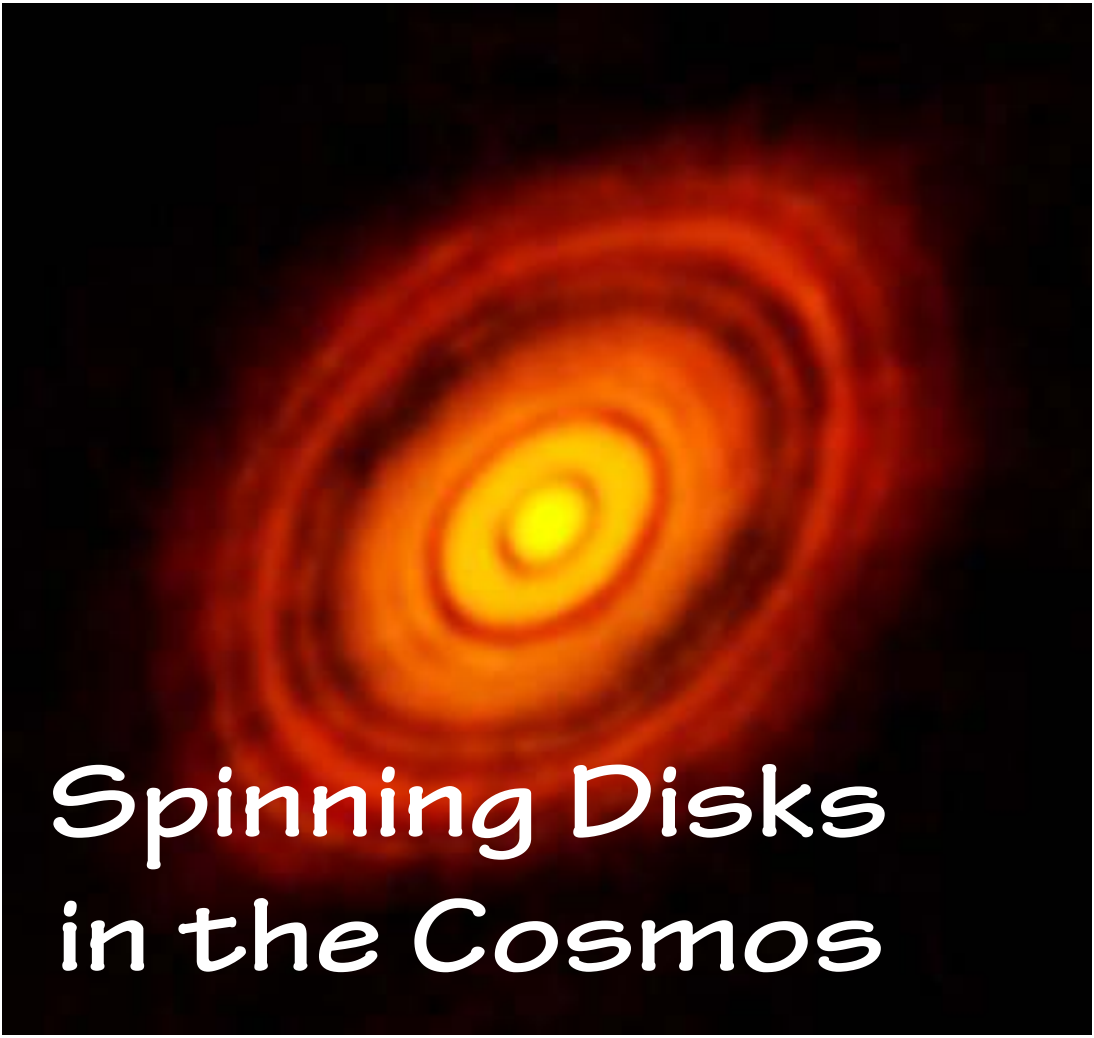
The Universe in My Pocket



Spinning Disks in the Cosmos

No. 47

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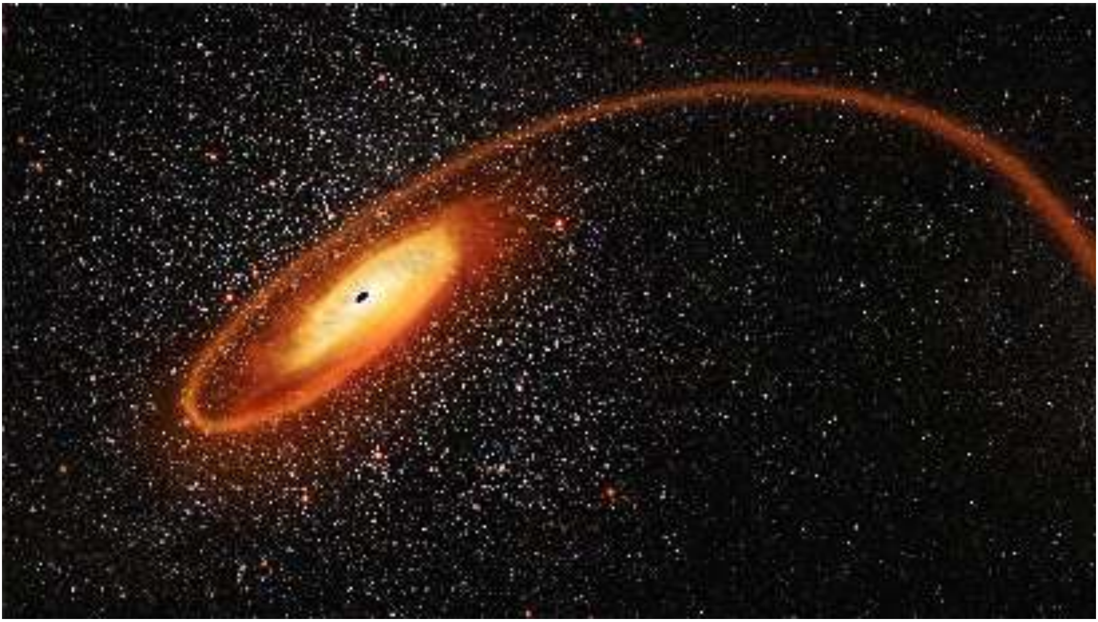
Saturn's Rings (NASA/ESA Hubble Space Telescope)

The motion of particles in circular orbits is by no means the simplest example of motion. When no force acts on a body, it moves in a straight line at a constant speed. But gravitational interaction bends the body's path. The orbit depends on two values: the body's energy and its angular momentum. Higher energy, for example of a comet, causes it to move away after orbiting about the Sun. Too little energy does not allow it to escape, and it remains trapped in an elliptical orbit about the Sun. Circular motion is a very special case of such motion.

Saturn's Rings

Who among us has not seen Saturn's rings? Perhaps through a telescope? Or at least in a picture? They are beautiful and eternal, at least from the perspective of human life. They look like rings when we look at them from above. But when we look from the side, they look like a very thin disk.

Saturn's rings are made of lumps of ice, with a small mixture of rocky debris. These lumps move in fixed circular orbits, practically without random collisions, which is why, after the initial chaos during the formation of the Solar System, they have lasted for millions of years. However, the few random collisions that do happen may cause the rings to disappear in about 300 million years.

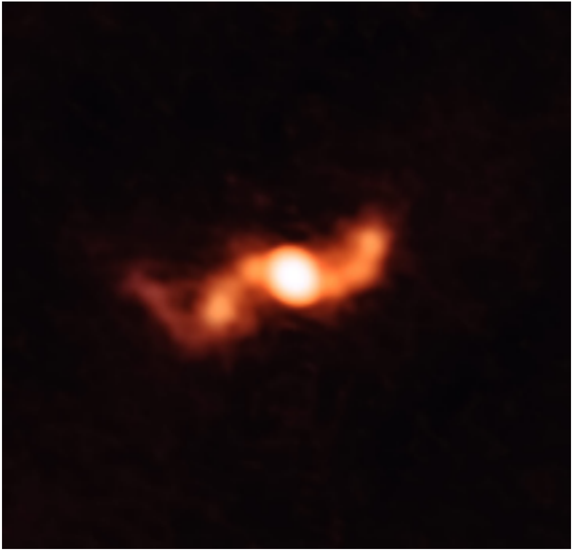


Formation of an accretion disk around a massive black hole as a result of a star being torn apart (NASA/ESA/D. Player (STScI), illustration).

Sometimes a star orbiting about a galactic center gets too close to the central black hole. The gravitational attraction of the black hole will change the orbit of the star, pulling it inward, and the star will be torn apart as it falls into the black hole. Some of its remnants may escape, but most will be trapped by the gravitational field; their orbits will become almost circular, and the material will form an accretion disk. The image above is not a photograph, but we do observe such phenomena.

Accretion Disks

Not all disks are so slightly visible, shining with reflected light. When a disk is made of gas, and is permeated by a magnetic field, the material in the disk churns dramatically, heats up, and shines by its own light. Losing energy and angular momentum, this hot plasma drifts towards the central object. These are known as accretion disks. This apparent paradox - losing energy but becoming hotter - comes from the fact that gravitational potential energy is lost and converted into kinetic (velocity) and thermal energy. The effect is strongest when the central object is compact, measured by the ratio of its radius to its mass. Such compact objects are neutron stars and black holes. There are many of them in space, and the process of matter falling onto them is quite common; it can last from seconds to years.



Object SS 433, microwave image, Credit: ALMA (ESO/NAOJ/NRAO)/K. Blundell (University of Oxford, UK), R. Laing, S. Lee & A. Richards, Ap J Letters.

Accretion disks around stellar black holes are tiny; it is impossible to obtain an image of the disk itself. However, the infall of matter onto a black hole is often accompanied by the ejection of a small amount of matter in the form of a jet - a stream of out-flowing material perpendicular to the disk. The image above shows a bipolar jet, with ejection occurring in opposite directions. We are still not sure how such jets are formed, although a strong magnetic field certainly plays a role.

Stellar Black Holes and Companions

In our galaxy - the Milky Way - there are likely many black holes with masses slightly larger than the Sun. Most are invisible, but if a stellar mass black hole has a close companion in the form of a normal star, it may pull matter away from the star, and this gas, before falling into the black hole, forms an accretion disk. These disks are visible in X-ray radiation. Some shine constantly, some erratically, depending on the rate of matter delivery to the disk or changes in the flow rate within the disk itself. This is a rare phenomenon - we know of only a few dozen such pairs in the Milky Way, and such objects are too faint to be easily observed in distant galaxies. The brightest objects in the Universe are long-duration gamma-ray bursts.

These tremendous bursts of energy arise from the final stages of stellar evolution, as a massive star collapses into a black hole. A disk may temporarily form there but it would be buried from our view by the exploding material.

Protoplanetary disks - images from ALMA, VLT, and Hubble telescopes. Credit: NASA, ESA, ESO, STScI, ALMA, S. Andrews (CfA), Bill Saxton (NRAO, AUI, NSF), T. Stolker (ALMA)

Planetary systems around young stars are formed in protoplanetary disks. The physics of this process is extremely complex. The images we obtain with telescopes allow us to better understand individual stages of the process. But theory is also important, because the images do not show how the first ice grains, the first rocks, and the seeds of planets form.

Young stars and Planet Formation

Some of the most complex accretion disks are those that form around young, newly-forming stars. Our Earth was formed from such a disk orbiting the Sun 4.5 billion years ago. That is why this process, occurring now around other stars, is so fascinating.

These disks consist of gas, ice grains, and rocky fragments. The material comes from the remnants of the cloud from which the star itself formed, but it undergoes constant transformations. Some gas falls into the star, some is blown away, some forms gas planets. Dust grains collide and stick together, growing larger and larger, and ultimately form rocky planets, but the process is slow and difficult to understand in detail. Therefore, all observations of this process are valuable.

Left: active galaxy J0742+2704 (NASA, ESA, K. Nyland (United States Naval Research Laboratory), J. DePasquale (STScI)), right: giant radio galaxy (Image credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA). The pink image shows radio emission, the white image is optical.

Distant active galaxies are often referred to as quasars (quasi-stellar objects), and observations often show only traces of the host galaxy or an outflowing jet. This is what the object on the left looks like. On the right, a jet is visible, much longer than the entire galaxy.

Active galactic nuclei

Massive black holes, hundreds of thousands , even millions of times more massive than the Sun, reside in the nuclei of all galaxies. Such black holes gravitationally attract surrounding matter, and accretion disks form around them; these are called active galactic nuclei.

Sucking up the matter is not easy, so the very brightest nuclei are quite rare: only about one galaxy in a million reaches this extreme level of activity. The luminosity of the accretion disks in these nuclei can be a thousand times greater than all of the stars in the host galaxy combined.

These active galaxies, like gamma-ray bursts, are often found at cosmological distances, at the limits of the observable Universe. But there are many of them, they live long, and whenever we point our telescopes we can find them.

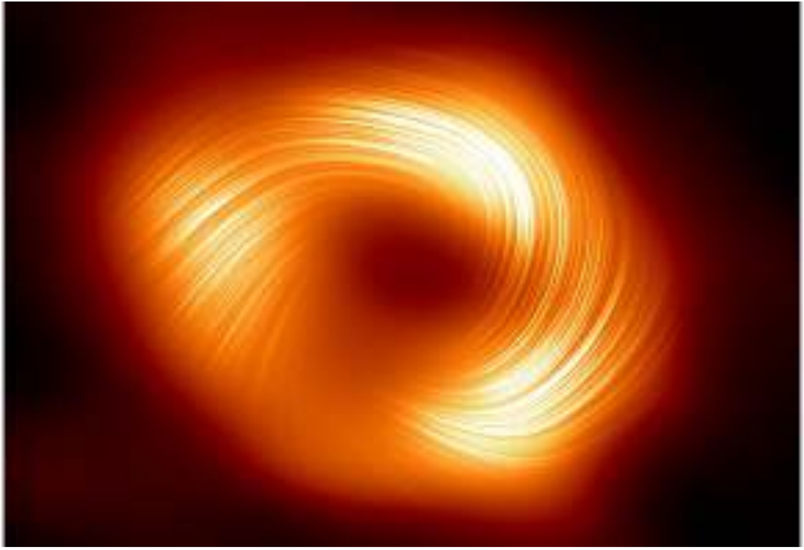


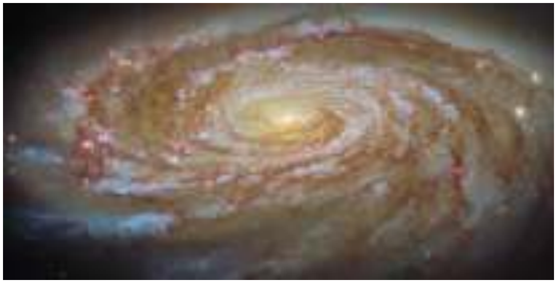
Image of the black hole at the center of the Milky Way, with the magnetic field lines indicated (EHT).

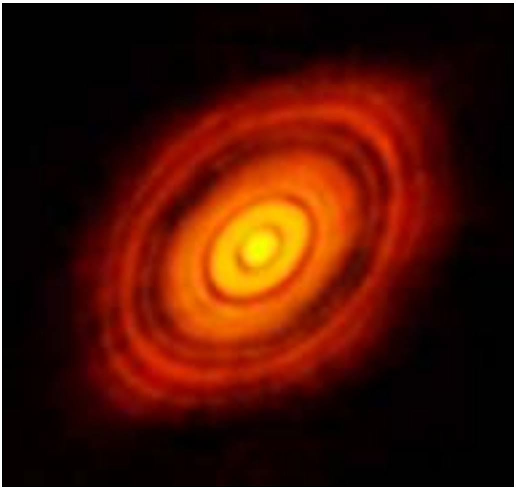
The center of our Galaxy cannot be seen with optical telescopes because there is too much dust in the way. But radio waves can pass through this dust and allow us to see the Galactic center. The image shown above was taken with millimeter radio waves. This allows the accretion disk to be seen. The shadow in the center is where the black hole is located; it does not shine itself. The image required the cooperation of many radio telescopes on Earth, each one contributing data used to form the image.

And what about our Galaxy? Is it active? Well, it depends on how you look at it. Yes, it has a black hole at its center, with a mass of four million solar masses, but matter barely trickles towards it, at a rate billions of times slower than in active galaxies. Something is happening, but we only see the effect because we are so much closer to our own Galactic center black hole.

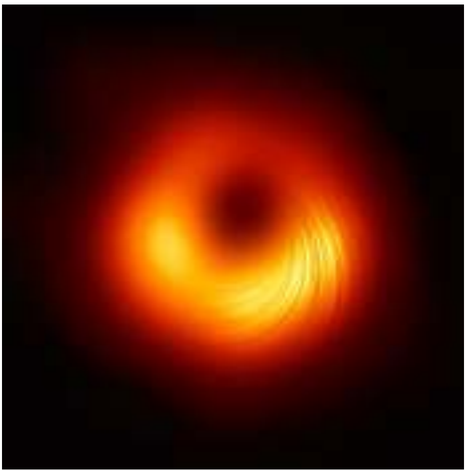
Thanks to the Event Horizon Telescope, we finally have its image. It was difficult to obtain and required a huge team effort. An accretion disk is visible, but it has little mass; it is made of very hot plasma, with a temperature of millions of degrees, like the interior of the Sun. It shines in X-rays, but not only that - fast electrons also shine in radio waves, and it is in this spectral band (more precisely, in the millimeter wave range) that the image was obtained.

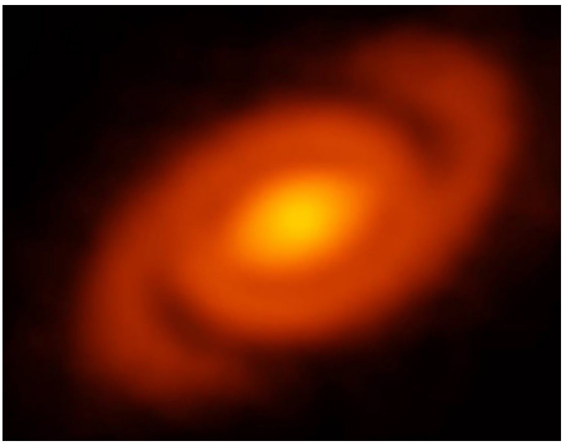
Can you guess...





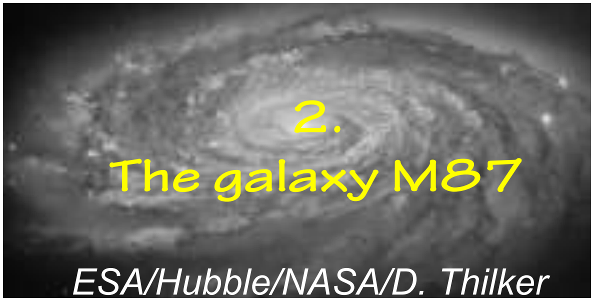
...which of these images does not show a disk?



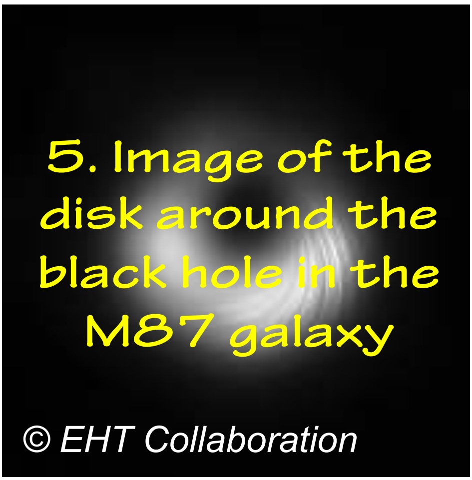


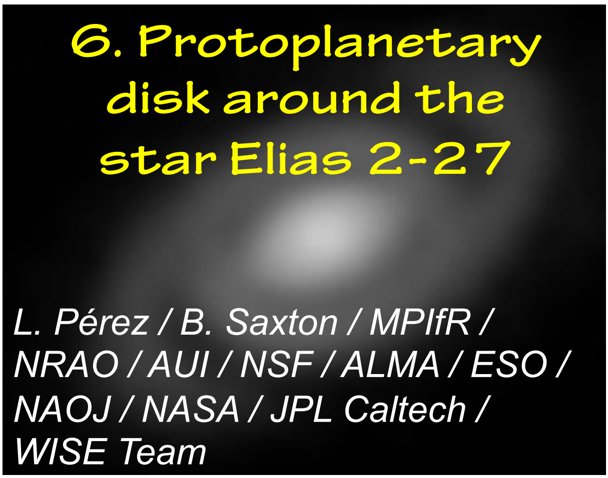
Try to figure it out.

Answer



Only the first image does not show a disk!





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This booklet was prepared in 2026 by Bożena Czerny from the Center for Theoretical Physics of the Polish Academy of Sciences in Warsaw and revised by Stan Kurtz from IRyA (Morelia, Mexico).

Cover: photo of the disk around the young star HL Tauri, where planets are currently forming. Credit: ALMA (ESO/NAOJ/NRAO)

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Translation: Stan Kurtz