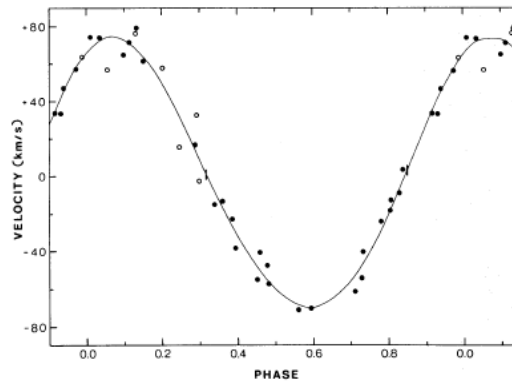


## Discovery of black holes

- First evidence for an object which 'must' be a black hole came from discovery of the X-ray source Cygnus

X-1

- Binary star system... black hole in orbit around a massive O-star; period = 5.6 days - not eclipsing
- Mass of x-ray emitting object 7-13 M- too high for a NS. Object emits lots of x-rays little optical light.
- X-rays produced due to accretion of stellar wind from O star
- 2kpc away



Velocity curve of the stellar companion  
It is a massive O star

$$f(M) = P_{\text{orb}} K_2^3 / 2\pi G = M_1 \sin^3 i / (1 + q)^2$$

$$q = M_2 / M_1$$

the value of the mass function is the absolute minimum mass of the compact star

Course evaluations are open- Please Respond!

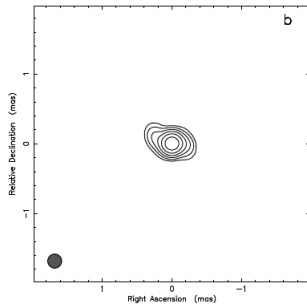
- [www.courseevalum.umd.edu](http://www.courseevalum.umd.edu)
- Why?
  - For the benefit of your peers
  - Because your comments count and we use it to improve our teaching and/or redesign the course
  - Because your opinion is used to evaluate our performance
- Don't put it off till Dec 11th!
- Only 3 people have responded so far!

**Table 1.** Confirmed black holes and mass determinations

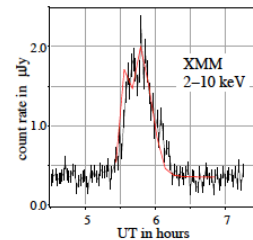
System	$P_{\text{orb}}$ [days]	$f(M)$ [ $M_{\odot}$ ]	Donor Spect. Type	Classification	$M_x$ † [ $M_{\odot}$ ]
GRS 1915+105 <sup>a</sup>	33.5	$9.5 \pm 3.0$	K/M III	LMXB/Transient	$14 \pm 4$
V404 Cyg	6.471	$6.09 \pm 0.04$	K0 IV	"	$12 \pm 2$
Cyg X-1	5.600	$0.244 \pm 0.005$	09.7 Iab	HMXB/Persistent	$10 \pm 3$
LMC X-1	4.229	$0.14 \pm 0.05$	07 III	"	$> 4$
XTE J1819-254	2.816	$3.13 \pm 0.13$	B9 III	IMXB/Transient	$7.1 \pm 0.3$
GRO J1655-40	2.620	$2.73 \pm 0.09$	F3/5 IV	"	$6.3 \pm 0.3$
BW Cir <sup>b</sup>	2.545	$5.74 \pm 0.29$	G5 IV	LMXB/Transient	$> 7.8$
GX 339-4	1.754	$5.8 \pm 0.5$	—	"	
LMC X-3	1.704	$2.3 \pm 0.3$	B3 V	HMXB/Persistent	$7.6 \pm 1.3$
XTE J1550-564	1.542	$6.86 \pm 0.71$	G8/K8 IV	LMXB/Transient	$9.6 \pm 1.2$
4U 1543-475	1.125	$0.25 \pm 0.01$	A2 V	IMXB/Transient	$9.4 \pm 1.0$
H1705-250	0.520	$4.86 \pm 0.13$	K3/7 V	LMXB/Transient	$6 \pm 2$
GS 1124-684	0.433	$3.01 \pm 0.15$	K3/5 V	"	$7.0 \pm 0.6$
XTE J1859+226 <sup>c</sup>	0.382	$7.4 \pm 1.1$	—	"	
GS2000+250	0.345	$5.01 \pm 0.12$	K3/7 V	"	$7.5 \pm 0.3$
A0620-003	0.325	$2.72 \pm 0.06$	K4 V	"	$11 \pm 2$
XTE J1650-500	0.321	$2.73 \pm 0.56$	K4 V	"	
GRS 1009-45	0.283	$3.17 \pm 0.12$	K7/M0 V	"	$5.2 \pm 0.6$
GRO J0422+32	0.212	$1.19 \pm 0.02$	M2 V	"	$4 \pm 1$
XTE J1118+480	0.171	$6.3 \pm 0.2$	K5/M0 V	"	$6.8 \pm 0.4$

## The Center of the Milky Way

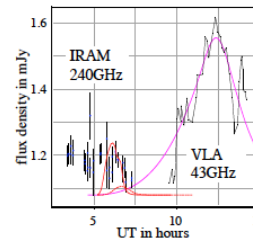
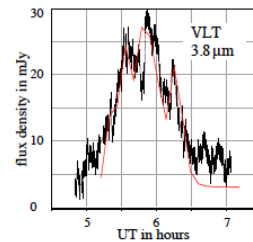
- The center of the MW is called Sagittarius A\* (SgrA\*) from the name of the radio source at the dynamical center of the MW.
- This is also the location of a weak, time variable x-ray ( $\log L_x \sim 34$ -100x less than a typical x-ray binary) and IR source
- The radio source is very small (VLBI) ( $< 0.0005'' < 50R_s$  for  $M = 4 \times 10^6 M_{\odot}$  BH at  $d = 8 \text{ kpc}$ )
- At SgrA\*  $1'' = 0.04 \text{ pc} = 1.2 \times 10^{17} \text{ cm}$ ,  $0.5 \text{ mas} = 6 \text{ AU}$



Radio image of SgrA\*



Radio,  
near IR  
and x-  
ray light  
curves

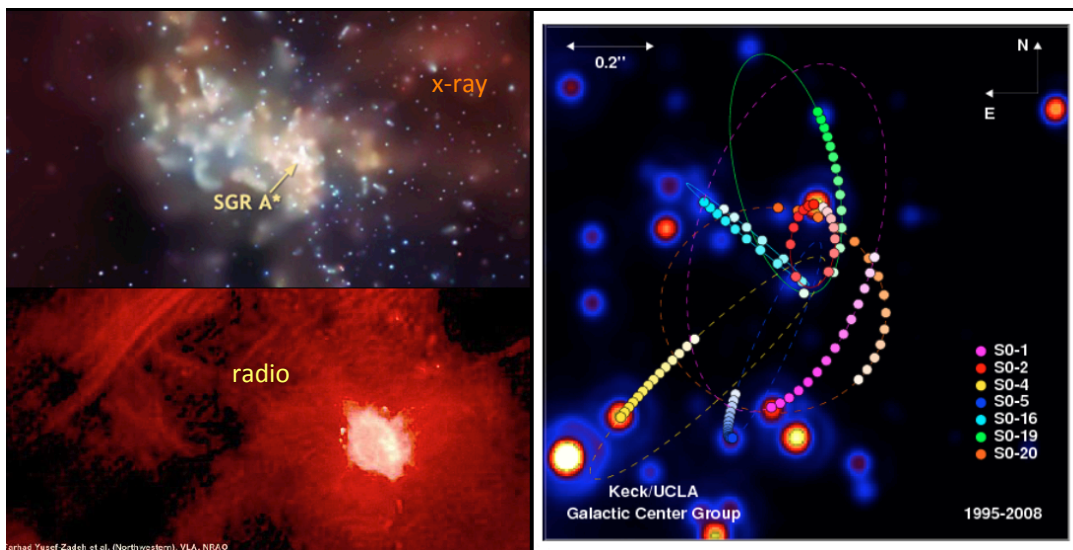


## Some Problems with Sgr A\*

- There is lots of gas for accretion in the galactic center from the ISM and stellar winds
- Yet the observed luminosity is very low ( $L/L_{\text{Edd}} \sim 10^{-10}$ )
- What happens to the accretion energy- where does the mass and energy go
- Sgr A\* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities **TODAY!** (AGN evolution)

## MW Galactic Center

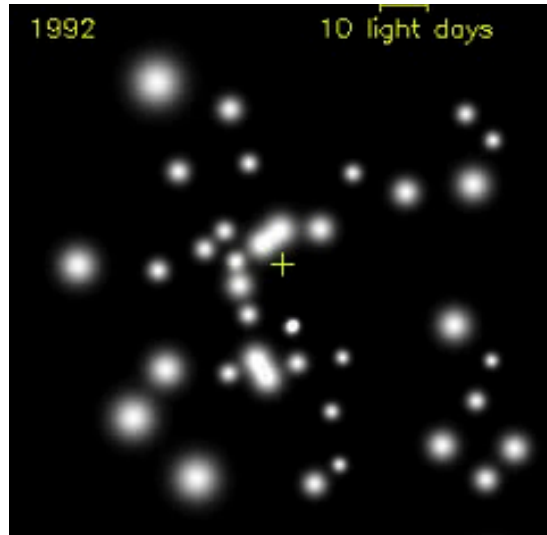
- galactic centers are 'special' places
- MW galactic center



Motion of Stars Around the Center of the Milkyway- see

<http://www.youtube.com/watch?v=ZDxFjq-scVU>

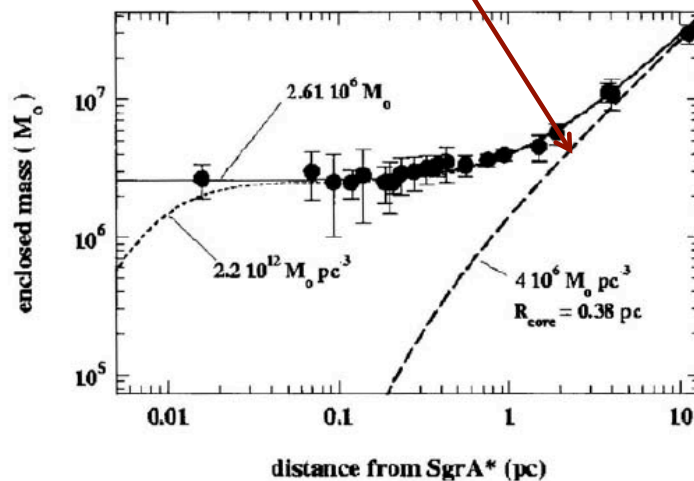
<http://www.mpe.mpg.de/ir/GC/>



- Two teams led by R. Genzel and A. Ghez have measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is  $>10^{12} M_{\odot} / \text{pc}^3$

### MW Center

Predicted mass from models of the Milkyway



- As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass  $2.6 \times 10^6 M_{\text{sun}}$ , and density  $20 M_{\text{sun}} \text{pc}^{-3}$  or greater can not be stable for more than about 10 million years

# Velocity Distribution of Stars Near the Center of the MW

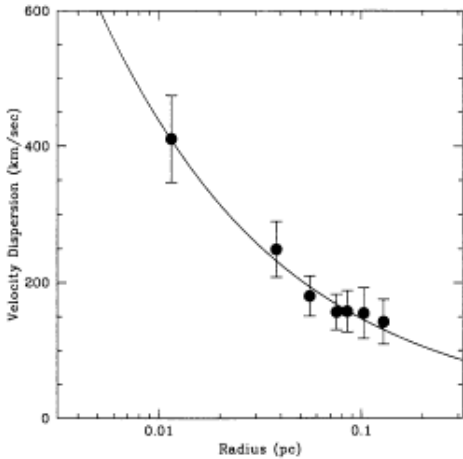
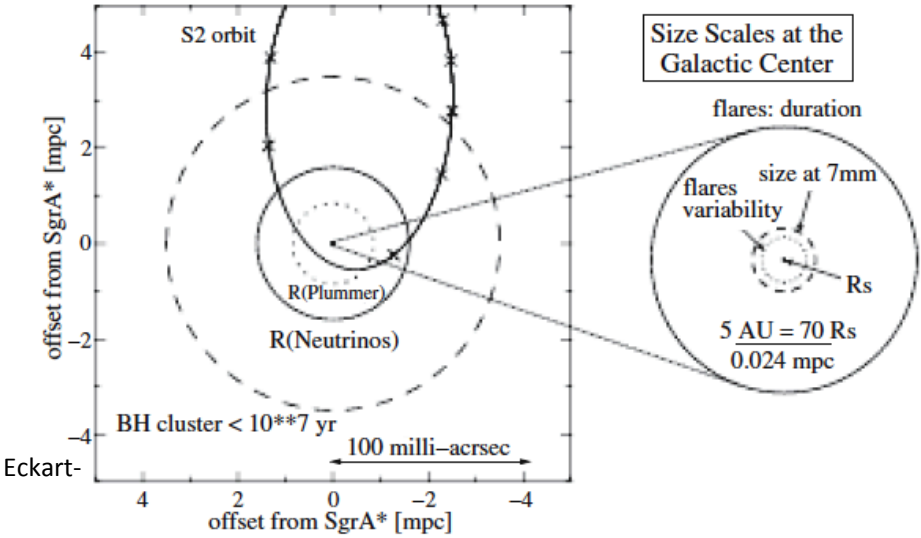


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A\* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

Ghez et al 1998

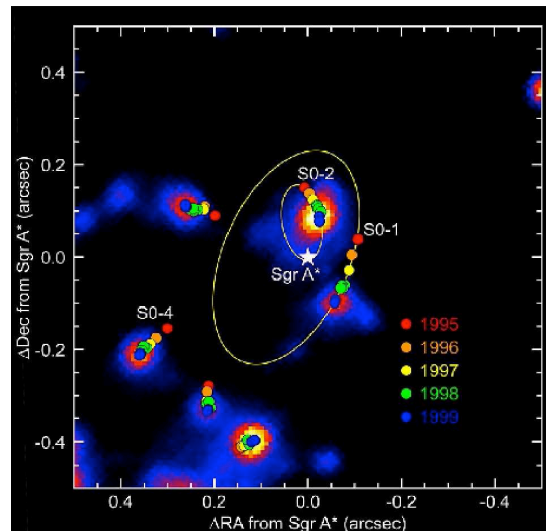


- While stars are moving very fast near the center (Sgr A\*) the upper limit on **its** velocity is 15 km/sec

If there is equipartition of momentum between the stars and SgrA\* then one expects

$$M_{\text{SgrA}^*} > 1000M_{\odot} (M_*/10M_{\odot})(v_*/1500\text{km/sec})(v_{\text{SgrA}^*}/15\text{km/sec})^{-1}$$

Where we have assumed that the star stars we see have a mass  $10M_{\odot}$  and a velocity of 1500 km/sec



## Schwarzschild and Kerr Metric

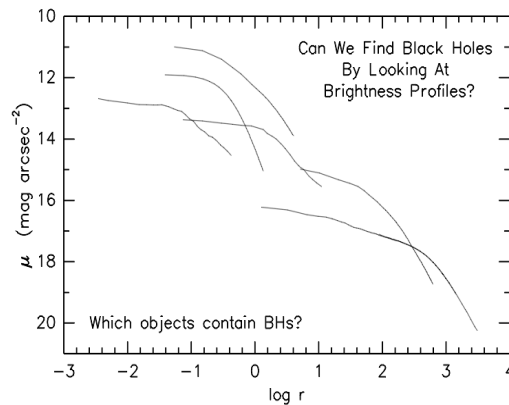
- for a Schwarzschild BH the innermost **stable** radius is  $3r_g=6GM/c^2$  - there are no stable circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- For a Kerr the innermost stable radius is at  $r_+=GM/c^2$  The spinning black hole drags the the inertial frame-
- The smaller critical radius allows more energy to be released by infalling matter
  - **For a Kerr BH, 0.423 of the rest mass energy can be released.**
- There is another 'fiducial' radius in the Kerr solution, that radius within which all light cones point in the direction of rotation, the 'static' radius,  $r_{\text{static}}$
- Between  $r_{\text{static}}$  and  $r_+$  is a region called the 'ergosphere' within which particles must rotate with the black hole and from energy might be extracted (Penrose process).

## Sizes and Time Variability (see Begelman, Fabian and Rees 2008, Fabian and Rees 1979)

- Assume each emitting region has a size  $L'$  in its co-moving frame and is causally connected over a time  $\Delta t'$  -- implying  $L' < c \Delta t'$
- In the laboratory frame the time scale is dilated to  $\Gamma \Delta t'$  ( $\Gamma = 1/\sqrt{1-\beta^2}$ ;  $\beta = v/c$ )
- From an observers point of view the duration is reduced by  $1/(1-\beta \cos \theta)$ - in the limit  $\beta \sim 1$  and  $\theta < 1/\Gamma$  this is  $\sim 2\Gamma^2$
- Thus a observed time scale  $L' < c t_{\text{var}} \Gamma$
- Generalized Efficiency argument (similar to the Eddington limit)
- the mass required to produce a total amount of energy  $E = \Delta L \Delta t = \epsilon M c^2$  ( $\epsilon$  is the efficiency of converting matter to energy)
- This is related to the optical depth  $\tau$  by  $M = 4R^2 \tau m_p / \sigma$  and the emitted photons emerge on a time scale  $\Delta t = R/c(1+\tau)$  - then minimize  $\Delta t$  for a given mass  $M$  giving  $\Delta L < \epsilon c^2 \Delta t m_p / \sigma$
- which for the Thompson cross section and 10% efficiency gives
- $\Delta L < 2 \times 10^{41} \epsilon_{0.1} \Delta t \text{ ergs/sec}$

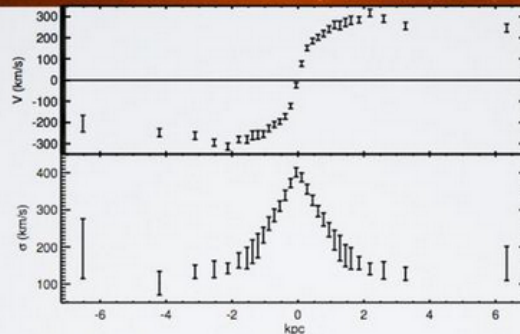
## What About Other Supermassive Black Holes

- At the centers of galaxies- much more distant than SgrA\*
- First idea: look for a 'cusp' of stars caused by the presence of the black hole- doesn't work, nature produces a large variety of stellar density profiles... need dynamical data
- Dynamical data: use the collisionless Boltzman eq (seen this before)
- $V =$  rotational term; velocity dispersion has 3 components  $\sigma_r, \sigma_\phi, \sigma_\theta$



$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G} \left[ -\frac{d \ln v}{d \ln r} - \frac{d \ln \sigma_r^2}{d \ln r} - \left( 1 - \frac{\sigma_\theta^2}{\sigma_r^2} \right) - \left( 1 - \frac{\sigma_\phi^2}{\sigma_r^2} \right) \right]$$

# MEASURE BH MASS



see Kormendy  
and Ho 2013  
sec 3 for a  
recent review

## Use orbit-based models to measure the mass distribution:

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



Remco van den Bosch

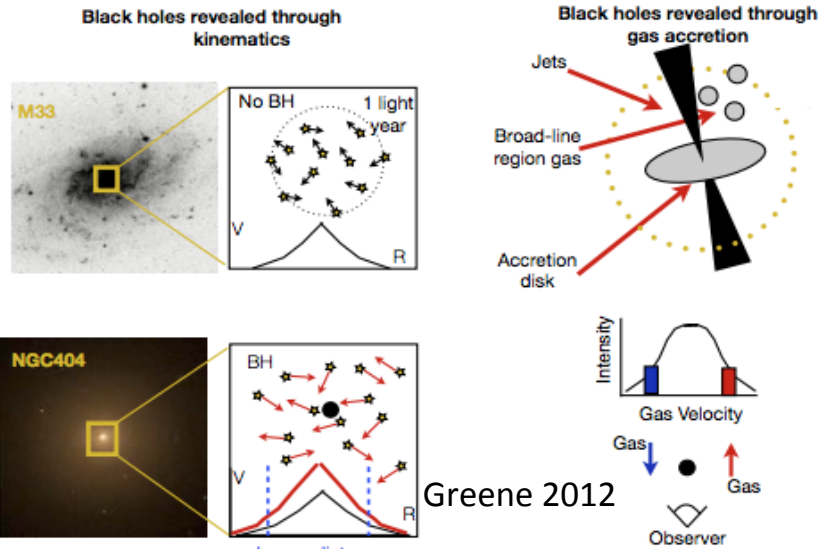
Please fill in your course evaluation!-

- [www.CourseEvalUM.umd.edu](http://www.CourseEvalUM.umd.edu)
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc?-or dull, boring, stodgy, unprepared?
- Your responses are strictly anonymous. I only see the statistics.
- Helps me and future students!



# Finding SMBHs

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

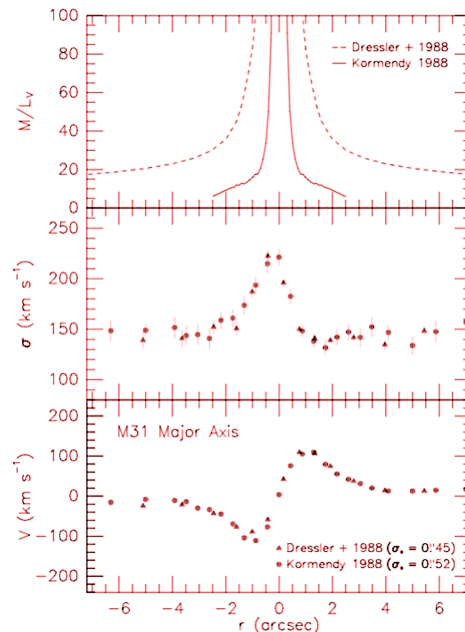


stars near BH move more rapidly because of BH

broad emission lines-gas moving rapidly near BH

## Example of data for the nearest galaxy M31

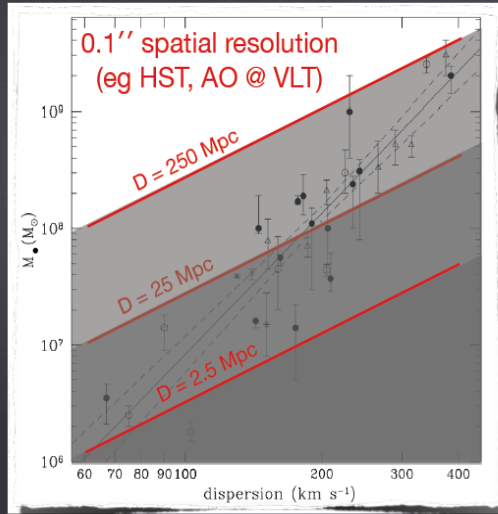
- Notice the nasty terms
- $V_r$  is the rotation velocity  $\sigma_r, \sigma_\theta, \sigma_\phi$  are the 3-D components of the velocity dispersion  $\nu$  is the density of stars
- All of these variables are 3-D; we observe projected quantities !
- The analysis is done by generating a set of stellar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



# Direct BH mass measurements

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

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



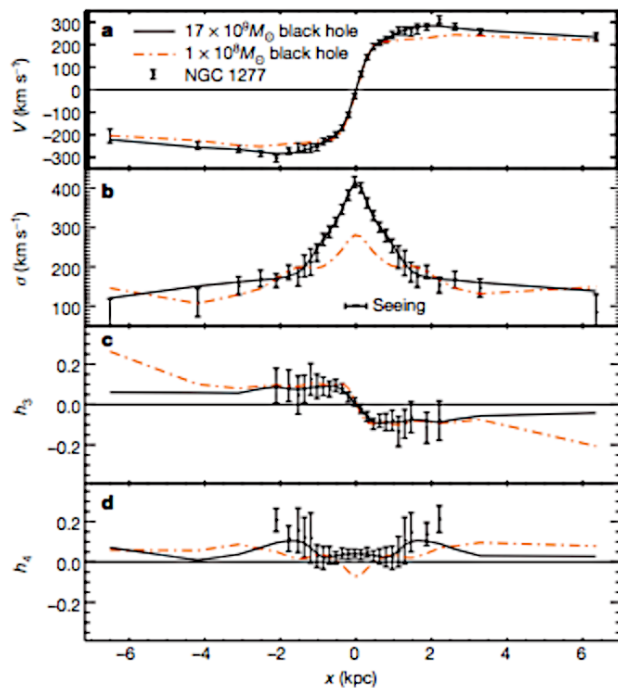
BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

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

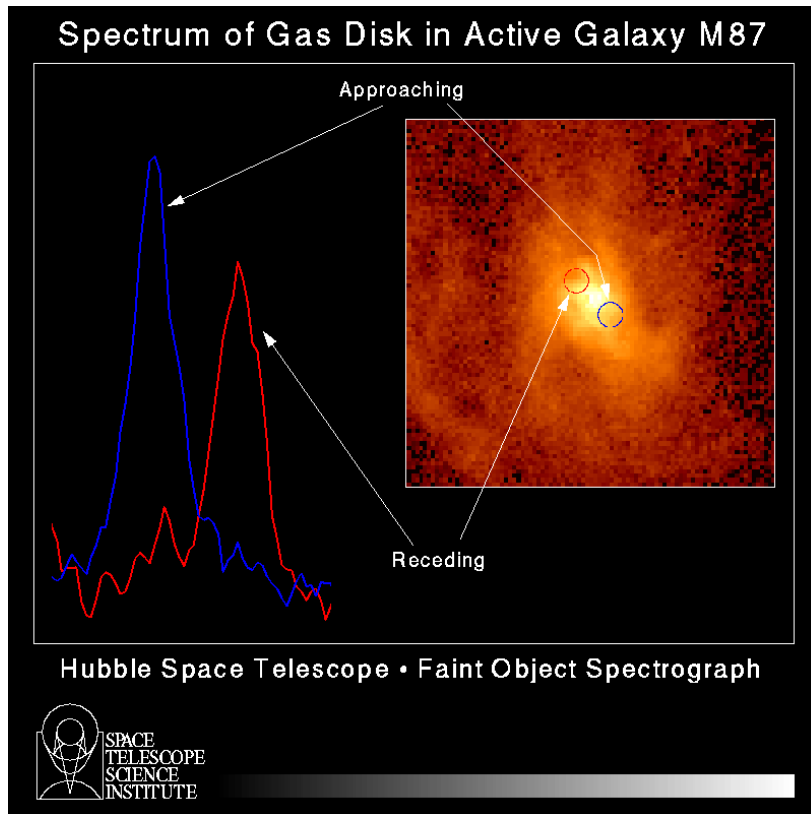
Marconi

## 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)

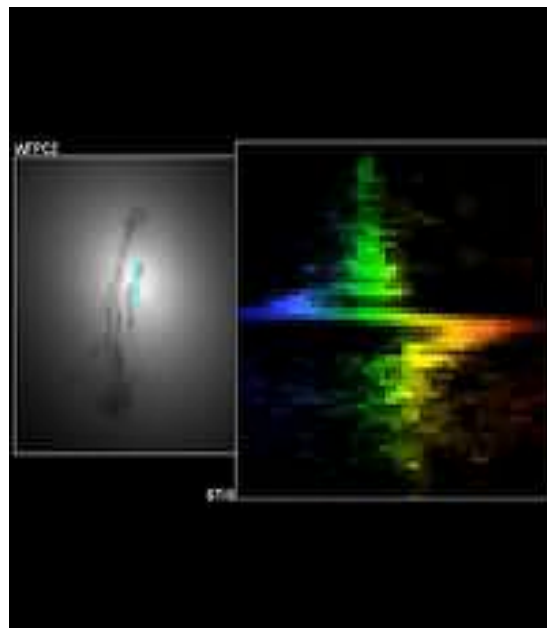


k  
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t



## 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<sup>-1</sup>, while the spatial axis (vertical) covers the central 3 arcsec;.

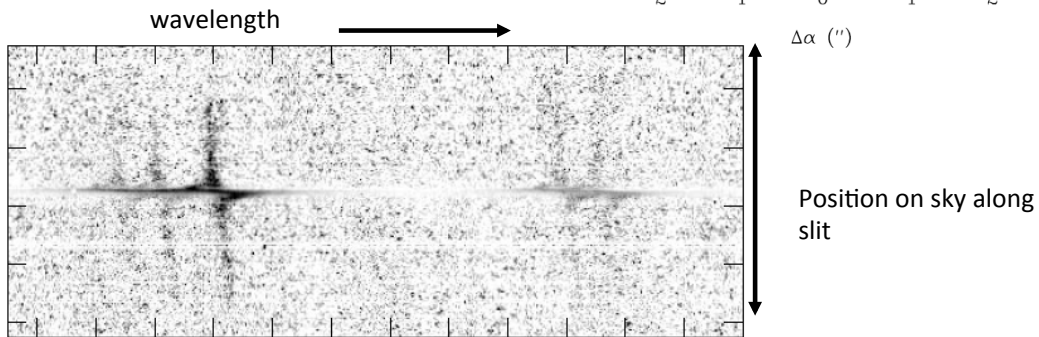
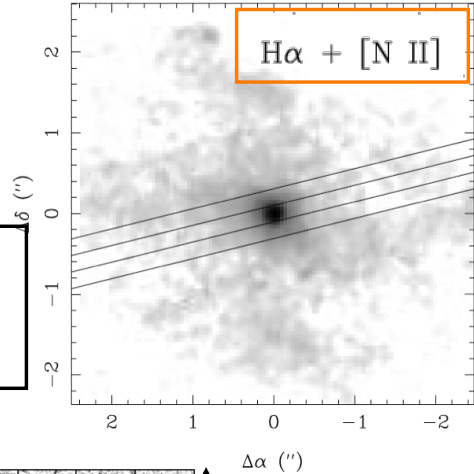


# Measurement of Kinematics c

## 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.



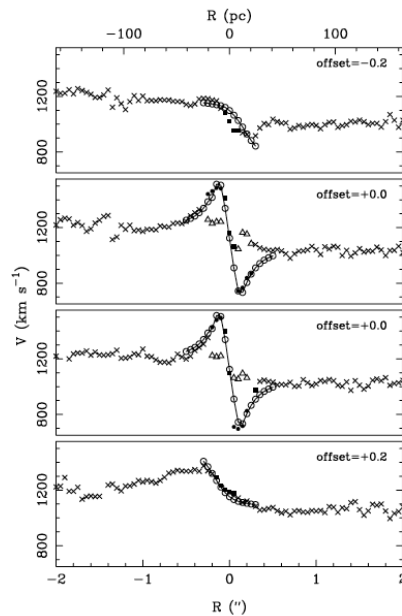
## Analysis of Spectral Data for M84

- Mass of central object  $1.5 \times 10^9 M_{\text{sun}}$

TABLE 1  
 KEPLERIAN DISK MODEL PARAMETERS

Parameter	Best Fit	Uncertainty Range
Black hole mass ( $M_{\odot}$ )	$1.5 \times 10^9$	$(0.9-2.6) \times 10^9$
Disk inclination (deg)	80	75-85*
Disk P.A. (deg)	83	80-85
Gas systemic velocity ( $\text{km s}^{-1}$ )	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 $\sigma$ (arcsec)	0.05	0.04-0.06

\* 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 )

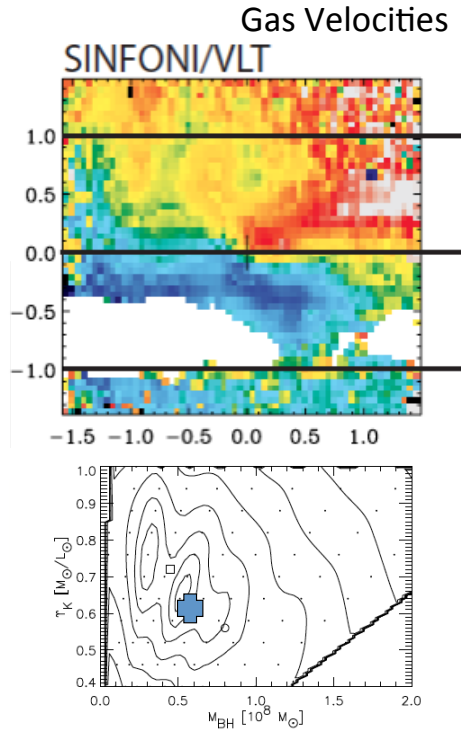
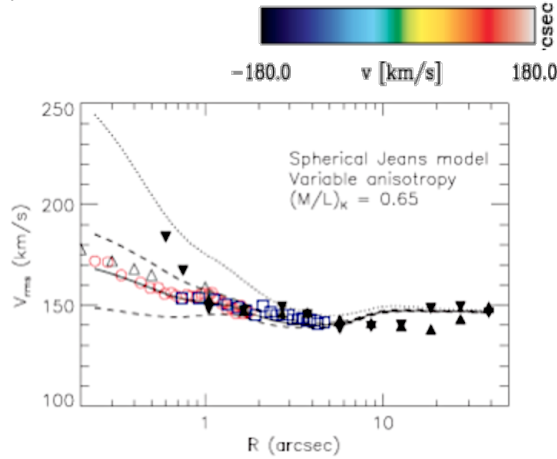
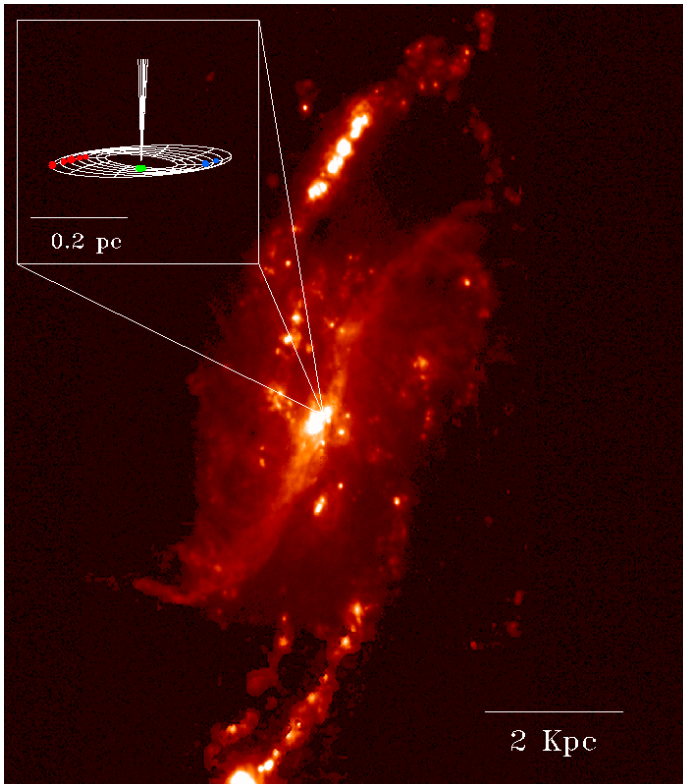


Figure 4: Spherical anisotropic Jeans model

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

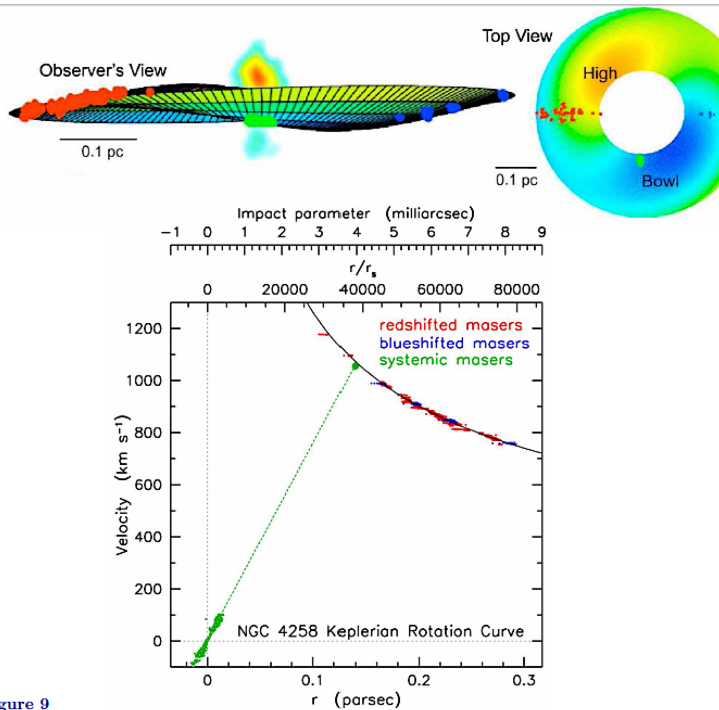
Constraints from stars compared to those from Gas Velocities



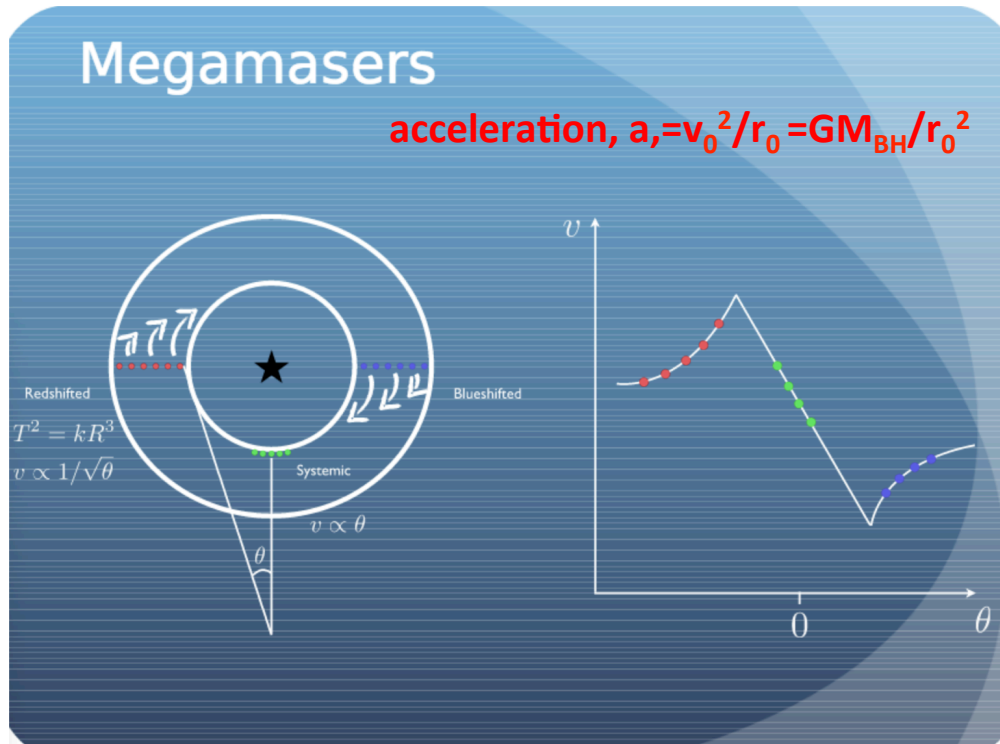
NGC4258

# Use of Masers for an AGN

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



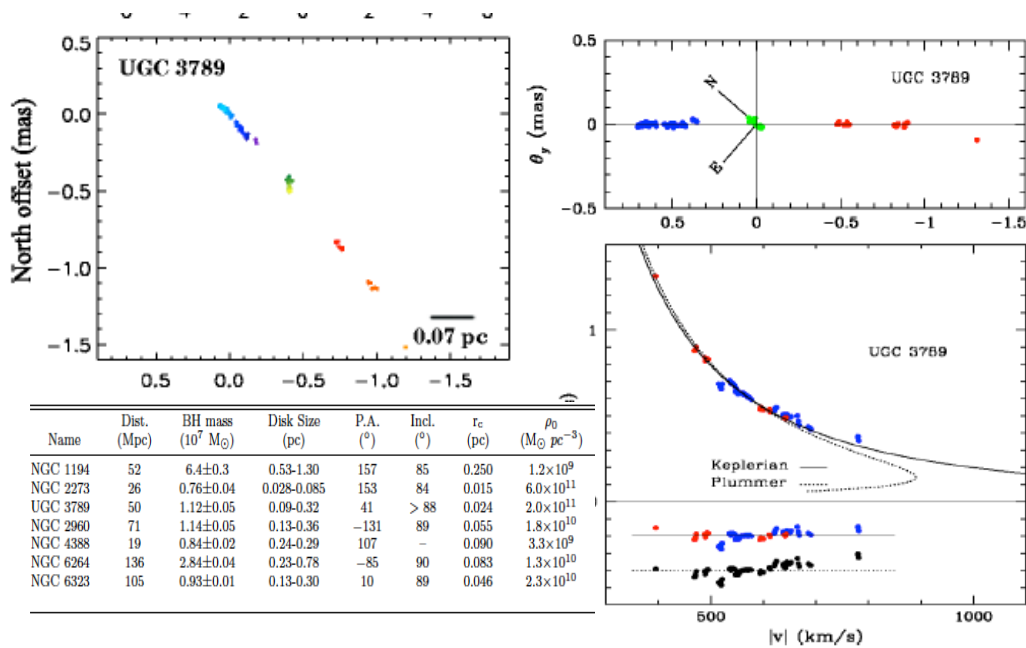
**Figure 9**  
 (top) Schematic views of the almost-edge-on, warped maser disk of NGC 4258 (from Moran 2008)  
 with warp parameters from Herrnstein et al. (2005) and including the inner contours of the radio jet.



- [http://www.not.iac.es/Onsala2012/presentations/Project1\\_presentation.pdf](http://www.not.iac.es/Onsala2012/presentations/Project1_presentation.pdf)

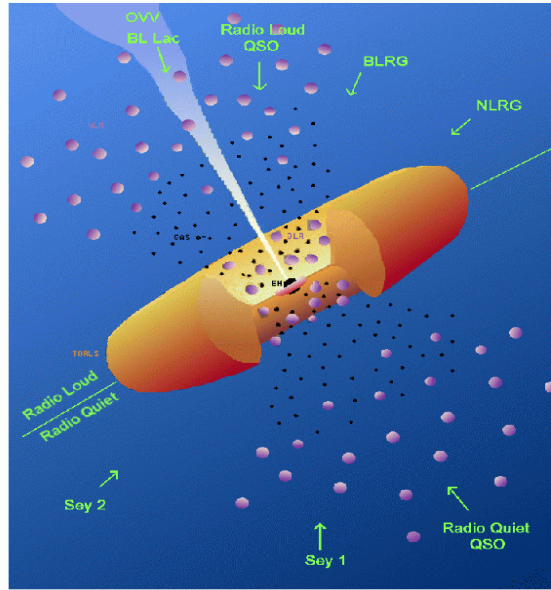
- The high-velocity masers in NGC 4258 (red and blue points in Figure ) almost exactly have  $V \propto r^{-1/2}$ , Using that  $M_{\bullet} = V^2 r / G$ . and assuming that all the masers move exactly toward or away from us.
- fit is  $V(r) = 2083/\sqrt{r} + 27 \text{ km s}^{-1}$ , where  $r$  is in milliarcsec. giving  $M_{\bullet} = 3.65 \times 10^7 M_{\odot}$ . (clearly  $M_{\bullet}$  depends on distance to galaxy)
- Finding maser disks is difficult, because they must be edge-on, and the orientation of the host galaxy gives no clue about when this is the case
- Distance to NGC4258 can also be determined accurately from the masers since one gets angular velocity as well as dynamical velocity from the masers.

## Other Masers



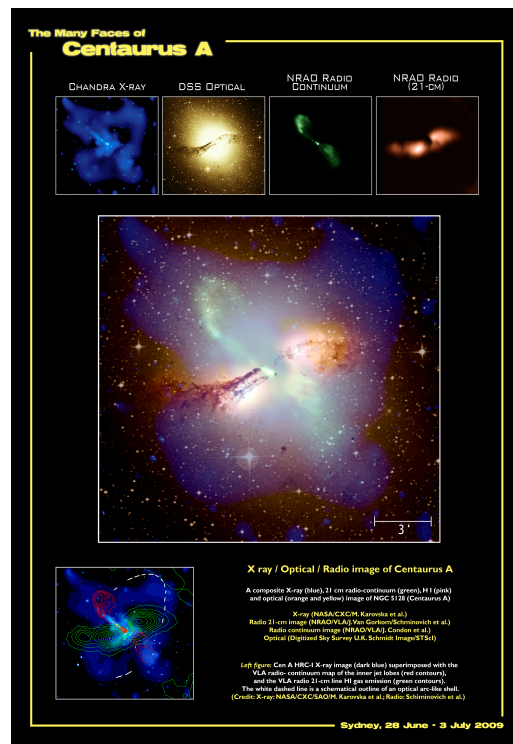
# AGN- Alias Active Galactic Nuclei

- AGN are 'radiating' supermassive black holes-
  - They go by a large number of names (Seyfert 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](http://nedwww.ipac.caltech.edu/level5/Cambridge/Cambridge_contents.html) for an overview



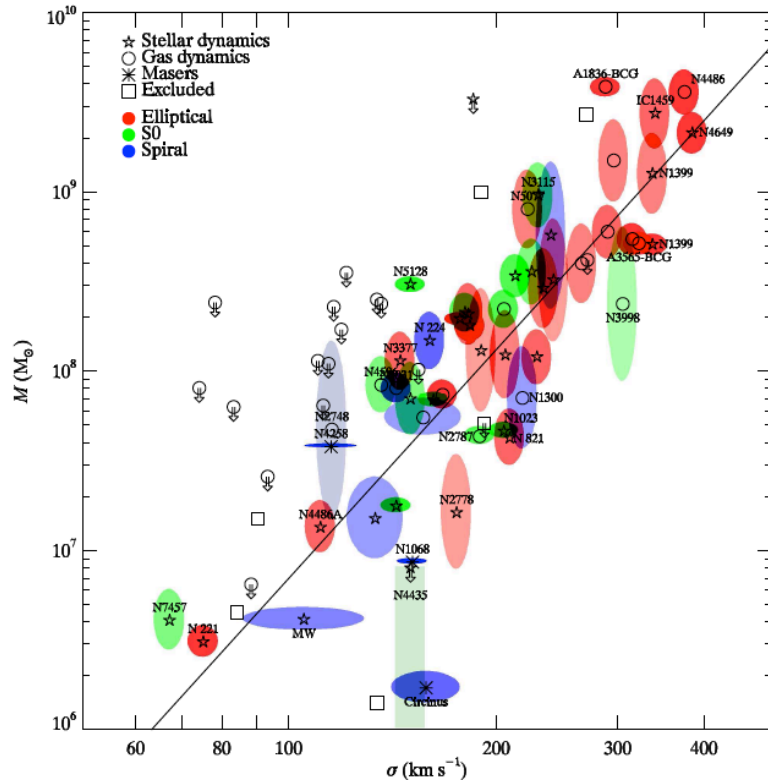
Urry and Padovani 195

# Centaurus-A The Nearest AGN



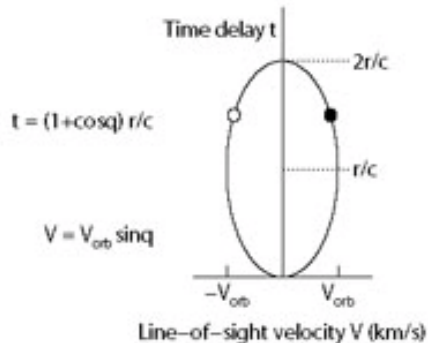
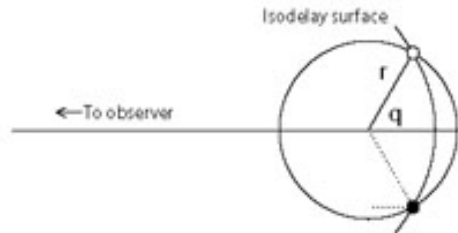


- All the Nearby Galaxies with Dynamical Masses for their Central Black Holes (Gultekin 2009)
- There seems to be a scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- Galaxies know about their BH and vice versa



## 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 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

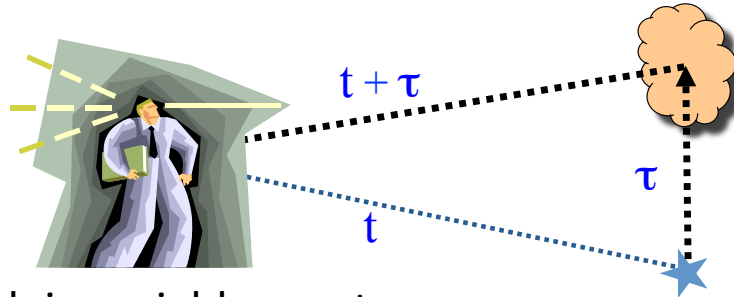
$$M_{\text{BH}} = f v^2 R_{\text{BLR}}/G$$

Reverberation Mapping:

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

- $v_{\text{BLR}}$

Line width in variable spectrum

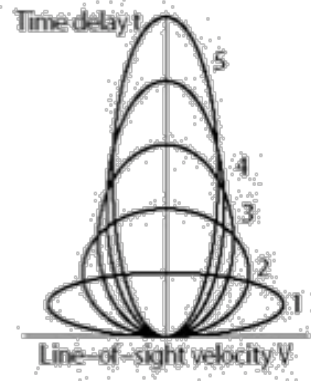
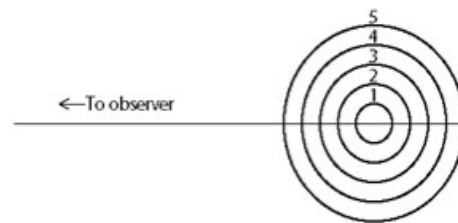


## The Geometry

- Points  $(r, \theta)$  in the source map into line-of-sight velocity/time-delay  $(V, \tau)$  according to  $V = -v_{\text{orb}} \sin(\theta)$ , where  $v_{\text{orb}}$  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

$$M_{\text{BH}} = f r v^2 / G$$

$f$  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 photoionization 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

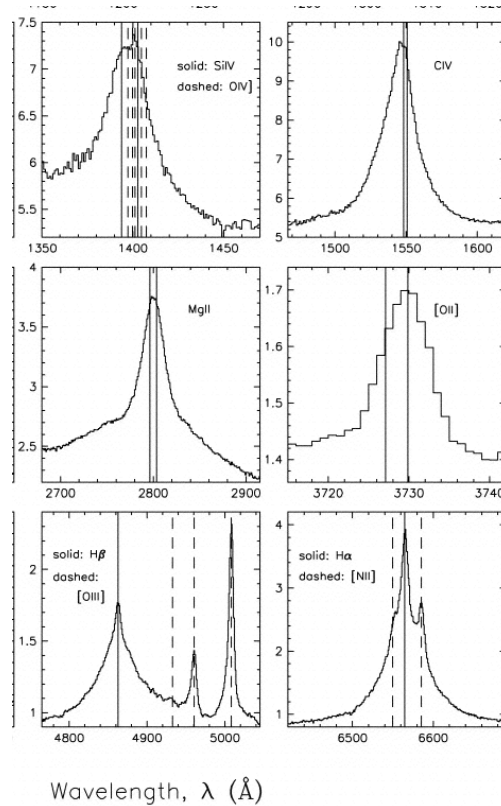
• Steady state ionization determined not by temperature, but by balance between photoionization ( $\sim F_E$  spectrum) and recombination ( $n_e$ ):

$$n_q \int F_E \sigma^{PI}(E) dE = n_{q+1} n_e \alpha(T_e)$$

• Ionization  $n_{q+1}/n_q \propto F/n_e \propto L/n_e r^2 \equiv \xi$

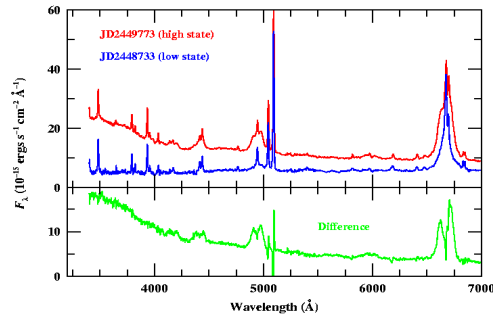
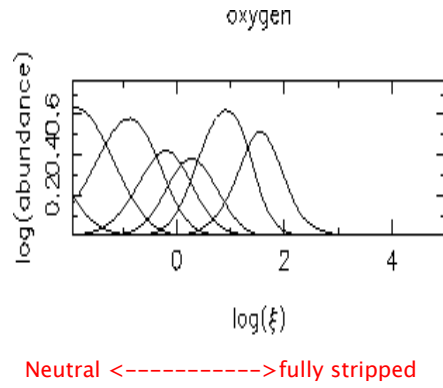
$\xi$  is the ionization parameter (also sometimes called U)

- 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  $\xi \sim L/n_e r^2$



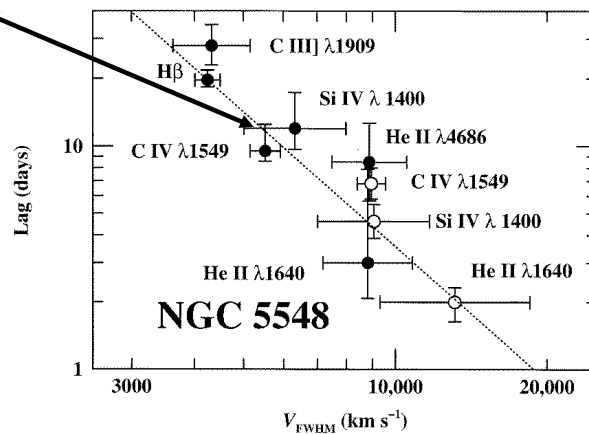
## In Other Words

- For each ion:
  - Ionization = recombination
  - $\sim$ photon flux  $\sim$ electron density
- For the gas as a whole
  - Heating = cooling
  - $\sim$ photon flux  $\sim$ electron density
- $\Rightarrow$  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) (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  $\sim 40$  sources
- At present  $M_{\text{BH}}$  can be estimated to within a factor of a few:  $M \propto \text{FWHM}^2 L^{0.5}$



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

(Peterson et al. 2011)

$$(\Delta V)^2 R = \text{constant} \sim M_{\text{BH}}$$

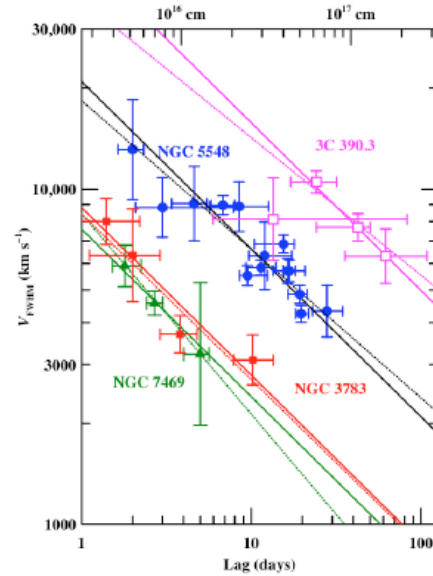
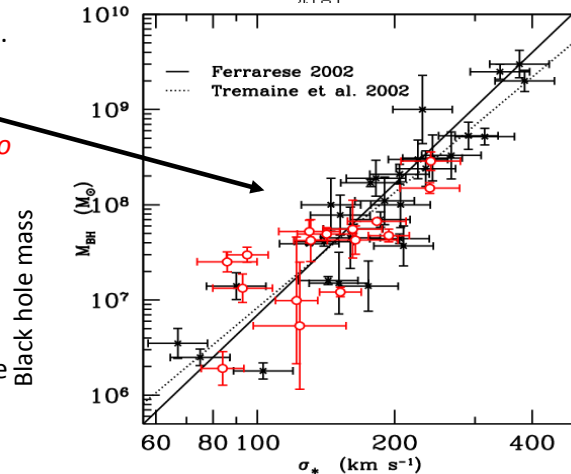
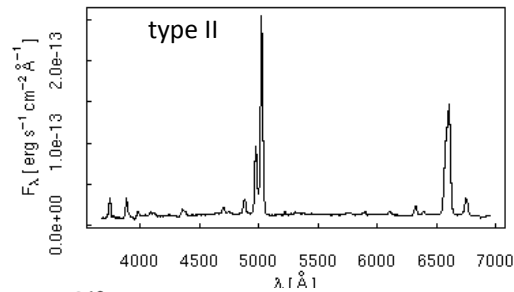


Figure 1: Line-width vs. emission-line lag (in days) for four reverberation-mapped AGNs. In each case consistent with a virial relationship, i.e.,  $V \propto \tau^{-1/2}$ . The dotted lines show the best-fit virial relationship [77, 78]. The solid lines show the best-fit virial relationship [77, 78].

### But What About Objects without a Strong Continuum

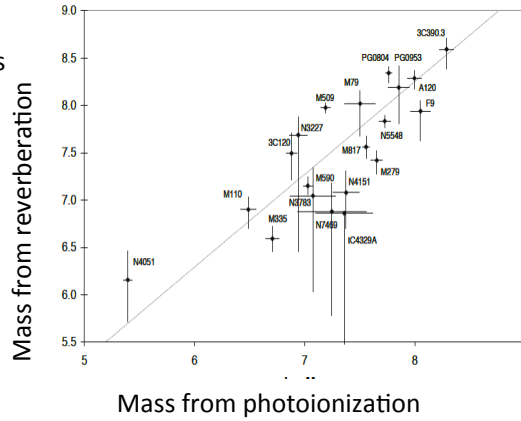
- There exists a class of active galaxies (type II) **which do not have broad lines and have a weak or absent 'non-stellar' continuum**
- Thus there is no velocity or luminosity to measure -rely on 'tertiary' indicators.
- It turns out (very surprisingly) that *the velocity dispersion of the stars in the bulge of the galaxy is strongly related to the BH mass*
  - This is believed 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) then we can just use the ionization parameter and velocity width ( $\sigma$ ) 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  $\sigma$  and normalize the relation (scaling relation)- amazingly this works !



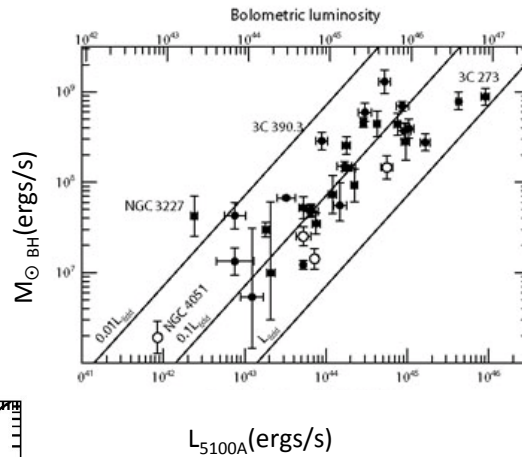
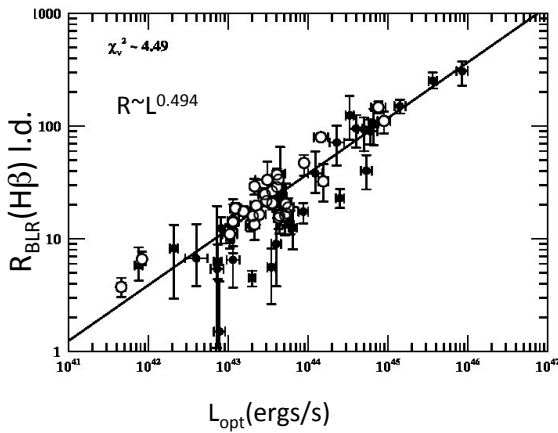
$$M_{BH} \sim K \sigma^2 L^{1/2}$$

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

This is just

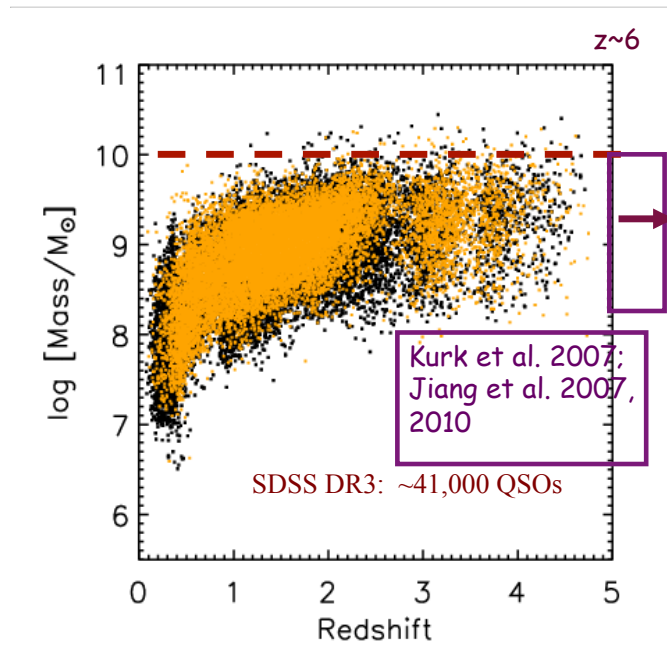
$$M_{BH} = v^2 R_{BLR} / G \text{ with an observable } (L) \text{ replacing } R_{BLR}$$

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



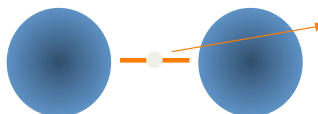
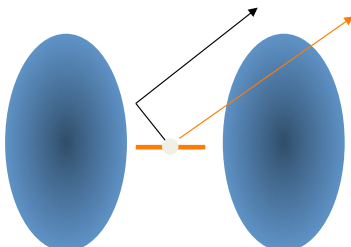
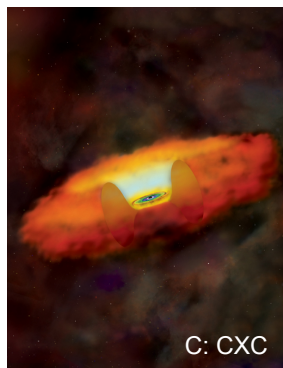
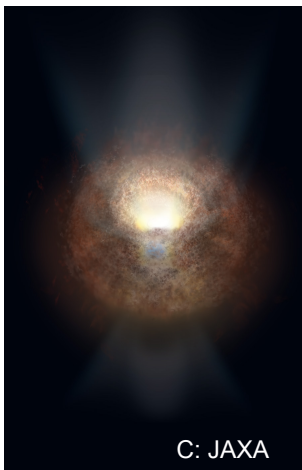
# Masses of Distant Quasars- M. Vestergaard

- 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. 2009)

## Some Variation in Geometry

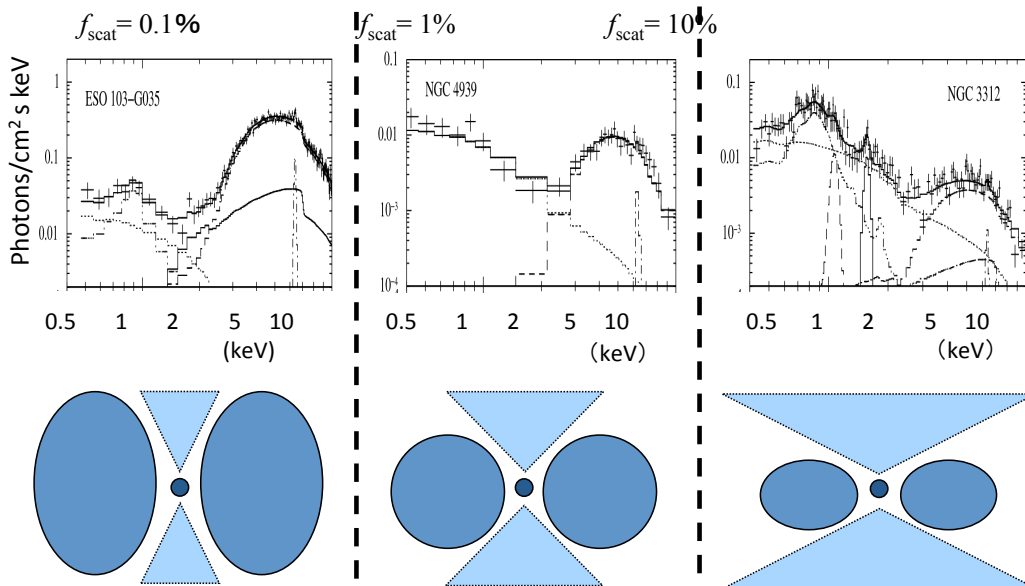


- Effects of geometry can be seen in the spectra

## Examples-

XMM

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



## 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)



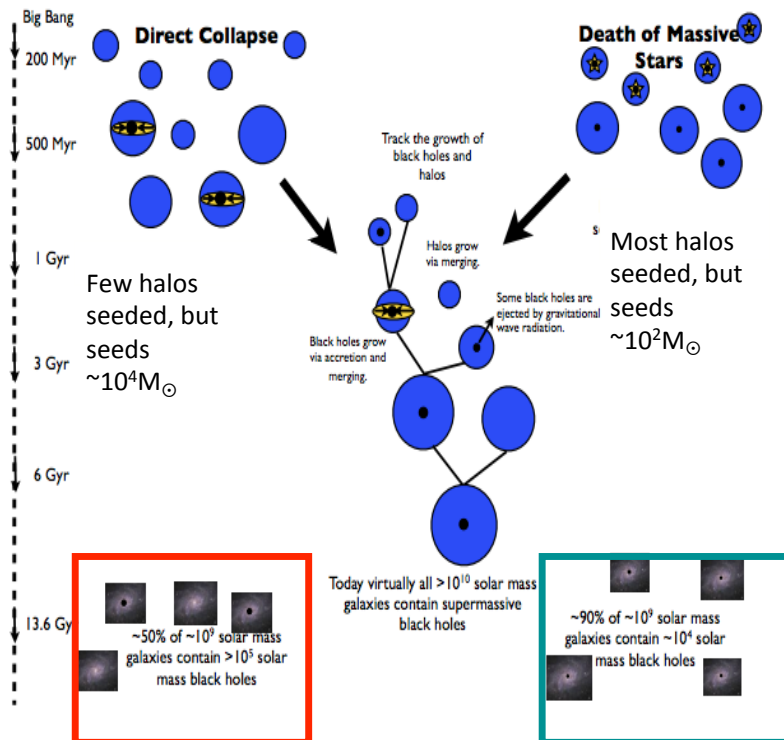
# Summary

- The most massive black holes today  $M \sim 10^8 - 10^{10} M_{\odot}$  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  $M \sim 10^9 M_{\odot}$  BH at  $z \sim 7$ - 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

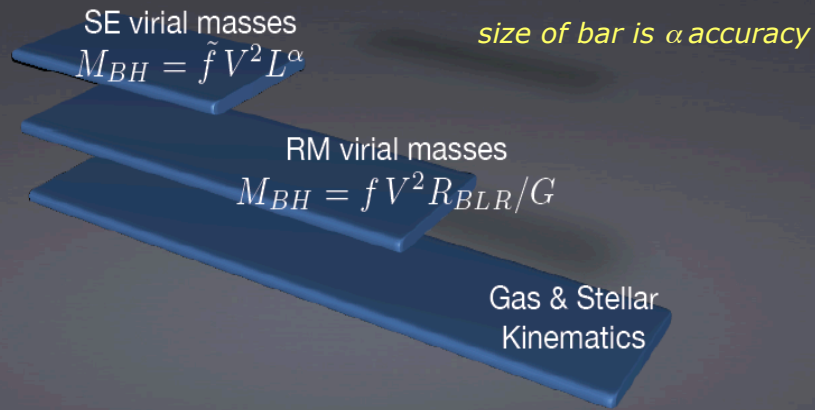
- To calculate how much mass has been accreted by black holes over cosmic time we need to know how they have grown (Soltan 1982)
  - that is measure the number per unit volume per unit time per unit mass.

### What we want to know

- ▶ How and when BHs accrete mass
- ▶ How and when BHs merge
- ▶ How and when BHs form
- ▶ How fast BHs spin

# The BH mass ladder

(Peterson 2002)



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

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

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

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

luminosity function

mass function

$$\mu = \text{Log } M$$

$$\ell = \text{Log } L_{bol}$$

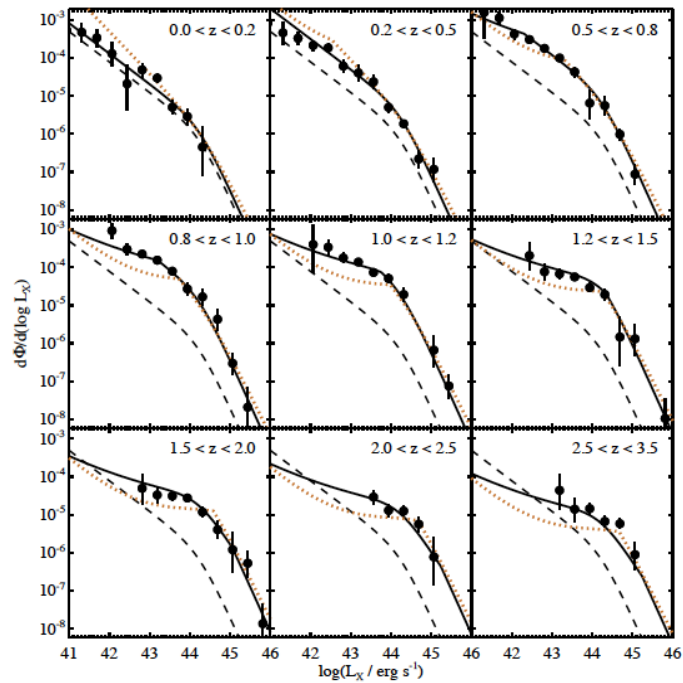
$$\dot{\mu} = \text{Log } \dot{M}$$

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

Aird et al 2009

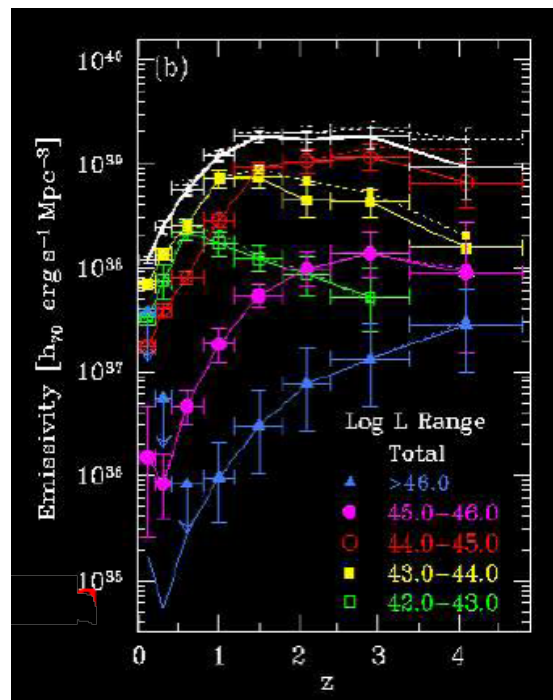
- The Evolution in the Luminosity Function of BH vs cosmic time
- #/Volume/ luminosity
- In each plot the dotted grey line is the z=0 function

Luminosity function vs z



### Transform Luminosity Function to Energy Emissivity

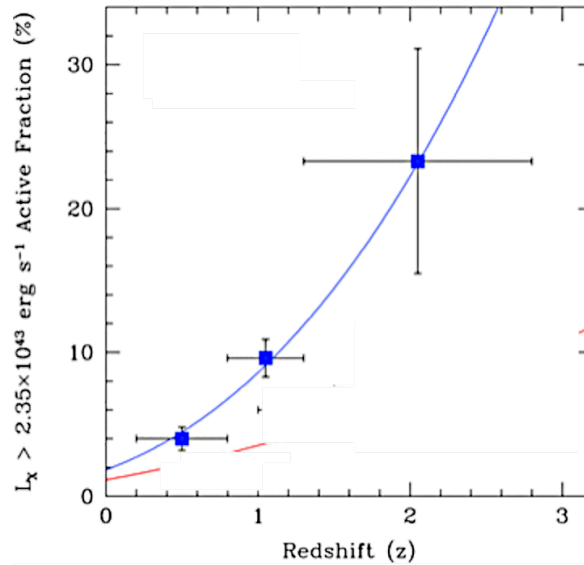
- Integrate the luminosity function in redshift shells
- Notice **downsizing** more luminous objects are more dominant at high redshift and that the evolution is a function of luminosity
- $E_{\text{AGN}} \sim 1.4 \pm 0.25 \times 10^{61}$  erg per galaxy since  $z = 3$ .
- Average AGN luminosity density of  $L_{\text{AGN}} \sim 10^{57}$  erg  $\text{Mpc}^3 / \text{Gyr}$  (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

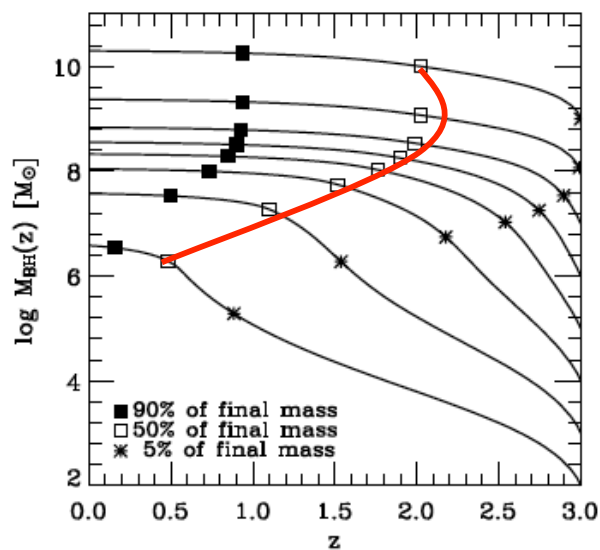


(Bluck et al 2011)

## One realization of BH growth

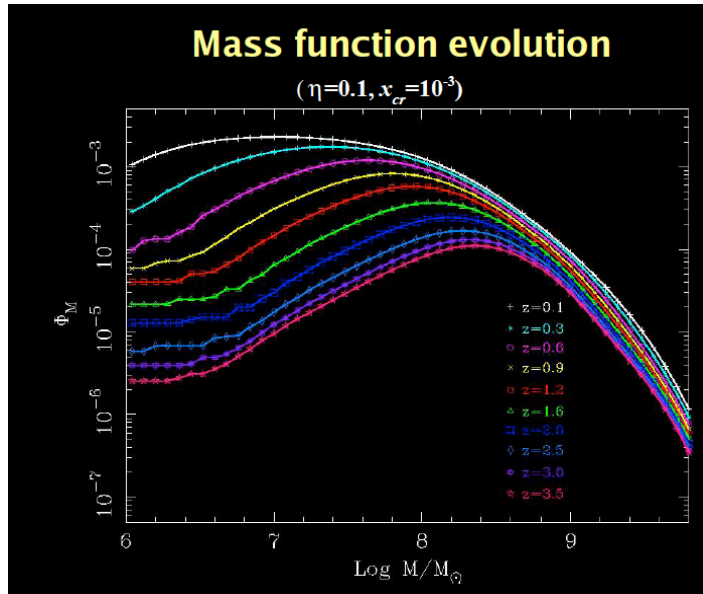
- Big BHs form in deeper potential wells  $\Rightarrow$  they form first.
- Smaller BHs form in shallower potential wells  $\Rightarrow$  they form later and take more time to grow.

– Marconi 2003, Merloni 2004

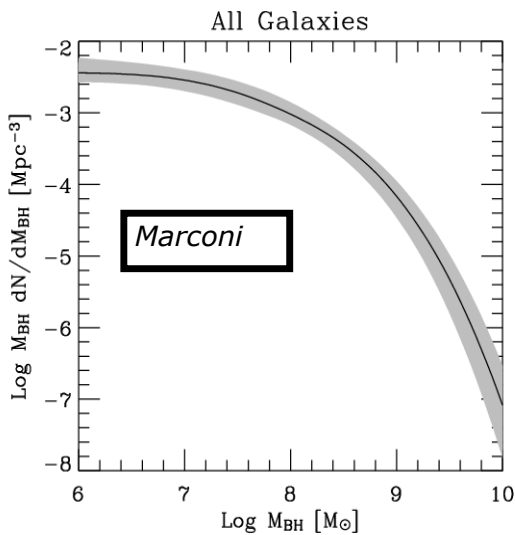


# Transform to Mass Growth

- 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  $M_{\text{BH}}-L_{\text{bul}}$  and  $M_{\text{BH}}-\sigma$  to obtain the local BH mass function.

–  $M_{\text{BH}}-L_{\text{bul}}$  and  $M_{\text{BH}}-\sigma$  provide consistent BH mass functions provided that dispersions are taken in to account (shaded area indicates uncertainties)

$$\rho_{\text{BH}} \sim 4.1^{+1.9}_{-1.4} \times 10^5 M_\odot \text{ Mpc}^{-3}$$

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

- In summary:  $3-5 \times 10^5 M_\odot \text{ Mpc}^{-3}$  (see Ferrarese & Ford 2005 for a review)