



# Black holes, other compact objects, accretion

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# A lot of problems in astrophysics can be solved approximately without complex calculations.

- We do not need computers for that but we still need to use some fundamental laws of physics, e.g., the law of universal gravitation.
- Such estimates are very important for our understanding of the universe, and they are very often used in actual research.
- Special cases of some difficult problems often can be simply solved. Such solutions are then very important for testing results of numerical calculations.
- I will discuss some of such simple solutions related to black holes and accretion.
- Please let me know if my presentation is either too simple or too complicated.

# How to weigh the Sun?

- The law of universal gravity: the force exerted on the Earth by the Sun equals  $GM_{\odot}M_{\oplus}/a^2$ , where  $M_{\odot}$  is the solar mass,  $M_{\oplus}$  is the Earth mass,  $G$  is the gravitational constant, and  $a$  is the Earth-Sun distance.
- Since the Earth does not fall on the Sun, that force has to be balanced by the centrifugal force,  $M_{\oplus}v^2/a$ , where  $v$  is the Earth velocity, equal to  $2\pi a/P$ , where  $P = 1$  year.
- By equating the two forces,  $GM_{\odot}M_{\oplus}/a^2 = M_{\oplus}(2\pi a/P)^2/a$ , we get  $M_{\odot} = 4\pi^2 a^3/GP^2$  (approximately the Kepler law). Substituting the numbers, we get  $M_{\odot} = 2 \times 10^{30}$  kg.

In similar way we can weight other stars,  
black holes, galaxies etc.

- We equate the gravitational and centrifugal force.
- For stellar systems, e.g., in galaxies, we use the average velocity or the velocity dispersion instead of a single velocity.
- We get  $M \sim v^2 a / G$ .
- This way we can measure masses of stars in binary systems, of supermassive black holes in galactic centers, and of galaxies.

# Determination of the masses in binary systems

Usually, the black hole masses are measured using the 2nd Newton's law, which can be formulated as the Kepler's law,

$$G(M_1+M_2)^2 = a^3(2\pi/P)^2,$$

where  $G$  is the gravitational constant,  $M_1$  and  $M_2$  are the component masses,  $P$  is the binary period,  $a$  is the distance between the centres of the stars.

Knowing from observations  $P$  and the stellar velocity,  $v$ , we can determine  $a$  from  $2\pi a = v/P$ . After some manipulation, we can obtain a useful quantity called the mass function,

$$f(M) = Pv_2^3/2\pi G = M_1 \sin^3 i / (1+M_2/M_1)^2; \quad M_1 > f(M),$$

where  $v_2$  is the observed (from motion of atomic lines) radial velocity amplitude of the companion star, and  $i$  is the angle of the normal to the orbit and the line to the observer. Knowing  $P$  and  $v_2$ , we have a lower limit on the mass of the object suspected to be a black hole. If, in addition, we can  $M_2$ , e.g., from the stellar type of the companion, and  $i$ , e.g., from eclipses, we can determine the mass of the compact object,  $M_1$ .

The maximum mass of a white dwarf is  $1.4M_\odot$ , and the maximum mass of a neutron star is  $<3M_\odot$ . Thus a measurement of  $M > 3M_\odot$  implies that the object is a black hole.

# How much internal energy is within the Sun?

- In stars, there is an approximate equality between the gravitational energy and the kinetic (of chaotic motion) energy of particles (the virial theorem). Thus, the particle energy within the Sun is  $U = GM_{\odot}^2/R_{\odot} \approx 4 \times 10^{41}$  J. We know it without the need to measure the distributions of the temperature and density within the Sun.
- We can calculate the time, during which the Sun will emit all of that energy,  $t \approx U/L$ , where  $L$  is the solar luminosity. It is  $\approx 30$  mln yr. In the XIX century it was thought that this is the characteristic lifetime of the Sun.
- However, it is  $\ll$  the actual age of the Sun,  $4.6 \times 10^9$  yr.
- The solution of this discrepancy is of course the production of energy within the Sun, in the synthesis of He from H, which was discovered in the 30-ties. This energy is sufficient for the next  $5.4 \times 10^9$  yr.

# Which energy release process is most efficient?

- The efficiency of the process  $4\text{H}\rightarrow\text{He}$  can be easily calculated by comparing the rest-mass energy of 4 H nuclei, about  $4m_p c^2$ , with the rest-mass energy of the He nucleus,  $3.97 m_p c^2$ . The released energy  $\approx 0.03m_p c^2$ . Comparing with the initial energy, the fractional efficiency is  $\approx 0.7\%$ .
- It is  $\sim 100$  mln times more than the efficiency of chemical reactions.
- But we can estimate that even more energy is released in the process of matter falling onto a black hole or a neutron star. This is the most efficient energy release process in nature.
- For a fall of a mass  $m$  from a large distance to the radius  $R$ , the maximal released energy is  $\sim GMm/R$ , where  $M$  is the mass of the star. A rotating black hole has the innermost stable circular orbit of  $\gtrsim GM/c^2$ . If we plug it into the formula for the max. energy, we get  $\lesssim 1mc^2$ . But a half of the energy remains in the circular motion. Considering GR, we get  $\lesssim 0.3mc^2$ , i.e., we can reach the max. efficiency with respect to the rest-mass energy of  $\approx 0.3mc^2/mc^2 = 30\%$ . A similar efficiency,  $\approx 20\%$ , has the process of matter falling onto a neutron star.
- We may see this energy in the form of radiation.

# Life of stars

- Stars are formed as gas clouds, within which thermonuclear reactions start, in particular  $4\text{H} \rightarrow \text{He}$ .
- But any fuel will become exhausted at some time.
- E.g., our Sun has the nuclear fuel sufficient for  $5.4 \times 10^9$  yr.
- The gravity keeps the star together, acting against the pressure of the hot gas heated by the thermonuclear reaction.
- Thus, a star will shrink after exhausting its fuel.
- As we know, our Sun, now of the radius of about a mln km, will shrink to the radius 100 times lower, of the order of the Earth radius, forming a white dwarf.

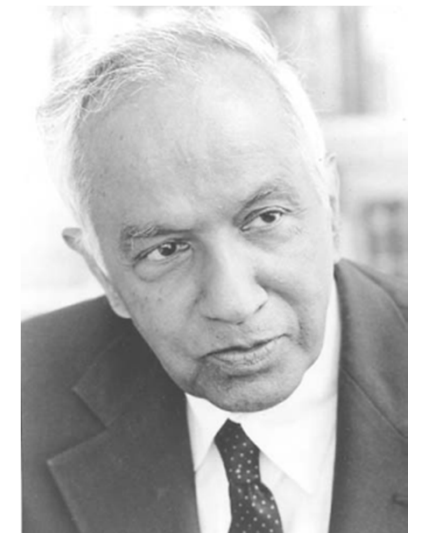
# What objects can be formed from stars which exhausted their fuel?



Wolfgang Pauli

- From the **Pauli's** exclusion principle we can infer that there are two kinds of stars supported by pressure even at zero temperature.
- The exclusion principle (1925) states that some kinds of particles (fermions) cannot occupy the same quantum state. Thus, this can provide pressure to balance gravity even without any energy release.
- The exclusion principle for electrons implies the existence of white dwarfs, consisting of electrons at very low energies and atomic nuclei.
- The maximal mass of a white dwarf  $\approx 1.4M_{\odot}$ . Above it, electrons recombine with protons, forming neutrons. A neutron star is formed. The maximum possible mass of a neutron star is  $\sim 2.5M_{\odot}$ .
- Those approximate masses can be estimated by a combination of fundamental constants (dimensional analysis),  $\hbar^{3/2}c^{3/2}/(G^{3/2}m_p^2) \approx 1.9M_{\odot}$ .

Subrahmanyan Chandrasekhar showed the existence of the maximum mass of a white dwarf (while sailing from India to graduate studies in Britain in 1930).

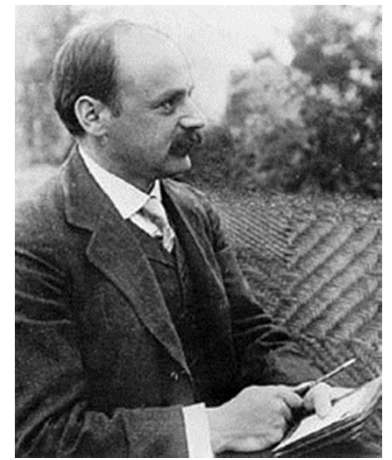


# What objects can be formed from stars which exhausted their fuel?

- We have four possibilities:
- A white dwarf, the end stage of stars of small and medium masses, supported by the quantum pressure of electrons. Its maximal mass of  $1.4M_{\odot}$  occurs due to recombination of electrons and protons.
- A neutron star, the end stage of stars of high mass,  $\gtrsim 8M_{\odot}$ , formed in supernova explosion, and supported by quantum pressure of neutrons. Its maximal mass of  $\sim 2.5M_{\odot}$  occurs due to the lack of stable configurations of nuclear matter above it.
- A black hole, the end stage of stars with very high initial mass,  $\gtrsim 25M_{\odot}$ , formed in a supernova explosion.
- Nothing. Some supernova explosions disperse all the stellar matter in the interstellar space. This happens for stars with very high initial mass.

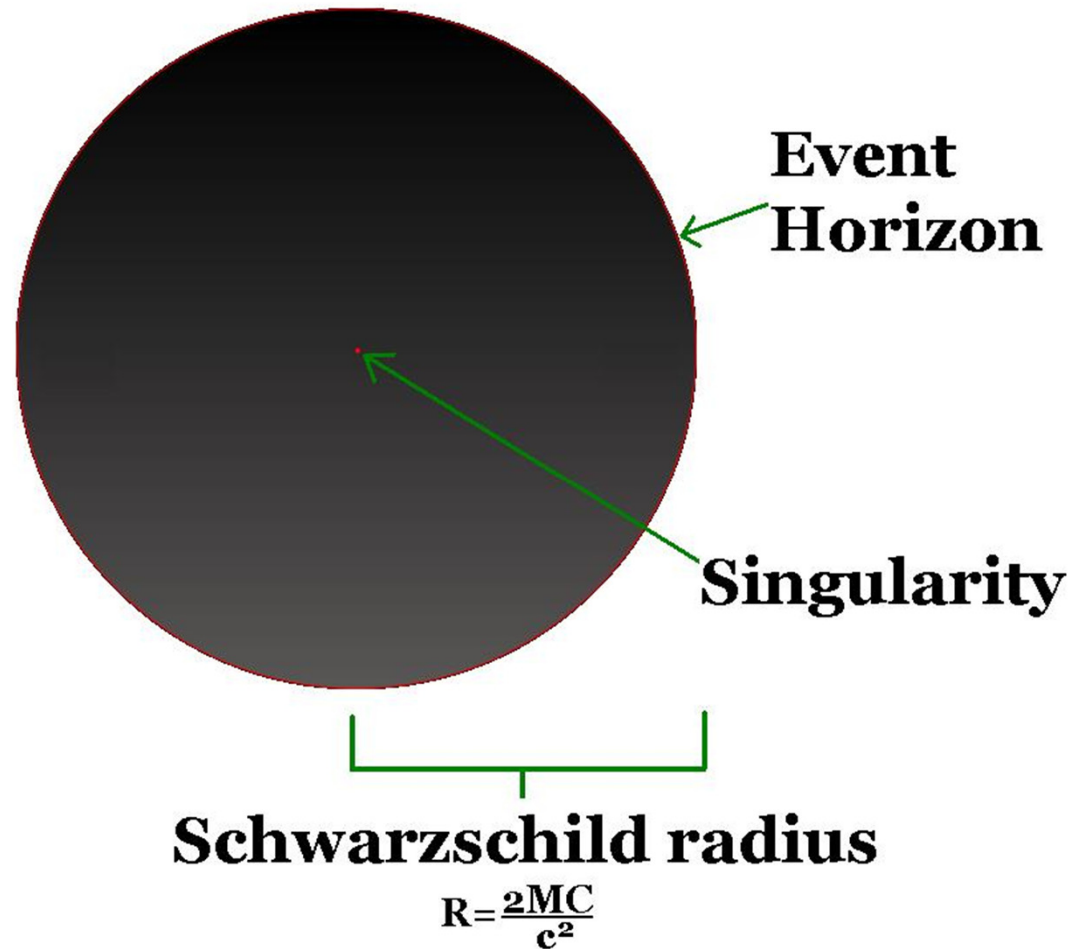
# Black holes

Karl  
Schwarzschild



- We cannot see interiors of black holes. We can only get information from above the horizon, which is 30 km for a non-rotating black hole of  $10M_{\odot}$ .
- The invisibility below the horizon is caused by the gravity, which is so strong that bends any emitted light back to the center.
- Gravity is a universal force. For a mass to be able to leave the gravity of an object, its initial velocity has to exceed the escape velocity,  $=\sqrt{2GM/R}$ , where  $M$  and  $R$  are the mass and radius. E.g., for Earth, the escape velocity equals 11.2 km/s.
- For a sufficiently large mass and small radius, the escape velocity can exceed the speed of light, and any emitted light will come back. The object is then invisible, and thus becomes a black hole.
- The Earth would become a black hole if we can shrink it to a radius of  $\approx 1$  cm.
- The horizon radius can be very roughly (and not fully correctly) estimated as follows:  $v^2 = 2GM/R$ , set  $v = c$ , we get the horizon radius  $= 2GM/c^2$ , which is still the correct value of the **Schwarzschild** radius.

# A non-rotating black hole



Matter inside a black hole is gravitationally collapsed to densities comparable with that of early Universe.

# History

- The idea of a black hole was first formulated by the English geologist John Mitchell in a paper sent to the British Royal Society in 1783:

„If the semi-diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of 500 to 1, a body falling from an infinite height towards it would have acquired at its surface greater velocity than that of light, and consequently supposing light to be attracted by the same force in proportion to its vis inertiae, with other bodies, all light emitted from such a body would be made to return towards it by its own proper gravity.”

*Amazingly, this very old estimate has an error of only 6%.*

# History

- The French mathematician Pierre Simon de Laplace proposed the same idea in 1796 in his book *Exposition du Systeme du Monde* (unfortunately it disappeared from later editions).
- The idea was not popular in the XIX century because light was considered to be a massless wave not undergoing gravity.
- However, we now know that light has gravitational mass and undergoes gravitational attraction. **The ideas of Mitchell and Laplace were correct.**

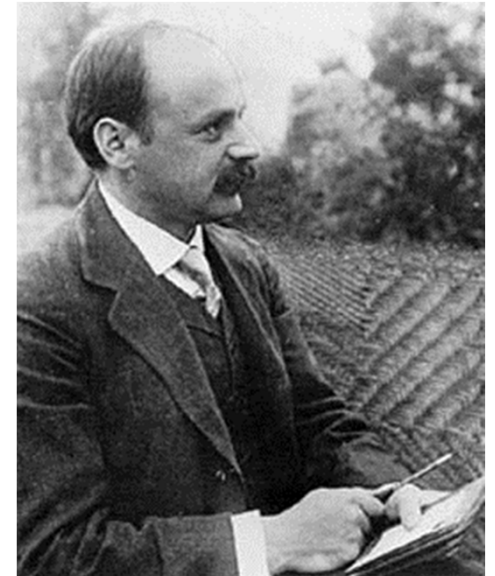


Pierre Simon  
de Laplace

# History

- After publishing his Special Relativity Theory in 1905, Einstein considered the effect of gravity on light. He showed that gravity affects propagation of light, and formulated his General Theory of Relativity (GR) in 1915.
- A few months later, Karl Schwarzschild (while serving as a 41-year old volunteer in the German Army on the Eastern front), found and published a solution of GR describing an object with its mass in a single point, within a strongly deformed spacetime. Schwarzschild himself considered this solution to be unphysical.

Karl Schwarzschild



# History



Eddington

In 1919, Arthur Eddington measured the deflection of stellar light during the total eclipse from the Príncipe Island. The measurement confirmed the General Theory of Relativity.



# Black holes are the simplest objects in the Universe

- An astrophysical black hole is completely described by only two parameters, its mass and spin (how fast it rotates). Two black holes with the same mass and spin are completely identical. The horizon radius is proportional to the mass.
- A black hole can, in principle, be charged, which would give a third parameter. However, a real black hole would immediately discharge itself to its surroundings.
- This contrasts any other object in the Universe, e.g. a star, for which a complete description would involve a huge number of parameters. Also, two stars can be similar, but they are never identical.

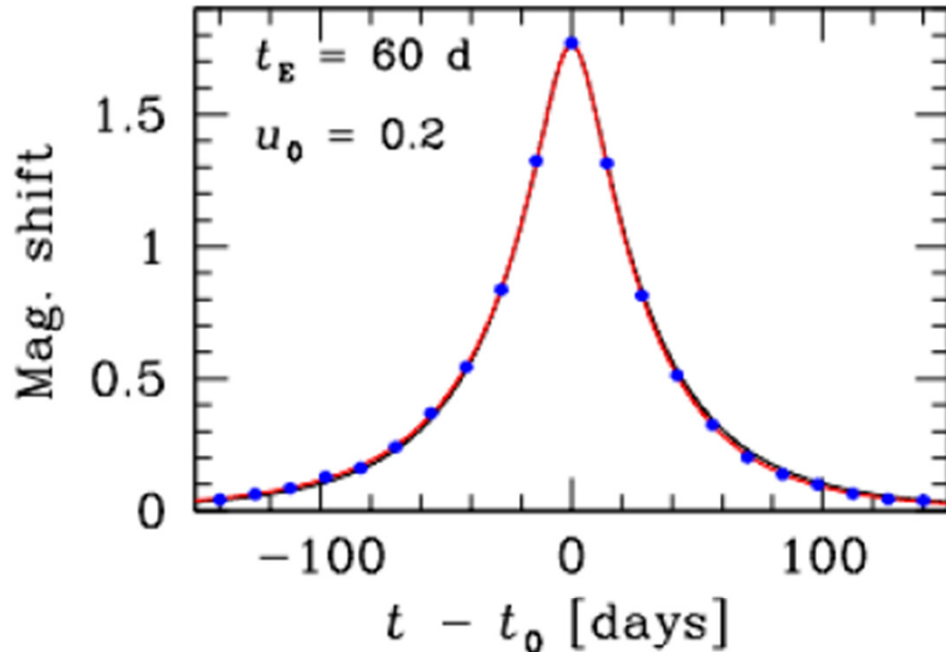


Roy Kerr first described rotating  
black holes

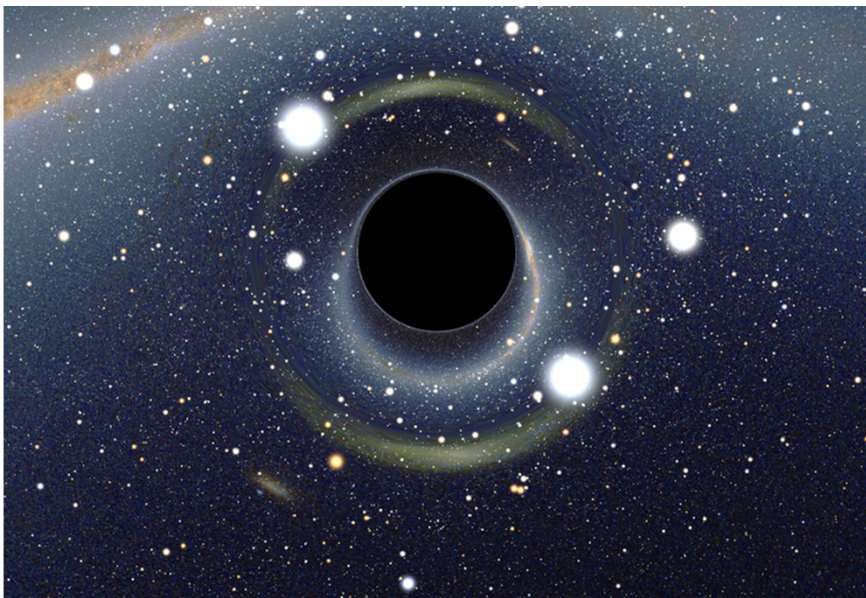
# Known astrophysical black holes form two groups:

- stellar mass black holes with masses from several to a few tens solar masses;
- supermassive black holes with masses more than  $10^5 M_{\odot}$  or so.
- There is still a discussion of the existence of black holes of intermediate masses,  $\sim(10^2-10^4)M_{\odot}$ , no proof so far.
- Stellar-mass black holes are easiest found in binary systems. A single stellar black hole is very difficult to find; the only way to find it is via gravitational focusing, so-called microlensing.
- There are  $\sim 100$  mln black holes in the Galaxy.
- Supermassive black holes are found in the centres of almost every galaxy.

# Gravitational focusing as a way to find isolated black holes



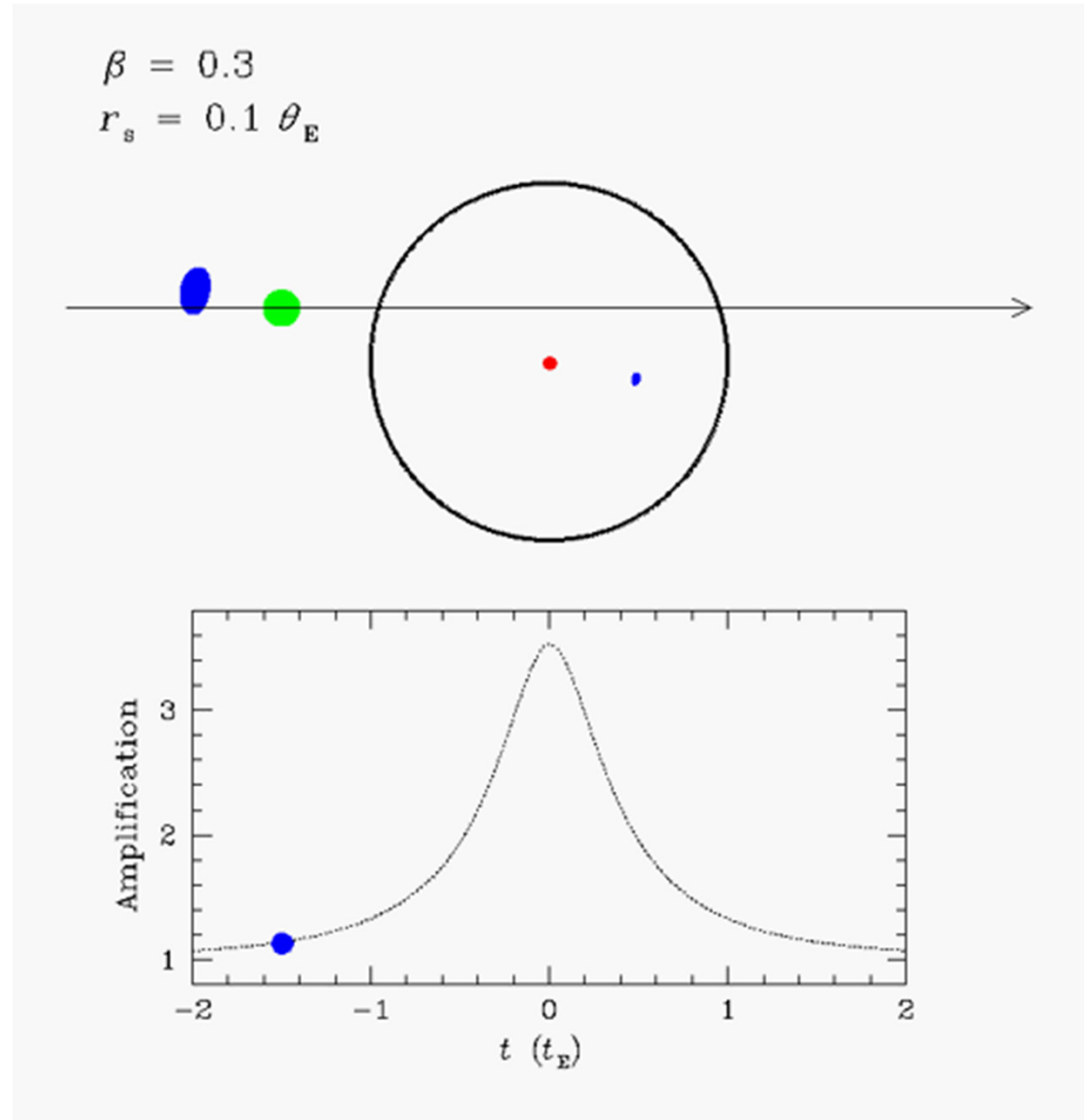
A star is moving in the background, a lens is in the foreground. The lens can be another star or a black hole. Gravitational focusing forms multiple images of the star and amplifies the signal.



So far no black hole found in this way, but the search with *HST* is ongoing.

# Gravitational focusing by stellar-mass objects: microlensing

Images:



The observed light curve:

# Stellar binary systems containing black holes

- The first discovered such system was Cyg X-1, X-ray radiation of which was discovered in 1972 during an early detector on a rocket.
- We now know several tens of binary systems with evidence for the existence of a black hole, which proof consists of measuring the mass of the compact object  $\gtrsim 3M_{\odot}$  (which thus cannot be a neutron star).
- The observed orbital periods of these systems are between 0.17 day (XTE J1118+480) to 34 day (GRS 1915+105), and the measured masses are between about  $5M_{\odot}$  and  $15M_{\odot}$ .

# Double black-hole binaries

- A binary born with two massive stars can end its life as a system of two gravitationally-bound black holes. They do not transfer matter and thus do not radiate. They can be detected when the two black holes merge, after losing their angular momentum by emission of gravitational waves. The merger is associated with emission of a huge bursts of gravitational waves. **So far, two such events have been detected by LIGO, see the lecture by Dorota Rosińska on Thursday.**
- The first event: merger of two black holes with the masses of  $35^{+5}_{-3}M_{\odot}$  and  $30^{+3}_{-4}M_{\odot}$ , which formed a single black hole with the mass  $62^{+4}_{-3}M_{\odot}$  at the distance of  $410^{+160}_{-180}$  Mpc.
- The second event: merger of two black holes with the masses of  $14.2^{+8.3}_{-3.7}M_{\odot}$  and  $7.5^{+2.3}_{-2.3}M_{\odot}$ , which formed a single black hole with the mass  $20.8^{+6.1}_{-3}M_{\odot}$  at the distance of  $410^{+160}_{-180}$  Mpc.

# Black holes and cosmic gamma ray bursts

- Cosmic gamma-ray bursts are the most energetic explosions in the Universe.
- They are formed when most massive stars explode as supernovae (called hypernovae), or as a result of a coalescence of two compact objects, e.g., two neutron stars.
- In both cases a black hole is formed.

# How many neutron stars and stellar-mass black holes are there in the Galaxy?

- We know 8 historical supernovae in our Galaxy. The last one was observed in 1604, but we have found remnants of two later ones. We have a rough estimate of 1 supernova per 100 yr.
- The age of the Galaxy is  $13.5 \times 10^9$  yr.
- Thus, we get ~100 mln neutron stars and black holes.
- In addition, black holes can be formed by a pure collapse of a massive star, without a supernova. From the initial mass function, we can estimate the number of stars sufficiently massive to form a black hole, which also gives ~100 mln black holes.
- Currently, we are able to detect only black holes which have stellar companions and with sufficiently fast mass transfer onto the black hole. In this way, we have found only ~30 binary systems containing black holes. Thus, we observe only a tiny fraction of the black holes existing in the Galaxy.

# A historic digression: Crab Nebula, the remnant of the supernova of 1054 July 4



Observation by the Hubble Space Telescope, the central object is a spinning neutron star

# The supernova of 1054 July 4

- We know the data accurately thanks to a Chinese document of the XI-th century. There are also some later Arabic sources, and a petroglif of the Pueblo Indians (North America).
- It was visible 24 h per day for 23 days, it was as bright that one could read books at night with its light. At night, it was visible for 653 days. But there are no European documents. Why?
- Arystoteles, whose philosophy dominated at that time in Europe, claimed the sky to be unchanging, and the appearance of the supernova contradicted that.
- The year 1054 is also the date of the schism of the Western and Estearn Christianity. On the 16th of July, when the supernova was at the maximum brightness, the Patriarch of Constantinopol was excomunicated. Perhaps those events were considered much more important.

# The supernova of 1054 July 4

- The first known European documents, which probably mention this supernova, are from the XVth century (but give incorrect dates of the event).

A 1450 painting: The Holy Roman Emperor Henry the 3rd (1017-1056) observes a new star above the roofs of the town of Tivoli.



# Supermassive black holes in the centres of galaxies

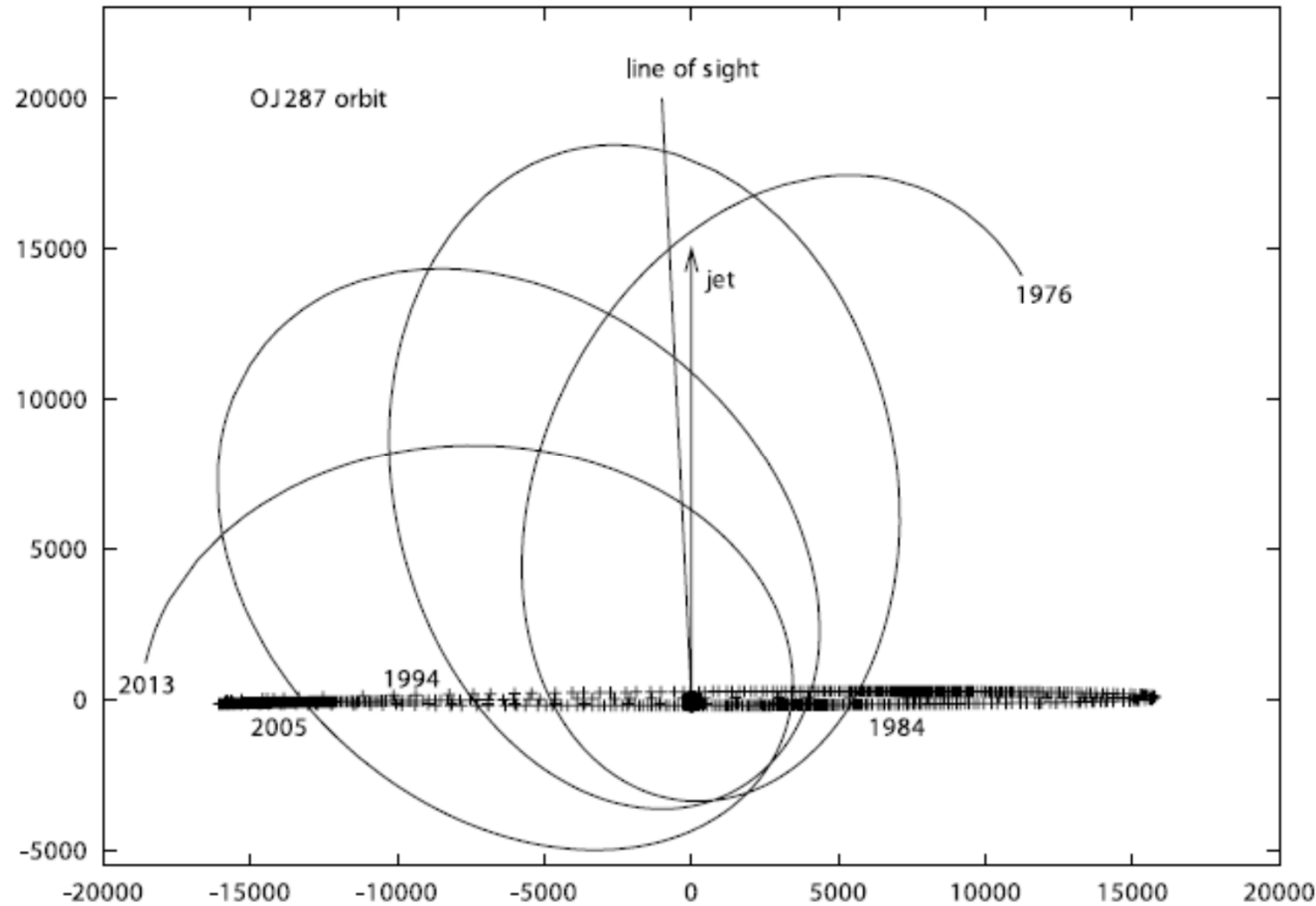
- Most known BHs. A central BH in almost every galaxy.
- Eg., quasars distant by  $\gtrsim 10^9$  light years. Formed early after the Big Bang and generated huge amounts of energy. BHs of masses of  $\sim 10^9 M_{\odot}$ . Either born in nuclei of young galaxies or formed by direct collapse before galaxies. Growth by accretion.
- Quasars: a class of active galaxies, which emit a lot of radiation from accretion.
- Most of BHs in centres of galaxies accrete very slowly - not active, e.g., the BH in the Galactic Centre.

What are the masses of BHs in galactic nuclei?

One of the lightest measured BHs: NGC 4395

$M \approx (3.6 \pm 1.1) \times 10^5 M_{\odot}$  from measurements of delay of emission in spectral lines (emitted at some distance from the BH) with respect to the continuum light curve (emitted close to the BH).

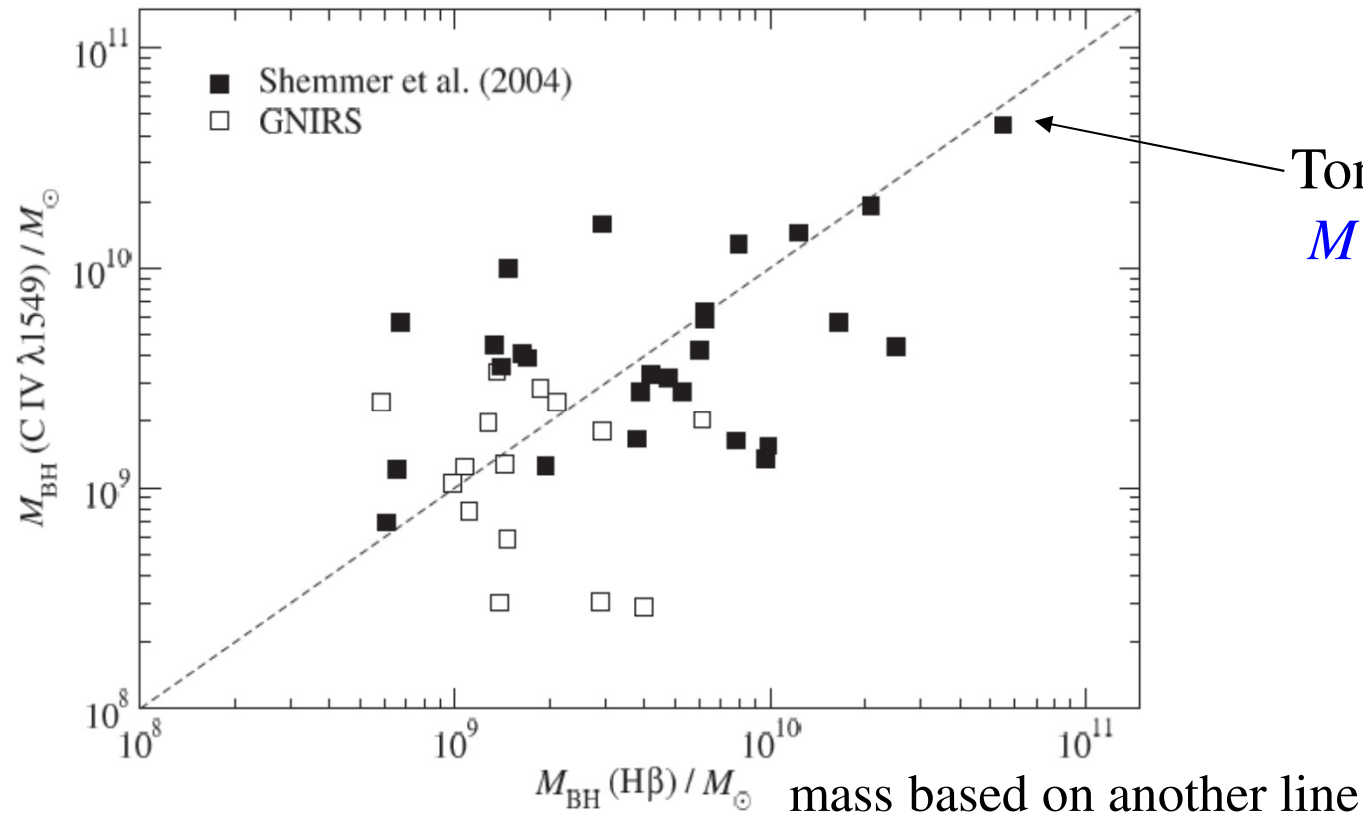
# The heaviest accurately measured BH, in OJ 287, an active galaxy at $z = 0.306$



Two massive BHs,  $1.8 \times 10^{10} M_{\odot}$  and  $10^8 M_{\odot}$ , with the binary period of 12 years. Mass measurement based on Kepler's law and relativistic effects (periastron precession).

# Rough estimates of the BH masses based on the width of spectral lines

mass based on one line



Ton 618,  $z \approx 2.2$   
 $M \sim 5 \times 10^{10} M_{\odot}$

$$M_{\text{BH}} = 1.05 \times 10^8 \left( \frac{L_{5100}}{10^{46} \text{ ergs s}^{-1}} \right)^{0.65} \left[ \frac{\text{FWHM}(\text{H}\beta)}{10^3 \text{ km s}^{-1}} \right]^2 M_{\odot}$$

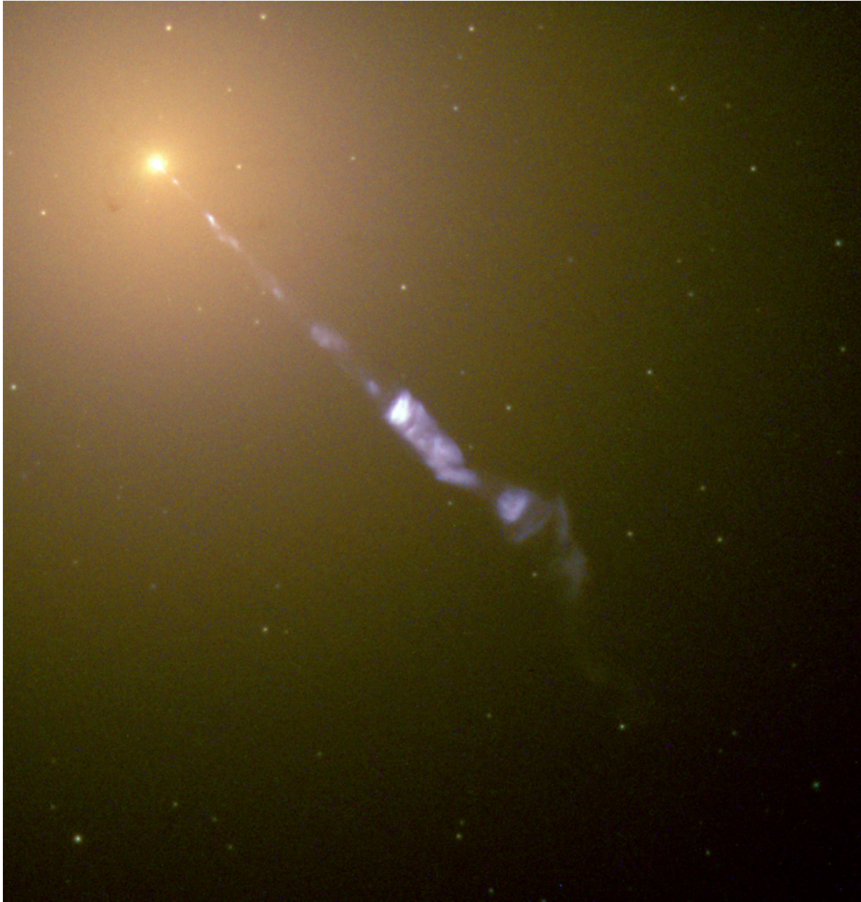
# How bright can be stars and accreting systems?

- Radiation interacts with the surrounding matter, exerting a force.
- Its strength depends on the opaqueness of matter. The most transparent: fully ionized medium; the dominant opacity: scattering on free electrons, cross section  $\sigma \approx 10^{-24} \text{ cm}^2$ .
- The force acting on an electron proportional to  $\sigma \times$  radiation flux,  $\propto R^{-2}$ ,  $R$  - the distance to the stellar centre.
- e bound to p; grav. force:  $GMm_p/R^2$ .
- Both forces  $\propto R^{-2}$ ; ratio is independent of the distance.
- The maximum possible luminosity for a star (or accreting compact object), the Eddington limit:  $4\pi GMm_p/\sigma \approx 1.3 \times 10^{38} (M/M_\odot) \text{ erg/s}$  for pure H.
- Exact derivation is the subject of one of the problems.

# Can the luminosity from accretion on the central supermassive black hole in a galaxy exceed the luminosity of all its stars?

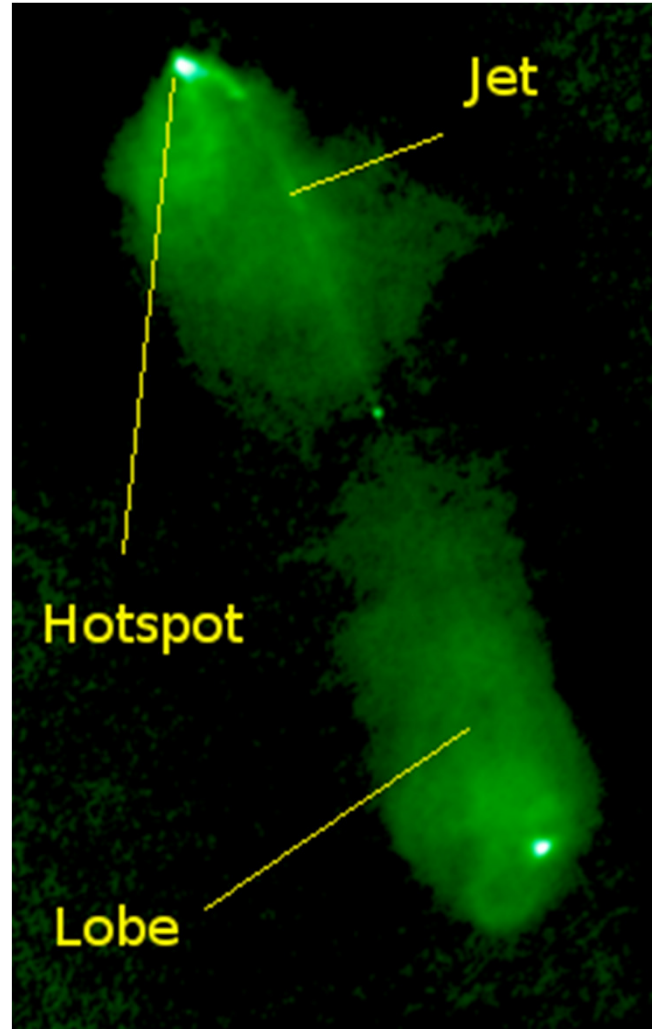
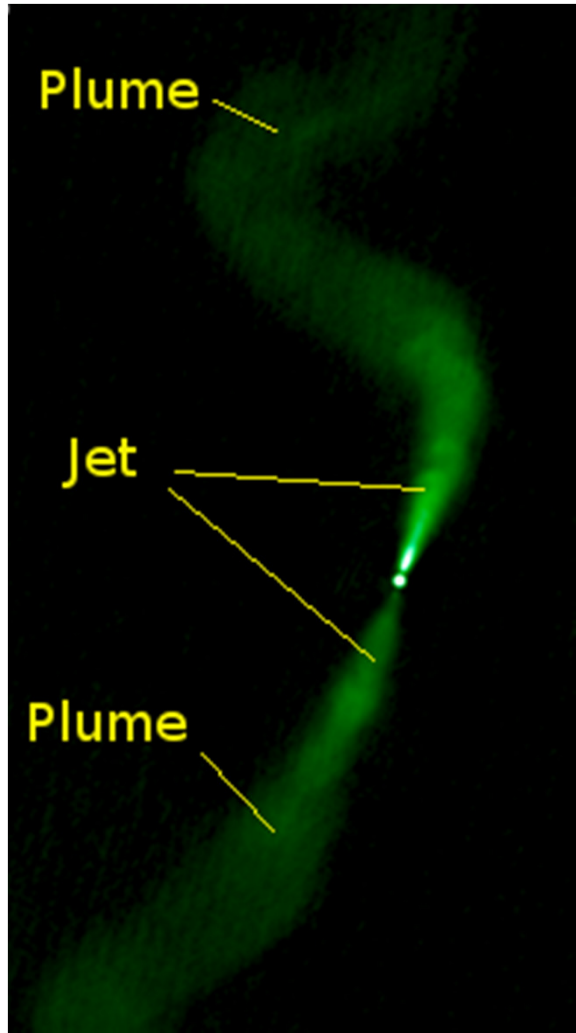
- The typical mass of a black hole  $\sim 10^9 M_{\odot}$ . The Eddington limit  $\sim 10^{47}$  erg/s.
- $\sim 10^{11}$  stars in a typical galaxy, emitting  $L_{\odot} \approx 4 \times 10^{33}$  erg/s,  $\rightarrow L \sim 4 \times 10^{44}$  erg/s.
- Accretion onto black holes  $\rightarrow$  a much higher  $L$  than that from stars.
- This situation occurs for active galaxies called quasars.
- Not for our Galaxy, which is not active, and the accretion on the central black hole is highly sub-Eddington.

# Accretion onto BHs often accompanied by ejections of spectacular jets



The galaxies M87 (in optical)  
and Centaurus A (in X-rays)

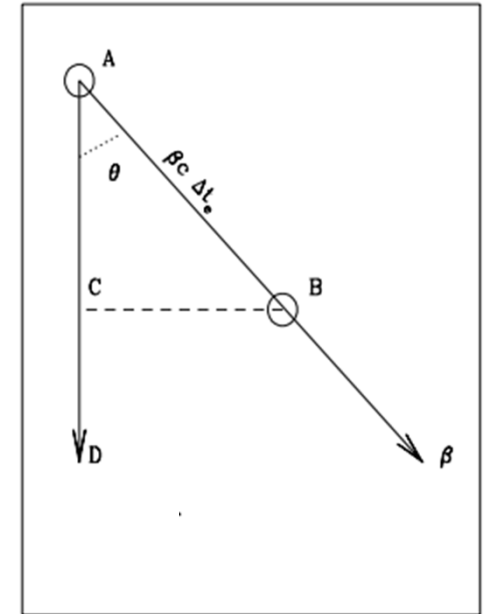
# Active galaxies observed in radio: large scale jets



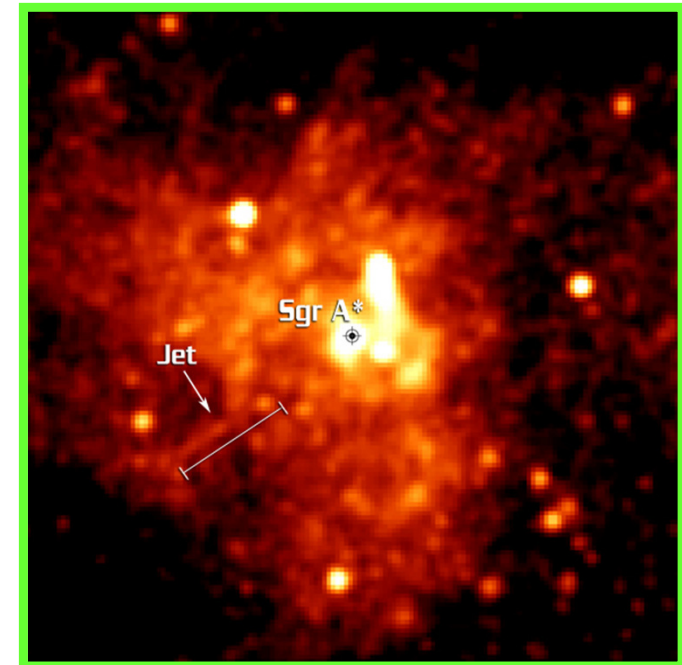
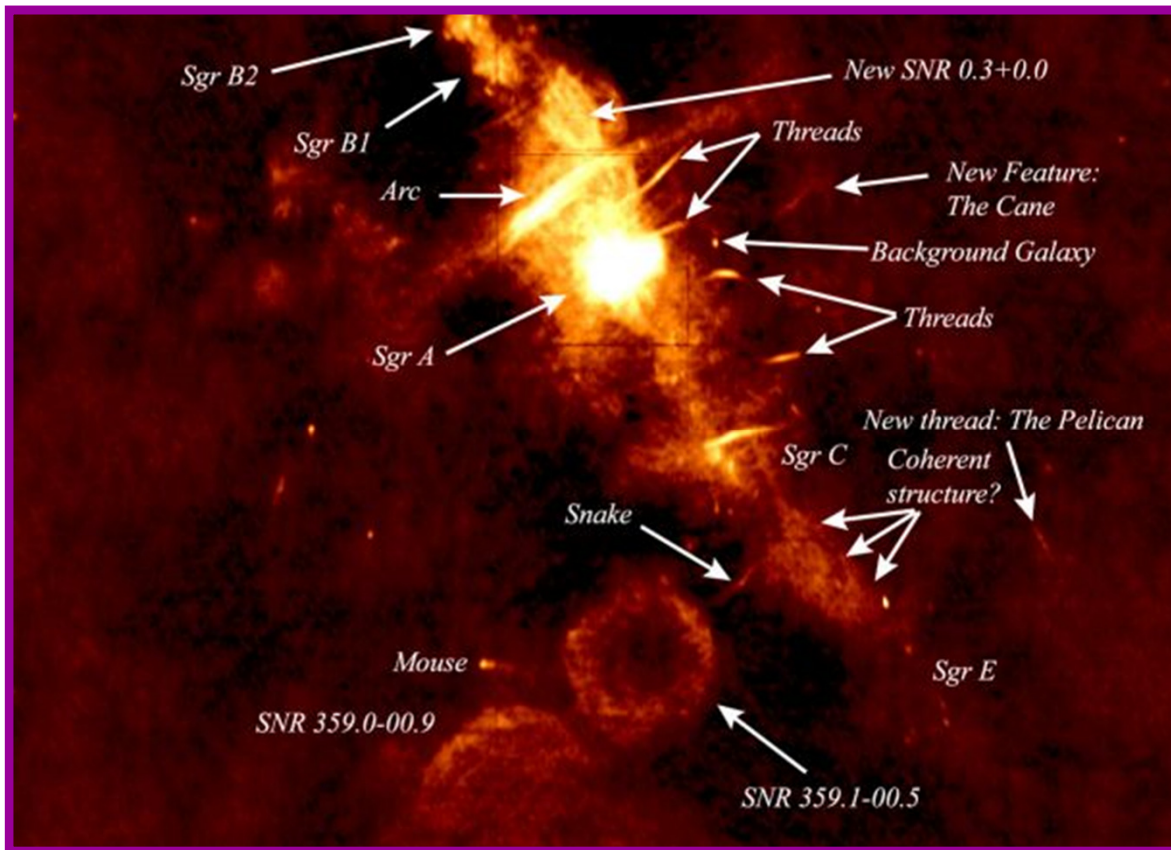
Radiogalaxies 3C 98, 3C 31 and Centaurus A

We often observe jet velocities projected on the sky exceeding the speed of light, even by a factor of several tens

- Naturally, the actual jet velocity is less than the speed of light.
- It turns out that we do not need even the Special Relativity to explain this phenomenon.
- A simple derivation is the subject of one of the proposed problems.

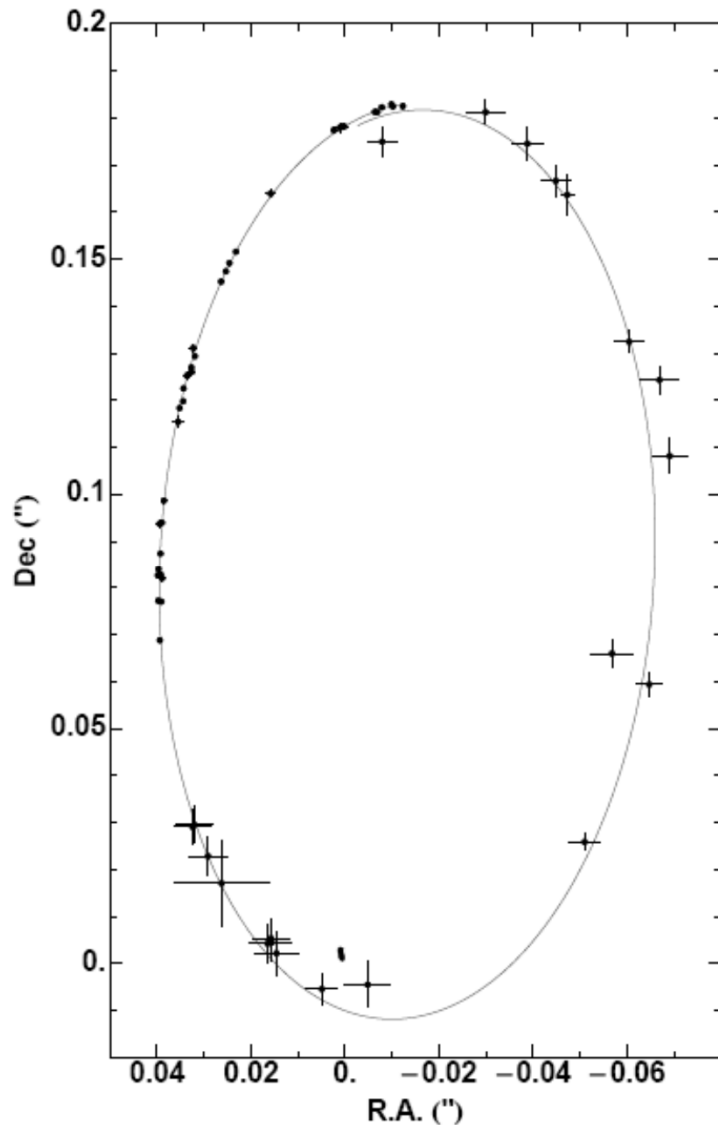


# The BH in our Galactic Centre, Sgr A\*

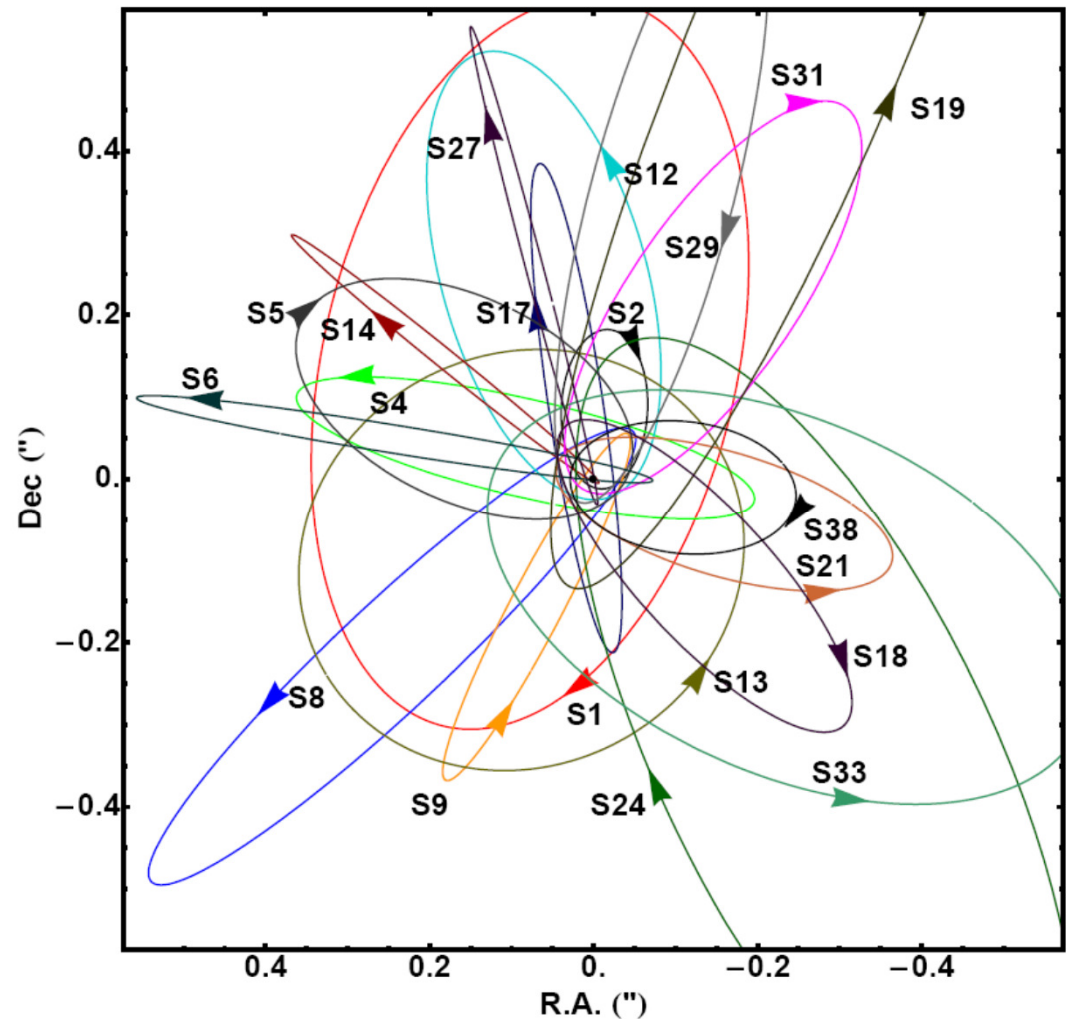


Sgr A\* contains a BH with the mass of  $4 \times 10^6 M_{\odot}$ , which has been measured from the Kepler law

The orbit of the star S2 around the Galactic Centre



The orbits of various stars around the Galactic Centre



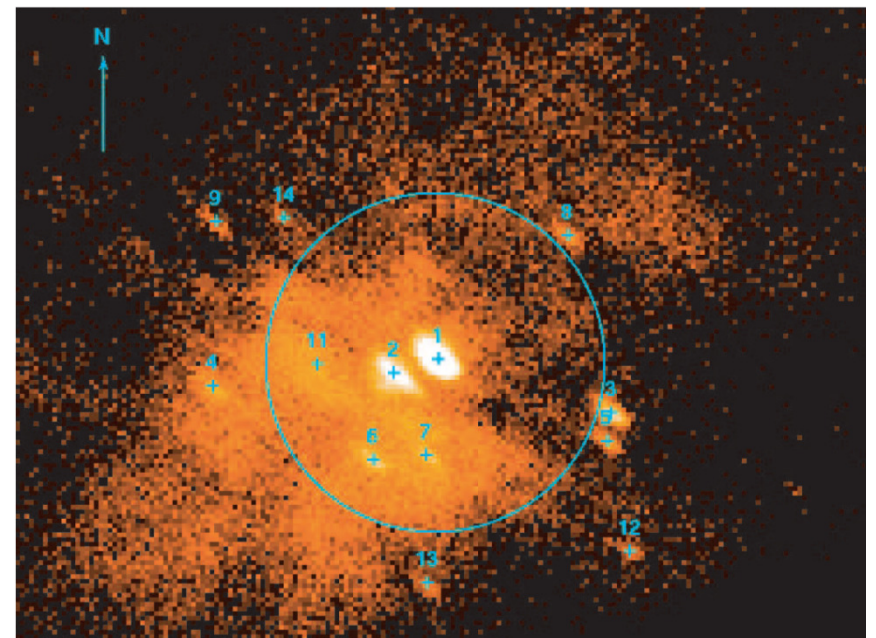
# Are there intermediate mass black holes, with $M \gtrsim 100M_{\odot}$ ?

$L$  of the source X41.4+60 in the galaxy M82 exceeds  $10^7 L_{\odot}$ , i.e. 200 Eddington luminosity for a BH with  $M = 10M_{\odot}$ . If  $M \approx 2000M_{\odot}$ ,  $L=L_{\text{Eddington}}$ .

It is within a dense stellar cluster MGG 11 (with radius of about 3 light yr). Collisions of stars within could have formed a BH with the  $M > 10^3 M_{\odot}$ .

Alternatively,  $M \sim 10M_{\odot}$ , but the emission is strongly beamed.

The Eddington limit for  $1M_{\odot}$  equals 50 000 of the Sun luminosities ( $L_{\odot}$ ).



# HLX-1, the Hyper-Luminous X-ray source in the galaxy ESO 243-49



- The luminosity of  $>3 \times 10^7 L_{\odot}$ ,  $\rightarrow M_{\text{BH}} > 500 M_{\odot}$ .
- This BH may be the central one of an accreted dwarf galaxy, which acquired a companion star by stellar collisions.
- Or the observed position may be a coincidence.

# Intermediate mass black holes in globular clusters?

Some claims:  $\omega$  Centauri, M31 G1.  
But no compelling evidence yet  
for central black holes in globular  
clusters.

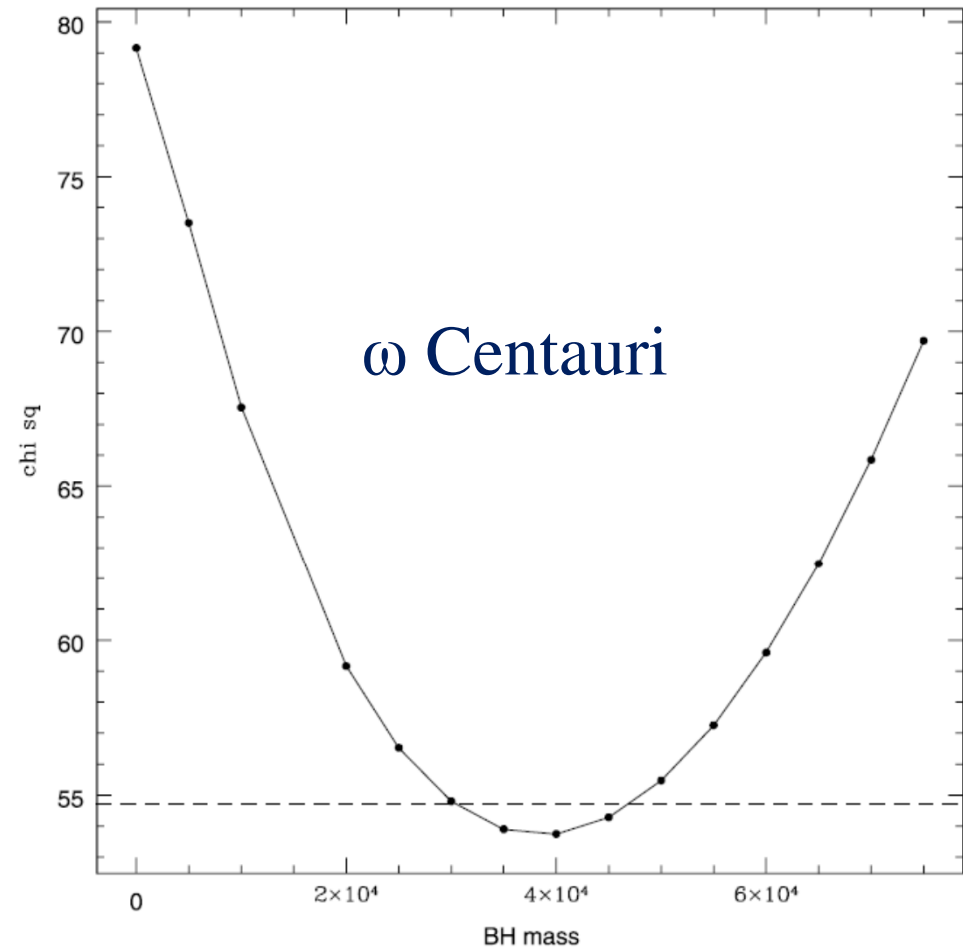


FIG. 5.—Plot of  $\chi^2$  vs. black hole mass. The minimum is found for a black hole mass of  $4.0 \times 10^4 M_{\odot}$ , with 68% confidence limit at  $3$  and  $4.75 \times 10^4 M_{\odot}$  marked by the dashed line. For our model assumptions, the no black hole model is excluded at greater than the 99% confidence

# Connection to supermassive black holes in centers of galaxies:

black hole mass

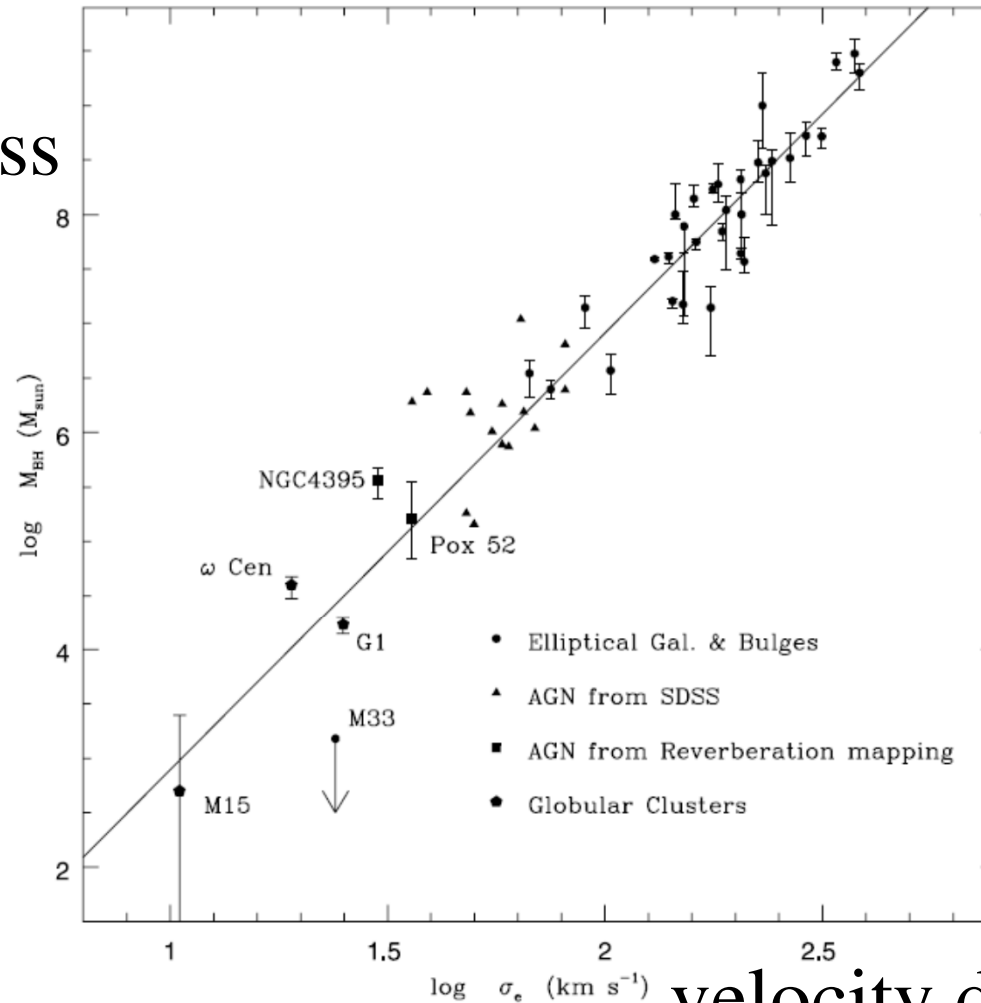


FIG. 9.—  $M_{\bullet}$ - $\sigma_{\text{vel}}$  relation for elliptical galaxies and bulges. The solid line is the relation in Tremaine et al. (2002).  $\omega$  Cen lies on the low-mass extrapolation and suggests a similarity between it and the galaxies. Different types of systems such as star clusters and low-luminosity AGNs appear to populate the low-mass end of the diagram.

# Accretion

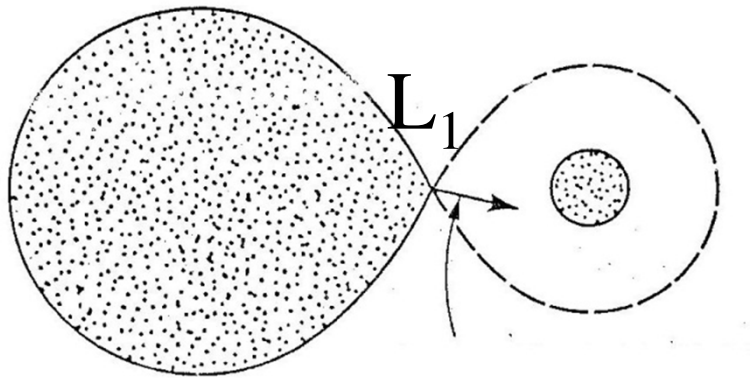
- Two modes of mass transfer between stars.
- Three modes of accretion onto a compact object.

# A common misconception:

- BHs are not cosmic vacuum cleaners, they do not suck everything from outside.
- BHs are very small, orders of magnitude smaller than stars of the same mass.
- Thus, it is very difficult for a body flying around to hit a BH and cross the event horizon.
- Any body orbiting a BH has to lose its angular momentum in order to fall in. But this requires interactions with other bodies. E.g., the Earth would not suddenly fall onto the Sun if it becomes a BH.
- From far away, the gravity of a BH is the same as that of a normal star.

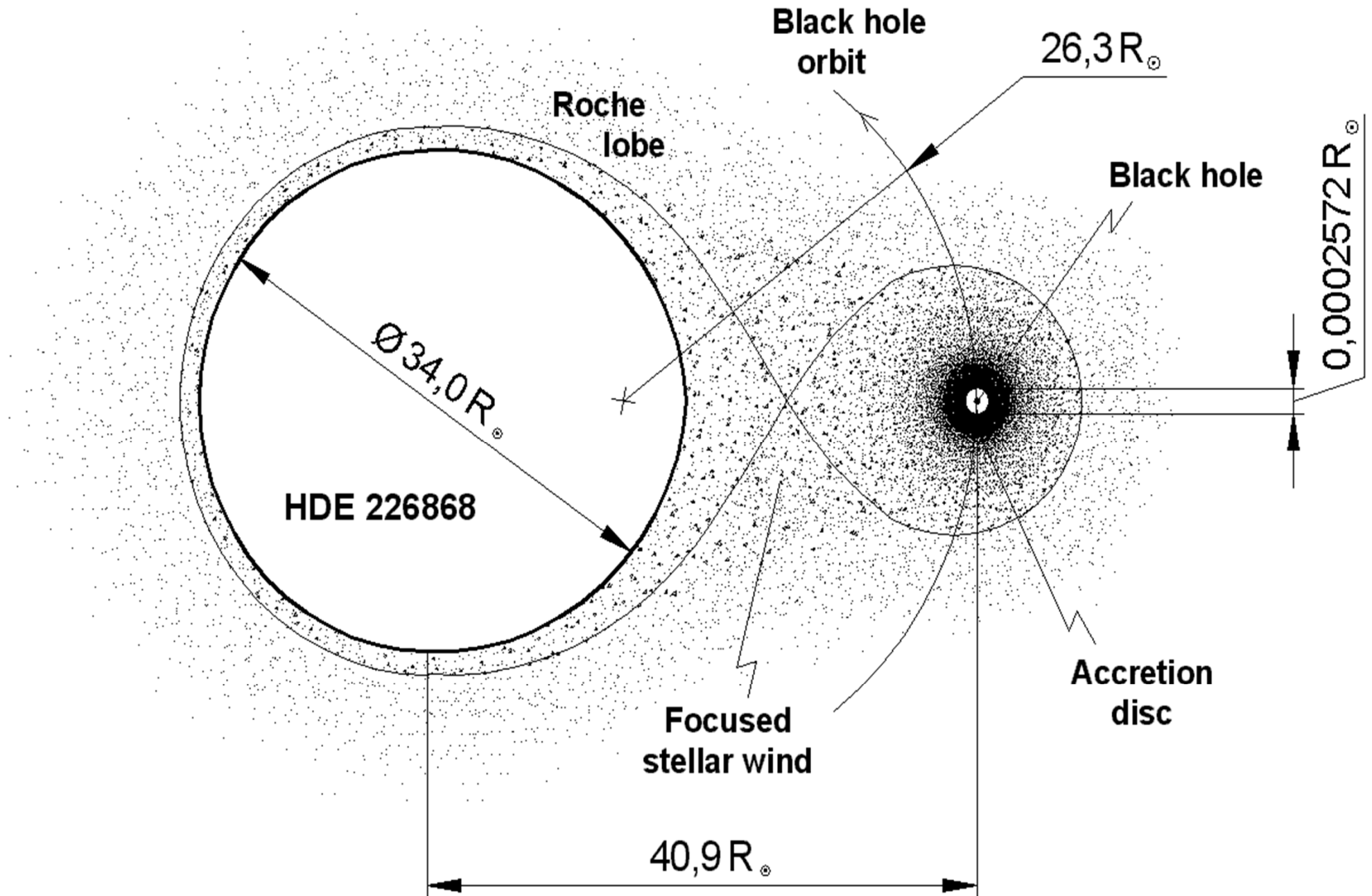
# 1. Roche-lobe overflow

- Equipotential surfaces in the comoving frame in a binary system. Around each star. Critical: intersecting surfaces, called Roche lobes.
- If one of the stars fills its Roche lobe: flow through the inner Lagrangian point,  $L_1$ :



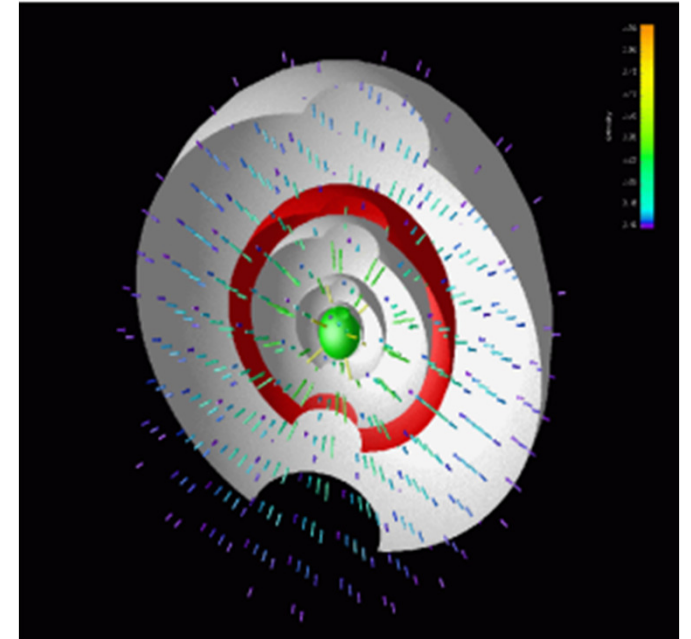
Édouard Albert Roche (1820–1883)

## 2. Wind accretion: Cygnus X-1:



# Three main modes of accretion

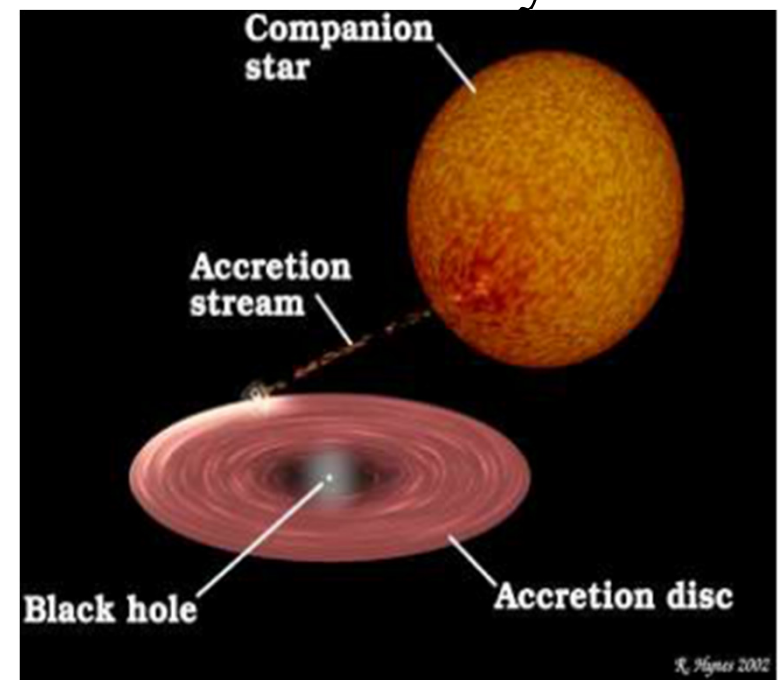
- 1. Spherical accretion from interstellar medium (Bondi).



- Adiabatic compression of the gas within the Bondi radius, which is given by free fall velocity equal to the thermal velocity. A very low energetic efficiency.
- Such mode of occurs, e.g., for the central BH in our Galaxy, Sgr A\*.

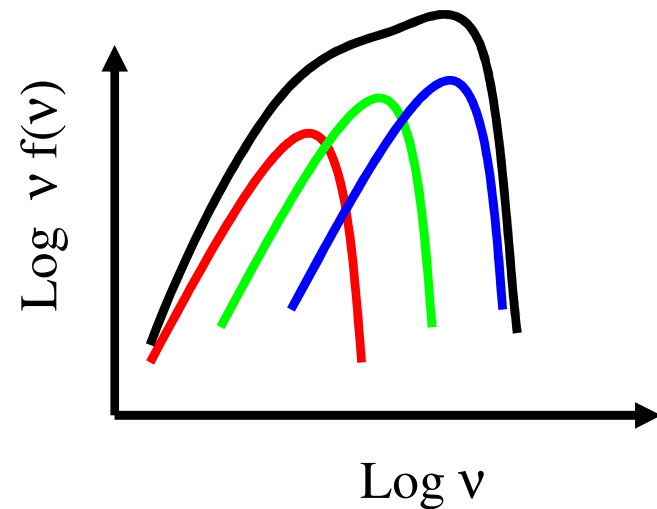
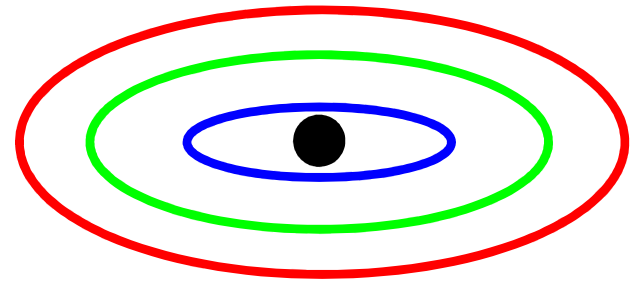
## 2. Disc accretion

- Under most of conditions, the accreting matter would have some angular momentum. Then it would not directly fall onto BH, but move on circular orbits around the black hole.
- Then, a mechanism to reduce the angular momentum is needed, otherwise the matter would never fall onto the black hole.
- The nature of such mechanism has been disputed for many years. Now it seems that it is magneto-rotational instability (MRI).
- Disc accretion in active galaxies and binary systems.



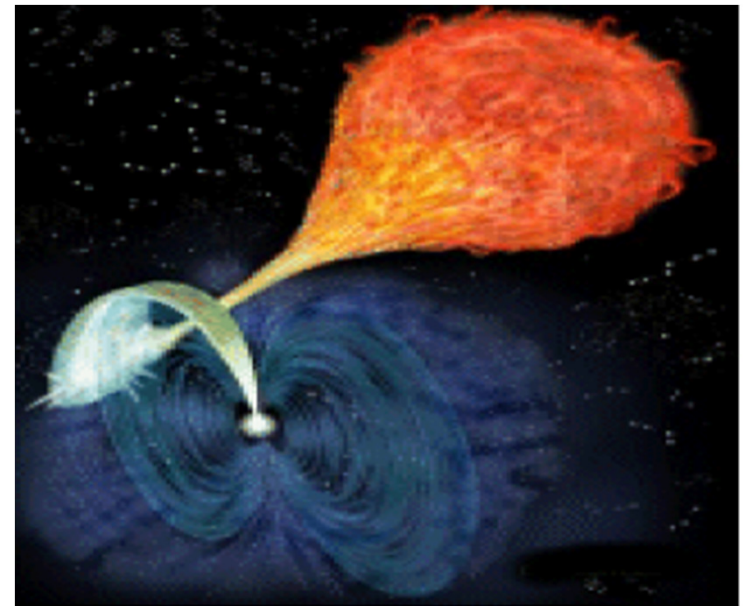
# Standard disc accretion

- Keplerian orbits, differential velocity, inner edge faster than outer edge.
- Frictional viscosity (MHD dynamo) transports angular momentum out so that material can fall inwards.
- Gravitational energy radiated as blackbody (Shakura & Sunyaev 1973).
- Robust optically-thick spectra;  $kT_e \sim 1$  keV, 10 eV (BHB, AGN) at  $L/L_{\text{Edd}} \sim 1$ .

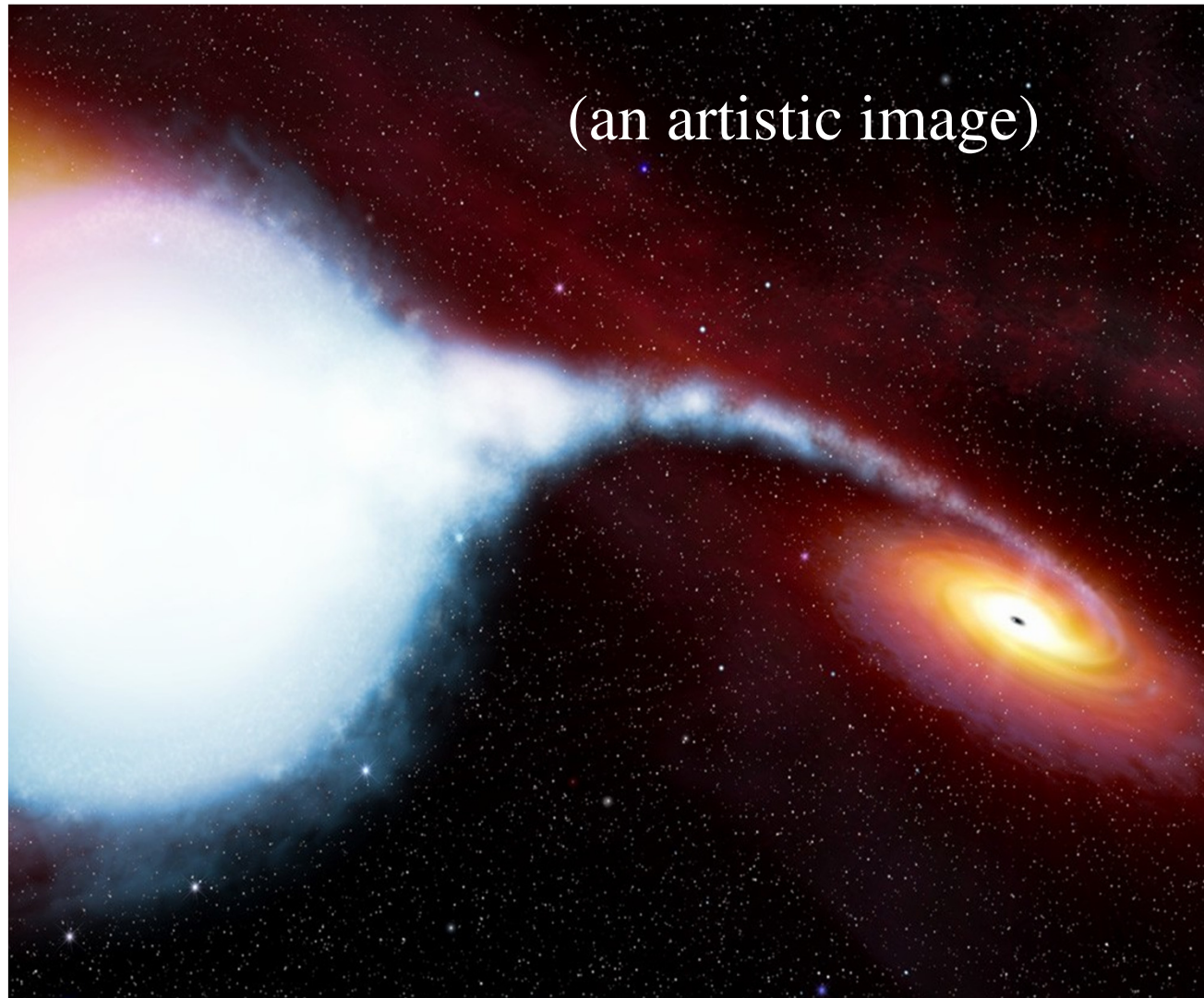


# 3. Column accretion

- In the presence of strong magnetic fields, the accreting matter can be unable to cross field lines. This happens below the Alfvén radius, at which the ram pressure of the accreting matter equals the magnetic pressure. The matter then flows along the field lines.
- This happens in accretion onto strongly magnetized neutron stars, X-ray pulsars. They have dipolar fields, and thus accretion is onto the poles.

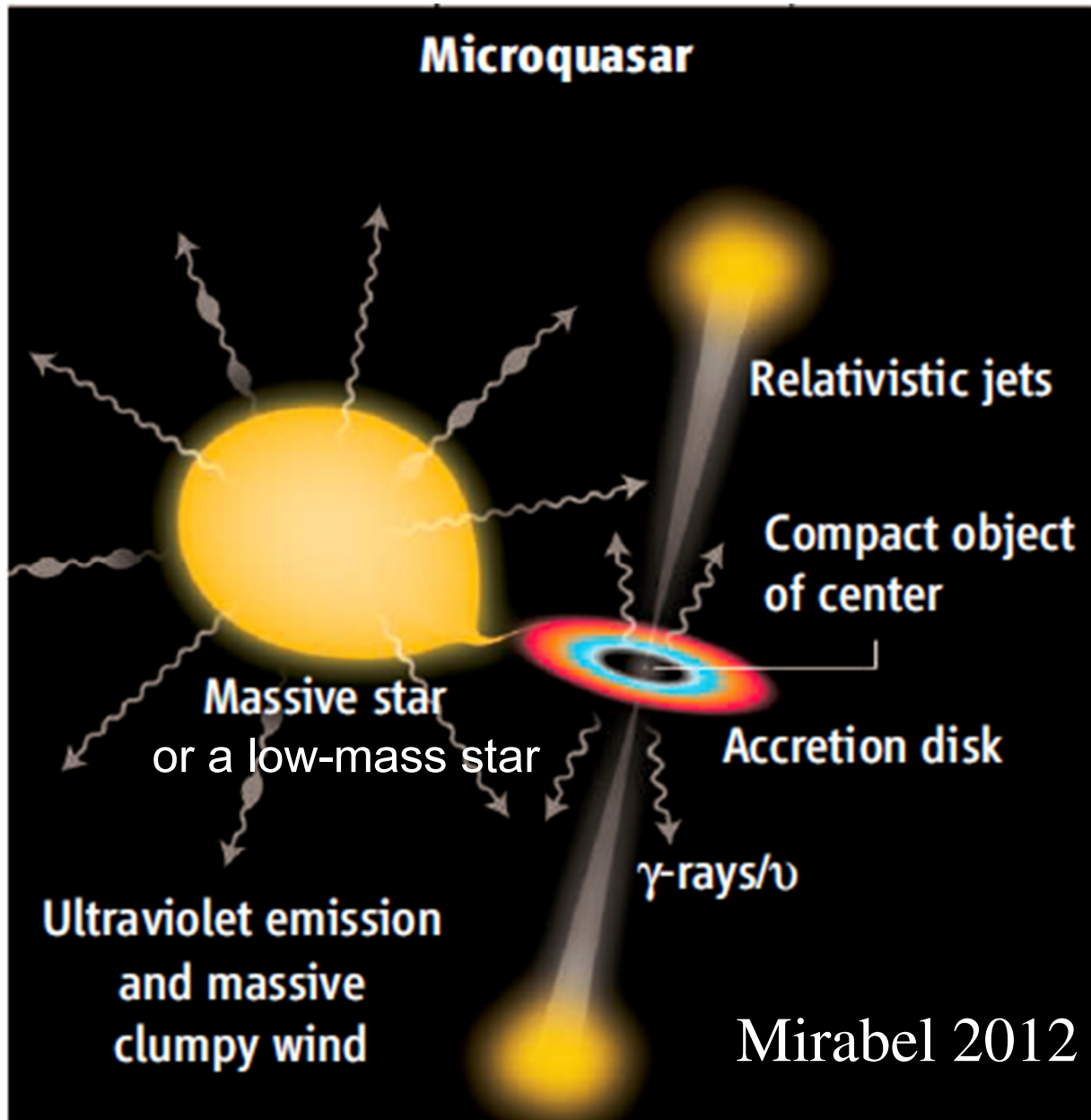


A stellar-mass black-hole source can accrete matter from the companion star and emit radiation from radio to gamma rays:



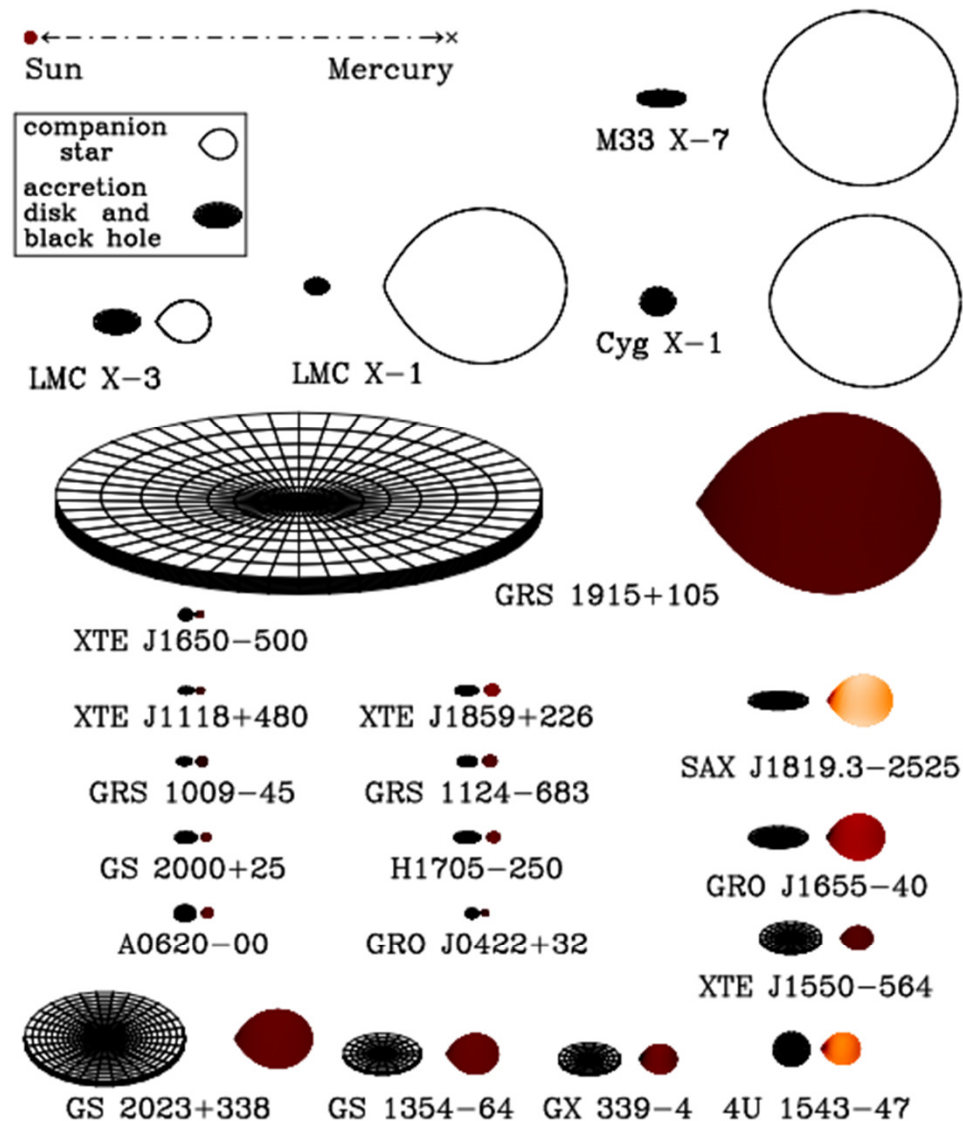
disc accretion

# Accreting stellar binary systems with a compact object (black hole or neutron star)



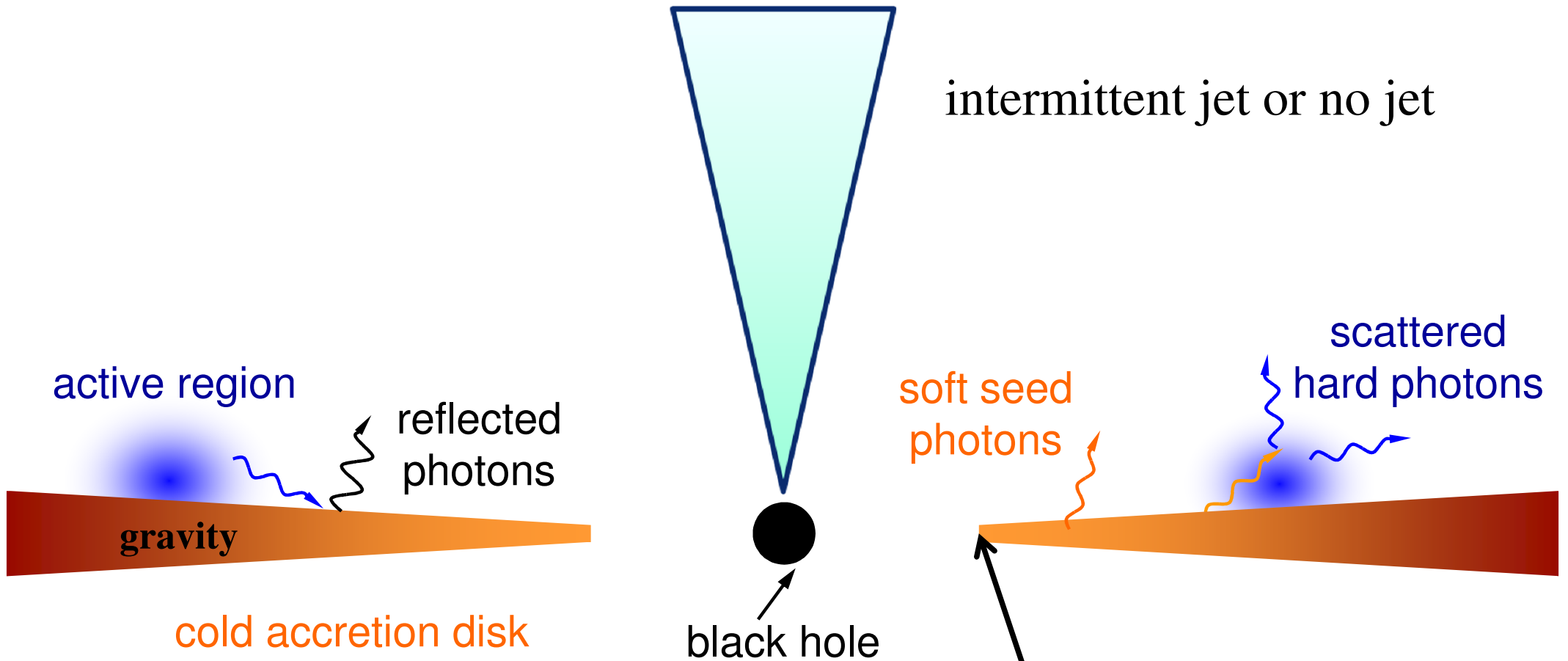
An example of an accreting binary. The donor can be either a high-mass or a low-mass star. Systems containing a BH and a massive donor are persistent, and those with a low-mass donor are usually transient.

# BH binaries:



**Fig. 1** Schematic sketch to scale of 21 black hole binaries (see scale and legend in the upper-left corner). The tidally-distorted shapes of the companion stars are accurately rendered in Roche geometry. The black holes are located in the center of the disks. A disk's tilt indicates the inclination angle  $i$  of the binary, where  $i = 0$  corresponds to a system that is viewed face-on; e.g.,  $i = 21^\circ$  for 4U 1543-47 (*bottom right*) and  $i = 75^\circ$  for M33 X-7 (*top right*). The size of a system is largely set by the orbital period, which ranges from 33.9 days for the giant system GRS 1915+105 to 0.2 days for tiny XTE J1118+480. Three well-studied persistent systems (M33 X-7, LMC X-1 and Cyg X-1) are located in the *upper-right corner*. The other 18 systems are transients. (Figure courtesy of J. Orosz.)

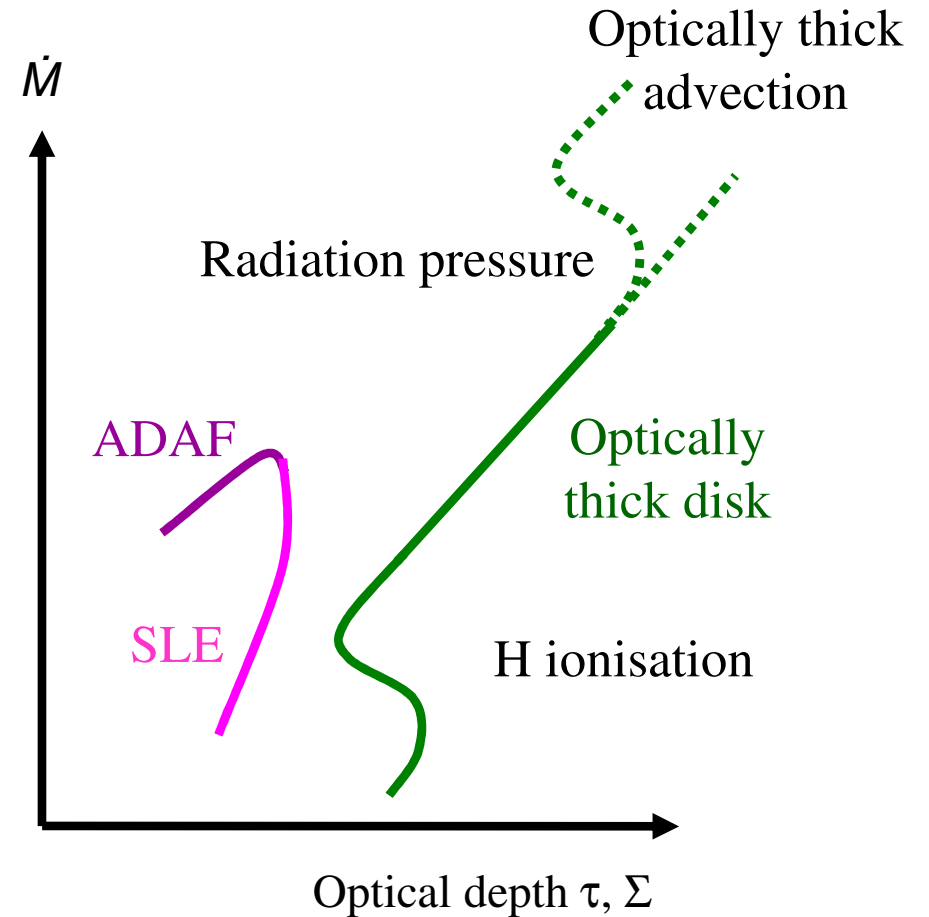
# The geometry of the soft state:



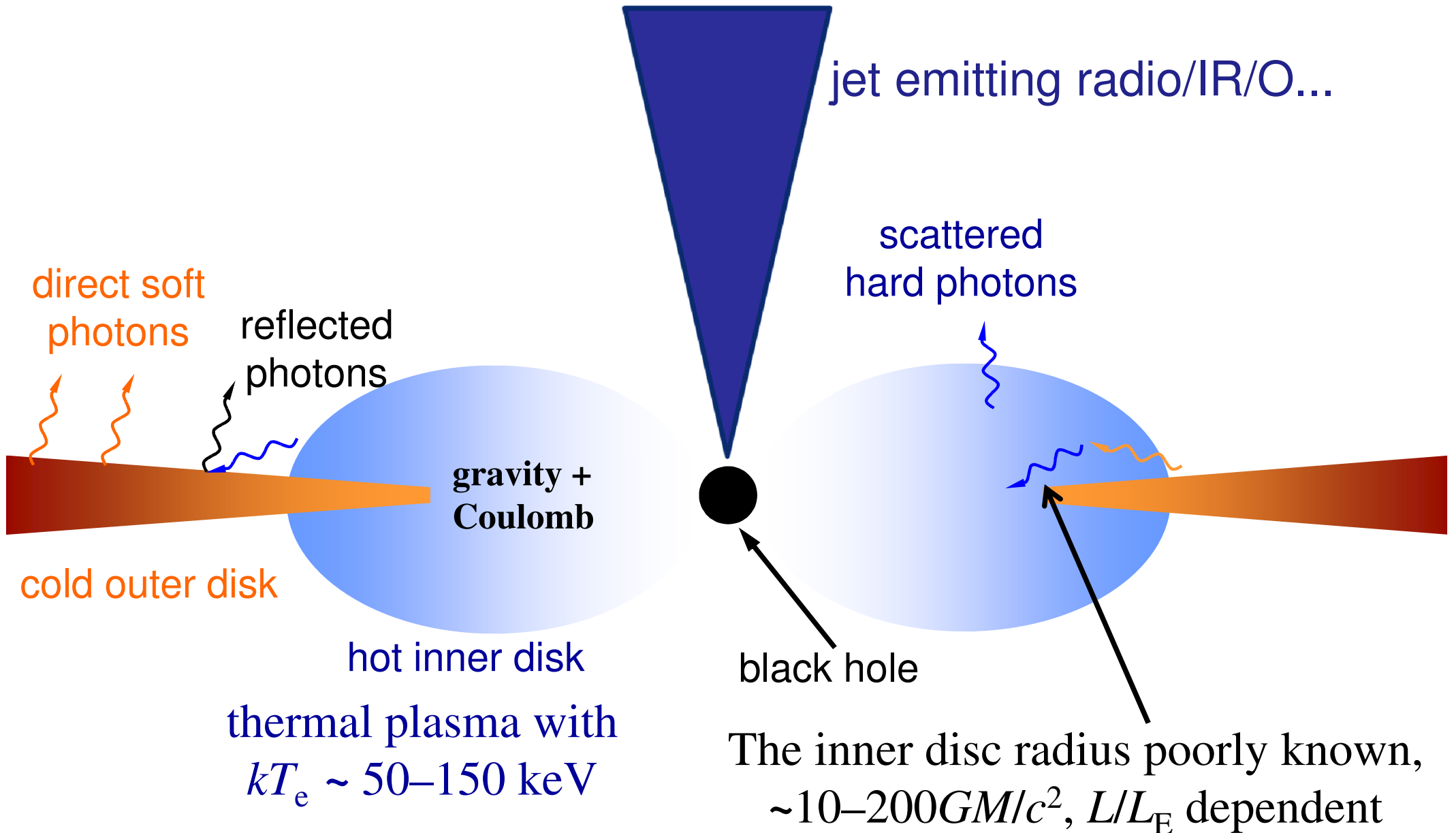
The inner disc radius probably at the innermost stable orbit,  $6GM/c^2$  or less for a rotating black hole

# Accretion solutions beyond the optically thick disc

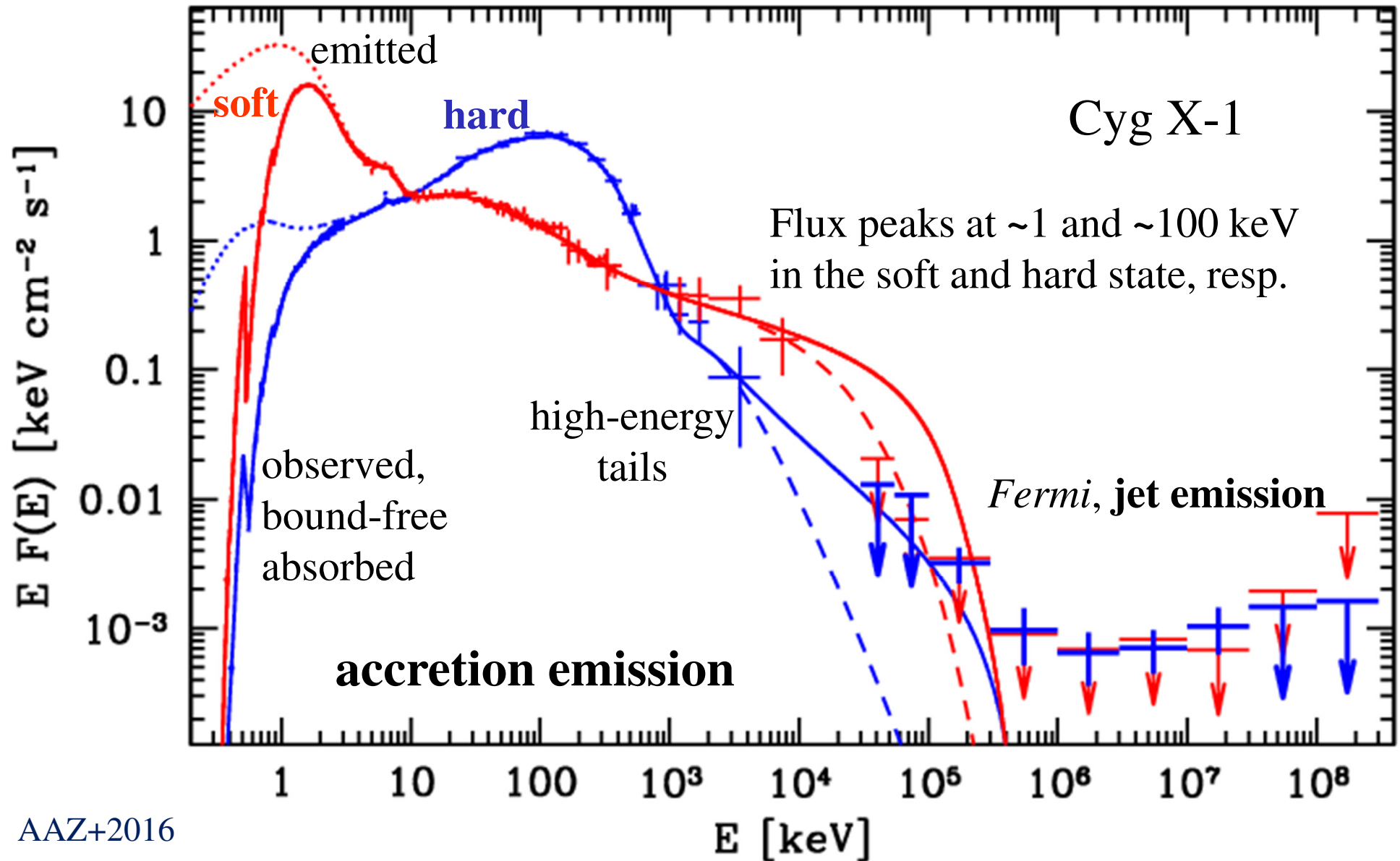
- Standard disc solutions assume protons & electrons at the same  $T$ . Not valid at low densities; protons heated by gravity, electrons by Coulomb collisions:  $2-T$  plasma.
- Cooled by Compton scattering and advection. Protons heated to virial temperature, electrons heated by Coulomb energy transfer from protons and directly,  $kT \sim 100\text{--}200$  keV.



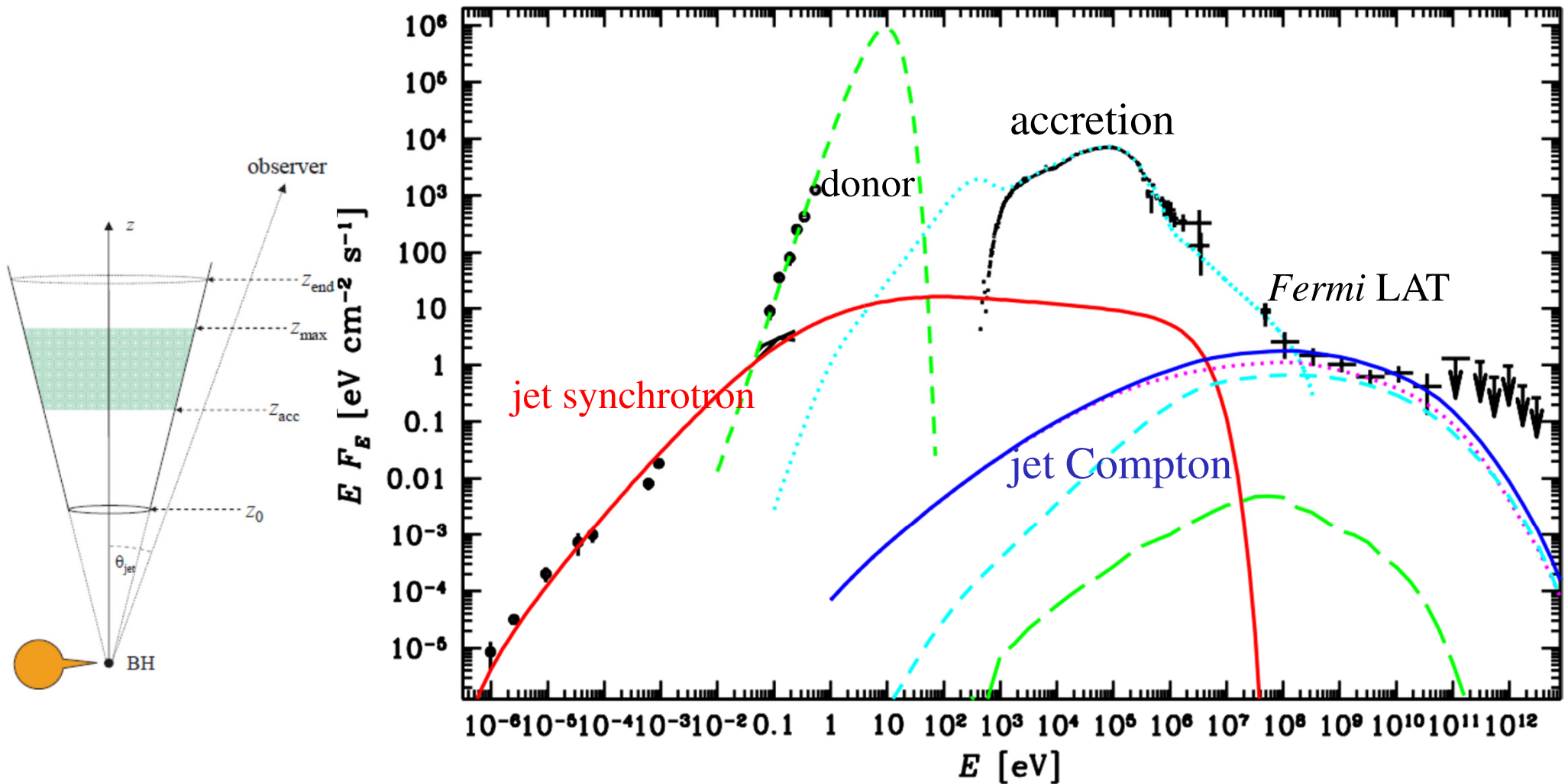
# The geometry of the hard state:



# Two main luminous states of accreting black hole binaries, hard and soft



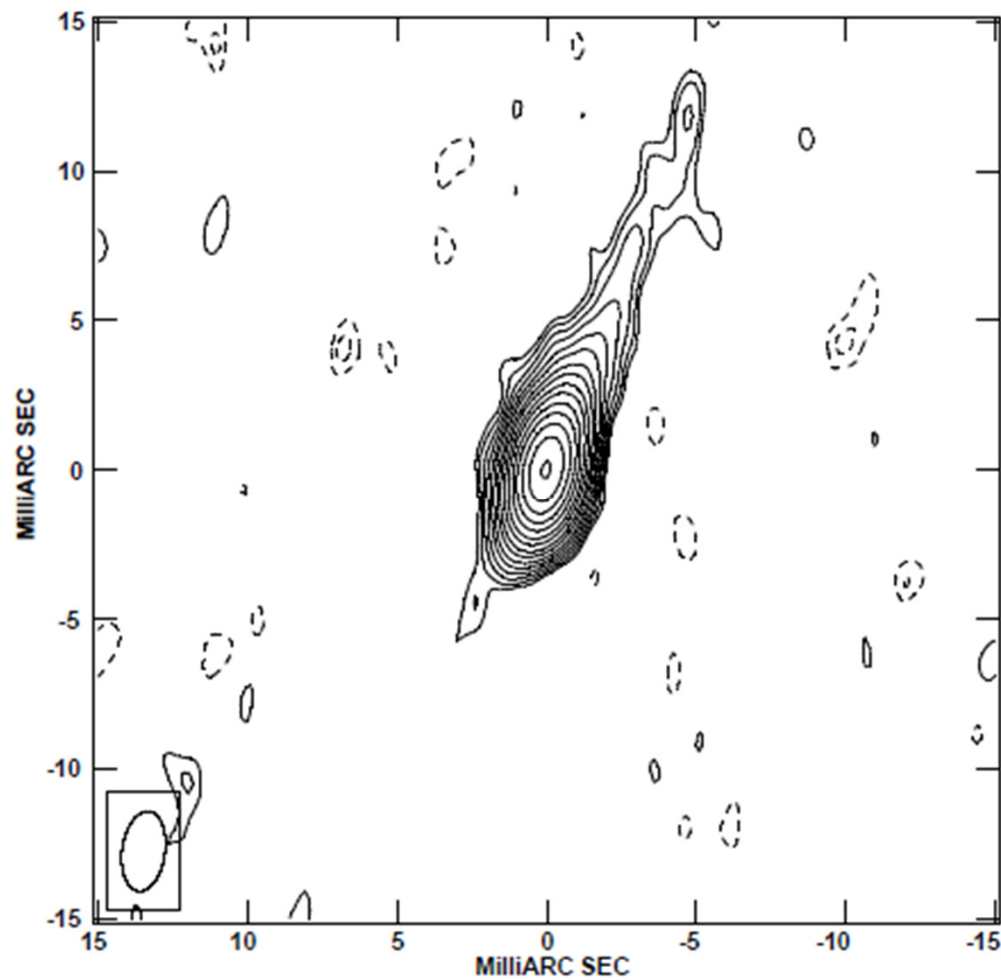
# An example of the broad-band spectrum in the hard state, Cyg X-1



# Two corresponding kinds of jets in black-hole binaries

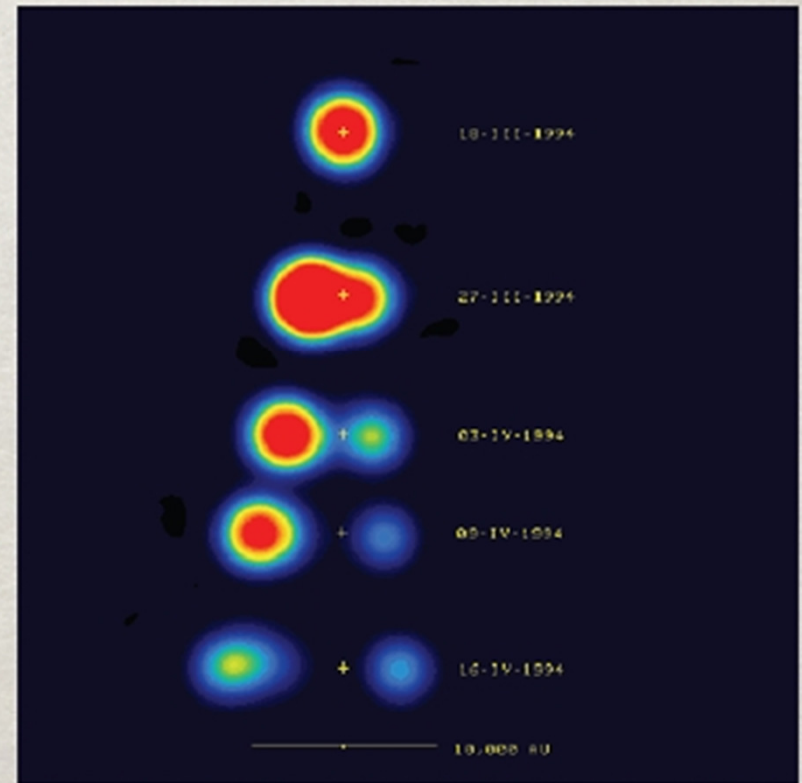
at highest  $L$ , soft states

steady and compact at low  $L$ , hard states



Cyg X-1, Stirling+ 2001, Rushton+ 2011

☀ Discrete ejections events  
(superluminal, ballistic).



Mirabel et al. 94

GRS 1915+105

# **Radiative processes in accreting sources**

# Main relevant radiative processes:

- Compton upscattering of low-energy photons by high-energy electrons;
- Compton downscattering of high-energy photons by low-energy electrons;
- synchrotron emission and absorption;
- free-free emission and absorption;
- electron-positron pair annihilation.

## Blackbody and Wien equilibria.

Electron distribution can be either thermal (Maxwellian), or hybrid, with a Maxwellian followed by a high-energy tail. Absorption of photons in bound-free transitions; sometimes followed by fluorescence.

Modification of photon spectra by relativistic effects close to a compact object.

# Compton scattering

*Electrons at rest.* Scattering changes the photon energy on average by:

$\Delta E/E = -E/m_e c^2$  for  $E \ll m_e c^2$ , the classical Thomson regime. At higher energies, the scattered photon loses a large part of its energy, and we are in the Klein-Nishina regime.

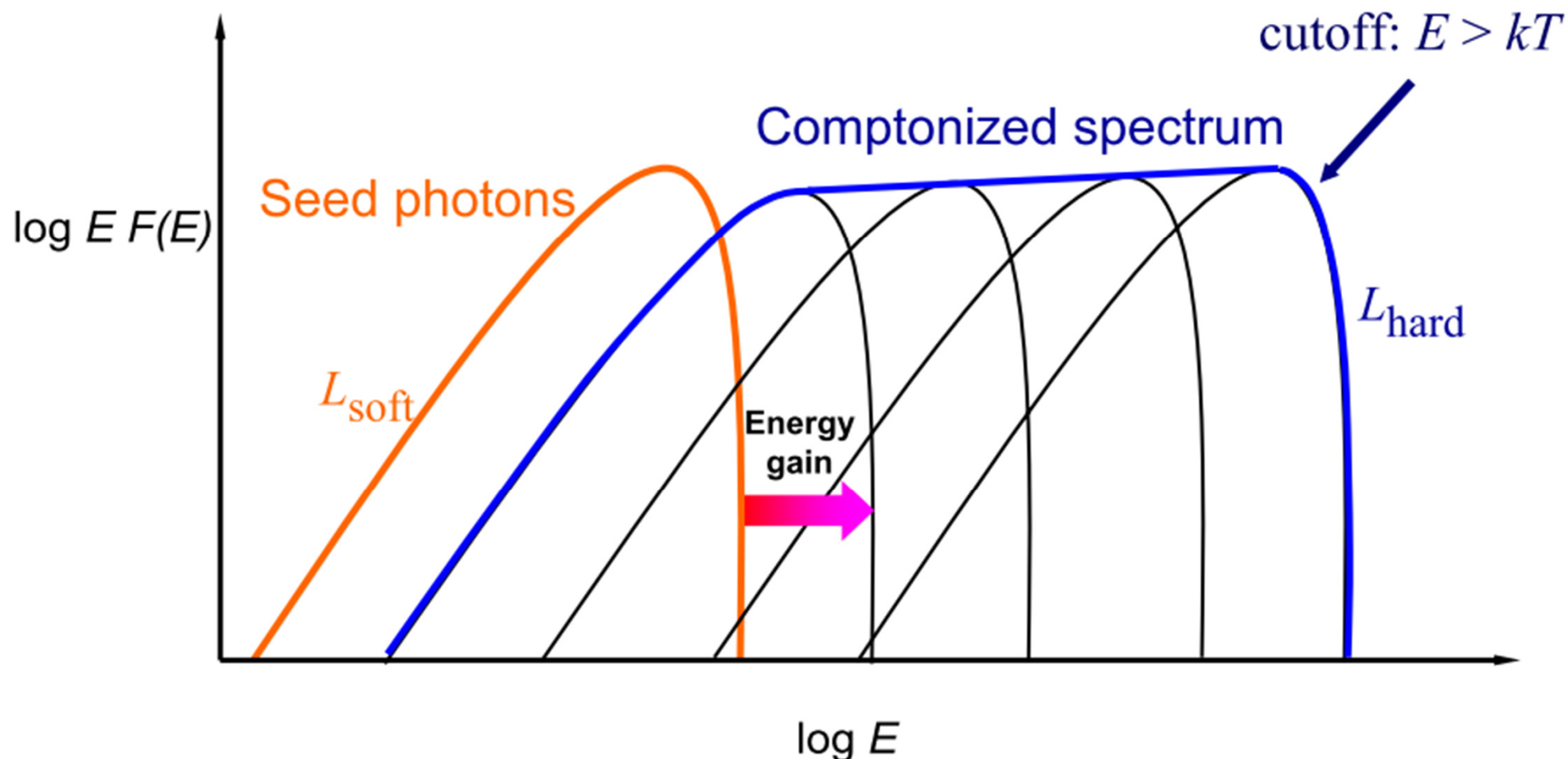
*Thermal nonrelativistic electrons:* Scattering changes the photon energy on average by:

$$\Delta E/E = (4kT - E)/m_e c^2 \text{ for } E \ll m_e c^2, kT \ll m_e c^2.$$

*Relativistic monoenergetic electrons:* Scattering increases the photon energy on average by:

$\Delta E/E = (4/3)\gamma^2$  for  $\gamma E \ll m_e c^2$  (the Thomson regime), where  $\gamma$  is the electron Lorentz factor.

# Thermal Comptonization of a narrow seed photon spectrum (Kompaneets 1956, ...)



The photon index,  $\Gamma$ , is a function of  $kT$  and  $\tau_T$  (the Thomson optical depth).

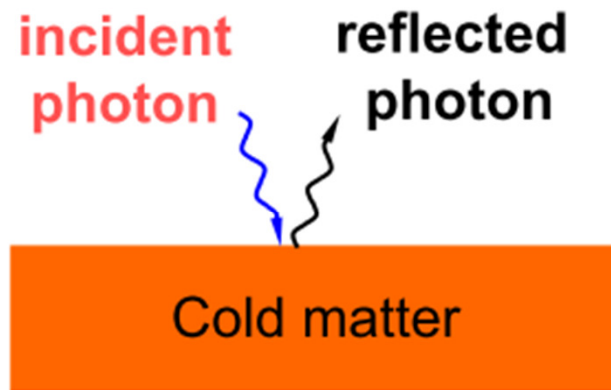
The parameters found in black-hole binaries:  $kT \approx 50-100$  keV,  $\tau_T \sim 1$ .

The amplification factor,  $L_{\text{hard}}/L_{\text{soft}}$  is also a function of  $kT$  and  $\tau_T$ .

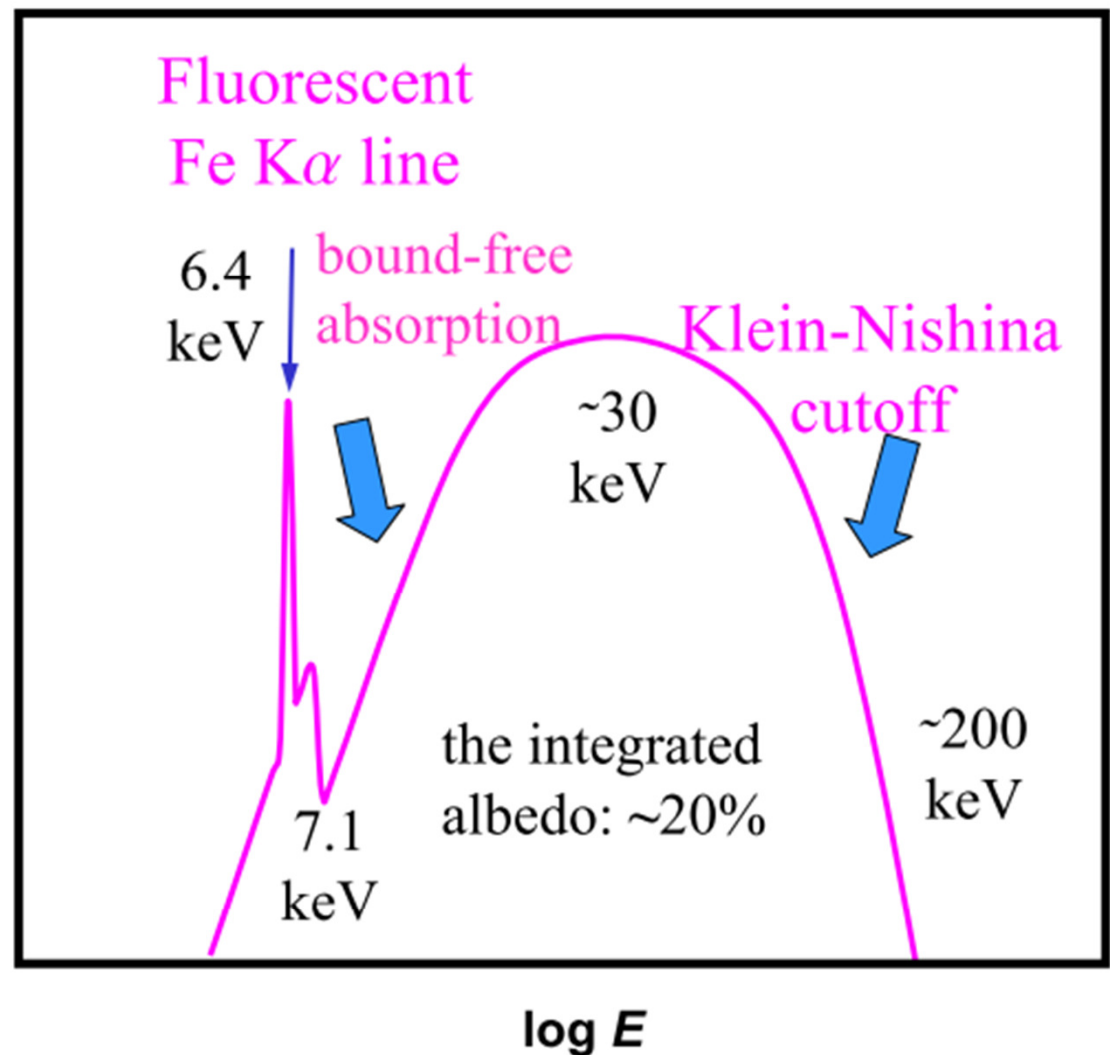
Compton reflection of a power-law incident spectrum from a medium with *the cosmic composition*, e.g., an accretion disk:

$$\langle \sigma_{\text{bound-free}} \rangle = \sigma_T \quad \log E F(E)$$

at  $E \approx 10 \text{ keV}$



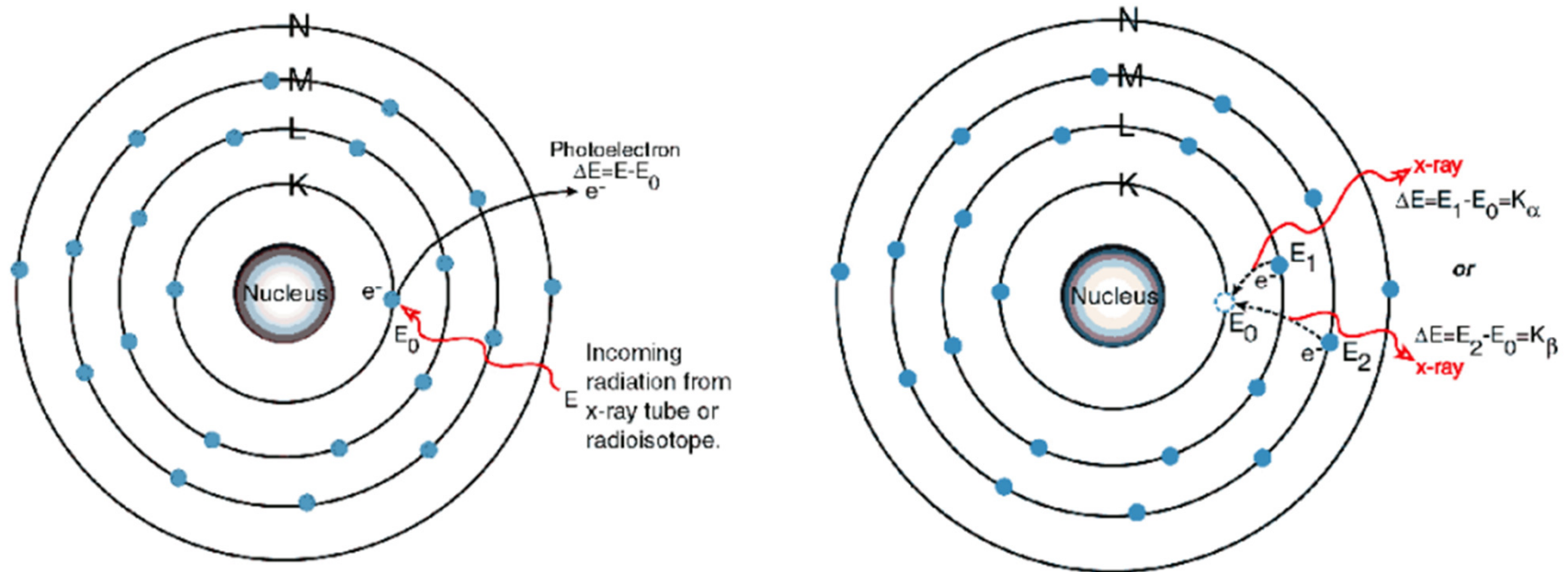
The relative reflection strength usually expressed as  $\Omega/2\pi$ .



Note that the albedo is  $\ll 1$ . The remaining energy is re-emitted as a (modified) blackbody spectrum with the temperature of the reflecting medium.

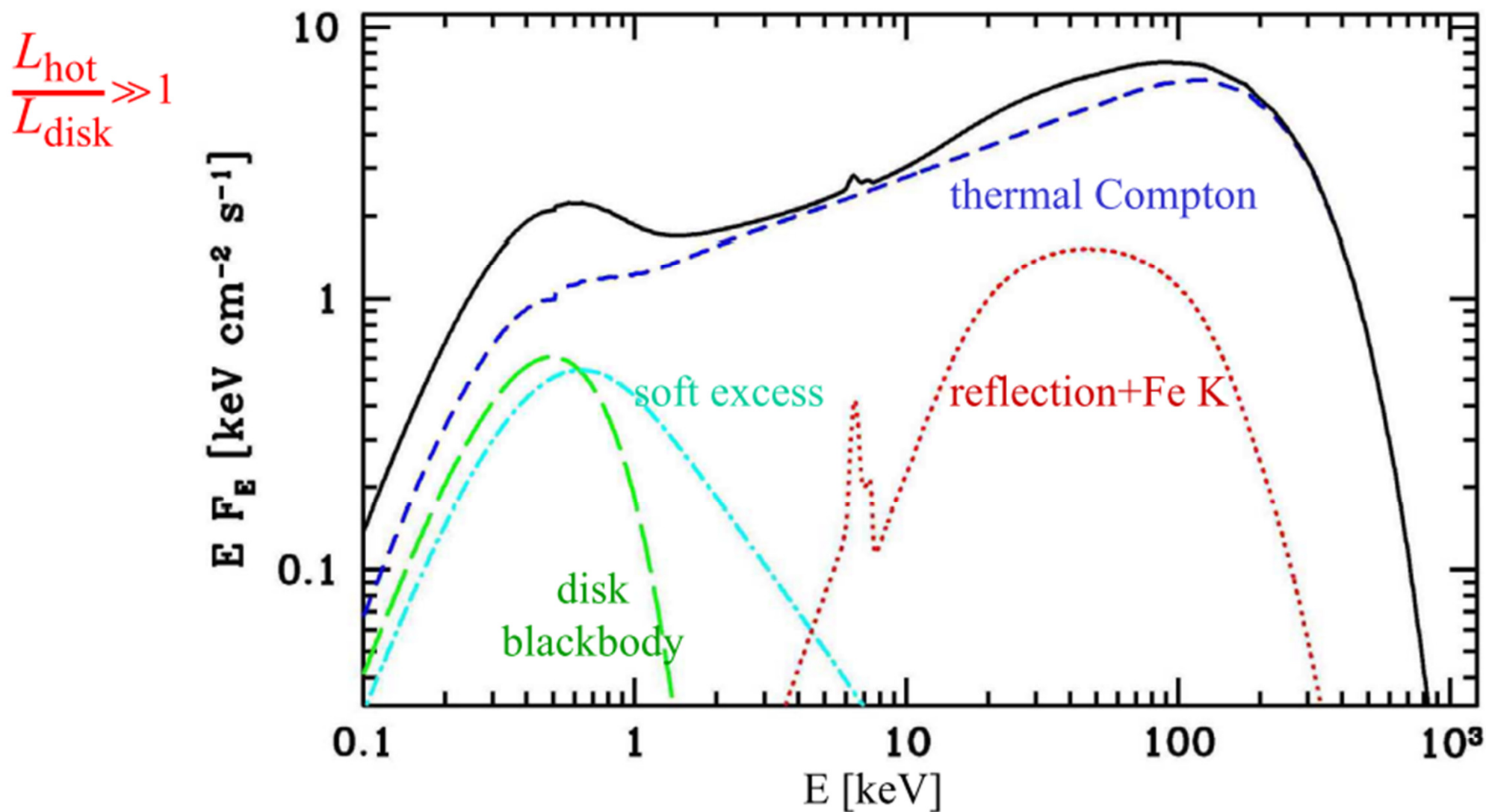
# Fe fluorescence

Fe fluorescence: a photon with  $E > 7.1$  keV ionizes the K shell of an Fe atom  $\rightarrow$  an excited state. Return to the ground state via either ejection of an outer electron or radiatively through an L $\rightarrow$ K transition with emission of a 6.4 keV photon.



Changes of the locally emitted energy due to relativistic effects: circular motion of the disc, gravitational redshift. Used for diagnostics of the accretion geometry.

# Cyg X-1: typical hard state spectrum



$kT_e \approx 100 \text{ keV}$ ,  $\tau \sim 1$ ,  $\Omega/2\pi \approx 0.3$ ,  $L \sim 1\text{-}2\%$  of  $L_E$

# Synchrotron emission from nonthermal power-law electrons

- Electrons often accelerated to relativistic energies, power-law distribution,  $dN/d\gamma = K_N \gamma^{-p}$ ;  $K_N$  – normalization,  $p$  – the power-law index. commonly found in supernova remnants, around pulsars, and in *jets*, in particular those formed during accretion onto black holes.
- Some magnetic field is always present, which gives rise to synchrotron radiation.



- The synchrotron radiation – a power-law distribution,  $dF/dE = K_F E^{-\alpha}$ ;  $K_F$  – normalization,  $\alpha = (p-1)/2$  – the power-law index.

# Electron acceleration

- Electron acceleration in the presence of magnetic field. The maximum possible acceleration rate:  $\sim$  acceleration time = the Larmor radius/ $c$ .
- $R_L = \gamma m_e c^2 / eB \approx 1700 \gamma / B$
- $d\gamma/dt(\text{max. acc.}) \approx c\gamma / R_L = eB / m_e c$
- Electrons also lose energy by emitting synchrotron radiation during the acceleration process.
- $-d\gamma/dt(\text{synchrotron}) = (4/3)(\sigma_T / m_e c)(B^2 / 8\pi)\gamma^2$
- This limits the maximum possible  $\gamma$  to  $(6\pi e / \sigma_T B)^{1/2}$
- The characteristic synchrotron energy  $(3/4\pi) \gamma^2 (h e B / m_e c)$
- Thus, the maximum synchrotron energy is  $(9/16)(m_e c^2 / \alpha_f)$ , where is  $\alpha_f$  the fine-structure function. Notably, it is a universal value,  $\sim 50$  MeV, independent of  $B$ .

# Summary of lecture 1

- 4 possible end stages of stars: white dwarf, neutron star, black hole, dispersion of the entire star.
- Invisibility of BH: escape  $v > c$ .
- Simplest objects, only mass and spin.
- Efficiency:  $L/\dot{M}c^2$ : 0.007 for  $4\text{H}\rightarrow\text{He}$ ;  $\lesssim 0.3$  for BH accretion, an often assumed value: 0.1.
- Kepler law: gravitational and centrifugal forces equal; mass function, BH: dynamical mass  $> 3M_{\odot}$ .
- Stellar mass BHs: isolated – microlensing; binary with a star: dynamical, accretion; two BHs – merger, GW.
- $\sim 100$  mln BHs in the Galaxy.

# Summary of lecture 2

- Supermassive BHs in centres of almost every galaxy,  $M > 10^5 M_{\odot}$ .
- Some of them accrete fast – active; most – quiet.
- $L \lesssim L_{\text{Eddington}}$
- If  $L \sim L_{\text{Eddington}}$ , the accretion  $L \gg$  the total stellar  $L$ .
- The existence of intermediate-mass BHs, with  $\sim(10^2-10^4)M_{\odot}$ , uncertain.
- Two modes of mass transfer between stars, Roche-lobe overflow and wind.
- Three modes of accretion onto a compact object: spherical (from ISM), disc (angular momentum), column (magnetic field).

# Summary of lecture 3

- Disc accretion can be optically thick, leading to blackbody-like spectra, or optically thin, in which electrons have high temperature,  $T \sim 10^9$  K.
- The two cases correspond to two main spectral states of accreting black holes, soft and hard.
- Spectra in the hard state are mostly due to thermal Comptonization of some soft seed photons.
- In addition, there is reflection from some cold medium present, in particular outer optically-thick disc.
- The dominant process in jets: synchrotron emission by non-thermal electrons.