Please Read Chapter 9 of S&G Active galactic nuclei

Course evaluations are open ! Due before Dec 11
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:

- assume spherical symmetry infalling matter experiences radiation pressure from the release of energy by the infalling matter
- Balancing gravity with radiation pressure calculate the outward force due to Thomson scattering by the electrons; scattering from protons is much less efficient because of their larger mass. (eqs. 9.3 and 9.4 in S&G)
- Force of gravity on test mass m from black hole mass M_{BH}

$F = Gm_pM_{BH}/r^2$; m_p is the proton mass

Radiation force on test mass $F_{rad} = \sigma_T L/4\pi r^2$ σ_T is the Thompson cross section

Set the two equal to each other

$L_{Eddington} \sim 1.3\times10^{38}\ M/M_\odot$ 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

$$r_g = \frac{GM}{c^2} = 1.5 \times 10^{13}\, M_8 \text{ cm},$$ **M_8 is the mass in 10^8 solar mass units**

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

$$r_g/c \simeq 500\, M_8 \text{ s.} \qquad 2.$$ **light crossing time**

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

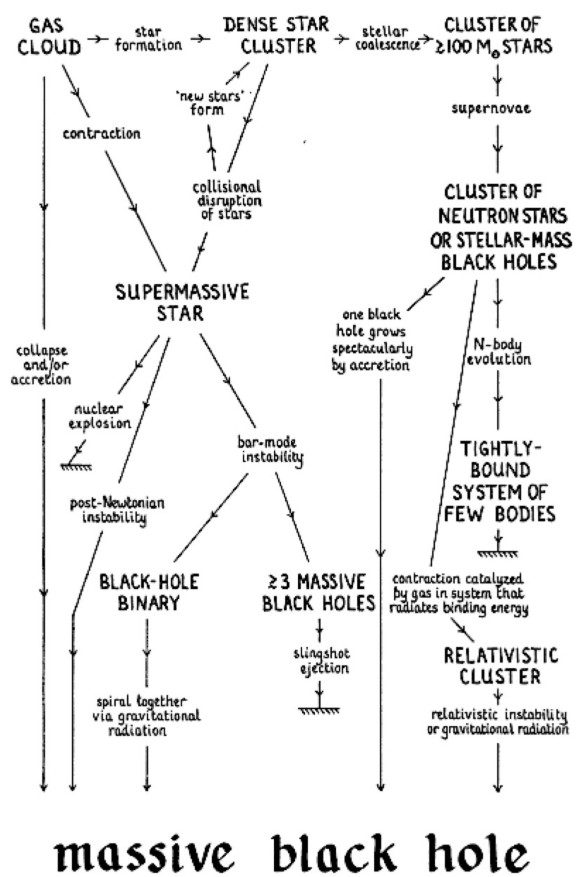
$$L_E = \frac{4\pi G M m_p c}{\sigma_T} \simeq 1.3 \times 10^{46}\, M_8 \text{ erg s}^{-1}. \qquad 3.$$

Related to this is another time scale

$$t_E = \frac{\sigma_T c}{4\pi G m_p} \simeq 4 \times 10^8 \text{ yr.}$$ **The time scale to grow a black hole if it were accreting at the Eddington luminosity**

How do we get supermassive black holes

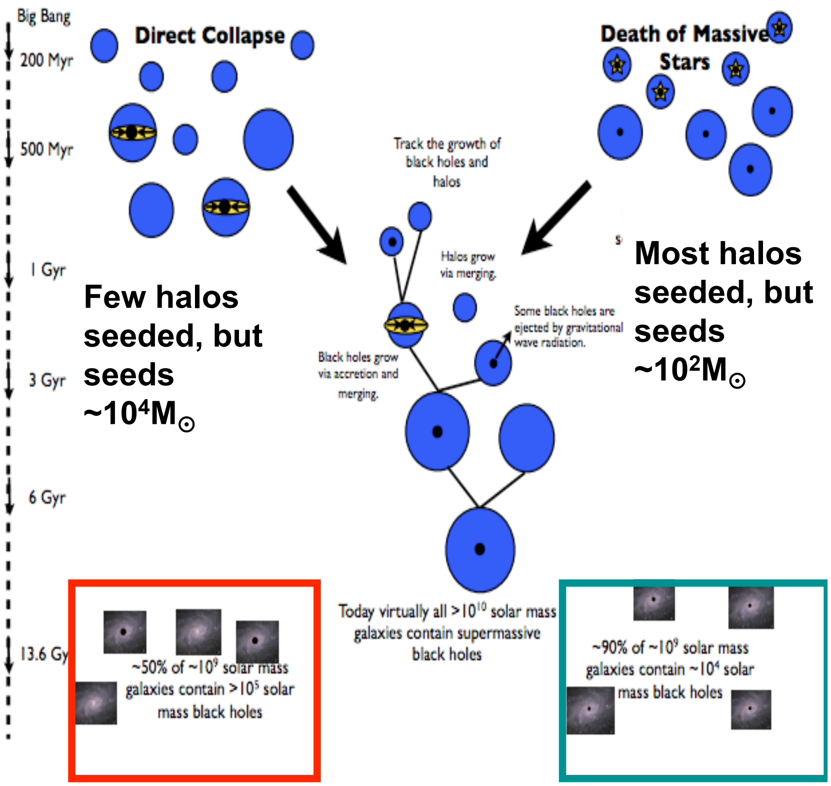
In a dense region all roads lead to a black Hole (Ress 1984 ARAA)



2 Scenarios for Birth of SMBHs

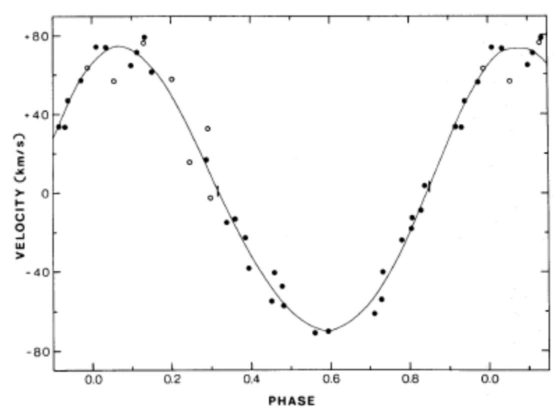
How do SMBHs get started?? Detect M~10^{9}M BH at z~7- need to grow fast!

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



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 $M_\odot$- <u>too high for a NS</u>. 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)

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

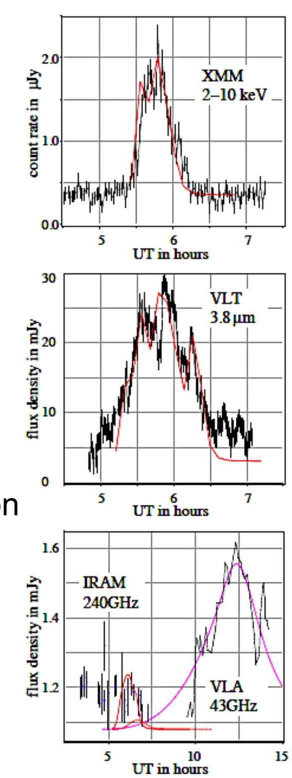
Stellar Mass Black Holes in the Milky Way

Table 1. Confirmed black holes and mass determinations

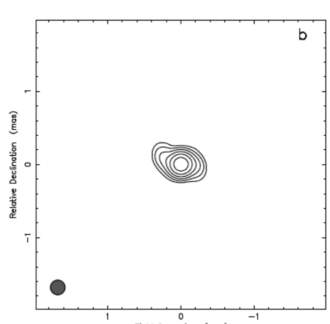
System	P_{orb} [days]	$f(M)$ $[M_\odot]$	Donor Spect. Type	Classification	M_x † $[M_\odot]$
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	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 erg/sec- 100x less than a typical x-ray binary) and IR source
- The radio source is very small (VLBI) (<0.0005"<$50R_s$ for $M=4\times10^6 M_\odot$ BH at d=8kpc)
- At SgrA* 1"=0.04pc=1.2×10^{17} cm ,0.5mas=6AU



Radio, near IR and x-ray light curves



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

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
- ***$R_s = 2GM_{BH}/c^2 \approx 3xM_{BH}$km. (M in solar masses) <u>eq 9.1 in S&G</u>***
- 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.**

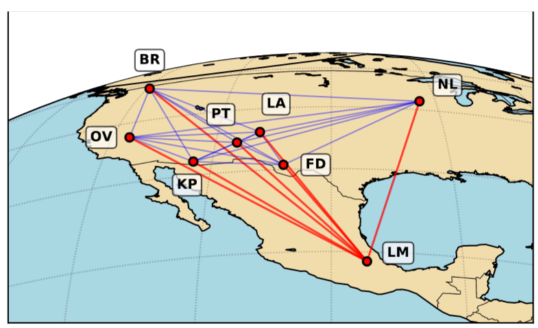
Best Image of SgrA*

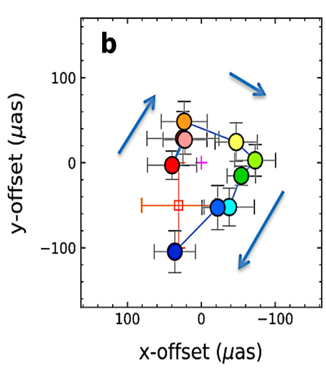
- (147±7μas)×(120±12μas), at position angle 88◦±7◦ (Ortiz-Léon 2016)
- This corresponds ~ 6.5 R_S for a $4x10^6 M_\odot$ black hole.
- Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA* -we are seeing

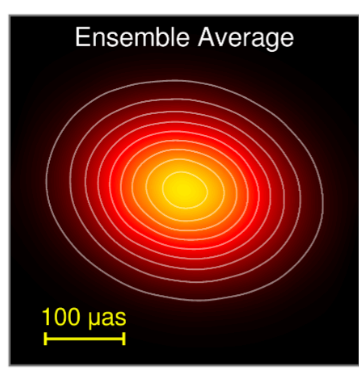
"face on"

- GRAVITY Collaboration 2018

arxiv.org/pdf/1810.12641.pdf







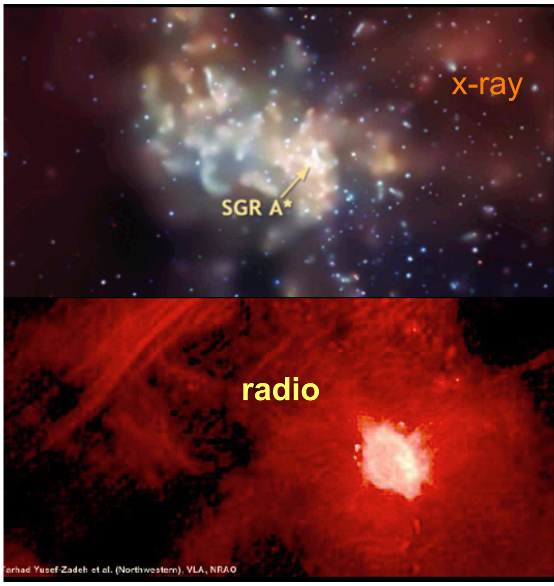
Some Problems with Sgr A*

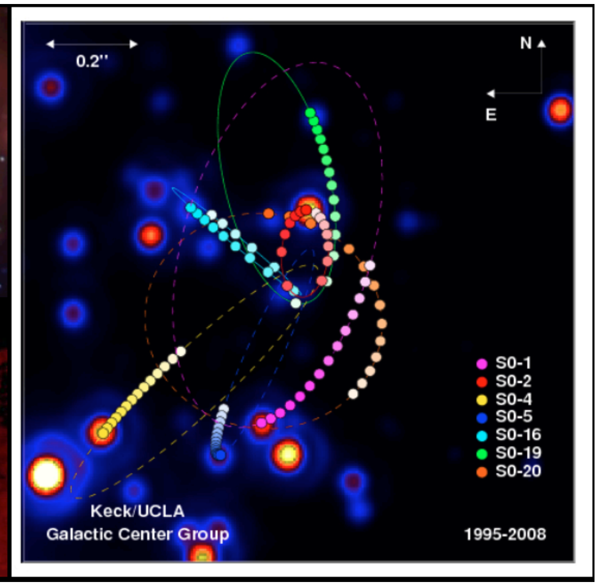
- There is lots of gas for accretion in the galactic center from the ISM and stellar winds
- Yet the observed luminosity is very low ($L/L_{Edd} \sim 10^{-10}$)
- What happens to the accretion energy- where does the mass and energy go

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

MW Galactic Center

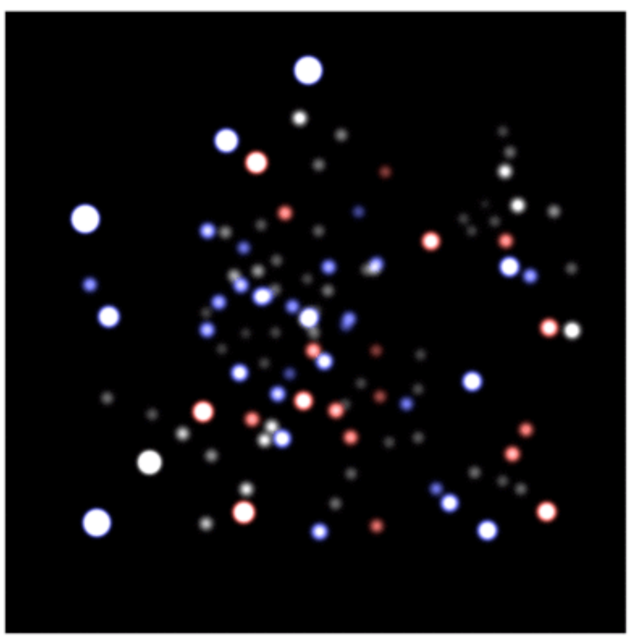
- galactic centers are 'special' places
- MW galactic center

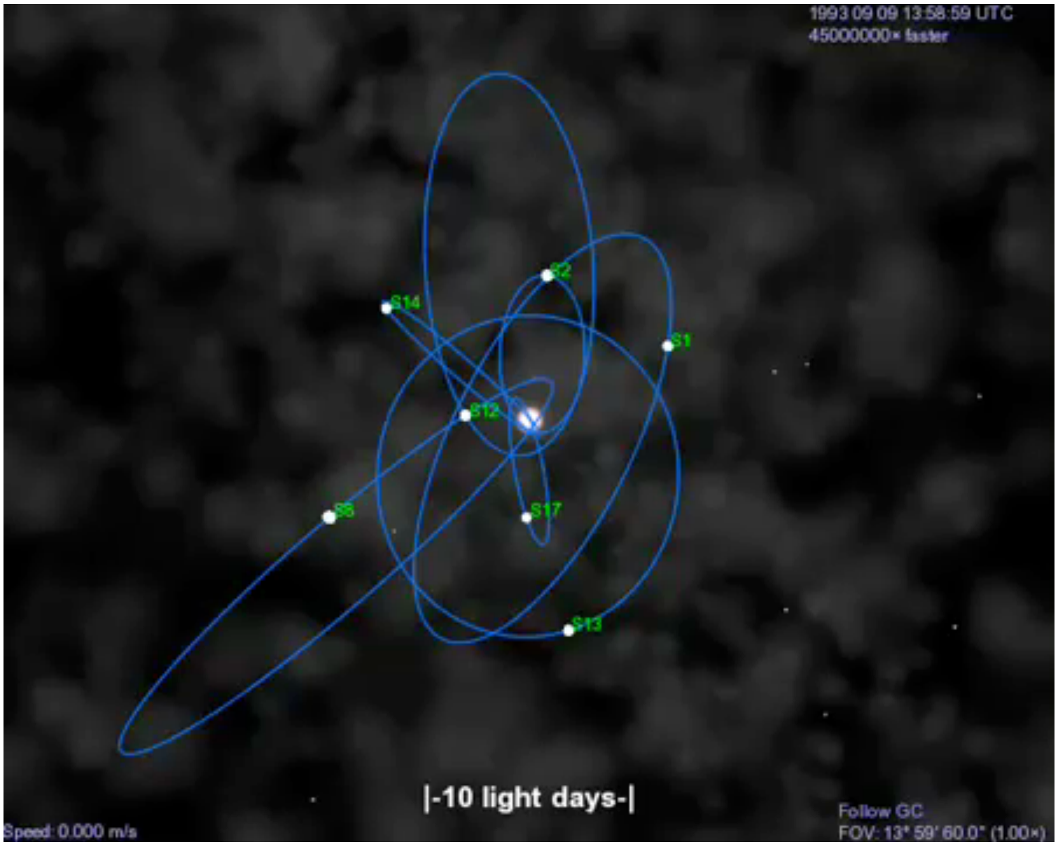




Motion of Stars Around the Center of the Milkyway- see
http://www.youtube.com/watch?v=ZDxFjq-scvU

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

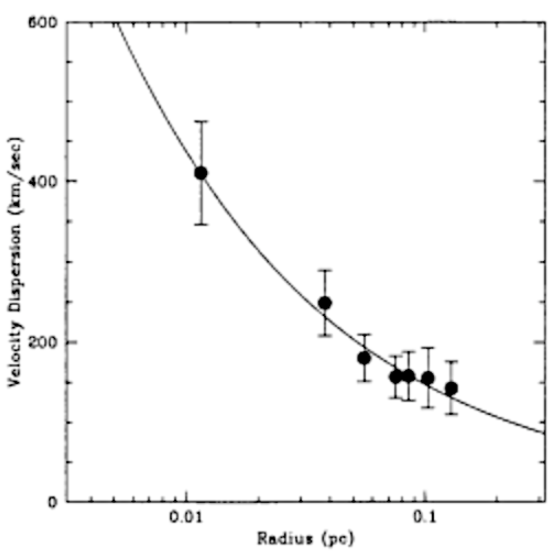


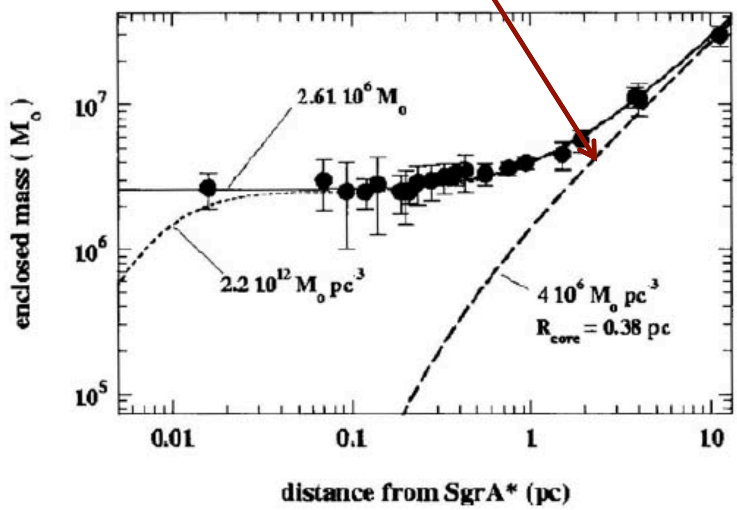
Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

Ghez et al 1998

MW Center

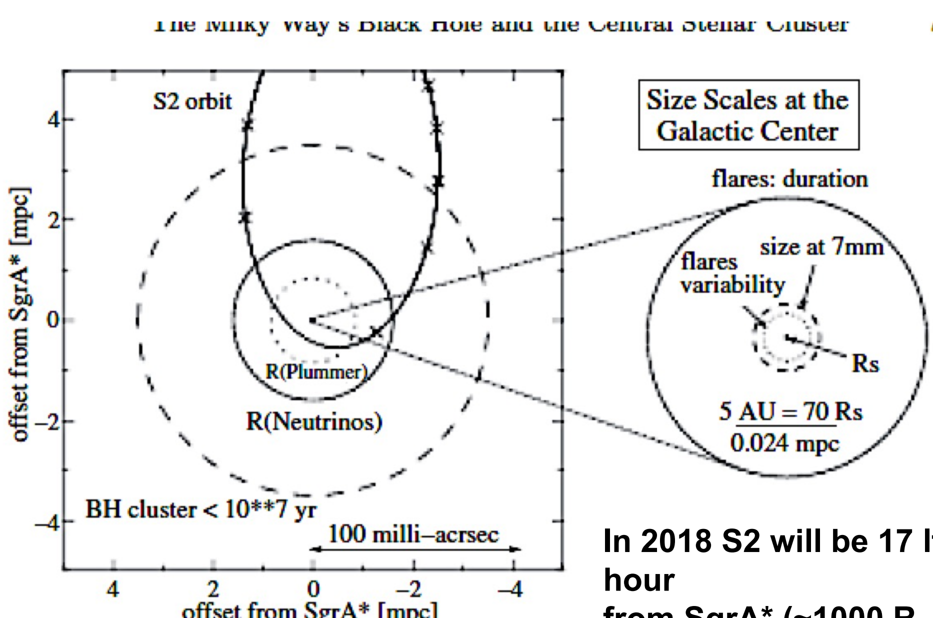
Predicted mass from models of the Milkway

- Two teams led by R. Genzel and A. Ghez have measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is $>10^{12} M_{\odot}/pc^3$



•As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass 2.6 x $10^6 M_{sun}$, and density

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



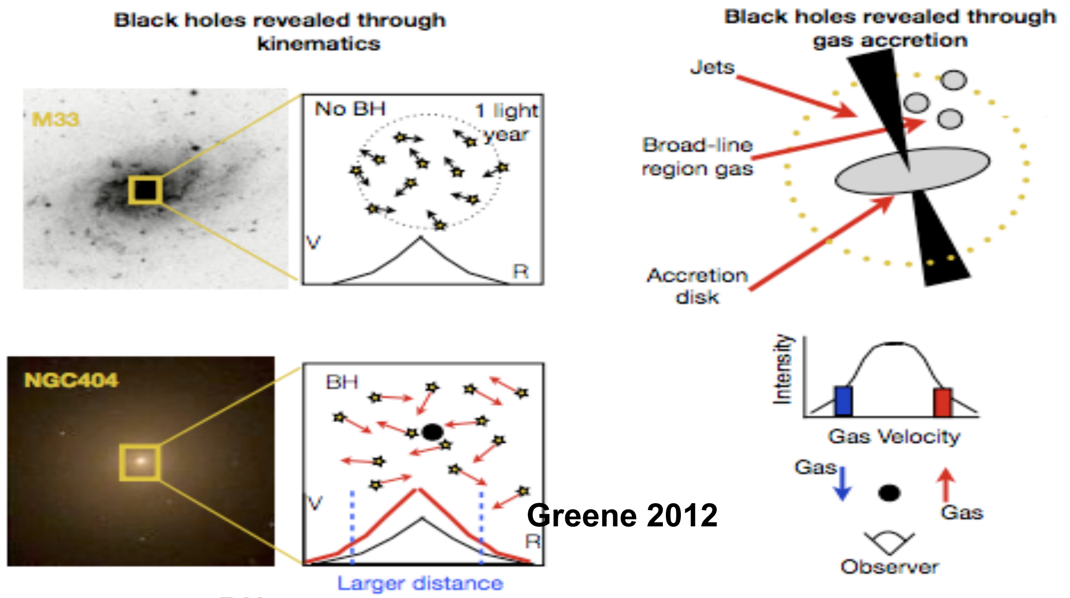
In 2018 S2 will be 17 lt-hour from SgrA* (~1000 R_S, v~0.25c)

Eckart-

Data has gotten much better- 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 $M_{galaxy}>10^{10}M$.



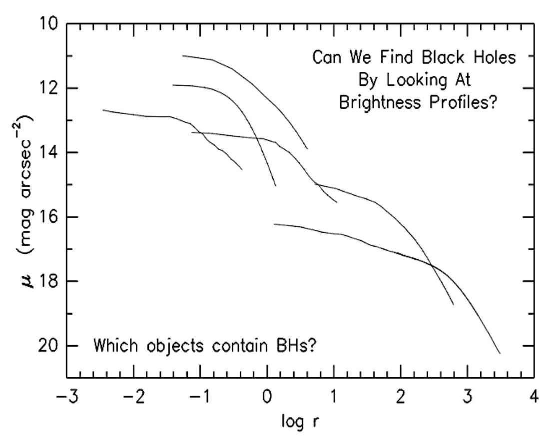
Greene 2012

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,

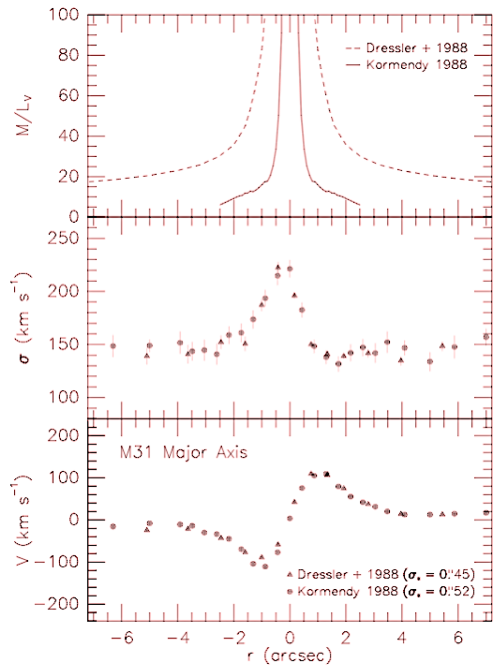


Kormendy and Richstone (2003)

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

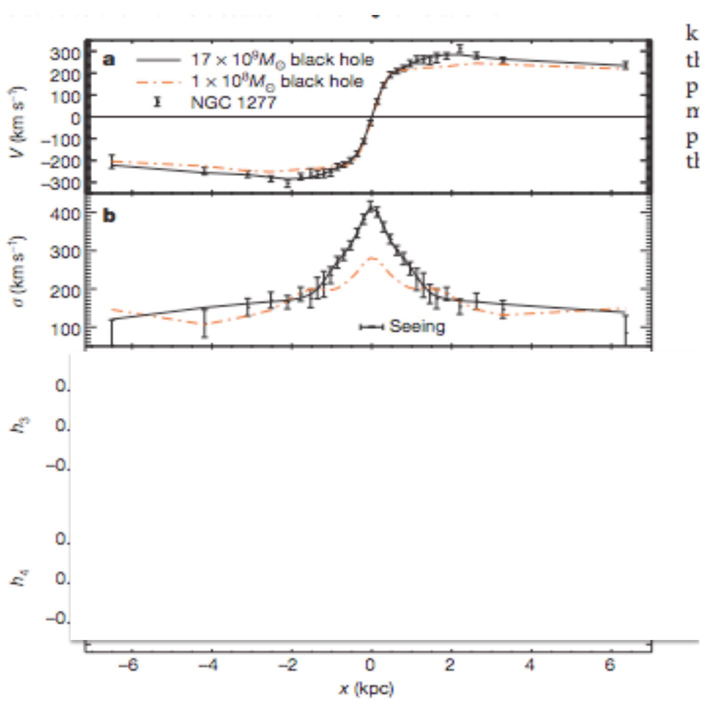
Example of data for the nearest galaxy M31

- 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

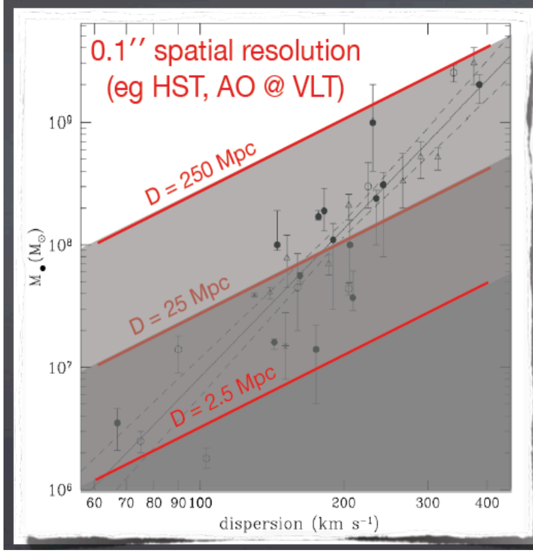
- Top is rotation curve vs distance from center
- Middle is velocity dispersion vs distance from center
-



Direct BH mass measurements

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

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

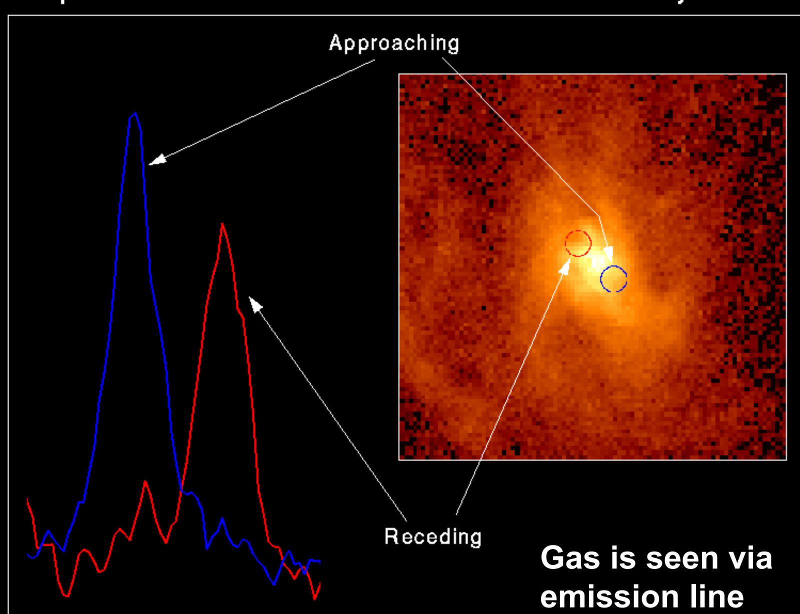


BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

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

Marconi

Spectrum of Gas Disk in Active Galaxy M87



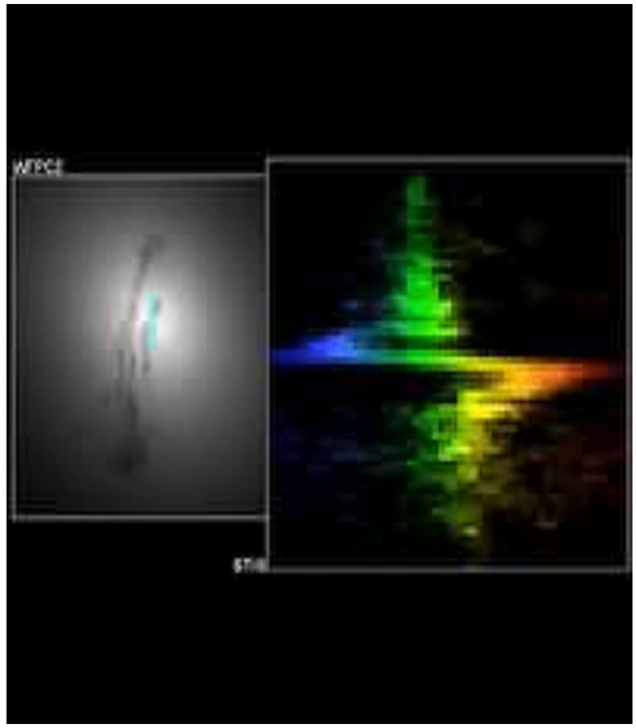
Hubble Space Telescope • Faint Object Spectrograph

SPACE TELESCOPE SCIENCE INSTITUTE

Harms et al 1999

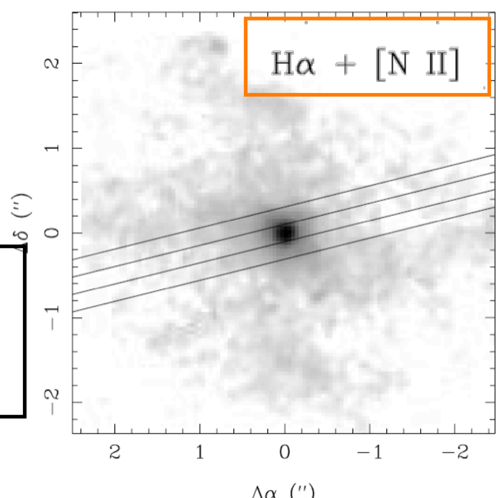
Measuring the Mass of a SuperMassive Black hole

- 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;.

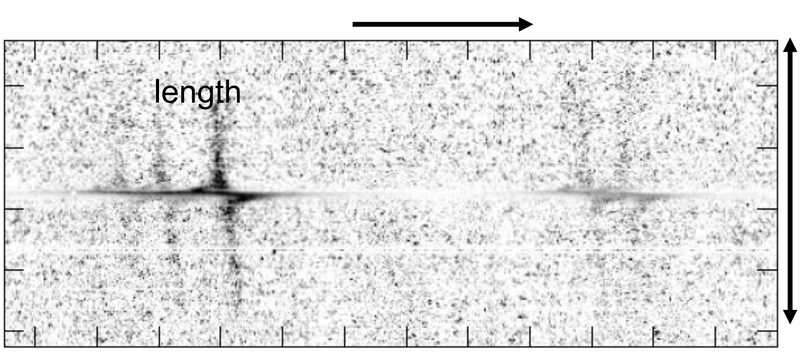


Measurement of Kinematics of Gas

- 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.

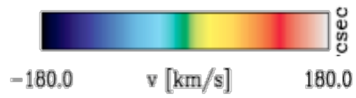


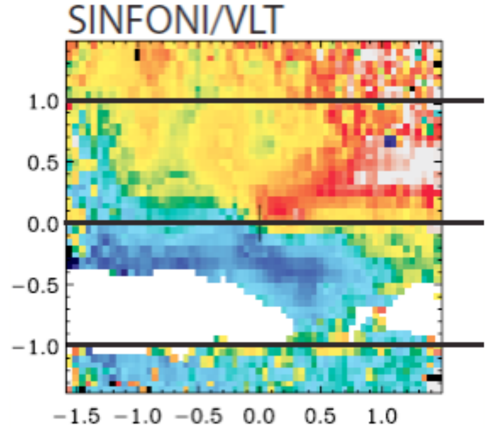
Position on sky along slit

Centaurus -A

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

Gas Velocities





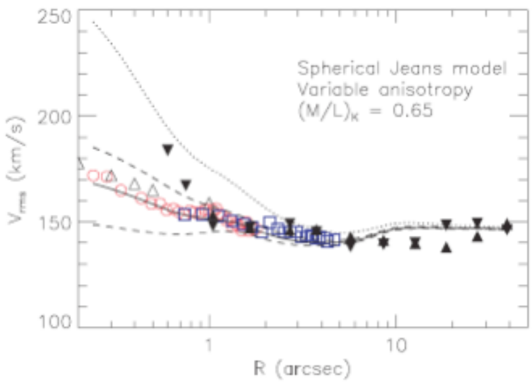
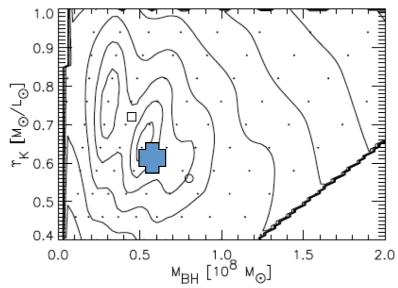
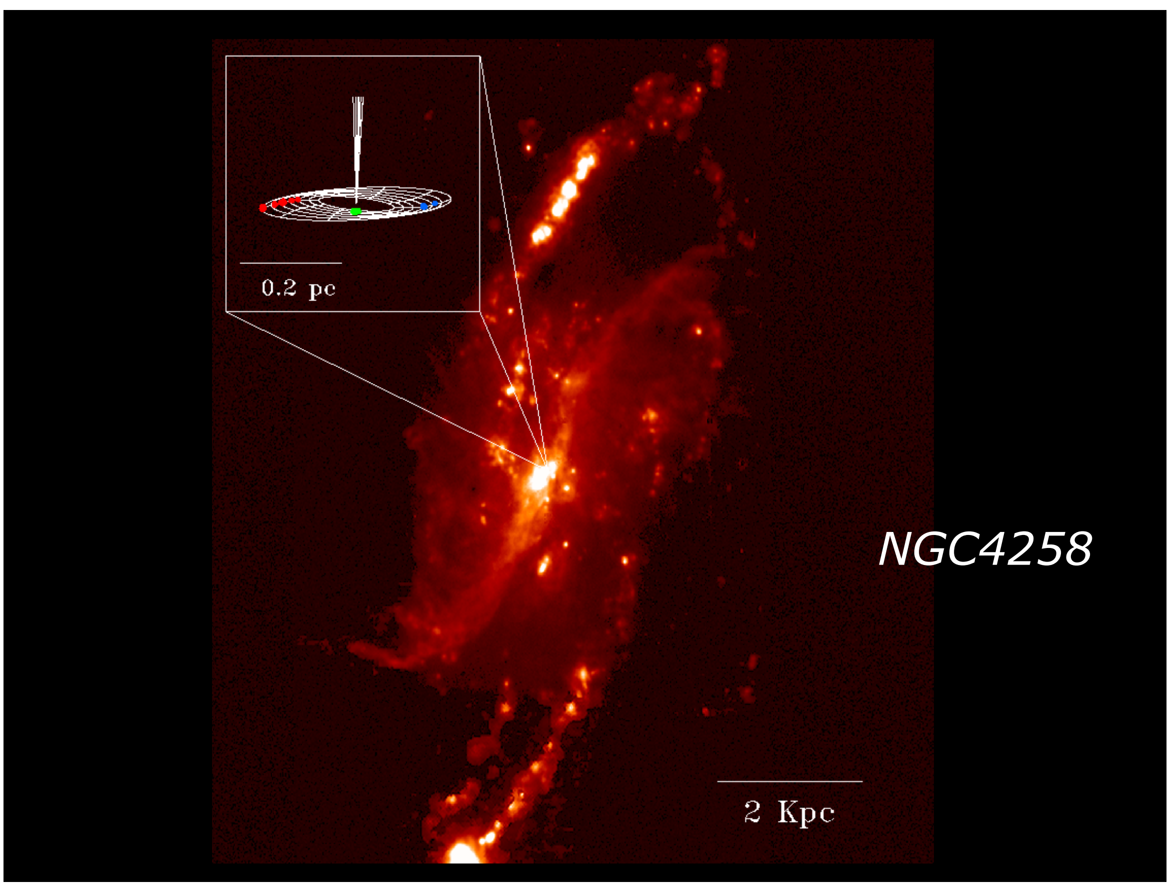


Figure 4: Spherical anisotropic Jeans model



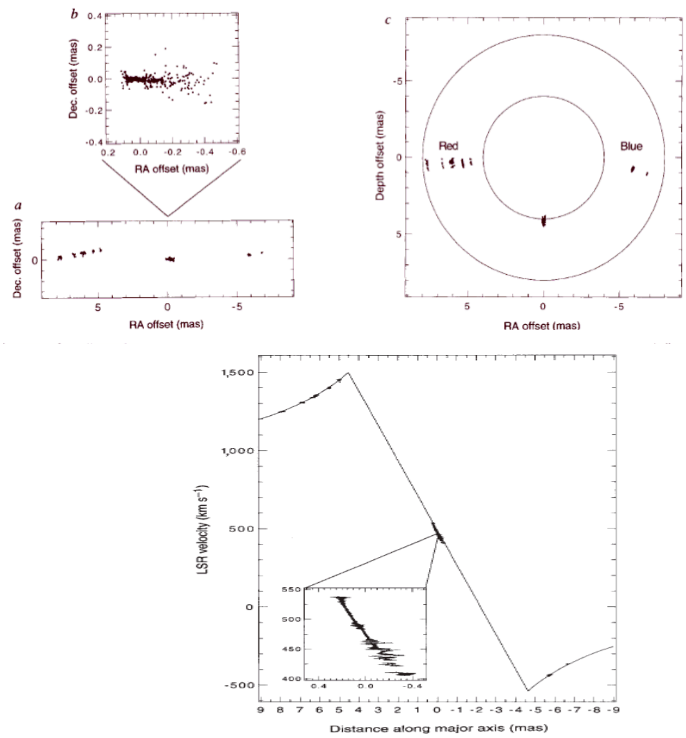
$$M_{\rm BH} = (5.5 \pm 3.0) \times 10^7 M_\odot.$$

Constraints from stars compared to those from Gas Velocities

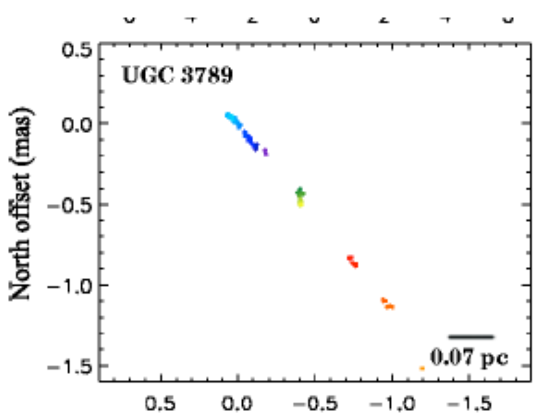


Use of Masers for an AGN BH Masses

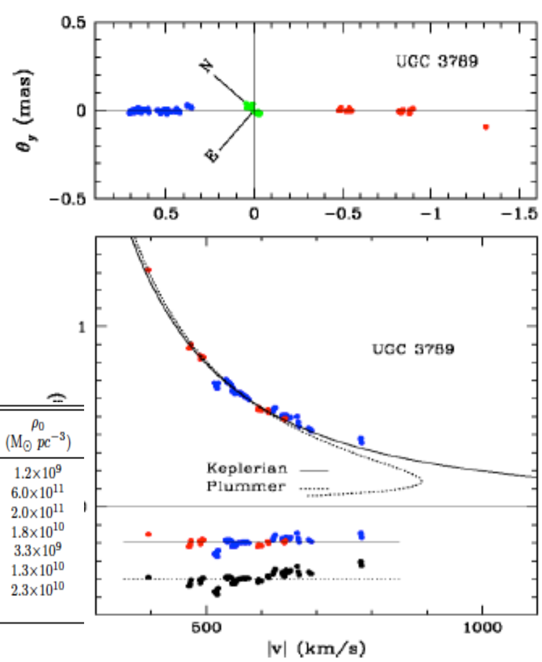
- The nearby galaxy NGC4258 has a thick disk which is traced by water maser emission
- Given the very high angular and velocity resolution possible with radio observations of masers the dynamics of the system are very well measured.



Other Masers



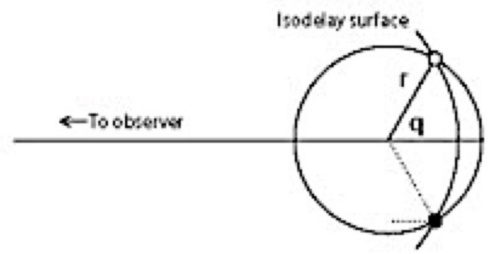
Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36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



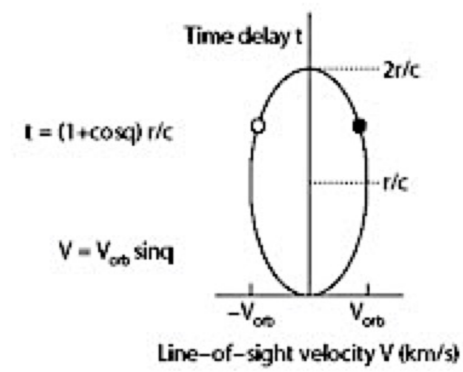
Kuo et al 2010

What About AGN in General??

- The enormous 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

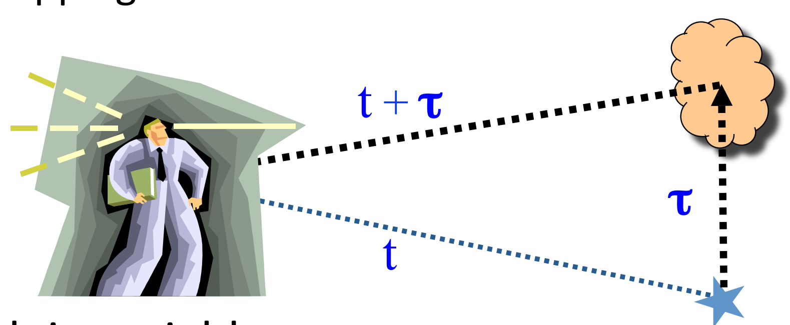


Virial Mass Estimates

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

Reverberation Mapping:

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

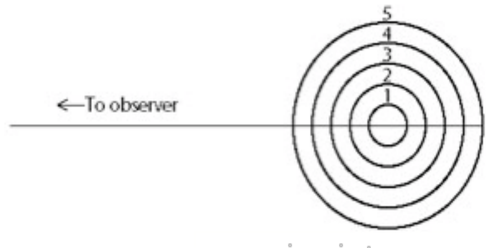


- v_{BLR}

  Line width in variable spectrum

The Geometry

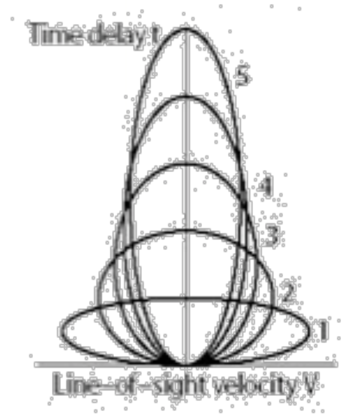
- Points (r, θ) in the source map into line-of-sight velocity/time-delay(τ) space (V, τ) according to $V = -V_{orb} \sin(\theta)$, where V_{orb} is the orbital speed, and $\tau = (1 + \cos(\theta))r / c$.



- 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

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

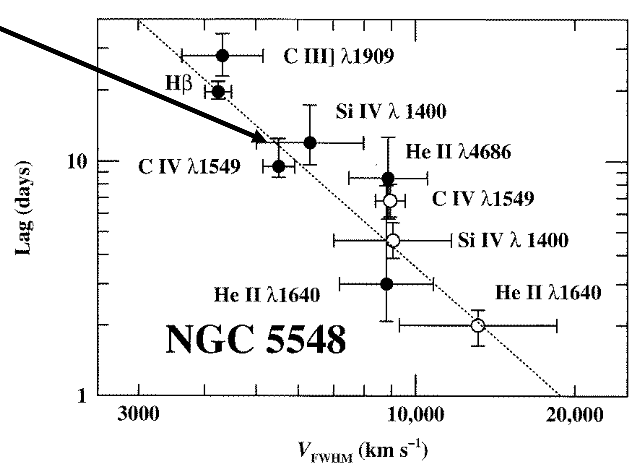
f is a parameter related to geometry- and the orbits of the gas clouds- assumption is that gas is in a bound orbit around the BH



r=ct, where t is the time delay

What is Observed??

- The higher ionization lines have a larger width (rotational speed) and respond faster (closer to BH
- Line is consistent with idea of photoionization, density $\sim r^{-2}$ and Keplerian motions 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