Please Read Chapter 9 of S&G Active galactic nuclei

Course evaluations are open until May 12th
https://www.irpa.umd.edu/Assessment/CourseEval/CourseEval.html
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!

How Luminous Can They Be

Eddington limit:

- assuming spherical symmetry infalling matter experiences radiation pressure from the release of energy by the infalling matter
- Balancing gravity with radiation pressure gives (eqs. 9.3 and 9.4 in S&G)

$$L_{Eddington} \sim 1.3x10^{38}\ M/M_{\odot}\ ergs/sec$$

Notice that this is MUCH more efficient than nuclear burning (~6% for accretion, 0.4% for nuclear fusion)

Some Scales (Rees 1984)

A central mass M has a gravitational radius

$$r_g = \frac{GM}{c^2} = 1.5 \times 10^{13}\ M_8\ \text{cm}, \qquad 1.$$

where M_8 is the mass in units of $10^8\ M_\odot$. The characteristic minimum time scale for variability is

$$r_g/c \simeq 500\ M_8\ \text{s}. \qquad 2.$$

A characteristic luminosity is the "Eddington limit," at which radiation pressure on free electrons balances gravity:

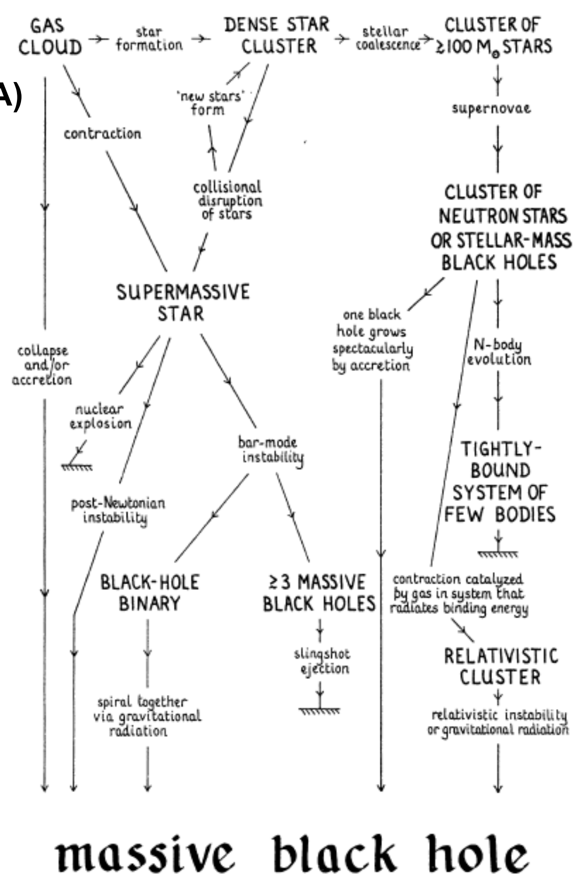
$$L_E = \frac{4\pi G M m_p c}{\sigma_T} \simeq 1.3 \times 10^{46}\ M_8\ \text{erg s}^{-1}. \qquad 3.$$

Related to this is another time scale

$$t_E = \frac{\sigma_T c}{4\pi G m_p} \simeq 4 \times 10^8\ \text{yr}. \qquad 4.$$

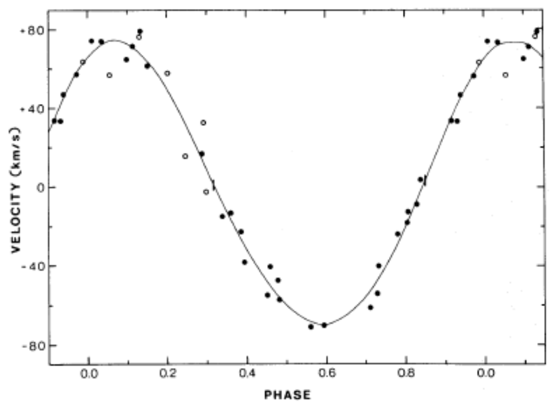
The time scale to grow a black hole if it Were accreting at the Eddington luminosity

In a dense region all roads lead to a black Hole (Ress 1984 ARAA)



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 $M_\odot$- 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

Keplers laws give (where K is the velocity of the companion)

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

$q = M_2/M_1$

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

Stellar Mass Black Holes in the Milky Way

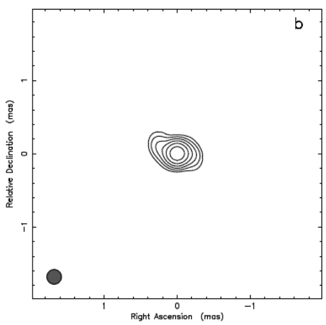
4 J. Casares

Table 1. Confirmed black holes and mass determinations

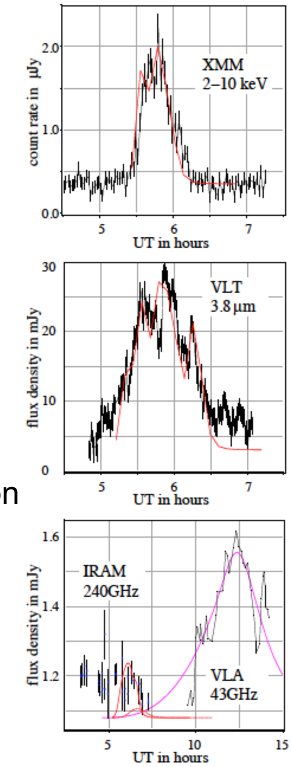
System	P_{orb} [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	M_x † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254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

The Center of the Milky Way

- The center of the MW is called Sagittarius A*(SgrA*) from the name of the radio source at the dynamical center of the MW.
- This is also the location of a weak, time variable x-ray source (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 $M=4x10^6M_\odot$ BH at d=8kpc)
- At SgrA* 1"=0.04pc=$1.2x10^{17}$ cm ,0.5mas=6AU



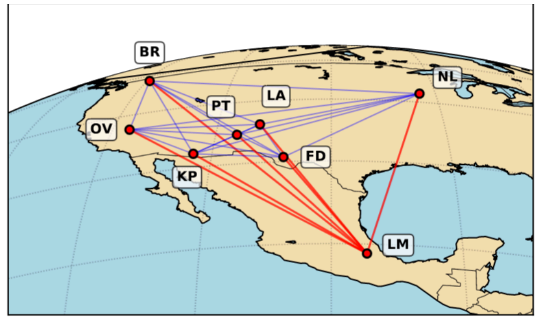
Radio image of SgrA*
Goal of the Event Horizon Telescope is to directly image at scales of R_S

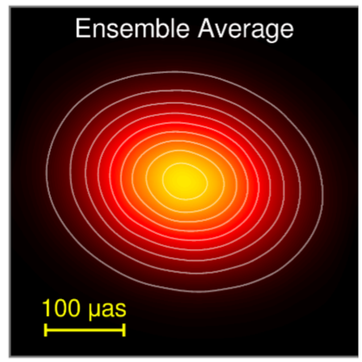


Radio, near IR and x-ray light curves

Best Image of SgrA*

- (147±7μas)×(120±12μas), at position angle 88°±7° (Ortiz-Léon 2016)
- This corresponds ~ 6.5 R_S for a $4x10^6$ $M_\odot$ black hole.





Schwarzschild and Kerr Metric

- for a <u>Schwarzschild</u> BH (non-spinning) the innermost stable radius is $3R_S=6GM/c^2$ - there are no stable circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- ***R_s = 2GMBH/c^2≈ 3xM_{BH}km. (M in solar masses) eq 9.1 in S&G***
- For a Kerr BH (at maximum spin) 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.**

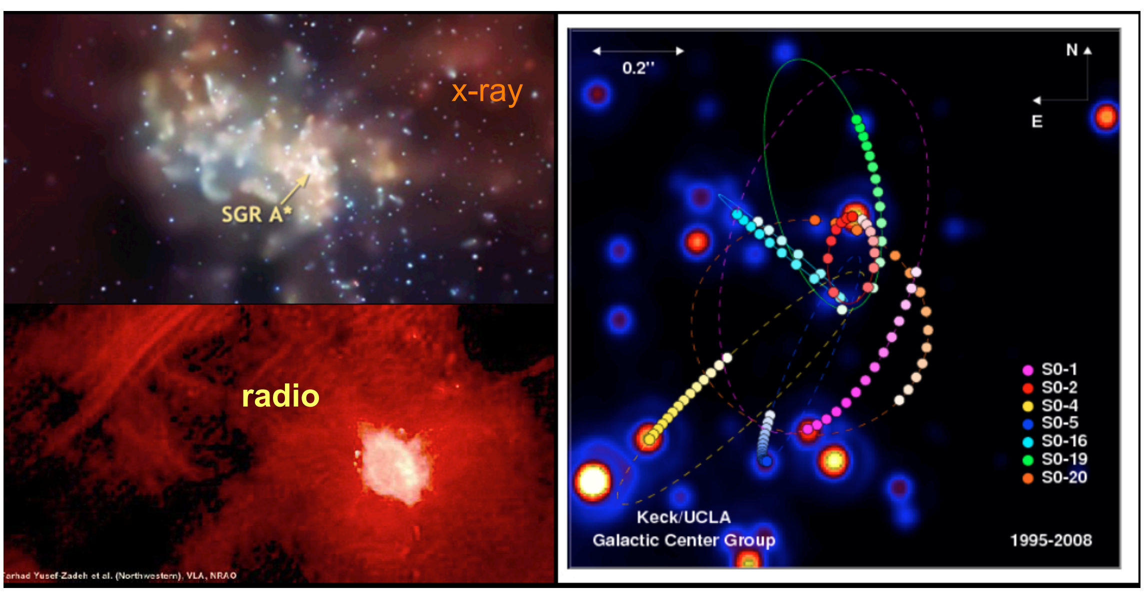
Some Problems with Sgr A*

- 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

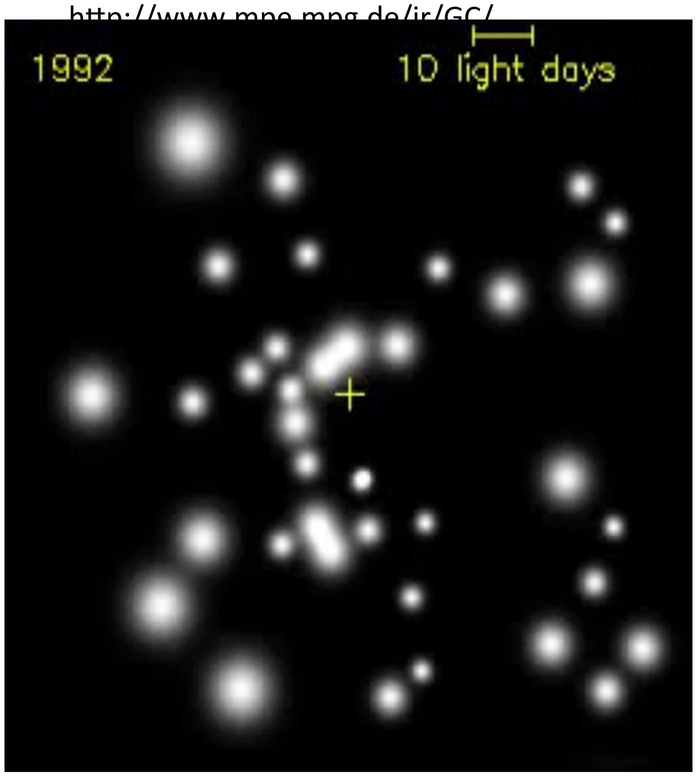
- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities **TODAY!** (AGN evolution)

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/



Velocity Distribution of Stars Near the Center of the MW

A Supermassive Black Hole in the Milky Way 29

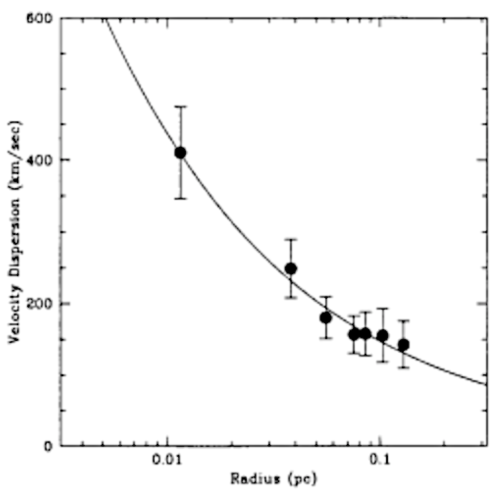
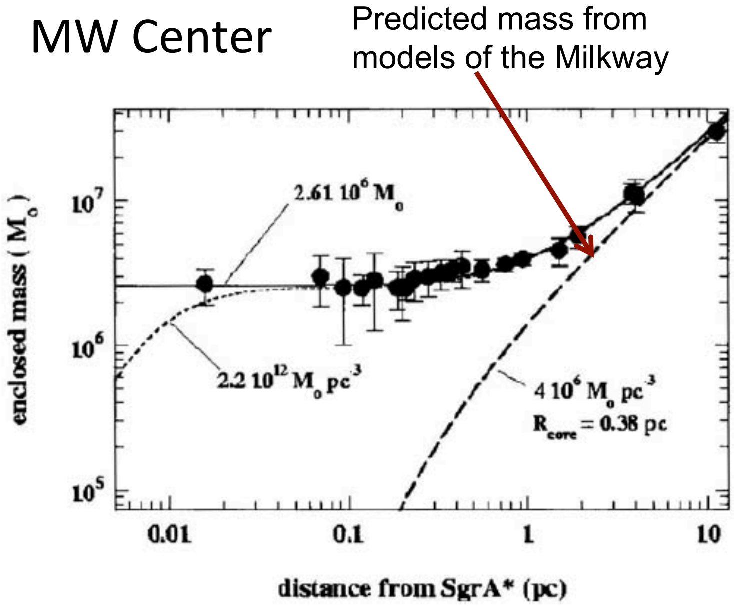


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

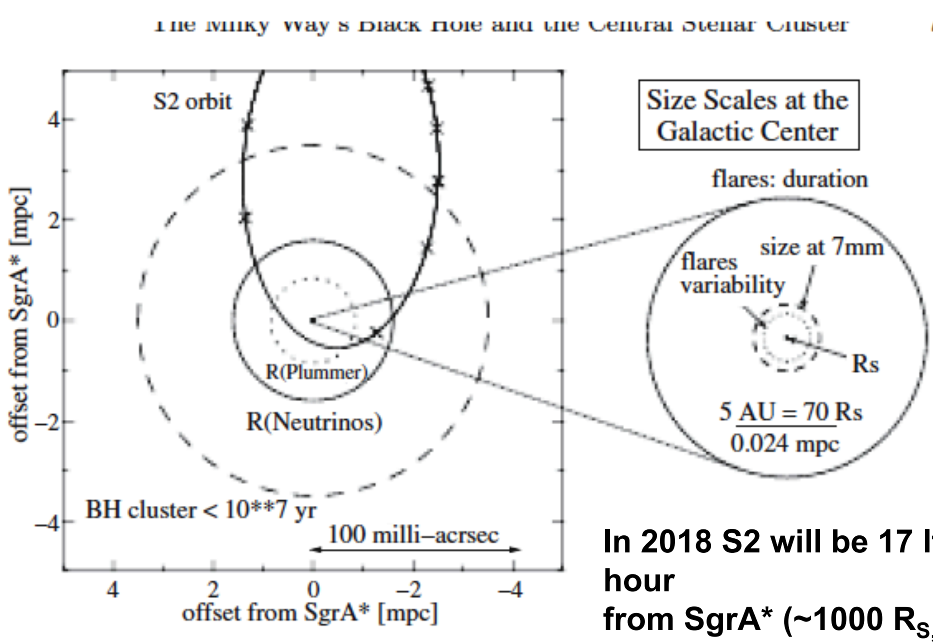
Ghez et al 1998

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



•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



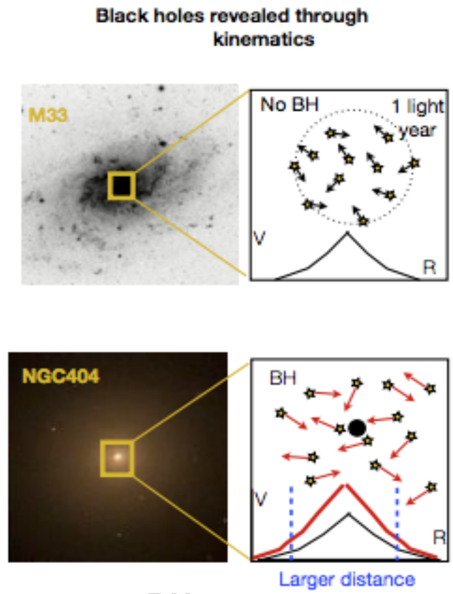
In 2018 S2 will be 17 lt-hour from SgrA* (~1000 R_S, v~0.25c)

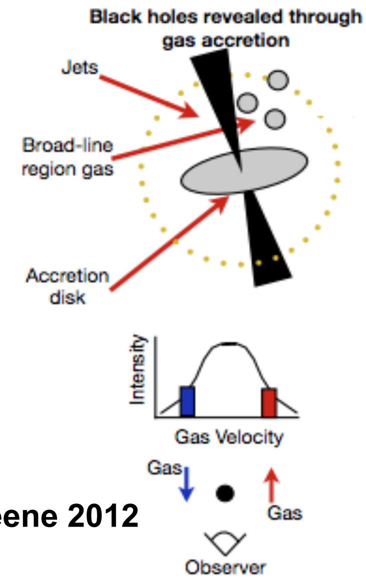
Eckart-

Data will get much better soon- GRAVITY at the VLT-
https://astronomynow.com/2016/06/23/successful-first-observations-of-galactic-centre-with-gravity-instrument/

Finding SMBHs

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





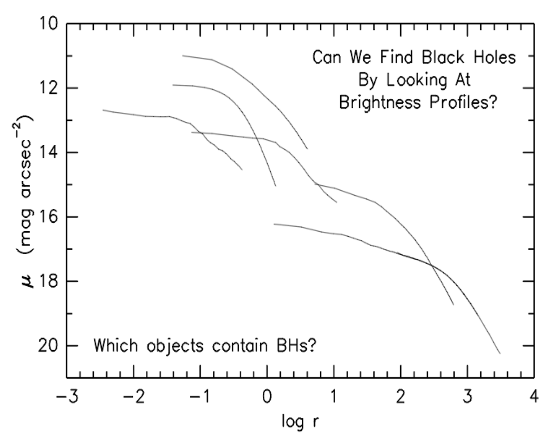
Greene 2012

stars near BH move more rapidly because of BH

broad emission lines-gas moving rapidly near BH

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

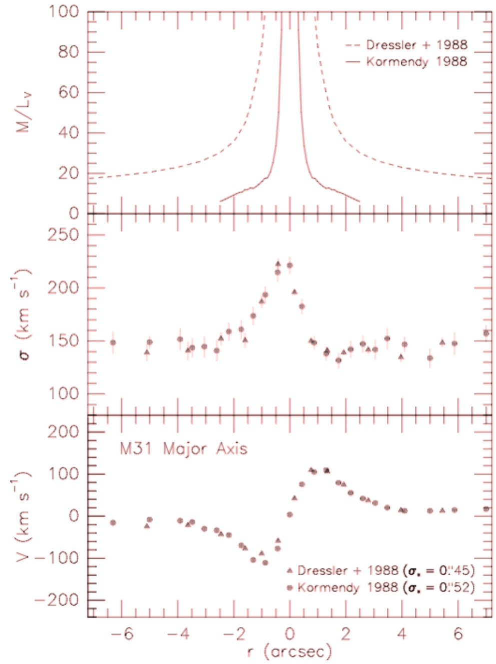


Kormendy and Richstone (2003)

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

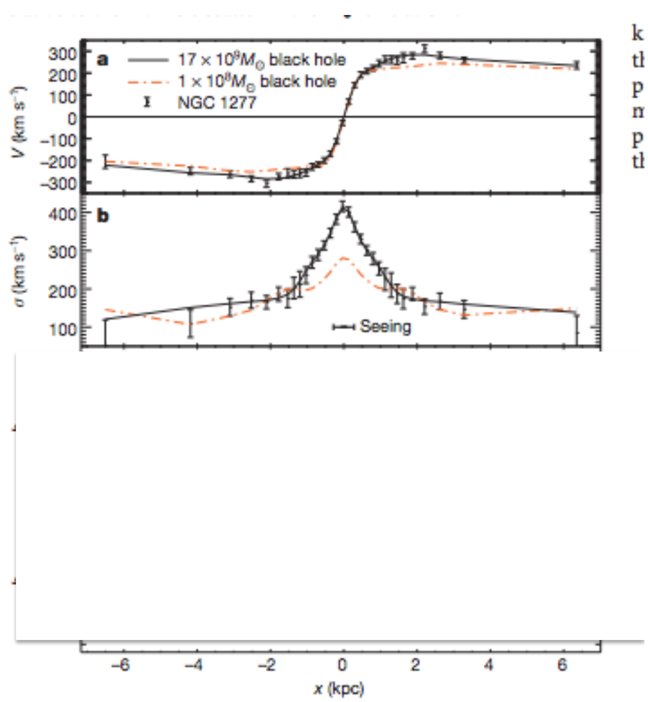
Example of data for the nearest galaxy M31

- 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 importan:t smear the image, reduce BH dynamical signal-



NGC1277- Velocity Data and BH Mass

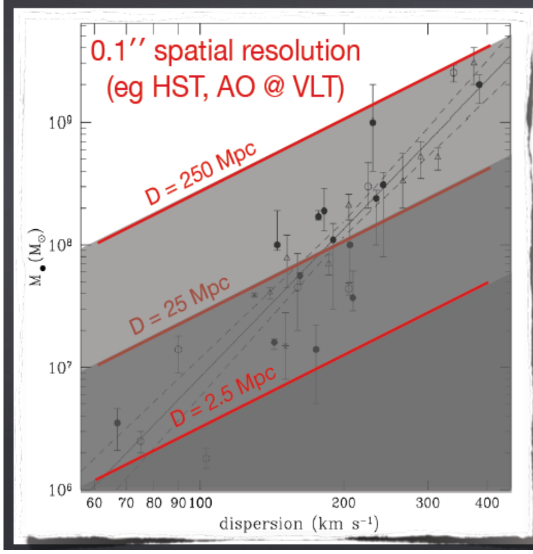
- Top is rotation curve vs distance from center
- Middle is velocity dispersion vs distance from center
-



Direct BH mass measurements

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

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

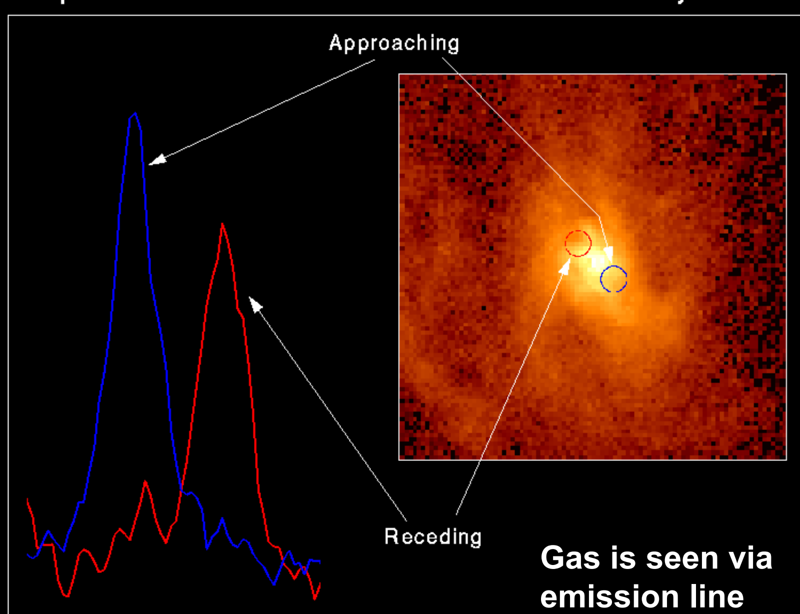


BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

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

Marconi

Spectrum of Gas Disk in Active Galaxy M87



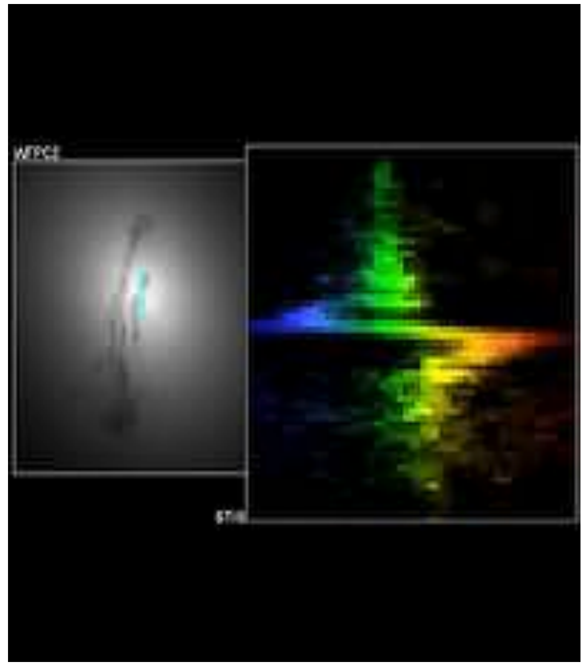
Hubble Space Telescope • Faint Object Spectrograph

SPACE TELESCOPE SCIENCE INSTITUTE

Harms et al 1999

Measuring the Mass of a SuperMassive Black hole

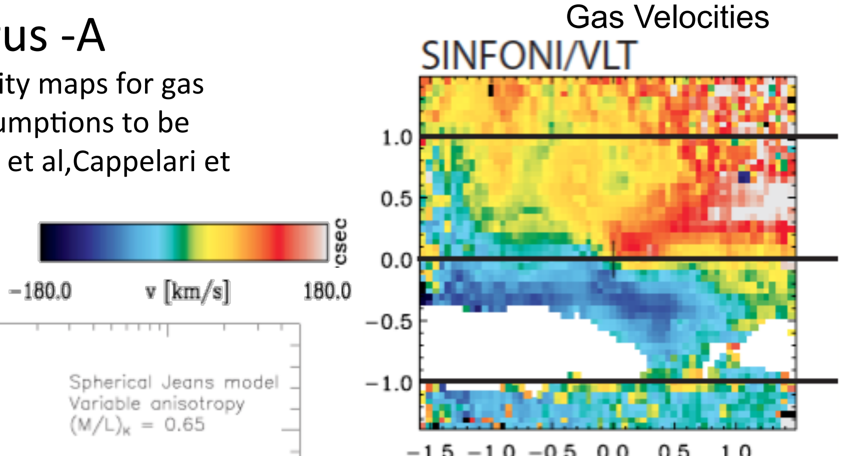
- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion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



Centaurus -A

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

Gas Velocities



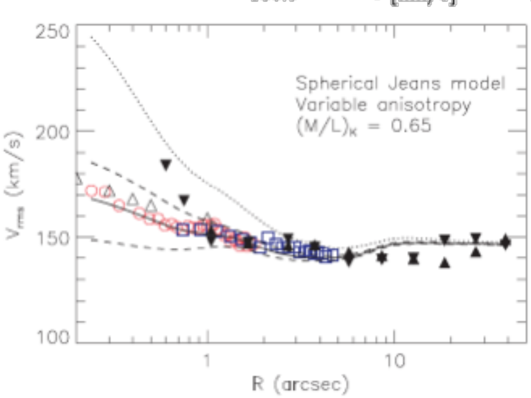
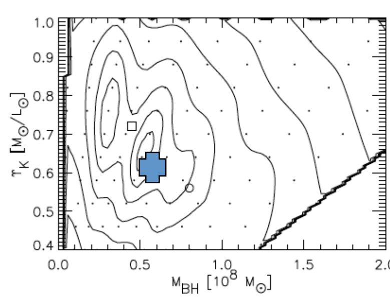
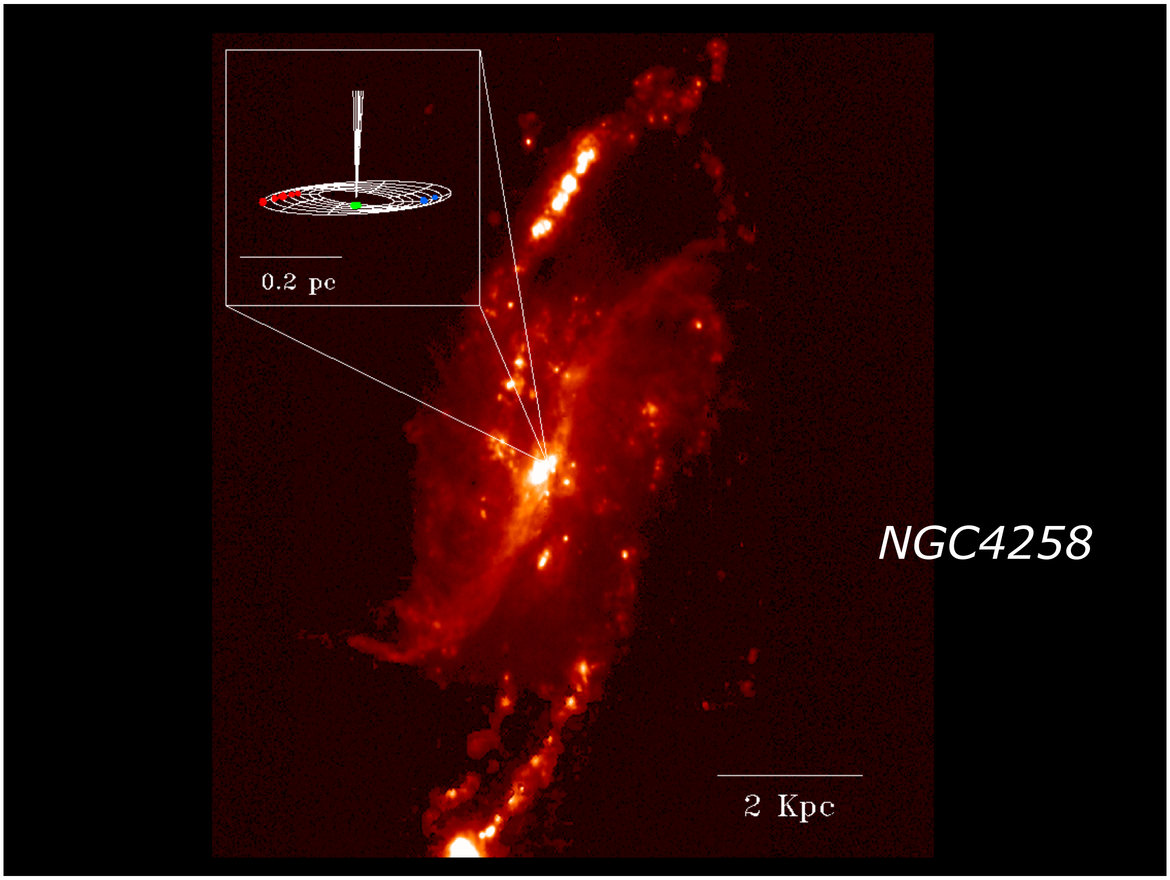


Figure 4: Spherical anisotropic Jeans model



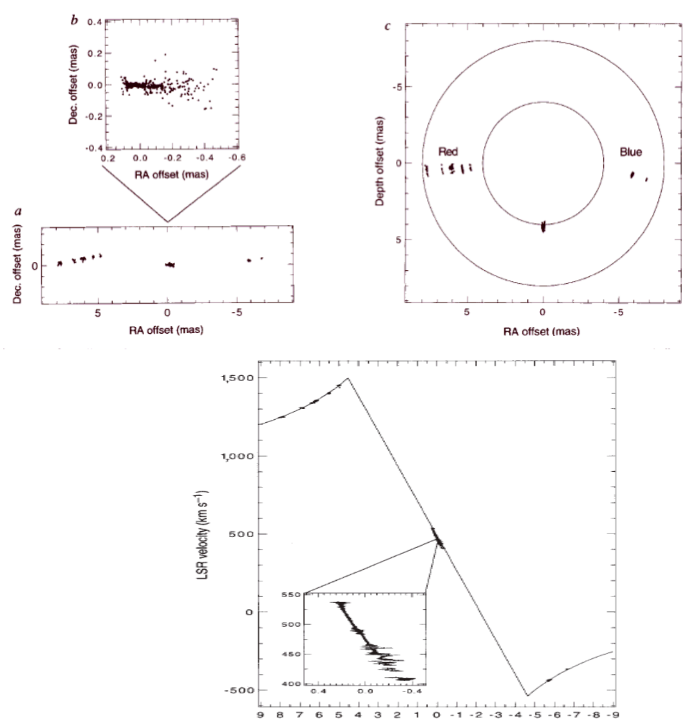
$$\boxed{M_{\rm BH} = (5.5 \pm 3.0) \times 10^7 M_\odot.}$$

Constraints from stars compared to those from Gas Velocities

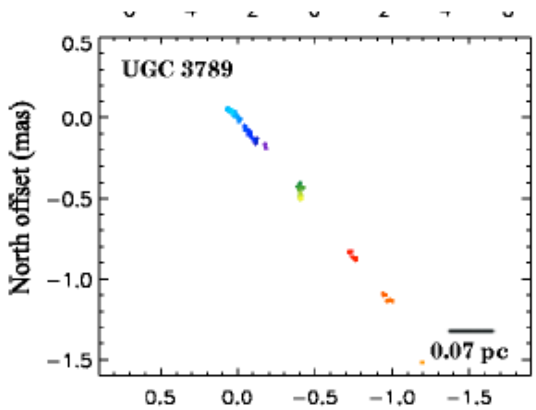


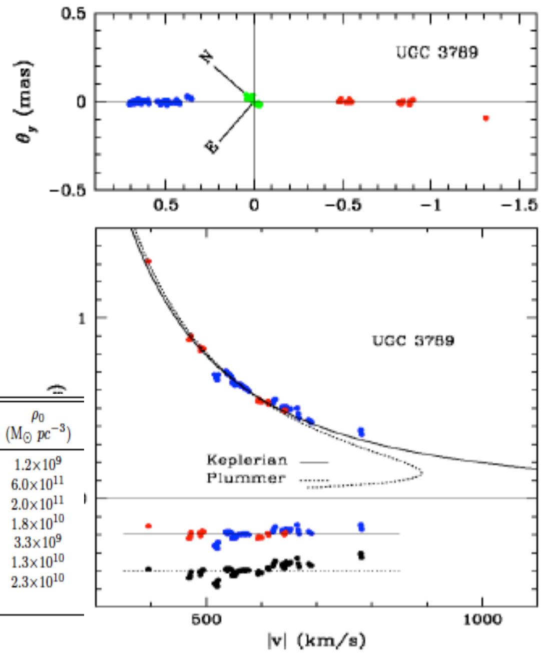
Use of Masers for an AGN BH Masses

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



Other Masers



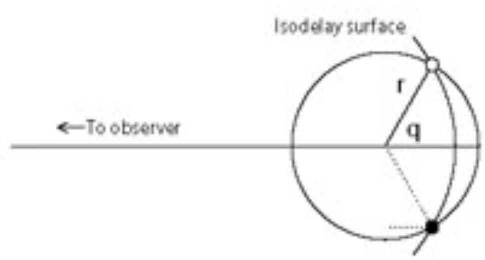


Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36	−131	89	0.055	1.8×10^{10}
NGC 4388	19	0.84±0.02	0.24-0.29	107	–	0.090	3.3×10^9
NGC 6264	136	2.84±0.04	0.23-0.78	−85	90	0.083	1.3×10^{10}
NGC 6323	105	0.93±0.01	0.13-0.30	10	89	0.046	2.3×10^{10}

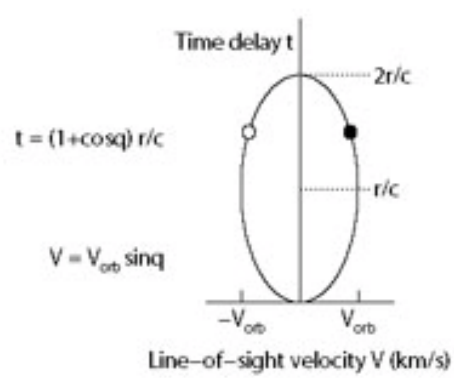
Kuo et al 2010

What About AGN in General??

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



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

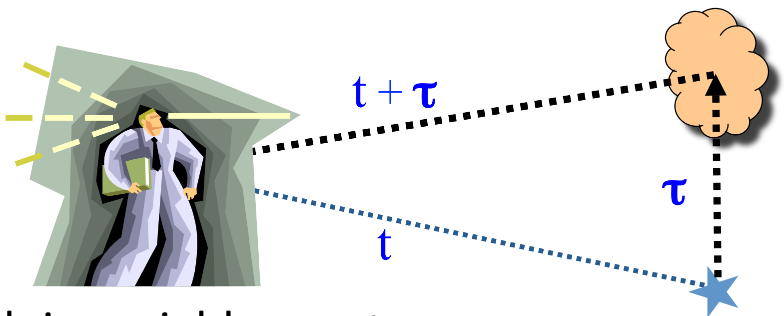


Virial Mass Estimates

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

Reverberation Mapping:

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



- v_{BLR}

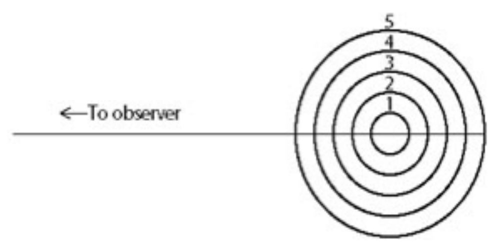
  Line width in variable spectrum

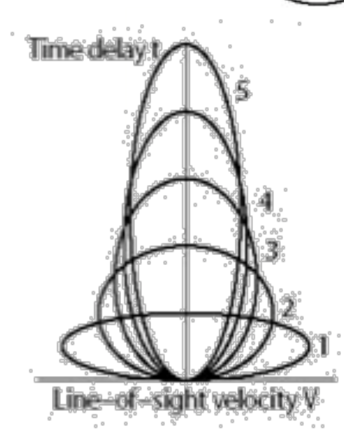
The Geometry

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



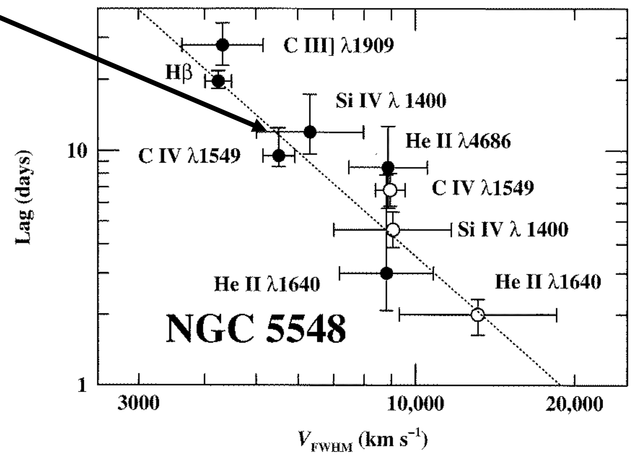


r=ct, where t is the time delay

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: $M \propto FWHM^2 L^{0.5}$



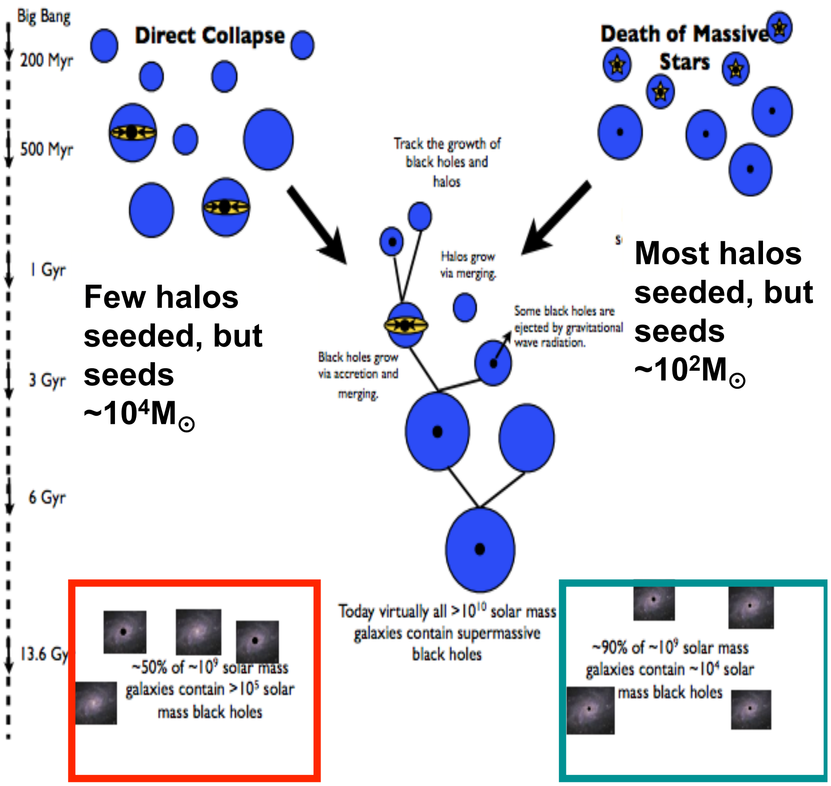
Dotted line corresponds to a mass of $6.8 \times 10^7\ M_\odot$
Peterson and Wandel 1999

End of Mass Determination

2 Scenarios for Birth of SMBHs

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

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



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.

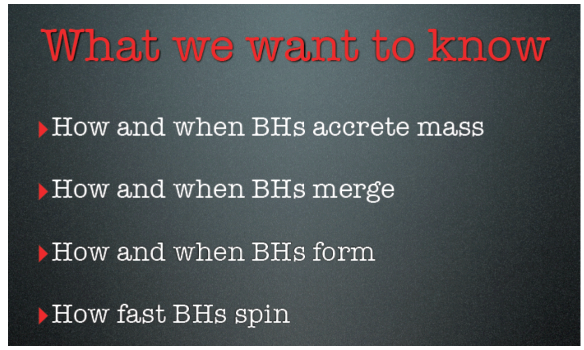
If these galaxies had modest black holes, and if the black holes also merged, one could grow the supermassive black holes that lie in most large galaxies observed today.

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.**

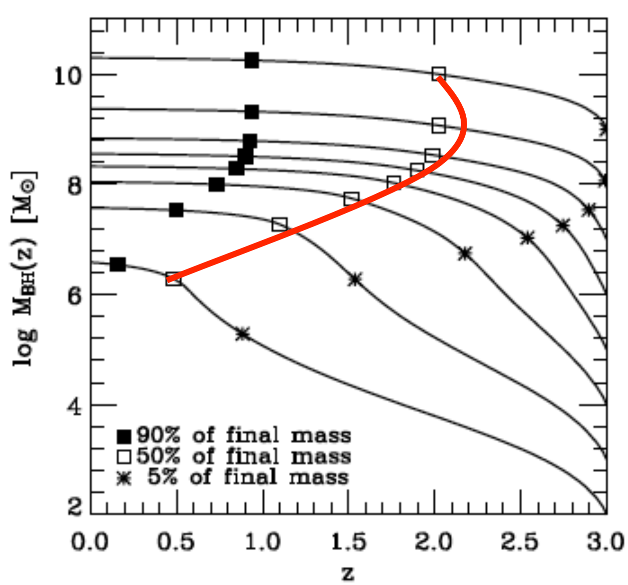
Constraints on Growth of Black Holes

- 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.



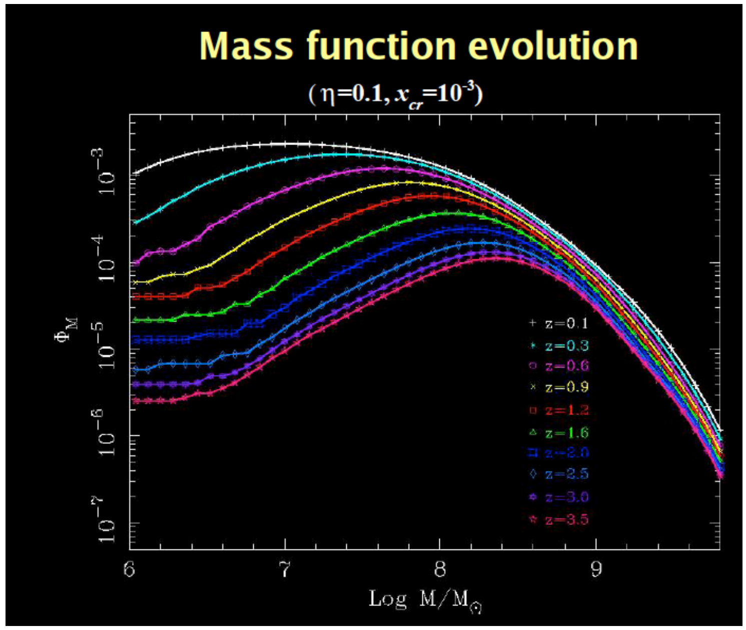
One realization of BH growth

- 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

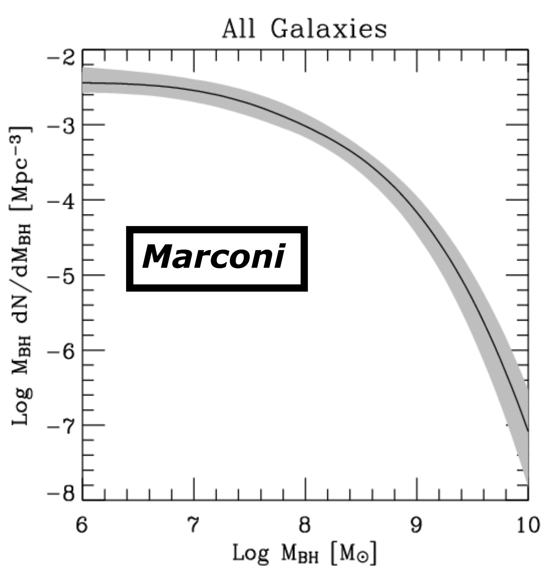


Transform to Mass Growth

- 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)

- (see Ferrarese & Ford 2005 for a review)

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,t_{var} gives a length 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
  $\Delta L<2\mathrm{x}10^{41}\varepsilon_{0.1}\Delta t$ ergs/sec

Course evaluations are open- Please Respond!

- https://www.irpa.umd.edu/Assessment/CourseEval/CourseEval.htmlWhy?
  - For the benefit of your peers
  - Because your comments count and we use it to improve our teaching and/or redesign the course
  - Because your opinion is used to evaluate our performance
- Don't put it off till May 12th!

End

Broad Range of Properties

- Luminosity
  - Range from $<10^{40}$ erg/s to $\sim 10^{48}$ 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 objects are blocked at all wavelengths)- type II
  - Level of obscuration connected to **viewing inclination**
- Presence of powerful relativistic (radio) jets
  - Radio-loud AGN : generate powerful jets, seen principally via synchrotron radiation in the radio band
  - Radio-quiet AGN : lack **powerful** jets (often possess weak jets)
  - Fundamental parameter controlling jet production **unknown** **(maybe black hole spin; or magnetic field configuration)**

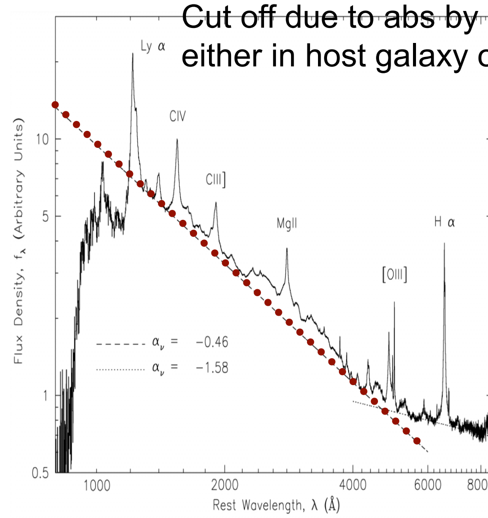
How Luminous Can They Be

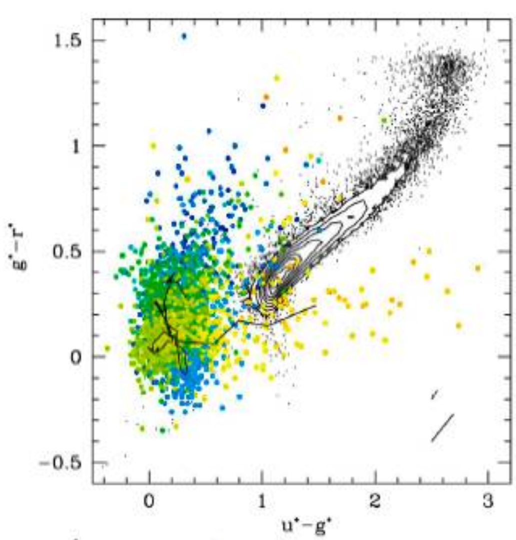
- Eddington limit:
  - assuming spherical symmetry infalling matter experiences radiation pressure from the release of energy by the infalling matter
  - Balancing gravity with radiation pressure gives (eqs. 9.3 and 9.4 in S&G)
- $L_{Eddington}$~ $1.3x10^{38}$ M ergs/sec= $1.3x10^{31}$ W

Optical Properties of AGN

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

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



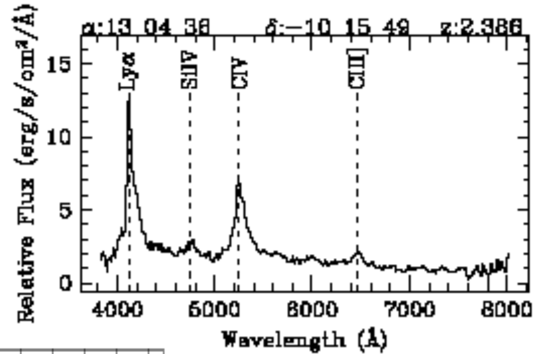


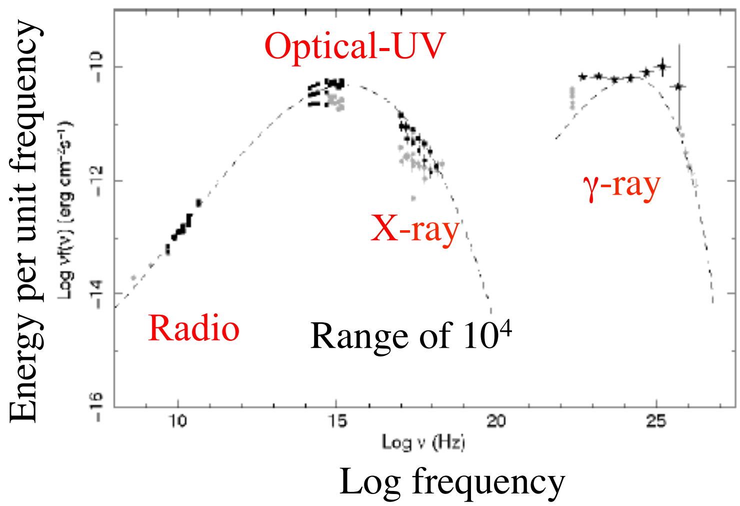
Unusual optical colors (Richards et al SDSS)- **quasars in color**, **stars are black**

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

Broad Band Properties of AGN

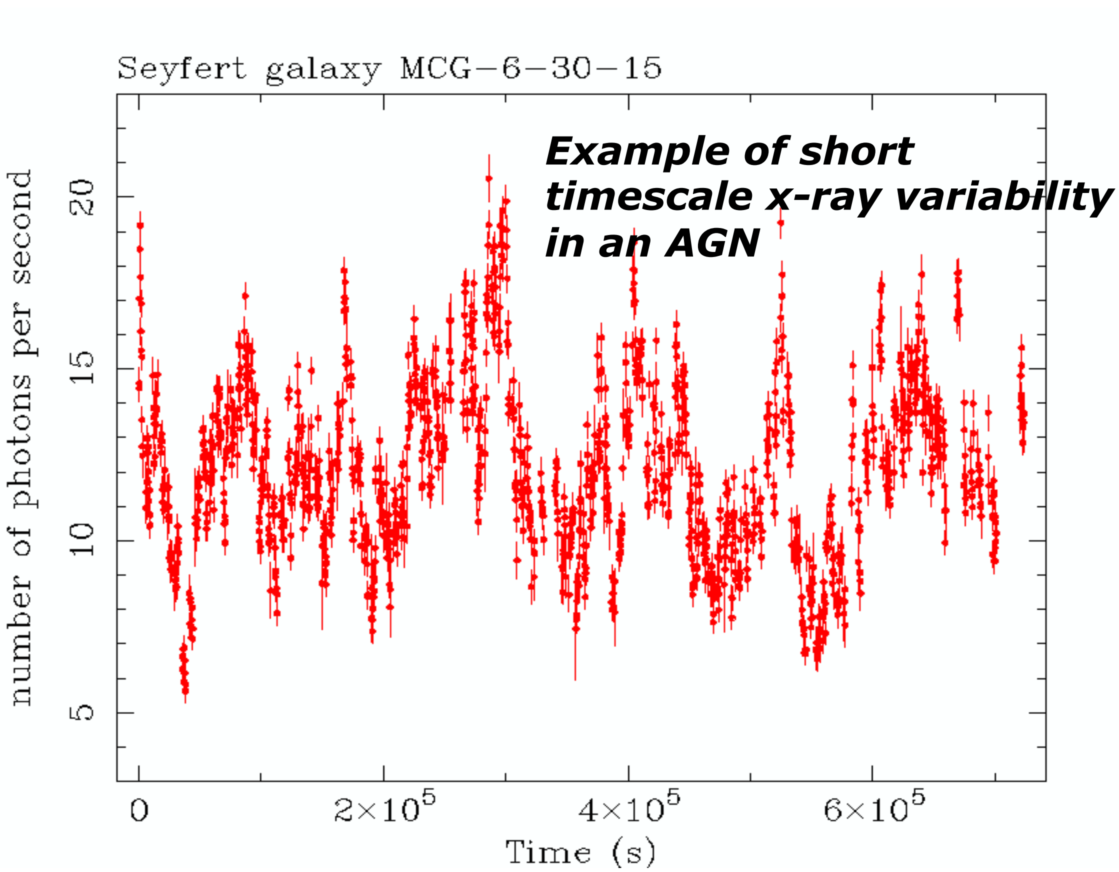
- **Broad band continuum- very different from stars or galaxies**
- **Strong UV lines not seen in stars** ….
- Can be very variable





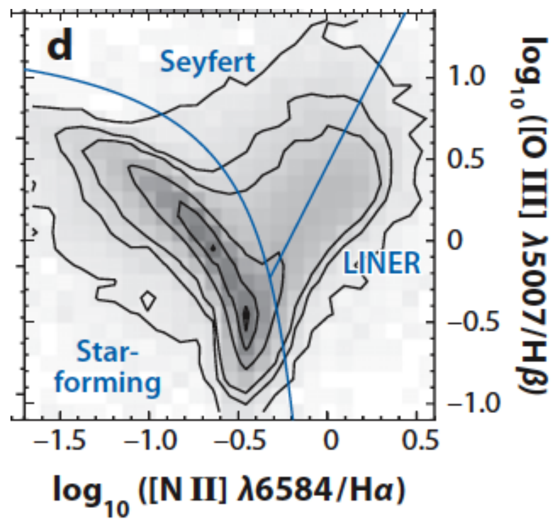
Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us

A large fraction of the total observed energy appears in the γ-ray band (due to relativistic beaming)



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)

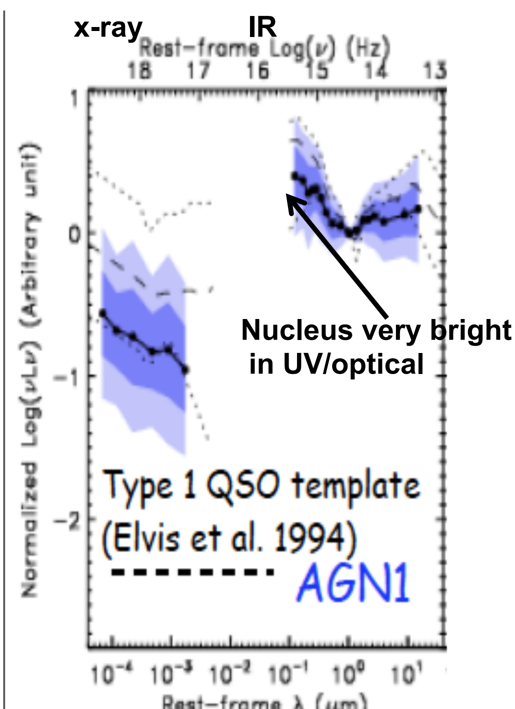


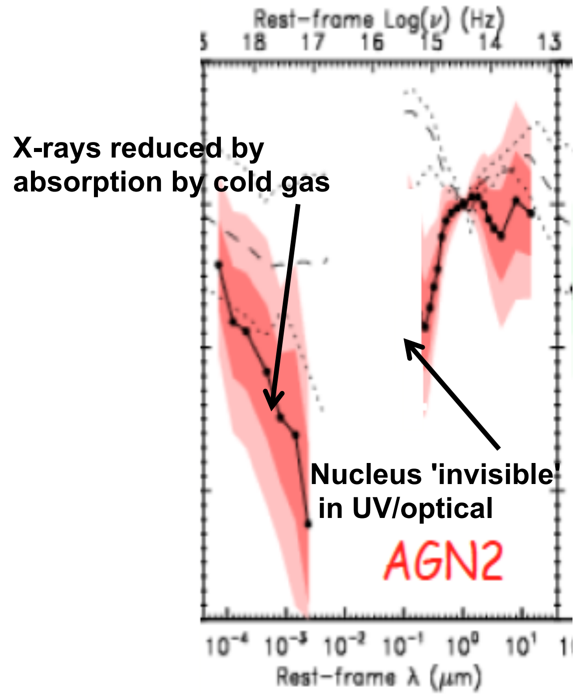
line ratio plot NII/Hα compared to OIII/Hβ−

AGN lie in a particular part of this diagram

Darkness of plot is log of the number of

Broad Band Continuum (IR-Xray)

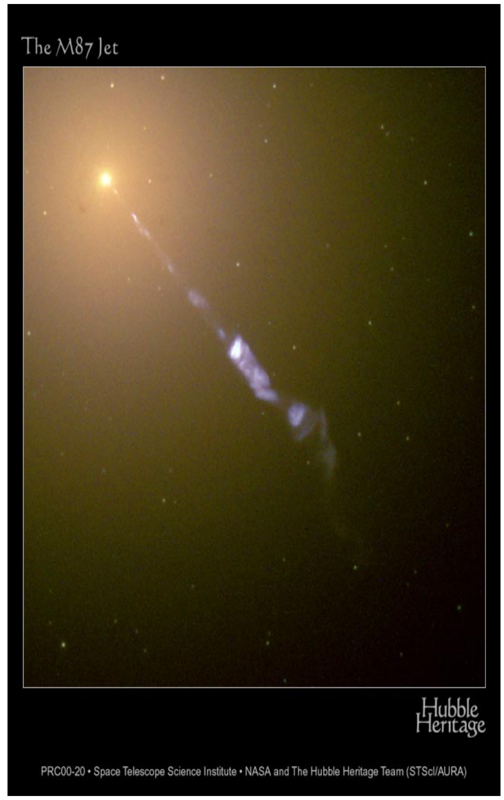




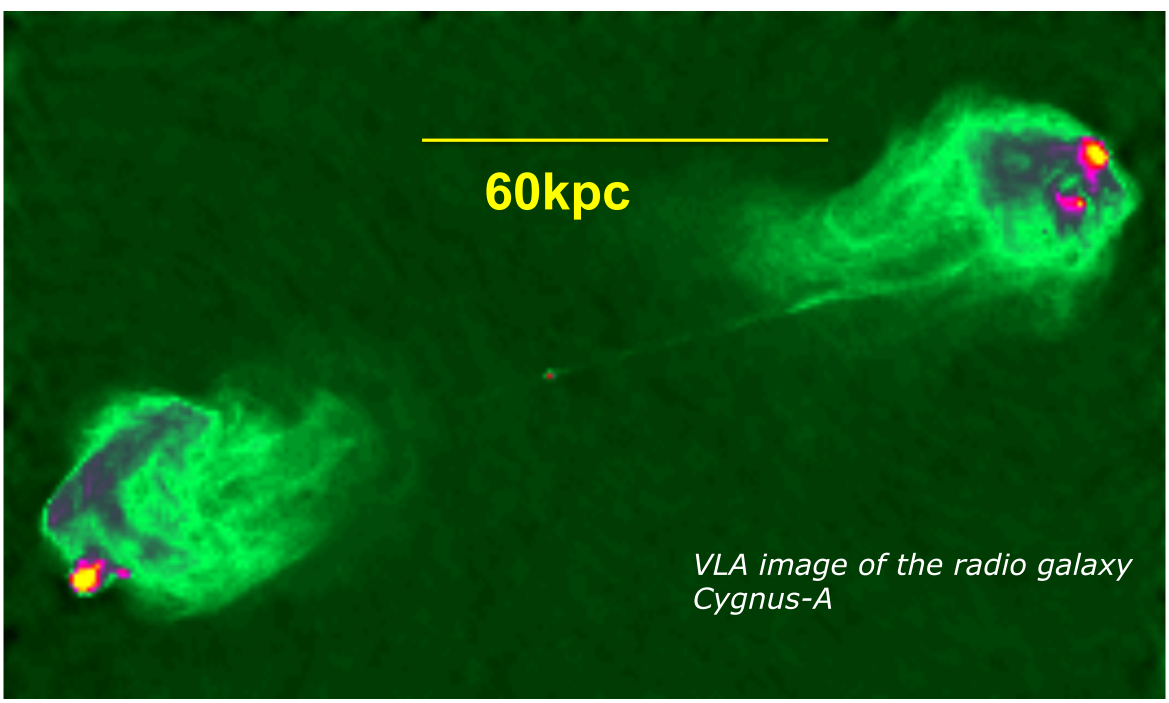
Active Galactic Nuclei

- 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

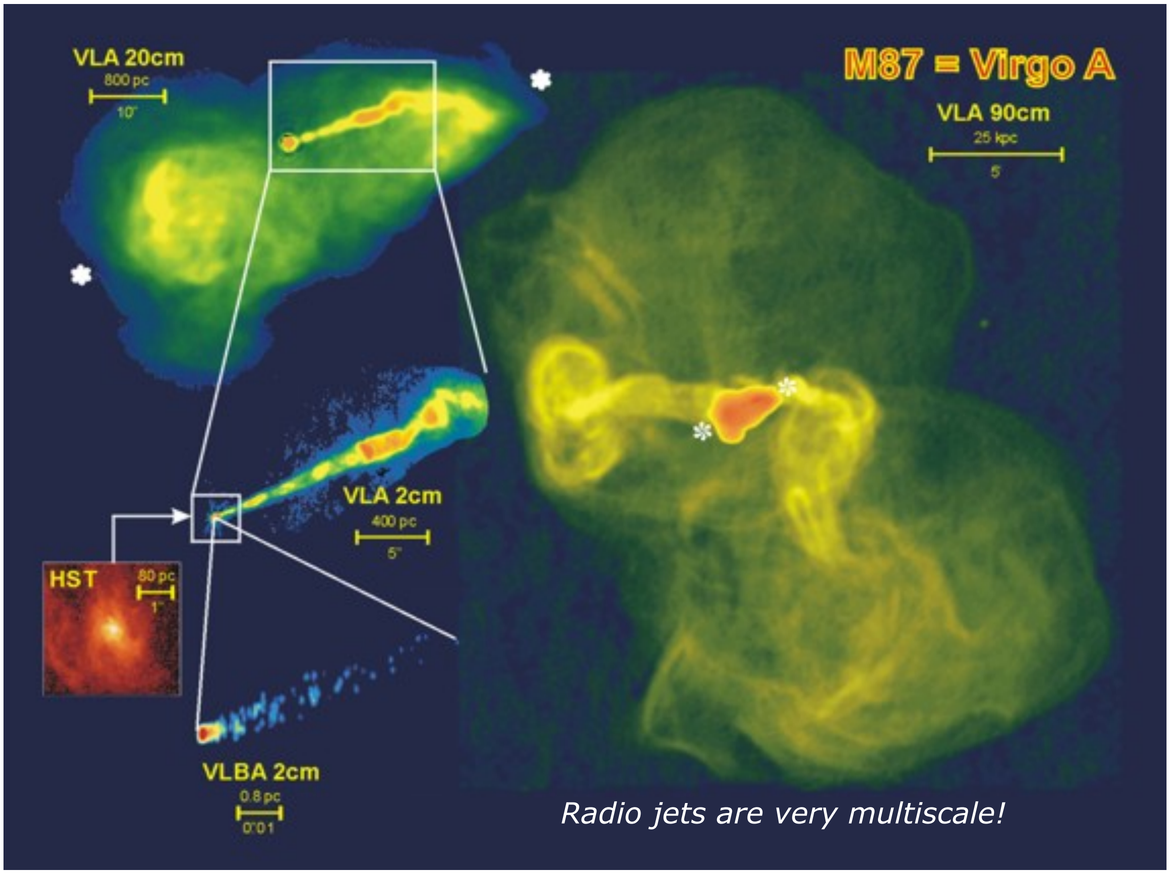
- The Jet
  - Jet of material squirted from vicinity of SMBH
  - Lorentz factor of >6
  - Can be very energetic (particle luminosity)
  - in radio to x-ray band jet radiation is primarily synchrotron (see text)- in gamma-ray it is inverse Compton
- What powers the jet?
  - Accretion power
  - Extraction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



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



VLA image of the radio galaxy Cygnus-A


VLA 20cm
800 pc
10"
M87 = Virgo A
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0".01
Radio jets are very multiscale!