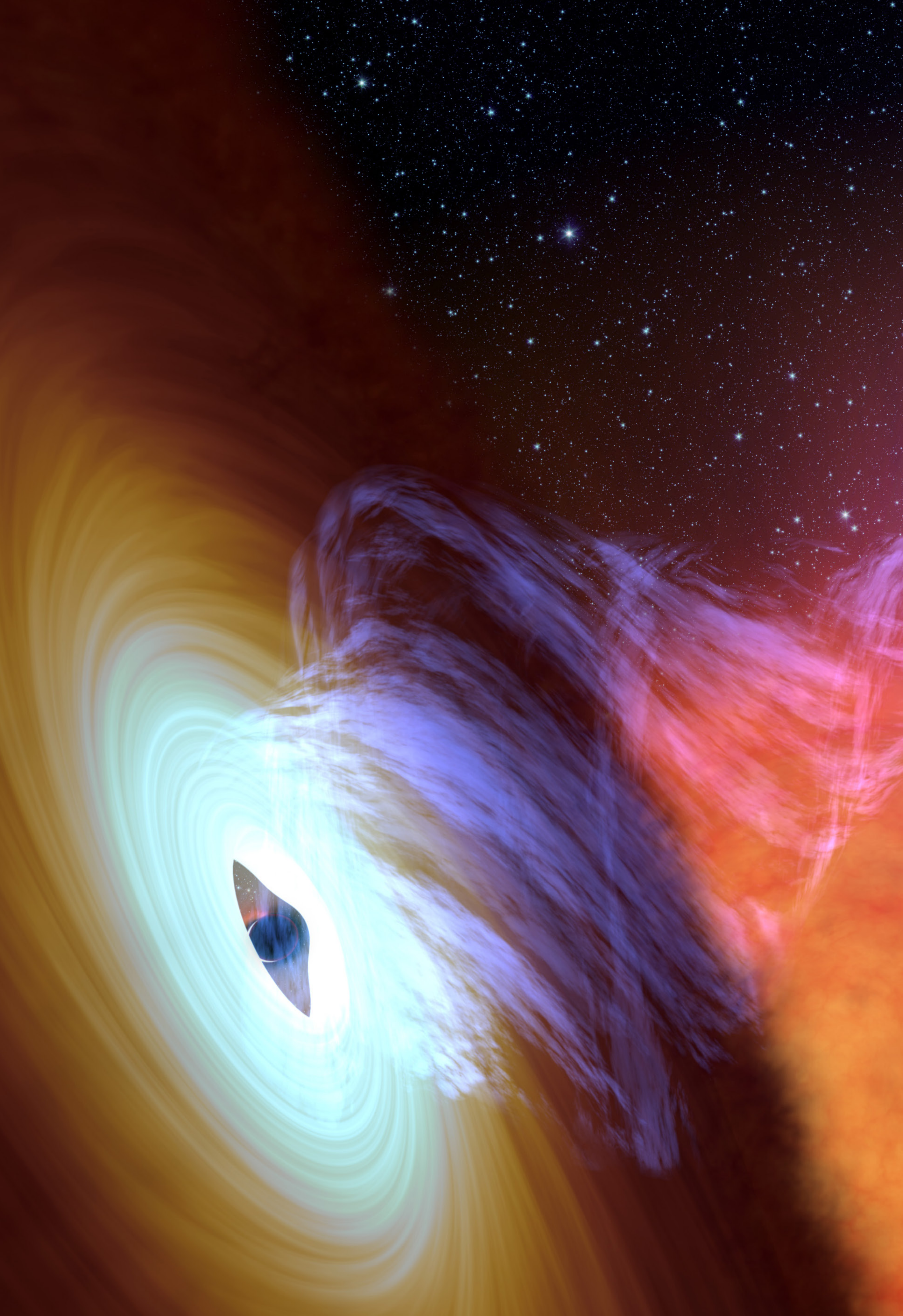


Bizarre Black Holes and the Observers Who Love Them

by Erin Kara

Even after a decade as a professional astronomer, I still get a dopamine rush right before taking a first glance at a new observation.

Those X-ray photons, produced at the heart of a distant galaxy, managed to escape the strong gravitational potential of a supermassive black hole, travel for billions of years through the expanding universe, only to land squarely on our detector, and regale us with stories of their long journey. And yes, sometimes those photons play coy, and it can be hard to interpret what they are saying, but, to me, that is all part of the fun. In this piece, I want to tell you my story, working with friends and colleagues at MIT and across the globe, to make sense of the most bizarre black hole we've ever seen. It is one of those black holes that keeps you up at night, wondering how nature has conspired to break all our "rules," and what is best of all: this phenomenon may be far more common than we ever realized.

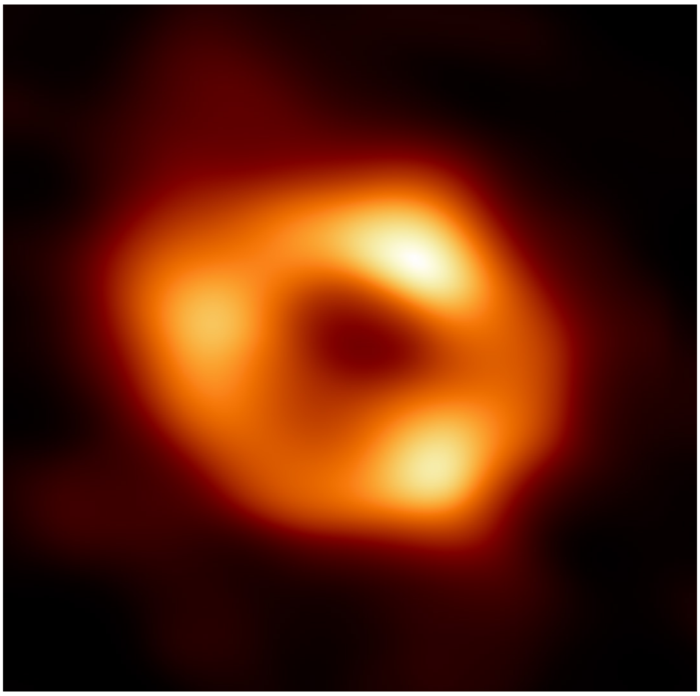


FIGURE 1: The Event Horizon Telescope image of Sagittarius A*, the supermassive black hole at the center of our Milky Way galaxy. Credit: EHT Collaboration

A supermassive black hole primer

Before we break the rules, let me tell you what those rules actually are. Sitting at the heart of every massive galaxy is a black hole that is a million to a billion times the mass of the Sun. These so-called supermassive black holes have garnered much media attention in recent years, thanks first to the pioneering work of 2020 Nobel Laureate and MIT alumna Andrea Ghez, who proved the existence of the black hole at the center of our Milky Way galaxy, followed by the Event Horizon Telescope image of the shadow of that very same black hole (*Fig. 1*). Our black hole (known as Sagittarius A*) is not actively feeding on much gas from the Milky Way. In fact, it is precisely because of the lack of active accretion of dense, million-degree Kelvin gas on to Sagittarius A* that we are able to get a clean, resolved image of the spacetime close to the event horizon. But not all black holes are so quiet.

About one percent of all supermassive black holes are known as Active Galactic Nuclei (AGN). These black holes are "active" because they are growing by about one solar mass of gas per year. In these AGN, gravitational forces pull gas towards the black hole, but collisions and angular momentum conservation cause the gas to form a dense, thin disk around the black hole [1]. The gas is hot and mildly ionized, so as it rotates around the black hole, it produces magnetic fields that create turbulence in the disk (*Fig. 2*). This turbulence transfers angular momentum outward, allowing material to fall towards the black hole. As material flows inward, gravitational energy is dissipated as heat, which causes the disk to emit thermal radiation, mostly at optical and ultraviolet wavelengths. So while the common trope is that black holes are dark, desolate objects, they are, in fact, the most luminous objects in the Universe.

Why do only one percent of black holes shine? Much evidence suggests that AGN are not special black holes; in fact, those that are quiescent are probably just quiescent, right now. The prevailing theory is that all supermassive black holes must have been active at some point (that is how they grew so big in the first place!), and they turn on and off every ~10 million years or so, as matter falls in episodically.

If we want to understand how black holes grow, and how they influence their environments, we need to understand the innermost regions of black holes, where most of the gravitational energy from inflowing matter is released. This region is best probed by X-ray observations. While the entire accretion disk shines brightly in optical and UV, copious amounts of X-rays originate from a hot (billion-degree) plasma close to the black hole called the X-ray corona (*Fig. 2*). Optical and UV photons from the accretion disk scatter off mildly relativistic electrons in the corona. This Inverse-Compton Scattering boosts the UV photons to X-ray energies [2]. While X-rays appear to be ubiquitous in AGN, astronomers have for years debated what this corona actually is, and how it is powered. Is it powered by the strong magnetic fields twisting, breaking and recombining close to the black hole? Is the corona tapping spin energy from the black hole itself? Could it be the launching point of the highly relativistic jets seen in some active galaxies?

We understand that X-rays are the telltale sign of active gas accretion on to a black hole, yet because the typical duty-cycle for black hole accretion to turn on and off is ~10 million years, it is challenging to probe the causal connection between gas inflow and radiation output. But sometimes nature throws you a bone, and that is where our real story begins.

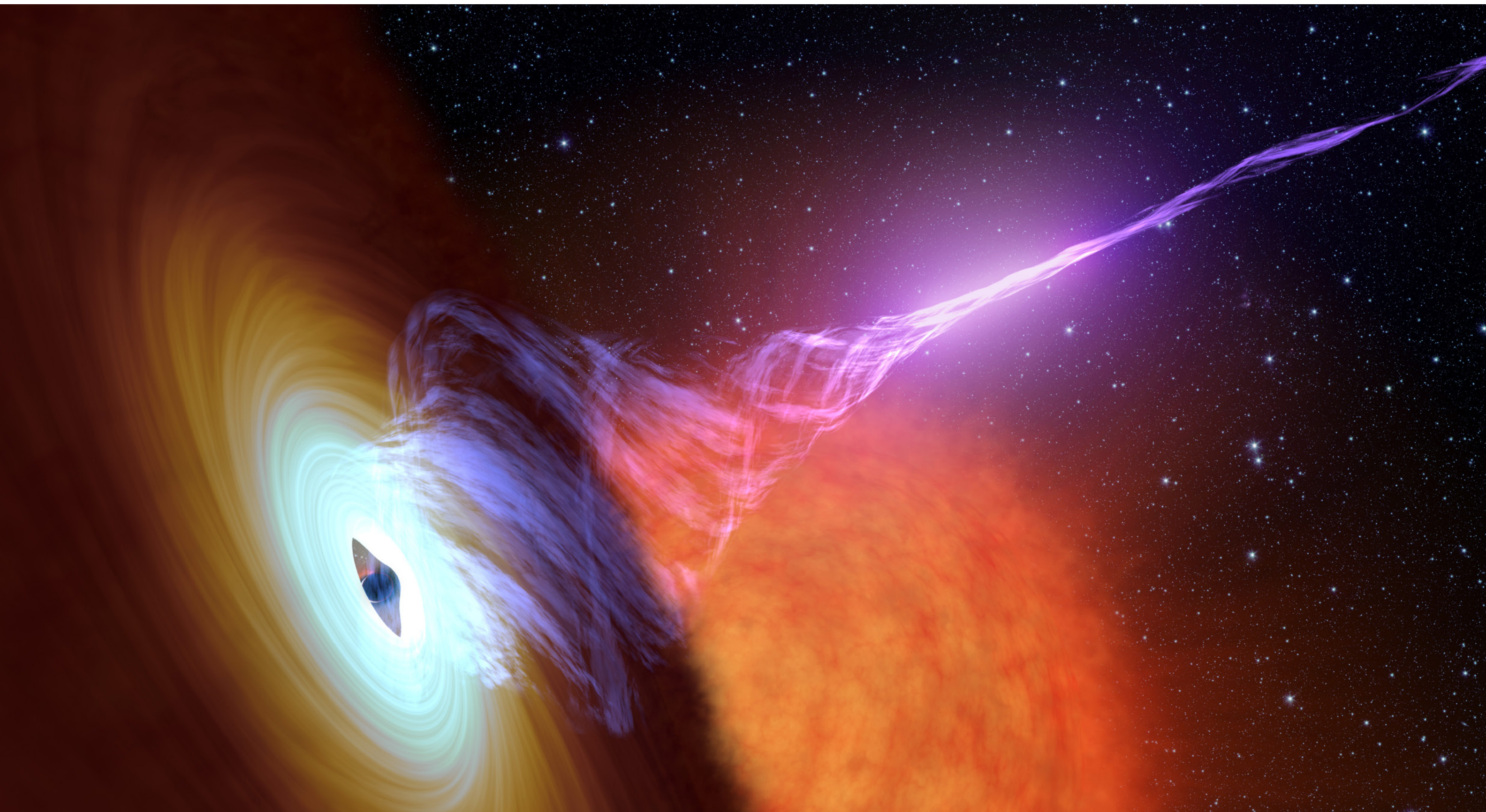
1ES 1927+654: The rebel black hole

In April 2018, my colleagues Iair Arcavi, Benny Trakhentbrot and Claudio Ricci came to me, asking my opinion about a puzzling AGN. They had found that the nucleus of a known AGN got suddenly brighter in the optical band. They originally suspected it was due to a supernova explosion near the center of that galaxy, but when they obtained spectra, they noticed that it was not a supernova explosion at all. This bright flash was due to an extreme accretion episode happening in this supermassive black hole, which resulted in a sharp rise in optical emission from the accretion disk.

Usually, material flowing in a thin accretion disk carries much angular momentum, which smooths over any rapid changes in the accretion rate to timescales of thousands of years. But it appeared my collaborators had found a black hole ramping up its accretion rate dramatically in just a few weeks. This black hole (called 1ES 1927+654, or 1ES for short)[3] is one of a new class of objects called "Changing-Look" AGN that are defying how quickly we thought you could feed a black hole. We do not yet know what causes this sudden inflow of gas, but we can use them as laboratories for seeing what happens when there is a sudden onset of gas accretion.

Needless to say, I was very excited about this exotic AGN and suggested we request X-ray observations with the newly launched

FIGURE 2: An artist's rendering of an actively accreting black hole, where gas funnels in towards the black hole through an accretion disk (orange), and X-rays are produced in a hot, relativistic plasma, called the corona (purple). Credit: NASA



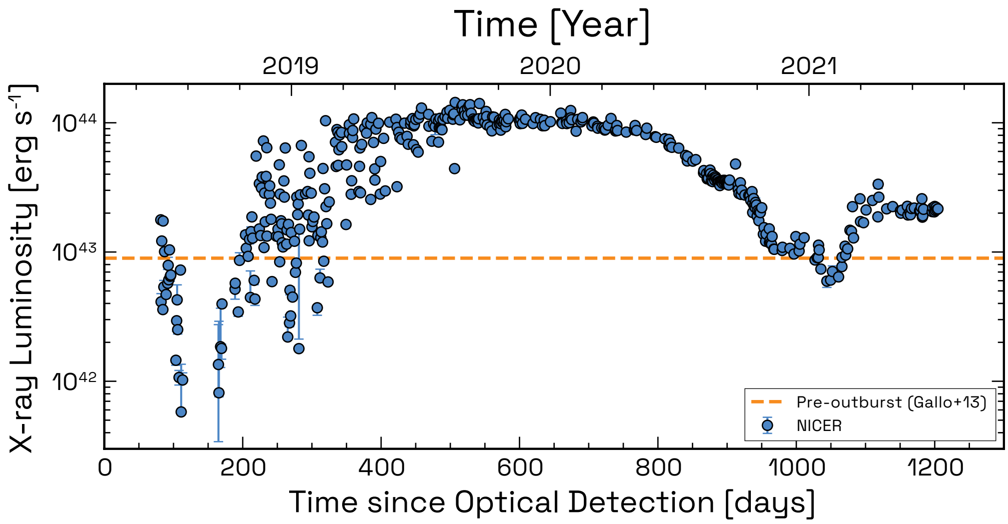


FIGURE 3: The X-ray luminosity over time of our exotic black hole, 1ES. For ~18 months, this AGN was the brightest AGN in the X-ray sky, but eventually returned to its pre-outburst luminosity. Credit: Adapted from Masterson, Kara, *et al.*, *The Astrophysical Journal*, 2022.

NICER Observatory, which is currently perched on the International Space Station. NICER is a joint NASA-MIT telescope, about the size of a washing machine, and while small, it is agile, and can observe several targets even in a single 90-min orbit around the Earth. This was the perfect observatory to keep track of this highly variable AGN, and to probe how its X-ray corona responded to a change in accretion on to the black hole. NICER principal investigator and MIT alumnus Keith Gendreau quickly started observing our exotic source, and what we observed was so compelling that NICER to this day continues taking observations every one to three days, making 1ES the most well-observed AGN in the NICER data archive (*Fig. 3*).

There is nothing more exciting than new data, and our rebel black hole did not disappoint. While the optical spectra had shown a sharp rise, the X-ray spectra (from NICER and other X-ray telescopes, *e.g.*, XMM-Newton and NuSTAR) revealed that the high-energy X-rays from the corona had disappeared (*Fig. 4*). High-energy X-rays are ubiquitous in AGN, but here for the first time, we were witnessing an AGN that had lost its corona. In its place, we observed low-energy thermal blackbody emission from a hot (10^6 K) inner accretion disk, and a very conspicuous and mysterious emission line at 1 keV (more on that later). Baffled, we continued to monitor the source.

Over the summer of 2018, every new NICER observation presented a new thrill. Usually X-ray coronae in typical AGN can exhibit ~40% variation in brightness from day to day, but 1ES had no X-ray corona (only thermal emission from the disk) and somehow was still varying by as much as two orders of magnitude in just a few hours. This kind of extreme, rapid variability has never been seen in any other AGN. Then, about 50 days into monitoring, the X-ray flux began to drop altogether. We thought, "Well, that was a fun ride," and started planning how to wrap up this project.

After about another 50 days of non-detections, NICER was about to throw in the towel and stop observing the source, when we got another surprise: the X-ray flux began to rise again! And not only that, as we watched the source for the next year, we found that the high-energy X-rays from the corona were also recovering. *We were witnessing the ignition of an X-ray corona for the first time.*

By the time I started my faculty position at the MIT Kavli Institute for Astrophysics and Space Research in July 2019, 1ES was the brightest AGN in the X-ray sky, and would remain so for almost a year. Our result was published in July 2020, and appeared in *MIT News* online with the headline, “In a first, astronomers watch a black hole’s corona disappear, then reappear.” I later learned that it was the #6 top-viewed story of 2020.

Digging deeper after a return to normal

During the following two years, 1ES settled into its new state. The X-ray emission began to stabilize, no longer showing dramatic, intra-day, order-of-magnitude variability. The corona slowly became hotter and more powerful. The accretion rate asymptoted back to its historic level, and the X-ray spectrum eventually looked just like it had before this whole thing started.

With this stabilization and return to normal, we thought it was a good moment to begin reflecting more deeply on what had actually just occurred. I pitched the project to then first-year graduate student Megan Masterson, and she quickly began to dive deep into this wealth of data (no small feat as we had accrued over 500 NICER spectra over three years). Each week, Megan and I would meet to try to make sense of its rich and unprecedented phenomenology. One key clue: the mysterious 1 keV spectral line.

We noticed early on that the spectrum of 1ES was not a simple thermal spectrum (as expected from the accretion disk). In addition, there was a strong, broad 1 keV line present (*Fig. 4*). Broad fluorescence lines are very common in AGN. The most prominent broad emission line is the iron K alpha line at 6.4 keV, which is caused by the high-energy corona shining brightly on the disk and exciting iron atoms therein. These lines are broadened by the relativistic nature of the inner accretion disk, where fluorescing atoms are rotating at a good fraction of the speed of light (thus

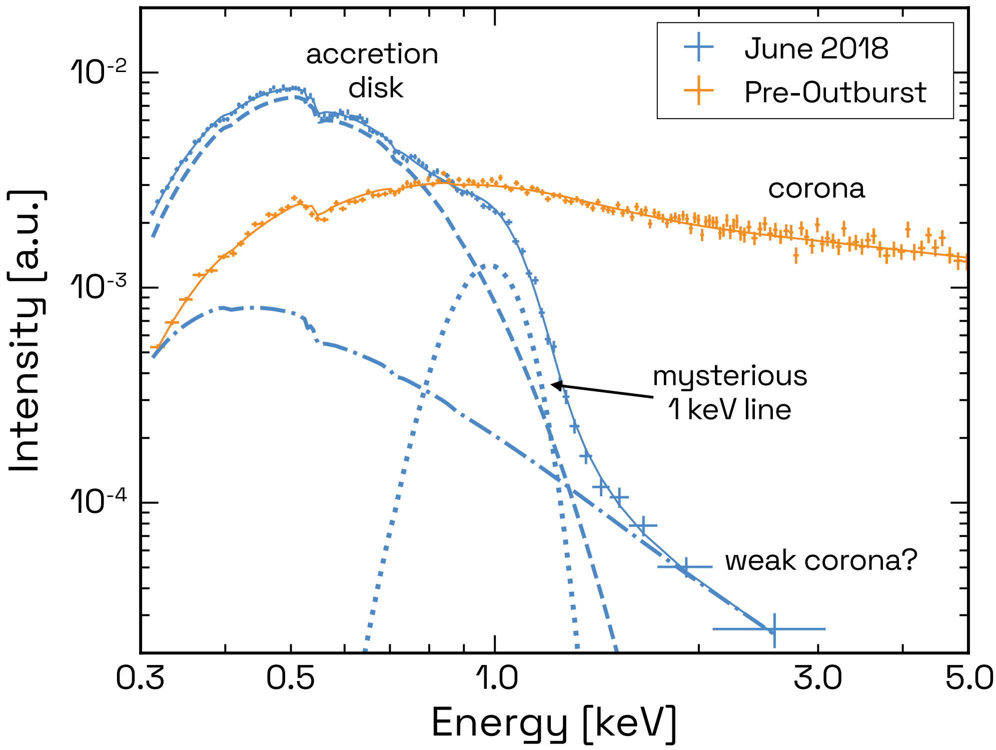


FIGURE 4: A comparison of the X-ray spectrum of 1ES pre-outburst (orange) and at the beginning of the outburst (blue). Before the outburst, this AGN showed a strong X-ray corona (as is standard in AGN), but the corona disappeared after onset of the strong accretion episode. Instead, we observed thermal emission from an accretion disk, and a broad line at 1 keV. Credit: Adapted from Masterson, Kara, *et al.*, *The Astrophysical Journal*, 2022.

producing strong relativistic Doppler shifts), and exist in the strongly curved spacetime around the black hole (causing the lines to be gravitationally redshifted). 1ES 1927+654, despite having no corona, still showed a strong broad line, but it was not at the energy expected from typical fluorescence lines. Moreover, Megan found that the 1 keV line was only present at the chaotic beginning of the accretion event, and then quickly subsided as the system stabilized.

The co-existence of the 1 keV line and the highly variable, thermal radiation is a strong constraint, and led us to an interpretation where the inner disk irradiates the remainder of the accretion disk at larger scales, causing a strong fluorescence line at low energies (*Fig. 5*). Because of their thin-disk geometry, typical AGN are not likely to exhibit much self-irradiation of their disks, but in highly accreting black holes the theoretical expectation is that the accretion disk becomes puffed up due to strong radiation pressure. In such a geometry, more radiation from the inner disk can intercept different portions of the disk. Moreover, when Megan modelled the observed spectra with this proposed scenario, she found the fluorescence lines were shifted to shorter wavelengths, indicating that the fluorescing gas is moving towards us with a velocity of up to 30% of the speed of light. Such velocities are expected for gas being lifted by radiation pressure in a highly accreting black hole. Future observations of 1ES and comparisons to other black holes undergoing such dramatic accretion episodes will allow us to confirm if this picture is robust. If so, the 1 keV line provides an important diagnostic for measuring the geometry and dynamics of accretion flows in a very poorly understood regime.

Next on the horizon

After its highly chaotic, rapid accretion episode, 1ES appears to have settled back down to its historic state, but we know better than to leave this AGN alone for too long. NICER continues to keep an eye on it, and Megan was recently awarded time with the XMM-Newton and NuSTAR Observatories for deep observations that will take place in summer 2022.

1ES has been one of the great pleasures of my work over the past two years. It got my creative juices flowing when I could otherwise only think about the running *NYTimes* COVID dashboard. In a time of isolation, it kept me connected to my students, collaborators and colleagues, as we collectively scratched our heads over this ever-changing puzzle. And it gives me hope and excitement for what comes next, as we discover more of these extreme transient events that are reshaping our view of the Universe.

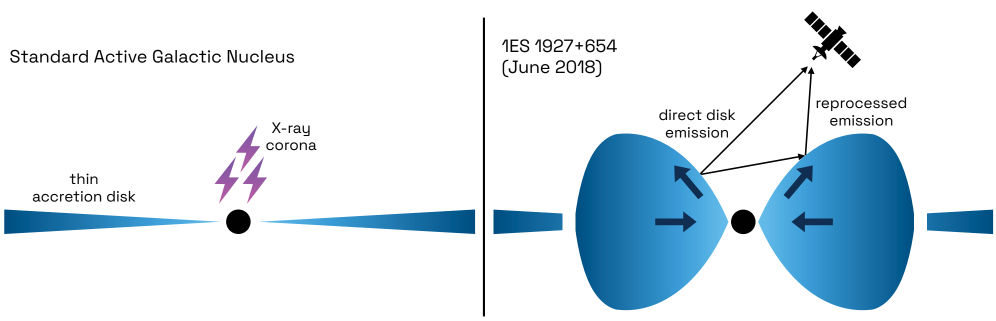


FIGURE 5: (Left) Schematic of a typical AGN, where the accretion disk (blue) is thin, and the corona (purple) is present. (Right) Schematic of our proposed geometry for 1ES, where rapid accretion leads to a very puffy accretion disk and destroys the corona. Credit: Adapted from Masterson, Kara, *et al.*, *The Astrophysical Journal*, 2022.

PROFESSOR ERIN KARA is an observational astrophysicist, working to understand the physics behind how black holes grow and affect their environments. She has advanced a new technique called X-ray reverberation mapping, which allows astronomers to map the gas falling onto black holes and measure the effects of strongly-curved spacetime close to the event horizon. She also studies a variety of transient phenomena, such as tidal disruption events and Galactic black hole transients. In addition to her observational astrophysics research, Kara works to develop new and future space missions, including the XRISM Observatory, a joint JAXA / NASA X-ray spectroscopy mission to launch in 2023, and is the Deputy Principal Investigator of the AXIS Probe Mission Concept.

Originally from Bethlehem, PA, Kara attended Barnard College of Columbia University, where she obtained a BA in physics with a minor in art history. After graduating in 2011, she moved to the UK on a Gates Cambridge Scholarship to study for a master's and a PhD from the Institute of Astronomy at the University of Cambridge. In 2015, she was awarded a NASA Hubble Postdoctoral Fellowship, which she took to the University of Maryland and NASA's Goddard Space Flight Center. In 2018, Kara became the Neil Gehrels Prize Postdoctoral Fellow at the University of Maryland, and joined the faculty of MIT as an assistant professor of physics in July 2019. Recently, the American Astronomical Society awarded her the 2022 Newton Lacy Pierce Prize for "outstanding achievement, over the past five years, in observational astronomical research."

ENDNOTES

[1] I recently told my 8.02 students that while people often think black holes indiscriminately suck everything in, the more puzzling question to physicists is how to overcome angular momentum, so that gas actually falls into the black hole. The answer: magnetic fields!

[2] The electrons in the corona are relativistic because the gas is so hot that the thermal speeds are roughly the speed of light. Each photon-electron scattering results in the electron depositing some of its momentum onto the photon, like a two-stage rocket.

[3] On the origin of the name 1ES 1927+654: Astronomers are notorious for giving the dullest names to the most exciting phenomena in the universe. The last seven numbers refer to the sky coordinates of the AGN, and 1ES identifies that this source was discovered by the Einstein Telescope (the first fully-imaging X-ray telescope, launched in 1978), in its first Slew Survey.