Astrophysical Objects

Black holes

Based on: An introduction to modern Astrophysics chapter 17

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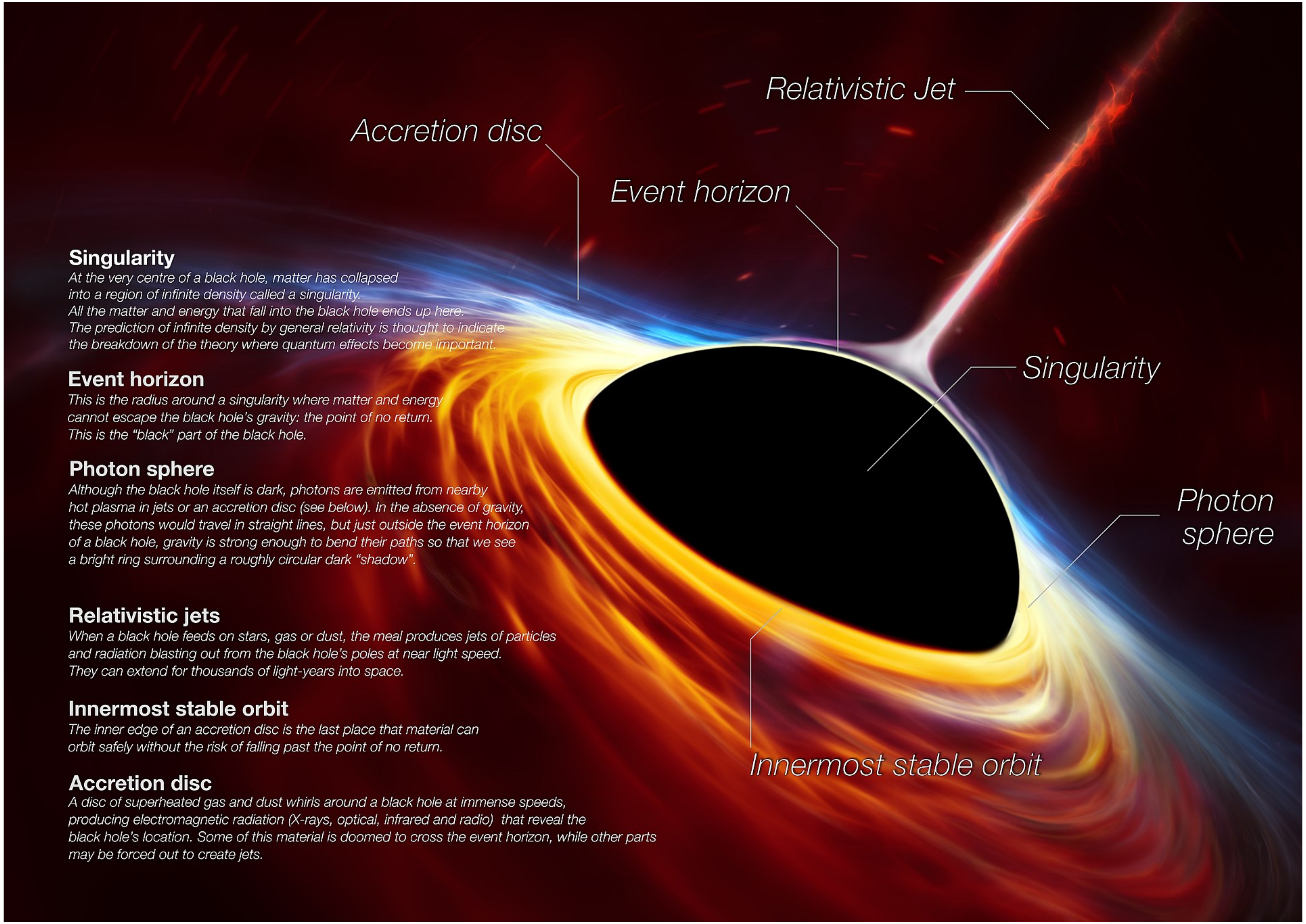
Black hole



https://en.wikipedia.org/wiki/Black_hole

Black holes

First ideas:

In 1783 John Michell (1724–1793), an amateur astronomer, considered if light were indeed a stream of particles, then it should be influenced by gravity. In particular, the gravity of a star 500 times larger than the Sun, but with the Sun's average density, would be sufficiently strong that even light could not escape from it. Even if this Newtonian derivation were correct, the resulting radius of such a **star seemed unrealistically small**, and so it held little interest for astronomers until the middle of the twentieth century.

In 1939 American physicists J. Robert Oppenheimer and Hartland Snyder (1913–1962) described the ultimate **gravitational collapse of a massive star that had exhausted its sources of nuclear fusion.** It was earlier that year that Oppenheimer and Volkoff had calculated the **first models of neutron stars.**

We have seen that a **neutron star cannot be more massive than about 3 $M_\odot$**. **What happens if a degenerate star exceed this limit?**

The upper mass limit of a neutron star is between 2.2 $M_\odot$ and 2.9 $M_\odot$ depending on the amount of rotation. We will adopt an approximate value of 3 $M_\odot$ for the purposes of this discussion.

The Schwarzschild radius

For the simplest case of a **nonrotating star,** the answer lies in the Schwarzschild metric

$$(ds)^2 = \left(c\,dt\sqrt{1-2GM/rc^2}\right)^2 - \left(\frac{dr}{\sqrt{1-2GM/rc^2}}\right)^2 - (r\,d\theta)^2 - (r\sin\theta\,d\phi)^2.$$

When the radial coordinate of the star's surface has collapsed to

$$\boxed{R_S = 2GM/c^2,}$$

called the **Schwarzschild radius, the square roots in the metric go to zero**. The resulting behavior of space and time at $r = R_S$ is remarkable. For example, the proper time measured by a clock at the Schwarzschild radius is $d\tau = 0$. **Time has slowed to a complete stop**, as measured from a vantage point that is at rest a great distance away. From this viewpoint, *nothing ever happens at the Schwarzschild radius*!

The Schwarzschild radius

This behavior is quite curious; does it imply that even light is frozen in time? The speed of light measured by an observer suspended above the collapsed star must always be c. But **from far away, we can determine that light is delayed as it moves through curved spacetime.** (The time delay of radio signals from the Viking lander on Mars.)

The **apparent speed of light**, the rate at which the spatial coordinates of a photon change, is called the ***coordinate speed of light*.** Starting with the Schwarzschild metric with ds = 0 for light,

$$0 = \left(c\,dt\sqrt{1 - 2GM/rc^2}\right)^2 - \left(\frac{dr}{\sqrt{1 - 2GM/rc^2}}\right)^2 - (r\,d\theta)^2 - (r\sin\theta\,d\phi)^2,$$

we can calculate the coordinate speed of a vertically traveling photon. Inserting $d\theta = d\phi = 0$ shows that, in general, the coordinate speed of light in the radial direction is

$$\frac{dr}{dt} = c\left(1 - \frac{2GM}{rc^2}\right) = c\left(1 - \frac{R_S}{r}\right).$$

The Schwarzschild radius

When r ≫ R_S, dr/dt ≃ c, as expected in flat spacetime. However, at r = R_S, dr/dt = 0. **Light is frozen in time at the Schwarzschild radius.**

The spherical surface at r = R_S acts as a barrier and prevents our receiving any information from within. For this reason, **a star that has collapsed down within the Schwarzschild radius is called a black hole.**

It is enclosed by the **event horizon**, **the spherical surface at r = R_S** . Note that the event horizon is a mathematical surface and need not coincide with any physical surface.

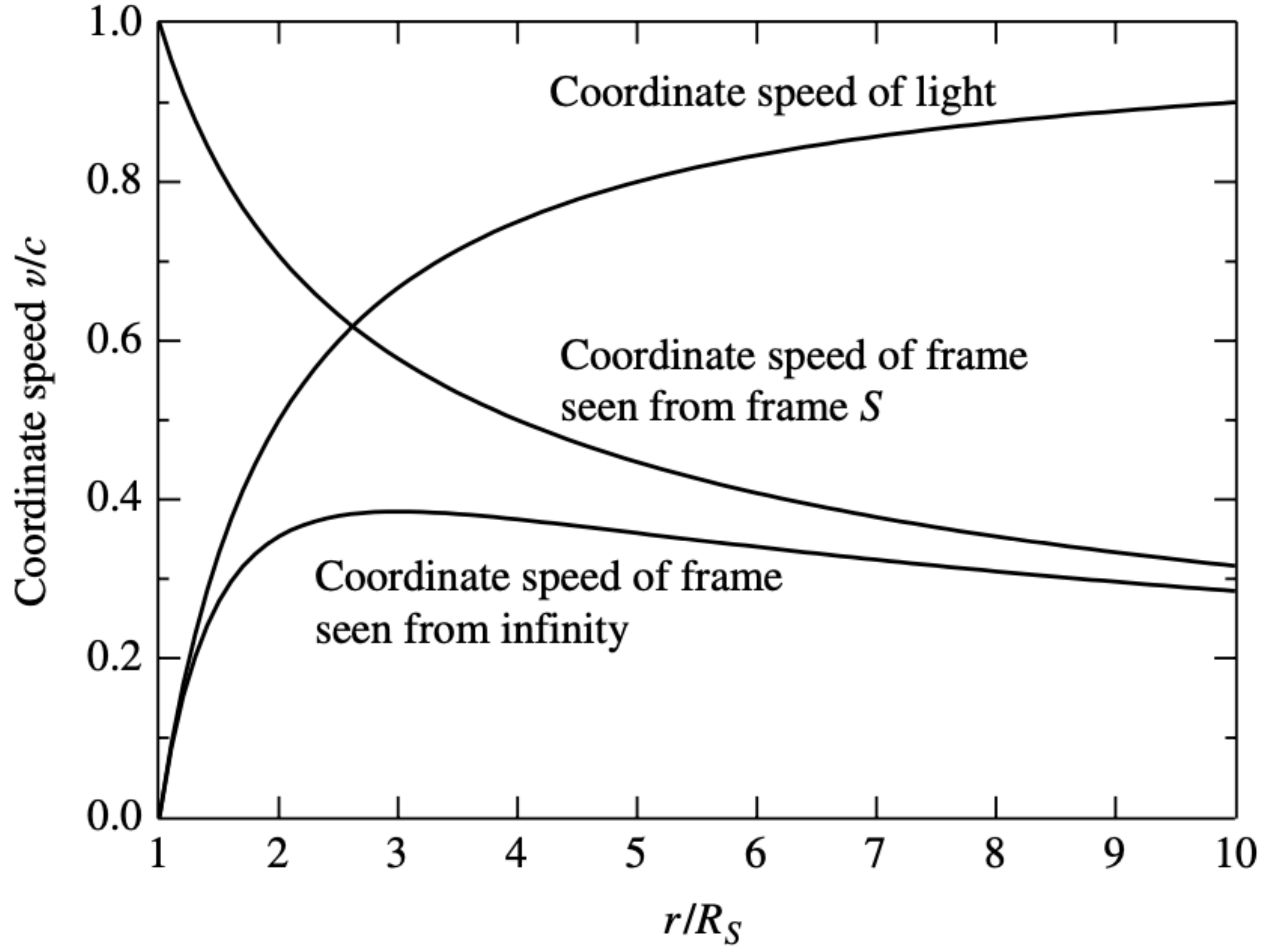


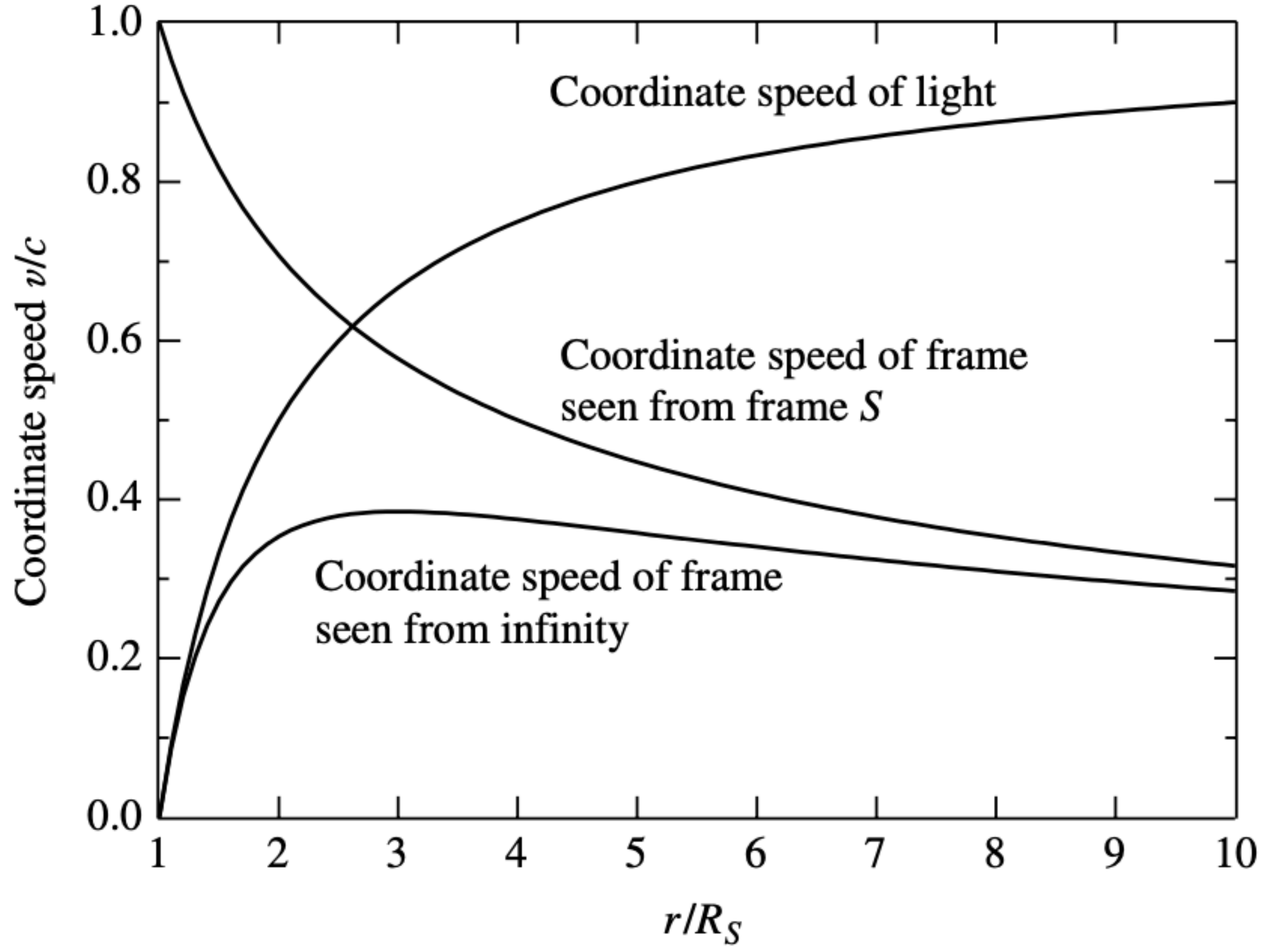
FIGURE 19 Coordinate speed of light, and coordinate speeds of a freely falling frame S seen by an observer at rest at infinity and by an observer in the frame S. The radial coordinates are in terms of R_S for a 10 $M_\odot$ black hole having a Schwarzschild radius of ≈ 30 km.

The Schwarzschild radius

Although the interior of a black hole, inside the event horizon, is a region that is forever hidden from us on the outside, its properties may still be calculated.

A nonrotating black hole has a particularly simple structure. At the center is the **singularity**, **a point of zero volume and infinite density where all of the black hole's mass is located.** Spacetime is infinitely curved at the singularity. Cloaking the central singularity is the event horizon, so **the singularity can never be observed**.

In fact, there is a hypothesis dubbed the ***"Law of Cosmic Censorship"*** that forbids a *naked singularity* from appearing unclothed (without an associated event horizon).



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Black holes

Imagine an attempt to investigate the black hole by starting at a safe distance and reflecting a radio wave from an object at the event horizon. **How much time will it take for a radio photon (or any photon) to reach the event horizon from a radial coordinate r ≫ R_S and then return?**

Since the round trip is symmetric, it is necessary only to find the time for either the journey in or out and then double the answer. It is easiest to integrate the coordinate speed of light in the radial direction,

$$\frac{dr}{dt} = c\left(1 - \frac{2GM}{rc^2}\right) = c\left(1 - \frac{R_S}{r}\right).$$

between two arbitrary values of r_1 and r_2 to obtain the general answer,

$$\Delta t = \int_{r_1}^{r_2} \frac{dr}{dr/dt} = \int_{r_1}^{r_2} \frac{dr}{c(1 - R_S/r)} = \frac{r_2 - r_1}{c} + \frac{R_S}{c} \ln\left(\frac{r_2 - R_S}{r_1 - R_S}\right),$$

assuming that $r_1 < r_2$. Inserting $r_1 = R_S$ for the photon's original position, we find that $\Delta t = \infty$.

Black holes

Now, since the trip is symmetric, the same result applies if the photon started at R_S. **According to the distant observer, the radio photon will *never* reach the event horizon.**

Instead, **according to gravitational time dilation, the photon's coordinate velocity will slow down until it finally stops at the event horizon in the infinite future.** In fact, any object falling toward the event horizon will suffer the same fate. **Seen from the outside**, even the surface of the star that collapsed to form the event horizon would be frozen, and so a black hole is in this sense a *frozen star*.

Black holes

A brave (and *indestructible*) astronomer decides to test this remarkable conclusion. Starting from rest at a great distance, she volunteers to fall freely toward a 10 M⊙ black hole ($R_S \simeq 30$ km). We remain behind to watch her local inertial frame S as it falls with coordinate speed dr/dt all the way to the event horizon. She gradually accelerates as she monitors her watch and **shines a monochromatic flashlight back in our direction once every second.**

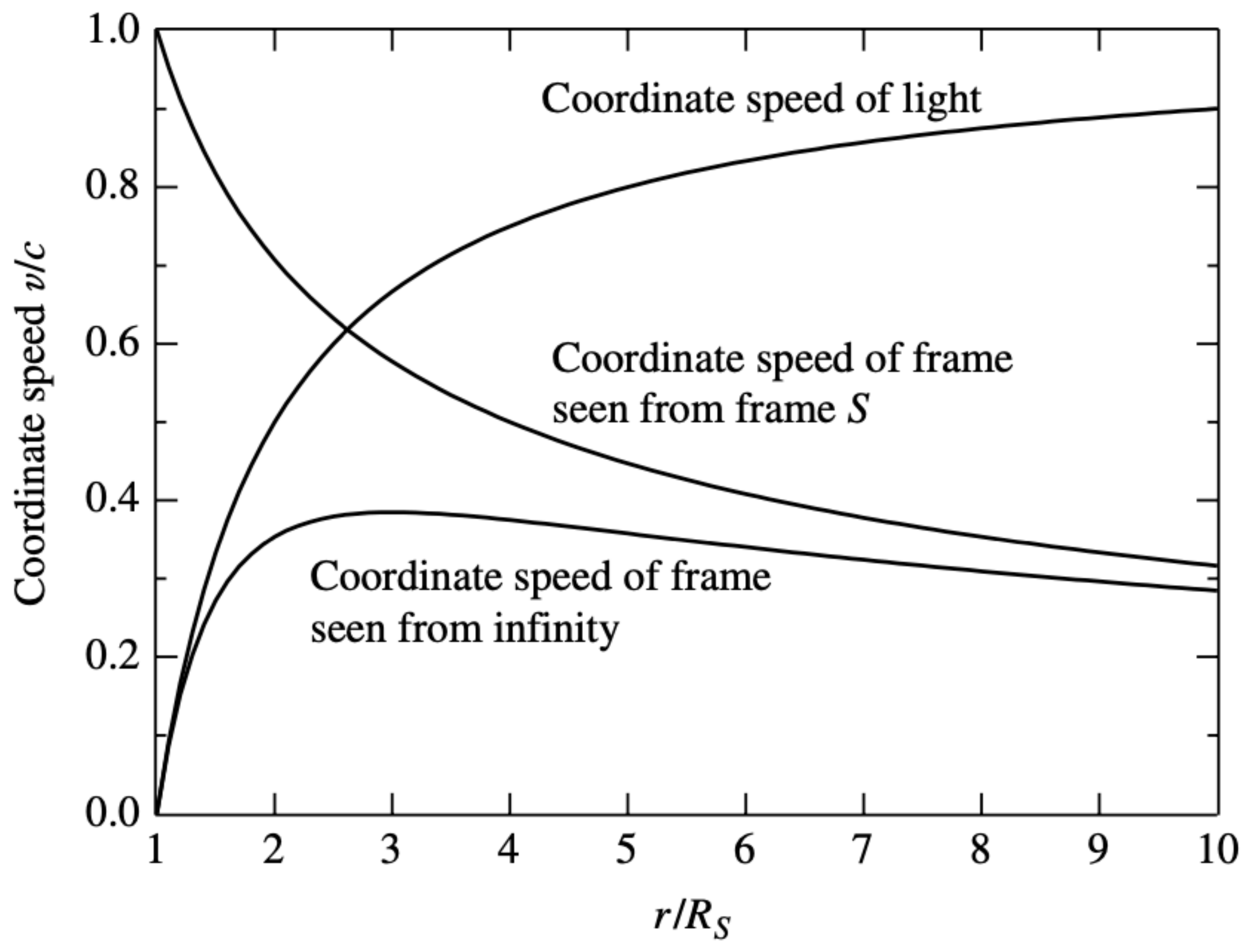
As her fall progresses, the light **signals arrive farther and farther apart** for several reasons: Subsequent signals must travel a longer distance as she accelerates, and her proper time **τ** is running more slowly than our coordinate time t due to her location (**gravitational time dilation)** and her motion (**special relativity time dilation**). Furthermore, the **coordinate speed of light becomes slower** as she approaches the black hole, so the signals travel back to us more slowly.

The **frequency of the light waves we receive is also increasingly redshifted.** This is caused by both her **acceleration away from** us and the **gravitational redshift.**

The **light becomes dimmer as well**, as the rate at which her flashlight emits photons decreases (seen from our vantage point) and the energy per photon (hc/λ) also declines.

Black holes

Then when she is about **$2R_S$ from the event horizon, the time between her signals begins to increase without limit** as the strength of the signals decreases. The light is redshifted and dimmed into invisibility as **time dilation brings her coordinate speed to zero** (see Figs. 19 and 20). She is frozen in time.



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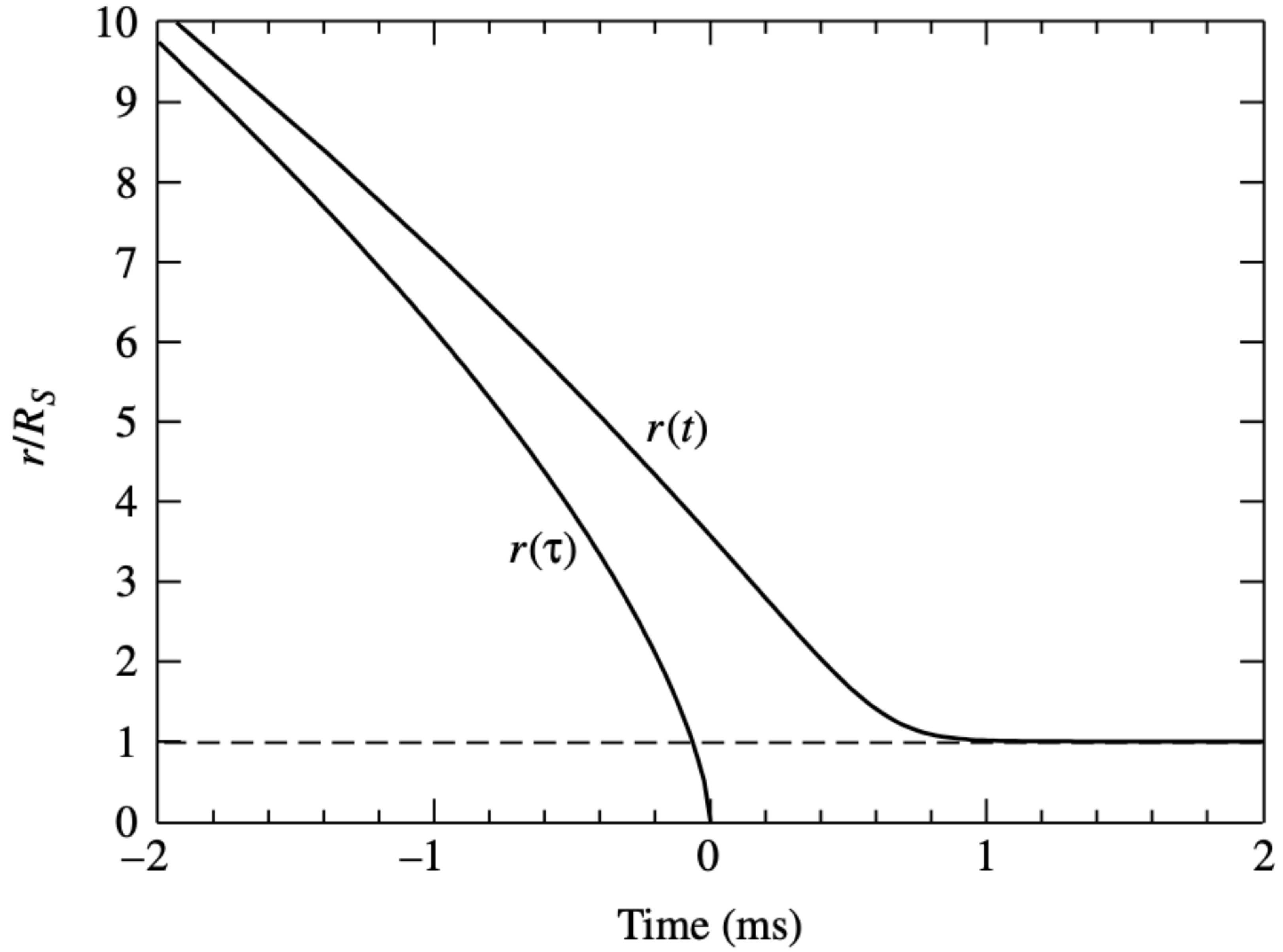


FIGURE 20 Coordinate $r(t)$ of a freely falling frame S according to an observer at rest at infinity, and $r(\tau)$ according to an observer in the frame S. The radial coordinates are in terms of R_S for a 10 $M_\odot$ black hole.

Black holes

How does all of this appear to the astronomer, freely falling toward the black hole?

Because gravity has been abolished in her local inertial frame, **initially she does not notice her approach to the black hole.** She monitors her watch (which displays her proper time, τ), and she turns on her flashlight once per second. However, **as she draws closer, she begins to feel as though she is being stretched in the radial direction and compressed in the perpendicular directions**. The gravitational pull on her feet (nearer the black hole) is stronger than on her head, and the variation in the direction of gravity from side to side produces a compression that is even more severe.

These **differential *tidal forces* increase in strength** as she falls. In other words, the size of her local inertial frame (where gravity has been abolished) becomes increasing smaller as the spatial variation in the gravitational acceleration vector, **g**, increases.

Were she not indestructible, our astronomer would be **torn apart by the tidal force** while still several hundred kilometers from the black hole.

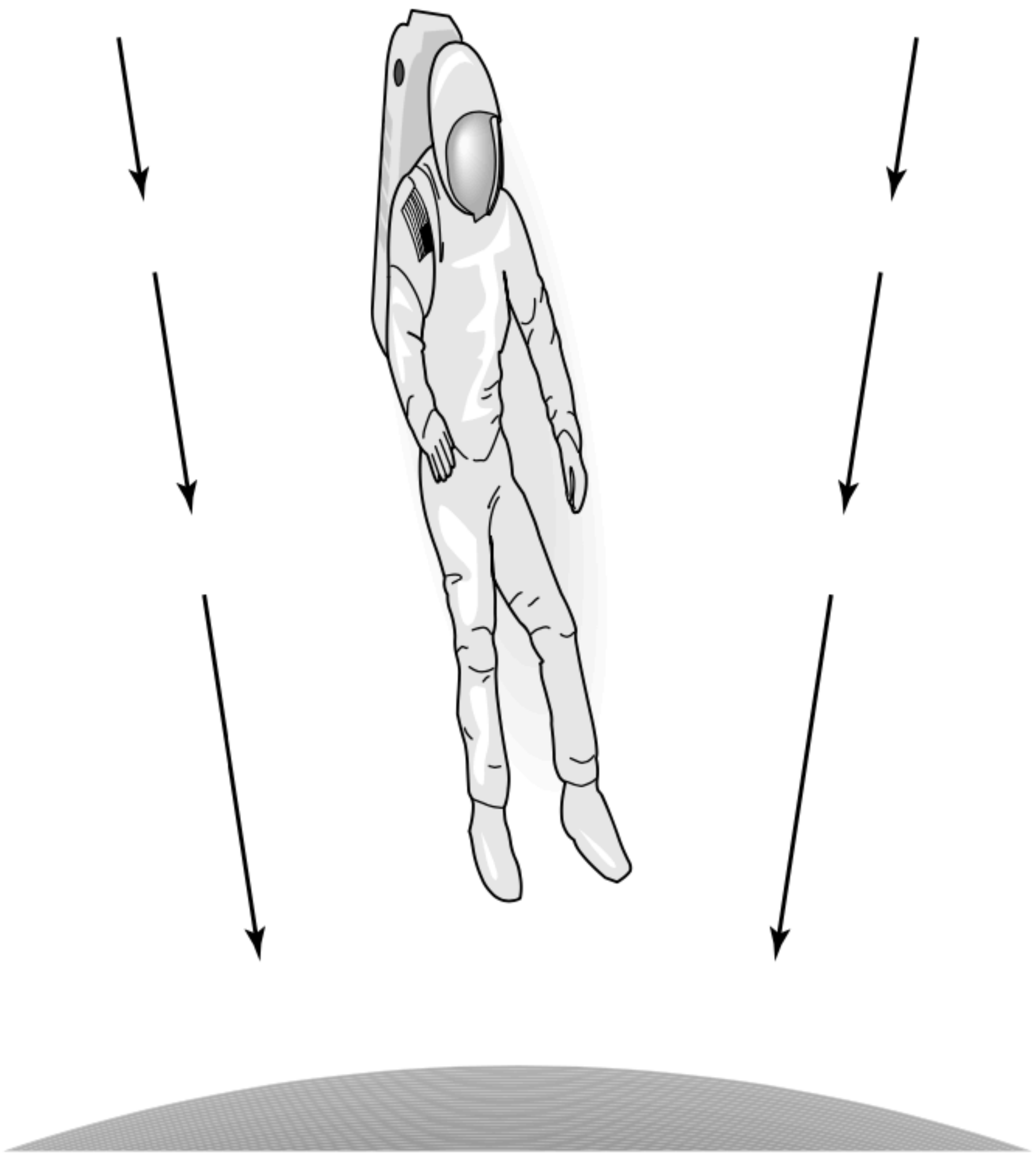


FIGURE 21 Tidal forces near a black hole.

Black holes

In **just two milliseconds (proper time), she falls the final few hundred kilometers to the event horizon and crosses it**.

Her proper time continues normally, and she encounters **no frozen stellar surface** since it has fallen through long ago. However, once inside the event horizon, her fate is sealed. **It is impossible for any particle to be at rest when** r < R_S , as can be seen from the Schwarzschild metric.

Using dr = dθ = dϕ = 0 for an object at rest, the interval is given by

$$(ds)^2 = (c\,dt)^2\left(1 - \frac{R_S}{r}\right) < 0$$

when r < R_S . This is a ***spacelike* interval,** which is not permitted for particles.

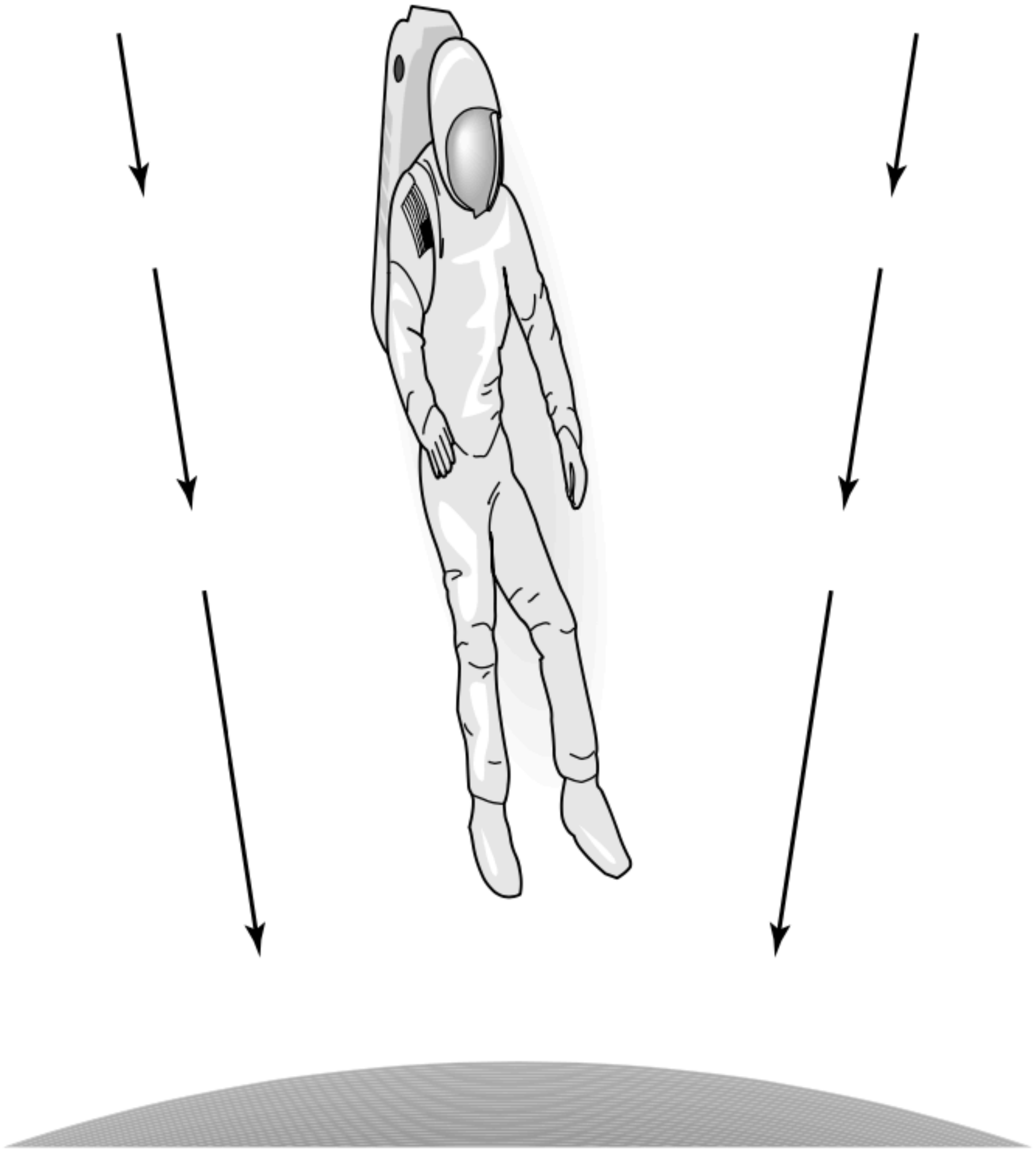


FIGURE 21 Tidal forces near a black hole.

Black holes

Therefore it is impossible to remain at rest where r < R_S . **Within the event horizon of a nonrotating black hole, all worldlines converge at the singularity.** Even photons are pulled in toward the center.

This means that the astronomer never has an opportunity to glimpse the singularity because no photons can reach her from there. She can, however, **see the light that falls in behind her from events in the outside universe**, but she does not see the entire history of the universe as it unfolds.

Although the elapsed coordinate time in the outside world does become infinite, the light from all of these events does not have time to reach the astronomer. Instead, these events occur in her "elsewhere."

Just **6.6 × 10^{-5} s of proper time after passing the event horizon, she is drawn to the singularity.**

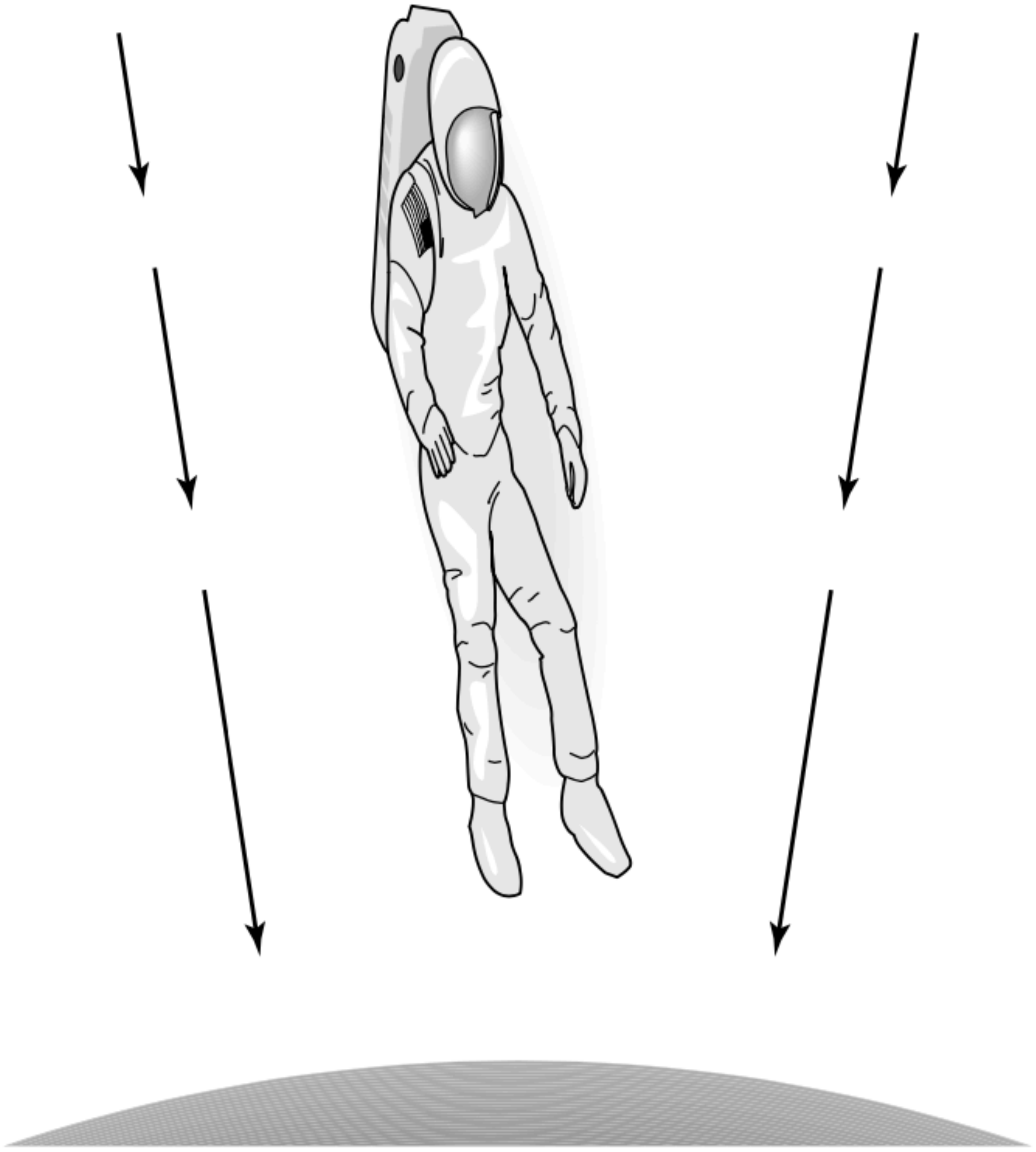


FIGURE 21 Tidal forces near a black hole.

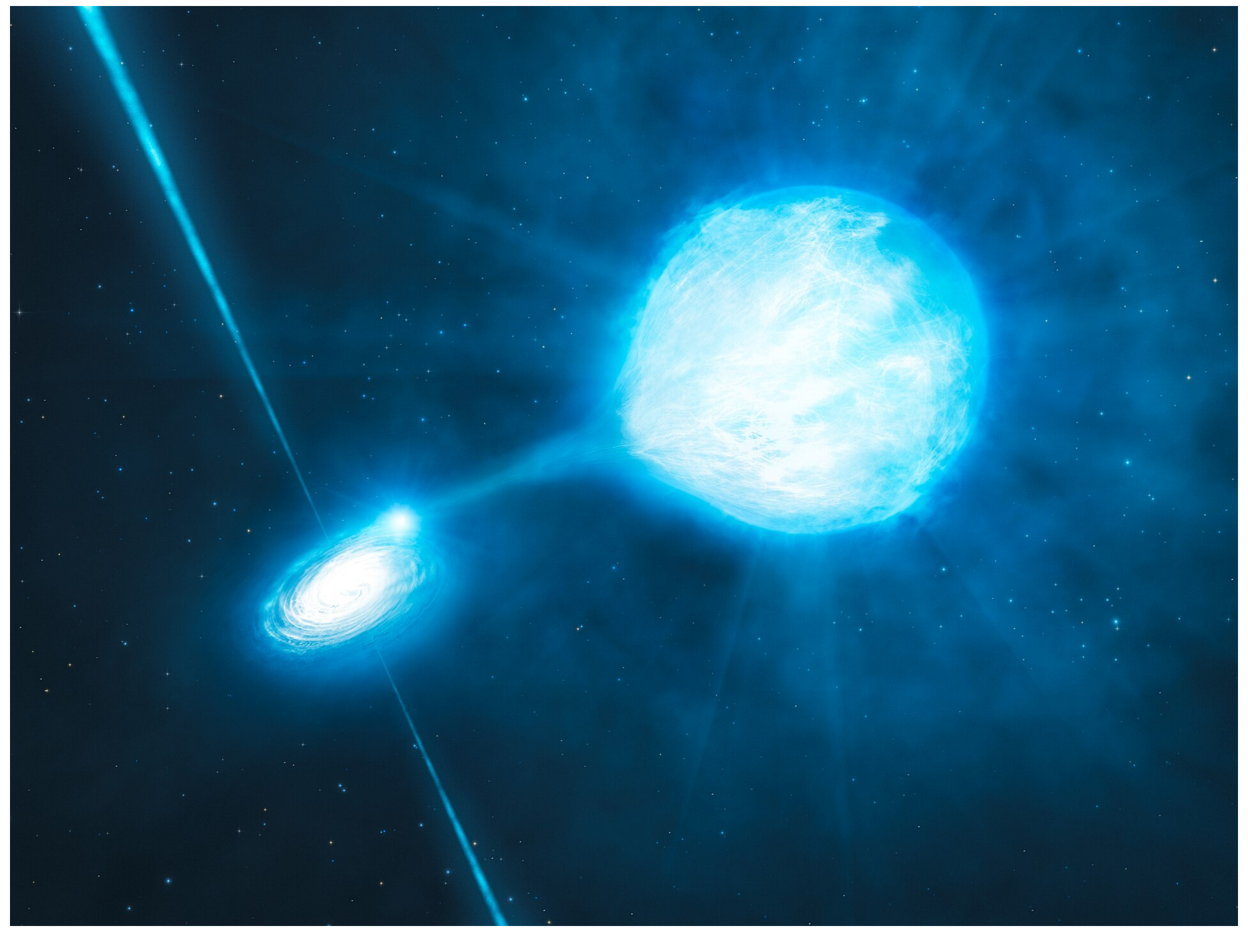
Mass ranges of black holes

Black holes appear to exist with a range of masses.

Stellar-mass black holes, with masses in the range of **3 to 15 M⊙** or so, may form directly or indirectly as a consequence of the **corecollapse of a sufficiently massive supergiant star**.

It is also possible that a **neutron star in a close binary system** may gravitationally strip enough mass from its companion that the neutron star's self-gravity exceeds the ability of the degeneracy pressure to support it, again resulting in a black hole.

Intermediate-mass black holes (IMBHs) may exist that range in mass from **roughly 100 M⊙ to in excess of 1000 M⊙** (or perhaps even greater than 10^4 $M_\odot$). Evidence for them exists in the detection of sources known as **ultraluminous X-ray sources** (ULXs) that have been discovered by satellites such as Chandra and XMM-Newton. It is not entirely clear how these objects might form, although the **correlation of IMBHs with the cores of globular clusters** and low-mass galaxies **suggests** that they may develop in these dense stellar environments either by the **mergers of stars** to form a supermassive star that then core-collapses, or by the **merger of stellar-mass black holes.**



Artist's impression of a stellar-mass black hole (left) in the spiral galaxy NGC 300; it is associated with a Wolf–Rayet star

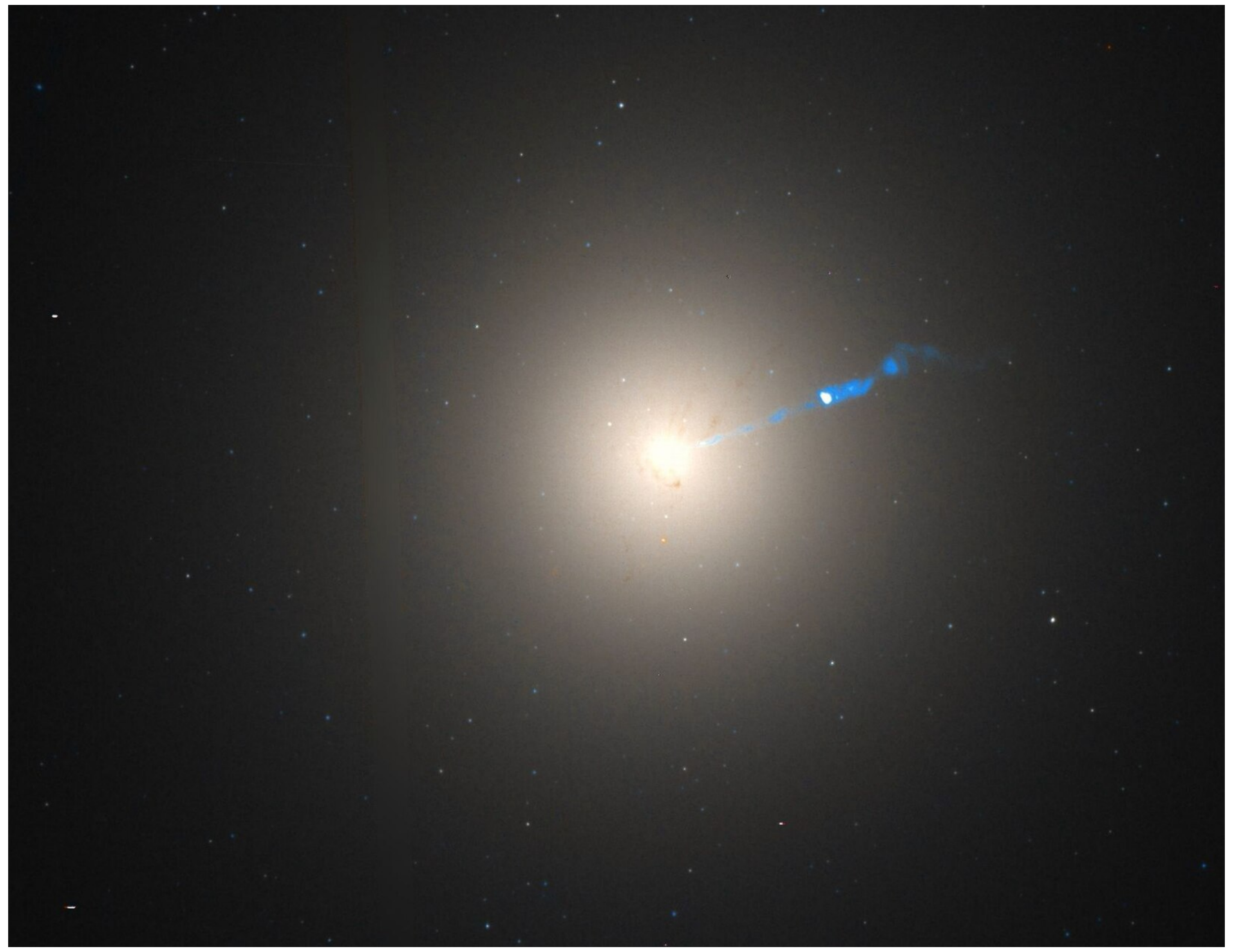
Mass ranges of black holes

Supermassive black holes (SMBH) are known to **exist at the centers of most galaxies.** These enormous black holes range in mass from **10^5 $M_\odot$ to 10^9 $M_\odot$** (our own Milky Way Galaxy has a central black hole of mass $M = 3.7 \pm 0.2 \times 10^6\ M_\odot$).

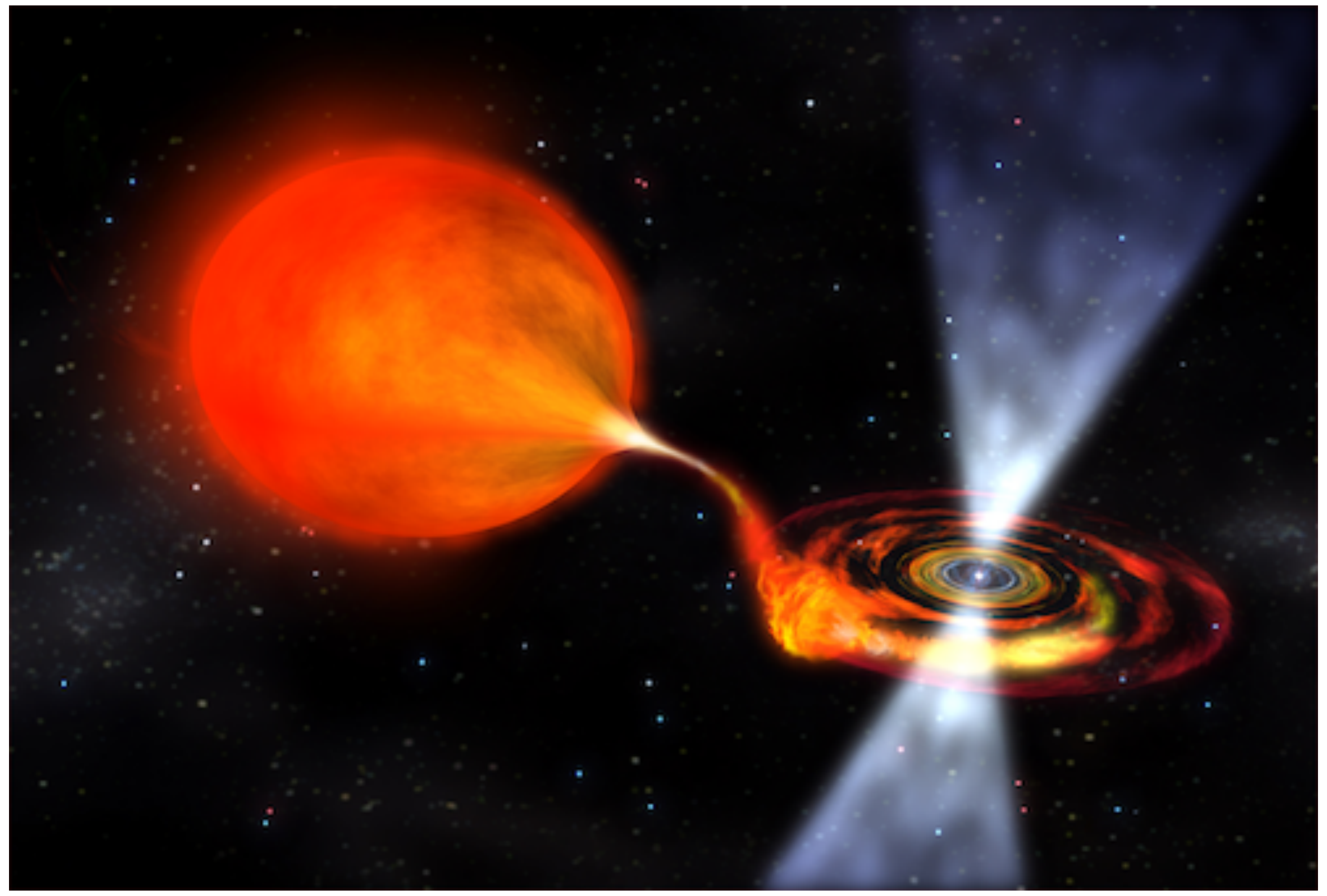
How these behemoths formed remains an open question. One popular suggestion is that they formed from **collisions between galaxies**; another is that they formed as an **extension of the formation process of IMBHs**. Whatever the process, SMBHs appear to be **closely linked with some bulk properties of galaxies, implying an important connection between galaxy formation and the formation of SMBHs.**

Black holes may have also been manufactured in the earliest instants of the universe. Presumably, these **primordial black holes** would have been formed with a wide range of masses, from 10^{-8} kg to 10^5 $M_\odot$. The only criterion for a black hole is that its entire mass must lie within the Schwarzschild radius.

M87



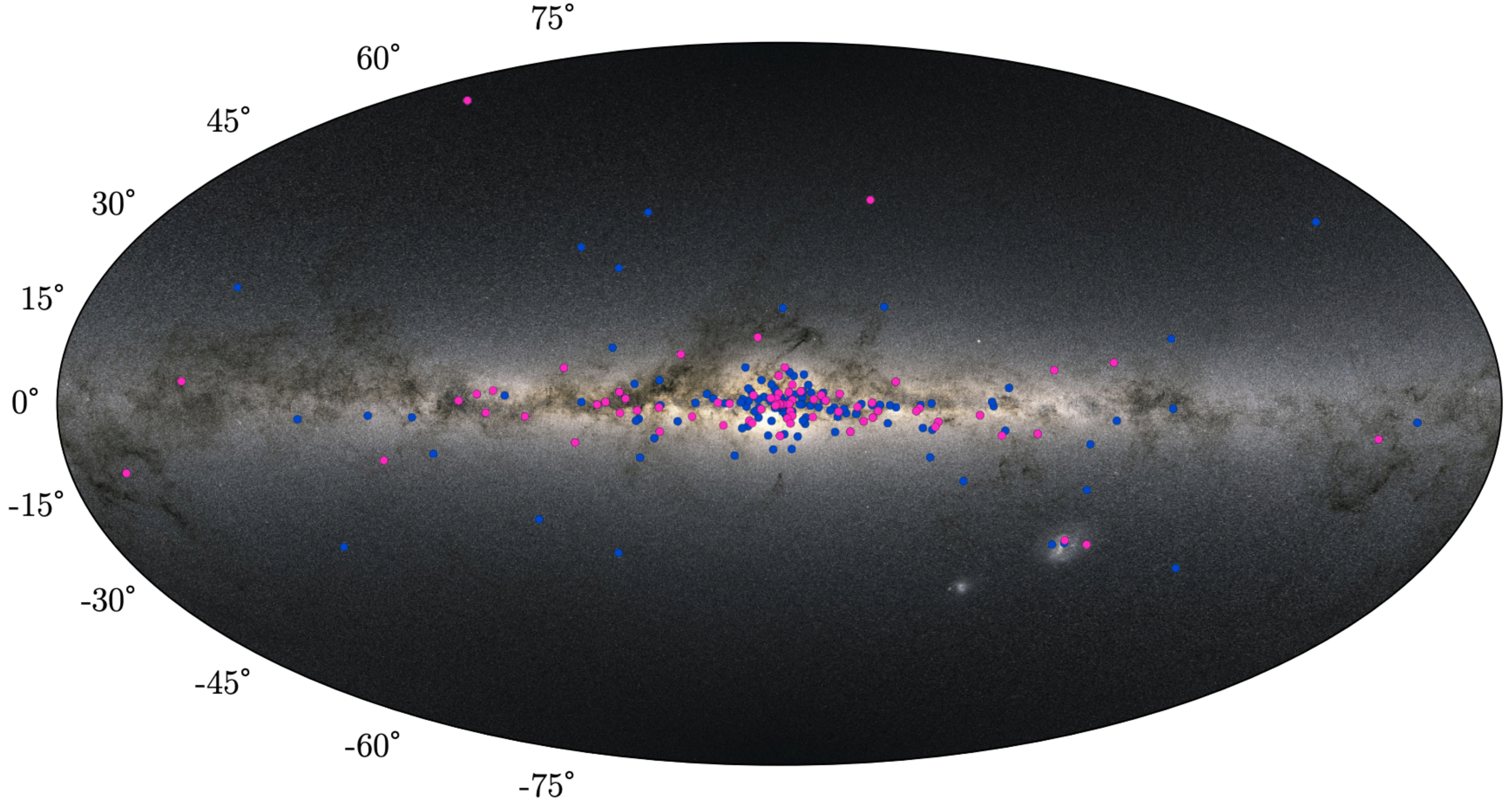
Binary X-ray sources



- What are binary X-ray sources?
- **Binary X-ray sources** can be **neutron stars or stellar mass black holes accreting matter** from inflated binary companions.
- In a **binary system** at some stage, the binary companion may become a red giant and fill up the Roche lobe. This would lead to a **transfer of mass** from the inflated companion star to the neutron star or the black hole.
- The matter accreting onto the neutron star from its companion will carry a considerable amount of angular momentum. This is **expected to increase the angular velocity of the accreting neutron star or black hole.**
- Eventually, when the red giant phase of the companion star is over (it may become a white dwarf or another neutron star), **the neutron star which has been spun up** by accreting matter with angular momentum **becomes visible as a millisecond pulsar**.
- Many X-ray sources were **found in the galactic plane**.
- They are also called **microquasars.**

Binary X-ray sources

- Many X-ray sources were **found in the galactic plane**. -> needs to be objects related to stars



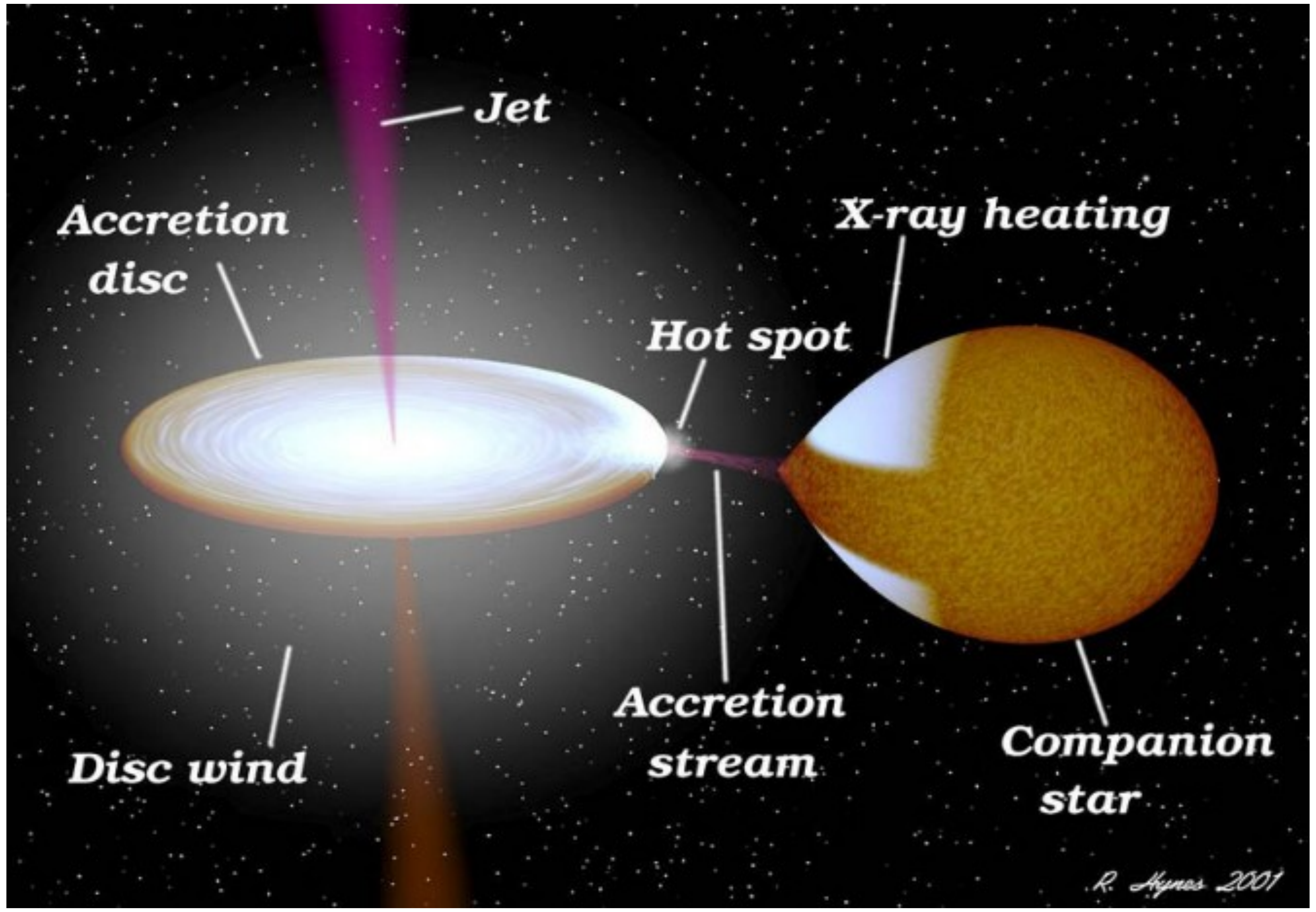
Bahramian and Degenaar 2022

Fig. 9 Distribution of a subset of known LMXBs in the sky overlaid on the Gaia all-sky image.

Binary X-ray sources

- Mass transfer between the two stars in a binary system:
- If, the mass m is dropped from infinity to a star of mass M and radius R, then the gravitational energy lost is:

$$\frac{GM}{R}m = \frac{GM}{c^2 R}mc^2.$$

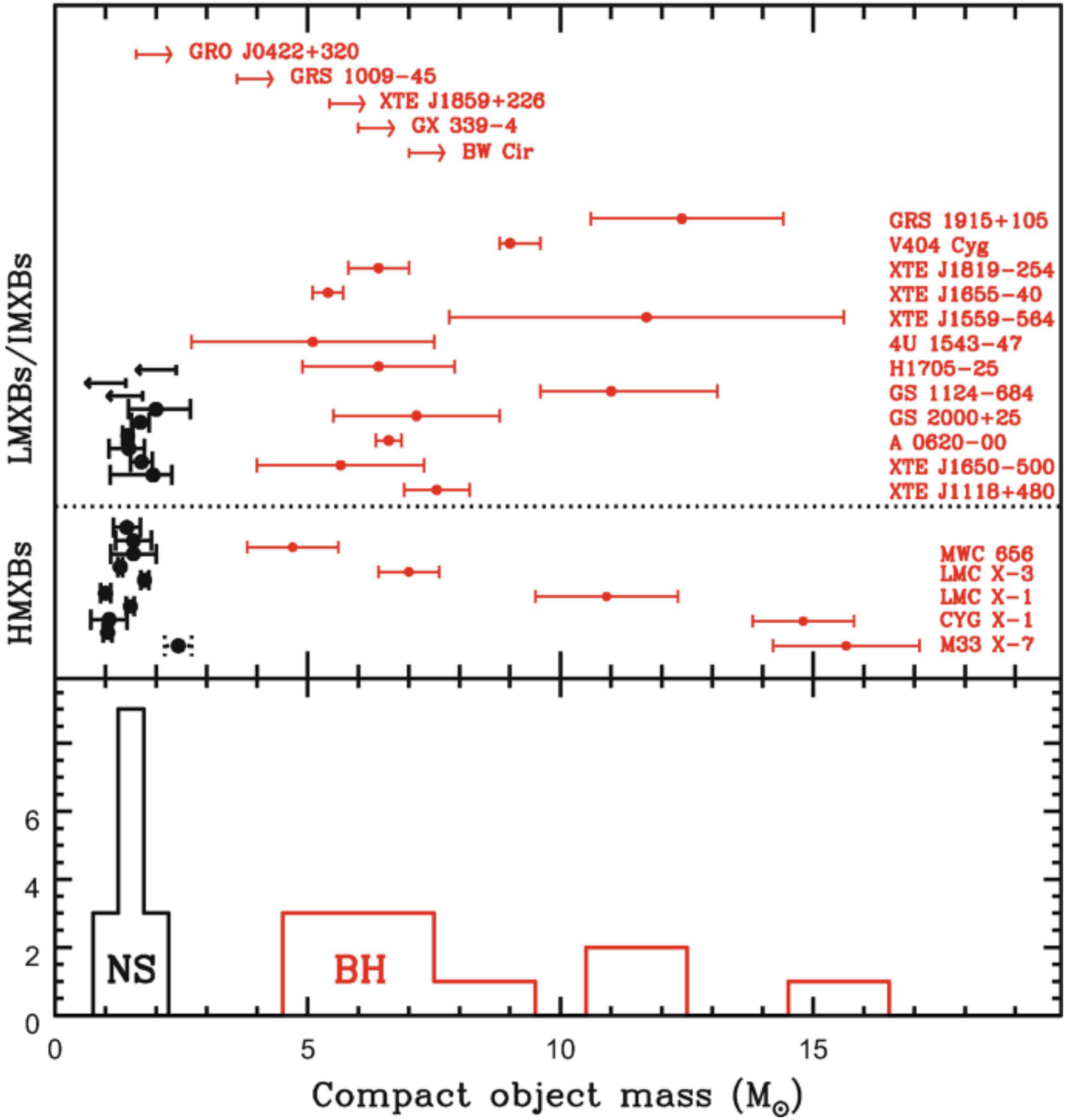


- For a typical neutron star of mass $1M_\odot$ and radius 10 km, the factor $GM/c^2 R$ turns out to be about 0.15.
- The **loss of gravitational energy** may be a very significant fraction of the rest mass energy, making such an infall of matter into the deep gravitational well of a compact object like a neutron star or a black hole a very **efficient process for energy release. -> radiation**
- Intense X-ray emission is released from the **inner region of the accretion disk** where it falls onto the collapsed star. The infalling material is heated to over a million degrees.

https://www.cosmos.esa.int/web/cesar/x-ray-binaries-monitoring

Binary X-ray sources

- **How do we know if the compact object is a neutron star or a black hole?**
- The Figure shows the masses of several neutron stars in binary systems.
- **There are binary X- ray sources with accreting objects which have masses higher than $3M_{\odot}$**. E.g. Vela X-1.
- The **central accreting object is a black hole,** since its estimated mass is well above the neutron star mass limit.



https://link.springer.com/referenceworkentry/10.1007/978-3-319-21846-5_111

Mass ranges of black holes

Example: If Earth could somehow (miraculously) be compressed sufficiently to become a black hole, its radius would only be $R_S = 2GM_\oplus/c^2 = \mathbf{0.009\ m.}$

A primordial black hole could be this size.

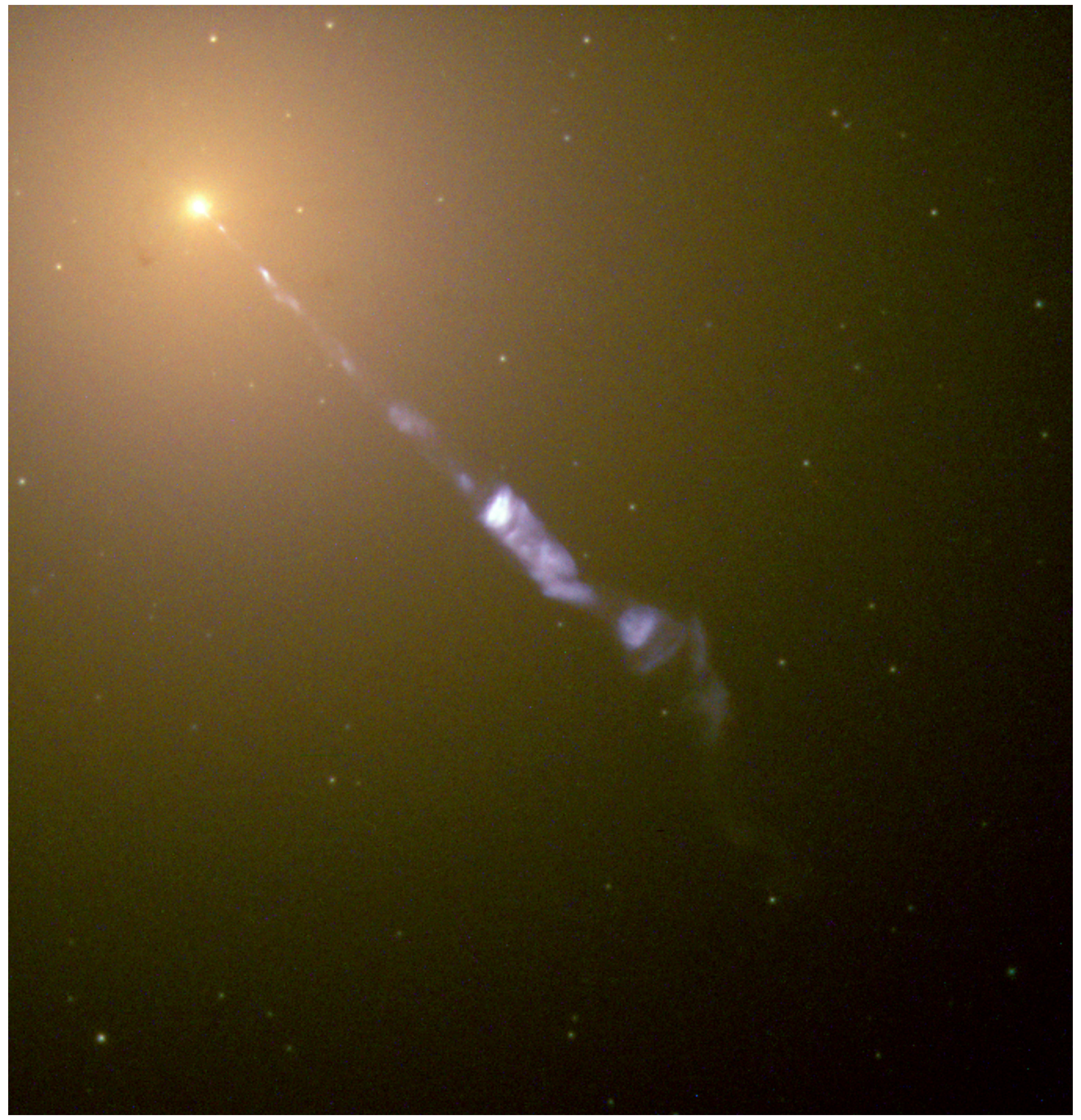
Supermassive black holes

Found in the centres of galaxies.

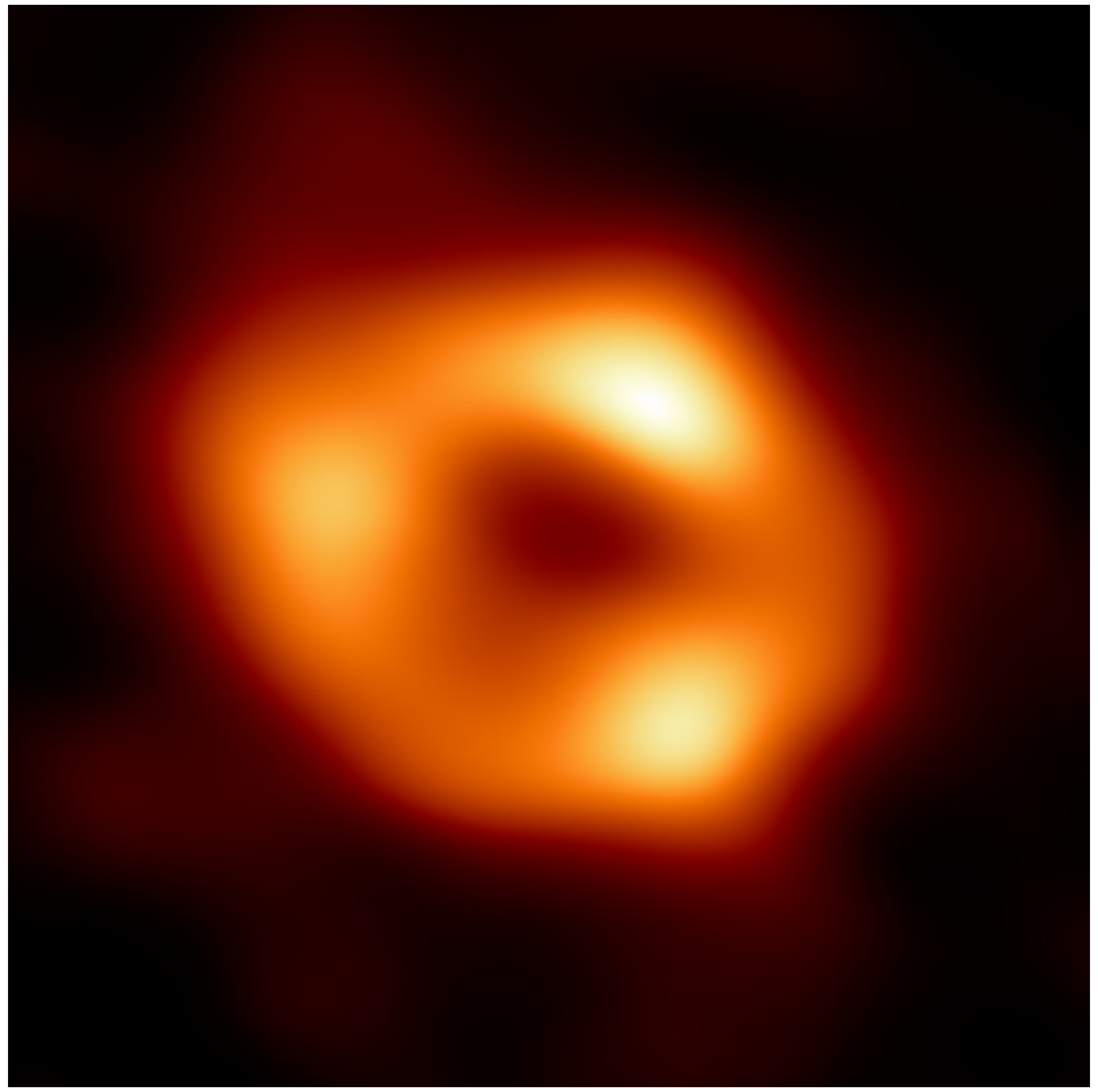
Observational evidence:

- AGN activity
- The motion of stars in the centre of the Milky Way
- Images of the Event Horizon telescope

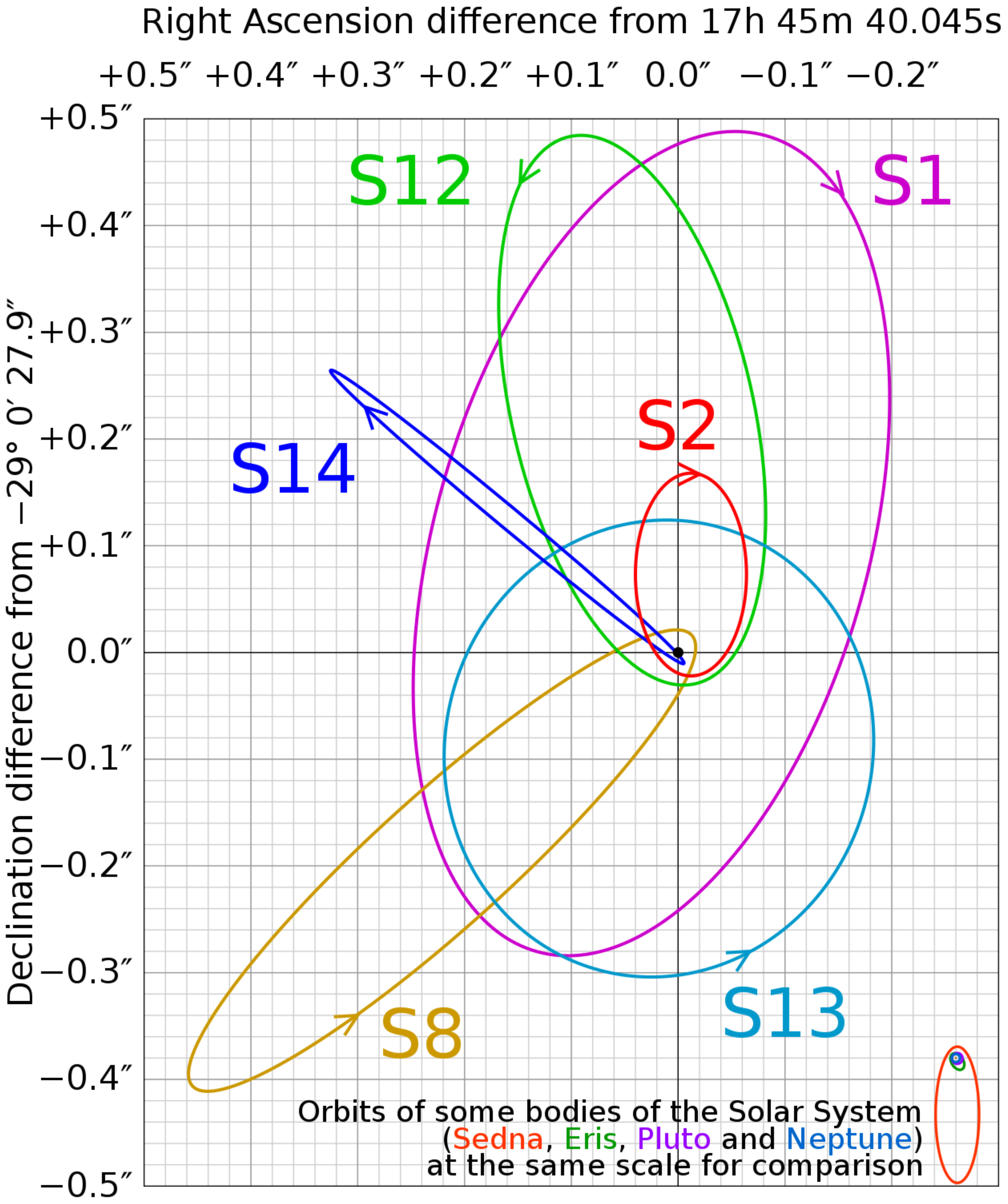
M87 optical jet



SgrA* in radio
with the Event Horizon Telescope



Motion of stars around SgrA*

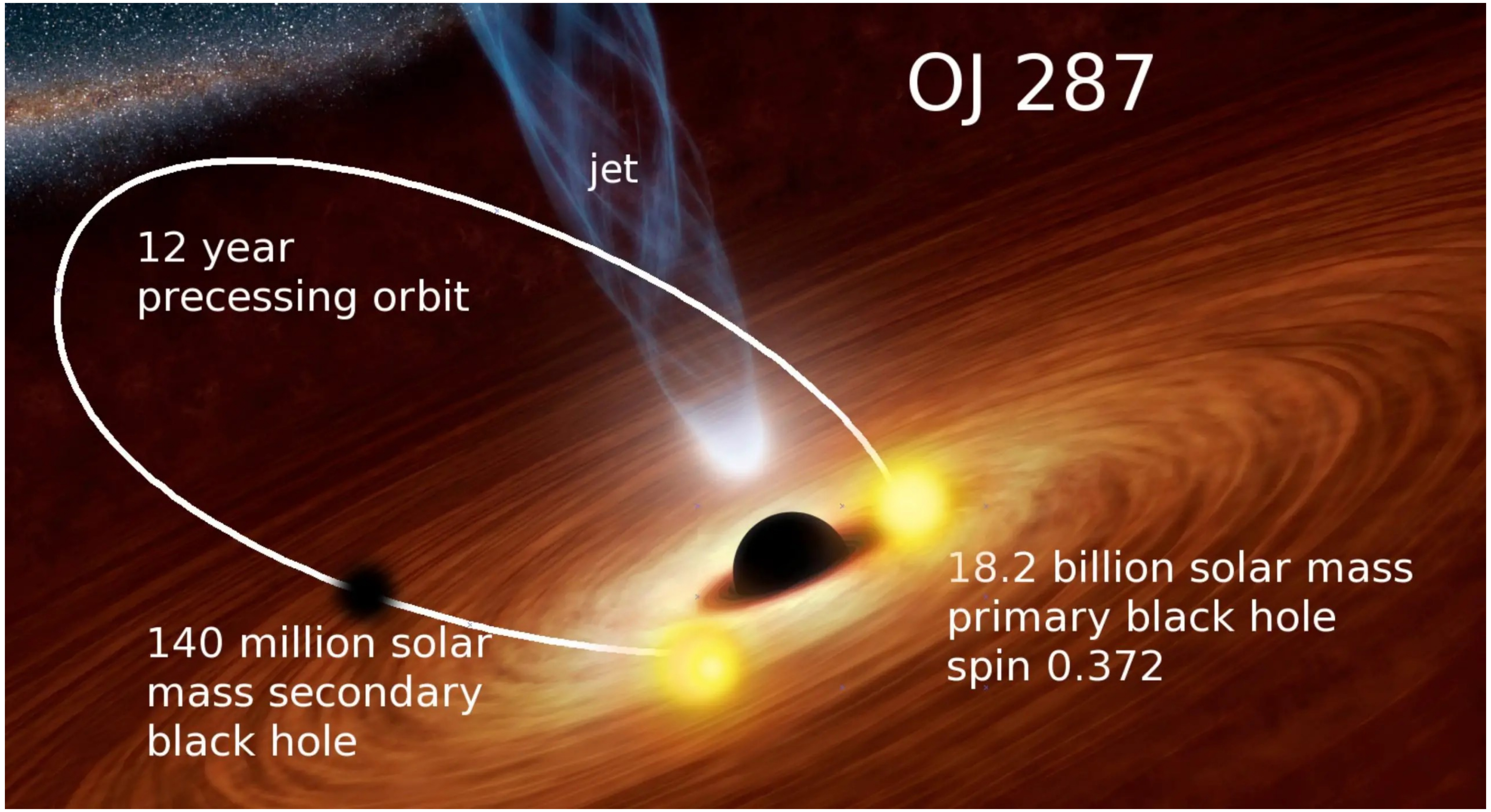


Supermassive black holes

Two supermassive black holes orbiting each other at the core of the distant galaxy OJ 287.

The orbital motion is revealed by a **series of flares** that arise when the **secondary black hole plunges regularly through the accretion disk of the primary black hole** at speeds that are a fraction slower than the speed of light.

This **heats the disk material** and the hot gas is **released as expanding bubbles.** These hot bubbles take months to cool while they radiate and cause a flash of light – a flare – that lasts roughly a fortnight and is brighter than a trillion stars.

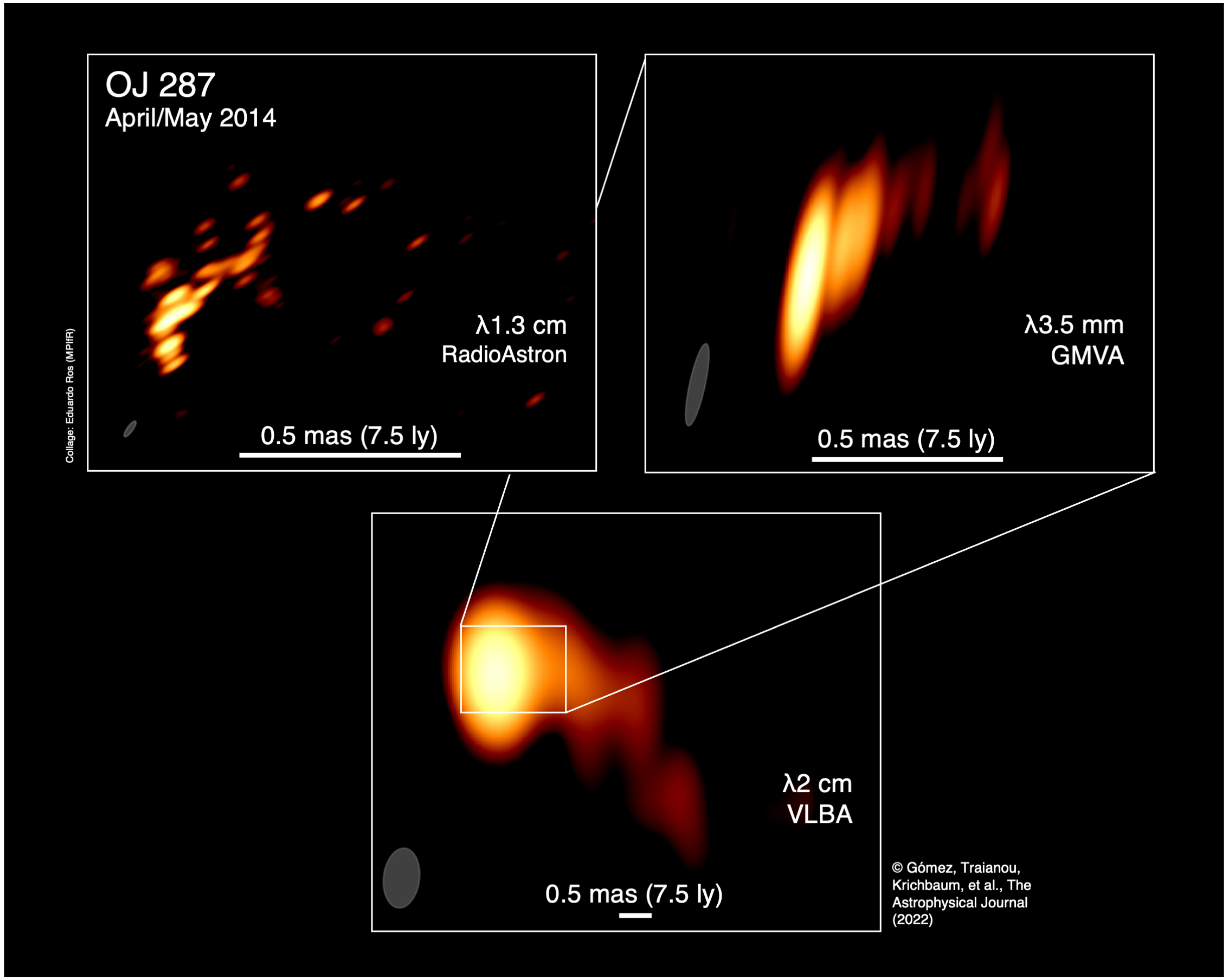


https://scitechdaily.com/flash-of-light-brighter-than-a-trillion-stars-leads-to-supermassive-black-hole-breakthrough/

Supermassive black holes

The jet of the bigger black hole bends because of the presence of the smaller black hole.

Image shows high resolution VLBI and space VLBI observations of the jet of the larger black hole.

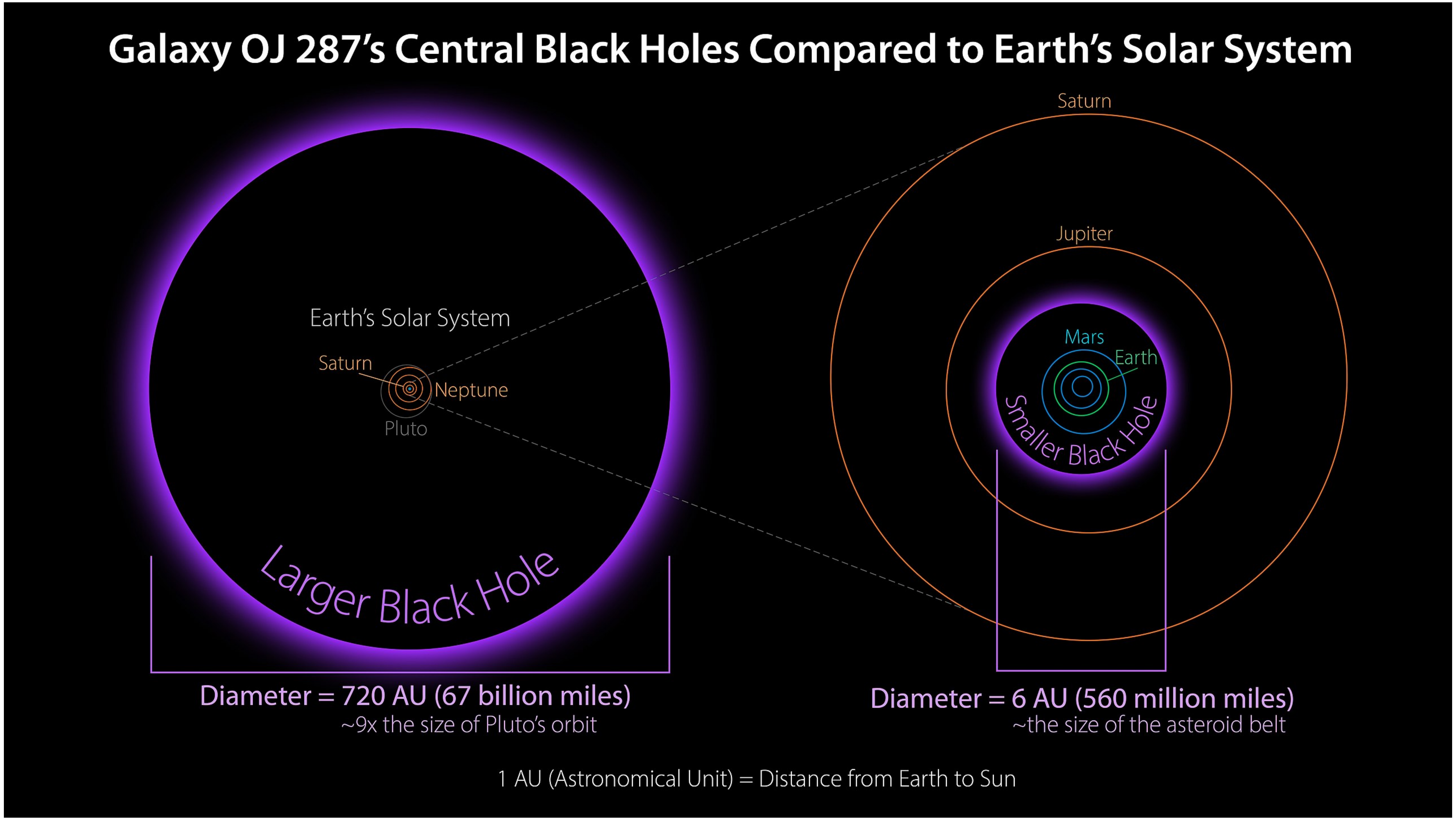


https://jive.eu/oj287-radiastron

Supermassive black holes

Two supermassive black holes orbiting each other at the core of the distant galaxy OJ 287.

The larger one, with about 18 billion times the mass of our sun (left), the smaller one is about 150 million times the mass of our sun (right).



https://en.wikipedia.org/wiki/Supermassive_black_hole

Rotating black holes

The formation processes of black holes are very complicated. For example, the **core-collapse of a star is almost certainly not symmetrical.** Detailed calculations have demonstrated, however, that any **irregularities are radiated away by gravitational waves**. As a result, once the surface of the collapsing star reaches the event horizon, the exterior spacetime horizon is spherically symmetric and described by the Schwarzschild metric.

Another complication is the fact that all **stars rotate**, and therefore **so will the resulting black hole.** Remarkably, however, **any black hole can be completely described by just three numbers: its mass, angular momentum, and electric charge**. Black holes have no other attributes or adornments, a condition commonly expressed by saying that "a black hole has no hair."

There is a firm upper limit for a rotating black hole's angular momentum given by

$$L_{\max} = \frac{GM^2}{c}.$$

If the angular momentum of a rotating black hole were to exceed this limit, there would be no event horizon and a naked singularity would appear, in violation of the Law of **Cosmic Censorship**.

Rotating black holes

Example 3.2. The maximum angular momentum for a solar-mass black hole is

$$L_{\max} = \frac{GM_\odot^2}{c} = 8.81 \times 10^{41}\ \mathrm{kg\ m^2\ s^{-1}}.$$

By comparison, the angular momentum of the Sun (assuming uniform rotation) is 1.63×10^{41} kg m^2 s^{-1}, about 18% of L_{max}. We should expect that many stars will have angular momenta that are comparable to L_{max}, and so rotation must be common for stellar-mass black holes.

Spacetime frame dragging

The structure of a maximally rotating black hole is shown in Fig 22.

The rotation has distorted the central singularity from a point into a flat ring, and the **event horizon has assumed the shape of an ellipsoid**. The figure also shows additional features caused by the rotation. As a massive object spins, it induces a **rotation in the surrounding spacetime**, a phenomenon known as **frame dragging**.

The ***Kerr metric* for a rotating black hole** was derived from Einstein's field equations by a New Zealand mathematician, Roy Kerr, in 1963

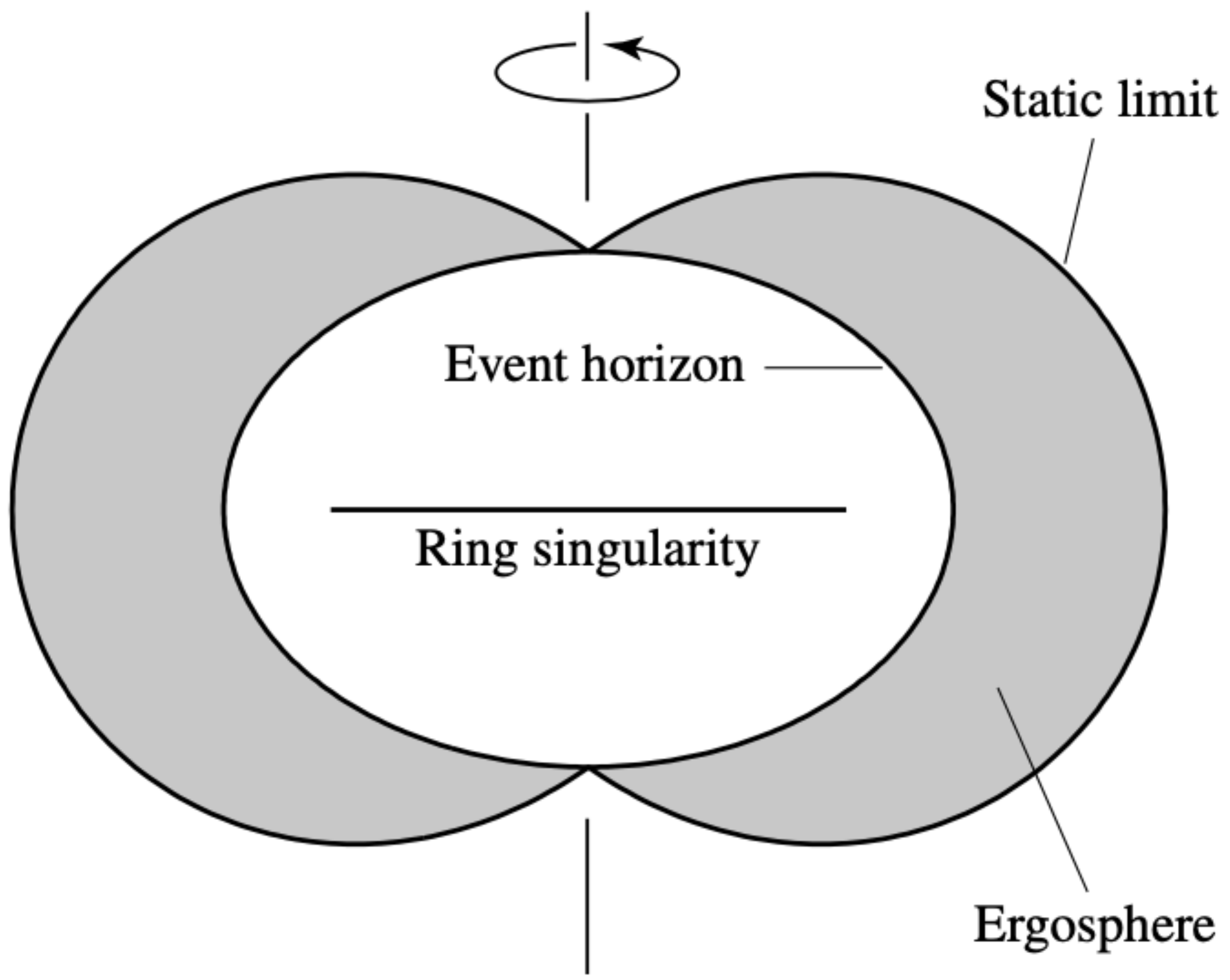


FIGURE 22 The structure of a maximally rotating black hole, with the ring singularity seen edge-on. The location of the event horizon at the equator is $r = \frac{1}{2}R_S = GM/c^2$.

Spacetime frame dragging

However, the rotating spacetime close to a massive spinning object produces a local deviation from the nonrotating frame that describes the universe at large. Near a rotating black hole, frame dragging is so severe that there is **a nonspherical region outside the event horizon** called the **ergosphere** **where any particle *must* move in the same direction that the black hole rotates.**

Spacetime within the ergosphere is rotating so rapidly that a particle would have to travel faster than the speed of light to remain at the same angular coordinate (e.g., at the same value of ϕ in the coordinate system used by a distant observer). The outer boundary of the ergosphere is called the **static limit**, so named because once beyond this boundary, a particle can remain at the same coordinate as the effect of frame dragging diminishes.

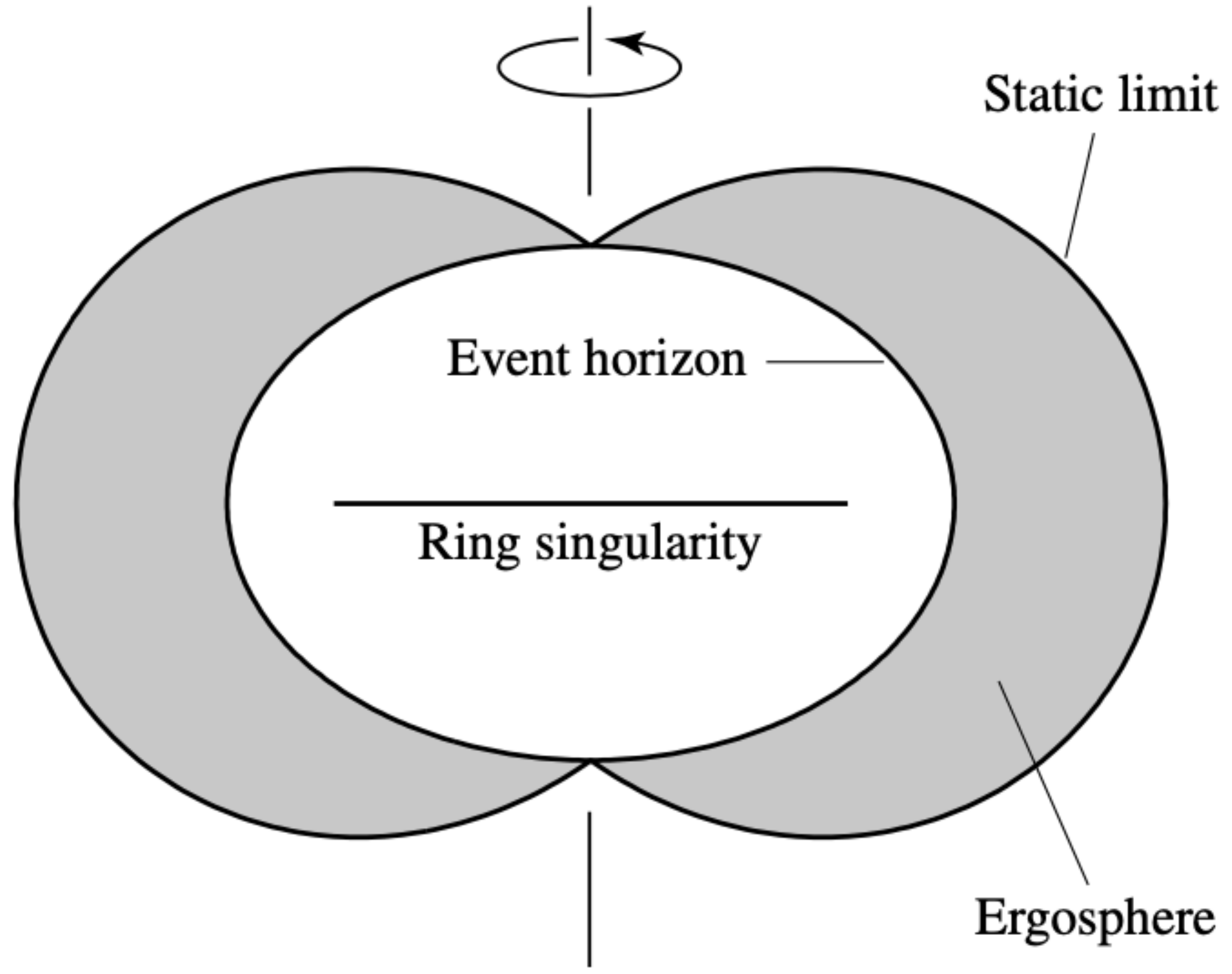
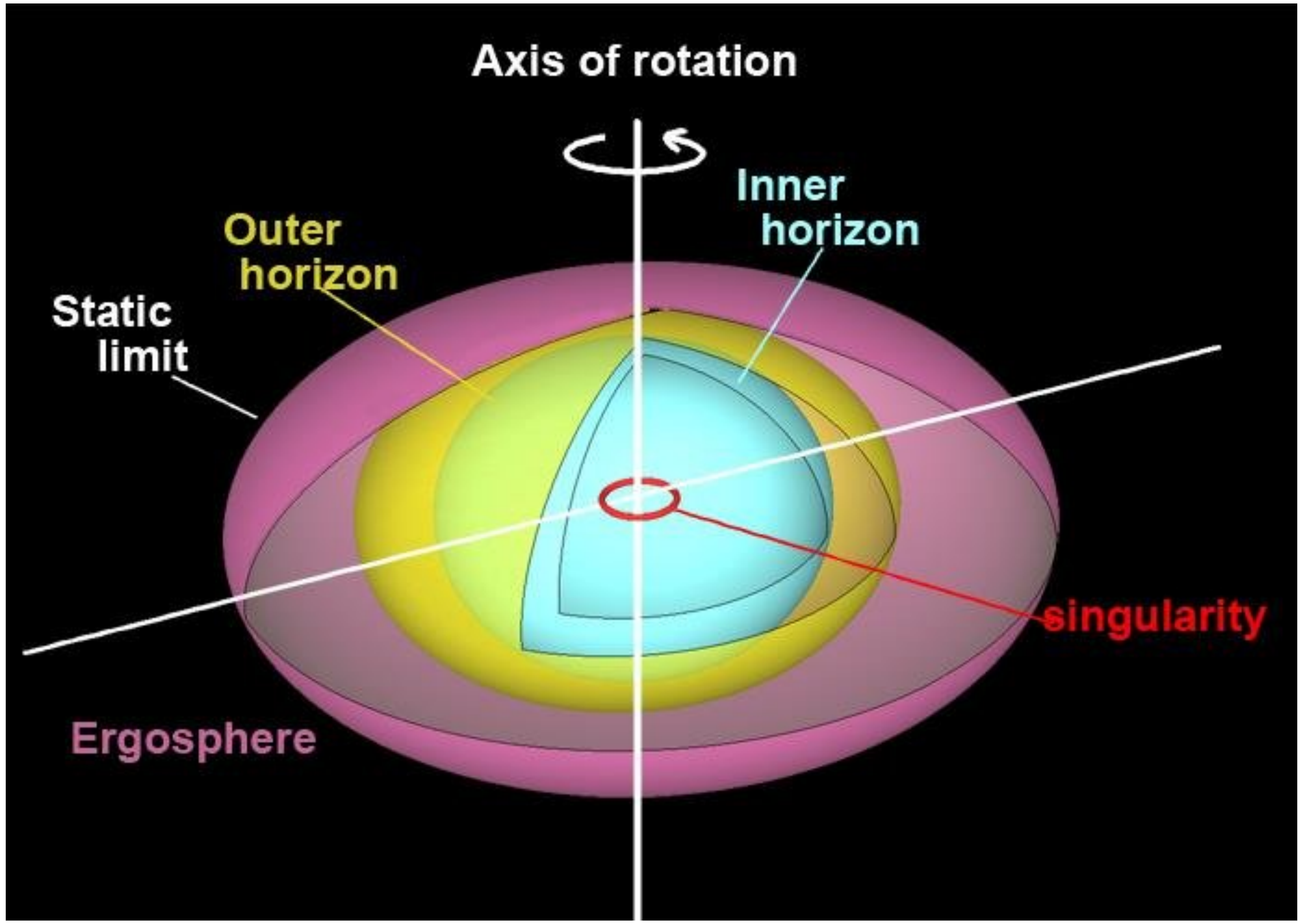


FIGURE 22 The structure of a maximally rotating black hole, with the ring singularity seen edge-on. The location of the event horizon at the equator is $r = \frac{1}{2}R_S = GM/c^2$.

Spacetime frame dragging

In terms of these properties, the four types of black holes can be defined as follows:

	Non-rotating ($J = 0$)	Rotating ($J > 0$)
Uncharged ($Q = 0$)	Schwarzschild	Kerr
Charged ($Q \neq 0$)	Reissner–Nordström	Kerr–Newman



Note that astrophysical black holes are **expected to have non-zero angular momentum**, due to their formation via collapse of rotating stellar objects, but **effectively zero charge**, since any net charge will quickly attract the opposite charge and neutralize and since observed astronomical objects do not possess an appreciable net electric charge.
For this reason the term **"astrophysical" black hole** is usually reserved for the **Kerr black hole**.

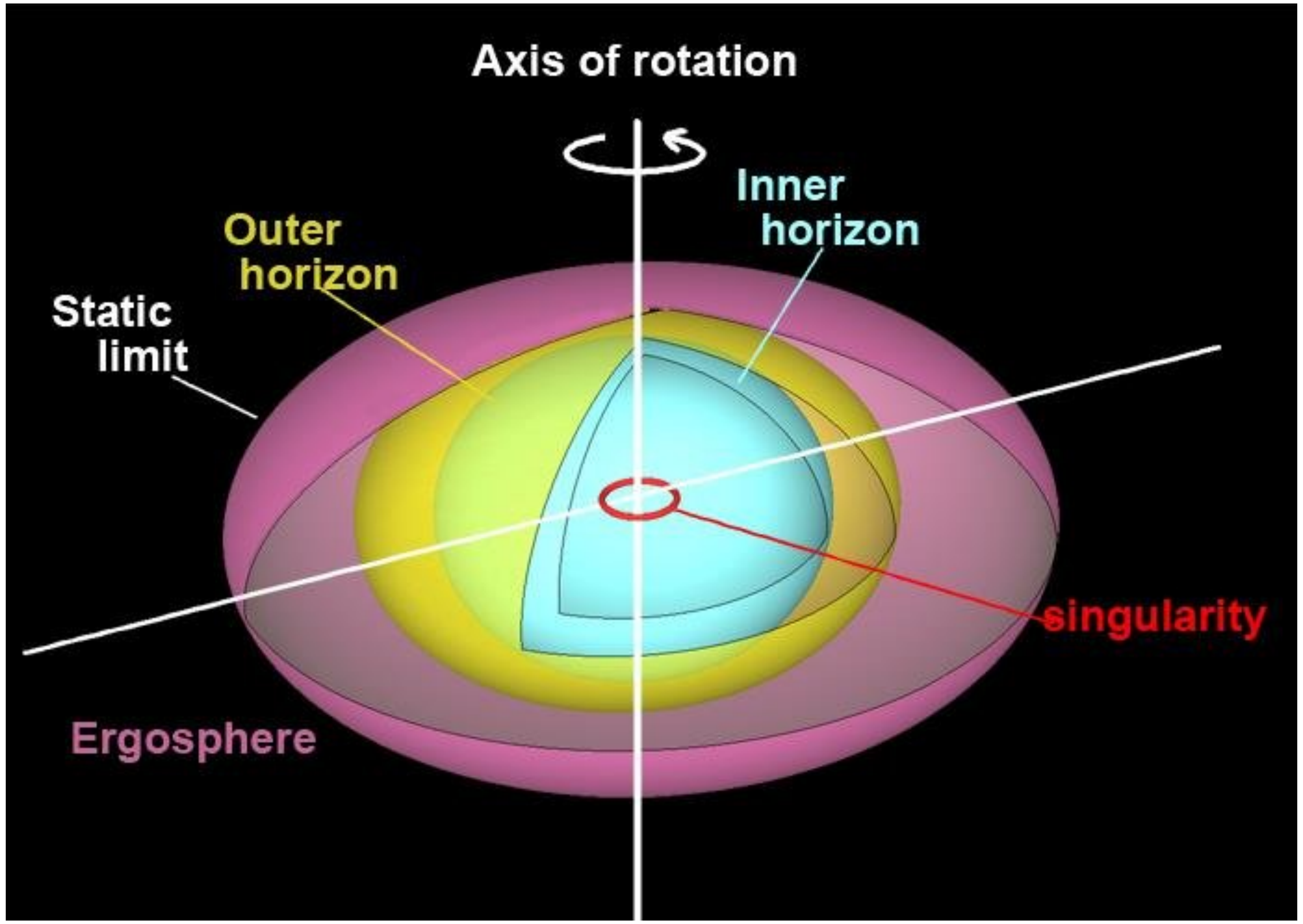
Spacetime frame dragging

There can be several horizons associated with a black hole.

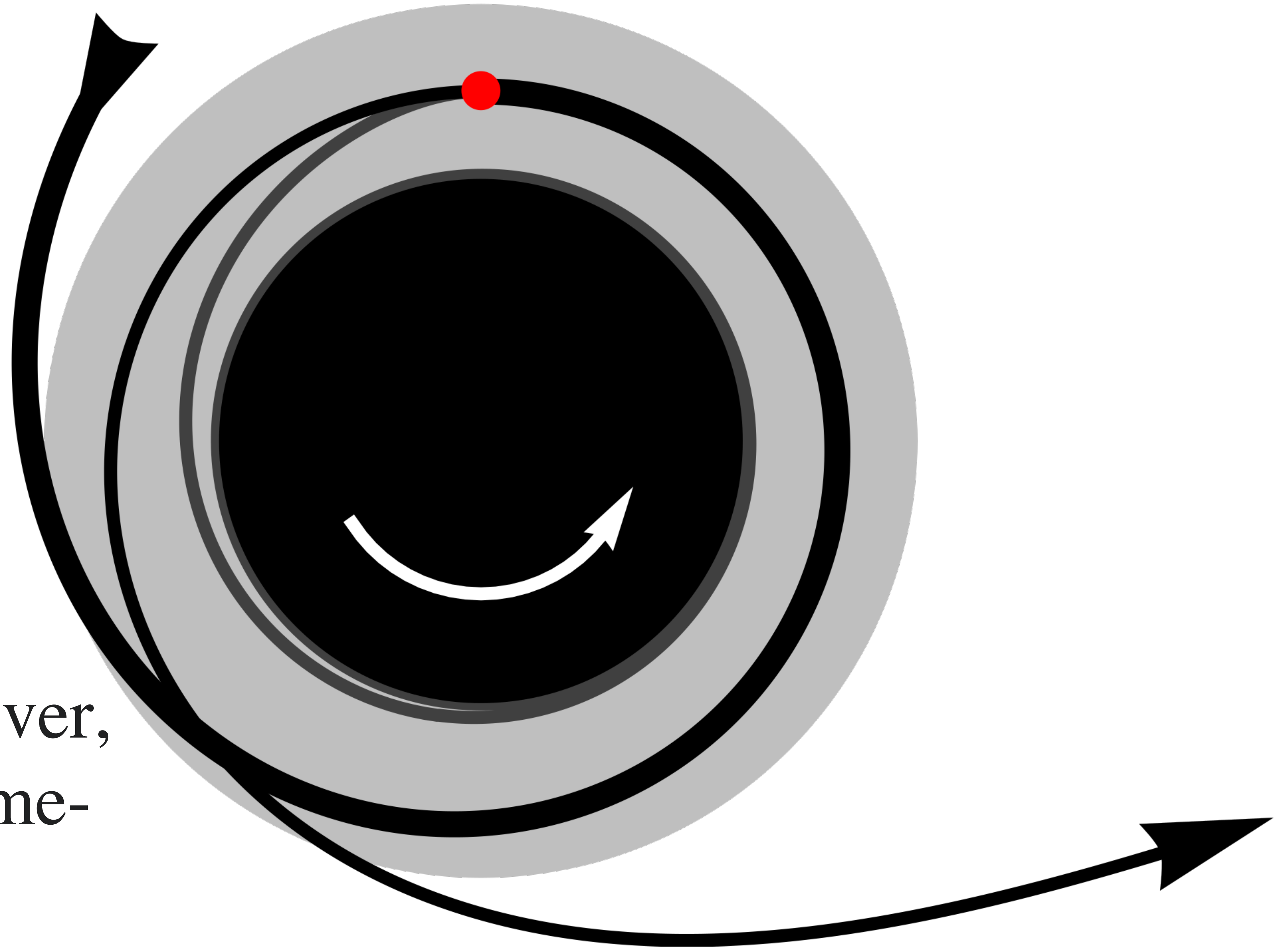
The outer horizon is the one associated with the **Schwarzschield radius** of a non-rotating black hole.

The inner horizon is usually the **Cauchy horizon**, is a light-like boundary of the domain of validity of a Cauchy problem. One side of the horizon contains closed space-like geodesics and the other side contains closed time-like geodesics.

There is also an **apparent horizon**, which is a surface that is the boundary between light rays that are directed outwards and moving outwards and those directed outward but moving inward.



The Penrose process



The Penrose process is a means whereby energy can be extracted from a rotating black hole.

- In the process, a body falls (black thick line in the figure) into the ergosphere (gray region).
- At its lowest point (red dot) the body fires a propellant backwards; however, to a faraway observer both seem to continue to move forward due to frame-dragging (albeit at different speeds).
- The propellant, being slowed, falls (thin gray line) to the event horizon of the black hole (black disk).
- The remains of the body, being sped up, fly away (thin black line) with an excess of energy (that more than offsets the loss of the propellant and the energy used to shoot it).

The maximum amount of energy gain possible for a single particle decay via the original Penrose process is 20.7% of its mass in the case of an uncharged black hole (assuming the maximal rotation of the black hole). **The energy is taken from the rotation of the black hole**, so there is a limit on how much energy one can extract by Penrose process and similar strategies.

https://en.wikipedia.org/wiki/Penrose_process

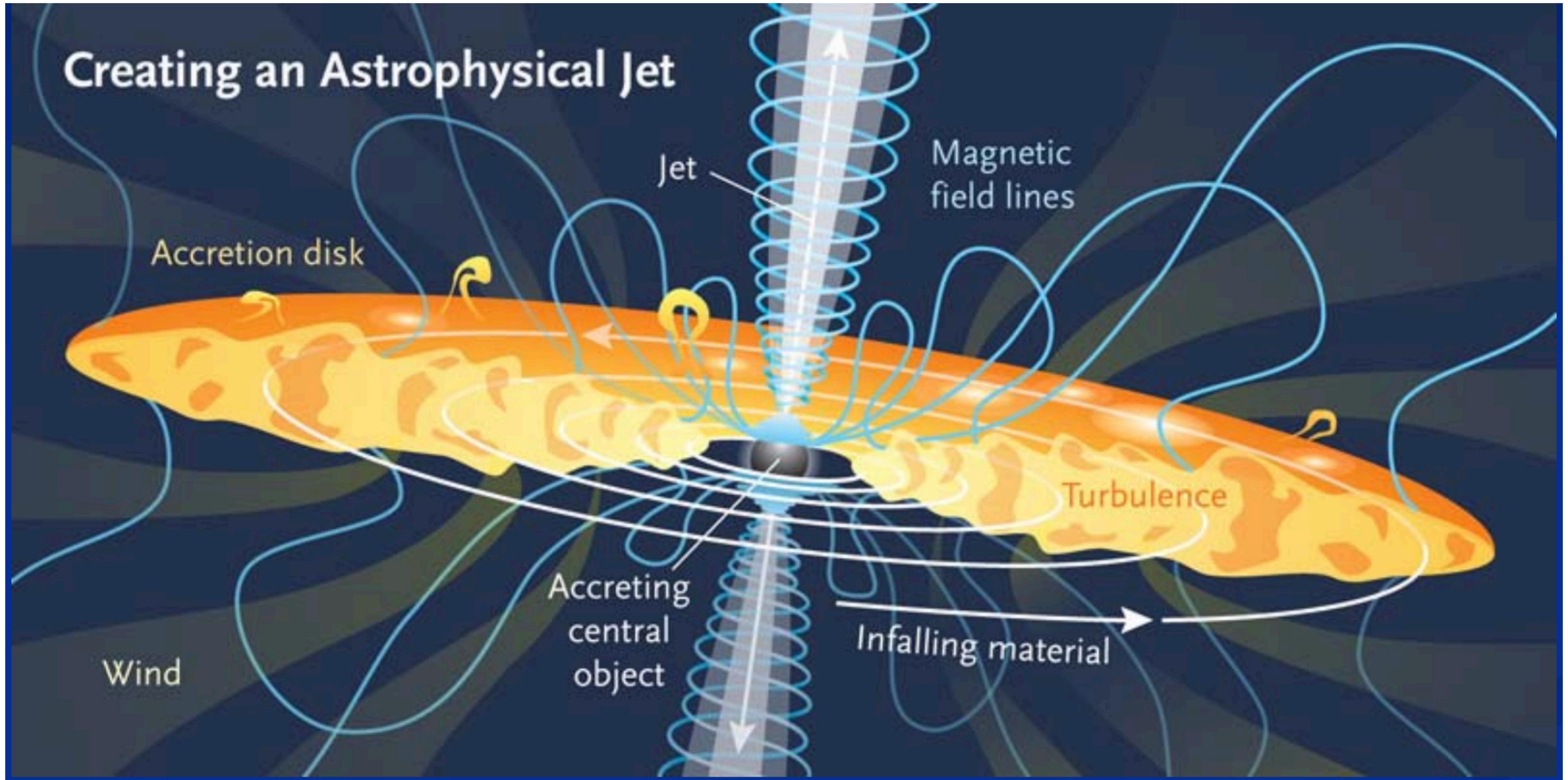
The Blandford-Znajek process

The **Blandford–Znajek process is a mechanism for the extraction of energy from a rotating black hole.** This mechanism is the most preferred description of how **astrophysical jets** are formed around spinning supermassive black holes. This is one of the mechanisms that power quasars, or rapidly accreting supermassive black holes.

The Blandford–Znajek process requires an accretion disc with a strong poloidal magnetic field around a spinning black hole. **The magnetic field extracts spin energy**, and the power can be estimated as the energy density at the speed of light cylinder times area:

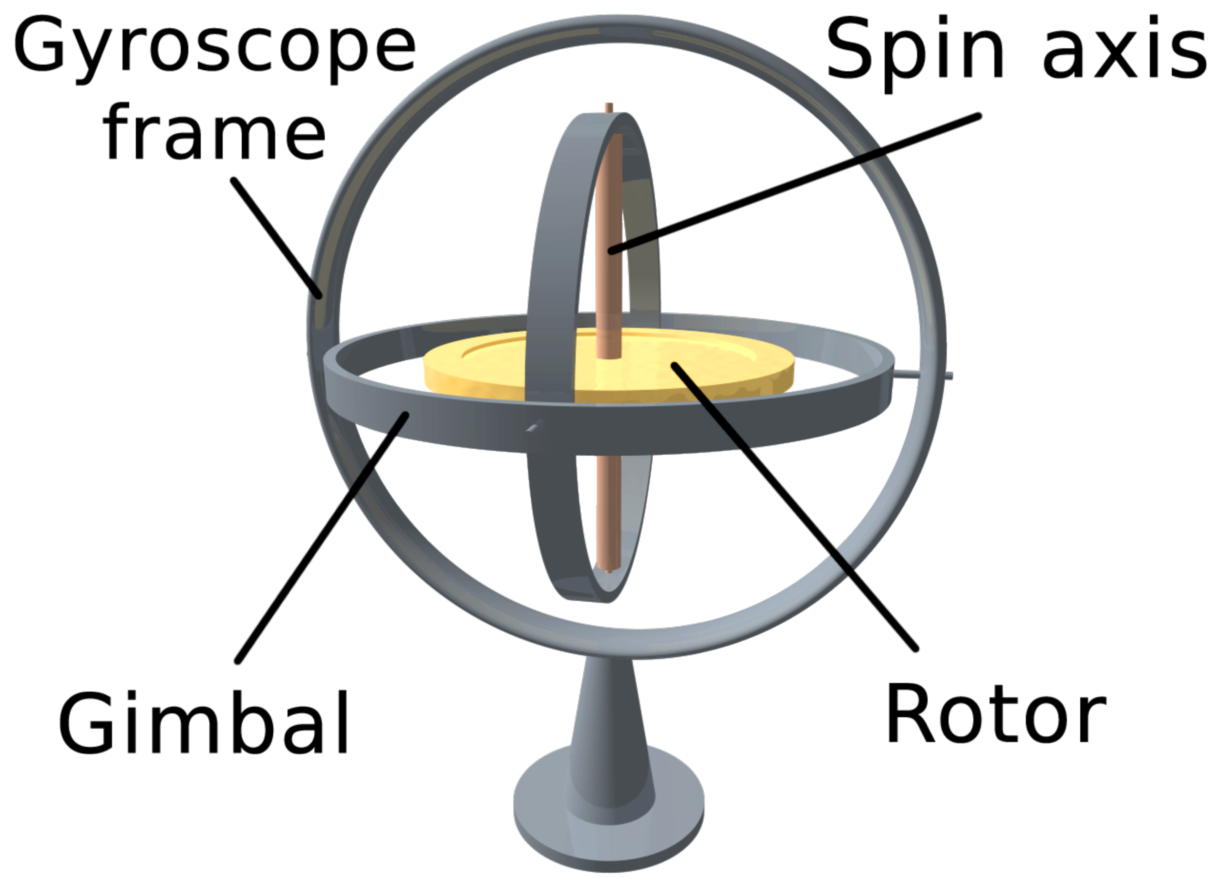
$$P = B^2 \left(\frac{r}{r_c}\right)^4 r_c c = \frac{B^2 r^4 \omega^2}{c},$$

where B is the magnetic field strength, is the Schwarzschild radius, and ω is the angular velocity.



Sky & Telescope (Apr 2010)

Spacetime frame dragging



Experiment to measure frame dragging: Even Earth's rotation produces very weak frame dragging. Detecting the effect of frame dragging was the mission of the **Stanford Gravity Probe B** experiment.

Launched in April 2004 and ended data collection in October 2005.

The experiment employed four superconducting gyroscopes made of precisely shaped spheres of fused quartz 3.8 cm in diameter. The gyroscopes were so nearly freely rotating that they formed an **almost perfect spacetime reference frame**. Although the predicted precession rate of the gyroscopes was only $0.042''\ \mathrm{yr}^{-1}$, the effect of frame dragging is cumulative. Measured frame dragging within 15% of the predicted value.

In addition to frame dragging, the experiment also measured the stronger geodetic effect.
The geodetic effect is an effect caused by **space-time being "curved" by the mass of the Earth**. A gyroscope's axis when parallel transported around the Earth in one complete revolution does not end up pointing in exactly the same direction as before.

Spacetime frame dragging

Previous descriptions of a black hole's structure inside the event horizon, such as Fig. 22, are based on **vacuum solutions to Einstein's field equations**. These solutions were obtained by ignoring the effects of the mass of the collapsing star, so the **vacuum solutions do not describe the interior of a real black hole.**

Furthermore, the present **laws of physics, including general relativity, break down under the extreme conditions found very near the center.** The details of the singularity cannot be fully described until a theory of quantum gravity is found.

In 1965 Roger Penrose, proved that *every* complete gravitational collapse must form a singularity.

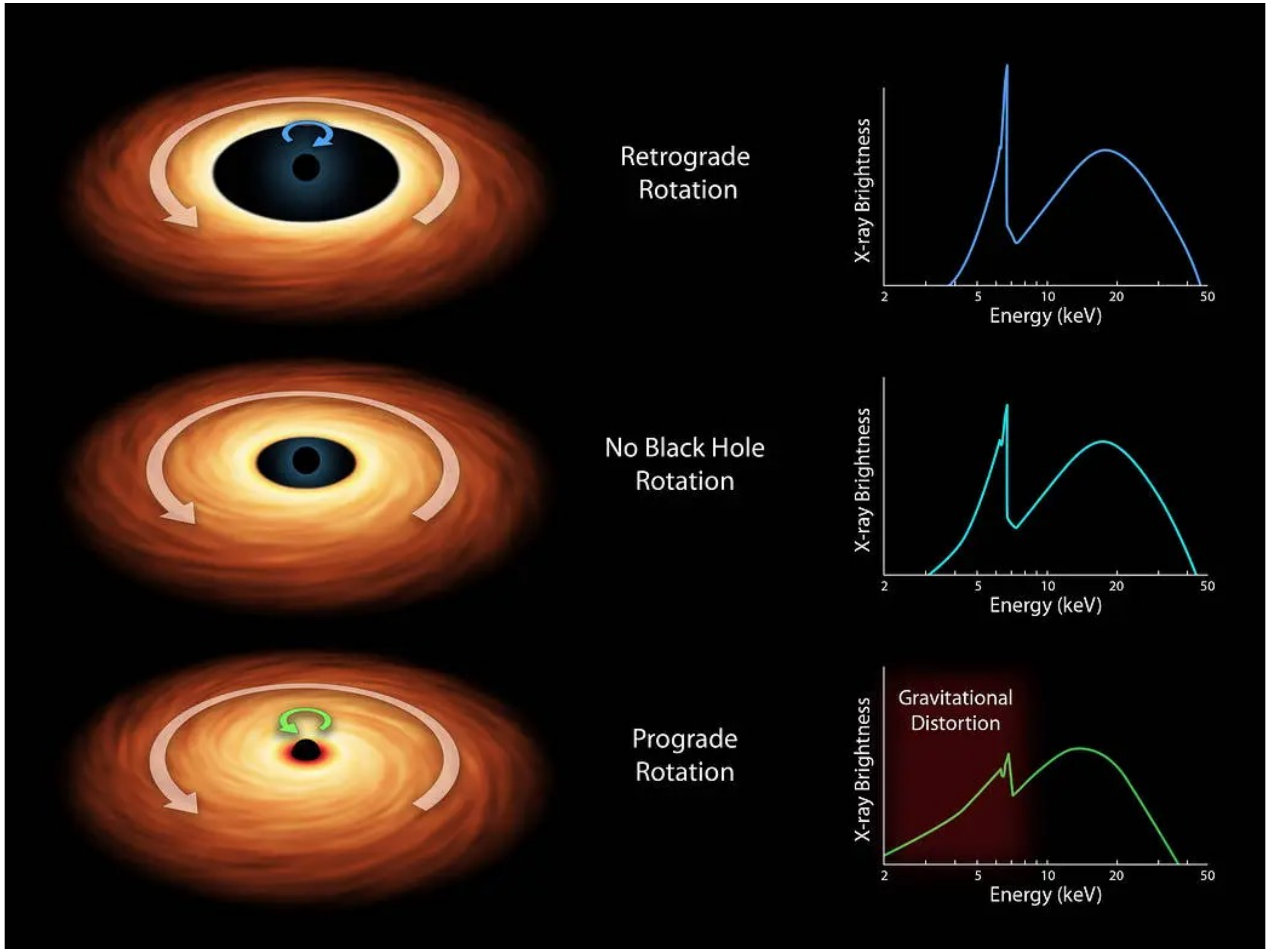
Measuring the spin of a black hole

Bending of light as it travels through space-time. By looking for these **light distortions in X-rays** streaming off material near black holes, researchers can gain information about their spin rates.

This chart illustrates the basic model for determining the spin rates of black holes. The different types of spin:

- **retrograde rotation**, where the disk of matter falling onto the hole, moves in the opposite direction of the black hole;
- **no spin;**
- and **prograde rotation,** where the disk spins in the same direction as the black hole.

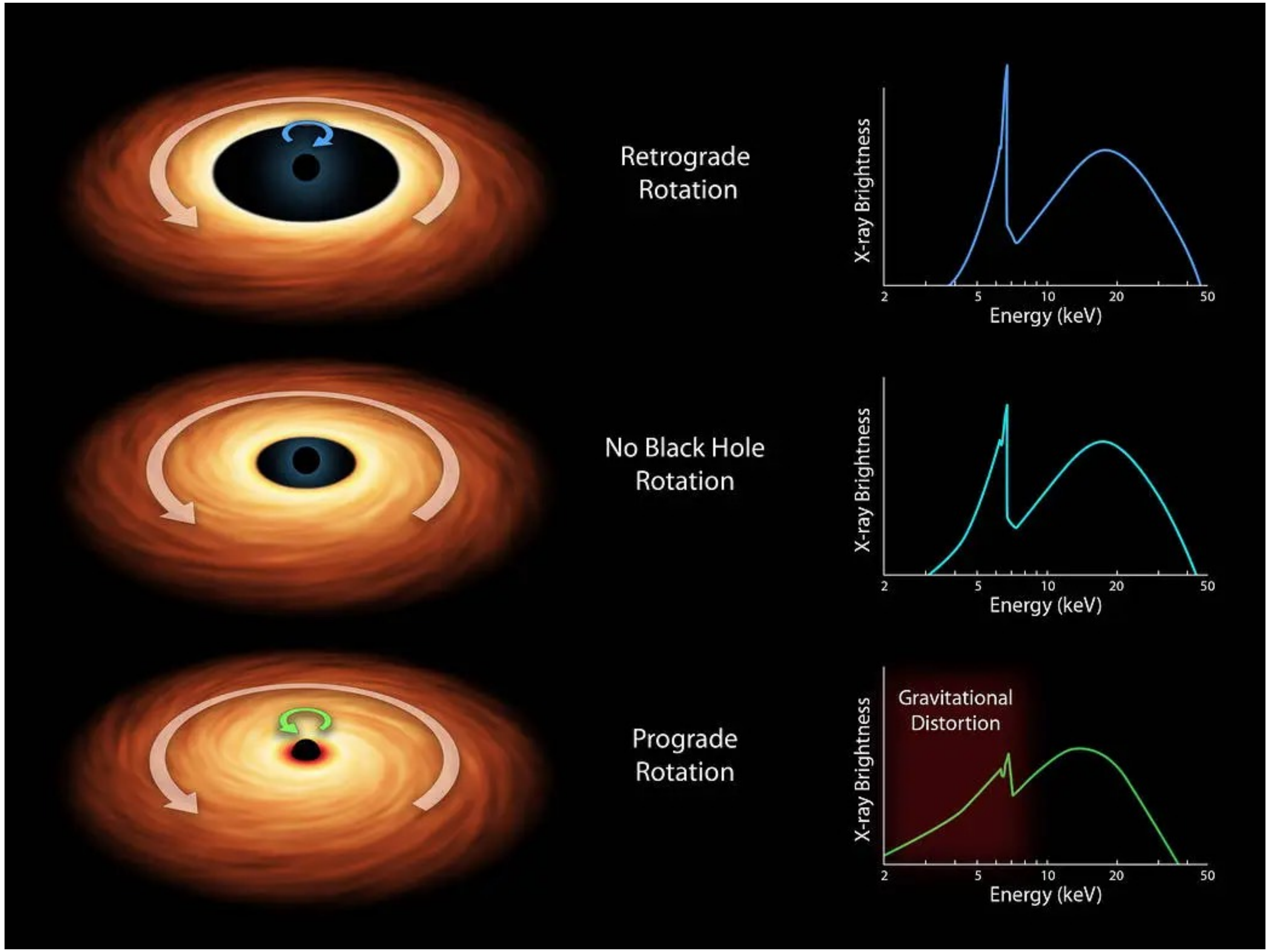
The faster a black hole spins, the closer its accretion disk can lie to it – another consequence of relativity.



https://www.nasa.gov/image-article/how-measure-spin-of-black-hole/

Measuring the spin of a black hole

How close the inner edge of an accretion disk comes to a black hole based the X-ray spectra. The spectra for the three spin scenarios are shown at right. The **sharp peak is X-ray radiation from iron atoms** circulating in the accretion disk. If the accretion disk is close to the black hole, the X-ray colors from the iron will be spread out by the immense gravity of the black hole. **The degree to which the iron feature is spread out**, a phenomenon referred to as the "red wing," reveals how close the accretion disk is to the black hole. Because this distance depends on the black hole's spin, the **spin rate can then be determined.**



https://www.nasa.gov/image-article/how-measure-spin-of-black-hole/

Tunnels in Spacetime

The possibility of using a black hole as a tunnel connecting one location in spacetime with another (perhaps in a different universe) has inspired both physicists and science fiction writers.

Most conjectures of spacetime tunnels are based on **vacuum solutions to Einstein's field equations** and as such **don't apply to the interiors of real black holes**.

Figure 23 depicts a spacetime tunnel called a **Schwarzschild throat** (**also known as an *Einstein–Rosen bridge***), which uses the Schwarzschild geometry of a nonrotating black hole to connect two regions of spacetime.

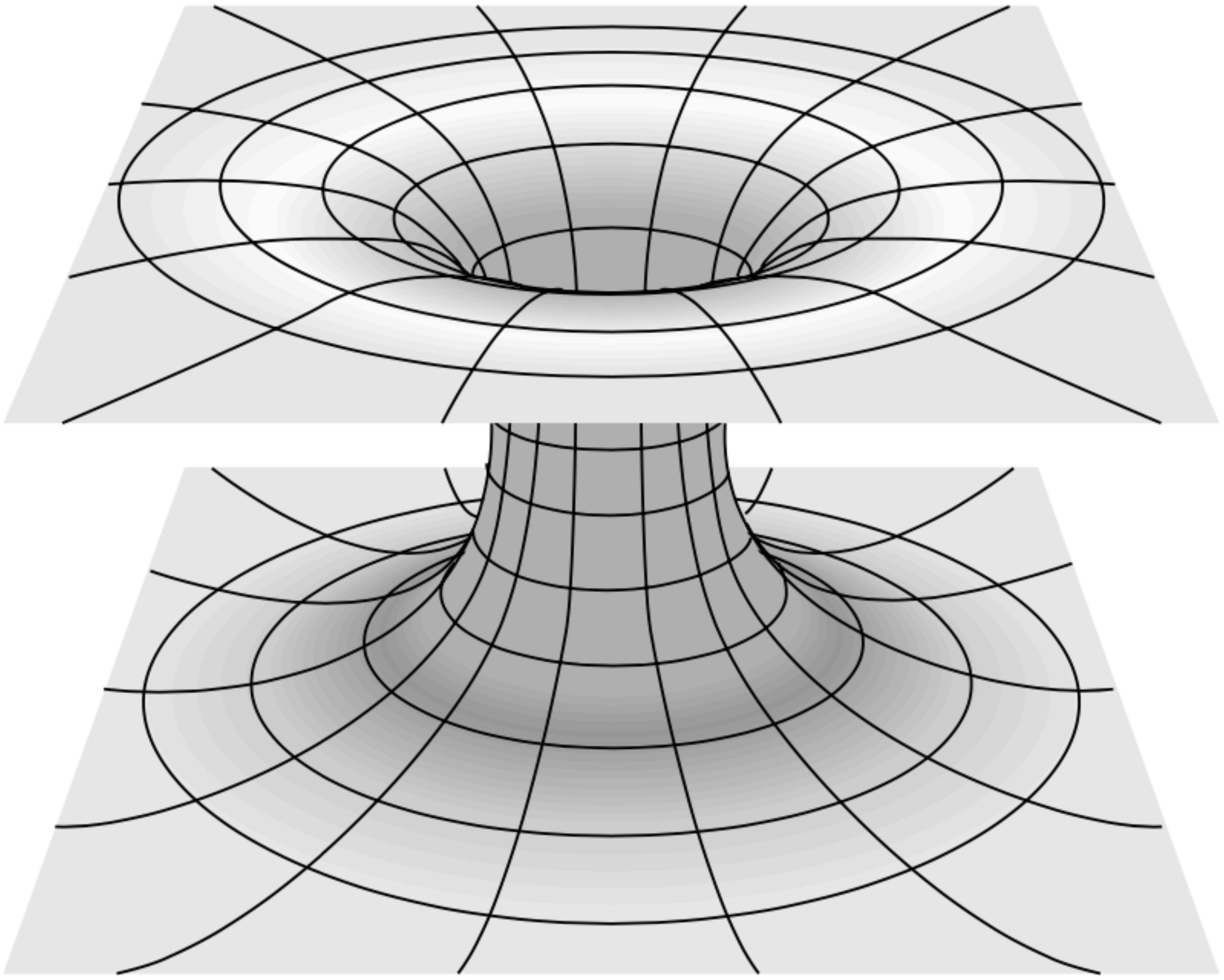


FIGURE 23 Depiction of a Schwarzschild throat connecting two different regions of spacetime. Any attempted passage of matter or energy through the throat would cause it to collapse.

Tunnels in Spacetime

The width of the throat is a minimum at the event horizon, and the “mouths” may be interpreted as opening onto two different locations in spacetime.

It is tempting to imagine this as a tunnel, and writers of speculative fiction have dreamed of ***white holes*** pouring out mass or serving as passageways for starships.

However, it appears that any attempt to send a tiny amount of matter or energy (even a stray photon) through the throat would cause it to collapse. **For a real nonrotating black hole, all worldlines end at the inescapable singularity, where spacetime is infinitely curved.** There is simply **no way to bypass the singularity.**

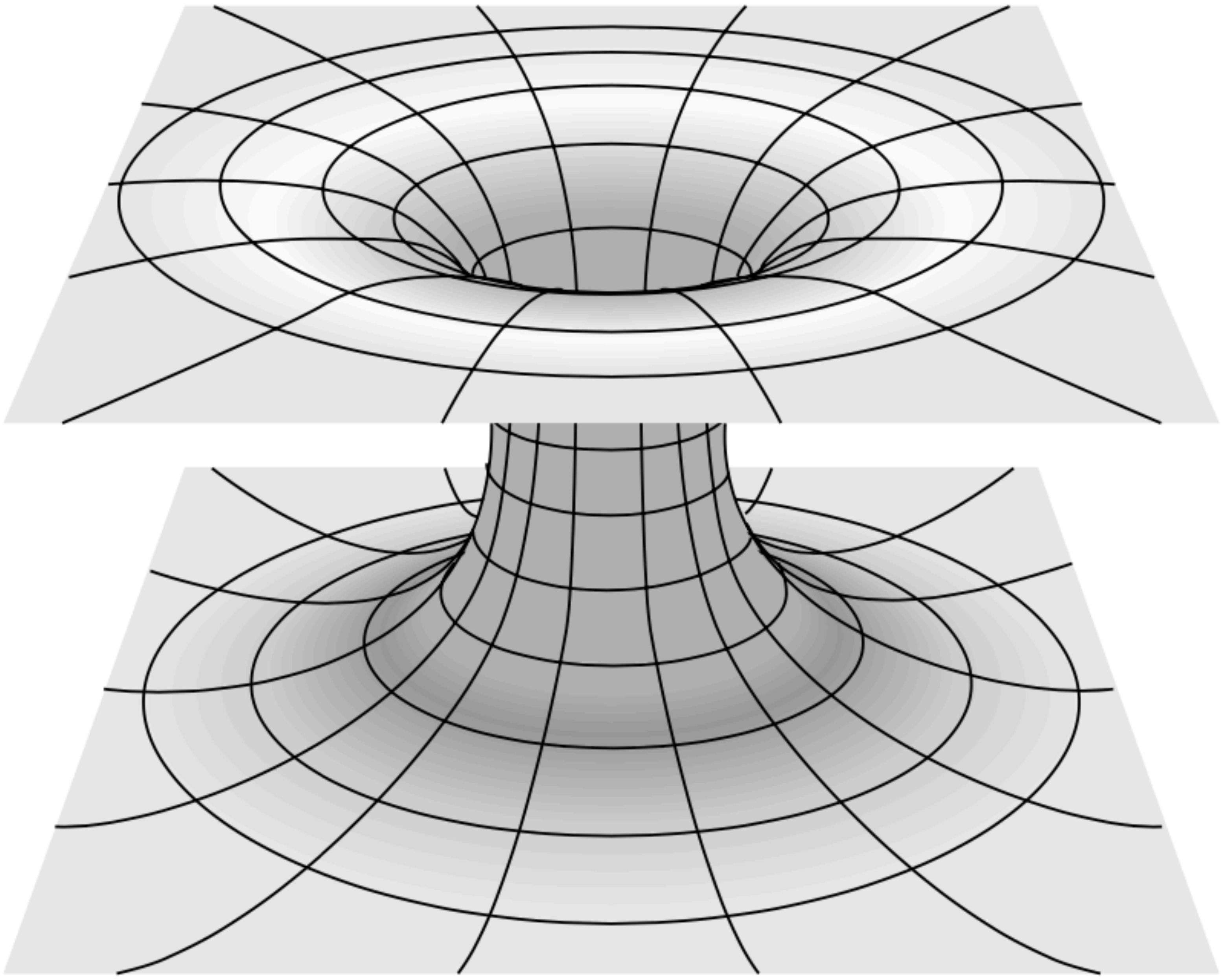


FIGURE 23 Depiction of a Schwarzschild throat connecting two different regions of spacetime. Any attempted passage of matter or energy through the throat would cause it to collapse.

Tunnels in Spacetime

The story is somewhat different for a **rotating black hole**.

Spacetime is still infinitely curved at the ring singularity, all worldlines need not converge there. In fact, **it is difficult for an infalling object to hit the singularity in a rotating black hole**.

Theorists have calculated worldlines for vacuum solutions that miss the singularity and emerge in the spacetime of another universe.

But just as for nonrotating black holes, **any attempt to pass the smallest amount of matter or energy along such a route would cause the passageway to collapse**.

In summary, it seems **extremely unlikely that black holes can provide a stable passageway** for any matter or energy. Any trip through a black hole would end up being **torn apart by the singularity.**

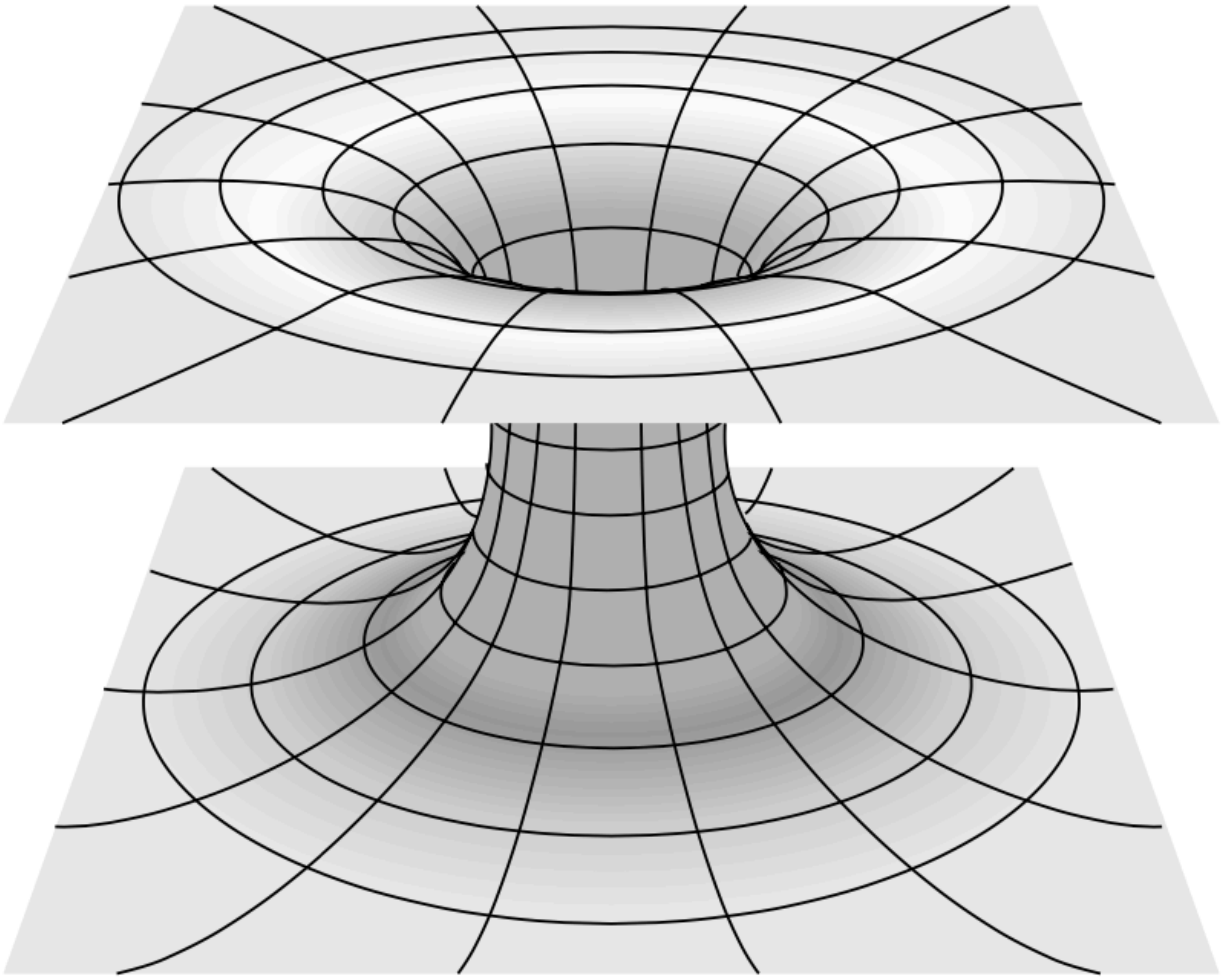


FIGURE 23 Depiction of a Schwarzschild throat connecting two different regions of spacetime. Any attempted passage of matter or energy through the throat would cause it to collapse.

Tunnels in Spacetime

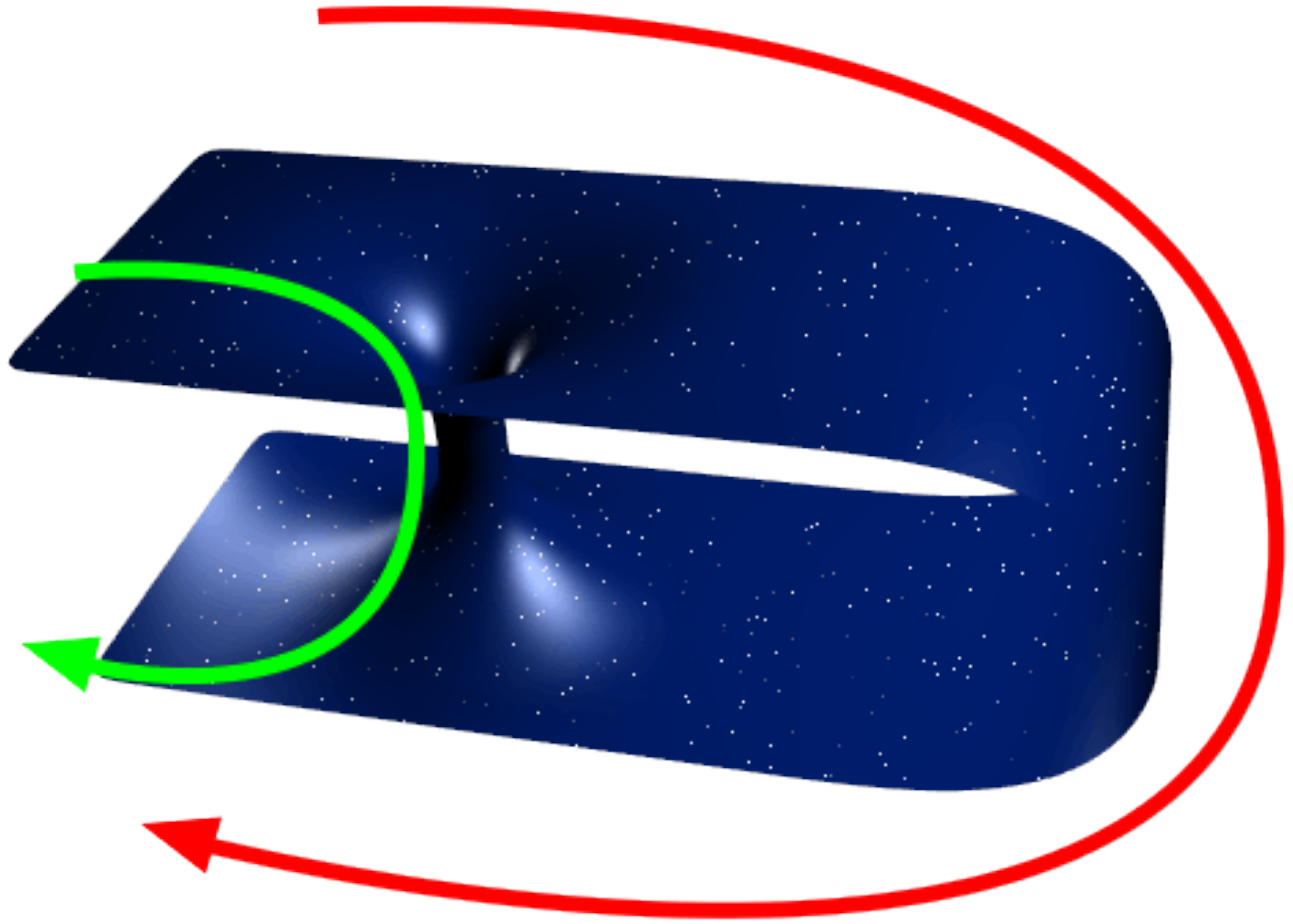
Another possibility is that of a **wormhole**, a **hypothetical tunnel between two points in spacetime separated by an arbitrarily great distance**.

We will briefly consider nonrotating, spherically symmetric wormholes. They are described by ***nonvacuum* solutions to Einstein's field equation**. In other words, a wormhole must be threaded by **some sort of *exotic material* whose tension prevents the collapse of the wormhole**.

There is no known mechanism that would allow a wormhole to arise naturally; it would have to be constructed by an incredibly advanced civilization.

These solutions to Einstein's field equations have no event horizon (permitting two-way trips through the wormhole) and involve survivable tidal forces.

Journey times from one end through to the other can be less than one year (traveler's proper time), although the ends of the wormhole may be separated by interstellar or intergalactic distances.



2D illustration of a wormhole
https://en.wikipedia.org/wiki/Wormhole

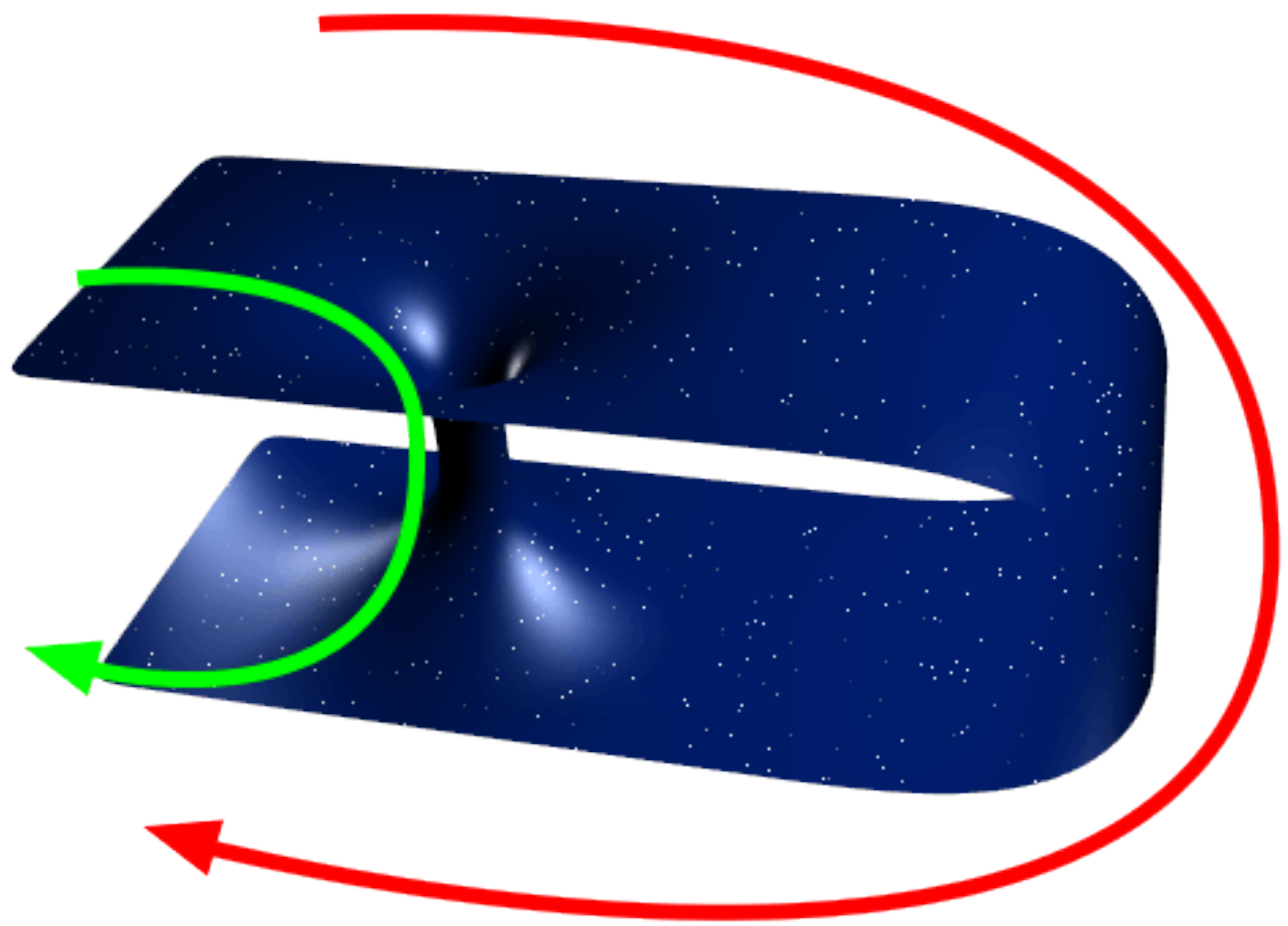
Tunnels in Spacetime

The catch, of course, is the **problematic existence of the exotic material needed to stabilize the wormhole**.

The unusual nature of the exotic material becomes apparent if we consider two light rays that converge on the wormhole and enter it, only to diverge when they exit the other end. This implies that the **exotic material must be capable of gravitationally defocusing light, an "antigravity" effect** involving the gravitational repulsion of the light by the material through which the rays pass.

Exotic material meeting this requirement would have a negative energy density ($\rho c^2 < 0$), at least as experienced by the light rays.

Although a negative **energy density arises in certain quantum situations**, it may or **may not be allowed physically on macroscopic scales.**



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Tunnels in Spacetime

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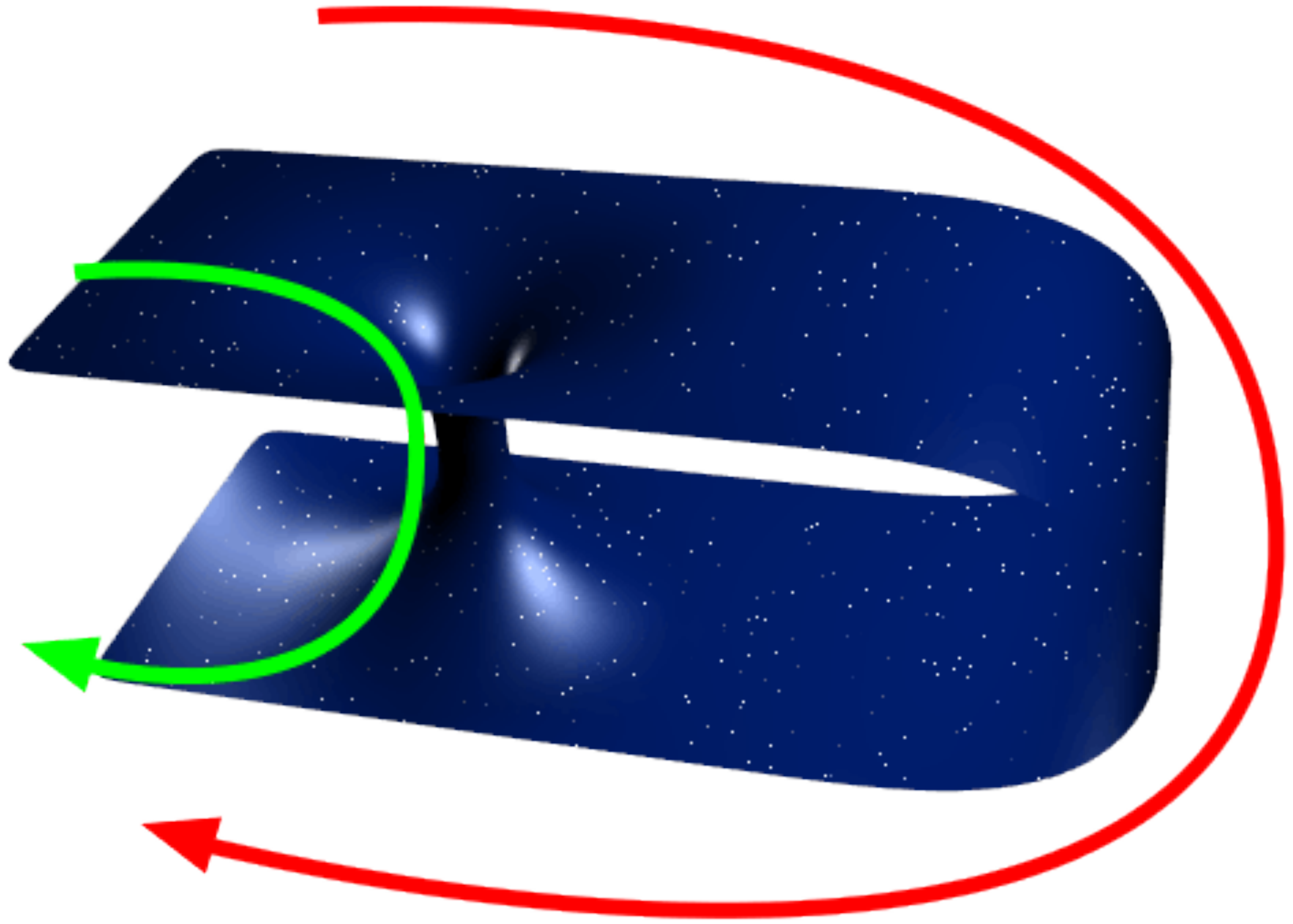

2D illustration of a wormhole
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Hawking radiation

The black holes of classical general relativity last forever. A very **general result** derived by Stephen Hawking states that **the surface area of a black hole's event horizon can never decrease.** If a black hole merges with any other object, the result is an even larger black hole.

In 1974, however, Hawking discovered a **loophole** in this law **when he combined quantum mechanics** with the theory of black holes and found that **black holes can slowly *evaporate*.**

The key to this process is **pair production**, the formation of a particle–antiparticle pair **just outside the event horizon of a black hole.** Ordinarily the particles quickly recombine and disappear, but **if one of the particles falls into the event horizon while its partner escapes**, as shown in Fig. 25, this disappearing act may be thwarted.

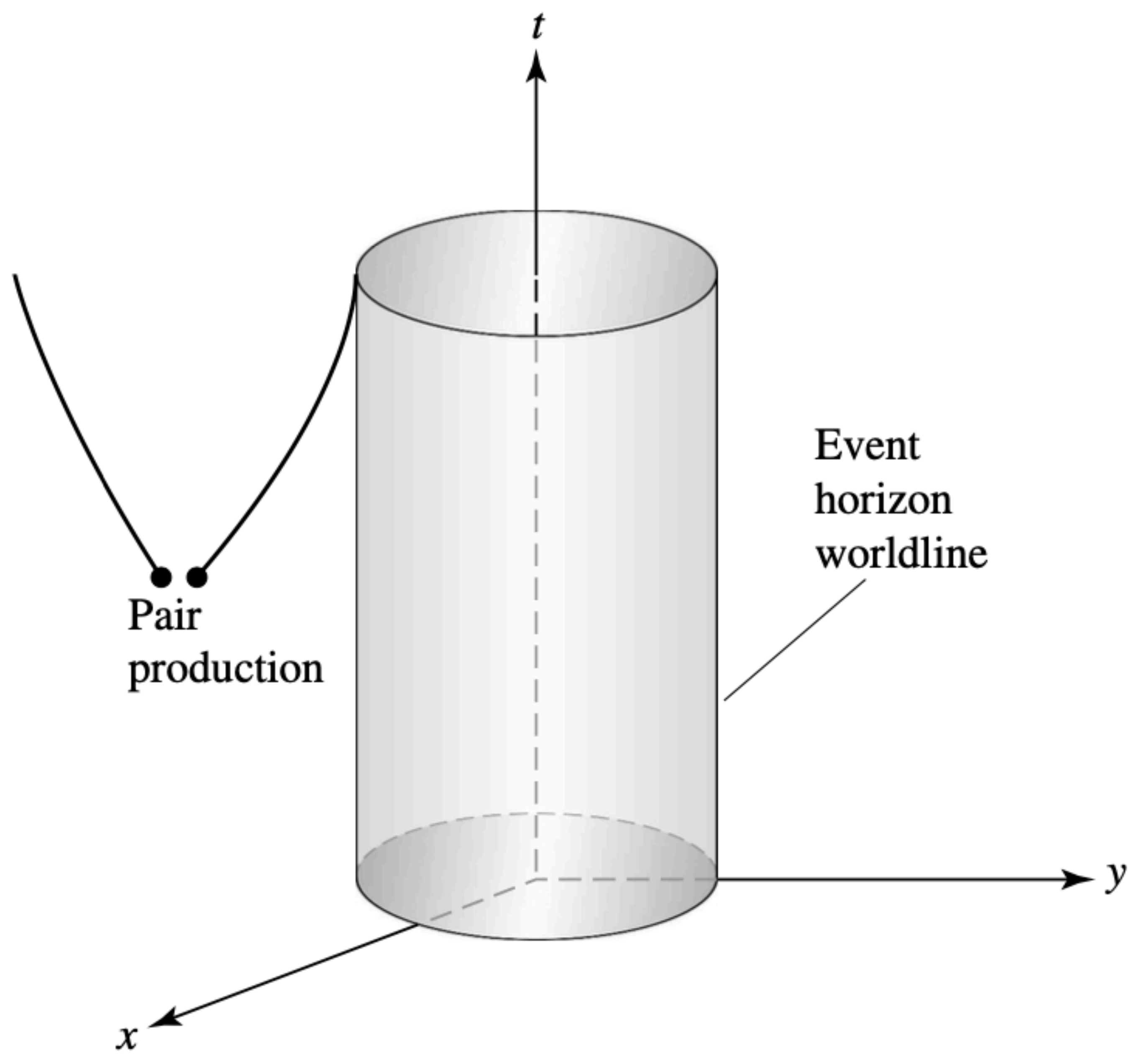

FIGURE 25 Spacetime diagram showing particle–antiparticle pairs created near the event horizon of a black hole.

Hawking radiation

The black hole's gravitational energy was used to produce the two particles, and so the **escaping particle has carried away some of the black hole's mass**. The net effect as seen by an observer at a great distance is the emission of particles by the black hole, known as **Hawking radiation**, accompanied by a reduction in the black hole's mass.

The rate at which energy is carried away by particles in this manner is inversely proportional to the square of the black hole's mass, or $1/M^2$.

For stellar-mass black holes, the emitted particles are photons and the rate of **emission is minuscule**.

As the black hole's mass declines, however, the rate of emission increases.

The **final stage of a black hole's evaporation proceeds extremely rapidly, releasing a burst of all types of elementary particles**. This tremendous explosion probably leaves behind only an empty region of flat spacetime.

Hawking radiation

The lifetime of a primordial black hole prior to its evaporation, t_{evap}, is quite long,

$$t_{\text{evap}} = 2560\pi^2 \left(\frac{2GM}{c^2}\right)^2 \left(\frac{M}{h}\right)$$

$$\approx 2 \times 10^{67} \left(\frac{M}{M_\odot}\right)^3 \text{ yr.}$$

Since the age of the universe is 13.7 billion years, this process is of **no consequence for black holes formed by a collapsing star.**

However, a **primordial black hole** with a mass of roughly 1.7×10^{11} kg would evaporate in about 13 billion years. -> should be in the f**inal, explosive stage of evaporation right now** and could possibly be detected.

The final burst of Hawking radiation is thought to release high- energy (≈ 100 MeV) **gamma rays** at a rate of 10^{13} W, together with **electrons, positrons, and many other particles**. The subsequent decay of these particles should produce additional gamma rays that would be observable by Earth-orbiting satellites.

Hawking radiation

The **information paradox** appears when one considers a process in which a black hole is formed through a physical process and then evaporates away entirely through Hawking radiation.

Hawking's calculation suggests that **the final state of radiation would retain information only about the total mass, electric charge and angular momentum of the initial state**. Since **many different states can have the same mass, charge and angular momentum,** this suggests that **many initial physical states could evolve into the same final state**. Therefore, **information about the** details of the **initial state would be permanently lost**; however, this violates a core precept of both classical and quantum physics—that, in principle, the state of a system at one point in time should determine its state at any other time.

It is now generally believed that information is preserved in black-hole evaporation referred to as Page curve. These questions about black hole evaporation have implications for how gravity and quantum mechanics must be combined, leading to the information paradox remaining an **active field of research within quantum gravity.**

Hawking radiation

To date, measurements of the cosmic gamma-ray background at this energy have **not detected anything that can be identified with** the demise of a nearby **primordial black hole**.

Although there is as yet no positive evidence that primordial black holes exist, this negative result is still important. It implies that on average there cannot be more than 200 primordial black holes with this mass in every cubic light-year of space.

Hawking radiation

Experiments to measure hawking radiation:

- The **Fermi space telescope**, which is searching for the terminal gamma-ray flashes expected from evaporating primordial black holes. As of Jan 1st, 2023, none have been detected.
- then CERN's **Large Hadron Collider** may be able to create micro black holes and observe their evaporation. No such micro black hole has been observed at CERN.
- **A sonic black hole,** dumb holes or **acoustic black hole**, is a phenomenon in which **phonons (sound perturbations) are unable to escape from a region of a fluid that is flowing more quickly than the local speed of sound.** They are called sonic, or acoustic, black holes because these **trapped phonons are analogous to light in astrophysical (gravitational) black holes**. Physicists are interested in them because they have many properties similar to astrophysical black holes and, in particular, emit a **phononic version of Hawking radiation.** The boundary of a sonic black hole, at which the flow speed changes from being greater than the speed of sound to less than the speed of sound, is called the event horizon. **Observations of Hawking radiation were reported, in sonic black holes** employing Bose–Einstein condensates.