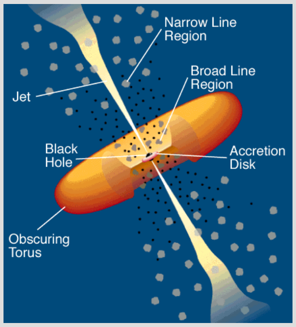
Active Galactic Nuclei

Evidence & (some) Physics of BH's



Arguments in Favour of SMBHs as the Engines of AGN

Theoretical arguments for SMBHs in AGN:
- Radiation pressure: Lower Limit on $M_\bullet$
- Radiation Efficiency of Accretion on BHs

Observational evidence for SMBH in Galaxies/AGN hosts:
- High central stellar velocity dispersions
- Megamaser disks
- Radial Velocities from Ionized Gas
- Broad Iron (Fe) Ka lines (relativ. accetion disk)
- Reverberation mapping
- Sgr A* in the Galactic Center

Radiation Pressure: BH mass limits

(Long-term) stability of the AGN gas requires that the graviational force exceeds or equals the radiation pressure from the AGN:

$F_{grav} > F_{rad}$

Radiation Force on an electron

$$\vec{F}_{\mathrm{rad}} = \sigma_e \frac{L}{4\pi r^2 c}\hat{r}$$

Gravitational Force on electron plus proton pair (medium must be neutral)

$$\vec{F}_{\mathrm{grav}} = -\frac{GM_\bullet(m_p+m_e)}{r^2}\hat{r}$$

Radiation Pressure: BH mass limits

Eddington Limit:

$$L \le \frac{4\pi G c m_p}{\sigma_e} M_\bullet \approx 6.31\times10^4 M_\bullet \ \mathrm{erg\,s^{-1}} \approx 1.26\times10^{38}(M_\bullet/M_{sun})\ \mathrm{erg\,s^{-1}}$$

This is known as the Eddington limit, which can be used to establish a minimum for the mass of the BH: $M_{\mathrm{E}} = 8\times10^5 L_{44}\, M_{\mathrm{sun}}$

For typical Seyfert galaxies $L \approx 10^{44}$ erg s^{-1}, so $M_{Sy} \approx 8 \times 10^5 M_{sun}$
QSOs $L \approx 10^{46}$ erg s^{-1}, so $M_{QSO} \approx 8 \times 10^7 M_{sun}$

The Eddington luminosity is the maximum luminosity emitted by a body of mass *M* that is powered by spherical accretion.

Radiation Pressure: BH mass limits

- Hence, the luminosity of an AGN sets a limit on its mass, independent from size/distance (both radiation pressure and gravity decrease as $1/r^2$).
- This does NOT imply a SMBH, but combined with an upper limits on the volume (e.g. from variability) it can limit alternatives (clusters of compact objects).

Why black hole?

- With the Eddington mass $>10^8 M_{sun}$ and the size constraints <1pc from variability one can derive a robust lower limit for the central mass density
  $\rho > 10^8 M_{sun}\ pc^{-3}$
- For comparison remember that
  - in our vicinity there are only a few stars within a parsec distance.
  - the central star cluster in our Galaxy has “only” ~4 $10^6 M_{sun}\ pc^{-3}$
- It was then suggested that the activity in the active nuclei was produced by a accreting black holes.
- NB: The term ``black hole'' was invented by John Wheeler in 1967 well after the concept was invented.

What is a black Hole

- A black hole is a concentration of mass so large, that even light cannot escape its gravitational attraction (i.e. space curvature).
- A black hole has only two parameters (we ignore charge):
  - the mass M_{bh} and
  - the spin $0 \leq a \leq 1$ in units of $M_{bh}\ c\ R_g = G\ M_{bh}^2/c$.
- A non-rotating black hole (a=0) is called a Schwarzschild hole
- A rotating black hole ($0<a \leq 1$) is called a Kerr hole.

What is a black Hole

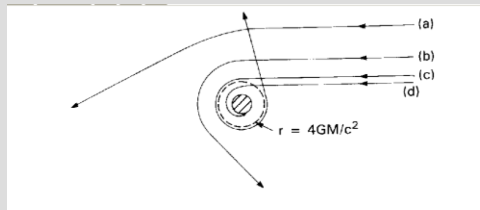


Fig. 7.1. Trajectories of a test particle interacting with a black hole. In the first two cases (a,b) the particle is deflected and escapes to infinity, in case (c) the particle approaches very close to the last stable orbit (the capture radius of 6 GM/c^2) and orbits many times before escaping to infinity, while in (d) the particle is captured and spirals towards the event horizon (2 GM/c^2) shown by the shaded circle.

Schwarzschild Radius et al.

- Equating kinetic and potential energy in a gravitating system yields: $\frac{1}{2}mv^2 = \frac{GM_\bullet m}{R_S} \overset{v=c}{\Rightarrow} R_S = 2\frac{GM_\bullet}{c^2}$
- This is called the Schwarzschild radius and defines the event horizon in the Schwarzschild metric (non-rotating black hole).
  - For the mass of the earth ($3\ 10^{-6} M_{sun}$) we have R_S=1 cm.
  - For a quasar with $M_\bullet = 10^8\ M_{sun}$ we have $R_S = 3\ 10^{13}$ cm = 2 AU.
- In theoretical papers one often uses G=c(=M)=1. The unit of length then is one gravitational radius $R_g = GM/c^2$ (or M).
- For a maximally rotating black hole (a=1) the event horizon is 1 $R_g = 0.5\ R_S$

Mass density

- The critical mass density of a black hole with
  $M_\bullet = M_8\ 10^8\ M_{sun}$ is
  $\rho_\bullet = M_\bullet / (4/3\ \pi\ R_S^3)$

  $= 1.8\ M_8^{-2}$ g cm^{-3}
- The mass density of water is 1 g cm^{-3}. So, if you fill the solar system completely with water it will turn into a black hole. Please make sure your faucets are closed when you leave your house!

Black Holes – not really black

- When mass falls onto a black hole, potential energy is converted into kinetic energy. This energy is either advected into and beyond the event horizon or released before.
- The potential energy of a mass element *dm* in a gravitational field is $U = \frac{GM\ m}{r}$
- The available energy (luminosity) then is

$$L = \dot{U} = G\frac{M}{r}\frac{dm}{dt} = GM\frac{\dot{M}}{r}$$

where we call M-dot the mass accretion rate.

Black Holes – not really black

- The characteristic scale of the emitting region will be a few gravitational radii, i.e. $r \sim r_{in} R_g$ ($R_g = GM/c^2$)

$$L = \frac{GM\dot{M}}{1}\frac{c^2}{r_{in}GM} = \eta\dot{M}c^2$$

  where we define here the efficiency $\eta = r_{in}^{-1}$.
- Therefore, for energy dissipation near the black hole with, e.g., r_{in}=10 we will have η=0.1 and hence a 10% efficiency in converting rest mass into energy.

Black Holes – not really black

- The efficiency η will depend on the spin (a) of the black hole:
  - for a=0 (Schwarzschild) we have η =6% and for a=1 (extreme Kerr) we have η =40%!
  - Note that for nuclear fusion we only have η =0.7%.
- For $L_{QSO}=10^{46}$ erg/sec and η =10% we have Mdot = $2M_{sun}$ yr^{-2}.
- The accretion rate to obtain the Eddington luminosity is $M_{dot,Edd}=L_{Edd}/\eta\, c^2 \sim 2.2\, M_8\, \eta^{-1}\, M_{sun}/yr$
- The Eddington accretion rate also depends type of accretion:
  - Spherical accretion: Eddington limit is strictly valid only for this type
  - ADAF (Advection Dominated Accretion Flow): Quasi-spherical accretion where energy is not radiated away, but carried into the black hole (η <<0.1). However, the efficiency increases towards the classical case when M->$M_{dot,Edd.}$
  - Disk accretion: much of the radiation escapes along rotation axis. However, strong radiation can induce a disk-wind which becomes significant near the Eddington limit.
- =>At least for very luminous AGN, the Eddington limit is robust.

Accretion Efficiency for Non-Rotating Black Holes

What is the amount of energy available before the gas falls into the central black hole at some radius nR_S ?

Newtonian Approximation:

Potential Energy: $V = GMm/(n R_S)$
Schwarzschild radius: $R_S = 2GM/c^2$

$$\boxed{E_{rad} \leq (1/2n)\, m\, c^2}$$

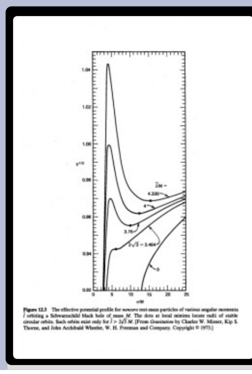
Accretion Efficiency for Non-Rotating Black Holes

What is n for a non-rotating Black Hole?
(section 5.1.3 of Krolik)

If n is O(few), then the efficiency can be as high a 50%, if a particle can effectively radiate that energy away!

Particles on plunging radial orbits (L=0) don't radiate efficiently, but particles with L>0 do, so let's consider those.

Accretion Efficiency for Non-Rotating Black Holes



For non-zero restmass particles with L>0: (G=c=1)

$$\frac{1}{2}\dot{r}^2 = \boxed{\frac{1}{2}E_\infty^2} - \boxed{\frac{1}{2}\left(1-\frac{2M}{r}\right)\left(1+\left(\frac{L}{r}\right)^2\right)}$$

Particle (pseudo) energy E* — Effective potential V_{eff}

Particles with L>0 will move in an accretion disk on (quasi) circular orbits (dr/dt=0), loosing their angular momentum and energy! (Krolik Chapt. 5)

Accretion Efficiency for Non-Rotating Black Holes

To find the circular orbit, we need to determine the extrema of V_{eff}

$$r_m = \frac{1}{2}\left(\frac{L}{M}\right)^2 \left[1 \pm \sqrt{1-12(M/L)^2}\right]$$

Extrema are only found if $L \geq \sqrt{12}\, M$ or $r_{ms} \geq 6\, GM/c^2$

Hence the "innermost stable" or "marginally stable" orbit is 6 times the Schwarzschild radius. Inside that radius NO circular orbits exist and the gas/particles plunge into the BH !

Accretion Efficiency for Non-Rotating Black Holes

What does this imply for the SMBH accretion efficiency?

How much energy is lost "down the road" from infinity till 6M ?

(a) Pseudo energy at 6 R_S : $E_*(6M) = 4/9$
(energy of particle)

(b) Associated $E_\infty = \sqrt{[2E_*(6M)]} = (\sqrt{8})/3$
(what is should be if no energy was lost)

(c) Binding energy: $E_B = 1 - E_\infty = 0.057$
(hence this is what was lost on the way)

Hence 6% (η=0.06) of the particle restmass has been converted to (mostly radiative) energy through loosing angular momentum (redshifting accounted for).

Accretion Efficiency for Rotating Black Holes

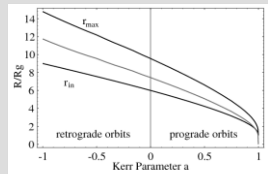
For rotating black holes the situations is more difficult (see Krolik), but the procedure is the same.

In this case: $r_{ms} \sim GM/c^2$

and η=1-1/√3 = 0.42 for a maximally rotating (Kerr) Black Hole

Hence η=0.06 - 0.42 for non- to maximally-rotating BHs

Inner Disk Radii

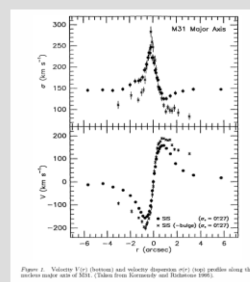


- The top line gives the radius of maximal energy dissipation
- The bottom line gives the location of the marginally stable radius, i.e. the inner disk radius.
- Values plotted as function of angular momentum a.

Direct observational evidence for massive objects in the centers of (AGN host) galaxies.

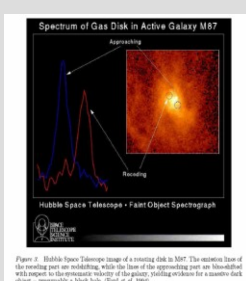
M31 – Andromeda: Stellar Kinematics

- Velocity dispersion increases to 250 km/s toward center
- Radial velocities increase to 200 km/s before passing through center
- Kormendy (1988) derived a mass of about 10^7 M_{sun}



M87 (Massive Elliptical): Gas Kinematics

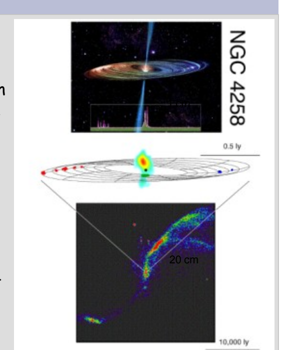
- Radial Velocity measurements using spectroscopy of emission lines of ionized gas
- Ford et al. conclude a mass of 2.4 x 10^9 M_{sun} within the inner 18 parsecs of the nucleus



NGC 4258: Megamasers

H_2O megamaser @ 22 GHz detected in NGC 4258 in a warped annulus of 0.14 – 0.28pc and less than 10^{15} cm of thickness, with a beaming angle of 11 (Miyoshi et al. 1995, Maloney 2002).

Combining the Doppler velocities (900km s^{-1}) and the time to transverse the angular distance (0.14 pc) gives the mass of the nucleus 3.9 x $10^7 M_{sun}$ within $r \lesssim 0.012$ pc



NGC 4258: Megamasers

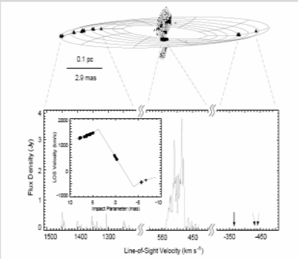


Figure 4. The warped disk model, the maser positions and the 22 GHz continuum emission of a sub-parsec-scale jet from VLBI observations of NGC 4258 (top). Also shown is the total spectrum with masers at the systematic velocity of ~ 470 km s^{-1} and the *high-velocity* masers Doppler shifted by ±1000 km s^{-1}. The inlay shows the line-of-sight velocity versus the the impact parameter for a Keplerian disk with the maser data superposed. (Taken from Herrnstein *et al.* 1999).

MCG-6-30-15: Kα Fe line

- X-ray spectroscopy in Seyferts has revealed highly broadened iron Kα lines on the order of 10^4 km/s
- Future X-ray observations will give better estimate on mass of central object
- Greene et al. derived a mass of about $5 \times 10^6\ M_{sun}$

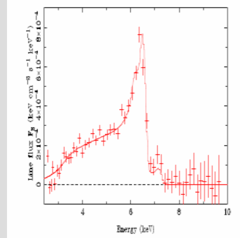
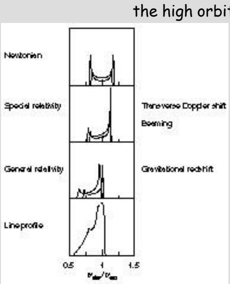


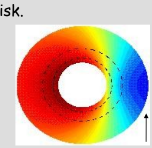
Figure 5. Continuum subtracted relativistic iron line profile from an XMM-Newton observation of MCG-6-30-15 (Taken from Fabian *et al.* 2002).

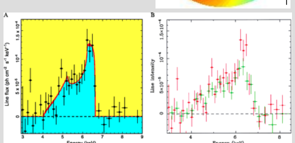
MCG-6-30-15: Kα Fe line

The profile is skewed with an extended red wing due to gravitational redshift, and a prominent blue wing which is relativisticaly boosted due to the high orbital velocities of the disk.



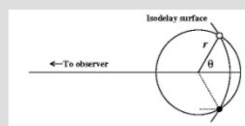
Accretion disk





Reverberation Mapping: SMBH Mass Measurement

The BLR is photoionized, since it responds to continuum variations, with a certain delay, which is a function of the BLR geometry, viewing angle, line emissivity, etc.



e.g., for a thin spherical shell, the BLR would respond at a delay time τ given by the parabolid

$$\tau = (1+\cos\theta)r/c$$

In general the line response is given by

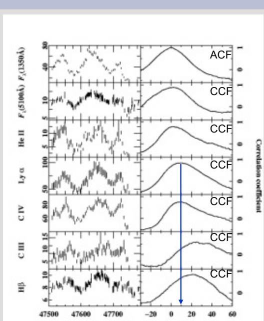
$$I(t) = \int \Psi(\tau) L(t-\tau) d\tau$$

where Ψ is called transfer function.

The centroid of the cross-correlation function between the continuum and the line gives the mean radius of emission: $\mathrm{CCF}(\tau) = \int \Psi(\tau')\mathrm{ACF}(\tau-\tau')d\tau'$

where ACF is the autocorrelation function of the continuum.

Reverberation Mapping: SMBH Mass Measurement



(Peterson 2001, data from Clavel et al. 1992, Peterson et al. 1992)

Measure time-lag

If the kinematics of the BLR are Keplerian, we can apply the virial theorem

$$\frac{GM_\bullet}{r_{\rm BLR}} = f\sigma^2$$

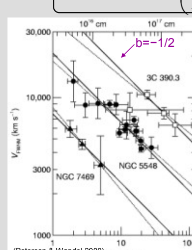
with f, a factor close to 1. Measuring the line widths (FWHM) of the emission lines, we have an estimate of the velocity dispersion σ.

Reverberation Mapping: SMBH Mass Measurement

The central mass is then given by:

$$M_\bullet \approx (1.45\times10^5 M_\odot)\left(\frac{c\tau}{\mathrm{lt-day}}\right)\left(\frac{v_{\rm rms}}{10^3\,\mathrm{km\,s^{-1}}}\right)^2$$

(Wandel, Peterson, & Malkan 1999)



Different lines give you the same answer, even if the r_{BLR} measured is different.

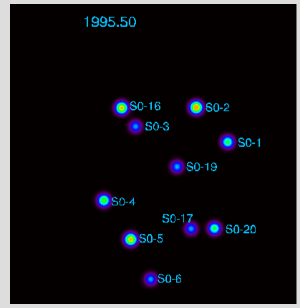
$$\log v_{\rm FWHM} = a + b \log c\tau$$

The masses derived by this method range from M = $10^7\ M_{sun}$ for Sy 1s (i.e., in the range of the LINER NGC 4258) to $M = 10^9\ M_{sun}$ for QSOs

The Galactic Center

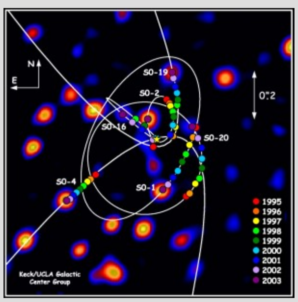
Sagittarius A*

- An unresolved bright continuum at radio wavelengths
- Essentially at rest
- Upper limit on size from radio measurements on order of 3 x 10^{10} km
- Several Stars in orbital motion around Sgr A*
- In particular S2
- Deduce an enclosed mass of 3.7 x 10^7 M_{sun}
- Other clues
  - X-ray flares
  - Tidal disruption of stars



Sagittarius A*

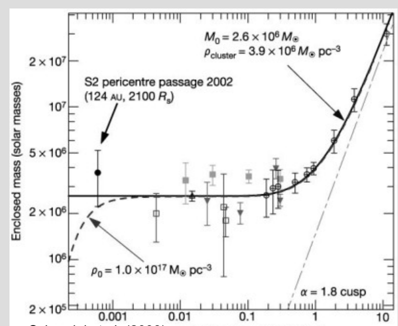
Overlay of Stellar Orbits on Image of 1" at Galactic Center



Andrea Ghez et al. (2003)

Sagitarius A*

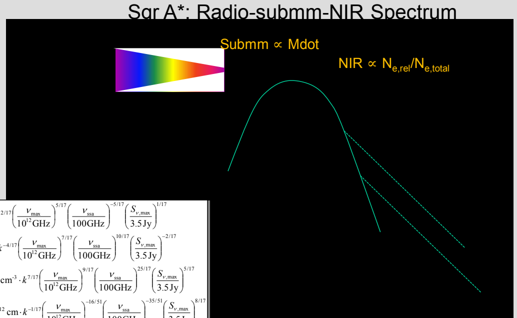
Limit on Enclosed Mass at the Galactic Center



Schoedel et al. (2003)

Constraining Sgr A* Parameters from its radio spectrum

Sgr A*: Radio-submm-NIR Spectrum



$$\gamma_e = 118 \cdot k^{2/17} \left(\frac{\nu_{max}}{10^{12}\,\mathrm{GHz}}\right)^{5/17} \left(\frac{\nu_{ssa}}{100\,\mathrm{GHz}}\right)^{-5/17} \left(\frac{S_{\nu,max}}{3.5\,\mathrm{Jy}}\right)^{1/17}$$

$$B = 75\,\mathrm{G} \cdot k^{-4/17} \left(\frac{\nu_{max}}{10^{12}\,\mathrm{GHz}}\right)^{7/17} \left(\frac{\nu_{ssa}}{100\,\mathrm{GHz}}\right)^{10/17} \left(\frac{S_{\nu,max}}{3.5\,\mathrm{Jy}}\right)^{-2/17}$$

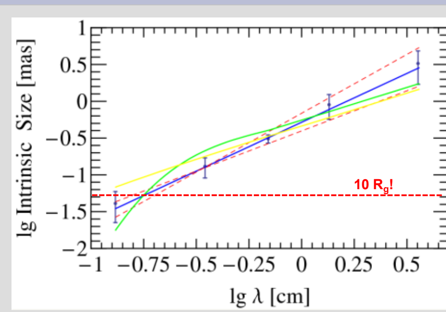
$$n_e = 2 \cdot 10^6\,\mathrm{cm}^{-3} \cdot k^{7/17} \left(\frac{\nu_{max}}{10^{12}\,\mathrm{GHz}}\right)^{9/17} \left(\frac{\nu_{ssa}}{100\,\mathrm{GHz}}\right)^{25/17} \left(\frac{S_{\nu,max}}{3.5\,\mathrm{Jy}}\right)^{5/17}$$

$$R = 1.5 \cdot 10^{12}\,\mathrm{cm} \cdot k^{-1/17} \left(\frac{\nu_{max}}{10^{12}\,\mathrm{GHz}}\right)^{-16/51} \left(\frac{\nu_{ssa}}{100\,\mathrm{GHz}}\right)^{-35/51} \left(\frac{S_{\nu,max}}{3.5\,\mathrm{Jy}}\right)^{8/17}$$

Falcke (1996)

Melia & Falcke (2001), Ann. Rev. A&A

Size of Sgr A*

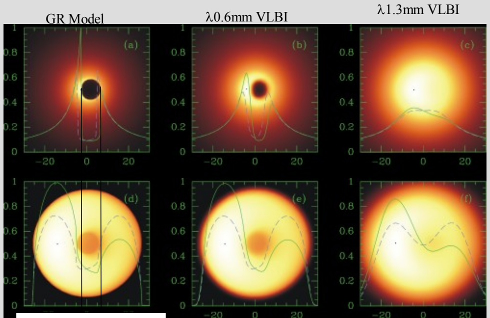


Falcke, Markoff, Bower (2008):
with data from Doeleman et al. 2008, Shen et al. 2006, Bower et al. 2005

The Shadow of a Black Hole
It's getting bigger!

a=0.998
$I=r^{-2}$

a=0
I=const

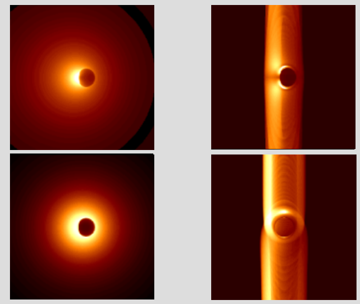


(Falcke, Melia, Agol 2000, ApJL)

Varying the Models

Infall:
a=0.998
i=90º
$I=r^{-2}$

Infall:
a=0
i=90º
$I=r^{-2}$

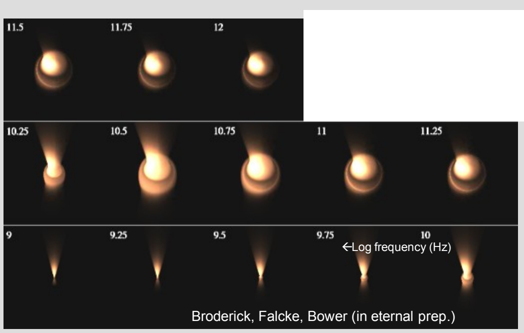


Jet:
a=0.998
i=90º
I=hollow

Jet:
a=0
i=45º
I=hollow

Agol, Falcke, Melia, et al. (2001), conf. proc.

Jet Model GR Ray Tracing



General Summary

- A massive (relativistic?) object is required to avoid highly ionized gas being blown away by radiation pressure.
- The accretion effeciency of SMBH can be 0.06-0.42, avoiding the problem with the "low" nuclear burning efficiency (~0.007) of stars (if they were the cause of AGN)
- Evidence for massive objects (SMBH) come from:
- Stellar/gas kinematics: Increasing to very small radii
- Mega-masers: Keplerian velocity of gas disks
- Broadened Fe lines: Relativistic accretion disks
- Reverberation Mapping: BLR response to continuum variability
- **Sgr A* !!!: Individial stellar orbits around Galactic center**