Please fill in your course evaluation!-

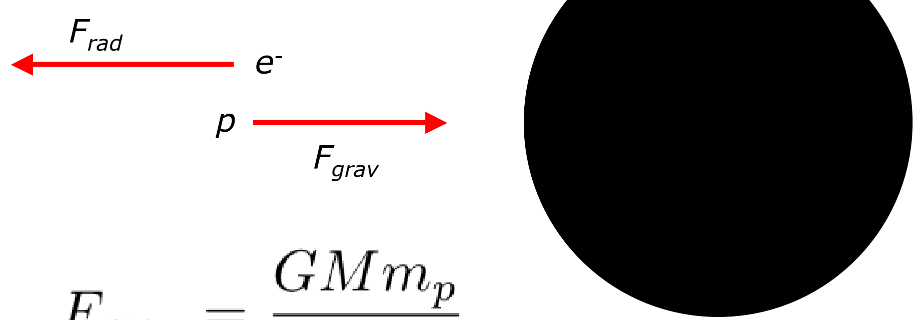
- www.CourseEvalUM.umd.edu
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc?-or dull,boring, stodgy, unprepared?
- Your responses are strictly anonymous. I only see the statistics.
- Helps me and future students!

- As of 12-12-2013 7/12 have filled it out

How luminous can an accreting black hole be?-Eddington limit

$$F_{\rm rad} = \frac{L\sigma_T}{4\pi c r^2}$$

radiation force due to Thompson scattering



$$F_{\rm grav} = \frac{GMm_p}{r^2}$$

gravitational force due to Newtonian gravity from a 'point source' at large r

Eddington Limit

- The accreting matter is pushed away if

$$F_{\rm rad} > F_{\rm grav}$$

- This is the Eddington limit (L_{Edd}). Acts effective upper limit to the luminosity of accretion powered object. Numerically:

$$L > \frac{4\pi G m_p c}{\sigma_T} M$$

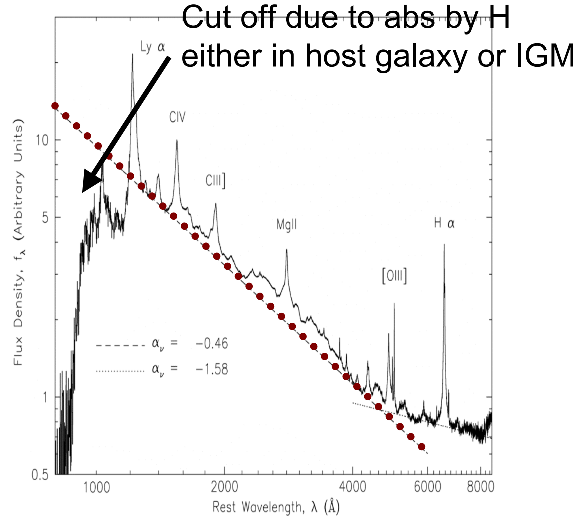
L_{Edd}~$1.3 \times 10^{46} M_8$ erg/s

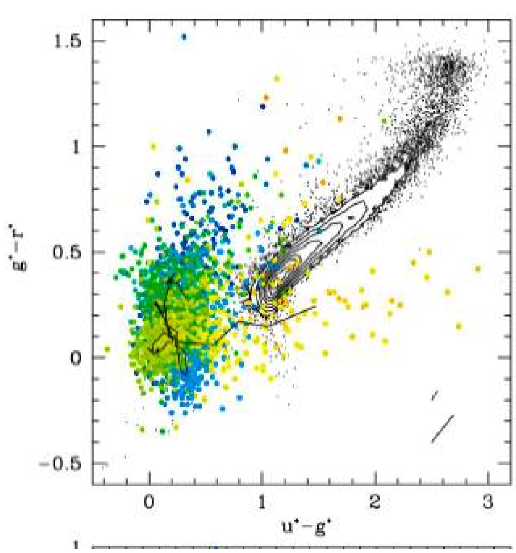
$$L_{\rm Edd} \approx 1.3 \times 10^{31} \left(\frac{M}{M_\odot}\right) \mathrm{W}$$

Fundamental assumptions: opacity dominated by Compton cross-section σ_T, all radiation sees all accreting material (spherical symmetry) , steady state

Optical Properties of AGN

- **Strong lines** of hydrogen, carbon, oxygen ….



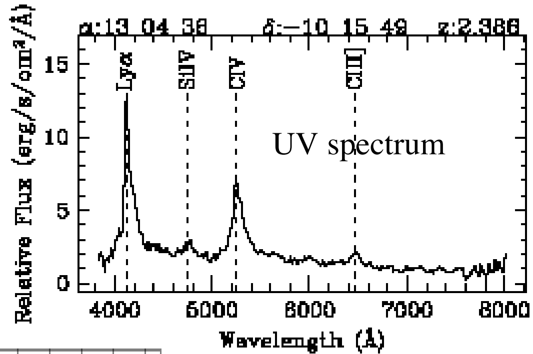


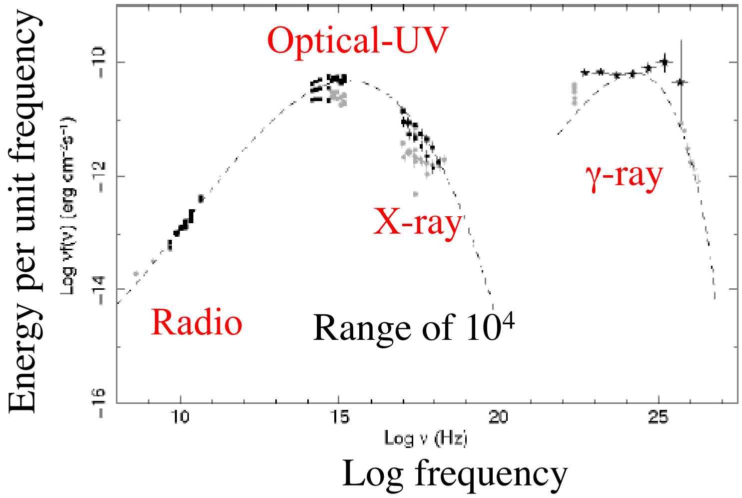
Unusual optical colors
(Richards et al SDSS)- **quasars in color**, **stars are black-** line is model of QSO continuum as a function of redshift

UV-Optical Continuum is thought to arise via thermal emission in an accretion disk

Broad Band Properties of AGN

- **Broad band continuum- very different from stars or galaxies**
- **Strong UV lines not seen in stars ….**
- Can be very variable



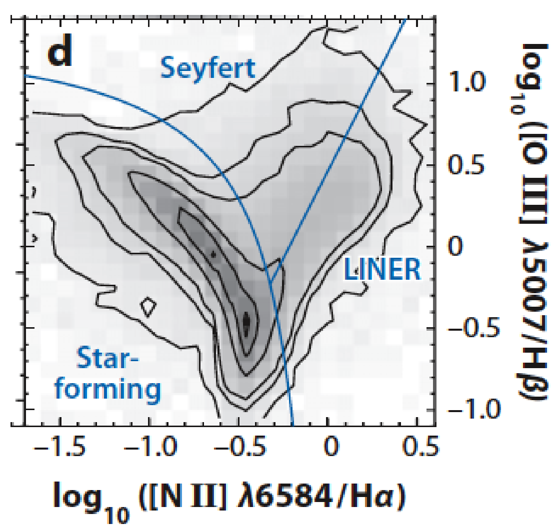


Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us)

A large fraction of the total energy appears in the γ-ray band

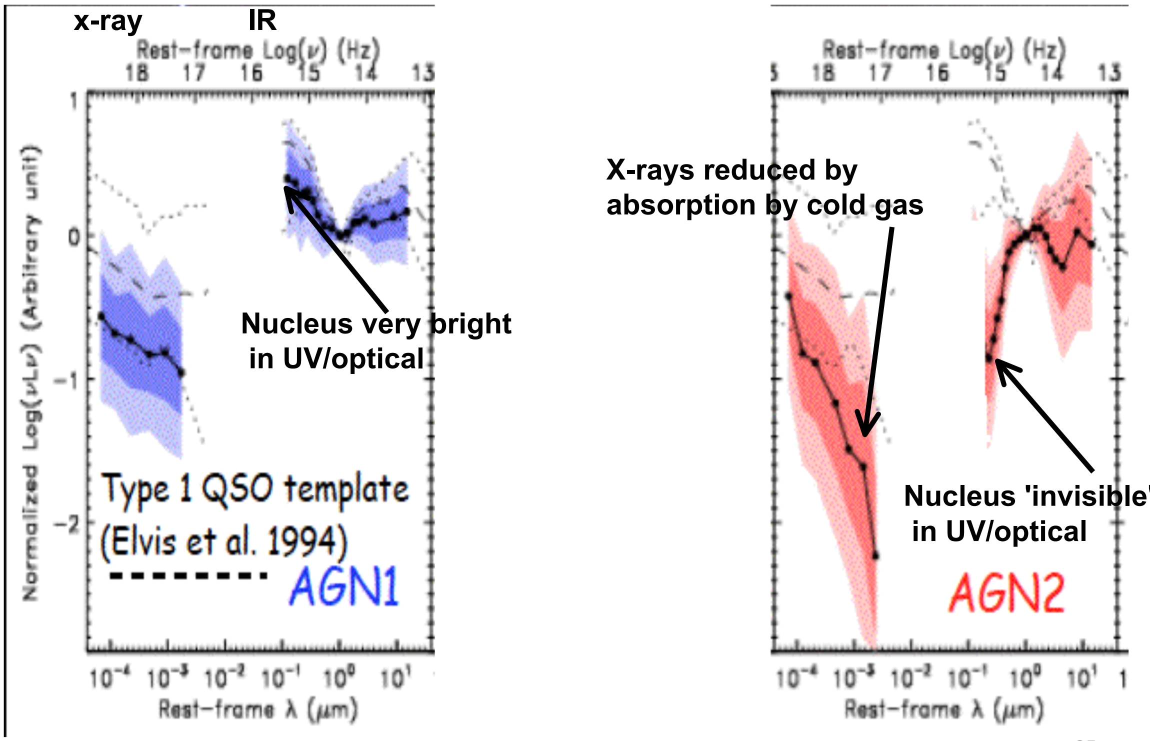
Optical Emission Lines

- Remember that star forming galaxies also can have strong emission lines
- *AGN emission line ratios are different*- indicating ionization by a different type of source ('harder' spectrum- more energy at shorter wavlengths than stars)



line ratio plot NII/Hα compared to OIII/Hβ– AGN lie in a particular part of this BPT diagram
Darkness of plot is log of the number of objects inside the contour (Kewley et al 2006)

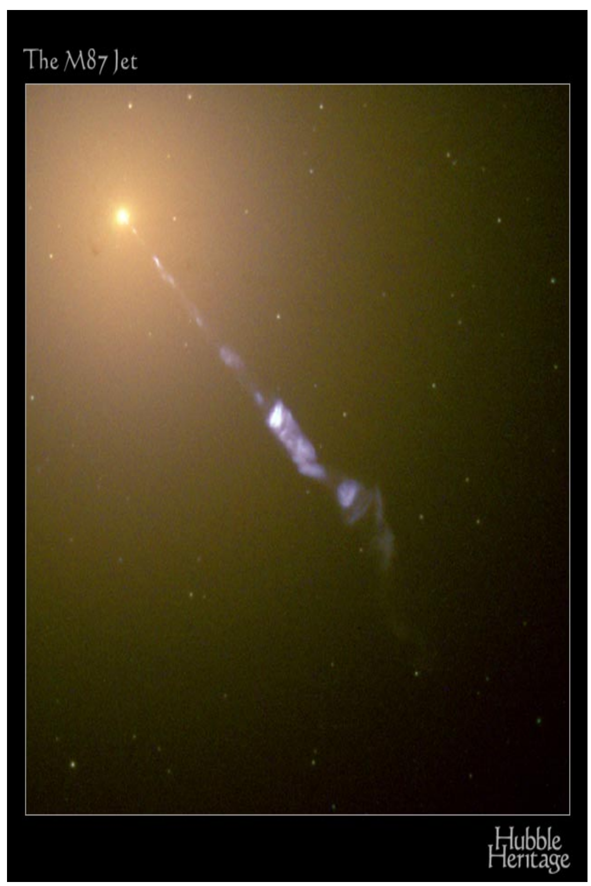
Broad Band Continuum (IR-Xray)



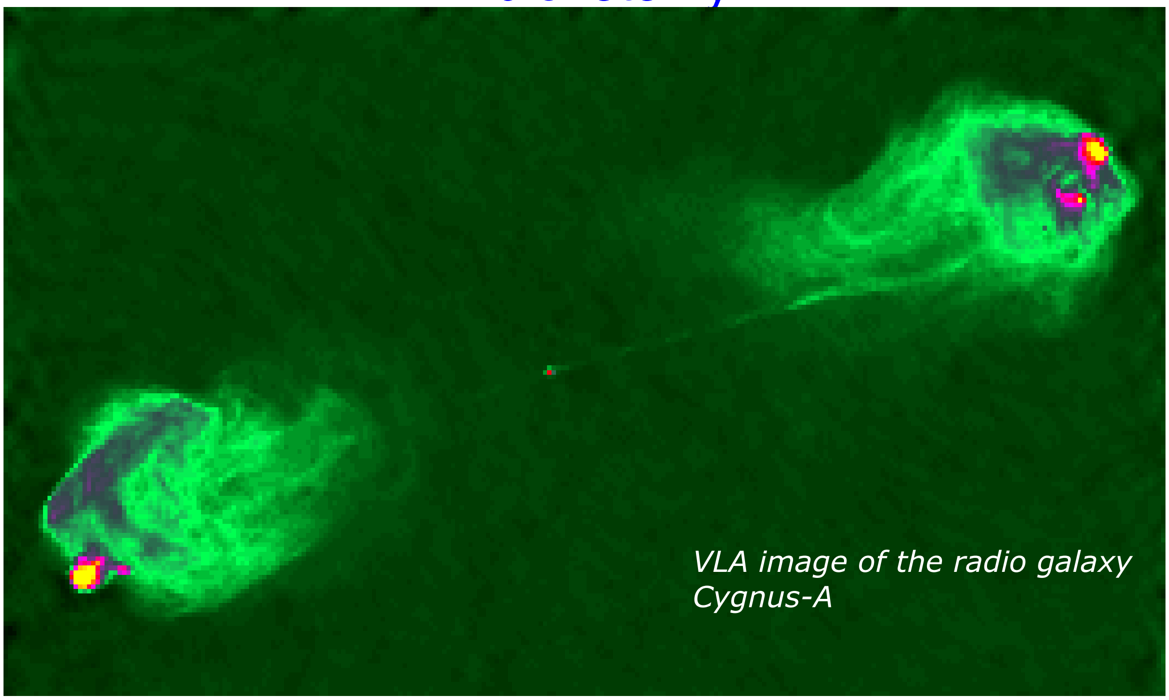
Active Galactic Nuclei

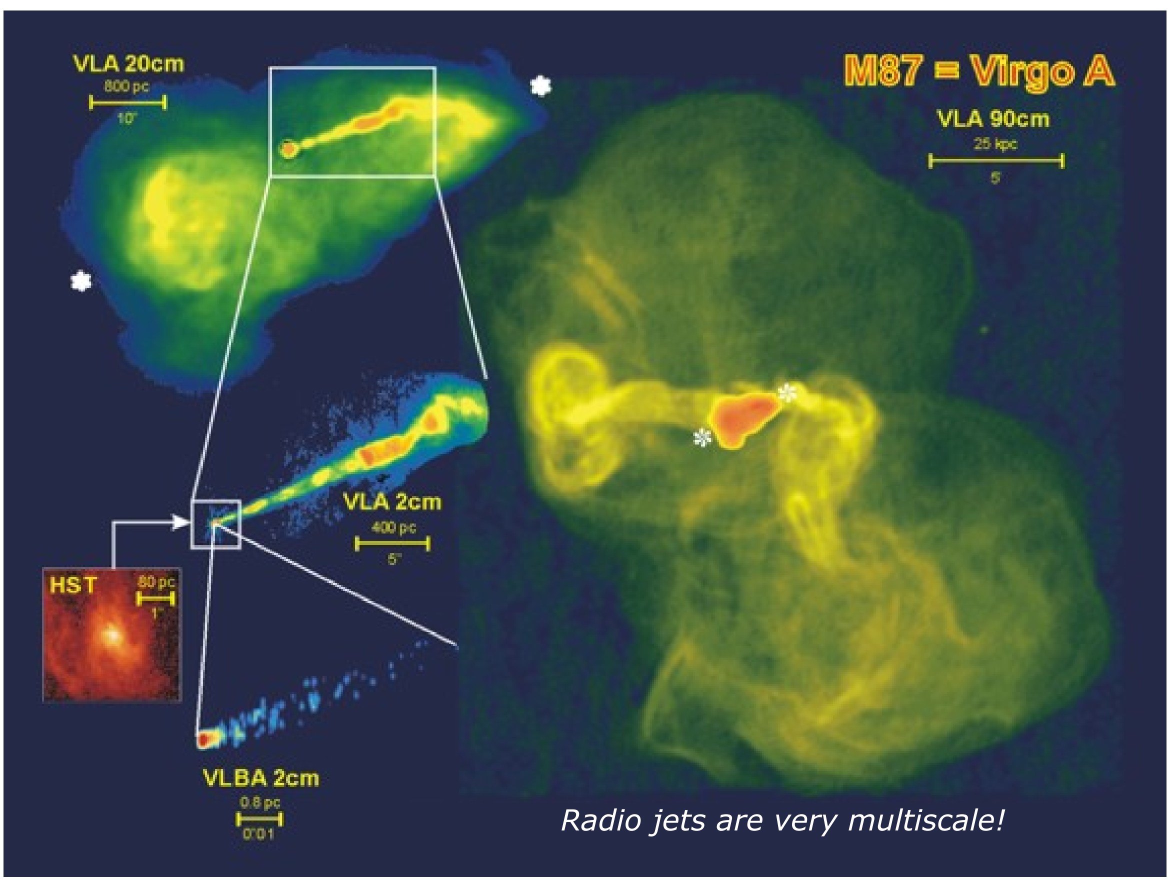
- M87 is example of a *radio loud* "active galactic nucleus"
- Material flows (accretes) into black hole
- Energy released by accretion of matter powers energetic phenomena

- The Jet
  - Jet of material squirted from vicinity of SMBH
  - Lorentz factor of >6
  - Can be very energetic (particle luminosity)
  - in radio to x-ray band jet radiation is primarily synchrotron (see text)- in gamma-ray it is inverse Compton
- What powers the jet?
  - Accretion power
  - Extraction of spin-energy of the black hole



AGN 'Types' The Radio-loud/Radio-quiet dichotomy

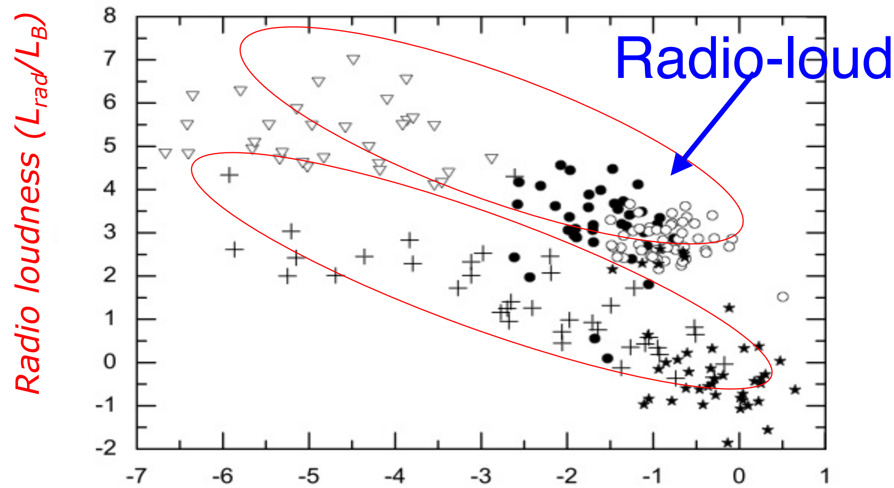




The Radio-loud/Radio-quiet dichotomy

Define relative importance of radio emission by ratio of radio luminosity L_{rad} **to optical luminosity** L_B

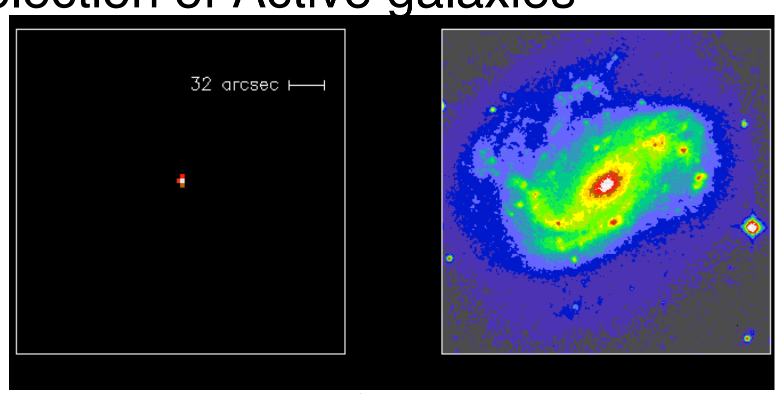
*-**8** order of magnitude range*



Sikora et al. (2007) *Accretion rate (Eddington Units)*

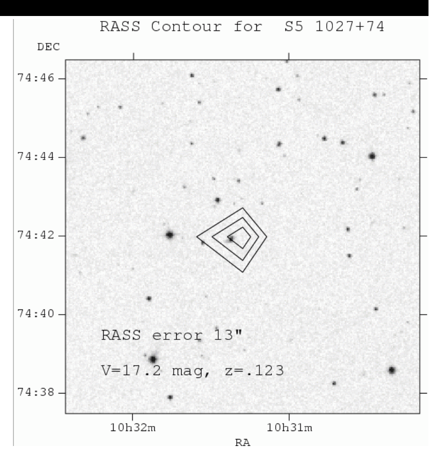
X-ray Selection of Active galaxies

- X-ray and optical image of a nearby AGN NGC4051-
- Note the very high contrast in the x-ray image
- Find x-ray AGN via
  - luminous* pointlike x-ray source in nucleus of galaxy
  - hard x-ray spectrum
  - frequently variable
  - often shows high line of sight absorption



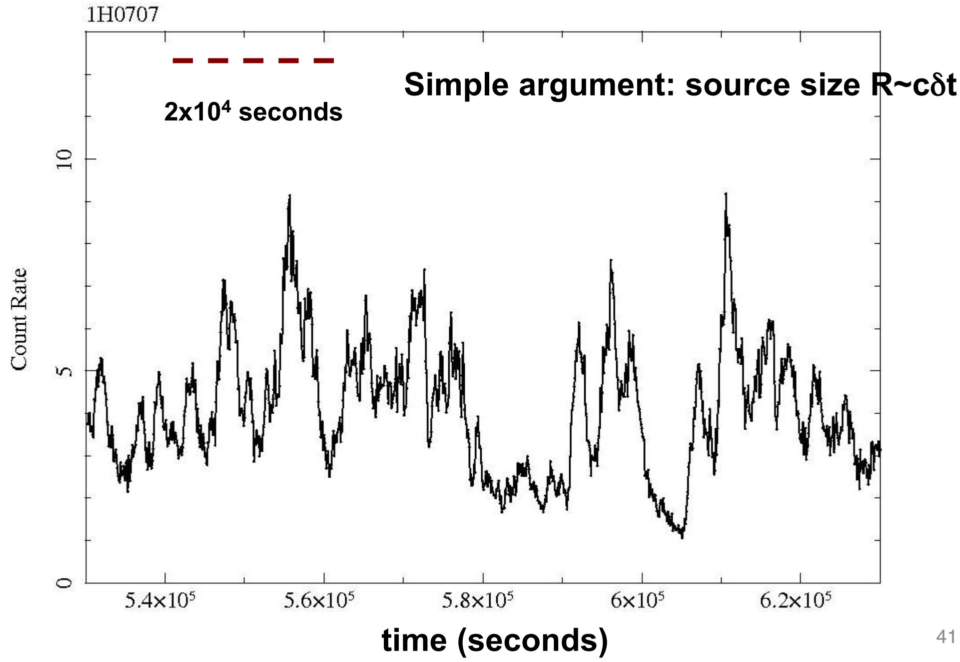
* Find lots of AGN 'hidden' at other wavelengths

Rosat x-ray all sky survey image overlaid on sky survey image

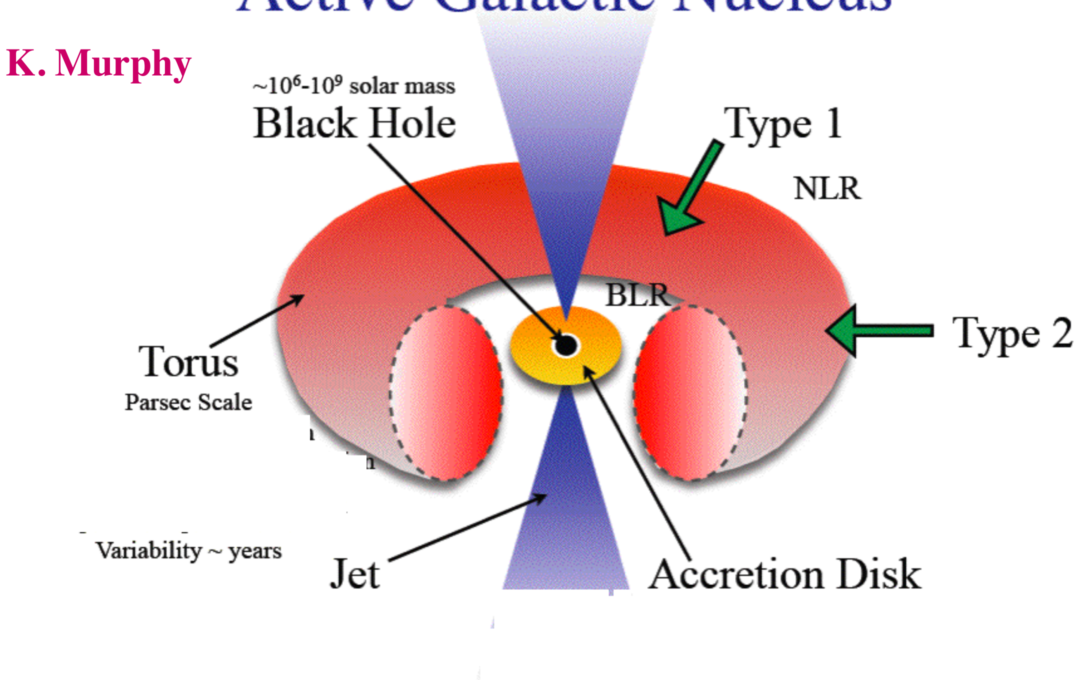


Rapid variability in AGN

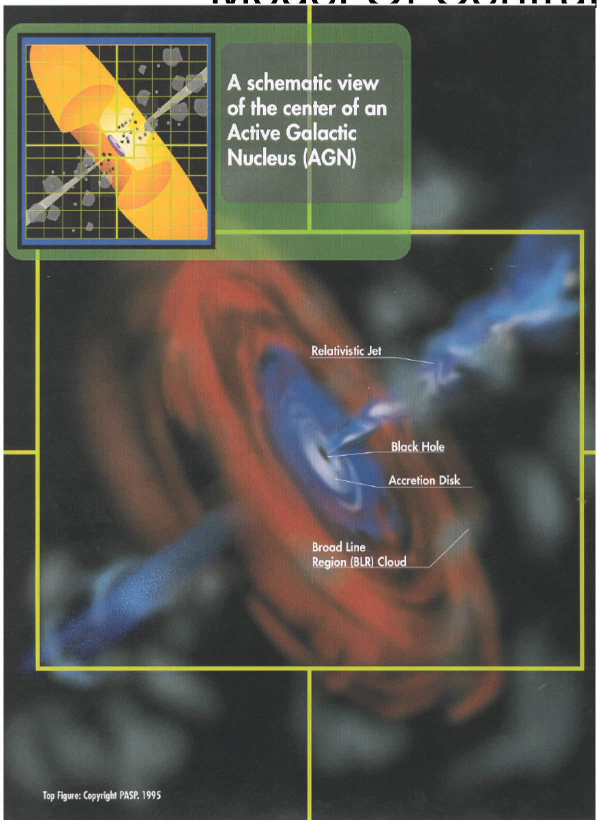
Source luminosity ~5x10^{43} ergs/sec



Active Galactic Nucleus



Model Of Central Region of AGN



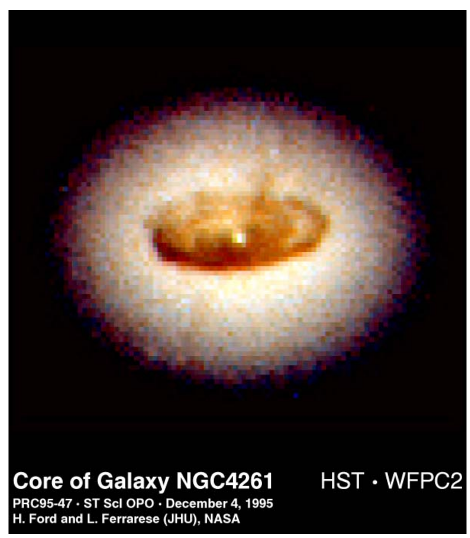
Source	Distance from central source
X-Ray Fe Kα	3-10 R_S
Broad-Line Region	600 R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

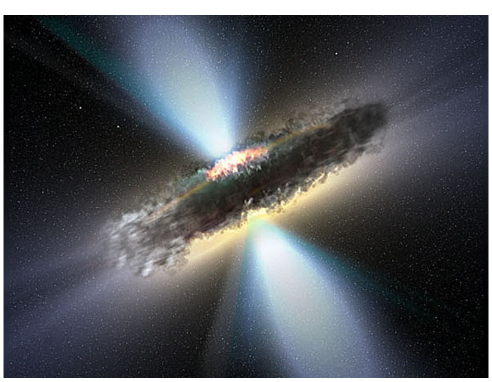
R_s= Schwarschild radius=$2GM/c^2$

$R_s=1.4\times10^{13}M_8$cm; $R_s/c\sim500M_8$ sec

The Dark Side of AGN

- ***Many AGN are obscured***- obscuring material is of several types
  - Located in the ISM of the host galaxy
  - A wind associated with the AGN
  - Perhaps a 'obscuring torus'
  - Etc
  - Lack of uniform sample not sensitive to absorption or emission from this structure has limited knowledge of true distribution of properties



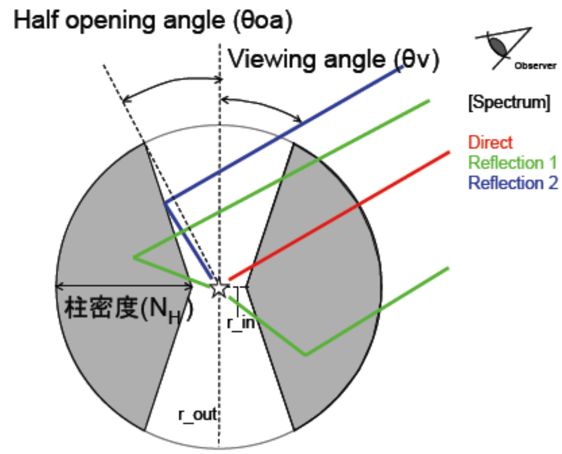


physical conditions in obscuring regions are not the same from object to object - can be complex with large and unpredictable effects on the spectrum

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 Accretion Disk are hidden by the dust

- However there are other complications like jets and a range in the geometry
- 'Radio loud' objects- e.g. with strong jets and/or luminous extended radio emission lie ONLY in elliptical galaxies!



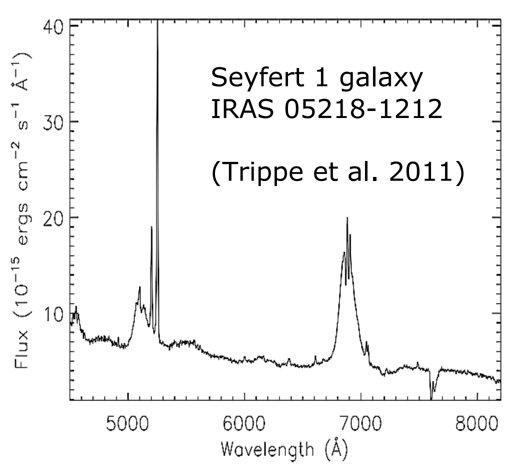
Radio Loudness	Optical Emission Line Properties		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	**Type 0** (Unusual)
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	
Radio-loud:	NLRG { FR I, FR II }	BLRG SSRQ FSRQ	Blazars { BL Lacs, (FSRQ) }
	decreasing angle to line of sight ->		

Table 1: AGN Taxonomy: A Simplified Scheme.

AGN Types

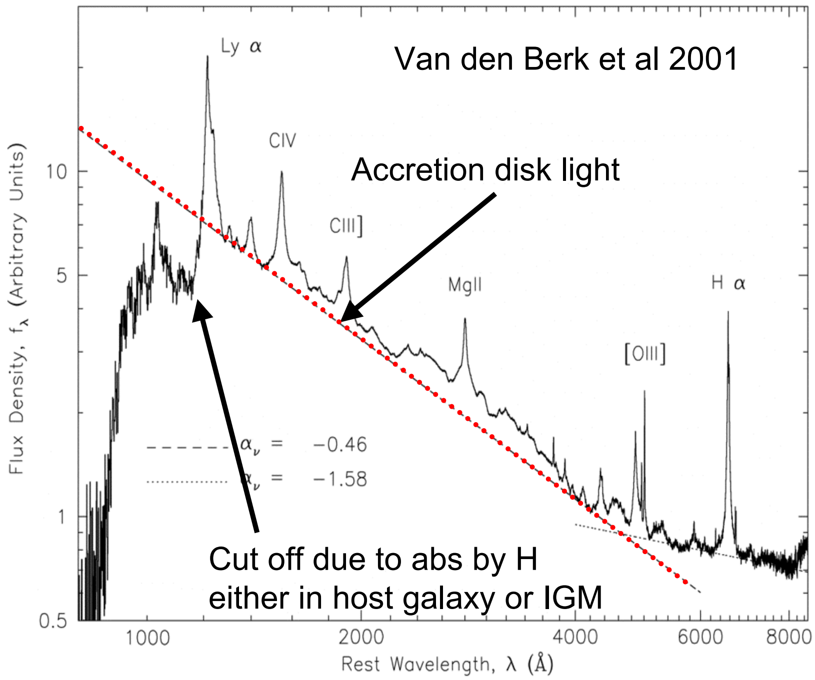
Broad line (type-1) objects

- 'Blue' optical/UV continuum
- Broad optical/UV lines
  - Emission lines from permitted (not forbidden) transitions
  - Photoionized matter $n>10^9 cm^{-3}$
  - FWHM~2000-20,000 km/s
- Narrow optical/UV lines
  - Emission lines from both permitted and forbidden transitions
  - FWHM~500km/s
  - Spatially resolved 0.1-1kpc



Hβ, [OIII], [NII],Hα

- AGN (type I) optical and UV spectra consist of a 'feature less continuum' with strong 'broad' lines superimposed
- Typical velocity widths (σ, 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



Origin of λ>4000Å continuum not known

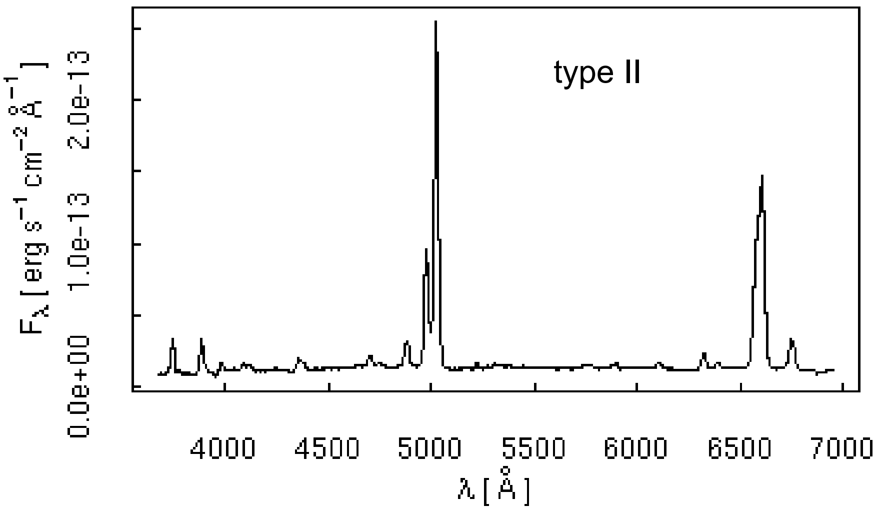
AGN Types

Narrow line (type-2) objects

- Reddened Optical/UV continuum
- Optical Emission line spectrum
  - "Full light" spectrum only shows narrow (~500km/sec) optical/UV lines
  - Broad optical/UV lines seen in *polarized* light… shows that there is a hidden broad line region seen via scattering (Antonucci & Miller 1985)
- **X-ray spectrum usually reveals highly absorbed nucleus ($N_H>10^{22}cm^{-2}$)**
- Intermediate type objects (type-1.2, 1.5, 1.8, 1.9) have obscurers which become transparent at sufficiently long/short wavelengths

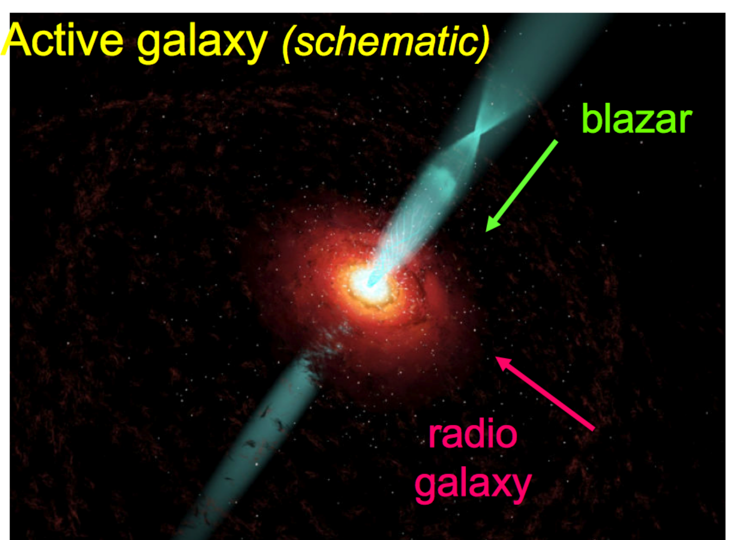
Objects without a Strong Continuum-e.g type II

- type II **<u>do not</u> have broad lines and have a weak or absent 'non-stellar' continuum**
- **Depending on the type of survey and luminosity range ~50% of all AGN are of type II**



AGN types
Blazar

- Featureless (no lines) broad band continuum radio-gamma rays
- Thought to be due to emission from jet in our line of sight
- Can be very luminous



July 2008 Aspen Center for Physics 1

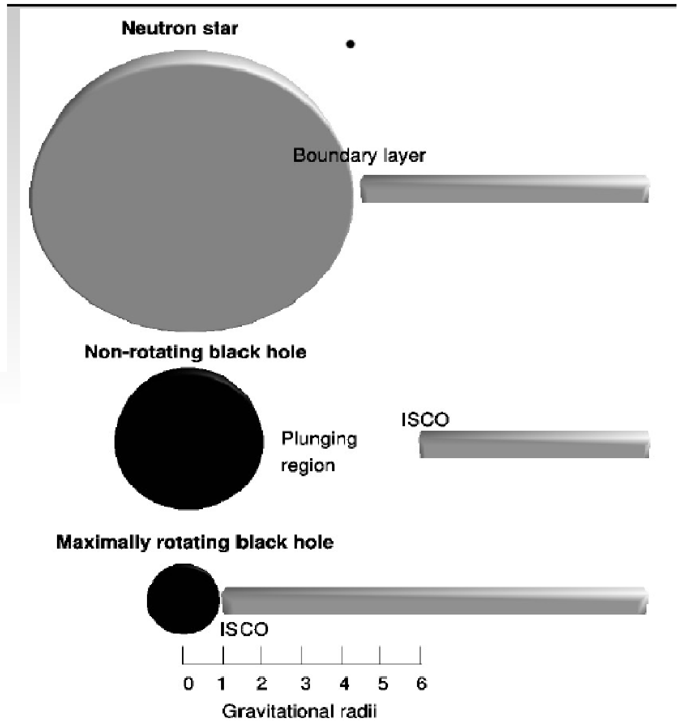
Radio Loudness	Names and Properties		No Lines
Radio quiet (weak or no jet)	Type II (narrow forbidden lines) Seyfert 2	Type I (broad permitted lines) Seyfert 1 QSO	
Radio Loud (strong jet)- **ONLY in ELLIPTICAL Galaxies**	FR I NLRG FR II	BLRG	Bl Lac Blazars FSRQ
X-ray Properties	Highly Absorbed- strong 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)

ISCO=innermost stable orbit-disk terminates there



What about spin ?

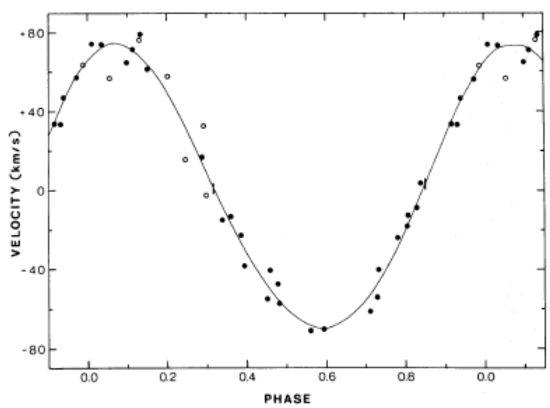
A non-rotating ("Schwarzschild") black hole has its event horizon at 2 R_G and its ISCO at 6 R_G

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

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

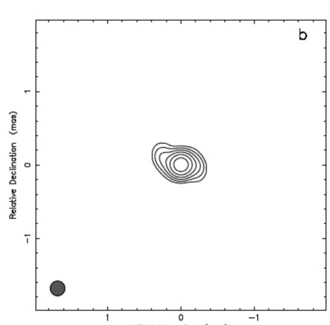
4 J. Casares

Table 1. Confirmed black holes and mass determinations

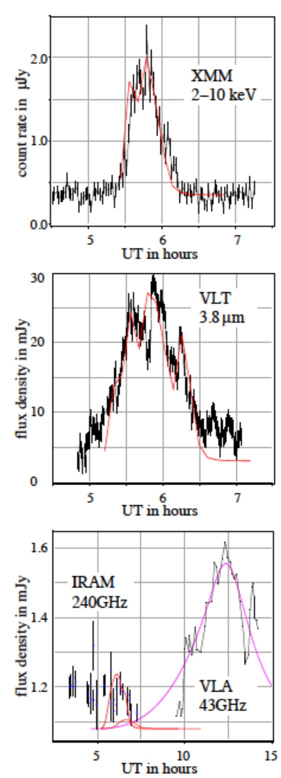
System	P_{orb} [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	M_x † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254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



Radio image of SgrA*



Radio, near IR and x-ray light curves

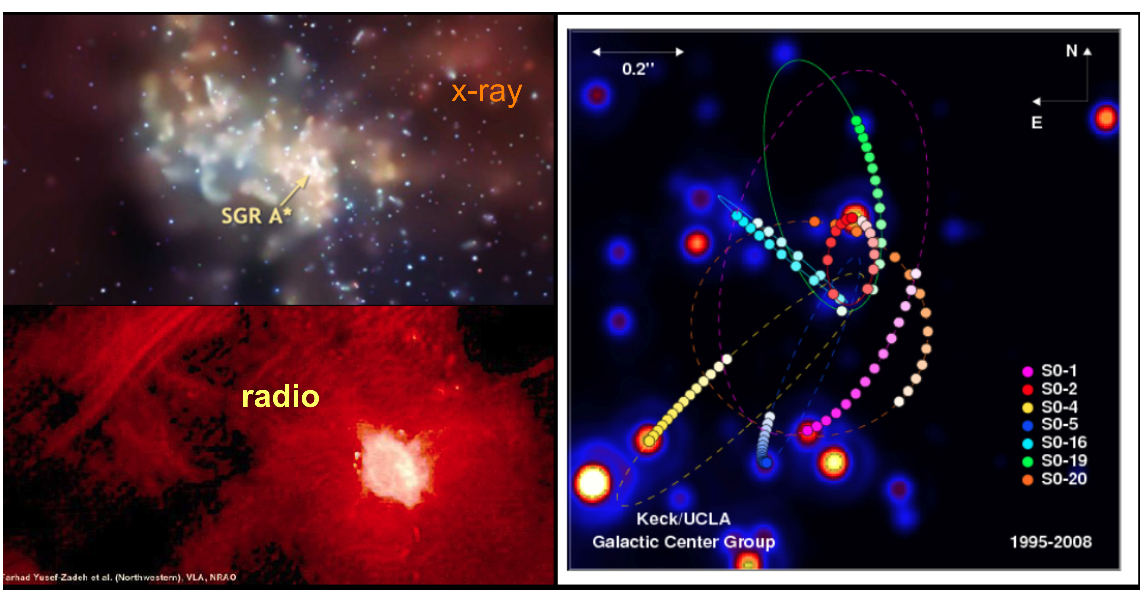
Some Problems with Sgr A*

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

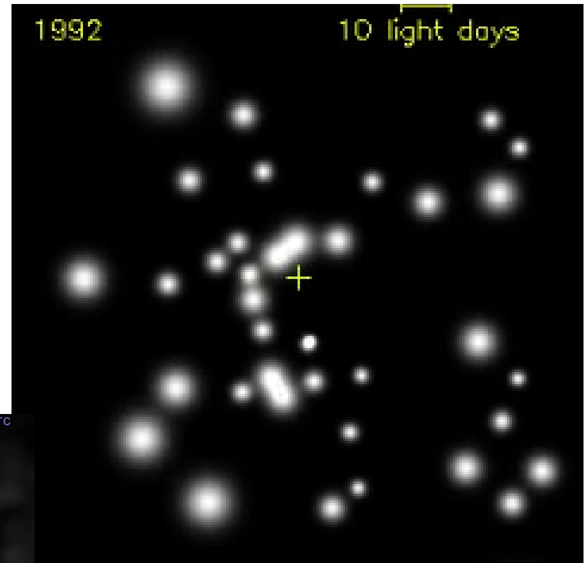
- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities **TODAY**! (AGN evolution)

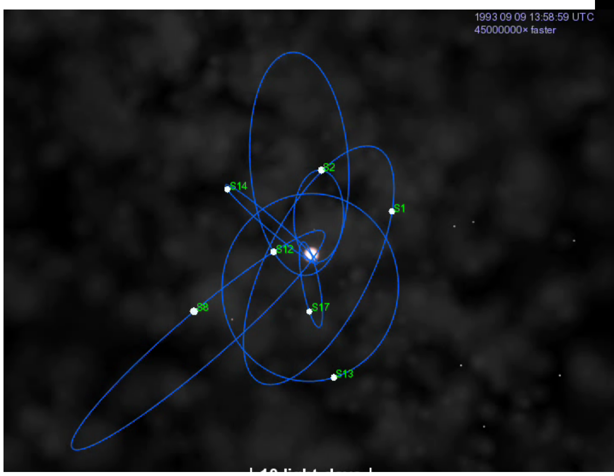
MW Galactic Center

- 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/

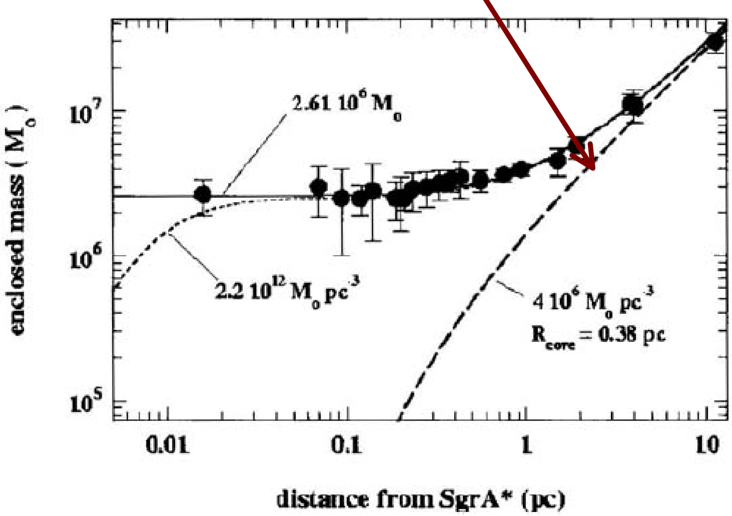




MW Center

Predicted mass from models of the Milkyway

- 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 $20 M_{sun} pc^{-3}$ 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

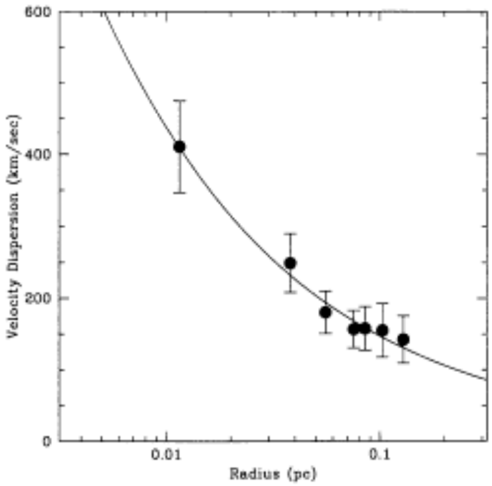
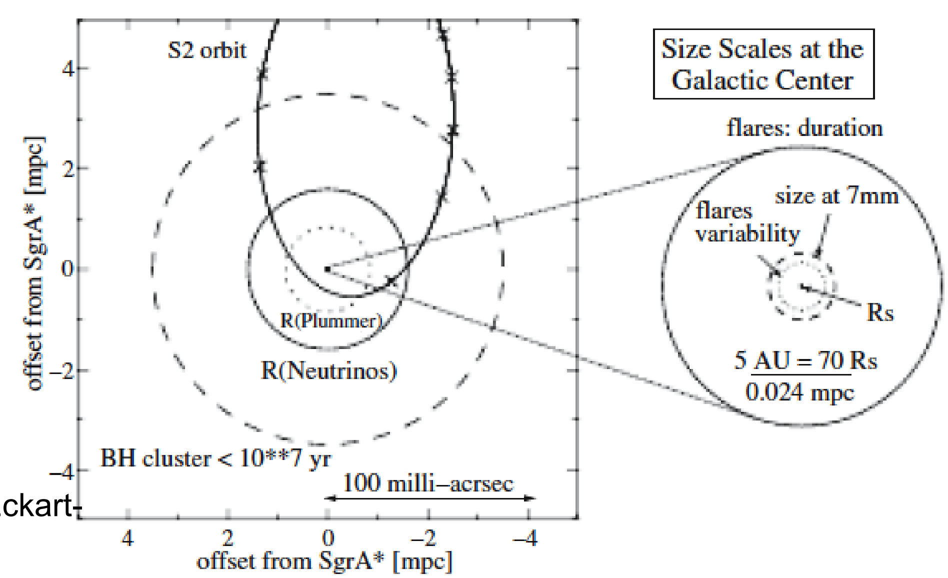


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

Ghez et al 1998

The Milky Way's Black Hole and the Central Stellar Cluster 7



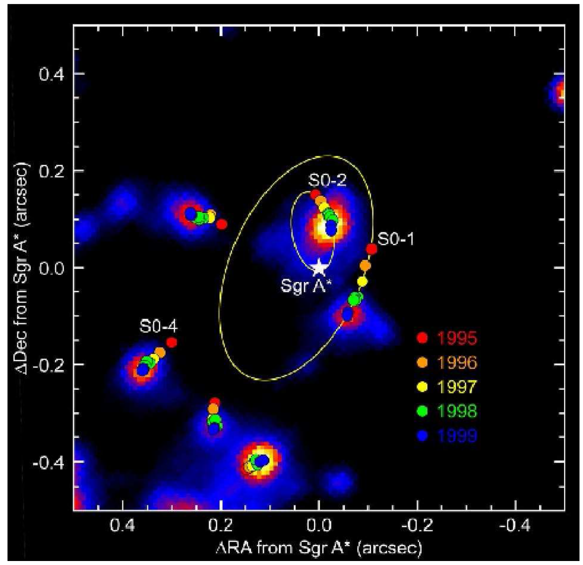
Eckart

- 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.**

- There is another 'fiducial' radius in the Kerr solution, that radius within which all light cones point in the directon of rotation, the 'static' radius, r_{static}.
- Between r_{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)

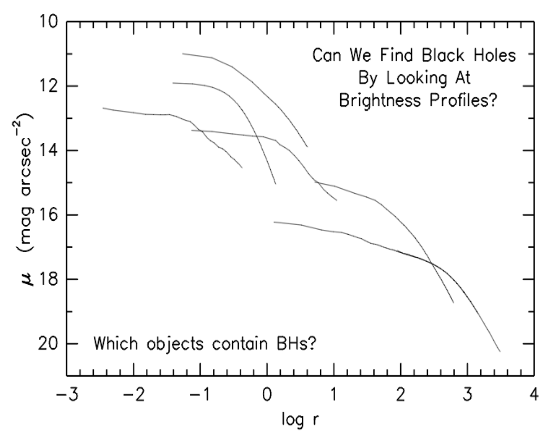
- Assume each emitting region has a size l' in its co-moving frame and is causally connected over a time $\Delta t'$ -- implying $l' < c\,\Delta t'$
- In the laboratory frame the time scale is dilated to $\Gamma\Delta t'$ ($\Gamma=1/\mathrm{sqrt}(1-\beta^2)$; $\beta=v/c$
- From an observers point of view the duration is reduced by $1/(1-\beta\cos\theta)$- in the limit $\beta\sim1$ and $\theta<1/\Gamma$ this is $\sim2\Gamma^2$
- Thus a observed time scale $l' < c\, t_{var}\Gamma$

- Generalized Efficiency argument (similar to the Eddington limit)
- the mass required to produce a total amount of energy $E=\Delta L\Delta t=\varepsilon Mc^2$ (ε is the efficiency of converting matter to energy)
- This is related to the optical depth τ 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 Δt for a given mass M

  giving $\Delta L<\varepsilon c^2\,\Delta t m_p/\sigma$
- which for the Thompson cross section and 10% efficiency gives
- $\Delta L<2\times10^{41}\varepsilon_{0.1}\Delta t$ 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 σ_r, σ_ϕ, σ_θ

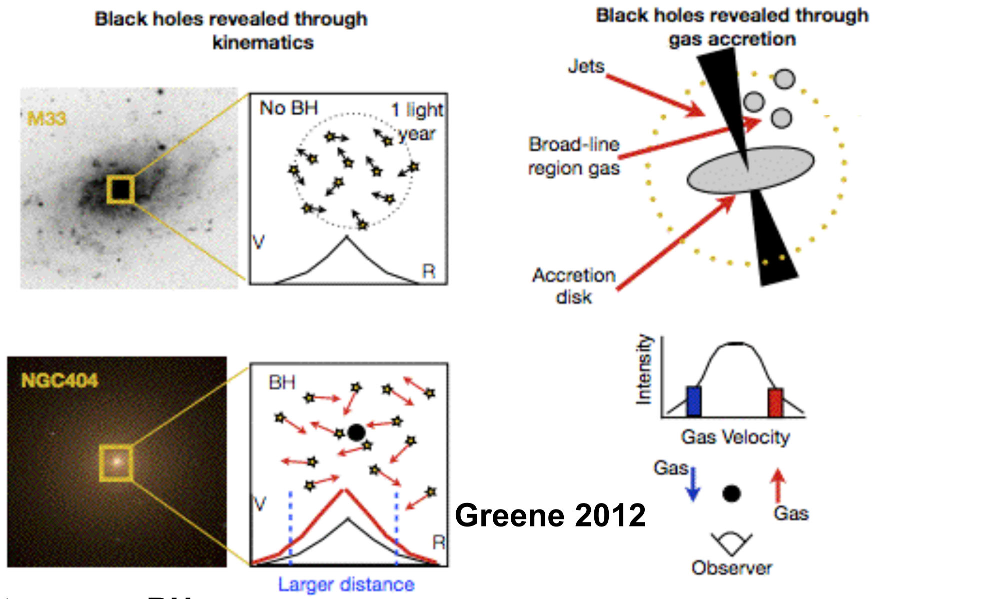


Kormendy and Richstone (2003)

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

Finding SMBHs

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



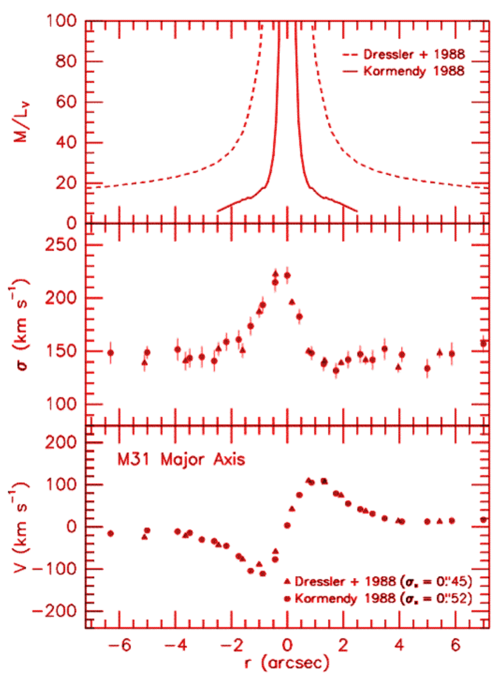
Greene 2012

stars near BH move more rapidly because of BH

broad emission lines-gas moving rapidly near BH

Example of data for the nearest galaxy M31

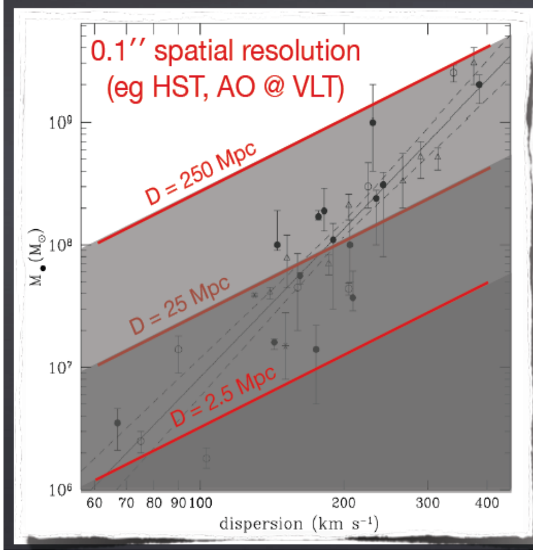
- Notice the nasty terms
- V_r is the rotation velocity σ_r σ_{θ}, σ_{ϕ} are the 3-D components of the velocity dispersion ν is the density of stars
- All of these variables are 3-D; we observe projected quantities !
- The analysis is done by generating a set of stellar orbits and then minimizing
- Rotation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



Direct BH mass measurements

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

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



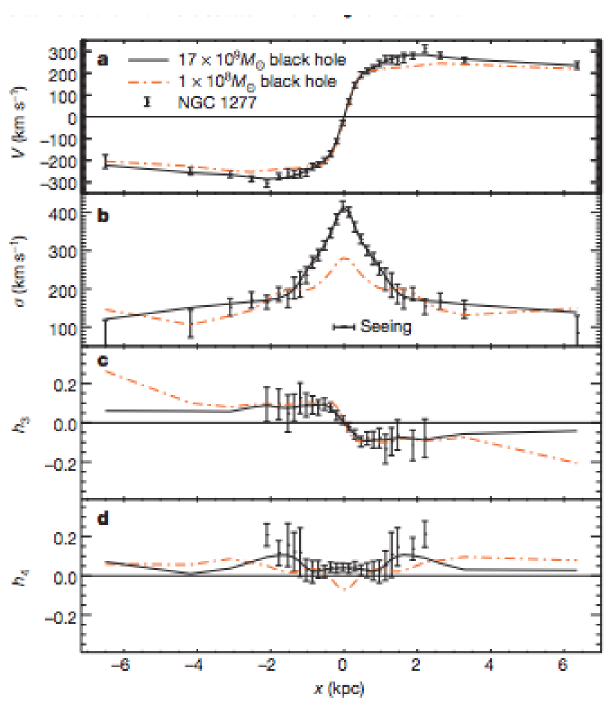
BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

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

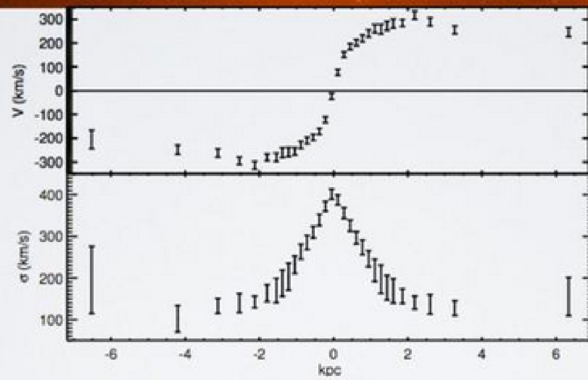
Marconi

NGC1277- Velocity Data and BH Mass

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



MEASURE BH MASS

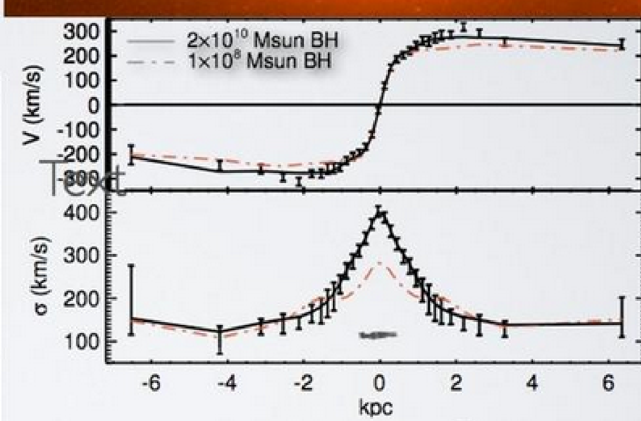


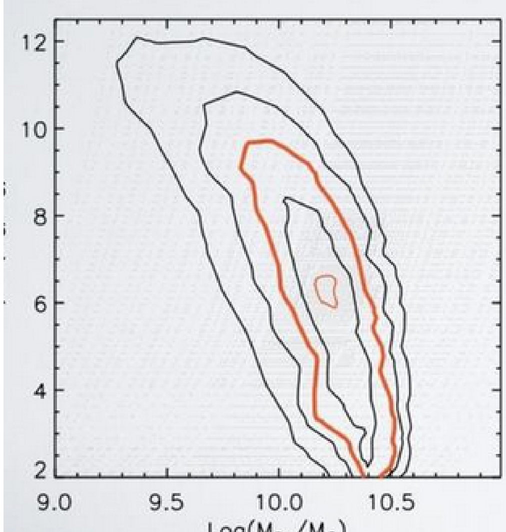
http://online.kitp.ucsb.edu/o
nline/bholes13/vandenbos
h/oh/29.html

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

A BIG BLACK HOLE N A SMALL GALAXY

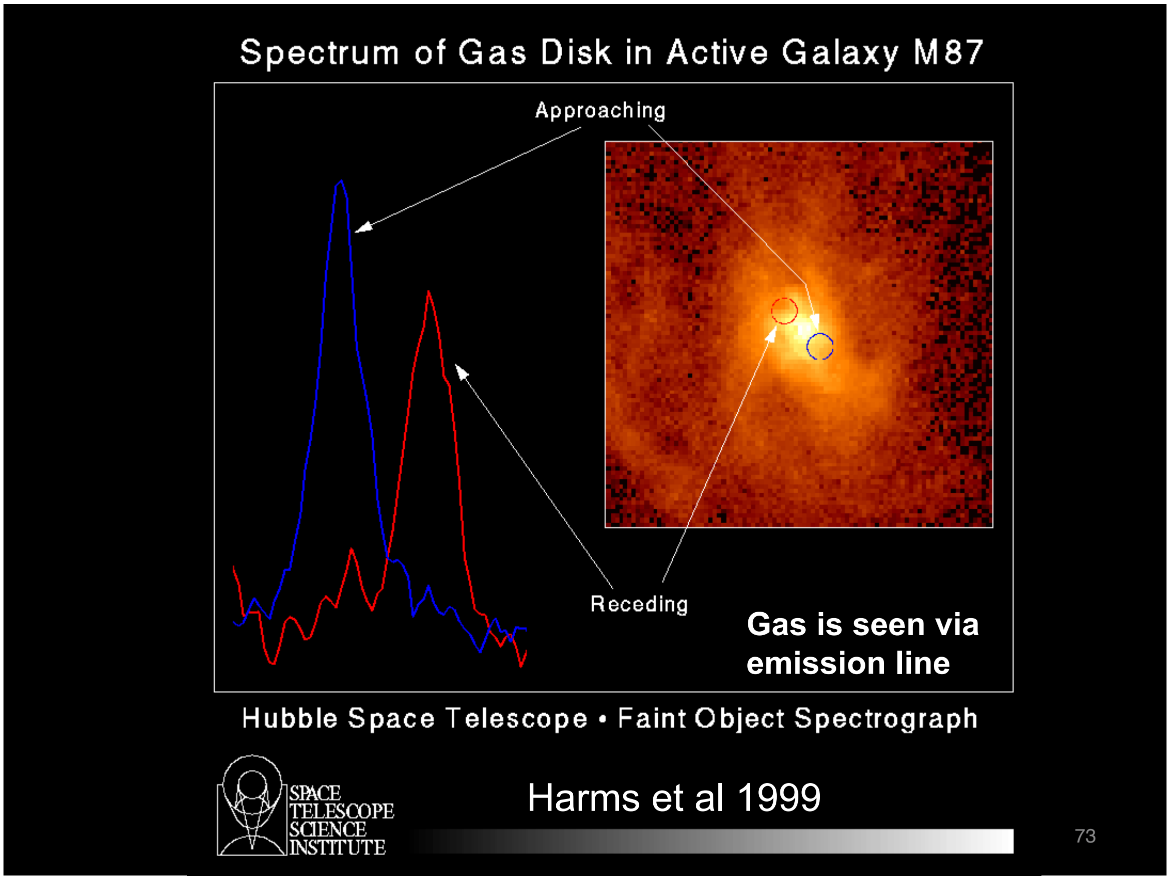




$$M_\bullet = 17 \pm 3 \times 10^9\,\mathrm{M}_\odot$$

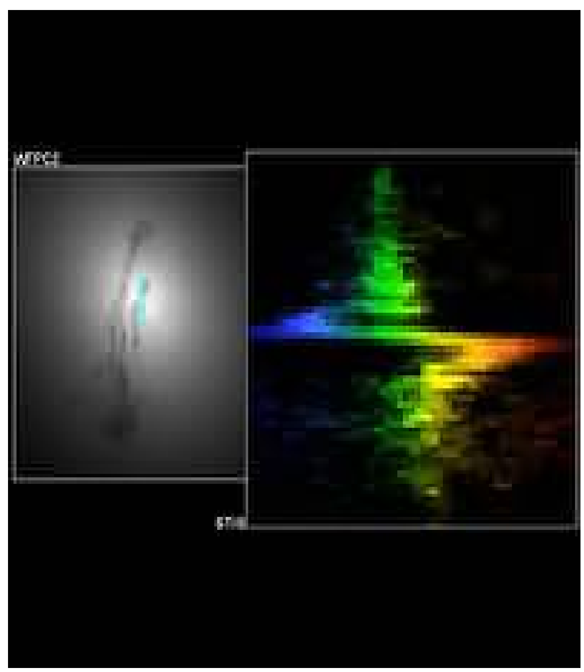
$$M_\star = 1.2 \times 10^{11}\,\mathrm{M}_\odot$$

$$\sigma_e = 230 - 360\,\mathrm{kms}^{-1}$$



Measuring the Mass of a SuperMassive Black hole

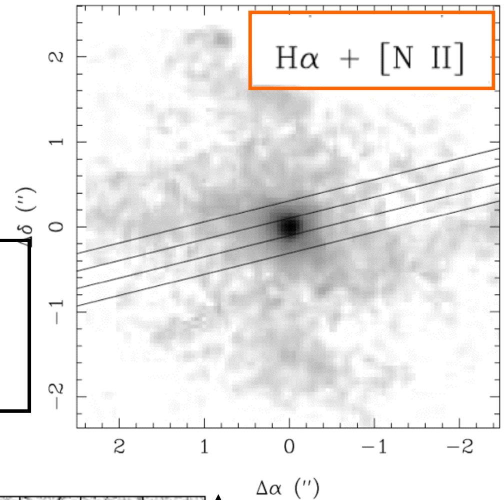
- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion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



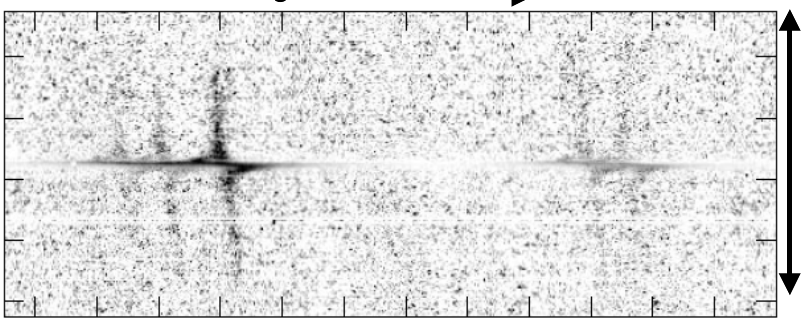
Measurement of Kinematics of Gas

- 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

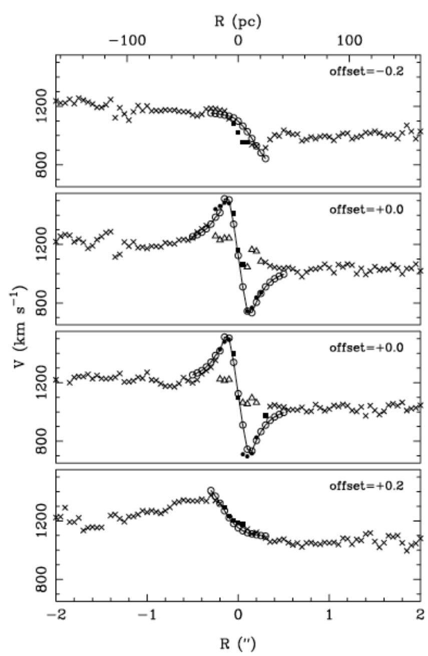
Analysis of Spectral Data for M84

- Mass of central object 1.5×10^9 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.

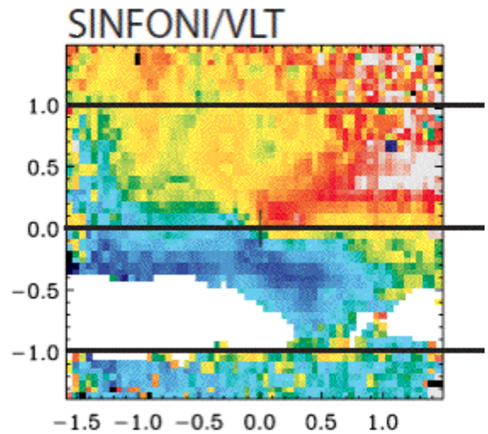


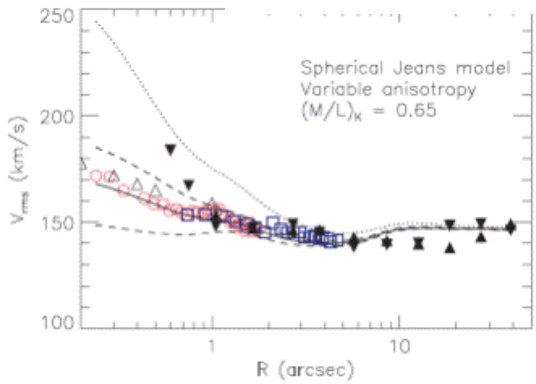
Velocity of gas vs distance from center of emission along 3 parallel lines

Centaurus -A

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

Gas Velocities





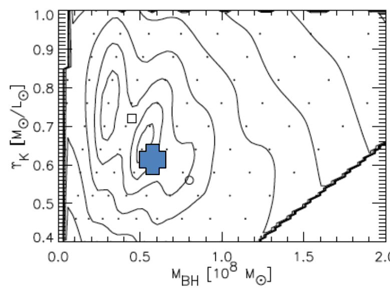
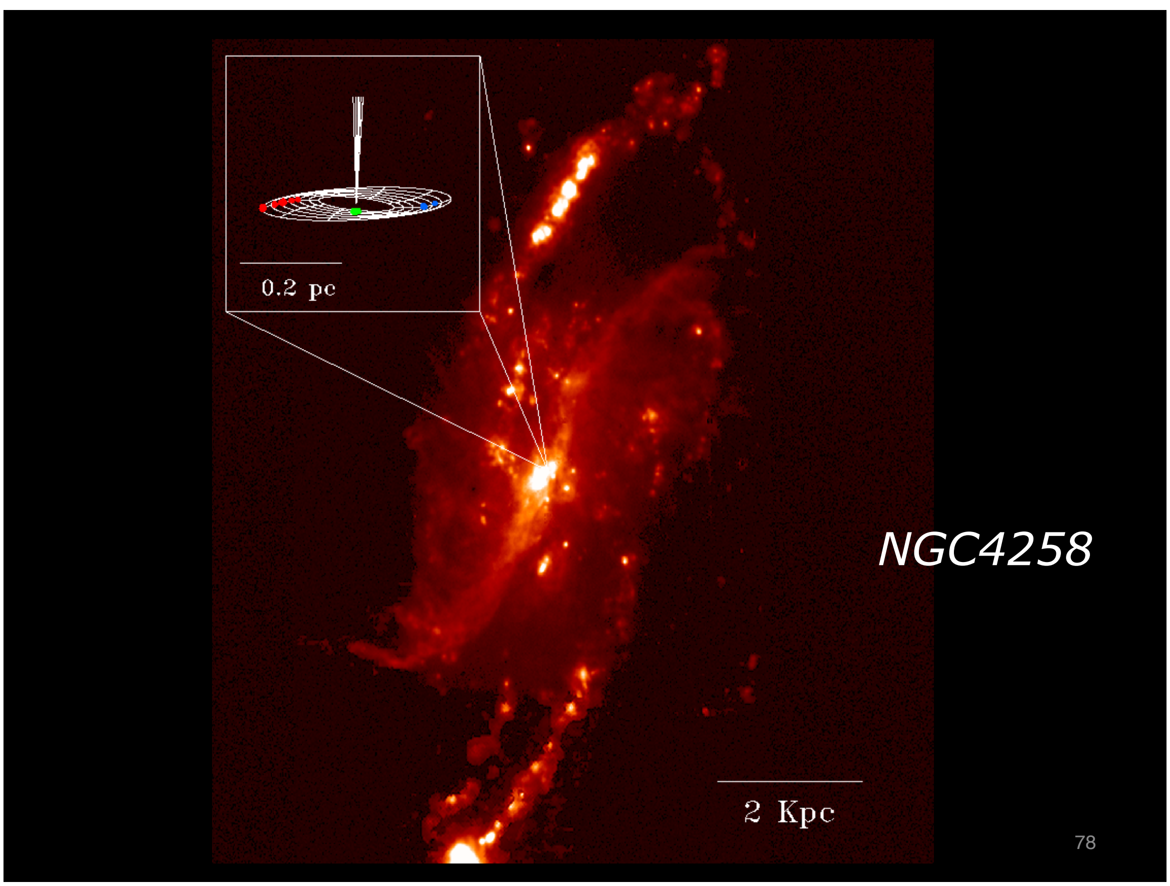


Figure 4: Spherical anisotropic Jeans model

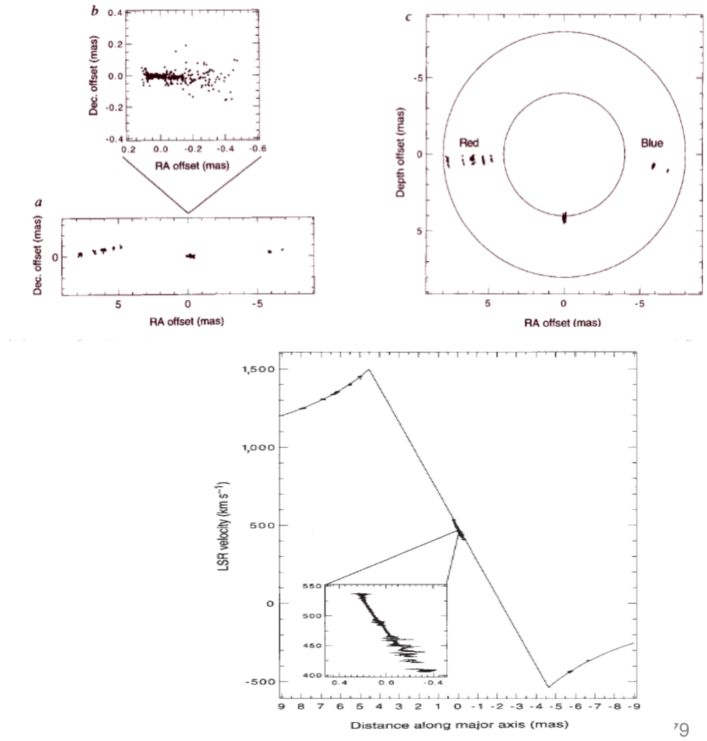
$$M_{\rm BH} = (5.5 \pm 3.0) \times 10^7 M_\odot.$$

Constraints from stars compared to those from Gas Velocities

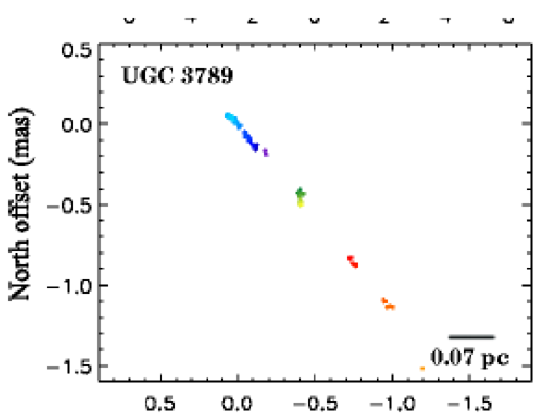


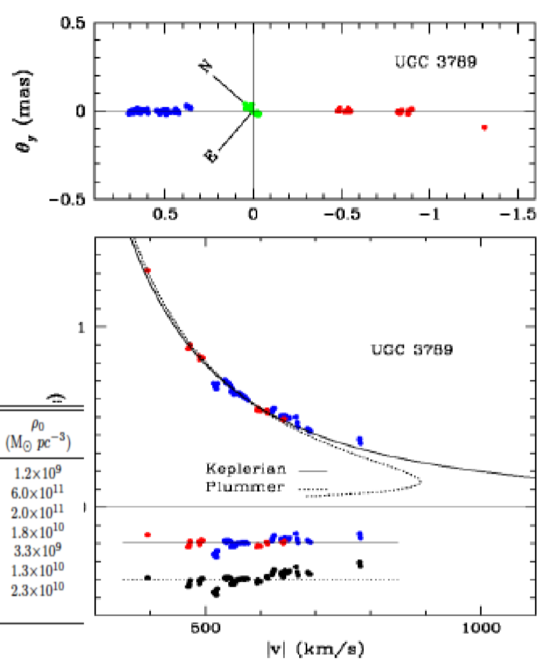
Use of Masers for an AGN

- 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

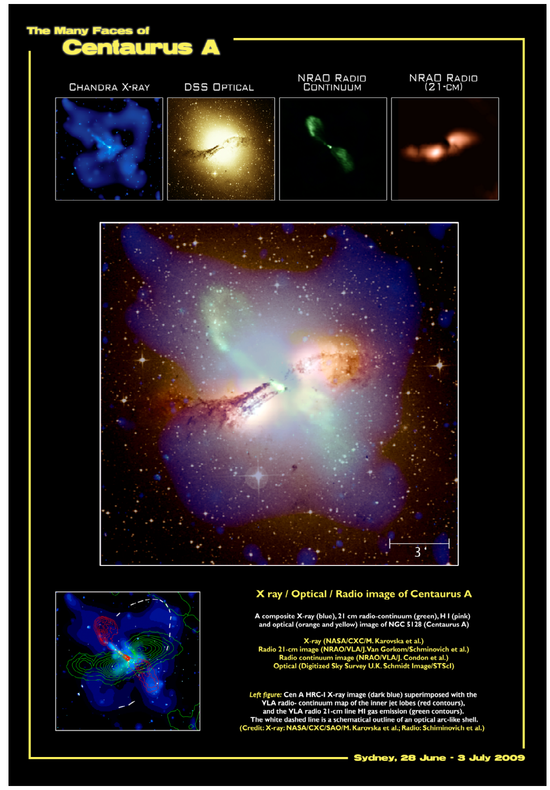




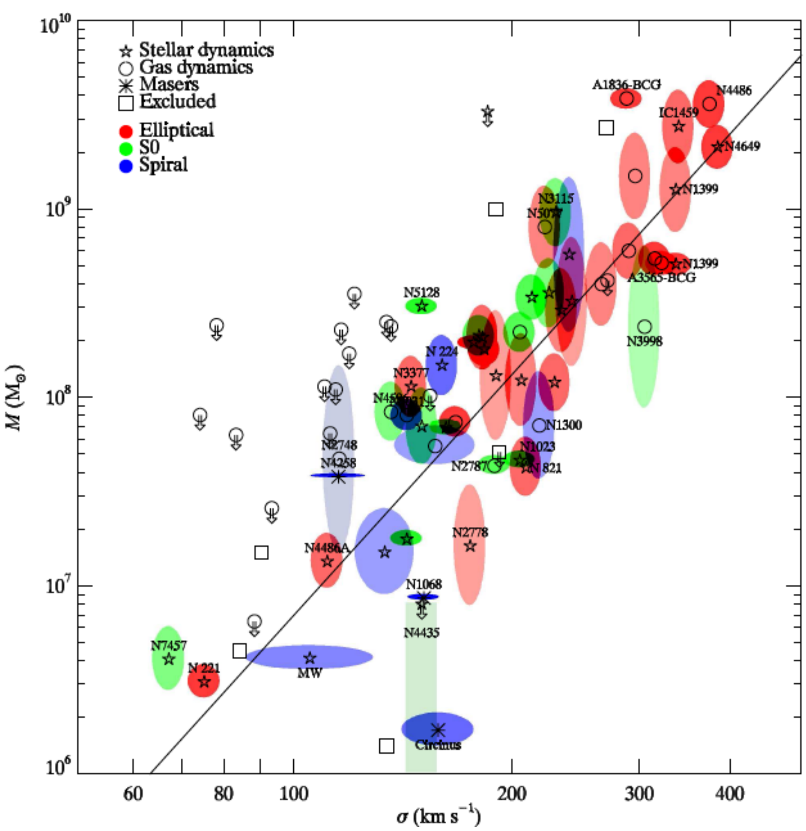
Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36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

Centaurus-A The Nearest AGN

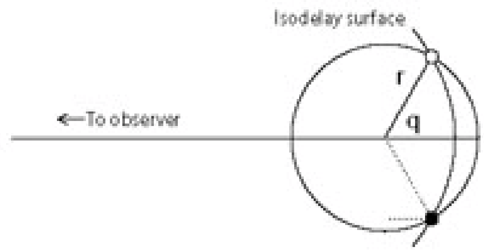


- All the Nearby Galaxies with Dynamical Masses for their Central Black Holes (Gultekin 2009)
- There seems to be a scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- Galaxies know about their BH and vice versa

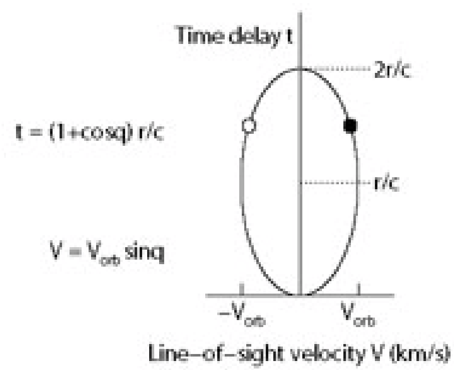


What About AGN in General??

- We believe that the incredible luminosity of AGN comes from accretion onto a black hole
- However the 'glare' of the black hole makes measuring the dynamics of stars and gas near the black hole very difficult



- Technique: reverberation mapping (Peterson 2003)
  - The basic idea is that there exists gas which is moderately close to to the Black Hole (the so-called broad line region) whose ionization is controlled by the radiation from the black hole
  - Thus when the central source varies the gas will respond, with a timescale related to how far away it is

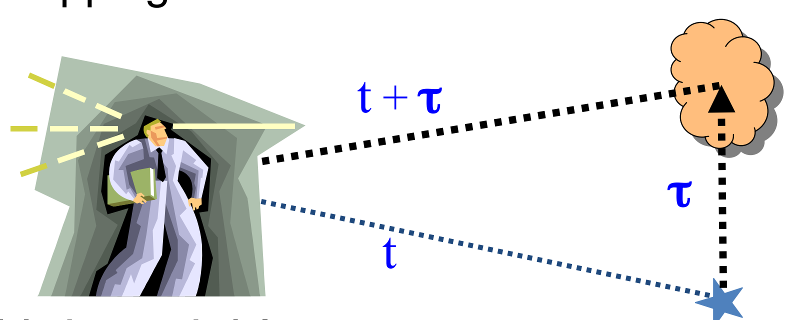


Virial Mass Estimates

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

Reverberation Mapping:

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



- v_{BLR}

  Line width in variable spectrum

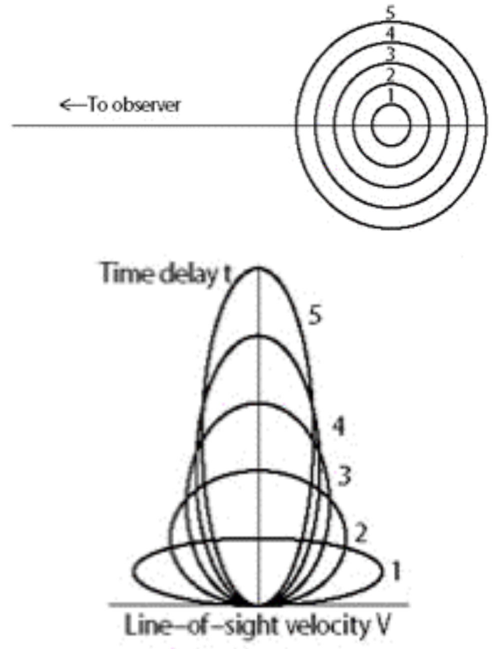
The Geometry

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

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

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

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



r=ct, where t is the time delay

Reverberation

Peterson et al 2011

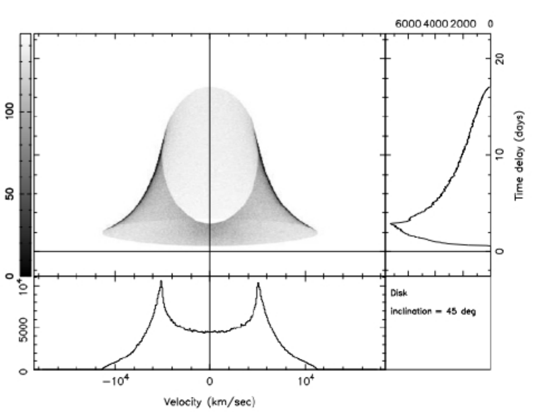
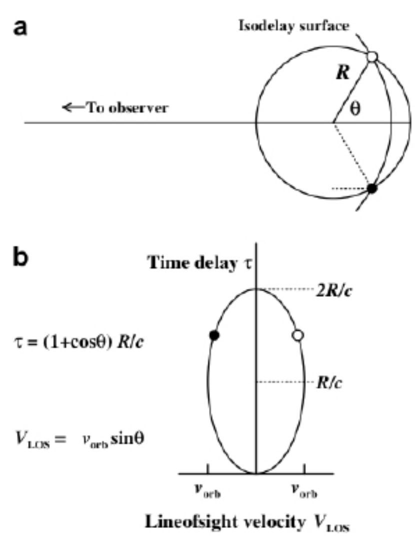


Fig. 2. Velocity–delay map for a thin disk at inclination $i = 45°$. The upper left panel shows in gray scale the velocity–delay map, i.e., the transfer function or the observed emission-line response as a function of line-of-sight velocity V_{LOS} and time delay τ. The upper right panel shows the one-dimensional transfer function, i.e., the velocity–delay map integrated over V_{LOS}, which is the response of the total emission line as a function of time. The lower left panel shows the emission-line response integrated over time delay; this is the profile of the variable part of the line.



A Quick Guide to Photoionized Plasmas

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

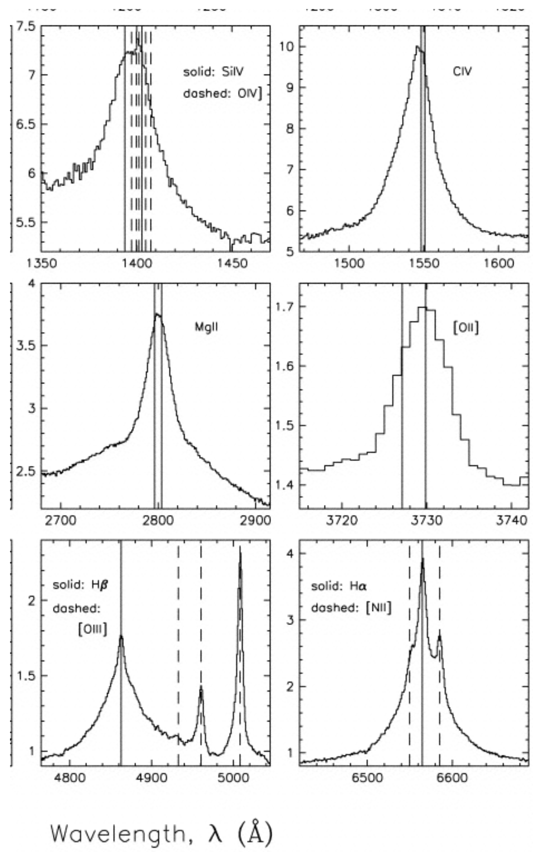
- Ionization of the plasma is determined by the balance between photionization and recombination
- Photoionization rate is proportional to the number of ionizing photons x number of ions x the cross section for interaction and the recombination rate to the number of ions x number of electrons x atomic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

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

ξ is the ionization parameter (also sometimes called U)

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

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

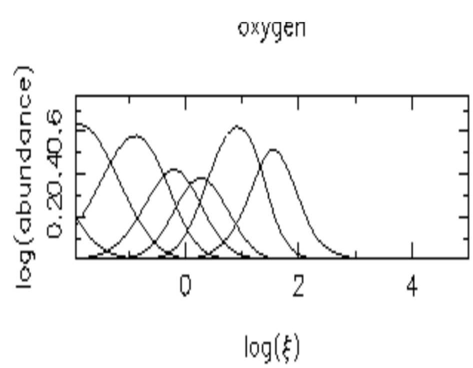


In Other Words

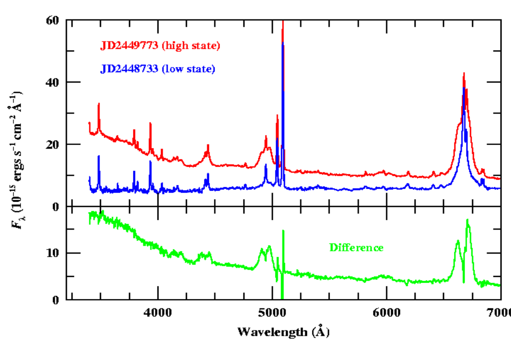
- For each ion:
  - Ionization = recombination
  - ~photon flux ~electron density
- For the gas as a whole
  - Heating = cooling
  - ~photon flux ~electron density

- => All results depend on the ratio photon flux/gas density or "ionization parameter"

- Higher ionization parameters produce more highly ionized lines (higher flux or lower density)



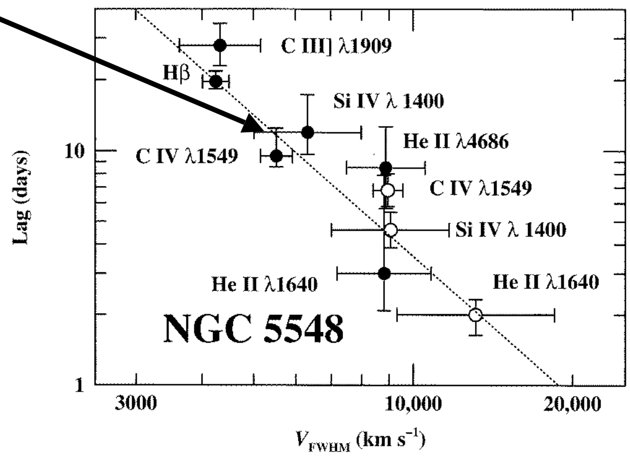
Neutral <----------->fully stripped



Peterson (1999)

What is Observed??

- The higher ionization lines have a larger width (rotational speed) and respond faster (closer to BH)
- Line is consistent with idea of photoionization, density ~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

Multiple Objects

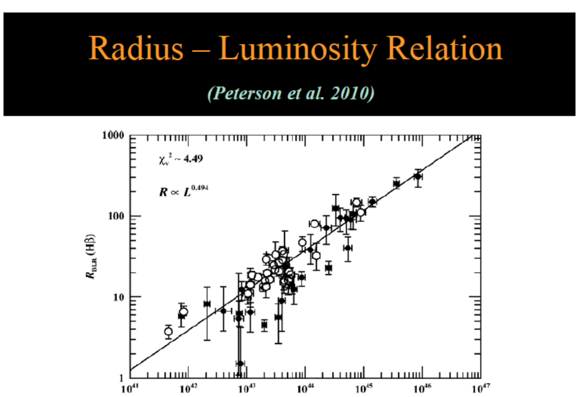


Figure 2. The R–L relationship for Hβ. The luminosity is $\lambda L_\lambda(5100\ \text{Å})$ and the BLR radius is measured in light days. The open circles indicate the highest-quality measurements. The slope of the fit to the highest-quality data is indistinguishable from that to all the data, but the scatter is only 0.11 dex.

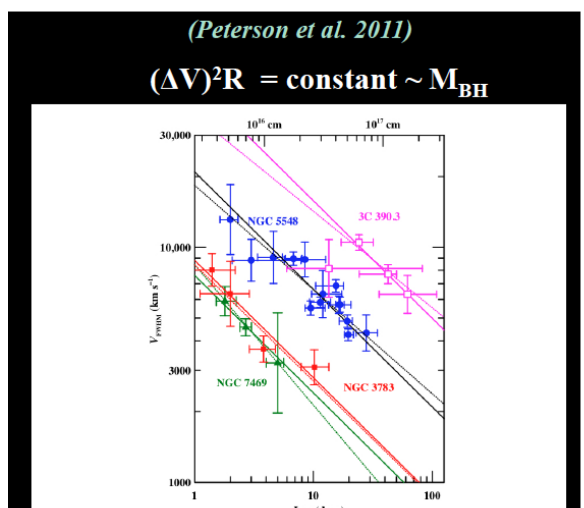
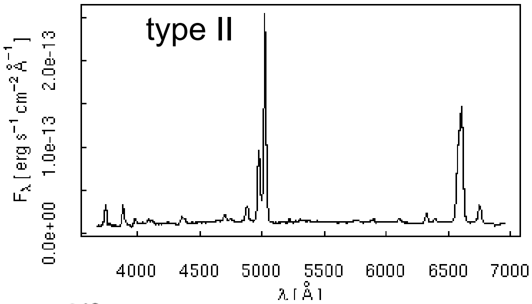
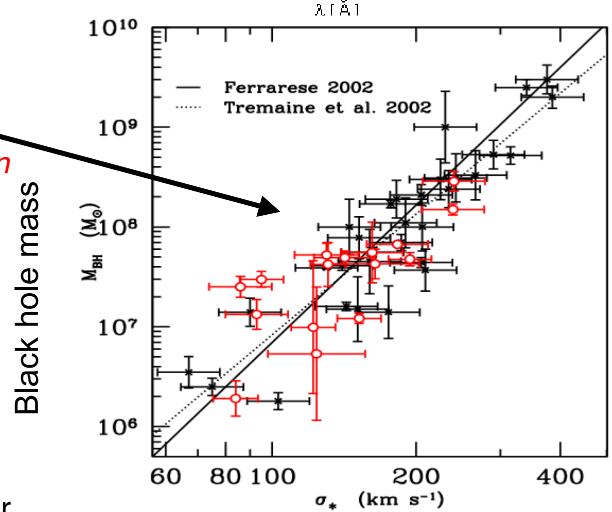


Figure 1: Line-width vs. emission-line lag (in days) for four reverberation-mapped AGNs. In each case, the data are consistent with a virial relationship, i.e., $V \propto \tau^{-1/2}$. The dotted lines are show the best-fit slopes and the solid lines show the best-fit virial relationship [77, 78].

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 believe to be due to 'feedback' (more later) the influence of the AGN on the formation of the galaxy and VV
  - The strong connection between the BH and the galaxy means that each know about each other

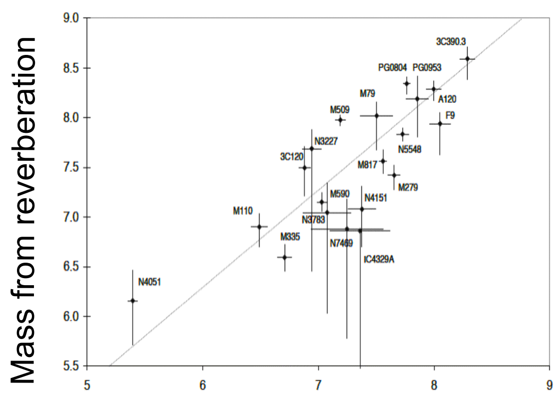




Velocity dispersion of stars in the bulge

Reverberation Masses and Dynamical Masses

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



Mass from photoionization

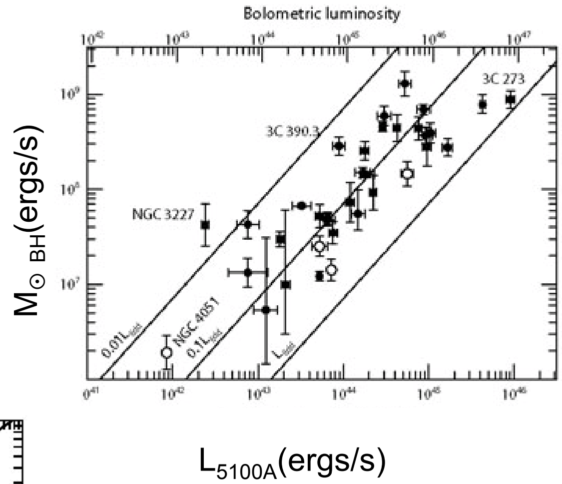
$M_{BH} \sim K\sigma^2 L^{1/2}$

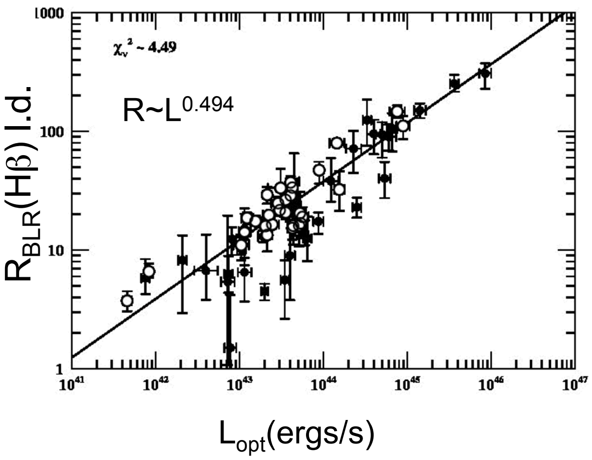
Where K is a constant (different for different lines which is determined by observations

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 $L^{1/2}$

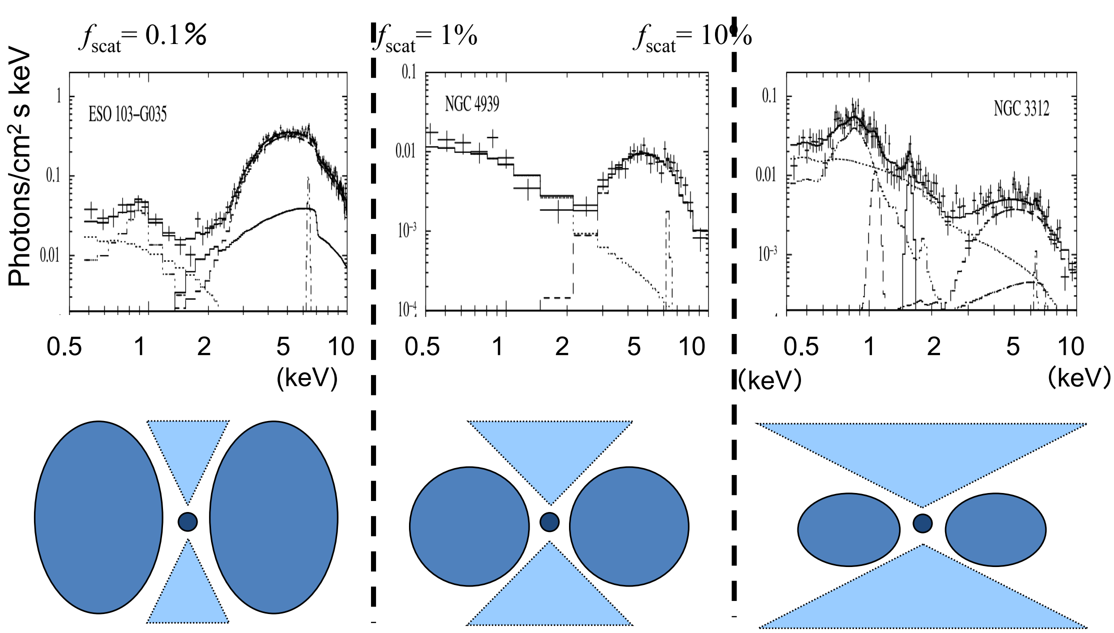




Examples-

XMM

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

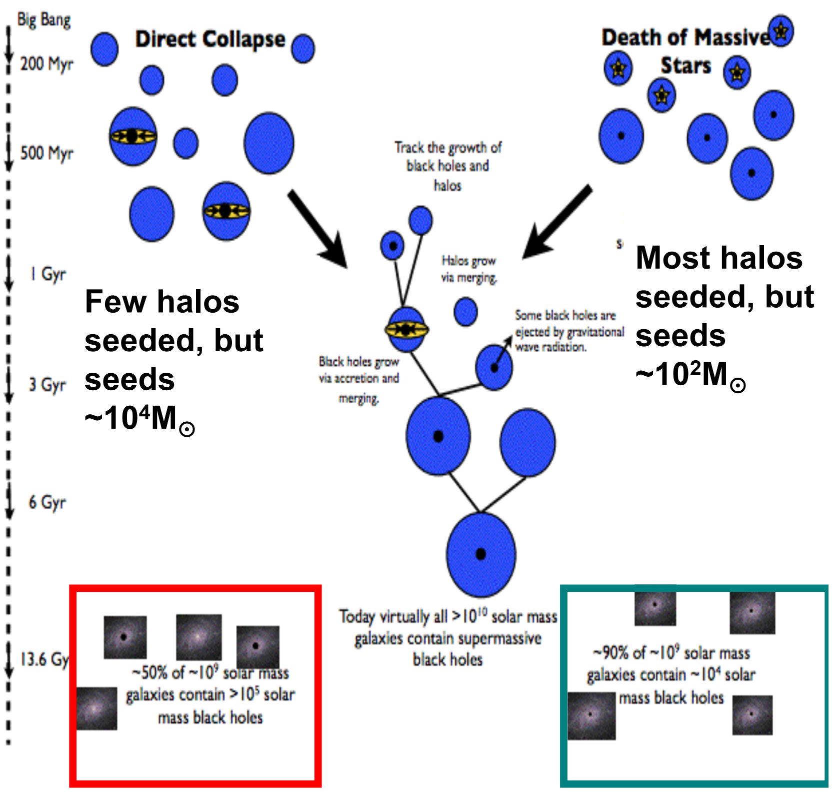


2 Scenarios for Birth of SMBHs

Volontieri 2011

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

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



Constraints on Rest Mass of Black Holes

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

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

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

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

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

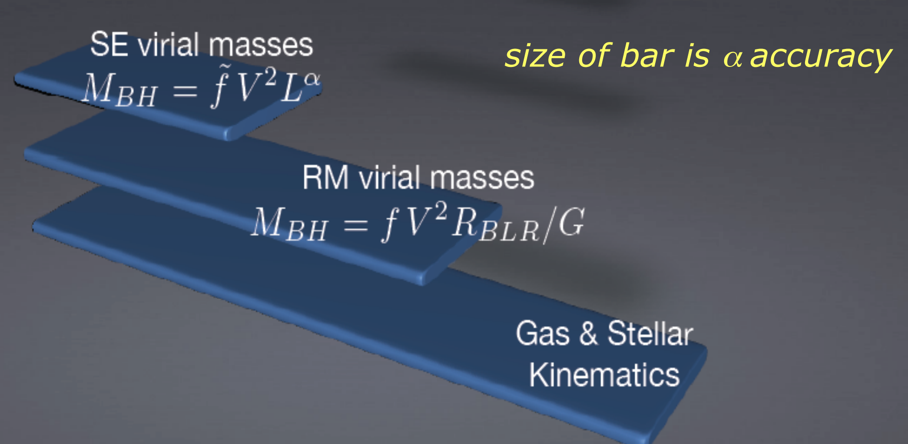
Constraints on Growth of Black Holes

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

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

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

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

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

luminosity function — mass function

$\mu = Log\, M$

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

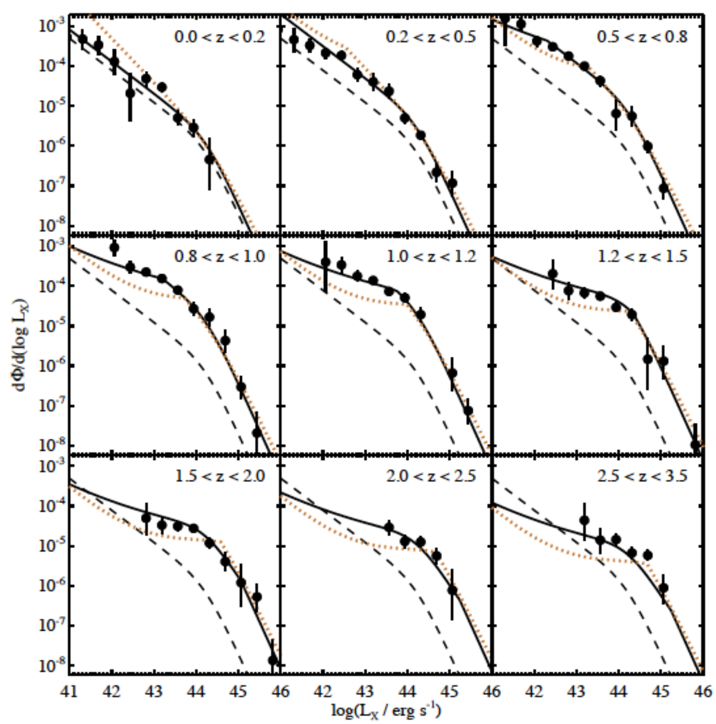
$\dot{\mu} = Log\, \dot{M}$

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

Luminosity function vs z

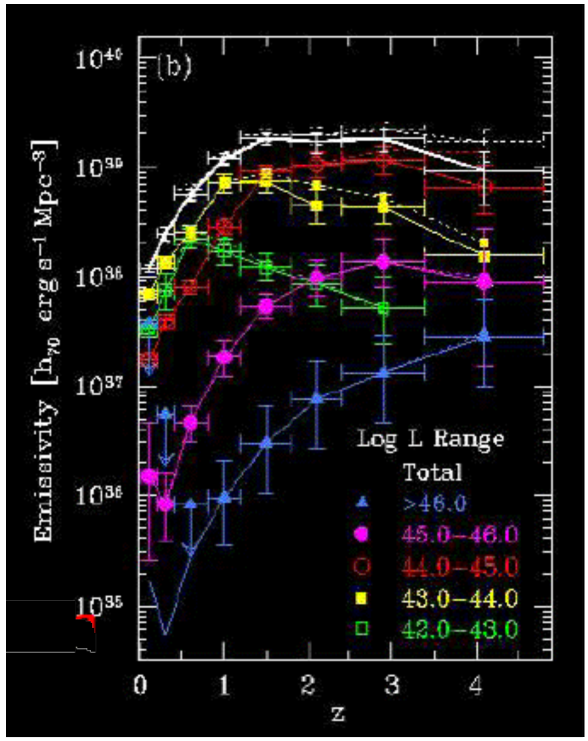
- The Evolution in the Luminosity Function of BH vs cosmic time
- #/Volume/luminosity
- In each plot the dotted grey line is the z=0 function

Aird et al 2009



Transform Luminosity Function to Energy Emissivity

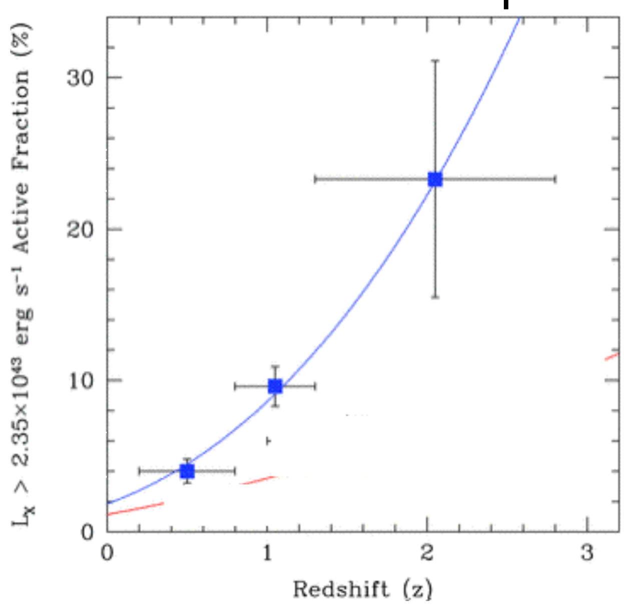
- Integrate the luminosity function in redshift shells
- Notice downsizing more luminous objects are more dominant at high redshift and that the evolution is a function of luminosity
- E_{AGN}~1.4 +/- 0.25 x10^{61} erg per galaxy since z = 3.
- Average AGN luminosity density of L_{AGN} ~10^{57} erg Mpc^3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



Brandt and Hasinger 2005 ARAA

Larger Fraction of Galaxies Active in the past

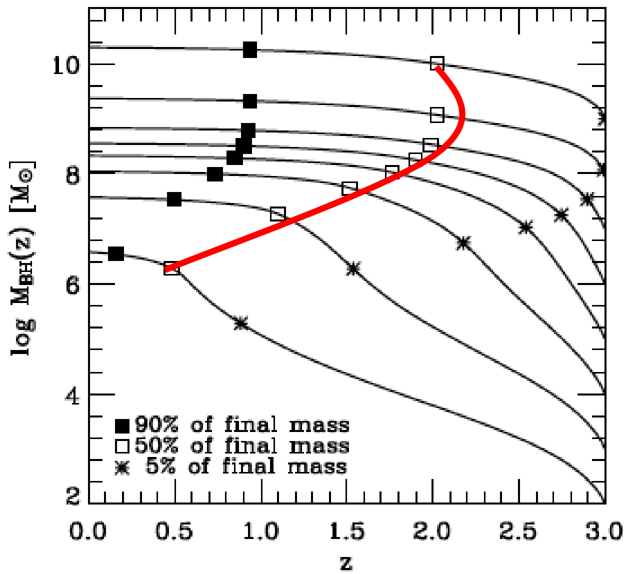
- The evolution seen in luminosity and number is reflected in the fact that a greater fraction of 'normal' galaxies host AGN at higher redshifts



(Bluck et al 2011)

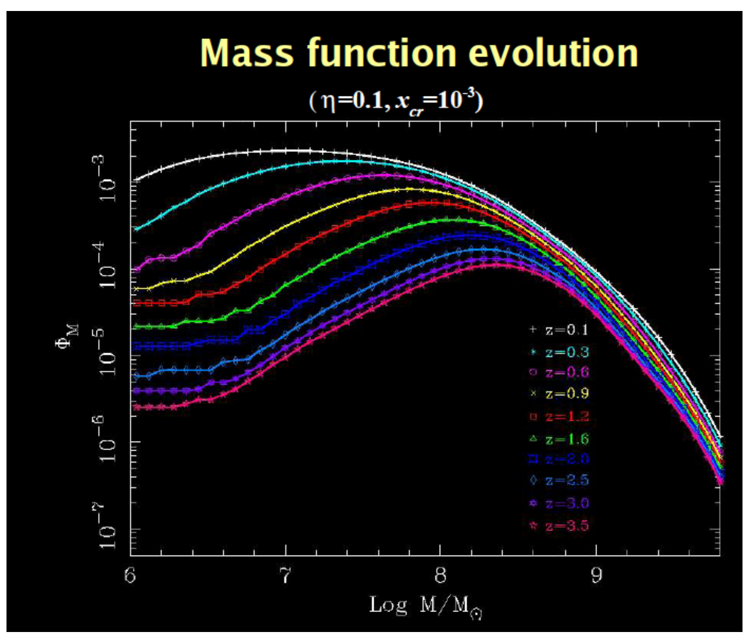
One realization of BH growth

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

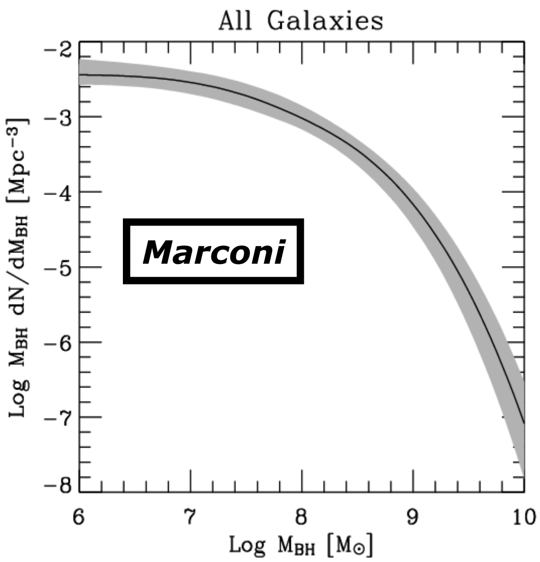


Transform to Mass Growth

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



The local Black Hole Mass Function



Marconi et al. 2004

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

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

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

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

Co-evolution of Galaxies and Black Holes-Summary

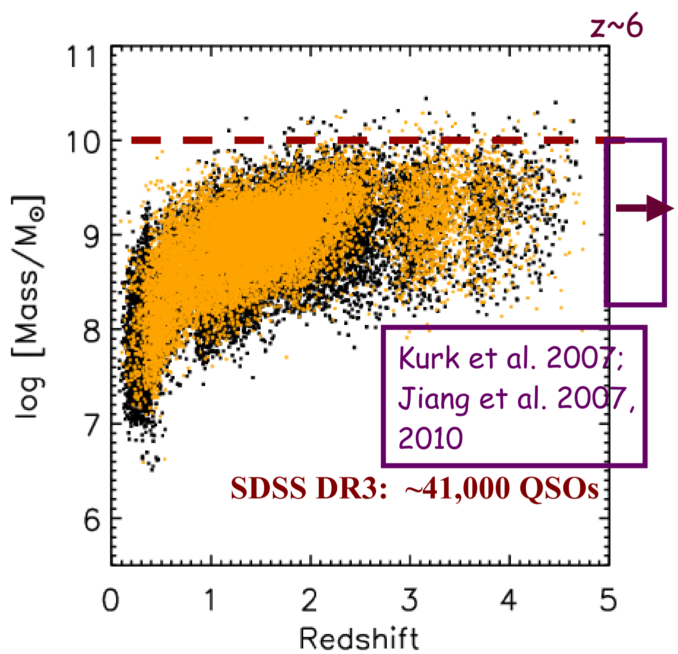
- Theoretical models for the coevolution of galaxies and supermassive black holes are based on combining analytic models and numerical simulation of structure formation in the dark matter with ideas about how star formation and black hole accretion operate in practice
- Over cosmic time, galaxies grow 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~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

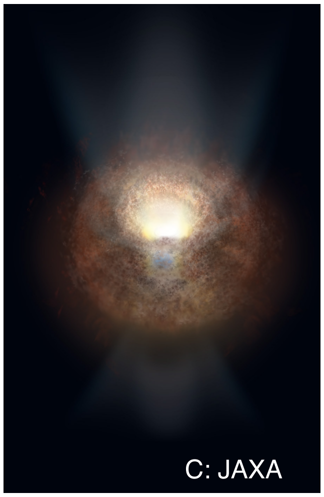
Masses of Distant Quasars- M. Vestergaard

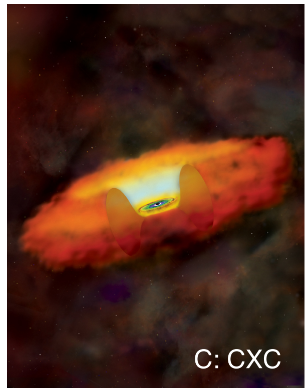
- Using this technique for a very large sample of objects from the Sloan Digital Sky Survey (SDSS)
- Maximum mass M_{BH} ~$10^{10} M_{\odot}$
- $L_{BOL} < 10^{48}$ ergs/s

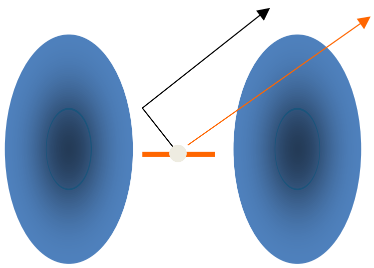


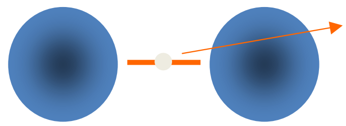
(DR3 Qcat: Schneider et al. 2005)

Some Variation in Geometry









- Effects of geometry can be seen in the spectra