Lots of Material!

Congratulations for hanging in!

- Going over the slides there were ~30 slides per lecture and 27 lectures- 800 slides!
- Wide variety of topics:

  stellar physics

  dynamics

  gas physics

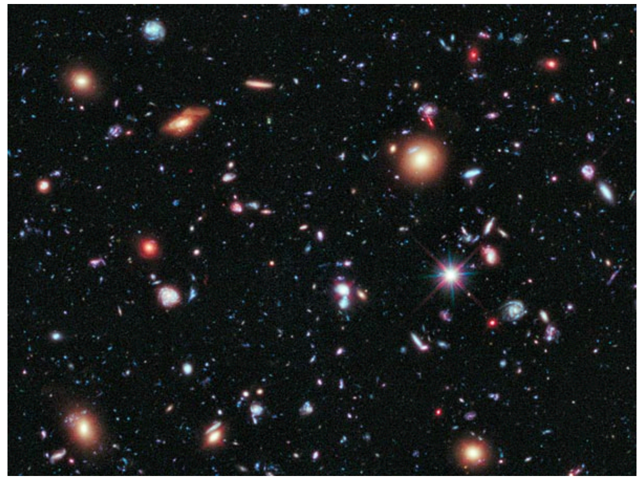
  dust

  star formation

  galaxy properties

  active galaxies .....

stuff not covered in text and the professors insistence on NOT covering stuff the text covers ...argh

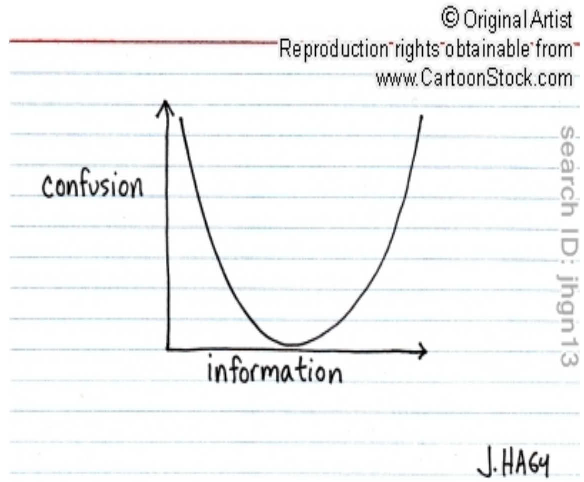


FINAL EXAM

Saturday, December 16 1:30pm-3:30pm

- Exam is in this room
- Cumulative, but with empha after the midterm
- No notes or books allowed
- **Bring calculator**

Maybe We Had a Bit of This



How do we know AGN are Black Holes??

Eddington ratio sets the minimum mass for an accreting object
$L \sim 10^{44}$ ergs /cm²/sec~ $M_{min} > 10^6 M_\odot$ (most massive Neutron stars $\sim 2M_\odot$)

Rapid variability sets a length scale $R \sim c\delta t$ (~1 hours ~ 10^{14} cm)

Huge mass inside small radius--- special object, but this is for AGN; what about non-AGN hosting galaxies?

But how can we measure the mass ??

Dynamics
Motion of stars
Motion of gas
'Reverberation' mapping

What do we need to dynamics

Need to examine the velocity field of the tracer at length scales where the mass of the black holes dominates the potential

In the Milky way this occurs at ~1-2pc for M_{BH} ~$4x10^6 M_\odot$

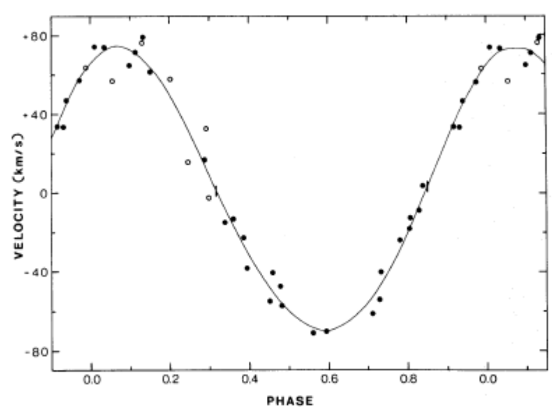
for similar MW like galaxies this corresponds to ~ 0.01 arc sec at distance of Virgo Clusters

So 'need' more massive BH in a region with high ratio of black hole to stellar mass.
Using E galaxy scaling laws for mass this occurs at
θ_{BH}**~0.11"[**$M_{BH}/10^8 M_\odot$**)(**σ**/200km/sec)**$^{-2}$**(D/20Mpc)**$^{-1}$

Thus need HST or next generation 30m telescopes with Adaptive optics

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

$f(M) = P_{orb}K^3_2 /2\pi G = M_1 \sin^3 i/(1 + q)^2$.
$q=M_2/M_1$
the value of the mass function is the absolute minimum mass of the compact star

Galactic black holes

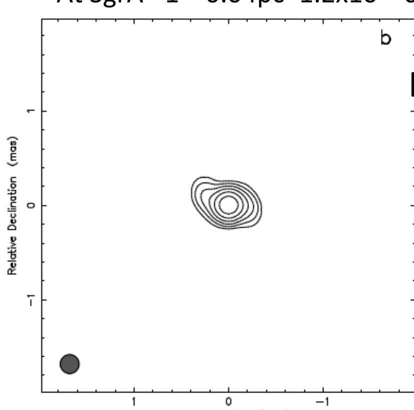
4 J. Casares

Table 1. Confirmed black holes and mass determinations

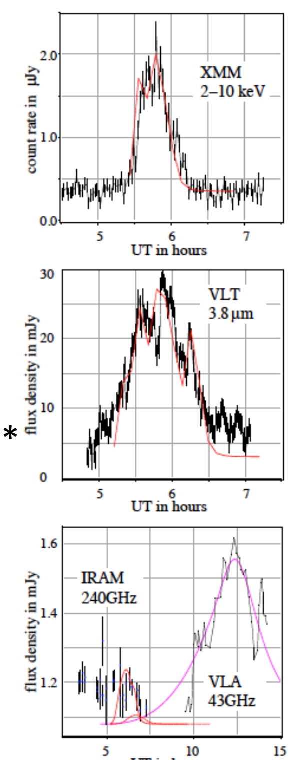
System	P_{orb} [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	M_x † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	"	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	"	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	"	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	"	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	"	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	"	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	"	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	"	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	"	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	"	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	"	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	"	6.8 ± 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~34- 100x less than a typical x-ray binary) and IR source
- The radio source is very small (VLBI) (<0.0005"<$50R_s$ for $M=4\times10^6 M_\odot$ BH at d=8kpc)
- At SgrA* 1"=0.04pc=1.2×10^{17} cm ,0.5mas=6AU



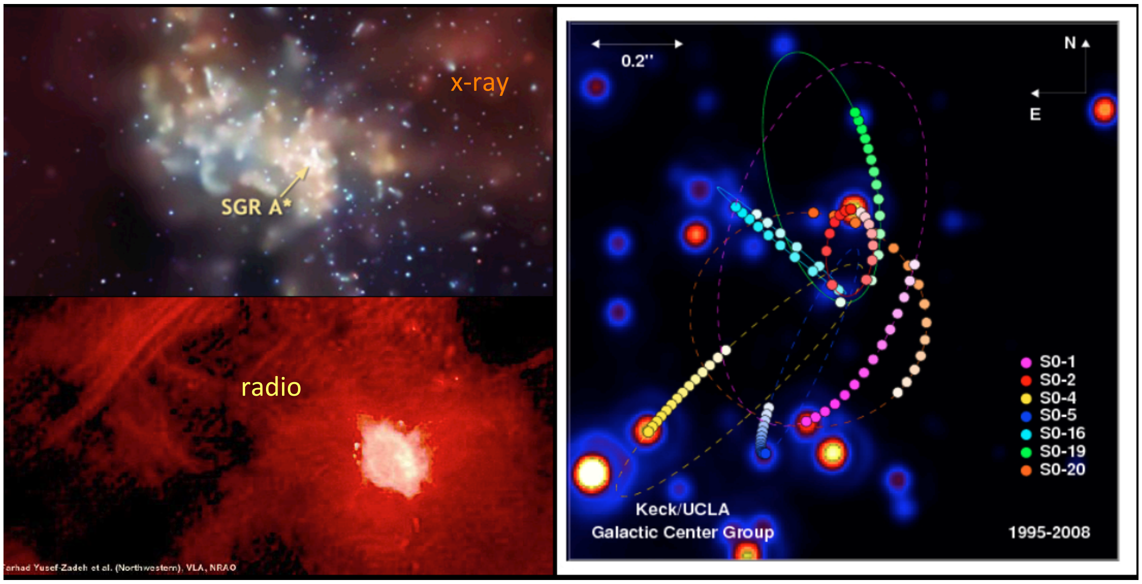
Radio image of SgrA*



Radio, near IR and x-ray light curves

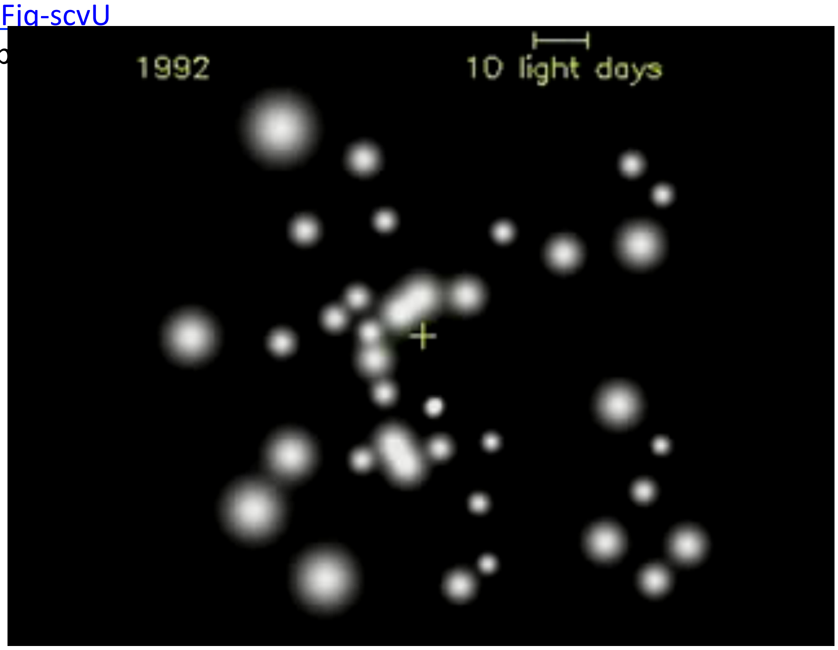
MW Galactic Center

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



Motion of Stars Around the Center of the Milky way- see http://www.youtube.com/watch?v=ZDxFjq-scvU

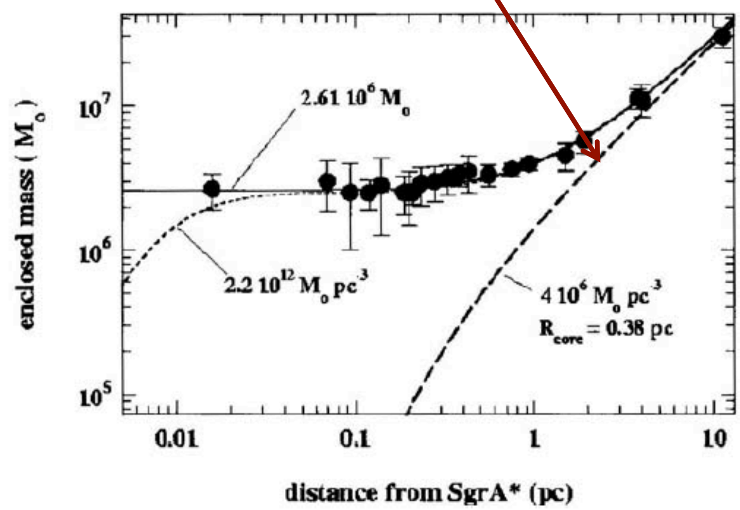
http://www.mp



MW Center

Predicted mass from models of the Milkway

- 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 $>10^{12}M_\odot/pc^3$



•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 $2.6 \times 10^6 M_{sun}$, and density

$20M_{sun}pc^{-3}$ or greater can not be stable for more than about 10 million years

Velocity Distribution of Stars Near the Center of the MW

A Supermassive Black Hole in the Milky Way 29

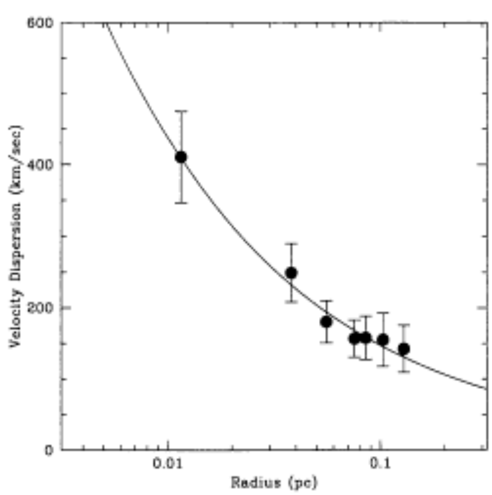
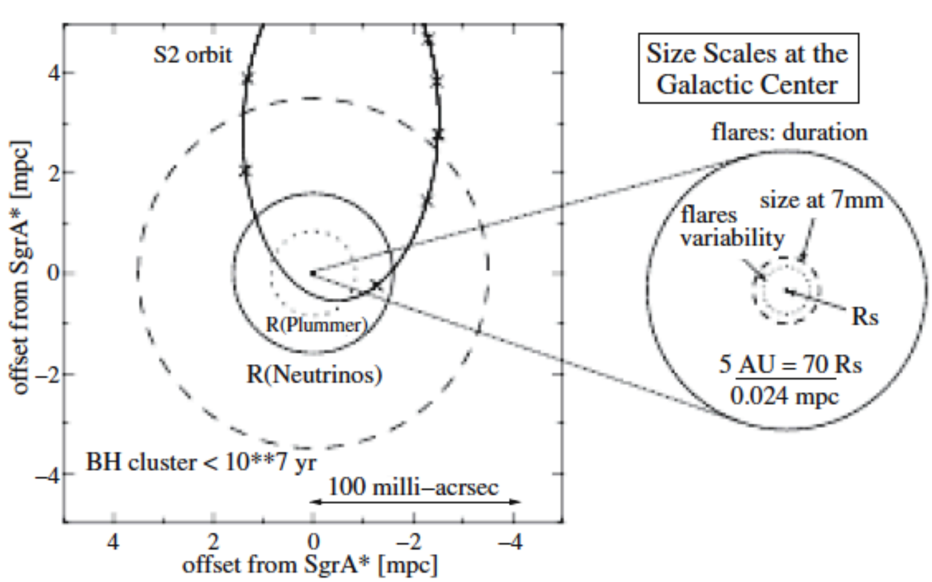


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

Ghez et al 1998



Eckart et al

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 ($L/L_{Edd} \sim 10^{-10}$)
- What happens to the accretion energy- where does the mass and energy go

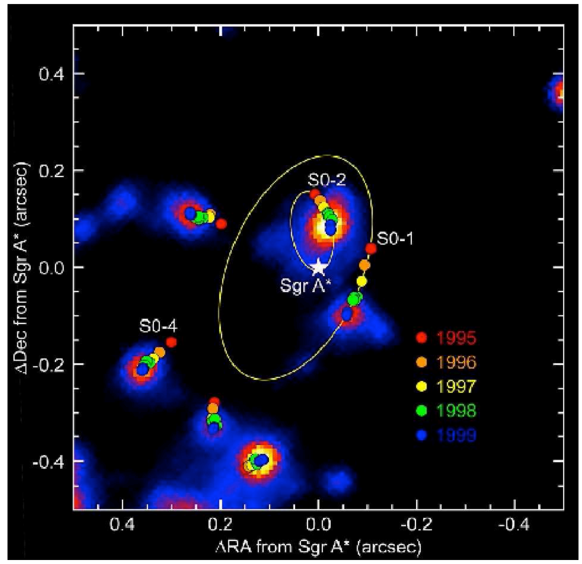
- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities **TODAY**! (AGN evolution)

- 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

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

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

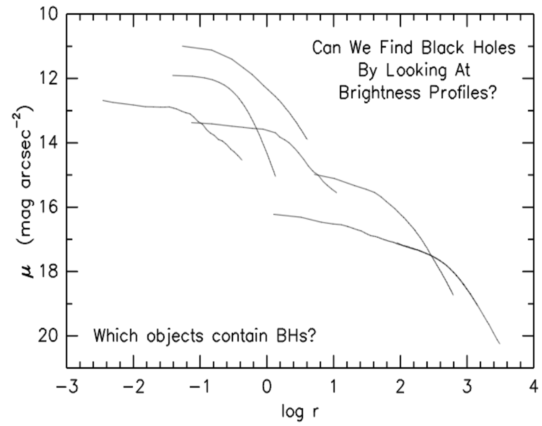


Schwarzschild and Kerr Metric

- 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.**

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 Boltzmann eq (seen this before)
- V=rotational term; velocity dispersion has 3 components σ_r, σ_ϕ, σ_θ



Kormendy and Richstone (2003)

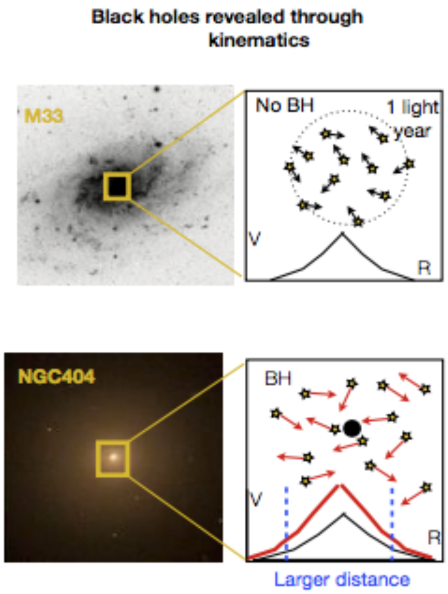
$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1-\frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1-\frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

Please fill in your course evaluation!-
4 people have done so as of this morning

- 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!

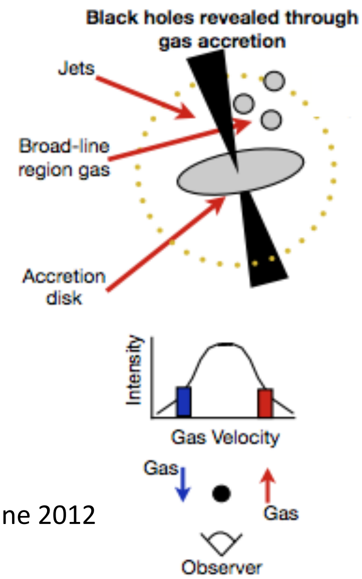
Finding SMBHs

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



stars near BH move more rapidly because of BH

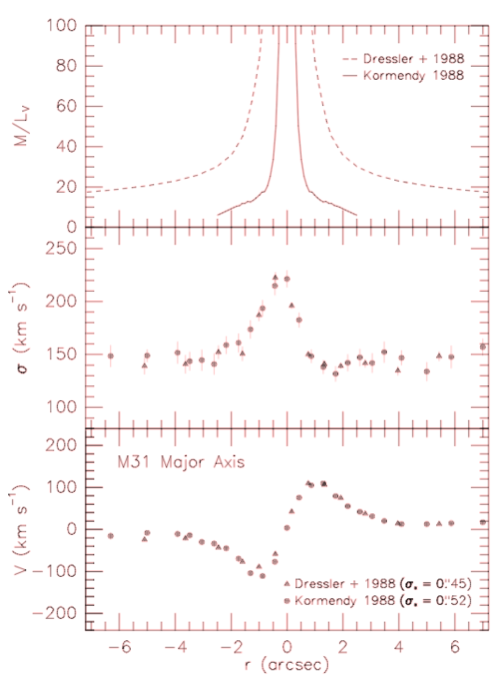
Greene 2012



broad emission lines-gas moving rapidly near BH

- Notice the nasty terms
- V_r is the rotation velocity σ_r σ_θ, 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 important smear the image, reduce BH dynamical signal-

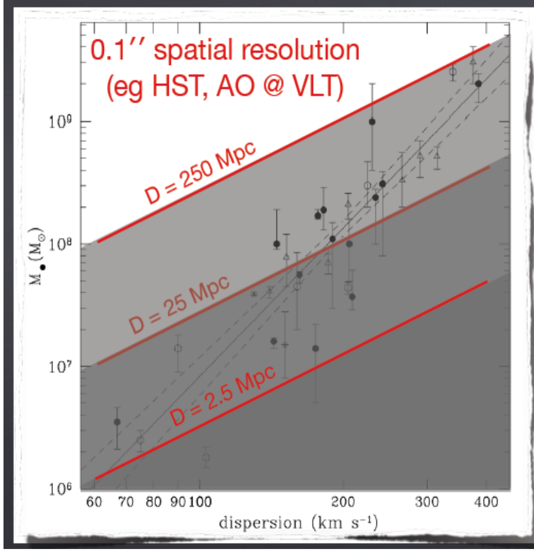
Example of data for the nearest galaxy M31



Direct BH mass measurements

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

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



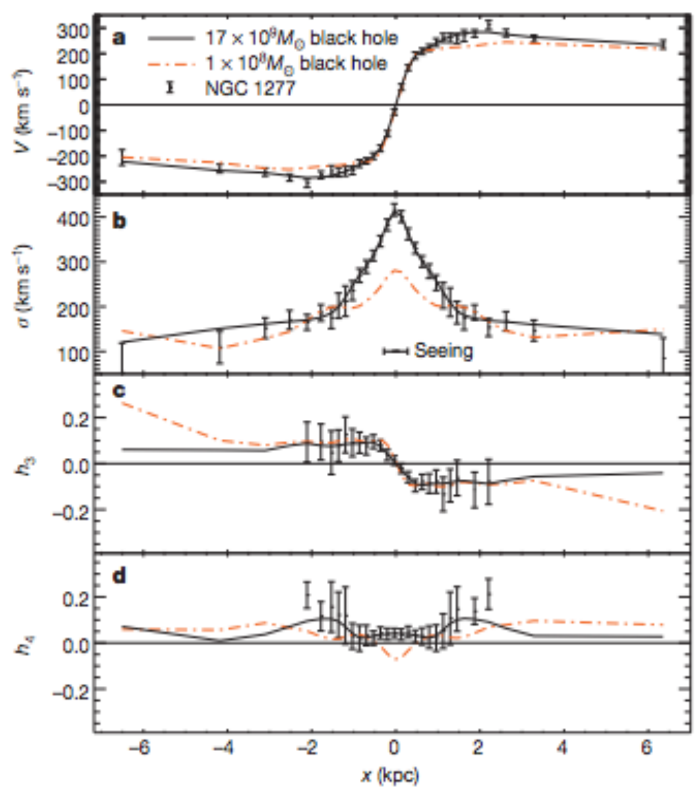
BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

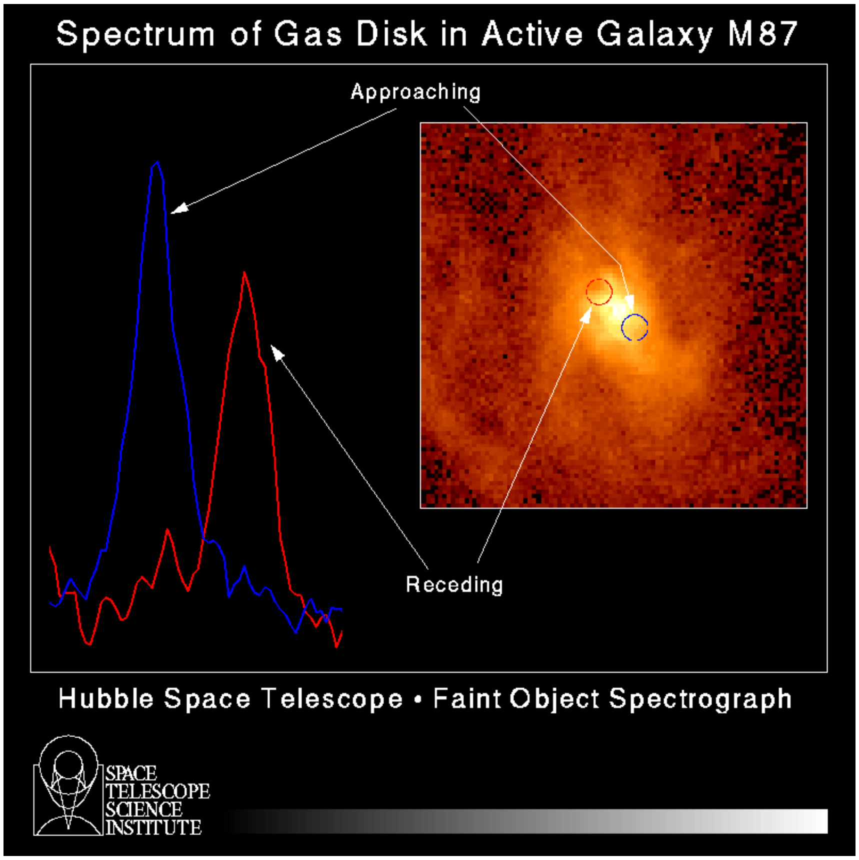
Need to calibrate indirect BH mass estimators like for the cosmological distance ladder

Marconi

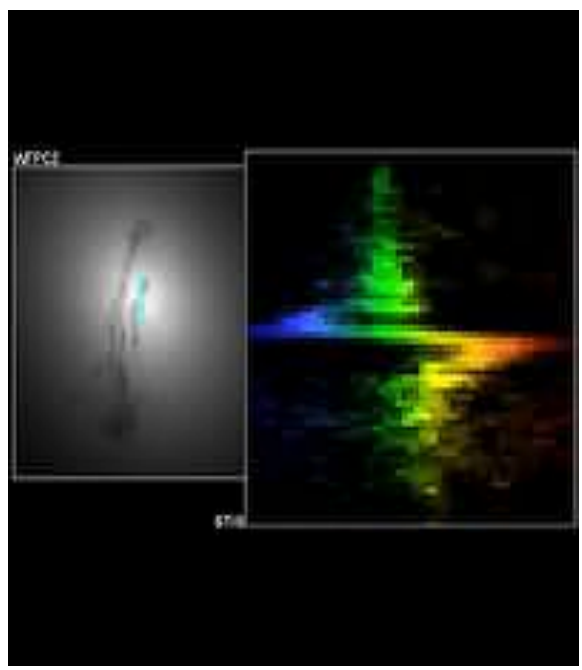
NGC1277- Velocity Data and BH Mass

- 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)
- Plate scale is 1kpc=13" so for this galaxy effect of BH on orbits is occurring at ~5", can do it from the ground





Measuring the Mass of a SuperMassive Black hole



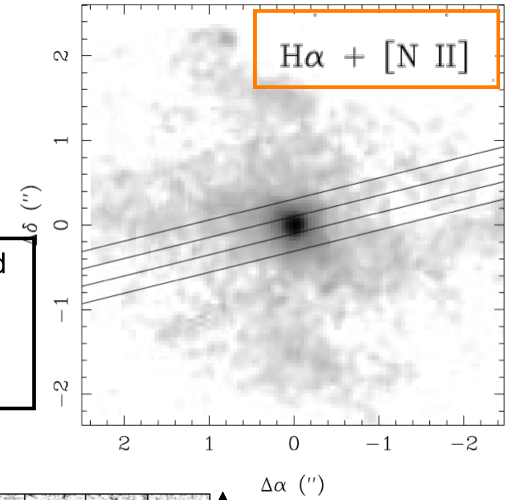
- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion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

  the central 3 arcsec;.

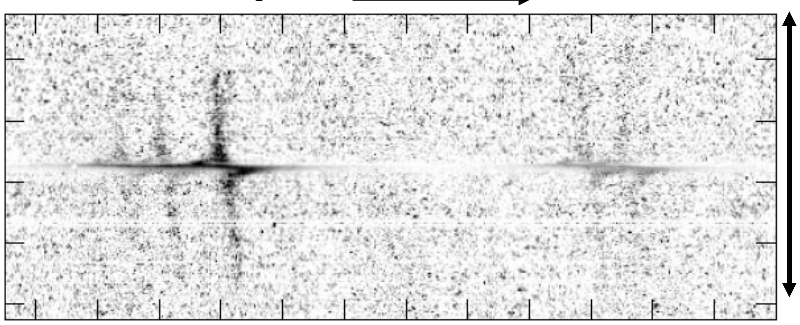
Measurement of Kinematics of Gas

- 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

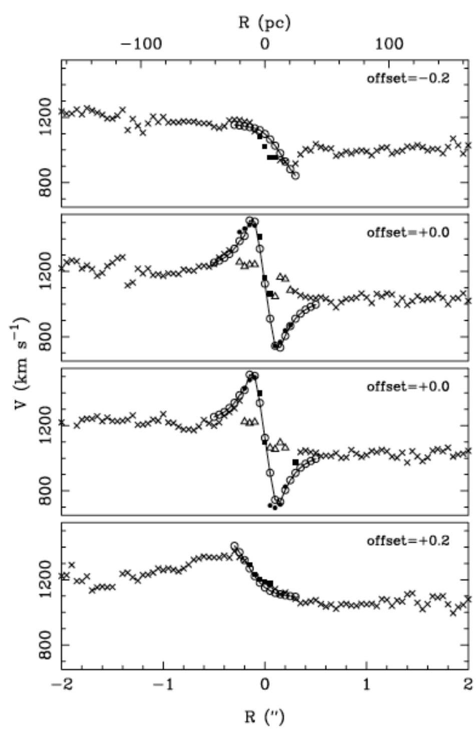
Analysis of Spectral Data for M84

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

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.

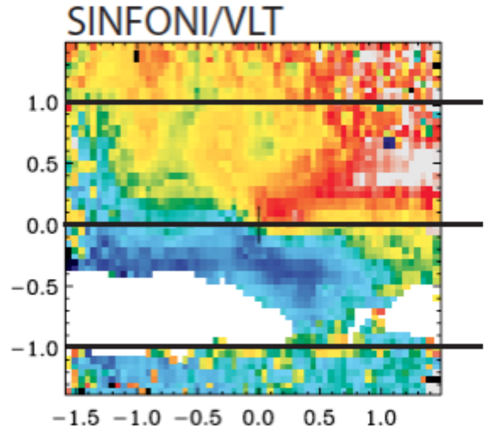


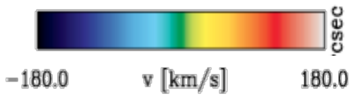
Velocity of gas vs distance from center of emission along 3 parallel lines

Centaurus -A

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

Gas Velocities





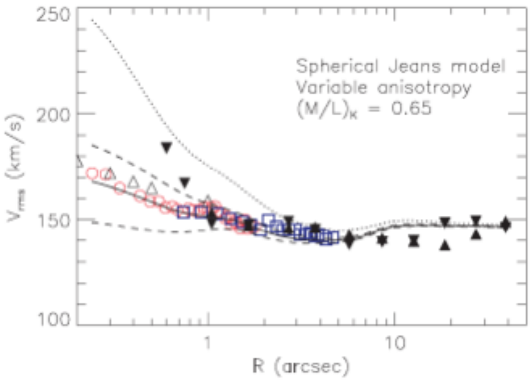
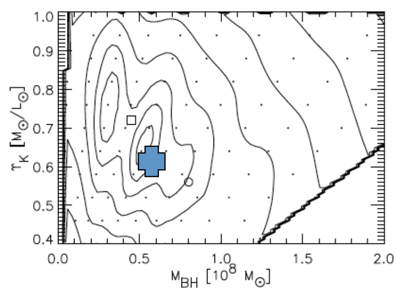
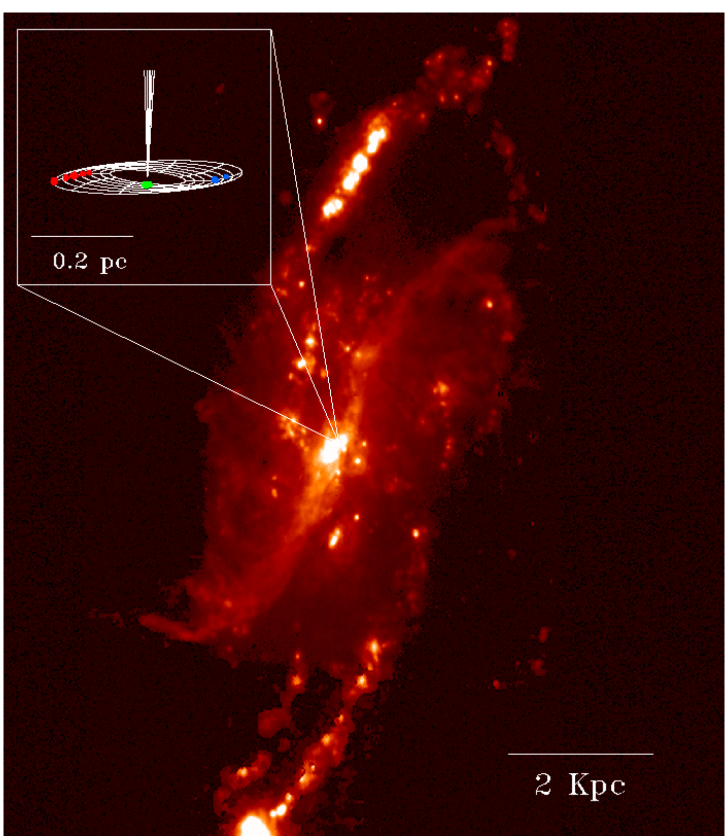


Figure 4: Spherical anisotropic Jeans model

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



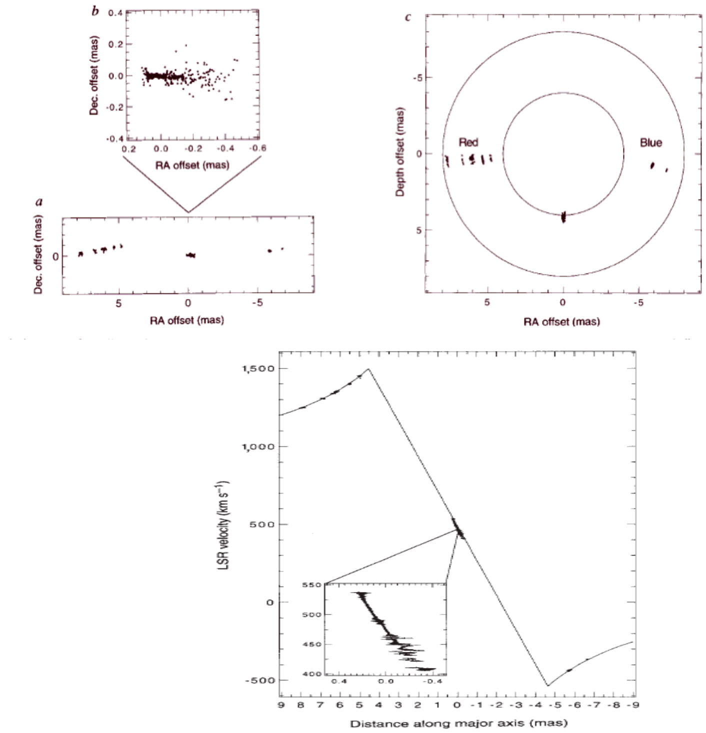
Constraints from stars compared to those from Gas Velocities



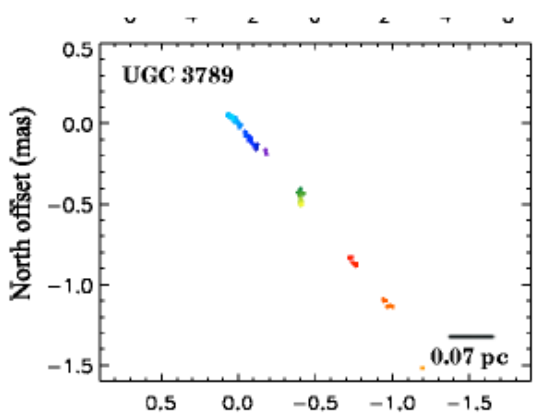
NGC4258

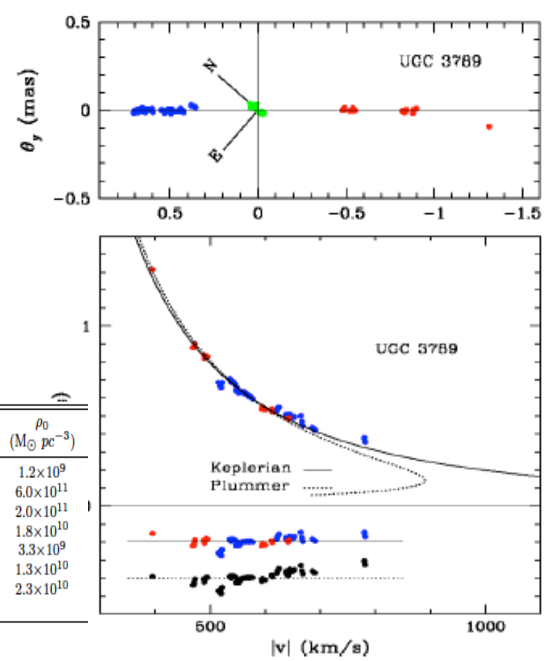
Use of Masers for an AGN

- 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



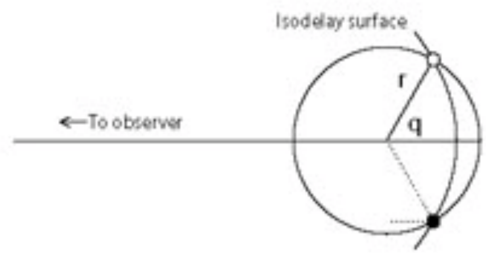


Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36	−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}

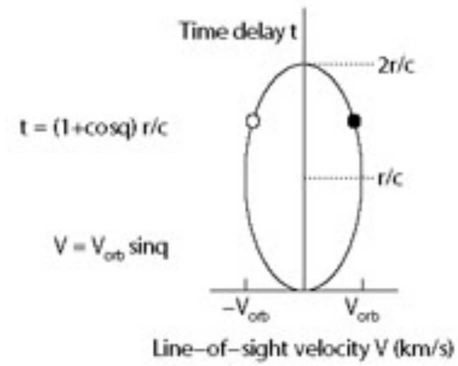
Kuo et al 2010

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

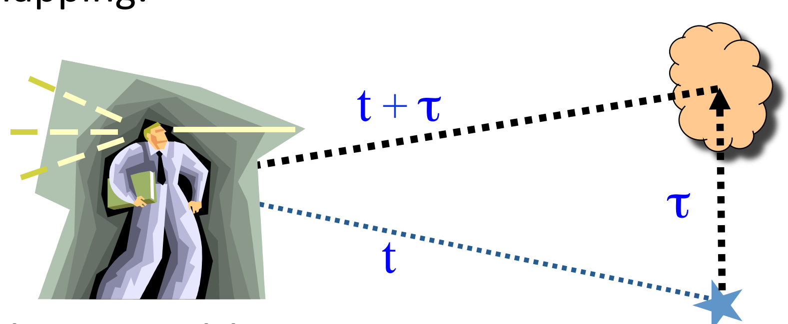


Virial Mass Estimates

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

Reverberation Mapping:

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

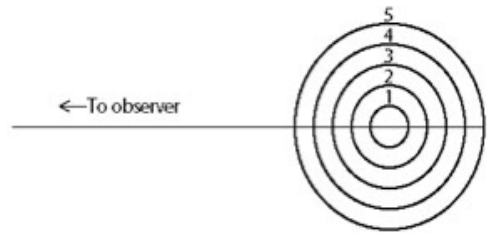


- v_{BLR}

  Line width in variable spectrum

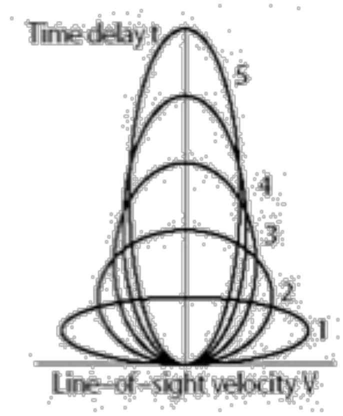
The Geometry

- 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

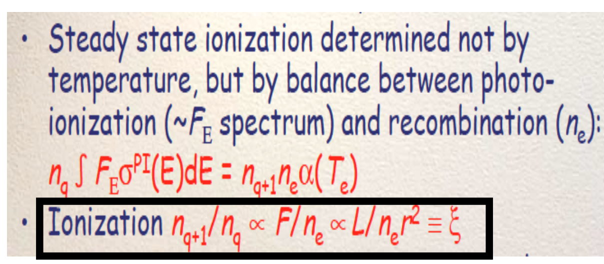


f is a parameter related to geometry- and the orbits of the gas clouds- assumption is that gas is in a bound orbit around the BH

r=ct, where t is the time delay

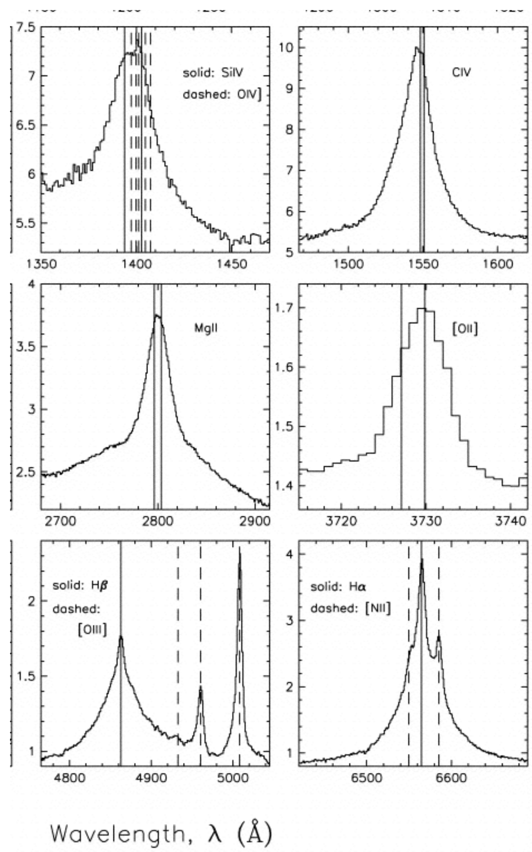
A Quick Guide to Photoionized Plasmas

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



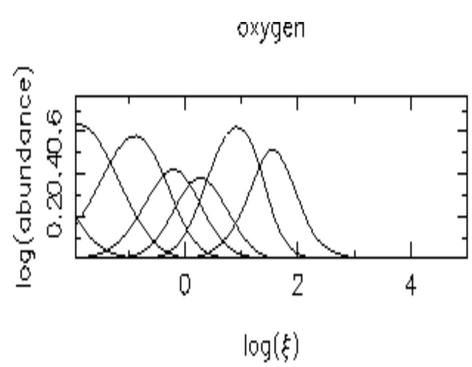
ξ is the ionization parameter (also sometimes called U)

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

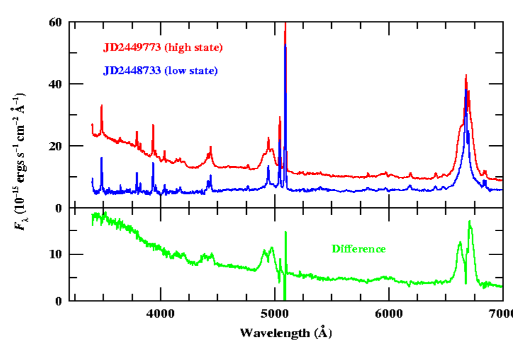


In Other Words

- 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"



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



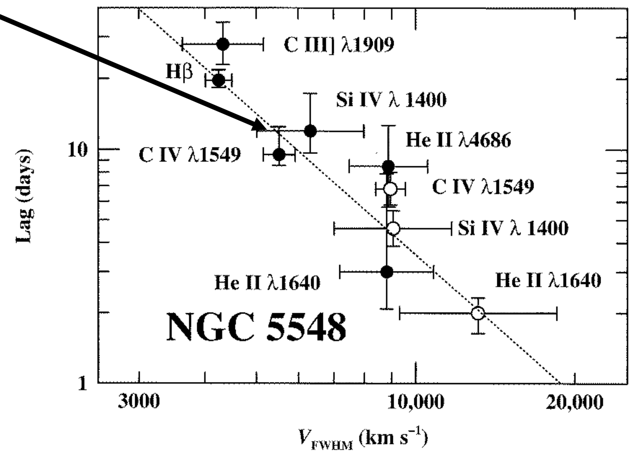
Peterson (1999)

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 ~r^{-2}

  and Keplerian motions dominating the line shapes

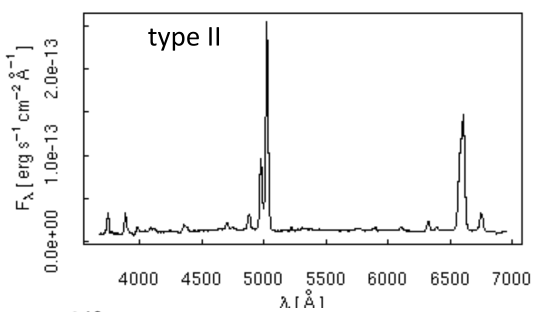
  ($v \sim r^{-1/2}$)
- Such data exist for ~40 sources
- At present M_{BH} can be estimated to within a factor of a few: $M \propto FWHM^2 L^{0.5}$

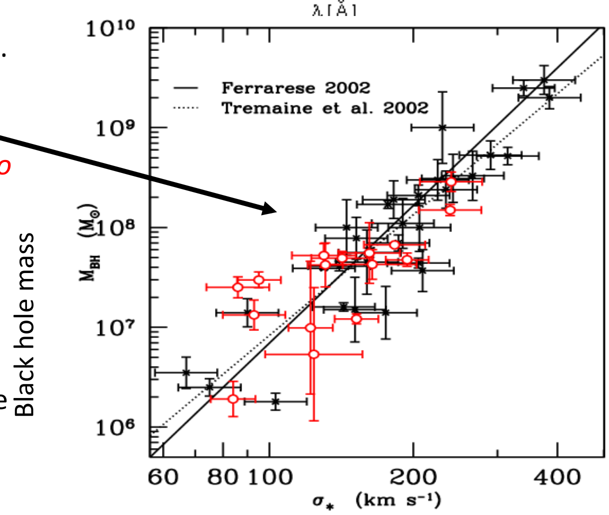


Dotted line corresponds to a mass of $6.8 \times 10^7 M_\odot$
Peterson and Wandel 1999

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

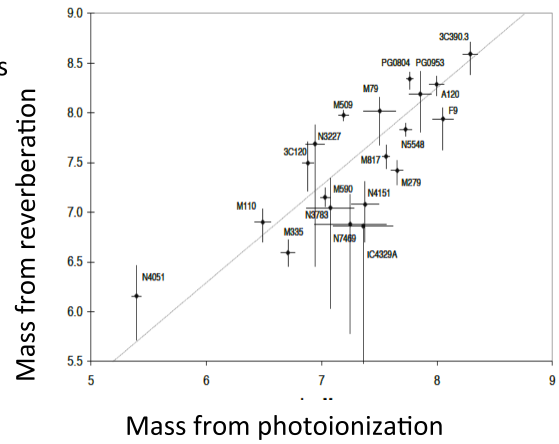




Velocity dispersion of stars in the bulge

Reverberation Masses and Dvnamical 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 !



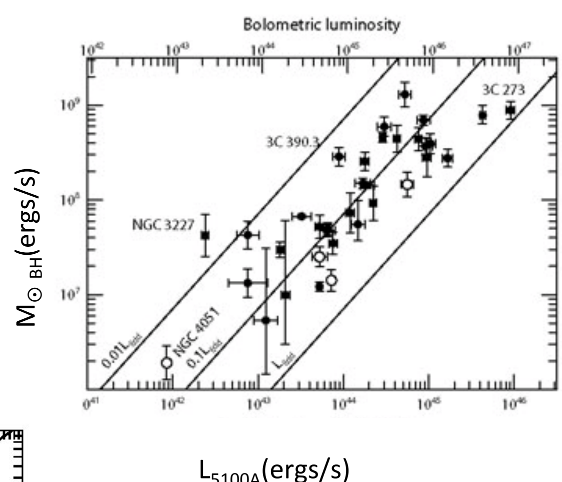
$M_{BH} \sim K\sigma^2 L^{1/2}$

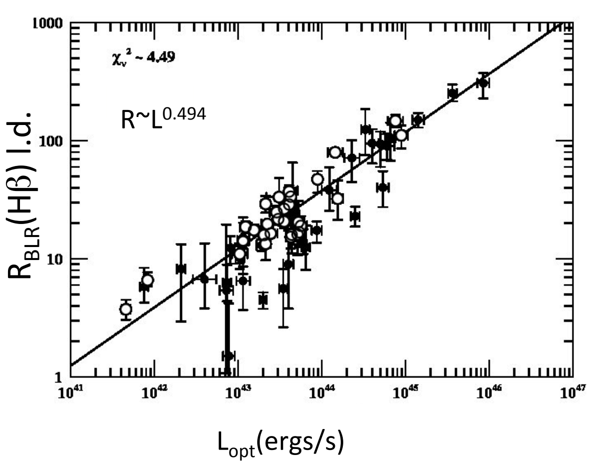
Where K is a constant (different for different lines which is determined by observations

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 $L^{1/2}$

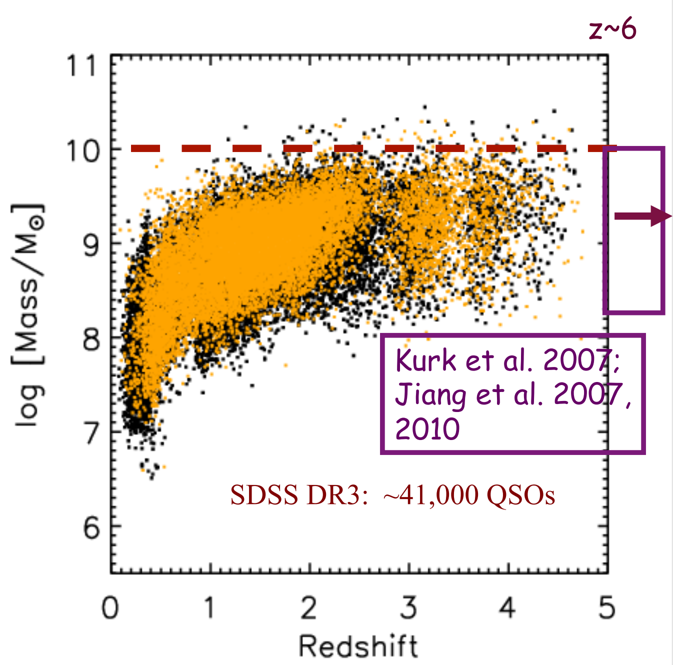




Masses of Distant Quasars- M. Vestergaard

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

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



(DR3 Qcat: Schneider et al. 2005)

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)

Constraints on Rest Mass of Black Holes

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

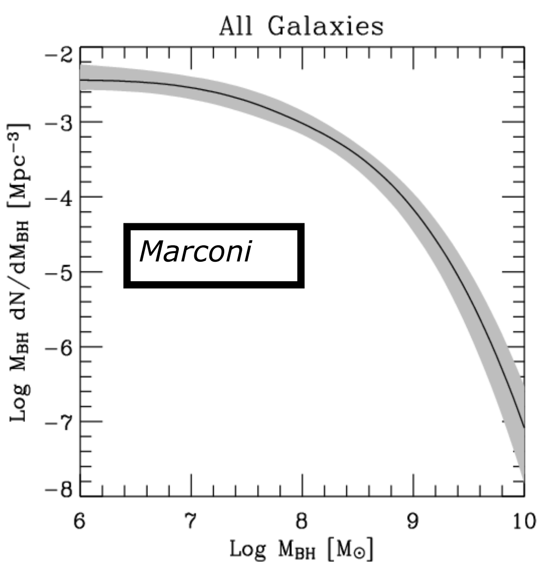
- It is thought that, at z>1 that many galaxies (esp. elliptical galaxies) grow through mergers.

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.**

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)

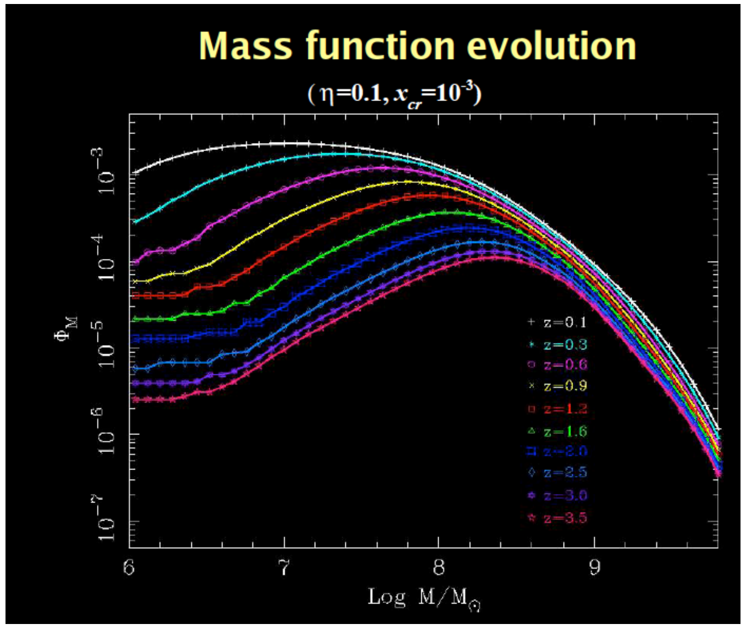
$\rho_{BH} \sim 4.1^{+1.9}_{-1.4} \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$

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

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

Transform to Mass Growth

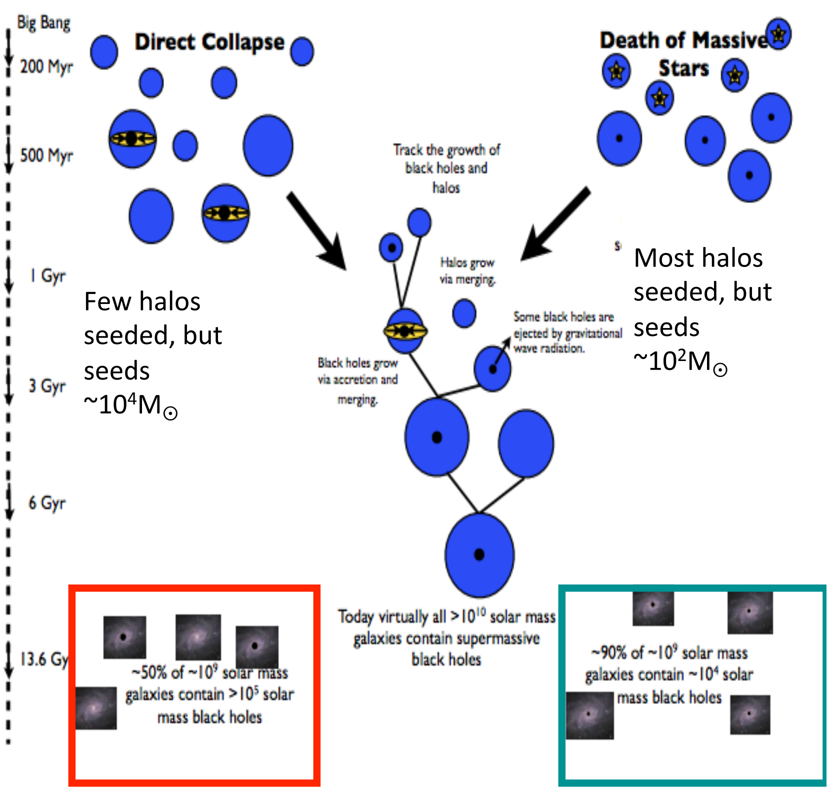
- Take accretion rate and some model of initial BH mass distribution and watch them grow (Merloni et al 2006)
- Notice 'down sizing' big black holes grow first and small black holes later



2 Scenarios for Birth of SMBHs

How do SMBHs get started??
Detect M~10^9M 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



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