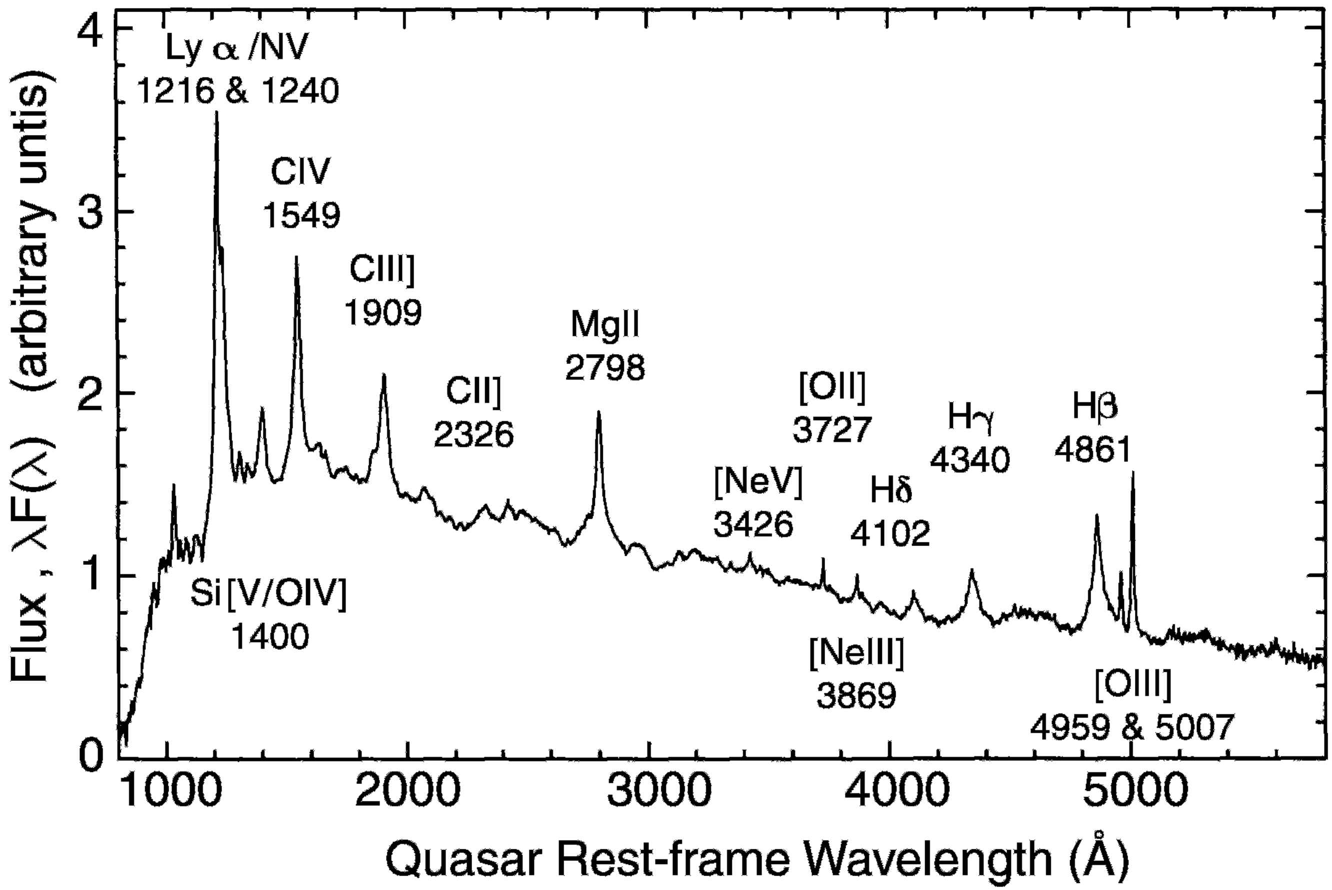
Active Galactic Nuclei

- Optical spectra
- History
- Luminosity and variability
- Need for black holes
- Accretion
- Eddington limit
- Growth of black holes
- Superluminal motion

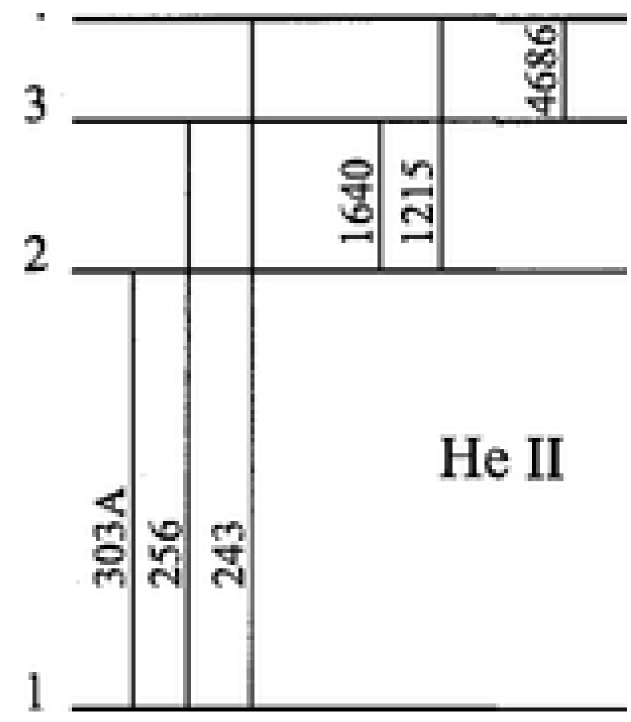
Optical spectrum of an AGN



- Variety of different emission lines
- Each line has centroid, area, width
- There is also continuum emission

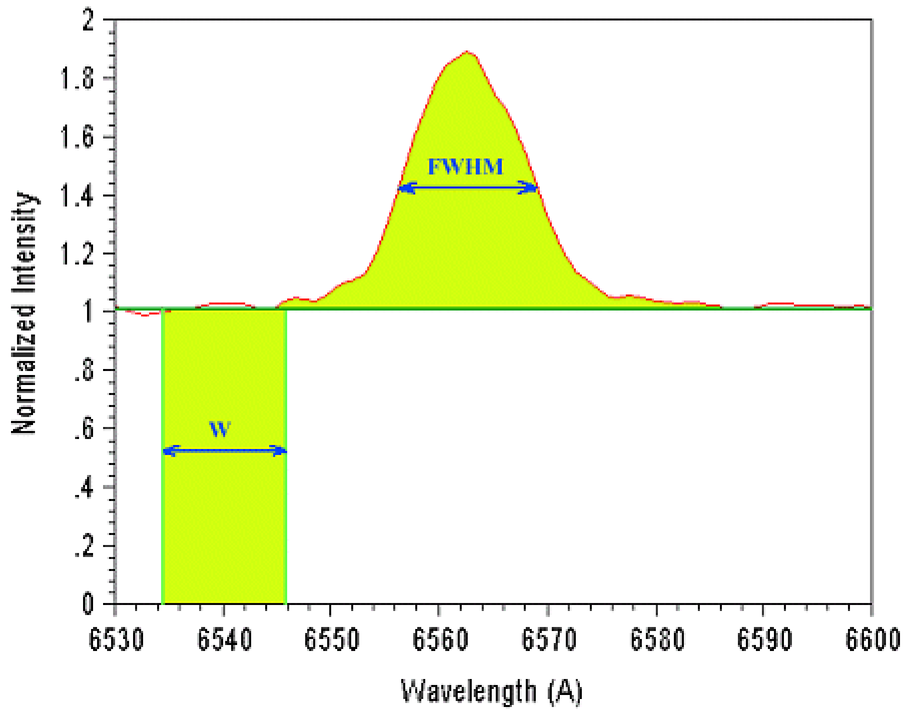
Line emission

- Measure centroid of each line.
- Correct for redshift of object (transform to rest frame).
- Compare each centroid versus tables of known emission lines and identify the element and ionization state producing the line.
- E.g. if one detects a line at 4868 A, then it is produced by fully ionized Helium.
- Full ionization of Helium requires 54.4 eV, thus even without direct detection of FUV photons, we know they must be present.
- "Allowed" transitions are dipole electric transitions.
- "Forbidden" transitions, e.g. [O III], cannot occur via electric dipole and are weaker. Forbidden transitions occur only in low density gas because the states are collisionally de-excited in dense gas.

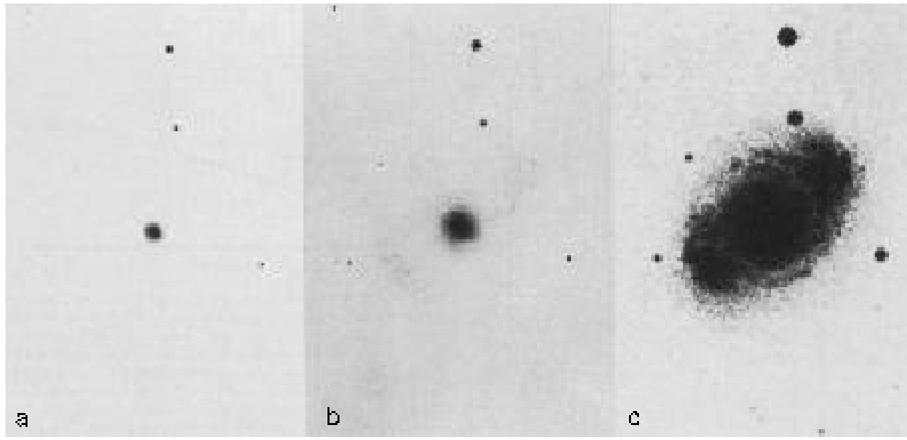


Emission lines

- Beyond centroid, each line has area and width.
- Area is proportional to the number of detected line photons or the line flux.
- Usually characterized by "equivalent width" or range in wavelength over which integration of the continuum produces the same flux as the line.
- The width is usually characterized by the "Full Width at Half Maximum". For a Gaussian FHWM = 2.35σ.
- The line profile is determined by the velocity distribution of the line emitting gas, $\Delta v/c = \Delta\lambda/\lambda$.



Early observations of AGN



- Very wide emission lines have been known since 1908.
- In 1959, Woltjer noted that if the profiles are due to Doppler motion and the gas is gravitationally bound then $v^2 \sim GM/r$. For $v \sim 2000$ km/s, we have

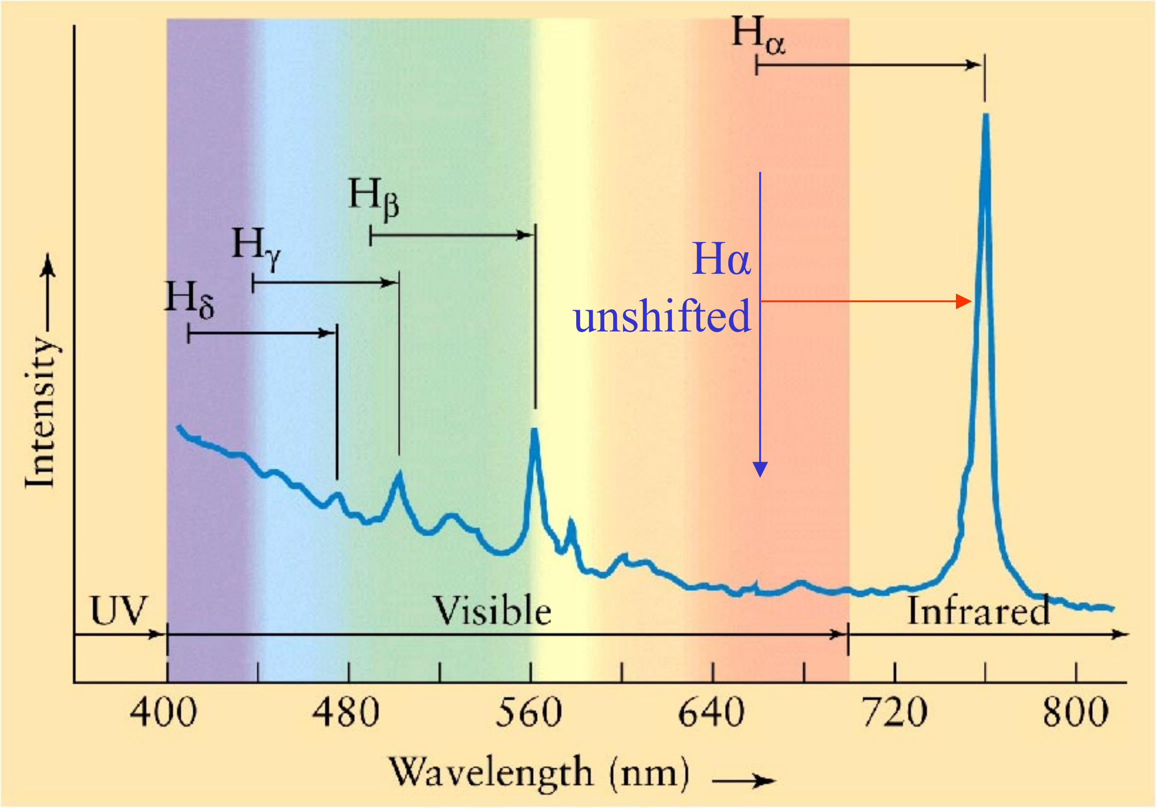
$$M \geq 10^{10} \left(\frac{r}{100\,\mathrm{pc}} \right) M_{\mathrm{Sun}}$$

- So AGN, known at the time as Seyfert galaxies, must either have a very compact and luminous nucleus or be very massive.

Quasars

- Early radio telescopes found radio emission from stars, nebulae, and some galaxies.
- There were also point-like, or star-like, radio sources which varied rapidly these are the `quasi-stellar' radio sources or quasars.
- In visible light quasars appear as points, like stars.

Quasar optical spectra

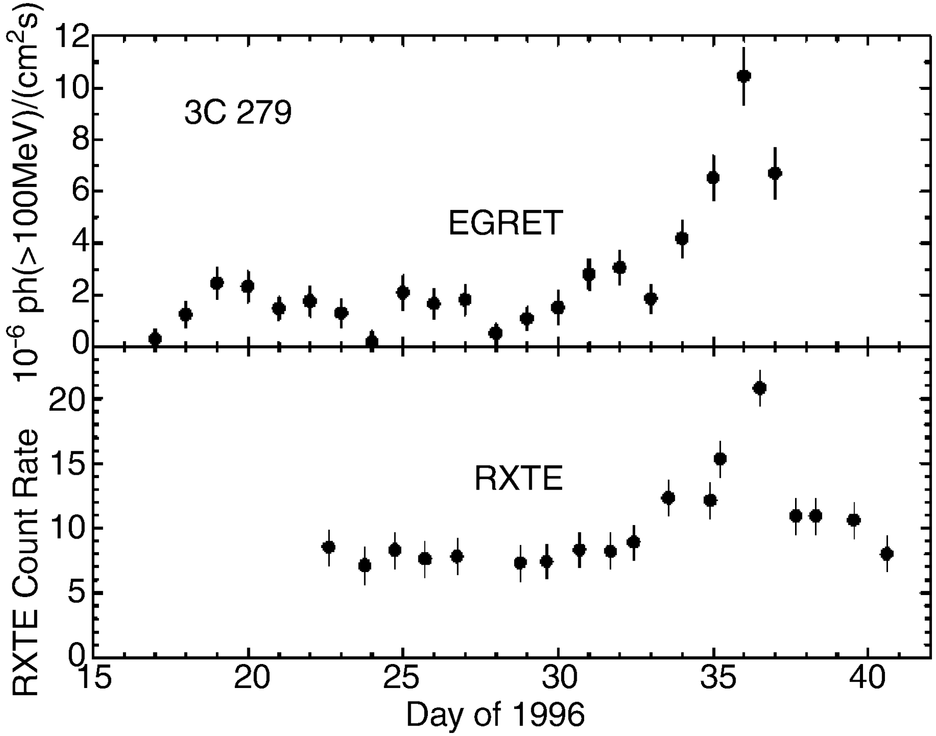


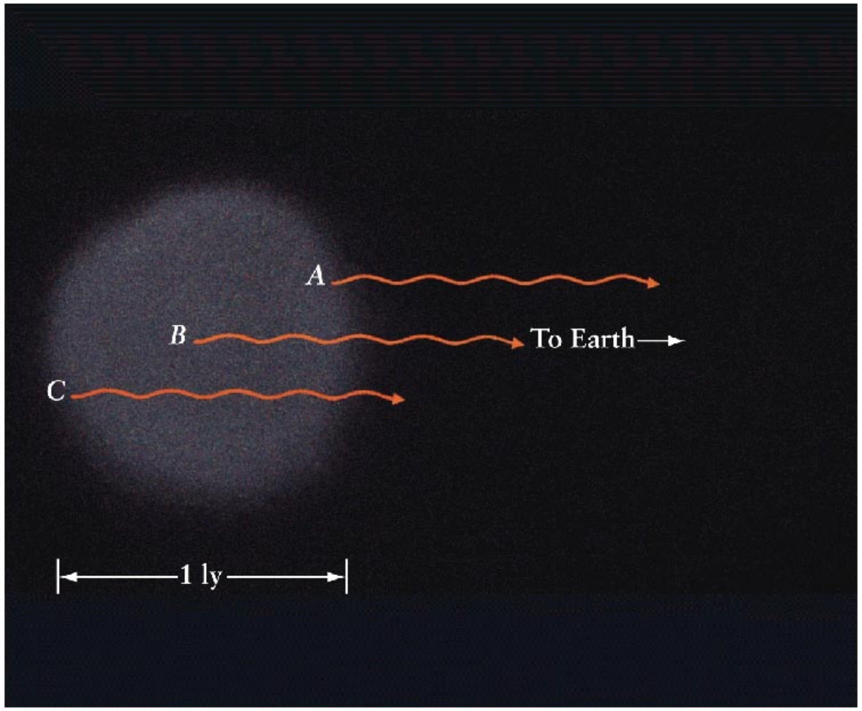
Redshift of 3C273 is 0.16.

3C273 is 2.6 billion light years away if redshift is due to Hubble expansion.

The luminosity of 3C273 is 10^{12} solar luminosities or 100 times the luminosity of the Milky Way.

Quasar variability and size



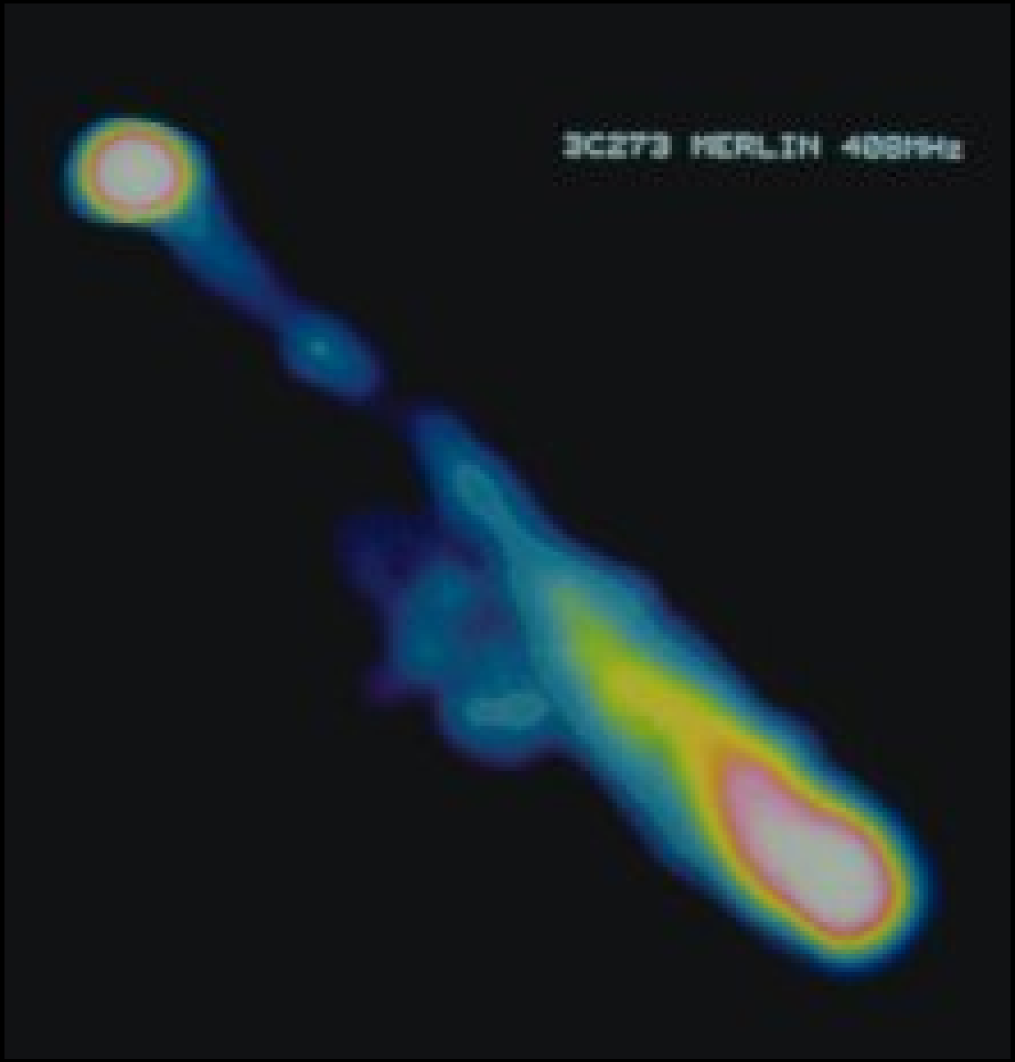


- Size places a limit on how fast an object can change brightness.
- Conversely, rapid variations place a limit on the size of the emitting object, e.g. strong variations on 1 day times scales limit the object size to less than 1 light-day.
- Quasar power source must be smaller than ~ 10^{15} cm.

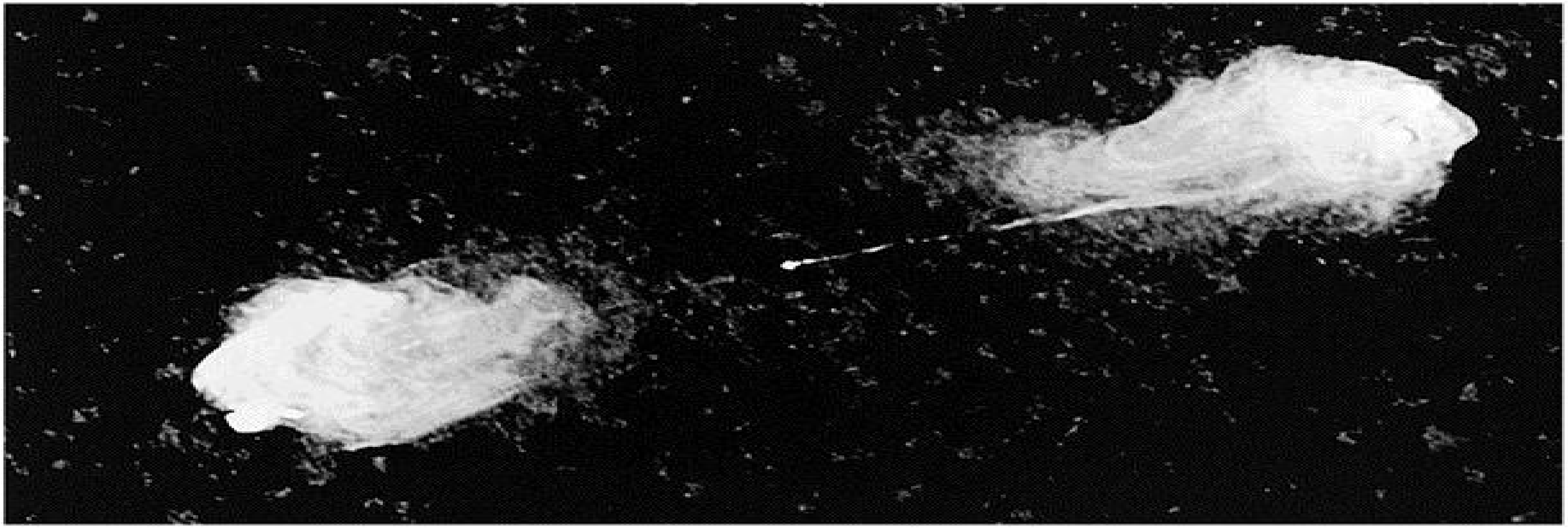
Quasar jets

Optical core →

Radio jet →



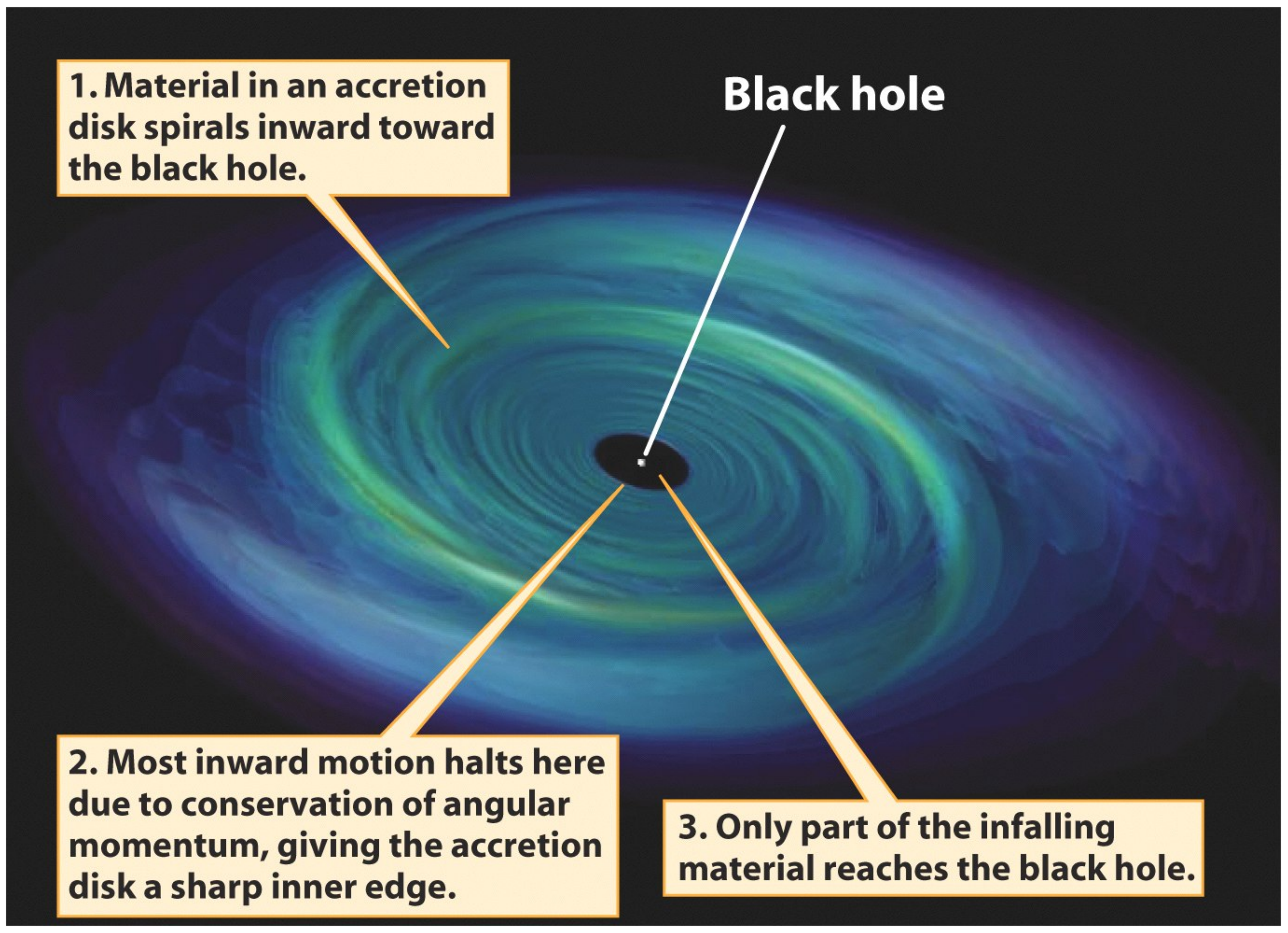
What is the lifetime of this jet?



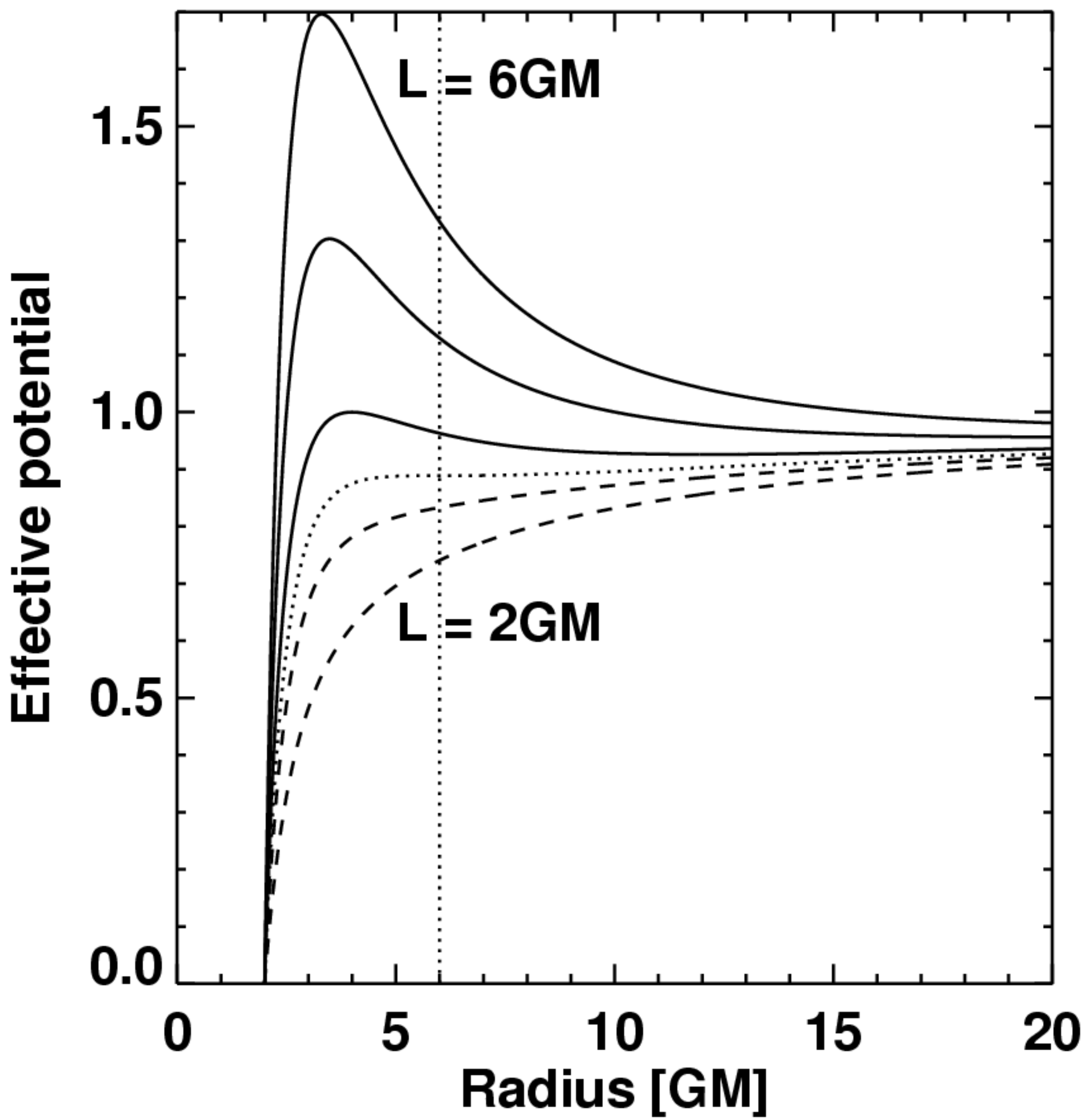
| -------------------- | = 150,000 light years

AGN are powered by black holes

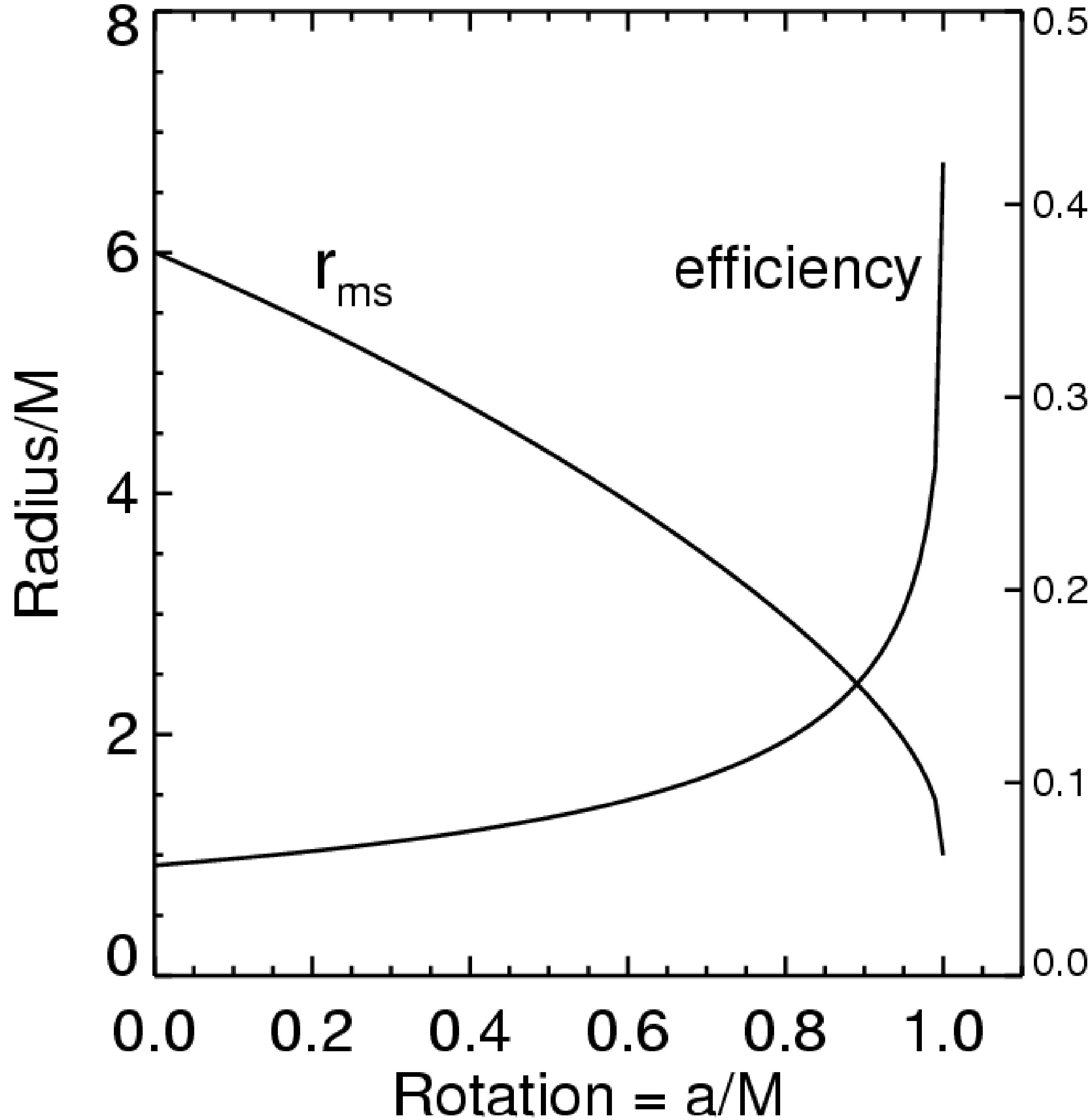
- Radio structures around AGN can reach sizes of ~1 Mpc requiring at least 10^7 years to form.
- Quasar luminosities reach 10^{47} erg/s. Best estimate of total energy is luminosity×age ~ 10^{47} erg/s × 10^7 years ~ 10^{61} erg.
- Nuclear burning releases of 0.008 of rest mass energy, thus this would require $m = E/\varepsilon c^2 = 10^{42}$ g.
- Schwarschild radius $r_s = 2GM/c^2 = 10^{14}$ cm.
- Size of quasars limited by variability to less than 10^{15} cm.
- Efficiency of black holes is 6% for non-rotating and ~30% for rapidly rotating.
- Conclude AGN host black hole because they are the most efficient power sources in the universe.


1. Material in an accretion disk spirals inward toward the black hole.
Black hole
2. Most inward motion halts here due to conservation of angular momentum, giving the accretion disk a sharp inner edge.
3. Only part of the infalling material reaches the black hole.

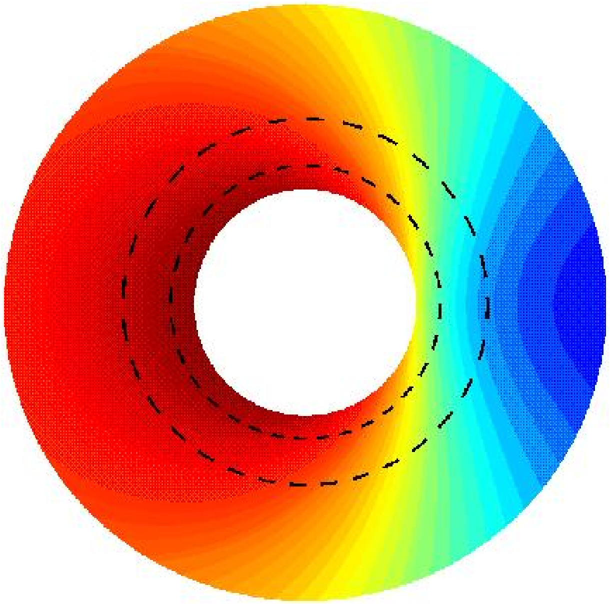
Orbits around Black Holes

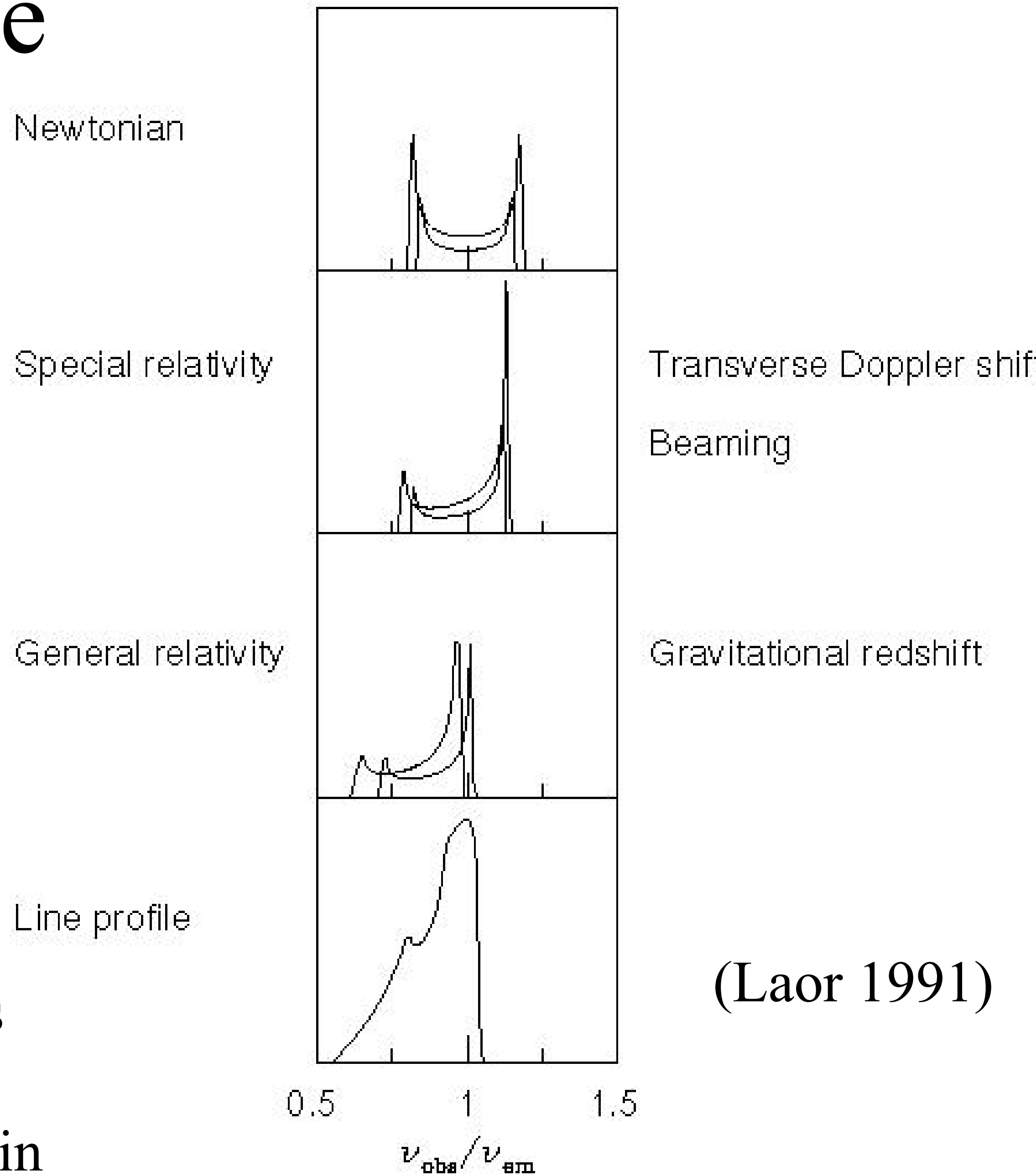


Orbits around Black Holes



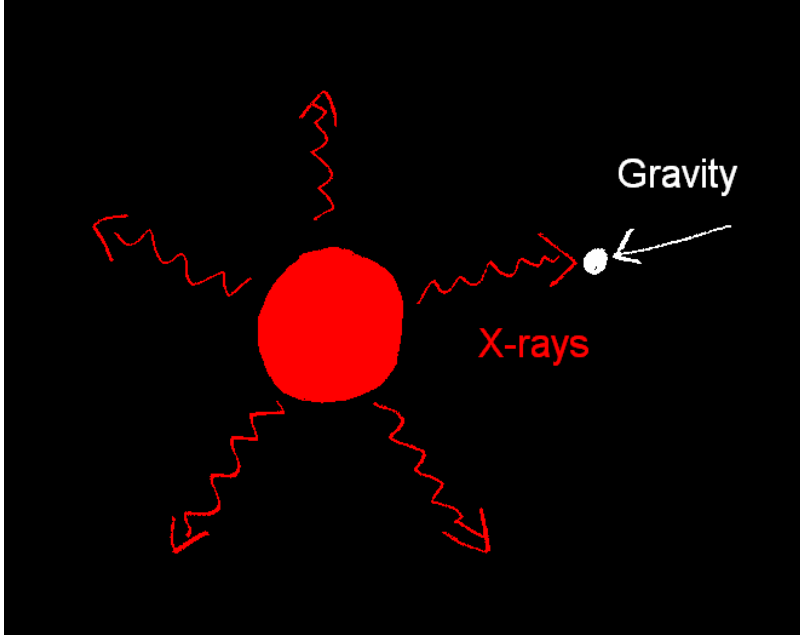
Relativistic line profiles





(Laor 1991)

Red edge of line depends on gravitational redshift, which depends on BH spin



Eddington Luminosity

- Gravitational force $F_{\mathrm{grav}} = GMm/r^2$
- Radiation force $\mathrm{F}_{\mathrm{rad}} = \sigma_{\mathrm{T}}L/4r^2c$
- Must have $F_{\mathrm{grav}} < \mathrm{F}_{\mathrm{rad}}$ for accretion to proceed.
- Limit on luminosity of accreting objects:

$$L < L_{\mathrm{edd}} = 1.3\times10^{38}\ \mathrm{erg/s}\ (M/M_{\mathrm{sun}})$$

Temperature of an accreting black hole

- For the spherical object, the total luminosity is $L = 4\pi R^2 \sigma T^4$ where T = temperature, R = radius, and σ = Stephan-Boltzman constant = 5.67×10^{-8} W/m^2 ·K^4.
- For a black hole at the Eddington limit $L = 1.3\times10^{38}$ erg/s (M/M_{sun}) and the length scale is set by the Schwarschild radius $r_s = 2GM/c^2$.
- Combining $kM = 4\pi\sigma T^4(2GM/c^2)^2$ thus $T \sim M^{-1/4}$
- For 1 solar mass BH, $T \sim 3\times10^7$ K, for 10^6 solar mass BH, $T \sim 1\times10^6$ K.
- The standard model for an accretion disk is a geometrically thin and optically thick disk with particles in Keplerian orbits at each radius. Viscosity causes the release of energy at each radius, so matter gradually moves in as its gravitational potential energy is converted to kinetic energy and heat.
- Within the accretion disk, temperatures vary as a function of radius $T \sim r^{-3/4}$ with the values calculated above near the inner edge.

Growth of an accreting black hole

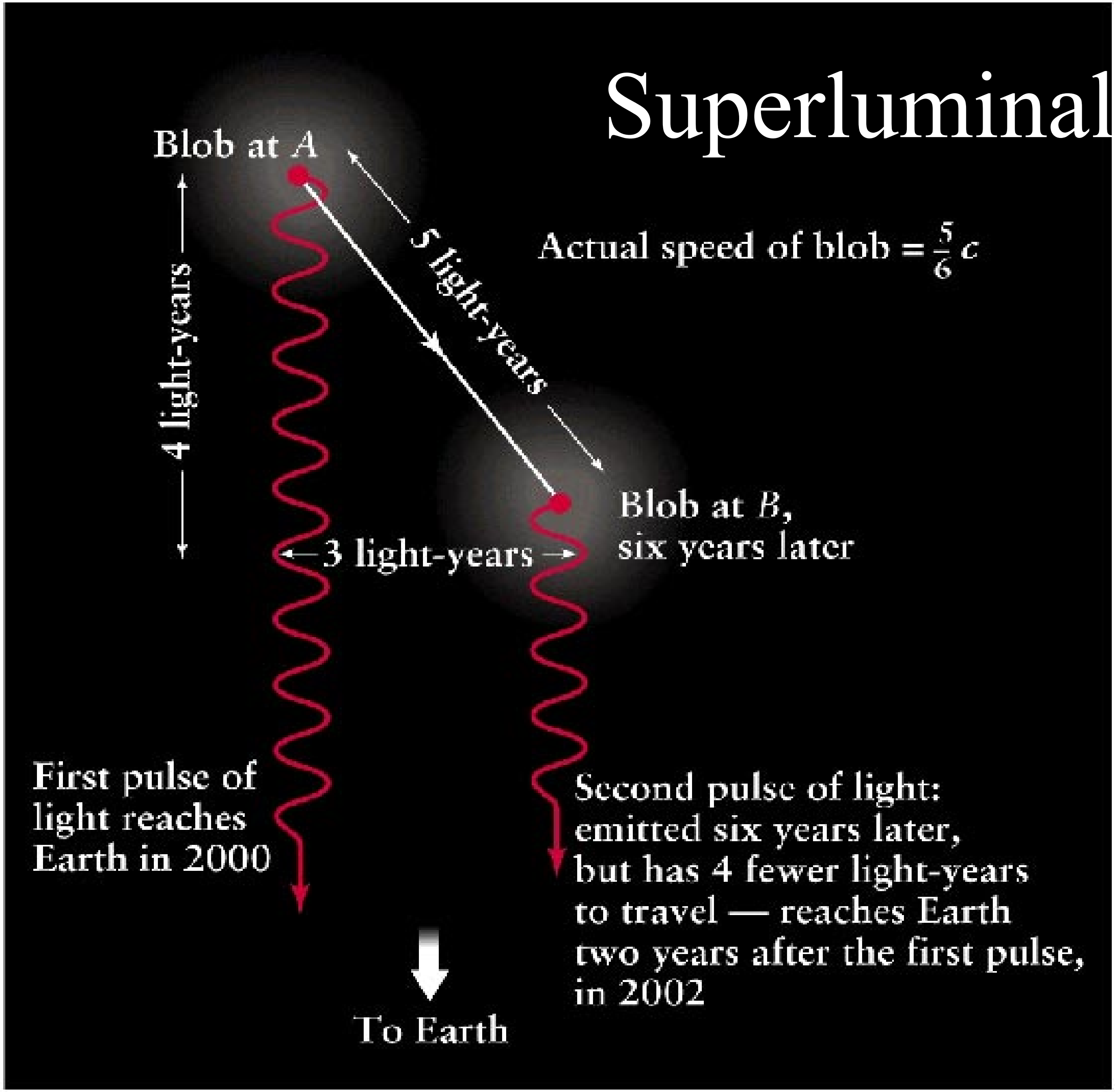
- The Eddington limit $L = 1.3\times10^{38}$ erg/s (M/M_{sun}) also sets the maximum rate at which matter accretes onto a black hole $(\mathrm{d}M/\mathrm{d}t)_{\mathrm{Edd}} = L_{\mathrm{Edd}}/c^2$.

- Since $\mathrm{d}M/\mathrm{d}t \sim M$, we have exponential growth. The time scale for the exponential is about 10^8 years.

- Thus, black holes can grow by accretion on cosmologically short time scales.

- However, there is a problem with the initial growth if the starting point is a stellar-mass, ~10 solar mass, black hole. Since to go from 10 to 10^6 solar masses requires ~ 10^9 years.

Superluminal motion



a View from above

For next class

- Read 5.2, 5.4-5.6.
- Read project paper.