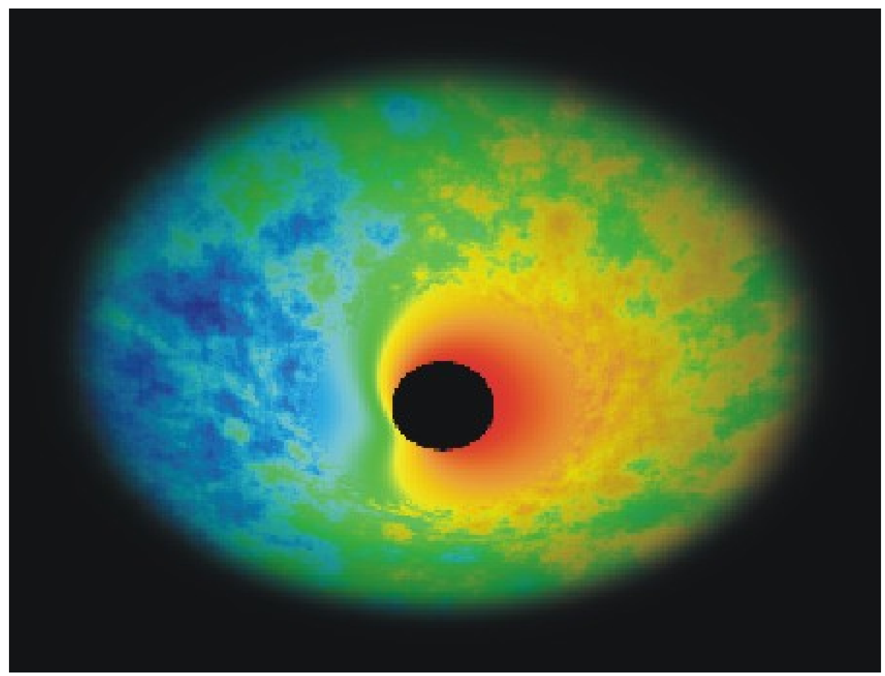
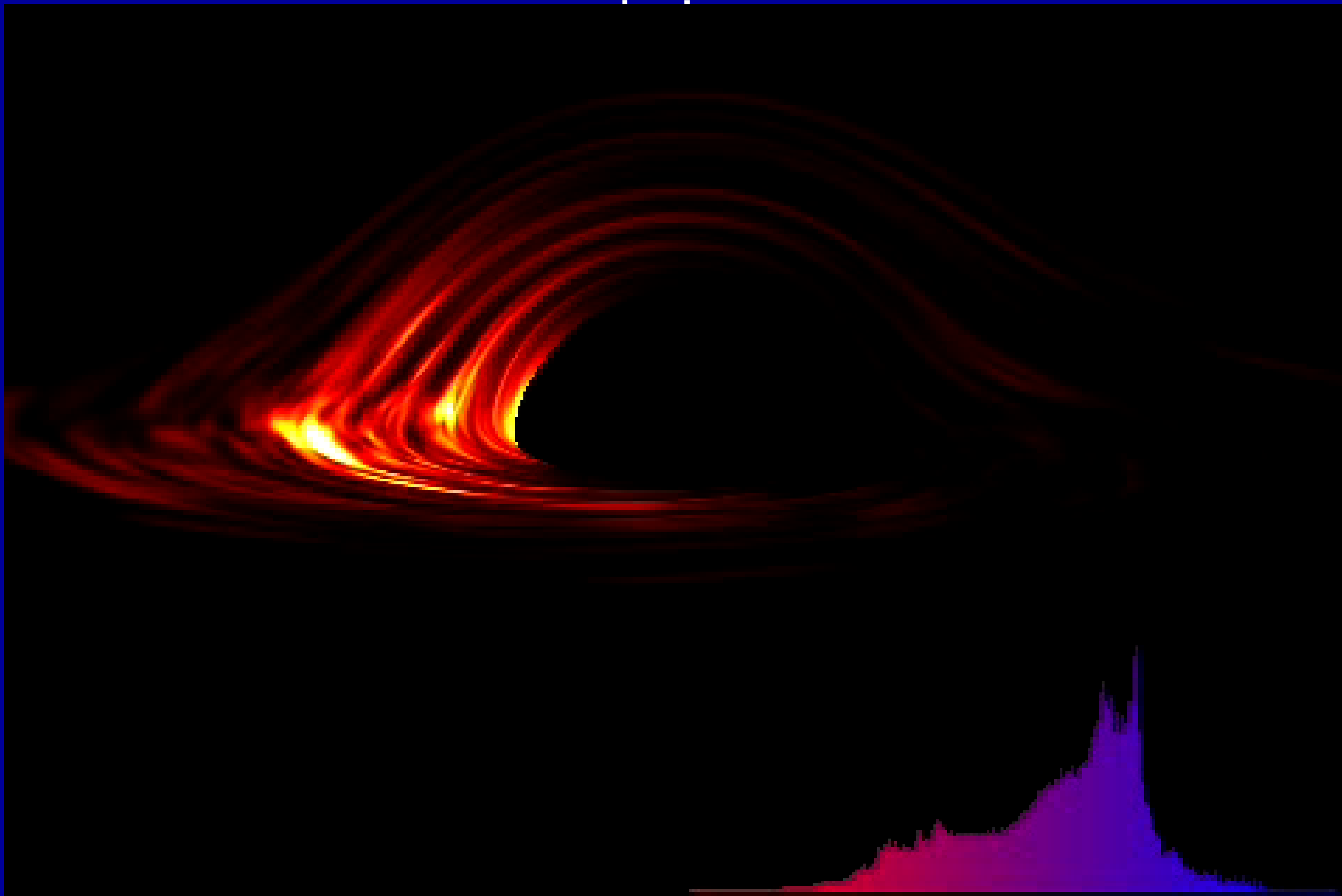
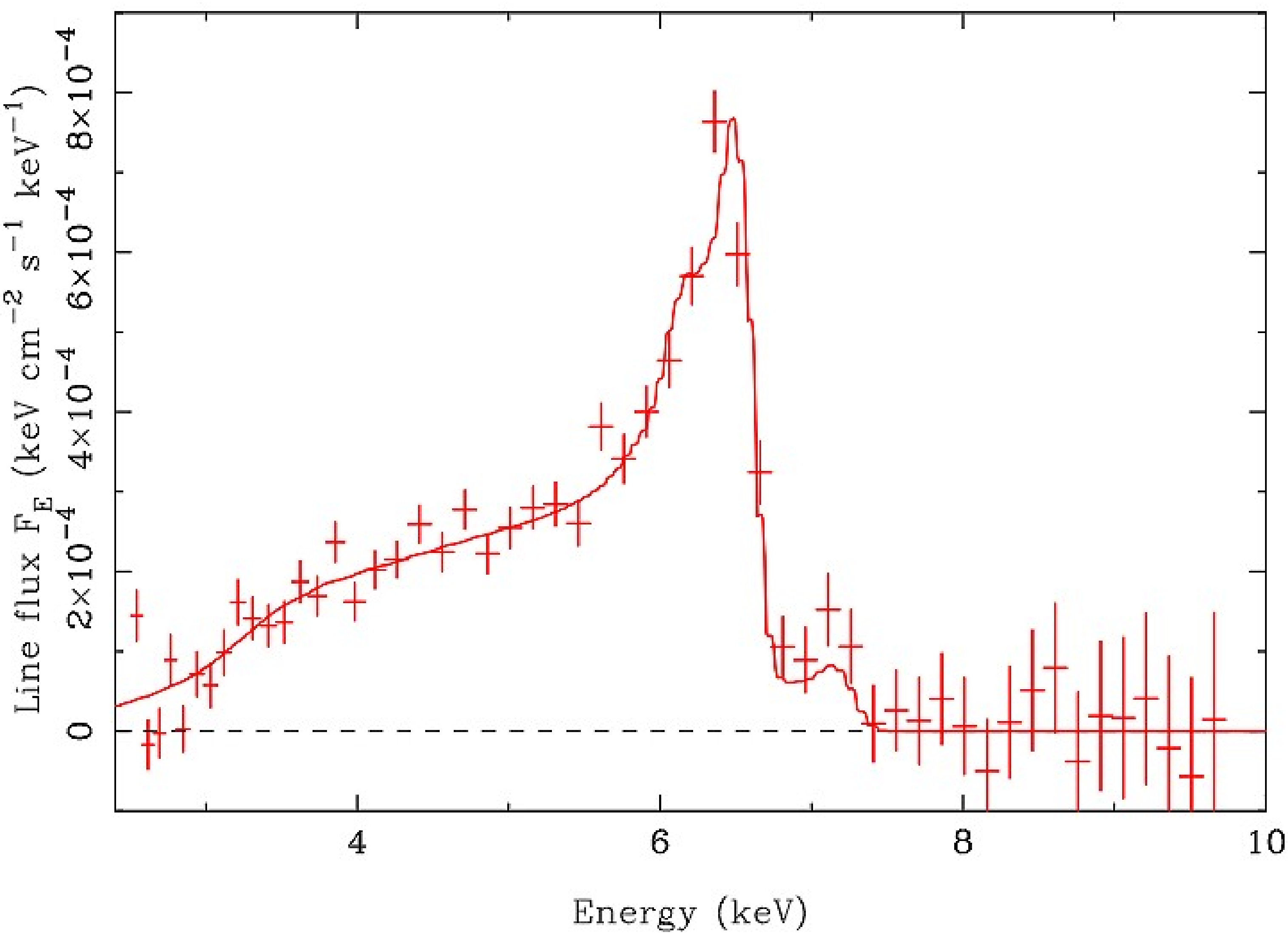
For the Mathematically Inclined

- The Schwarzschild solution for the metric around a point mass is
- $ds^2=-(1-2GM/c^2r)c^2dt^2 +(1-2GM/c^2r)^{-1}dr^2+r^2(d\theta^2+\sin2d\phi\theta^2)$
- Notice singularity at $r=2GM/c^2$ (can be gotten rid of in a coordinate transformation)
- A static observer measures proper time $c^2d\tau^2=-ds^2=-(1-2GM/c^2r)c^2dt^2$
- $d\tau/dt=\mathrm{sqrt}(1-2GM/c^2r))=1+z_{grav}$



Numerical Simulation of Gas Accreting Onto a Black





Broad iron line in MCG-6-30-15 (Fabian et al. 2002)

So what is the actual size ?

$R_G \sim 1.5\ (M / M_\odot)$ km

So how close are neutron stars to being black holes ?

Neutron stars are only about a factor 2—3 larger than their event horizons

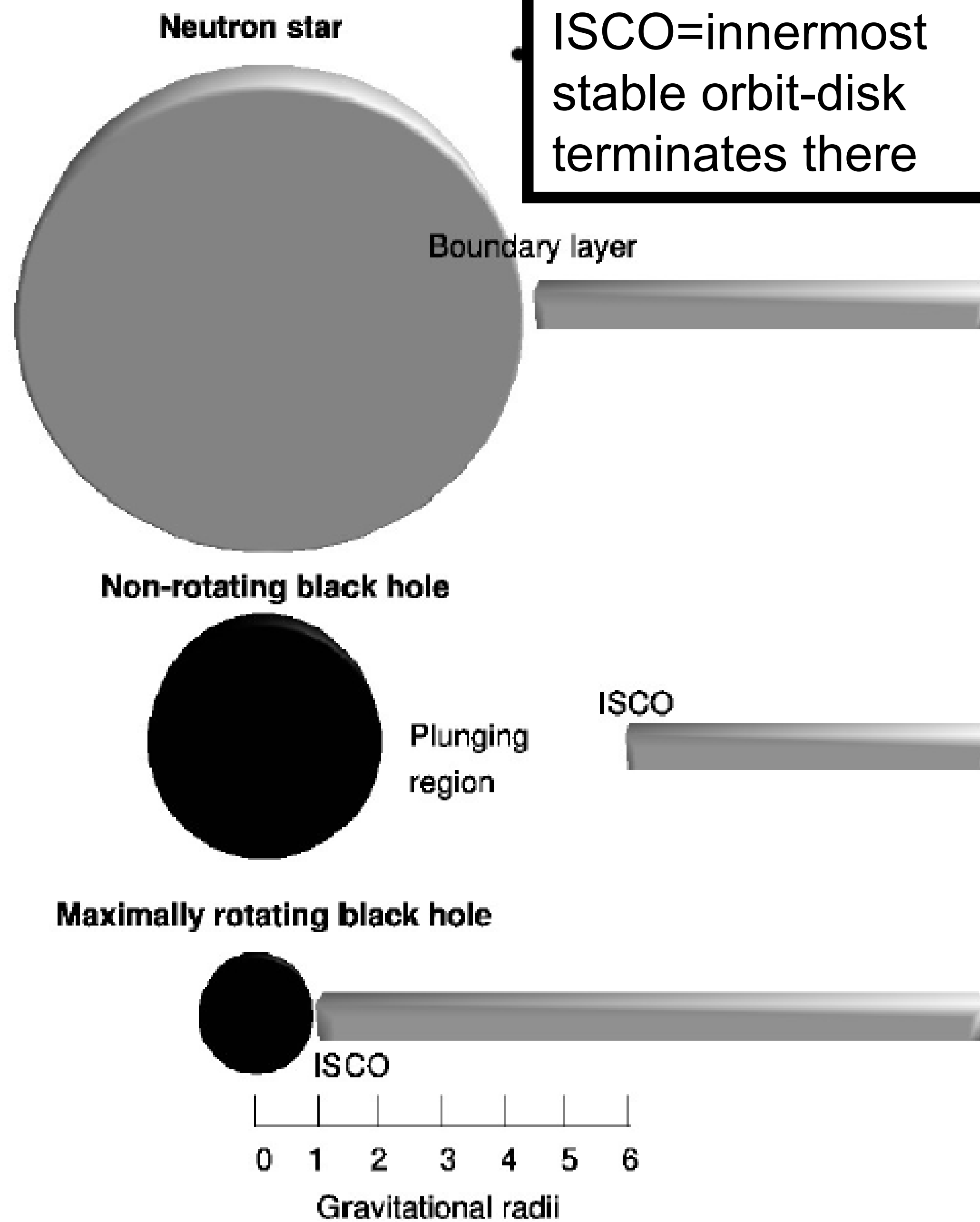
What about spin ?

A non-rotating ("Schwarzschild") black hole has its event horizon at 2 R_G and its ISCO at 6 R_G

A maximally rotating ("Maximal Kerr") black hole has both its event horizon and ISCO at R_G

→ Spinning black holes are more compact → potentially more radiatively efficient

ISCO=innermost stable orbit-disk terminates there



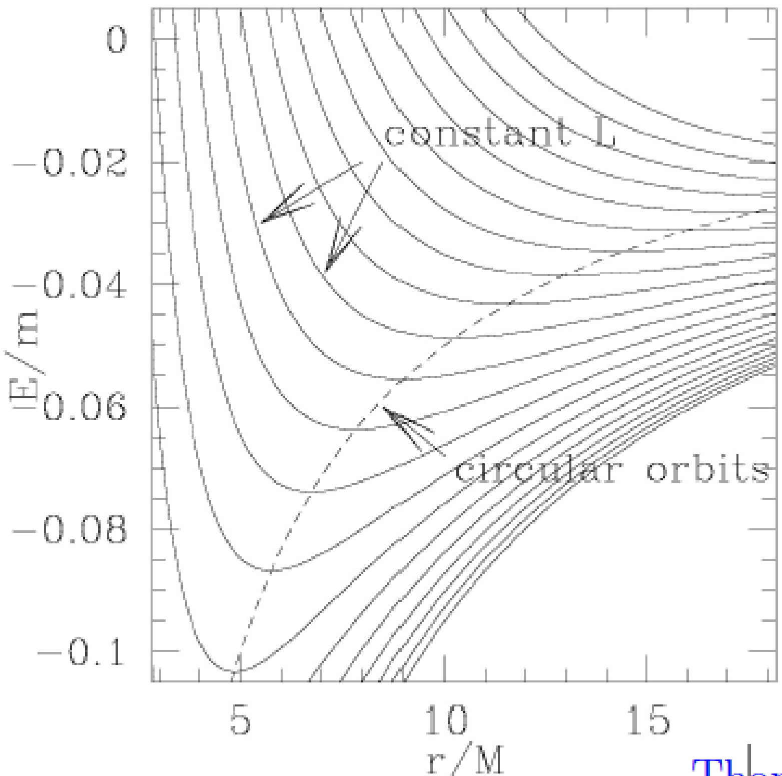
R. Fender 2007

The innermost stable circular orbit (ISCO)

circular orbit extremizes binding energy E of test mass m at const. angular momentum L

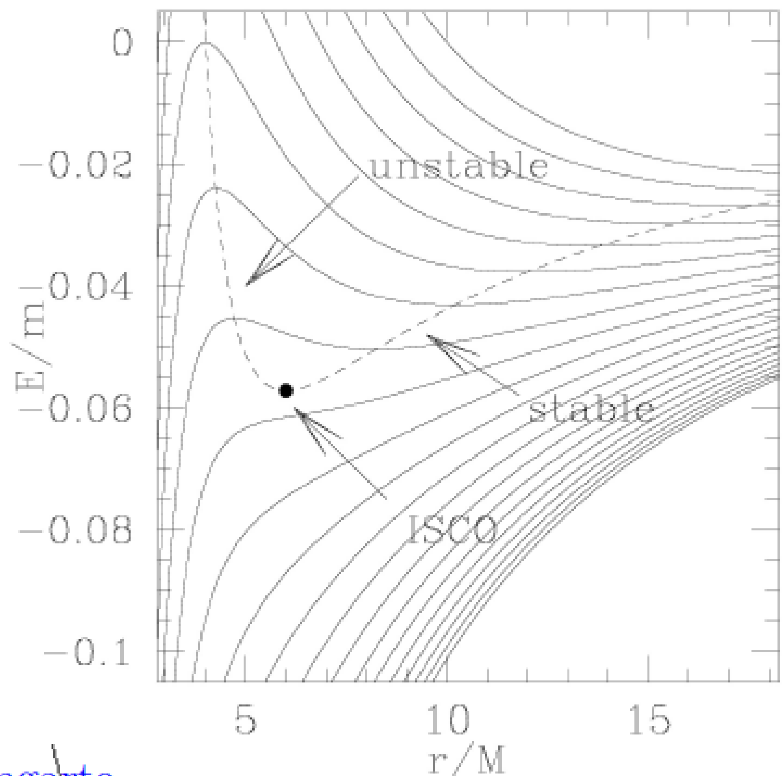
Newtonian point mass

$$\frac{E}{m} = -\frac{M}{r} + \frac{L^2}{2r^2}$$



Schwarzschild black hole

$$\frac{E}{m} = \left(\left(1 - \frac{2M}{r}\right)\left(1 + \frac{L^2}{r^2}\right)\right)^{1/2} - 1$$

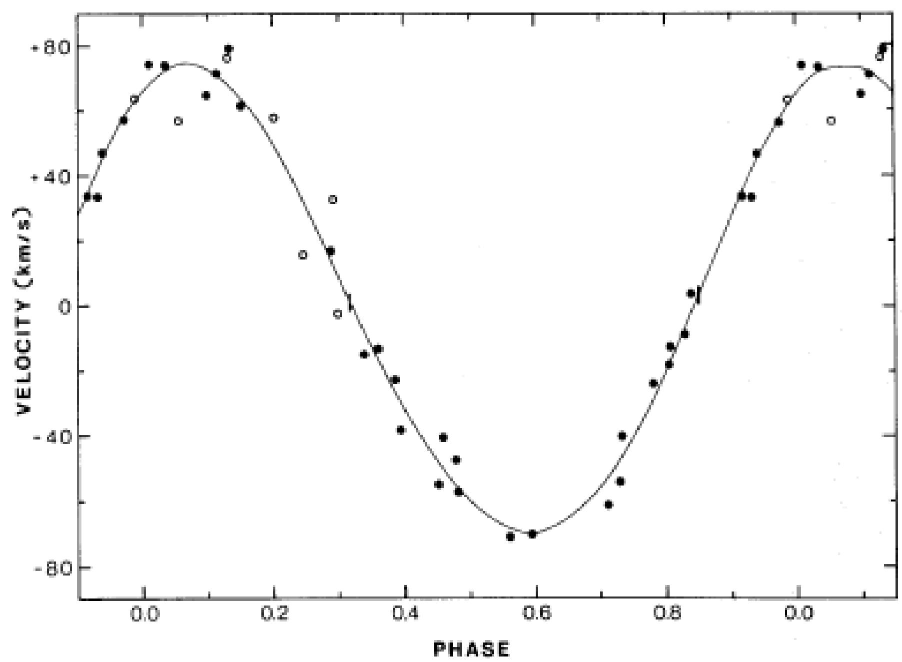


Thomas Baumgarte

Bowdoin College

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

$f(M) = P_{orb}K^3_2 / 2\pi G = M_1 \sin^3 i/(1 + q)^2.$

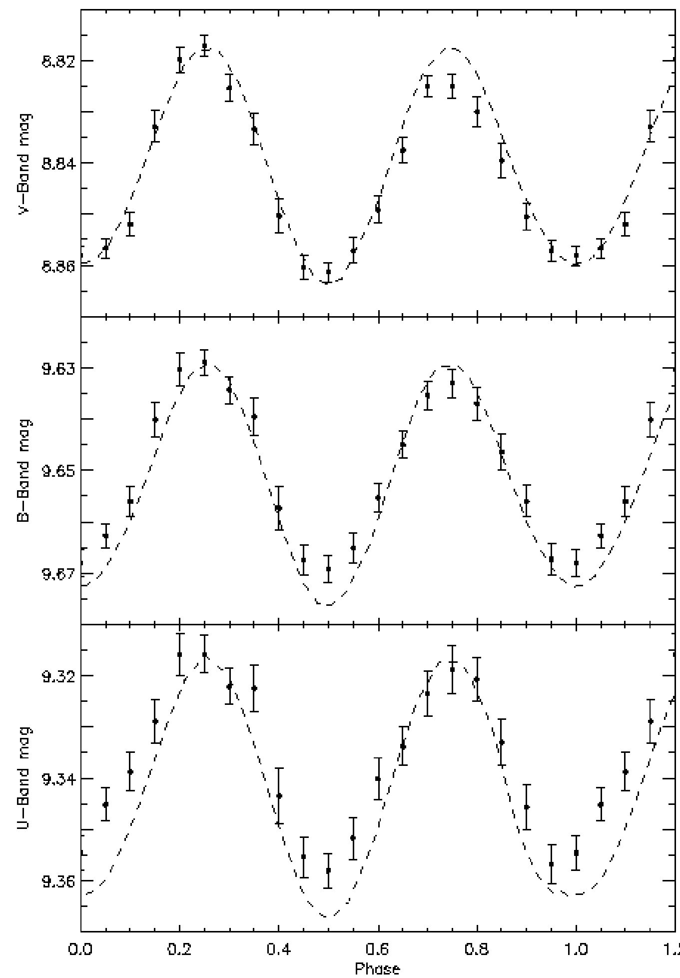
$q=M_2/M_1$

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

How do we know the black hole mass?

- Can constrain black hole mass from orbit of companion star
  - Period 5.6 days
  - K = V sin i = 75km/s
  - Analysis of orbit gves the mass function
  - M_{BH}>f
  - Cyg X-1… f=0.24M_{BH}

$$f = \frac{K^3 P}{2\pi G} = \frac{M_1^3 (\sin i)^3}{(M_1 + M_2)^2}$$



Brocksopp et al. (1998)

- Detailed solution at http://imagine.gsfc.nasa.gov/YBA/cyg-X1-mass/mass-solution.html

- we have the mass functions
- $m_2^3 \sin^3 i/(m_1+m_2)^2 = v^3{}_1 P/2\pi G$
- In the case of Cygnus X-1, however, only one of the stars can be seen (Cygnus X-1's visual companion), so in order to determine the mass of the unseen object, it is necessary to know, or to estimate, the mass of the companion star. In this case, $m_1$and v_1 refer to the companion star and m2 refers to Cygnus X-1, the unknown mass for which we want to solve.

Re-arrange to get a cubic eq
$m_2^3 \sin^3 i = (v^3{}_1 P/2\pi G)/(m_1+m_2)^2$
And expand $(m_1+m_2)^2$ to get a standard cubic
$m_2^3 - Pv^3{}_1 m_2^2/2\pi G \sin^3 i - 2Pv^3{}_1 m_1 m_2/2\pi G \sin^3 i - Pv^3{}_1 m_1^2/2\pi G \sin^3 i = 0$

So in the standard cubic eq solution we can solve this if we know P,v_1,i and m_1
P,v_1 are measured , m_1 is estimated from the optical nature of the companion star and so the mass of the system can be expressed as an uncertainty in the inclination

Set of Solutions for the Mass as a Function of Inclination

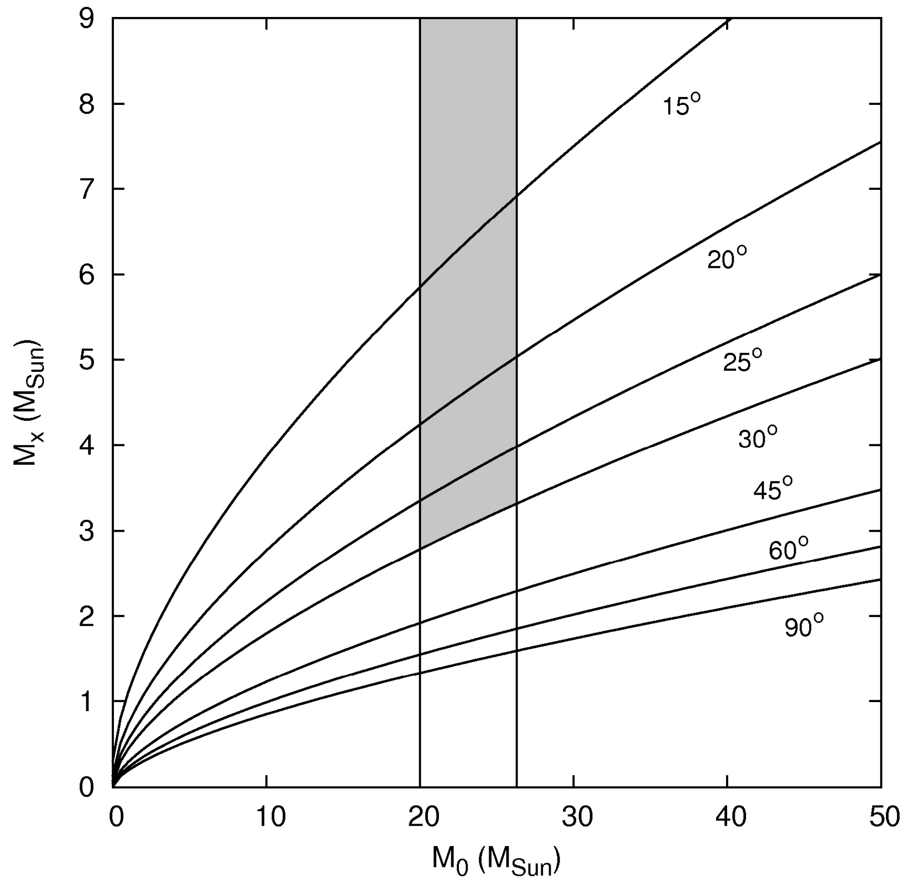
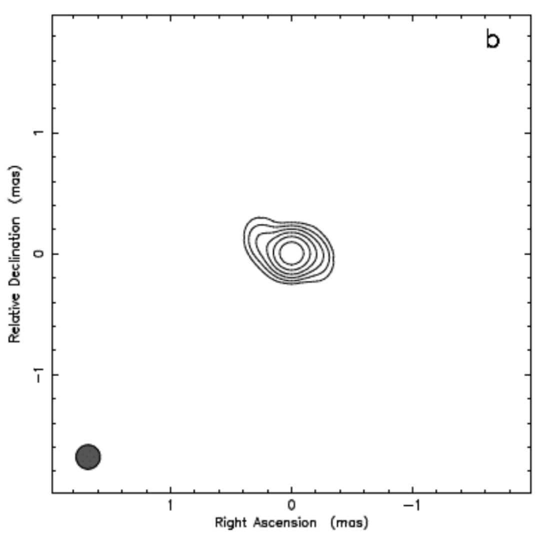


Table 1. Confirmed black holes and mass determinations

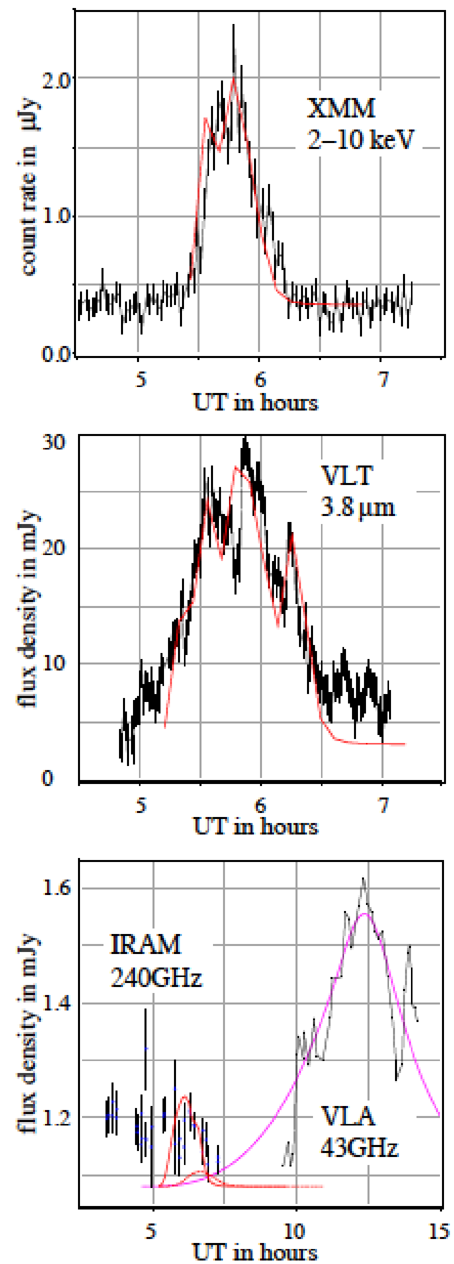
System	P_{orb} [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	M_x † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	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 Sagitarius 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 xray binary) and IR source
- The radio source is very small (<0.0005"<50R_s for $M=4x10^6M_\odot$ BH at d=8kpc)
- At SgrA* 1"=0.04pc=1.2x10^{17} cm ,0.5mas=6AU



Radio image of SgrA*



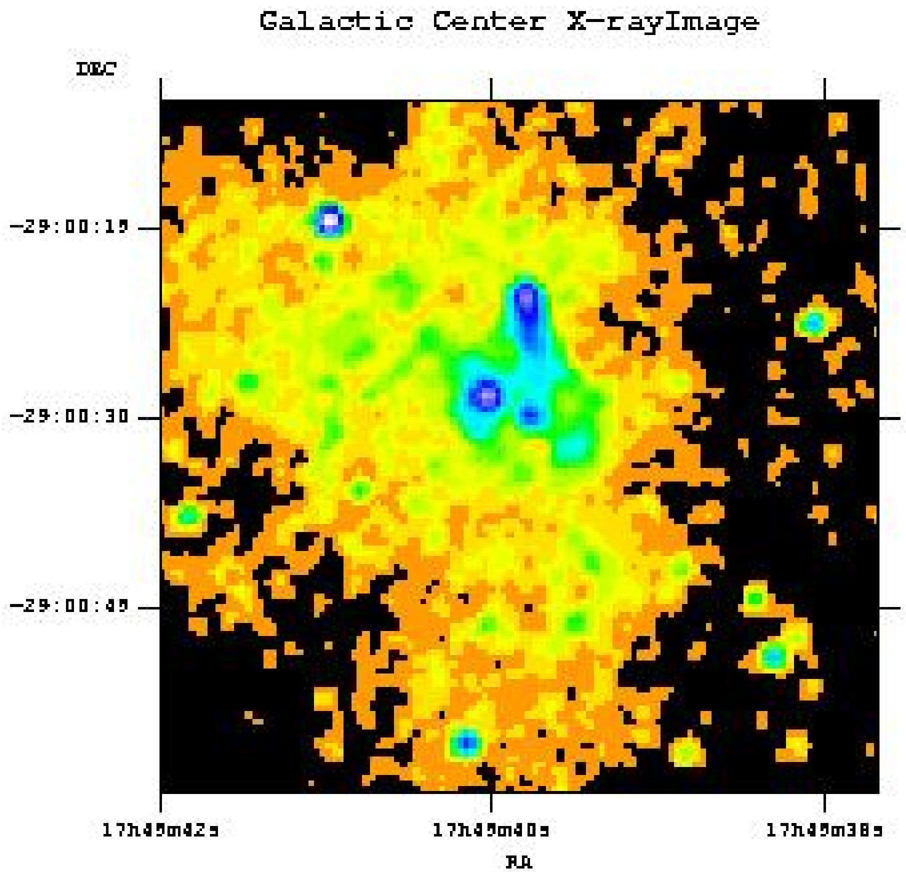
Radio, near IR and Radi light curves

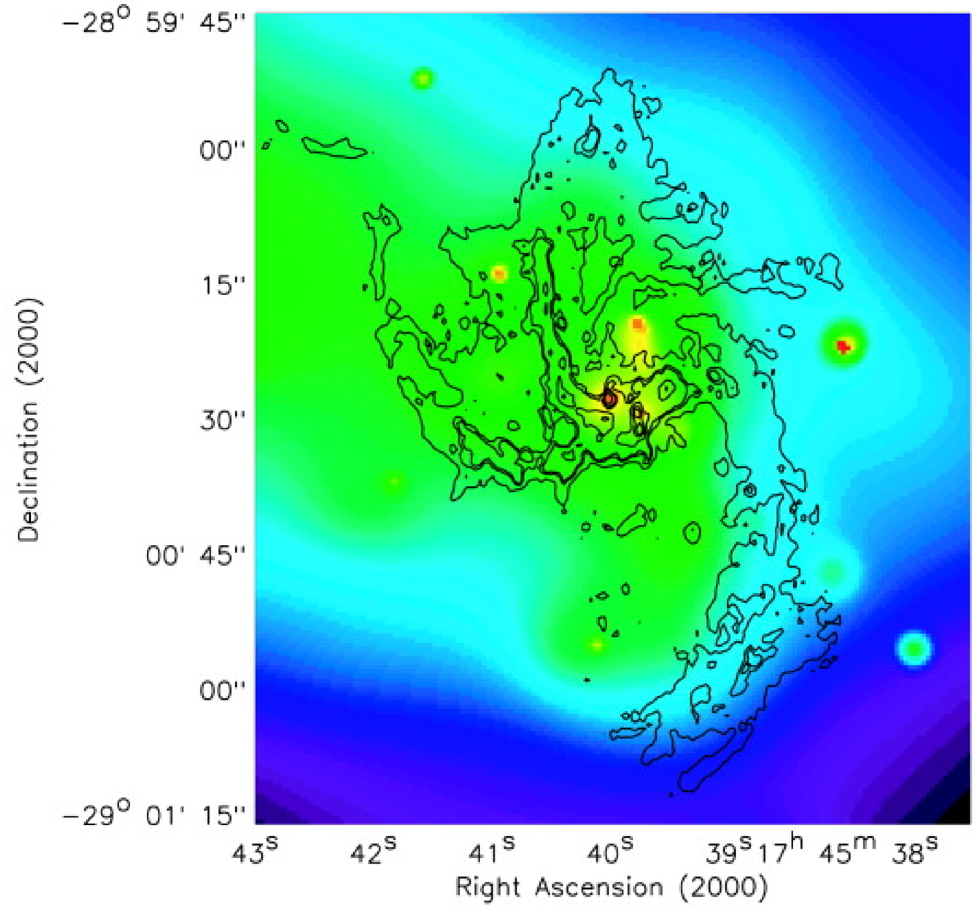
Some Problems with Sgr A*

- There is lots of gas for accretion in the galactic center from the ISM and stellar winds
- Yet the observed luminosity is very low ($L/L_{Edd} \sim 10^{-10}$)
- What happens to the accretion energy- where does the mass and energy go

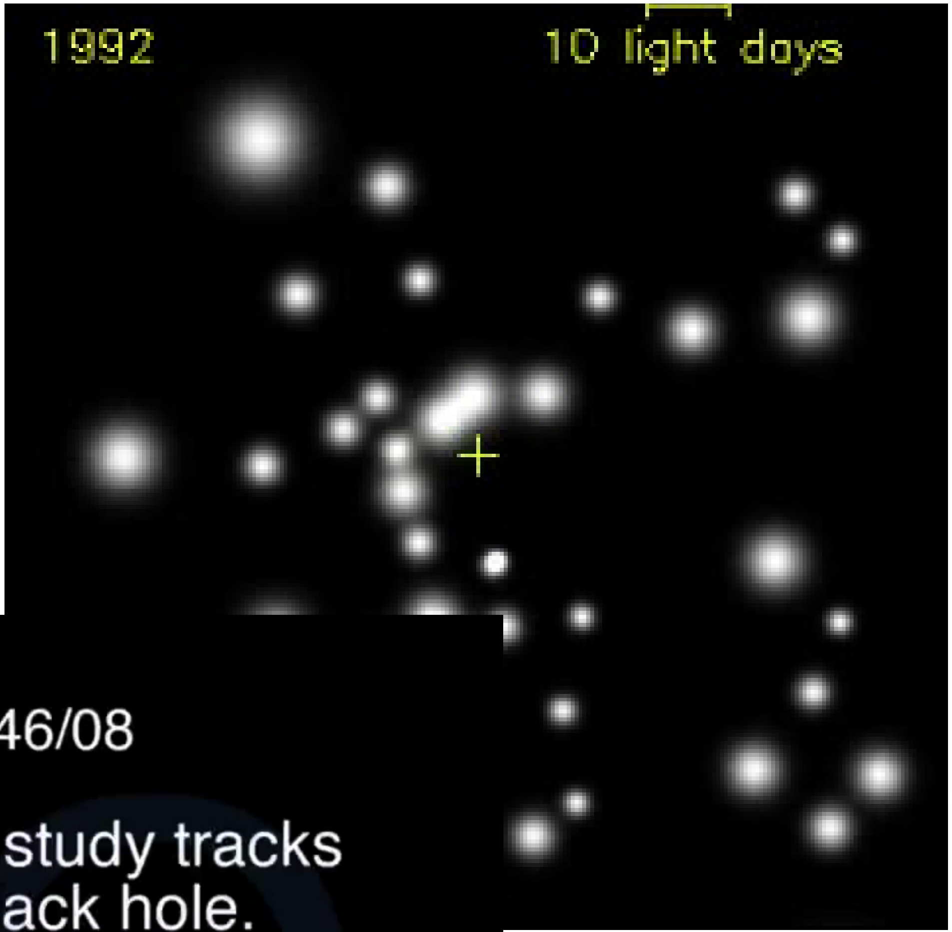
- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities

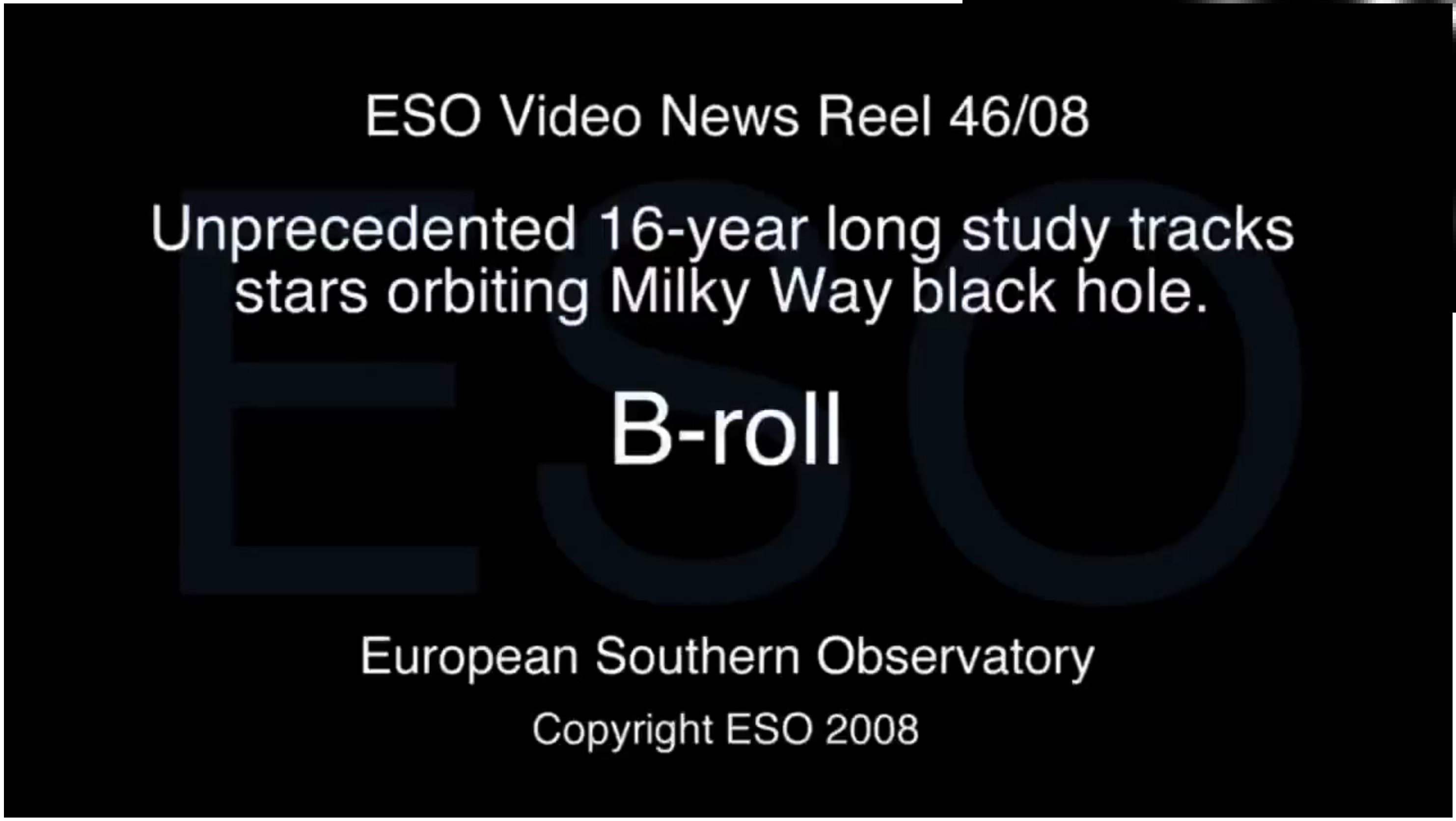
Radio and X-ray Image of MW Center





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/

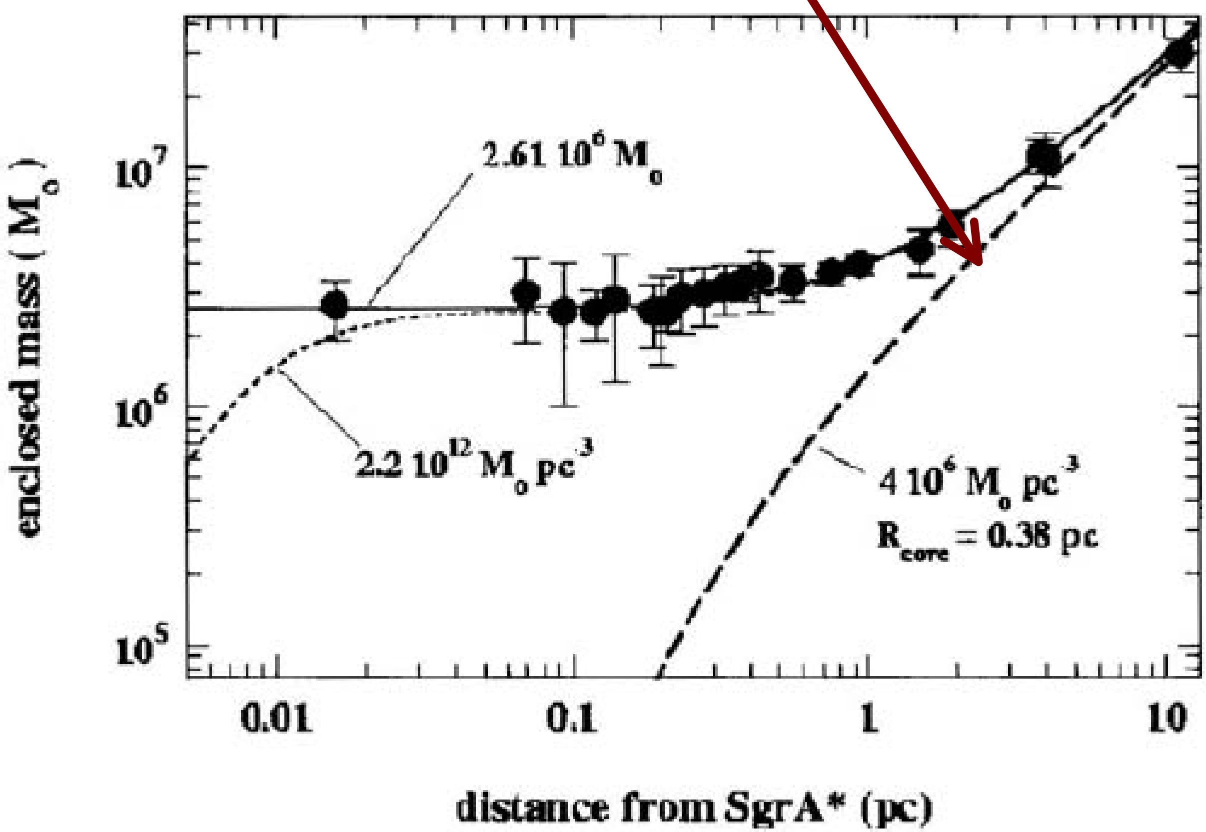




MW Center

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

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 $2.6 \times 10^6 M_{sun}$, and density $20 M_{sun} pc^{-3}$ 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

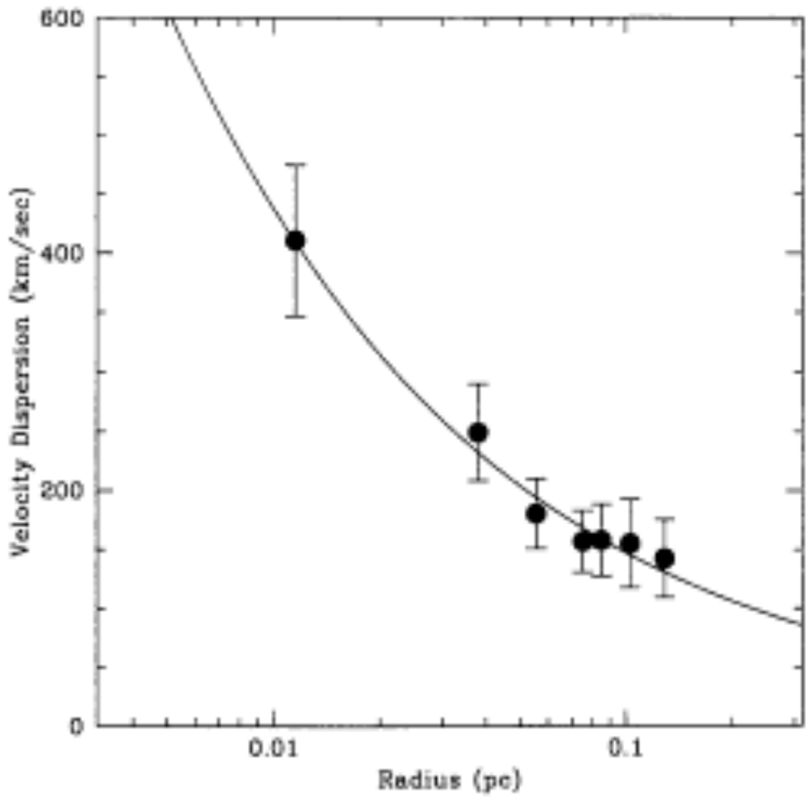


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

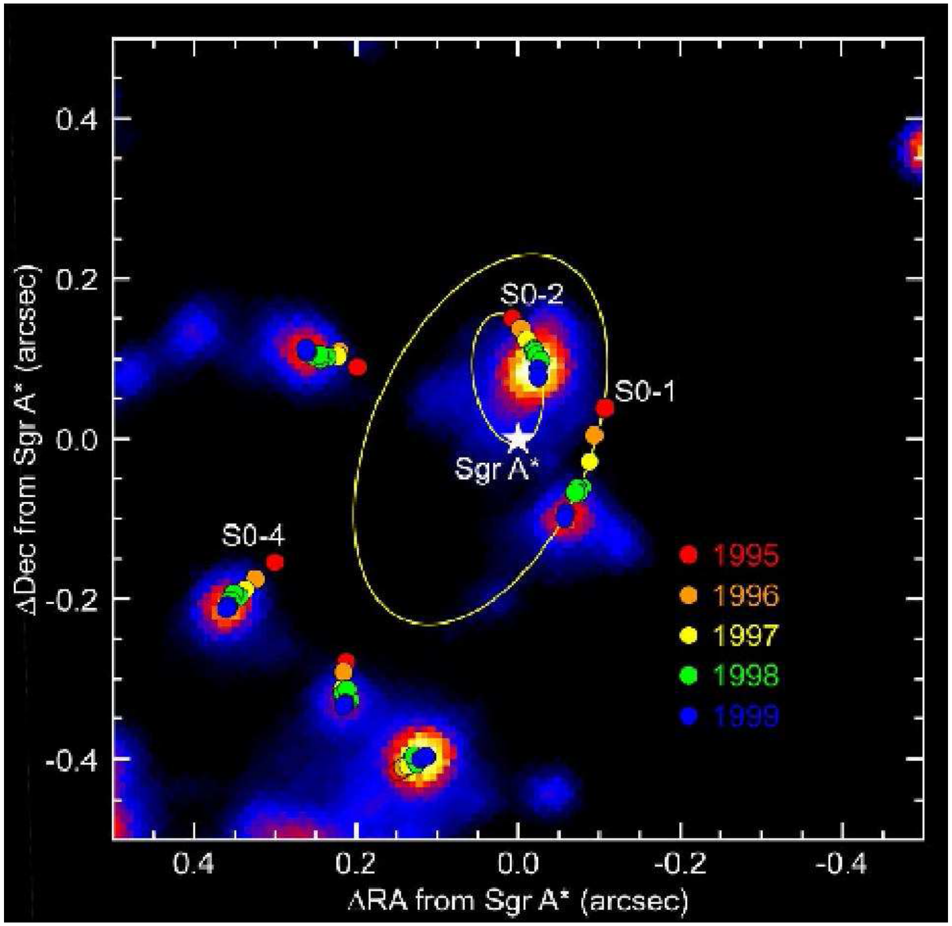
Ghez et al 1998

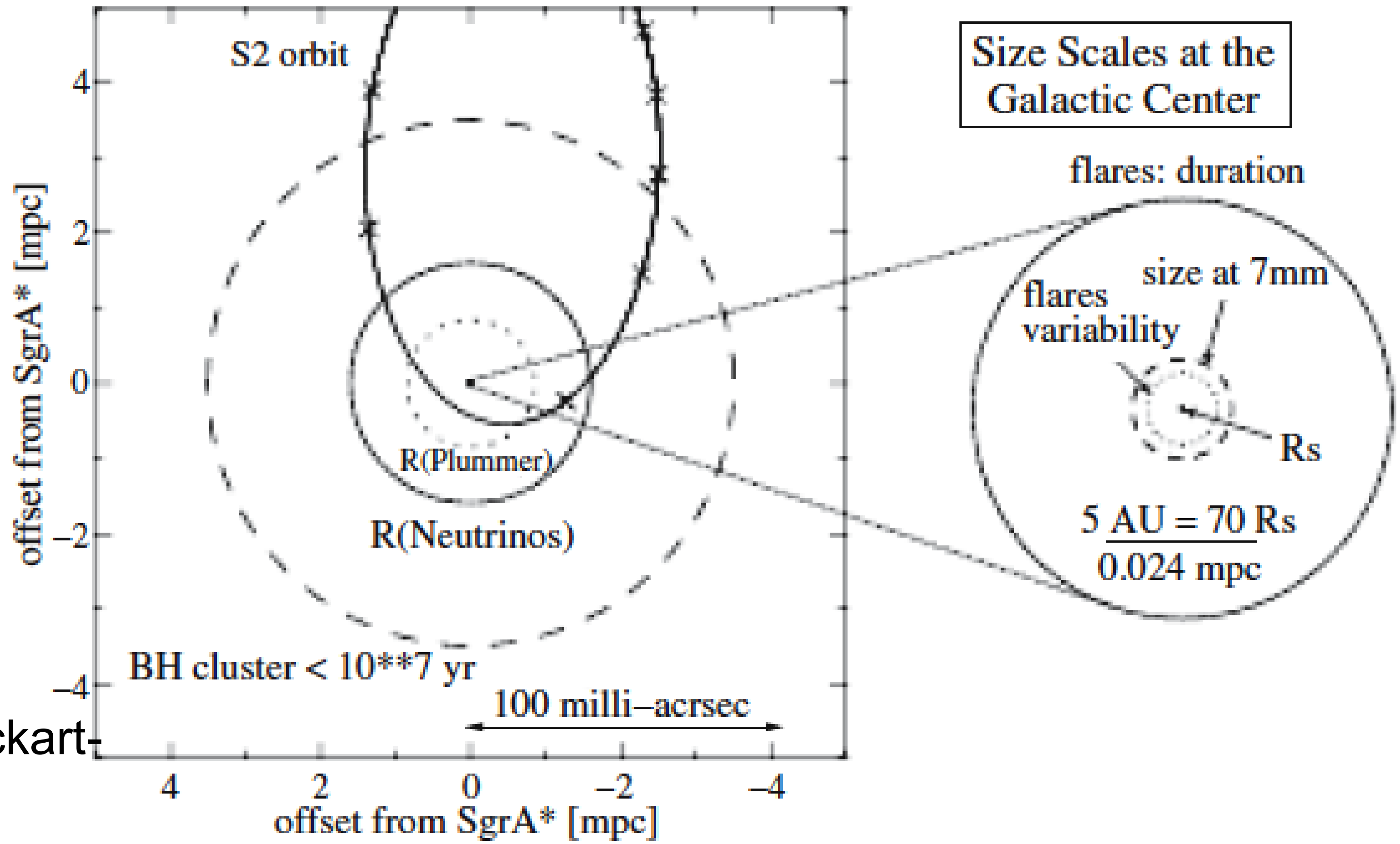
- While stars are moving very fast near the center (Sgr A*) the upper limit on its velocity is 15 km/sec

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

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

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

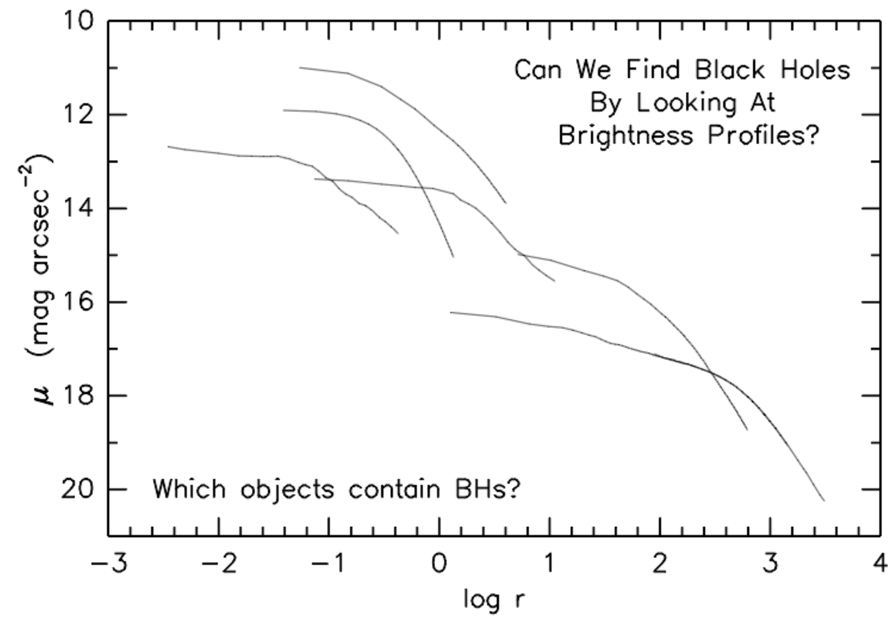



S2 orbit
Size Scales at the Galactic Center
flares: duration
size at 7mm
flares variability
Rs
5 AU = 70 Rs
0.024 mpc
R(Plummer)
R(Neutrinos)
BH cluster < 10**7 yr
100 milli–acrsec
offset from SgrA* [mpc]
offset from SgrA* [mpc]
4
2
0
–2
–4

Eckart-

What About Other Supermassive Black Holes

- At the centers of galaxies- so much more distant than galactic stellar mass black holes
- 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 (conceptionally identical to the use of gas temperature to measure mass, but stars have orbits while gas is isotropic)

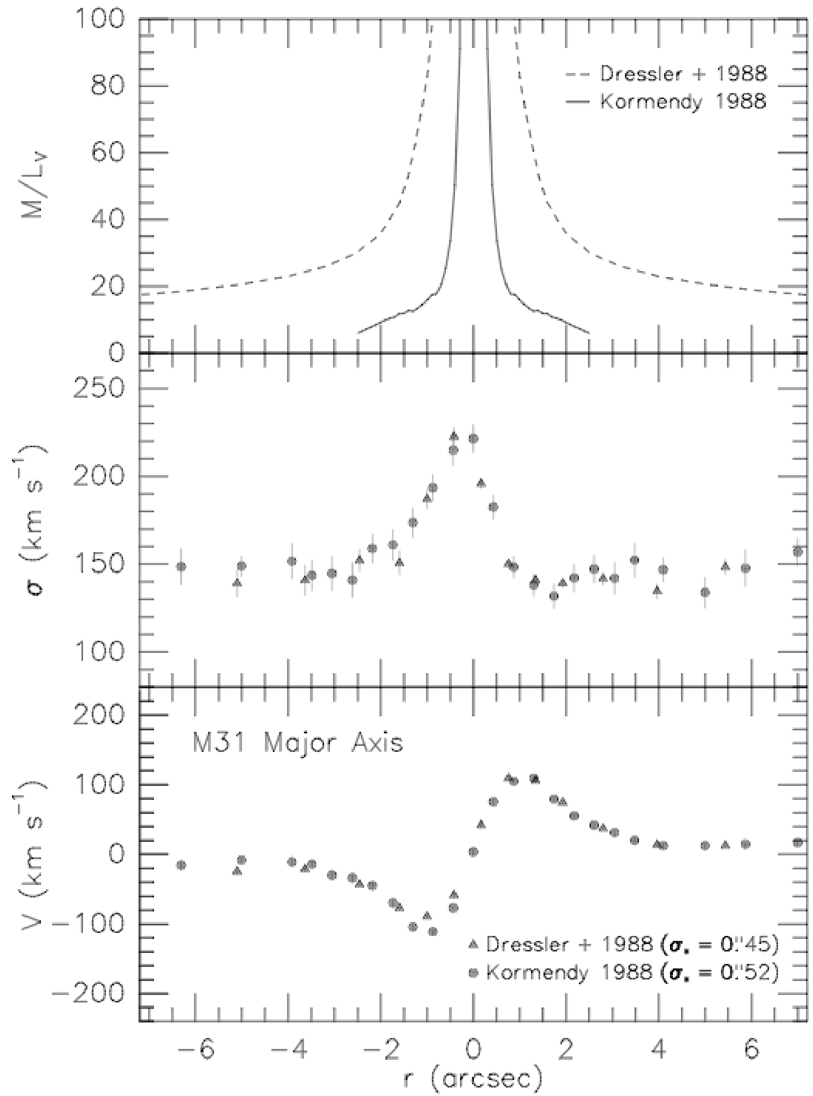


Kormendy and Richstone (2003)

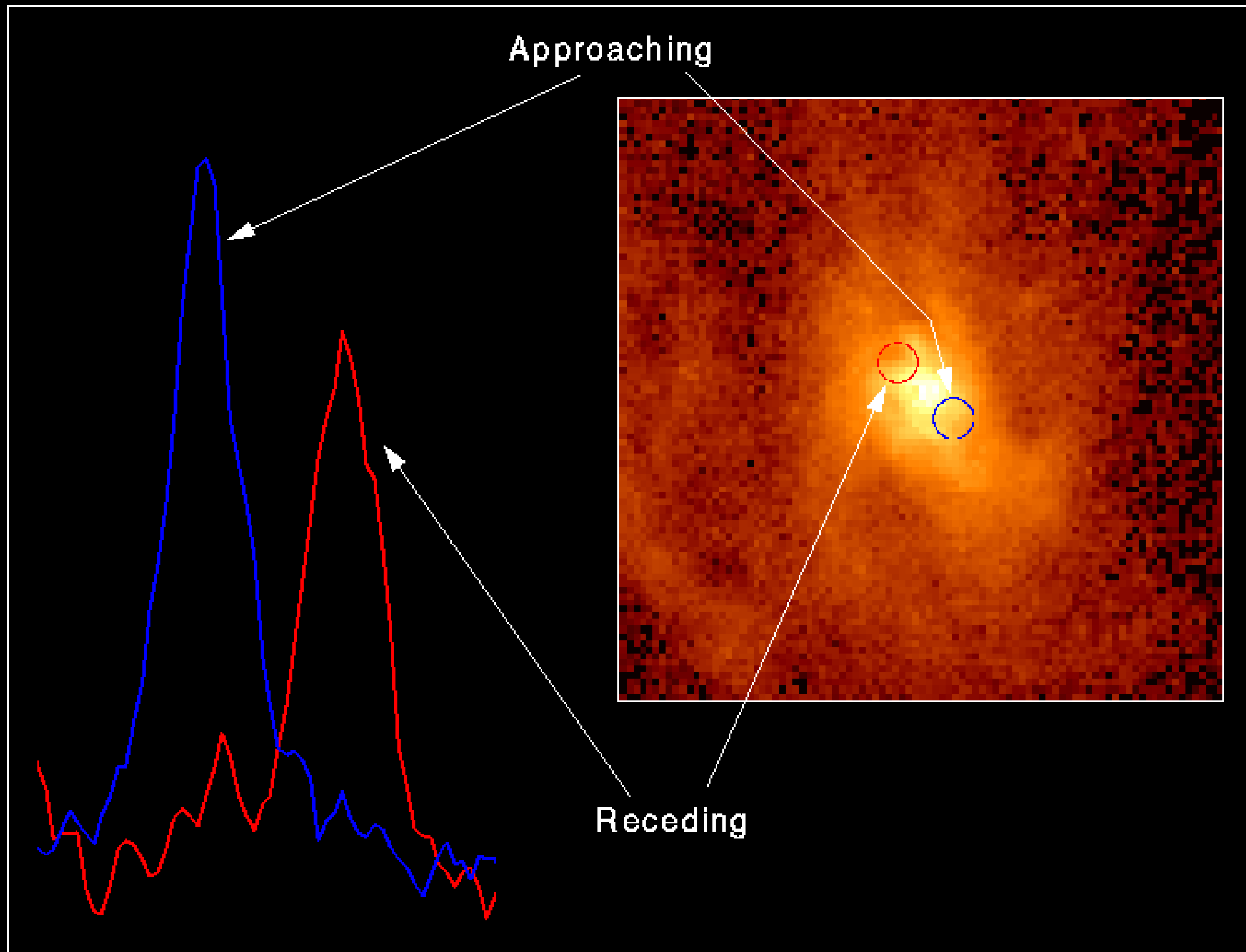
$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1 - \frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1 - \frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

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 important- Hubble data



Spectrum of Gas Disk in Active Galaxy M87



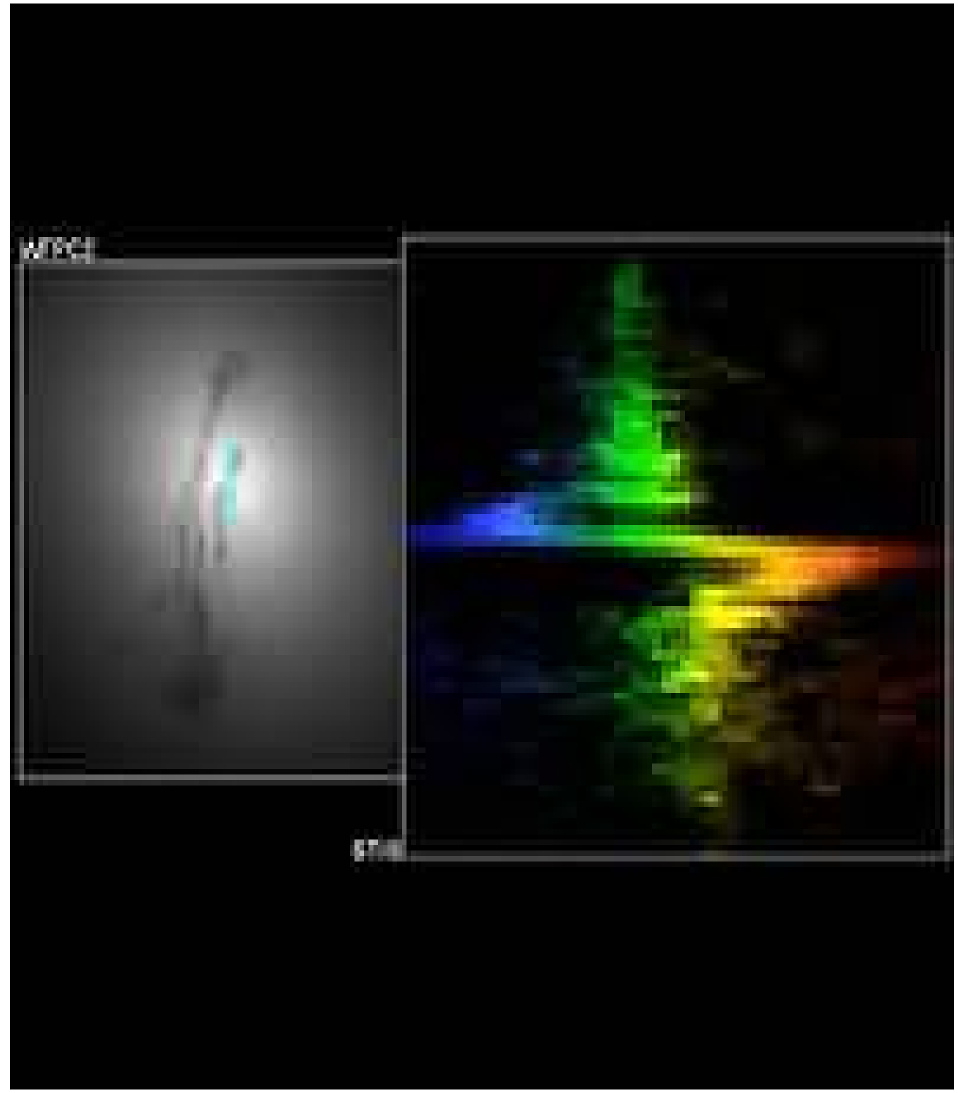
Hubble Space Telescope • Faint Object Spectrograph

SPACE TELESCOPE SCIENCE INSTITUTE

Harms et al 1999

How to Measure the Mass of a SuperMassive Black hole

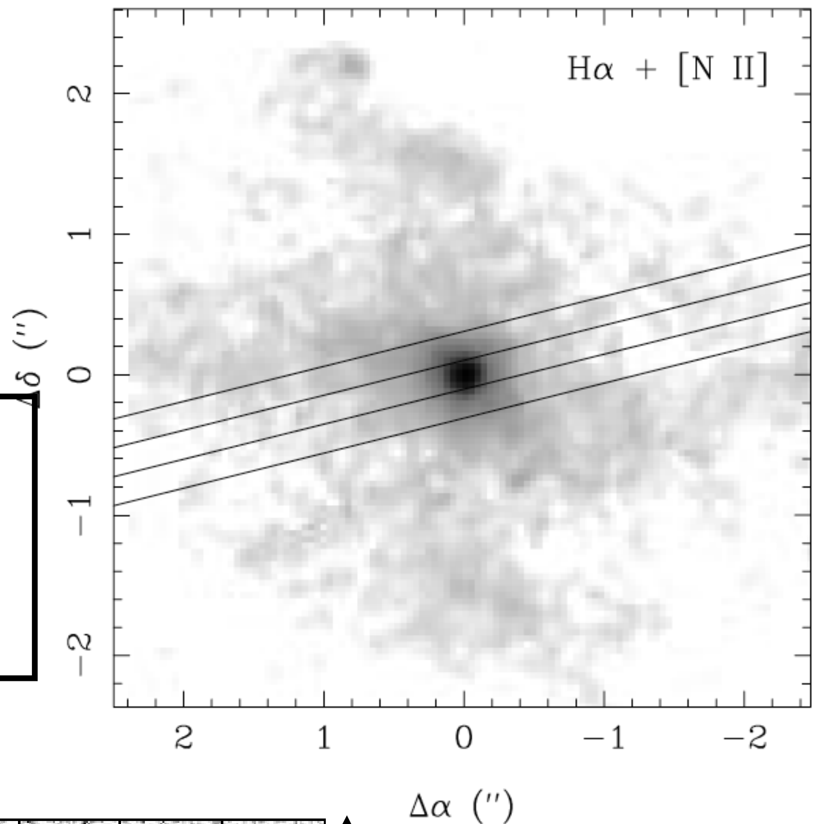
- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion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



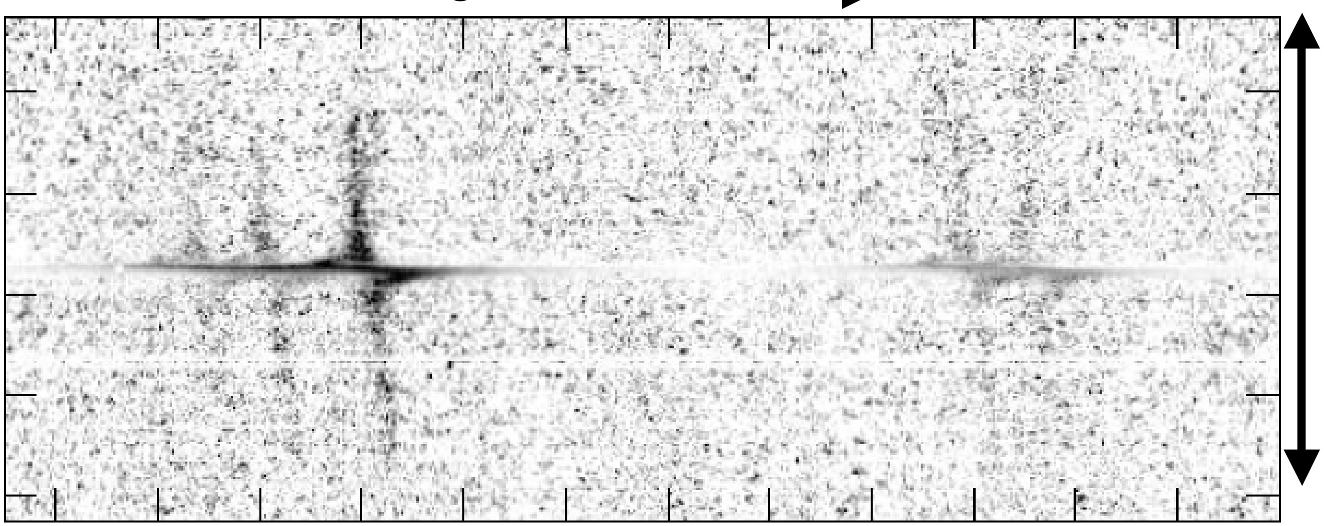
Measurement of Kinematics of Gas

- 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 $1.5 \times 10^9\ M_{sun}$

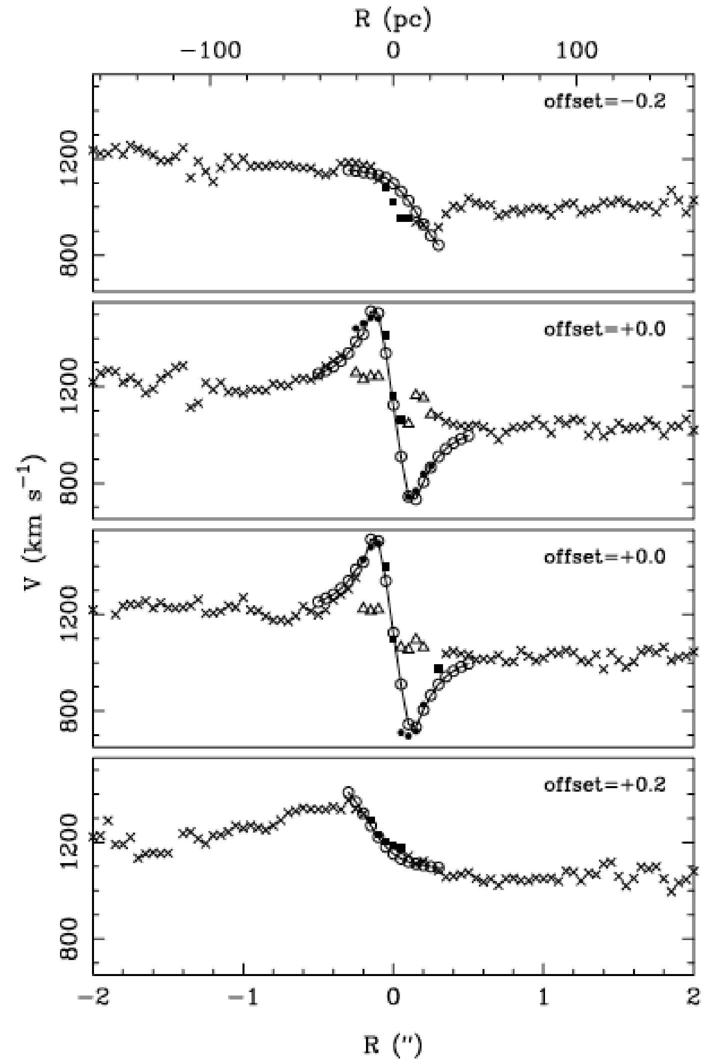


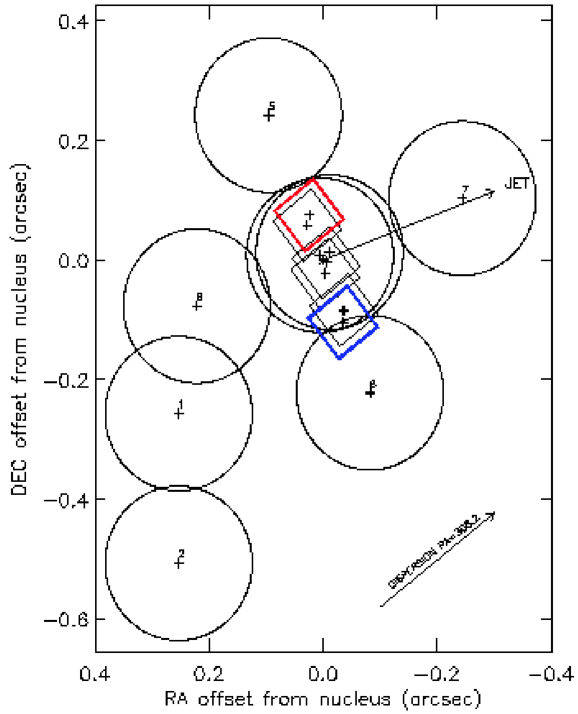
TABLE 1
KEPLERIAN DISK MODEL PARAMETERS

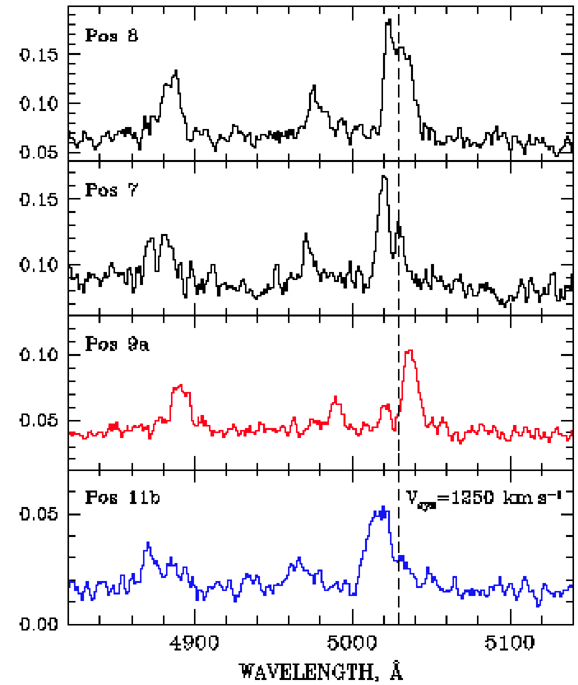
Parameter	Best Fit	Uncertainty Range
Black hole mass ($M_\odot$)	1.5×10^9	$(0.9–2.6) \times 10^9$
Disk inclination (deg)	80	75–85[a]
Disk P.A. (deg)	83	80–85
Gas systemic velocity (km s^{-1})	1125	1100–1150
Intensity law	$I(r) \propto r^{-1}$	...
$I(r)$ inner radius (pc)	1	0.3–3
$V(r)$ inner radius (pc)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

[a] Lower mass requires lower inclination.

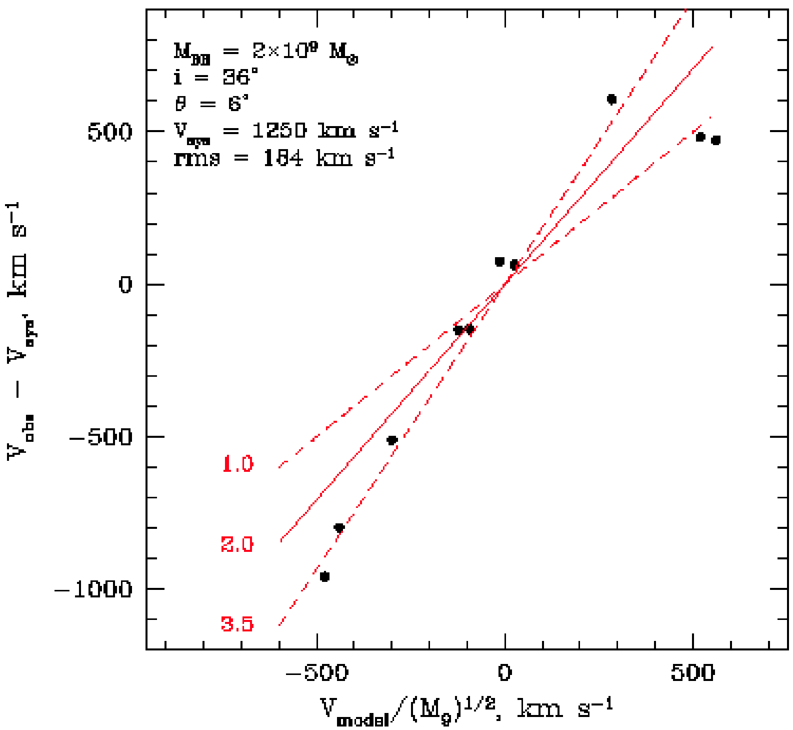
Velocity of gas vs distance from center of emission along 3 parallel lines

- M84- Fit of data to a keplerian disk- slope gives the mass

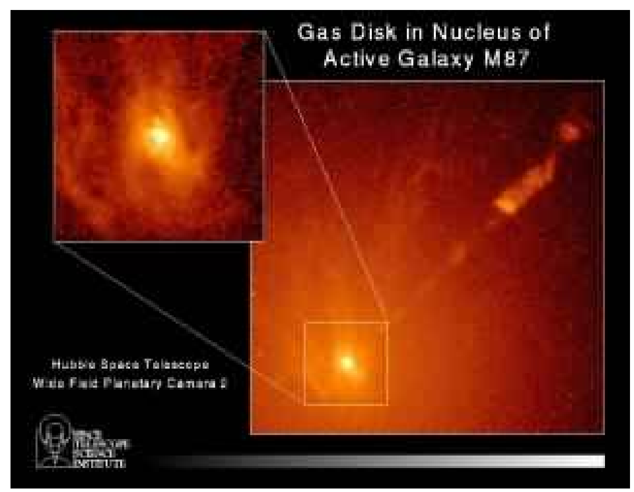




M_{BH}=2x10^{9}M_{sun}

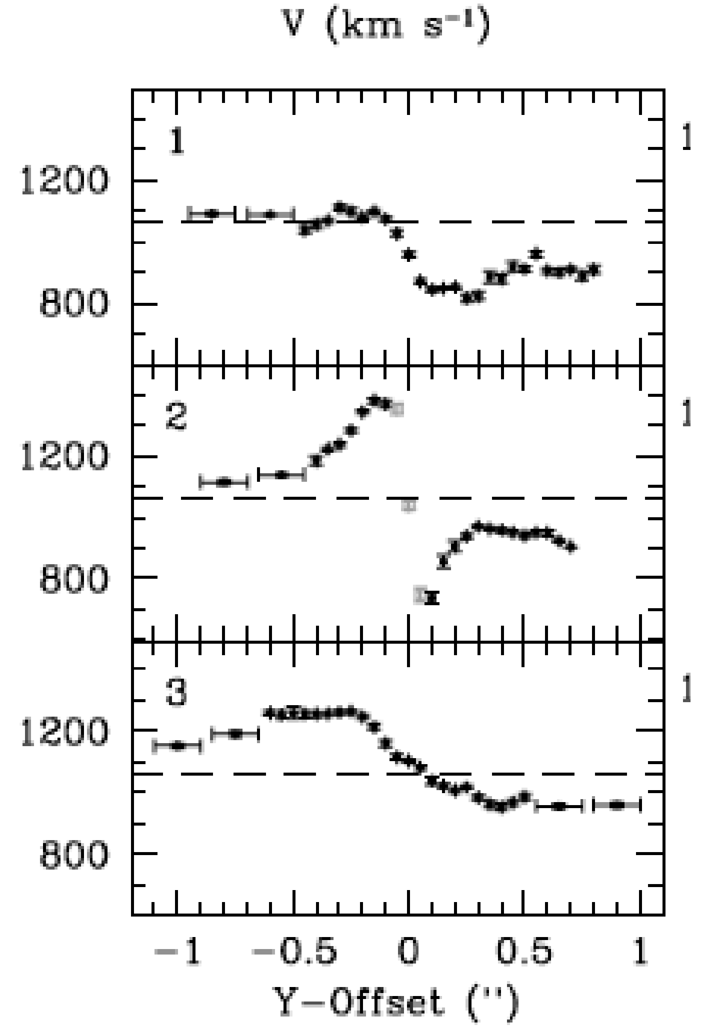


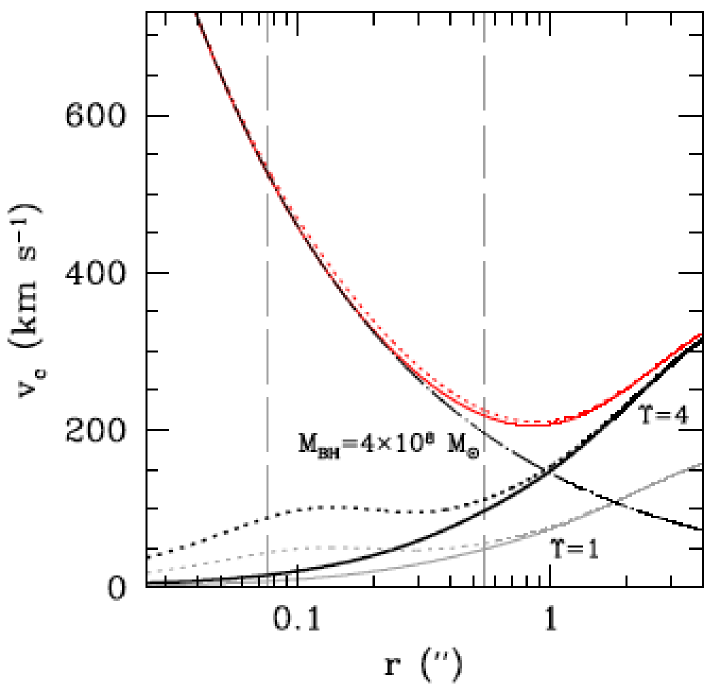
HST Observations of motions of gas around the Supermassive black hole in M87

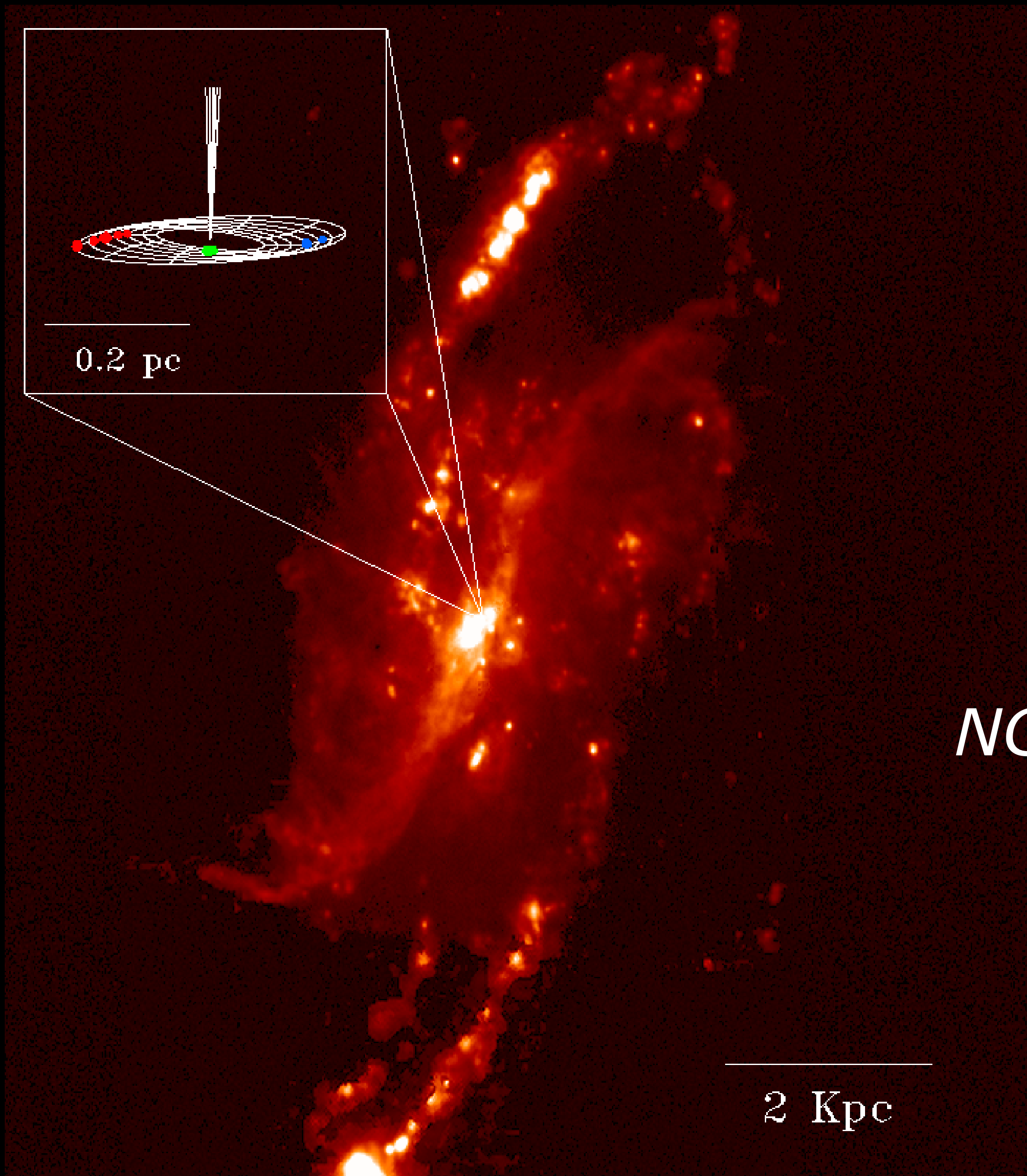


- For a few objects the mass of supermassive black holes can be measured by determining the velocity of the gas or stars near the center of the galaxy
- The best case is for the Milky Way.

M84 velocity vs position
Along 3 different position angles



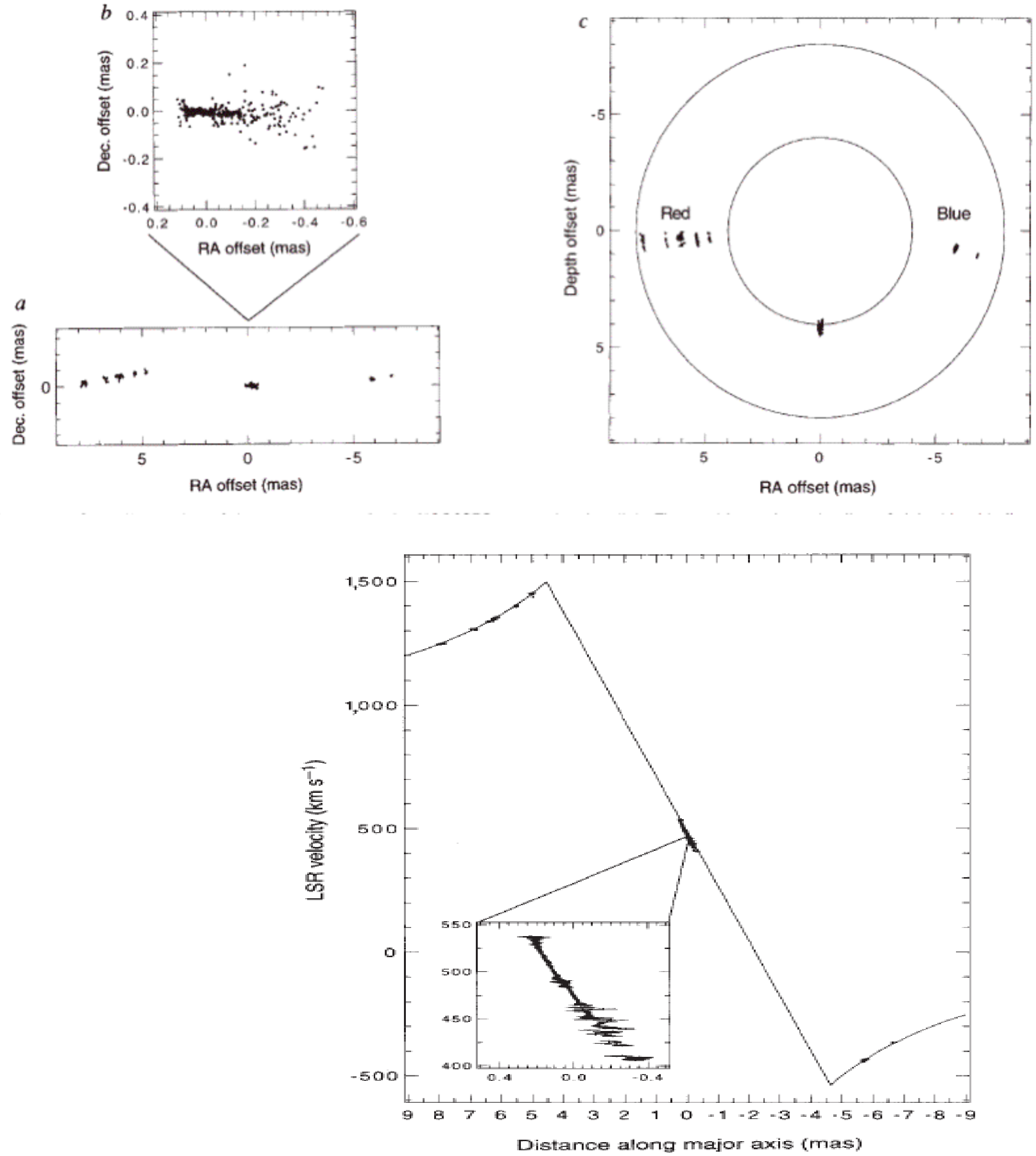




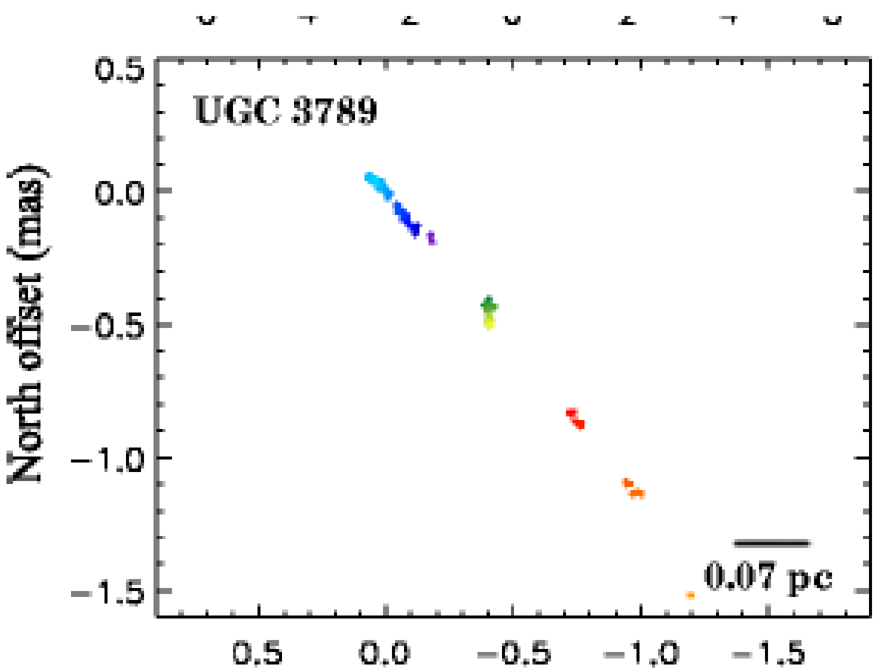
NGC4258

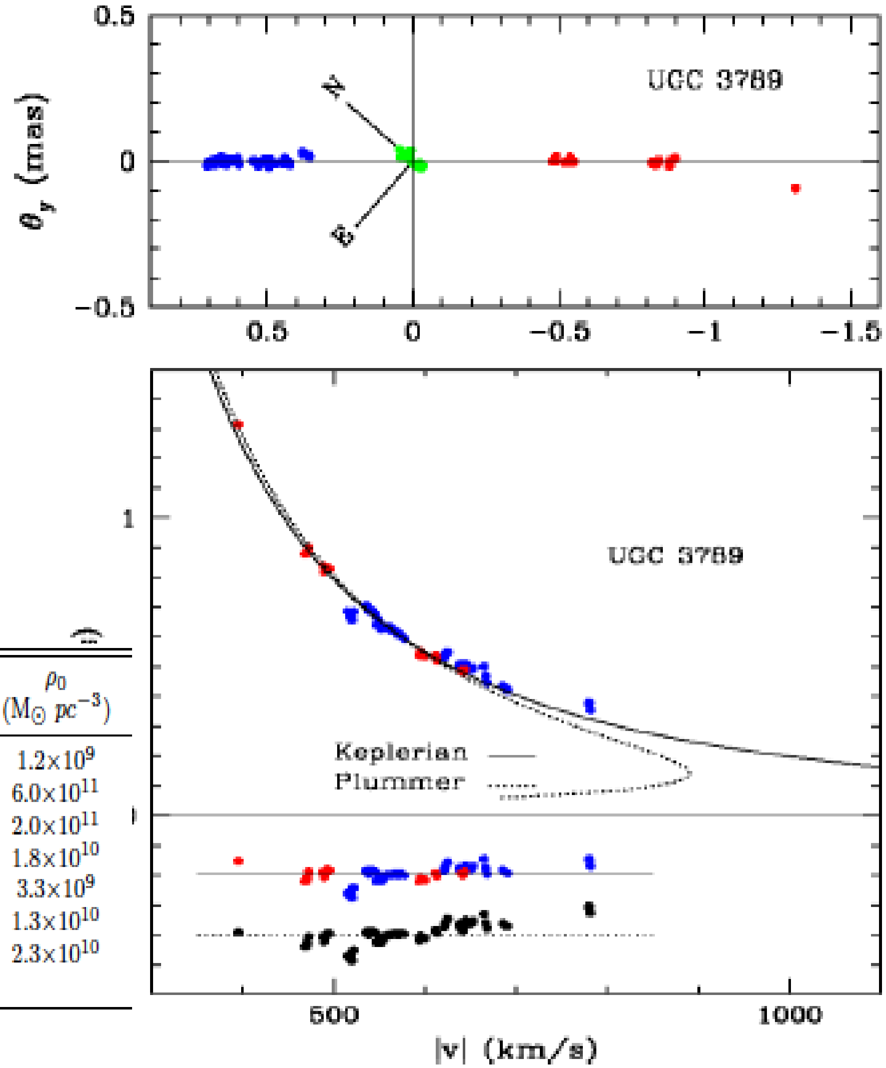
Another Excellent Case and the First for an AGN

- 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

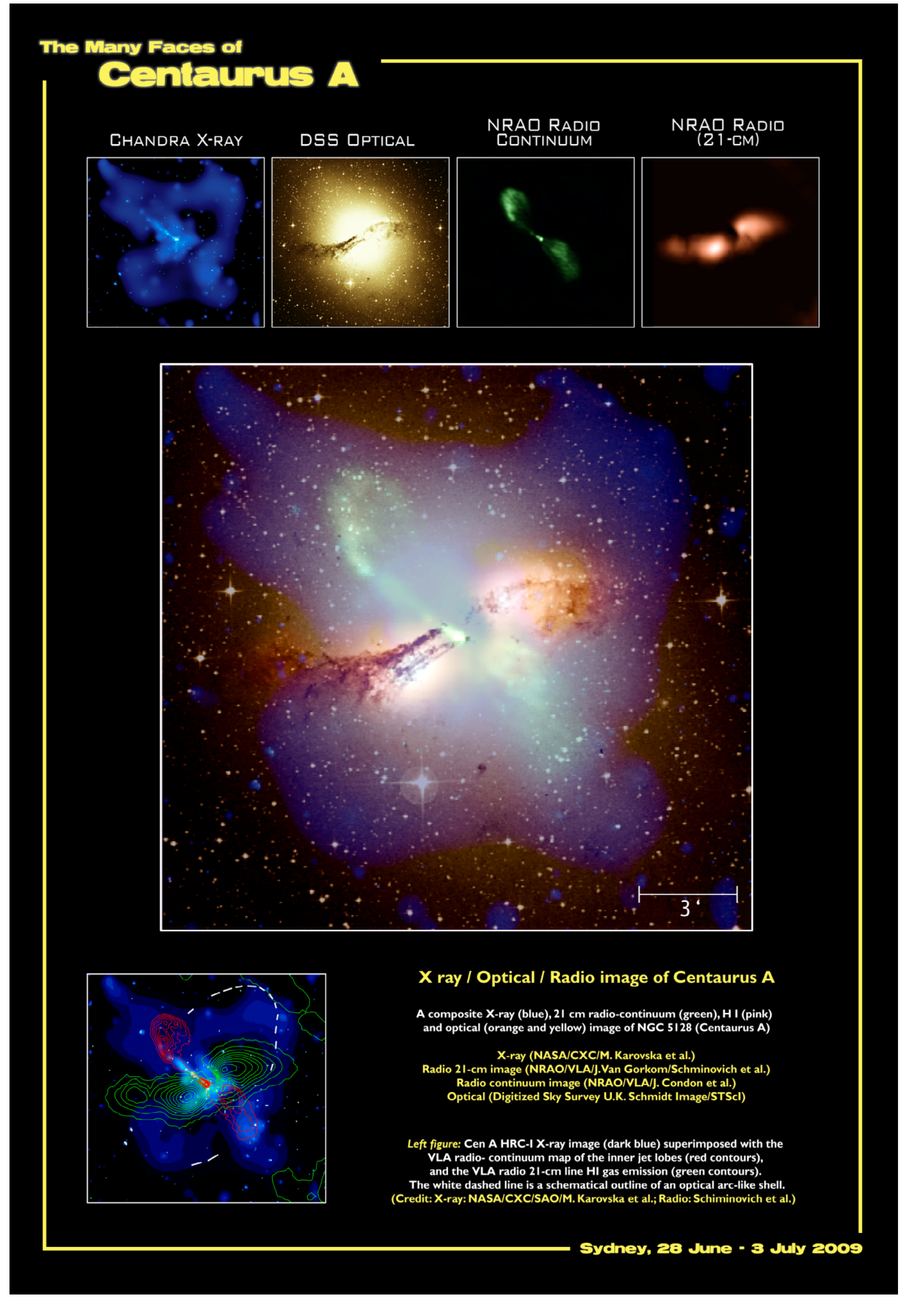




Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36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

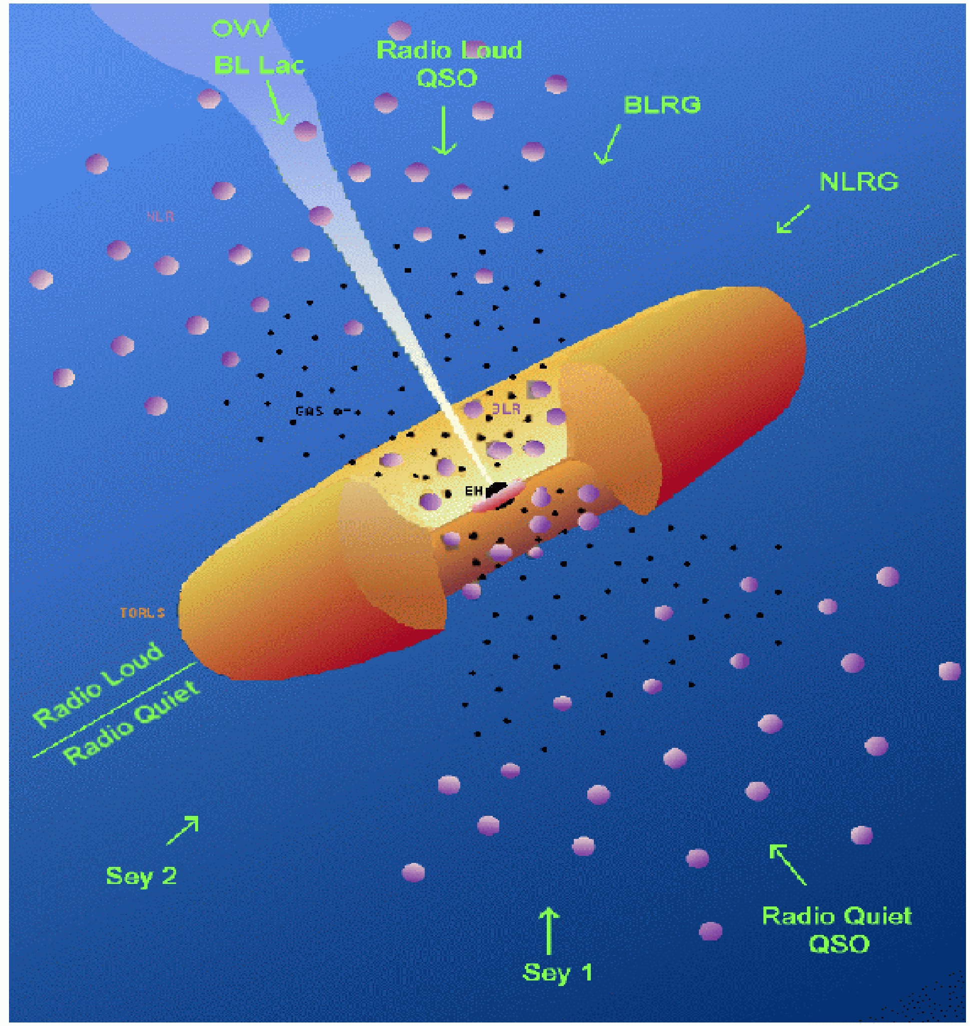
Centaurus-A The Nearest AGN



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

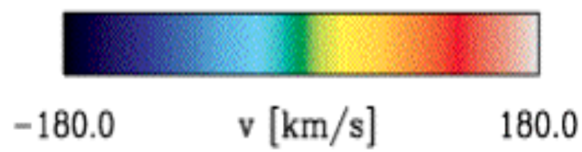


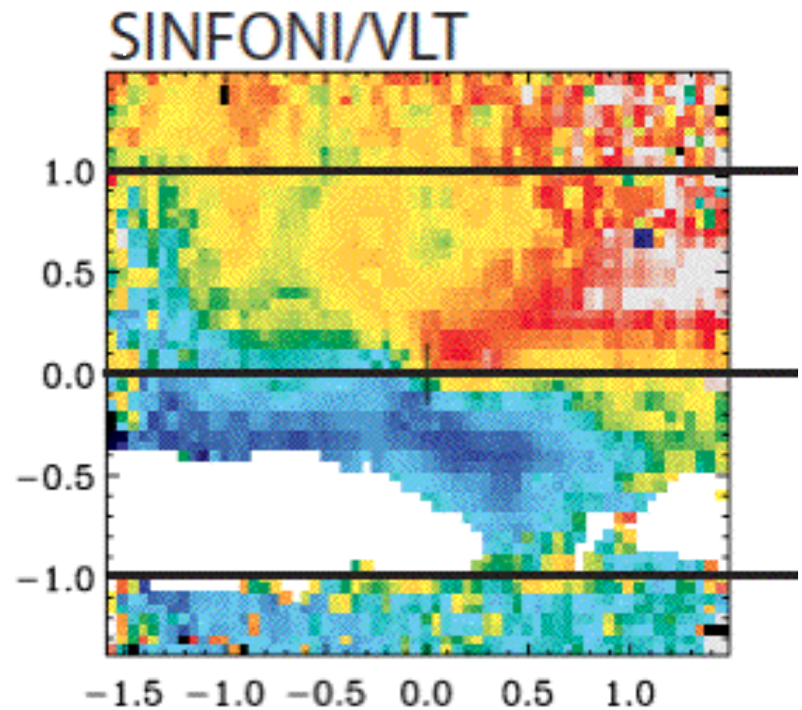
Urry and Padovani 195

Centaurus -A

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

Gas Velocities





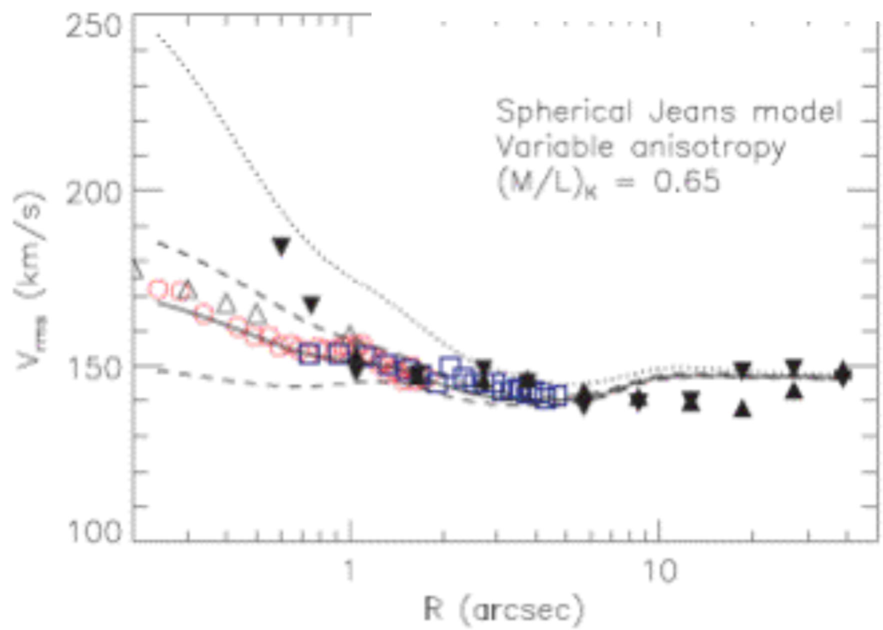
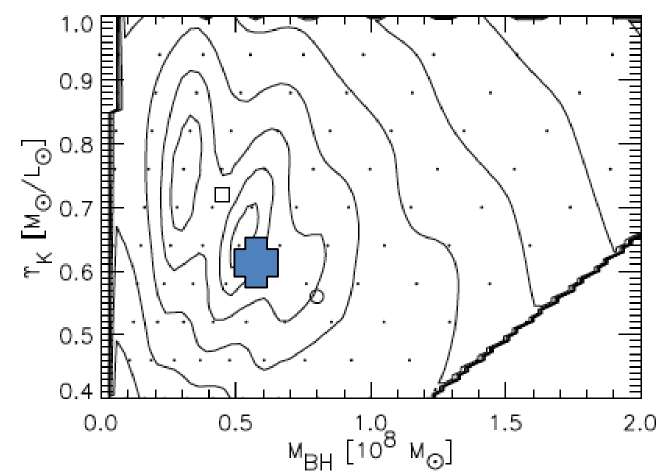


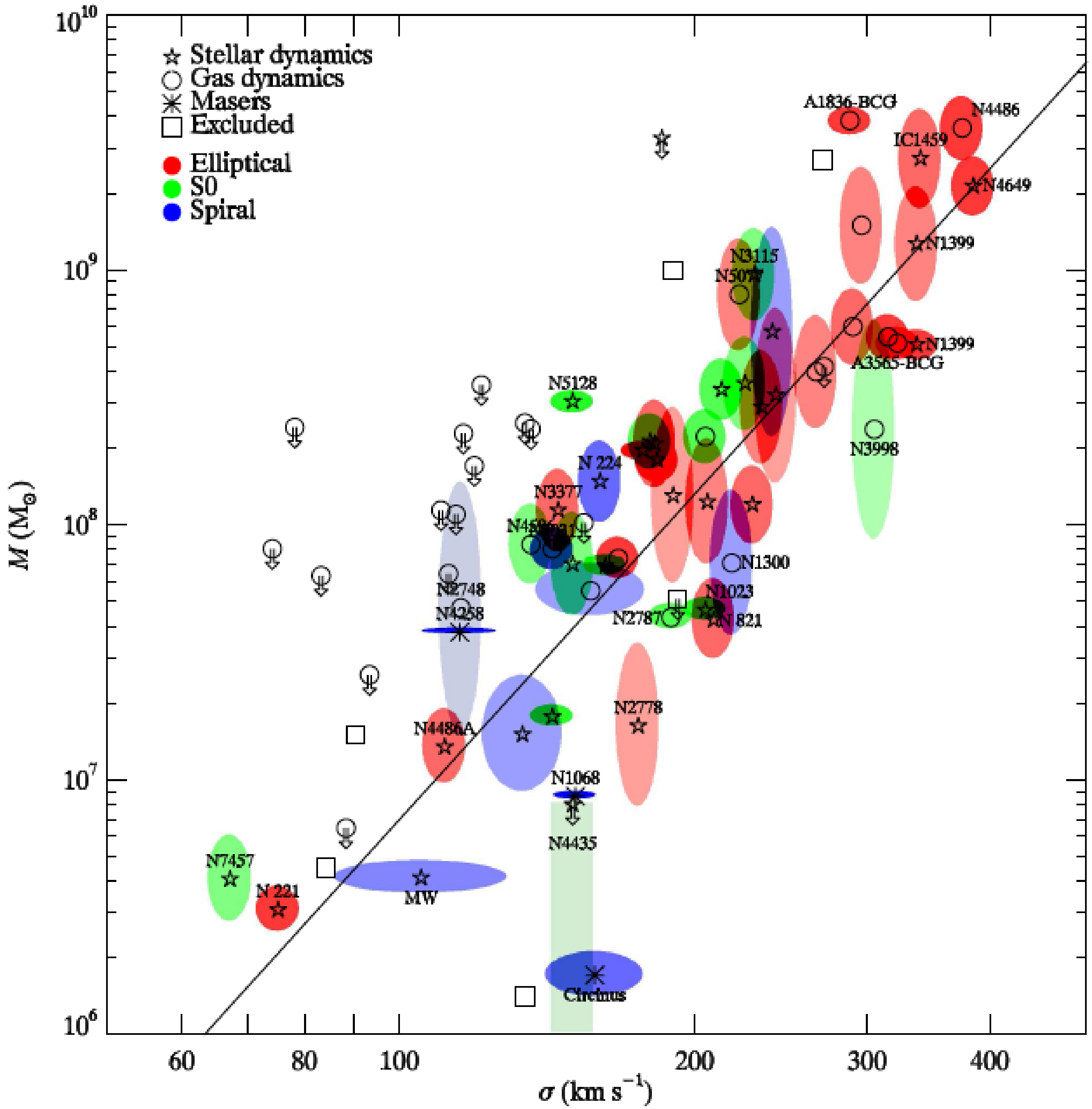
Figure 4: Spherical anisotropic Jeans model

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



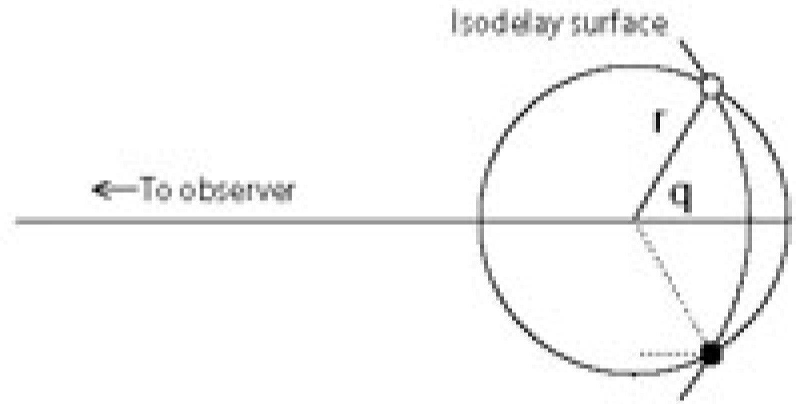
Constraints from stars compared to those from Gas Velocities

- 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

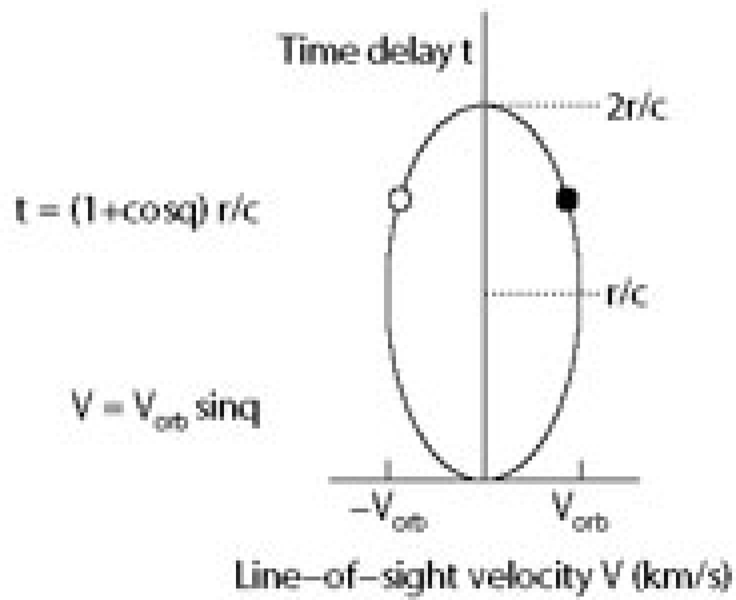


What About AGN in General??

- 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



- New 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

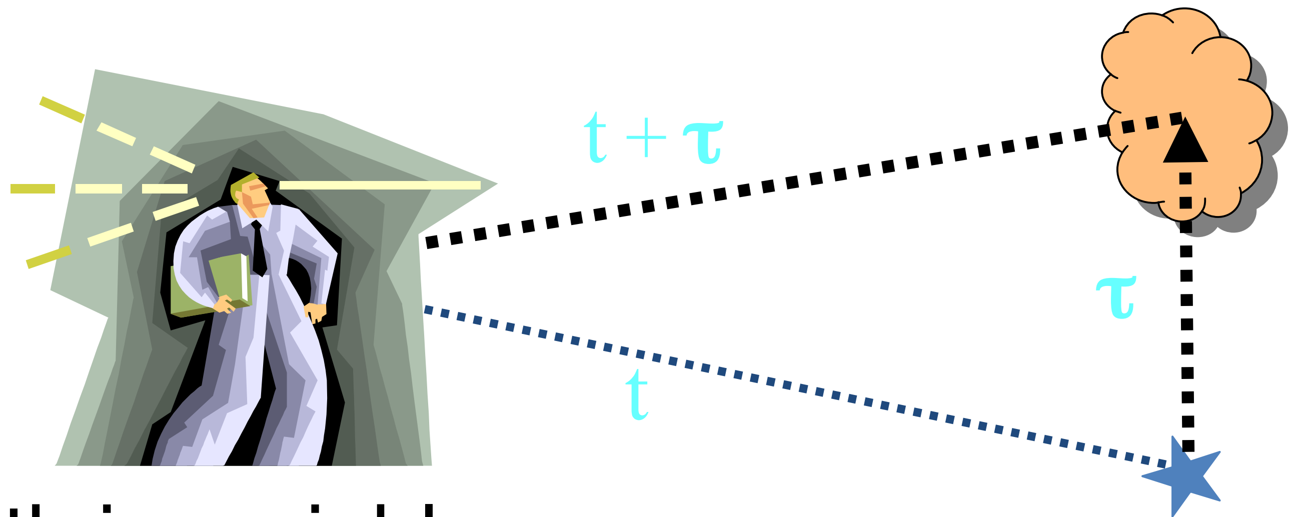


Virial Mass Estimates

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

Reverberation Mapping:

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



- $\mathbf{v_{BLR}}$

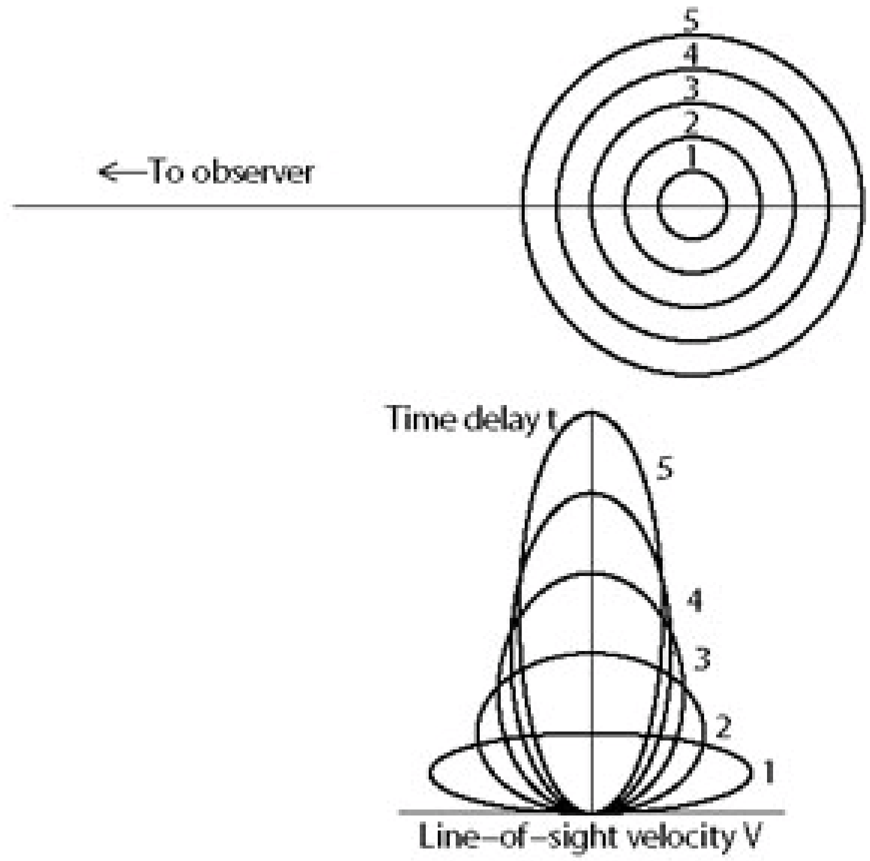
  Line width in variable spectrum

The Geometry

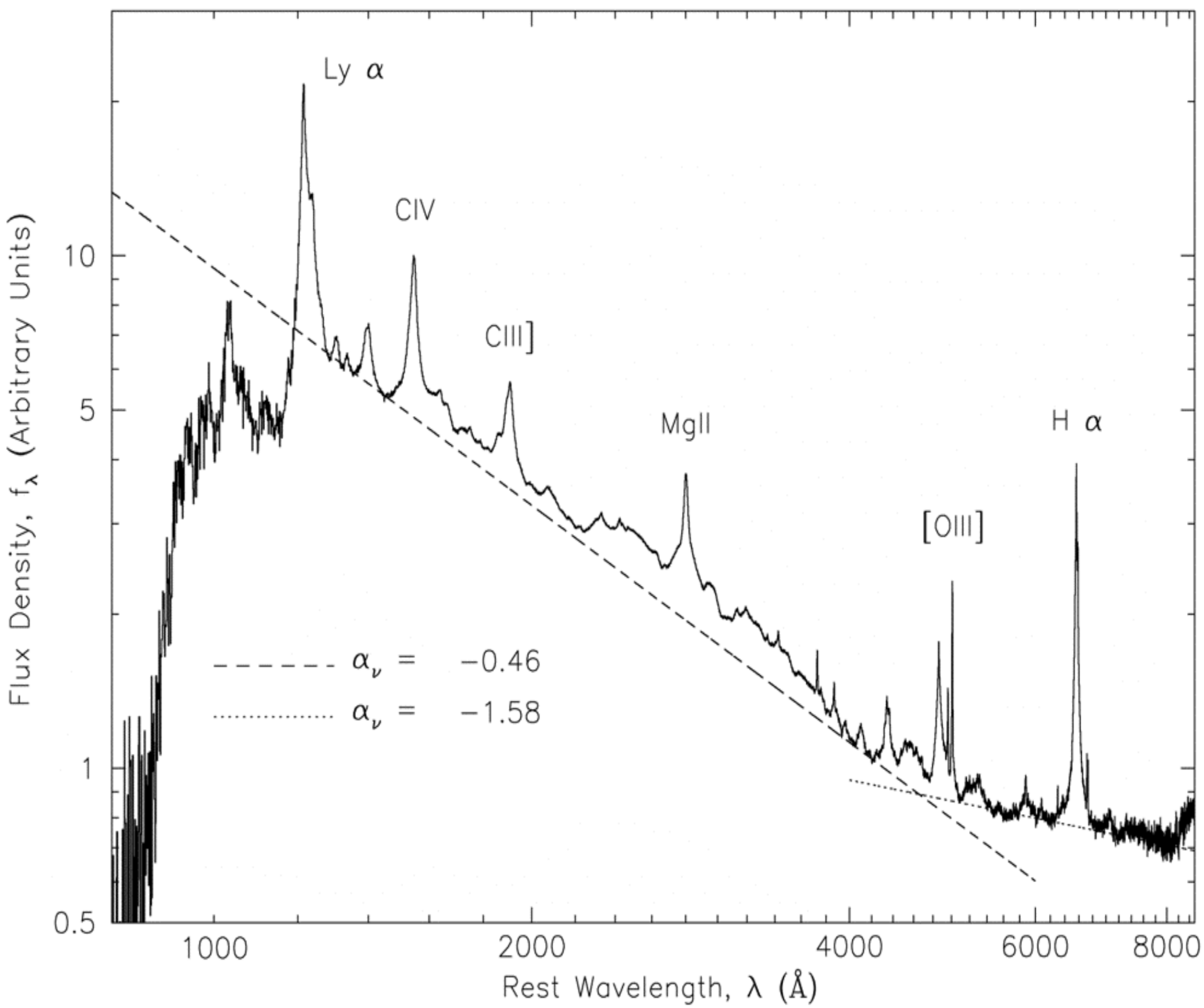
- Points (r, θ) in the source map into line-of-sight velocity/time-delay(τ) space (V, τ) according to $V = -V_{orb} \sin(\theta)$, where V_{orb} is the orbital speed, and $\tau = (1 + \cos(\theta))r / c$.
- The idea is that the broad line clouds exist in 'quasi-Keplerian' orbits (do not have to be circular) 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

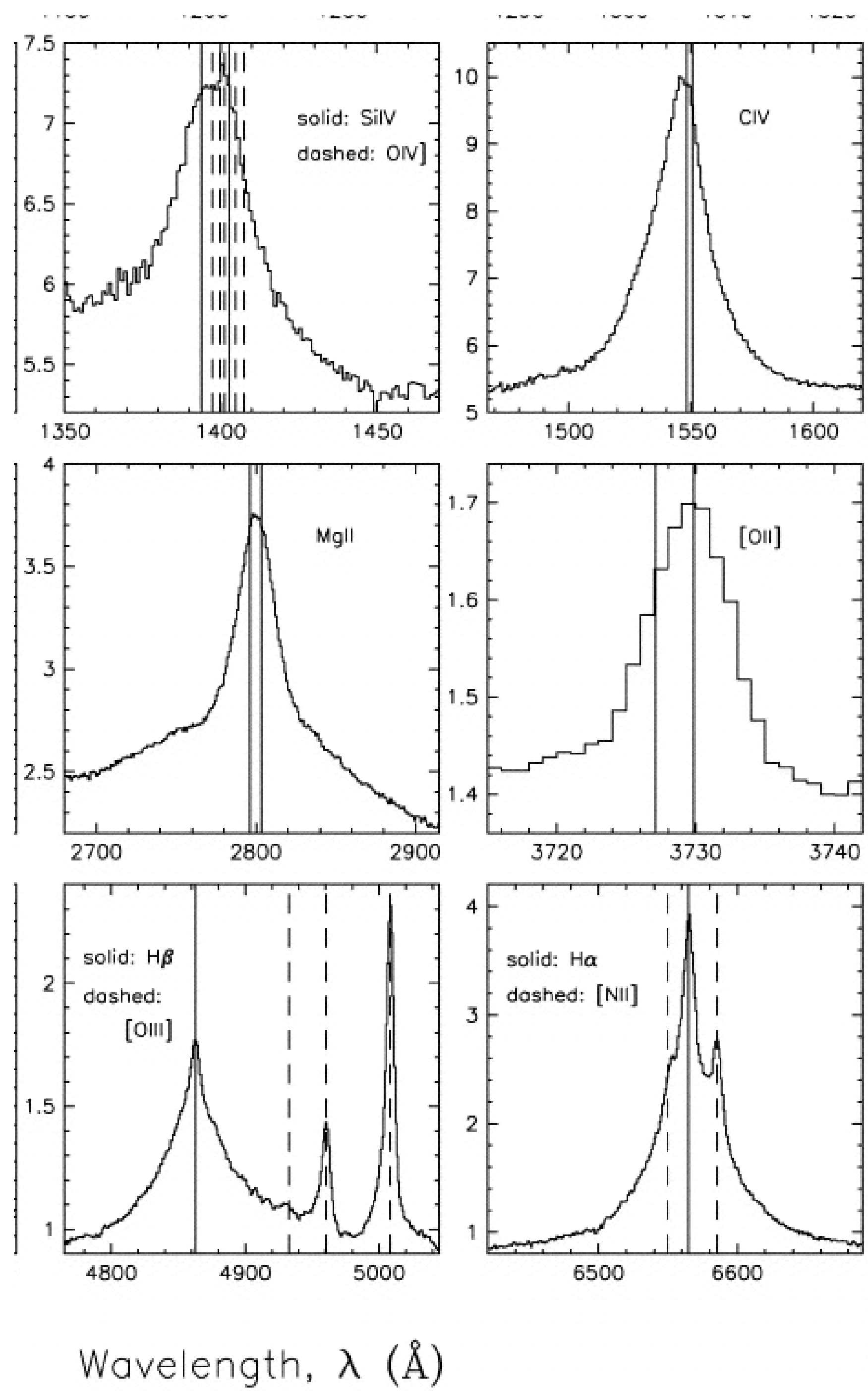


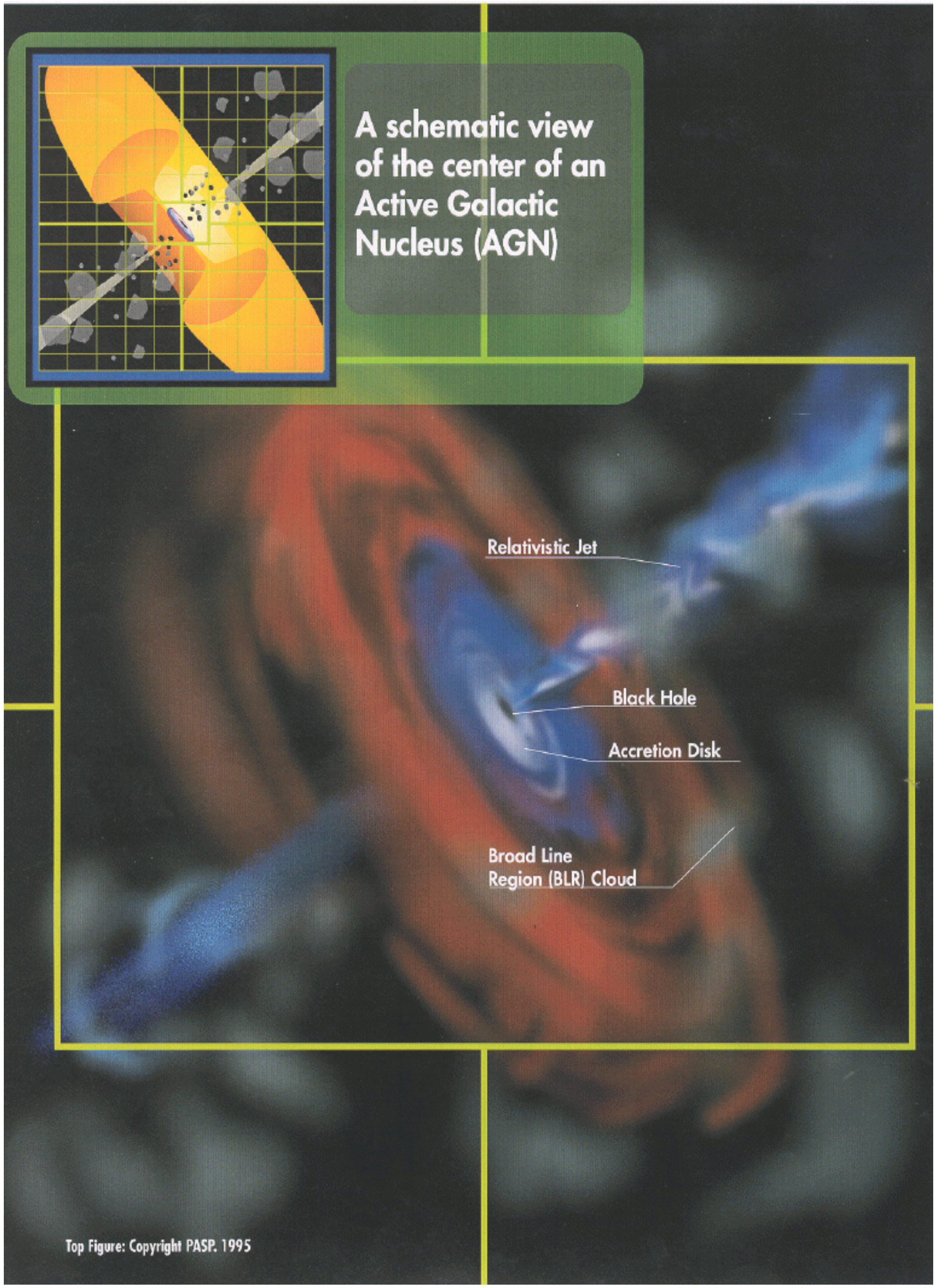
- AGN (type I) optical and UV spectra consist of a 'feature less continuum' with strong 'broad' lines superimposed
- Typical velocity widths (s, the Gaussian dispersion) are ~2000-5000km/sec
- The broad range of ionization is due to the 'photoionzation' of the gas- the gas is not in collisional equilibrium
- At short wavelengths the continuum is thought to be due to the accretion disk



Van den Berk et al 2001

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

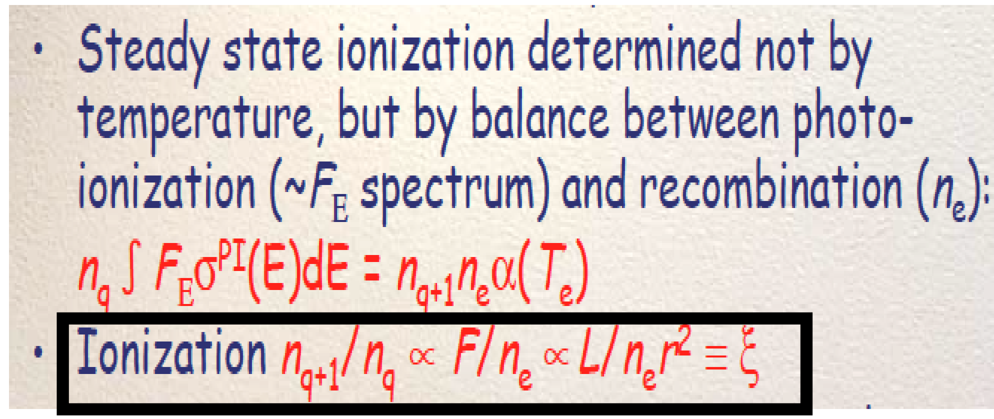




Source	Distance from central source
X-Ray Fe K^{α}	3-10 R_S
Broad-Line Region	600 R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

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 ionsxthe 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 ($\sim F_E$ spectrum) and recombination (n_e):

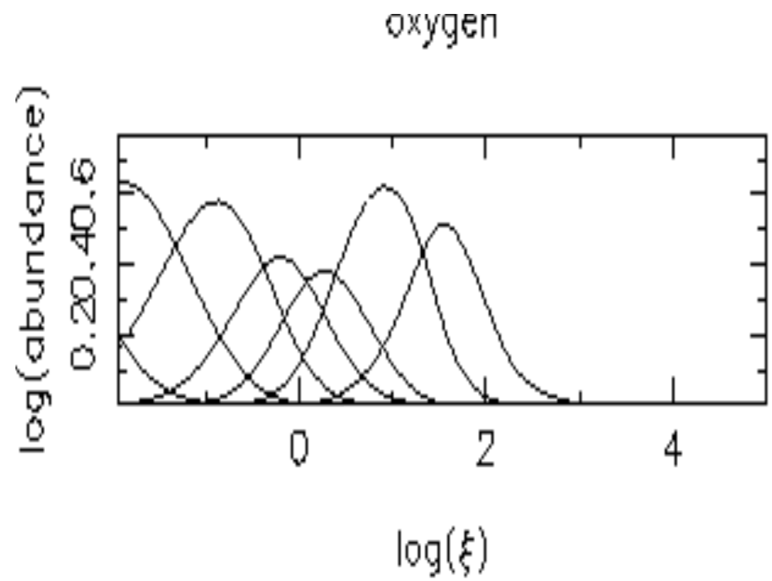
$$n_q \int F_E \sigma^{PI}(E)dE = n_{q+1} n_e \alpha(T_e)$$

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

ξ is the ionization parameter (also sometimes called U)

In Other Words

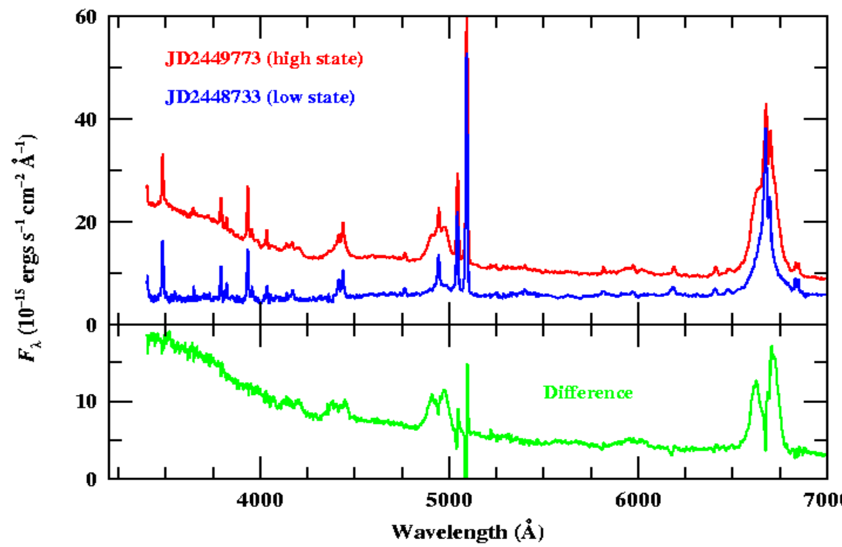
- For each ion:
  - Ionization = recombination
  - ~photon flux ~electron density
- For the gas as a whole
  - Heating = cooling
  - ~photon flux ~electron density



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

- => 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)



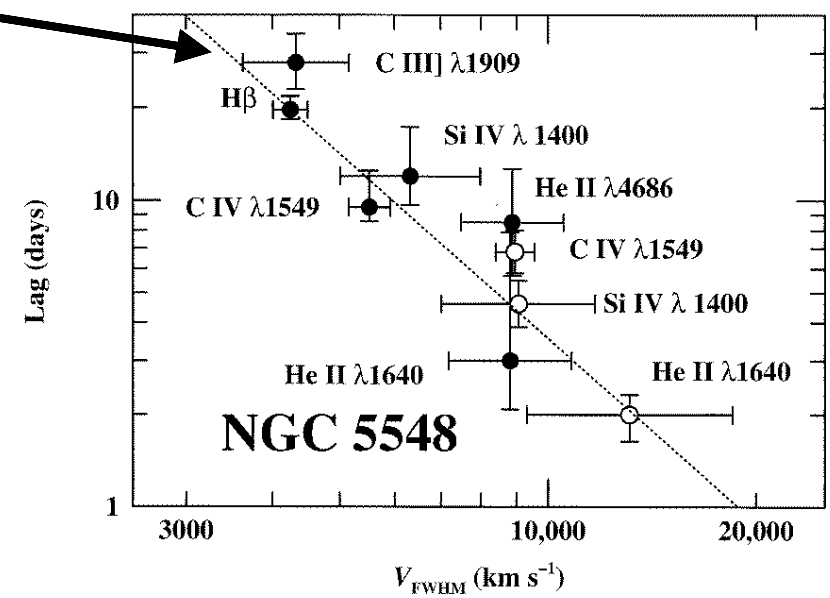
Peterson (1999)

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 dominate the line shapes ($v \sim r^{-1/2}$)

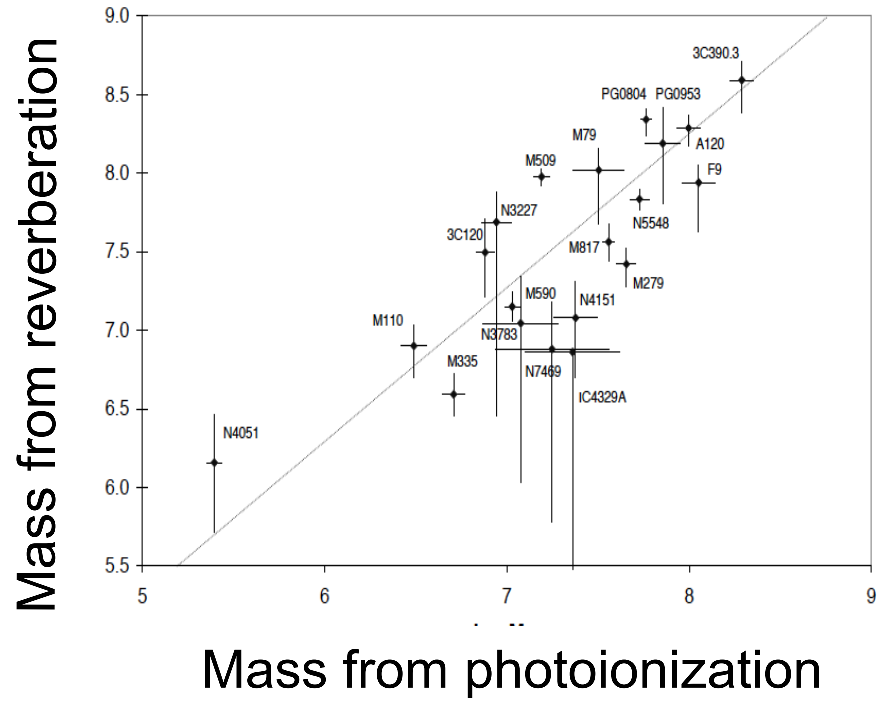
- Such data exist for ~40 sources
- At present M_{BH} can be estimated to within a factor of a few: $M \propto FWHM^2 L^{0.5}$



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

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
  - dyanmical 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 !



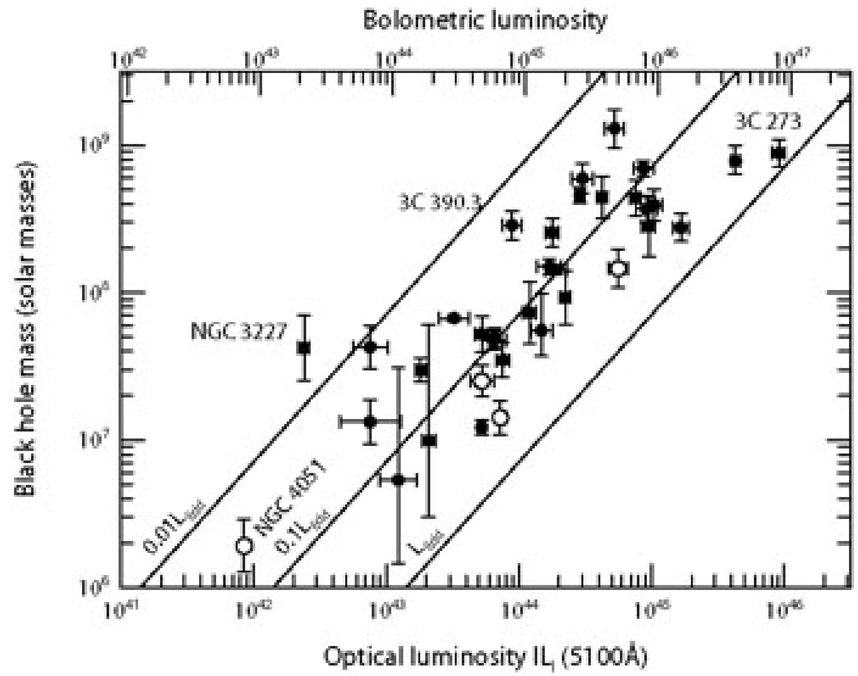
$M_{BH} \sim K\sigma^2 L^{1/2}$

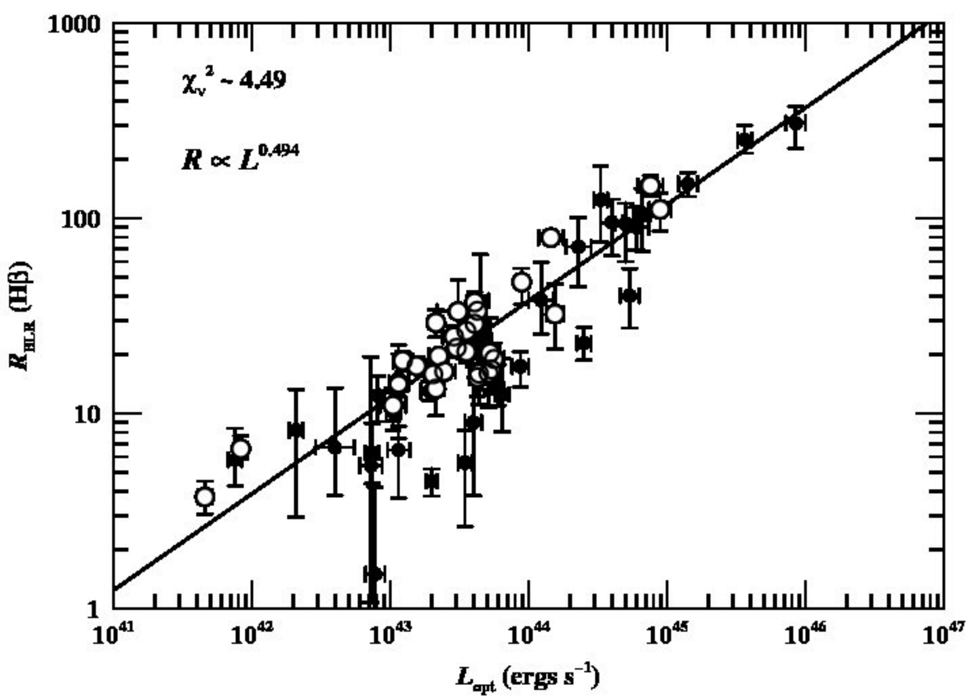
Where K is a constant (different for differnet lines which is determined by observations

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 $^{1/2}$



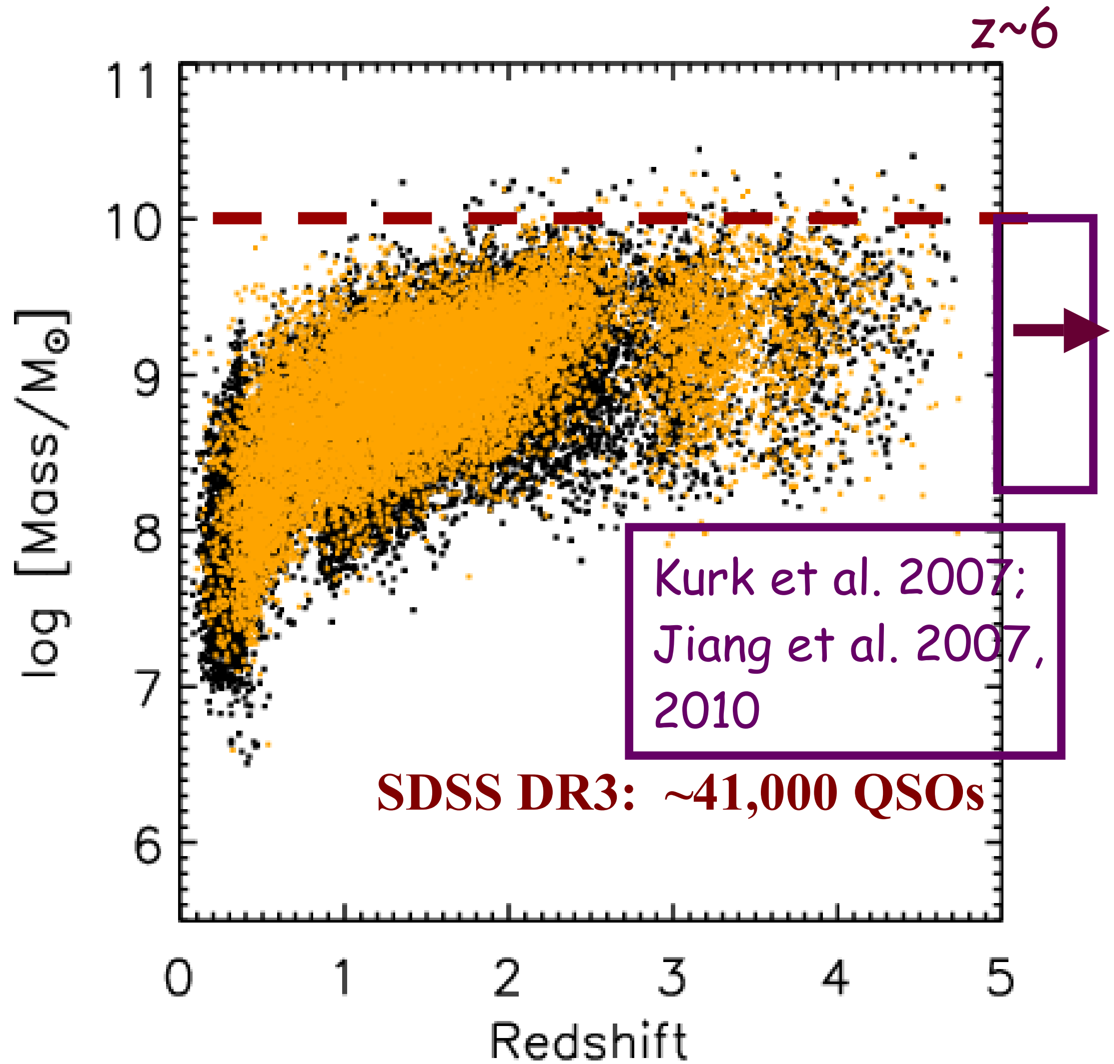


Masses of Distant Quasars- M. Vestergaard

- Using this techniqu a very large sampl objects from the Sl Digital Sky Survey (SDSS)

- Ceilings at $M_{BH} \approx 10^{10} M_{\odot}$
- $L_{BOL} < 10^{48}$ ergs/s

- $M_{BH} \approx 10^{9}\, M_{\odot}$

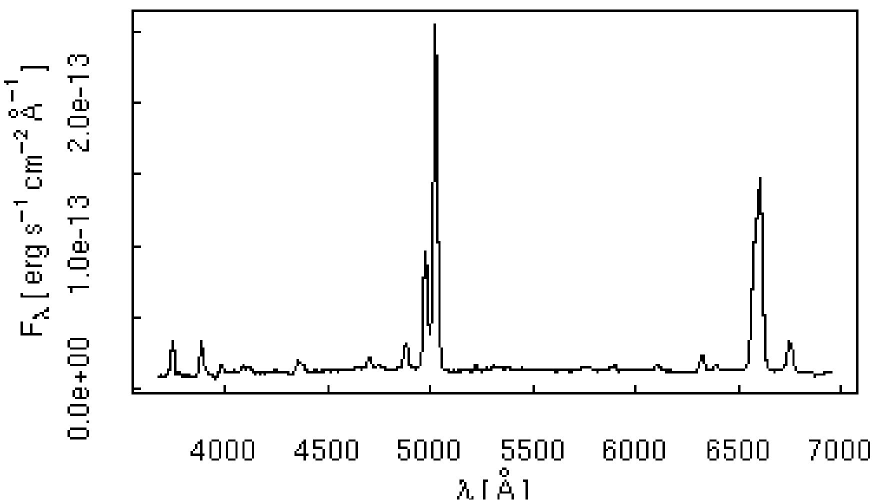


(DR3 Qcat: Schneider et al. 2005)

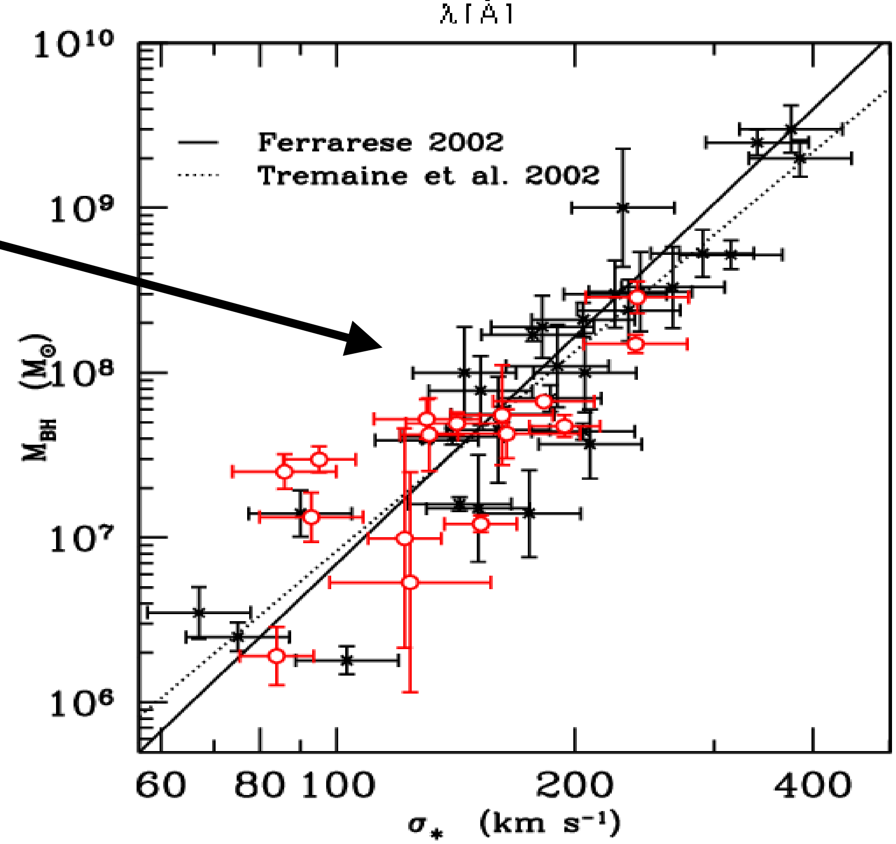
(MV et al. in prep)

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 -
- We thus 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



Black hole mass



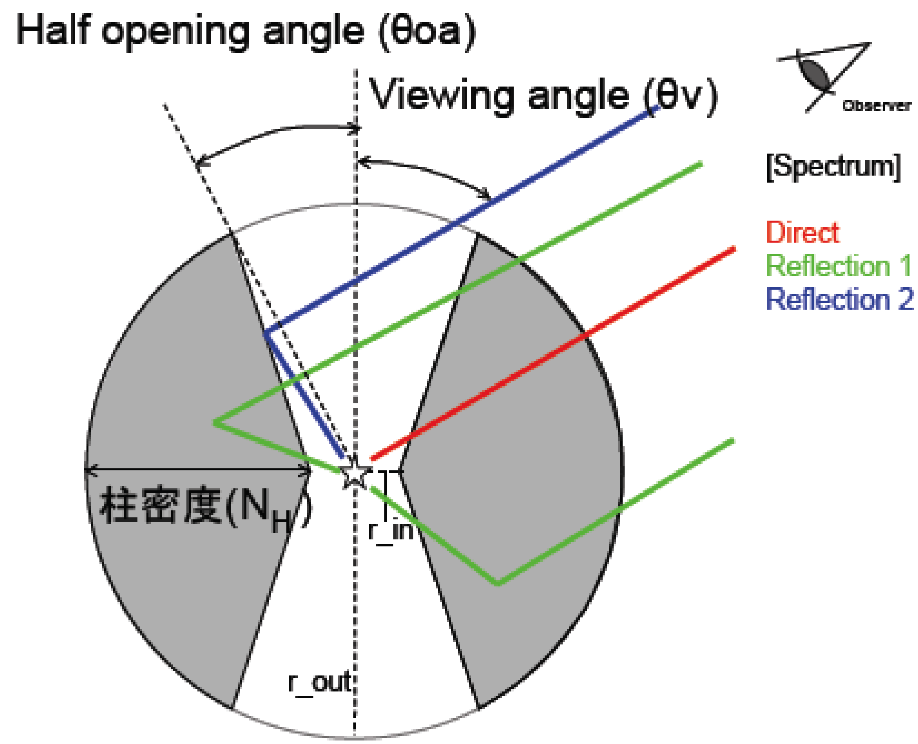
Velocity dispersion of stars in the bulge

Radiating black holes

- Finish how to get the masses of black holes
- The AGN Zoo
- Black Hole systems
  - The spectrum of accreting black holes
  - X-ray “reflection” from accretion disks
  - Strong gravity effects in the X-ray reflection spectrum

AGN Zoo

- In a simple unification scenario broad-lined (Type 1) AGN are viewed face-on
- narrow-lined (Type 2) AGN
  - the broad emission line region (BELR) the soft X-rays and much of the optical/UV emission from the AD are hidden by the dust
- However there are other complications like jets and a range in the geometry



Radio Loudness	Optical Emission Line Properties		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	**Type 0** (Unusual)
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	
Radio-loud:	NLRG { FR I / FR II }	BLRG SSRQ FSRQ	Blazars { BL Lacs / (FSRQ) }
	decreasing angle to line of sight ->		

Table 1: AGN Taxonomy: A Simplified Scheme.

Radio Loudness

Optical Properties

			No Lines
Radio quiet (weak or no jet)	Type II (narrow forbidden lines) Seyfert 2	Type I (broad permitted lines) Seyfert 1 QSO	
Radio Loud (strong jet)	FR I NLRG FR II	BLRG	Bl Lac Blazars FSRQ
X-ray Properties	Highly Absorbed- strong narrow Fe K line, strong low E emission lines	Not absorbed- or ionized absorber often broad Fe K line- low energy spectrum with absorption lines	Featureless continuum- highly variable γ-ray sources

table 27-2 Properties of Active Galactic Nuclei (AGNs)

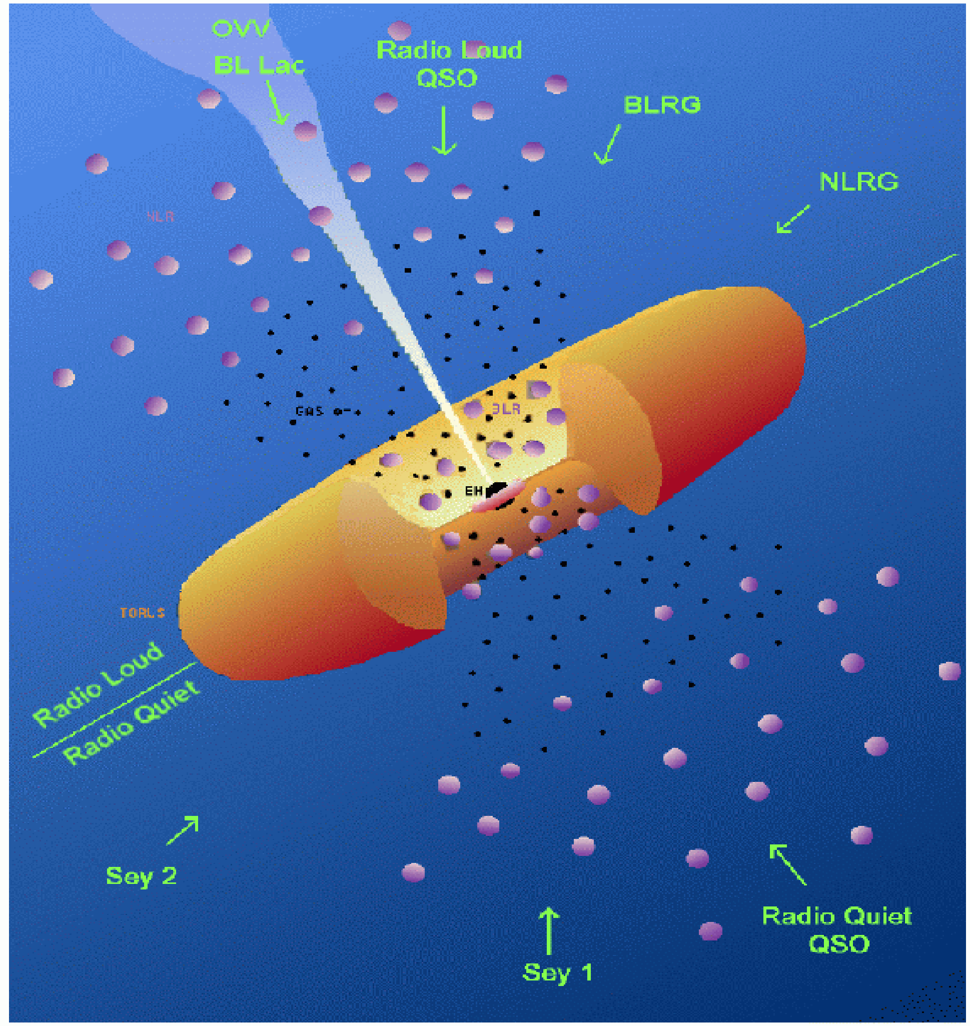
Object	Found in which type of galaxy	Strength of radio emission	Type of emission lines in spectrum	Luminosity (watts)	Luminosity (Milky Way Galaxy = 1)
Blazar	Elliptical	Strong	Weak (compared to synchrotron emission)	10^{38} to 10^{42}	10 to 10^{5}
Radio-loud quasar	Elliptical	Strong	Broad	10^{38} to 10^{42}	10 to 10^{5}
Radio galaxy	Elliptical	Strong	Narrow	10^{36} to 10^{38}	0.1 to 10
Radio-quiet quasar	Spiral or elliptical	Weak	Broad	10^{38} to 10^{42}	10 to 10^{5}
Seyfert 1	Spiral	Weak	Broad	10^{36} to 10^{38}	0.1 to 10
Seyfert 2	Spiral	Weak	Narrow	10^{36} to 10^{38}	0.1 to 10

- Some of different classes of AGN are truly different 'beasts'- (e.g. radio loud vs radio quiet) but
- Much of the apparent differences are due to geometry/inclination effects- this is called the Unified Model for AGN (e.g. type I vs Type I radio quiet objects, blazars - radio loud objects observed down the jet)
- The ingredients are: the black hole, accretion disk, the jet, some orbiting dense clouds of gas close in (the broad line region), plus a dusty torus that surrounds the inner disk, some less dense clouds of gas further out (the narrow line region) (adapted from T. Treu)

AGN- Alias Active Galactic Nuclei

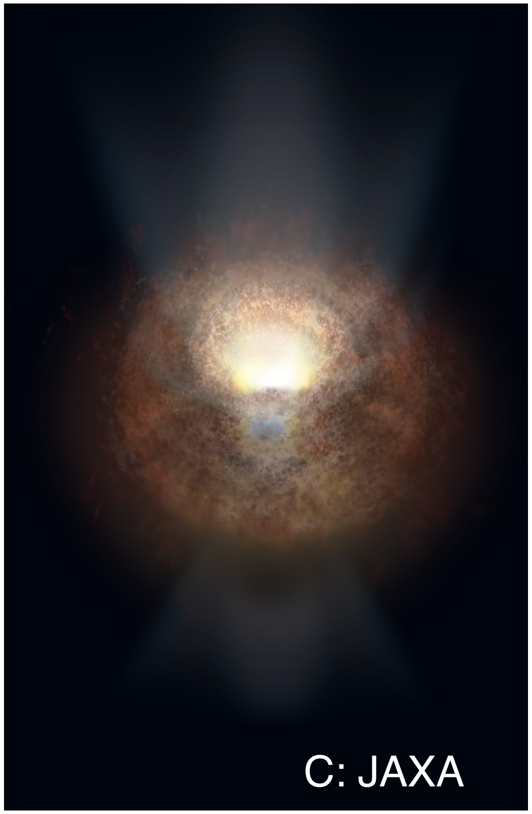
- AGN are 'radiating' supermassive black holes-
  - They go by a large number of names (Seyert I, Seyfert II, radio galaxies, quasars, Blazars etc etc)
  - The names convey the observational aspects of the objects in the first wavelength band in which they were studied and thus do carry some information

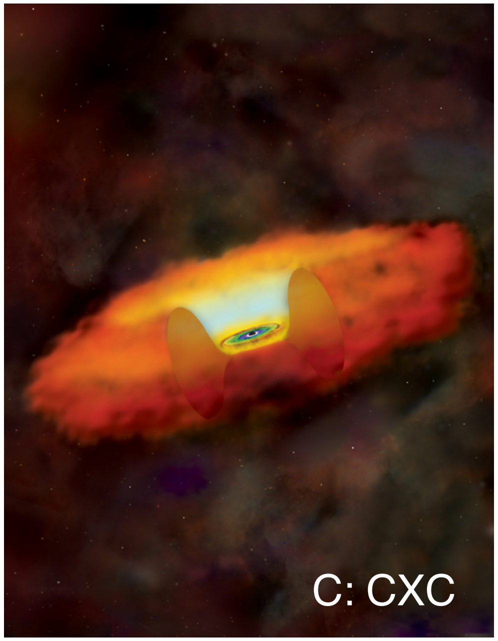
- See http://nedwww.ipac.caltech.edu/level5/Cambridge/Cambridge_contents.html for an overview

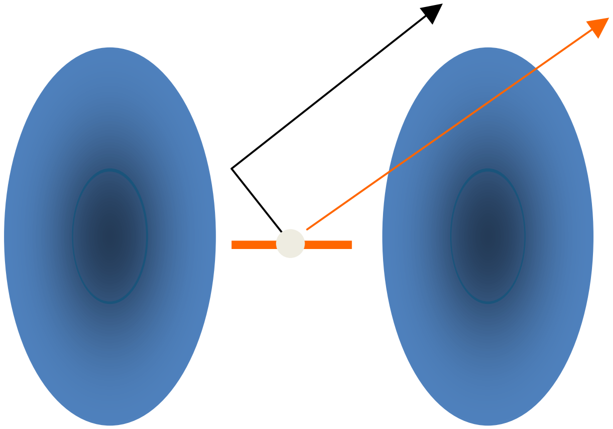


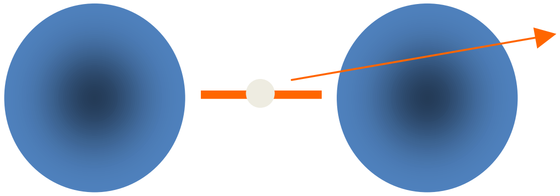
Urry and Padovani 195

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)