AstroTalk: Behind the news headlines; December 2023

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Black hole "cannon fodder"

Black holes are gatherers, not hunters. They lie in wait until a hapless star wanders by. When the star gets close enough, the black hole's gravitational grasp violently rips it apart and sloppily devours its gasses while belching out intense radiation.

Astronomers using the *Hubble Space Telescope* recently recorded a star's final moments in great detail. The violent death throes associated with a star's demise by a black hole are known as "tidal disruption events." But the wording belies the complex, raw violence of the encounter. Black holes are messy eaters.

Hubble can't photograph the "AT2022dsb" tidal event's mayhem up close, since the munched-up star is located nearly 300 million light-years away in the core of the galaxy ESO 583–G004. But astronomers used *Hubble*'s powerful ultraviolet sensitivity to study the light from the shredded star, which included evidence of the presence of hydrogen, carbon, and other chemical elements.

About 100 tidal disruption events associated with massive black holes have been detected so far. In March 2021, NASA reported that several of its high-energy space observatories spotted a black hole tidal disruption event in another galaxy. Unlike *Hubble*'s visible-light observations, data was collected in X-ray emission from an extremely hot corona around the black hole that formed after the star had already been torn apart.

> "*However, there are still very few tidal events that are observed in ultraviolet light given the observing time required. This is really unfortunate because there's a lot of information that you can get from ultraviolet spectra*," said Emily Engelthaler of the Center for Astrophysics (CfA) at Harvard University (USA). "*We're excited because we can get details about what the debris is doing. The tidal event can tell us a lot about a black hole*."

Changes in the doomed star's condition are usually taking place on timescales of days or months. For any given galaxy containing a quiescent supermassive black hole at its centre, it's estimated that stellar shredding happens only a few times per 100,000 years.

The AT2022dsb stellar snacking event was first caught on 1 March 2022 by the "All-Sky Automated Survey for Supernovae," a network of ground-based telescopes that surveys the sky roughly once a week for violent, variable and transient events. This energetic collision was close enough and bright enough for the *Hubble* astronomers to perform ultraviolet spectroscopy over a longer than normal period of time.

> "*Typically, these events are hard to observe. You get maybe a few observations at the beginning of the disruption when it's really bright. Our program is different in that it is designed to look at a few tidal events over a year to see what happens*," said Peter Maksym, also of the CfA. "*We saw this early enough that we could observe it at these very intense black hole accretion stages. We saw the accretion rate drop as it turned to a trickle over time*."

The *Hubble* spectroscopic data are interpreted as coming from a very bright, hot, donut-shaped area of gas that was once a star. This area, known as a "torus," is the size of our solar system and is swirling around a black hole in the middle.

> "*We're looking somewhere on the edge of that donut. We're seeing a* stellar wind *from the black hole sweeping over the surface that's being projected towards us at speeds of 20 million miles per hour*," said Maksym. "*We really are still getting our heads around the event. You shred the star and then it's got this material that's making its way into the black hole. And so you've got models where you think you know what is going on, and then you've got what you actually see. This is an exciting place for scientists to be: right at the interface of the known and the unknown*."

But while the AT2022dsb event was the one-off violent "goodbye" associated with a supermassive black hole, in other parts of the Universe black holes tend to feed at a more sedate pace. As a case in point, astronomers at the University of Leicester (UK) recently discovered a star like our own Sun in a nearby galaxy that is gradually being eaten away by a small but ravenous black hole—losing the equivalent mass of three Earths every time it passes close.

Their discovery provides a "missing link" in our knowledge of black holes disrupting orbiting stars. It suggests that a whole menagerie of stars in the process of being consumed still lie undiscovered.

The Leicester astronomers were alerted to the Sun-like star by a bright X-ray flash that seemed to come from the centre of a nearby galaxy known as 2MASX J02301709+2836050, located around 500 million light-years from us. Named Swift J0230, it was spotted the moment it happened for the first time using a new tool the astronomers had developed for the *Neil Gehrels Swift Observatory*.

The scientists rapidly scheduled further *Swift* observations of the object, finding that instead of decaying away as expected, it would shine brightly for 7–10 days and then abruptly switch off, repeating this process roughly every 25 days.

Similar behaviour has been observed in so-called "quasi-periodic eruptions" and "periodic nuclear transients," where a star has material ripped away by a black hole as its orbit takes it close by, but they differ in how often they erupt and in whether it is in X-rays or visible light that the explosion is most dominant. The regularity of Swift J0230's emissions fell between the two, suggesting that it forms the "missing link" between the two types of outburst.

Using the models proposed for these two classes of event as a guide, the Leicester scientists concluded that the Swift J0230 outburst represents a star of a similar size to our own Sun in an elliptical orbit around a low-mass black hole at the centre of its galaxy. As the star's orbit takes it close to the intense gravitational pull of the black hole, material equivalent to the mass of three Earths is wrenched from the star's atmosphere and heated up as it falls into the black hole.

The intense heat, around 2 million degrees Celsius, releases a huge amount of X-rays, which were first picked up by the *Swift* satellite. Phil Evans, from the University of Leicester, said, "*This is the first time we've seen a star like our Sun being repeatedly shredded and consumed by a low-mass black hole*."

> "*So-called 'repeated, partial tidal disruption' events are themselves quite a new discovery and seem to fall into two types: those that outburst every few hours, and those that outburst every year or so. This new system falls right into the gap between these, and when you run the numbers, you find the types of objects involved fall nicely into place too*."

Rob Eyles-Ferris, a recent Ph.D. student at the University of Leicester, explained,

> "*In most of the systems we've seen in the past the star is completely destroyed. Swift J0230 is an exciting addition to the class of partially disrupted stars, as it shows us that the two classes of these objects already found are really connected, with our new system giving us the missing link*."

The team estimates that the black hole is some 10,000 to 100,000 times the mass of our Sun, which is quite small for the supermassive black holes usually found at the centres of galaxies. The black hole at the centre of our own Milky Way is thought to be 4 million solar masses.

This is the first discovery to be made using the newly built transient detector for the *Swift* satellite. When an extreme event takes place, causing an X-ray burst in a region of the sky where there were previously no X-rays, astronomers call it an "X-ray transient." Despite the extreme events they herald, these events are not easy to find, or at least, not quickly—and so their new tool was developed to look for new types of transients in real time.

Dr. Evans adds,

> "*This type of object was essentially undetectable until we built this new facility, and soon after it found this completely new, never-before-seen event.* Swift *is nearly 20 years old and it's suddenly finding brand new events that we never knew existed. I think it shows that every single time you find a new way of looking at space, you learn something new and find there's something out there you didn't know about before*."

As already alluded to, among the more regular transient X-ray events are those that repeatedly flare up on year-long timescales. Meanwhile, in the *eROSITA* all-sky survey, scientists at the Max Planck Institute for Extraterrestrial Physics (MPE) in Germany found such an interesting repeating event. In an otherwise quiescent galaxy, an X-ray flare was found to repeat every 220 days, indicating that a star orbiting the central black hole "feeds" the gravity monster on subsequent orbits.

Occasionally, a star might wander too close to a galaxy's central black hole and be disrupted by its strong tidal forces. Tidal disruption events result in the star losing its material to the black hole, temporarily increasing the fuelling rate of the gravity monster, and producing an X-ray flare as the stellar matter is consumed. Periodic or repeating flares could be due to stars that are fortunate to survive their first encounter. Instead of being disrupted completely, the remnant orbits the supermassive black hole, losing parts of its outer layers and fuelling the black hole with each passage.

> "*Such repeating partial disruption events could be effective tools to explore the accretion process around supermassive* black holes," points out Zhu Liu, the lead author of the study at MPE. "*With* eROSITA *we found a very intriguing repeating nuclear transient in an otherwise quiescent galaxy*."

During its all-sky survey, the *eROSITA* X-ray telescope observed every position on the sky multiple times, thereby uncovering high-energy transients in galaxies that showed no signatures of prior activity in their centres. The new source, J0456–20, is located in a quiescent galaxy about 1 billion light-years away. It is one of the most variable X-ray sources seen by *eROSITA*, with the X-ray intensity dropping by a factor of 100 within a week.

In total, the astronomers observed three complete cycles of repeating X-ray flares from the source, with a recurrence time of around 220 days. Follow-up optical observations showed a typical quiescent galaxy, while the repeating X-ray flares strongly suggest a repeating partial tidal disruption event.

> "*We estimate that the star orbiting the black hole lost the equivalent of 5%, 1.5% and 0.5% of the mass of our Sun in its first, second, and third visit, respectively*," explains Dr. Adam Malyali, also based at the MPE. "*These losses are small enough that the star could survive several partial disruption episodes*."

Through a collaboration with the Australia Telescope Compact Array radio astronomy facility, the scientists also discovered transient radio emission from J0456–20, indicating the launch of an outflow of gas or a jet. Together with the characteristic X-ray evolution, there is compelling evidence for changes in the structure of the accretion disk around the supermassive black hole.

> "*More follow-up observations are needed to pin down the exact details of the physical processes*," says Andrea Merloni, *eROSITA* principal investigator. "*Nevertheless, the discovery of this repeating X-ray event*

already provides solid evidence that there are stars in tightly bound orbits around supermassive black holes *beyond our own Milky Way galaxy. These offer ideal laboratories to test General Relativity in the strong field regime*."

With the imminent launch of the *Einstein Probe* X-ray observatory in January 2024, led by Chinese scientists and engineers, the future of X-ray astronomy looks solid, leaving us on the cusp of many new insights into the most violent events occurring in the Universe today!

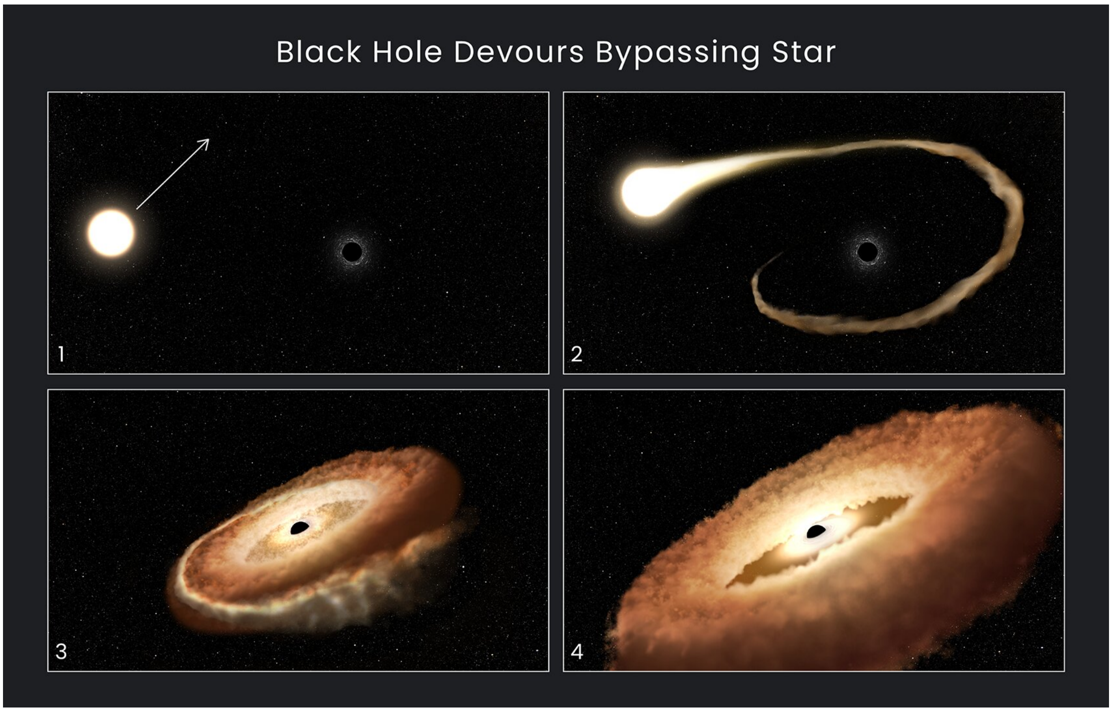

Figure 1: This sequence of artist's illustrations shows how a black hole can devour a bypassing star. 1. A normal star passes near a supermassive black hole in the centre of a galaxy. 2. The star's outer gasses are pulled into the black hole's gravitational field. 3. The star is shredded as tidal forces pull it apart. 4. The stellar remnants are pulled into a donut-shaped ring around the black hole and will eventually fall into the black hole, unleashing a tremendous amount of light and high-energy radiation. (*Credit: NASA, ESA, Leah Hustak; Space Telescope Science Institute*)

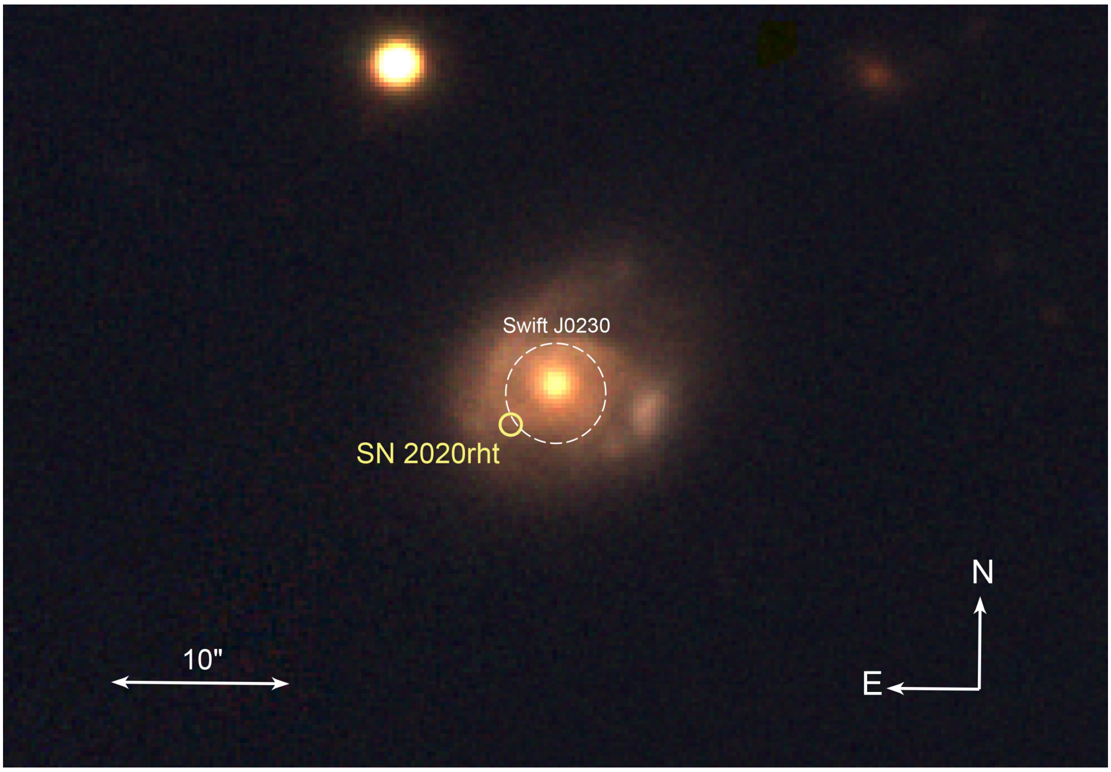

Figure 2: Optical image of the galaxy in which the AT2022dsb event occurred, taken from archival *PanSTARRS* data. The X-ray object was located to somewhere inside the white circle, which is about the size a pinhead 100 m away would appear. The position of a 2-year-old supernova is also shown. (*Credit: Daniele B. Malesani / PanSTARRS*)

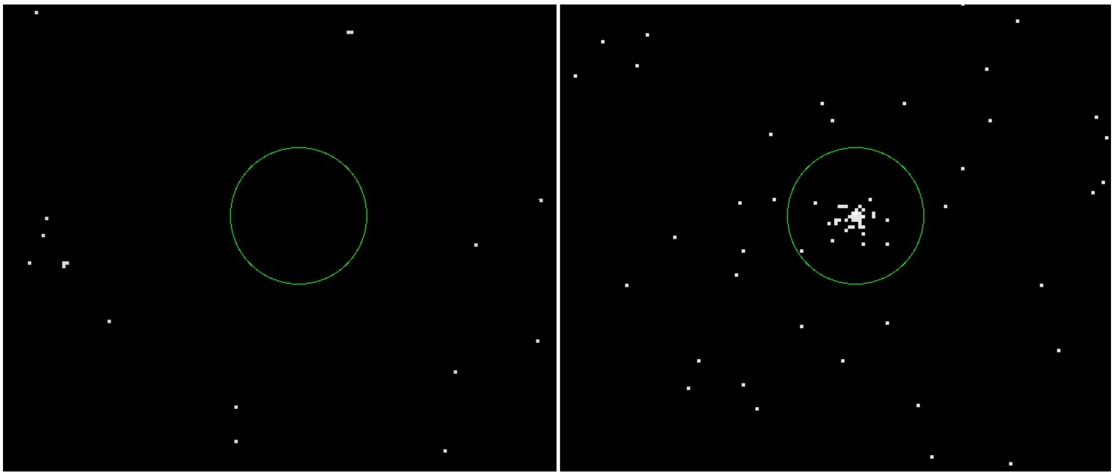

Figure 3: Now you don't see it, now you do! X-ray images of the same location on the sky before (*left*) and after (*right*) Swift J0230 erupted. These images were taken with the X-ray Telescope onboard the *Swift* satellite. *Credit: Phil Evans (University of Leicester) / NASA Swift*

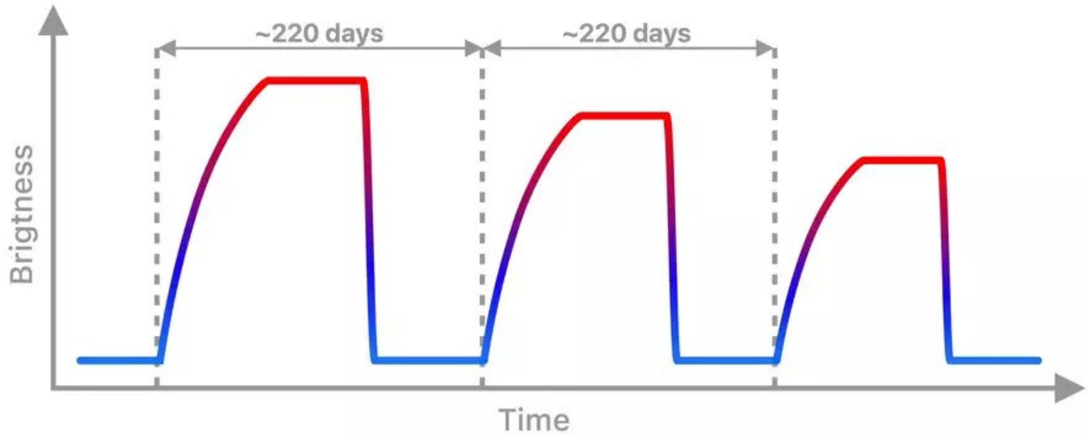

Figure 4: The light-curve of the new source, J0456-20, shows four distinctive phases: The X-ray flux plateau phase lasts about two months and then drops rapidly (by a factor of 100) within one week. A faint X-ray stage follows this for about 2–3 months before it starts the X-ray rising phase again. The whole cycle lasts about 220 days. (*Credit: MPE*)

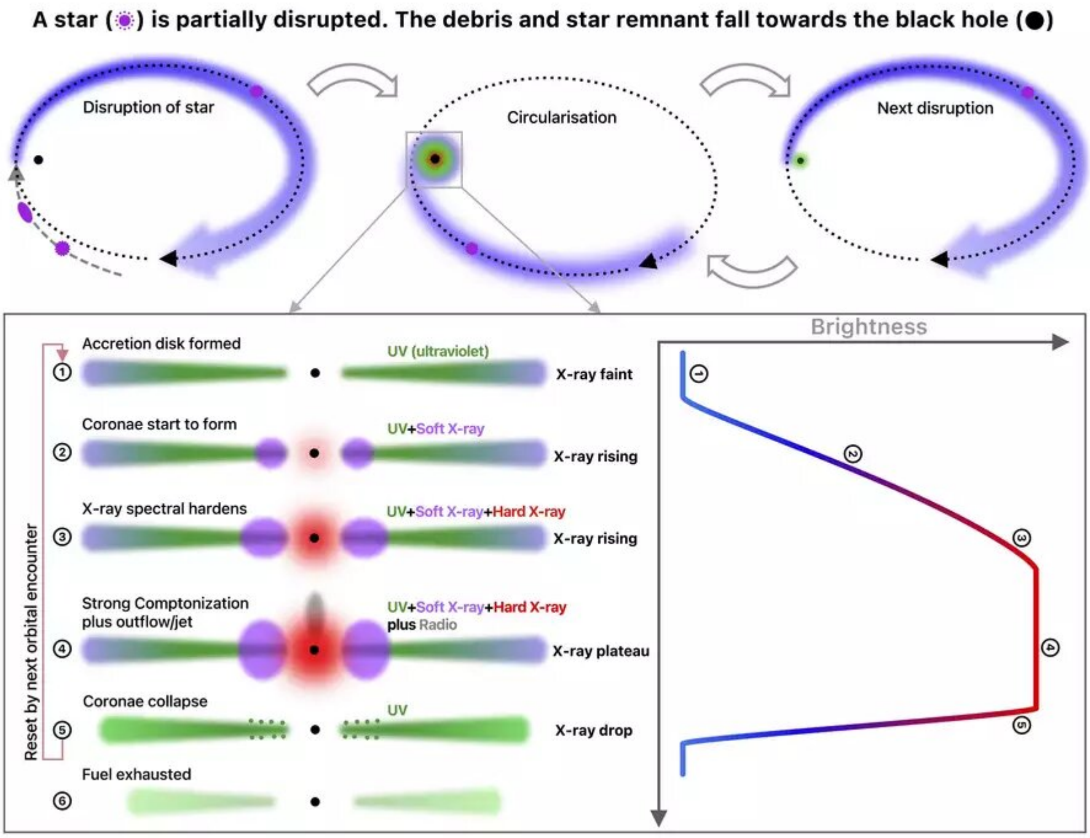

Figure 5: Sequence of events that could explain the evolution of the light curve in J0456–20: A star is partially disrupted when coming close to a supermassive black hole (*top*). The stellar debris forms an accretion disk (blue), with the accretion proceeding in various stages (1–5) with changing emission signatures. Eventually, the fuel is completely exhausted (6) and no more X-ray flares will be detected. (*Credit: MPE*)

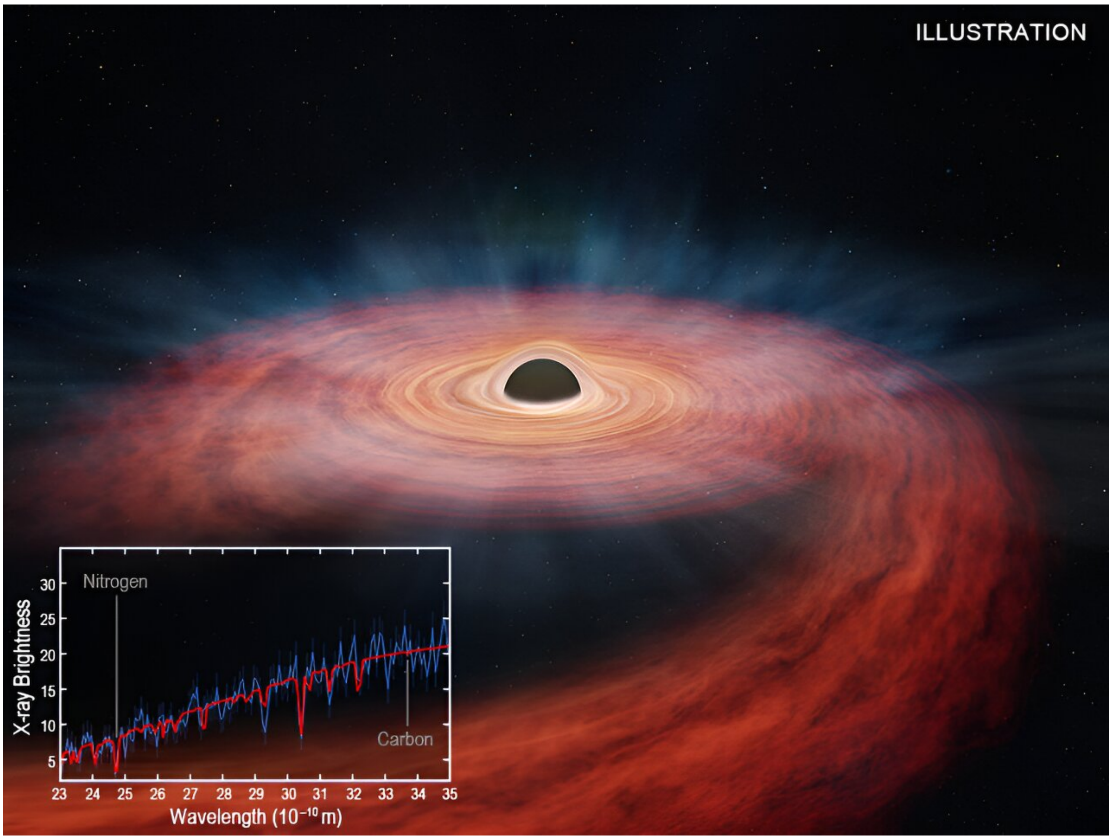

Figure 6: Artist's illustration of stellar debris swirling around a giant black hole. The debris field represents the remains of a star with three times the mass of our Sun, which was ripped apart by the black hole's immense gravity. The tidal disruption event pictured is known as ASASSN–14li. At the centre of the illustration is the black hole, half-submerged in the debris field, which resembles the top half of a jet black ball. The ball sits at the core of the disk-shaped debris field, which is composed of distinct orange and red rings. A long, wide ribbon of red cloud, representing part of the star's residual gas, enters the illustration at our lower left. This ribbon of gas sweeps toward our centre right across the black, starry sky. There, the gas curves back to the left, behind the black hole. Drawn in by gravity, the ribbon of gas encircles the ringed disk of red and golden orange stellar debris. This debris orbits, and eventually falls into, the black hole. Faint blue mist appears to radiate from the black hole and the orbiting stellar debris field. This mist represents the portion of stellar gas driven away from the ringed disk by a wind. (*Credit: NASA*)

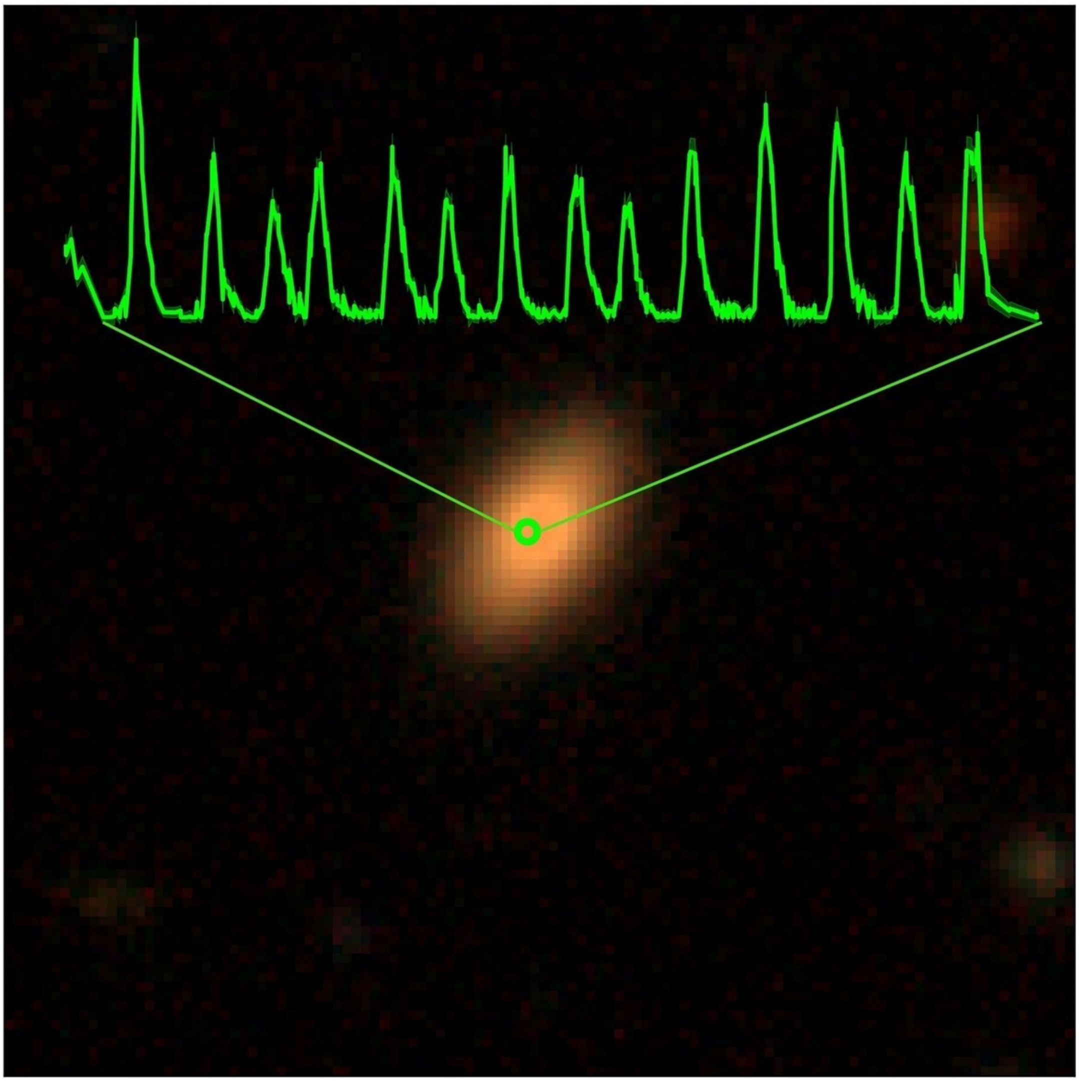

Figure 7: Optical image of the first galaxy found with quasi-periodic eruptions in the *eROSITA* all-sky data; the X-ray light-curve is overplotted in green. The galaxy was identified as 2MASS 02314715–1020112. About 18.5 hours pass between the peaks of the X-ray outbursts. *Credit: MPE; optical image: DESI Legacy Imaging Surveys/D. Lang (Perimeter Institute)*

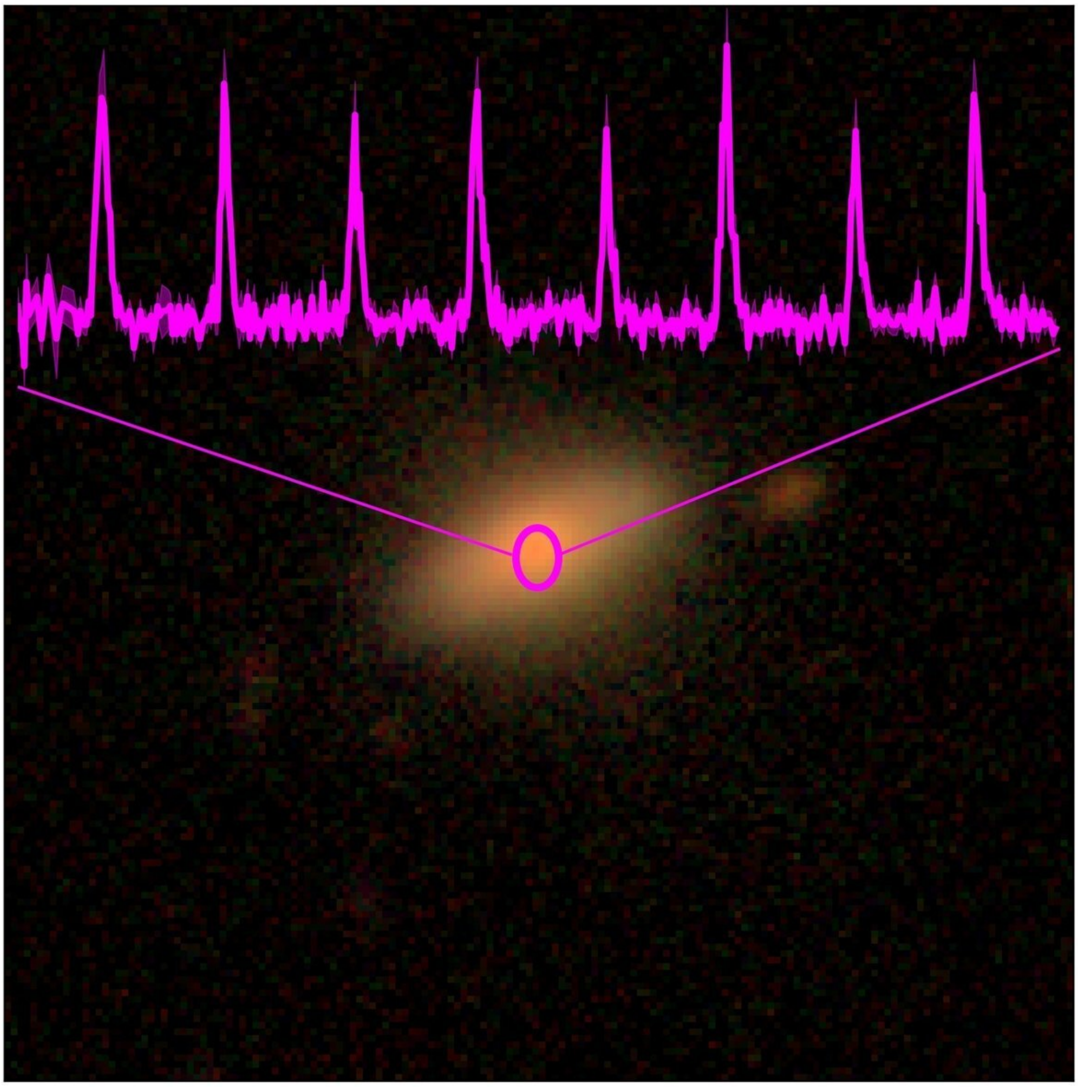

Figure 8: Optical image of the second galaxy found with quasi-periodic eruptions in the *eROSITA* all-sky data; the *XMM–Newton* X-ray light-curve is overplotted in magenta. The galaxy was identified as 2MASX J02344872–4419325. This source shows much narrower and more frequent eruptions, approximately every 2.4 hours. *Credit: MPE; optical image: DESI Legacy Imaging Surveys/D. Lang (Perimeter Institute)*

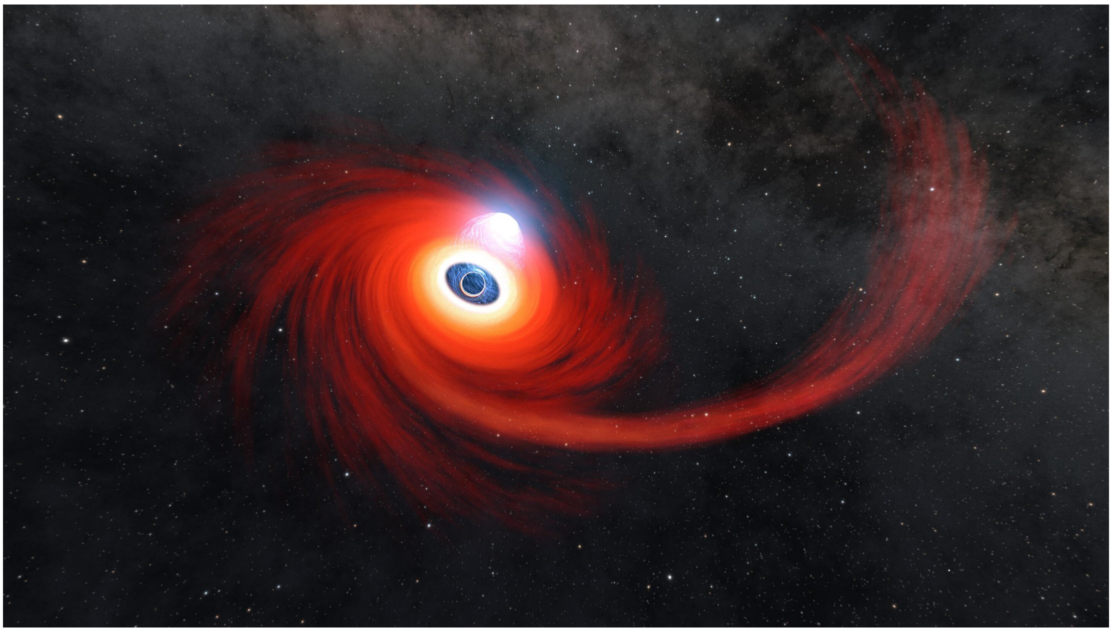

Figure 9: A disk of hot gas swirls around a black hole in this illustration. Some of the gas came from a star that was pulled apart by the black hole, forming the long stream of hot gas on the right, feeding into the disk. It can take just a matter or weeks or months from the destruction of the star to the formation of the disk. The gas gets hotter the closer it gets to the black hole, but the hottest material can be found above the black hole. This hottest material is cloud of plasma (gas atoms with their electrons stripped away) known as a corona. (*Credit: NASA/JPL-Caltech*)