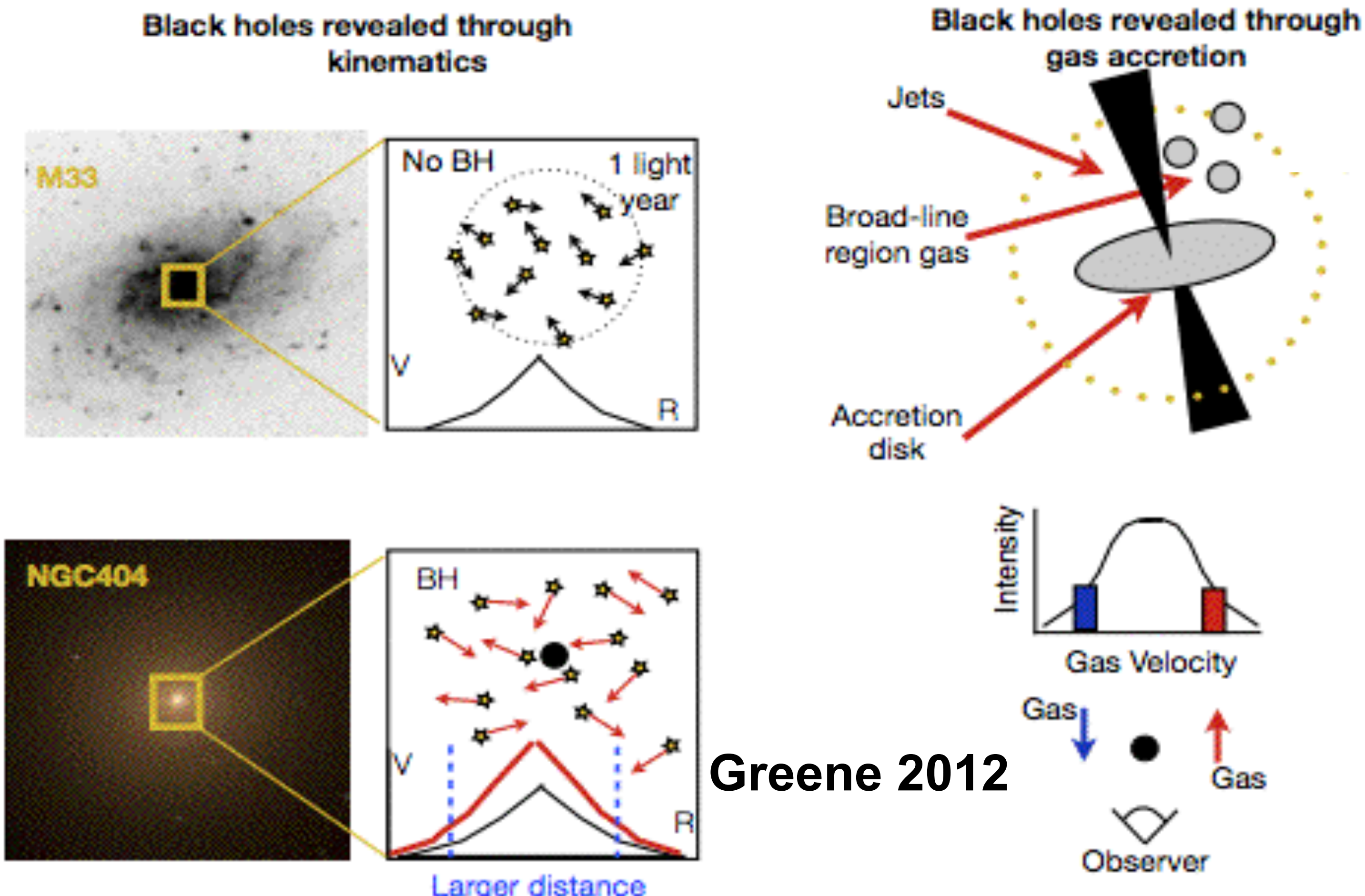
Finding SMBHs

- Detect SMBHs via presence of an AGN (~10% today) OR
- Via dynamics (motion of stars or gas)... imply ~100% at $M_{galaxy}>10^{10}M$.



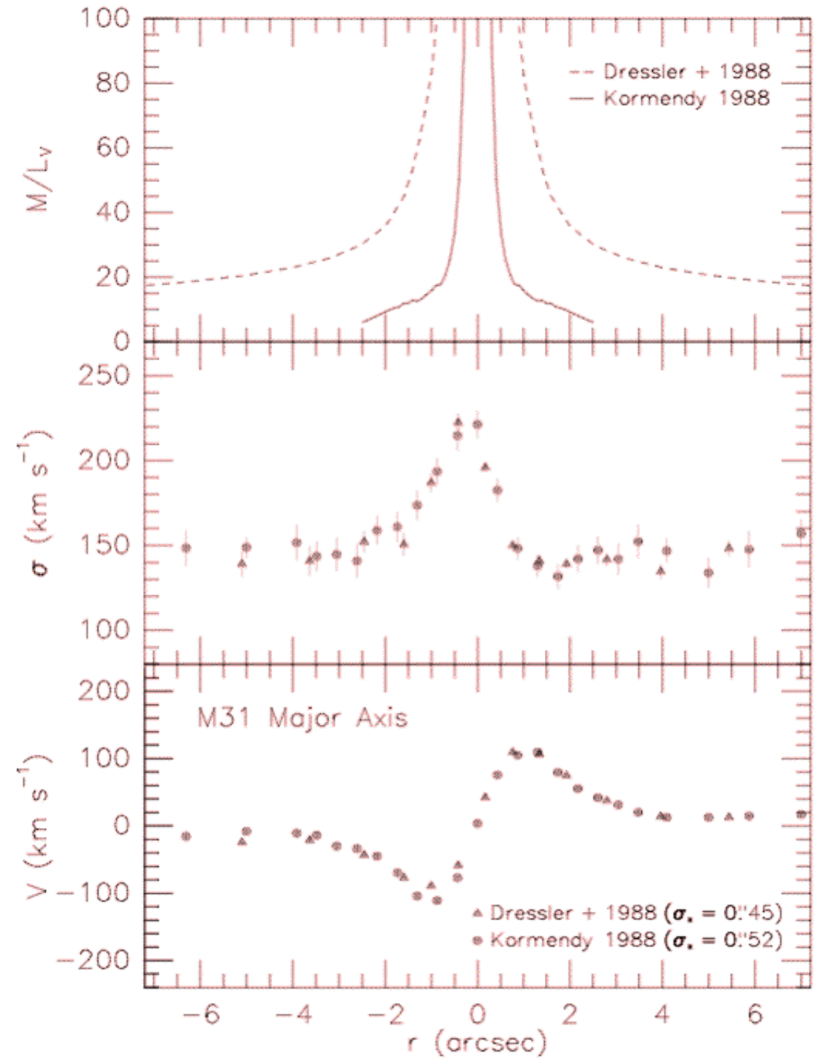
Greene 2012

stars near BH move more rapidly because of BH

broad emission lines-gas moving rapidly near BH

Example of data for the nearest galaxy M31

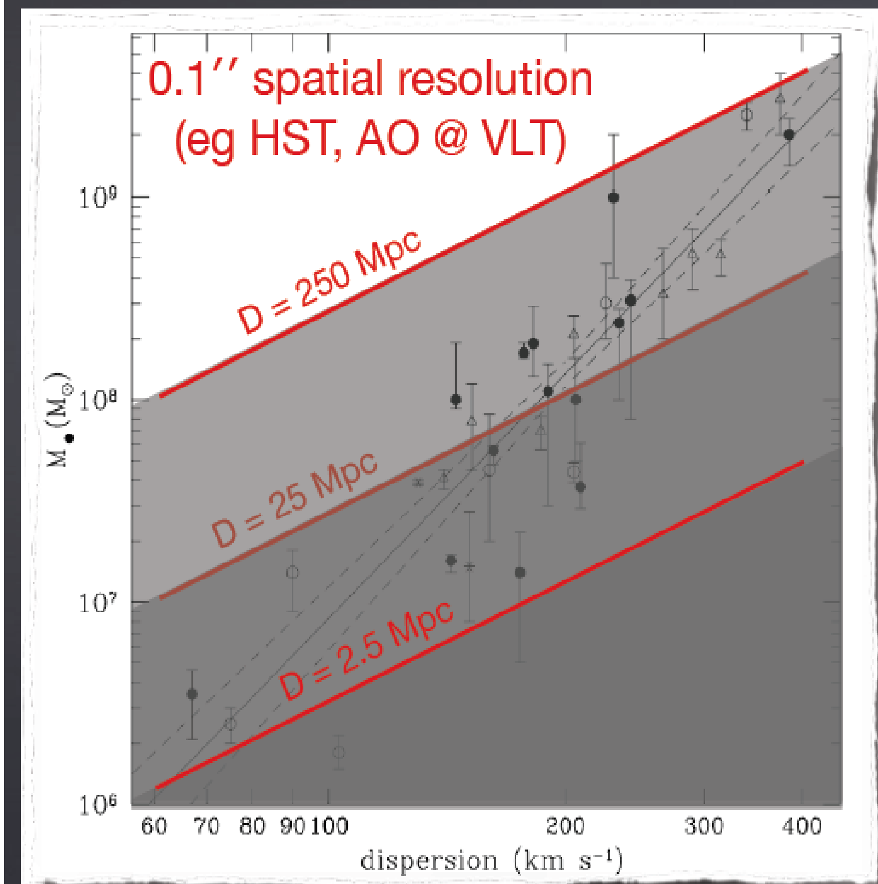
- Notice the nasty terms
- V_r is the rotation velocity σ_r $\sigma_{\theta,}$ σ_ϕ are the 3-D components of the velocity dispersion ν is the density of stars
- All of these variables are 3-D; we observe projected quantities !
- The analysis is done by generating a set of stellar orbits and then minimizing
- Rotation and random motions (dispersion) are both important.
- Effects of seeing (from the ground) are importan:t smear the image, reduce BH dynamical signal-



Direct BH mass measurements

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

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



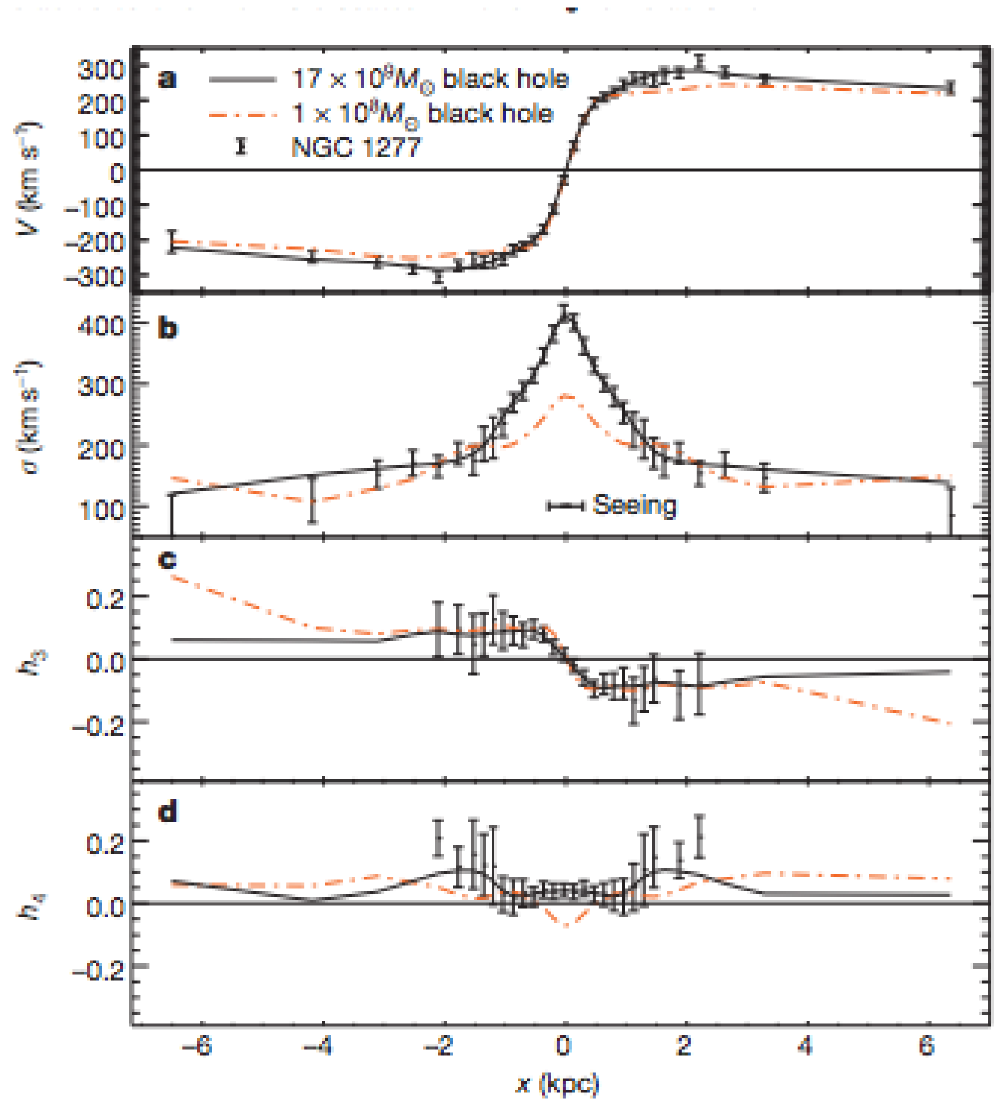
BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

Need to calibrate indirect BH mass estimators like for the cosmological distance ladder

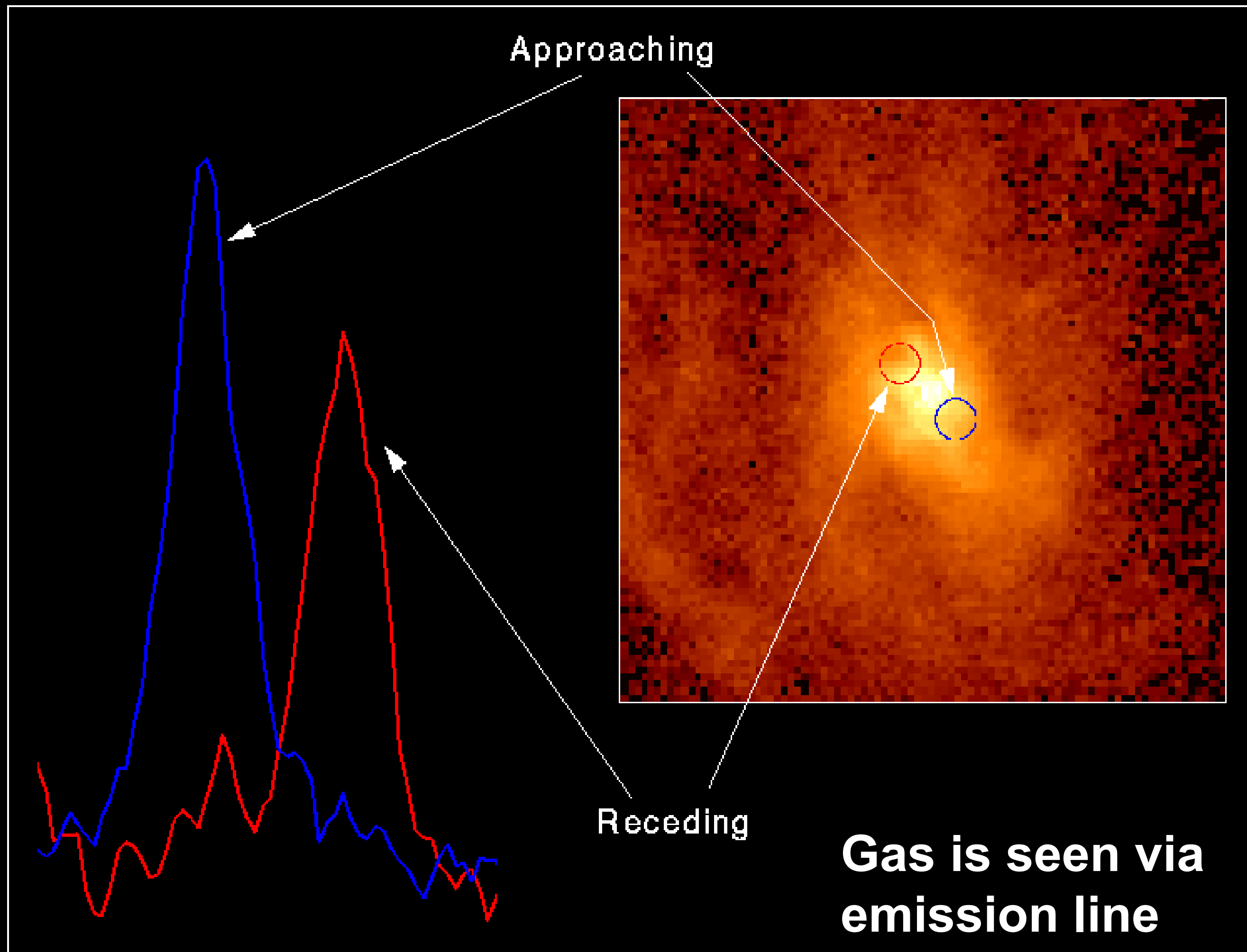
Marconi

NGC1277- Velocity Data and BH Mass

- Top is rotation curve vs distance from center
- Middle is velocity dispersion vs distance from center
- Bottom 2 curves are measures of the non-gaussianity of the velocity field (sensitive to distribution of orbits)



Spectrum of Gas Disk in Active Galaxy M87



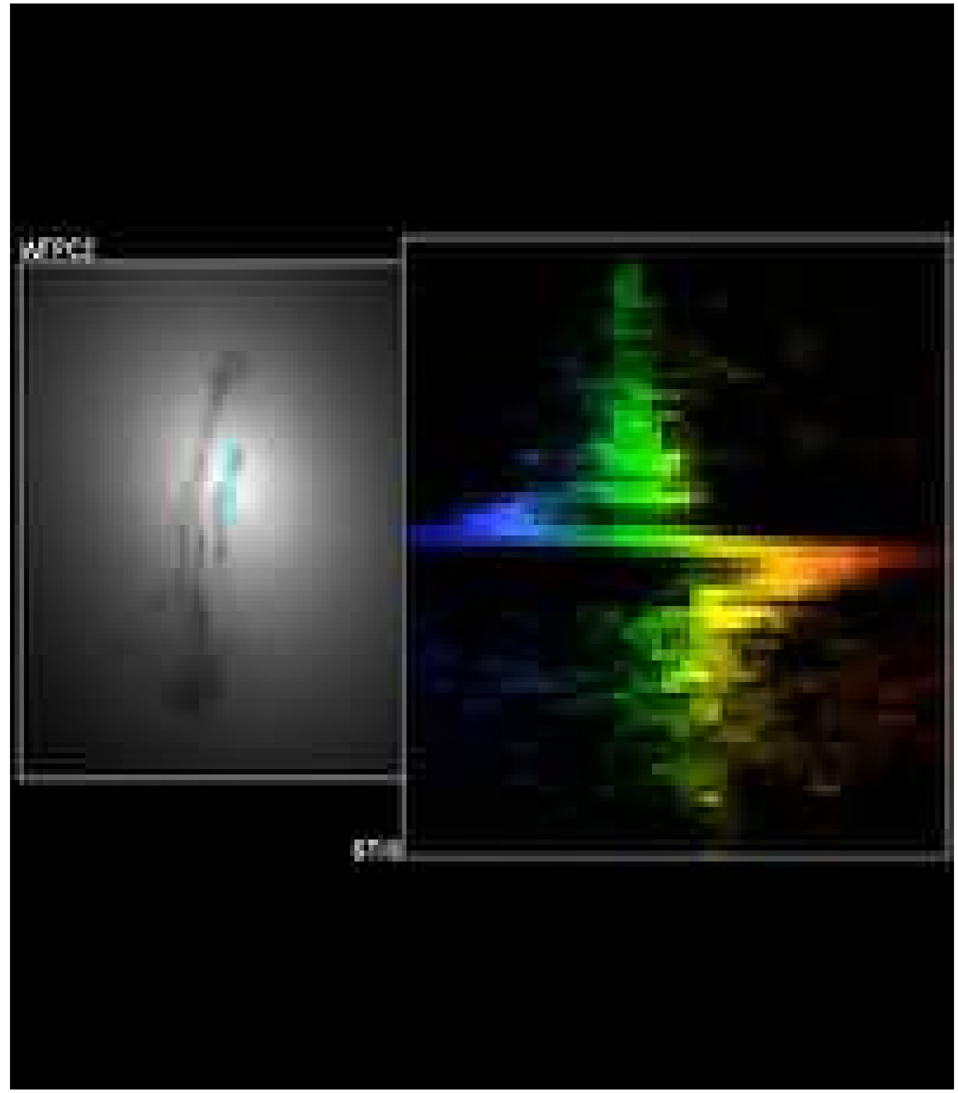
Hubble Space Telescope • Faint Object Spectrograph

SPACE TELESCOPE SCIENCE INSTITUTE

Harms et al 1999

Measuring the Mass of a SuperMassive Black hole

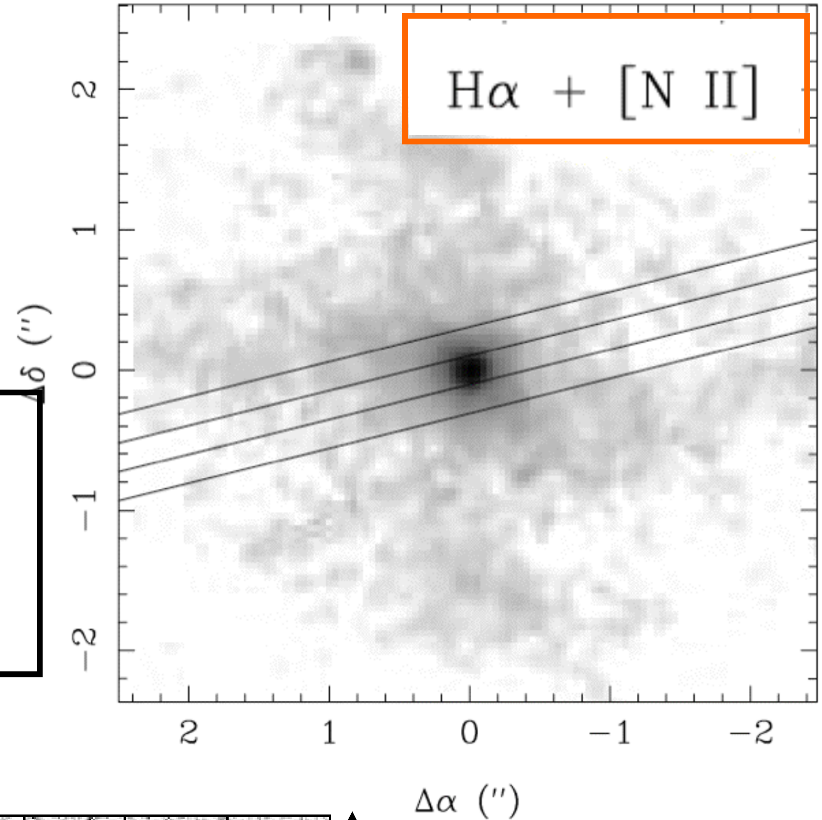
- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion axis (horizontal) covers a velocity interval of 1445 km s-1, while the spatial axis (vertical) covers the central 3 arcsec;.



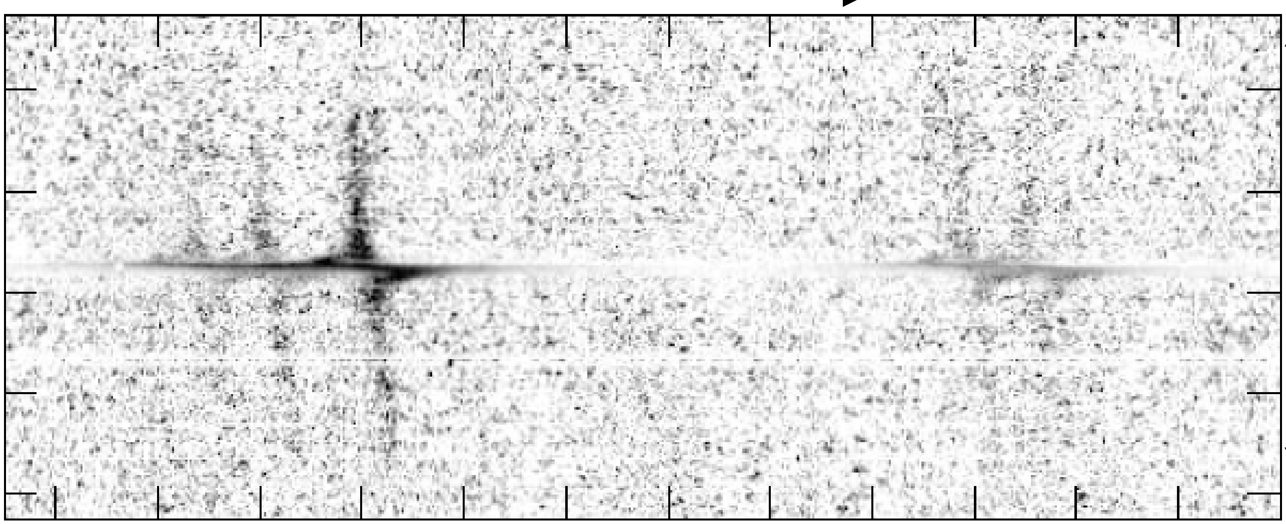
Measurement of Kinematics of Gas

- Image of optical emission line emitting gas around the central region of the nearby giant galaxy M84

HST STIS Observations of the Nuclear Ionized Gas in the Elliptical Galaxy M84
G. A. Bower, R. F. Green, D.



wavelength



Position on sky along slit

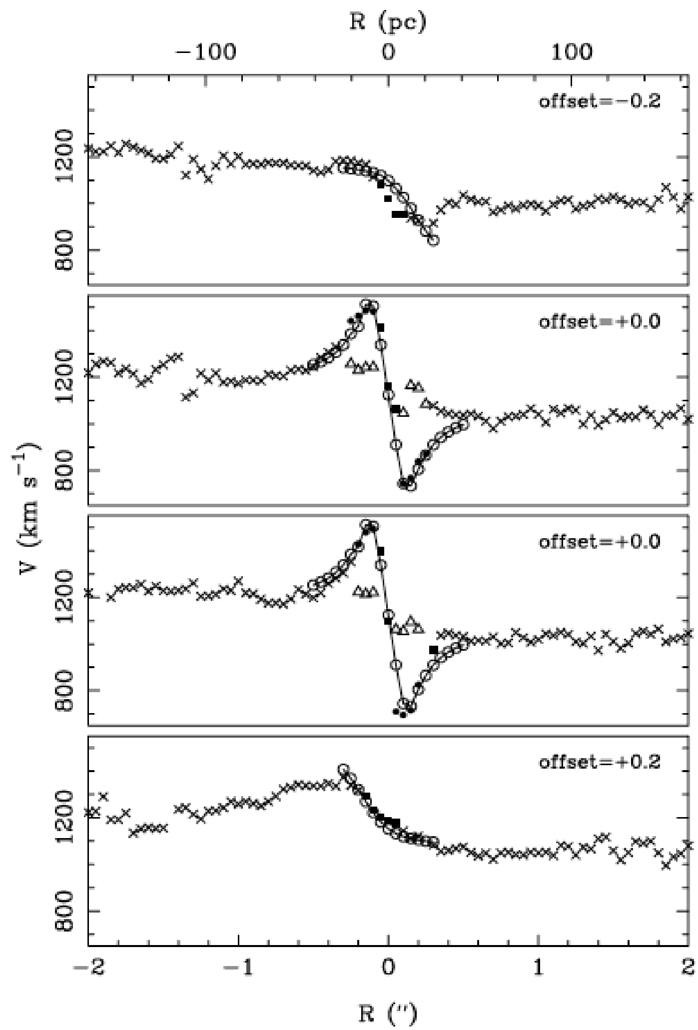
Analysis of Spectral Data for M84

- Mass of central object 1.5x10^9 M_{sun}

TABLE 1
KEPLERIAN DISK MODEL PARAMETERS

Parameter	Best Fit	Uncertainty Range
Black hole mass ($M_\odot$)	1.5×10^9	$(0.9–2.6) \times 10^9$
Disk inclination (deg)	80	75–85[a]
Disk P.A. (deg)	83	80–85
Gas systemic velocity (km s^{-1})	1125	1100–1150
Intensity law	$I(r) \propto r^{-1}$	...
$I(r)$ inner radius (pc)	1	0.3–3
$V(r)$ inner radius (pc)	0.03	0.01–0.1
PSF σ (arcsec)	0.05	0.04–0.06

[a] Lower mass requires lower inclination.

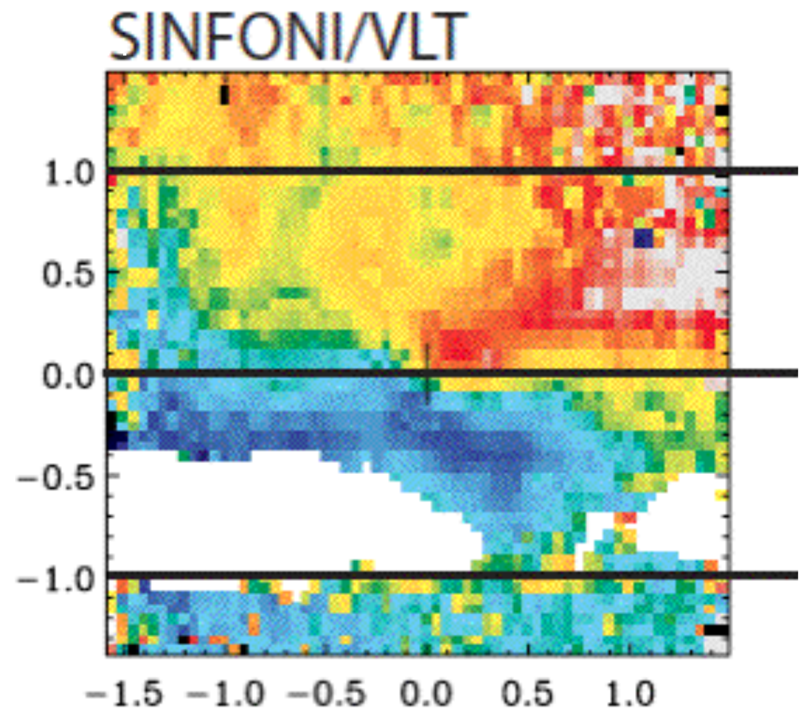


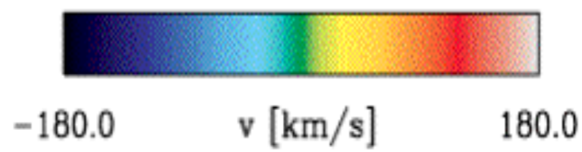
Velocity of gas vs distance from center of emission along 3 parallel lines

Centaurus -A

- 2 dimensional velocity maps for gas and stars allow assumptions to be checked (Neumayer et al,Cappelari et al)

Gas Velocities





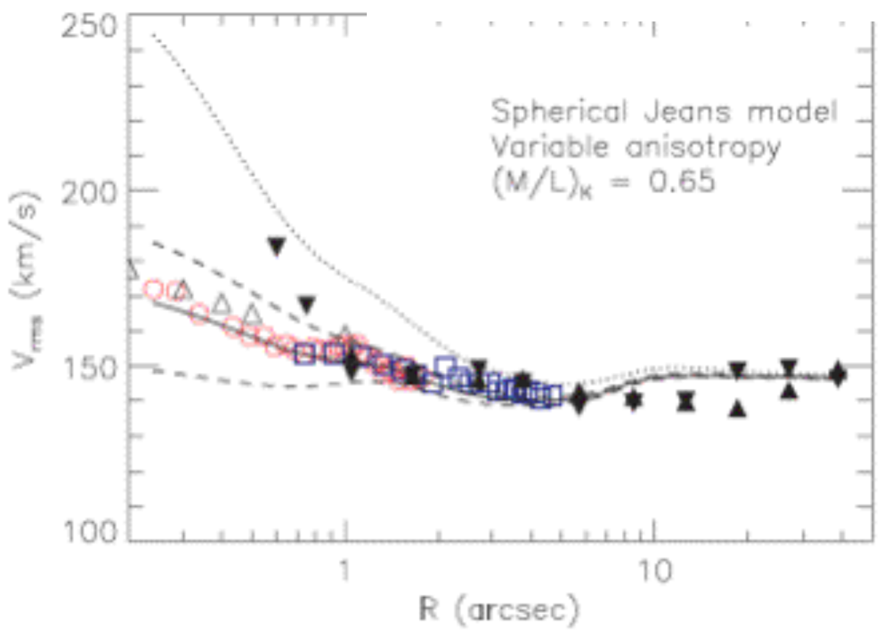
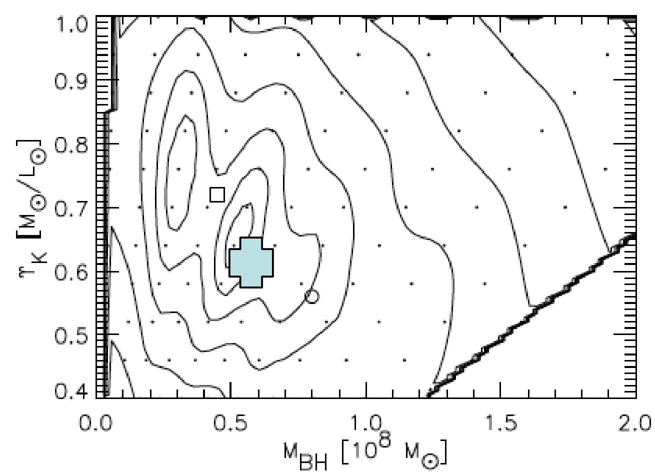
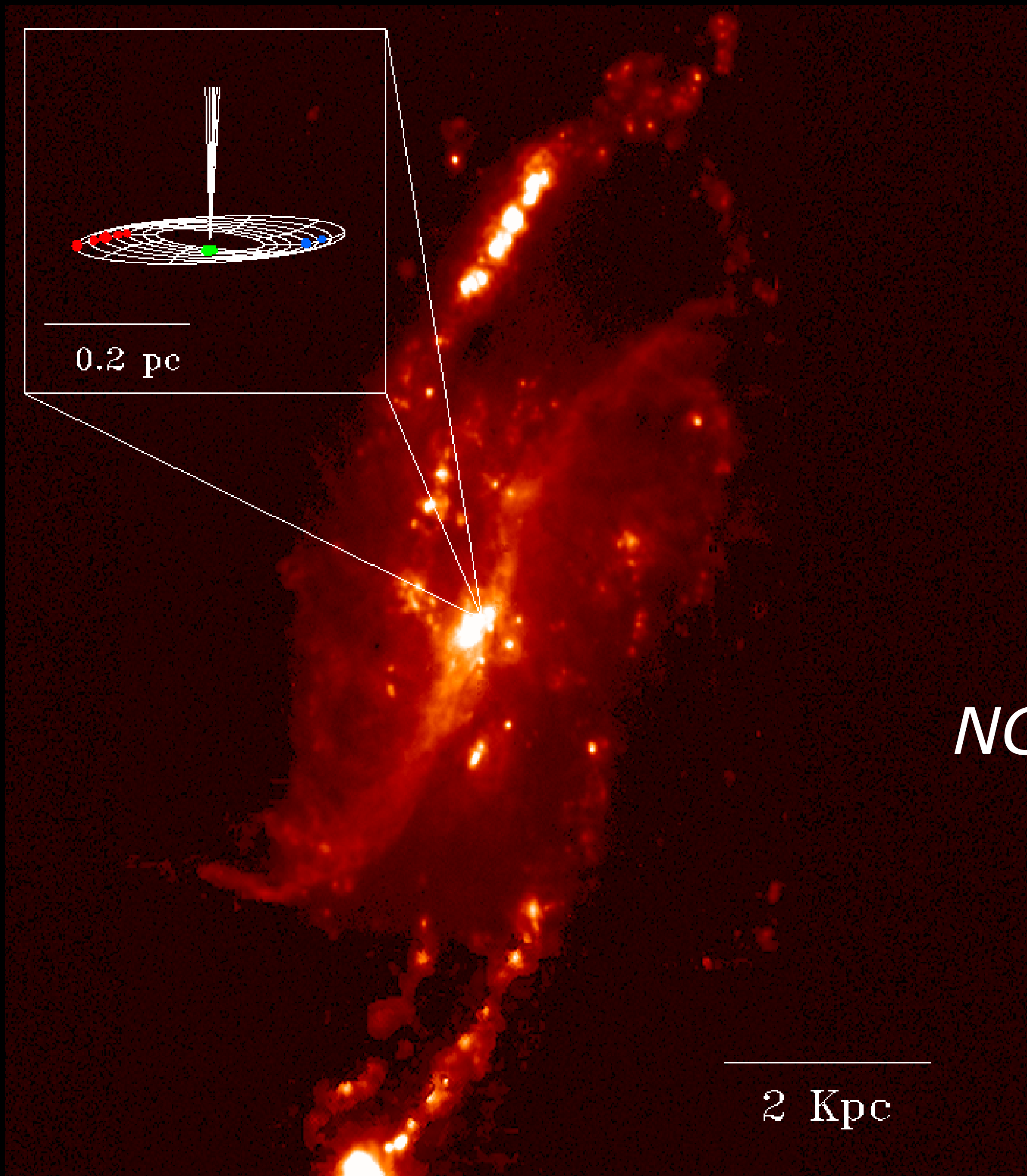


Figure 4: Spherical anisotropic Jeans model



$$M_{\rm BH} = (5.5 \pm 3.0) \times 10^7 M_{\odot}.$$

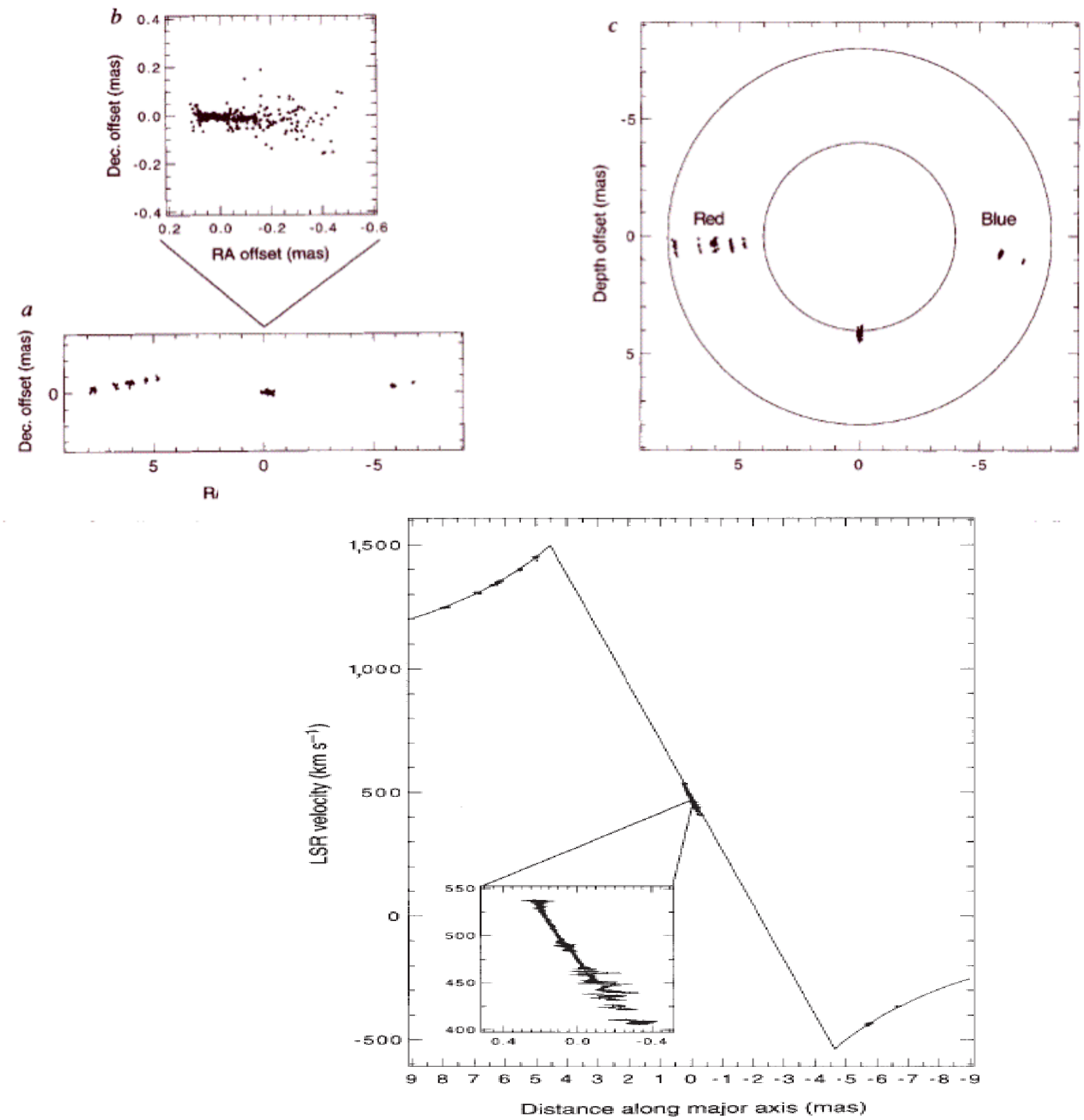
Constraints from stars compared to those from Gas Velocities



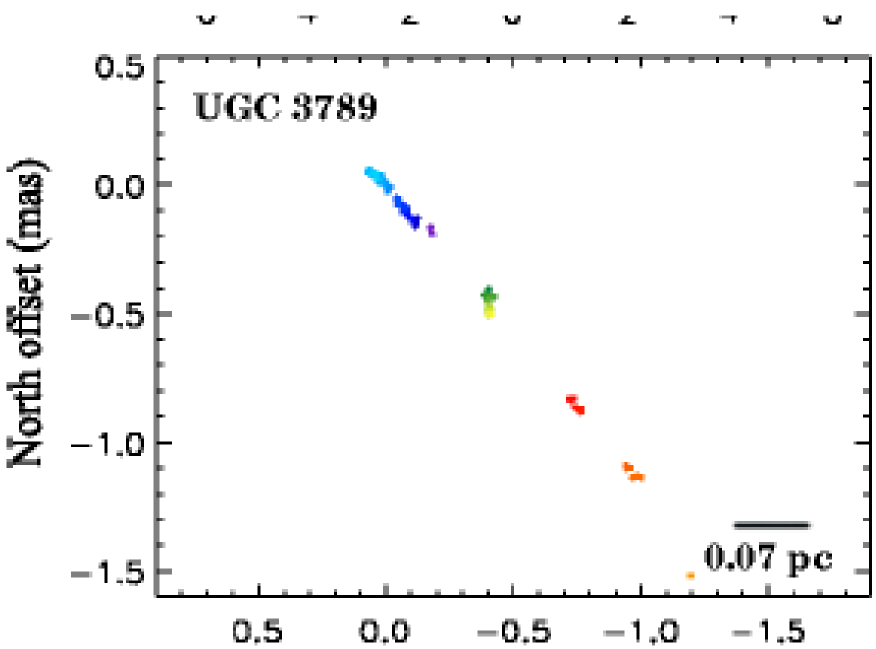
NGC4258

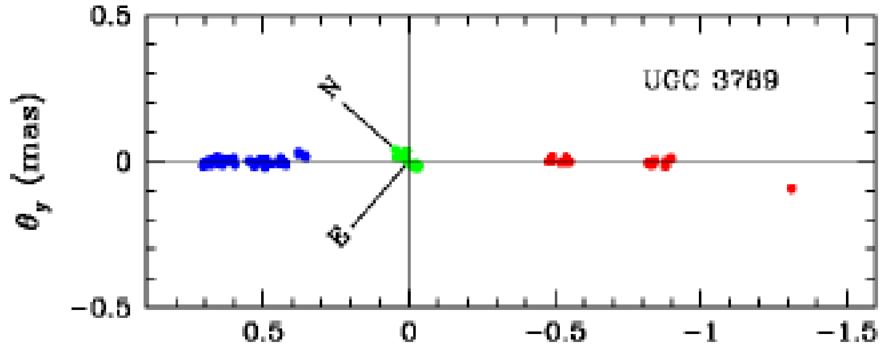
Use of Masers for an AGN

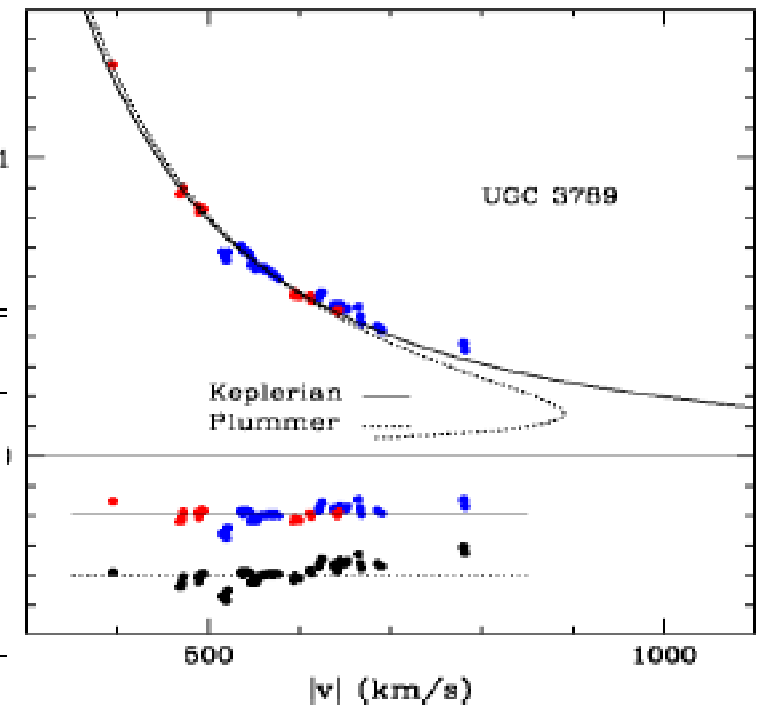
- The nearby galaxy NGC4258 has a think disk which is traced by water maser emission
- Given the very high angular and velocity resolution possible with radio observations of masers the dynamics of the system are very well measured.



Other Masers







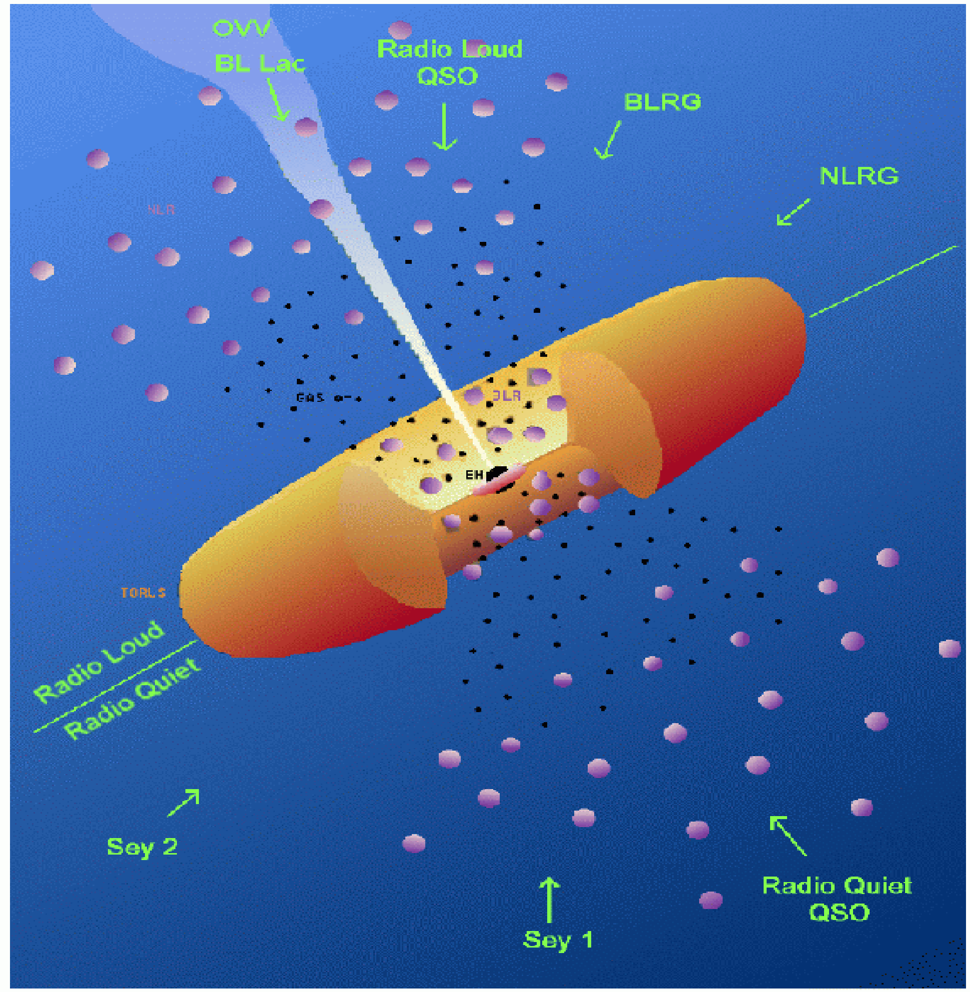
Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36	−131	89	0.055	1.8×10^{10}
NGC 4388	19	0.84±0.02	0.24-0.29	107	–	0.090	3.3×10^9
NGC 6264	136	2.84±0.04	0.23-0.78	−85	90	0.083	1.3×10^{10}
NGC 6323	105	0.93±0.01	0.13-0.30	10	89	0.046	2.3×10^{10}

Kuo et al 2010

AGN- Alias Active Galactic Nuclei

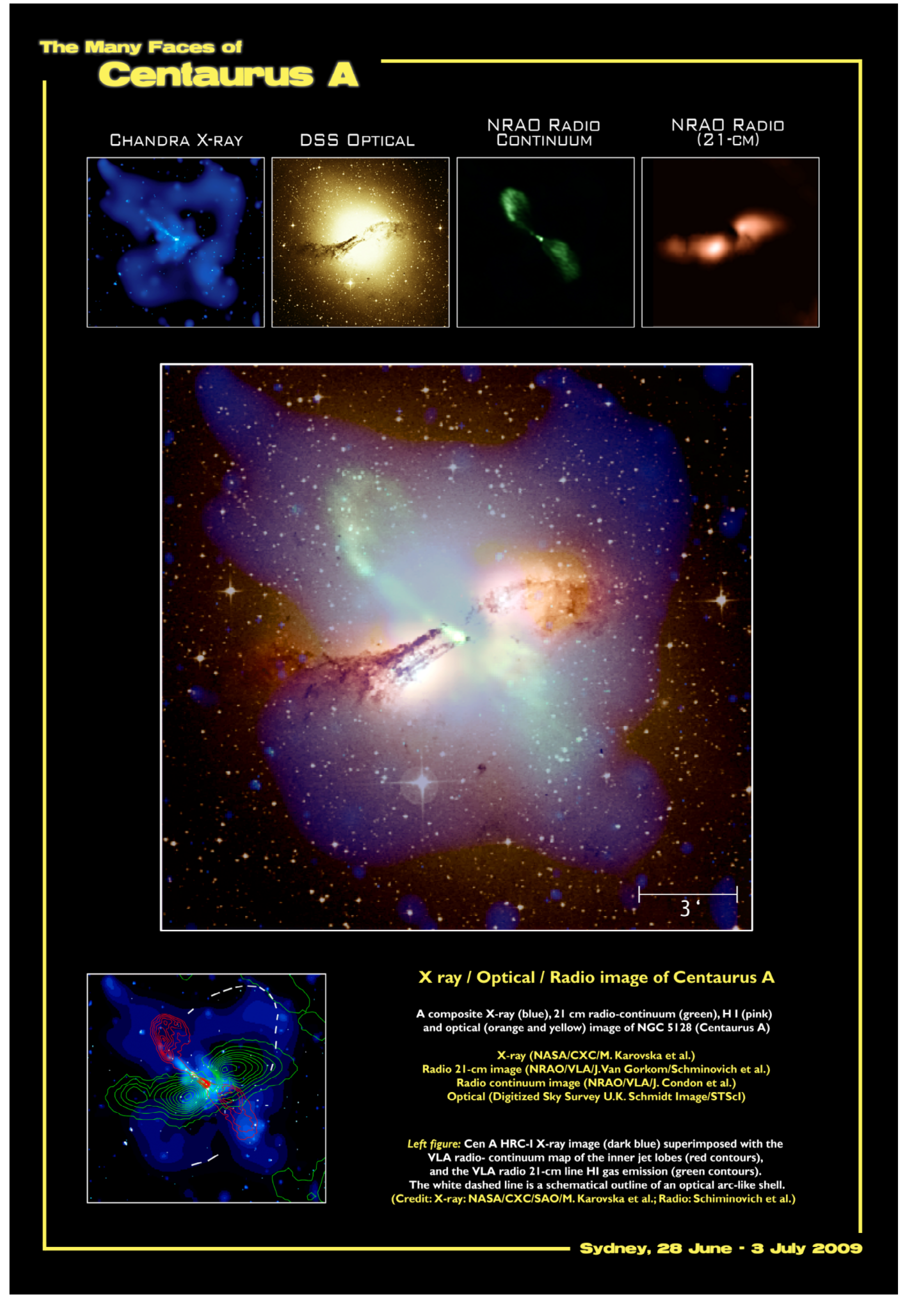
- AGN are 'radiating' supermassive black holes-
  - They go by a large number of names (Seyert I, Seyfert II, radio galaxies, quasars, Blazars etc etc)
  - The names convey the observational aspects of the objects in the first wavelength band in which they were studied and thus do carry some information

- See http://nedwww.ipac.caltech.edu/level5/Cambridge/Cambridge_contents.html for an overview

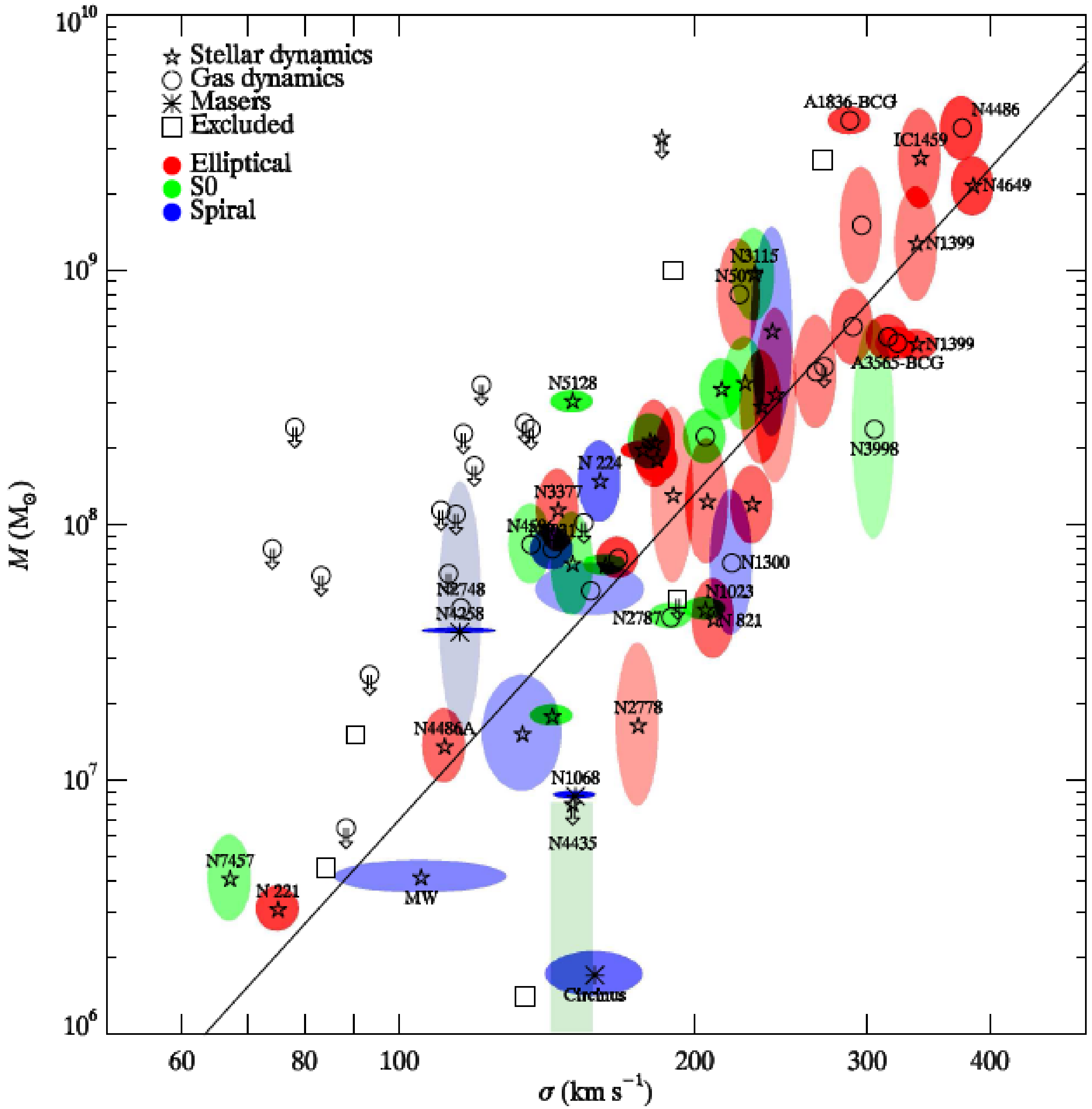


Urry and Padovani 195

Centaurus-A The Nearest AGN

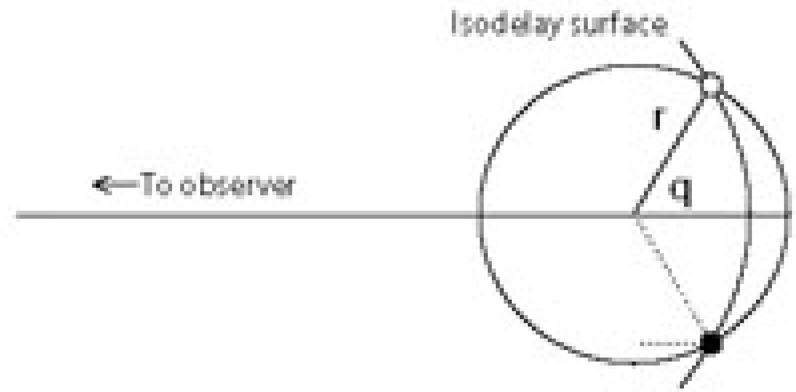


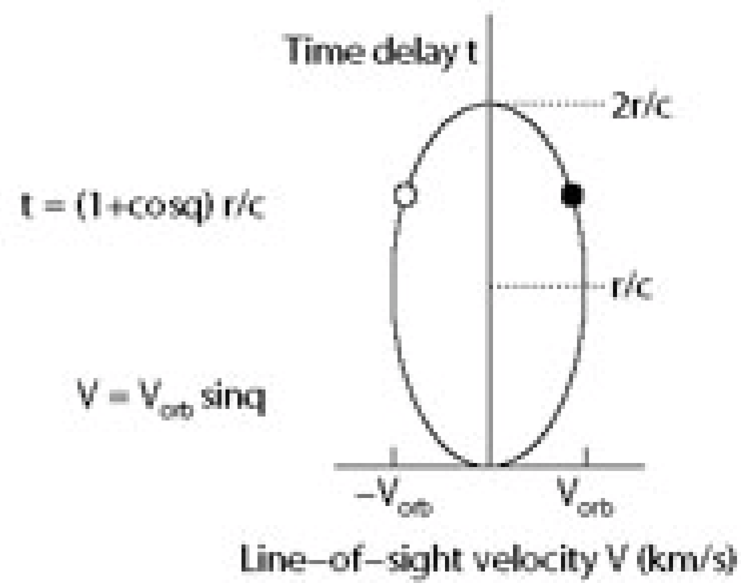
- All the Nearby Galaxies with Dynamical Masses for their Central Black Holes (Gultekin 2009)
- There seems to be a scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- Galaxies know about their BH and vice versa



What About AGN in General??

- We believe that the incredible luminosity of AGN comes from accretion onto a black hole
- However the 'glare' of the black hole makes measuring the dynamics of stars and gas near the black hole very difficult
- Technique: reverberation mapping (Peterson 2003)
  - The basic idea is that there exists gas which is moderately close to to the Black Hole (the so-called broad line region) whose ionization is controlled by the radiation from the black hole
  - Thus when the central source varies the gas will respond, with a timescale related to how far away it is



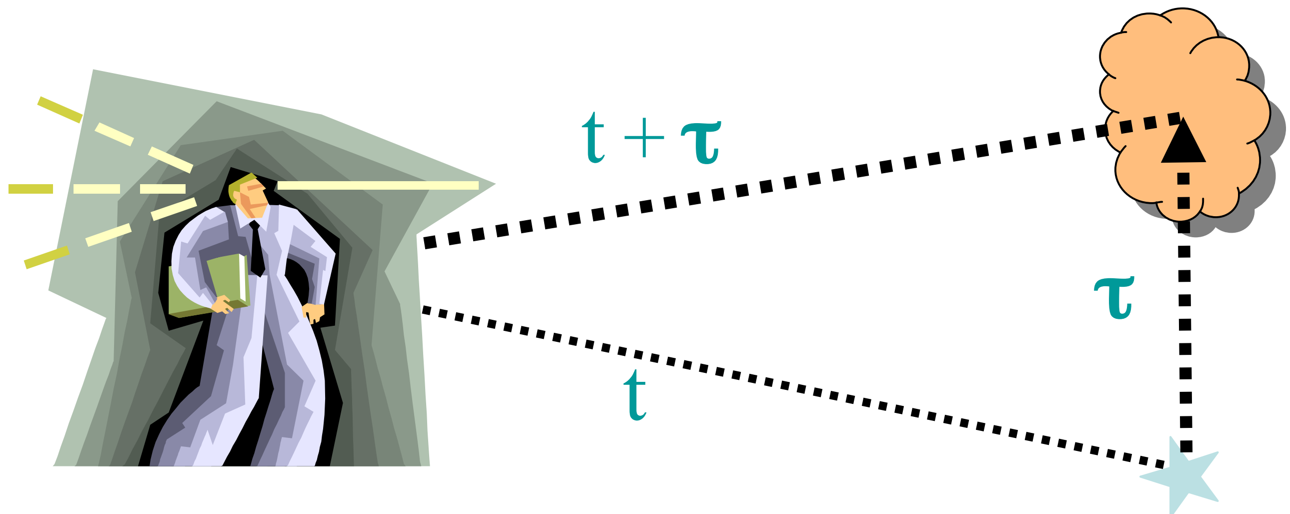


Virial Mass Estimates

$$M_{BH} = f \; v^2 \, R_{BLR}/G$$

Reverberation Mapping:

- $R_{BLR} = c\,\tau$



- v_{BLR}

  Line width in variable spectrum

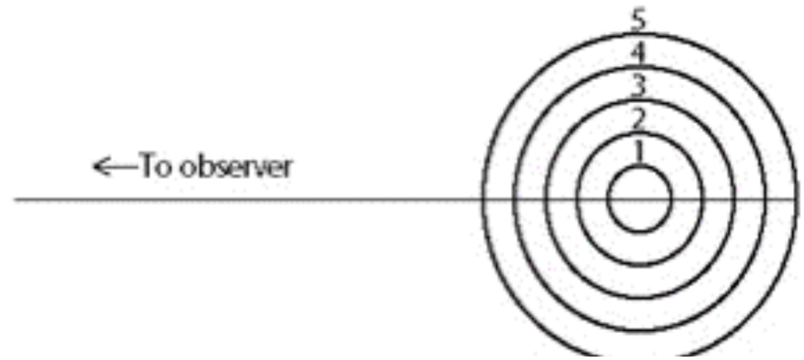
The Geometry

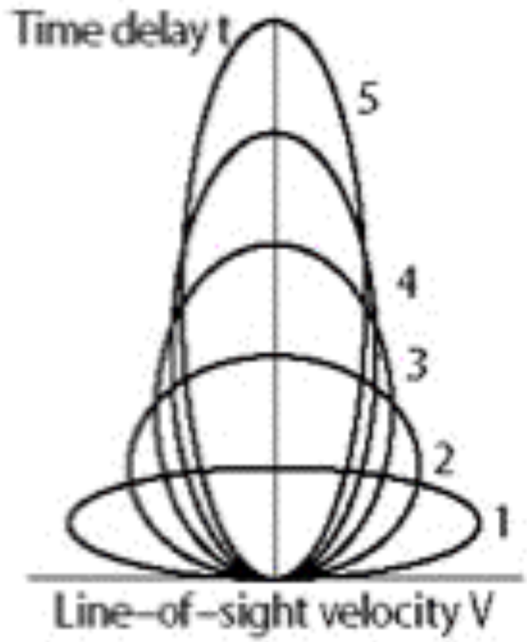
- Points (r, θ) in the source map into line-of-sight velocity/time-delay(τ) space (V, τ) according to $V = -V_{orb} \sin(\theta)$, where V_{orb} is the orbital speed, and $\tau = (1 + \cos(\theta))r / c$.

- The idea is that the broad line clouds exist in 'quasi-Keplerian' orbits and respond to the variations in the central source. Lower ionization lines are further away from the central source.
- So

$$M_{BH}=frV^2/G$$

f is a parameter related to geometry- and the orbits of the gas clouds- assumption is that gas is in a bound orbit around the BH





r=ct, where t is the time delay

A Quick Guide to Photoionized Plasmas

- Fundamental idea photon interacts with ion and electron is ejected and ion charge increased by 1
- $X^{+q} + h\nu \rightarrow X^{+(q+1)} + e^-$

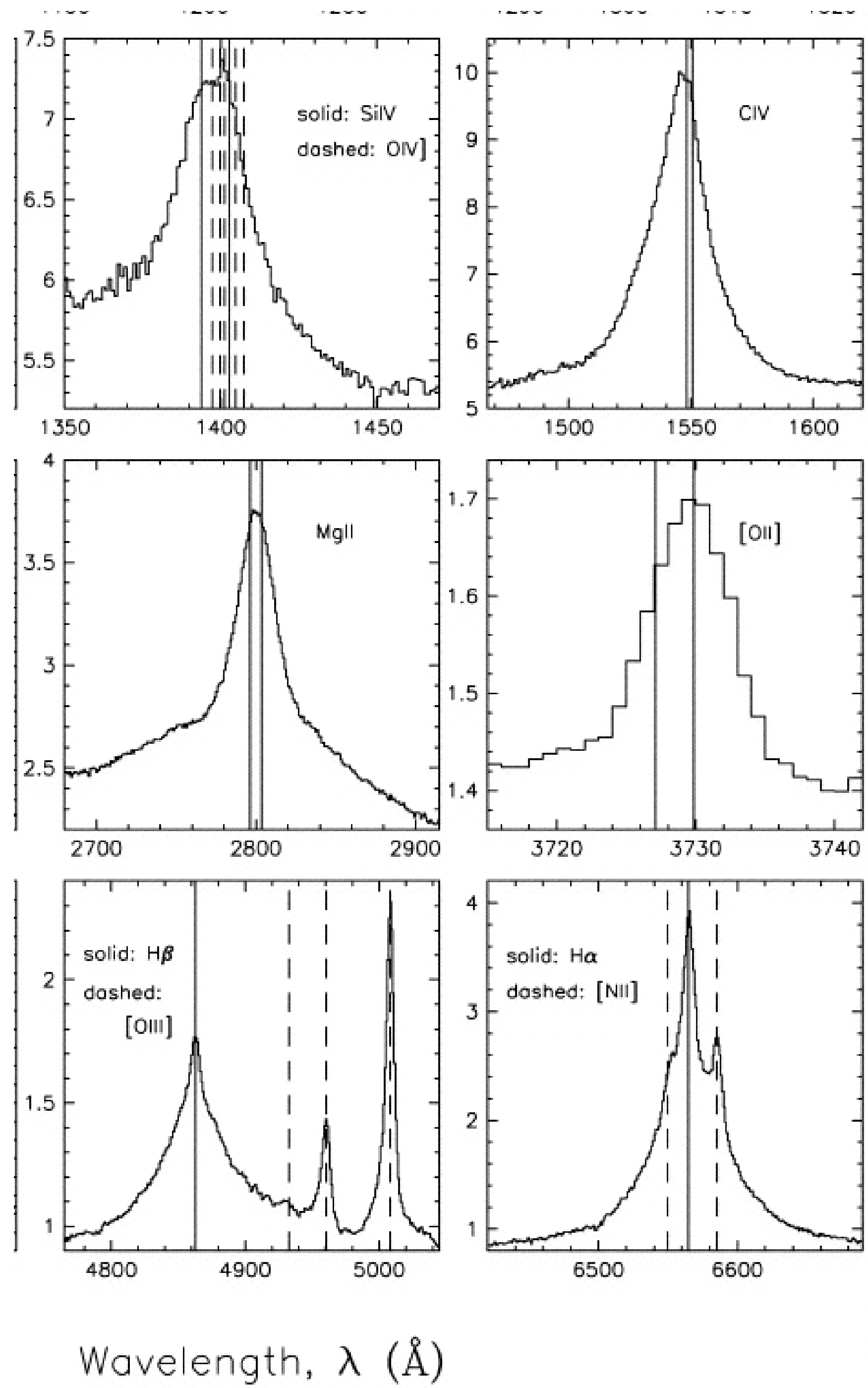
- Ionization of the plasma is determined by the balance between photionization and recombination
- Photoionization rate is proportional to the number of ionizing photons x number of ions x the cross section for interaction and the recombination rate to the number of ions x number of electrons x atomic physics rates

- Steady state ionization determined not by temperature, but by balance between photo-ionization (~F_E spectrum) and recombination (n_e):
  $n_q \int F_E \sigma^{PI}(E) dE = n_{q+1} n_e \alpha(T_e)$
- Ionization $n_{q+1}/n_q \propto F/n_e \propto L/n_e r^2 \equiv \xi$

ξ is the ionization parameter (also sometimes called U)

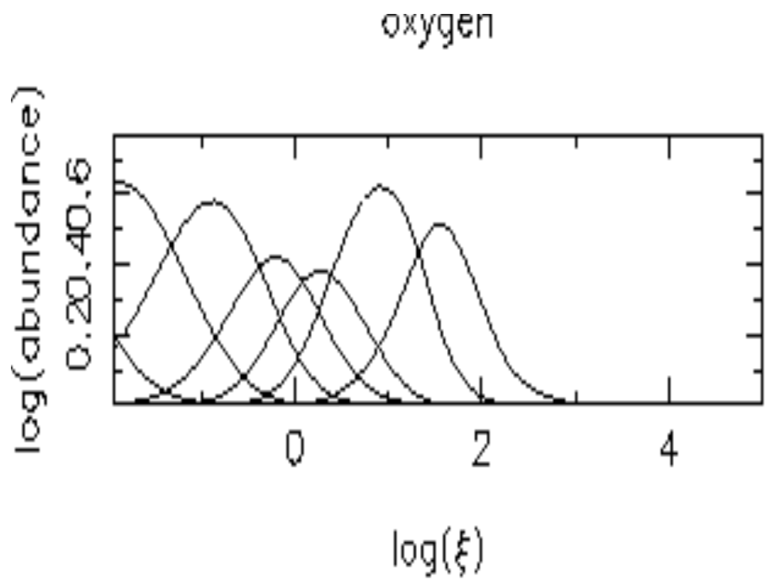
- A selection of emission lines ranging from high ionization CIV to low ionization Mg II

- Ionization state corresponds to higher values of the ionization parameter $\xi \sim L/n_e r^2$

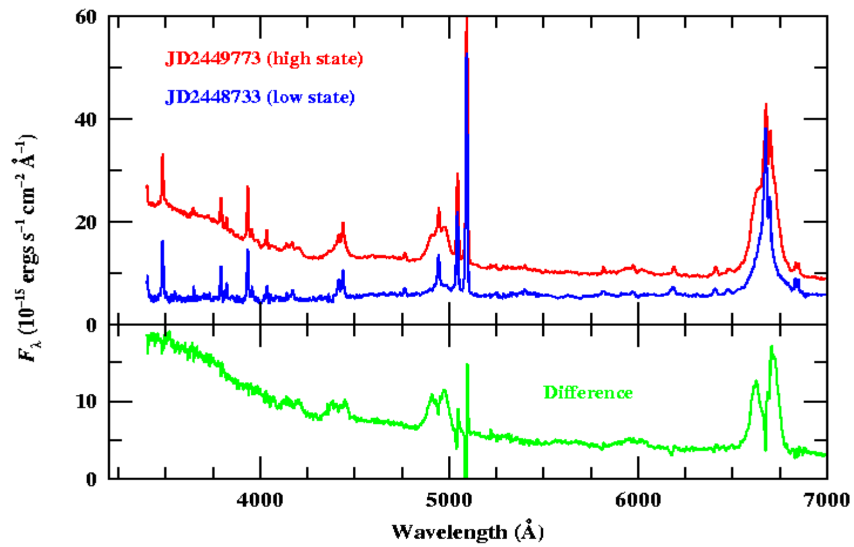


In Other Words

- For each ion:
  - Ionization = recombination
  - ~photon flux ~electron density
- For the gas as a whole
  - Heating = cooling
  - ~photon flux ~electron density
- => All results depend on the ratio photon flux/gas density or "ionization parameter"
- Higher ionization parameters produce more highly ionized lines (higher flux or lower density)



Neutral <------------>fully stripped

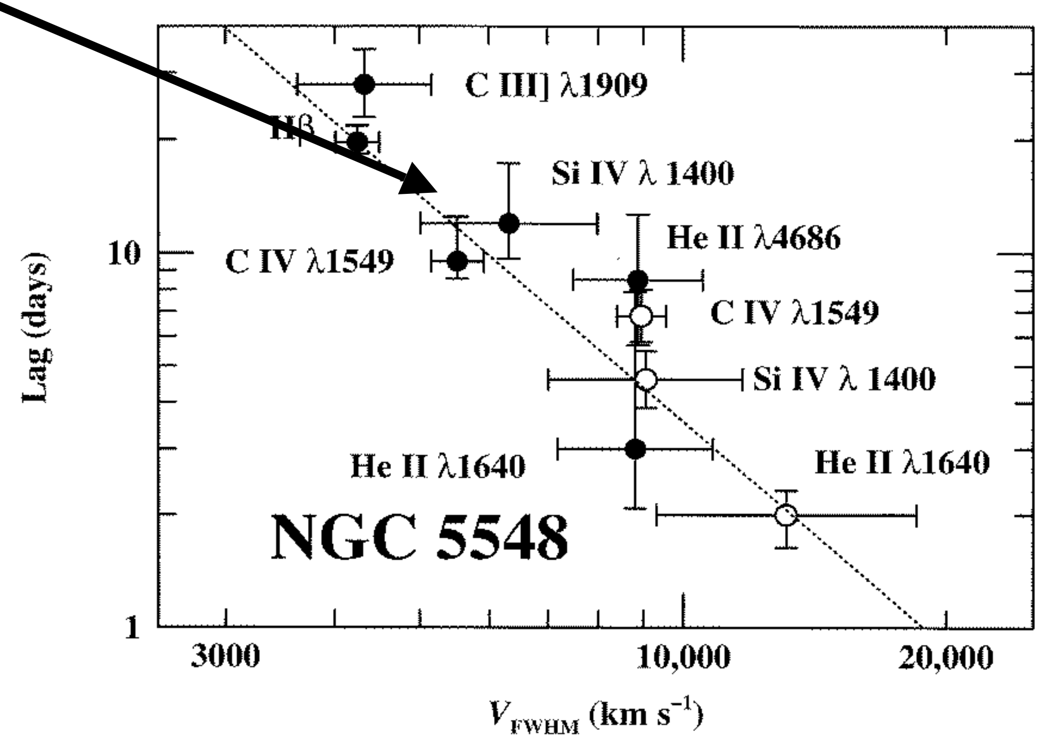


Peterson (1999)

What is Observed??

- The higher ionization lines have a larger width (rotational speed) and respond faster (closer to BH)
- Line is consistent with idea of photoionization, density $\sim r^{-2}$ and Keplerian motions dominating the line shapes ($v \sim r^{-1/2}$)

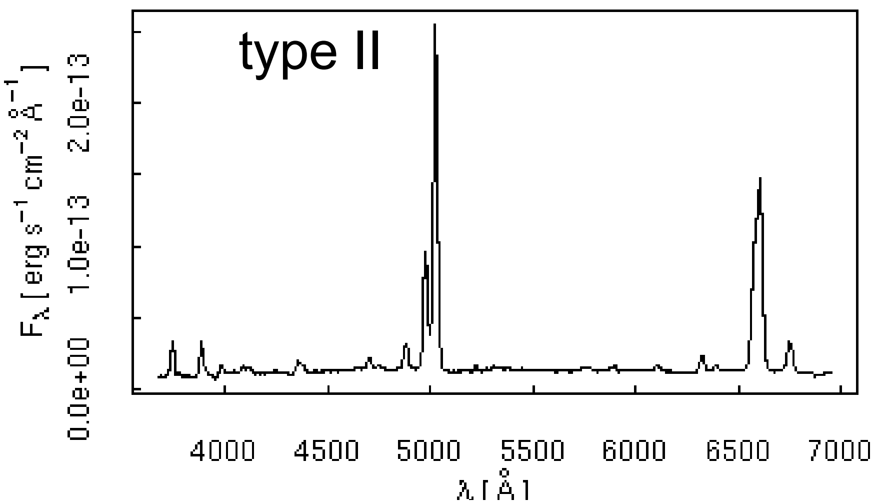
- Such data exist for ~40 sources
- At present M_{BH} can be estimated to within a factor of a few: $M \propto FWHM^2 L^{0.5}$

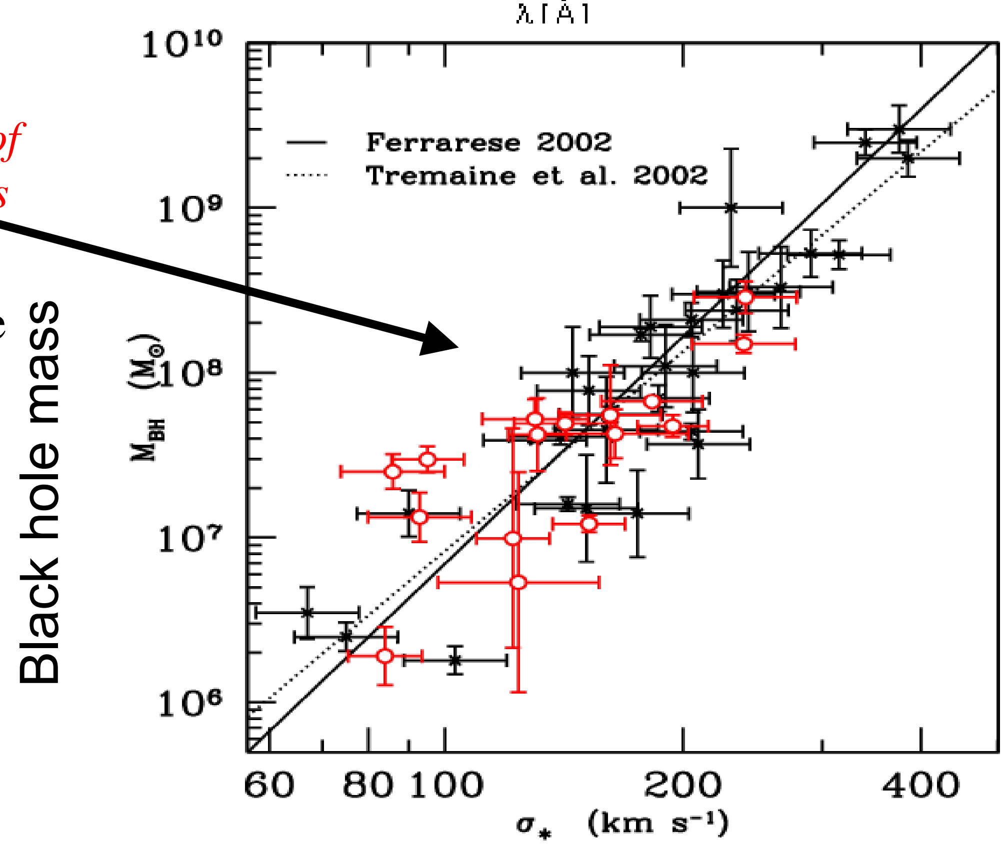


Dotted line corresponds to a mass of $6.8 \times 10^7 M_\odot$
Peterson and Wandel 1999

But What About Objects without a Strong Continuum

- There exists a class of active galaxies (type II) **which do not have broad lines and have a weak or absent 'non-stellar' continuum**
- Thus there is no velocity or luminosity to measure -rely on 'tertiary' indicators.
- It turns out (very surprisingly) that *the velocity dispersion of the stars in the bulge of the galaxy is strongly related to the BH mass*
  - This is believe to be due to 'feedback' (more later) the influence of the AGN on the formation of the galaxy and VV
  - The strong connection between the BH and the galaxy means that each know about each other

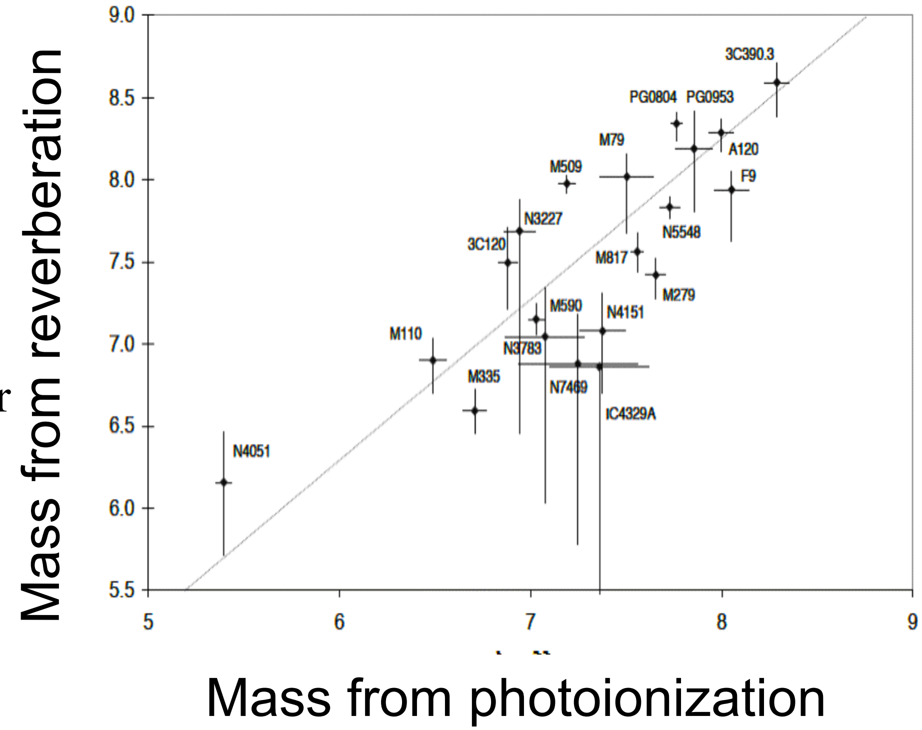




Velocity dispersion of stars in the bulge

Reverberation Masses and Dynamical Masses

- In general for the same objects mass determined from reverberation and dynamics agree within a factor of 3.
- This is 'great' but
  - dynamical masses very difficult to determine at large distances (need angular resolution)
  - Reverberation masses 'very expensive' in observing time (timescales are weeks-months for the response times)
  - If AGN have more or less similar BLR physics (e.g. form of the density distribution and Keplerian dynamics for the strongest lines) them we can just use the ionization parameter and velocity width (σ) of a line to measure the mass $\xi = L/n_e r^2$- find that $r \sim L^{1/2}$
  - Or to make it even simpler just L and σ and normalize the relation (scaling relation)- amazingly this works !



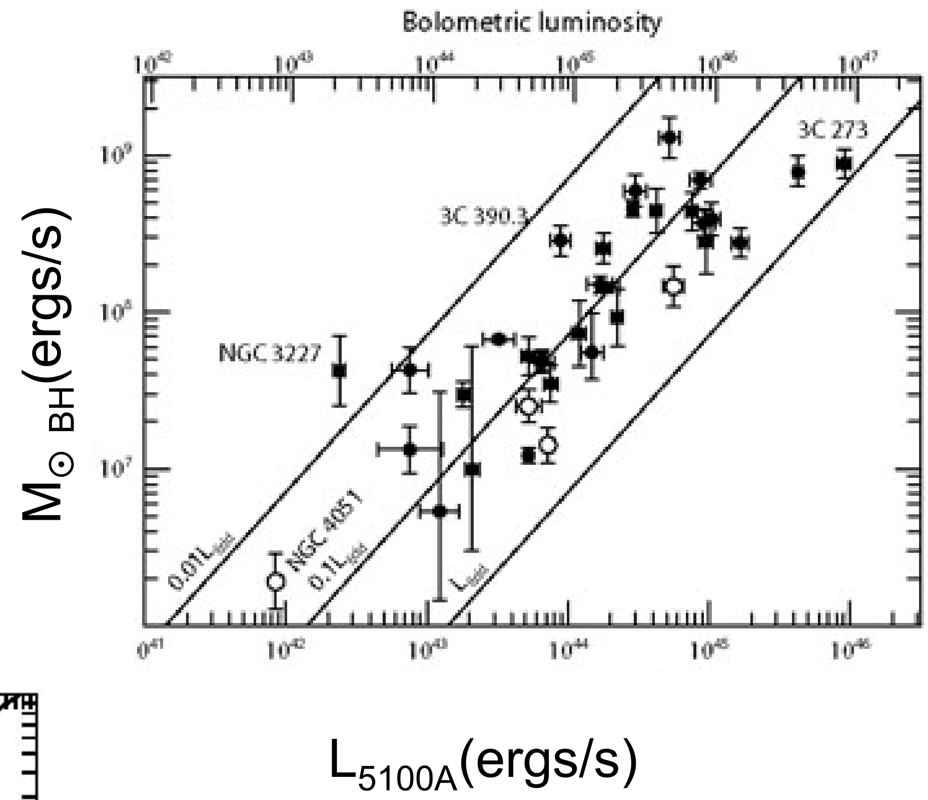
$M_{BH} \sim K\sigma^2 L^{1/2}$

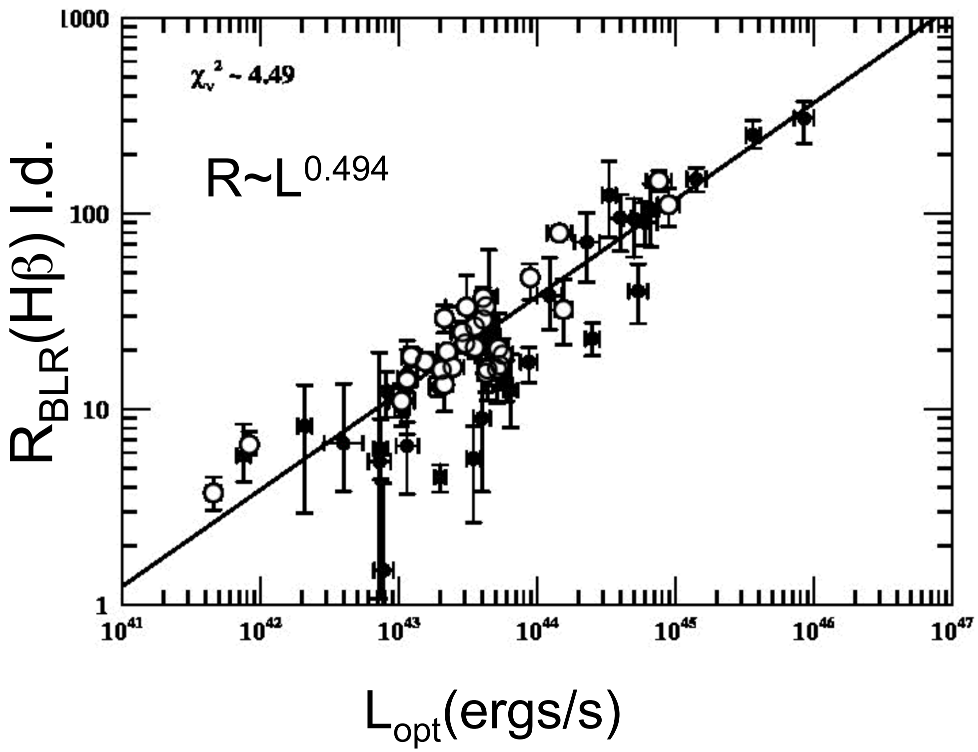
Where K is a constant (different for different lines which is determined by observations

This is just

$M_{BH} = v^2 R_{BLR}/G$ with an observable (L) replacing R_{BLR}

- Nature has chosen to make the size of the broad line region proportional to L $^{1/2}$

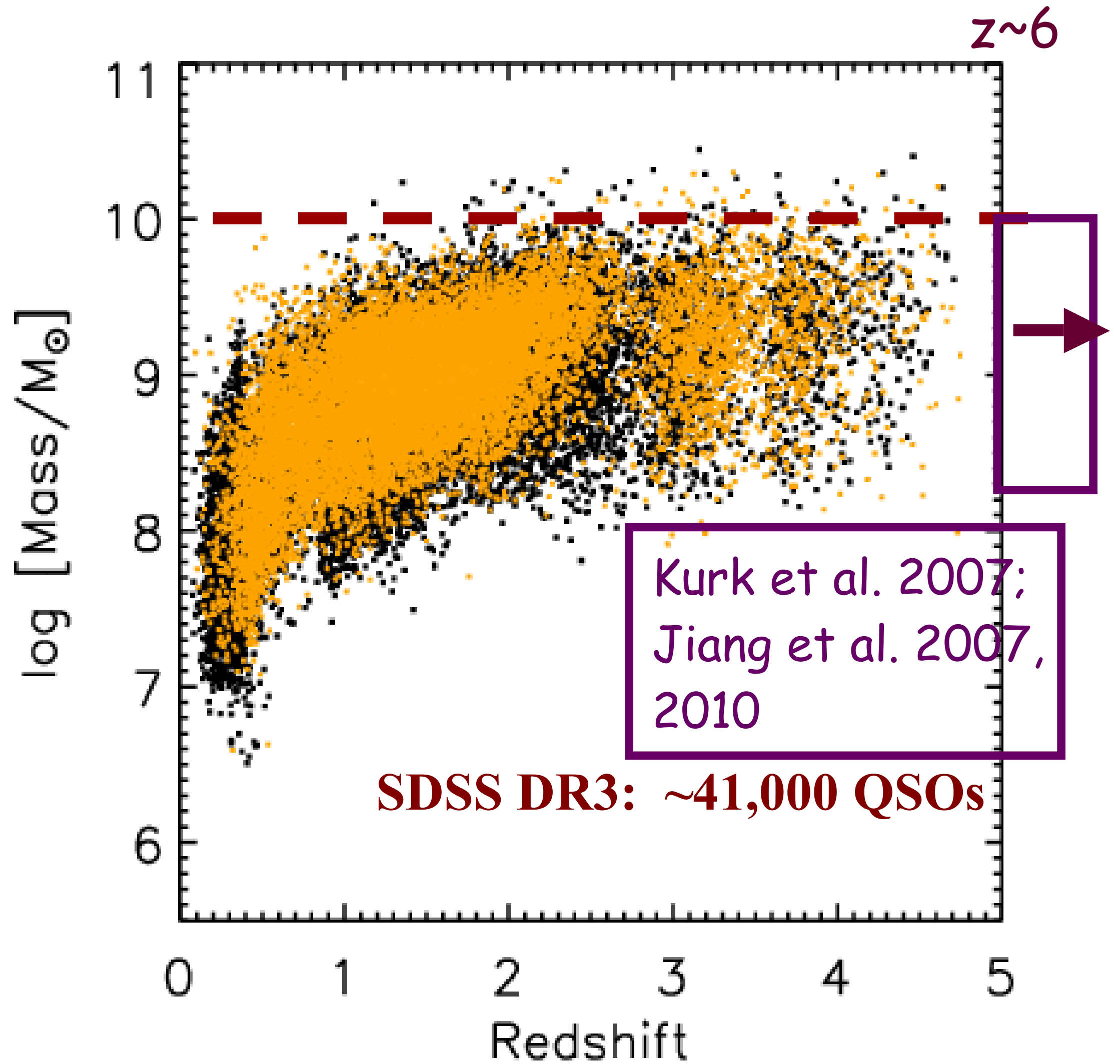




Masses of Distant Quasars- M. Vestergaard

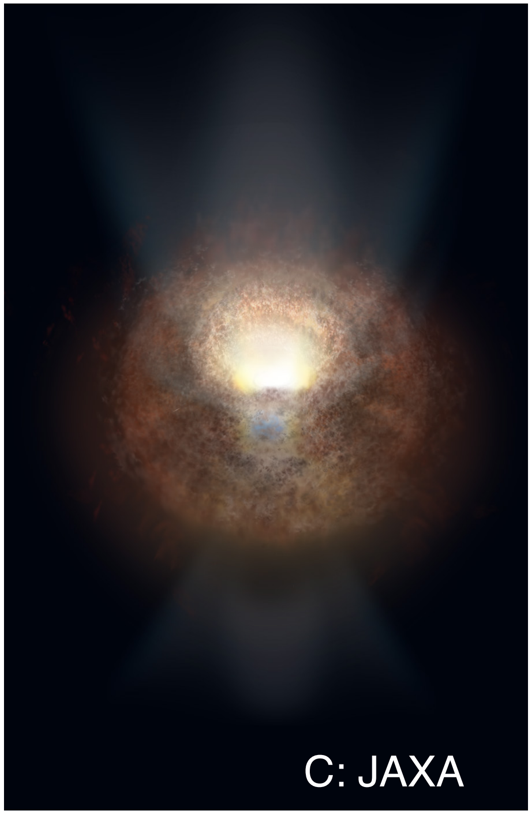
- Using this technique for a very large sample of objects from the Sloan Digital Sky Survey (SDSS)

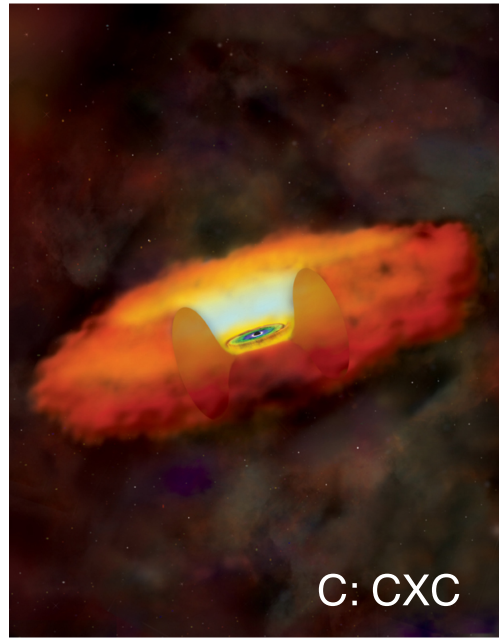
- Maximum mass $M_{BH} \sim 10^{10} M_{\odot}$
- $L_{BOL} < 10^{48}$ ergs/s

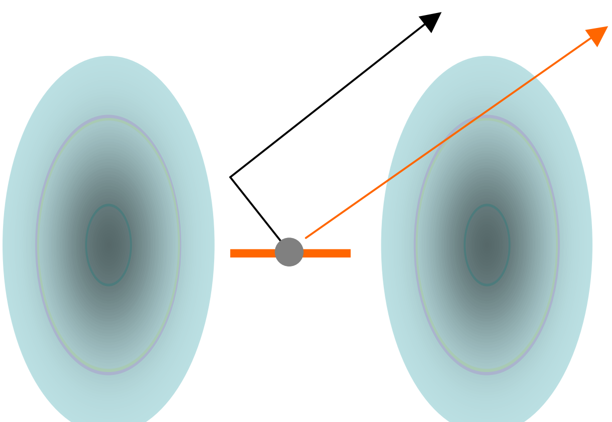


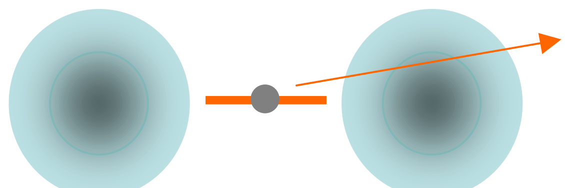
(DR3 Qcat: Schneider et al. 2005)

Some Variation in Geometry







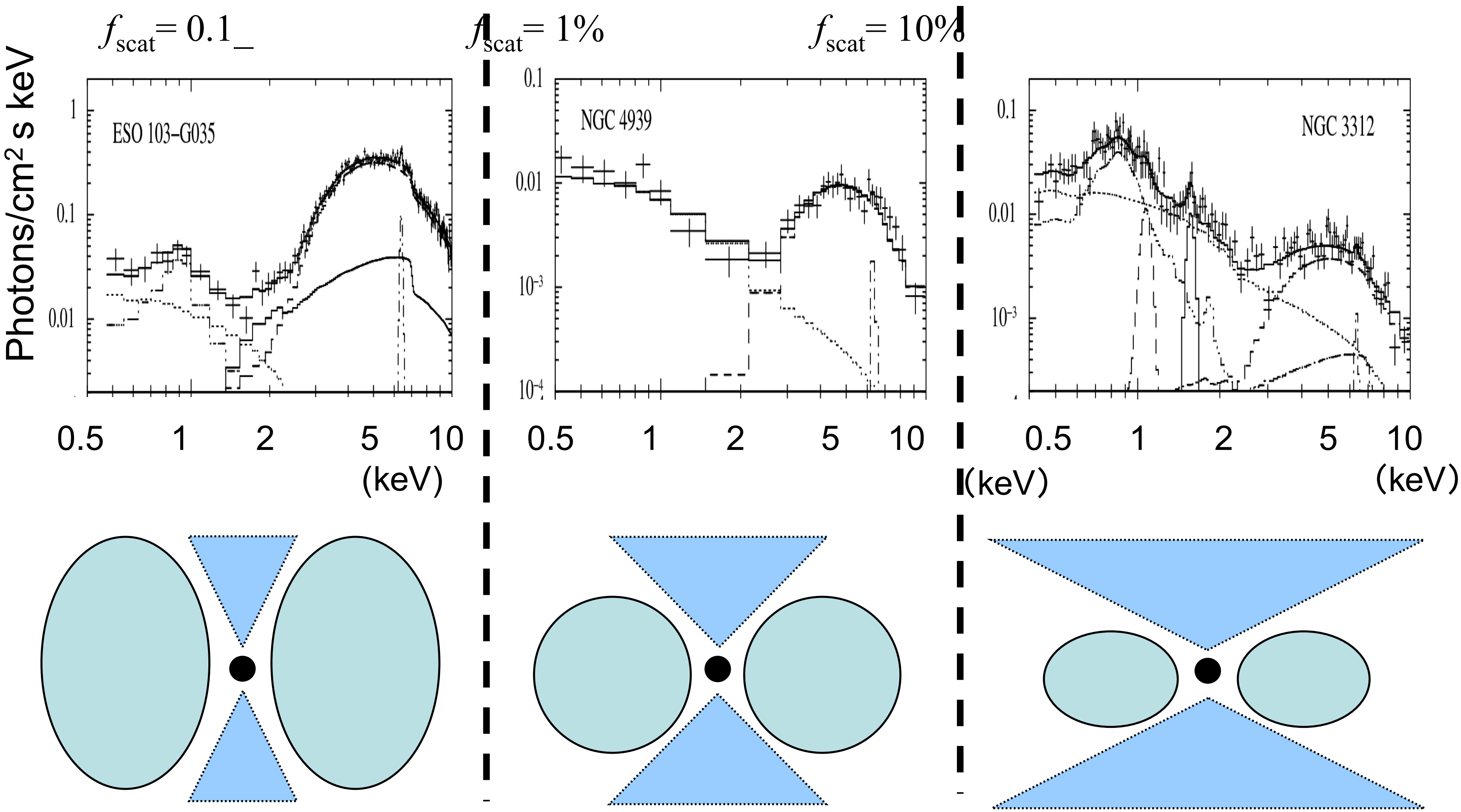


- Effects of geometry can be seen in the spectra

Examples-

XMM

f_{scat}= F(0.5-2) / F(2-10) (absorption corrected)



Co-evolution of Galaxies and Black Holes-Summary

- Theoretical models for the coevolution of galaxies and supermassive black holes are based on combining analytic models and numerical simulation of structure formation in the dark matter with ideas about how star formation
  and black hole accretion operate in practice
- Over cosmic time, galaxies grow through two main mechanisms: accretion of gas and mergers
- In a merger, the disk component of each galaxy is scrambled and tidal forces between the two galaxies drain away angular momentum from the cold gas in the disk of the galaxy, allowing it to flow into the inner region, delivering gas to the supermassive black hole.
- The scrambled disk material settles into a newly created spheroid.
- If the each of the merging galaxies contained their own supermassive black
  holes, these too might merge to form a single larger one.
- The release of energy from the merger-induced AGN and starburst is so intense that it may blow away most or all of the remaining gas in a powerful outflow.
- The end result is a single galaxy with a larger bulge and a substantially more massive black hole (Heckman and Kauffmann 2012)

Summary

- The most massive black holes today $M \sim 10^8 - 10^{10}$ M are no longer accreting a substantial amount of gas; thus, their masses are growing very slowly
- These black holes are found in the most massive galaxies with the most massive bulges
- Such galaxies are currently forming stars at a much smaller rate than in the distant past, and are lacking cold gas

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- $X^{+q} + h\nu \rightarrow X^{+(q+1)} + e^-$

- Ionization of the plasma is determined by the balance between photionization and recombination
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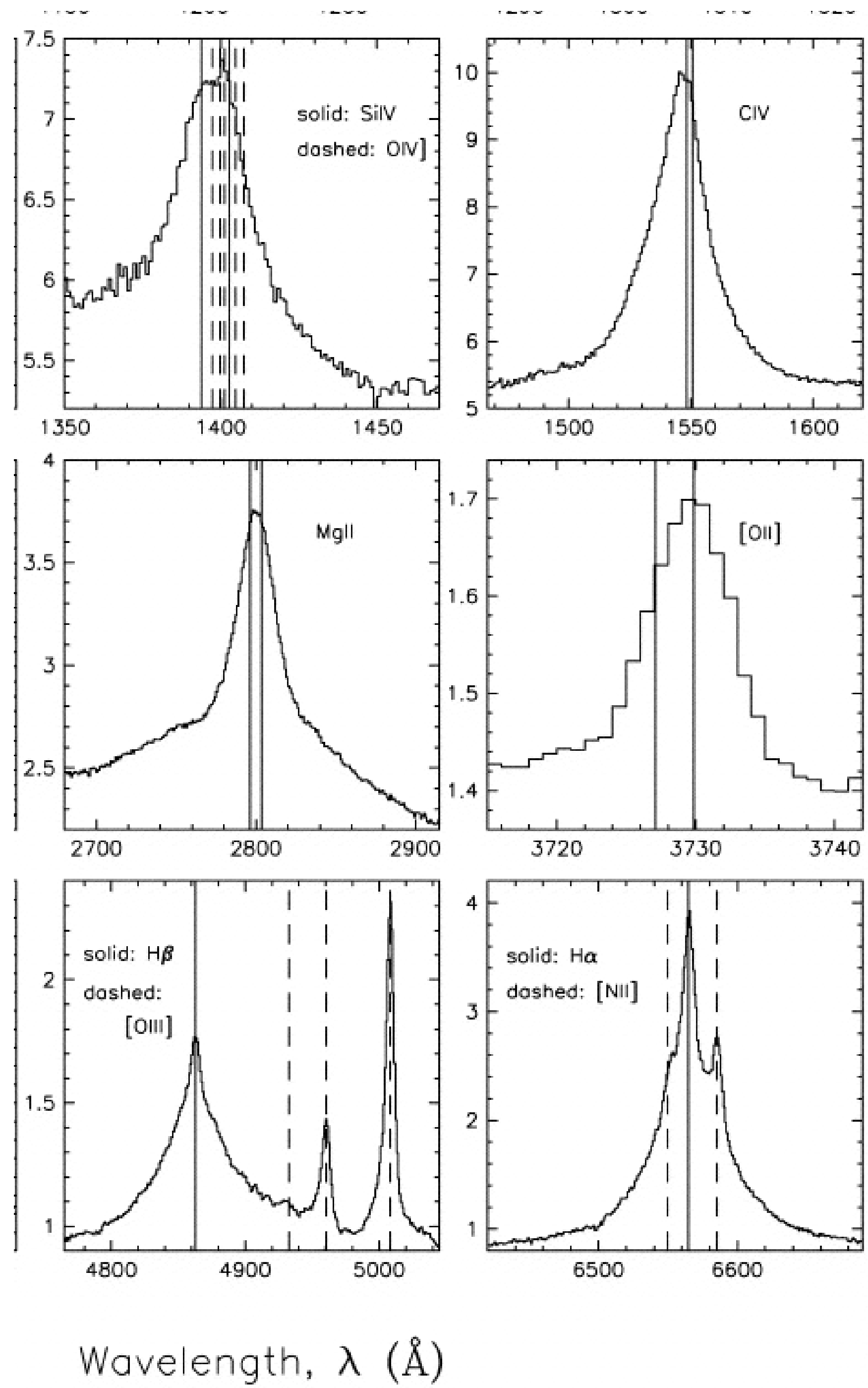
ξ is the ionization parameter (also sometimes called U)

- A selection of emission lines ranging from high ionization CIV to low ionization Mg II

- Ionization state corresponds to higher values of the ionization parameter $\xi \sim L/n_e r^2$



Co-evolution of Galaxies and Black Holes-Summary

- Theoretical models for the coevolution of galaxies and supermassive black holes are based on combining analytic models and numerical simulation of structure formation in the dark matter with ideas about how star formation and black hole accretion operate in practice
- Over cosmic time, galaxies grow through two main mechanisms: accretion of gas and mergers
- In a merger, the disk component of each galaxy is scrambled and tidal forces between the two galaxies drain away angular momentum from the cold gas in the disk of the galaxy, allowing it to flow into the inner region, delivering gas to the supermassive black hole.
- The scrambled disk material settles into a newly created spheroid.
- If the each of the merging galaxies contained their own supermassive black holes, these too might merge to form a single larger one.
- The release of energy from the merger-induced AGN and starburst is so intense that it may blow away most or all of the remaining gas in a powerful outflow.
- The end result is a single galaxy with a larger bulge and a substantially more massive black hole (Heckman and Kauffmann 2012)

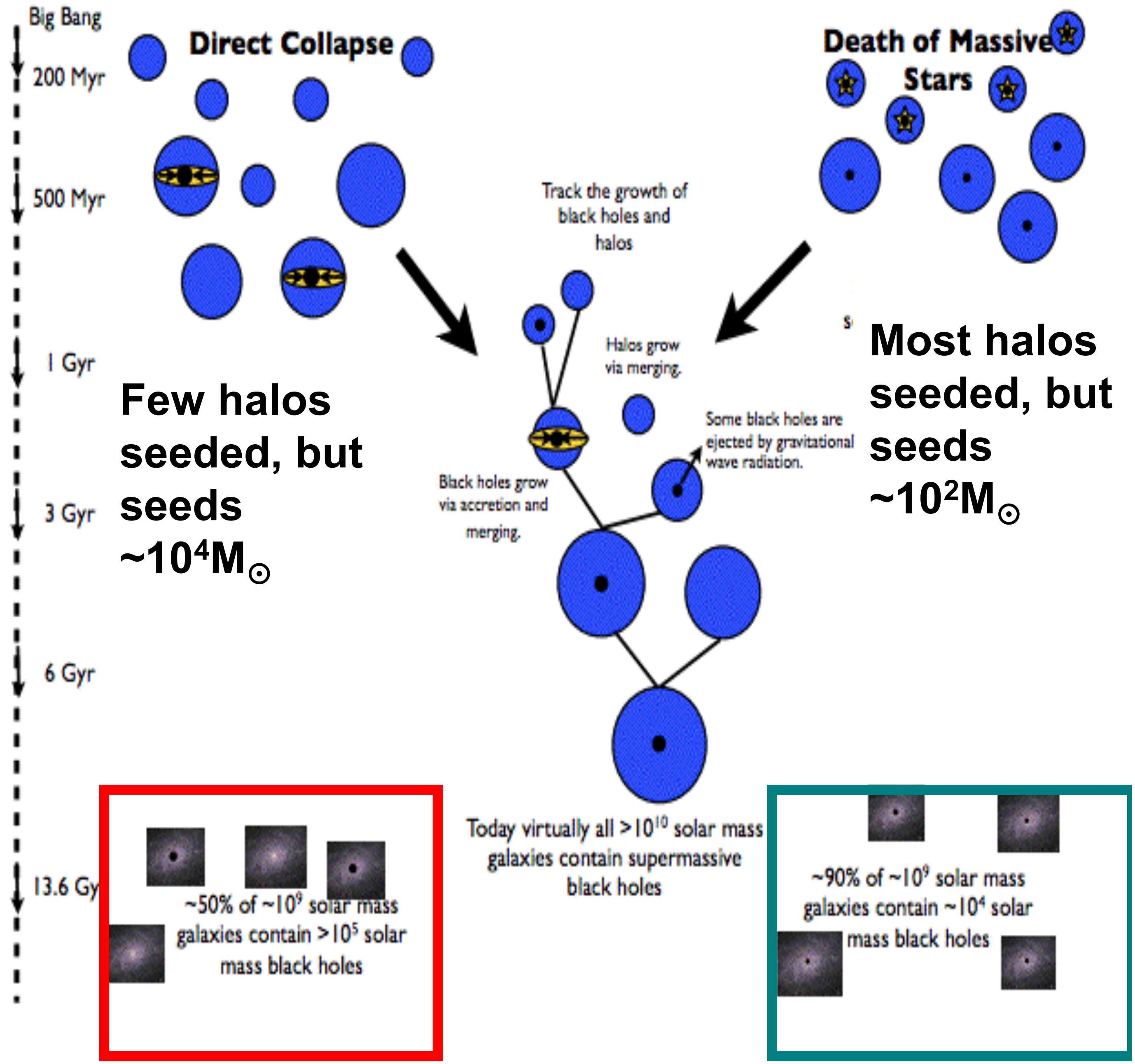
Summary

- The most massive black holes today $M \sim 10^8\text{-}10^{10}$ M are no longer accreting a substantial amount of gas; thus, their masses are growing very slowly
- These black holes are found in the most massive galaxies with the most massive bulges
- Such galaxies are currently forming stars at a much smaller rate than in the distant past, and are lacking cold gas

2 Scenarios for Birth of SMBHs

How do SMBHs get started??
Detect $M \sim 10^9 M$ BH at z~7- need to grow fast!

Distinguish the 2 paths based on the fraction of *small* galaxies that today contain SMBHs
Greene 2012



Constraints on Rest Mass of Black Holes

- Black holes can grow via two paths
  - accretion
  - merger

- It is thought that, at $z>1$ that many galaxies (esp elliptical galaxies) grow through mergers.

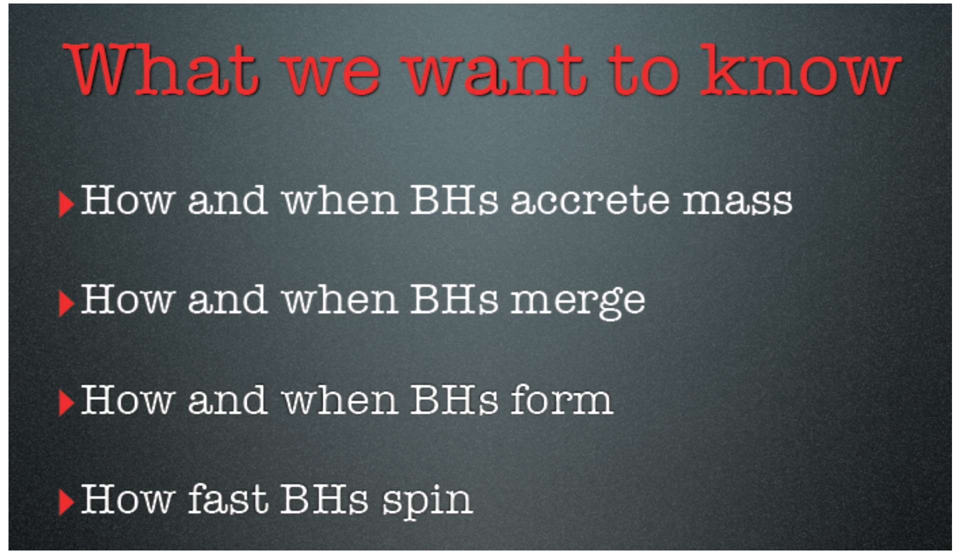
If these galaxies had modest black holes, and if the black holes also merged, one could grow the supermassive black holes that lie in most large galaxies observed today.

This process would produce strong gravitational radiation which is the goal of the LISA mission

- Alternatively (or in parallel) we know that BHs are growing via accretion- e.g. **see AGN.**

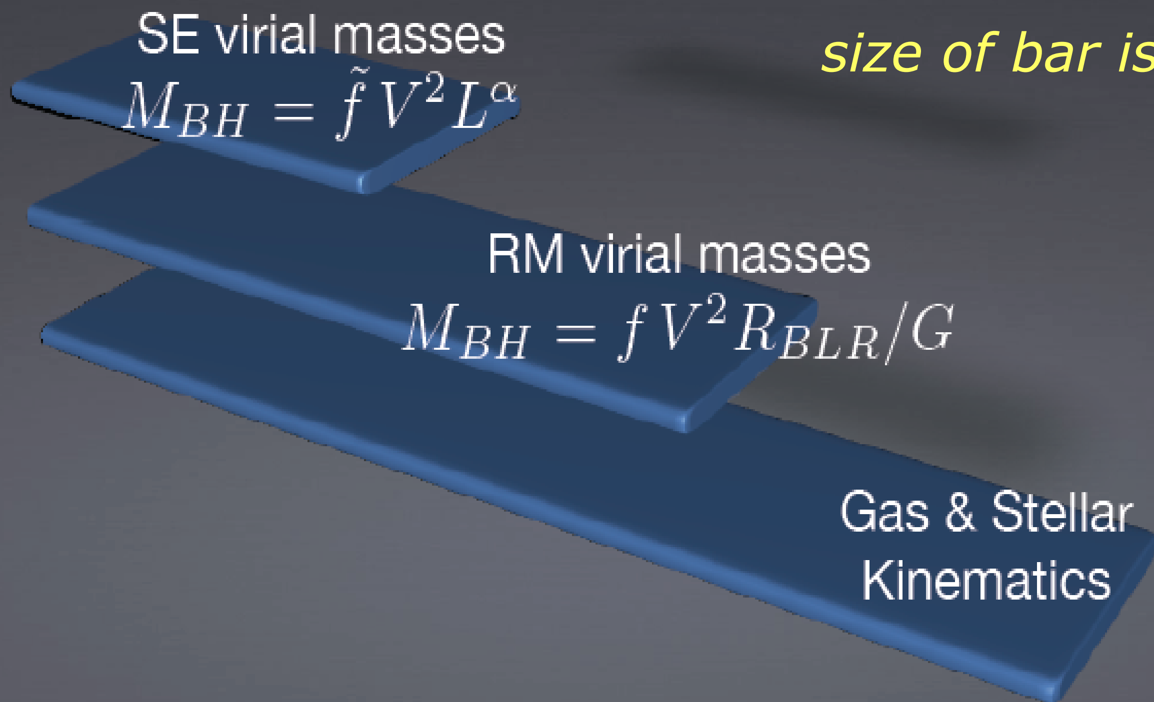
Constraints on Growth of Black Holes

- To calculate how much mass has been accreted by black holes over cosmic time we need to know how they have grown (Soltan 1982)
  - that is measure the number per unit volume per unit time per unit mass.



The BH mass ladder (Peterson 2002)

size of bar is α accuracy



1. Spatially resolved gas & stellar kinematics
2. Virial masses based on Reverberation Mapping (RM) observations (R_{BLR} = c T, T time lag of BLR emission lines, eg. Onken +04)
3. Virial masses based on Single Epoch (SE) spectra (R from continuum luminosity using R_{BLR}-L relation by Kaspi +00, +05, eg Vestergaard & Peterson 06)

Continuity equation for SMBH growth

Need to know simultaneously mass function $\Psi(M,t_0)$
and accretion rate distribution F(dM/dt,M,t) ["Fueling function"]

$$\frac{\partial\psi(M,t)}{\partial t} + \frac{\partial}{\partial M}\left(\psi(M,t)\int \dot{M} F(\dot{\mu},\mu,t)\,\mathrm{d}\dot{\mu}\right) = 0$$

$$\phi(\ell,t) = \int F(\dot{\mu},\mu,t)\psi(\mu,t)\,\mathrm{d}\mu$$

luminosity function — mass function

$\mu = Log\,M$

$\ell = Log\,L_{\rm bol}$

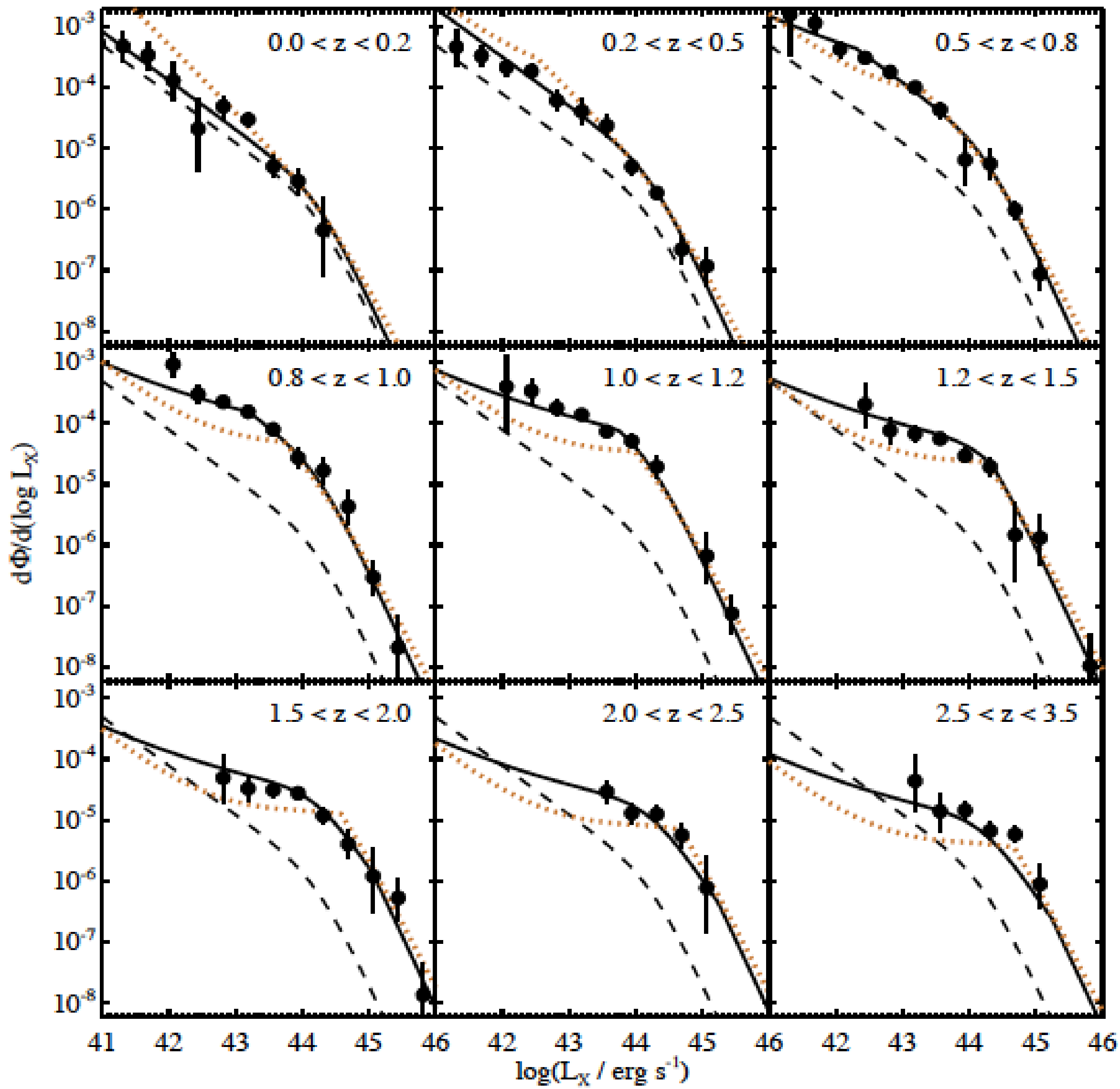
$\dot{\mu} = Log\,\dot{M}$

Cavaliere et al. (1973); Small & Blandford (1992); Marconi et al. (2004); Merloni (2004)

Luminosity function vs z

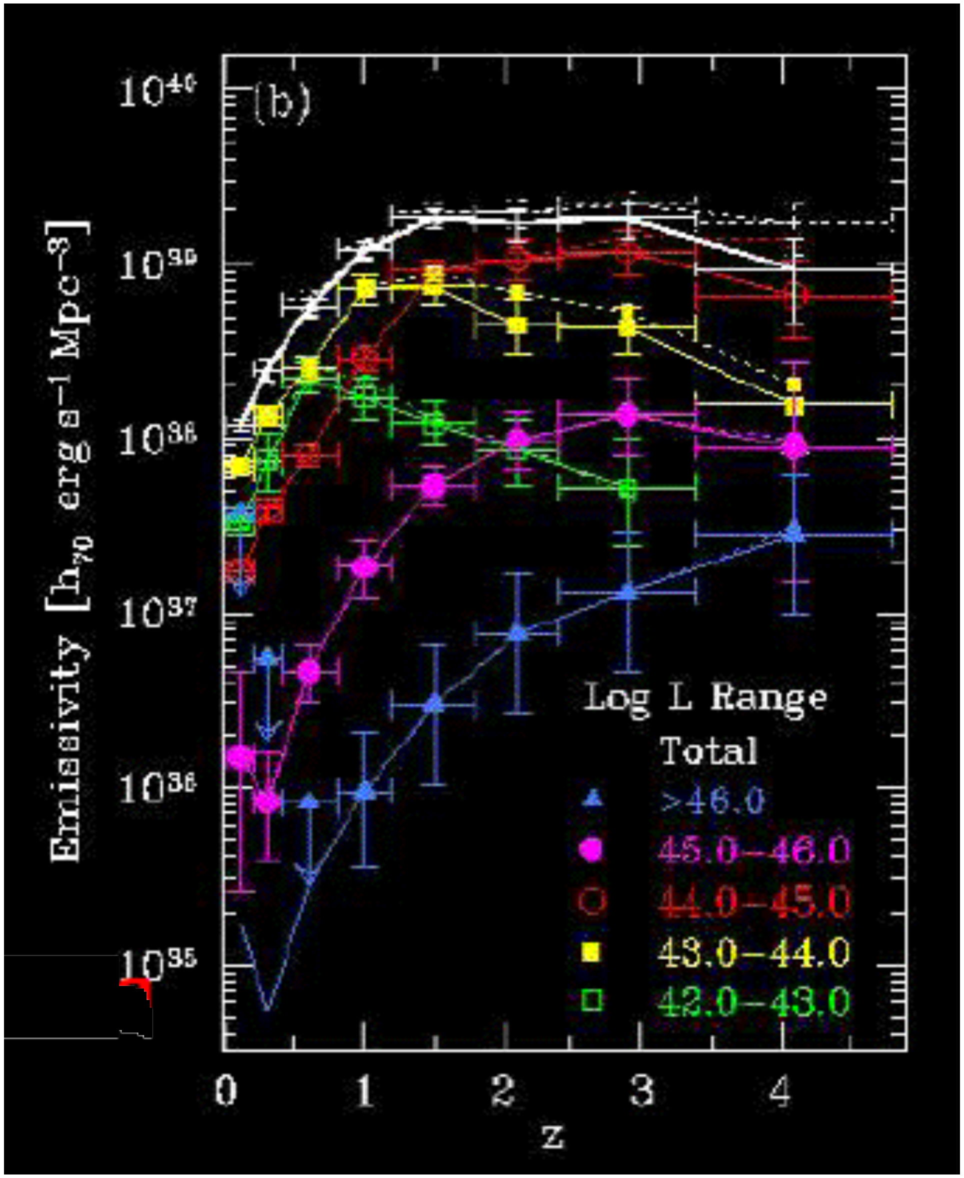
- The Evolution in the Luminosity Function of BH vs cosmic time
- #/Volume/luminosity
- In each plot the dotted grey line is the z=0 function

Aird et al 2009



Transform Luminosity Function to Energy Emissivity

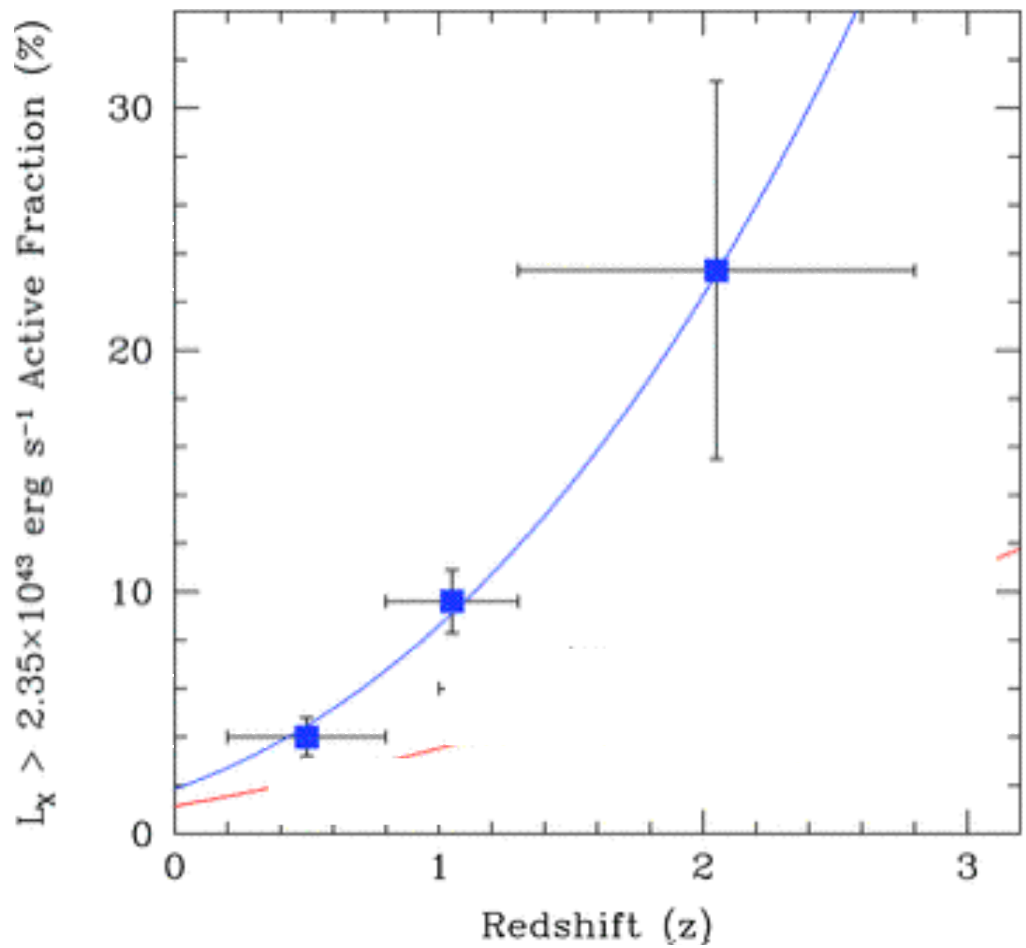
- Integrate the luminosity function in redshift shells
- Notice downsizing more luminous objects are more dominant at high redshift and that the evolution is a function of luminosity
- E_{AGN}~1.4 +/- 0.25 x10^{61} erg per galaxy since z = 3.
- Average AGN luminosity density of L_{AGN} ~10^{57} erg Mpc^3 /Gyr (Bluck et al 2011)



Brandt and Hasinger 2005 ARAA

Larger Fraction of Galaxies Active in the past

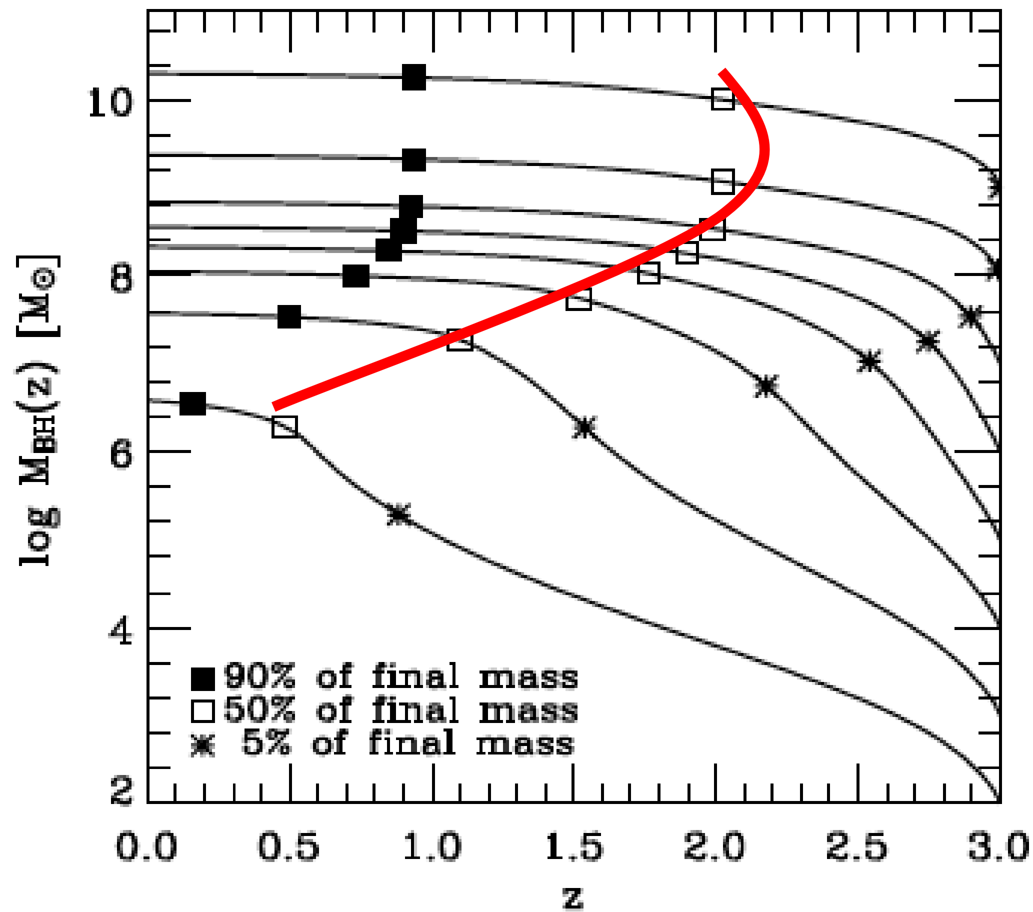
- The evolution seen in luminosity and number is reflected in the fact that a greater fraction of 'normal' galaxies host AGN at higher redshifts



(Bluck et al 2011)

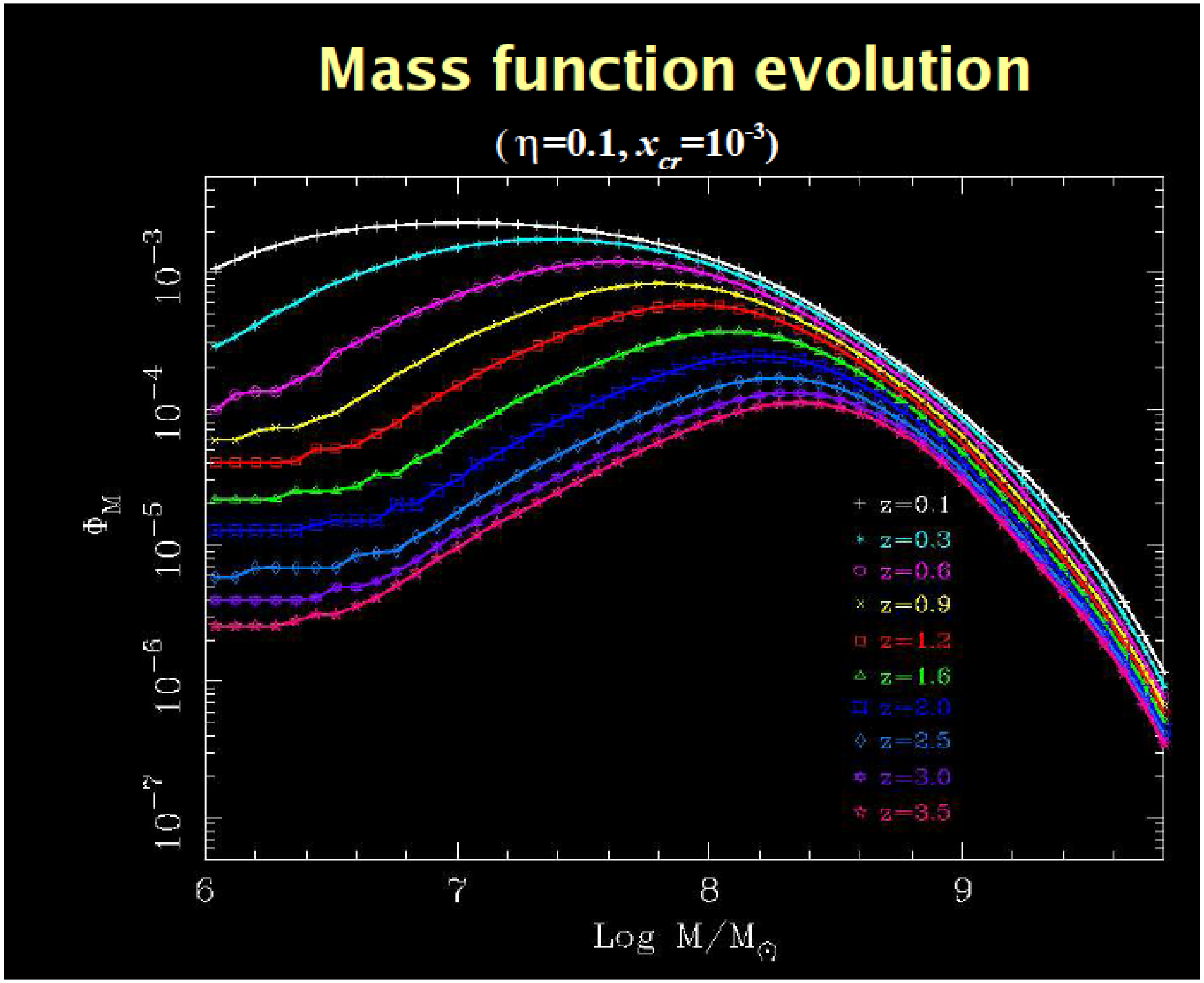
One realization of BH growth

- Big BHs form in deeper potential wells ⇨ they form first.
- Smaller BHs form in shallower potential wells ⇨ they form later and take more time to grow.
  - Marconi 2003, Merloni 2004

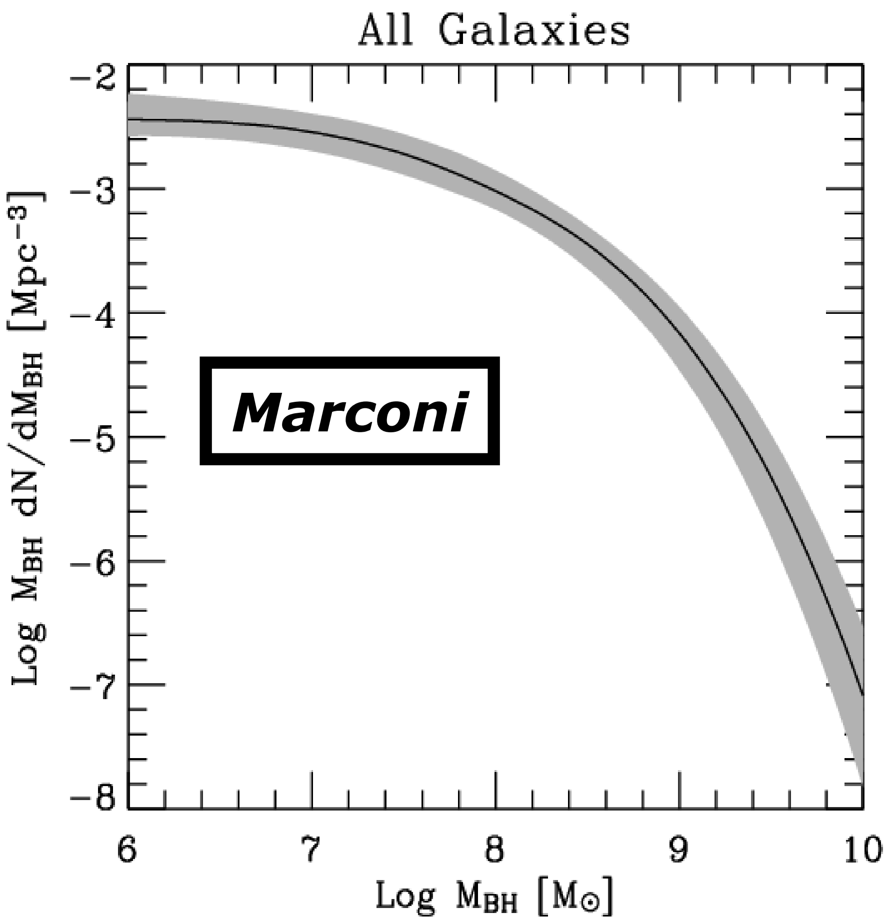


Transform to Mass Growth

- Take accretion rate and some model of initial BH mass distribution and watch them grow (Merloni et al 2006)
- Notice 'down sizing' big black holes grow first and small black holes later



The local Black Hole Mass Function



Marconi et al. 2004

- Convolve Galaxy Luminosity functions with M_{BH}-L_{bul} and M_{BH}-σ to obtain the local BH mass function.
  - M_{BH}-L_{bul} and M_{BH}-σ provide consistent BH mass functions provided that dispersions are taken in to account (shaded area indicates uncertainties)

$\_{BH} \sim 4.1^{+1.9}_{-1.4}$ _10^5 $M_\odot$ Mpc^{-3}

(cf. Merritt & Ferrarese 2001, Ferrarese 2002, Shankar et al. 2004)

- In summary: 3-5 _10^5 $M_\odot$ Mpc^{-3} (see Ferrarese & Ford 2005 for a review)