BLACK HOLE PHYSICS

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4. Search for black holes

Newtonian mechanics is used to determine the mass of the BH candidates.

Denote by M_1 and M_2 masses of `visible' and `invisible' components of a binary system, respectively. Let P be its period, and $K = v_1 \sin i$ be the maximal line-of-sight Doppler velocity of the visible star. Here i is the inclination angle of binar orbit. Then

$$\frac{K^3 P}{2\pi \mathrm{G}} = f(M_2, i) = \frac{M_2 \sin^3 i}{(1 + M_2 / M_1)^2} < M_2$$

$f(M_2, i)$ is called the mass function. It can be directly measured in observations.

Eddington luminosity

Thomson scattering of black hole radiation on electrons generates pressure. Accretion stops when this pressure is larger than gravitational attraction. The corresponding condition is known as the *Eddington luminosity*

$$L_{\mathrm{Edd}} = (1.3\times 10^{38}\,\mathrm{erg/s})\,\mu\left(\frac{M}{M_{\odot}}\right)$$

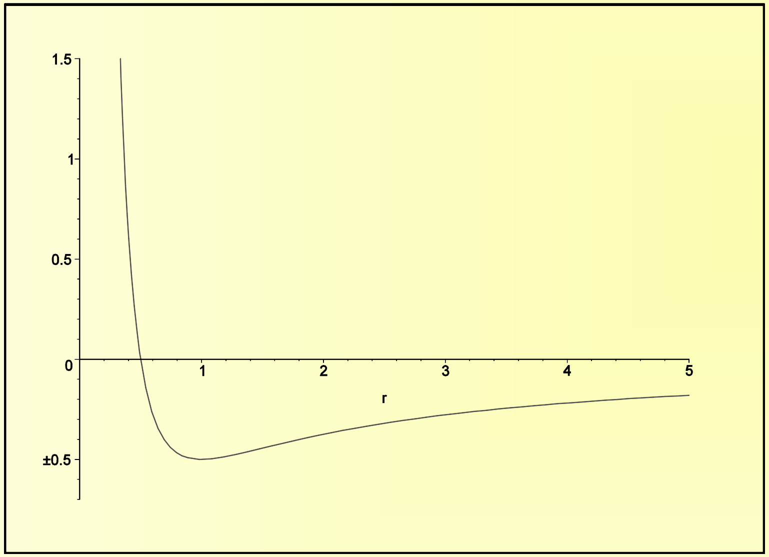
If one assumes that the luminosity of the object L is not larger than L_{Edd} one obtains the lower limit of the black hole mass M.

GR is required to obtain confirmations

Matter, falling onto BH, forms an accretion disk. ISCO radius determines its inner edge, as well as temperature and luminosity of the disk and shortest period of fluctuations of its radiation

Celestial Mechanics: ISCO

Existence of the innermost stable circular orbits (ISCOs) differs GR from Newtonian mechanics



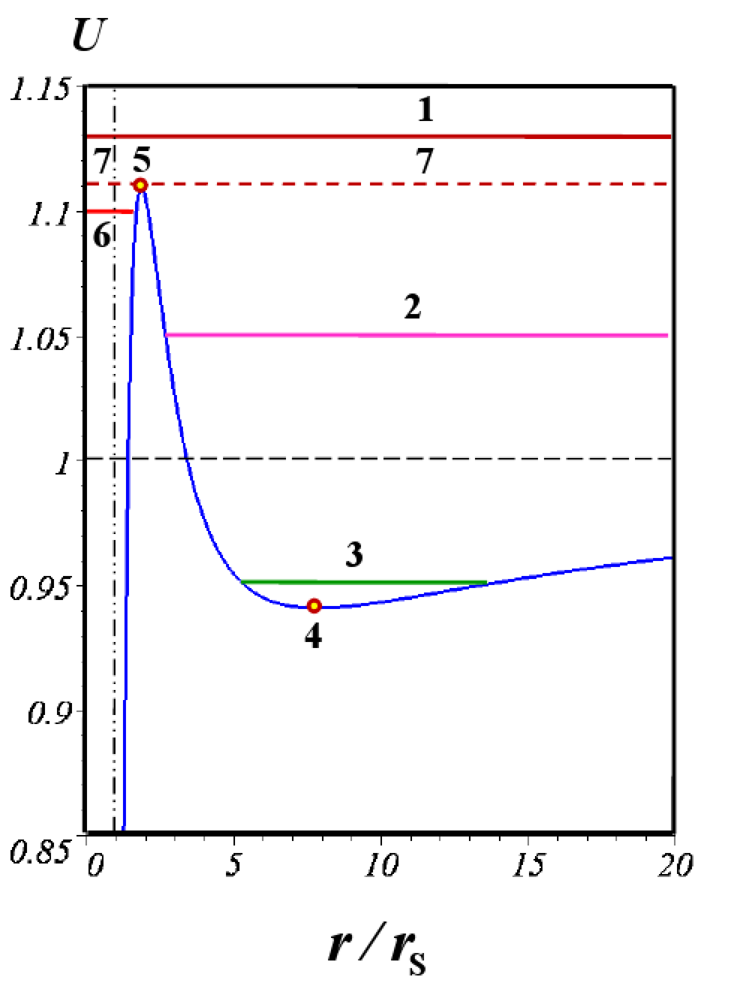
$$U = -\frac{GmM}{r} + \frac{L^2}{2mr^2};$$

$$U' = 0 \Rightarrow r = \frac{L^2}{GmM};$$

In Newtonian theory the radius of a circular orbit can be arbitrary small

(No stable bounded orbits in HD gravity !)
Anthropic principle excludes D>4 with

$$L_{e\dim} = \infty$$



Schwarzschild BH:

$r_{ISCO} = 3r_g = 6M$

$E_{ISCO} / m = \sqrt{8/9}$

BH efficiency: 5.72%

Extremal Kerr BH ($J/M^2=1$):

$r_{ISCO} = M$

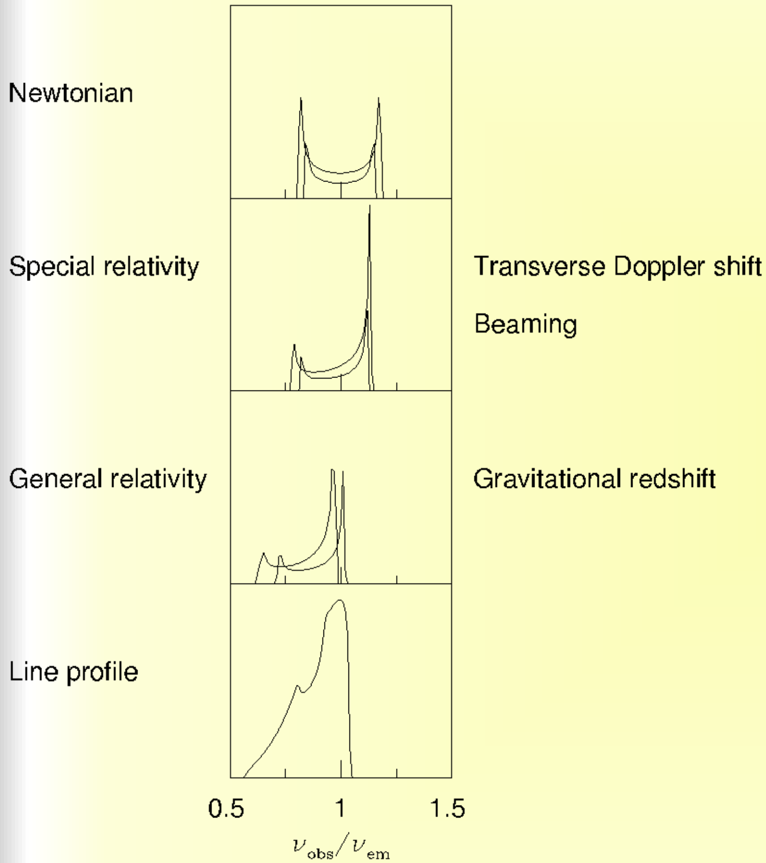
$E_{ISCO} / m = \sqrt{1/3}$

BH efficiency: 42.36%

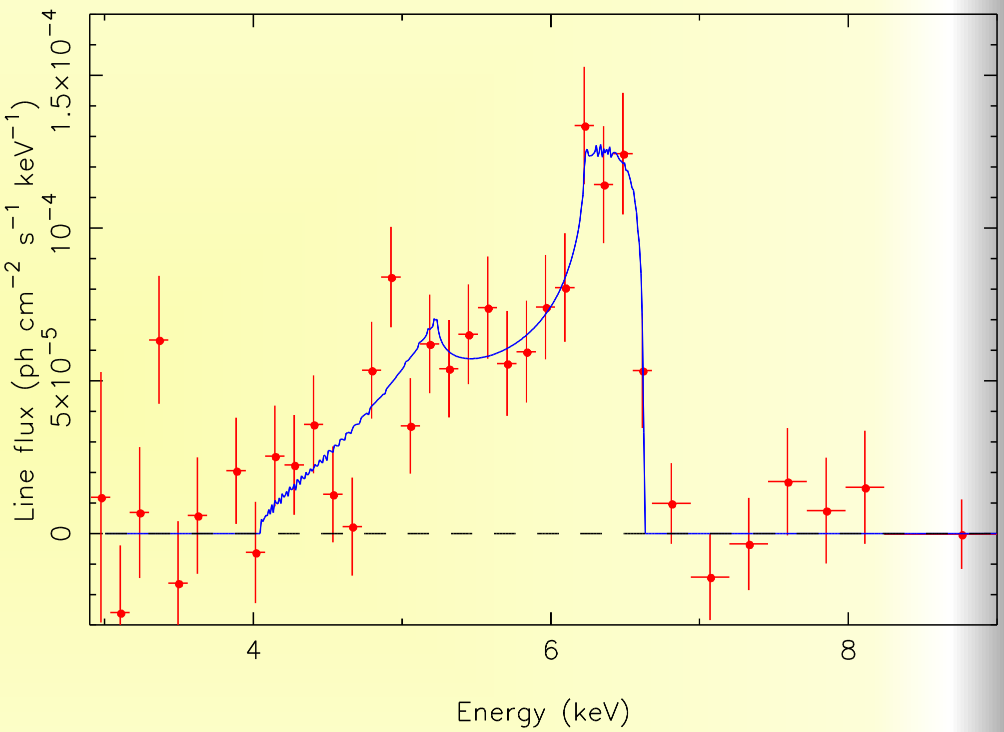
Iron X-ray line broadening

Important information about stellar mass black holes can be obtained by observations of the broadening of the Fe Kα line. This line is associated with iron emission at 6.4 keV. At low temperature the line is very narrow. Its width is less than 100 eV. For the emission from the black hole binaries the observed spectrum differs from the sharp original line. It becomes much broader. The form of the broadened line can be explained if one takes into account that a line emitted by a matter in the inner part of the rotating accretion disk is modified by the Doppler effect, gravitational redshift and relativistic beaming.

$K\alpha$ line broadening



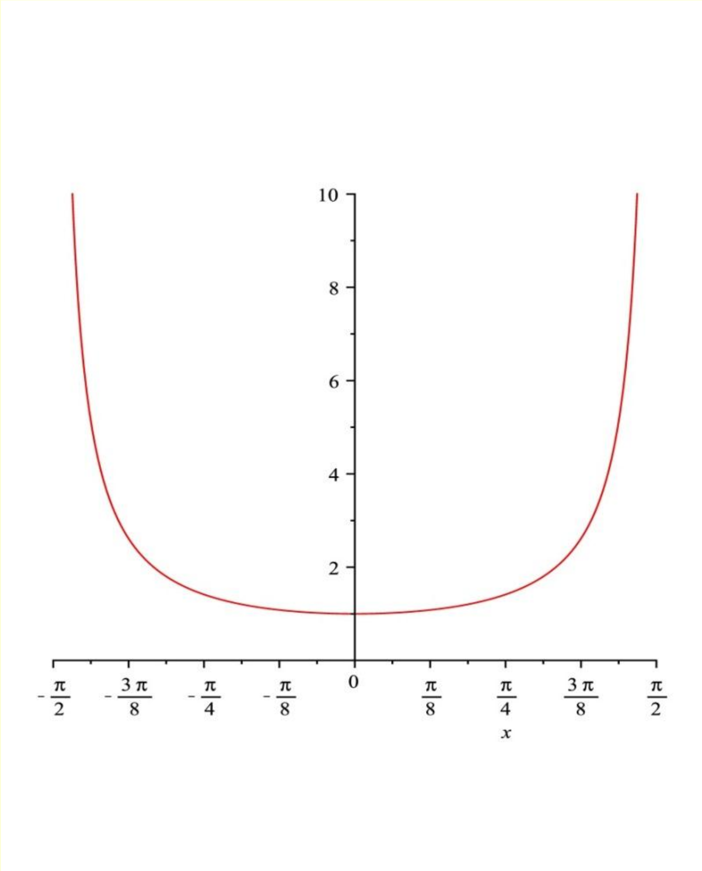
$K\alpha$ line broadening



The profile of Fe $K\alpha$ line from Seyfert galaxy MCG-6-30-15

(From P.Jovanovic, New Astronomy Review **56,** 37 (2012))

Newtonian limit



$$v_n = -v_n^0 \cos(\Omega t)$$

$$\omega \sim \omega_0 (1 + v_n)$$

$$\frac{dN}{d\omega} \sim (dN/dt)/(d\omega/dt)$$

$$\sim \frac{1}{\sqrt{(v_n^0)^2 - v_n^2}}$$

How to measure a black hole spin

While at large distances the gravitational force in the Newtonian theory and the General Relativity is practically the same, in the vicinity of the black hole Einstein gravity is effectively much stronger than the Newtonian one. At the same time, the effects connected with rotation of a massive body do not exist in the Newtonian gravity. These effects in the weak field limit exhibit themselves as the Lense-Thirring force. Close to a rapidly rotating massive body this effect of dragging spacetime into rotation becomes much more profound.

In the black hole binaries there exist a simple mechanism which speeds up the rotation of the black hole. Matter in the accretion disk, surrounding the black hole, preserves its angular momentum. It changes slowly. The rate of the change is determined by the viscosity effects, which is relatively small. The slow change of the angular momentum of an element of the matter in the disk results in the decrease of its Keplerian orbit. It comes closer and closer to the black hole until it reaches the **innermost stable circular orbit**. After this matter falls into the black hole almost freely. Such falling matter brings with it not only energy, but also angular momentum. Because of this effect one can expect that the rotation parameter of the black hole in such systems may be quite high, or even close to its extremal value $J = M^2$.

Rotating black holes

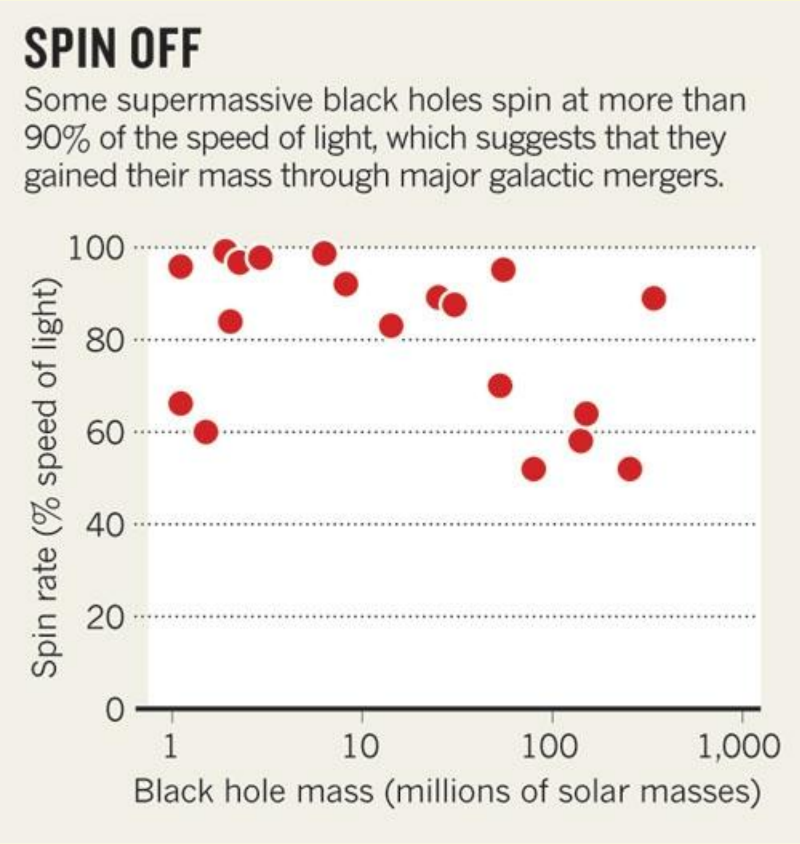
For a non-rotating (Schwarzschild) black hole of mass M
the innermost stable circular orbit is at $6GM/c^2 = 3r_S$,
while for an extremely rotating Kerr black hole a co-rotating
circular orbit can be as close as $GM/c^2 = r_{horizon}$.

The energy of the particles of the accretion disk, which can be transformed into the radiation before they reach the critical orbit, is about 5.7% of their proper energy, for a non-rotating black hole, and is about 42.4% for the extremely rotating one.

“Black Hole Spin via Continuum Fitting and the Role of Spin in Powering Transient Jets”, Jeffrey E. McClintock, Ramesh Narayan, James F. Steine
http://arxiv.org/pdf/1303.1583.pdf

Strong observational and theoretical evidence links the inner-disk radius to the radius of ISCO, which is trivially related to the dimensionless spin parameter. The ten spins that have so far been measured for stellar mass black holes by this continuum-fitting method range rotation rapidity range widely from small value to $a>0.95$.

Method used to measure spin was introduced in 1995 and is based on measurement of X-rays emitted by superheated accelerated matter spiraling around the event horizon. By now about 20 supermassive black holes have had their mass and spin measured by astronomers until today which relatively sufficient degree of precision.



Source: Christopher Reynolds, Univ. Maryland

Using data from NASA's NuSTAR space telescope – which was launched in June 2012 – along with data from the European Space Agency's XMM-Newton space telescope Risaliti and colleagues concluded that the spinning black hole did affect the iron and other X-rays spectrum emitted from the accretion disc in the galaxy NGC136 (of 2 million solar mass). Their conclusion is that this BH is rapidly rotating.

Black Holes classification

- **Stellar-mass black holes with** $M \sim 3-30 M_{\odot}$
- **(Super)massive black holes with** $M \sim 10^5 - 10^9 M_{\odot}$
- **Intermediate-mass black holes with** $M \sim 10^3 M_{\odot}$
- **Primordial black holes with mass up to** $M \sim M_{\odot}$
- **Micro black holes** $M > M_{Planck}$

$$M_{Planck} = \sqrt{\frac{\hbar c}{G}} \approx 10^{-5} g$$

The quantum gravity effects become important for black holes with $M \geq M_{Planck}$. The black holes of smaller mass do not exist, at least in the standard classical sense.

Supermassive Black Holes

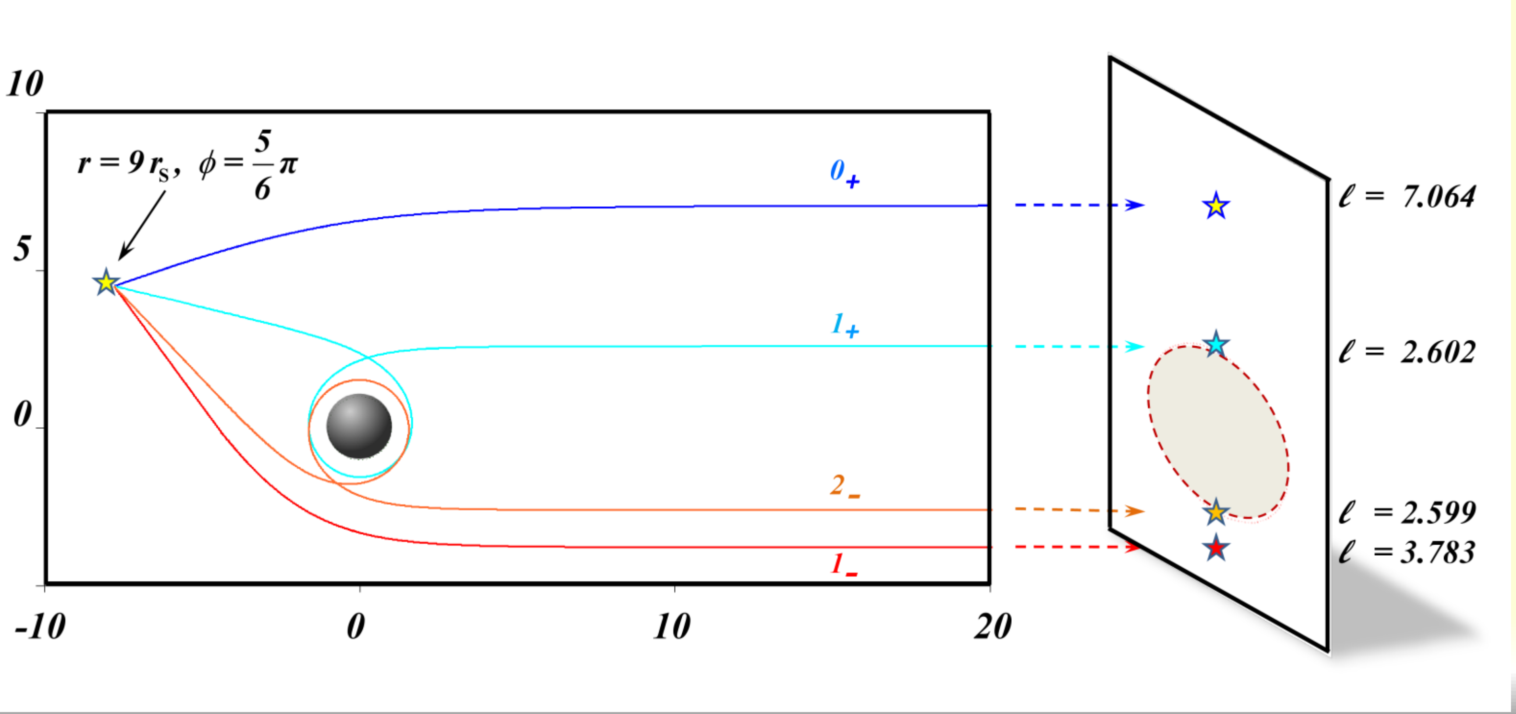
Stellar mass black holes were predicted by the theory. The discovery of supermassive black hole in quasars and at the center of galaxies was more surprising.

Black holes in center of galaxies

Most of the galaxies have compact central regions with dense gas and star populations. They are called the galactic nuclei. A small part (approximately 1%) of galaxies have active galactic nuclei. Physical processes in active galactic nuclei generate powerful electromagnetic radiation in the X-ray, ultraviolet and radio bands. One of the types of such galaxies are quasars. Quasars are the most powerful sources of the radiation in the Universe. Their total luminosity reaches $10^{47} - 10^{48}\ erg/s$ **This is about 3 orders of magnitude higher than the optical luminosity of their parent galaxy. The first quasars were discovered at the end of 1950s in the radio telescope observations. More than 200,000 quasars are known now. Fast variation of the radiation from some of the quasars allowed one to prove that this radiation comes from a small size compact region.**

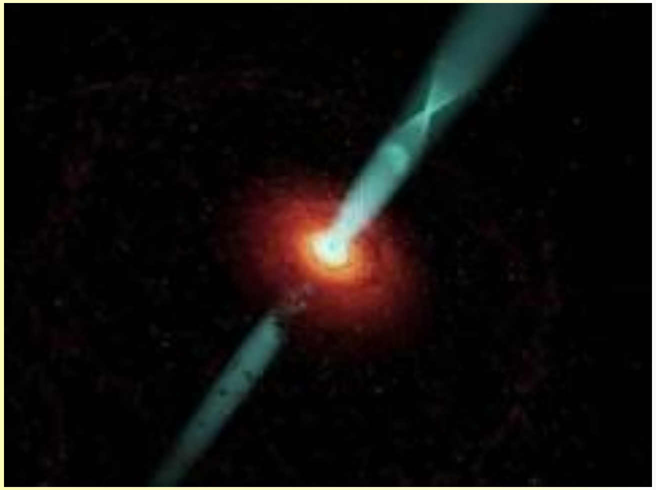
Multiple images

The strong gravitational field of a black hole deflects the light. The light rays passing near a black hole with the impact parameter close to the critical one have a large bending angle. As a result, the black hole will create more than one image of a distant object. This strong field lensing effect can be used to identify and study black holes. The qualitative study of this and similar effects requires the development of the ray tracing methods in the gravitational field of a black hole.



Relativistic jets

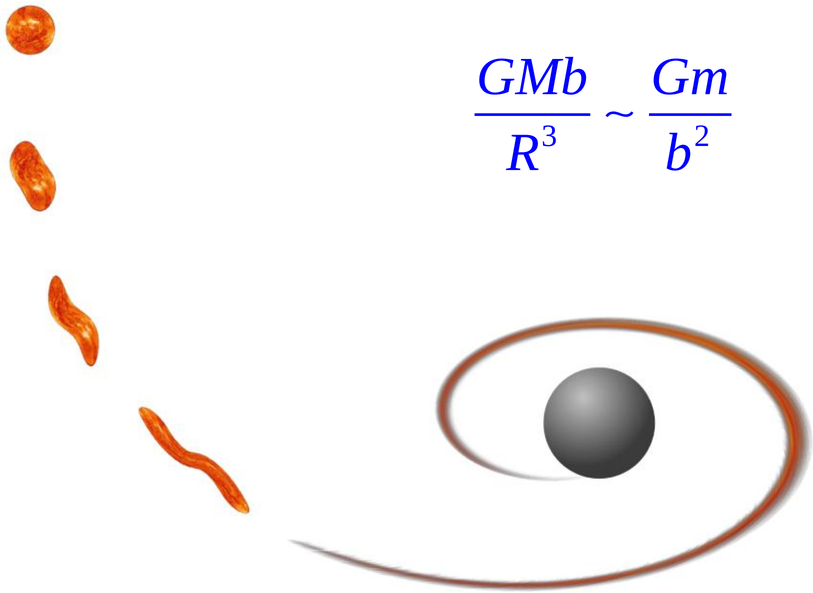
Relativistic jets are extremely powerful streams of relativistic plasma which are observed in some active galaxies and quasars. They are similar to the jets in microquasars, but have much bigger scale and power. In some of these objects, the visible length of jets reaches hundred and thousands light years. For example, for the quasar 3C 273, which was the first discovered quasar, the jet size is 62 kpc. It is believed that the energy for the jets is provided by the rotating black hole surrounded by the accreting matter. The magnetic field trapped inside the ionized accreting matter plays an important role in this process. It also provides the collimation of the jets.



Star disruption

There is another interesting process which results in the mass increase of the central black hole. This is a stellar capture and stellar disruption.

In the Newtonian theory a condition of tidal disruption of a star of mass *m* and radius *b* passing at a distance *R* from the mass *M* follows from the relation



$$\frac{GMb}{R^3} \sim \frac{Gm}{b^2} \quad \rightarrow \quad R = \left(\frac{M}{m}\right)^{1/3} b,$$

Maser effect

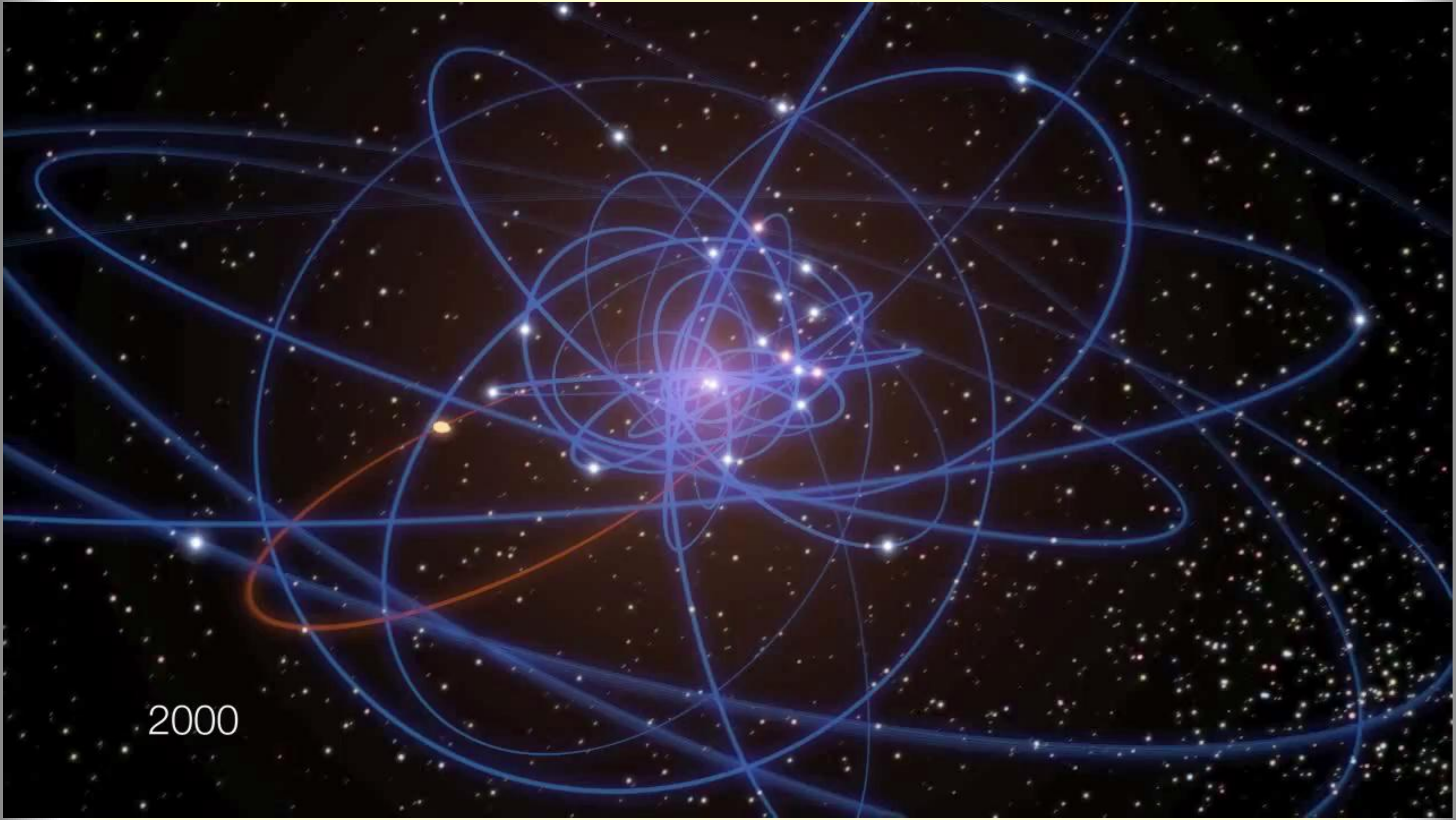
Maser radiation is similar to the laser. It is generated when a coherent beam of electromagnetic radiation passes through media with a pumped population inversion. Such a beam induces transition from upper occupied energy levels to a lower energy one and gain the energy in this process. There are many types of molecules which can produce the maser effect in the astrophysical environments. Observations confirm the existence of water vapor and other molecules which can produce stimulated microwave emission in the accretion disks around supermassive black holes.

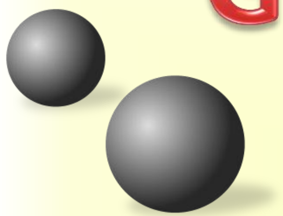
The spectral lines emitted by masers are very bright and narrow. These lines are observed as broaden by the Doppler effect because of the Keplerian motion of the matter of the disk, emitting and amplifying these lines. The broad spectral lines are used as probes of this motion and give an additional information about the black hole mass.

Black hole in Milky Way

This is the case of the best known black hole. The object, known as 'Sagittarius A*', is located in the center of our Galaxy, which is about 27,000 light-years from the Earth. In a 16-year-long study of this object there were found very strong indications on the presence there of a black hole with the mass about 4 million solar masses. Basically, the method used for the estimation of the mass of the `invisible' central object is based on finding the mass function from observations of `visible' stars moving around it. Very accurate estimation of the black hole mass was obtained by watching the motion of about 30 stars in the central region. These observations also allowed astronomers to pinpoint the center of the Galaxy with great precision. One particular star, known as S2, orbits the Milky Way's center so fast that it has completed already one full revolution within the 16-year period of the study. The better resolution of the central, close to the black hole, region will be obtained by combining the light from the four 8.2-meter VLT unit telescopes and using the interferometry technique.

Milky Way Black Hole





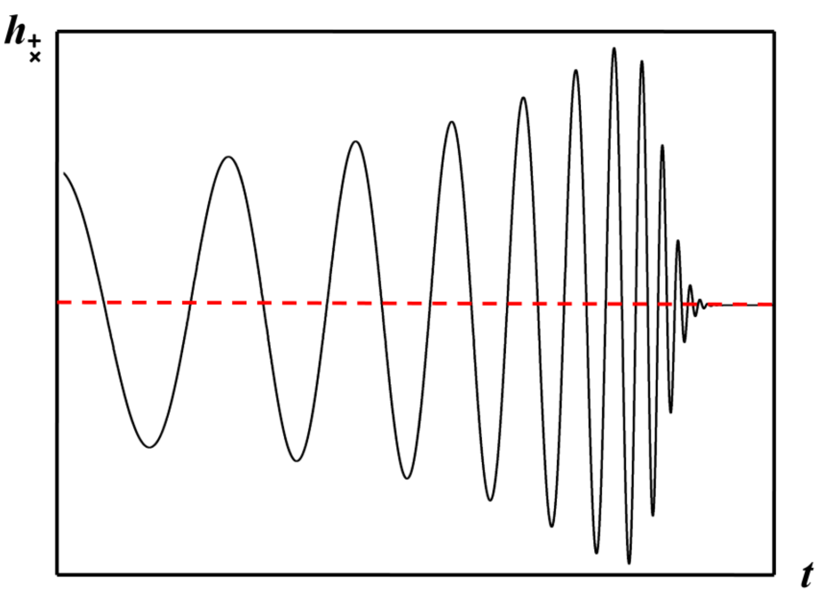
Gravitational radiation from black hole binaries

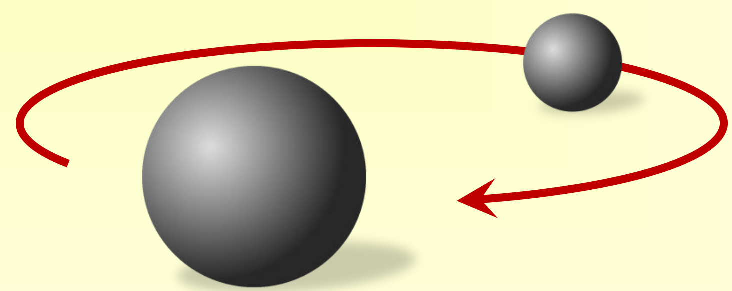
The evolution of a black hole binary has several phases:

Inspiral: As the binary evolves the frequency and amplitude of the gravitational wave grow. One can expect that the most powerful radiation comes from the binary at the moment just before the coalescence;
Collision: After reaching the last stable orbit black holes fall into one another;
Merger: As a result of the black hole collision a single black hole surrounded by horizon is formed.
Ringdown: The newly born black hole is in its `excited' state. Relaxation to a nal stationary configuration is also combined with emission of gravitational waves. The characteristic frequencies of these waves are determined by the spectrum of the quasinormal modes.
Tails: After exponential decay of the ringing radiation there still remain power-law tails of the gravitational radiation.

Typical wave form

The characteristic form of the time dependence of the gravitational wave amplitude





Kick effect

An exciting discovery of the numerical relativity is a prediction that the merger of two black holes can result in a kick of the newly born black hole up to the very high velocity. The kick effect in a binary system is a result of asymmetry in the emission of the momentum carried by the gravitational waves. As a result of this emission the center of mass of the binary gets a recoil velocity.

If the masses of the black holes are the same, the center of mass motion remains at rest. This conclusion follows from the symmetry.

When the masses are different, the motion of the black hole of smaller mass is faster, and its radiation is more collimated. The net momentum is ejected in the plane of rotation along the velocity direction of this mass. The recoil motion of the center of mass is periodic. Averaged over the period it vanishes. In the black hole binaries two effects are important. At the late inspiral phase the radius of the orbit changes significantly with time, so that there will be a non-vanishing accumulative effect in the center of mass recoil. What is more important, there exists a final kick, which arises when binary approaches the plunge, and the averaging is not effective.

The kick velocity essentially depends on the black holes spins and their orientation.

Numerical calculations for non-spinning black hole binary inspiral shows that the maximal kick of *175 km/s* is achieved for the symmetric mass ratio parameter

$$\nu = M_1 M_2/(M_1 + M_2)^2 = 0.195 \pm 0.005$$

Much larger kick velocities exist in the binary system of two rotating black holes. It was demonstrated that the maximal kick velocity can be *2,500 km/s* for equal mass black holes with antialigned spins

$$J/M^2 \approx \pm 0.8$$

in the orbital plane.

This kick velocity is so high that the final black hole formed in the merger of two massive black holes, would escape from dwarf elliptic and spheroidal galaxies (with typical escape velocity of below *300 km/s*) and from giant elliptic galaxies with the escape velocity *2,000 km/s*

The kick velocity of more than *1,000 km/s* are quite rare. For certain configurations of black hole spins and masses the predicted kick velocities are up to a maximum of *4,000 km/s*. Much higher recoil velocity up to of 10,000 km/s (superkick) are expected for the hyperbolic encounter of binary black.

There are indications that some of the quasars may have unusually large velocities. Two such objects, quasars E1821+643 (at z = 0.287) and SDSS J1054.35+345631.3 (at z = 0.272) have velocities *2,100 km/s* and *3,000 km/s*, respectively. They are discussed as possible candidates for black hole recoil after merging supermassive black holes.