Supermassive Black Holes in Galactic Nuclei: Demography and relation with AGN activity

Alessandro Marconi
INAF-Osservatorio Astrofisico di Arcetri

Marco Salvati
Roberto Maiolino
Guido Risaliti
Roberto Gilli

Guillermo Haro Workshop on AGN Surveys

June 23 – July 11, 2003

A brief history

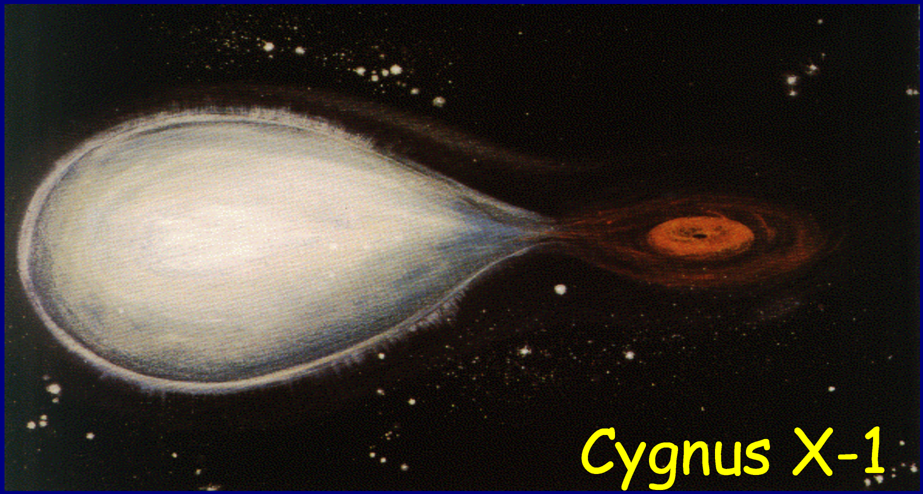
- 1783 - 1796: John Michell and Pierre-Simon Laplace hypothesized the existence of "dark stars": objects with $\rho = \rho_{\odot}$ with R = 500 R would have escape speed larger than c. $M_{\text{Dark Star}} = 1.1 \times 10^8\ M_{\odot}$!
- WRONG assumptions (corpuscolary theory of light; Newtonian mechanics) but CORRECT formula for the "Schwarzschild" radius .
- 1916: Schwarzschild solves Einstein equations and find the "Black Hole" solution.
- 1968: John Wheeler coins the term "Black Hole"
- Beginning of 1970s: X-ray source Cygnus X-1 is the first BH candidate with $M \sim 12\ M_{\odot}$
- 1978: Sargent et al. showed that images and spectra of the central region of M87 could be explained only with the presence of a BH with $M \sim 3 \times 10^9\ M_{\odot}$


Laplace

What types of BHs?

Stellar mass Black Holes
(~1-10 $M_\odot$)

- Endpoints of the life of massive stars



Intermediate Mass Black Holes (~10^2-10^5 $M_\odot$) ???

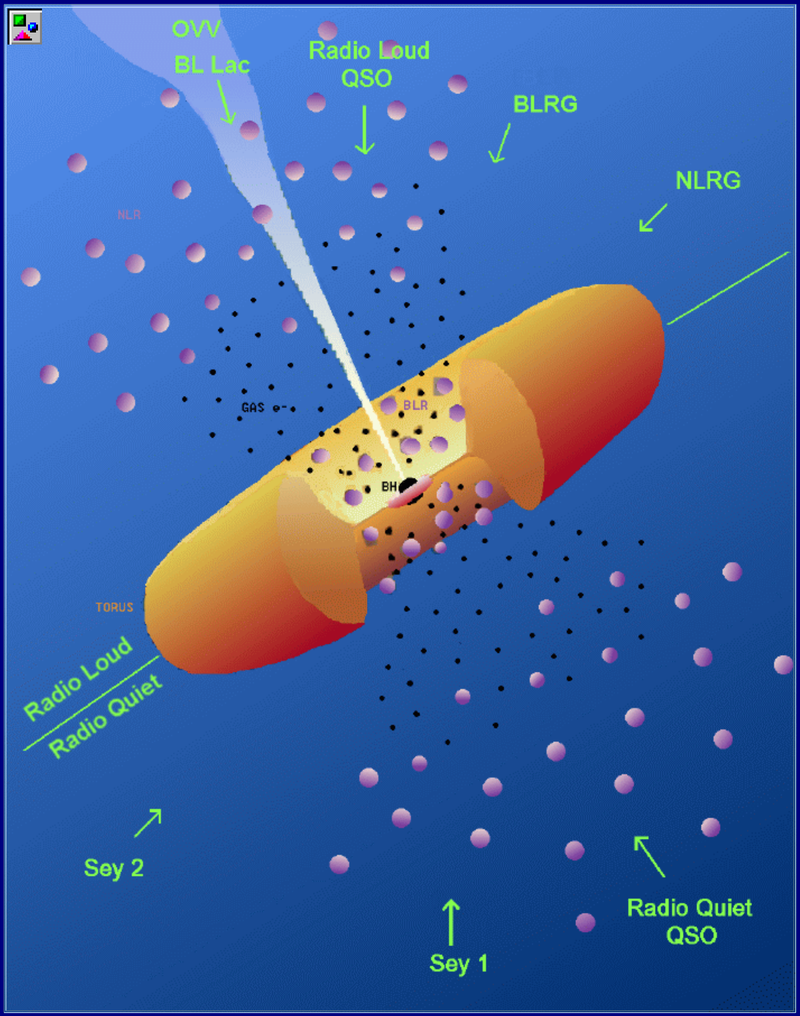
Supermassive Black Holes
(~10^6-10^9 $M_\odot$)

- in galactic nuclei

Active Galactic Nuclei

- Mass accretion onto a massive BH ($>10^6$ $M_\odot$) is widely accepted as the powering mechanism of AGNs.
- It satisfies observational requirements:
  - ✓ high efficiency ($\varepsilon \sim 0.1$)
  - ✓ relativistic motions (e.g. superluminal jets)
  - ✓ rapid time variability (e.g. $c\Delta\tau < 1$ light-day)
  - ✓ compactness (e.g. Cen A, r <10 light-days)
- If the Eddington limit applies an AGN with $L = 10^{12}\ L_\odot$ must have

$$M_{BH} \gtrsim 2.6 \triangle 10^7\ M_\odot$$



Urry & Padovani

Why Black Holes in Normal Galaxies?

- Accretion onto a massive BH is the powering mechanism of Active Galactic Nuclei
- Observed evolution of AGNs (at z~2-3 luminous quasars where ~2 orders of magnitude more numerous than they are now)
- Significant fraction of luminous galaxies should host a BH in their nuclei as a "remnant of past glory"

Why Black Holes in Normal Galaxies?

- ✎ Integrated comoving energy density from AGNs:

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

- ✎ Accretion efficiency $\varepsilon \Rightarrow$ present day mass density:

$$\rho_u = \frac{u}{\varepsilon c^2} = 2.2\times 10^4 \varepsilon^{-1}\,\mathrm{M_\odot\,Mpc^{-3}}$$

Soltan 1982;
Chokshi & Turner 1992

- ✎ Mass density of bulges $\rho_{\mathrm{Bulges}} \simeq 5.3\times 10^8 h\ \mathrm{M_\odot\,Mpc^{-3}}$

$$\frac{M_{BH}}{M_{Bulge}} \simeq 4.2\times 10^{-5} \varepsilon^{-1} h^{-1} = 6\times 10^{-4}\ \ [h=0.7\,;\varepsilon=0.1]$$

How can we find a BH?

Use Gas/Stars as tracers to get velocity field V around the BH

↓

Determine gravitational potential ϕ which gives rise to observed V

$\phi = \phi_{Stars} + \phi_{BH}$

→

Get ϕ_{Stars} from observed light distribution in galaxy nucleus ($L \Rightarrow M$)

↑

$\phi_{BH} = G\ M_{BH}\ R^{-1}$

$(R > R_{Schwarzschild})$

Black Hole Sphere of Influence

- Gravitational field of BH = Galactic gravitational field

$$r_{BH} = \frac{GM_{BH}}{\sigma_\star^2} = 4.3\,\mathrm{pc}\left(\frac{M_{BH}}{10^7\,\mathrm{M}_\odot}\right)\left(\frac{\sigma_\star}{100\,\mathrm{km/s}}\right)^{-2}$$

- For a galaxy at distance D, r_{BH} corresponds to an angular size:

$$\theta_{BH} = 0.1''\left(\frac{M_{BH}}{10^7\,\mathrm{M}_\odot}\right)\left(\frac{\sigma_\star}{100\,\mathrm{km/s}}\right)^{-2}\left(\frac{D}{10\,\mathrm{Mpc}}\right)$$

- Need <u>high spatial resolution</u> to probe within the BH sphere of influence and detect its effects! This is why the Hubble Space Telescope has produced such a major impact in the field.

Gas Kinematics vs Stellar Dynamics

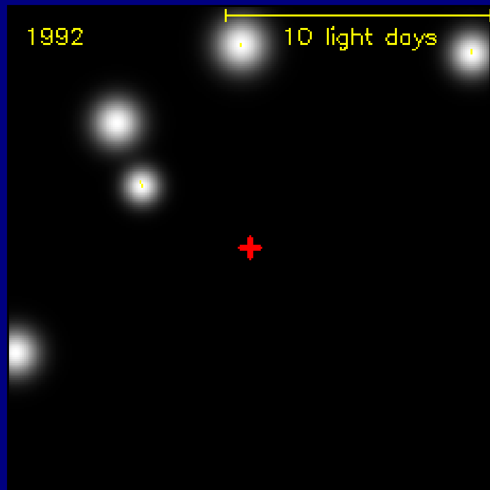
Gas:

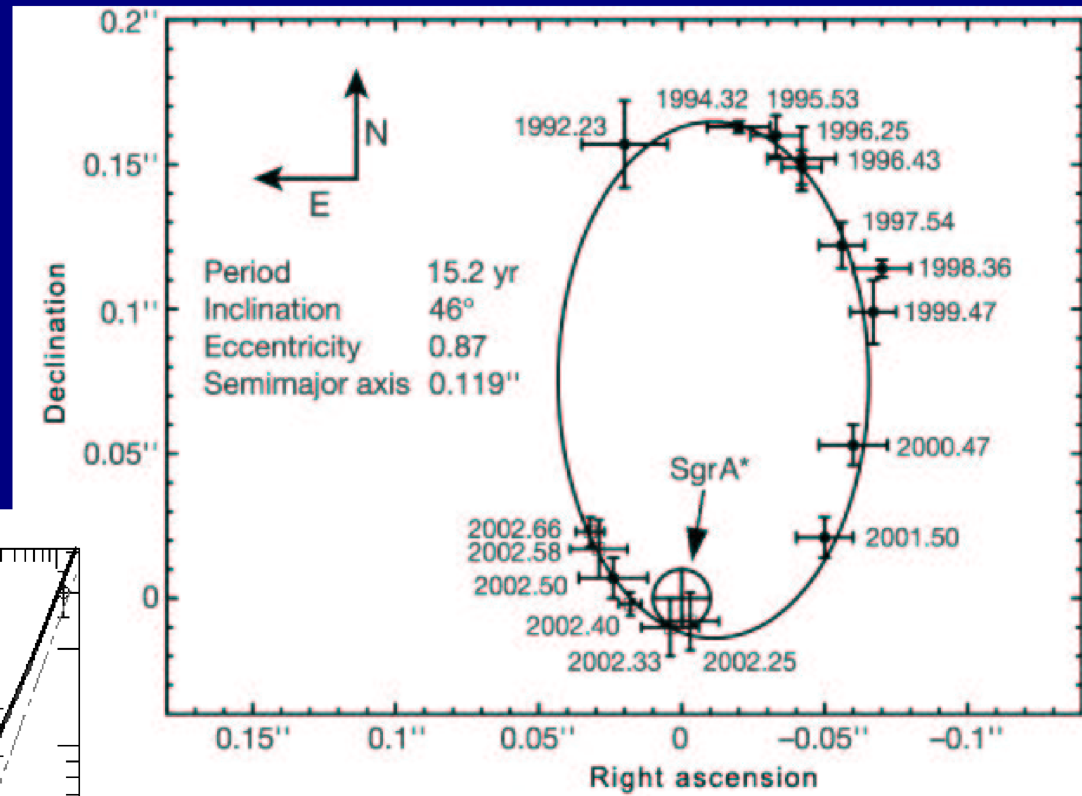
- high surface brightness, short integration times
  - but not in all galaxies
- easy interpretation
  - only if system is a circularly rotating disk

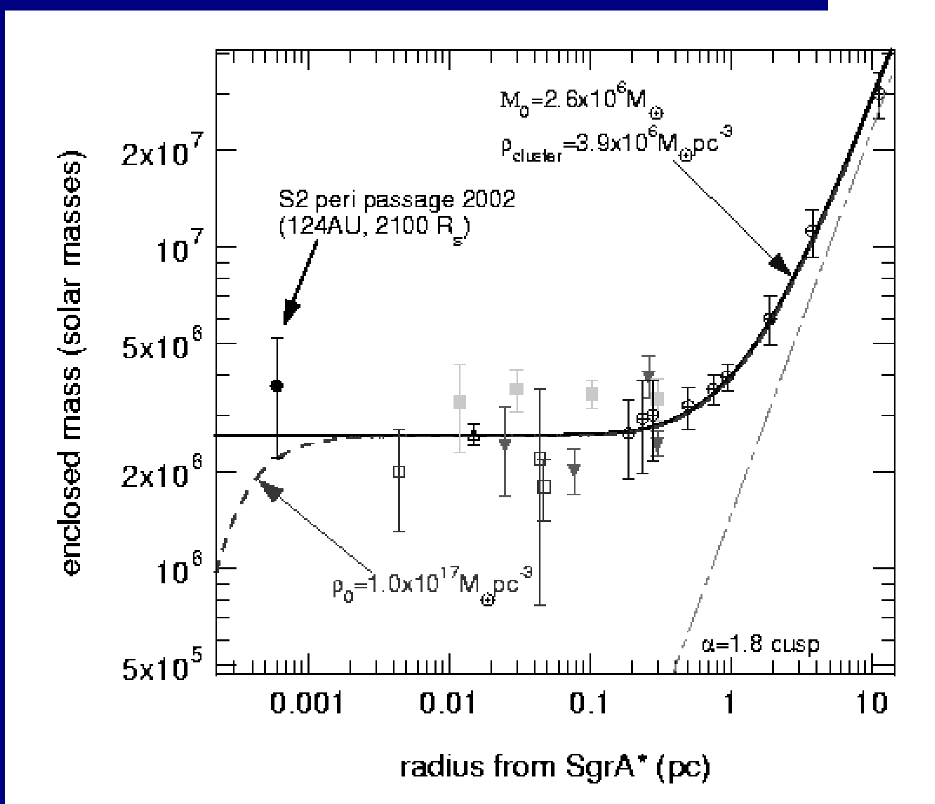
Stars:

- completely gravitational motions
  - but interpretation difficult (complex orbital structure)
- available in all galaxies
  - but observations require long integration times

The Galactic Center



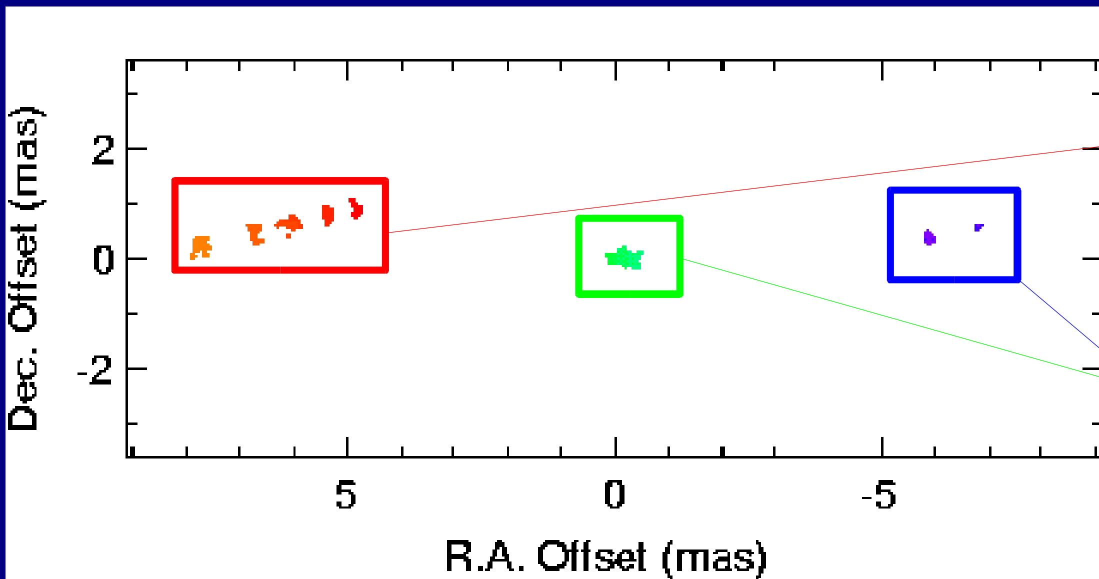


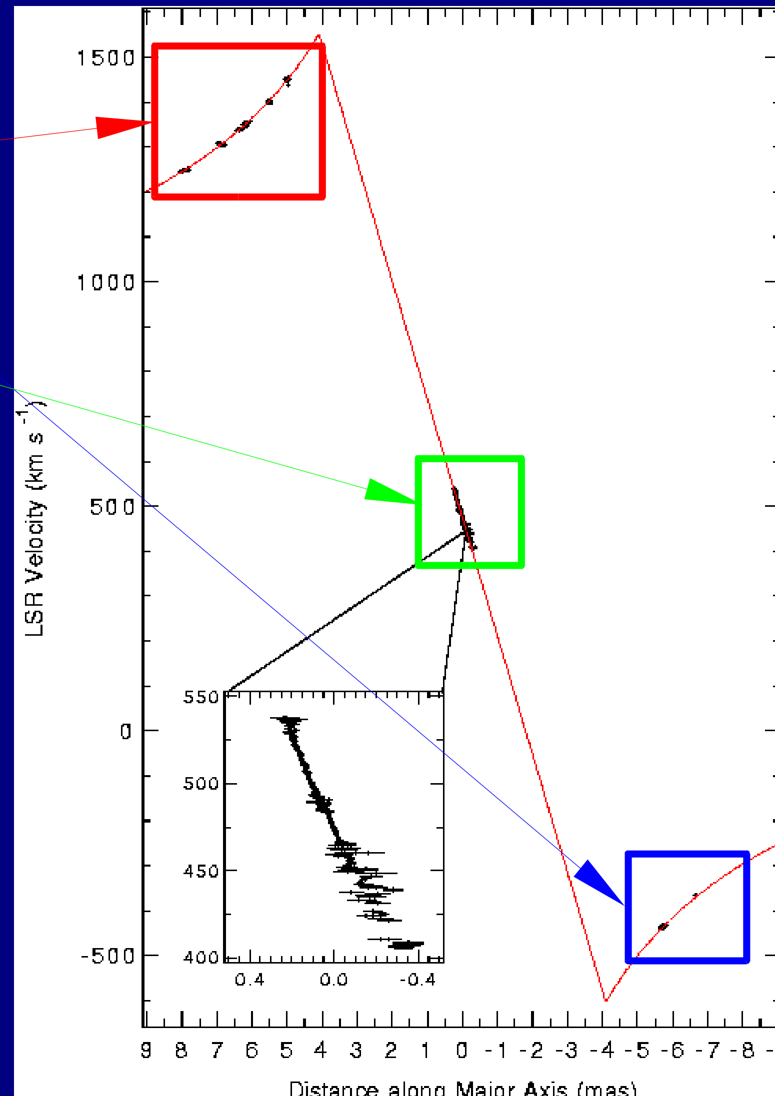


$$M_{BH} = 2.6 \times 10^6 M_\odot$$

Genzel et al. 2000; Schodel et al. 2002

Extragalactic BHs: NGC 4258



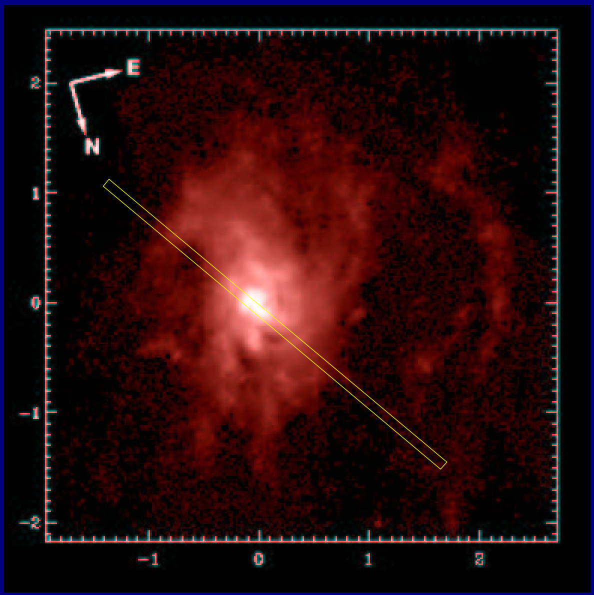


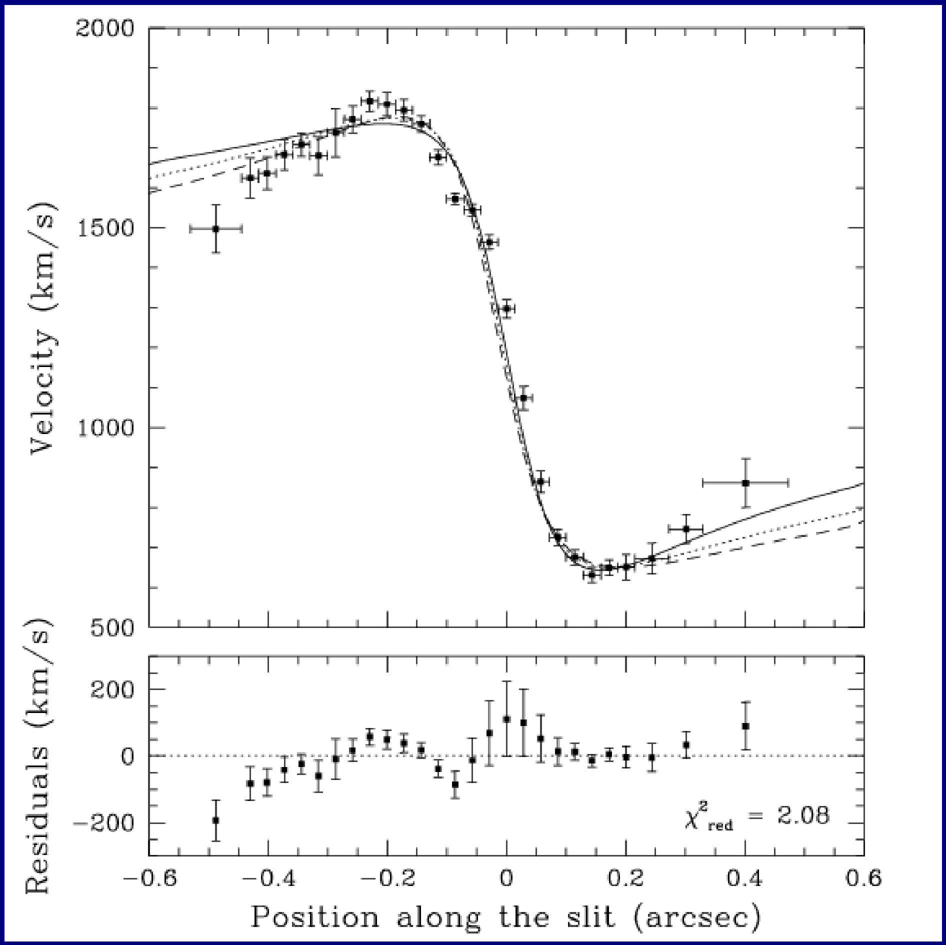
High spatial resolution VLBI observations of H_2O maser emission at the nucleus of NGC4258

$M_{BH} = 4 \triangle 10^7 M_\odot$

Miyoshi et al. 1995; Greenhill et al. 1995

M87

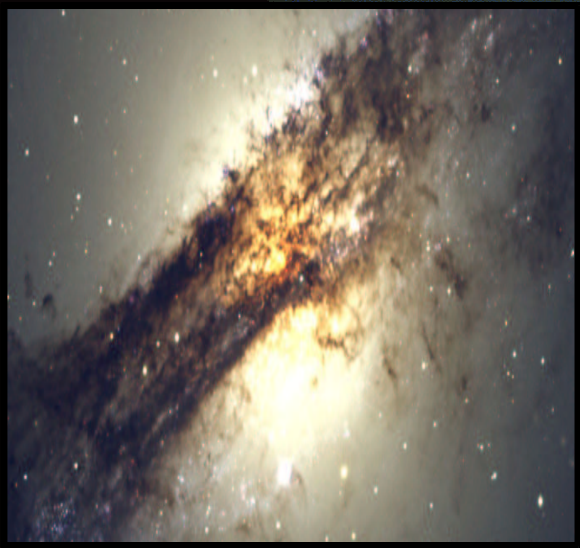




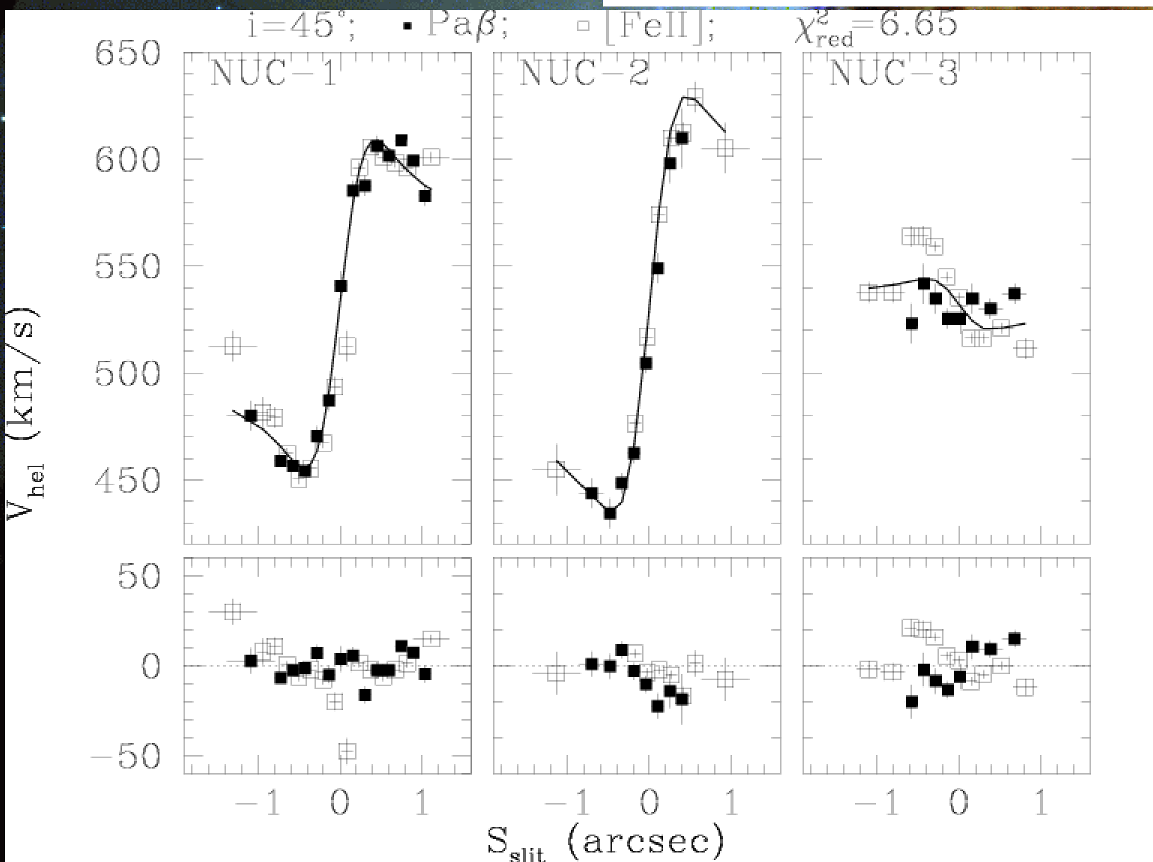
- Hubble Space Telescope longslit rotation curve from emission line [OII] λ 3727 Å (0.1" spatial resolution)
- To account for the observed rotation curve one requires
  $M_{BH}=(3.2 \pm 0.9) \times 10^9\ M_\odot$
- $L/L_{Edd} < 10^{-6}$; quasar relic?

Macchetto, Marconi, et al. 1997

Centaurus A

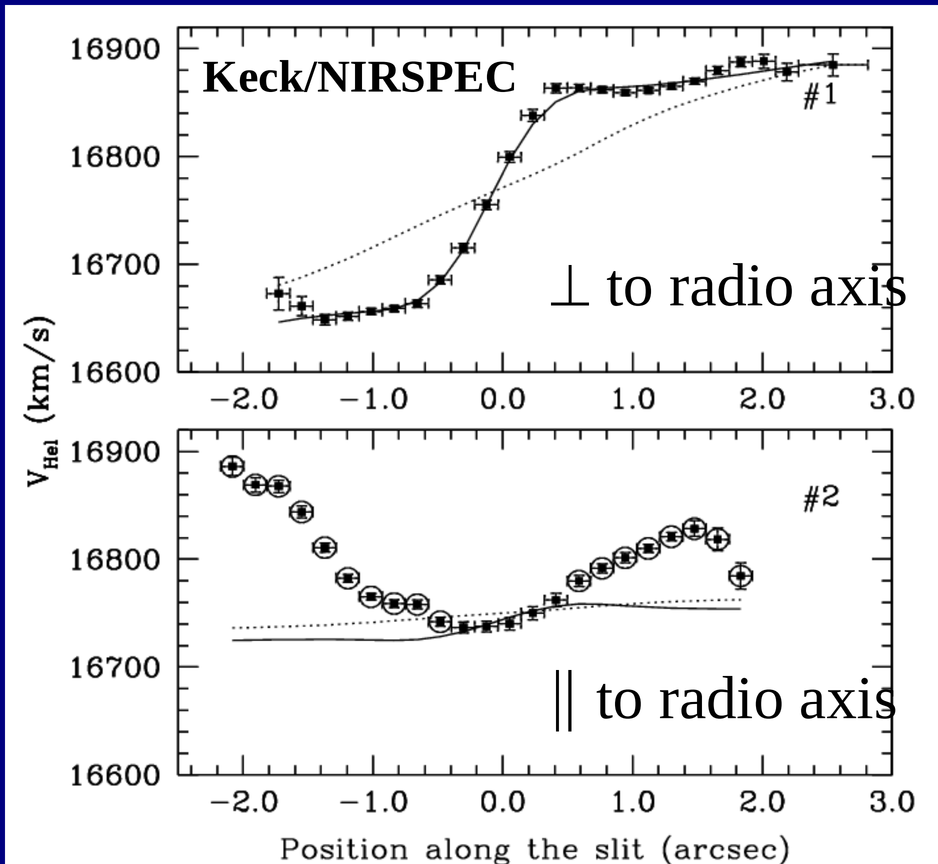


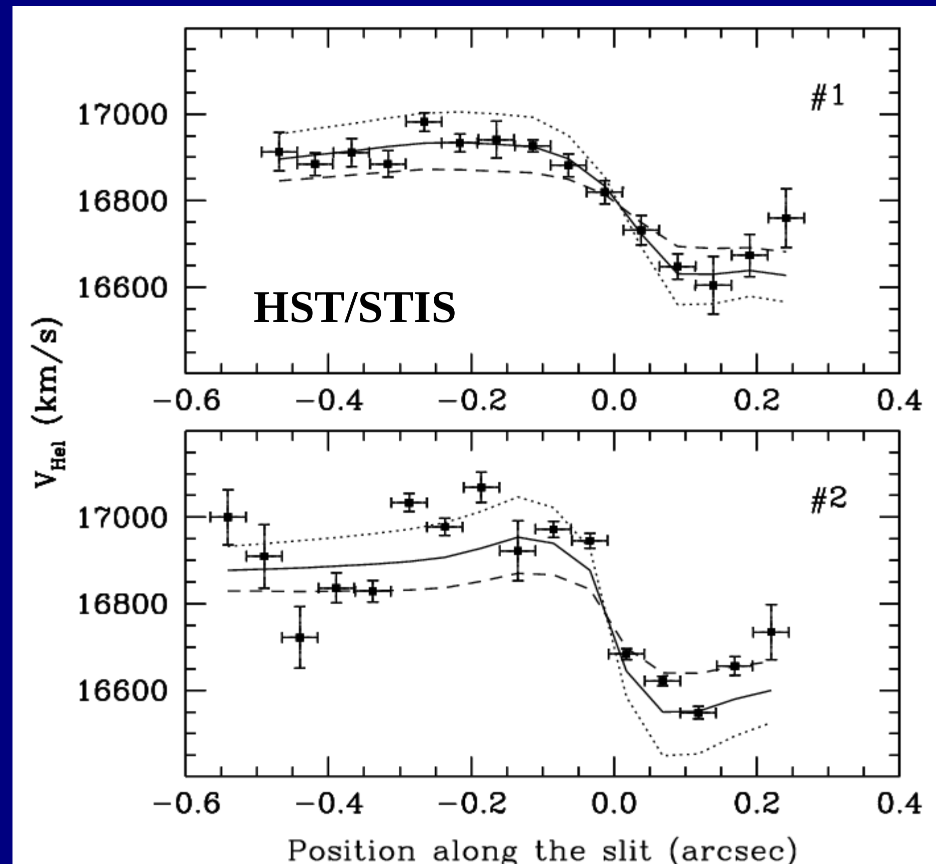
Marconi et al. 2001



- A_v~7 toward nuclear region require near-IR spectroscopy which is not possible from the Hubble Space Telescope!
- We used the ESO-VLT to get medium resolution spectra in the J band with good seeing (0.5”)
- Fit of the rotation curve requires: $M_{BH} \sim 2 \times 10^8 M_\odot$
- L/L_{Edd} ~ 10-3, low level of activity!

Cygnus A

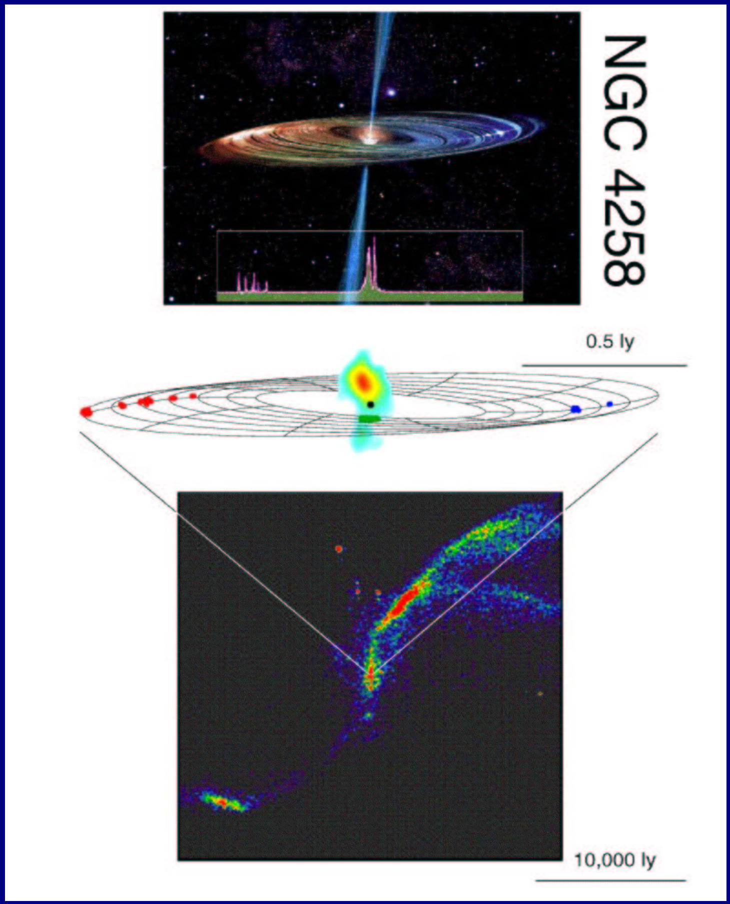




Tadhunter, Marconi, et al. 2003

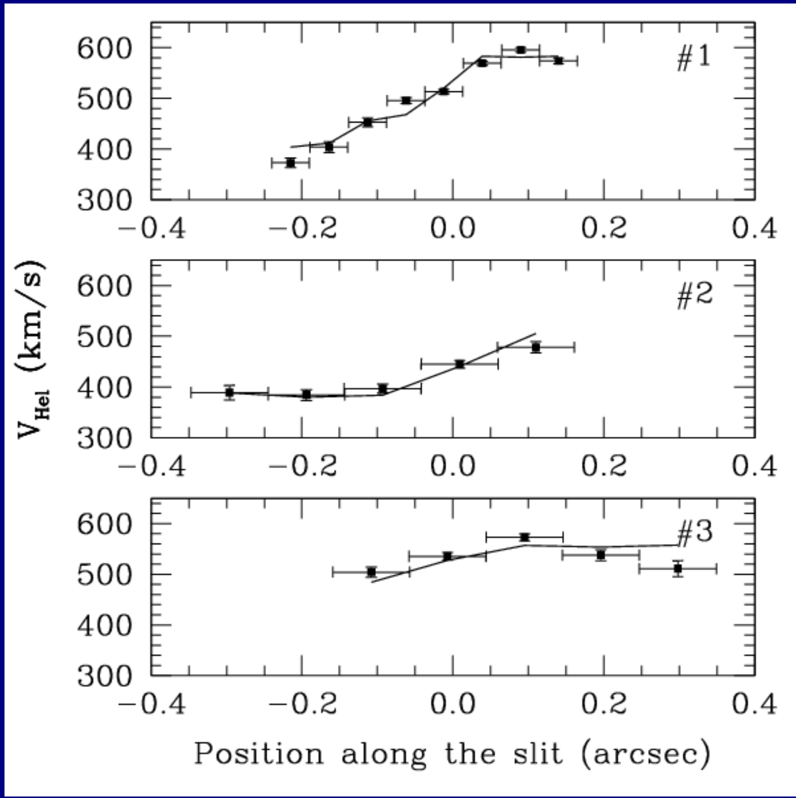
- $M_{BH} = 2.7^{+0.7}_{-1.3}$ △ $10^9 M_\odot$
- First time that the BH mass is measured in an AGN with Quasar-like luminosity (L $10^{12} L_\odot$)
- L/L_{Edd} 0.02; is it the relic of an even more powerful AGN?

NGC 4258



Miyoshi et al. 1995

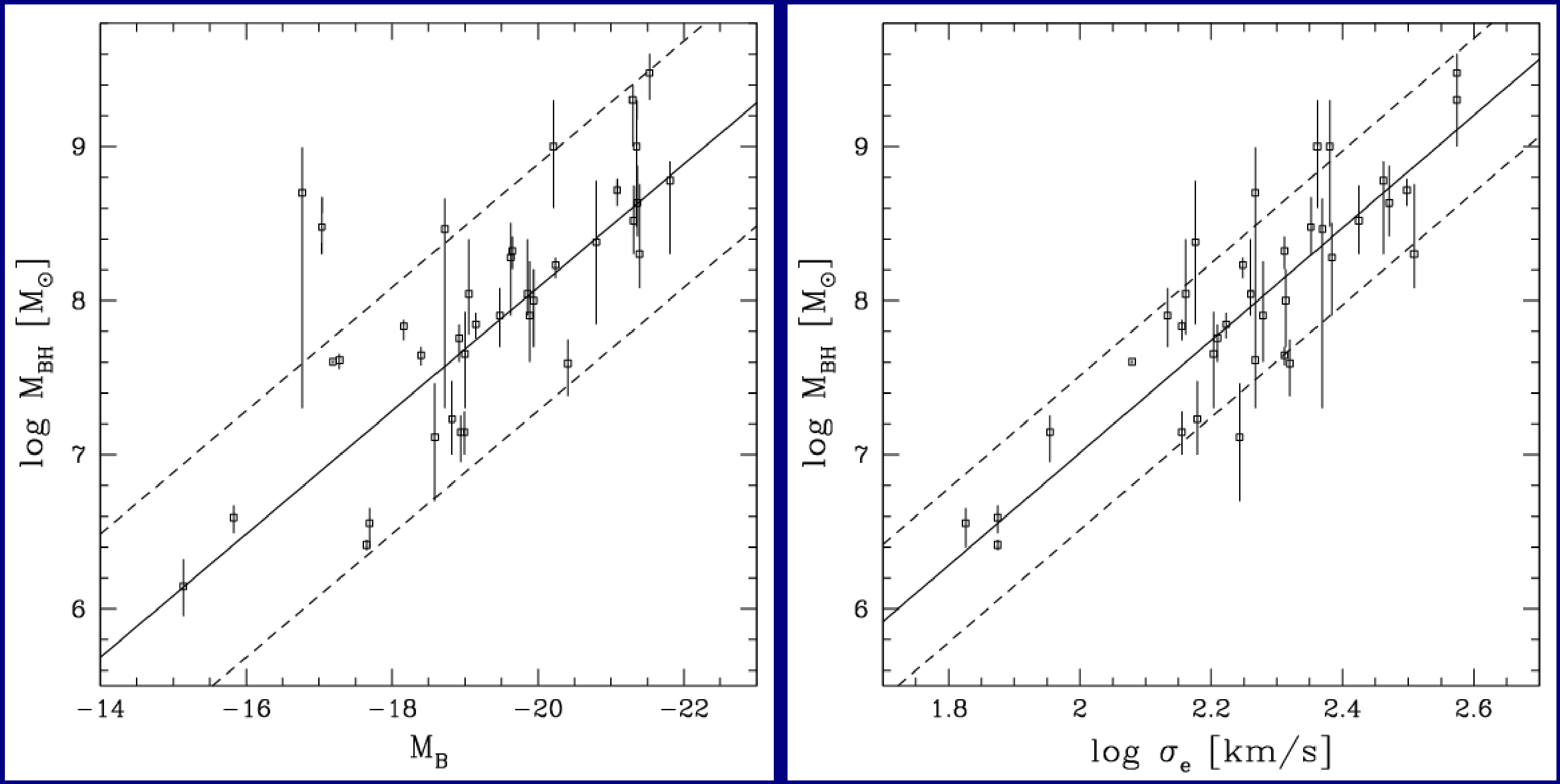
- In NGC 4258 a BH has been detected from kinematics of H_2O masers ($M_{BH} = 4\times10^7\ M_\odot$)
- Second best case for a SMBH after our galactic center and is a crucial test for the gas kinematical method!



Axon, Marconi, et al. 2003

- HST observations, 3 parallel slits
- $M_{BH} = 4^{+4}_{-2} \times10^7\ M_\odot$ in agreement with maser data!
- Gas Kinematics and Stellar Dynamics give the same answer!

Massive Black Holes in Galactic Nuclei



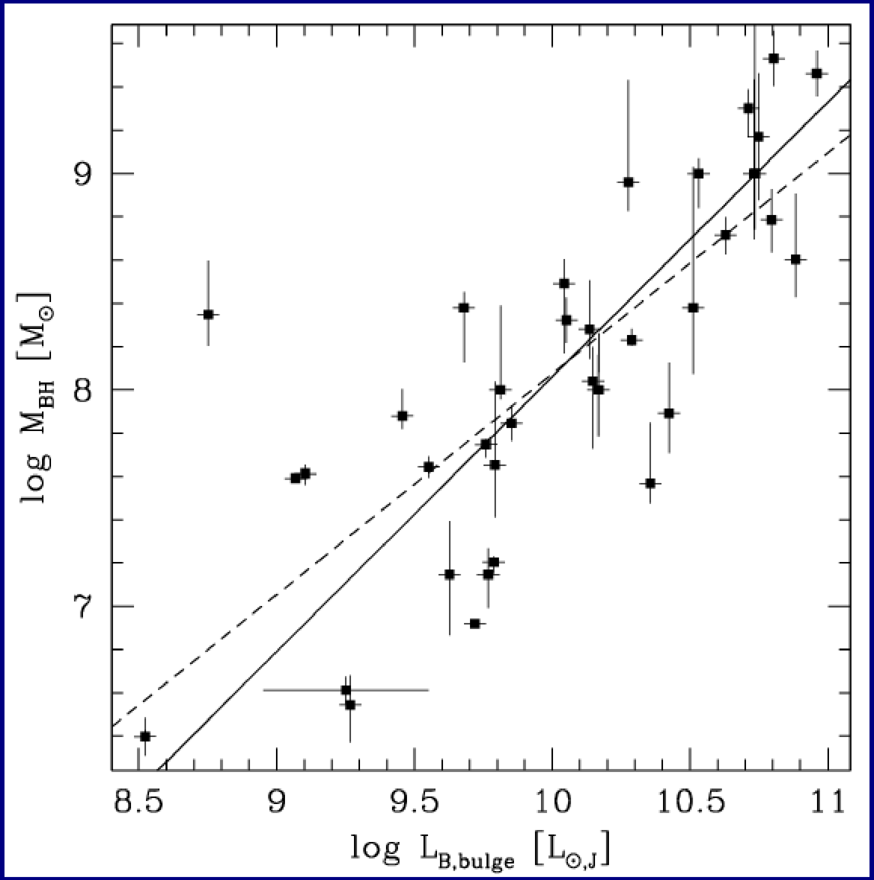
Kormendy & Richstone 1995; Merritt & Ferrarese 2000; Gebhardt et al. 2000

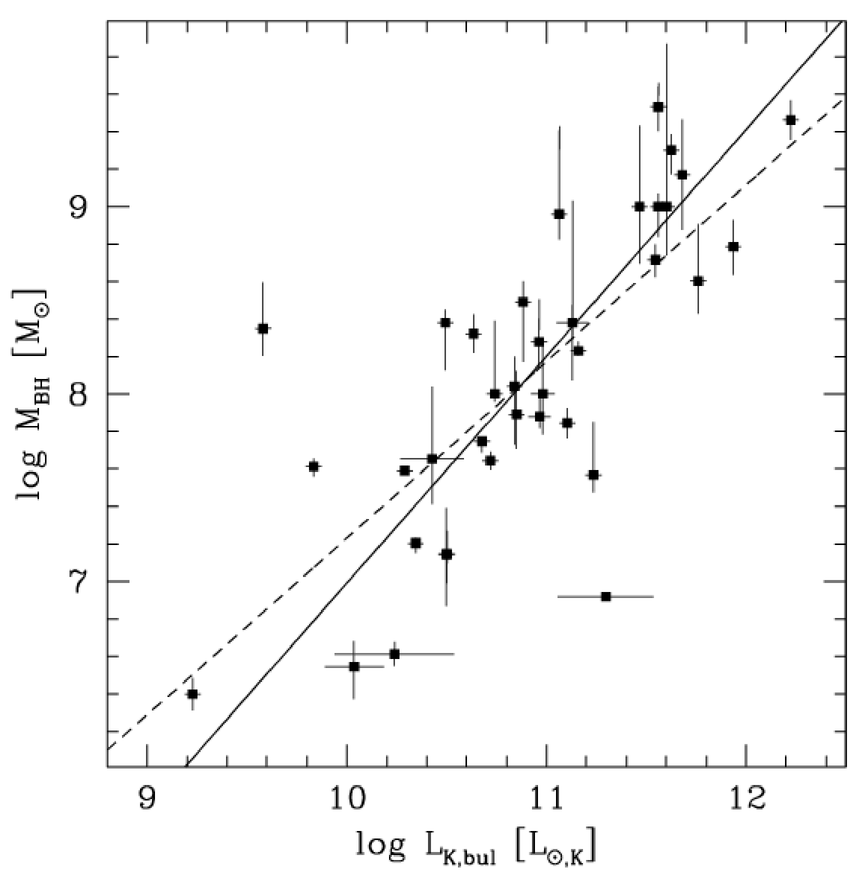
- ➢ Observations currently suggest that massive Black Holes are present in ALL galaxies.
- ➢ The BH mass correlates with the luminosity of the host spheroid and stellar velocity dispersion.

BH Mass vs Host Galaxy Properties

- M_{BH}-σ_e is believed to be tighter than M_{BH}-$L_{B,bul}$ (rms 0.25 vs 0.5 in log M_{BH}) suggesting that bulge dynamics (mass) drives the correlations (e.g. Tremaine et al. 2002)
- What is the reason of the larger scatter of M_{BH}-$L_{B,bul}$?
- Marconi & Hunt (2003) have investigated the M_{BH}-L_{bul} relation in the near-IR (reduce reddening and M/L effects on scatter).
- 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.
- Divide sample in 2 Groups: in Group 1 place galaxies with reliable BH masses (e.g. BH sphere of influence resolved, BH mass well constrained by data).

B band (literature) vs K band (new)



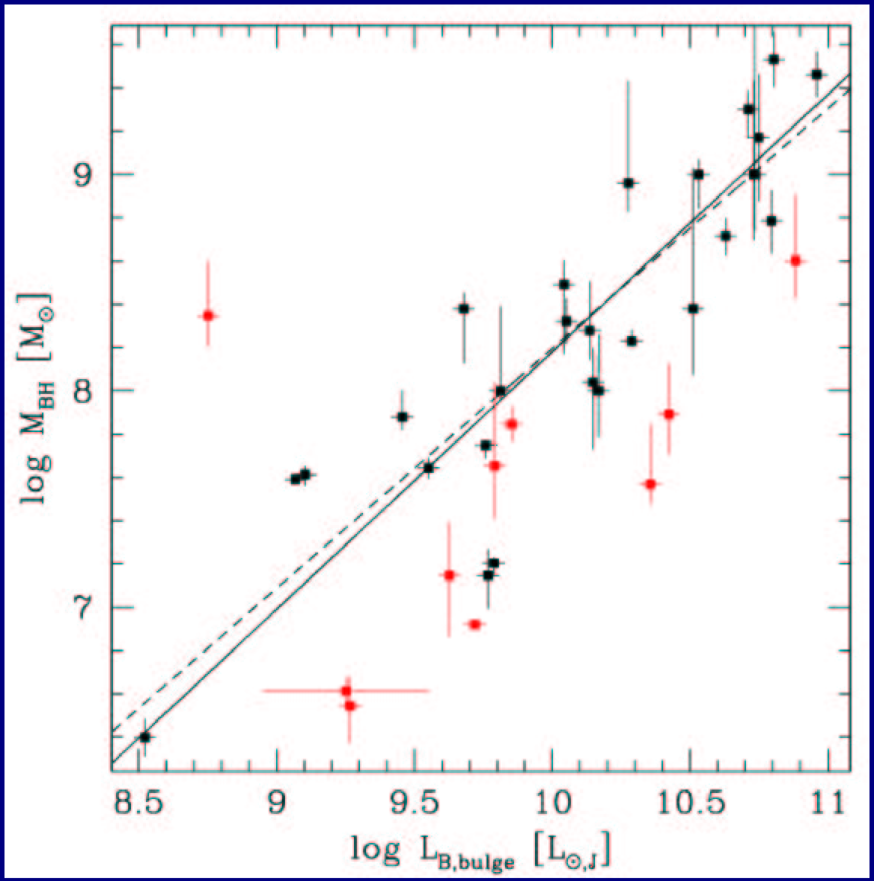


B band: rms 0.5

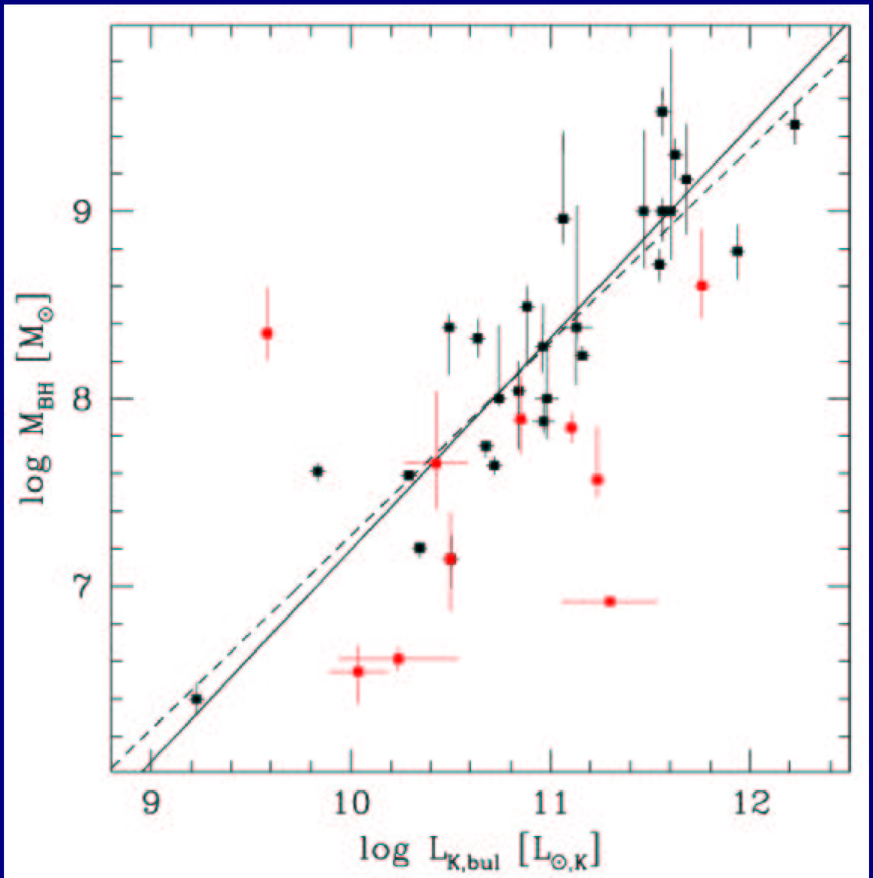
K band: rms 0.5

Marconi & Hunt 2003

B band vs K band: only Group 1 galaxies



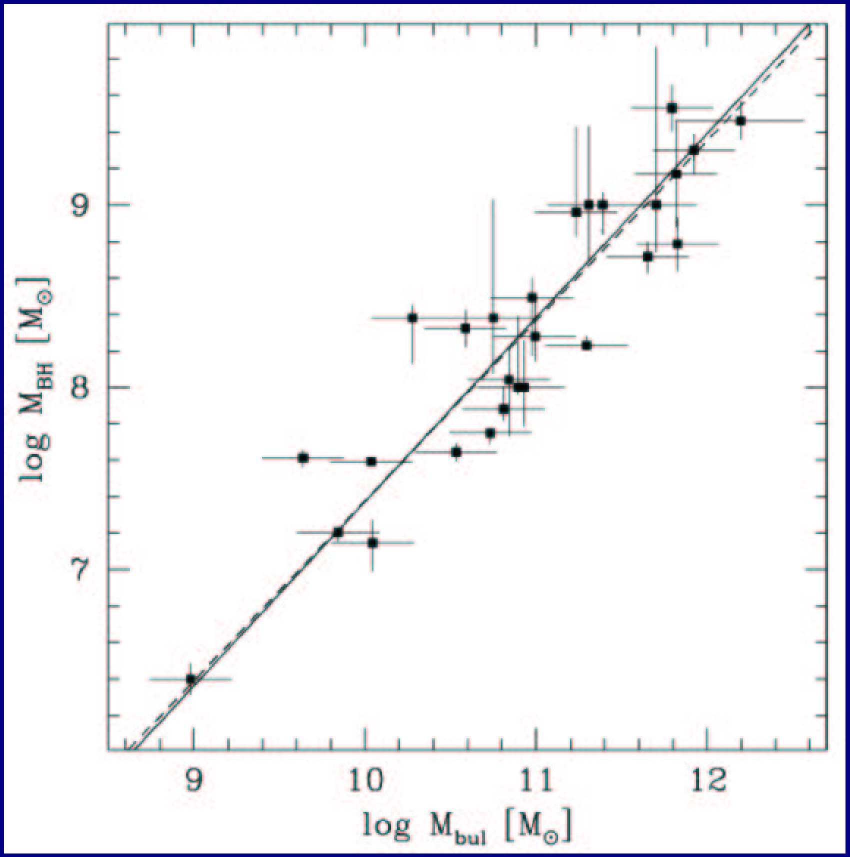
B band: rms 0.3



K band: rms 0.3

Marconi & Hunt 2003

M_{BH} vs M_{bul}



rms 0.25 (all 0.5)

- Tight correlation between M_{BH} and virial bulge mass

  $(M_{bul} \propto R_e\, \sigma_e^{\,2})$

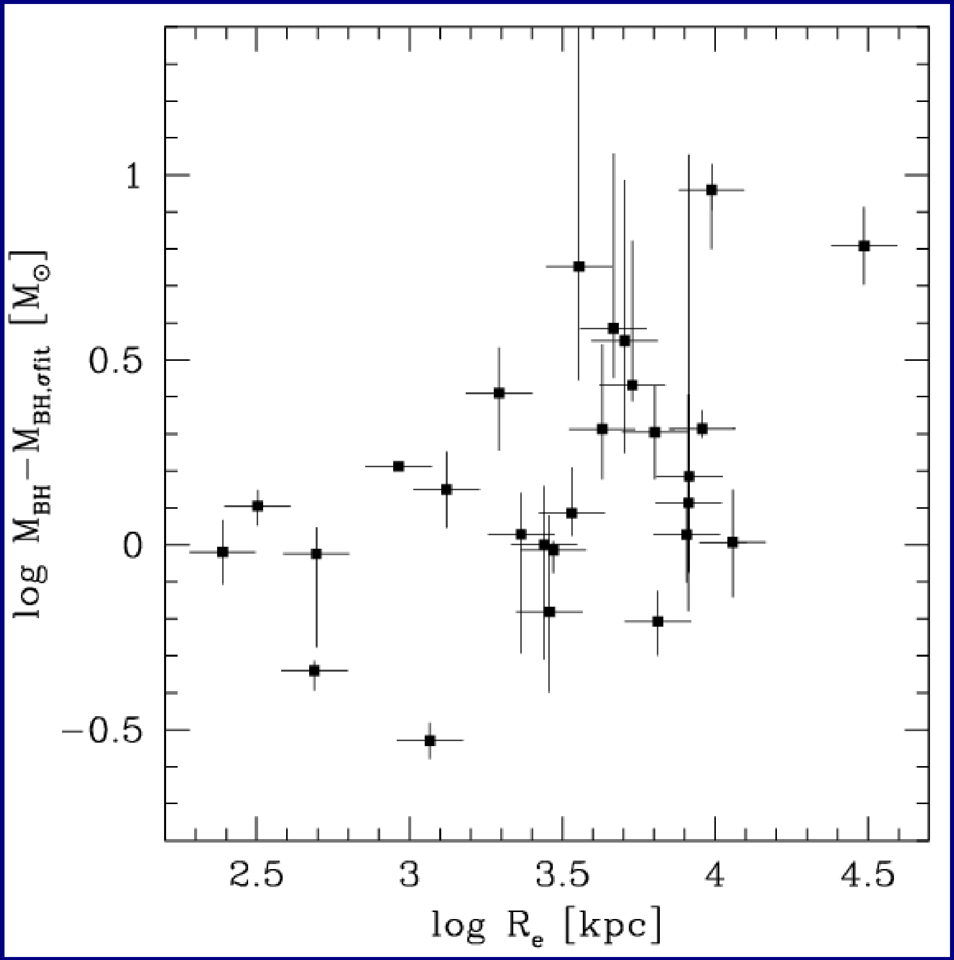
- linear slope (0.96+/-0.07)
- Average ratio

  $M_{BH/}M_{bul} \simeq 0.002$

- Merritt & Ferrarese (2001) find -2.9 (estimate M_{BH} in sample of galaxies using M_{BH}-σ_e). With their method we find -2.8.

What is the origin of the correlations?

- M_{BH}-L_{bul} : from M_{BH}-M_{bul}!
  - $M_{BH} \sim L_{bul}^{1.15}$ and $M_{BH} \sim M_{bul}$ are consistent if $(M/L)_{bul} \sim L_{bul}^{0.15}$ consistent with literature data
- Are M_{BH}-σ_e and M_{BH}-$R_e\sigma_e^2$ the same? i.e. is M_{BH}-$R_e\sigma_e^2$ a consequence of M_{BH}-σ_e combined with the known σ_e-Re correlation?
- Partial correlation analysis shows that M_{BH} correlates with both σ_e and R_e (after removing the effects of σ_e-Re), i.e. M_{BH} depends on both σ_e and R_e!



A weak, but significant correlation between the residuals of M_{BH}-σ_e and the effective radius R_e. With these data we can not say more!

- M_{BH}-$L_{NIR,bul}$ correlate and, if only secure BH masses are considered, the spread of M_{BH}-L_{bul} is similar to that of M_{BH}-σ_e regardless of photometric band (B, J, H and K)
- M_{bul} tightly correlates with M_{BH} (M_{BH}/M_{bul}~0.002)
- M_{BH} depends on both σ_e and R_e and both variables are necessary to drive the correlations between BH mass and other bulge properties.

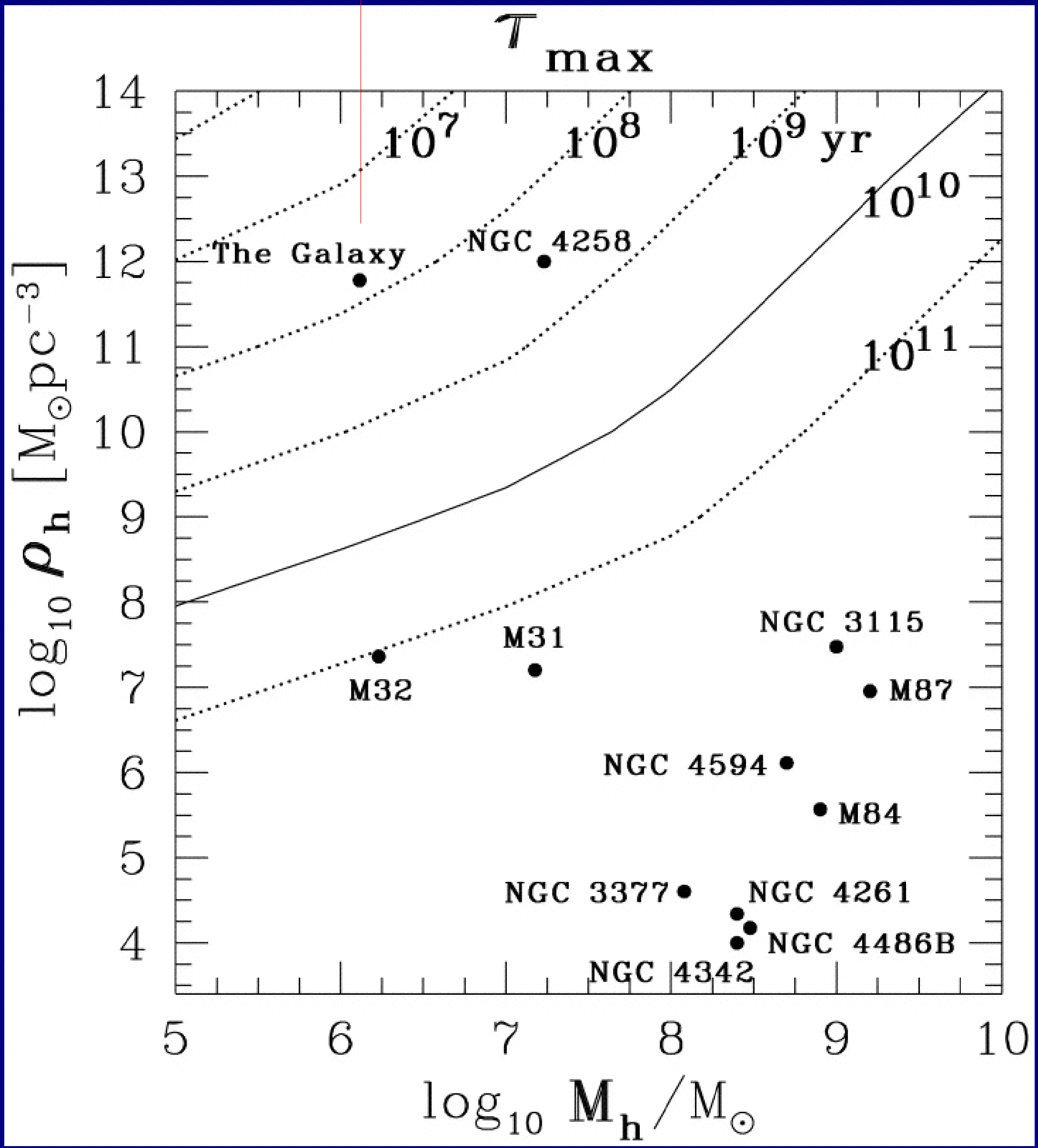
Are they really massive BHs?

In reality, stellar and gas kinematical observations detect *Massive Dark Objects* (MDO), not Black Holes!

Only in a few cases (e.g. GC, NGC 4258) an alternative explanation to a BH can be confidently ruled out.

The proof that a MDO is a BH is the detection of relativistic motions close to the Schwarzschild radius (Kormendy & Richstone 1995)!

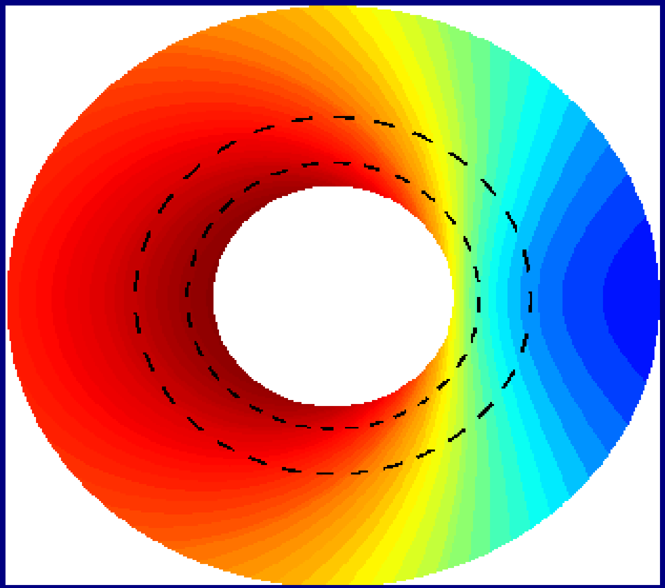
MDO: are they SMBH?



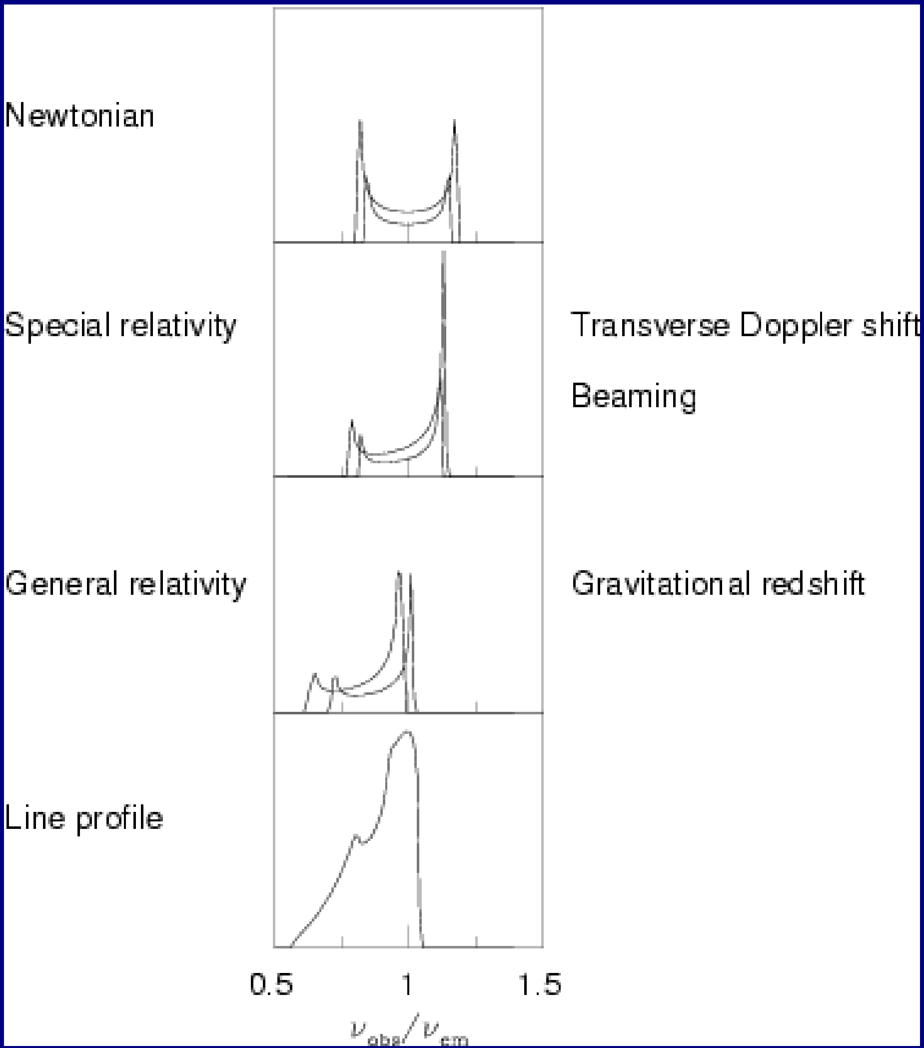
τ_{MAX} is the Survival Time for a Cluster of dark objects (stellar remnants, brown dwarfs, planets)

In τ_{MAX} core collapse or collisions will produce a massive BH, eventually embedded in a dark cluster

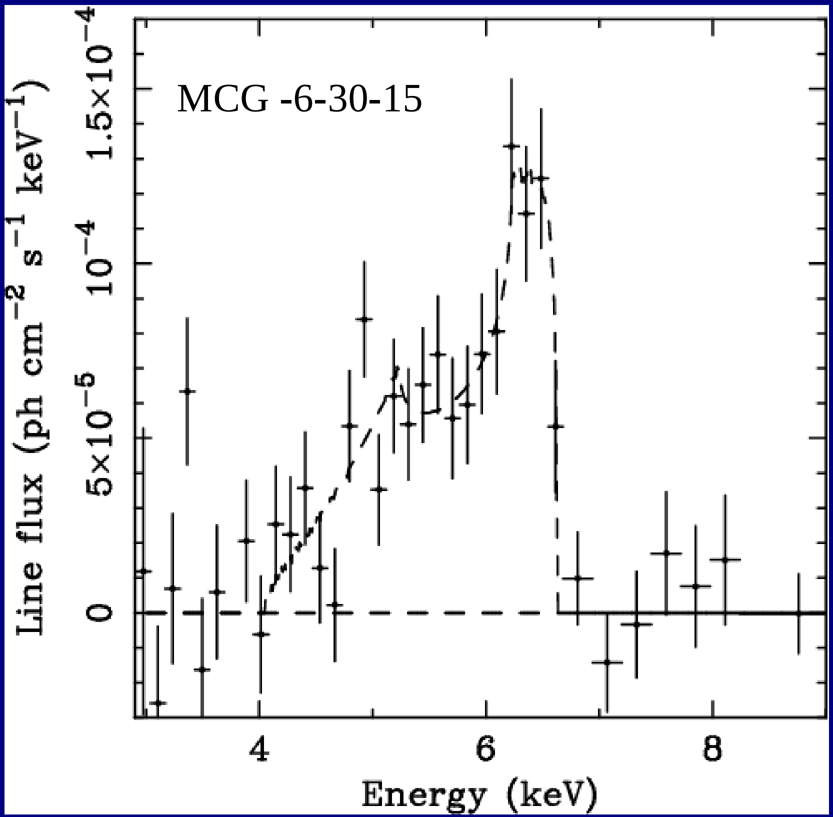
Fe Kα at 6.4 keV: broad red wing from relativistic effects!



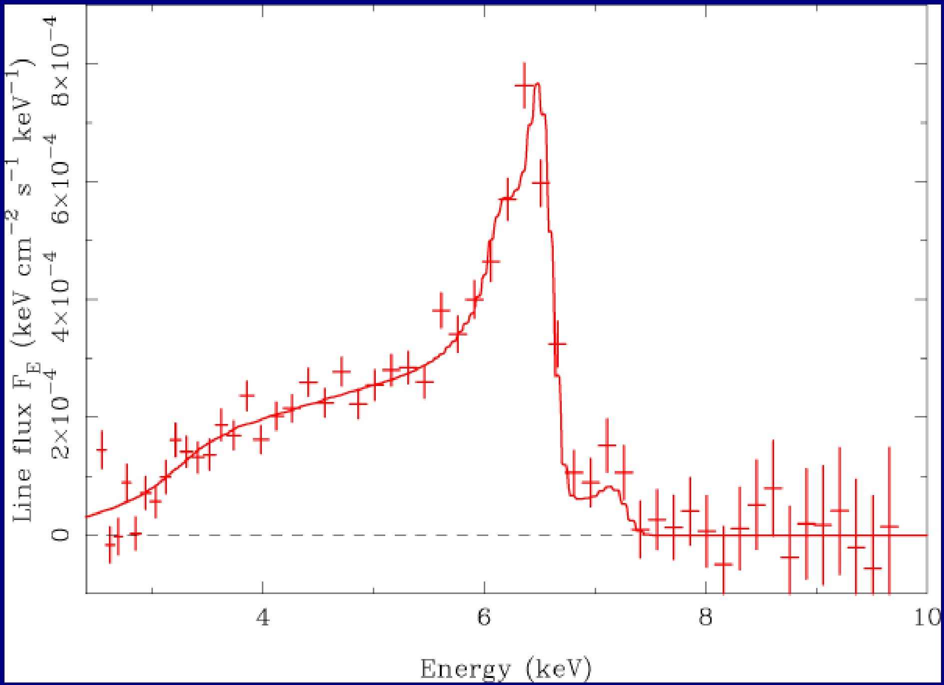
Fabian et al. 2000



A broad red wing in Fe Kα at 6.4 keV



ASCA -Tanaka et al., 1995



XMM – Fabian et al., 2002

But this is not conclusive yet!

Relic Black Holes

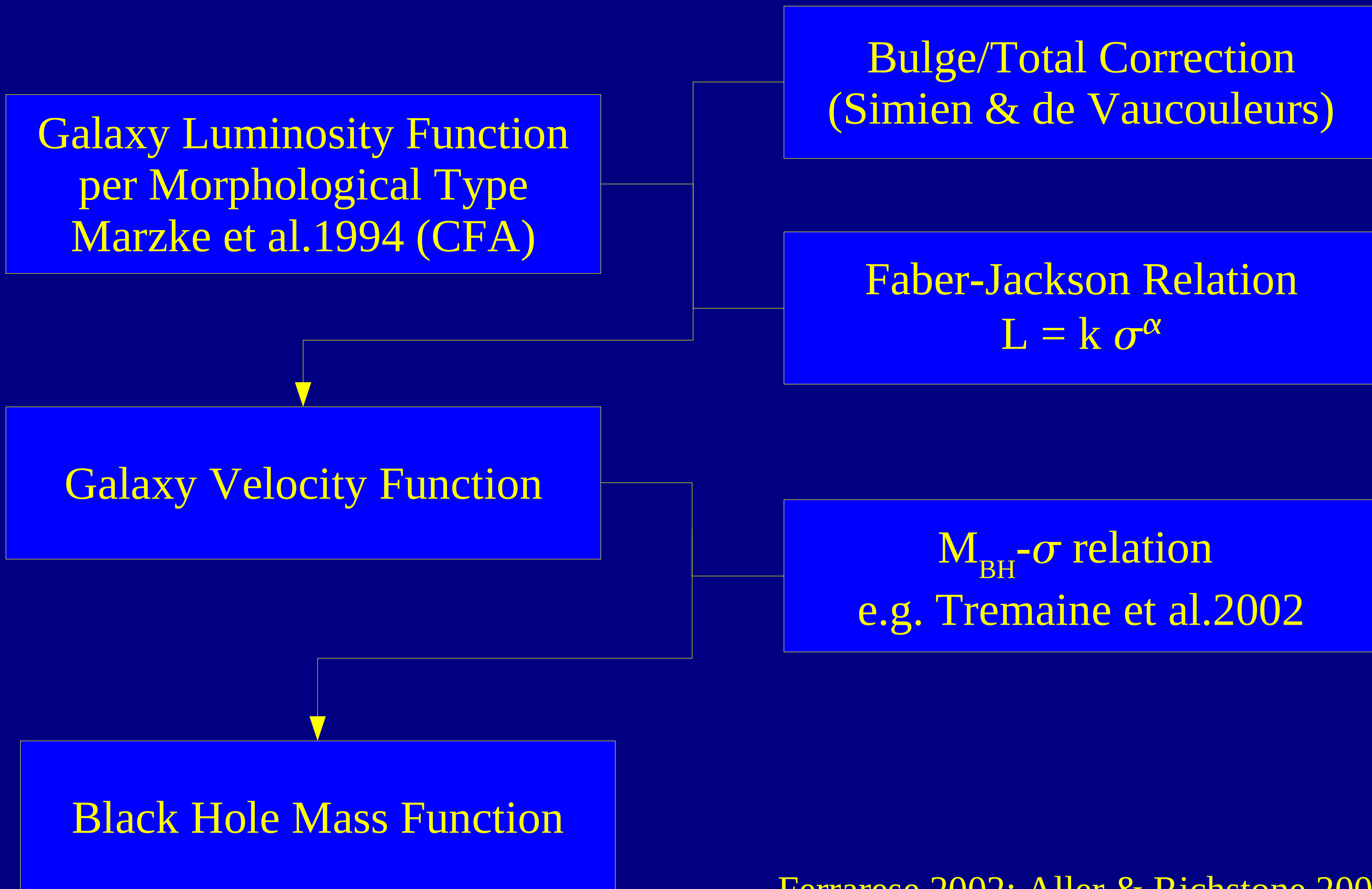
- Are local BHs relics of past AGN activity?
- One needs to compare past AGN activity with local BHs: this can be achieved by comparing local BH mass function with the BHMF of AGN relics.
- From the comparison of the two (not only densities!) one can find if there are inconsistencies.
- Recently various authors have been saying that there are inconsistencies at large masses, $M_{BH} > 10^8 M_\odot$ (e.g. Ferrarese 2002, Yu & Tremaine 2002)!

Local BH mass function [$dN = \phi(M_{BH})\, dM_{BH}$]

- There are ~30 galaxies with a DIRECT BH mass determination and these are not enough to estimate the BHMF.
- One can use galaxy Luminosity/Velocity functions [$\phi(L)$ or $\phi(\sigma)$], apply the known correlations between BH mass and galaxy properties and obtain the BHMF
  - $\phi(M_{BH}) = \phi(L) dL/dM_{BH}$ with $\log M_{BH} = a + b \log L_{bul}$ and $L_{bul} = f\, L$
  - $\phi(M_{BH}) = \phi(\sigma) d\sigma/dM_{BH}$ with $\log M_{BH} = c + d \log \sigma$ (this is thought to be more “reliable”)

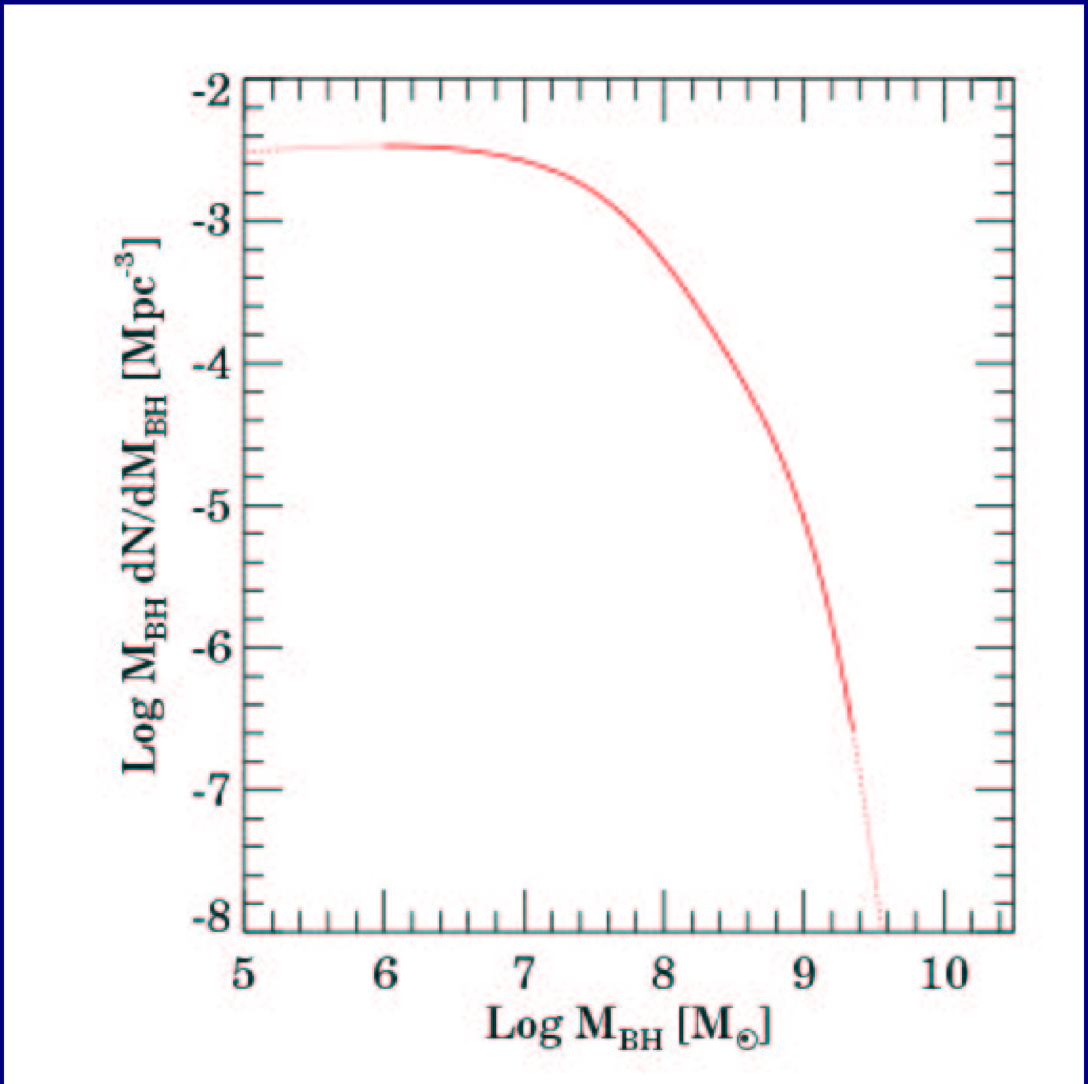
Salucci et al. 1998; Marconi & Salvati 2001; Ferrarese 2002; Aller & Richstone 2002

The Local BH Mass Function



Ferrarese 2002; Aller & Richstone 2002

The Local BH Mass Function



Aller & Richstone 2002

$\rho_{BH} = 2.1 \triangle 10^{5}\ M_{\odot}\ Mpc^{-3}$

Cosmology:

h=0.7

Ω_M=0.3

Ω_Λ=0.7

Continuity equation

We use the Small & Blandford (1982) formalism and write the *continuity equation* for the BH mass function *N(M,t)* as

$$\frac{\partial N(M,t)}{\partial t}+\frac{\partial}{\partial M}\left[N(M,t)\langle\dot{M}(M,t)\rangle\right]=0$$

Note that no source term is present, i.e. no merging of BHs.

Assume that a BH with mass M at time t accretes at the Eddington rate ($L=Mc^2/t_E$) with a duty cycle δ(M,t), thus

$$\langle\dot{M}\rangle N=\frac{1}{\varepsilon t_E}\delta(M,t)MN(M,t)=\frac{1}{\varepsilon t_E}\left[\phi(L,t)\right]_{L=\frac{M}{t_E}c^2}$$

ϕ(L,t) is the AGN luminosity function ε is the accretion efficiency (ε = 0.1 fixed)

Evolution of BH mass function

Finally we get

$$\frac{\partial N(M,t)}{\partial t} = -\frac{c^2}{\varepsilon t_E^2}\left(\frac{\partial \phi(L,t)}{\partial L}\right)_{L=\frac{M}{t_E}c^2}$$

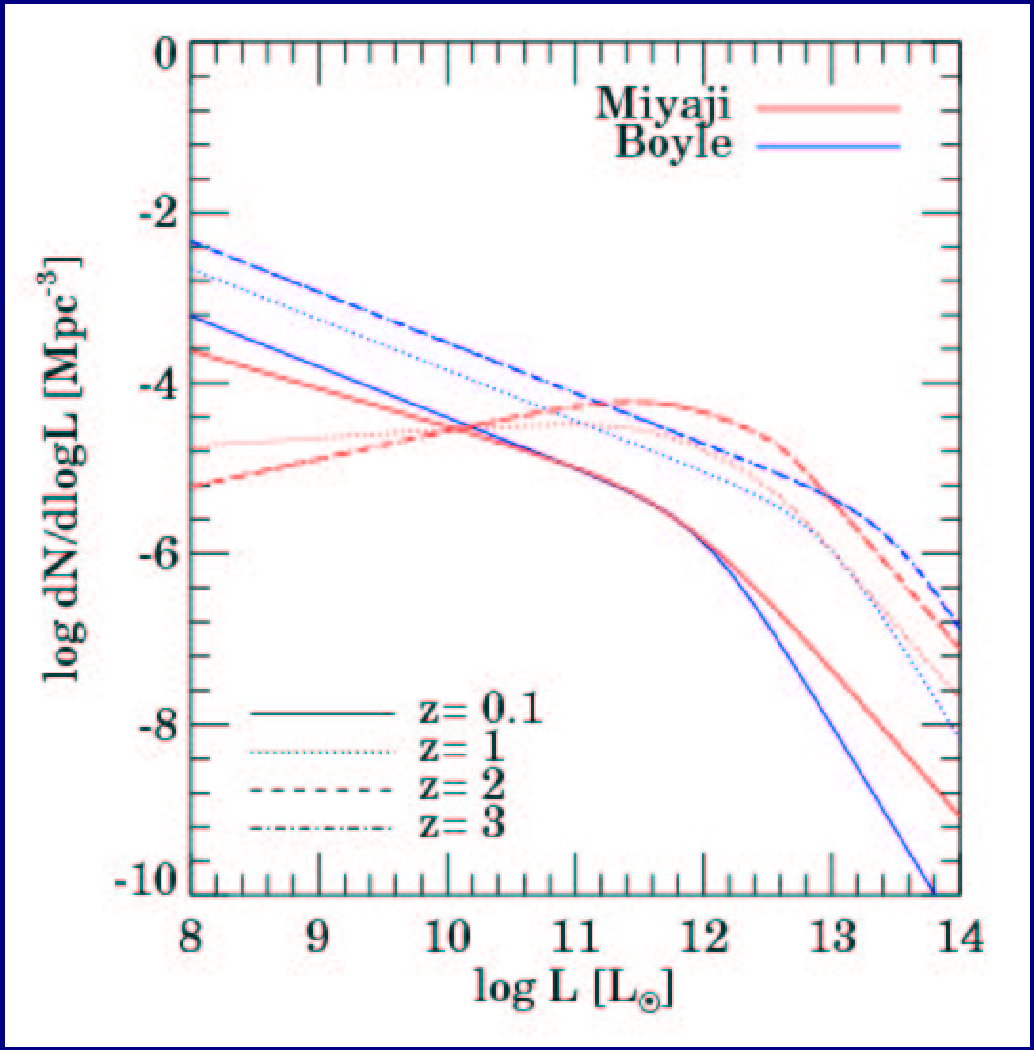
which can be easily integrated given the AGN luminosity function AND the initial conditions.

For the initial conditions we assume that at the starting redshift z_o [$t_o = t\,(z_o)$] ***ALL*** Black Holes are active, i.e. $\delta(M,t\,(z_o))=1$

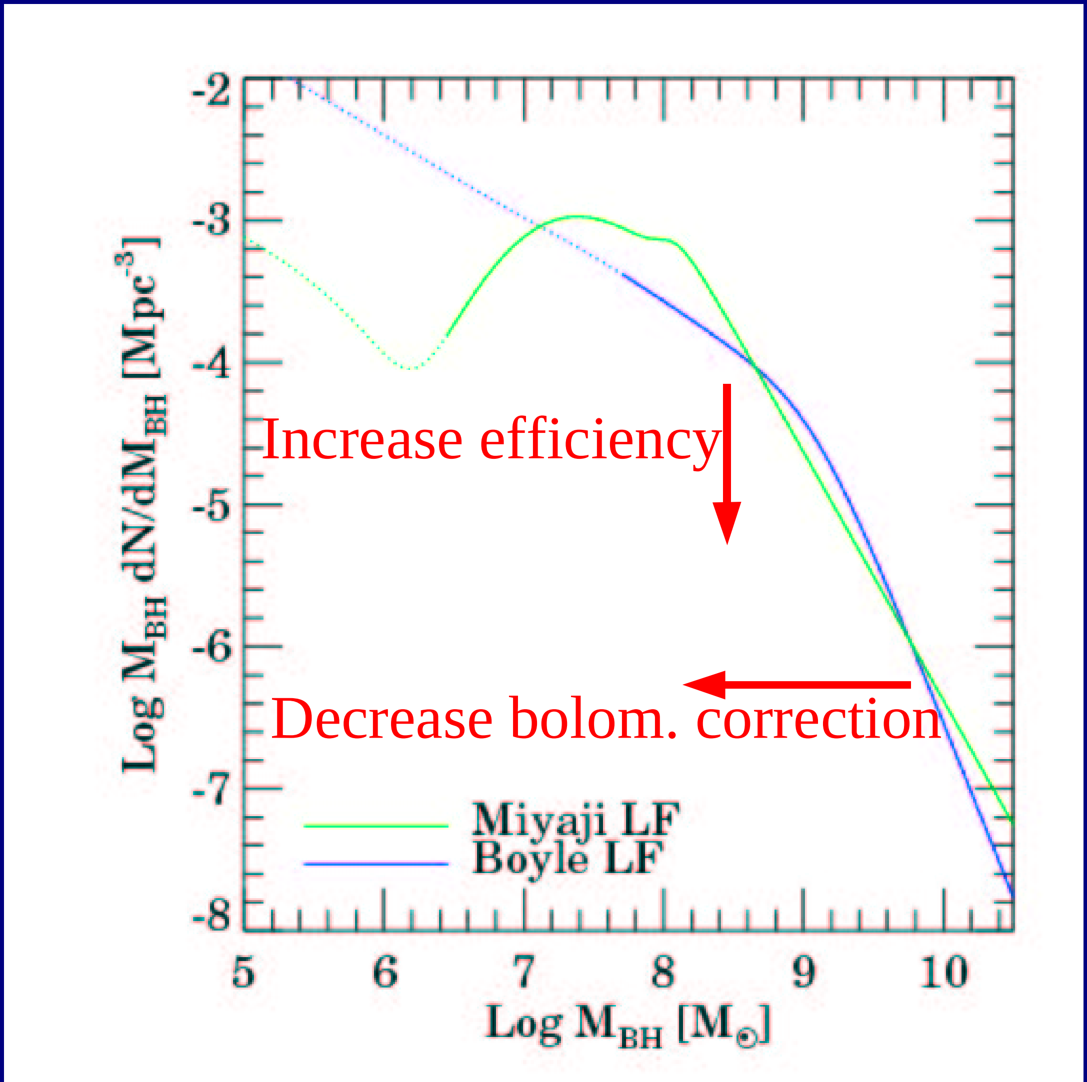
$$M\,N(M,t_0) = \left[\phi(L,t_0)\right]_{L=\frac{M}{t_E}c^2}$$

Luminosity Functions

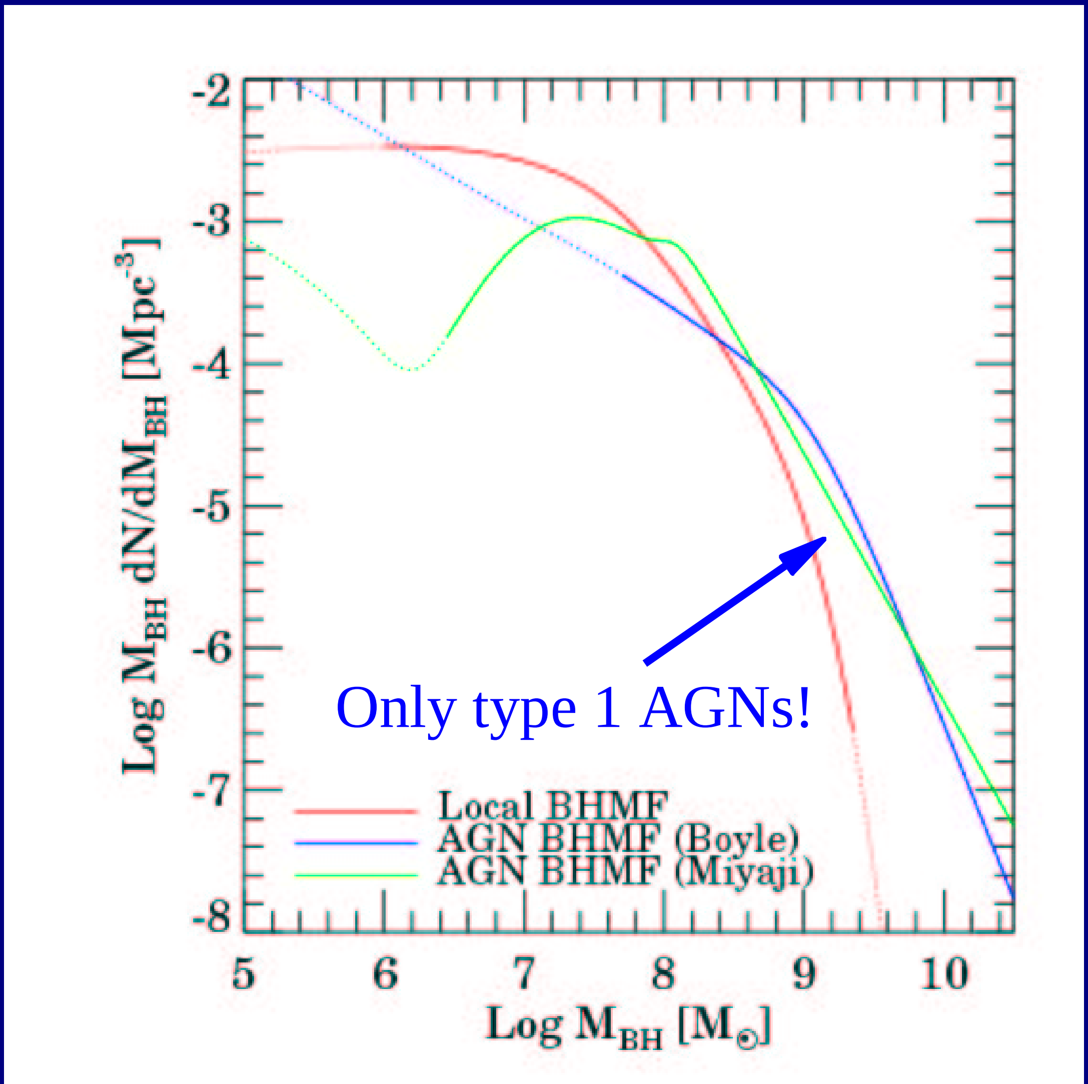
- LF of optically selected quasars (Boyle et al. 2000)
- LF of X-ray selected AGNs (Miyaji et al. 2000; these are mostly type 1s, ~80%)
- These 2 LFs refer only to type 1 objects!
- With bolometric corrections from B and 0.5-2 keV one can get the AGN LF $\phi(L,t)$.



Apply continuity equation...



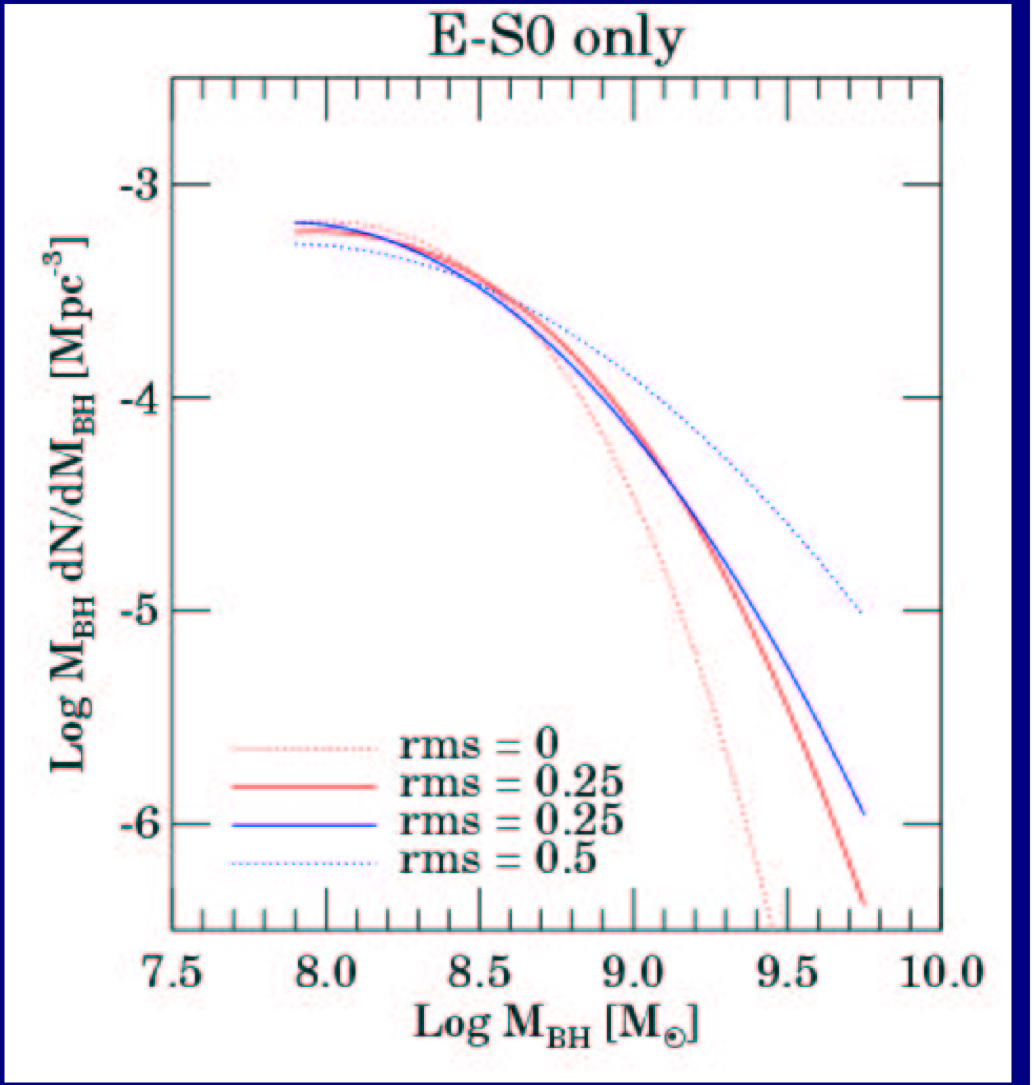
Local BHMF vs Relic BHMF



- The relic BHMF has an excess at large masses!
- Are the Bolometric corrections too high or is the Efficiency (0.1) too low?
- Yu & Tremaine (2002) conclude that:
  - high M BHs must be rapidly rotating
  - low M BHs are either “obscured” or emitting t low efficiency.

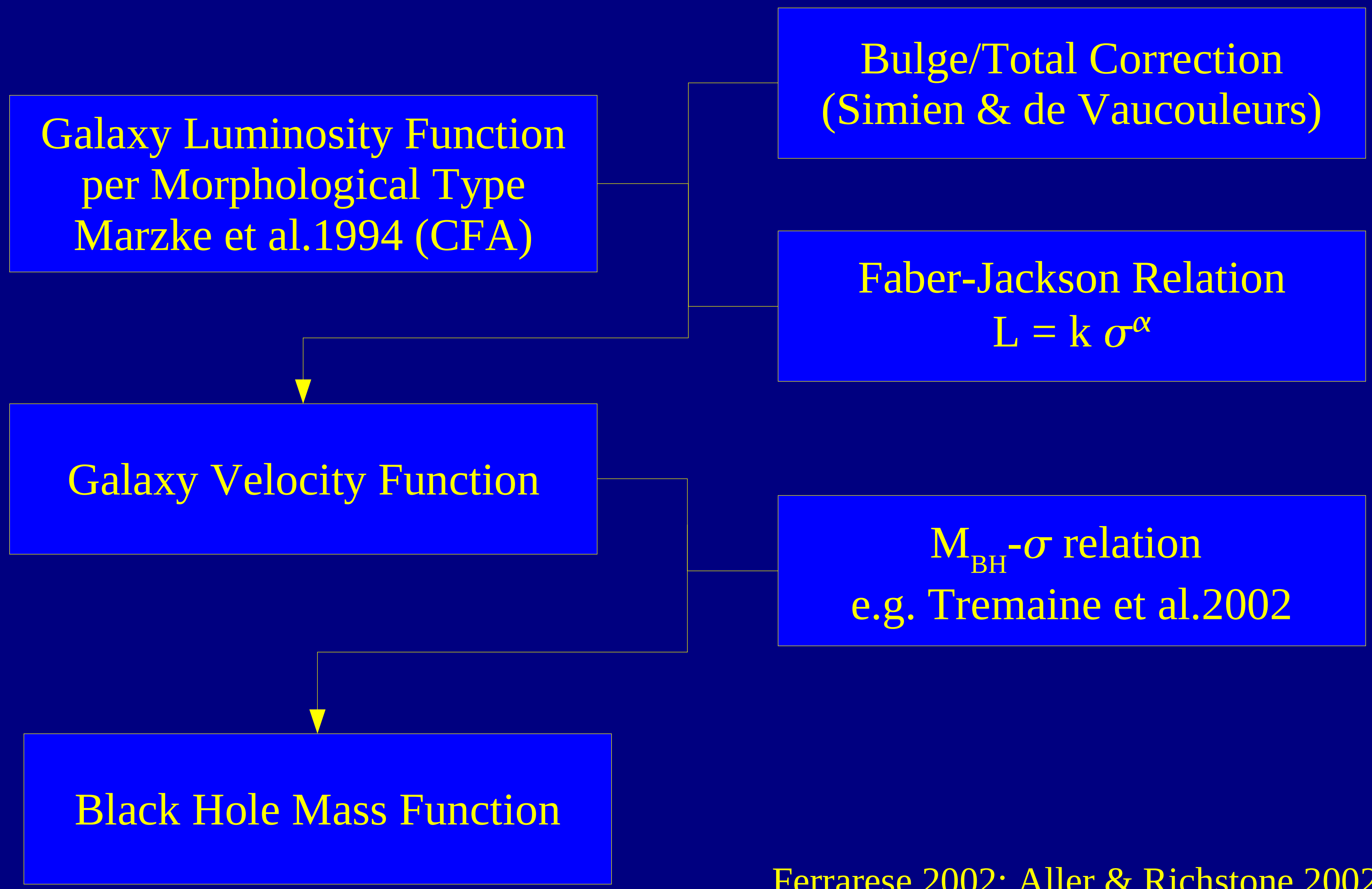
Where is the problem?

- Is the M_{BH}-σ relation as good as we think (i.e. rms=0) ?
- Is the M_{BH}-L_{bul}, not usable because it is less "tight"?
- SDSS has produced $\phi(\sigma)$ and $\phi(L)$ for 9000 Early type galaxies (Bernardi et al. 2003, Sheth et al. 2003) which can be used to test the correlations.
- M_{BH}-σ (~ 0-0.3) and M_{BH}-L_{bul} (0.5?) have dispersions to be taken into account: $\rho_{BH} = \rho_0 \exp[0.5\ (\mathrm{rms}\ \ln 10)^2]$!
- But Marconi & Hunt (2003) have shown that M_{BH}-σ and M_{BH}-L_{bul} have similar dispersion (~0.3)!
- Indeed they give the same BHMF only if they have the same dispersion !



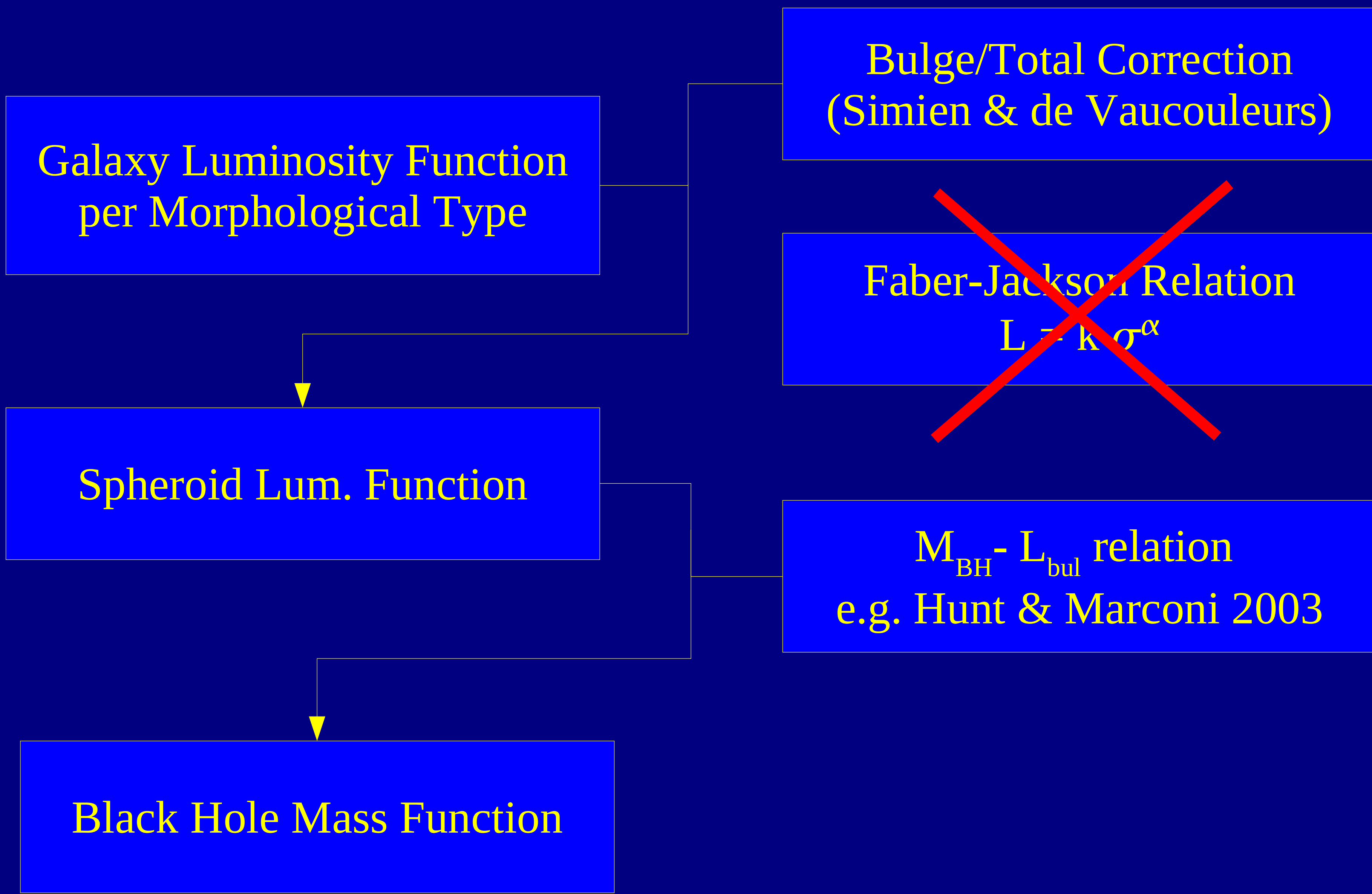
ρ_{BH} ↕	rms→	0.0	0.25	0.25
	MBH-σ	2.7	3.2	
	MBH-Lbul		3.1	4.8

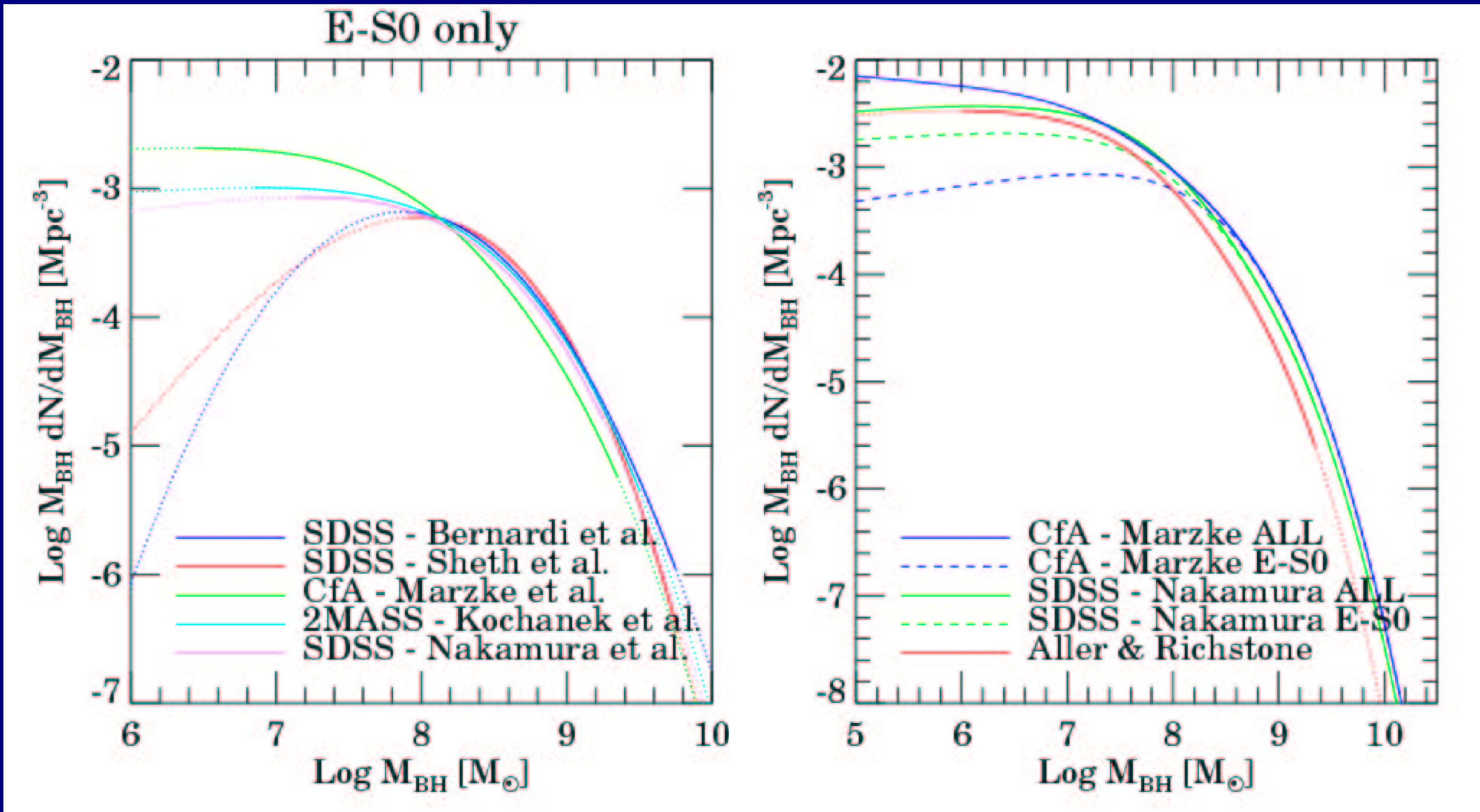
The Local BH Mass Function: use of $M_{BH} - \sigma$



Ferrarese 2002; Aller & Richstone 2002

The Local BH Mass Function: use of M_{BH} - L_{bul}



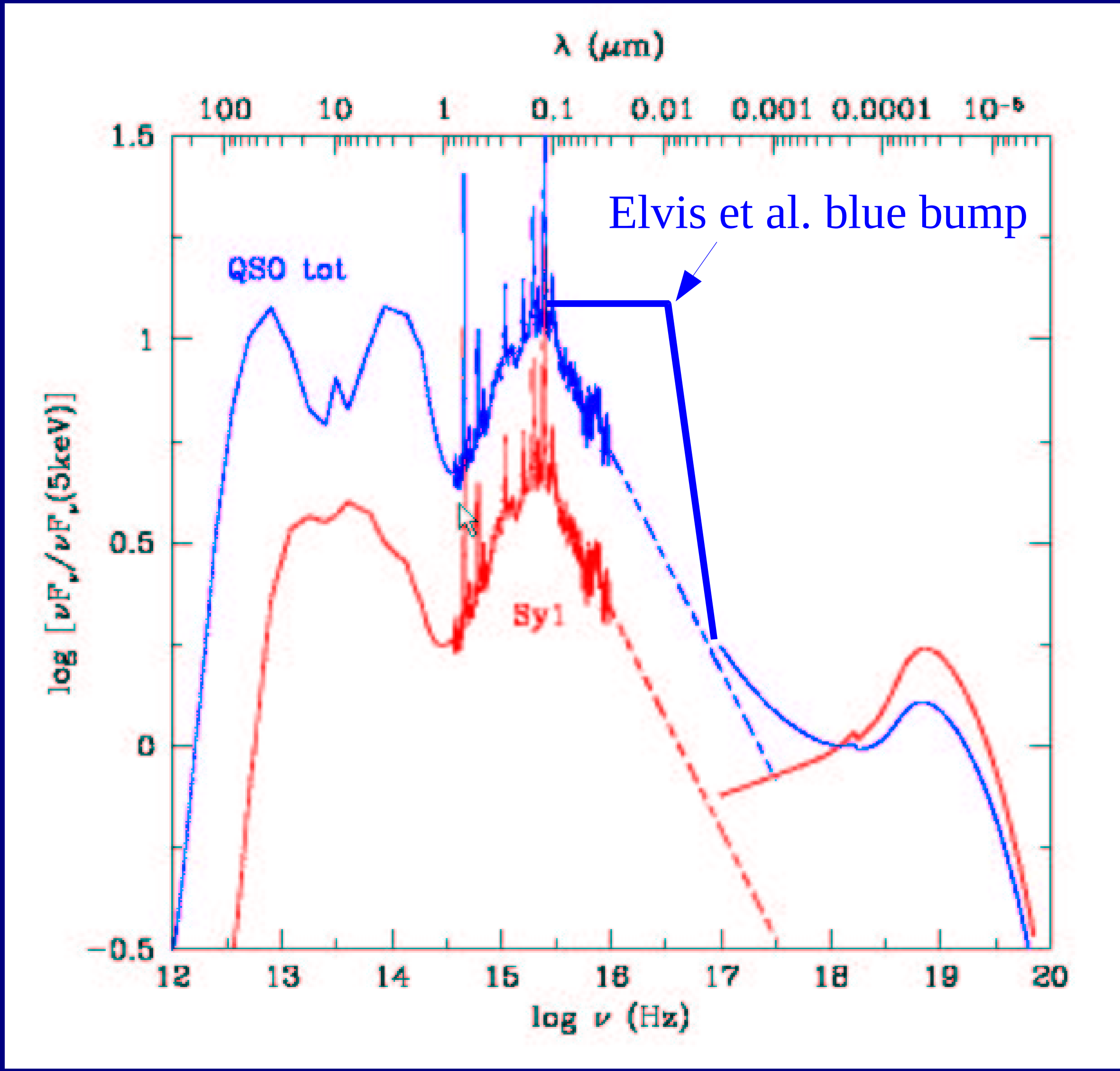


$\rho_{BH} = 3.1 \stackrel{def}{=} 0.1 \triangle 10^{5}\ M_{\odot}\ Mpc^{-3}$

$\rho_{BH} = 4.1 \stackrel{def}{=} 0.3 \triangle 10^{5}\ M_{\odot}\ Mpc^{-3}$

ρ_{BH} = 2.5 (Aller & Richstone)!

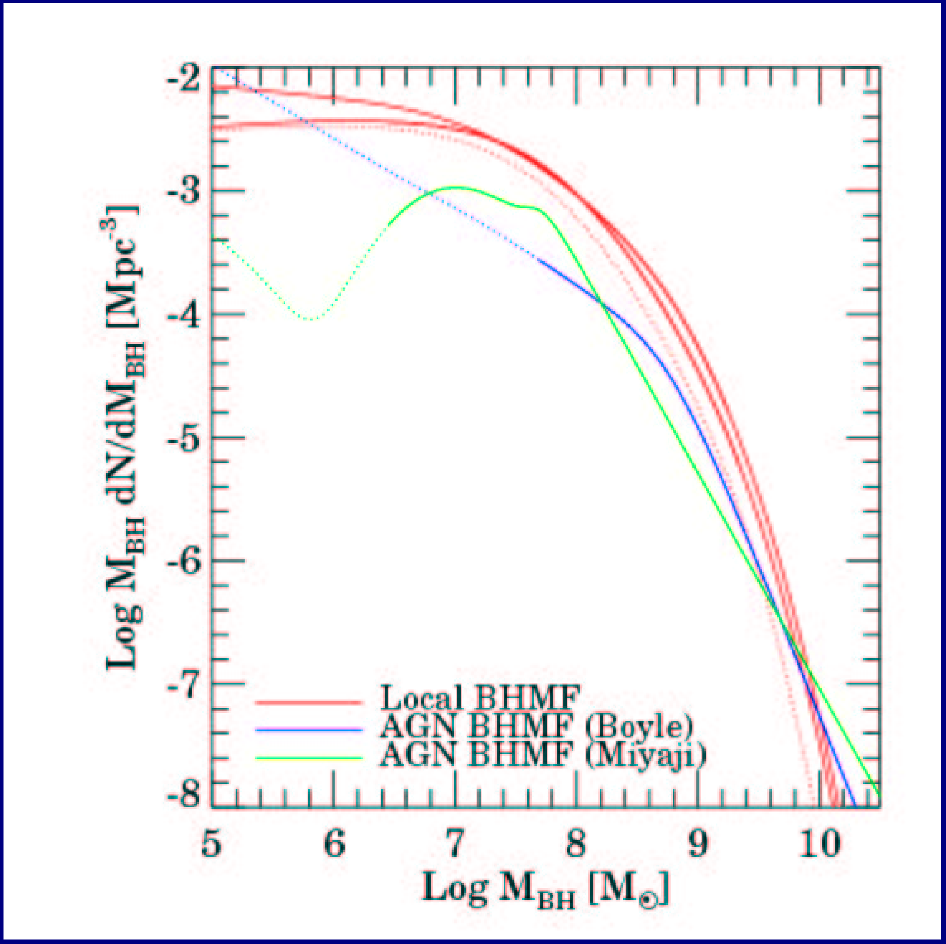
AGNs: bolometric corrections



- For AGNs ... bolometric corrections!
- Elvis et al. (1994) overestimated by a factor 2!
- SEDs for Seyferts and QSOs compiled by Maiolino & Granato (2003, in prep.)
- Elvis et al. 1994 (used previously) overestimated L/(νL_ν+$_B$ by roughly a factor2!

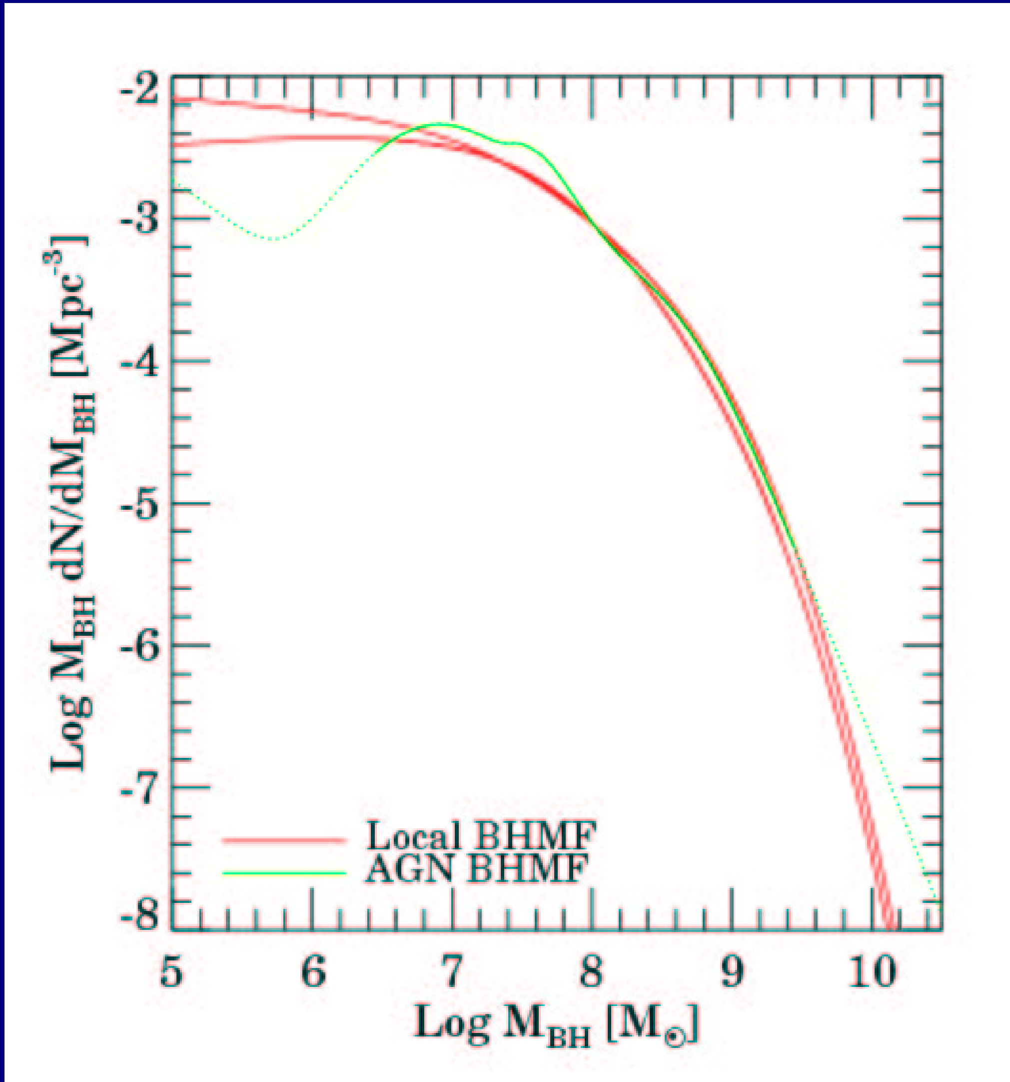
Local BHMF vs Relic BHMF "reloaded"

- The disagreement at high masses have disappeared (mostly due to Bol. Corr.)!
- Quasars produce $M_{BH}>10^8\ M_\odot$
- The relic BHMF is from type 1 AGN only!
- The assumptions on initial conditions are not important.
- Putting in type 2 AGNs, all is consistent with BH mass growth during AGN activity!

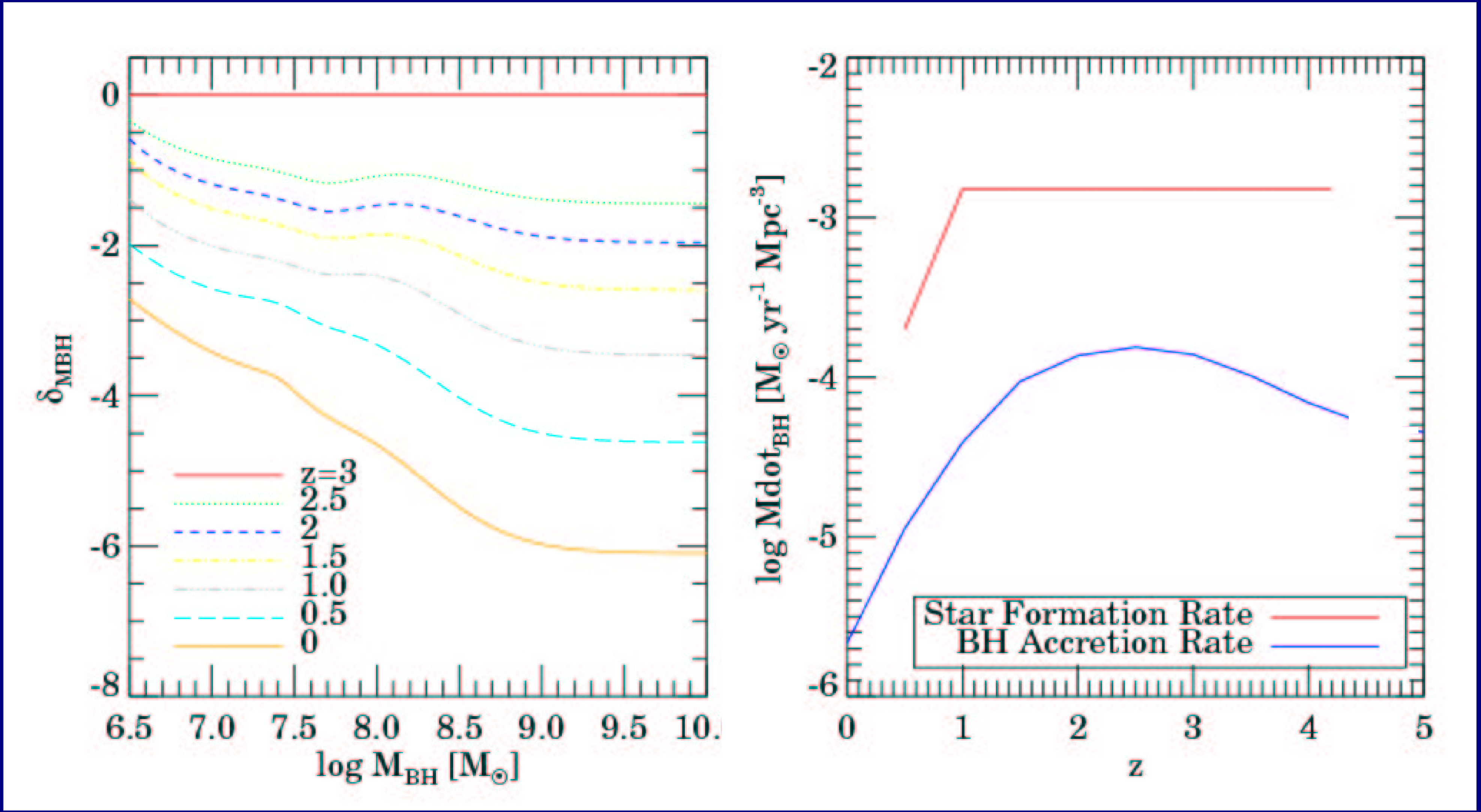


Local BHMF vs Relic BHMF "reloaded"

- Combining LFs (X-ray at low L, Optical at high L) and assuming Type2/Type1=3 we get a reasonable agreement between Local and Relic BHMF
- Remember the underlying assumption that BH growth take place in AGNs emitting at Eddington L with 0.1 efficiency!



Local BHMF vs Relic BHMF "reloaded"



δ = fraction of 'Active' BHs

Accretion rate onto BHs

Future: the X-ray Backgr. constrain

- Elvis, Risaliti & Zamorani (2002) from a reanalysis of Fabian & Iwasawa (1999) argument find that the density in relics BHs is $\geqslant$ (7.5-16.8) $\triangle 10^5$ (ε/0.1) $M_\odot$ Mpc^{-3} much higher than the density in local BHs (4.1≝0.3).
- The further development is to use the luminosity functions and Type2/Type1 ratios (with their *z* dependence) needed to fit the X-ray background and number counts.
- If it is not possible to fit the XRB with the a *small* number of type 2's then we might really need to conclude that the efficiency is larger than 0.1 and that “Most supermassive Black Holes must be rapidly spinning” (Elvis, Risaliti & Zamorani)

Conclusions

- Current observational evidence suggests that most, possibly all, luminous galaxies host a massive Black Hole in their centers.
- The Black Hole mass correlates with mass/luminosity of the bulge in which it resides and ALL correlations are equally good!
- Hypothesis that AGNs are powered by accretion onto a massive BH combined with the observed redshift evolution of AGNs suggests that these massive BHs are relics of past activity.
  - Local BHs have density $(4.1 \pm 0.3) \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$
  - Quasars make $M > 10^8\ M_\odot$ BHs
  - The majority of BH mass is produced during AGN activity
  - Type 1/Type ~ 3
- With "reasonable" values of the free parameters compatible with current knowledge, accretion on AGNs can reproduce the local BH mass function!

Thanks very much
to the organizers!