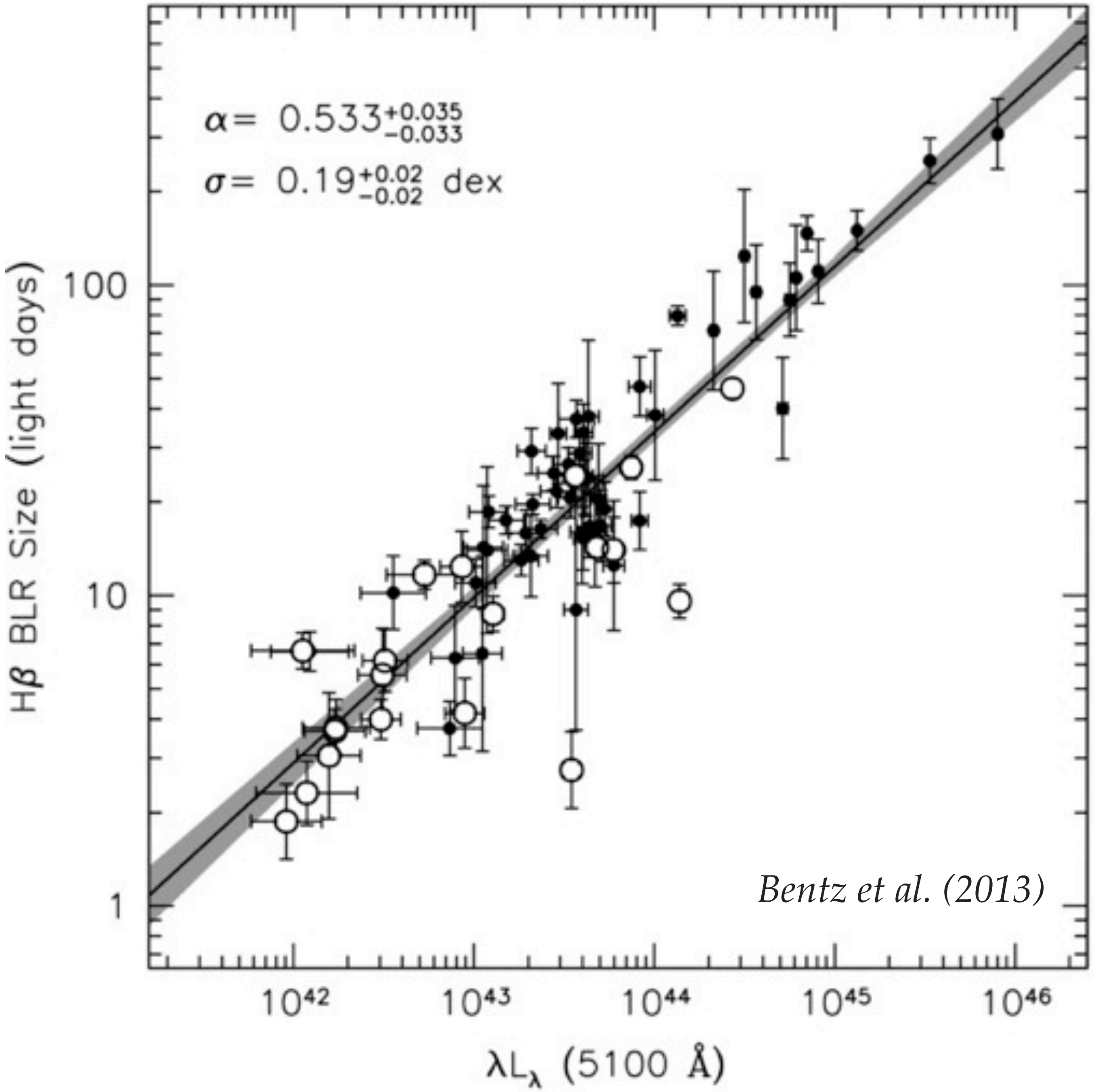
Virial BH Masses for Type 1 AGNs



Peterson et al. (2002)

$$M_{\text{virial}} = f\,RV^2/G$$

- f geometric fudge factor
- R BLR radius
- V BLR velocity dispersion

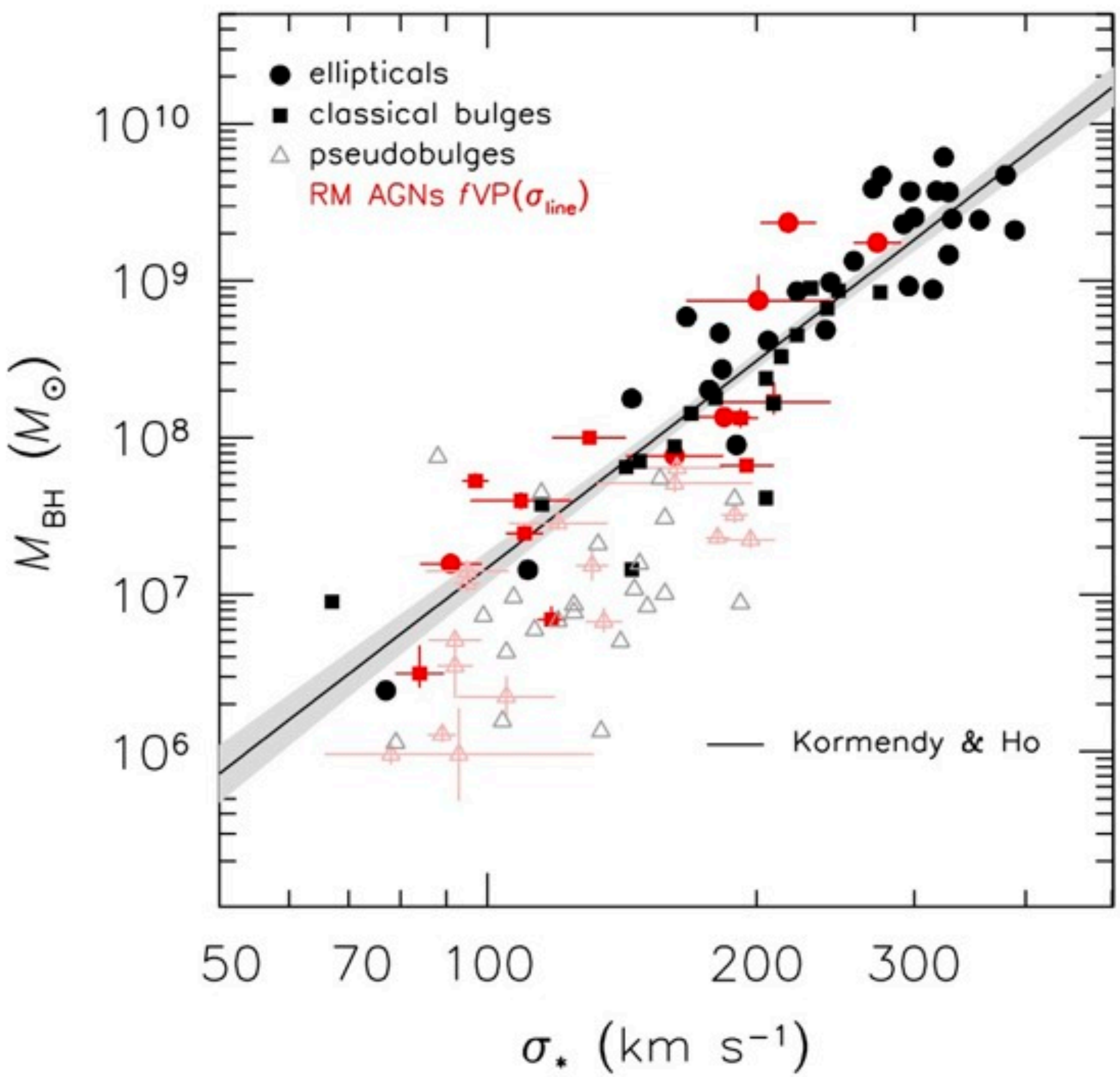


Virial BH Masses for Type 1 AGNs

$$M_{\text{virial}} = f\, RV^2/G$$

- f geometric fudge factor
- R BLR radius
- V BLR velocity dispersion

Ho & Kim (2014, 2015)



Virial BH Masses for Type 1 AGNs

$$M_{\rm virial} = f\, R V^2/G$$

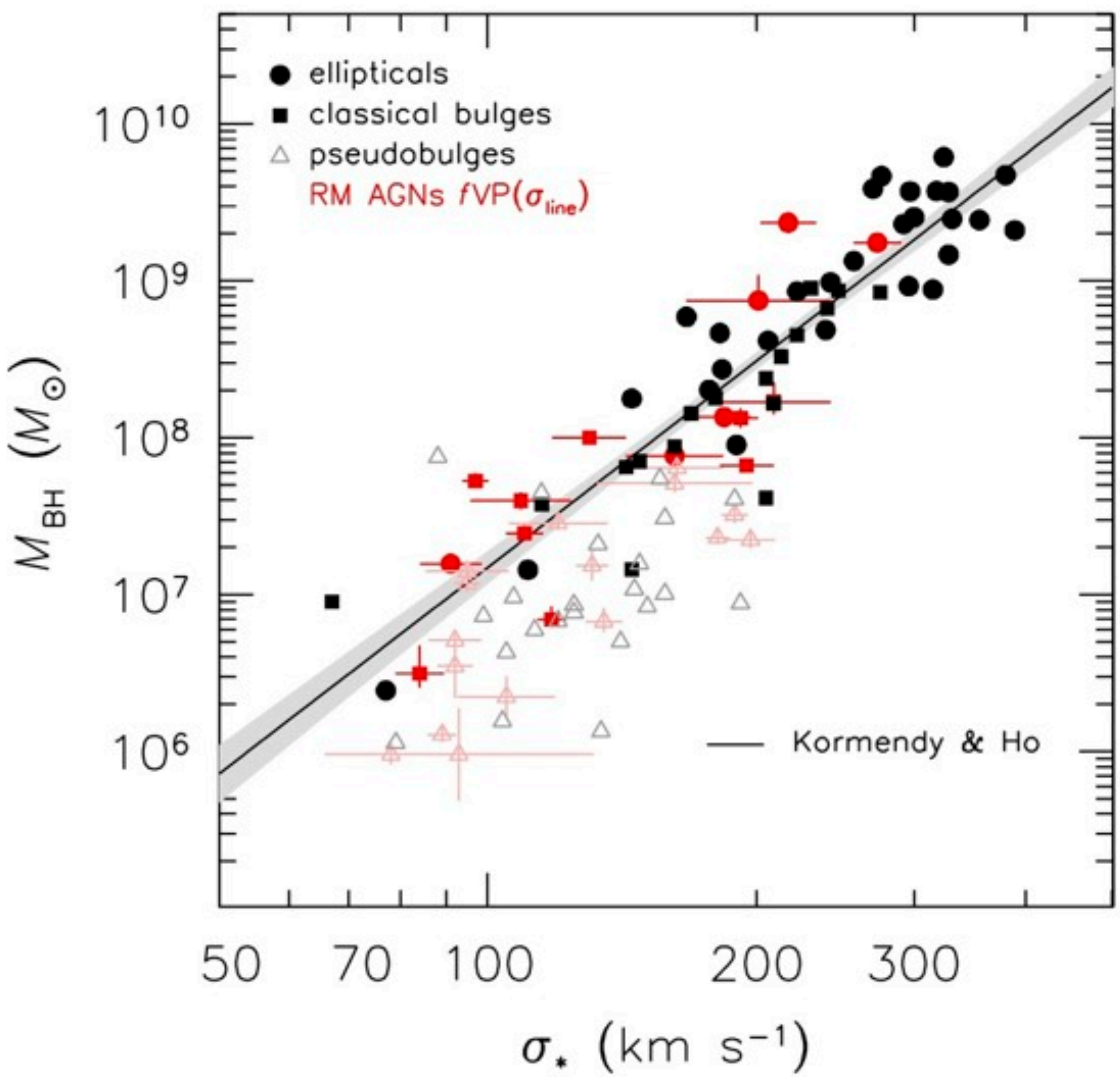
f geometric fudge factor

R BLR radius

V BLR velocity dispersion

Virial BH Masses for Type 1 AGNs

Ho & Kim (2014, 2015)



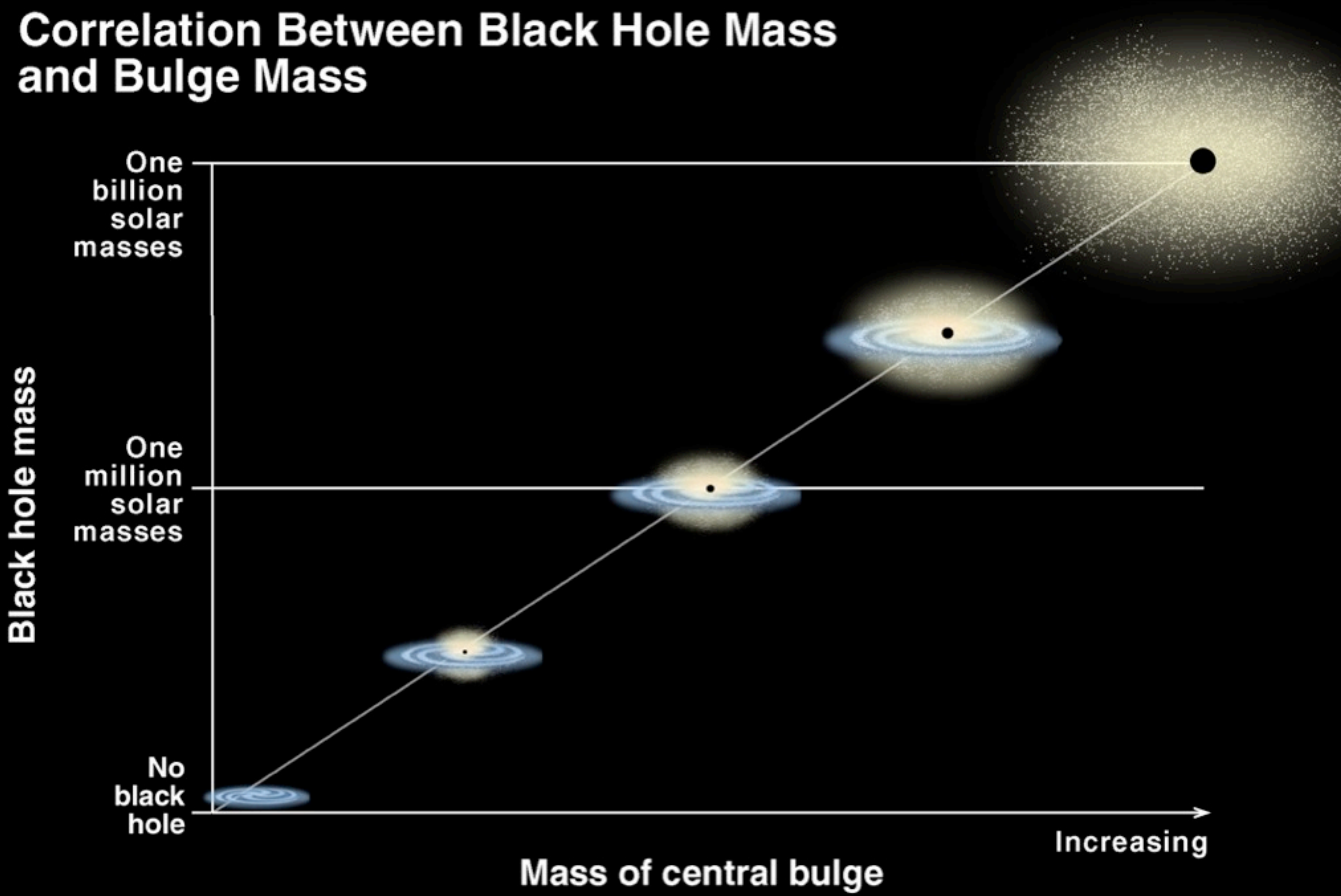
$$M_{\rm virial} = f\,RV^2/G$$

f geometric fudge factor

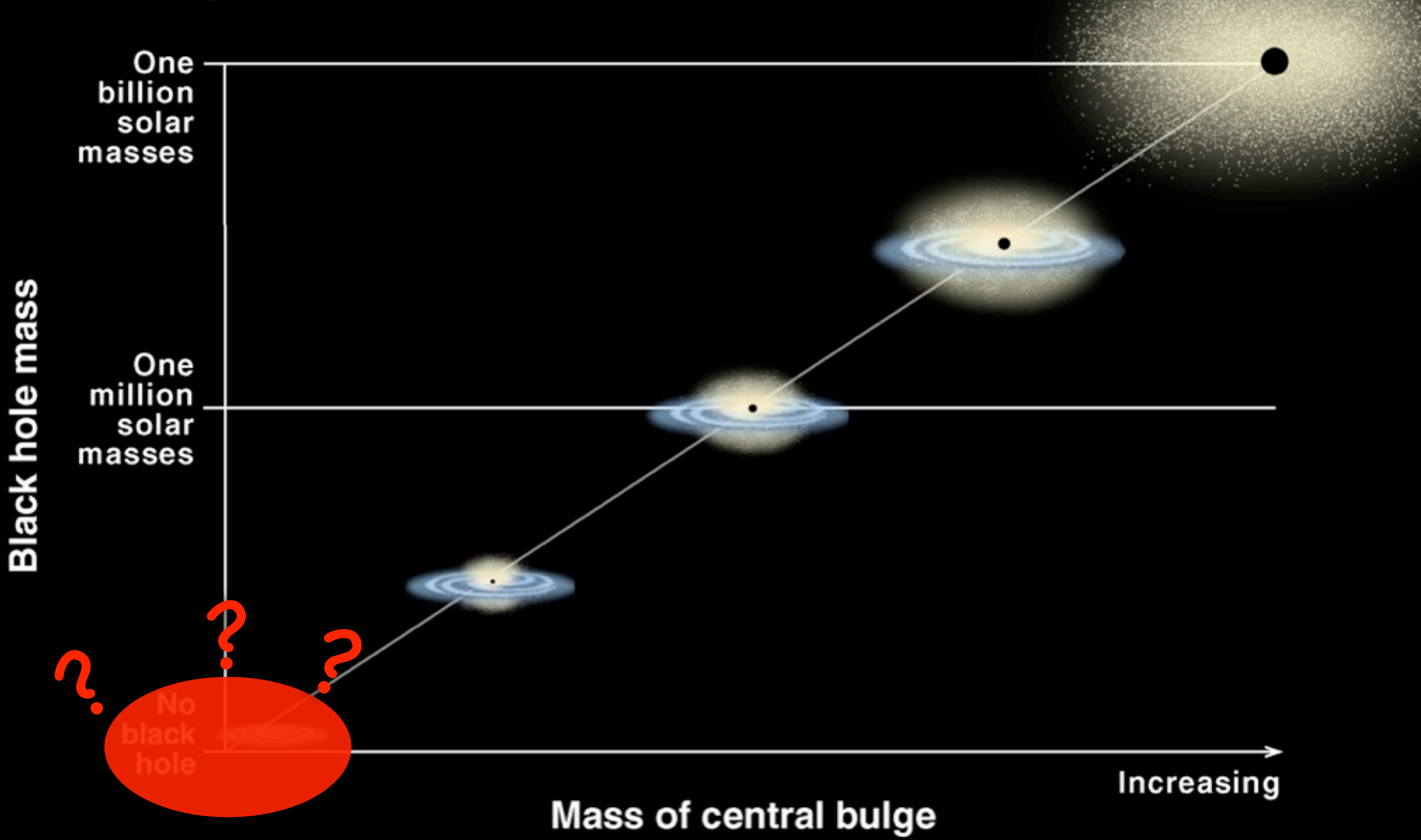
R BLR radius

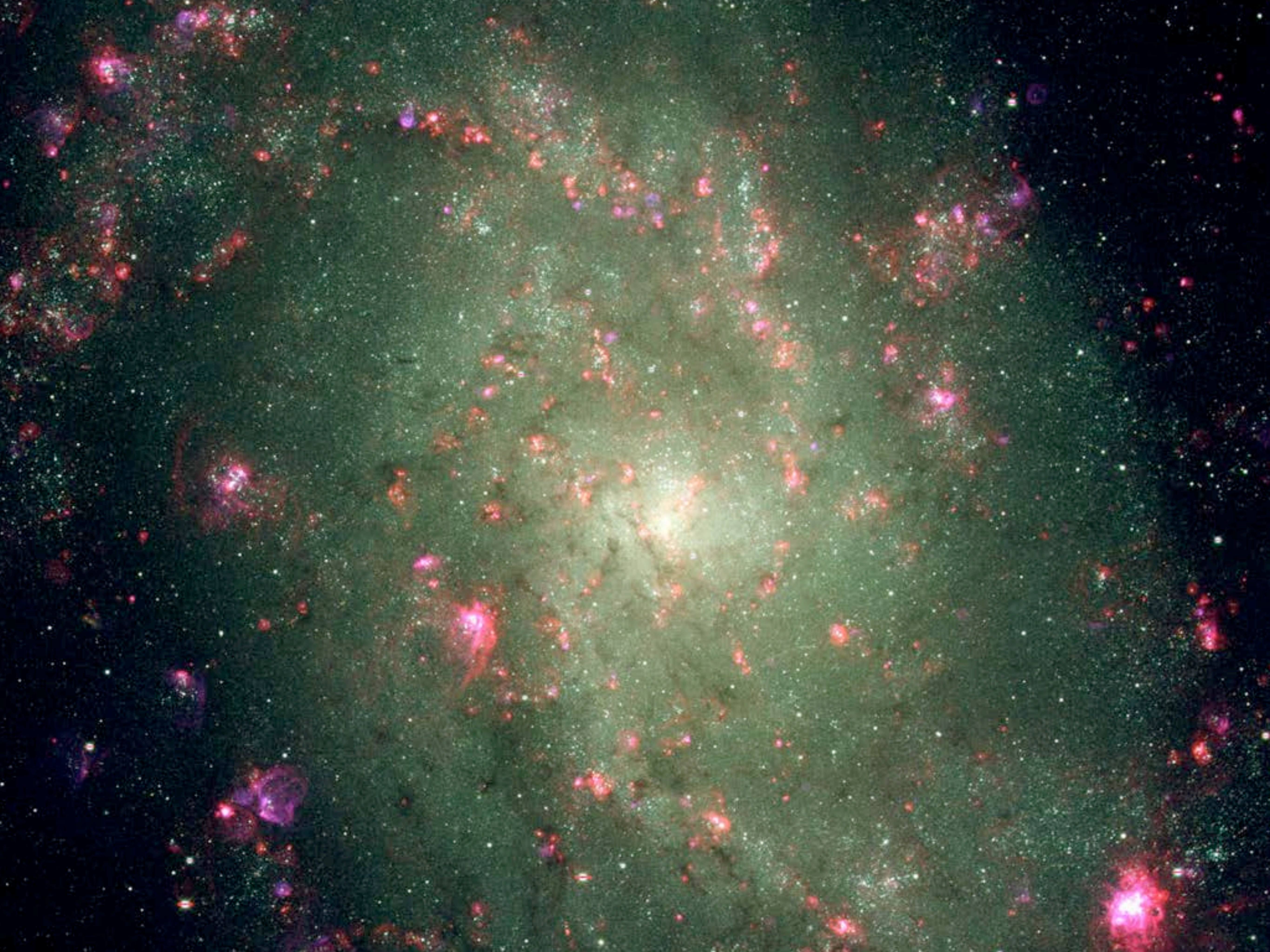
V BLR velocity dispersion

$M_\bullet$ can be estimated to an accuracy of ~0.3 − 0.5 dex for $z \approx 0 - 6$


Correlation Between Black Hole Mass and Bulge Mass
One billion solar masses
One million solar masses
No black hole
Black hole mass
Increasing
Mass of central bulge

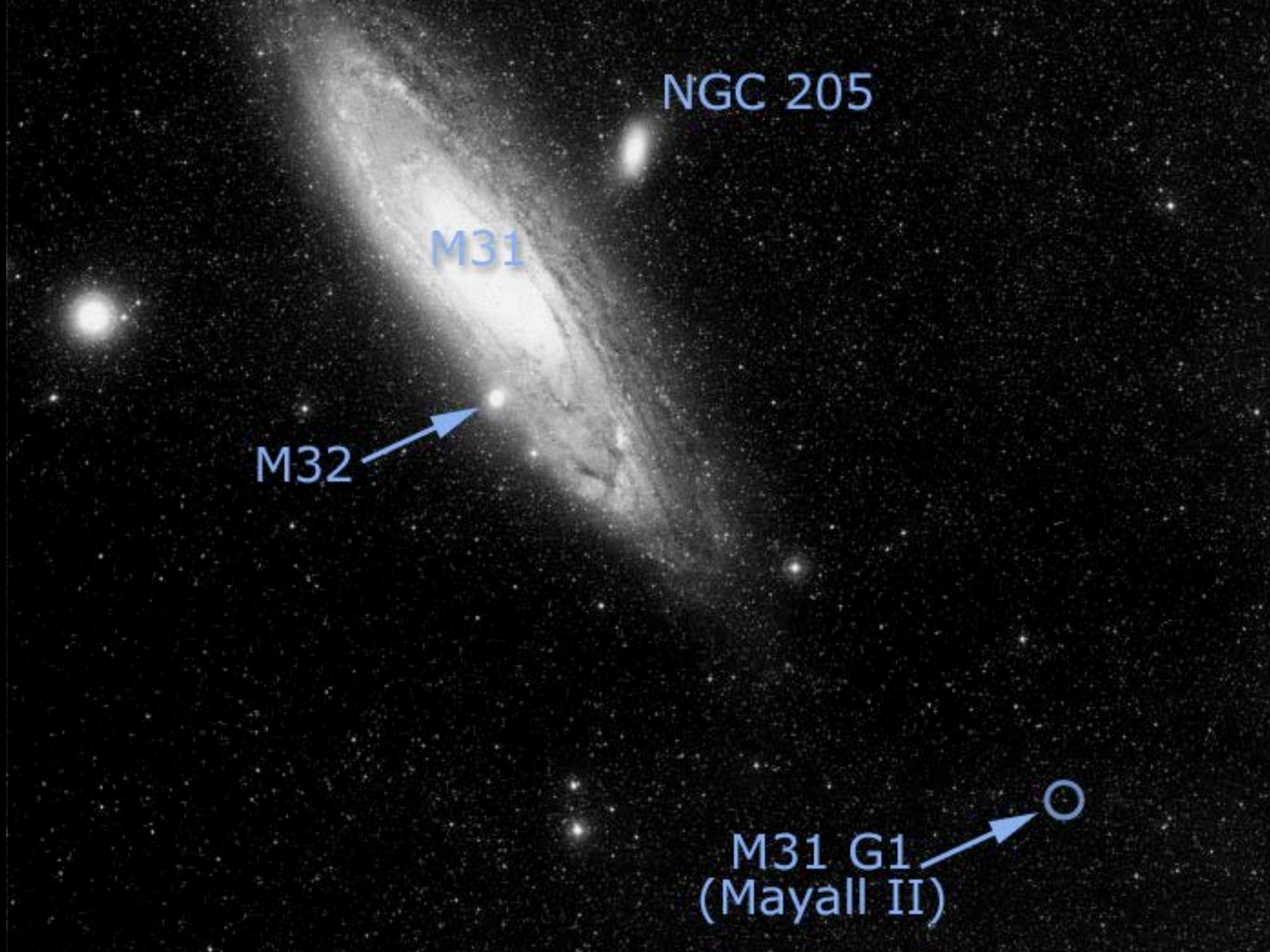
Correlation Between Black Hole Mass and Bulge Mass

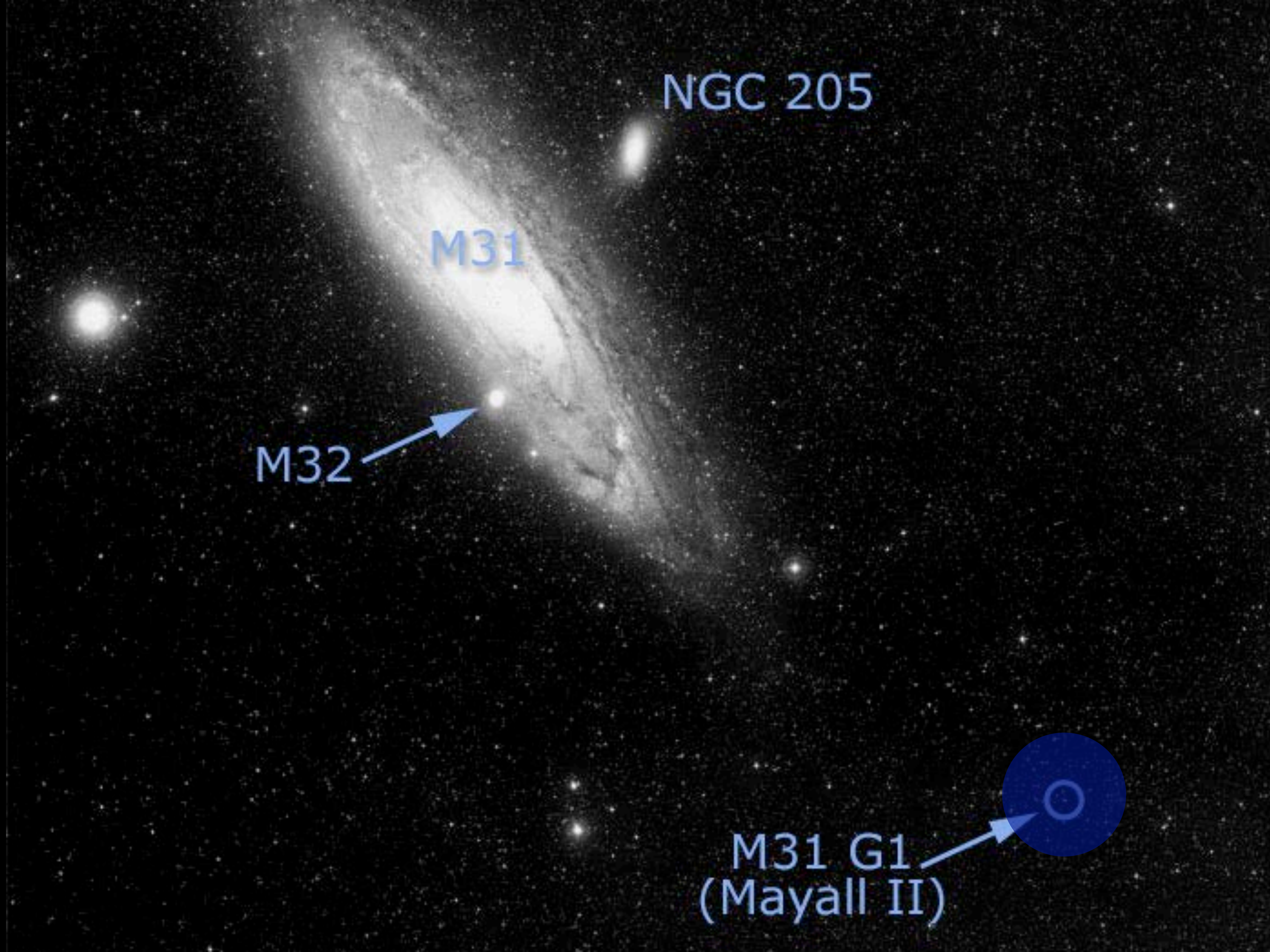





M33: $M_\bullet < 1500\ M_\odot$


M33: $M_\bullet < 1500\ M_\odot$

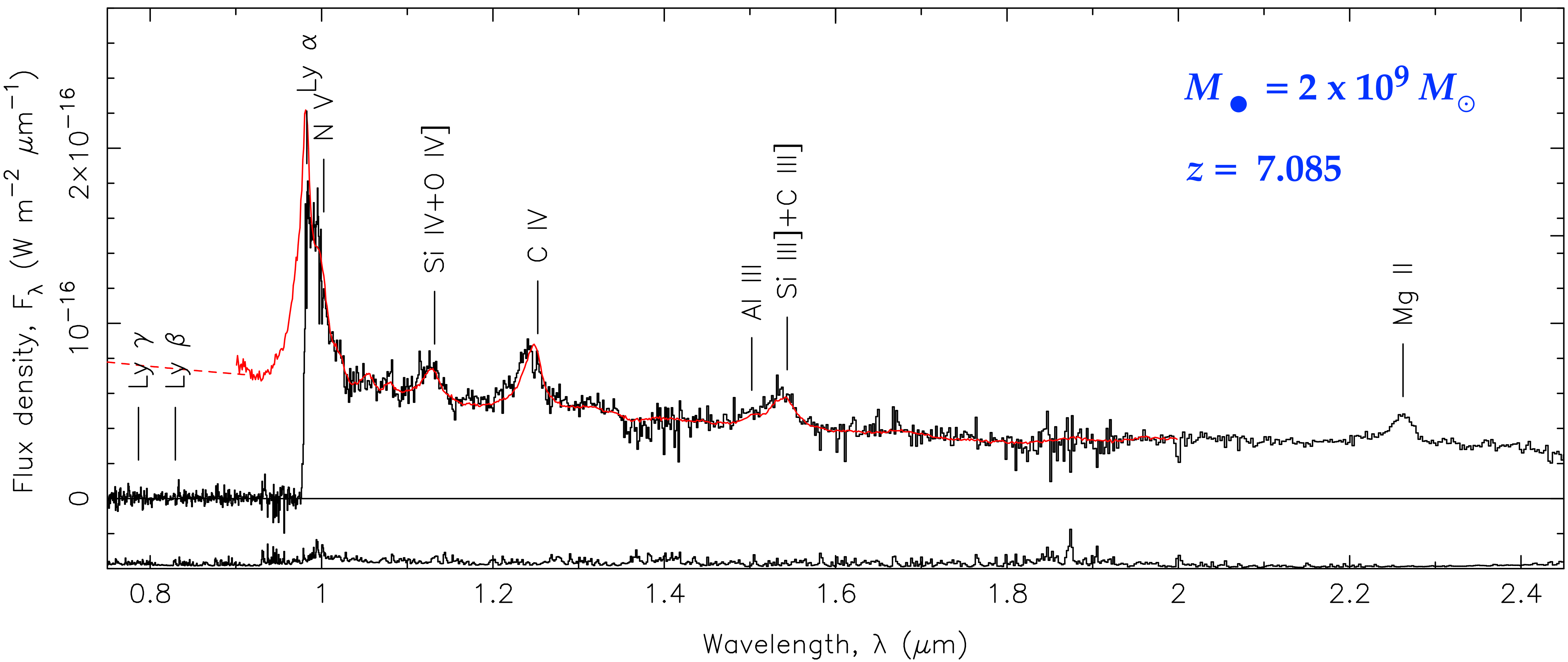

NGC 205
M31
M32
M31 G1
(Mayall II)

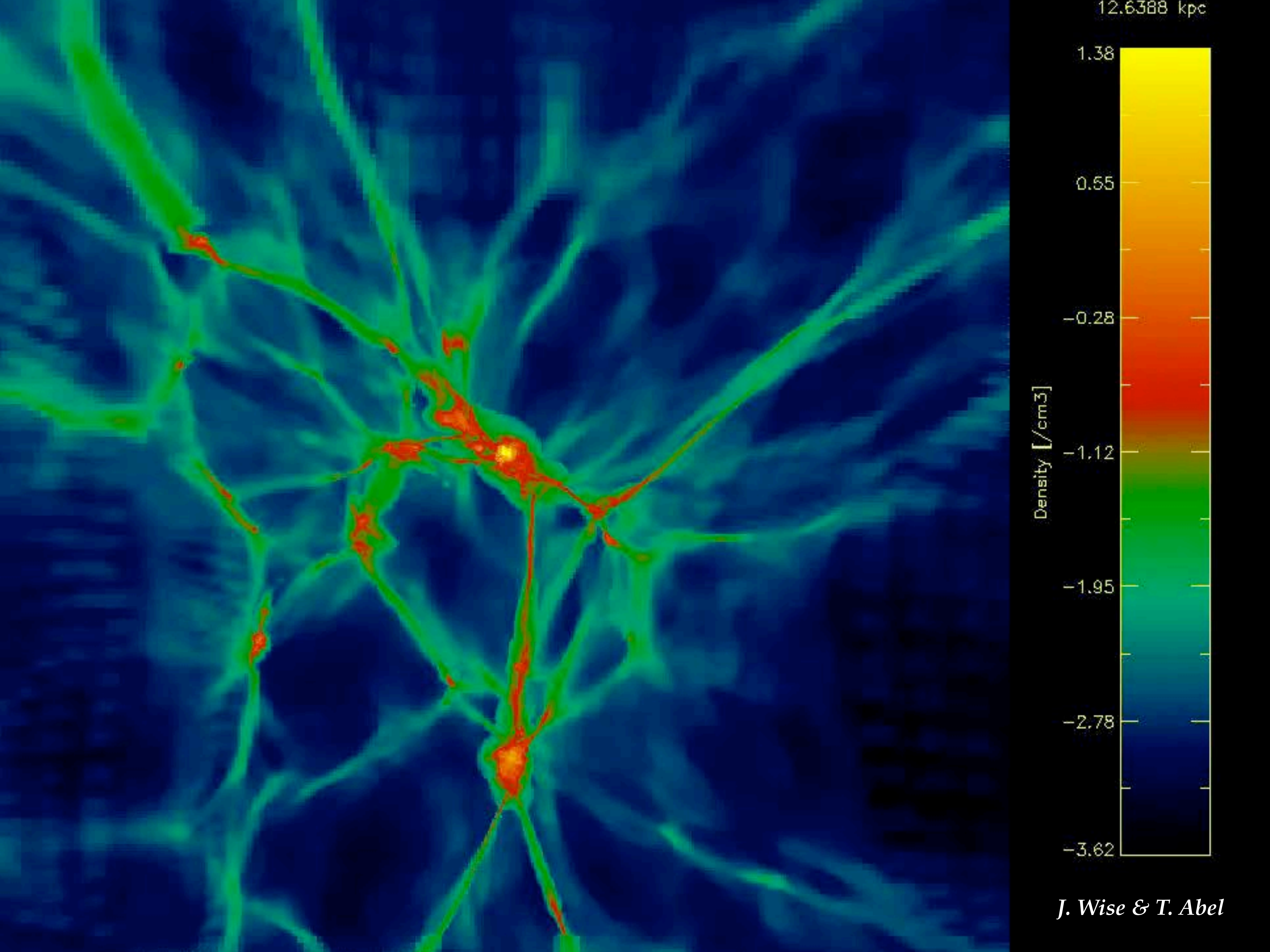

NGC 205
M31
M32
M31 G1
(Mayall II)

G1: $M_\bullet = 2 \times 10^4\ M_\odot$

Gebhardt, Ho & Rich (2005)

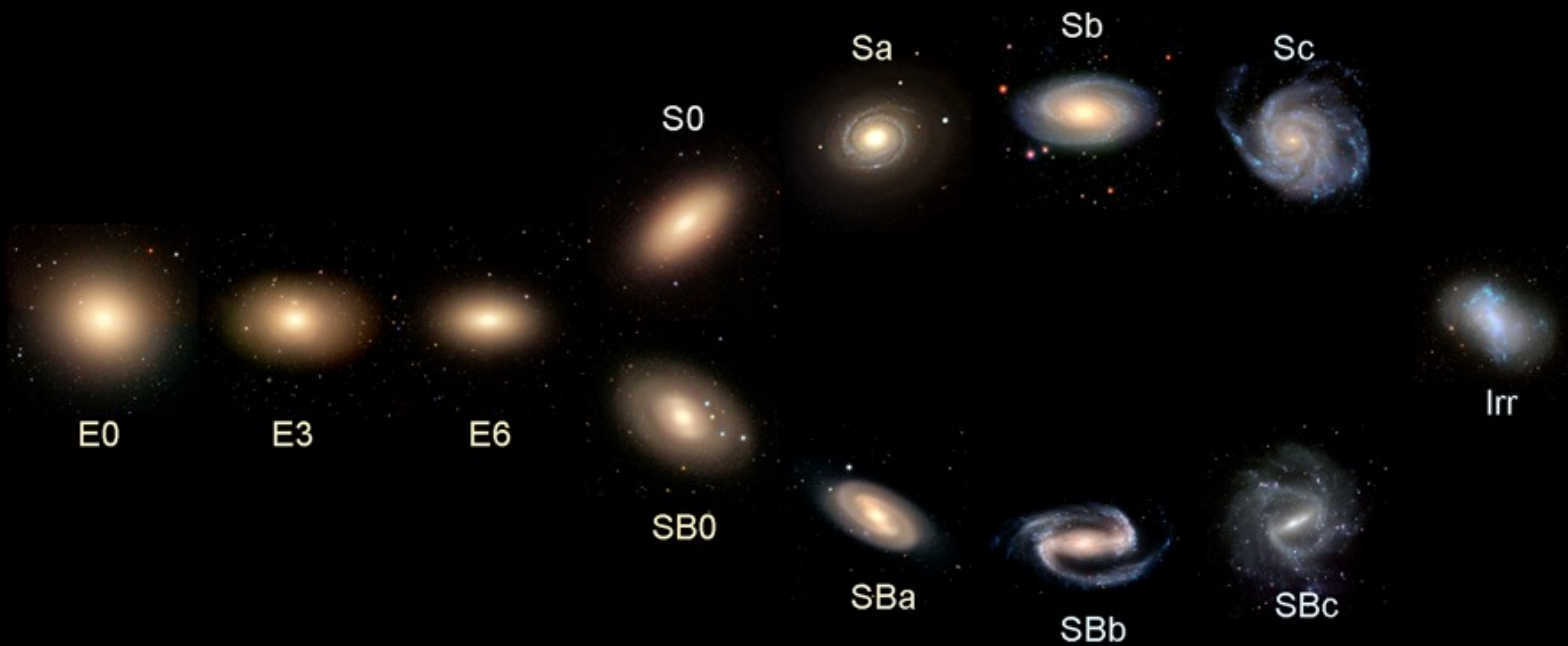
Mortlock et al. (2011)

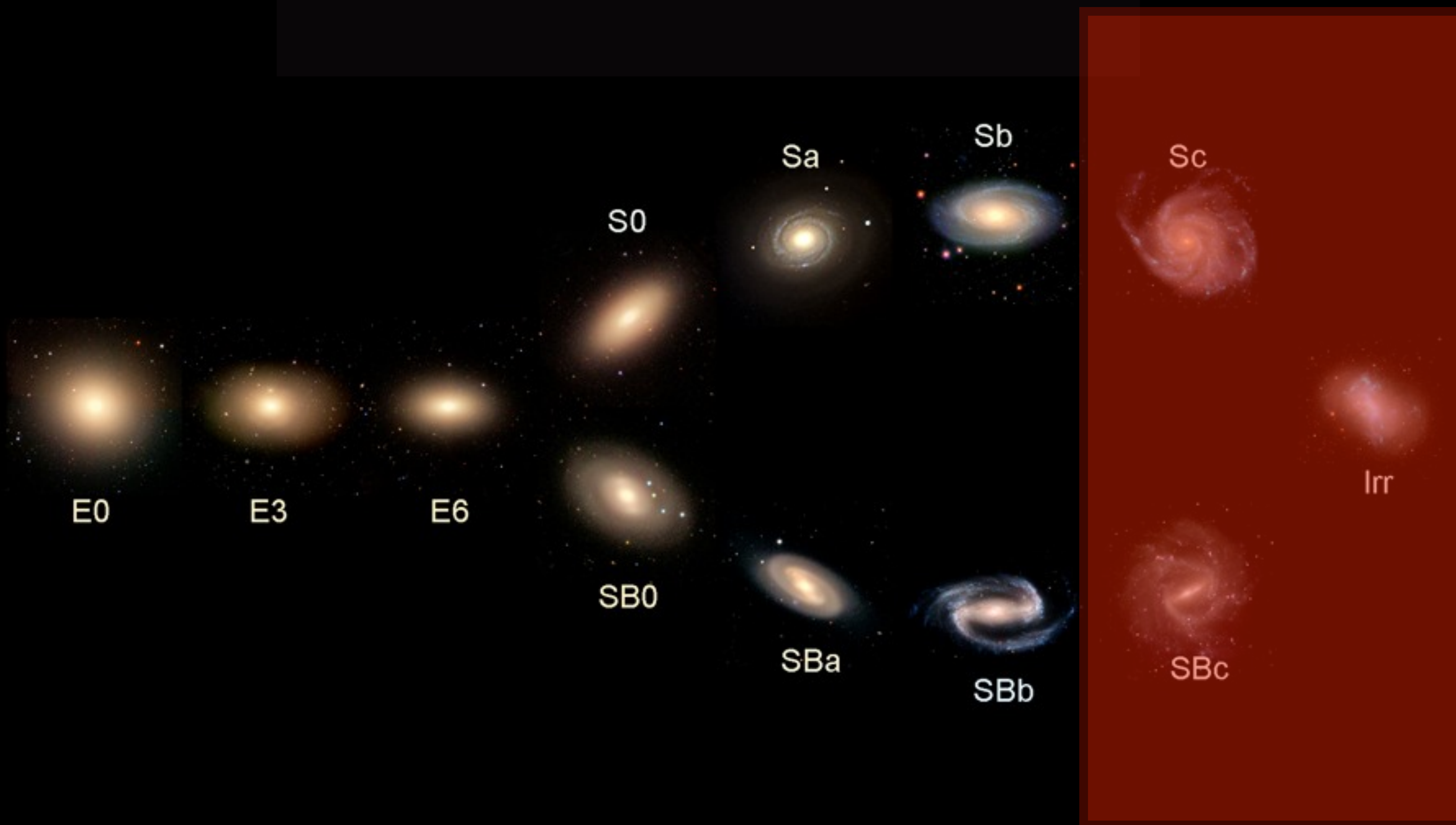




J. Wise & T. Abel

[redacted]

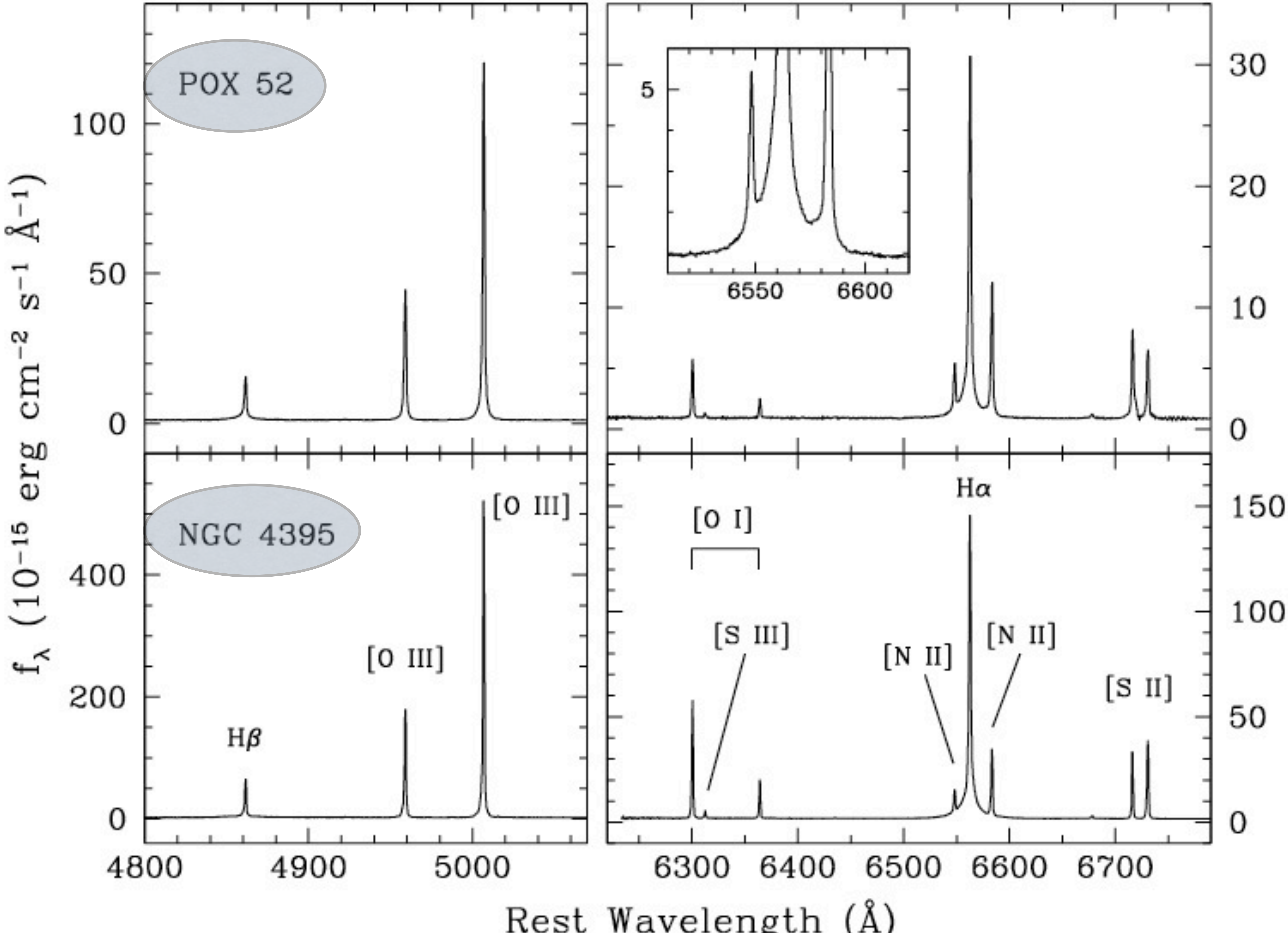




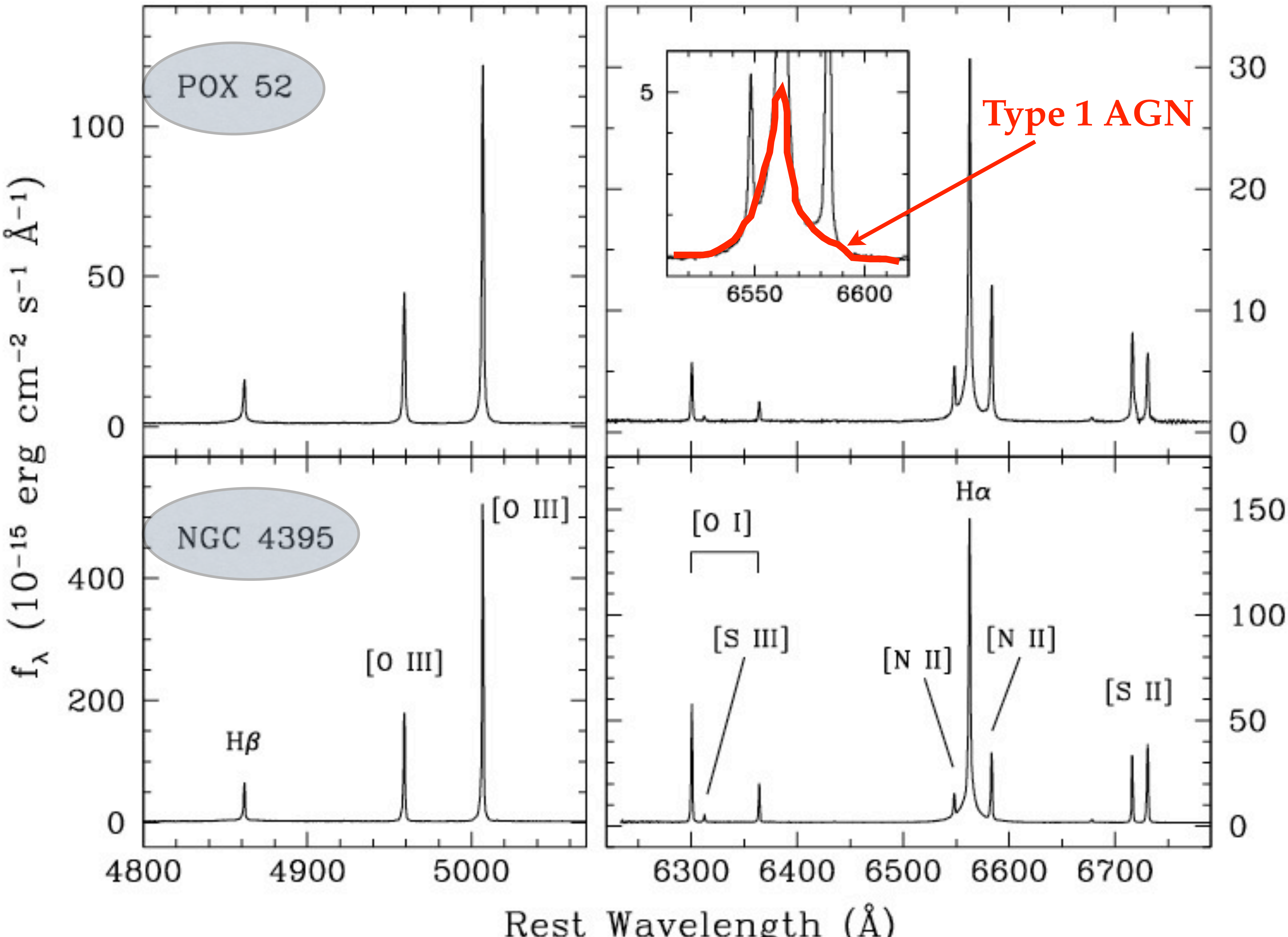
Sa
Sb
S0
Sc
E0
E3
E6
Irr
SB0
SBa
SBb
SBc

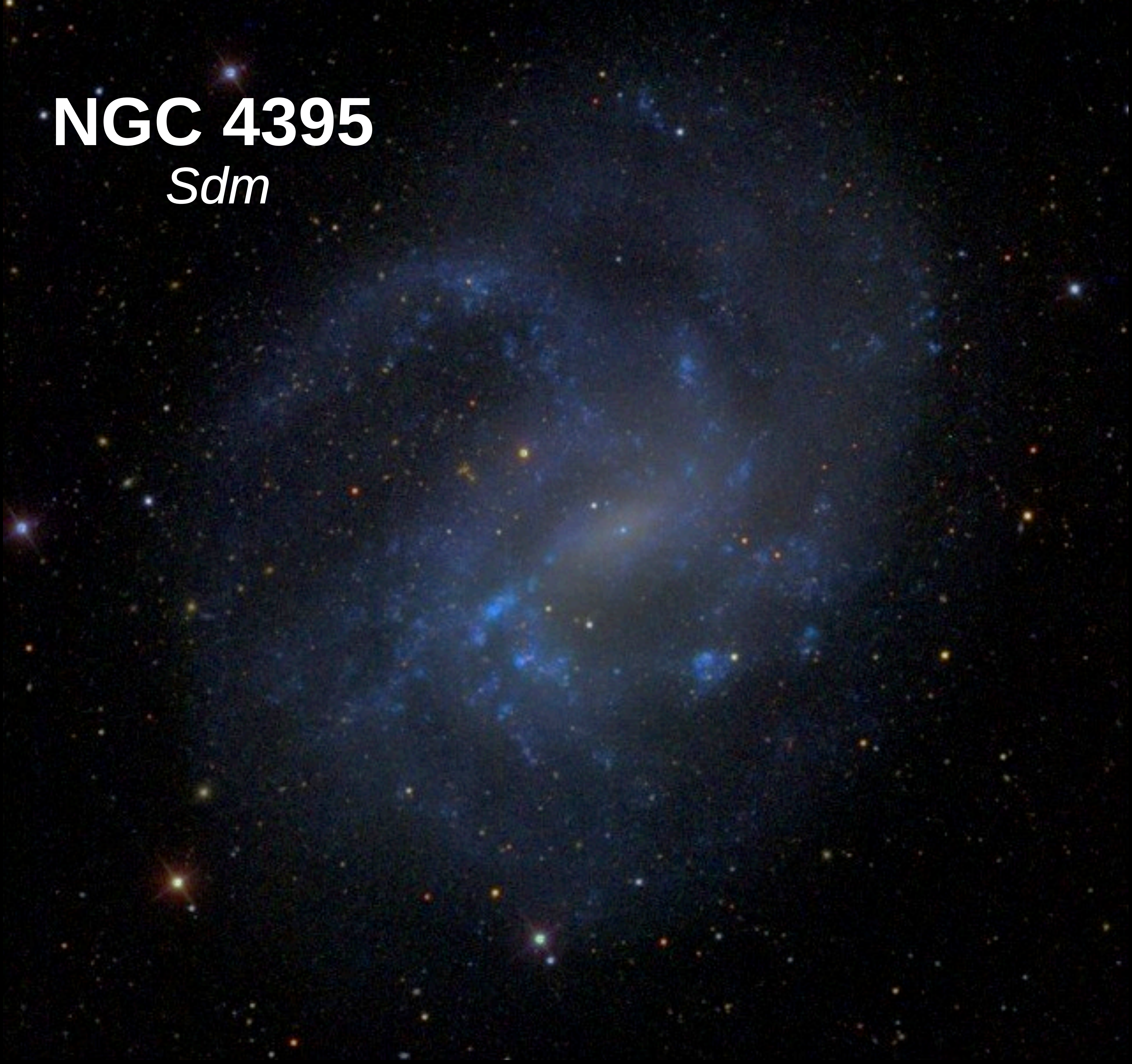

Are there mini-quasars in
these "simpler" galaxies?

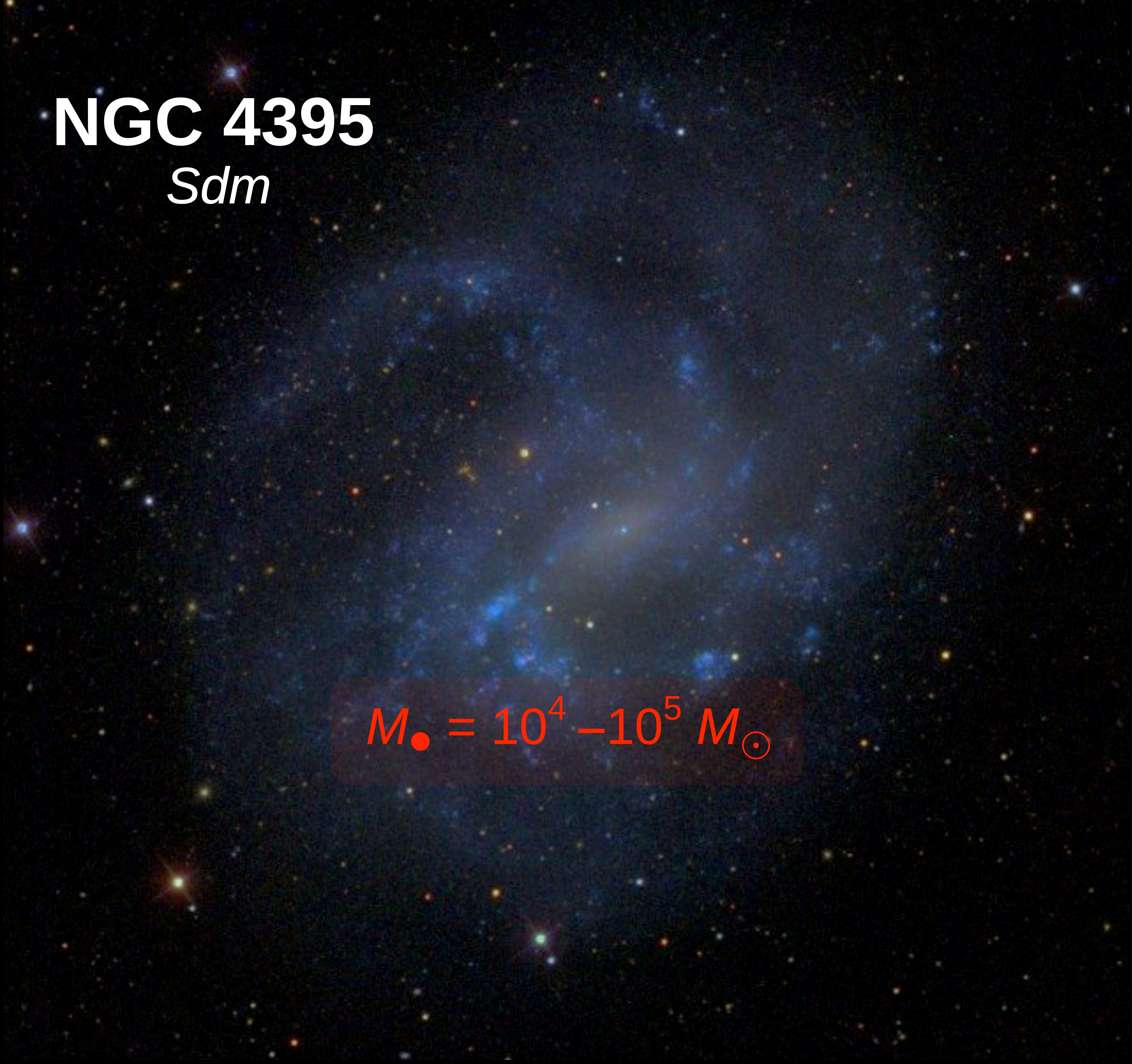
Filippenko & Ho (2003); Barth et al. (2004); Ho (2008, ARA&A)

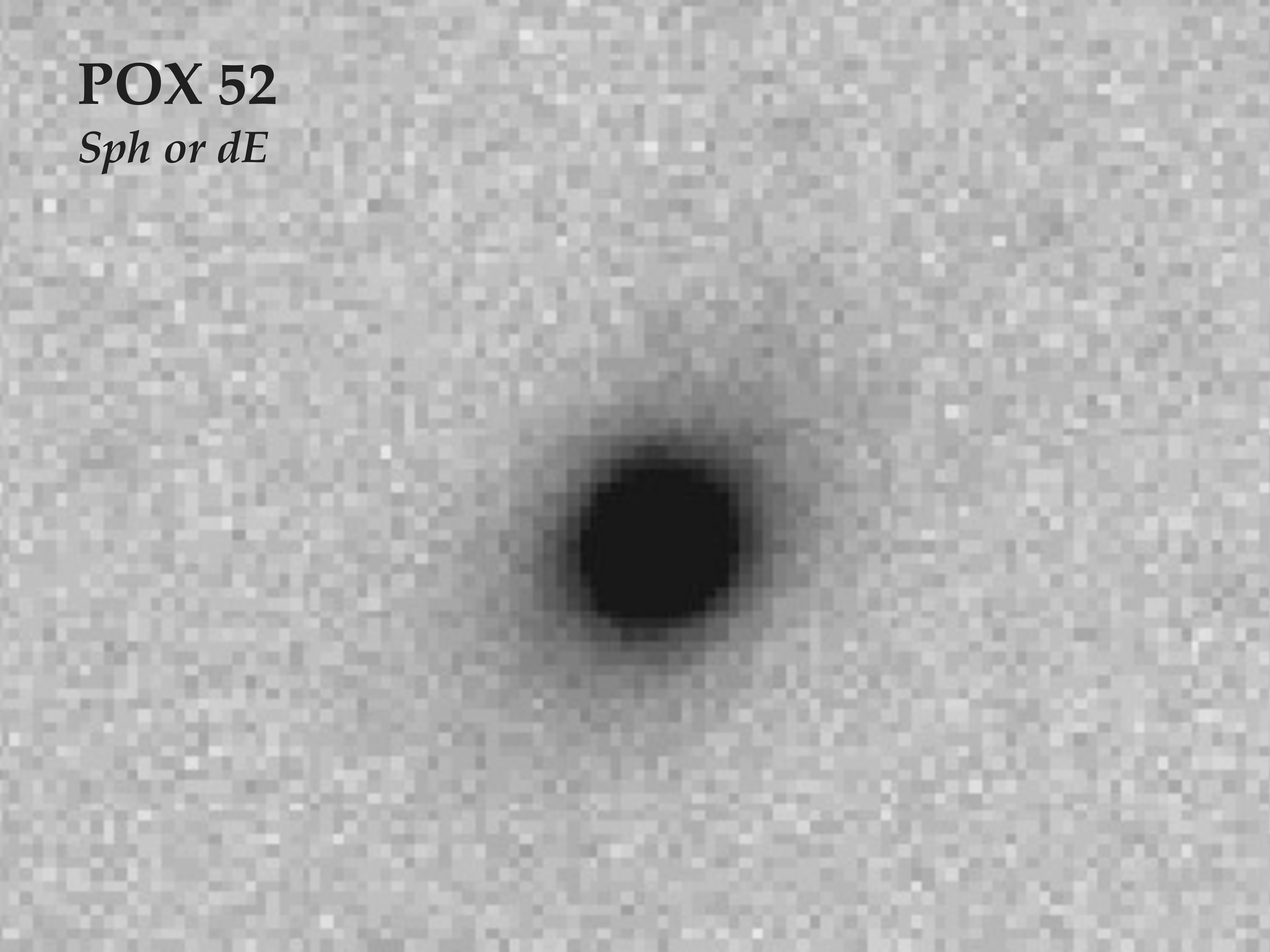


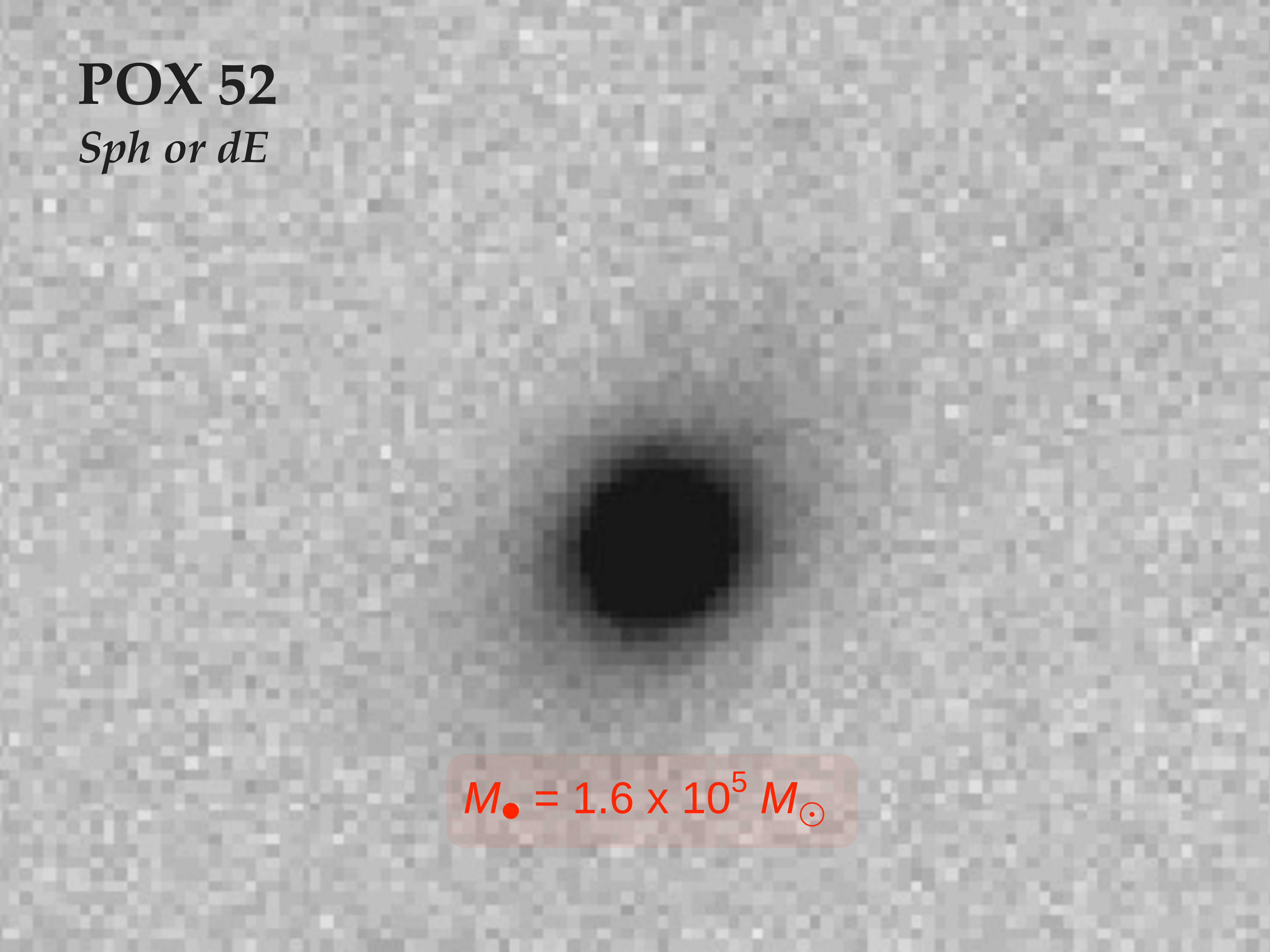
Filippenko & Ho (2003); Barth et al. (2004); Ho (2008, ARA&A)

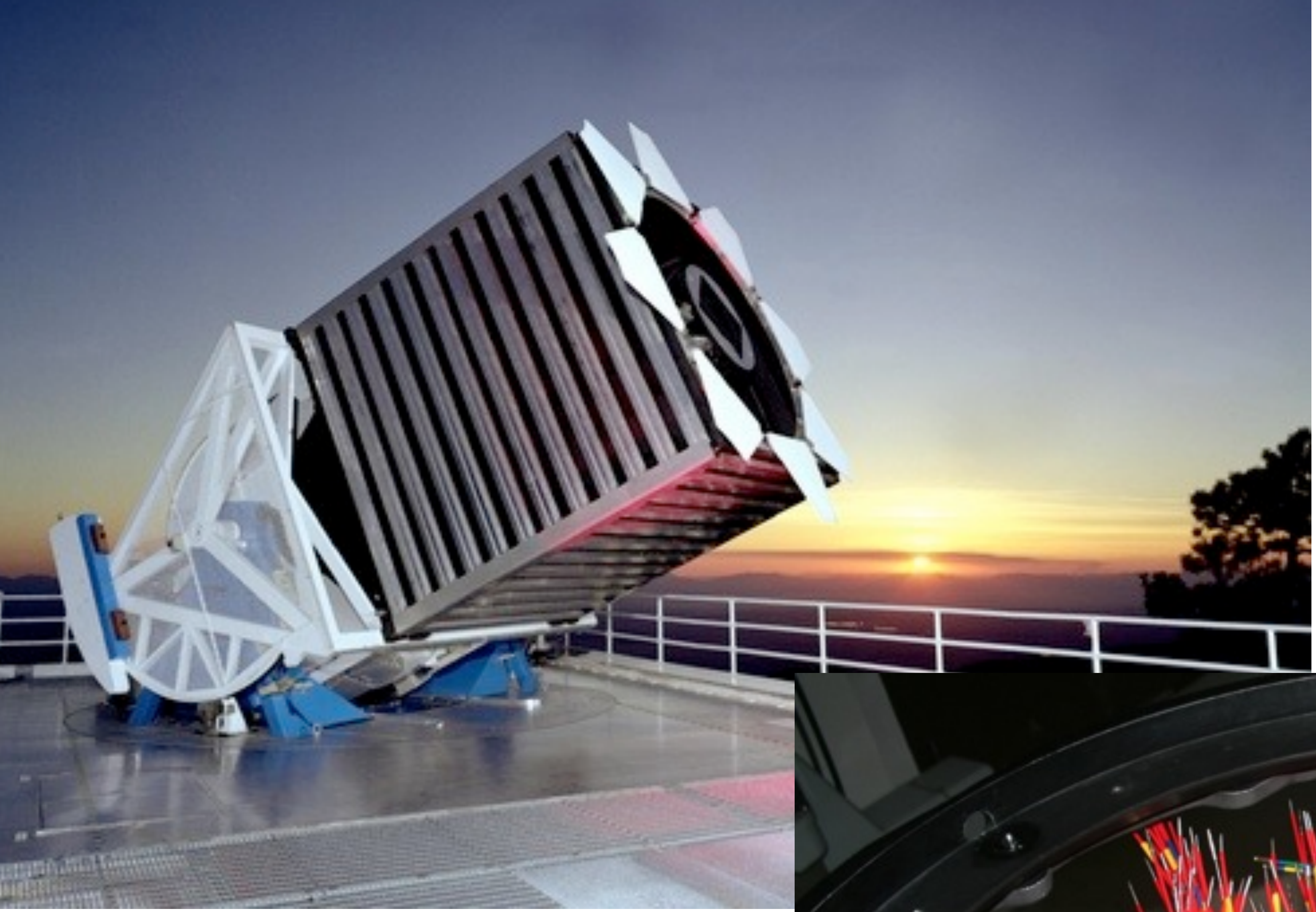


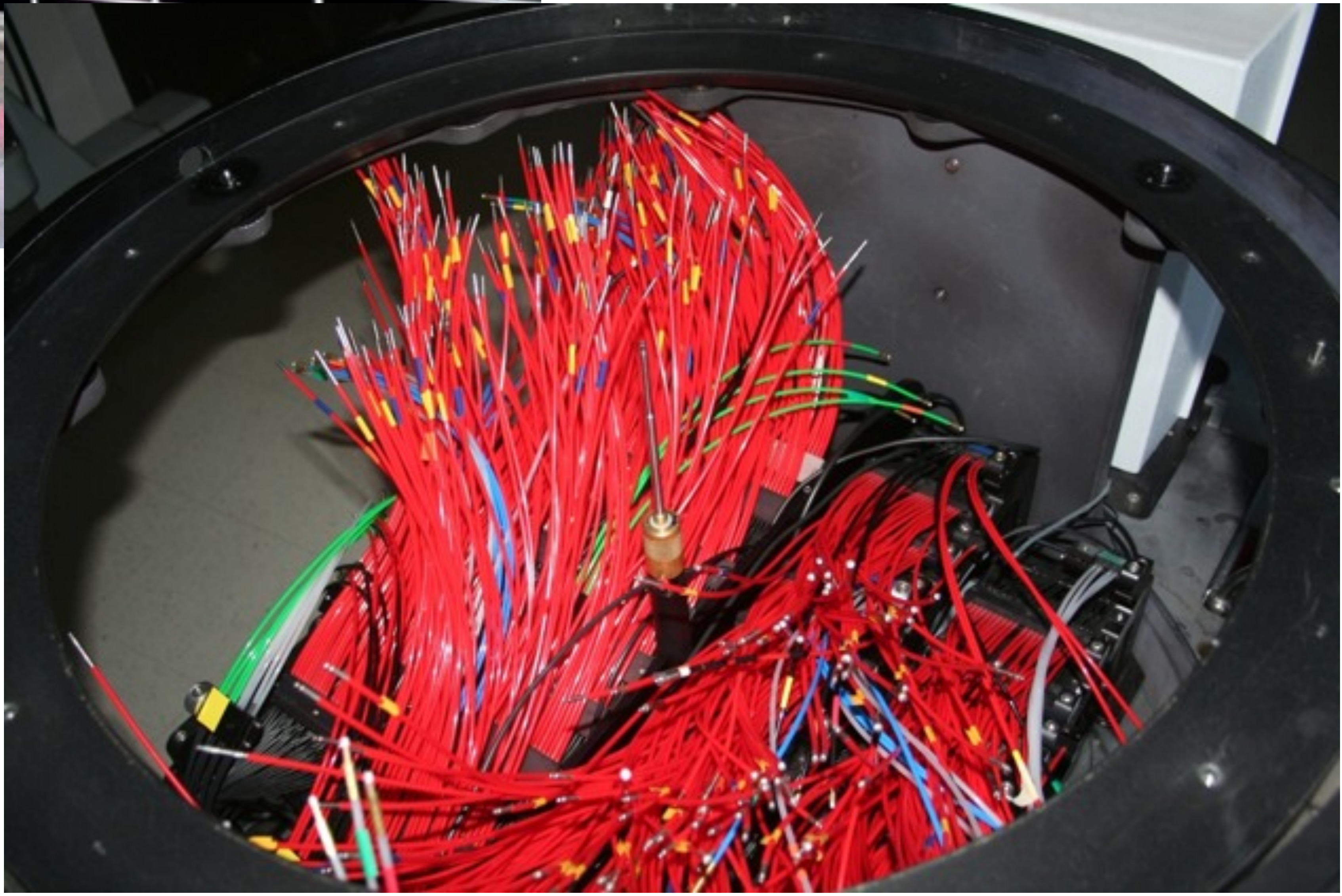

NGC 4395
Sdm


NGC 4395
Sdm
$M_\bullet = 10^4 – 10^5\ M_\odot$

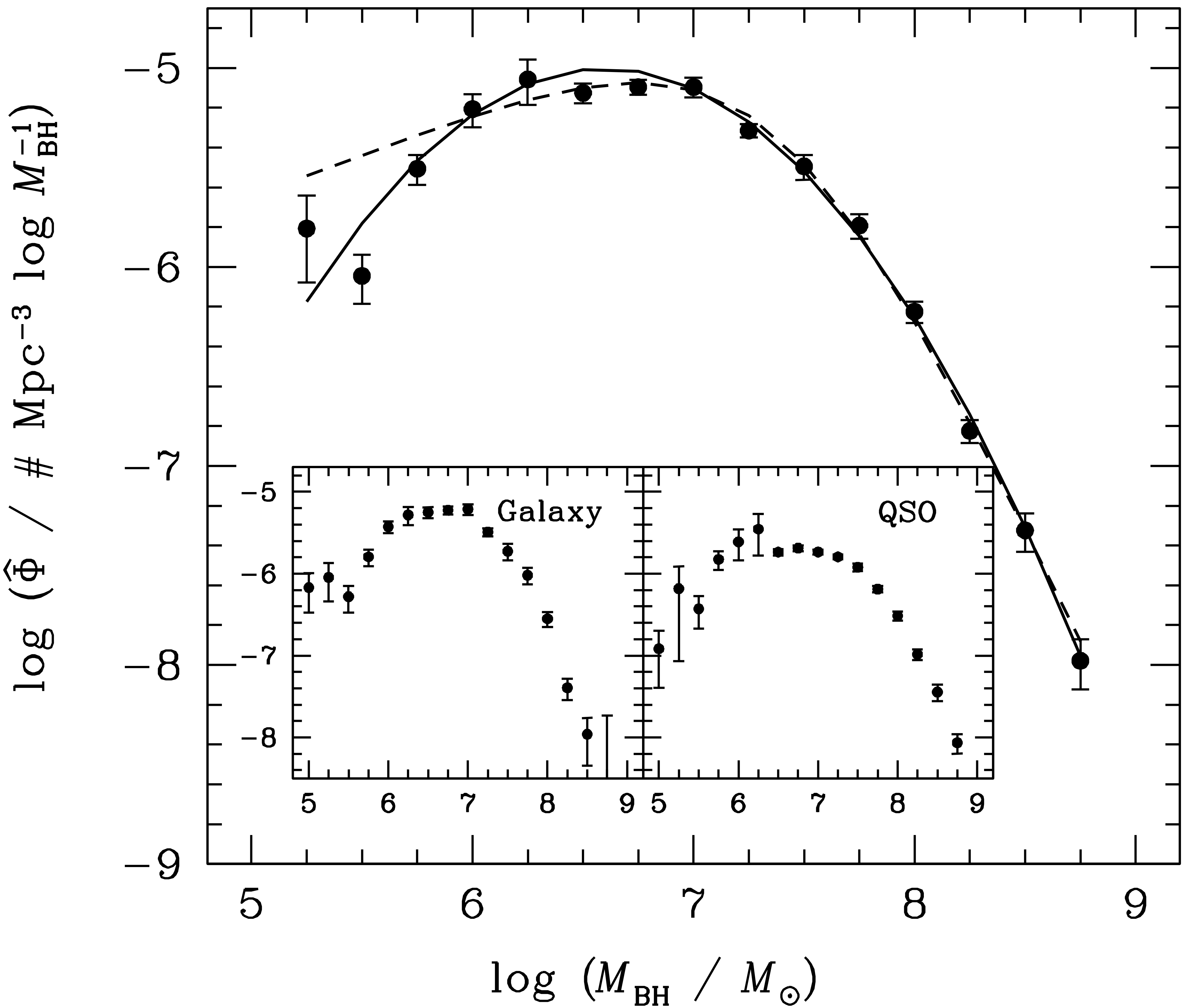

POX 52
Sph or dE

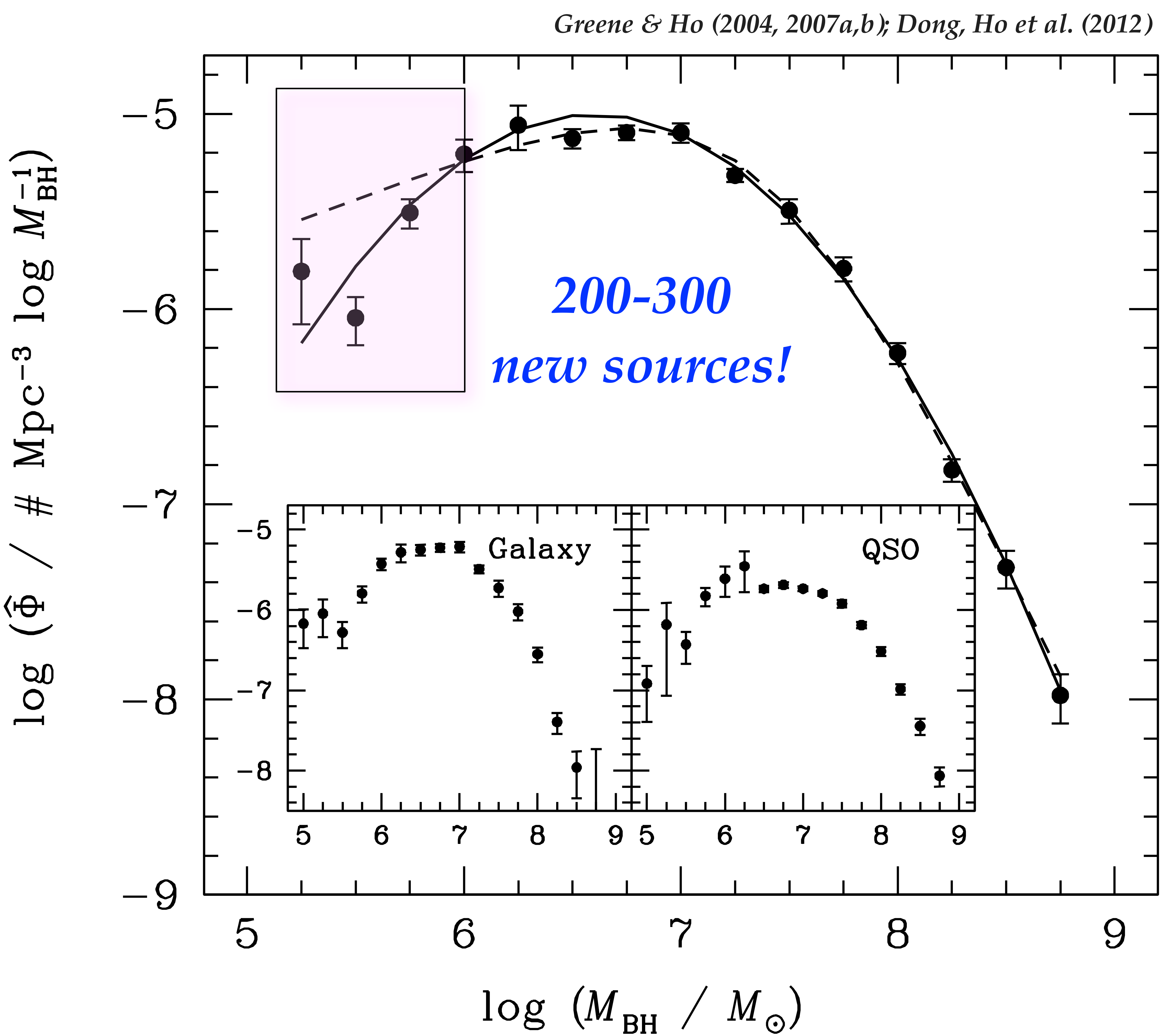

POX 52
Sph or dE
$M_\bullet = 1.6 \times 10^5 \, M_\odot$





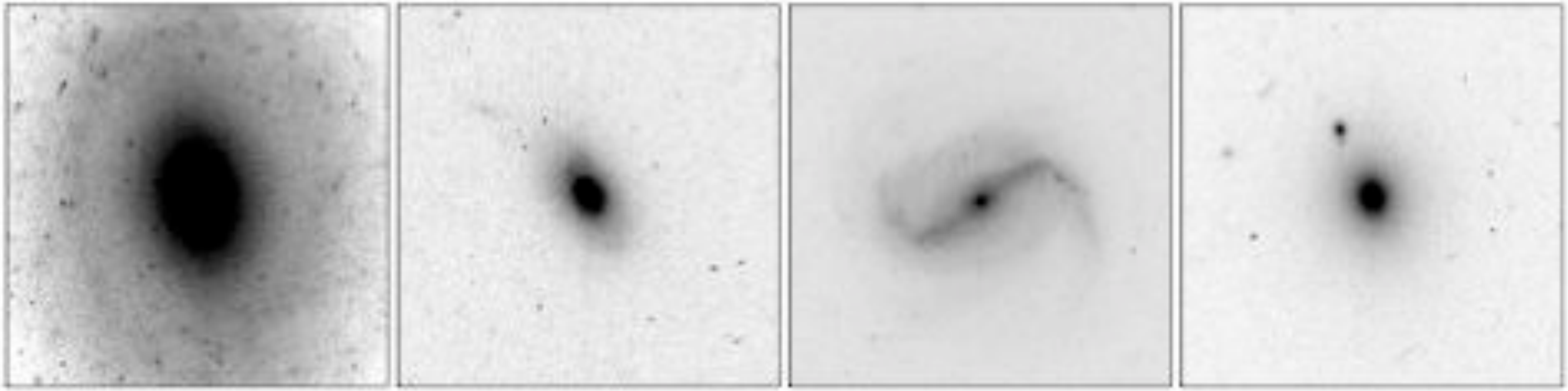
Greene & Ho (2004, 2007a,b); Dong, Ho et al. (2012)



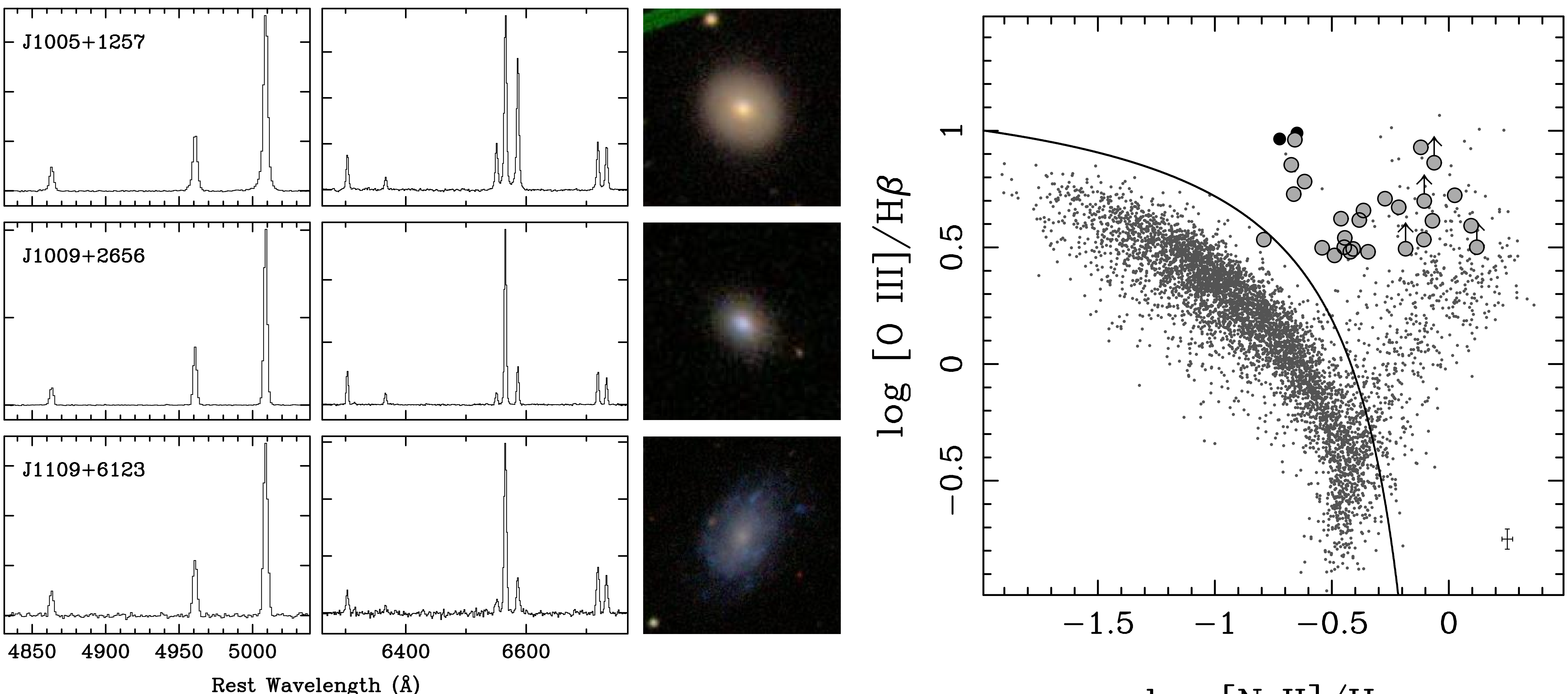

Greene & Ho (2004, 2007a,b); Dong, Ho et al. (2012)
200-300
new sources!
Galaxy
QSO
log ($\hat{\Phi}$ / # Mpc^{-3} log $M_{\rm BH}^{-1}$)
log ($M_{\rm BH}$ / $M_\odot$)

HST/ACS

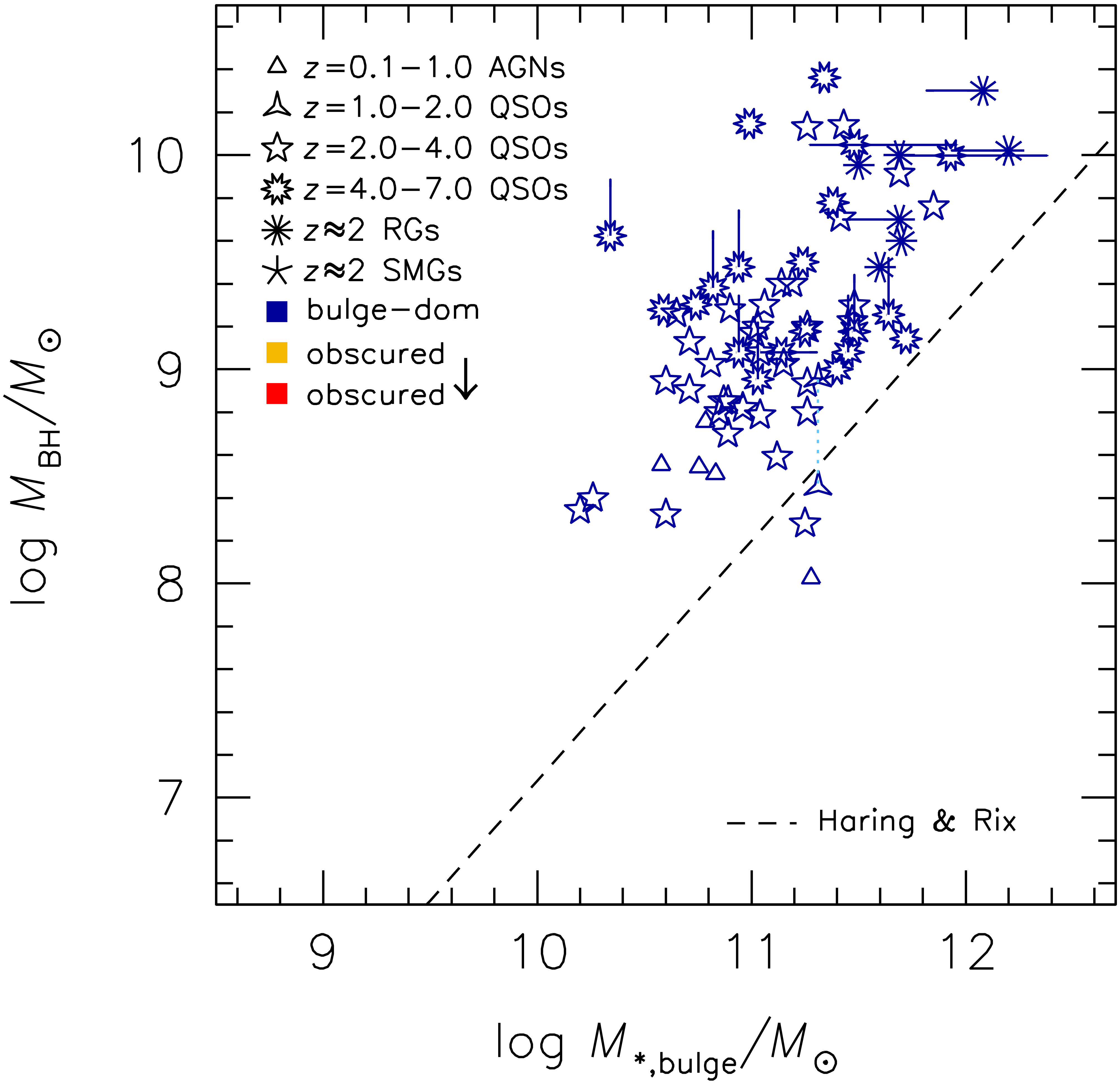
Greene, Ho & Barth (2008); Jiang, Greene & Ho (2011a, b)



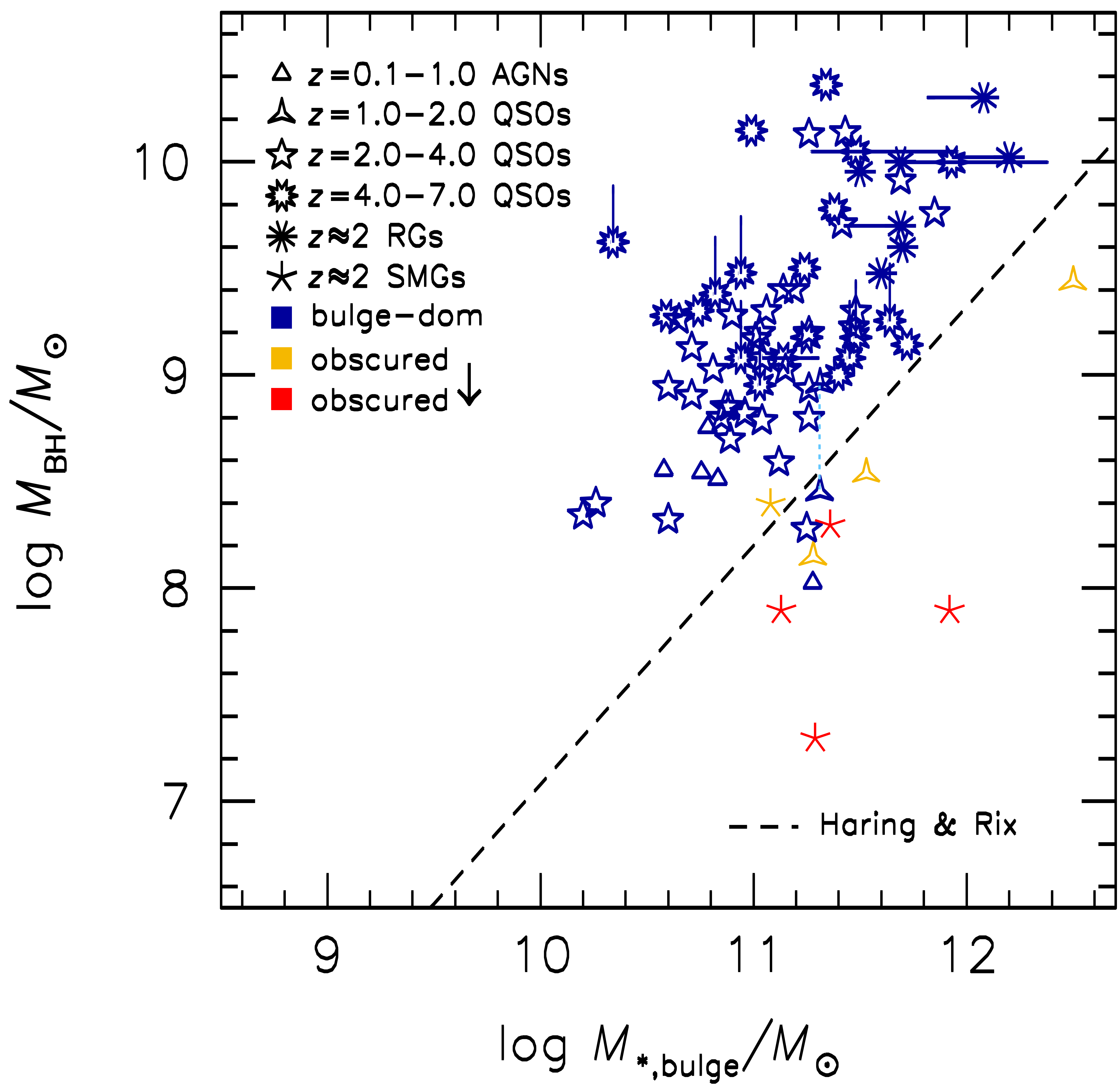
Moran et al. (2014); cf. Barth, Greene & Ho (2008)



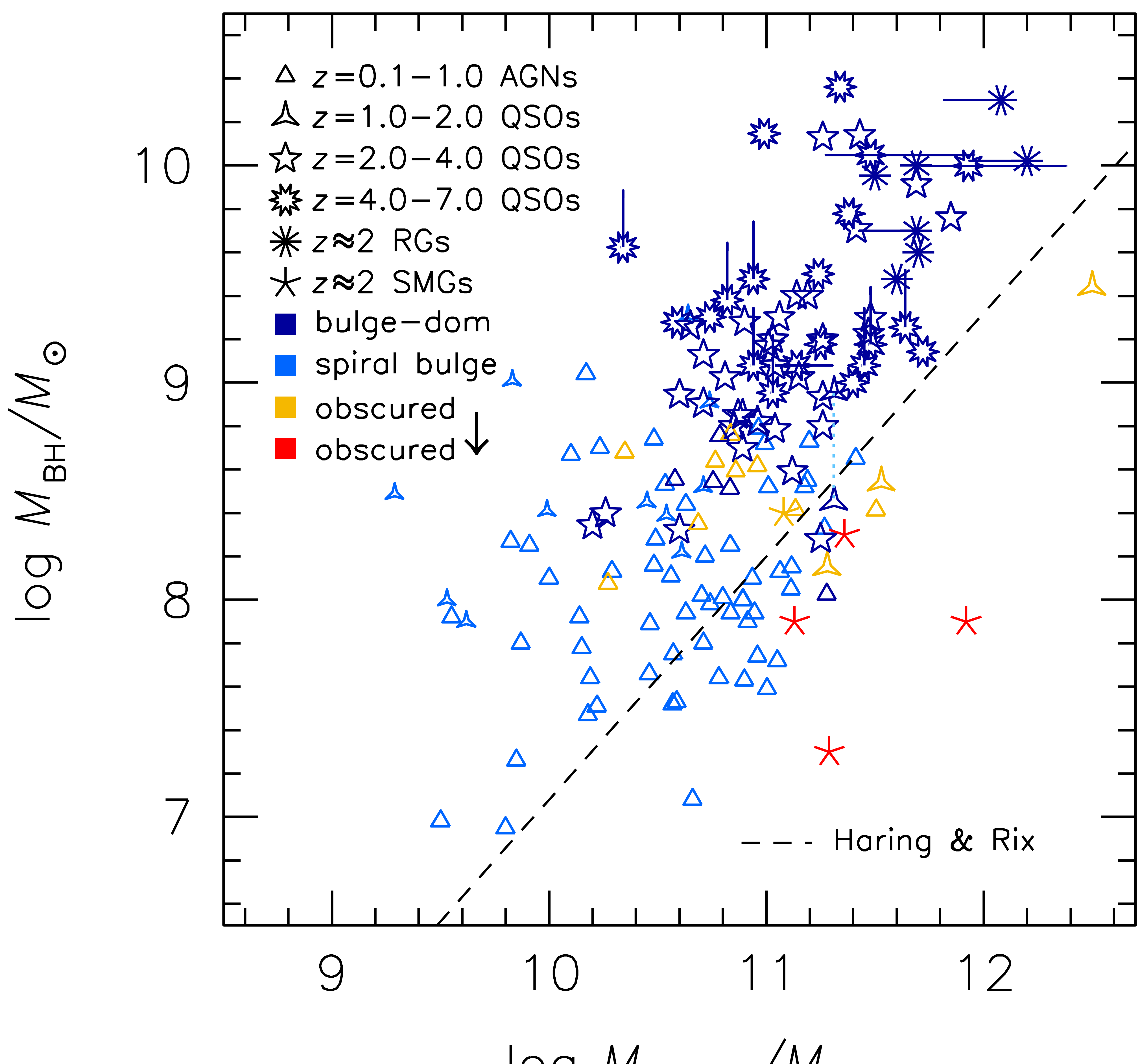
$M_g > -18$ mag $\quad$ $M_* = 10^8 - 10^9\ M_\odot$



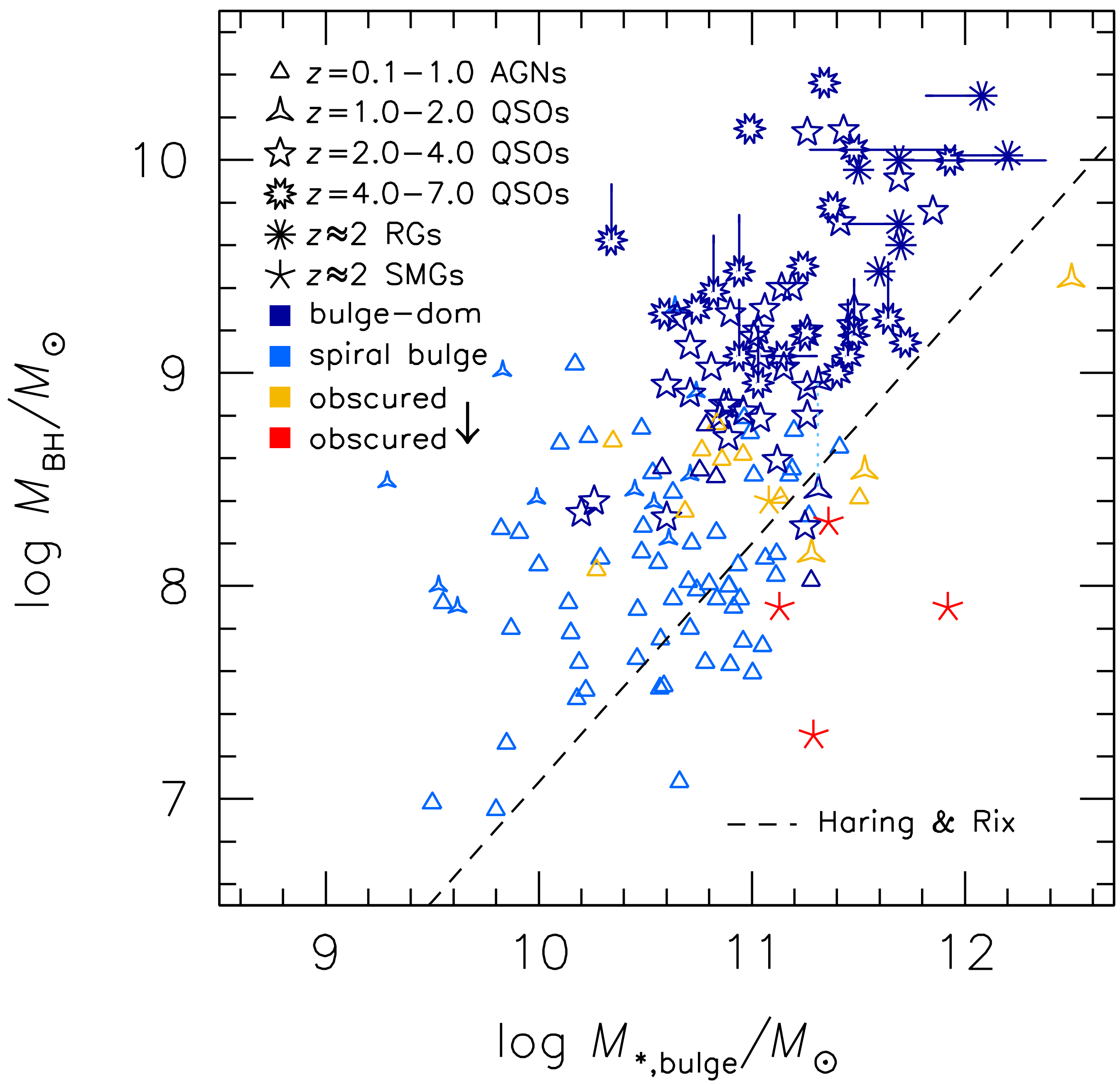
z=0.1−1.0 AGNs
z=1.0−2.0 QSOs
z=2.0−4.0 QSOs
z=4.0−7.0 QSOs
z≈2 RGs
z≈2 SMGs
bulge−dom
obscured
obscured ↓
Haring & Rix
log $M_{BH}/M_{\odot}$
log $M_{*,bulge}/M_{\odot}$
7
8
9
10
9
10
11
12



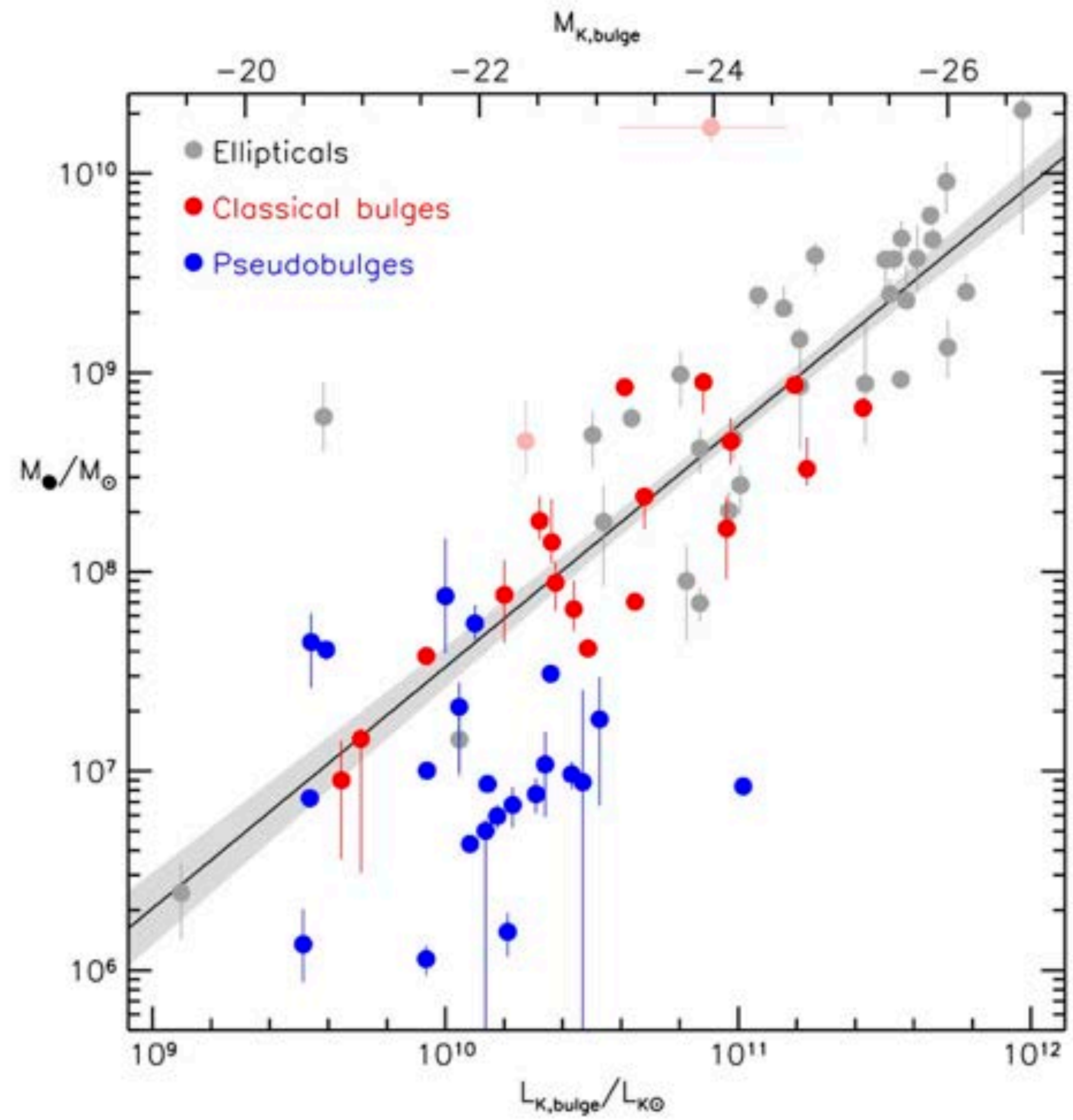
z=0.1−1.0 AGNs
z=1.0−2.0 QSOs
z=2.0−4.0 QSOs
z=4.0−7.0 QSOs
z≈2 RGs
z≈2 SMGs
bulge−dom
obscured
obscured
Haring & Rix
log $M_{BH}/M_{\odot}$
log $M_{*,bulge}/M_{\odot}$
7
8
9
10
9
10
11
12



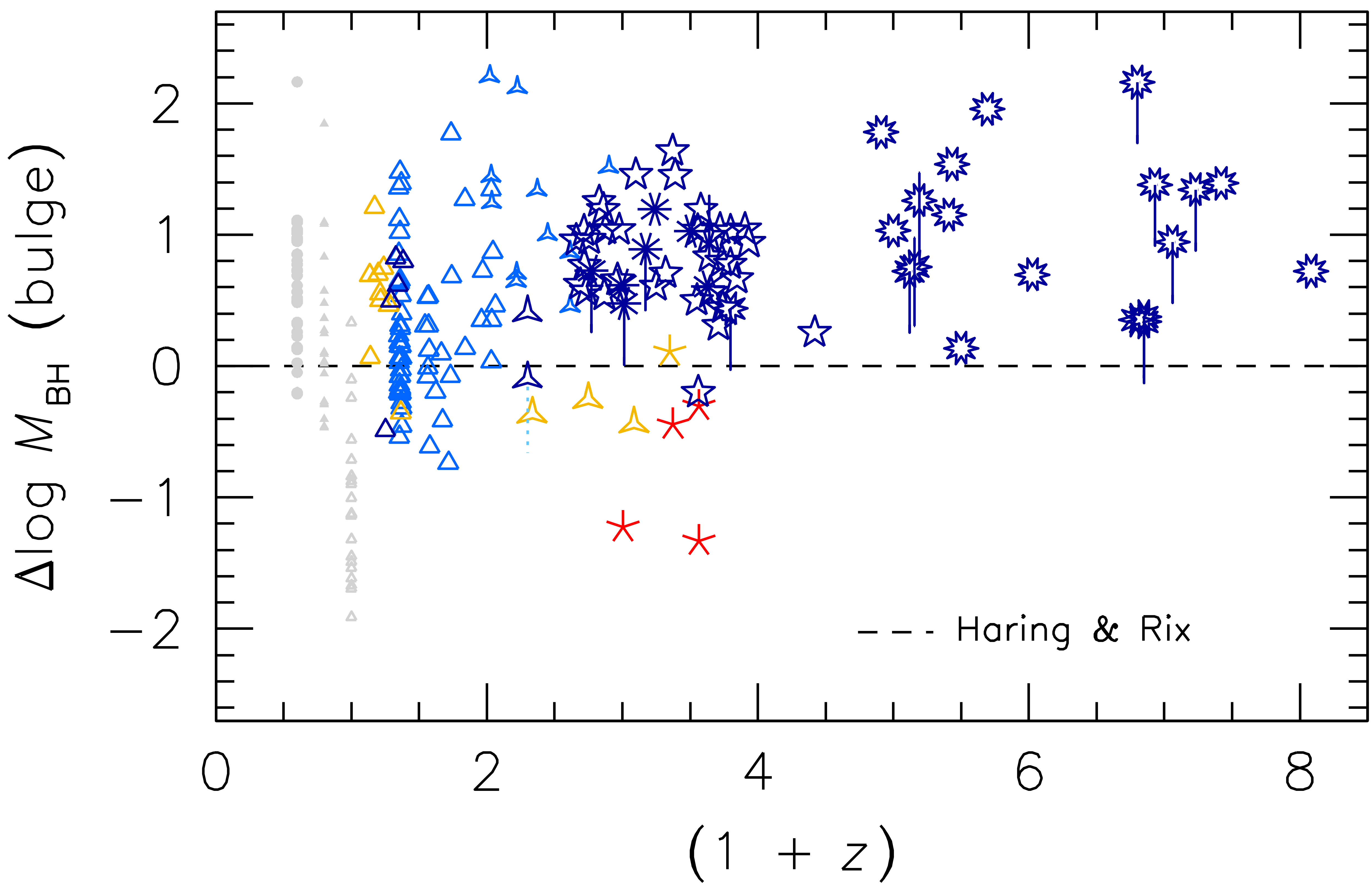
z=0.1−1.0 AGNs
z=1.0−2.0 QSOs
z=2.0−4.0 QSOs
z=4.0−7.0 QSOs
z≈2 RGs
z≈2 SMGs
bulge−dom
spiral bulge
obscured
obscured
Haring & Rix
log M_BH/M_⊙
log M_*,bulge/M_⊙
10
9
8
7
9
10
11
12



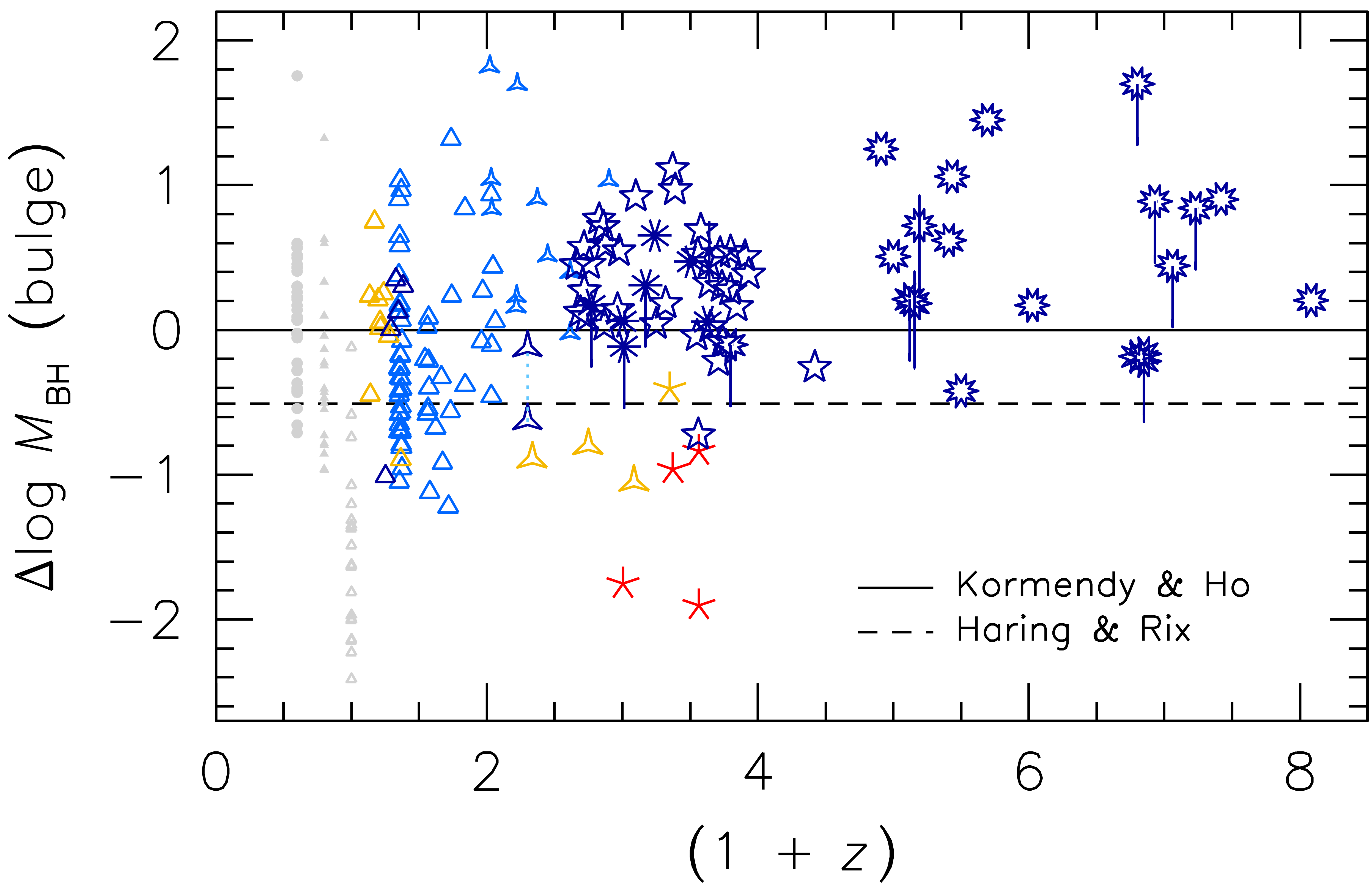
z=0.1−1.0 AGNs
z=1.0−2.0 QSOs
z=2.0−4.0 QSOs
z=4.0−7.0 QSOs
z≈2 RGs
z≈2 SMGs
bulge−dom
spiral bulge
obscured
obscured
Haring & Rix
log $M_{BH}/M_{\odot}$
log $M_{*,bulge}/M_{\odot}$



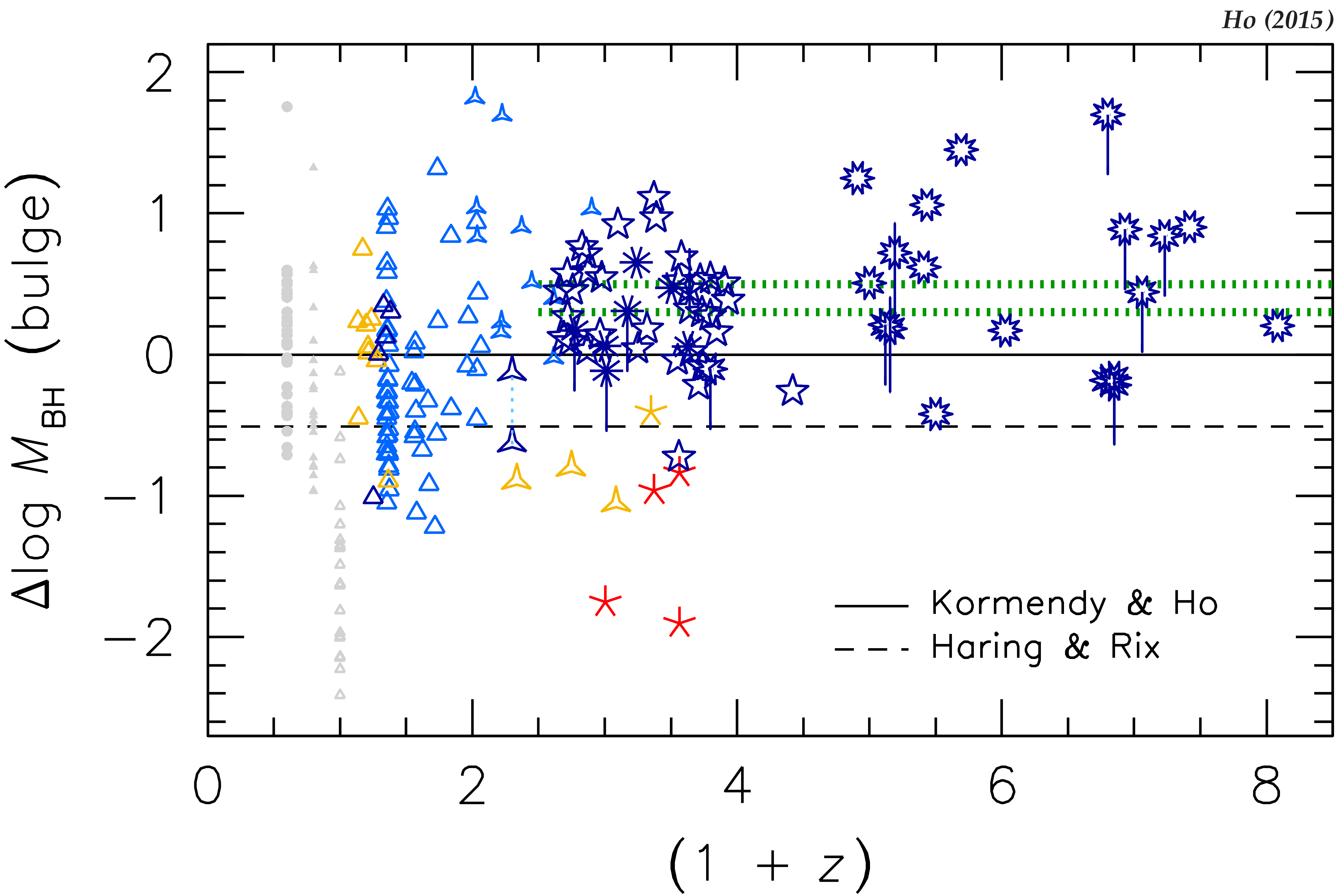
$M_{K,bulge}$
Ellipticals
Classical bulges
Pseudobulges
$M_{\bullet}/M_{\odot}$
$L_{K,bulge}/L_{K\odot}$

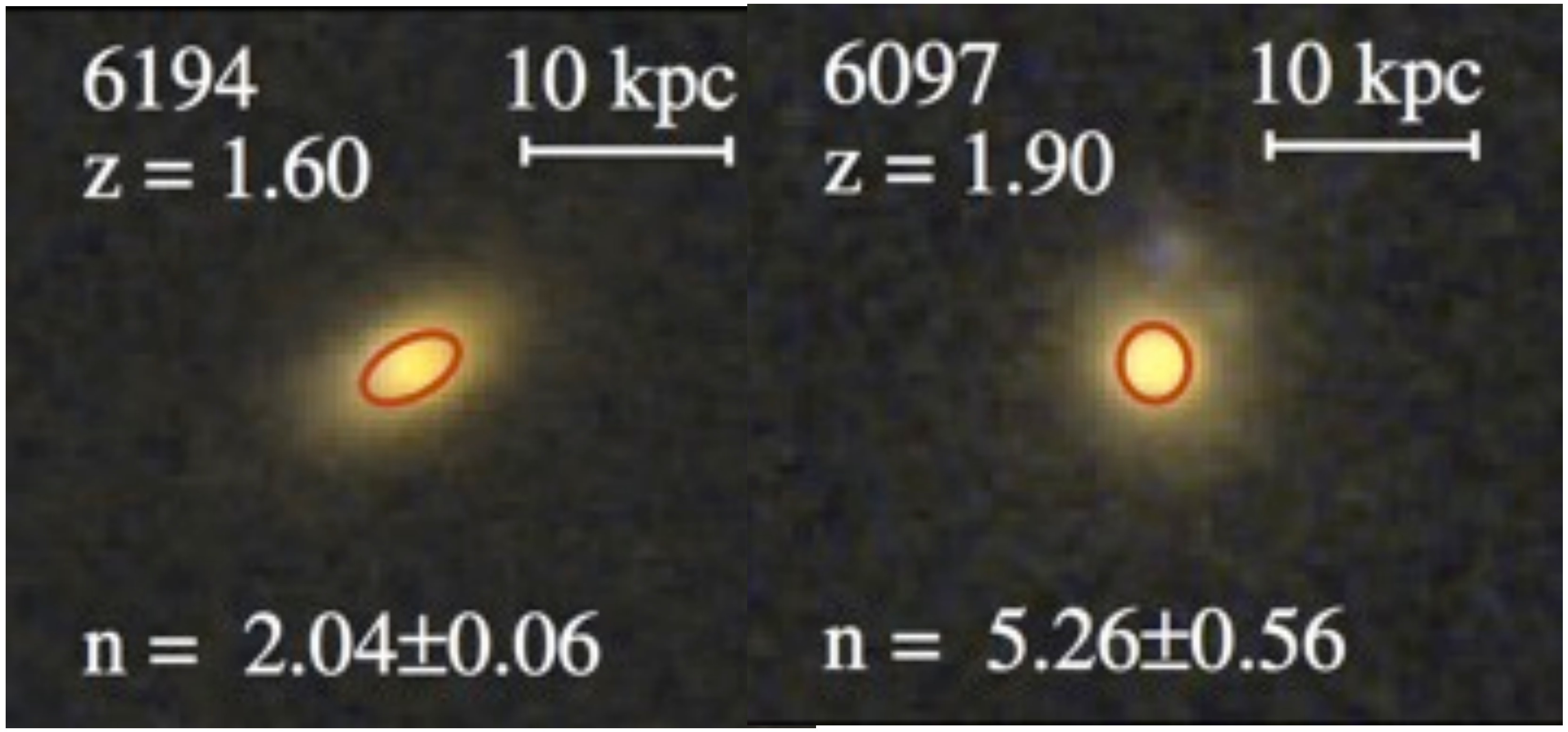


$\Delta\log M_{BH}$ (bulge)
2
1
0
−1
−2
0
2
4
6
8
$(1 + z)$
Haring & Rix

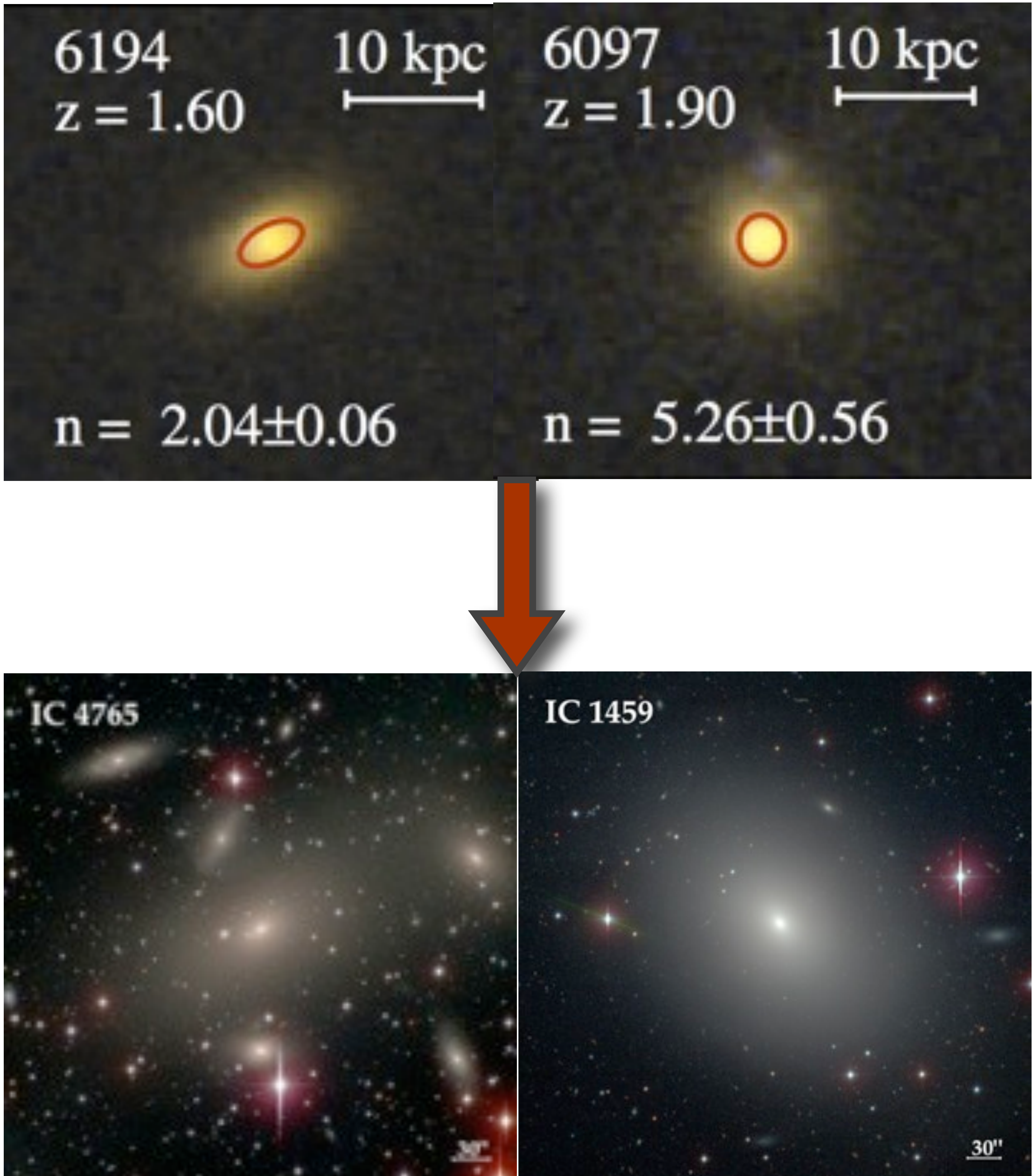


$\Delta \log M_{BH}$ (bulge)
$(1 + z)$
2
1
0
−1
−2
0
2
4
6
8
Kormendy & Ho
Haring & Rix


Ho (2015)
Δlog M_{BH} (bulge)
(1 + z)
Kormendy & Ho
Haring & Rix
2
1
0
−1
−2
0
2
4
6
8



z=2



z=2

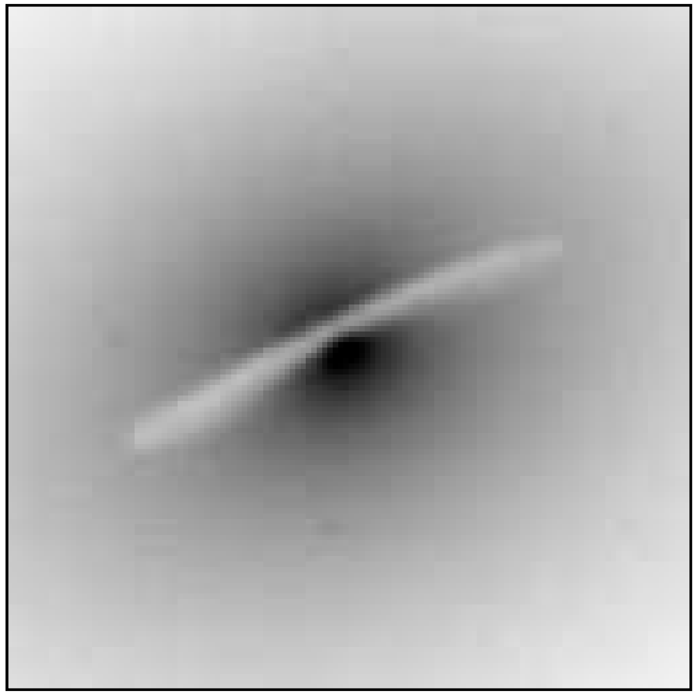
z=0

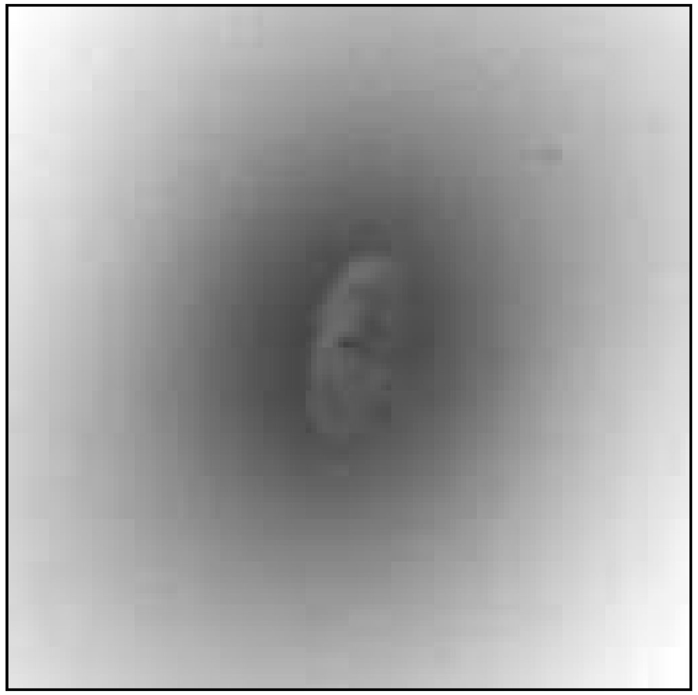
Huang, Ho et al. (2013a, b)

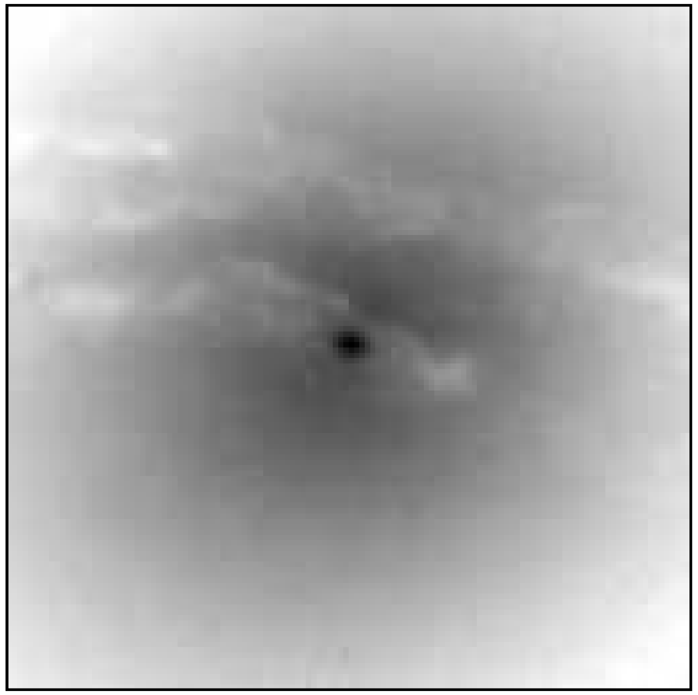
Recent Updates

- Central BHs detected from $10^4 - 10^{10}\ M_\odot$
- All bulges contain BHs, but not all BHs live in bulges
- $M_\bullet \sim M_{\rm bulge}^{1.2}$ $\quad\langle M_\bullet / M_{\rm bulge}\rangle \sim 0.5\%$
- $M_\bullet \propto \sigma^{4.4}$
- $M_\bullet - \sigma$ and $M_\bullet - M_{\rm bulge}$ relations have similar scatter
- Scaling relations only tight for classical bulges and Es
- Scaling relations already in place for high-z QSOs
- Mild evolution only for most massive BHs
- AGN feedback effective only for classical bulges and Es

Opportunities with ALMA

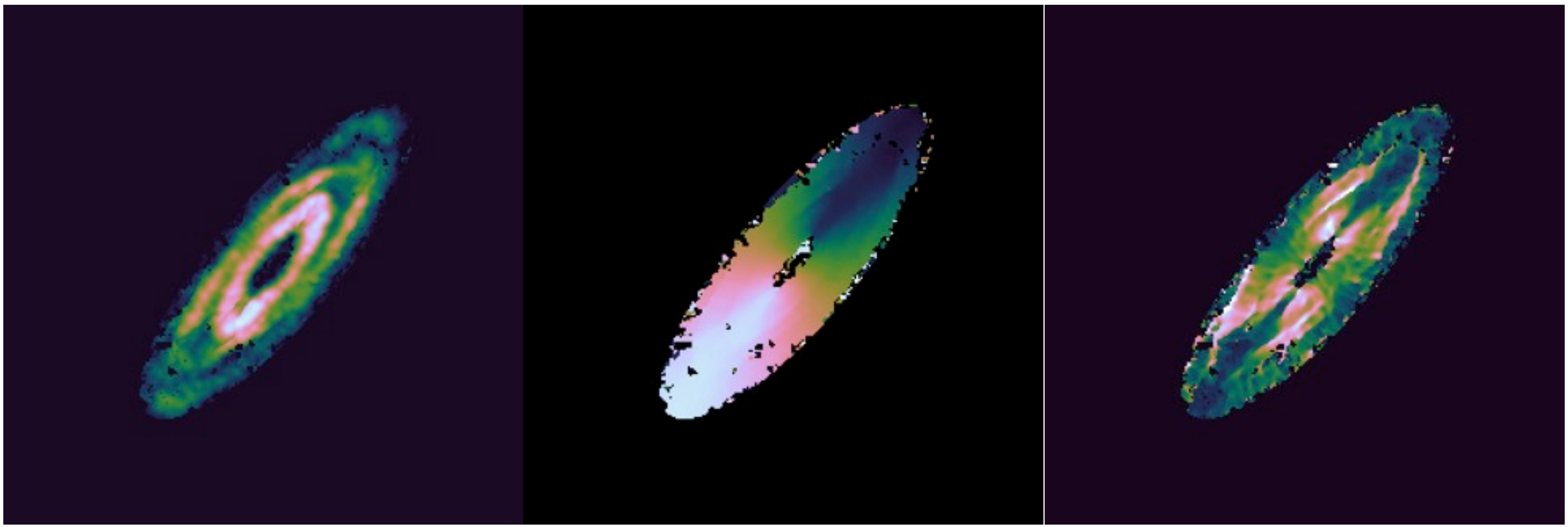


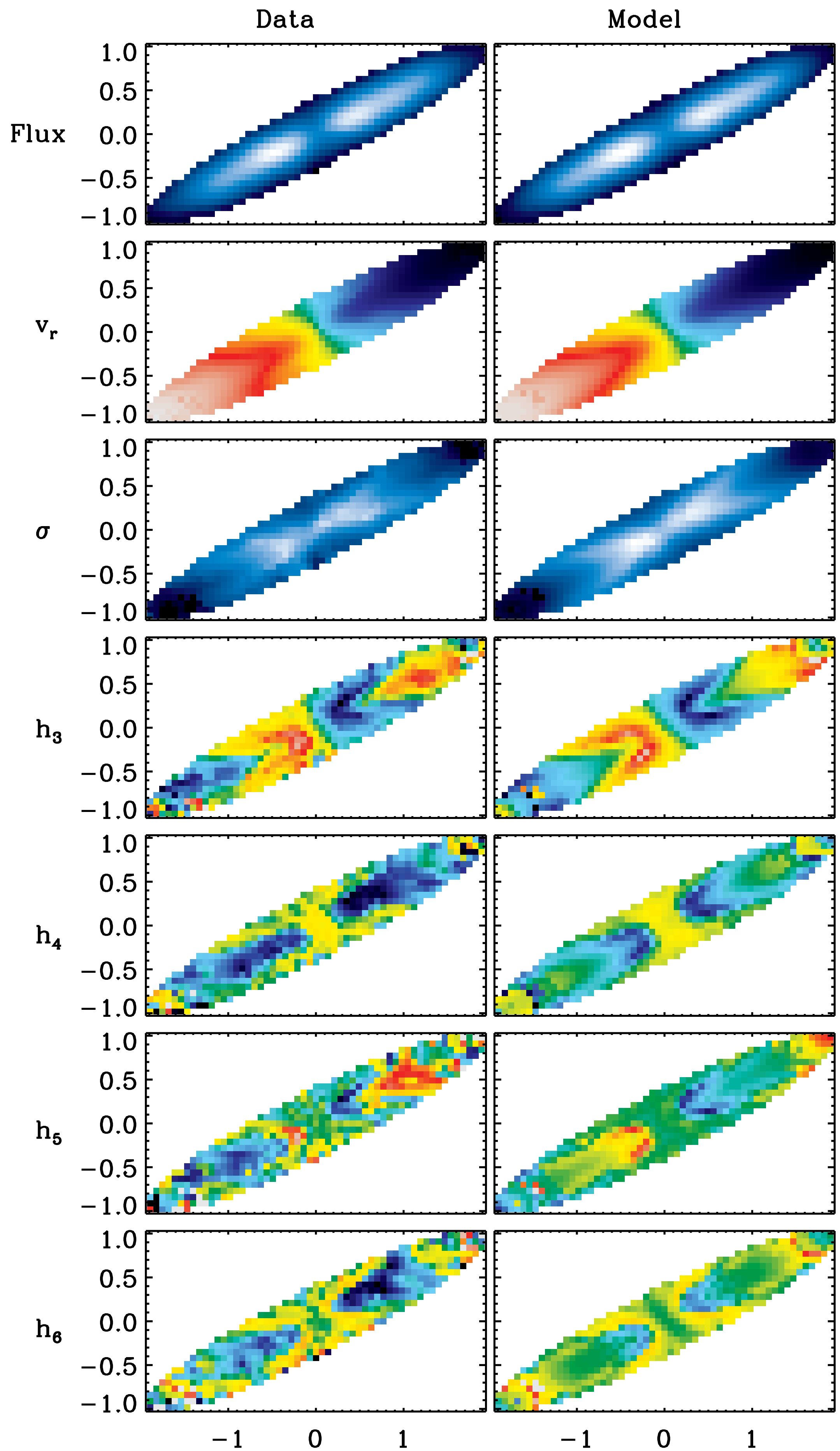




Barth, Ho, Baker, Darling

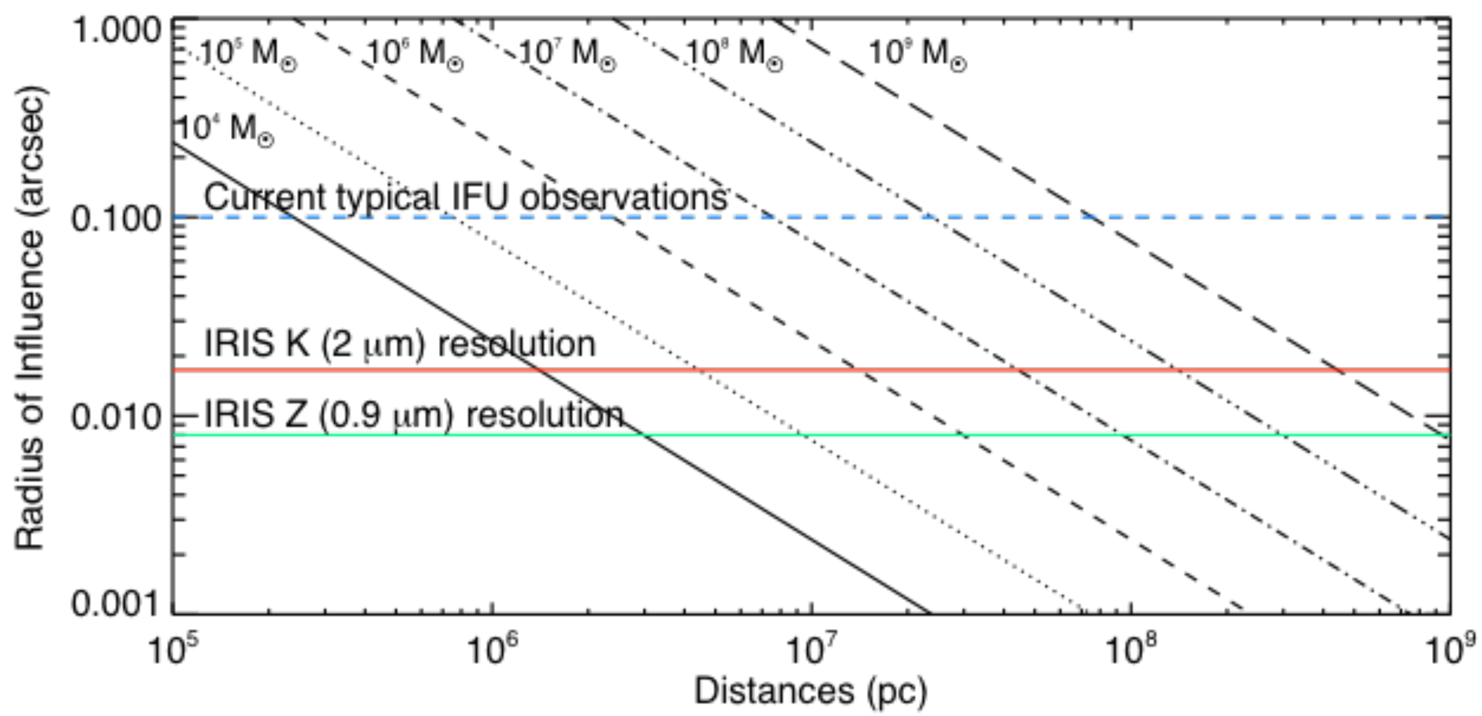
- **BH masses using nuclear (cold) gas disks**
- **ISM content of quasars at all redshifts**
- **Dynamical masses of quasar host galaxies (CO ladder, [C II])**
  Gas distribution and kinematics

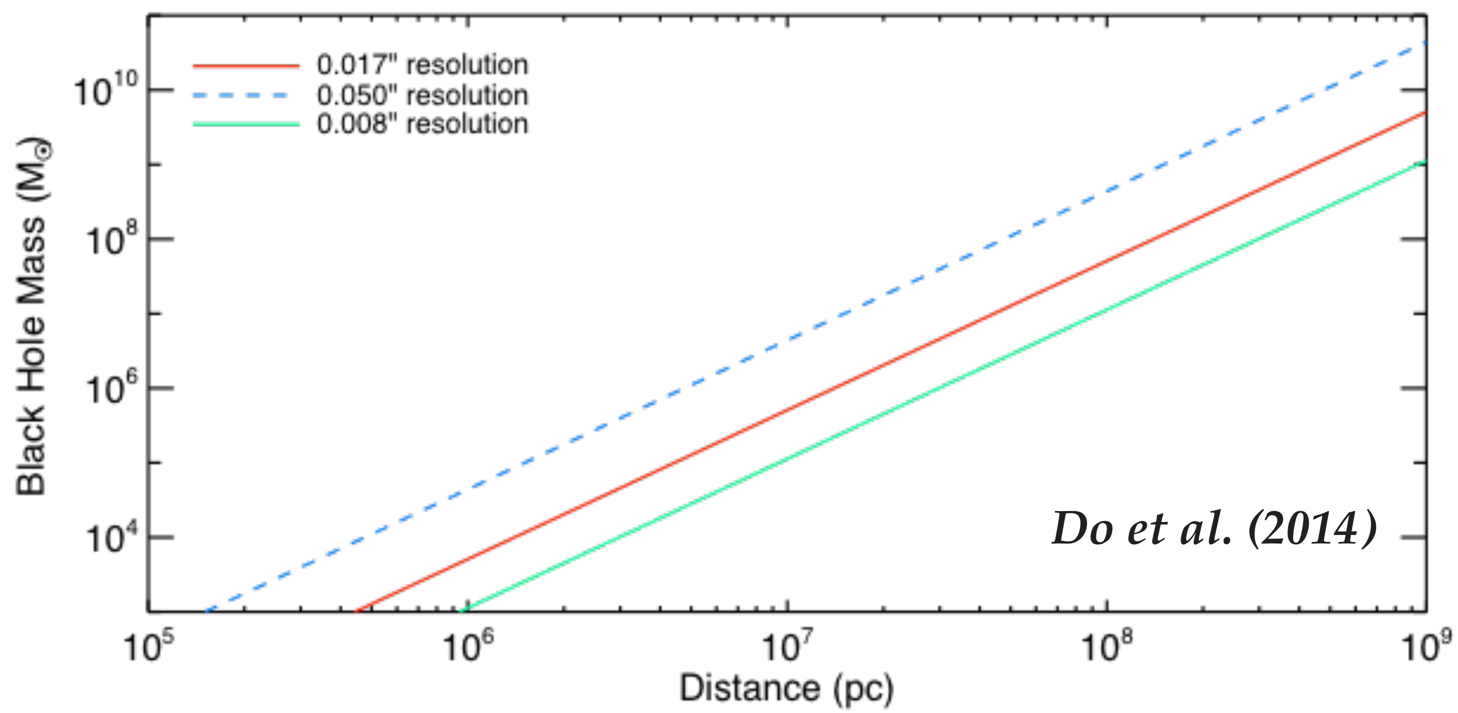



Data
Model
Flux
v_r
σ
h_3
h_4
h_5
h_6
1.0
0.5
0.0
−0.5
−1.0
−1
0
1


Thirty Meter Telescope

Future Directions with TMT





Future Directions with TMT

- **Direct measurement of low-mass BHs in dwarf galaxies**
- **Direct measurement of BH masses in high-*z* inactive galaxies**
- **Direct measurement of BH-host scaling relations at high-*z***
- **Calibration of BH masses in reverberation-mapped AGNs**
- **Stellar orbital structure of centers of BCGs, constrain growth mechanism of most massive BHs**