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Observational evidences and demography of Black Holes

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Dinamica delle galassie – Nuclei galattici attivi

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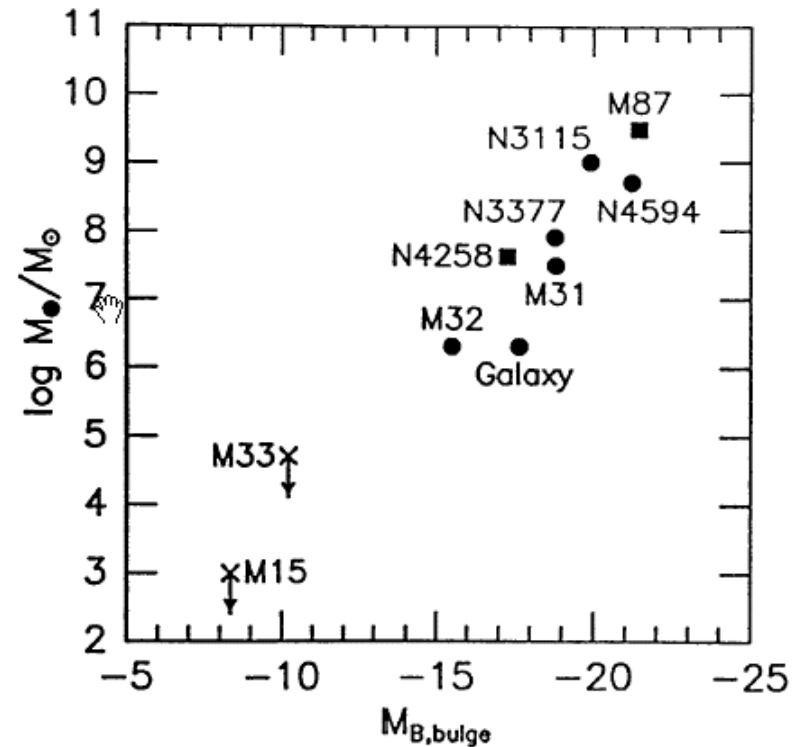


Outline of Lectures

- Lecture 1
 - Observational evidences for supermassive black holes and mass measurements.
- Lecture 2
 - Relations with the host galaxy and demography of local black holes.
- Lecture 3
 - Local supermassive black holes and Active Galactic Nuclei.
 - Future developments: VLT interferometry (?)

First hints of BH-galaxy relations

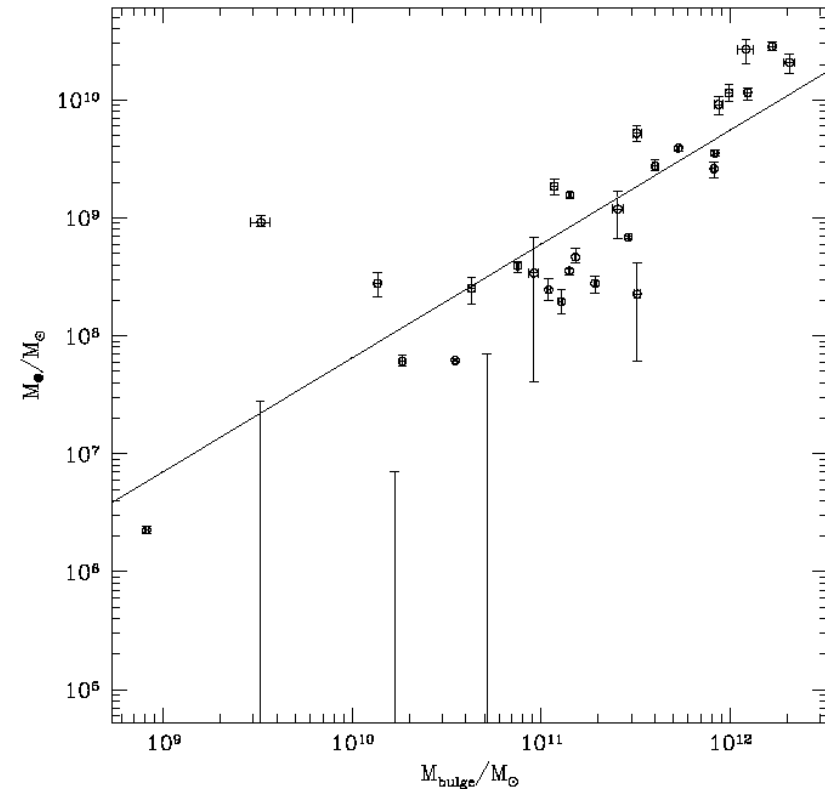
- Kormendy & Richstone (1995) suggest the existence of a correlation between the total blue magnitude of the host spheroid ($M_{B,bulge}$) and M_{BH} .
 - bulge (spheroid) = entire galaxy in case of an elliptical



Kormendy & Richstone 1995

More evidence ...

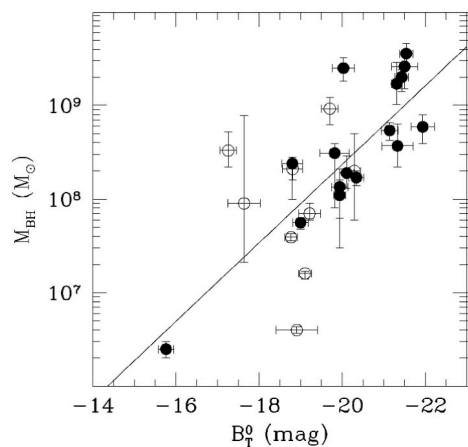
- Magorrian et al. (1998) find a correlation between M_{BH} and bulge masses (“Magorrian” relation)
 - They use mostly low resolution ground based data.
 - Use stellar kinematics with axisymmetric 2-l dynamical models.
 - They find $M_{\text{BH}}/M_{\text{bulge}} \sim 0.006$.



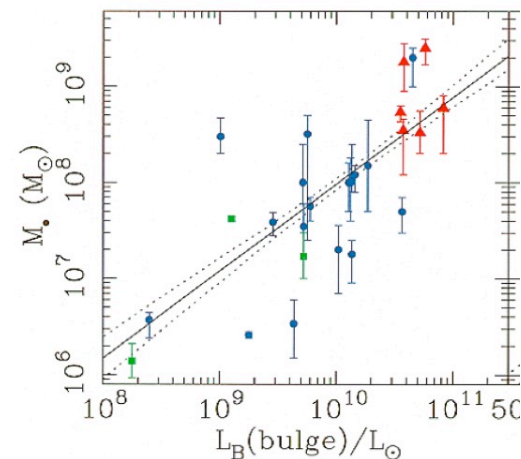
Magorrian et al. 1998

The $M_{\text{BH}}-\sigma$ correlation

- Two groups (Ferrarese & Merritt 2000, Gebhardt et al. 2000) independently find a tight relation between M_{BH} and the velocity dispersion of the stars in the galaxy σ (within R_e or $R_c=R_e/8$).
 - ▼ Big and hot debate about the slope $M_{\text{BH}} \sim \sigma^5$ (FM00) and $M_{\text{BH}} \sim \sigma^4$ (G00).



Ferrarese & Merritt 2000

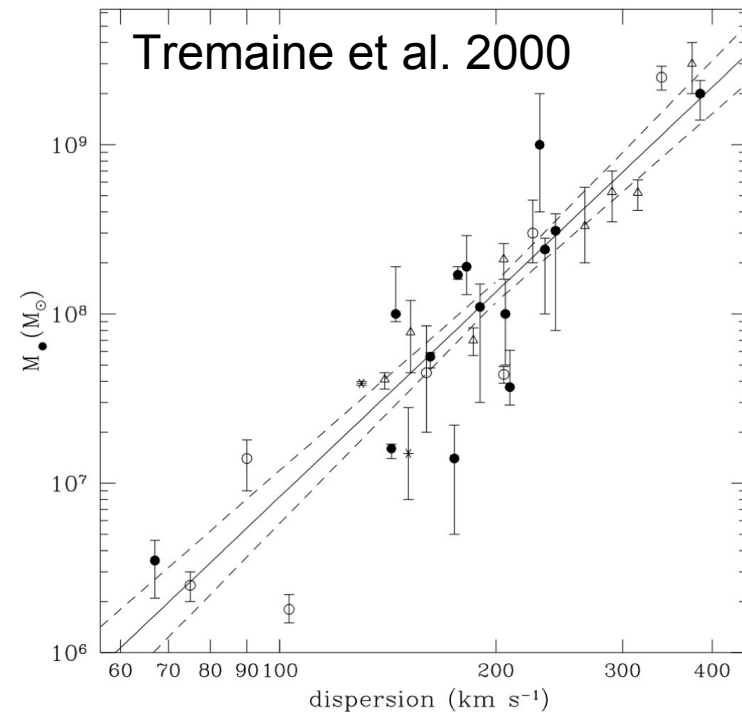


Gebhardt et al. 2000

σ^4 or σ^5 ??

Why different slopes?

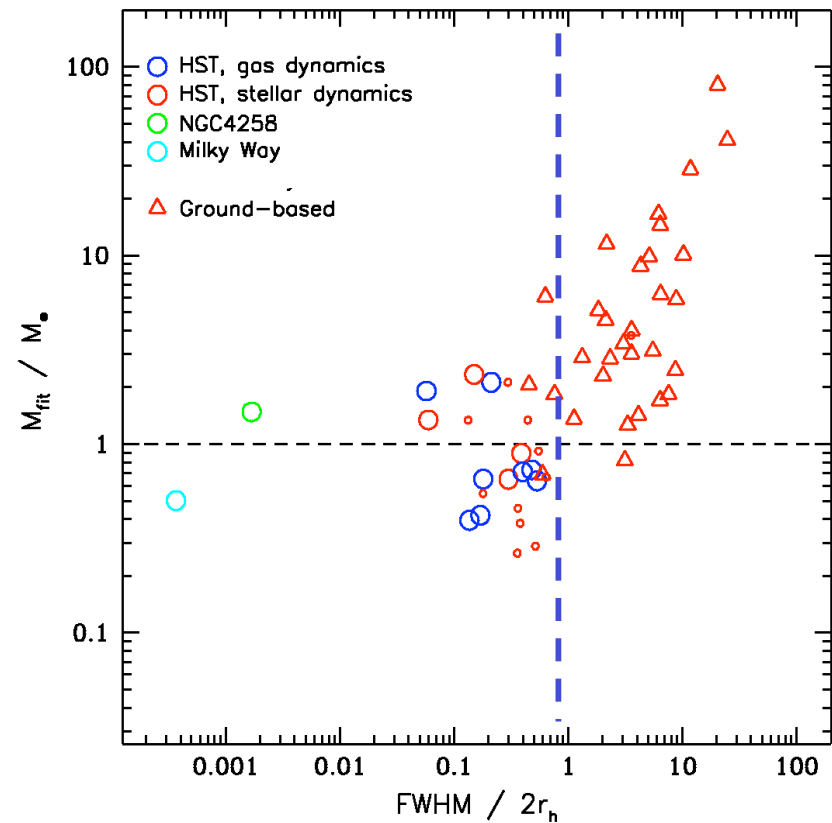
- ✓ Different samples, different σ 's, different fit of a straight line ...
- ✓ FM00 select only “secure” M_{BH} i.e. where the BH sphere of influence is resolved.
- ✓ Few points concentrated in 10^7 - 10^9 range and slope of correlations is dominated by few points at the extremes (e.g. M32, Milky Way, M87).



- ✓ This relation has a very small intrinsic scatter compared to $M_{\text{BH}}-M_{\text{B,bulge}}$ and $M_{\text{BH}}-M_{\text{bulge}}$.
- ✓ At a fixed M_{BH} the intrinsic scatter (taking into account measurement errors) is ≤ 0.3 in $\log M_{\text{BH}}$ for $M_{\text{BH}}-\sigma$ (factor of 2) and >0.5 for $M_{\text{BH}}-M_{\text{B,bulge}}$ and $M_{\text{BH}}-M_{\text{bulge}}$ (factor of 3).

Revisiting the Magorrian relation

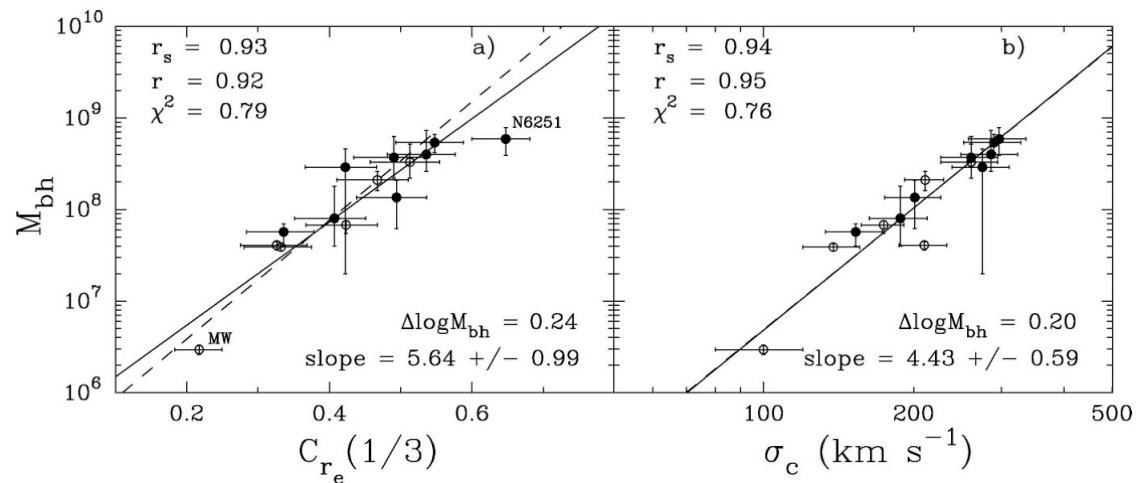
- Merritt & Ferrarese (2000) re-analyzed the “Magorrian” relation.
- They combined M_{bulge} from Magorrian et al. 1998 with M_{BH} from $M_{\text{BH}}-\sigma$
- M_{BH} 's overestimated!
- Reasons:
 - low spatial resolution (R_{BH} not resolved)
 - 2-I axysimmetric models might bias M_{BH} (better 3-I ...)



- $M_{\text{BH}}-M_{\text{bulge}} \sim 0.001$
- scatter does not seem to change.

M_{BH} vs bulge light concentration

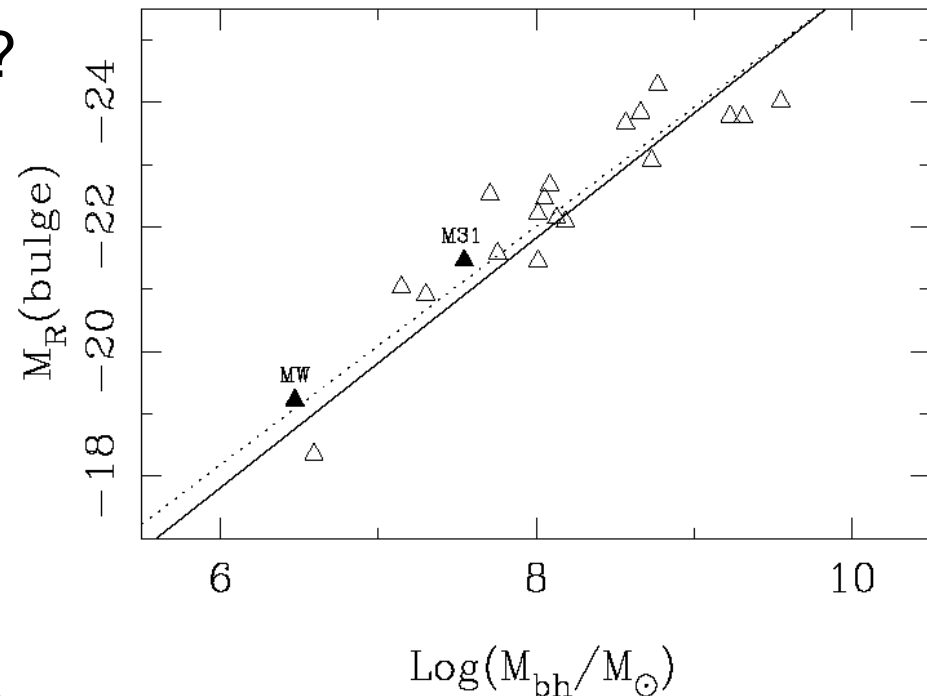
- Graham et al. (2001) found that M_{BH} is tightly correlated with the concentration index of bulge light [$C_{\text{Re}}(1/3) = F(R_e/3)/F(R_e)$]
 - same dispersion as $M_{\text{BH}}-\sigma$



Graham et al. (2001)

Intrinsic scatter of M_{BH} -bulge

- Is the scatter of M_{BH} - $M_{\text{B,bulge}}-M_{\text{bulge}}$ really worse?
- People usually derive $M_{\text{B,bulge}}$ from $M_{\text{B,total}}$ (RC3 catalogue) and apply a Bulge-to-Total correction from Simien & de Vaucoulers (1986)
- McLure & Dunlop (2002) use R band and “real” photometric decomposition on each galaxy and find that $M_{\text{BH}}-M_{\text{R,bulge}}$ has the same scatter as $M_{\text{BH}}-\sigma$
- however ... limited sample!



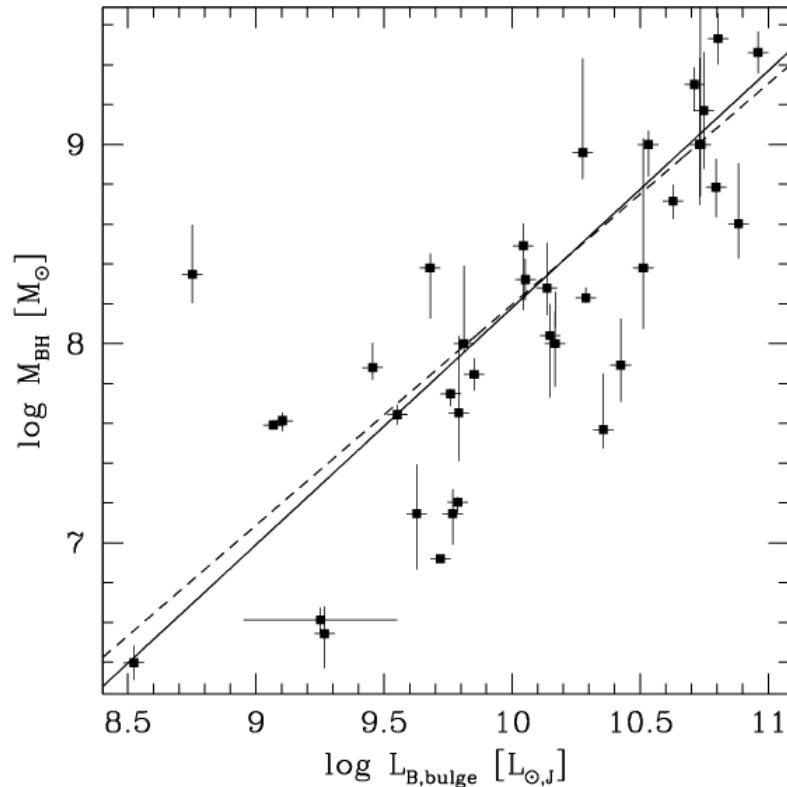
McLure & Dunlop (2002)



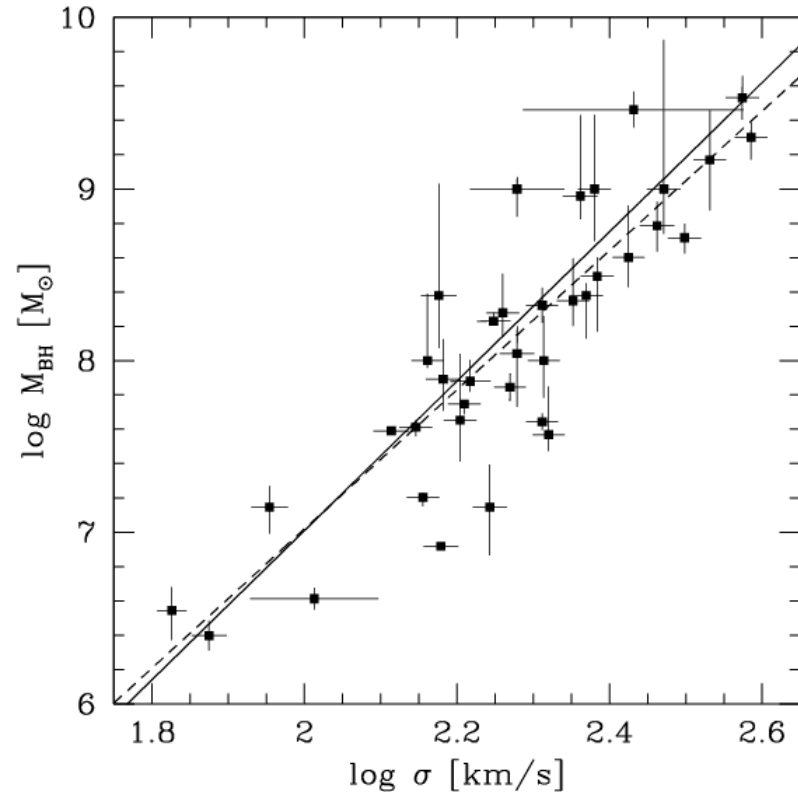
Intrinsic scatter of M_{BH} -bulge

- Marconi & Hunt (2003) have investigated the M_{BH} - L_{bul} relation in the near-IR (**reduced reddening and M/L effects**).
- Sample is 37 galaxies with DIRECT BH mass determination (ALL with stellar dynamics or gas kinematics).
- Measure near-IR galaxy structural parameters using J, H and K images from 2MASS using 2D image analysis.
- Consider **only** galaxies with **reliable BH masses and galaxy structural parameters** (e.g. BH sphere of influence resolved, BH mass well constrained by data) .

M_{BH} vs Host Spheroid in the NIR



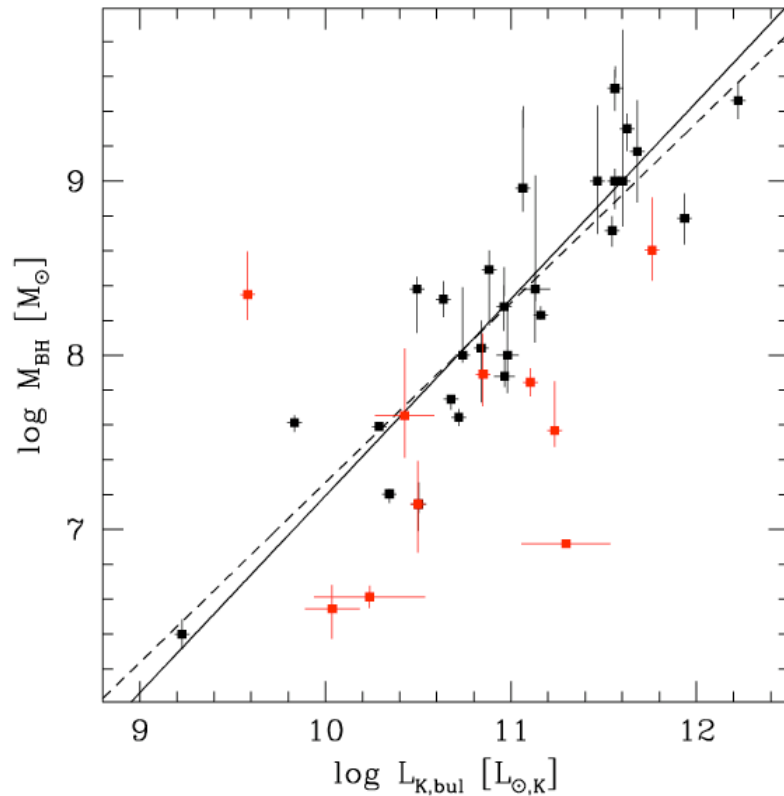
$M_{\text{BH}}-L_{\text{B,bul}}$ (*rms* 0.5 in $\log M_{\text{BH}}$)



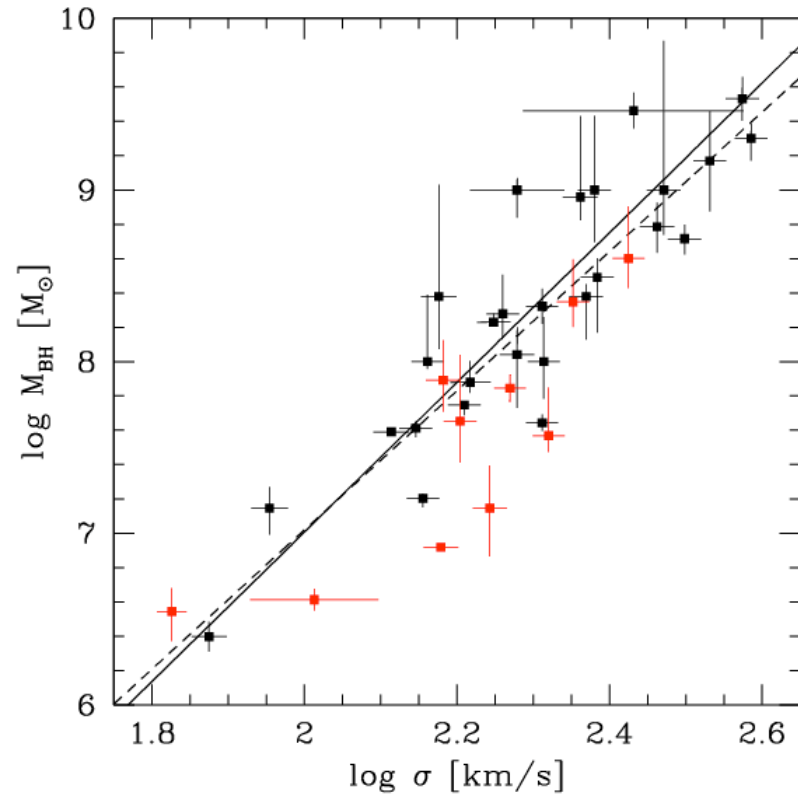
$M_{\text{BH}}-\sigma_e$ (*rms* 0.3 in $\log M_{\text{BH}}$)

- What is the reason of the larger scatter of $M_{\text{BH}}-L_{\text{B,bul}}$? Reddening, different stellar populations (M/L)?
- Investigate the $M_{\text{BH}}-L_{\text{bul}}$ relation in the near-IR and consider *only secure BH masses* and galaxy structural parameters.

M_{BH} vs Host Spheroid in the NIR

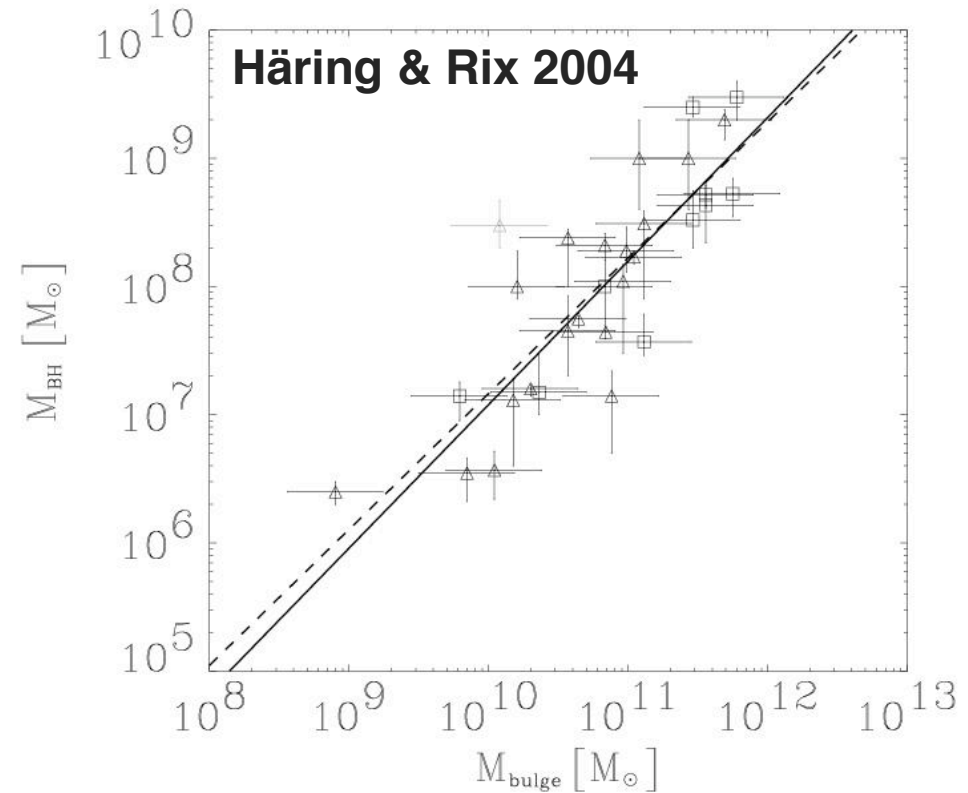
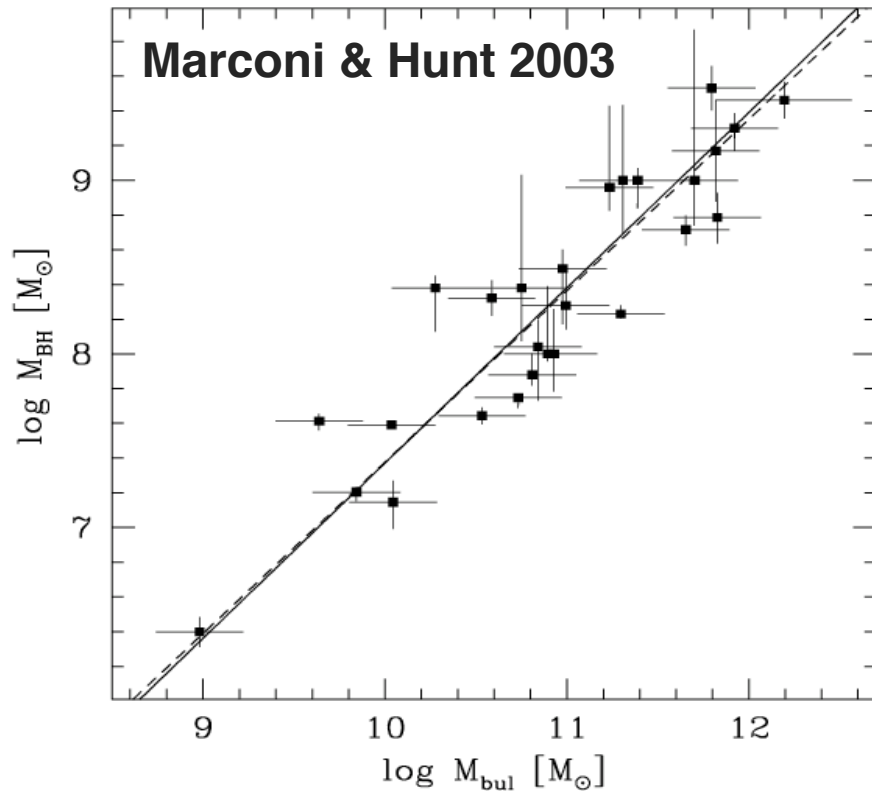


$M_{\text{BH}}-L_{\text{K,bul}}$ (*rms* 0.3 in $\log M_{\text{BH}}$)



$M_{\text{BH}}-\sigma_e$ (*rms* 0.25 in $\log M_{\text{BH}}$)

M_{BH} vs M_{bul}



- Tight correlation between M_{BH} and virial bulge mass ($\approx R_e \text{--} e^2$) with *rms* 0.25 (all 0.5).
- Linear slope (0.96 ± 0.07), average ratio $M_{\text{BH}}/M_{\text{bul}} \approx 0.002$.
- Häring & Rix 2004 find *rms* ~ 0.3 in $\log M_{\text{BH}}$ with M_{bul} from dynamical models.



M_{BH} vs host spheroid: a summary

- $M_{\text{BH}} \sim L_{\text{bulge}}^{1.2}$ (Kormendy & Richstone 1995, McLure & Dunlop 2002, Marconi & Hunt 2003)
- $M_{\text{BH}} \sim M_{\text{Sph}}$ (Magorrian et al. 1998, Marconi & Hunt 2003, Häring & Rix 2004)
- $M_{\text{BH}} \sim -e^{4-5}$ (Ferrarese & Merritt 2000, Gebhardt et al. 2000)
- $M_{\text{BH}} \sim C^{5.5}$ (Concentration index, Graham et al. 2001)

- Are these correlations independent?



Are relations independent?

- Assume the basic correlation is $M_{\text{BH}} \sim M_{\text{bulge}}$
- Combine with galaxy scaling relations:
 - $M_{\text{BH}} \sim L_{\text{bulge}}^{1.2}$ consistent with $M_{\text{BH}} \sim M_{\text{bulge}}$ if $(M/L)_{\text{bulge}} \sim L_{\text{bulge}}^{0.2}$ (consistent with fundamental plane)
 - Faber-Jackson $L \sim \sigma^4$ implies $M_{\text{BH}} \sim (\sigma^4)^{1.2} \sim \sigma^{4.8}$
 - ✓ Kormendy relation (Σ_e vs R_e) + relation between Sersic index n and R_e [$I(r) \sim \exp(-r^{1/n})$ Caon et al. 1993] can be used to derive M_{BH} vs C correlation.
- All M_{BH} -galaxy correlations can be explained as the result of a fundamental relation (e.g. $M_{\text{BH}} \sim M_{\text{bulge}}$) combined with galaxy scaling relations.
- Big Black Holes are in big galaxies!
- However, galaxy scaling relations have intrinsic scatter much larger than that of M_{BH} -galaxy relations: is there something more fundamental that we are missing?

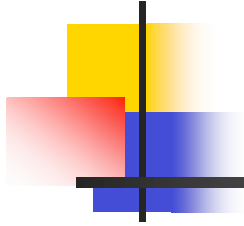


- Most M_{BH} measurements:
 - barely resolve R_{BH}
 - are in 10^7 - 10^9 range
 - are in Early type galaxies
- Not all measurements are equally reliable
- We can exclude large BHs in small galaxies.
- We cannot exclude small BHs in big galaxies.
- Valid at $z=0$!

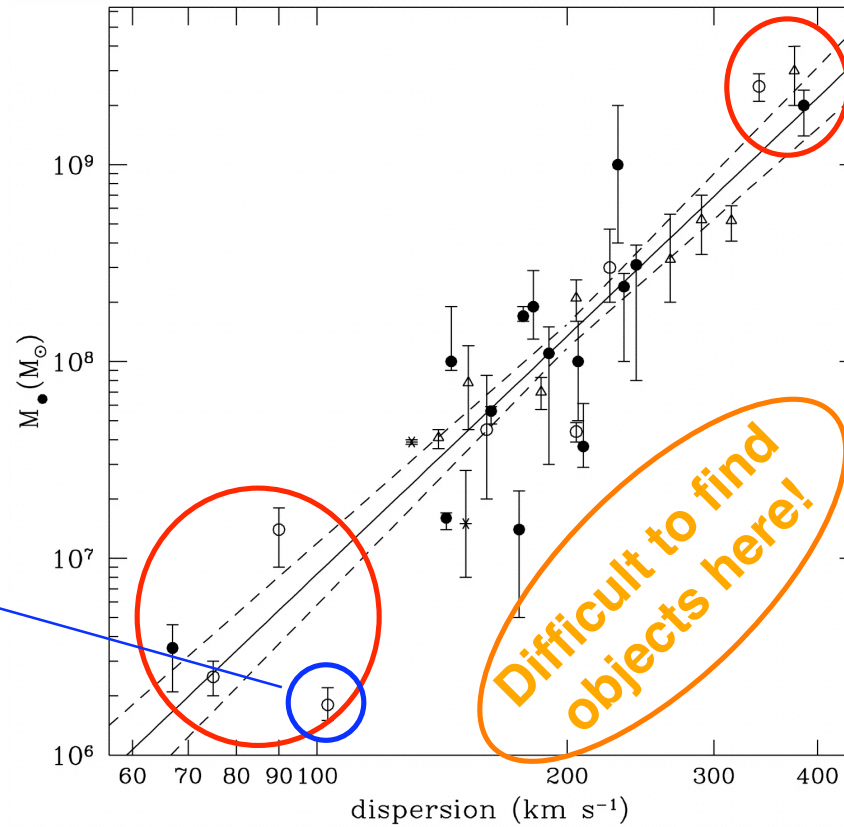
TABLE II
Complete list of SBH mass detection based on resolved dynamical studies.

Object	Hubble Type	Distance (Mpc)	M_{\bullet} ($10^8 M_{\odot}$)	M_{\bullet} Ref. & Method	σ (km s^{-1})	$M_{B,T}^0$ (mag)	$L_{B,bulge}/L_{B,total}$	r_h/r_{res}
MW	SbI-II	0.008	$0.040^{+0.003}_{-0.003}$	1,PM	100 ± 20	-20.08 ± 0.50	0.34	1700
N4258	SAB(s)bc	7.2	$0.390^{+0.034}_{-0.034}$	2,MM	138 ± 18	-20.76 ± 0.15	0.16	880
N4486	E0pec	16.1	$35.7^{+10.2}_{-10.2}$	3,GD	345 ± 45	-21.54 ± 0.16	1.0	34.6
N3115	S0	9.7	$9.2^{+3.0}_{-3.0}$	4,SD	278 ± 36	-20.19 ± 0.20	0.64	22.8
I1459	E3	29.2	$26.0^{+11.0}_{-11.0}$	5,SD	312 ± 41	-21.50 ± 0.32	1.0	17.0
N4374	E1	18.7	$17^{+12}_{-6.7}$	6,GD	286 ± 37	-21.31 ± 0.13	1.0	10.3
N4697	E6	11.7	$1.7^{+0.2}_{-0.3}$	7,SD	163 ± 21	-20.34 ± 0.18	1.0	10.2
N4649	E2	16.8	$20.0^{+4.0}_{-6.0}$	7,SD	331 ± 43	-21.43 ± 0.16	1.0	10.1
N221	cE2	0.8	$0.025^{+0.005}_{-0.005}$	8,SD	76 ± 10	-15.76 ± 0.18	1.0	10.1
N5128	S0pec	4.2	$2.0^{+3.0}_{-1.4}$	9,GD	145 ± 25	-20.78 ± 0.15	0.64	8.41
M81	SA(s)ab	3.9	$0.70^{+0.2}_{-0.1}$	10,GD	174 ± 17	-20.42 ± 0.26	0.33	5.50
N4261	E2	31.6	$5.4^{+1.2}_{-1.2}$	11,GD	290 ± 38	-21.14 ± 0.20	1.0	3.77
N4564	E6	15.0	$0.56^{+0.03}_{-0.08}$	7,SD	153 ± 20	-19.00 ± 0.18	1.0	2.96
CygA	E	240	$25.0^{+7.0}_{-7.0}$	12,GD	270 ± 87	-20.03 ± 0.27	1.0	2.65
N2787	SB(r)0	7.5	$0.90^{+6.89}_{-0.69}$	13,GD	210 ± 23	-18.12 ± 0.39	0.64	2.53
N3379	E1	10.6	$1.35^{+0.73}_{-0.73}$	14,SD	201 ± 26	-19.94 ± 0.20	1.0	2.34
N5845	E*	25.9	$2.4^{+0.4}_{-1.4}$	7,SD	275 ± 36	-18.80 ± 0.25	1.0	2.28
N3245	SB(s)b	20.9	$2.1^{+0.5}_{-0.5}$	15,GD	211 ± 19	-20.01 ± 0.25	0.33	2.10
N4473	E5	15.7	$1.1^{+0.5}_{-0.8}$	7,SD	188 ± 25	-19.94 ± 0.14	1.0	1.84
N3608	E2	22.9	$1.9^{+1.0}_{-0.6}$	7,SD	206 ± 27	-20.11 ± 0.17	1.0	1.82
N4342	S0	16.7	$3.3^{+1.9}_{-1.1}$	16,GD	261 ± 34	-17.74 ± 0.20	0.64	1.79
N7052	E	66.1	$3.7^{+2.6}_{-1.5}$	17,GD	261 ± 34	-21.33 ± 0.38	1.0	1.53
N4291	E3	26.2	$3.1^{+0.8}_{-2.3}$	7,SD	269 ± 35	-19.82 ± 0.35	1.0	1.52
N6251	E	104	$5.9^{+2.0}_{-2.0}$	18,GD	297 ± 39	-21.94 ± 0.28	1.0	1.19
N3384	SB(s)0-	11.6	$0.16^{+0.01}_{-0.02}$	7,SD	151 ± 20	-19.59 ± 0.15	0.64	1.12
N7457	SA(rs)0-	13.2	$0.035^{+0.011}_{-0.014}$	7,SD	73 ± 10	-18.74 ± 0.24	0.64	0.92
N1023	S0	11.4	$0.44^{+0.06}_{-0.06}$	7,SD	201 ± 14	-20.20 ± 0.17	0.64	0.89
N821	E6	24.1	$0.37^{+0.24}_{-0.08}$	7,SD	196 ± 26	-20.50 ± 0.21	1.0	0.74
N3377	E5	11.2	$1.00^{+0.9}_{-0.1}$	7,SD	131 ± 17	-19.16 ± 0.13	1.0	0.74
N2778	E	22.9	$0.14^{+0.08}_{-0.09}$	7,SD	171 ± 22	-18.54 ± 0.33	1.0	0.39

Table from Ferrarese & Ford 2005 review



Milky Way
only “genuine”
Black Hole



Tremaine et al. 2001

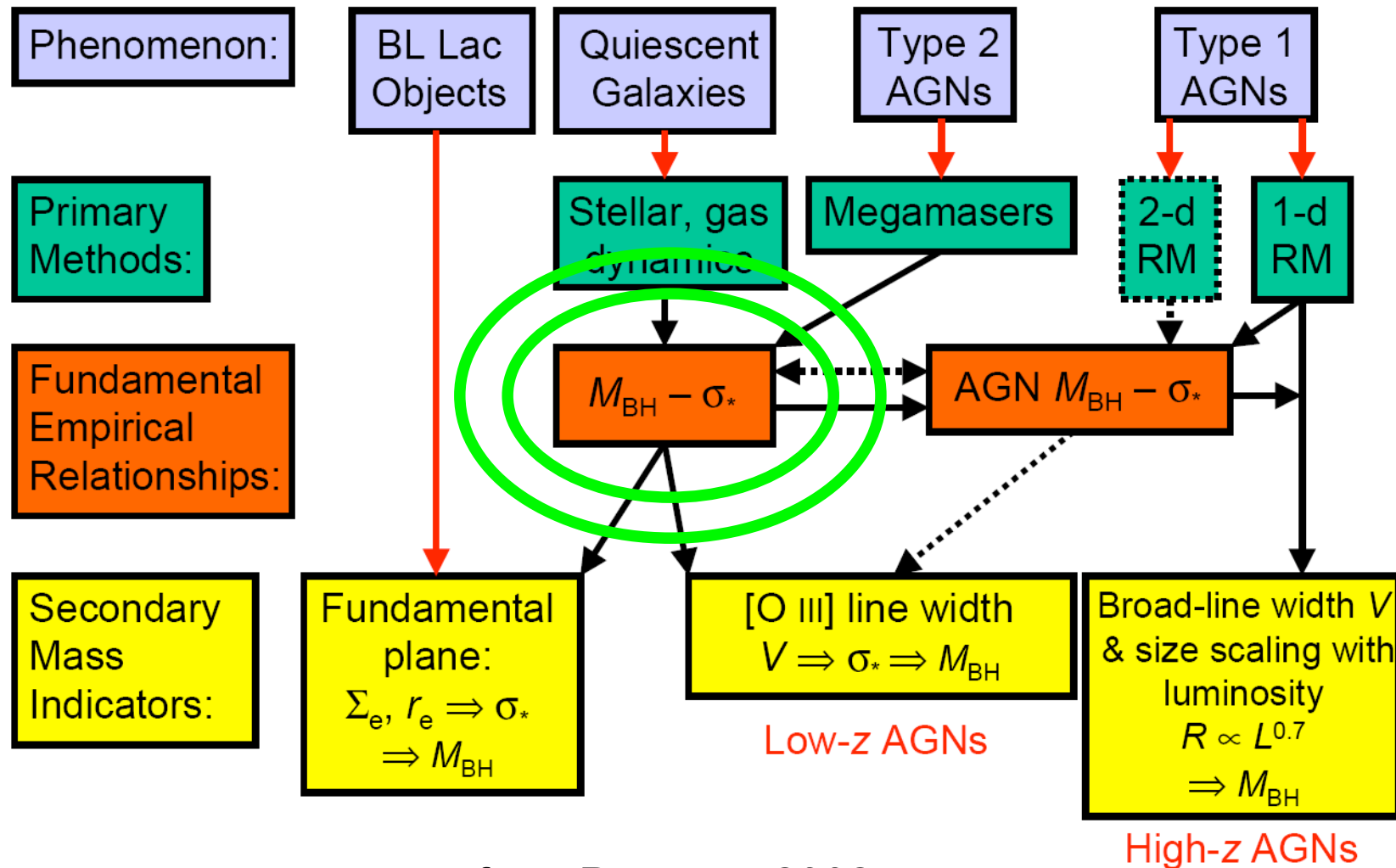


M_{BH} vs host spheroid: a summary

- $M_{\text{BH}} - L_{\text{Sph}}$ (Kormendy & Richstone 1995, McLure & Dunlop 2002, Marconi & Hunt 2003)
- $M_{\text{BH}} - M_{\text{Sph}}$ (Magorrian et al. 1998, Marconi & Hunt 2003, Häring & Rix 2004)
- $M_{\text{BH}} - \sigma_e$ (Ferrarese & Merritt 2000, Gebhardt et al. 2000)
- $M_{\text{BH}} - C$ (Concentration index, Graham et al. 2001)

- The $M_{\text{BH}} - \sigma_e / L_{\text{Sph}} / M_{\text{Sph}}$ relations:
 - indicate close link between BH growth and galaxy evolution
 - provide a way to estimate BH masses
 - allow a demography of BHs

The BH mass “ladder”



from Peterson 2002

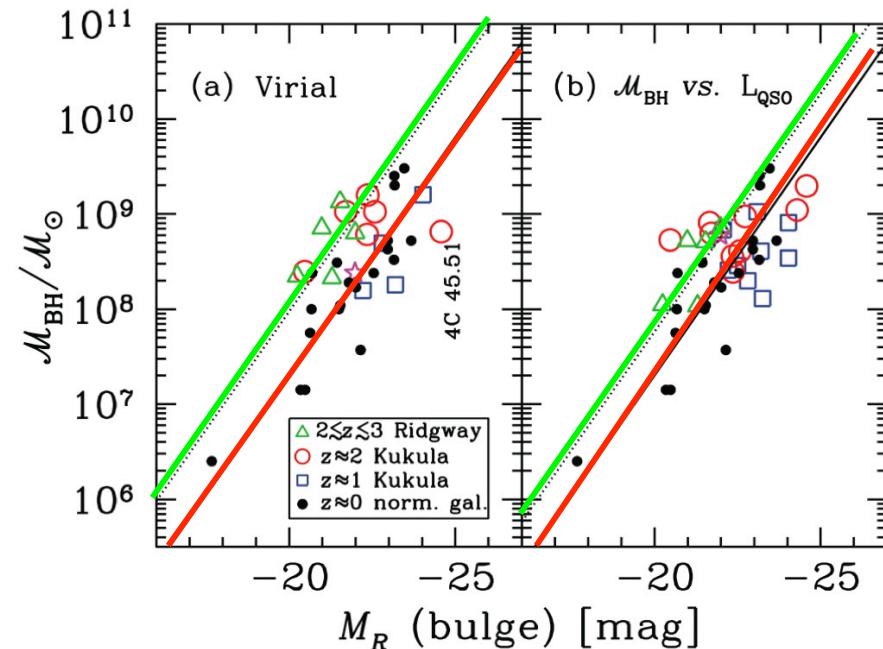
Cosmic evolution?

- Work **very** much in progress but there are evidences that BHs grow to their final mass earlier than their host galaxies.
- Quasar at $z \sim 6.41$ has $M_{\text{BH}} \sim 3 \times 10^9 M_{\odot}$ (Willott et al. 2004).
 - Can we have a galaxy of $\sim 10^{12} M_{\odot}$ already formed at $z \sim 6$???
 - Small galaxy dynamical mass from CO observations (Walter et al. 2003)
- Evidence from the $M_{\text{BH}} - L_{\text{bulge}}$ relation (e.g. Peng et al. 2006, and many others).

Local relation

$z > 2$ relation

$M_{\text{BH}}/M_{\text{bulge}} \sim 3-6$ larger at $z > 2$



Peng et al. 2006



Link BH growth - galaxy evolution

- The BH-galaxy scaling relations imply a tight link between BH growth and galaxy evolution.
- This link is provided by AGN feedback on the host galaxy.
- Physical models of galaxy evolution are now including AGN feedback as a fundamental ingredient to reproduce M_{BH} -galaxy relations (eg. Granato et al. 2004).
- Many papers in the literature presenting simple physical models to explain $M_{\text{BH}}-\sigma$ (e.g. Silk & Rees 1998; Fabian 1999; Adams et al. 2001, 2003; King 2004).
- v In a simple host galaxy (isothermal sphere) winds from the AGN sweep and accelerate the gas in the host galaxy.
- v The $M_{\text{BH}}-\sigma$ relation is found requesting that the gas is accelerated up to the escape velocity from the host galaxy. If during the process:
 - v energy is conserved (gas cannot cool) $\Rightarrow M_{\text{BH}} \sim \sigma^5$
 - v momentum is conserved (gas can cool) $\Rightarrow M_{\text{BH}} \sim \sigma^4$



Demography of Black Holes

- Merritt & Ferrarese (2001) estimate average $M_{\text{BH}}/M_{\text{bulge}}$ ratio:
 - M_{bulge} from Magorrian et al. (1998) analysis
 - M_{BH} applying the $M_{\text{BH}}-\sigma$ relation
 - $M_{\text{BH}}/M_{\text{bulge}} \sim 0.0013$
- Mass density in bulges is:
 - ✓ $\rho_{\text{bulge}} \sim 3.7 \times 10^8 M_{\odot} \text{pc}^{-3}$
- ✓ Mass density in local black holes is then
 - ✓ $\rho_{\text{BH}} \sim 4.8 \times 10^5 M_{\odot} \text{pc}^{-3}$



Origin of local black holes?

- So_tan's argument (So_tan 1982, Choskhi & Turner 1992):
 - quasar luminosity function in B band; transform L_B to bolometric luminosity L (e.g. $L \sim 10 \nu_B L_{\nu,B}$)

$$\phi(L_B, z) dL_B = \phi(L, z) dL$$

- integrated comoving energy density from quasars is

$$u = \int_0^\infty dz \int_0^\infty dL \phi(L, z) L \frac{dt}{dz} = 1.3 \times 10^{-15} \text{ erg cm}^{-3}$$

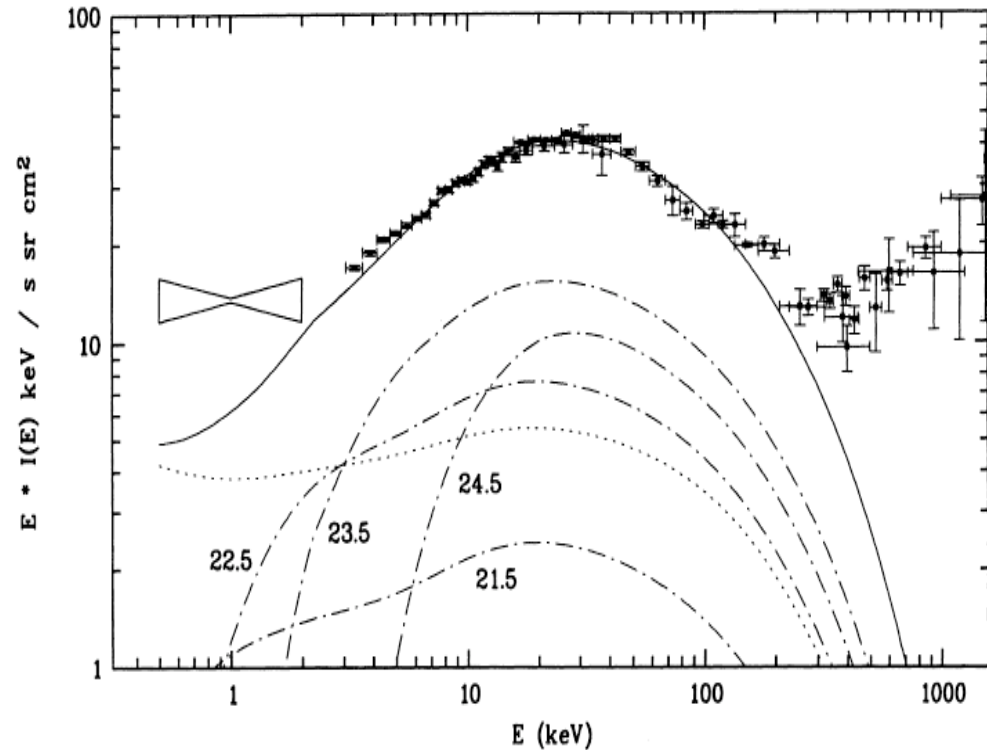
- with efficiency ε , the expected local mass density is

$$\rho_u = \frac{(1 - \varepsilon)u}{\varepsilon c^2} = 2.2 \times 10^5 M_{\text{sun}} \text{ Mpc}^{-3} \quad \text{with } \varepsilon = 0.1$$

- the “observed” local black hole mass density is
 - ▼ $\rho_{\text{BH}} \sim 4.8 \times 10^5 M_{\square} \text{ pc}^{-3}$, consistent within a factor 2 (AGNs are not only quasars!)

Constraints from XRB

- Start from X-ray Background (XRB; Fabian & Iwasawa 1999, Salucci et al. 1999; revised by Elvis, Risaliti & Zamorani 2002):
 - XRB spectrum above 30 keV unaffected by absorption;
 - assume typical AGN continuum power law with photon index 2 (no K-correction)
 - assume emission dominated from objects at $z \sim 2$
 - extrapolate to 2-10 keV band (rest frame)
 - apply bolometric correction and get total energy density



Comastri et al. 1995

$$\rho_{BH}(\text{XRB}) = \frac{1 - \epsilon}{\epsilon c^2} (1 + \langle z \rangle) U_T^*$$



Constraints from XRB

$$\rho_{BH}(\text{XRB}) = \frac{1 - \epsilon}{\epsilon c^2} (1 + \langle z \rangle) U_T^*$$

- Apparently $\rho_{BH}(\text{XRB}) \approx (7.5-16.8) \times 10^5 (\epsilon/0.1)^{-1} M_{\odot} \text{Mpc}^{-3}$ much higher than $\rho_{BH}(\text{local}) (4.5 \pm 1.5)$ (Elvis, Risaliti & Zamorani 2002). High ϵ , and rapidly spinning BHs?
- $\rho_{BH}(\text{XRB})$ depends on $\langle z \rangle$ of XRB sources! They used $\langle z \rangle \approx 2$ but we now know that $\langle z \rangle \approx 1$ then $\rho_{BH}(\text{XRB}) = 4.9-10.1$ is consistent with $\rho_{BH}(\text{local}) = 3.0-6.0$ (e.g. Comastri 2003)!

Summary of ρ_{BH} estimates

TABLE V
Summary of SBH mass densities.

ρ_{\bullet} ($M_{\odot} \text{ Mpc}^{-3}$)	Reference
Local quiescent galaxies ($z < 0.025$)	
$2.3^{+4.0}_{-1.5} \times 10^5$	Wyithe and Loeb (2003)
$2.4 \pm 0.8 \times 10^5$	Aller and Richstone (2002)
$\sim 2.5 \times 10^5$	Yu and Tremaine (2002)
$2.8 \pm 0.4 \times 10^5$	McLure and Dunlop (2004)
$4.2 \pm 1.0 \times 10^5$	Shankar <i>et al.</i> (2004)
$\sim 4.5 \times 10^5$	Ferrarese (2002a)
$4.6^{+1.9}_{-1.4} \times 10^5$	Marconi <i>et al.</i> (2004)
$\sim 5 \times 10^5$	Merritt and Ferrarese (2001a)
$\sim 5.8 \times 10^5$	Yu and Tremaine (2002)
QSOs optical counts ($0.3 < z < 5.0$)	
$\sim 1.4 \times 10^5$	Shankar <i>et al.</i> (2004)
$\sim 2 \times 10^5$	Fabian (2003)
$\sim 2.1 \times 10^5$	Yu and Tremaine (2004)
$\sim 2.2 \times 10^5$	Marconi <i>et al.</i> (2004)
$2-4 \times 10^5$	Ferrarese (2002a)
AGN X-ray counts ($z(\text{peak}) \sim 0.7$)	
$\sim 2 \times 10^5$	Fabian (2003)
$\sim 4.1 \times 10^5$	Shankar <i>et al.</i> (2004)
$4.7-10.6 \times 10^5$	Marconi <i>et al.</i> (2004)

- Overall the BH mass density in the local universe seems consistent with that expected from AGNs.
- To be continued ...