Los Angeles Times | SCIENCE

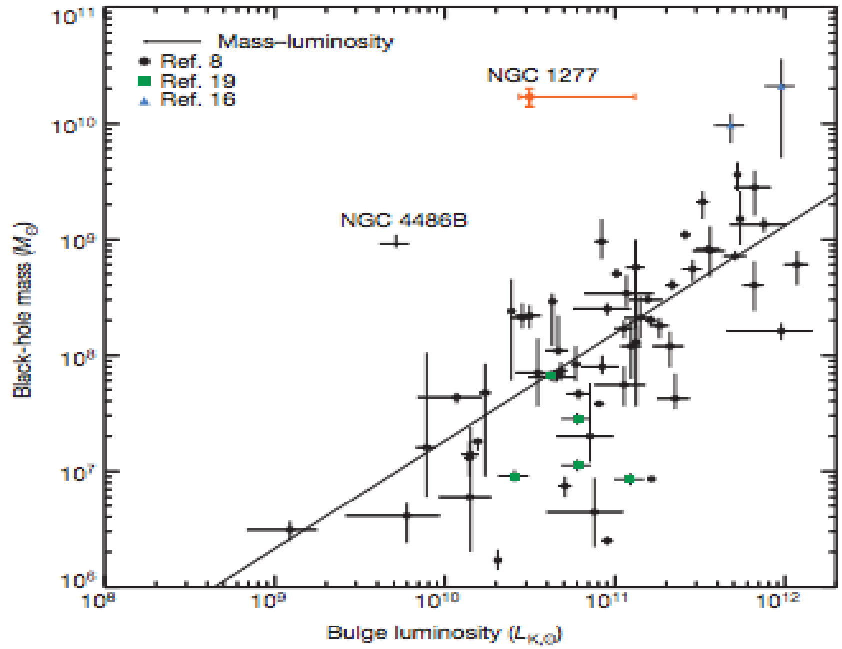
Gargantuan black hole baffles scientists

A hunt for supermassive black holes reveals a monstrous one at the heart of galaxy NGC 1277, which may force theorists to rethink their understanding of black holes.

The enormous black hole was found at the center of NGC 1277, a flat, compact yellowish galaxy near the center of this galaxy cluster in the constellation Perseus. (David W. Hogg-Michael Blanton, SDSS Collaboration / November 29, 2012)

Related photos »

Today's News



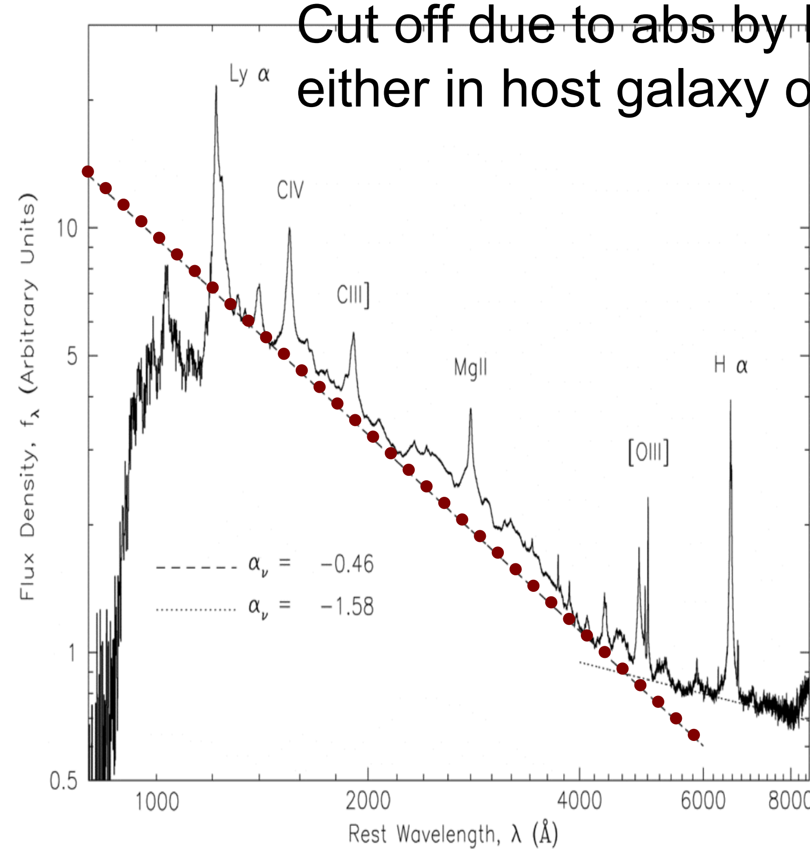
- Yesterday In Nature the object with the highest ratio of BH mass to total galaxy mass 2:3 was discovered.

- But NGC 1277 is stranger still and could help advance our theories of how black holes evolve in the first place.

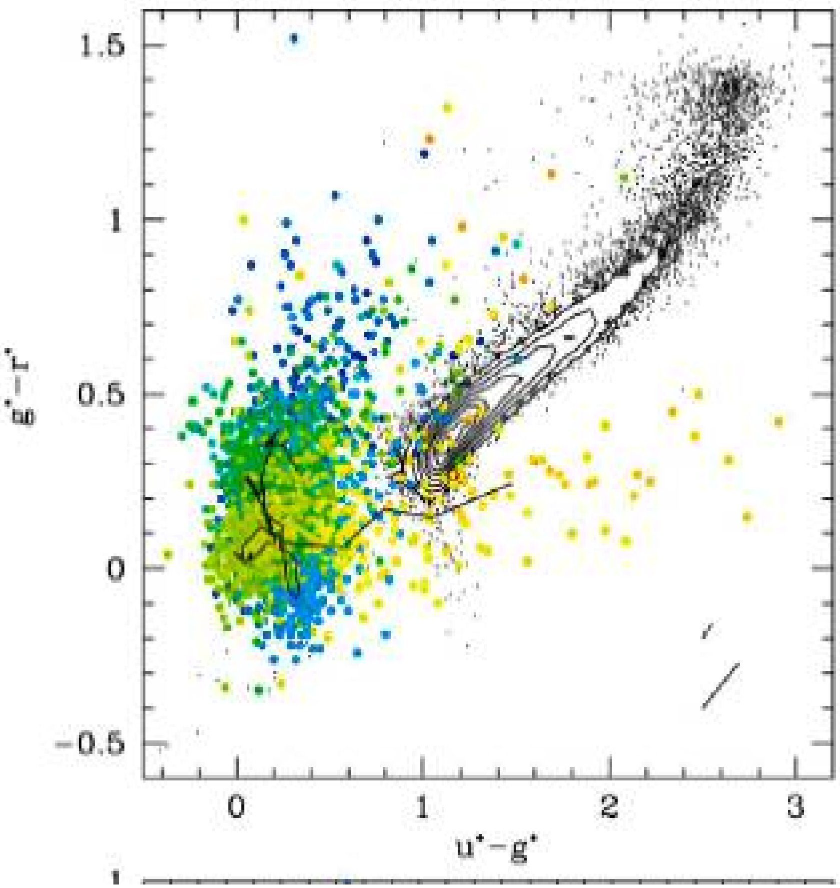
- "This galaxy seems to be

Optical Properties of AGN

Cut off due to abs by H either in host galaxy or IGM



- Strong lines of

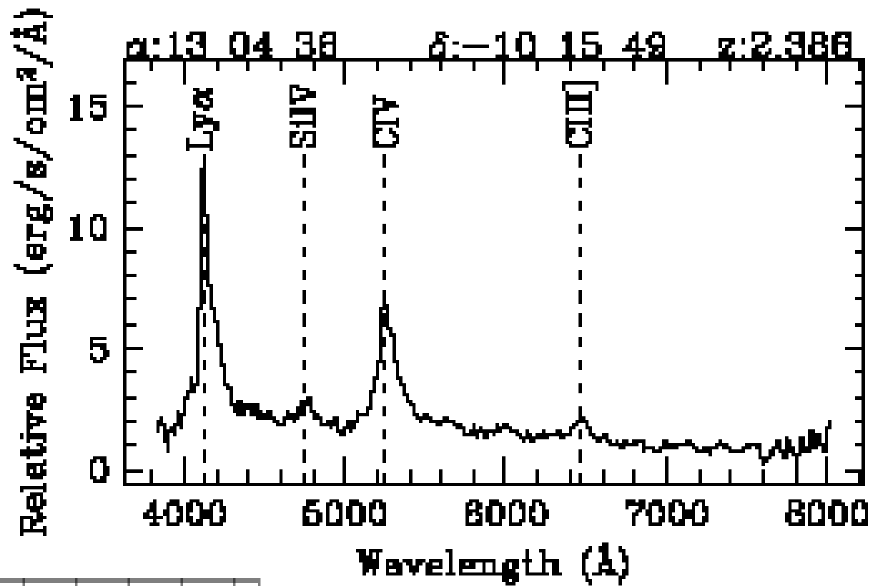


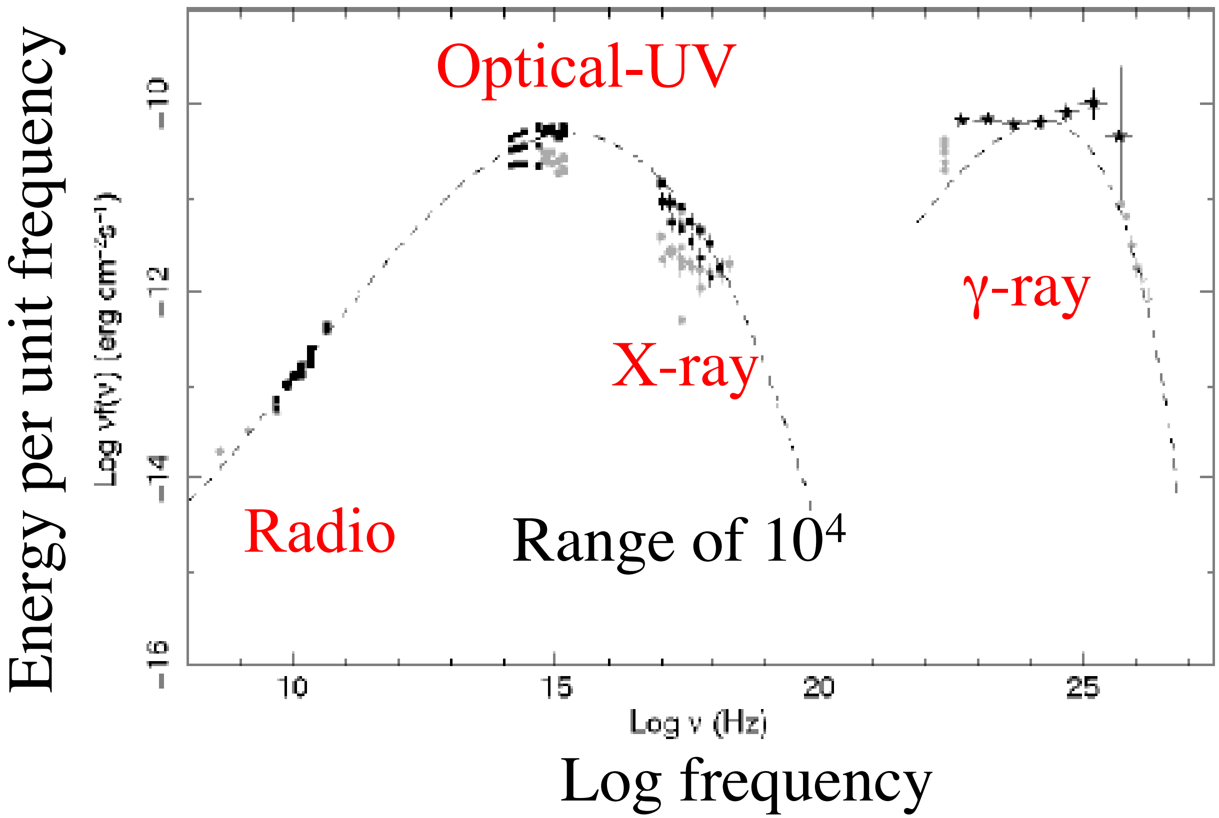
Unusual optical colors (Richards et al SDSS)- **quasars in color**, **stars are black**

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

Broad Band Properties of AGN

- **Broad band continuum, very**



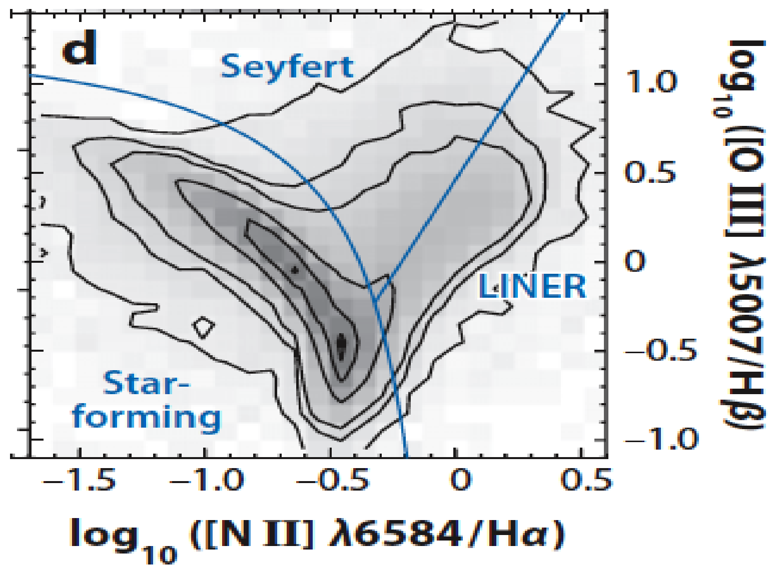


Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us

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

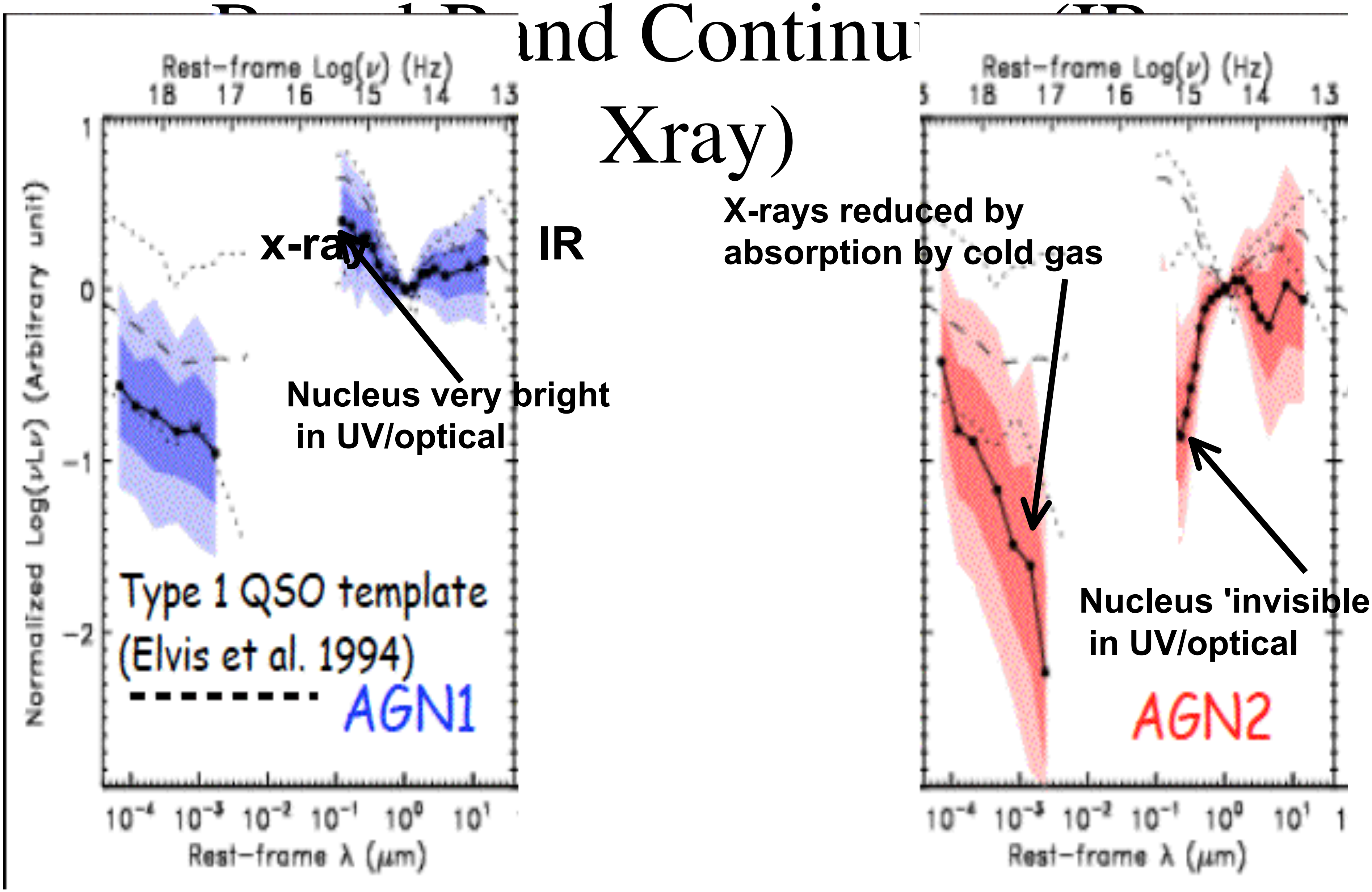
Optical Emission Lines

- 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'



line ratio plot NII/Hα compared to OIII/Hβ– AGN lie in a particlar part of this diagram Darkness of plot is log of the number of objects inside the contour

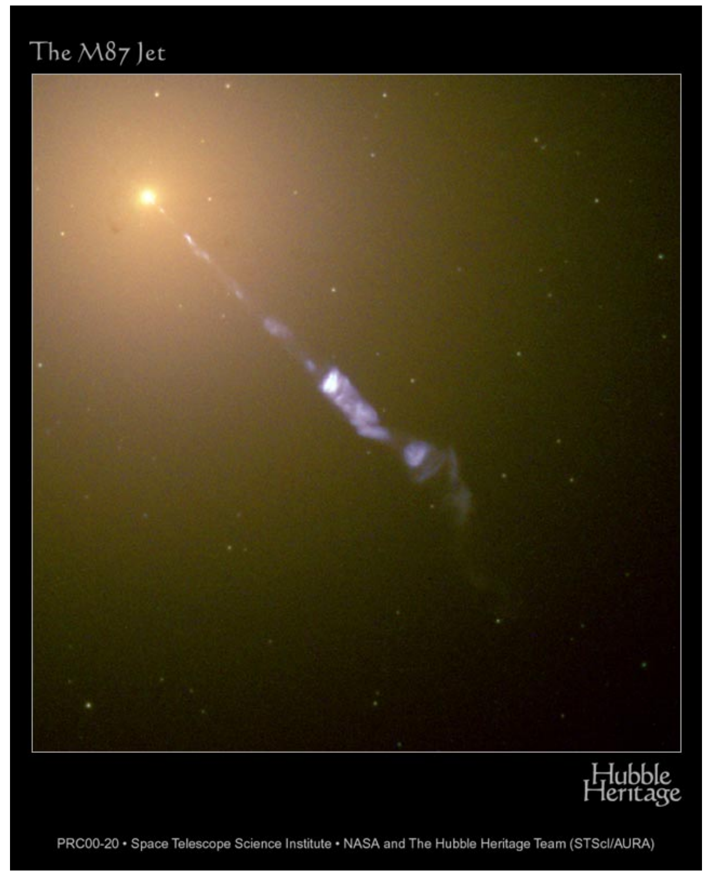
…and Continu… Xray)



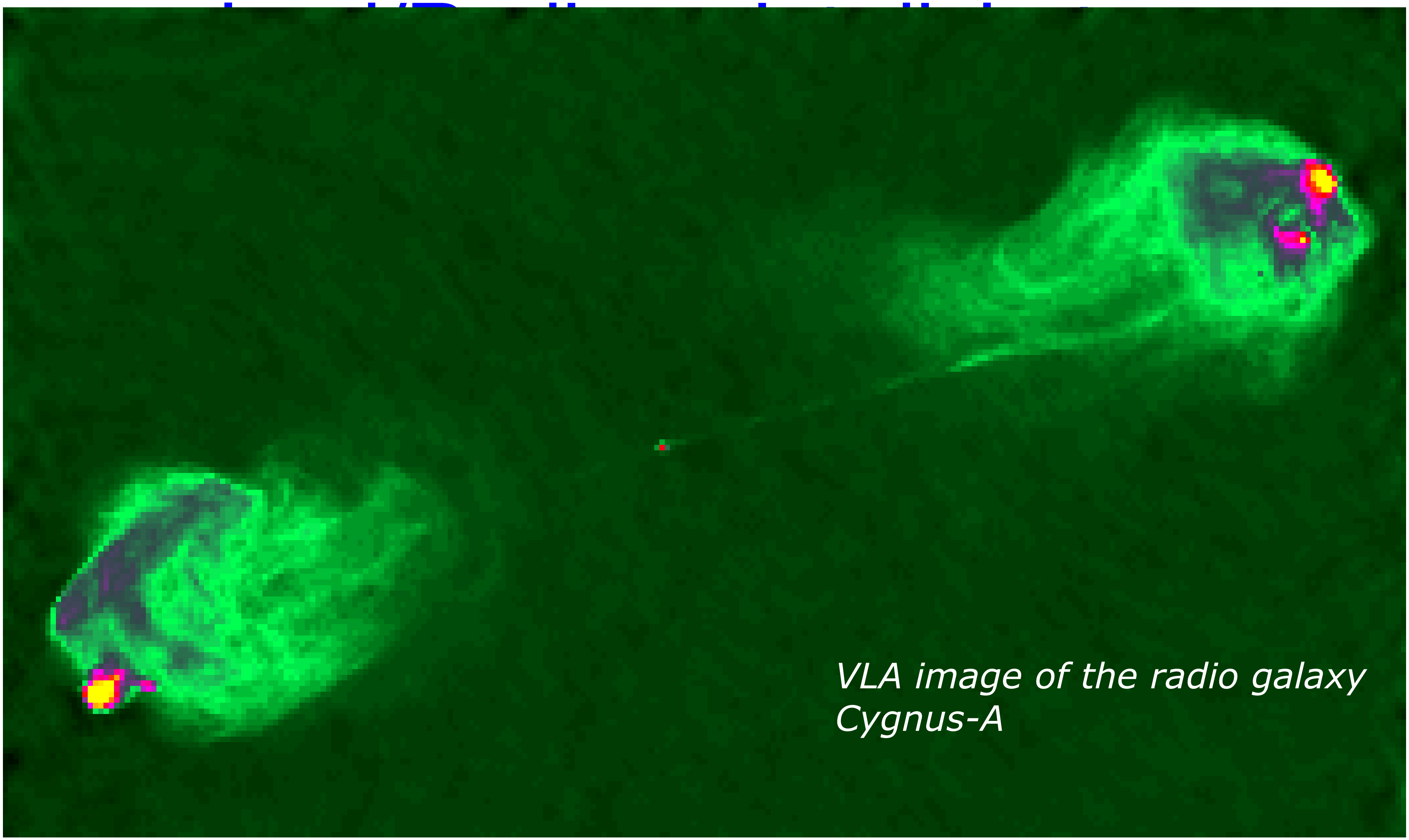
Active Galactic Nuclei

- 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

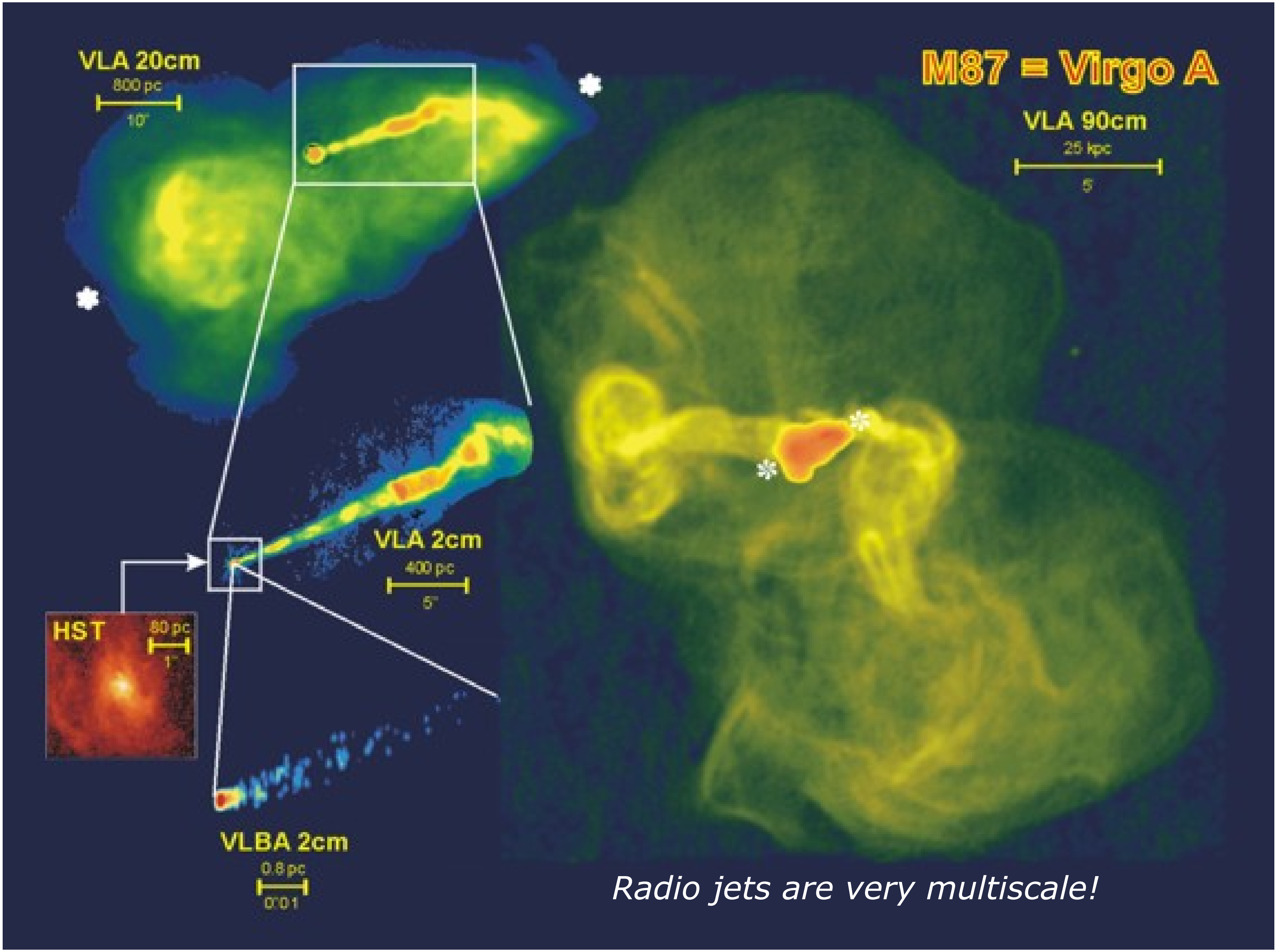
- The Jet
  - Jet of material squirted from vicinity of SMBH
  - Lorentz factor of >6



AGN 'Types' The Radio-



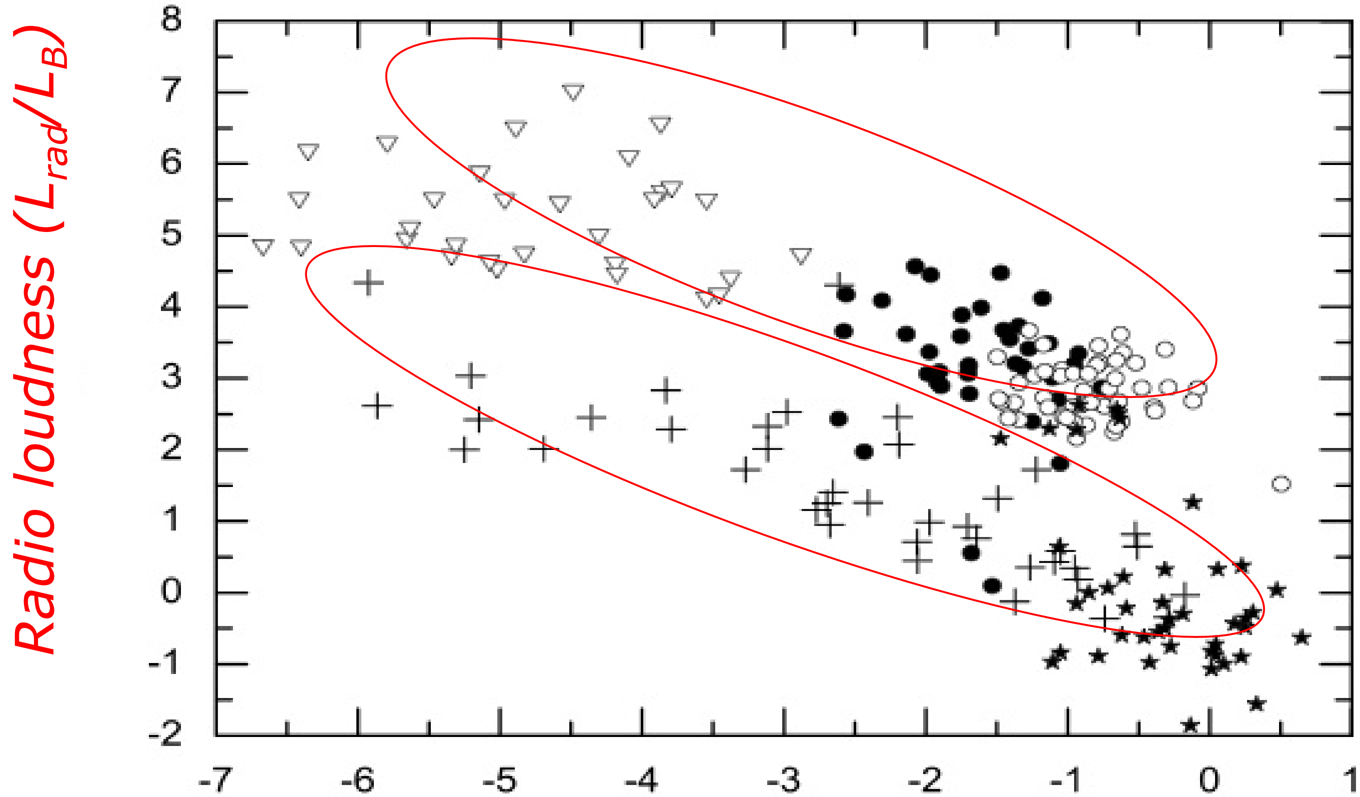
VLA image of the radio galaxy Cygnus-A



Radio jets are very multiscale!

The Radio-loud/Radio-quiet dichotomy

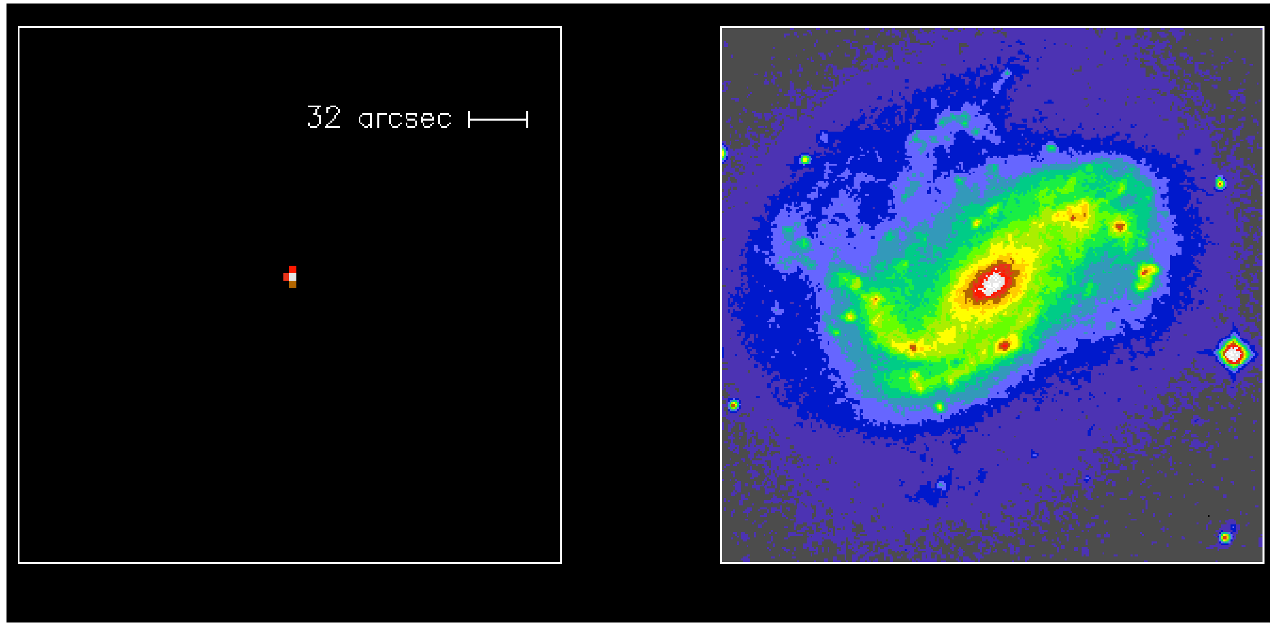
Define relative importance of radio emission by ratio of radio luminosity *L_{rad}* **to optical luminosity** *L_B- **8** order of magnitude range*



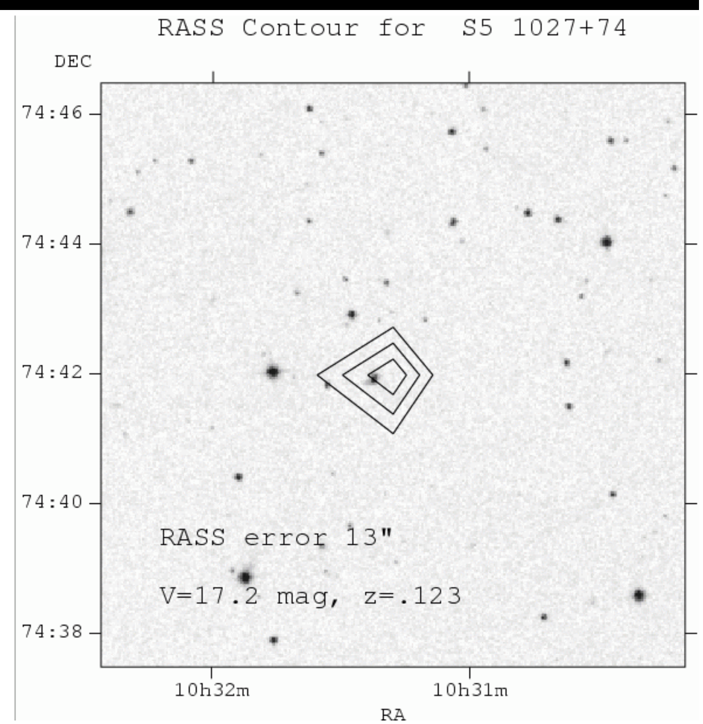
Sikora et al. (2007) *Accretion rate (Eddington Units)*

X-ray

- 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

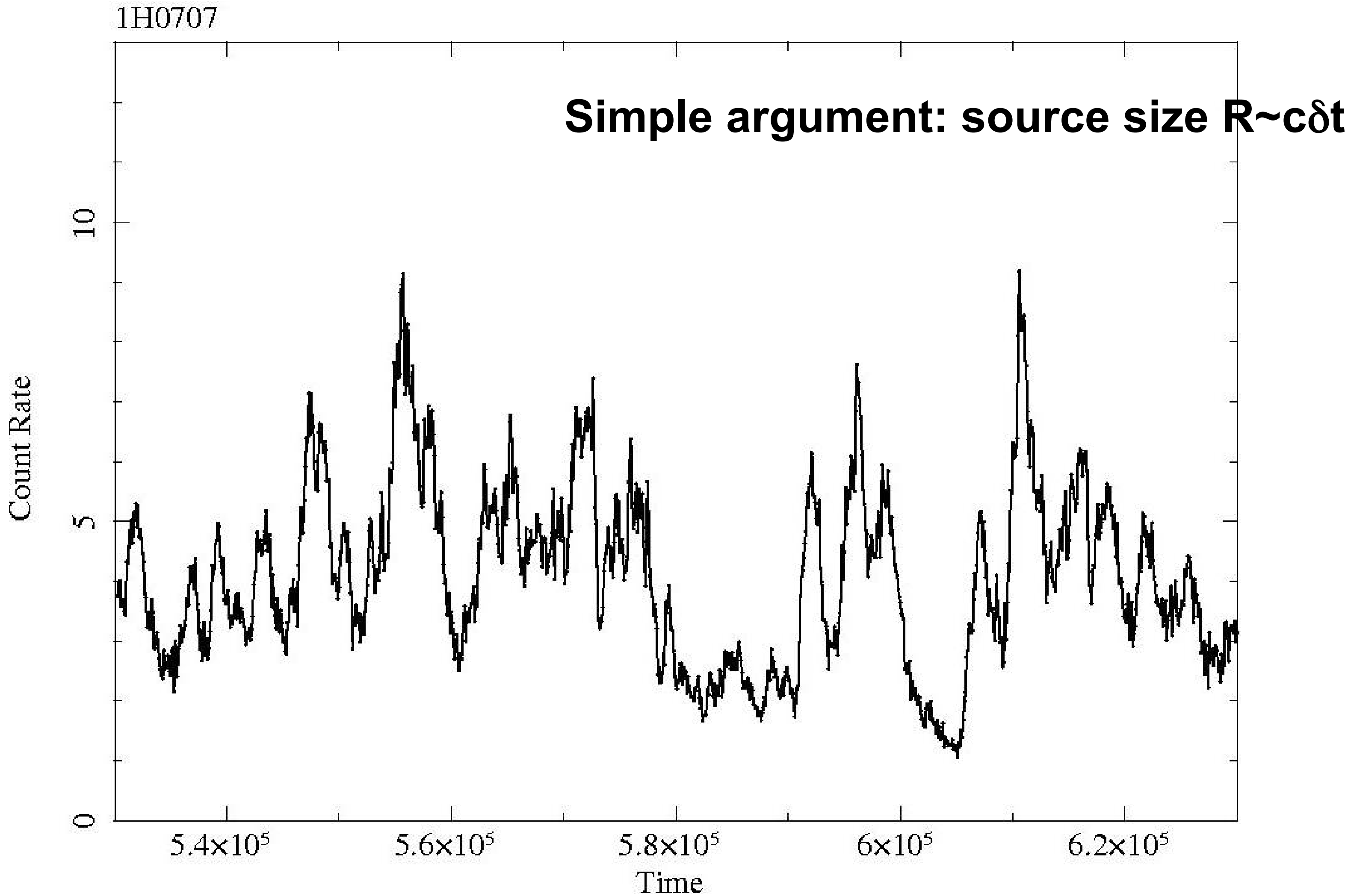


Rosat x-ray all sky survey image overlaid on sky survey image



Rapid variability in AGN

Source luminosity ~5×10^{43} ergs/sec

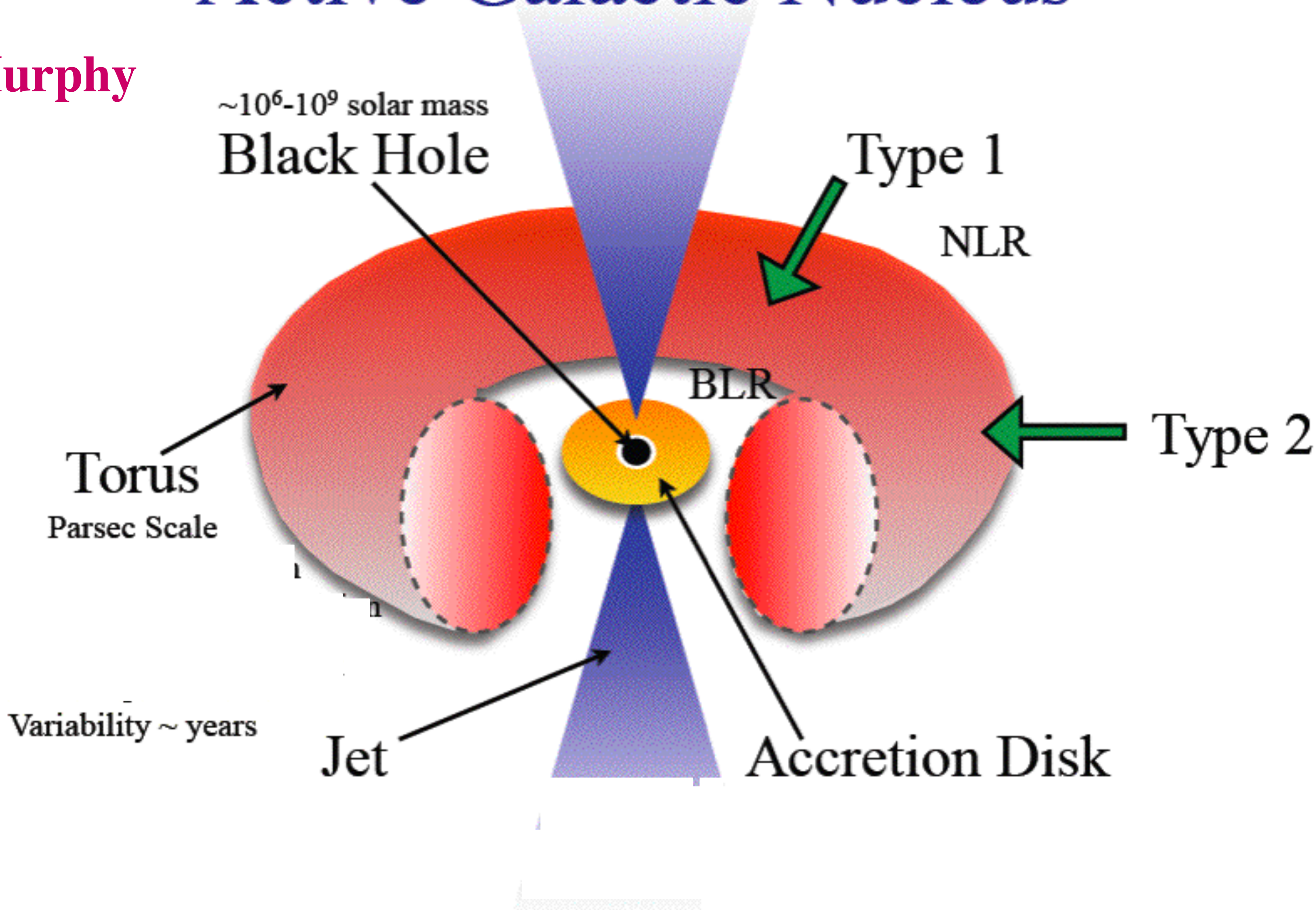


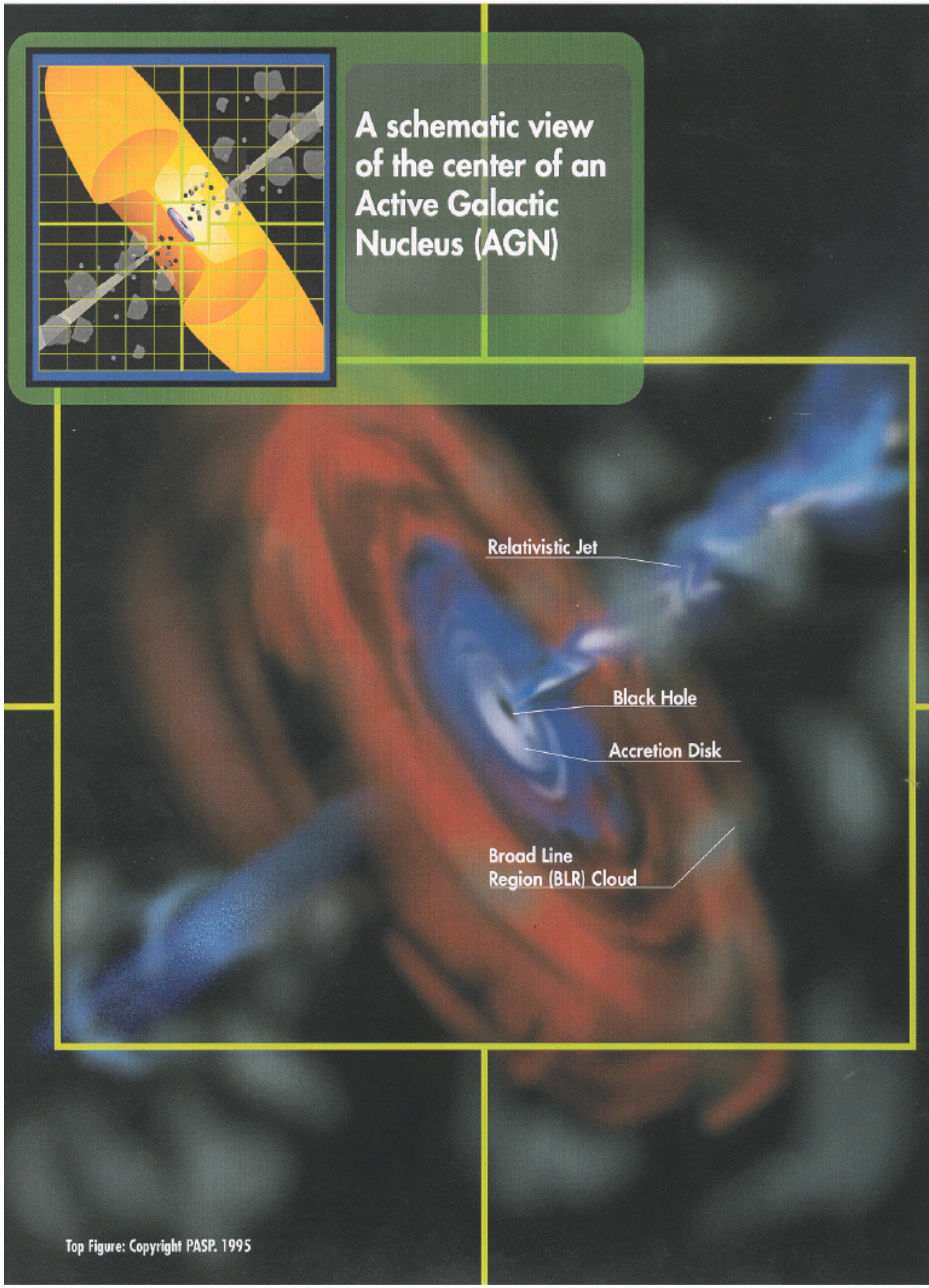
Broad Range of Properties

- Luminosity
  - Range from $<10^{40}$ erg/s to $\sim10^{48}$ erg/s
  - Fundamental parameters controlling L are **mass and mass accretion rate**
  - Most Powerful objects (quasars)- AGN totally outshines host galaxy
- Level of obscuration- how much material is in our line of sight
  - In some objects, can see all of the way down to the SMBH (type I)
  - In other objects, view at some wavelengths is blocked by obscuring material (some

Active Galactic Nucleus

K. Murphy





tral Region of GN

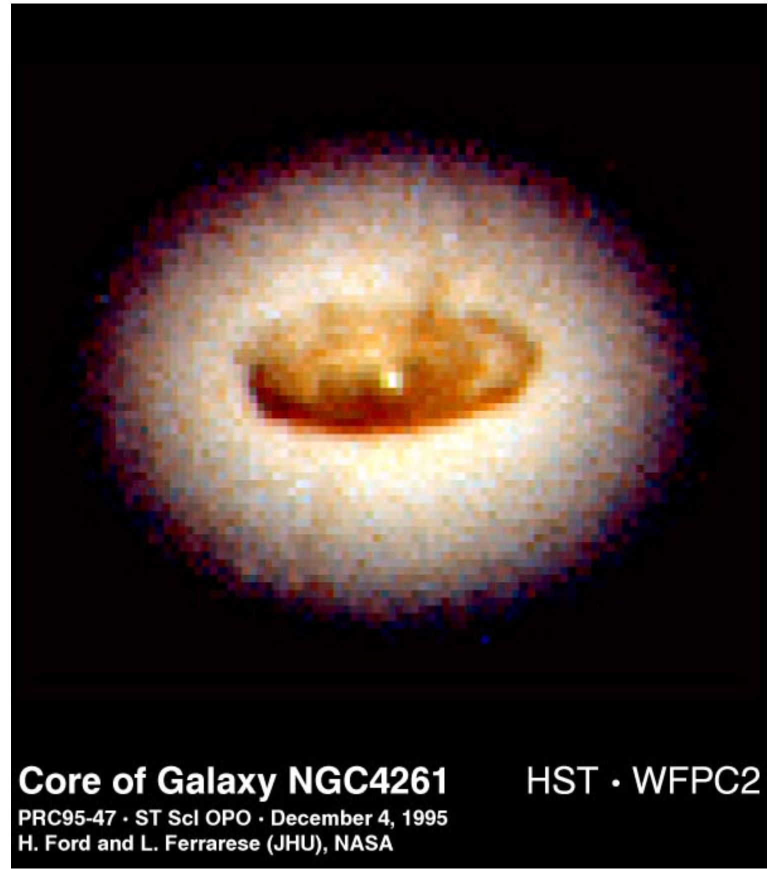
Source	Distance from central source
X-Ray Fe Kα	3-10 R_S
Broad-Line Region	600 R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

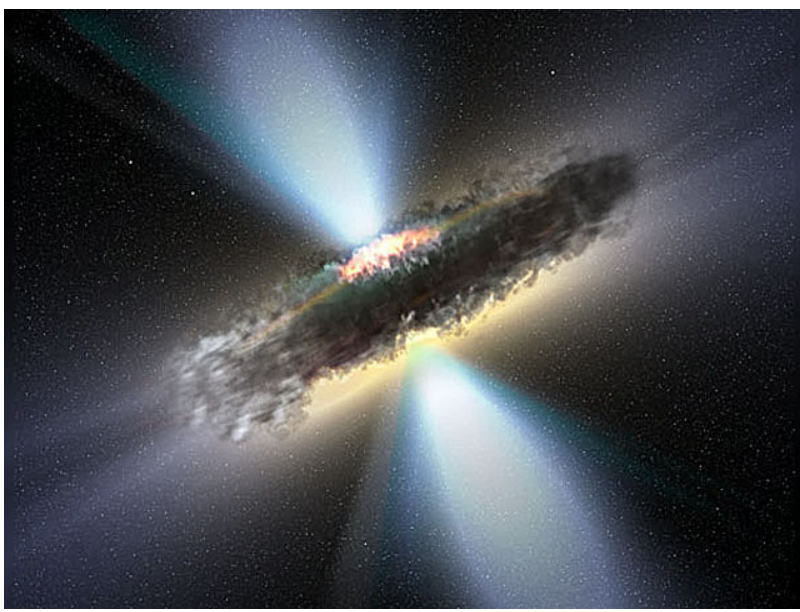
R_s= Schwarschild radius=$2GM/c^2$

R_s=$1.4 \times 10^{13} M_8$ cm; $R_s/c \sim 500 M_8$ sec

The Dark Side of AGN

- ***Many AGN are obscured***- obscuring material is of several types
  - Located in the ISM of the host galaxy





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

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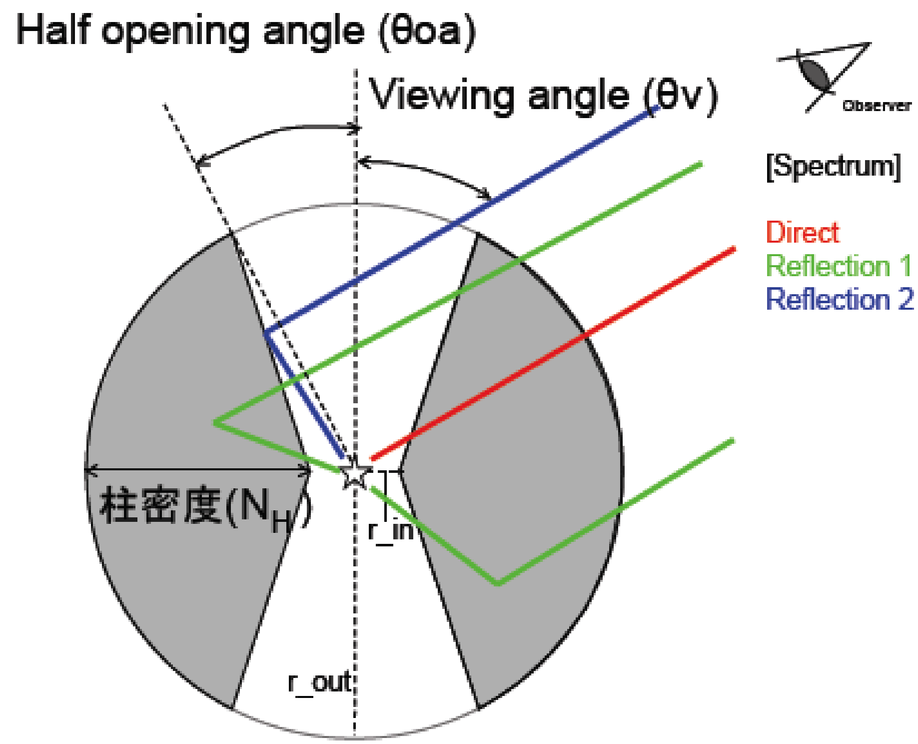
AGN Zoo

- 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



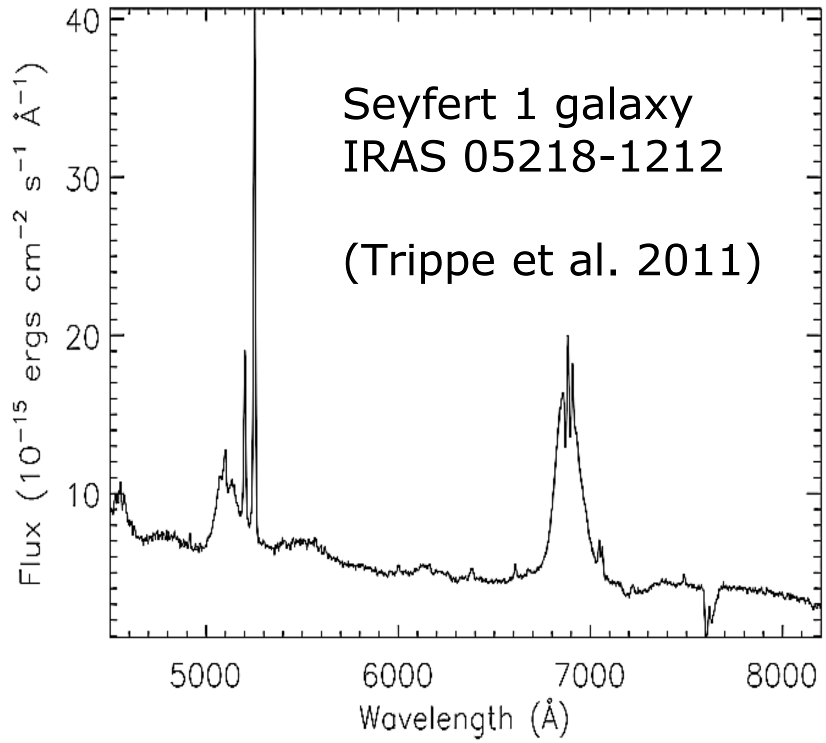
Radio Loudness	Optical Emission Line Properties		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	**Type 0** (Unusual)
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	
Radio-loud:	NLRG { FR I / FR II	BLRG SSRQ FSRQ	Blazars { BL Lacs / (FSRQ)
	decreasing angle to line of sight ->		

Table 1: AGN Taxonomy: A Simplified Scheme.

AGN Types

Broad line (typ

- 'Blue' optical/UV continuum
- Broad optical/UV lines
  - Emission lines from permitted (not forbidden) transitions
  - Photoionized matter $n>10^9 cm^{-3}$



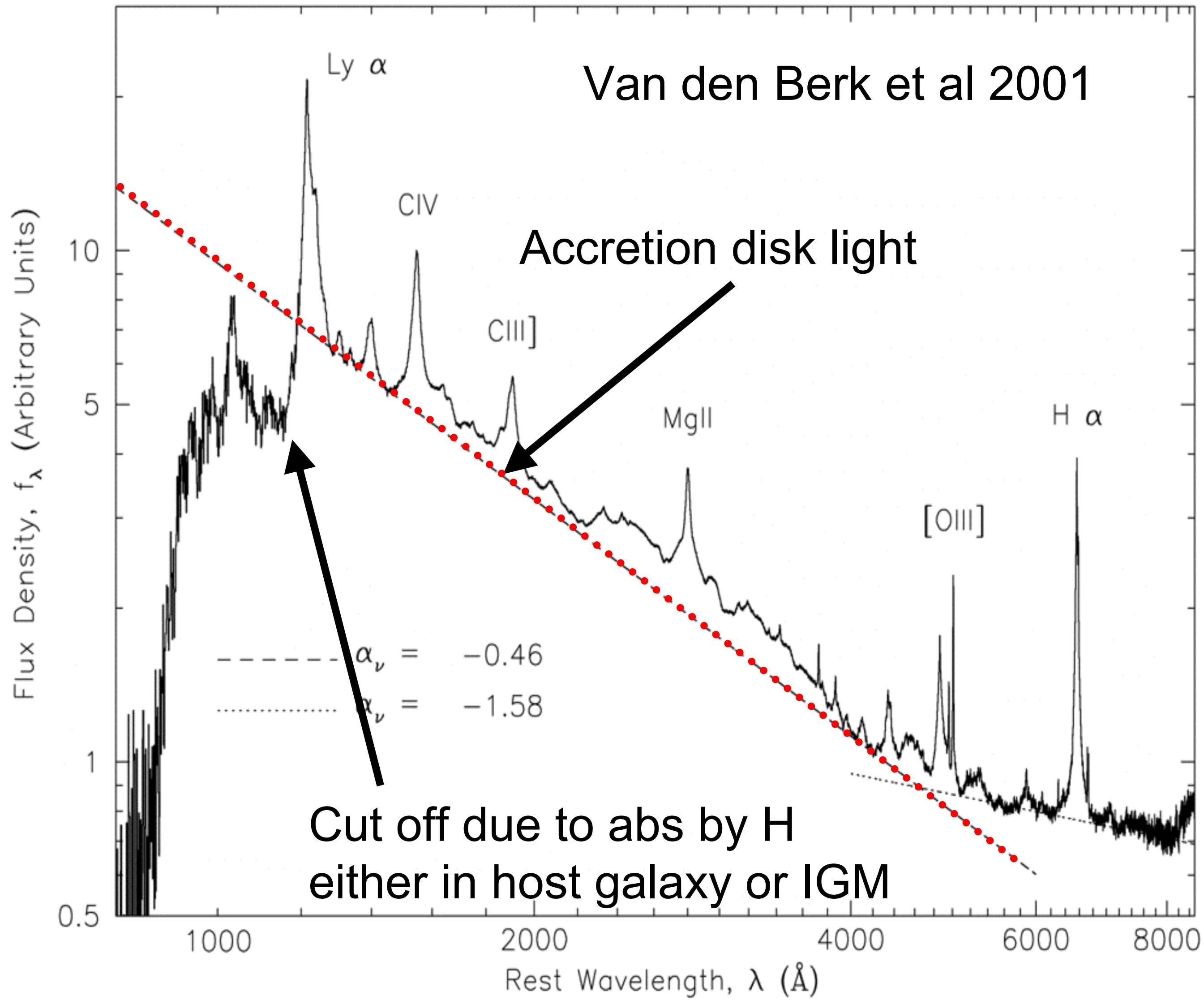
Hβ, [OIII], [NII],Hα

- 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



Origin of λ>4000Å continuum not known

AGN Types

Narrow line (type-2) objects

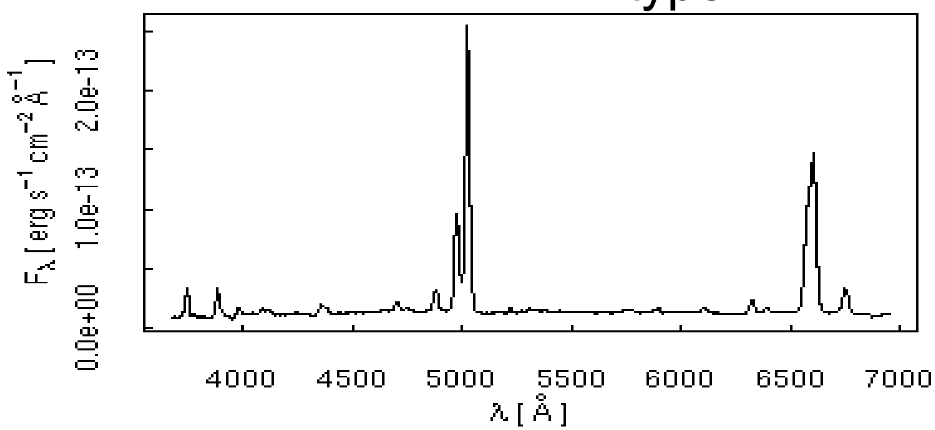
- Reddened Optical/UV continuum
- Optical Emission line spectrum
  - "Full light" spectrum only shows narrow (~500km/sec) optical/UV lines
  - Broad optical/UV lines seen in *polarized* light… shows that there is a hidden broad line region seen via scattering (Antonucci & Miller 1985)
- **X-ray spectrum 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

Objects without a Strong Continuum- e.g type II

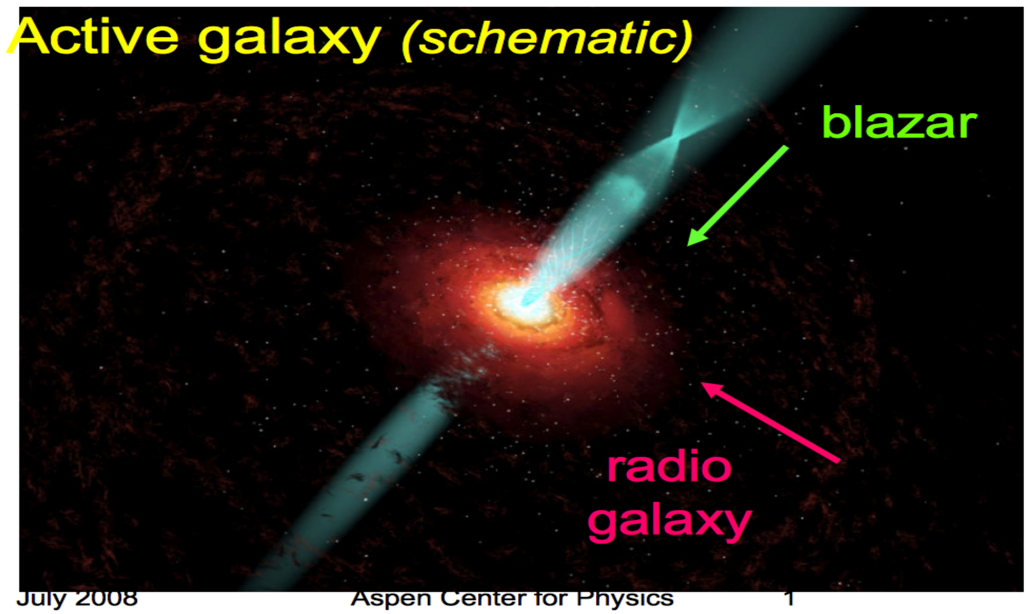
- type II **<u>do not</u> have broad lines and have a weak or absent 'non-stellar' continuum**

- **Depending on the type of survey and luminosity range ~50% of all**

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

Names and Properties

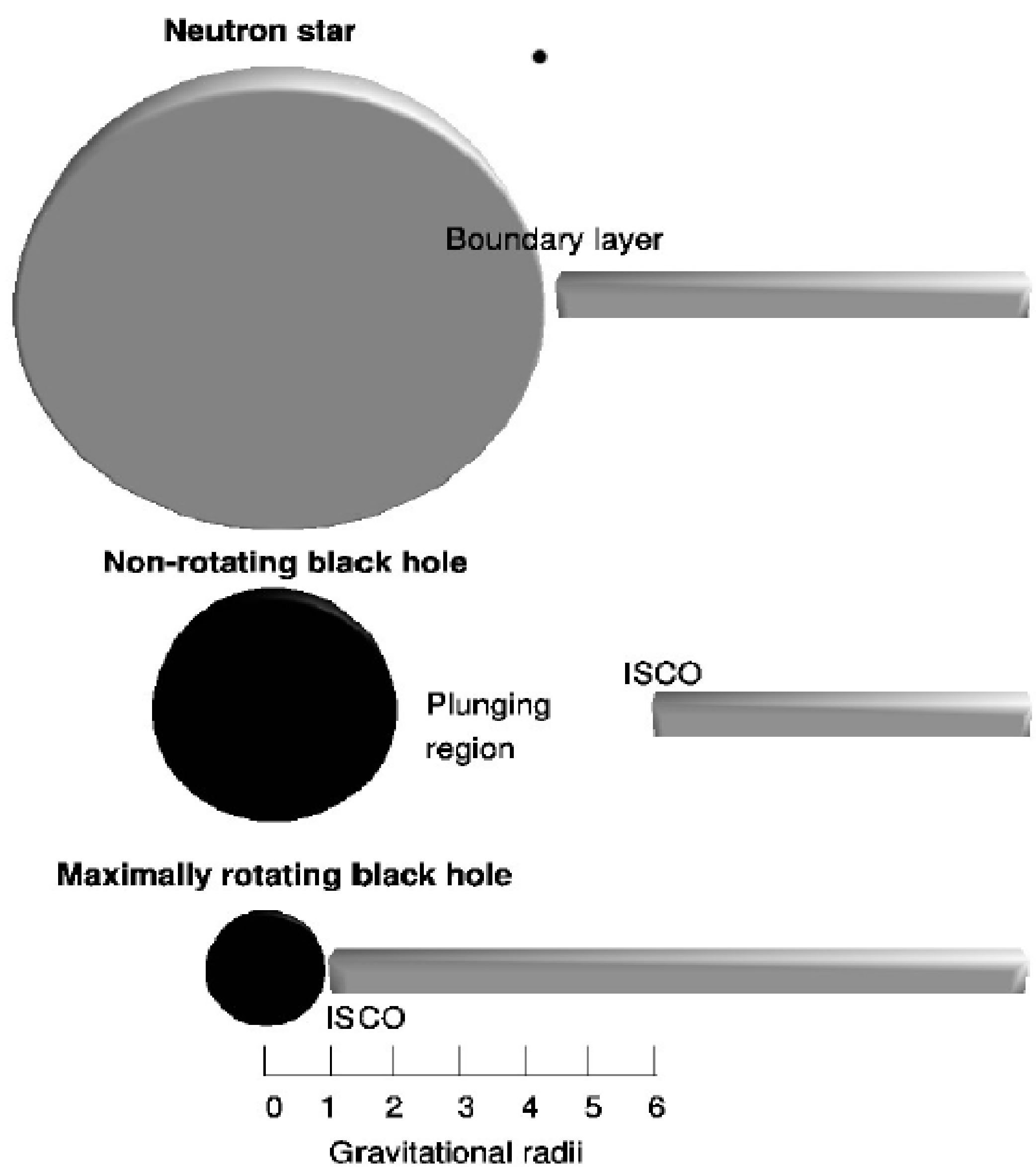
Radio Loudness			No Lines
Radio quiet (weak or no jet)	Type II (narrow forbidden lines) Seyfert 2	Type I (broad permitted lines) Seyfert 1 QSO	
Radio Loud (strong jet)- **ONLY in ELLIPTICAL Galaxies**	FR I NLRG FR II	BLRG	Bl Lac Blazars FSRQ
X-ray Properties	Highly Absorbed- strong narrow Fe K line,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

ISCO=innermost stable orbit-disk terminates there



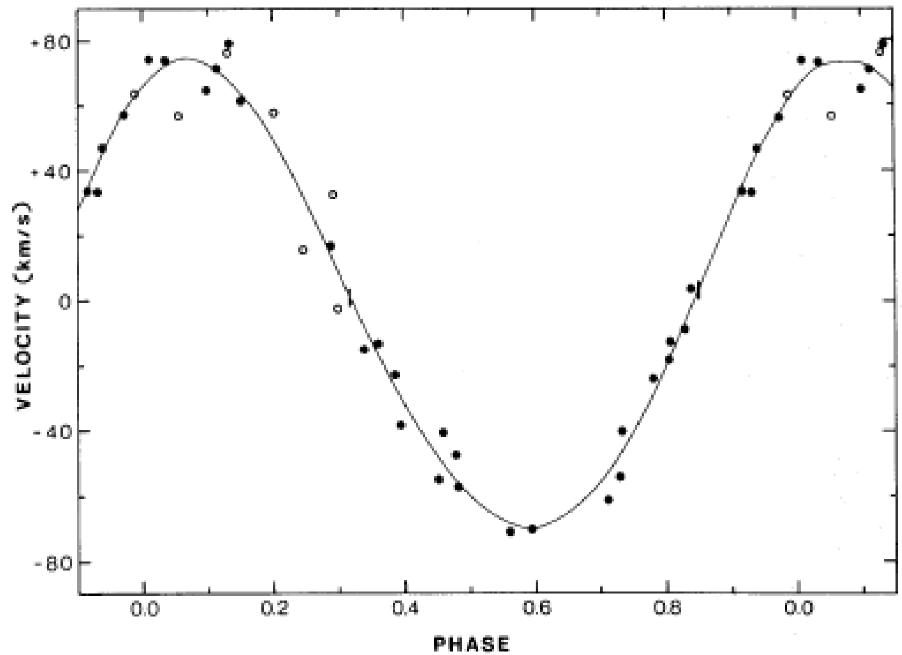
What about spin ?

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 o



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

- 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

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

$q=M_2/M_1$

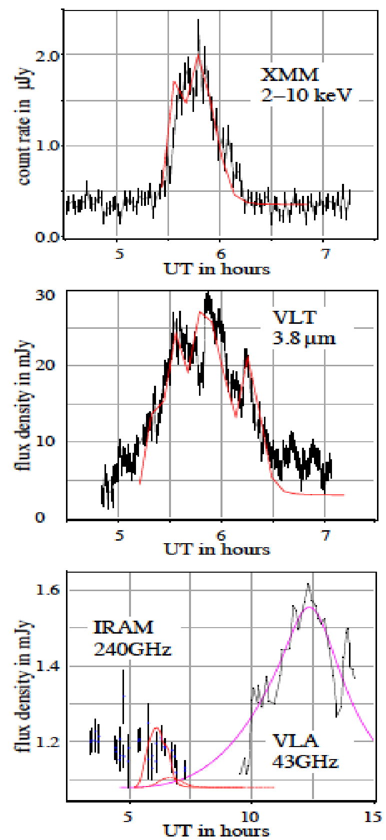
the value of the mass function is the absolute minimum mass of the compact star

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

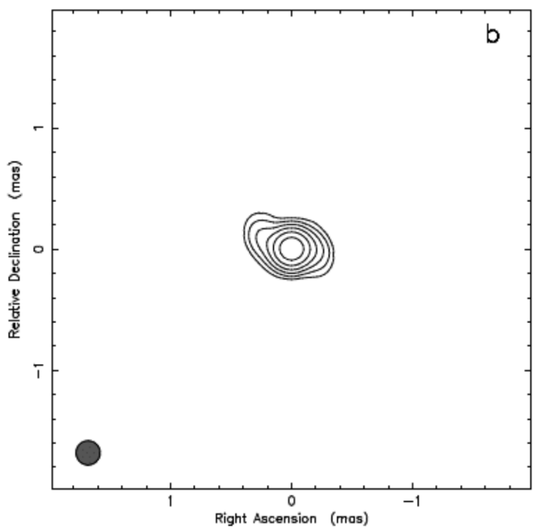
Radio, near IR and x-ray light curves



- The center of the MW is called Sagitarius A*(SgrA*) from the name of the radio source at the dynamical ... he MW.

... o the location of a ... e variable x-ray ... l- 100x less than a ... ay binary) and IR

... source is very



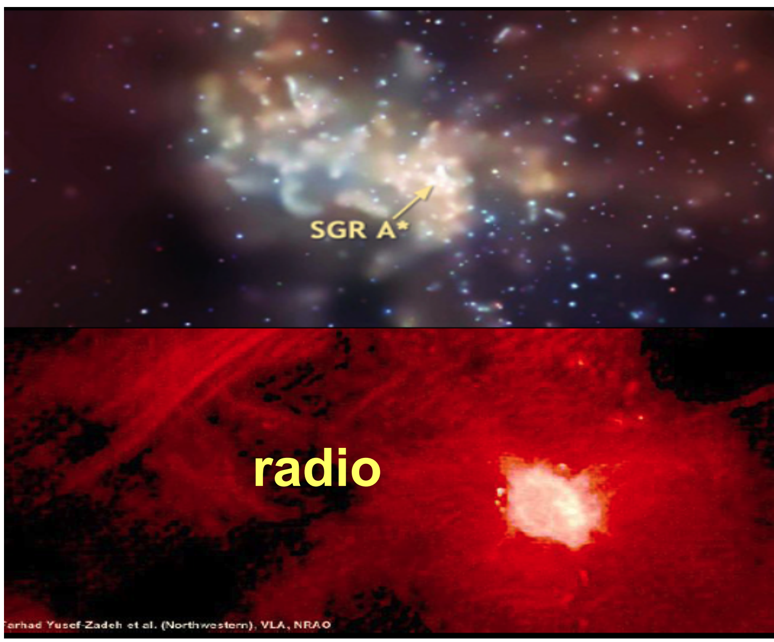
Radio image of SgrA*

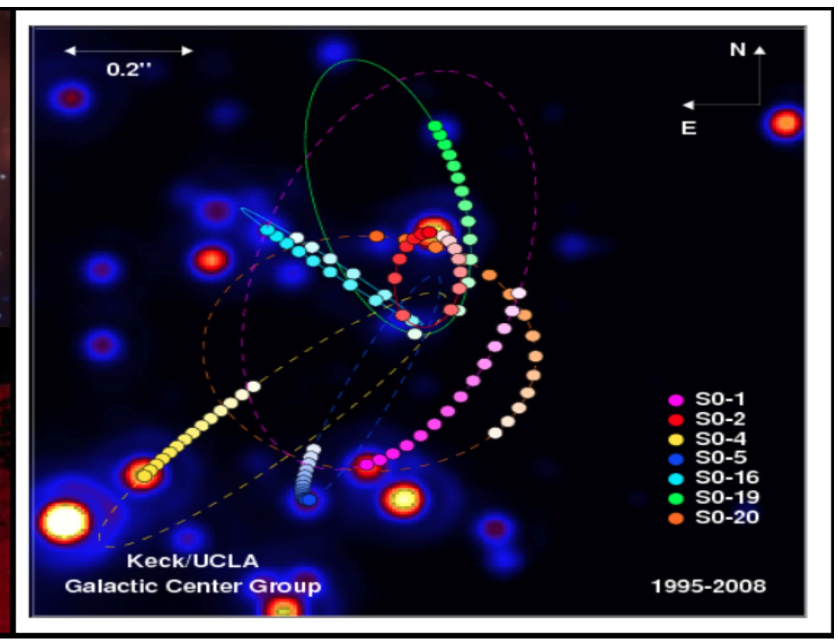
Some Problems with Sgr A*

- 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

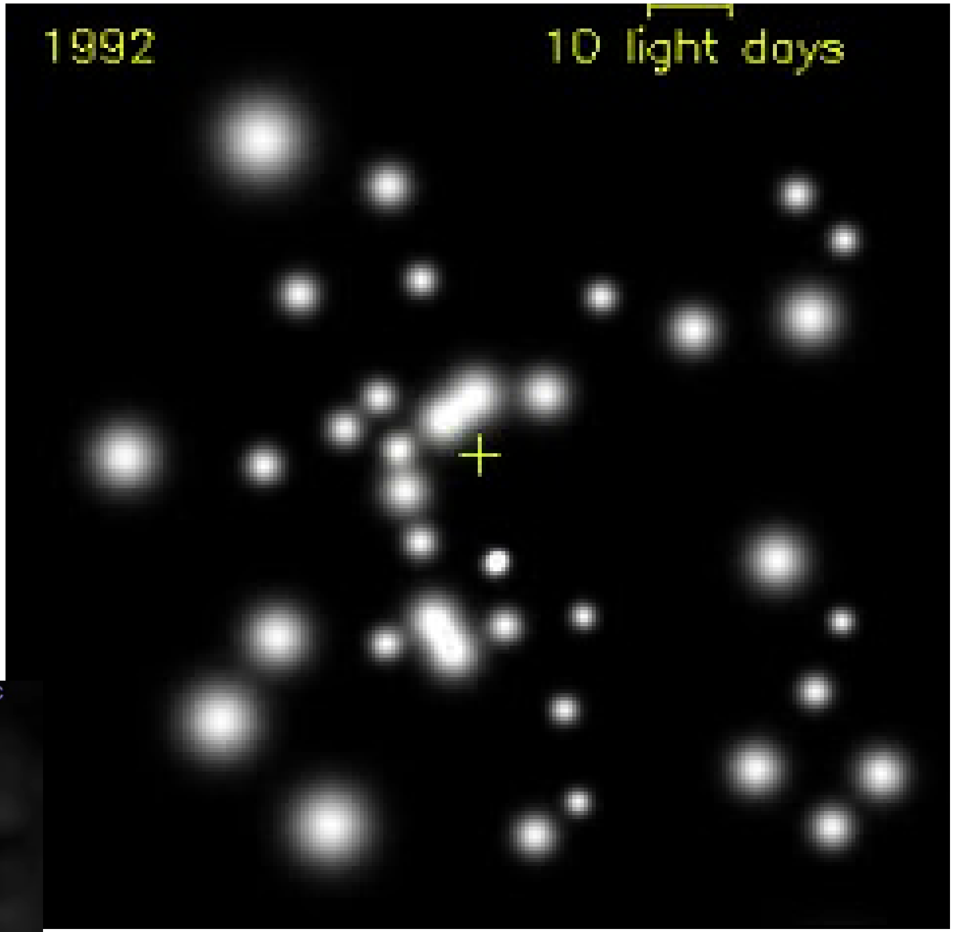
MW Galactic Center

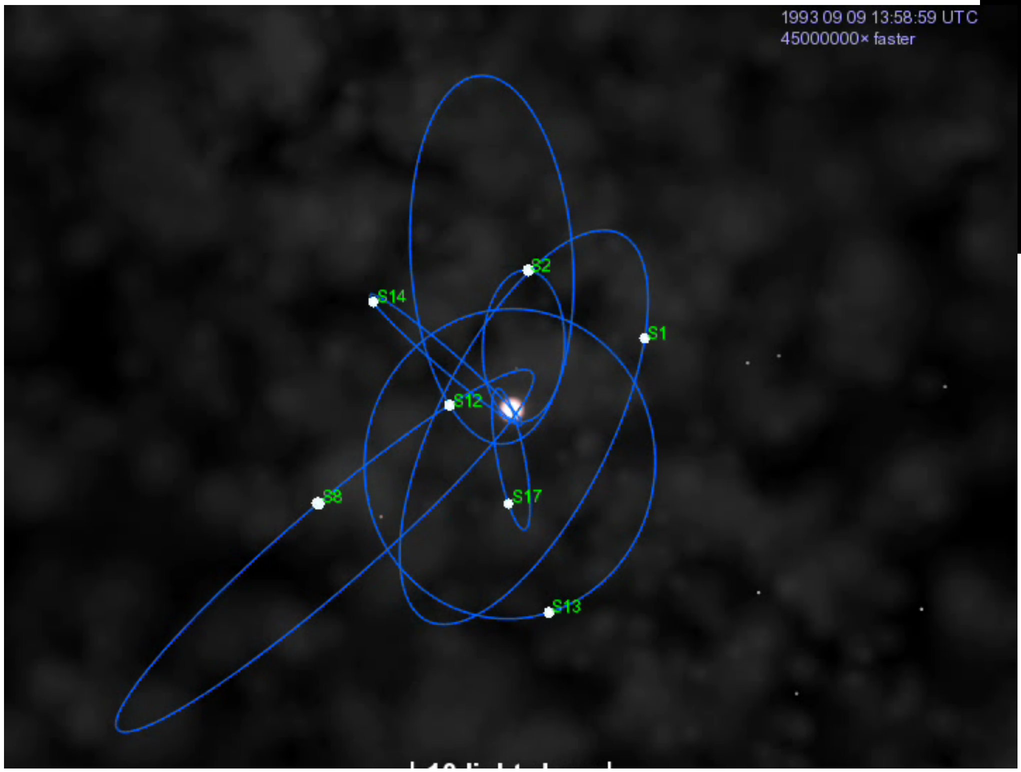
- galactic centers are 'special' places
- MW galactic center





the Center of the Milkyway- see http://www.youtube.com/watch?v=ZDxFjq-scvU http://www.mpe.mpg.de/ir/GC/

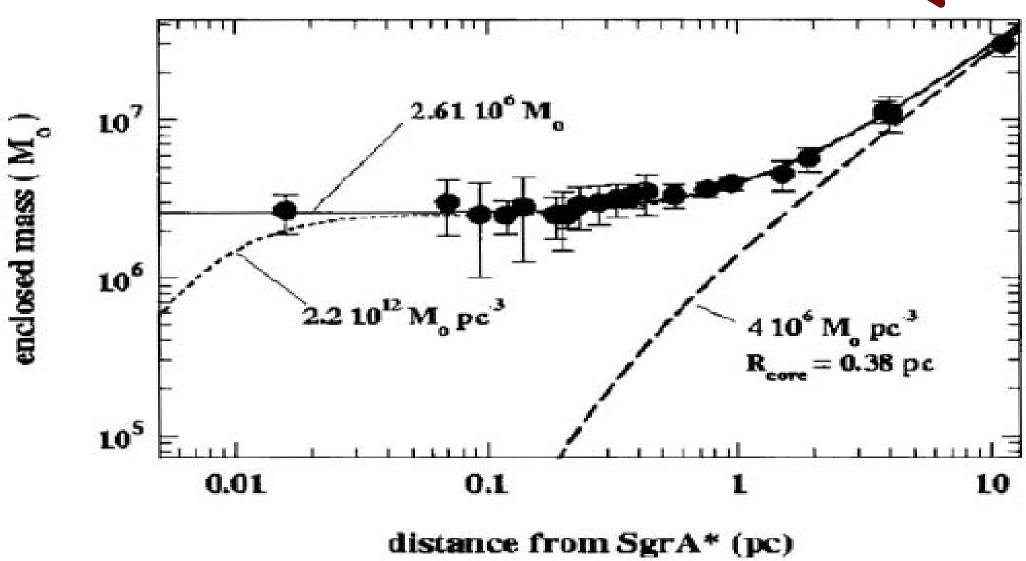




Predicted mass from models of the Milkway

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



•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 x 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

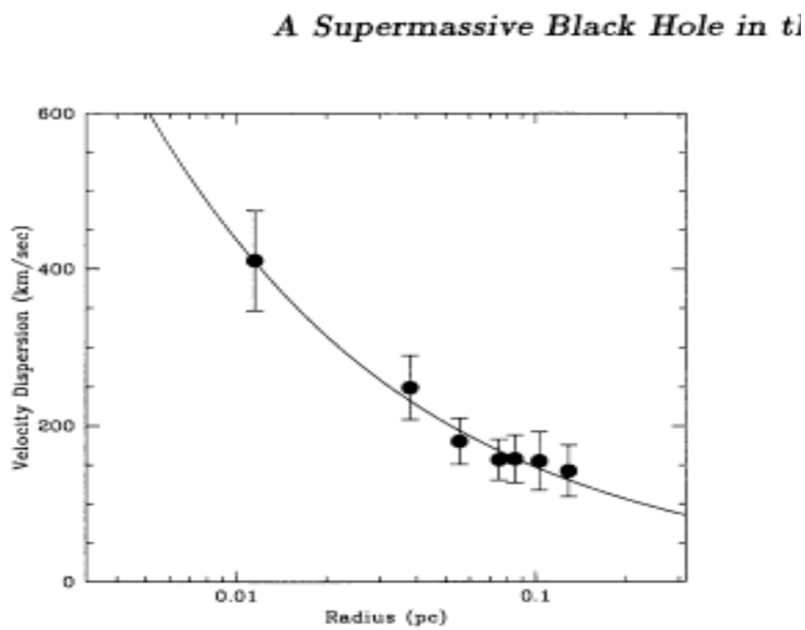
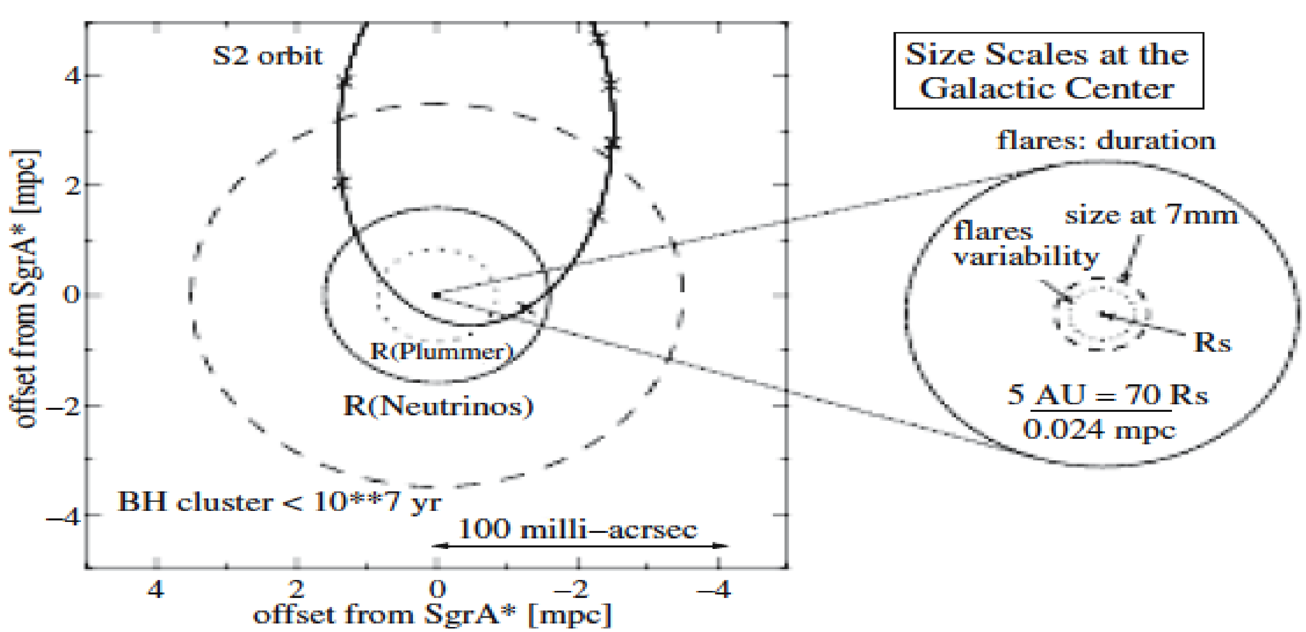


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

Ghez et al 1998


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

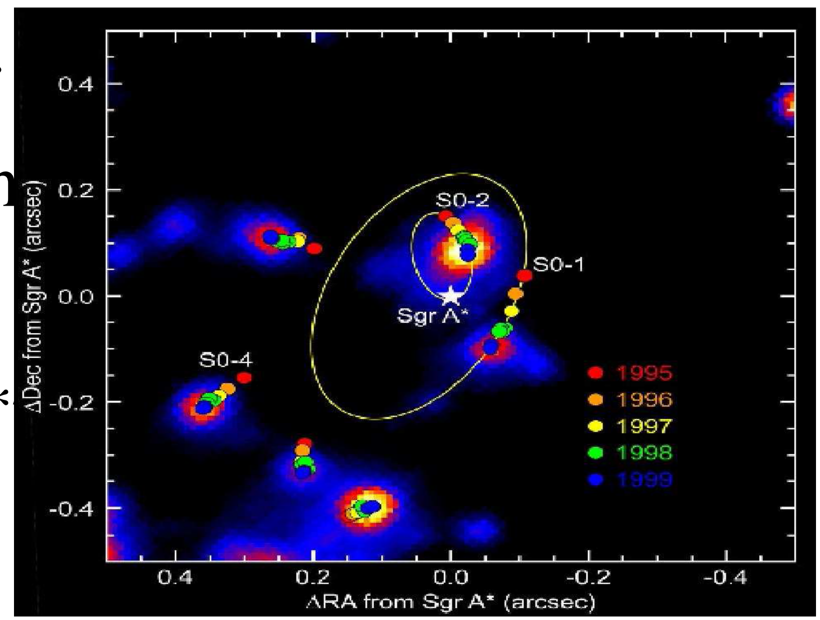
Eckart-

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

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

If there is equipartition of stars and SgrA* then on

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



Schwarzschild and Kerr Metric

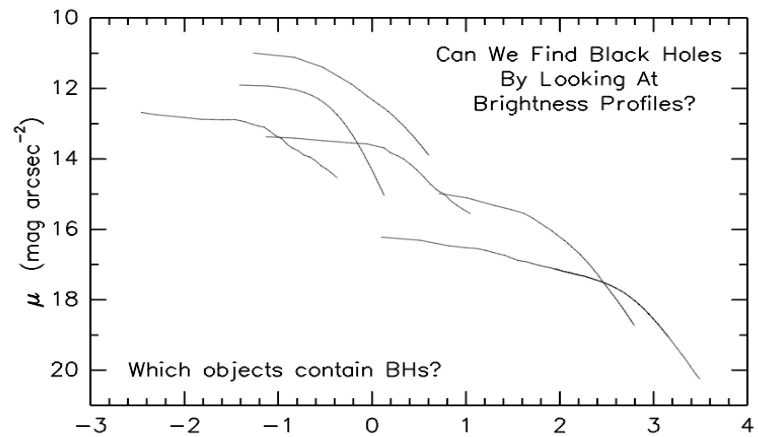
- for a Schwarzschild BH the innermost stable radius is $3r_G = 6GM/c^2$ - there are no stable circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- For a Kerr the innermost stable radius is at $r_+ = GM/c^2$ The spinning black hole drags the the inertial frame-
- The smaller critical radius allows more energy to be released by infalling matter

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 $l' < c\ t_{var}\Gamma$

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

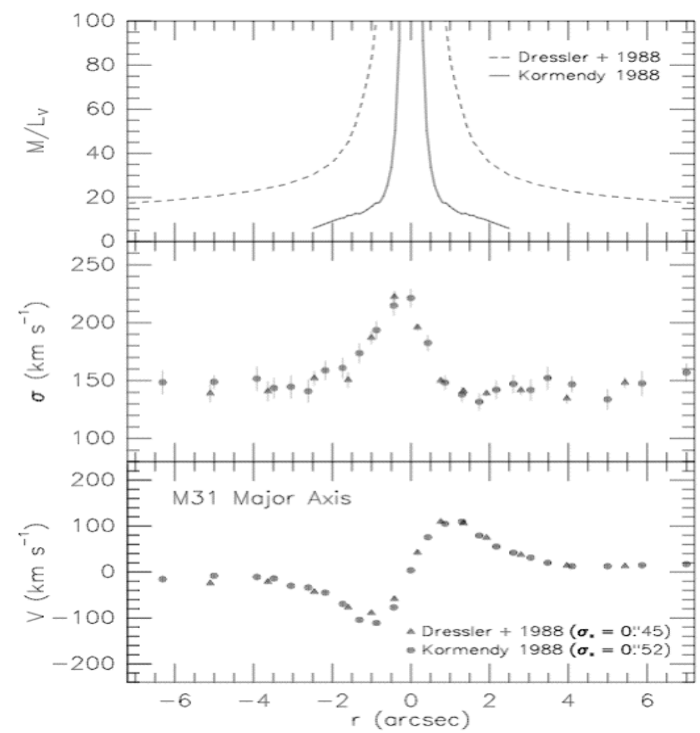


Kormendy and Richstone (2003)

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

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 !

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