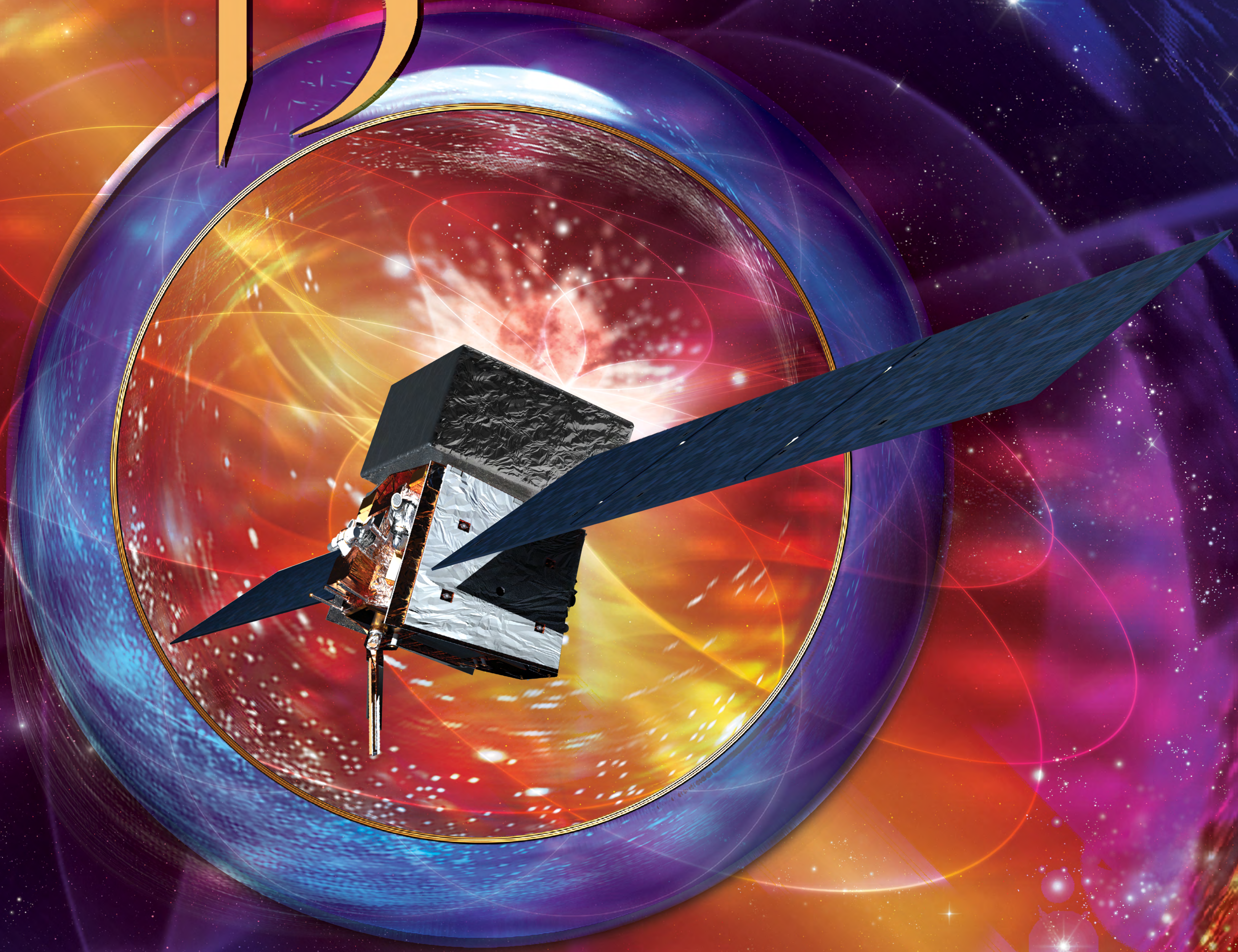
National Aeronautics and Space Administration

OUR HIGH-ENERGY UNIVERSE

15 YEARS



WITH THE FERMI GAMMA-RAY SPACE TELESCOPE

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OUR HIGH-ENERGY UNIVERSE

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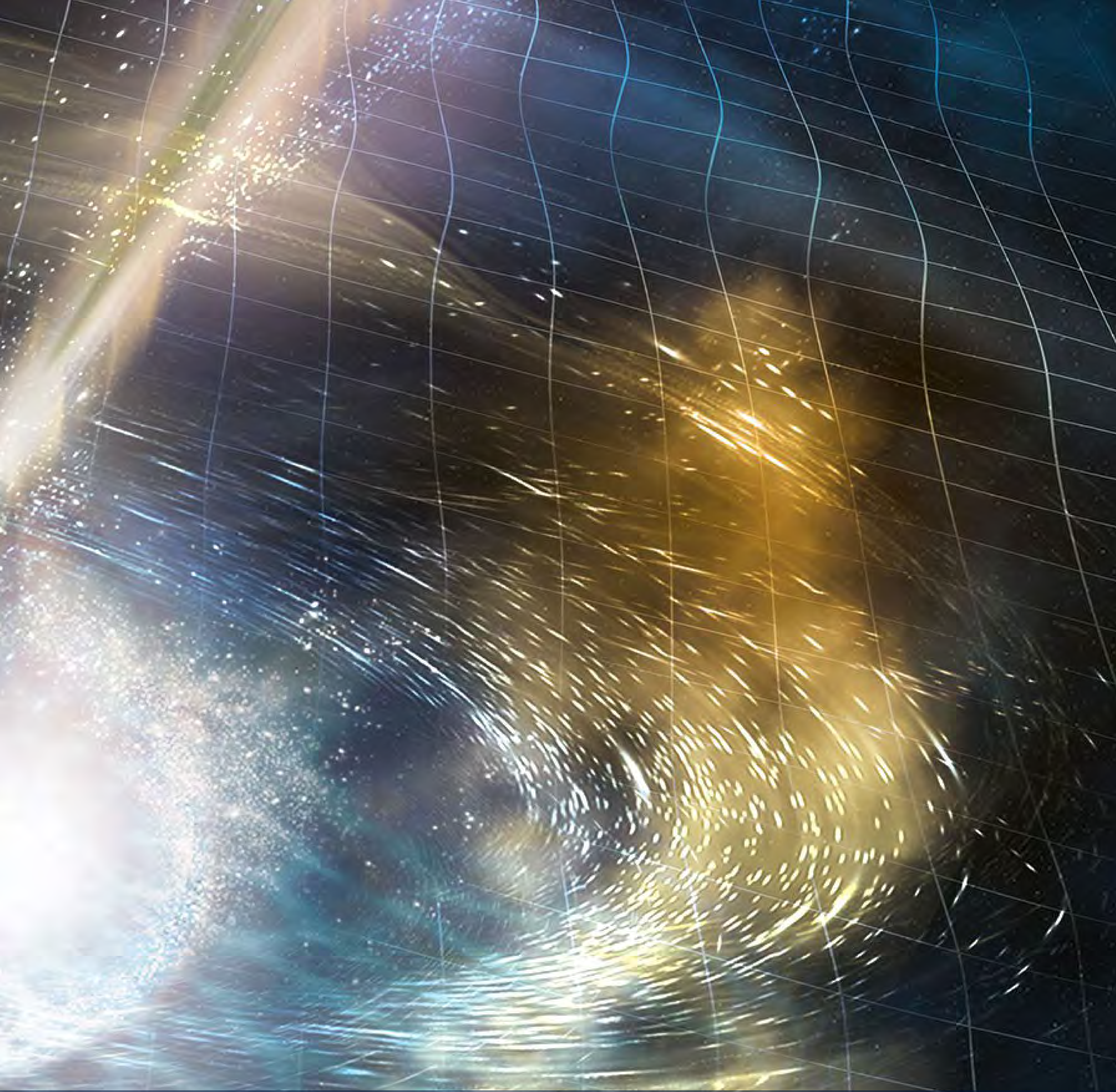
Cover Art Credit: NASA/Sonoma State University, Aurore Simonnet

Our universe is full of wonder and mystery. There are blinding novae, massive black holes, and an unfathomable number of galaxies with an incomprehensible number of stars. Scientists study these mysteries and countless others, working to enhance our understanding of the universe we call home. For 15 years, NASA's Fermi Gamma-ray Space Telescope has been an integral part of the mission of scientific exploration. This e-book will guide you from the telescope's inception and construction to its daily operations and untold discoveries. You will journey across the universe, from our planet to distant galaxies, learning about gamma-ray astrophysics and Fermi's contributions along the way. Importantly, you will learn that Fermi's mission is far from over; there are many more questions to be asked and Fermi is already at work answering them. So join us on this journey through the cosmos and get ready to learn more about the incredible inner workings of our high-energy universe.



This illustration shows two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the burst of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted, glowing with visible and other wavelengths of light.

Credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet

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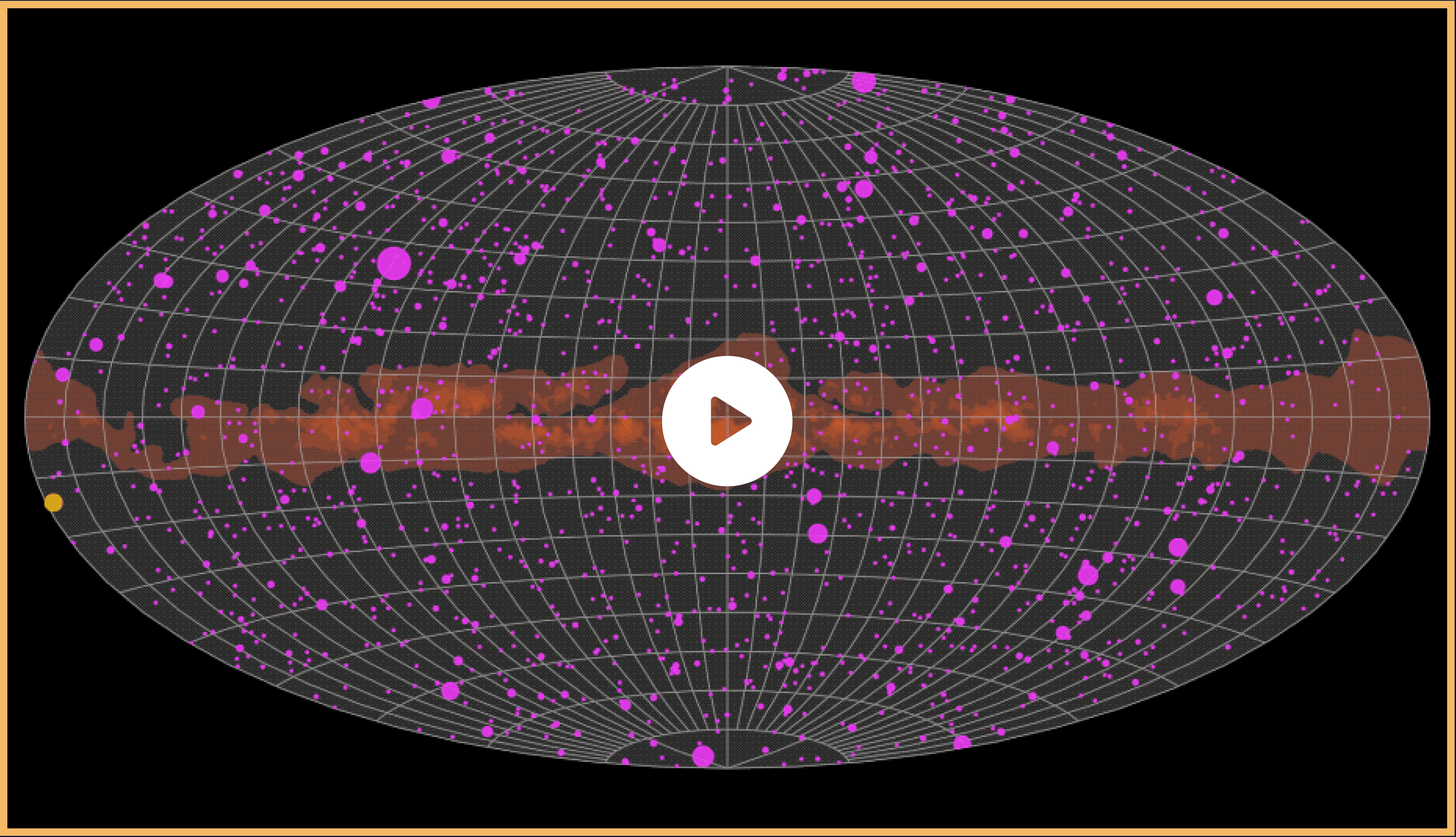


Watch a cosmic gamma-ray fireworks show in this animation using data from Fermi's Large Area Telescope (LAT) from February 2022 to February 2023. Each object's magenta circle grows as the source brightens and shrinks as it dims. The yellow circle represents the Sun following its apparent annual path across the sky. The animation shows a subset of the LAT gamma-ray records now available for more than 1,500 objects.

Credit: NASA's Marshall Space Flight Center/Daniel Kocevski

On sunny June 11, 2008, NASA's Gamma-ray Large Area Space Telescope (GLAST) launched from Cape Canaveral on Florida's eastern coast. The telescope soared above anxious crowds and into the clouds on a Delta II rocket until it reached its destination safely, 350 miles above Earth. For the next two months, scientists tested and calibrated GLAST's instruments as the telescope orbited Earth every 96 minutes. The telescope worked as planned. On August 26, 2008, it adopted a new name chosen through a public competition: the Fermi Gamma-ray Space Telescope, named for pioneering physicist Enrico Fermi. Though its primary mission was to last five years, the spacecraft has surpassed all hopes and expectations, reaching 15 years of operation with no sign of slowing down. Every day, Fermi provides unprecedented gamma-ray data that shapes groundbreaking discoveries for astronomers and astrophysicists around the world.

Scientists began conceptualizing the nearly $1 billion Fermi satellite more than 16 years before its launch. The astronomical community had long wanted a telescope to better study high-energy physics, a desire only heightened by the retirement and intentional deorbiting of NASA's Compton Gamma Ray Observatory in 2000. NASA built Fermi as Compton's direct descendent, with a team that included many of the same people who worked on Compton. Fermi has always been an international collaborative effort, with important contributions from the U.S. Department of Energy and partners and academic institutions in France, Germany, Italy, Japan, and Sweden. When Fermi began operations in 2008, the speed and depth of its observations astounded scientists. In just 95 hours, Fermi generated a map of the gamma-ray sky that took years for Compton to produce.

Scientists and their families watch the GLAST launch from NASA's Goddard Space Flight Center on June 11, 2008.

Credit: National Archives (255-GSD-G-2008-0298-019)

Fermi studies some of the highest-energy light in the universe: gamma rays. We can't see gamma rays with our unaided eyes. Earth's atmosphere protects us from the damaging nature of high-energy light, but it also prevents ground-based telescopes from observing it directly. Fermi provides a unique view of the universe and allows us to study some of its most curious phenomena. Fermi's position in low-Earth orbit enables it to detect thousands of gamma-ray sources and reveal new high-energy discoveries. Fermi is the first imaging gamma-ray telescope to survey the entire sky each day, with one full survey taking only three hours. Importantly, Fermi does not work alone; some of its important discoveries have also relied on observations from the likes of NASA's Neil Gehrels Swift Observatory, Hubble Space Telescope, and James Webb Space Telescope.

Fermi's groundbreaking observations enable us to study phenomena from cosmic rays and dark matter to colliding neutron stars and gigantic gamma-ray-emitting structures in our Milky Way galaxy known as the Fermi Bubbles. Today, scientists carry out research at the forefront of astronomy and astrophysics using Fermi, and will continue to do so as we keep probing the wonders of our high-energy universe.

NASA's Gamma-Ray Large Area Space Telescope (GLAST) launched from Cape Canaveral Air Force Station's Launch Pad 17-B at 12:05pm EDT on June 11, 2008.

Credit: NASA/Jerry Cannon, Robert Muray

Fermi's Namesake

The Fermi mission undertook great efforts to select a name for the pioneering GLAST satellite. Enrico Fermi, a trailblazer in high-energy physics, was ultimately the right fit.

Enrico Fermi was born on September 29, 1901, in Rome, Italy. The son of a railway inspector and a schoolteacher, he showed promise in math and physics from an early age, completing his Ph.D. in physics by age 21. In 1926, Fermi discovered the laws that govern a type of subatomic particle now called fermions. He spent much of his early career studying general relativity and statistical and quantum mechanics. In 1934, Fermi showed that almost every element can undergo nuclear transformation when bombarded with neutrons, a discovery that helped lead to nuclear fission — the process that drives nuclear power plants. He received the Nobel Prize in Physics in 1938 and immigrated to the United States shortly thereafter. At the University of Chicago, Fermi directed a series of experiments that led to the first sustained nuclear chain reaction. As an expert on nuclear physics, Fermi was invited to become the associate director of the Manhattan Project at Los Alamos National Laboratory in New Mexico and was present for the Trinity test, where he calculated the force of the first atomic detonation. When he returned to Chicago in 1945, he turned his sights to high-energy physics — specifically, the origin of cosmic rays and subatomic particles.

Fermi passed away from cancer on November 28, 1954, in Chicago. He is remembered as a brilliant theoretical and experimental physicist. His legacy lives on in institutions such as the Fermi National Accelerator Laboratory outside Chicago; honors such as the U.S. Department of Energy's prestigious Enrico Fermi Award for science and technology; fermium, the 100th element in the periodic table; and the Fermi Gamma-ray Space Telescope.

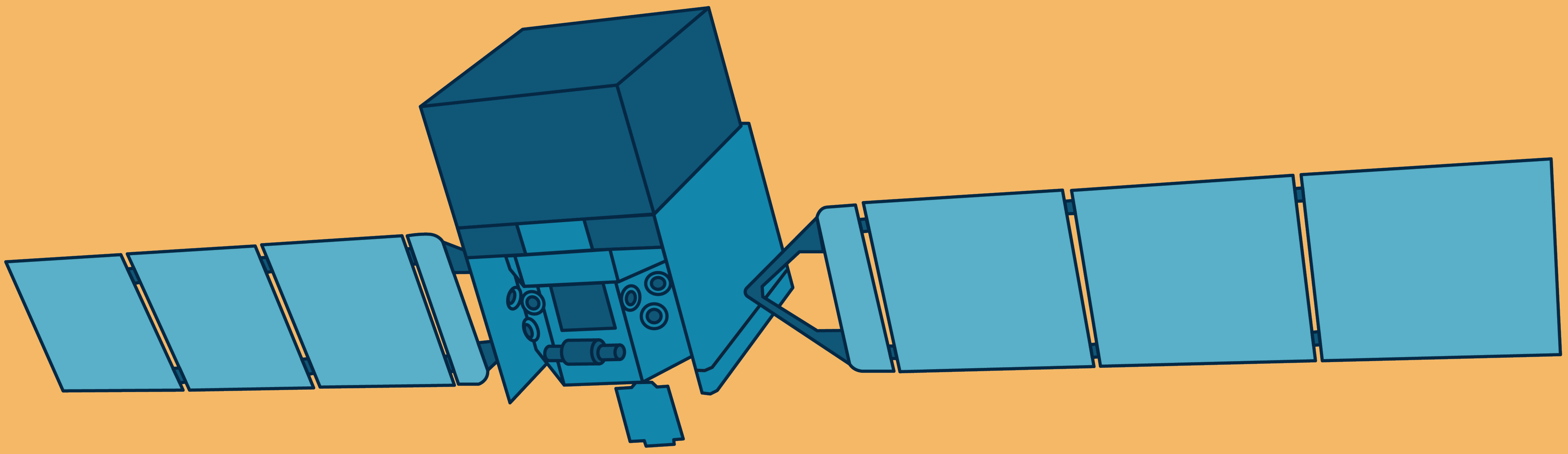
Enrico Fermi was a pioneer of high-energy physics and is the namesake for NASA's premier gamma-ray space telescope.

Credit: National Archives (434-OR-7(24))

Fun Fact:
An Incredible Name

About four months before Fermi, then called GLAST, launched into space, NASA put out a public request: help name the observatory. NASA wanted a name that would engage the public in gamma-ray science while conveying the excitement of the mission. The name also needed to be catchy, easy to say, and a good candidate for dinner table and classroom discussions.

While Enrico Fermi, the eventual namesake, would grant the observatory a name fitting all those criteria, the public had another candidate in mind. When results rolled in, one name kept appearing: The Incredible Hulk. While not a scientific figure, the Hulk brought gamma-ray science to the public over four decades before Fermi's historic mission began. In the popular comic series, a physicist named Bruce Banner gets transformed into the Hulk due to an accident involving gamma rays. This creative, if scientifically untrue, use of gamma rays in popular culture is an example of just how compelling high-energy science can be. While the observatory doesn't carry his name, we can thank Hulk for making people all over the world aware of the fascinating world of gamma rays – a goal Fermi hopes to advance.



An illustration of the Fermi spacecraft.

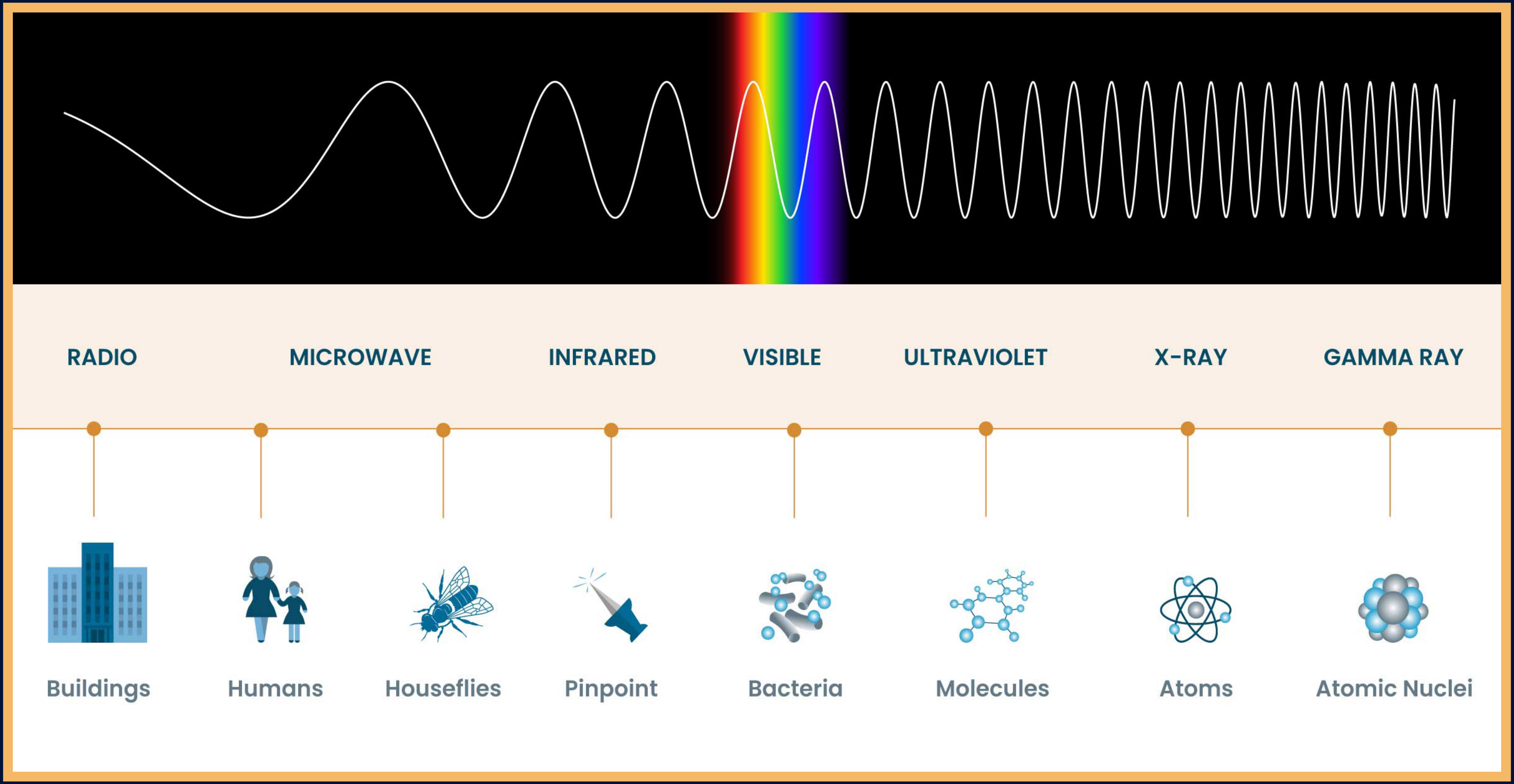
Credit: NASA

Gamma Rays

Seeing the Light

If you've ever made a phone call or seen a sunset, you've interacted with radiation. Radiation is the name for energy that moves from one place to another in a form that can be described as particles or waves. There are many types of radiation, and electromagnetic radiation — radiation that has both electric and magnetic fields — is represented on what's known as the electromagnetic spectrum. The scale on the electromagnetic spectrum is often in wavelengths, or the distance between peaks (or troughs) of each wiggle of a wave of radiation, which directly translates to energy. The scale can also be in the wave's frequency or energy. You may already think of sound or light as traveling in waves, but this is true for all electromagnetic radiation; each type has a characteristic band of wavelengths that scientists can use to identify it.

Visible light is only one part of the electromagnetic spectrum, encompassing all that we see with our eyes. The band of wavelengths for visible light is typically 380 to 700 nanometers, with energies from 3.3 to 1.8 electron volts, respectively. Stars, galaxies, and material around black holes in our universe emit radiation with wavelengths and energies far outside the range of visible light. Telescopes help us view this radiation and piece together the hidden picture our universe is showing us.



The electromagnetic spectrum, showing the frequency of light waves at the top and the relative size of photons at the bottom. Gamma rays are the highest-energy form of light and span over eight orders of magnitude.

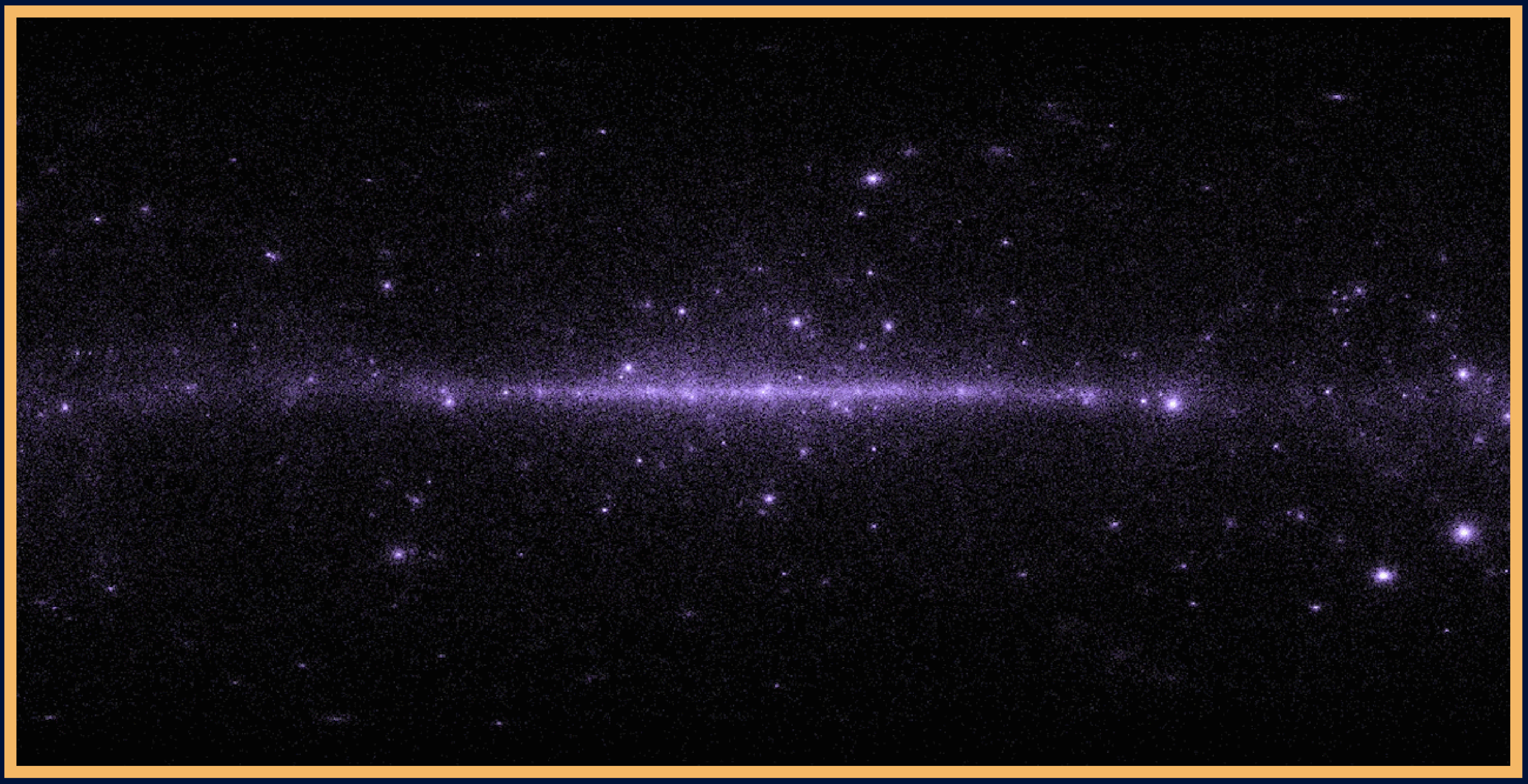
Credit: NASA and the Space Telescope Science Institute

What Are Gamma Rays?

Gamma rays are especially hard to understand because they are the form of electromagnetic radiation with which most people have the least familiarity. We use radio waves to play music in our cars, microwaves to cook our food, and X-rays to look at our bones; we feel infrared waves as heat from the radiator in the winter and ultraviolet rays from the sun in the summer. Of course, we see visible light, which lends itself exceedingly well to space images from telescopes like Hubble. Gamma rays are the least present in our everyday life, and we should be thankful — their radiation is harmful to our bodies.

Fermi is specifically designed to capture gamma rays, the type of electromagnetic radiation with the shortest wavelengths (fewer than 0.01 nanometers) and highest energies (greater than 500,000 electron volts). In fact, while the lower-energy boundary of gamma rays overlaps with the highest-energy X-rays, there is no known limit to how energetic a gamma ray can be. Fermi's range spans over eight orders of magnitude, and some observatories that study very high-energy gamma-rays have seen even more energetic particles than that! Gamma rays come from the hottest and most energetic objects in our universe, like neutron stars and the regions around black holes. Radioactive materials and thunderstorms also generate gamma rays here on Earth. If we were to see the night sky in gamma rays, it would be unfamiliar to us. Each time we looked upward, we would spot new sources of gamma rays among a consistent spattering of shining dots. Our Milky Way would glow constantly, and roughly once a day, a bright gamma-ray burst would catch our eye, lasting from fractions of a second to minutes. One might think of a cosmic firework show more than the starry constellations that have become familiar.

Since gamma-ray wavelengths are so short, they cannot be captured and reflected by mirrors, a crucial part of observatories like NASA's Hubble and Webb. Gamma rays would pass right through the spaces between the mirrors' atoms! Furthermore, Earth's atmosphere absorbs gamma rays, preventing scientists from building observatories on the ground that detect them directly. Fermi and previous gamma-ray observatories have had to take a different approach with the instruments they design to record gamma rays and reveal the mysteries our universe holds.



A gif of the gamma-ray sky as it might appear over the course of a year.

Credit: NASA's Goddard Space Flight Center Scientific Visualization Studio

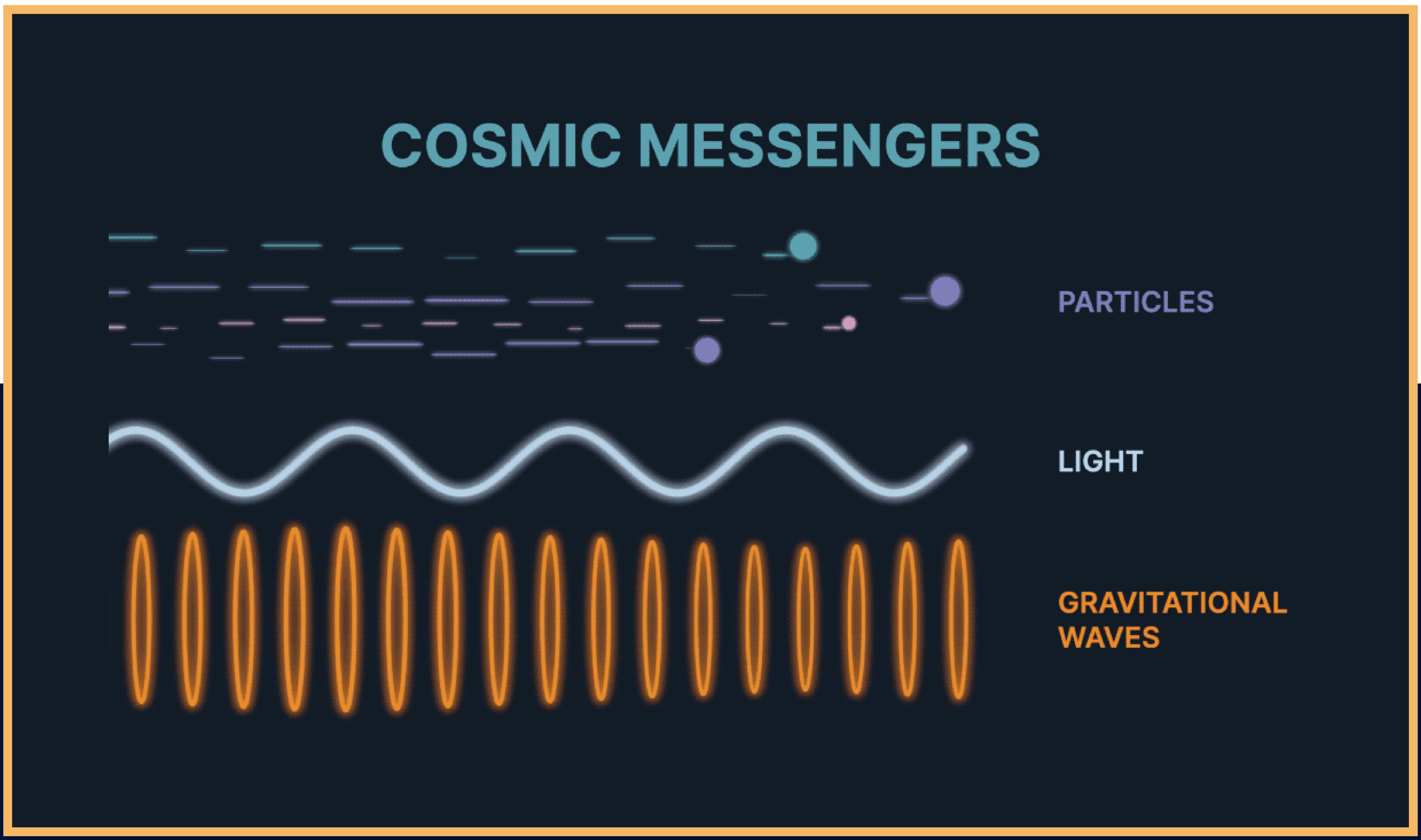
An artist's rendering of the jet of a gamma-ray burst breaking out of a collapsing star.

Credit: DESY, Science Communication Lab

Multimessenger Astronomy

Scientists use light across the electromagnetic spectrum to learn about the wonders of space. There are also cosmic signals outside of light that can tell us fascinating things. Light and other signals are powerful on their own, but they are even more illuminating when used together. We can think of them like our senses. On its own, the sense of sight is powerful — it can give us a sense of what an object is (for example, a radio). Combining sight with hearing can tell us both what the object is, and what it is doing (for example, a radio that is playing the jazz station). Using this technique in astronomy is known as multimessenger astronomy, and it is one of Fermi's most important areas in science.

The most common messengers are light, particles, and gravitational waves. Telescopes like Hubble, Webb, and Fermi detect light. Sensitive particle detectors exist on Earth and in space to catch neutrinos, highly energetic particles formed when cosmic rays interact. Gravitational wave detectors on Earth measure the ripples in space-time that travel across the universe. Scientists have also devised clever ways to search for gravitational waves using radio and gamma-ray telescopes. When scientists work together across all three messengers, we learn more about the universe than we can working independently. Collaboration is crucial for interpreting all the information that the universe is sending us.



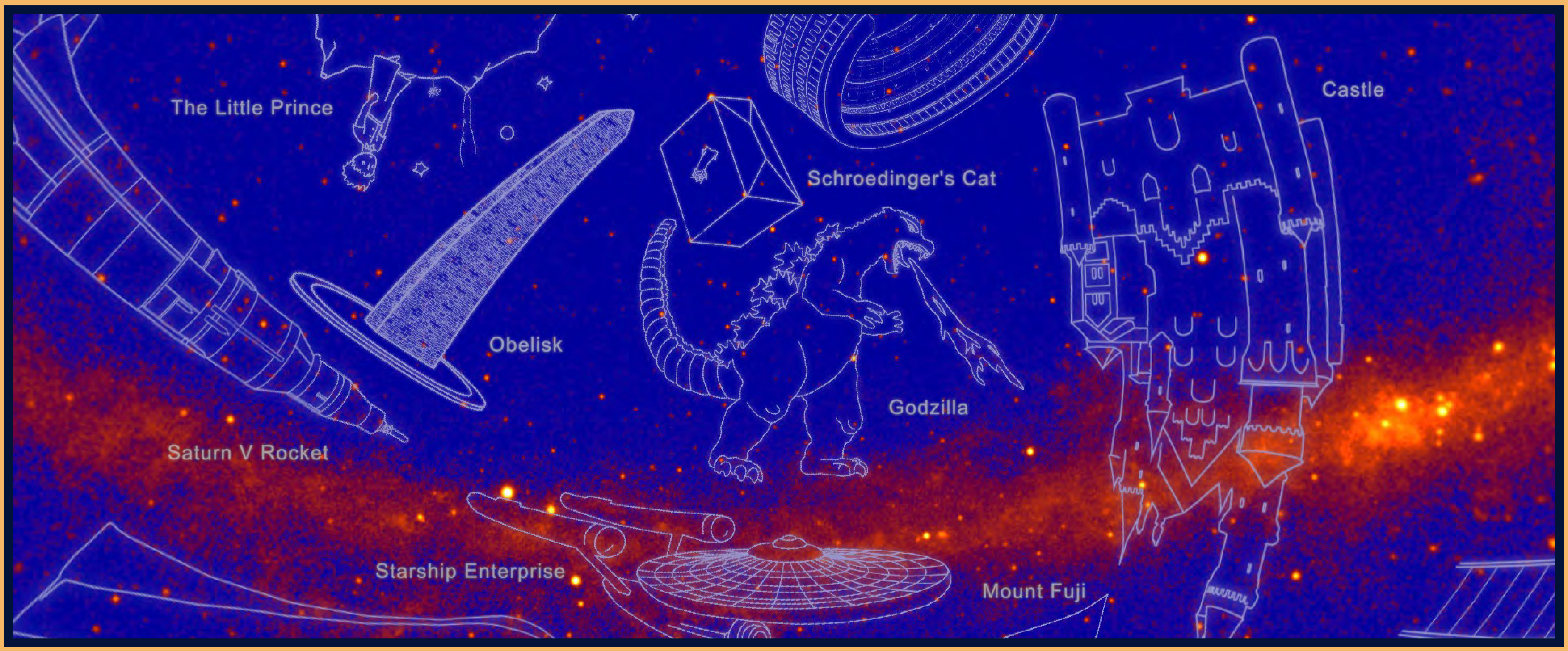
An animation of three messengers in multimessenger astronomy as they travel through space. Particles are shown on top, light in the middle, and gravitational waves on the bottom.

Credit: NASA's Goddard Space Flight Center

Fun Fact:
A Curious Kind of Constellation

Within the first decade of Fermi's mission, the science team had cataloged more than 3,000 individual gamma-ray sources — comparable to the number of bright stars that make up the constellations. To celebrate the achievement, the Fermi team created 21 of their own, unofficial constellations. What appear as "stars" in these constellations are in fact different bright gamma-ray sources like blazars, pulsars, and even normal galaxies similar to our Milky Way. Since we can't see gamma rays with our own eyes, we can only imagine the Fermi constellations as invisible shapes against our usually dark night sky.

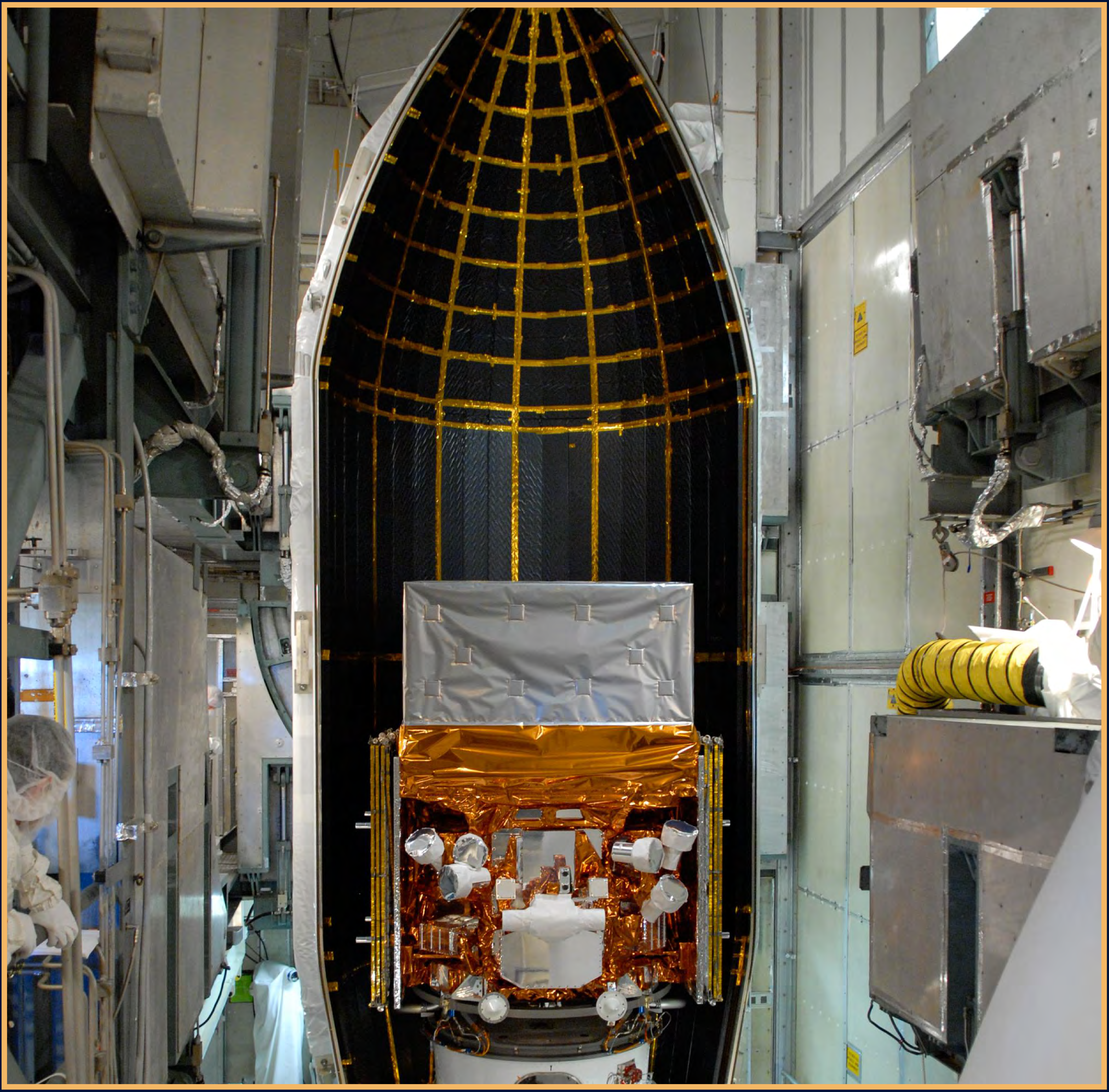
Some of the most popular Fermi constellations are Godzilla, the USS Enterprise from "Star Trek," the TARDIS from "Doctor Who," and the Incredible Hulk. Some constellations give nods to Fermi's partner nations, like Mt. Fuji to represent Japan and the Colosseum to represent Italy. Still others reference high-energy science, like Albert Einstein and a black widow spider, which references a type of star system where one star slowly devours another. The Fermi spacecraft itself makes an appearance, its solar panels stretched wide. The goal of the Fermi constellations is to celebrate the observatory's exciting discoveries, and to engage the public by tying pop culture to the frontier of gamma-ray science.



To celebrate the mission's 10th year of operations, the Fermi team devised a set of unofficial gamma-ray constellations, some of which are shown above. The prominent red band is the plane of our Milky Way; bright colors indicate brighter gamma-ray sources.

Credit: NASA

Observatory Design



The Fermi Gamma-ray Space Telescope when it was still GLAST, installed in the Delta II rocket that would carry it into space.

Credit: NASA/Jim Grossman

Hundreds of scientists and engineers collaborated to design and build an observatory that could meet the challenges of studying gamma rays. The technology had to be sensitive enough to detect the smallest-wavelength and highest-energy radiation, all while withstanding the harsh temperature, pressure, and radiation of space.

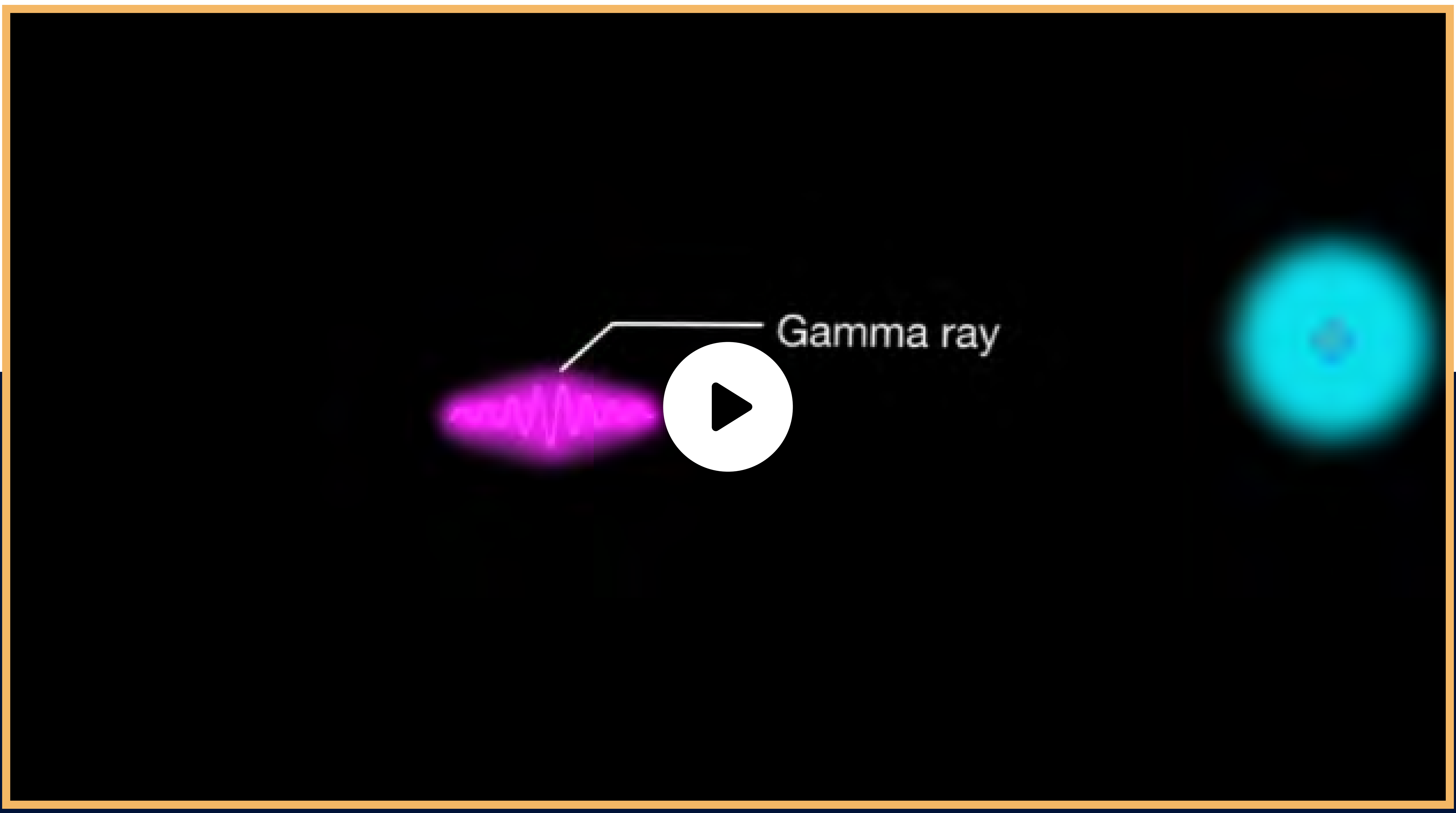
Not including its antenna and solar arrays, Fermi is 9.2 feet (2.8 meters) tall and 8.2 feet (2.5 meters) wide — about as tall as an ostrich and as wide as a school bus. With the solar arrays, Fermi is as big as a tennis court. Fermi weighs three tons and has nearly a million electronic channels. Despite its size, Fermi uses less energy than the average hair dryer. This is thanks to its low-power electronics, some of which engineers designed just for Fermi. Fermi's technology allowed for an impressive jump in the frequency and accuracy of gamma-ray observations over previous telescopes.

Engineers assemble Fermi's Large Area Telescope (LAT) instrument.

Credit: Courtesy of SLAC Communications

To capture and record elusive gamma rays, Fermi has two instruments: the primary Large Area Telescope (LAT) and the complementary Gamma-ray Burst Monitor (GBM). Scientists and engineers designed these instruments to survey the whole sky continuously to catch as many gamma rays as possible. The LAT views about one-fifth of the entire sky at all times, with the ability to locate bright gamma-ray sources to within one arcminute (about 1/30th the apparent diameter of the full Moon). The GBM can see two-thirds of the entire sky at any time, since Earth blocks the other third from view.

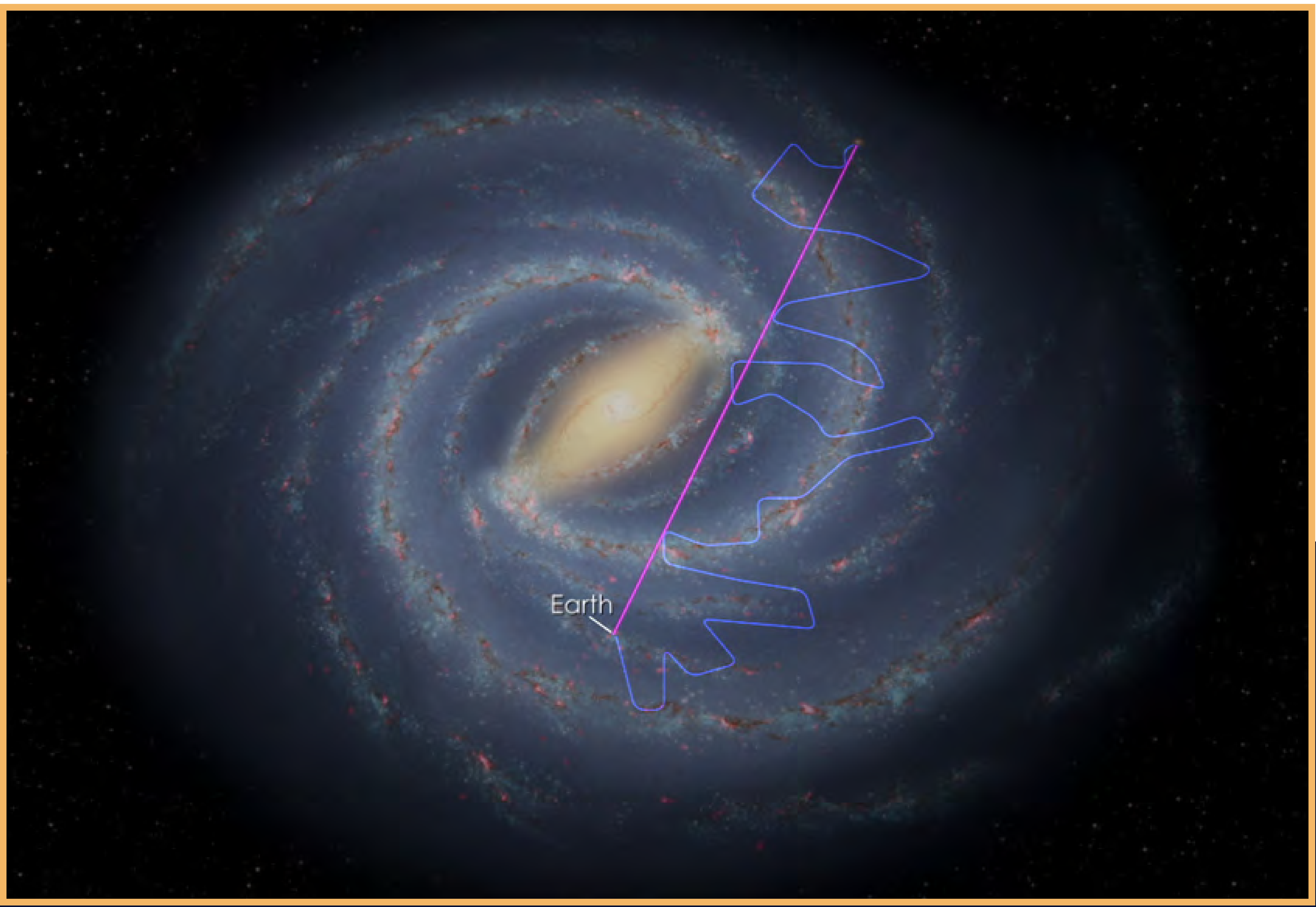
The LAT is a pair-production telescope, which works by converting gamma rays into pairs of electrons and positrons, the antimatter counterpart of the electron. When a gamma ray enters the telescope, it passes through many sheets of thin tungsten metal, which converts it into such a pair. A part called the tracker, composed of silicon detectors interleaved with the tungsten sheets, measures the path of the particle pair to determine the direction from which it entered the LAT. Next, the pair enters a device called the calorimeter, which measures the energies of the particles and — through conservation of energy — the original gamma ray's energy. The calorimeter is made of cesium iodide and works by producing a blue glow with intensity proportional to the energy of the particle pair. The LAT is around 30 times more sensitive than any previous space-based gamma-ray instrument.



Pair production occurs when a gamma ray grazes an atom and interacts with it. The reaction annihilates the gamma-ray photon and creates an electron and a positron — a matter/antimatter pair. The light energy converts into matter according to Einstein's famous equation, E=mc2.

Credit: NASA's Goddard Space Flight Center

One of the biggest challenges with detecting gamma rays is knowing what to filter out. Cosmic rays, highly energetic particles moving near the speed of light, can mask the fluxes of gamma rays that hit the LAT. For every gamma ray that enters Fermi, 100,000 to 1,000,000 cosmic rays do, too! Therefore, the LAT is built to reject 99.999% of the signals that cosmic rays generate. To do this, before hitting the main part of the instrument, all particles first enter an apparatus called the anticoincidence detector (ACD), the first line of defense against cosmic rays. Since cosmic rays are charged and gamma rays are not, cosmic rays passing through this detector produce a signal that tells the LAT to reject those data. The ACD is not perfect though, and some cosmic rays still sneak by. As the cosmic rays pass through the rest of the instrument, they leave additional clues (such as their shape and energy) that allow software to filter them out of the gamma-ray data. The carefully engineered system enables Fermi to identify the signals that come from gamma rays, and uncover our universe's high-energy mysteries.

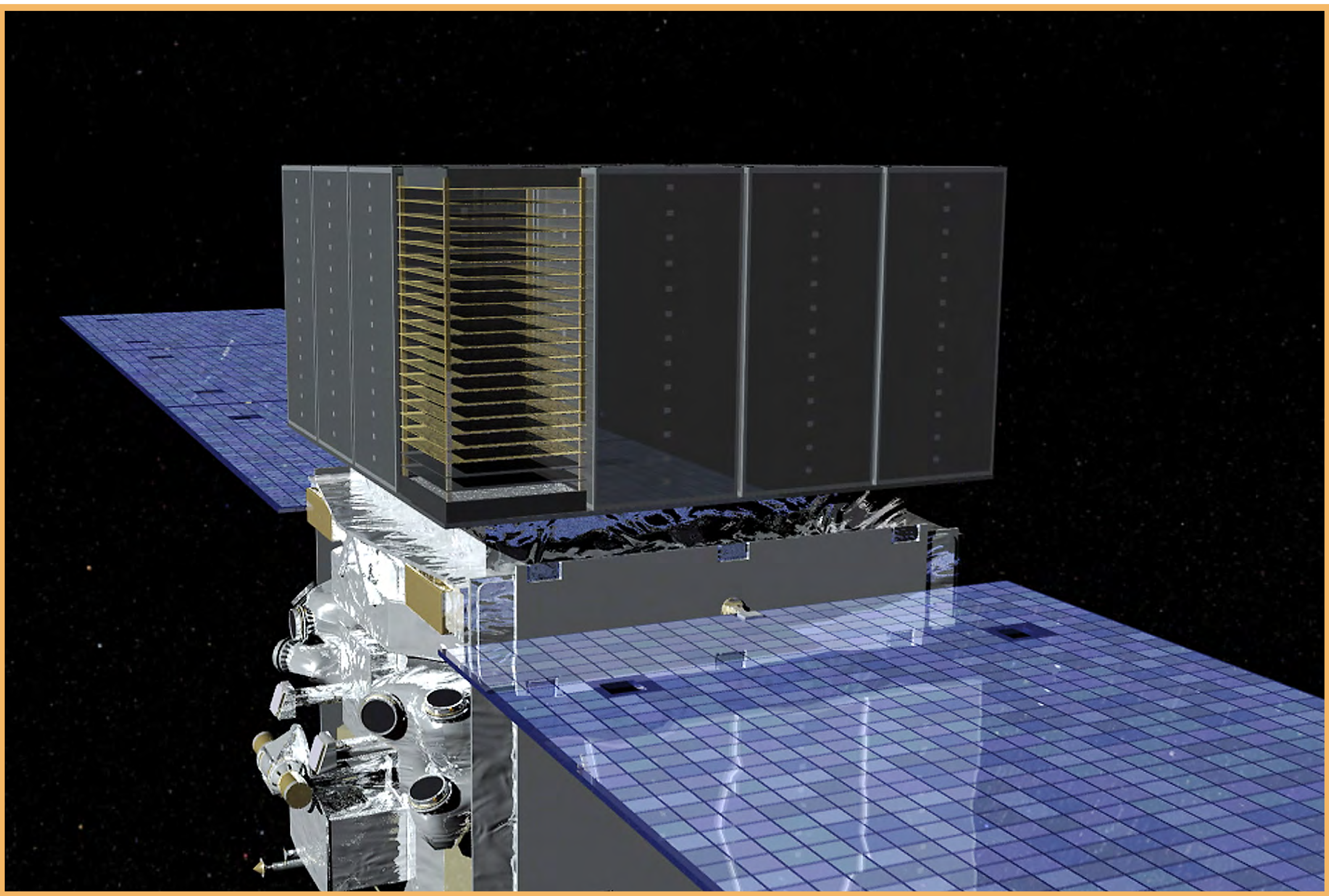


Cosmic rays (blue) wander randomly through the galaxy, while gamma rays (magenta) travel to Earth straight from their source.

Credit: NASA's Goddard Space Flight Center

The LAT primarily operates in "sky-survey mode." When surveying, the LAT views the entire sky in only three hours, detecting gamma rays with energies from 20 million to more than 300 billion electron volts. Fermi can also target specific areas of the sky for more focused observations. The U.S. Department of Energy and NASA collaborated to fund the LAT's development, with important contributions from academic institutions and partners in France, Italy, Japan, Sweden, and the United States.

In Palestine, Texas, on Aug. 4, 2001 — nearly seven years before launch — scientists flew a prototype of the LAT to around 100,000 feet via a scientific balloon to test its ability to operate in space-like conditions. This step is a crucial proof of concept when engineering a new type of space instrument. To the LAT team's delight, the instrument operated as planned, signaling that the design worked and that the materials could withstand space. This test was made possible through NASA's Balloon Program Office and Columbia Scientific Balloon Facility.



Fermi's LAT detects gamma rays by tracking the electrons and positrons they produce after striking layers of tungsten metal. The LAT is built to reject 99.999% of cosmic rays, which enter the instrument in significantly greater numbers than gamma rays.

Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

Fun Fact:
Dressing to Impress

The days surrounding Fermi's launch were full of excitement and anticipation. The engineers who had spent years designing and building the telescope hoped everything would work as planned, and the scientists were eager to see what Fermi would show them of the gamma-ray universe. After launch, there was an intricate sequence of instrument tests necessary to check the telescope's condition. The Fermi team was especially anxious to test the LAT, Fermi's primary instrument.

On the day the LAT was to be turned on, the LAT operations team decided on an unofficial dress code to celebrate: Hawaiian shirts. The control room was a blur of color as scientists and engineers came in to work flaunting their favorite florals, flip-flops, and leis. When the LAT turned on successfully, the team deemed their outfits a good luck charm. Hawaiian shirts have been an unofficial uniform for important days in Fermi's life ever since. After 15 years in orbit, the outfits have seemingly remained a good luck charm!

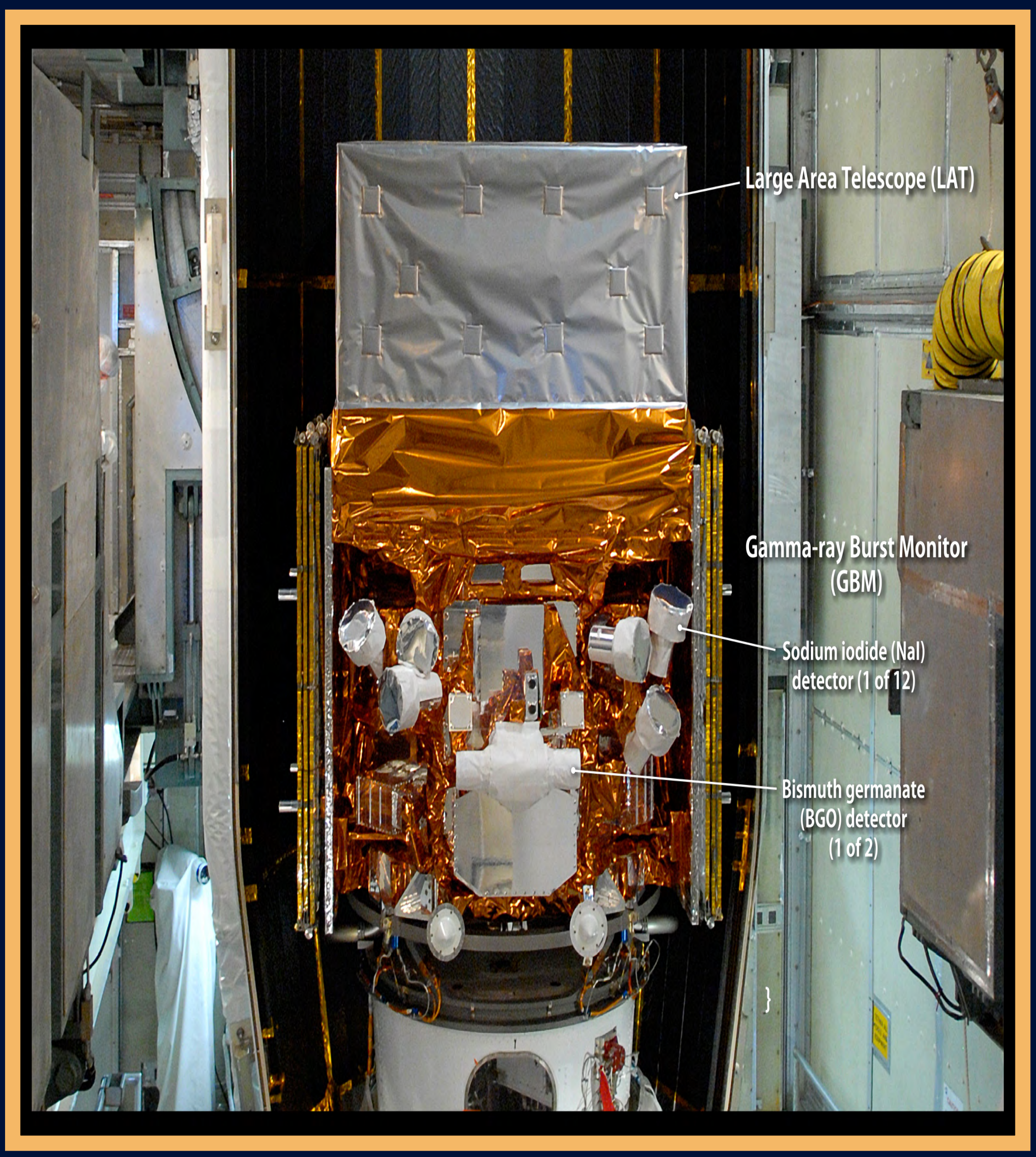
The Fermi LAT team sporting their unofficial uniforms.

Credit: Courtesy of Jana Thayer

As for the GBM, engineers and scientists specifically designed it to detect gamma-ray bursts, which are sudden flashes of gamma rays that occur about once a day anywhere in the sky. The GBM has a total of 12 low-energy detectors that detect gamma rays on the lower end of Fermi's range, 8,000 to 1 million electron volts. These detectors are shaped like thin disks and made out of sodium iodide. When a low-energy gamma ray enters one of these disk-shaped detectors, it produces a faint glow of visible light proportional to the energy of the gamma ray, which a sensor called a photomultiplier tube registers. Detectors pointed toward the gamma-ray burst glow more than detectors pointed away from the burst, since they detect more individual photons. Since the GBM detectors are spaced around the spacecraft, the instrument compares the rate of flashes from multiple detectors to triangulate the direction from where the gamma-ray burst came.

A Fermi scientist sets up the GBM detectors inside a test chamber at NASA's Marshall Space Flight Center. The chamber is temperature- and pressure-controlled so scientists can ensure the detectors will function well in space.

Credit: NASA



Fermi's GBM also has two high-energy detectors made of a compound called bismuth germanate. These detectors catch gamma rays from about 150,000 to 30 million electron volts, overlapping in range with both the GBM's low-energy detectors and (narrowly) the LAT. They are positioned on opposite sides of Fermi, enabling gamma-ray burst monitoring for nearly the whole sky at once. Combined, the low-energy and high-energy detectors help the GBM detect around 240 gamma-ray bursts each year, as well as solar flares, terrestrial gamma-ray flashes, and other sparse gamma-ray events. NASA's Marshall Space Flight Center, the University of Alabama at Huntsville, and the Max Planck Institute for Extraterrestrial Physics in Garching, Germany collaborated to develop and construct the GBM.

This image, taken in May 2008 as the Fermi Gamma-ray Space Telescope was being readied for launch, highlights the detectors of the Gamma-ray Burst Monitor (GBM). The GBM is an array of 14 crystal detectors designed for transient lower-energy gamma-ray outbursts.

Credit: NASA/Jim Grossman

One of the most technically demanding challenges for any spacecraft is its launch into space. Situated on a Delta II rocket, Fermi needed to withstand speeding up to 10 times the acceleration due to gravity on Earth, which made the three-ton telescope feel like 30 tons. During the launch, Fermi also needed to survive acoustic and vibration shocks from the rocket's roaring and shaking. Engineers carefully designed the instruments to withstand temperatures from minus 4 to more than 130 degrees Fahrenheit (minus 20 to 54 degrees Celsius), though milder temperatures of 32 to 68 F (0 to 20 C) are actually experienced in orbit. Though we usually think of launches as hot, the instruments sit at the front of the rocket where it pushes through the cold atmosphere. The body surrounding Fermi's instruments and spacecraft is aluminum, and the different parts are held together with graphite epoxy — both can withstand the intense heat and vibrations of launch. The mechanical structure of the LAT is made of strong carbon fiber. Other exposed surfaces on the telescope are covered in thermal control paint or solar cell cover glass, both of which resist radiation and heat.

Before launch, engineers fastened thermal blankets over the telescope to further protect it from extreme temperatures. The blankets also protect the spacecraft from micrometeoroids — pieces of rock and debris in space that are smaller than grains of sand. Since the instruments must function in absolute darkness, if micrometeoroids moving at rapid speeds were to puncture them, they would no longer do their jobs. Micrometeoroids could also damage the electronics and detectors within the instruments. The multilayered thermal blankets include layers of foam; heat-resistant synthetic fiber called Kevlar; ceramic fabric; and Kapton foil, a special, metallic-looking film that can withstand temperatures around 750 F (399 C). The blankets help maintain controlled temperatures for the instruments while shielding the detectors from micrometeoroid damage.

The spacecraft shortly before launch. The solar panels are folded at the sides. The LAT (top) is covered in a silver micrometeoroid shield to protect the instrument from damage in orbit.

Credit: NASA/DOE/Fermi LAT Collaboration

Fermi also boasts two large solar panels which provide the power for the telescope's instruments and spacecraft systems. Each time the panels come into view of the Sun on the spacecraft's orbit around Earth, they charge the batteries on board with enough energy to keep the instruments and spacecraft running. Fermi's 15 years of operation have proven it to be a well-designed and exceptionally reliable spacecraft. In fact, the only piece of hardware that has failed is the device that controls the movement of one of the solar panels. In 2018, 10 years after launch, one of the solar panels froze in a slightly over-rotated position. This forced the Fermi mission to change the pattern of rocking the telescope up and down so the solar panel could view the Sun enough to generate sufficient energy for orbit. The team proved their problem-solving ingenuity by making sure Fermi could keep viewing as much of the sky as possible regardless of the freeze.

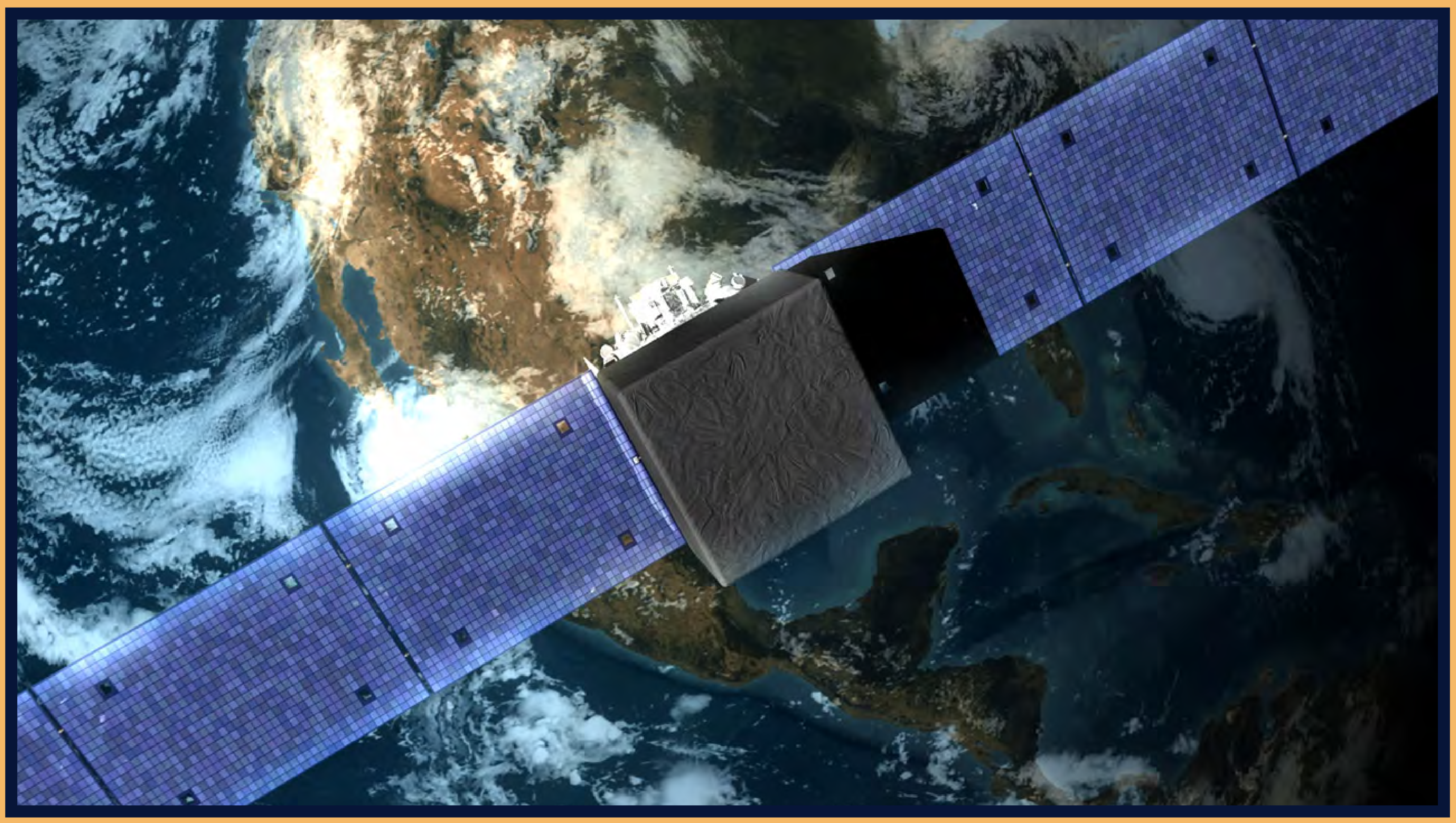
Over the past 15 years, the LAT and GBM have been responsible for many compelling advances in our understanding of high-energy astrophysics. The instruments continue to be in good condition and provide scientists with the data they need to study our universe's most energetic events, from black hole mergers to supernovae.

Fun Fact:
Adapting to the Freeze

Just past 1:00 a.m. on March 16, 2018, the Fermi flight operations team got a concerning message: the observatory had entered safe mode. Used only rarely in a telescope's life, safe mode occurs when an issue arises that endangers a spacecraft's instruments or subsystems. It activates software that automatically instructs the observatory to power off its instruments and wait for further instructions. Members of the Fermi team rushed to the mission operations center at the Goddard Space Flight Center to examine the source of the issue, which turned out to be a nonfunctioning part for a solar array called a rotational drive. Fermi gets its daily power from batteries powered by two solar arrays, which are angled to receive maximum sunlight each time they come into view of the Sun. The drive would not respond to commands, meaning that one of the solar panels was effectively frozen.

One of the most important considerations when building a spacecraft is adaptability. Even when a crucial spacecraft element goes awry, it's the job of scientists and engineers to find a way to keep producing valuable science. Such was the case with Fermi: by March 28, partial science operations resumed with one fully functioning solar array. The spacecraft was tilted at a fixed angle that put the faulty solar array in view of the Sun. The GBM resumed functioning that same day, but the LAT was allowed time to reset to its optimal temperature before resuming operations on April 8.

In the years since the freeze, Fermi has continued to produce remarkable science data with no other signs of hardware failures. The main change to its operations has been its rocking pattern. With one solar array locked in place, there are fewer directions Fermi can point while keeping the total generated power the same. This constraint emerges after gamma-ray bursts: the LAT used to automatically repoint to follow the afterglow of a very bright burst, but no longer does so. Learning to overcome mechanical failures to preserve science is an important part of all NASA missions.



Fermi, illustrated here, scans the entire sky every three hours as it orbits Earth.

Credit: NASA's Goddard Space Flight Center

Operations

Fermi mission operators gather in Fermi's Mission Operations Center at NASA's Goddard Space Flight Center.

Credit: NASA's Goddard Space Flight Center

Behind the Curtain

In a set of interior rooms at NASA's Goddard Space Flight Center in Greenbelt, Maryland, sit numerous old monitors, whirring computers, and racks of servers: the Fermi mission operations center. Here, a dedicated team of five — the Fermi flight operations team — works to make sure the telescope is properly surveying our high-energy sky.

Much like doctors, the flight operations team works on call, always ready to communicate with the space telescope and tackle any problems that arise. Much of the team's job involves sending commands that tell Fermi how to observe our universe. Fermi orbits Earth every 96 minutes, constantly rocking up and down so the LAT can observe the whole sky. Each week, the flight operations team receives guidelines from an important group called the Fermi Science Support Center (FSSC), which is in charge of the planning and scheduling for Fermi. With help from the LAT and GBM teams, the FSSC develops a schedule for how Fermi should rock for optimal observing. Prior to 2018, the year of the solar panel freeze, the rocking pattern would also note when the telescope should track a specific area of the sky for a few hours or days following a significant gamma-ray event.

After the FSSC relays the schedule, the flight operations team creates commands for the telescope that include the schedule, usual spacecraft activities, and any other necessary communications. They confirm all these data with a branch of Goddard in White Sands, New Mexico, which manages the Tracking and Data Relay Satellite System (TDRSS, pronounced TEE-driss). This is NASA's network of orbiting communications satellites that passes commands and data between Earth and other spacecraft, like Fermi. Many telescopes and satellites across NASA and other government agencies use TDRSS, so the timing for sending commands must be precise. When the schedule gets confirmed, the flight operations team programs it and sends it up to Fermi through TDRSS. The whole process, from getting the FSSC schedule to communicating with Fermi, takes about three weeks. While Fermi can communicate directly with massive ground-based satellite dishes in NASA's Near Space Network by pointing at Earth, its wealth of science data is too large to transmit without TDRSS.

The Fermi Flight Operations team discusses plans to avoid a collision with defunct satellite Cosmos 1805 in 2012.

Credit: NASA'S Goddard Space Flight Center

In addition to commanding Fermi's movements, the flight operations team continually checks on its health. After receiving health and safety data from the spacecraft, as well as health, safety, and scientific data from the instruments, they send it to the SLAC National Accelerator Laboratory, a Department of Energy lab operated by Stanford, or to the GBM Instrument Operations Center in Huntsville, Alabama. SLAC processes LAT data using a supercomputer in Menlo Park, California, while Huntsville processes GBM data. After processing, the groups send the data to the FSSC, which receives and distributes all the data to the scientists and engineers who use it. All of Fermi's data are cleaned and made public so that anyone around the world can conduct gamma-ray science.

The Mission Operations Center sifts through Fermi's health and safety data to automatically scan for anomalies. The Fermi team is constantly refining what the data should look like, and which observations should be flagged for oddities. Some of the most important data the flight operations team receives concern the thermal range of Fermi's instruments. Making sure the instruments are not overheating is crucial to maximizing their lifespan. If any anomalies occur, temperature-related or otherwise, the on-call engineers are quick to address them, often calling in a dedicated Anomaly Response Team for backup. The team, which includes the mission director, project scientists, and the instrument manufacturers, among others, is trained to deal with high-pressure situations, even coming in overnight or on holidays. As the flight operations engineers say, there are things that may never fail on Fermi that they have plans to handle.

The LAT and GBM each have dedicated teams who supervise their instrument's operations, with the LAT instrument operations team located at SLAC in California and Goddard Space Flight Center and the GBM instrument operations team working at NASA's Marshall Space Flight Center in Huntsville, Alabama. Many institutes around the world also support the operations of the two instruments.

Within the LAT and GBM teams, there are important groups called burst and flare advocates. It is their job to monitor when Fermi detects short-duration gamma-ray events, also called transients. The most common short transients are gamma-ray bursts and solar flares, which can be as fast as fractions of a second to minutes. The most common longer transients are extreme brightening of blazars, which can last from hours to months. When a transient occurs, Fermi software automatically notifies the astronomy community within seconds, and the burst and flare advocates follow up with more details and analysis. The advocates work on an on-call schedule to cover all 24 hours of the day, checking the Fermi data and analyzing the origin of the gamma rays. The advocates also check to see if the origin matches with a known gamma-ray source. Flare and burst advocates encourage other telescopes to follow up on Fermi's discoveries at other energies to get as much multiwavelength data as possible on these infrequent events.

Flare and burst advocates are located all around the globe, from the U.S. to Europe, Africa, and East Asia. Being a flare or burst advocate comes with a special advantage: whoever is on call when a transient occurs gets dibs on conducting the corresponding science. Many burst advocates are graduate students or postdocs, or retired scientists who want to keep being involved in the gamma-ray world. In Fermi's first 15 years, the LAT detected 231 gamma-ray bursts, while the GBM detected 3,538. In the past few years, the Sun has been especially active. Since gravitational wave detectors began operating in 2015 to search for small ripples in space-time, the LAT and GBM burst advocates have also been helping in the hunt for gamma-ray bursts associated with gravitational waves. Flare advocates specifically have been searching for gamma-ray counterparts to the small, energetic particles known as neutrinos.

A visualization showing colliding neutron stars which blast debris away in particle jets moving at nearly the speed of light. Such an event produces a brief burst of gamma rays.

Credit: NASA's Goddard Space Flight Center/Conceptual Image Lab

How Scientists Use Fermi

Since Fermi's inception, NASA knew it wanted a unique approach to conducting science with the observatory. Fermi's data stands out from observatories around the world for a crucial reason: it helped usher in a modern era of astrophysics where everyone has access to the data at the same time. Starting from one year after science operations began, all Fermi data has been available for download immediately upon processing (the first year was set aside for instrument calibration, generating a list of gamma-ray sources to study, and modeling the background levels of gamma-rays). Previous missions gave the scientist who requested to use the telescope special access to the data for at least a year, but Fermi's model has become standard for NASA missions.

Fermi generates a lot of complex data. Luckily, it has dedicated team members that work to filter it, clean it, publish it, and create tools to help anyone with a computer process it. The Fermi Science Support Center leads all of these efforts. At the FSSC, managing Fermi's data and providing instructions on how to use it are some of their most important jobs. Scientists all around the world download Fermi's data to conduct science, and they direct any processing questions to the FSSC's help desk. The gamma-ray science community includes thousands of scientists all over the globe training their efforts on the high-energy sky. Altogether, users have downloaded one petabyte of data from Fermi — that's about as much data as 4,000 smartphones can store.

Fermi's transparent approach to science has enabled groundbreaking high-energy discoveries to happen not just at NASA, but at institutions around the world. The Fermi Bubbles are one example of how Fermi's open-access data policy has been a boon to its scientific impact.

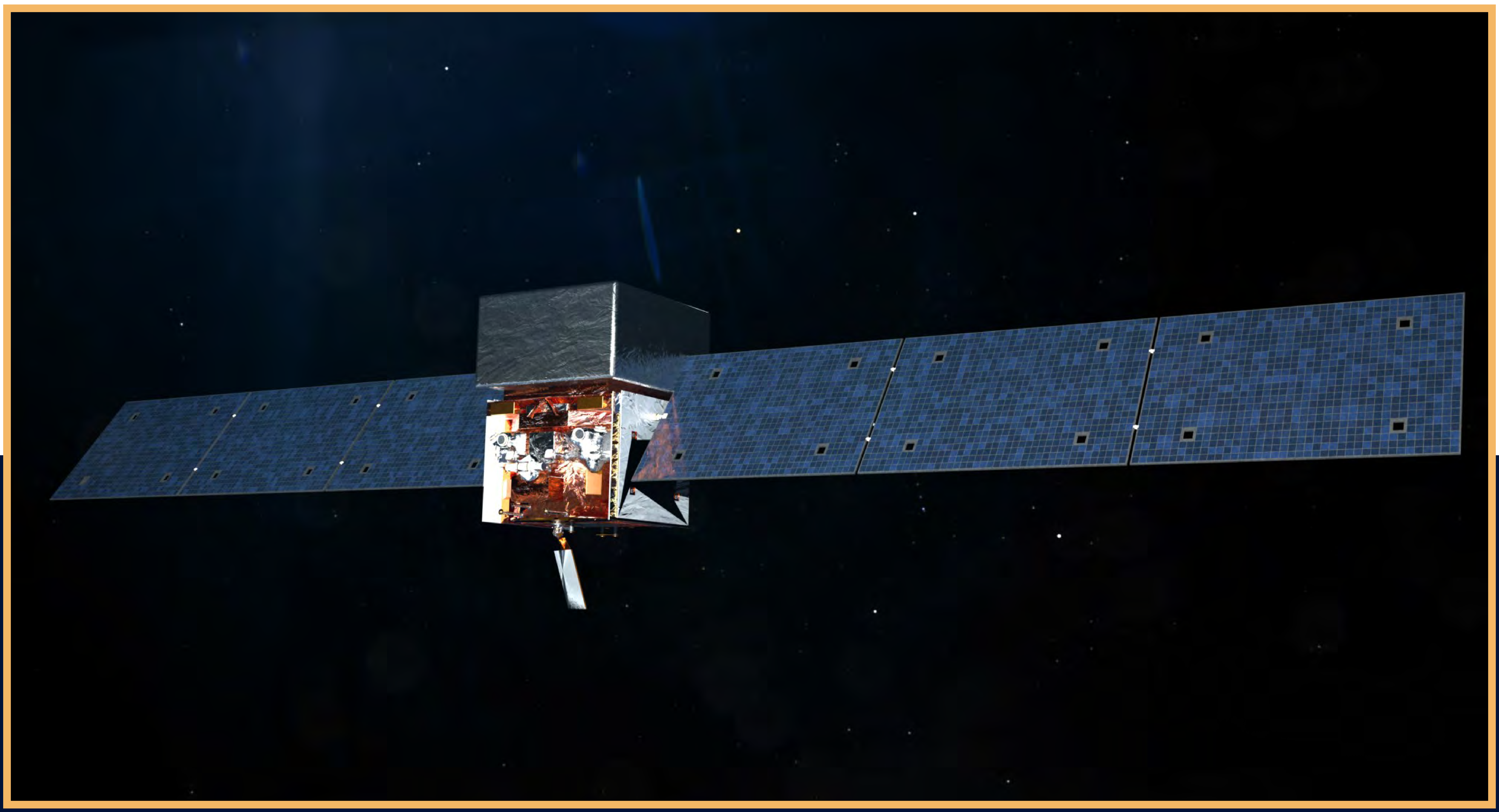
Another crucial benefit of NASA's open-access data is its archival nature. Anyone can look back in time to see what Fermi viewed on any particular date, enabling scientists to check for a specific phenomenon or analyze patterns over long time scales. The LAT archive contains a record of the individual gamma-ray photons, the direction they came from in the sky, and their energies, among other measurements. The GBM archive contains data about the brightness, energy, duration, and detection time of all observed gamma-ray bursts, along with a continuous stream of gamma-ray data for other research. The archive also includes data about the spacecraft, such as where it was in the sky relative to Earth and where it was pointing during a given observation.

Unlike observatories like NASA's Hubble and Webb, Fermi does not train its eye on specific objects. This is in large part due to the effectiveness of its all-sky survey mode and large fields of view. When Fermi's LAT used to look at one area of the sky for a few hours or days at a time following a significant event, it would miss the interesting gamma-ray signals coming from other angles. This means that scientists don't submit proposals to use time on Fermi — a process that, on other telescopes, determines where the telescope will point. This also makes Fermi a much more accessible telescope to scientists.

Another way Fermi encourages scientists to get involved with gamma-ray science is through the Fermi Guest Investigator (GI) Program, which is managed by the FSSC. The GI Program provides funding to U.S.-based scientists for a variety of projects, like conducting investigations using Fermi data, designing analysis techniques for Fermi data, or carrying out theoretical investigations that support Fermi's observations. Scientists can also apply for observing time on partner radio, optical, X-ray, and gamma-ray observatories, and for high-end computing resources that support their research.

Fermi's all-sky nature renders it a helpful counterpart to other telescopes' observations. If, for example, the High-Altitude Water Cherenkov Observatory (HAWC) near Puebla, Mexico observes a phenomenon in very high-energy wavelengths, the Fermi team can look at their data collected at the same time. This process also works in the reverse; if scientists notice an interesting pattern caught by Fermi, they can look back at HAWC's archival data. Astronomers can even go beyond archives to request time on other telescopes to look at the same area of the sky where Fermi saw something interesting.

The sprawling archive of available Fermi data has taken gamma rays from a lesser-studied wavelength to an important counterpart to observations across the electromagnetic spectrum and other astrophysical signals. Open-access data not only expands scientific research on the Fermi mission, but signals to the world that gamma-ray science is meant for sharing and collaboration.

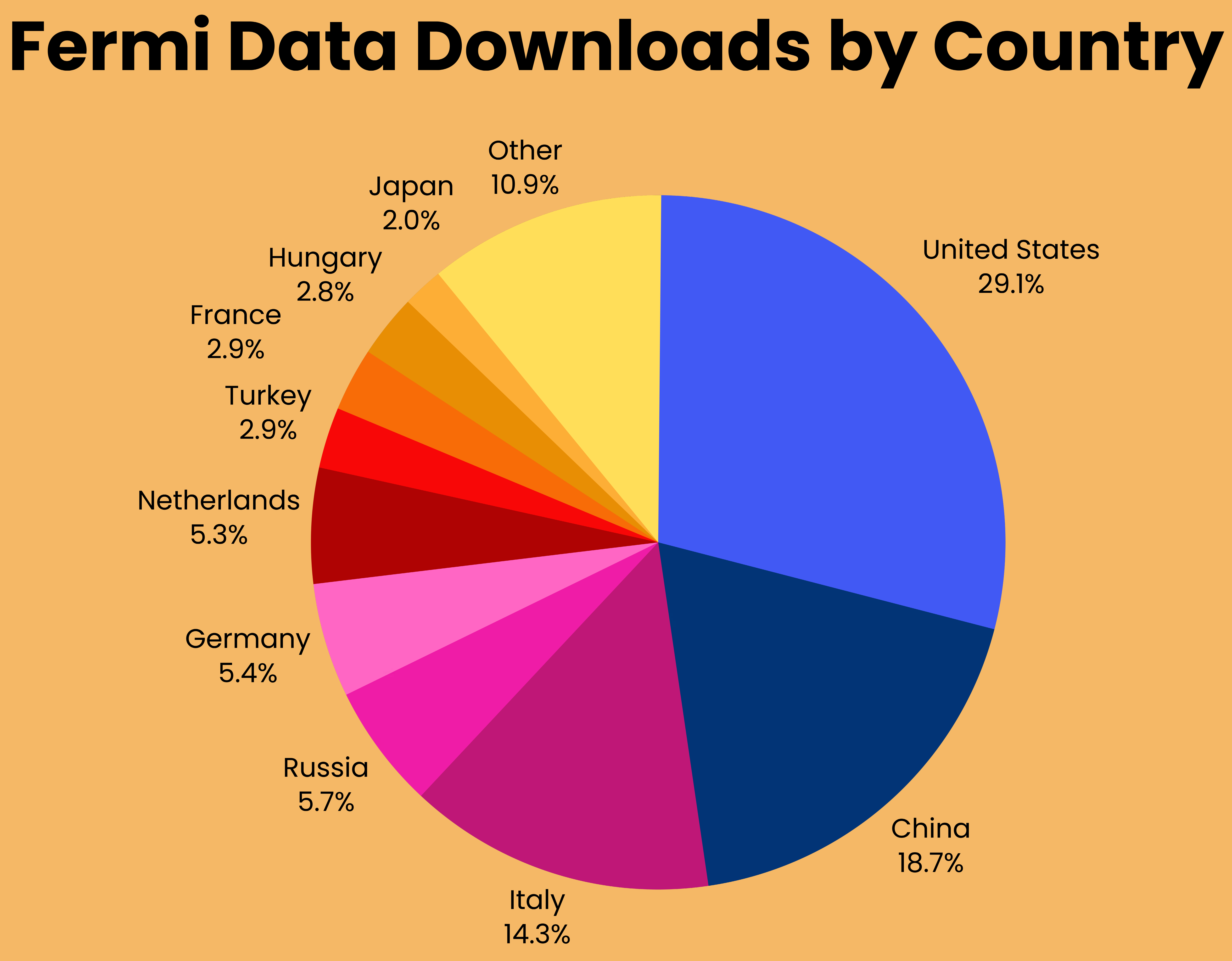


An illustration of Fermi in orbit.

Credit: NASA's Goddard Space Flight Center

Fun Fact:
The Global Gamma-Ray Community

Around the globe, scientists engage with the fascinating world of gamma rays. Fermi's public archival data enables people from Texas to South Africa to work on high-energy astrophysics, regardless of their affiliation with NASA. Based on data downloads recorded by the Fermi Science Support Center, here is the breakdown of where people around the world are studying gamma rays using Fermi.



Credit: NASA's Goddard Space Flight Center/Hannah Richter (SURA)

Visualizing Gamma Rays

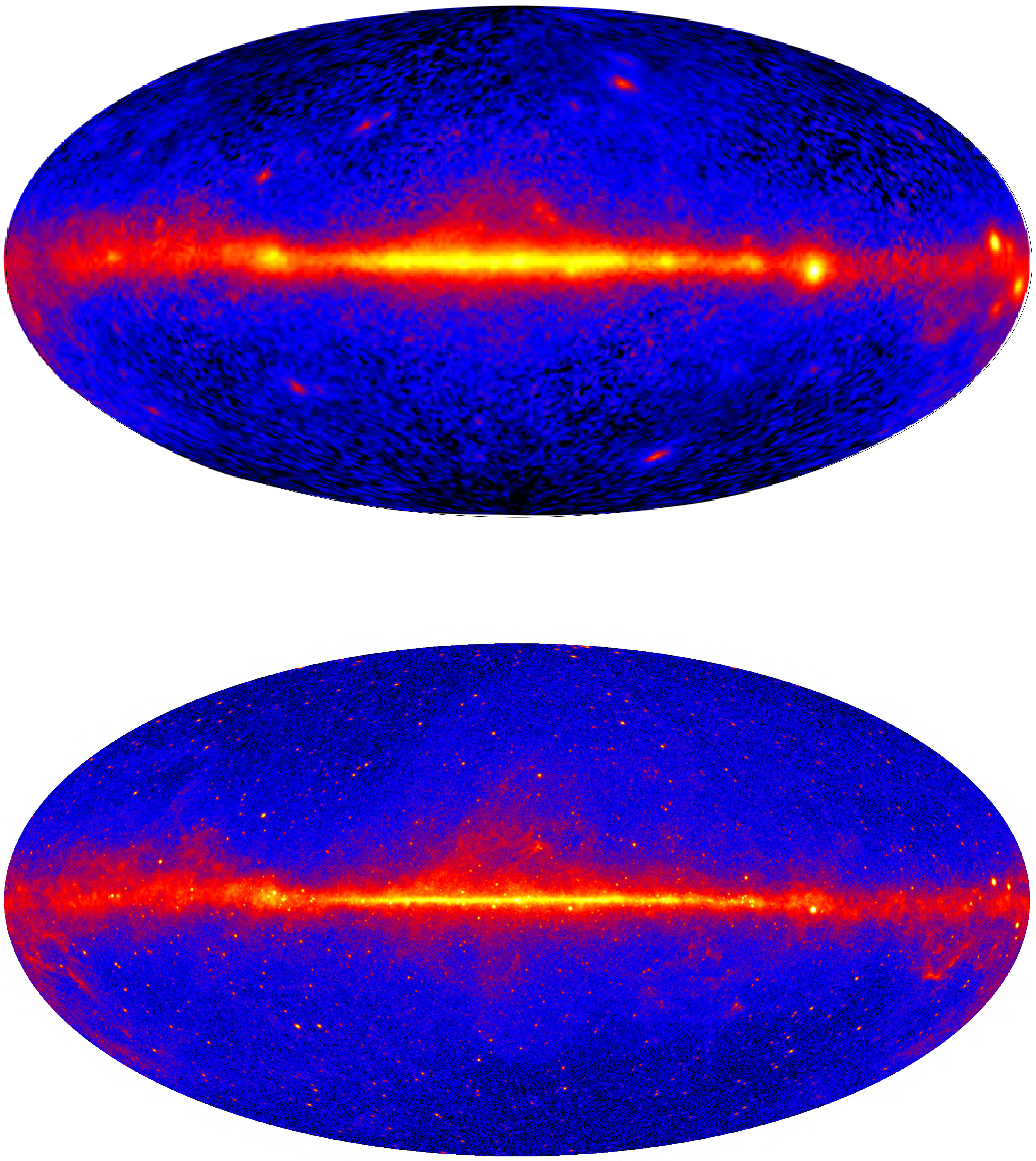
Every time an image of space gives you wonder, a team of scientists and visualizers worked hard to elicit that emotion. Astrophysics and astronomy are complex fields built on nuanced science; making them accessible through imagery and video is an important part of the NASA mission.

Though a flood of visible light permeates the cosmos, gamma rays are few and far between. The higher-energy the gamma ray, the more rare it is within our universe. This means that scientists can take high-resolution images in visible light, but gamma-ray sources appear blurred. In other words, we look at the gamma-ray sky through foggy glasses. As Fermi continues to detect gamma rays, its images will sharpen.

All the information Fermi collects about gamma rays starts out as data: numbers about the energy of the light, where it came from, the time at which it was observed, and more. It is the scientists' job to build images and plots based on this data, and the visualizers' job to make these images accessible and eye-catching. Some plots go into peer-reviewed scientific papers, and some images are used as communications materials to help audiences understand high-energy astrophysics.

Since we don't see gamma rays with our own eyes, scientists and graphic designers often choose to represent them as blobs or bursts overlaid on visual-light images. Fermi's gamma-ray emission is most often shown in the color magenta. Using this technique helps us place the occurrences of gamma rays in the sky, and also provides an opportunity for meaningful cross-collaboration with other telescopes.

Fermi's most famous LAT image, its all-sky map, depicts gamma-ray sources as bright spots against a sky pocked with smaller gamma-ray sources. The orange-red band of gamma rays at the center represents what Fermi observes from the central plane of our galaxy. Fiery tendrils appear to stretch out from the band, spattering glowing embers in all directions — emissions from cosmic rays that are interacting with material in our galaxy. Above and below the galactic band, extragalactic gamma-ray sources appear as small dots distributed evenly across the sky. Fermi's all-sky map builds on that created by NASA's Compton Gamma Ray Observatory, Fermi's predecessor, by adding depth and thousands of new gamma-ray sources. The all-sky map has helped to give Fermi a signature look.



The gamma-ray sky above 100 megaelectron volts (MeV) as seen by EGRET on NASA's Compton Gamma Ray Observatory (top) and the LAT on Fermi (bottom). Both visualizations were made from nine years of science data. Brighter colors indicate greater numbers of gamma rays. The most prominent feature is the central plane of the galaxy, which runs across the middle of the map. In the bottom visualization, many more bright gamma-ray sources can be seen throughout the universe, and the galactic gamma-ray emissions are more refined.

Credit (top): NASA/EGRET Team. Credit (bottom): NASA/DOE/Fermi LAT Collaboration

Some images and videos, like those of Fermi orbiting Earth or of the jets from a blazar, are artistic renderings. Without space-based cameras to photograph Fermi, nor the ability to travel to faraway gamma-ray sources, we must leave some images up to a combination of science and imagination. The Fermi team works with artists to develop beautiful depictions of the universe's most energetic phenomena.

Graphics are another helpful tool in understanding high-energy astrophysics. Scientists and visualizers can use graphs, charts, and symbols to explain a complicated process or new discovery. Graphics can be made for a variety of audiences, from scientists to elementary schoolers.

While Fermi images do not reflect what space "looks" like to us — as only images and videos in visible light can — they are still factual depictions of the beauty and science of astronomy. Making the non-visible visible is one of the most important parts of Fermi's mission and has helped expand public understanding of fascinating high-energy science.

One of Fermi's most famous illustrations is of the Fermi Bubbles, two giant gamma-ray-emitting lobes depicted above in purple.

Credit: NASA's Goddard Space Flight Center

JOURNEY THROUGH THE COSMOS

EARTH

SOLAR SYSTEM

THE GALAXY

NEARBY GALAXIES

THE DISTANT UNIVERSE

Credit: NASA/Sonoma State University, Aurore Simonnet

Science

Like every NASA mission, Fermi launched with explicit mission objectives. These are goals that help scientists cater their research and observations to the questions the observatory was designed to answer. Fermi's five mission objectives are:

1. Explore the most extreme environments in the universe, where nature harnesses energies far beyond anything possible on Earth.

2. Search for signs of new laws of physics and what composes the mysterious dark matter.

3. Explain how black holes accelerate immense jets of material to nearly light speed.

4. Help crack the mysteries of the stupendously powerful explosions known as gamma-ray bursts.

5. Answer long-standing questions across a broad range of topics, including solar flares, pulsars, and the origin of cosmic rays.

Over Fermi's first 15 years in orbit, astronomers and astrophysicists have made invaluable progress toward each of these objectives. As is typical of science, though, each new answer opened even more questions!

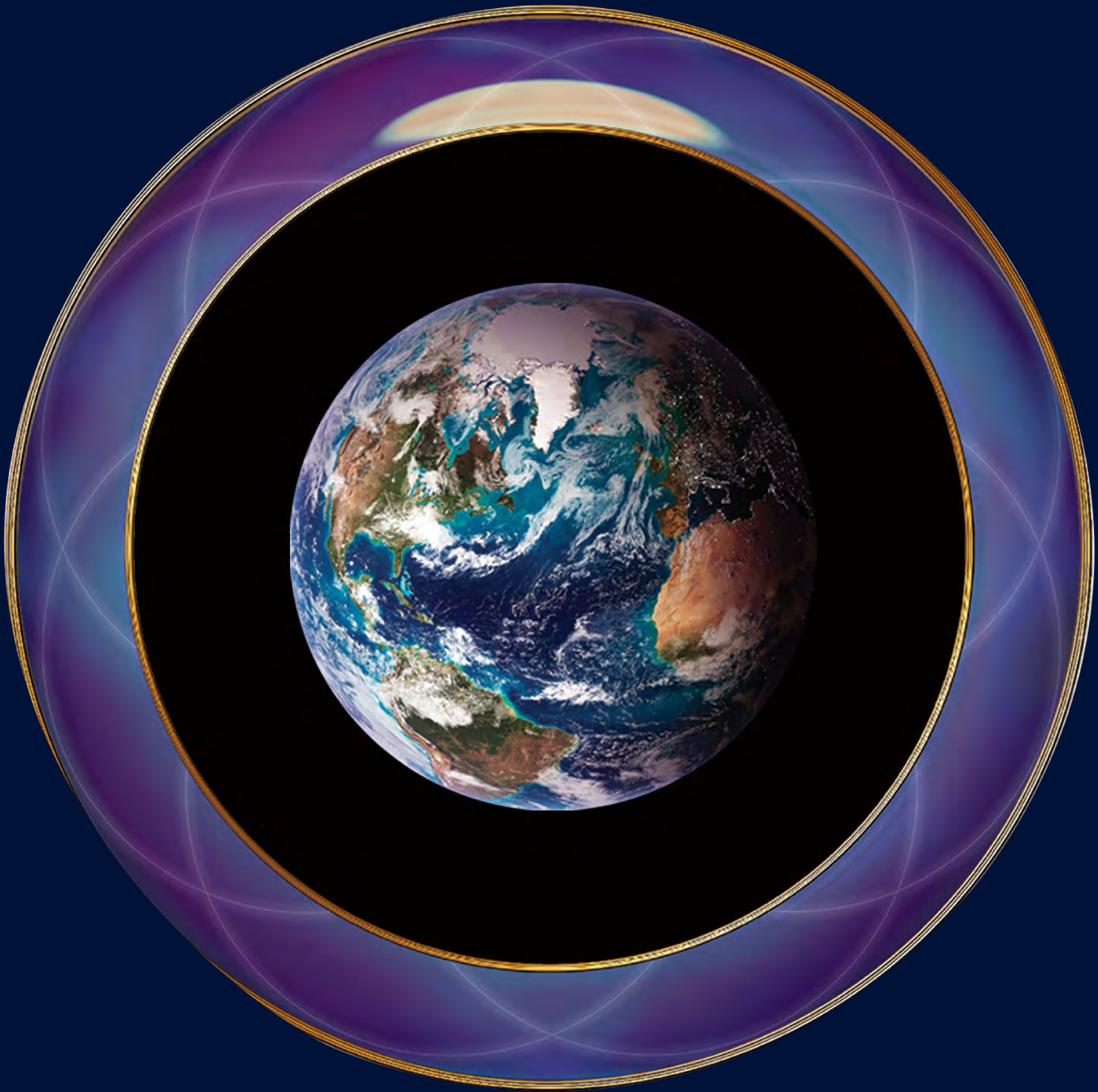
The following sections take you on a journey from Earth, through our solar system and galaxy, to the distant reaches of the universe. Each section covers different high-energy phenomena where Fermi has moved the needle of discovery. Scientists working with Fermi have developed new theories in physics, found more cosmic objects, and brought gamma-ray science to the forefront of astrophysics. Despite monumental progress, there is always more to learn about our universe — which is precisely the beauty of scientific exploration.

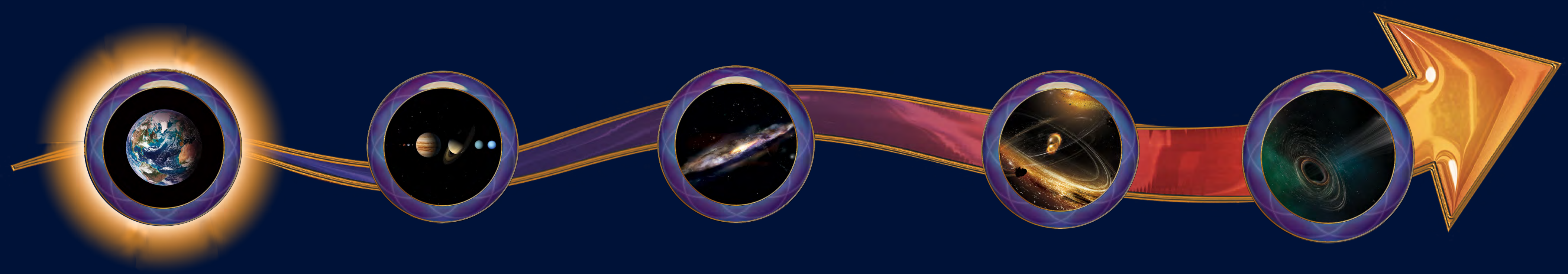
Read on to go on a cosmic journey through Fermi's majestic and mystifying gamma-ray universe.

This illustration shows a gamma-ray-producing outburst on the surface of an old, dense star. This type of outburst happens in many cosmic objects from near to far.

Credit: NASA's Goddard Space Flight Center/Chris Smith (USRA)

Earth





Credit: NASA/Sonoma State University, Aurore Simonnet

Terrestrial Gamma-ray Flashes

Earth's most powerful natural particle accelerators are actually daily events: thunderstorms. In a thunderstorm, rain, snow, and ice in Earth's atmosphere collide and build up electrical charge. Generally, positively charged particles gather in the upper layers of a storm, while negatively charged particles gather in the lower layers. When these opposing electrical regions become strong enough to break down air's insulating properties, they produce a powerful discharge of energy that we see as lightning. This sudden energy release accelerates electrons upward through the storm. When these speedy electrons pass close to the nuclei in atoms of air molecules, their paths deflect and they emit gamma rays. This phenomenon is called a terrestrial gamma-ray flash, or TGF.

Scientists discovered the first TGFs in 1994 using Compton. Today, Fermi detects TGFs using its GBM, which can record TGFs within 500 miles of Fermi's location. During Fermi's first 10 years in operation, the telescope detected more than 4,000 TGFs, most of them seven to nine miles above Earth's surface where the atmosphere is thinner. However, this number is likely a massive underestimate of how many actually occur; scientists predict that around 1,100 TGFs happen in Earth's atmosphere each day. Many may occur closer to the planet's surface, where Earth's thick atmosphere obscures the gamma-ray signal. Some TGFs even occur in powerful volcanic eruptions. In general, TGFs are as short as one-thousandth of a second and release gamma rays with 100 million electron volts of energy (for comparison, visible light is 2 to 3 electron volts). They can come from any thunderstorm, regardless of its strength.

These images are based on a TGF simulation by Joseph Dwyer at the Florida Institute of Technology. Electric fields near the top of a storm create an upward-moving avalanche of electrons (yellow). When molecules in the air deflect their paths, the electrons emit gamma rays (pink).

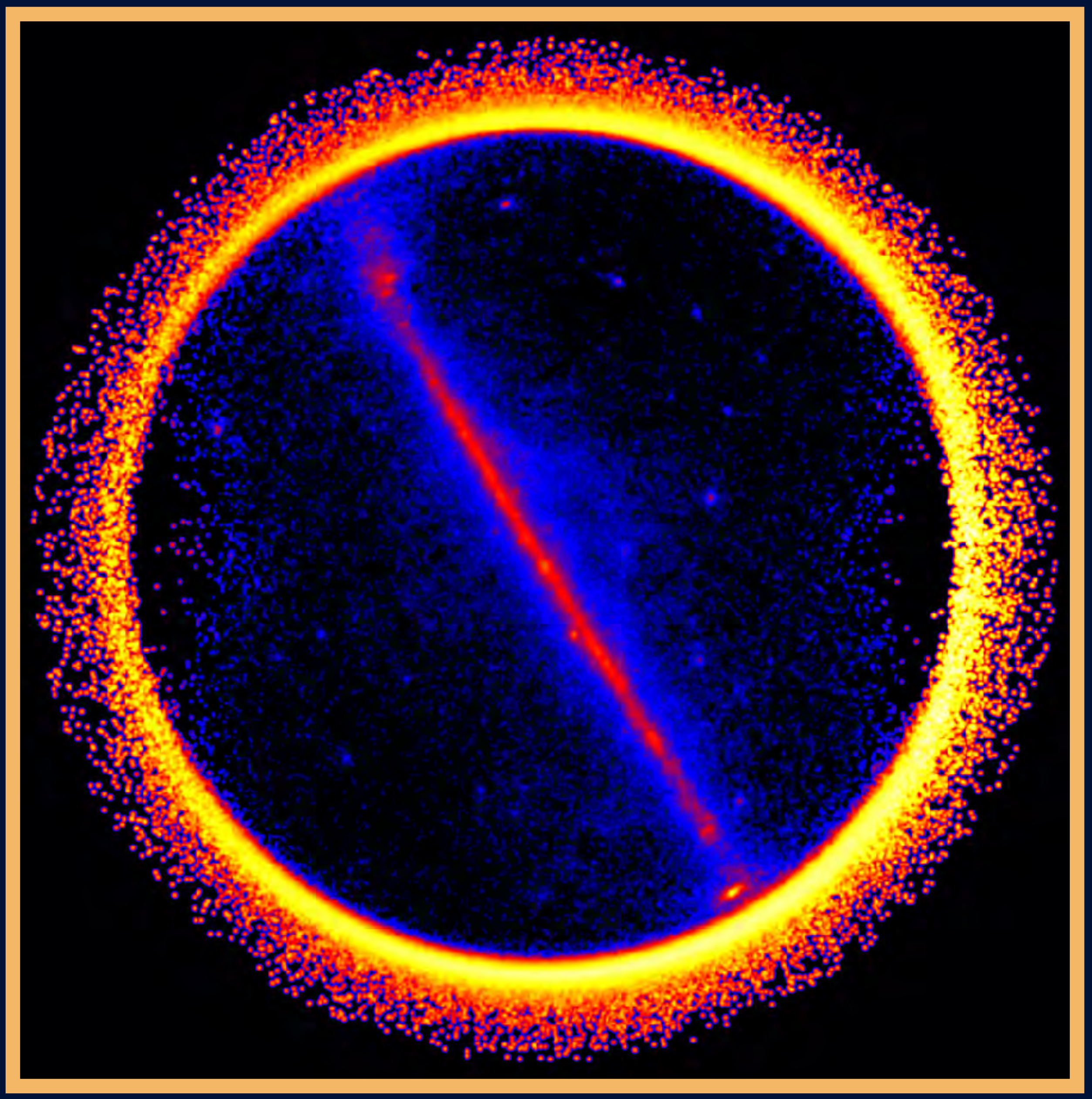
Credit: NASA's Goddard Space Flight Center/J. Dwyer, Florida Inst. of Technology

Earth’s Limb

Images of Earth taken from space often show a halo around our planet. This is our atmosphere, the edge of which is known as Earth’s limb. Earth’s atmosphere consists mostly of nitrogen and oxygen and stretches over 60 miles above the planet’s surface. The atmosphere can be thought of in layers, the uppermost of which are too thin for our eyes to distinguish them. This is because the pressure is very low, so the gas molecules are spread far apart. Images of Earth’s limb thus typically capture the edge of an atmospheric layer called the mesosphere, which begins about 30 miles above Earth’s surface and is 22 miles thick. There, the pressure is far too low for any person to breathe. Due to the spread-out gas molecules, the average temperature at the top of this layer is around minus 90 degrees Fahrenheit!

Images of the limb can be used to monitor changes in the ozone layer, which shields Earth from the Sun’s intense radiation. In the past, Fermi’s LAT has observed Earth’s limb to calibrate its instruments and test that the telescope was working, since Earth is a prominent source of gamma-ray emission from sources like lightning and radioactive decay. Earth’s limb also appears to emit gamma rays as energetic protons from cosmic rays hit Earth’s atmosphere and burst into many smaller particles. Generally, though, Fermi also relies on the limb specifically to help it avoid viewing Earth, because the limb is a bright source of background emission that can obscure Fermi’s observations. Since the LAT surveys the whole sky, scientists must optimize its field of view by pointing Fermi away from our planet. Historically, if Fermi observed a gamma-ray burst that dipped behind our planet, it would automatically execute a process known as “limb tracing,” whereby its instruments followed the outline of the limb until they could view the burst again. Since the solar panel freeze in 2018, this process no longer occurs.

Fermi’s GBM, on the other hand, uses Earth’s limb as a tool. Since the GBM sees the whole sky, when a known bright source dips behind — or appears from behind — Earth, the GBM can detect its change in brightness. This helps scientists monitor sources that change over time, like the Crab.



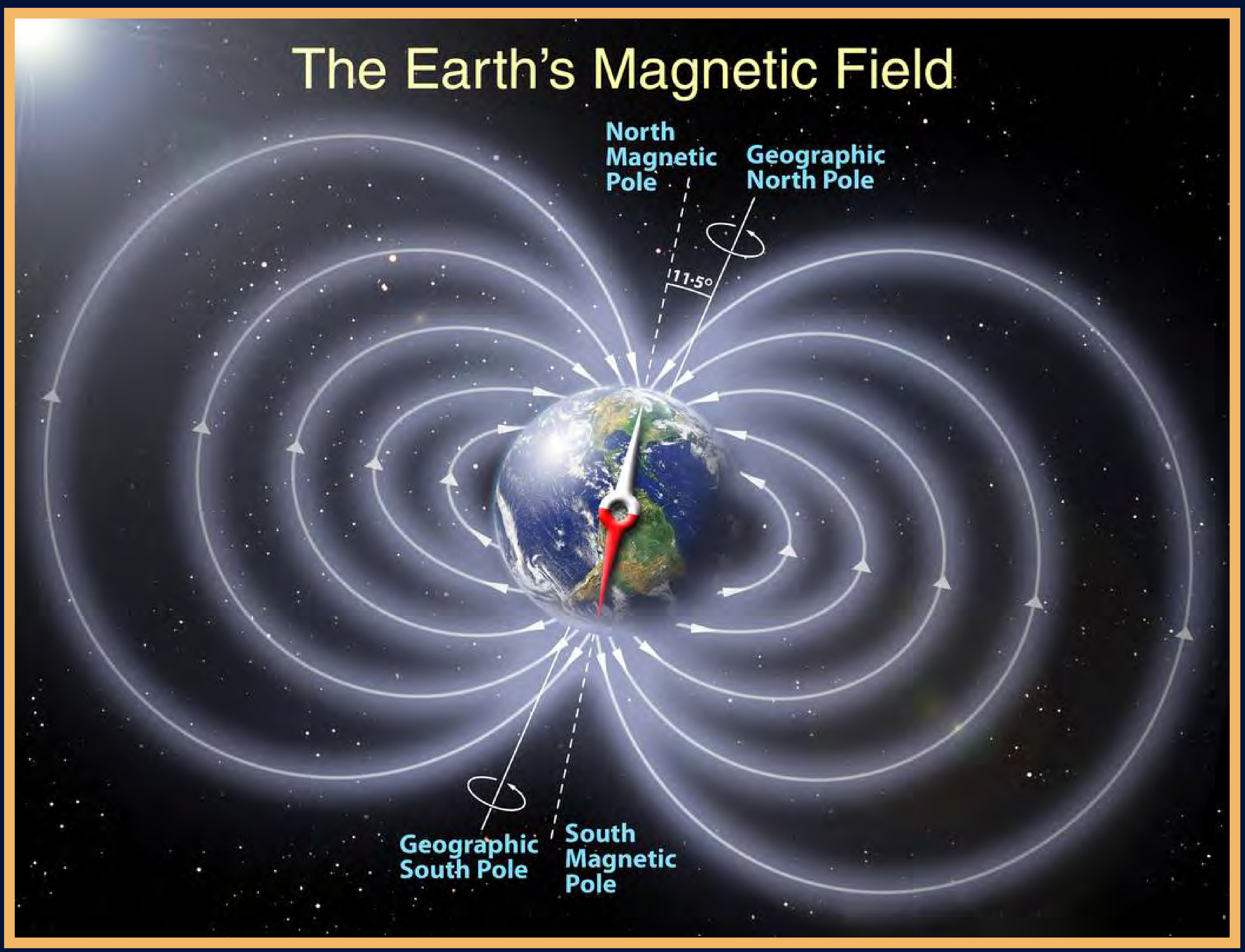
Earth is actually the brightest source of gamma rays that Fermi detects. This image shows a view of Earth and the galaxy from Fermi’s perspective. Since Earth is so bright in gamma rays, its limb floods the side of Fermi’s view with photons. In this image, low-intensity gamma rays are blueand high-intensity gamma rays are yellow.

Credit: International Fermi LAT Collaboration, NASA, DOE

Local Electrons and Positrons

Electrons, the tiny negatively charged particles in every atom, are one of the smallest known particles in the universe. Positrons are their antimatter counterpart: equally small but with a positive charge. When the nucleus of a cosmic ray interacts with low-density interstellar gas, it produces a slew of particles, including pairs of electrons and positrons. Antimatter does not exist long in space before getting annihilated by matter. Therefore, scientists know that any positrons we detect at high energies — meaning that they were created somewhat recently — must be created close to Earth. In 2008, a study reported an excess of nearby positrons compared to scientists' expectations from theoretical models. This hints that there are high-energy phenomena happening close by. The Fermi mission wants to help figure out what they are.

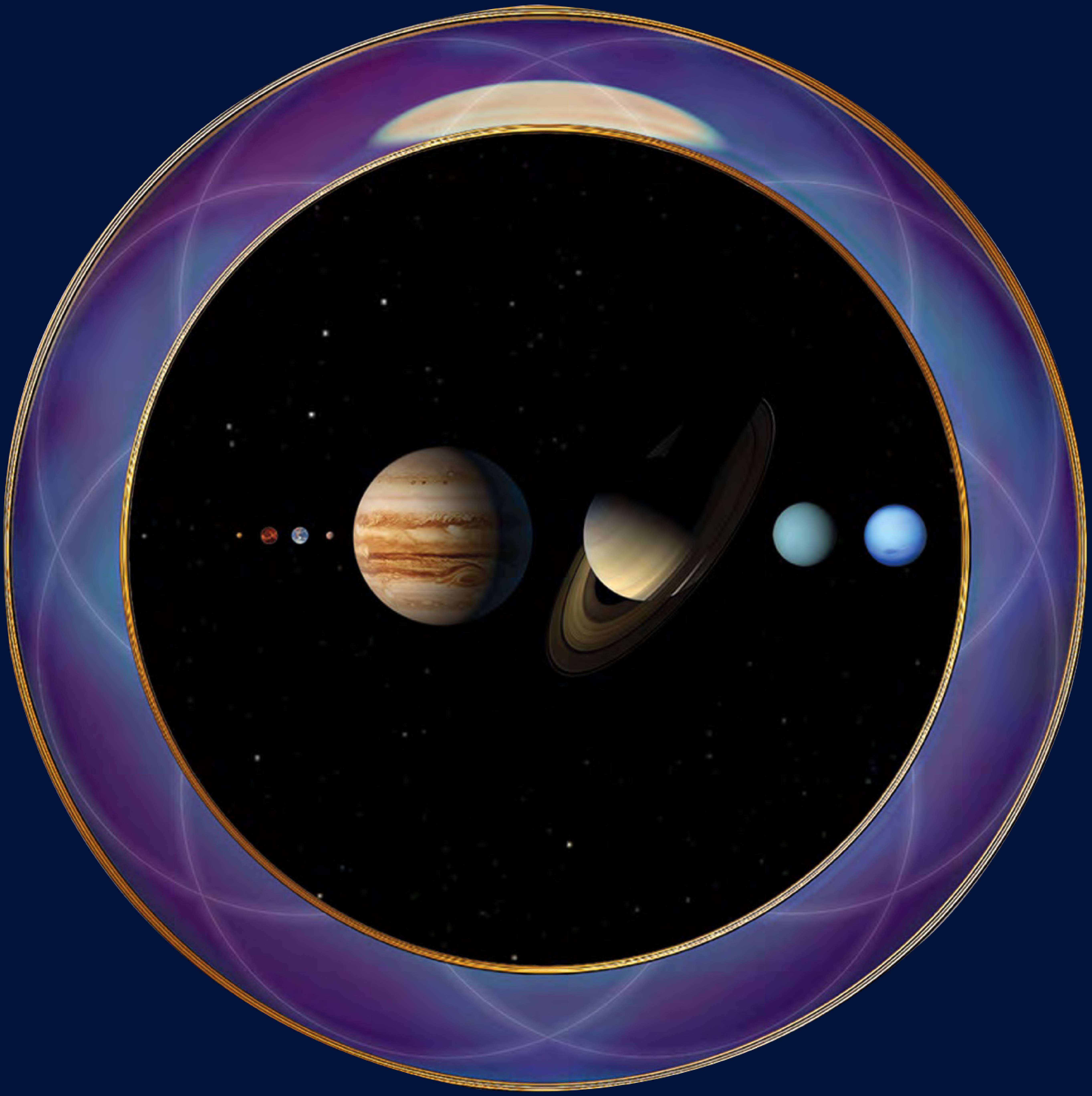
The first spacecraft to detect these excess positrons was the WiZard collaboration's Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA), a now-decommissioned but still-orbiting satellite designed to study cosmic rays. PAMELA had a central magnet that it used to measure the fraction of positrons and electrons in cosmic rays that hit its detector. While Fermi's Anticoincidence Detector is an excellent particle detector, Fermi itself lacks the magnet crucial to PAMELA. Luckily, there was one close by that Fermi could borrow: Earth. Earth generates a strong magnetic field in its interior that extends outward into space. This magnetic field protects our atmosphere — and therefore life — from charged particles, radiation, and space weather. The Fermi team used a precise map of Earth's magnetic field strength and direction to find areas where Earth blocked positrons but not electrons and vice versa. Using this technique, the LAT confirmed what PAMELA had found: an excess of high-energy positrons near Earth. One prominent theory for this exciting result is that nearby dark matter particles annihilate into matter-antimatter pairs in the form of electrons and positrons. While not proven, this theory is one of the puzzle pieces that could help scientists find dark matter.

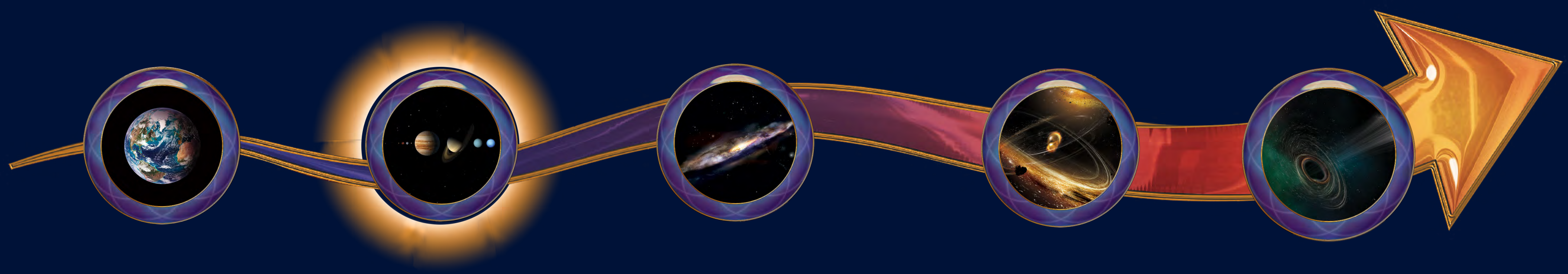


An illustration of the invisible magnetic field lines generated by Earth. Fermi used Earth's magnetic field to find high-energy positrons near Earth.

Credit: Peter Reid, The University of Edinburgh

Solar System





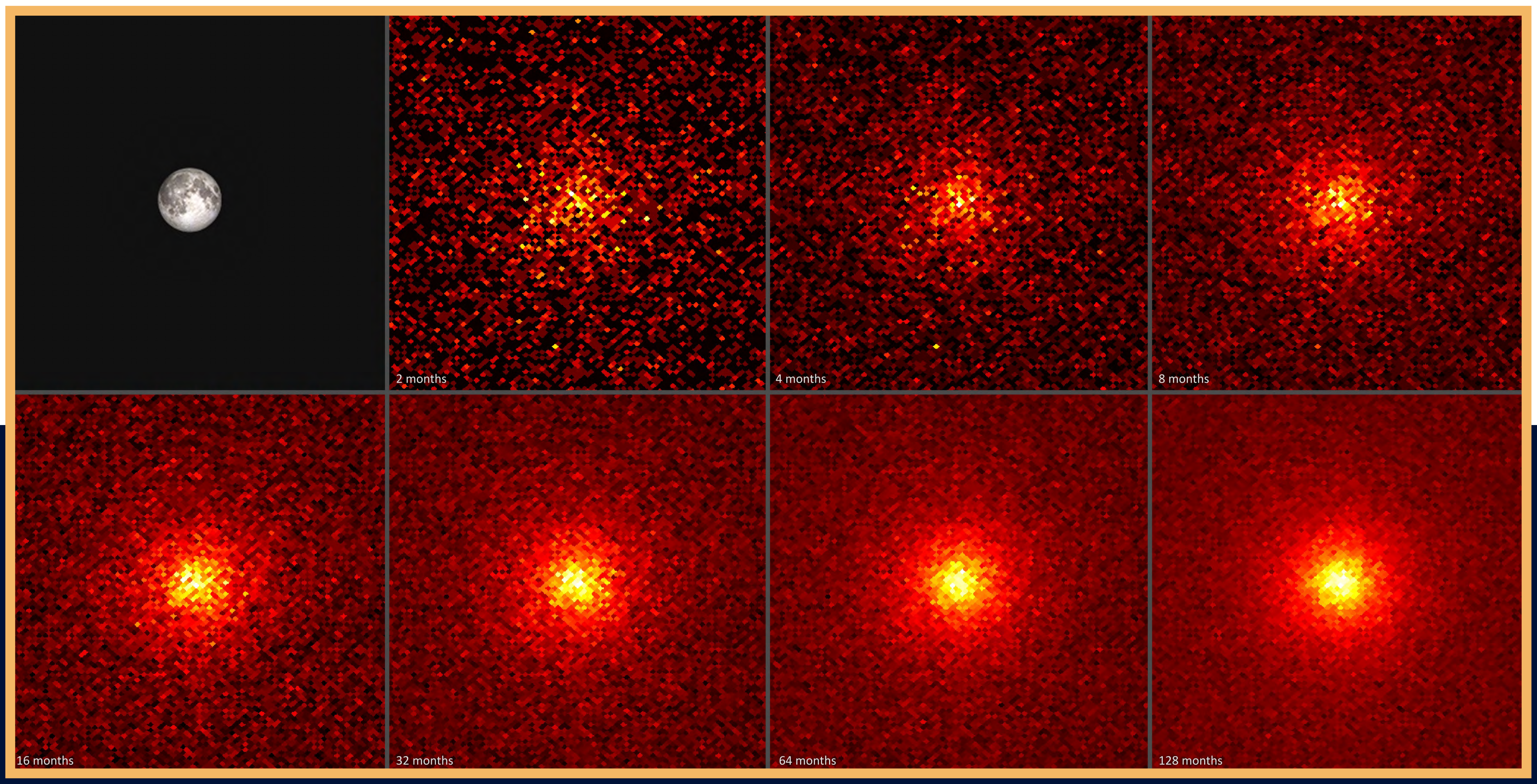
Credit: NASA/Sonoma State University, Aurore Simonnet

Sun and Moon

It's not hard to tell if the Sun or Moon shines brighter in visible light. But if you thought the Sun was brighter in gamma rays, too, you'd be wrong! The Moon's lack of a magnetic field allows electrically charged cosmic rays to reach its surface. When the cosmic rays interact with the powdery surface of the Moon, called regolith, they produce gamma rays, some of which escape and Fermi detects.

Since the LAT's spatial resolution is limited, Fermi's view of the moon is relatively blurry. Additionally, since cosmic rays bounce off in all directions, they emit gamma rays in all directions. Without one single direction of illumination, like when the Sun's light hits the Moon, the Moon appears to shine as one constant sphere — in other words, we can't see its phases in gamma rays. Fermi's view has steadily improved over the years, though. Astronomers found that the Moon's gamma-ray brightness changes over time, largely due to the rate of cosmic-ray impacts. The rate changes due to variations in the Sun's intense magnetic field, which affects how many cosmic rays reach the Moon.

Normally, the Sun's magnetic field deflects low-energy cosmic rays from reaching its own surface. However, high-energy cosmic rays on the order of 1 billion electron volts and higher do pass through the Sun's magnetic field, making it shine brighter than the Moon at high energies.



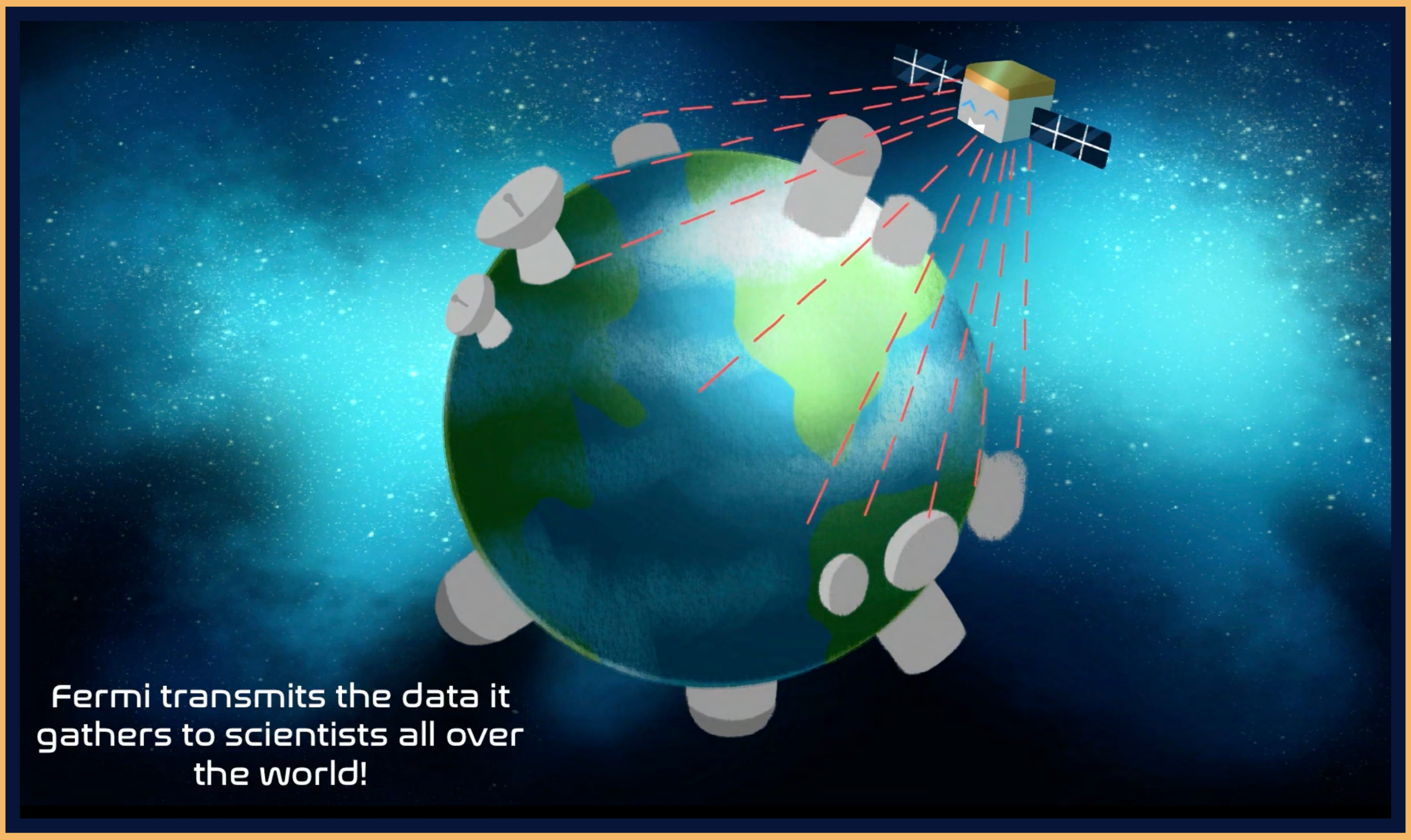
These images show the Fermi telescope's improving view of the Moon's gamma-ray glow over time. Brighter colors correspond to greater numbers of gamma rays above 31 million electron volts, tens of millions of times the energy of visible light. At these energies, the Moon is actually brighter than the Sun. The glow comes from cosmic rays, particles that constantly bombard the lunar surface. The Moon has no magnetic field, which would screen out lower-energy particles. So instead they strike and interact with the surface, which produces gamma rays.

Credit: NASA/DOE/Fermi LAT Collaboration

Fun Fact:
Adding Artistry to Astronomy

The Fermi team knows that science is meant to be shared. One creative way to carry out that conviction is through a partnership called AstroAnimation with the Maryland Institute College of Art (MICA) in Baltimore. Since 2013, Fermi scientists and MICA undergraduate students have partnered in an animation class to create projects that explain high-energy astrophysics in a visual way. The animations span a variety of styles and topics fit to the students preferences and interests. Some of the most memorable visualizations have focused on the Fermi bubbles, dark matter, and binary stars.

During the yearly collaboration, MICA students work in small groups with scientist mentors who help answer questions about the chosen science topics. The students also get to tour NASA's Goddard Space Flight Center, where they can see Fermi scientists in their usual jobs. At the end of the class, students present their work, which is often shown at museums, art and science festivals, and Goddard itself. The AstroAnimation partnership is an example of the increasingly popular concept of STEAM, which incorporates art into traditional STEM (Science, Technology, Engineering, and Math) disciplines like astrophysics. Studies conducted about this unique partnership report that the students feel positively about the science they learn, while the scientists enjoy seeing their work represented in engaging and public-friendly ways. Many students from the AstroAnimation course go on to intern at Goddard, where they create visualizations for different NASA missions. You can check out the animations and learn more about the collaboration here: https://www.astroanimation.org/ ▶.



Each year since 2013, MICA students have designed animations featuring Fermi and gamma-ray science. The students work with scientist mentors and even get to present their final animations at museums, art and science festivals, and NASA's Goddard Space Flight Center.

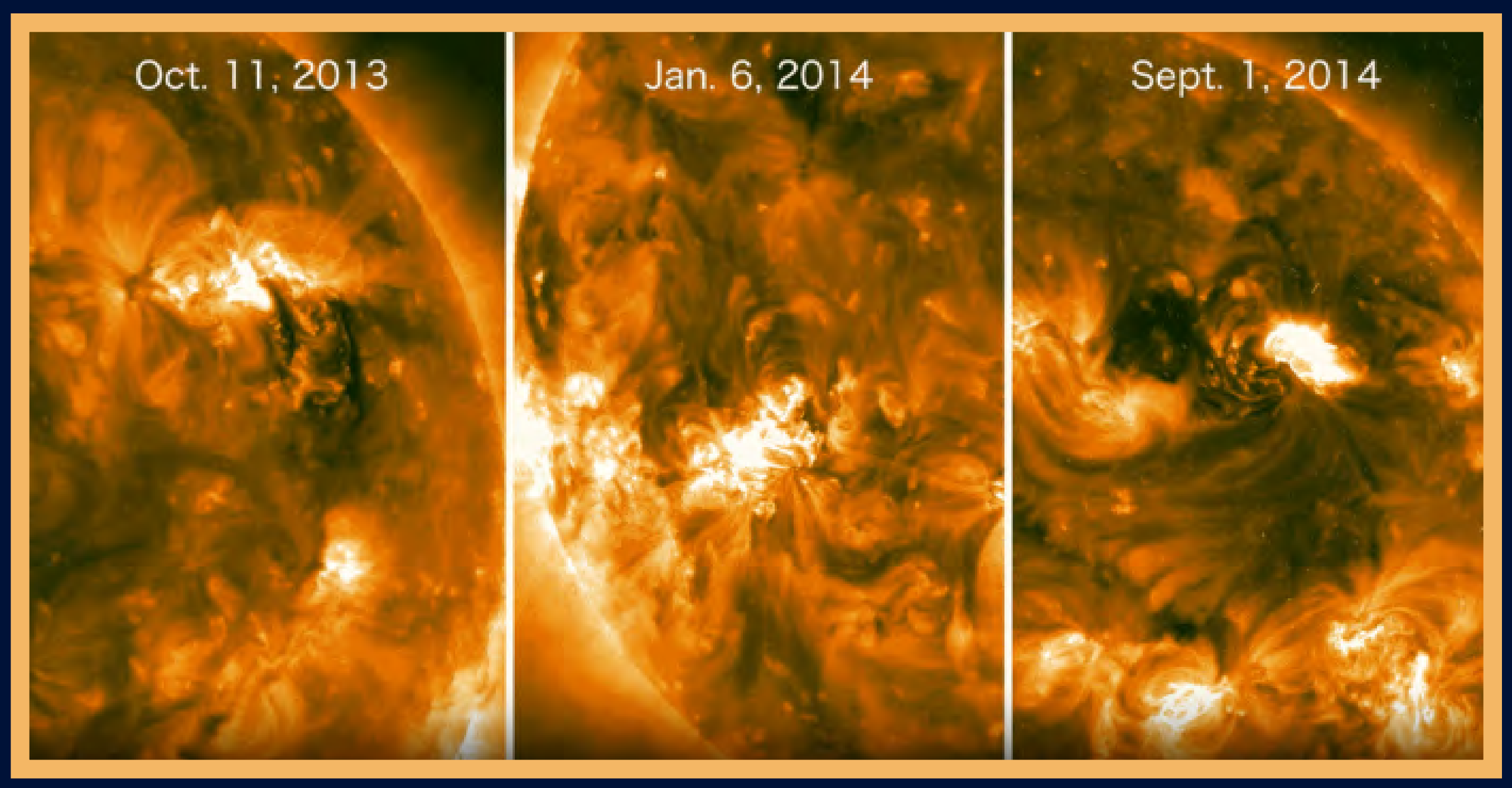
Credit: Charlie Cornwell

Solar Flares

Millions of miles away, our Sun sometimes releases enormous bursts of energy. These bursts are called solar flares, and they can last from minutes to hours. Solar flares occur on areas of the Sun with strong magnetic fields. Such areas are called sunspots because they appear darker on the Sun due to their relatively lower temperature — around 6,500 degrees Fahrenheit. When the magnetic fields near sunspots tangle, cross, and reorganize, they can become unstable and suddenly release electromagnetic radiation. Such a burst appears bright on the surface of the Sun in X-ray and ultraviolet radiation.

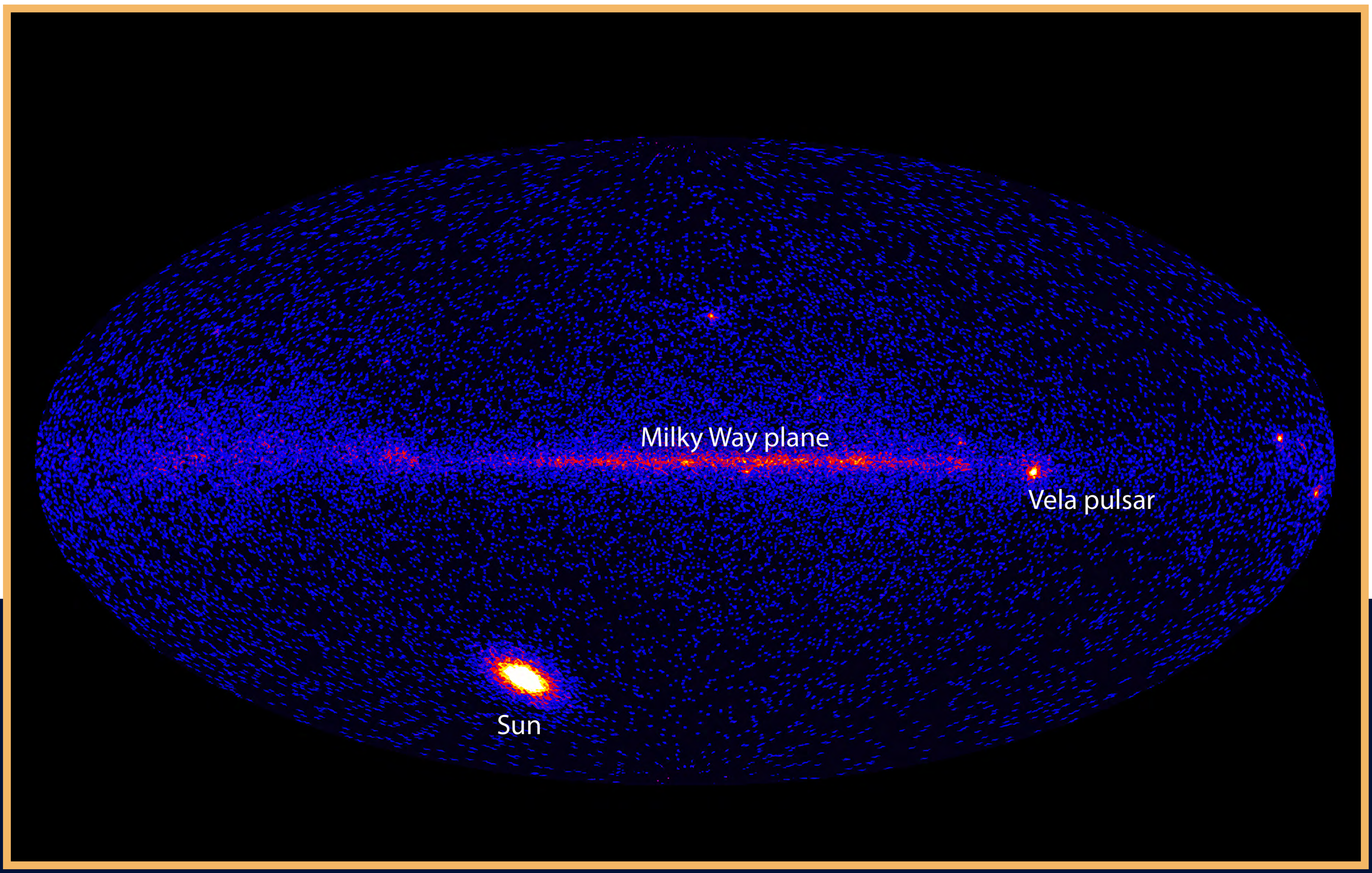
The Sun's energetic activity occurs on an 11-year cycle. When the number of sunspots peaks, this is called the solar maximum. The last solar maximum occurred in 2014, and we are approaching the next one, which is set to occur in 2025. The solar cycle has a small influence on Earth's climate, so better understanding it can improve our knowledge of life on Earth. Interestingly, studies suggest that the Sun emits fewer gamma rays during its solar maxima and more during its solar minima. This may be because gamma rays come from cosmic rays — highly energetic charged particles — colliding with particles in the Sun's atmosphere, and the Sun's winds are ebbing during solar minima, allowing more cosmic rays to sneak by.

Fermi detects solar flares from their gamma-ray emission. Within Fermi's lifetime, its LAT has recorded more than 40 solar flares and its GBM has recorded almost 8,000. In 2012, Fermi's LAT caught the highest-energy emission ever detected from the Sun, which lasted over 20 hours and temporarily made the Sun the brightest object in the gamma-ray sky. Fermi has even detected emissions from solar flares that were partially hidden behind the Sun, known as "behind-the-limb flares." In theory, the Sun should block direct light from these flares. In order for the LAT to detect them, the charged particles released in the flare must travel around 300,000 miles within five minutes to strike the side of the Sun facing Earth and produce gamma rays there. Fermi's detection of behind-the-limb light in 2013 and 2014 led scientists to explore how charged particles from solar flares can move around the Sun.



In 2013 and 2014, when NASA's STEREO satellites were located on the far side of the Sun from Earth, they imaged solar flares, seen above, in extreme ultraviolet light. From these events, Fermi detected high-energy gamma rays. Scientists believe the flares accelerated particles that rained onto the Earth-facing side of the Sun to produce the gamma rays.

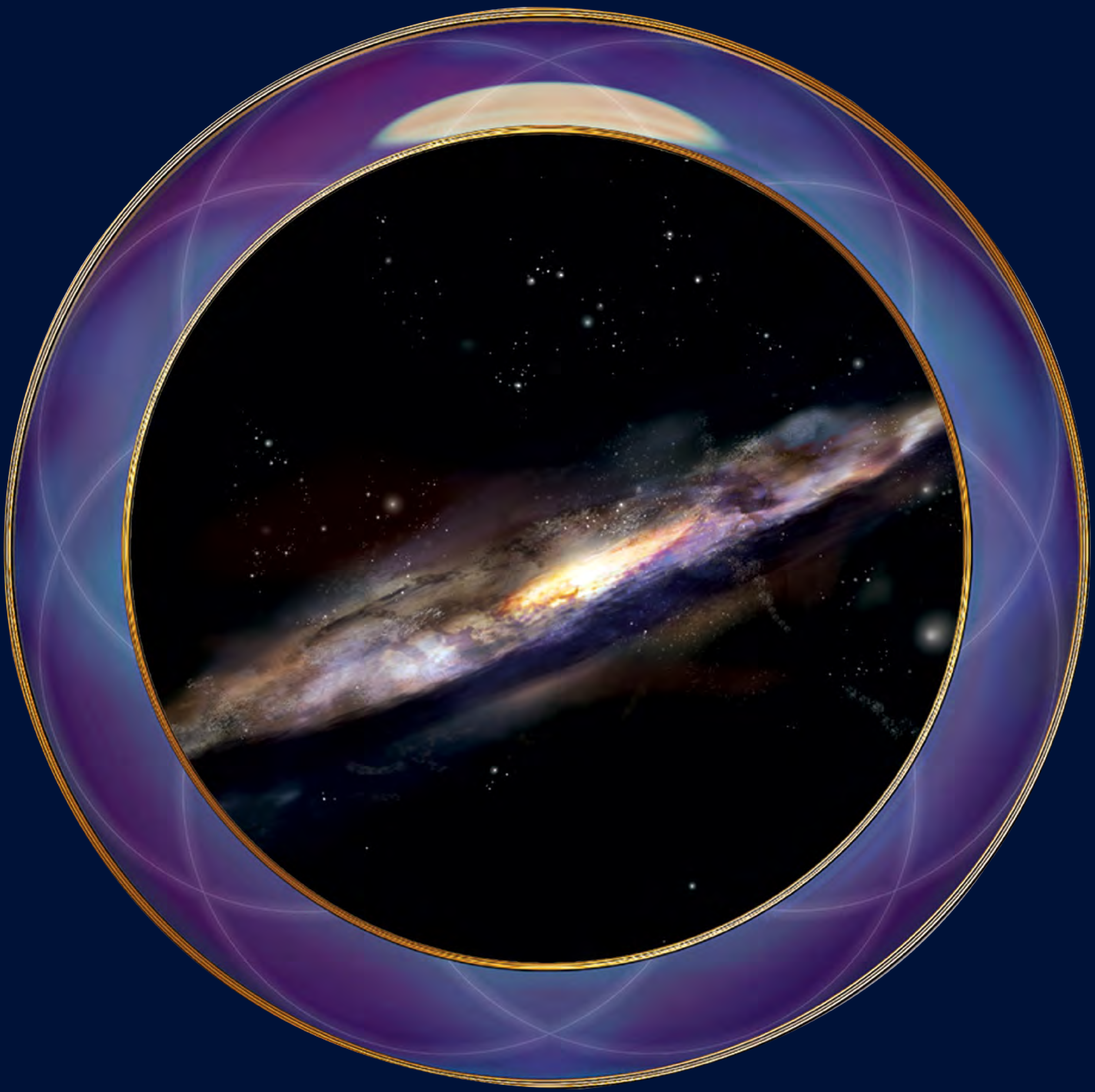
Credit: NASA/STEREO

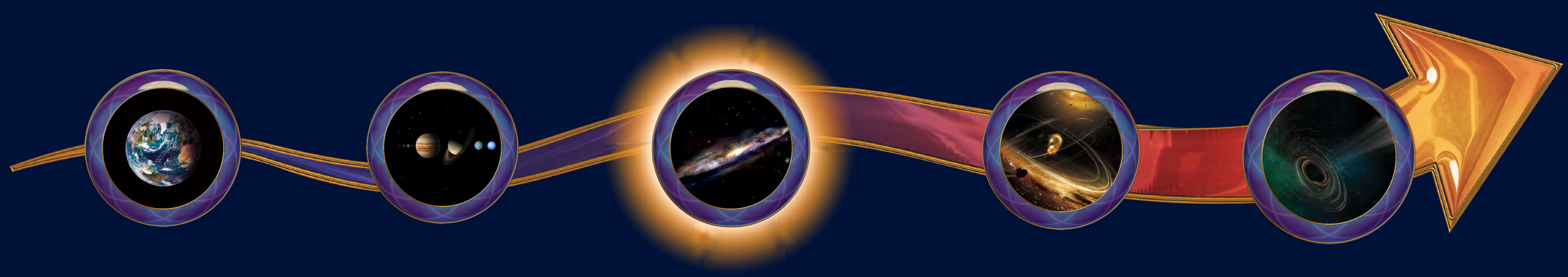


This image from Fermi's LAT shows how the entire sky looked on March 7, 2012, in gamma-ray light brighter than 100 megaelectron volts (MeV). On this day, the Sun was the brightest gamma-ray source, at over 1,000 times its normal brightness. Usually, the Vela pulsar is the brightest continuous gamma-ray source Fermi's LAT sees.

Credit: NASA/DOE/Fermi LAT Collaboration

The Galaxy



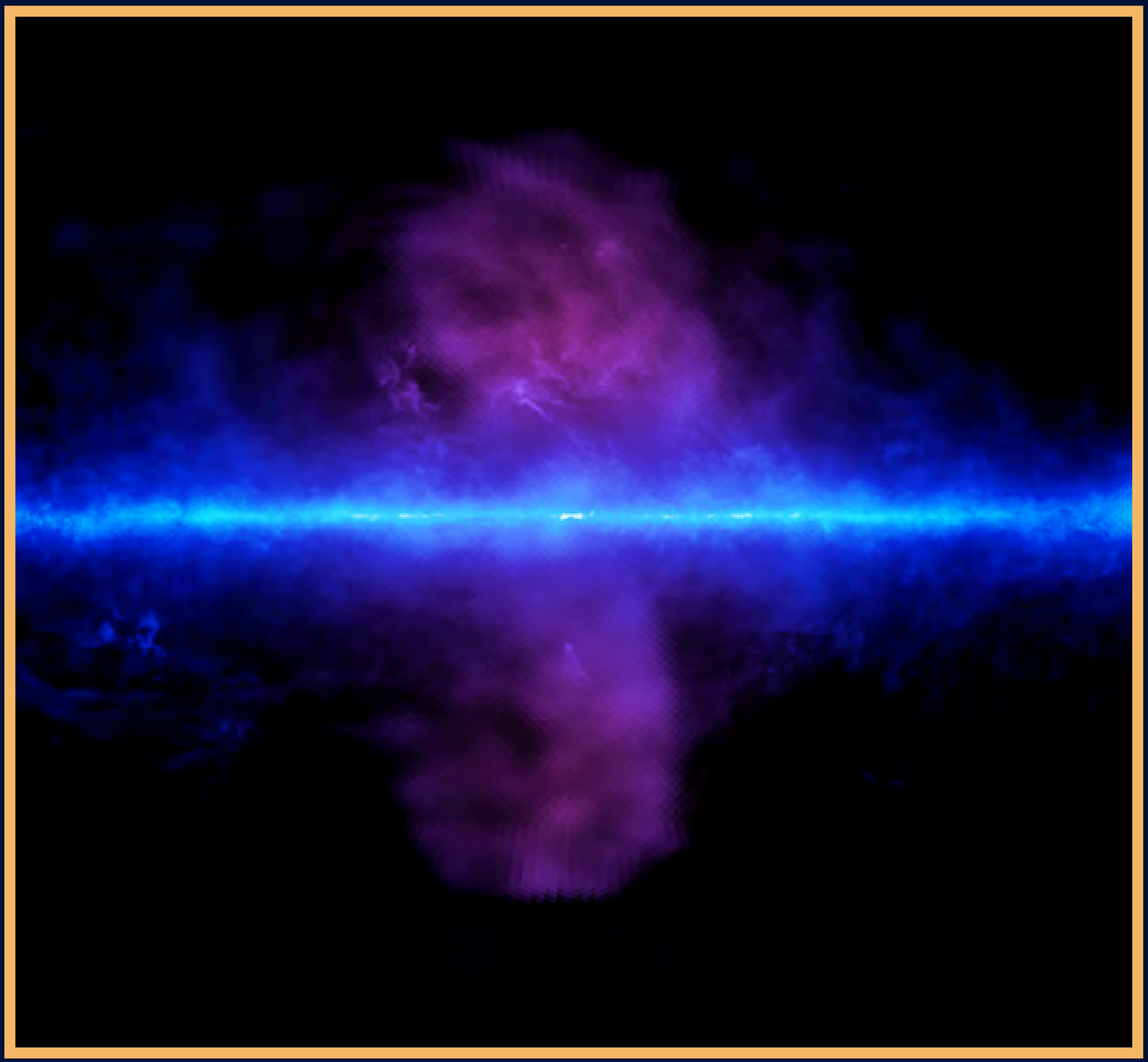


Credit: NASA/Sonoma State University, Aurore Simonnet

Galactic Diffuse Emission

Sources all around the universe emit streaming gamma rays, sending the highest-energy form of light barreling toward Fermi. We can think of these sources kind of like a person shouting — we hear them loud and clear. Amid the streams, there is also underlying gamma-ray emission from our galaxy, whose signals create what is known as "galactic diffuse emission." There is also an extragalactic component known as the "extragalactic gamma-ray background." Both underlying emission sources are like groups of nearby people whom you hear chatting, but you cannot make out their words. More than half of all of the gamma rays the LAT sees come from such underlying sources, so modeling them is vital to determine when gamma-ray sources stand out. There are many potential sources for galactic diffuse emission, and astrophysicists have been studying them since Fermi began taking data.

Scientists largely attribute the diffuse emission to a broad "halo" of cosmic rays in the Milky Way that is interacting with interstellar gas to produce gamma rays. The size of the halo may be bigger than we think, or we may not fully grasp the density of the interstellar gas, both of which would contribute to more gamma rays than scientists' models show. The Fermi Bubbles may also contribute gamma rays to the diffuse emission. Another exciting theory is that the higher-energy diffuse emission may signal the presence of decaying dark matter particles. Such a finding would give scientists a clearer idea of where dark matter exists, and what its properties are. Despite all of the potential sources of galactic diffuse emission, models still have yet to be consistent with the actual amount of gamma rays that the LAT observes. Galactic diffuse emission tells us that the galaxy is far more energetic than we previously believed, and determining the inner workings of the high-energy physics taking place all around us is one of Fermi's most important research projects.



This model shows the galactic plane as a sharp blue line and its galactic diffuse emission as wispy, darker blue tendrils. The galaxy glows brightly in diffuse gamma rays emitted when high-energy particles interact with gas and starlight. The Fermi Bubbles (magenta) are also featured prominently.

Credit: NASA/DOE/Fermi LAT Collaboration

Gamma-ray Pulsars

When massive stars explode, the crushed cores they leave behind can become rotating stars called pulsars. These small but incredibly dense stars are a type of neutron star, which squeeze more mass than the Sun into a ball the size of a city. One reason pulsars spin rapidly is the same reason a figure skater does when they pull in their arms — shrinking in size while maintaining the same mass causes an object to spin faster in order to conserve a property called angular momentum. Pulsars emit light across the electromagnetic spectrum, though their emissions are concentrated in the gamma-ray and radio bands. As the star rotates, a lighthouse-like beam swings around the sky, periodically sweeping past Earth and producing the pulses of radiation that give these objects their name.

There are about 3,400 known pulsars, and Fermi has detected gamma rays from more than 300 of them. In 2008, Fermi's LAT became the first instrument to discover pulsars solely through their gamma-ray emission; previously, scientists relied on X-ray or radio emission to confirm a pulsar discovery. In fact, Fermi revealed that many pulsars do not even emit observable radio waves, enabling the detection of previously hidden pulsar populations. The LAT team combines its observations with those of collaborations of radio telescopes to keep discovering pulsars at record rates. Fermi has also detected a type of pulsar called millisecond pulsars, which are pulsars that begin to spin faster when "recycled," or spun up by gaining matter from a companion star. Fermi's GBM can actually track some pulsars as they change speed. Knowing the type of radiation a pulsar emits and the period of its pulses helps to determine its characteristics, like age and rate of energy loss. For example, while some gamma-ray pulsars are only thousands of years old, the recycled ones can have ages greater than a billion years.

In this illustration, a pulsar spinning hundreds of times per second periodically swings its radio (green) and gamma-ray (magenta) beams past Earth. Fermi has detected over 300 pulsars in gamma rays.

Credit: NASA's Goddard Space Flight Center

Spider Binaries

Two types of two-star systems, called binaries, have deadly namesakes: black widow and redback spiders. These cosmic killers contain a low-mass star next to a millisecond pulsar, a faster class of pulsars that spin at up to 60,000 revolutions per minute. Much like the spiders, the millisecond pulsars in black widow and redback binaries are devouring their partners! They do so by siphoning away a stream of gas from the lower-mass star, which energizes the pulsar and speeds it up. This occurs as the millisecond pulsar spins: its high-energy emission and wind superheat and blow away the lower-mass star's material until, after millions or billions of years, the wind has eaten away the entire star. Black widow systems host companion stars less than 5% of the Sun's mass, whereas redback systems have companions between 10-50% of the Sun's mass. Interestingly, while pulsars usually appear alone, more than half of all discovered millisecond pulsars have a stellar partner. This suggests that interactions between a pulsar and a low-mass star can give new life to the pulsar, causing it to spin even faster than before. With Fermi's help, astronomers have found at least 18 black widow and nine redback systems within the Milky Way.

Since pulsars are a strong source of gamma rays, Fermi is excellent at detecting them. When a millisecond pulsar blows away the material of the companion star, ionized gas fills the system, through which only high-energy emissions easily pass — perfect for Fermi's LAT. Using Fermi, scientists have discovered more than 144 gamma-ray millisecond pulsars. A prominent strategy for detecting these pulsars is to target Fermi gamma-ray sources with radio telescopes, which can help tease out the timing and speed of the pulsing signal. Using black widow and redback binaries, scientists aim to observe how a low-mass star intercepts energy from a millisecond pulsar, and thus glean more details about pulsar emission.

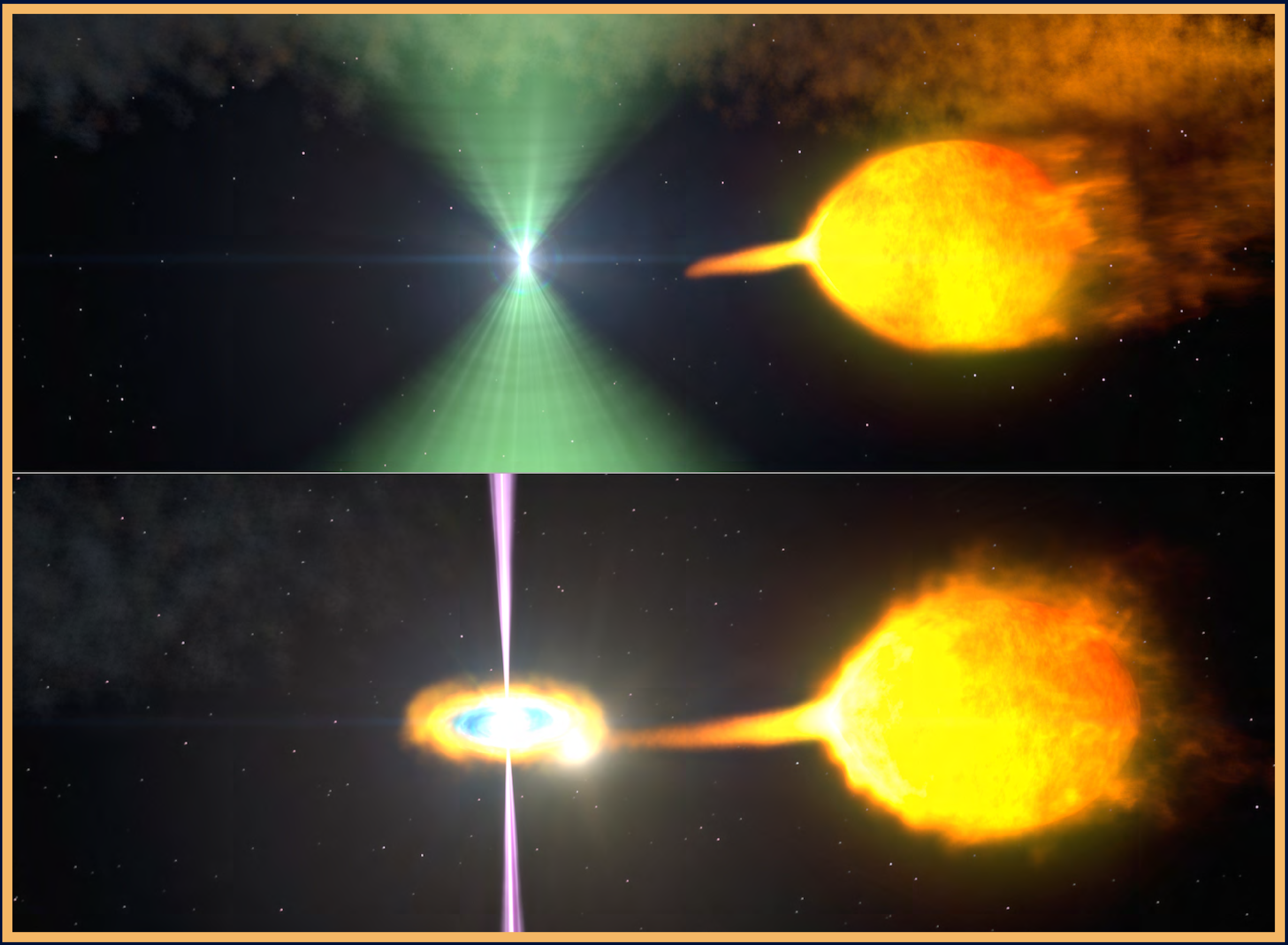
This artist's rendering shows a pulsar (top left) blowing away material from a lower-mass star (bottom). This system is called a spider binary.

Credit: NASA/Sonoma State University, Aurore Simonnet

Transitional Pulsars

Scientists have long known that pulsars, the crushed cores of massive stars, emit radiation across the electromagnetic spectrum. More recently, they discovered that some of them do so in a unique way: by switching rapidly between types of emission. Called transitional pulsars, they will emit one type of radiation — radio, for example — and then switch over a few days or weeks to emitting a different kind, like X-rays. Transitional pulsars are part of a binary system, where two stars — one of them a millisecond pulsar — orbit each other. Scientists believe that the transition occurs as the millisecond pulsar strips matter off of its companion star, subsequently changing the nature of its powerful "wind" of high-energy particles. As the wind changes, so does the emission that escapes the system and travels across the universe to Fermi and other telescopes.

Fermi can find transitional pulsars because the pulsar already emits a gamma-ray signal, which brightens at the same time as the radio-to-X-ray transition. In 2013, a binary system called AY Sextantis showed this exact phenomenon — one of the first of its kind to flip from radio to gamma-ray emission. Another binary system, IGR J18245-2452, also discovered in 2013, flipped between radio and X-ray emission. Fermi observed AY Sextantis, helping scientists to hypothesize that they were viewing the last stages of the millisecond pulsar stripping matter from its companion. The discovery of transitional pulsars helped further astrophysicists' understanding of how millisecond pulsars form.



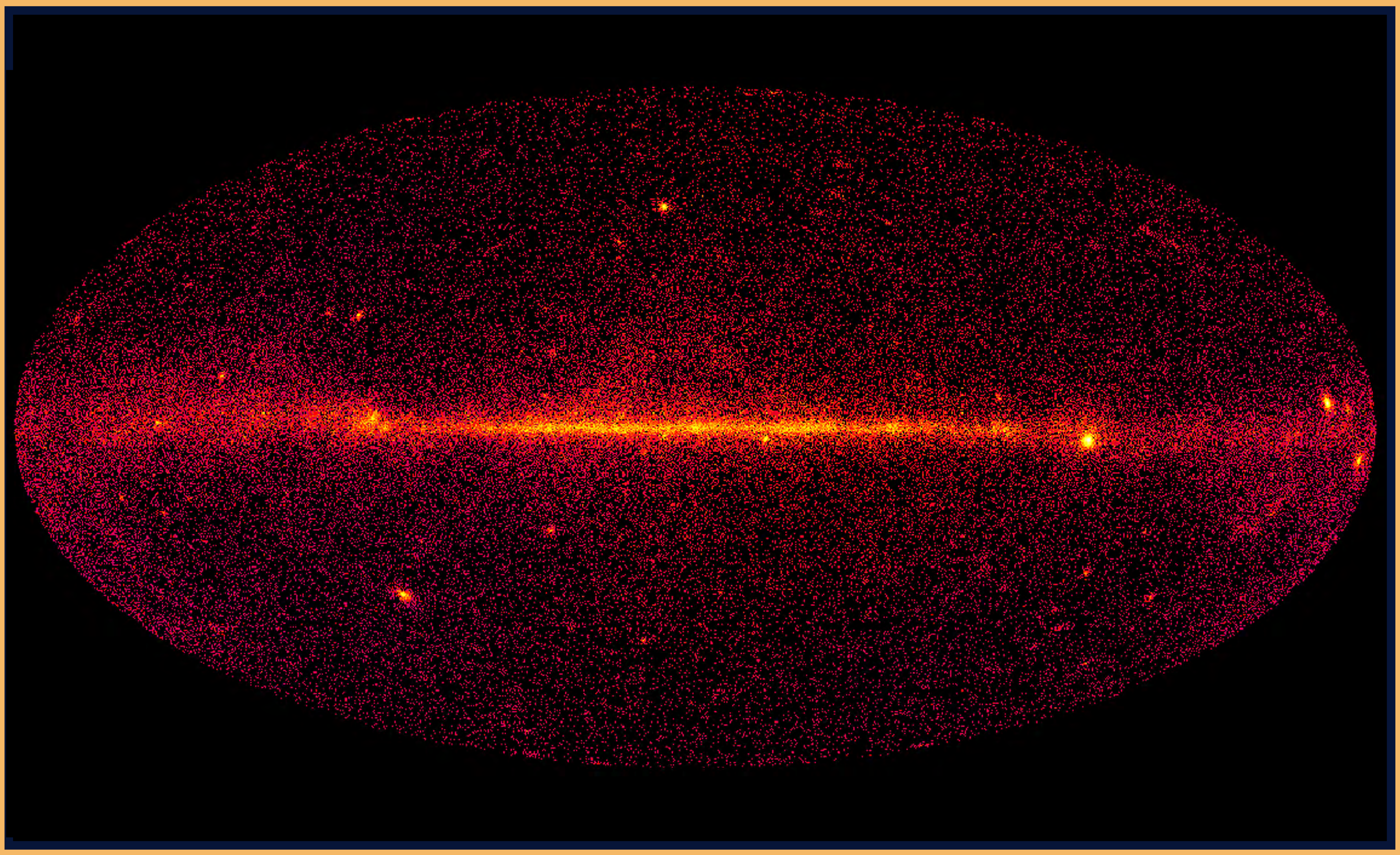
One model of the AY Sextantis system before (top) and after (bottom) its radio beacon (green) vanished. When the millisecond pulsar's high-energy wind changed, gamma-ray particle jets (magenta) obscured the radio beam.

Credit: NASA's Goddard Space Flight Center

Fun Fact:
A Gamma-Ray Self-Portrait

When Fermi began surveying the sky in 2008, scientists were excited to see what it would discover first. From faraway gamma-ray bursts to energetic blazars, the options seemed plentiful. However, when they sat down to analyze Fermi's science data, the first gamma-ray source Fermi had seen was our own galaxy.

The result was not surprising. The Milky Way is exceptionally bright in gamma rays, and happened to be the first source scientists saw with Compton and previous gamma-ray satellites. In fact, back in the 1950s, the first cosmic gamma rays scientists predicted they could find were those from our galaxy. Much of this light is actually a diffuse gamma-ray glow rather than specific gamma-ray sources. As cosmic rays from supernovae hit interstellar gas and light, they accelerate particles to produce gamma rays. Since its first gamma-ray observations, Fermi's picture of the Milky Way has gotten tremendously clearer. Fermi's first observation was a good reminder that while Fermi and other NASA observatories are designed to tell us more about our expansive universe, they are simultaneously helping us learn more about the place we call home within it.



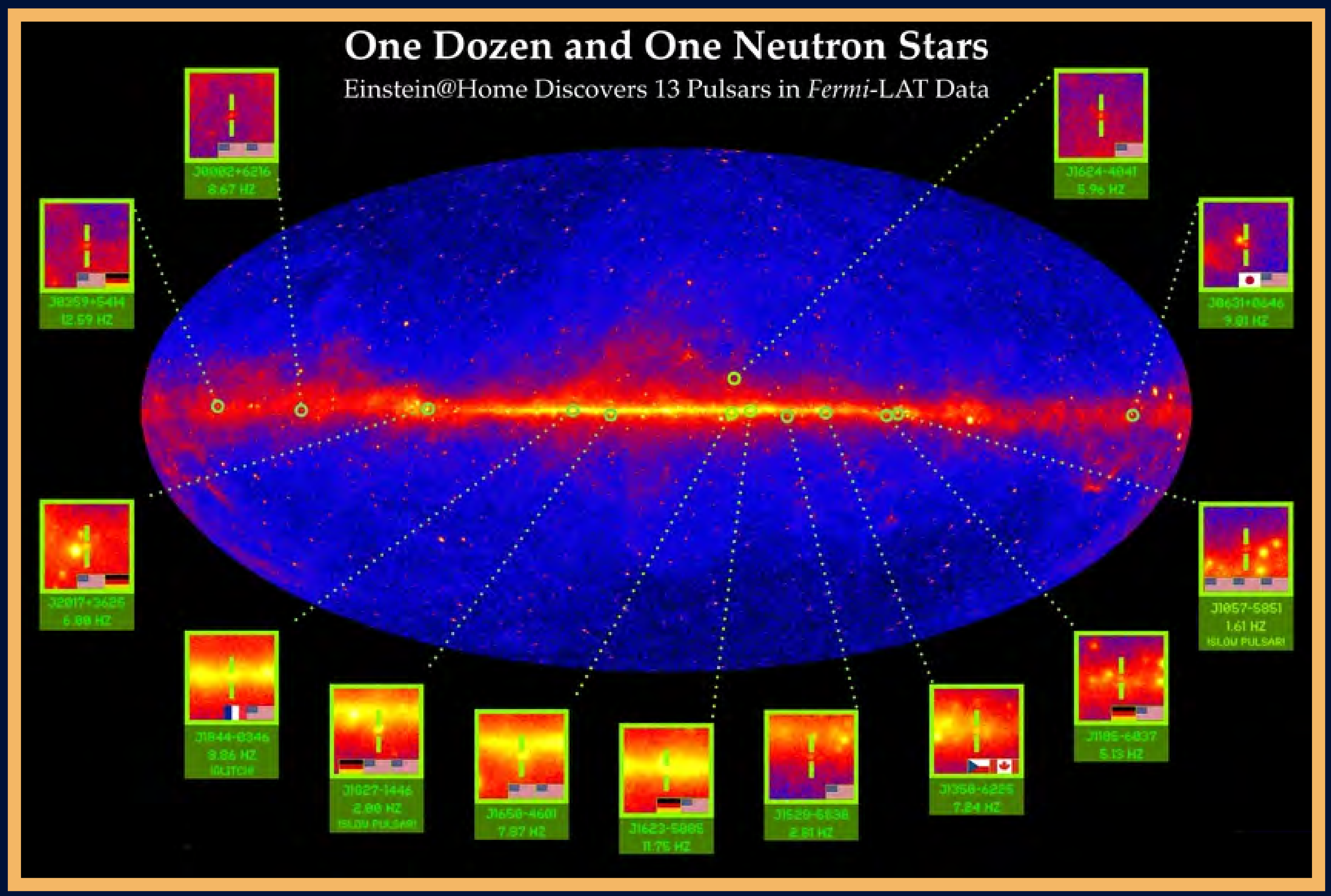
The Fermi all-sky map after one week of observations.

Credit: NASA/DOE/Fermi LAT Collaboration

Einstein@Home

Did you know your computer can do astrophysics when you're not looking? A citizen science project called Einstein@Home enables volunteers to download software to search for weak astrophysical signals in their computer's idle time. These signals are hidden in massive amounts of raw data that telescopes like Fermi collect while observing the universe. Sifting through all of these data to find patterns and signals takes enormous amounts of time, so scientists developed Einstein@Home to speed up the process. The program allows your computer to comb through astronomical data, specifically looking for signals from spinning neutron stars known as pulsars. Searching for signals without knowing specific information about the pulsars beforehand is called blind searching. The public's computers have discovered about 50 new neutron stars since Einstein@Home's launch in February 2005.

Fermi's LAT Source Catalog contains more than 2,000 unidentified gamma-ray sources, but Einstein@Home sifts through just 118. These objects, whose emissions resemble pulsars, make up the Fermi Gamma-ray Pulsar Search. Another hunt, called the Fermi Gamma-ray Pulsars in Binaries Search, focuses on pulsar-like sources which seem to occur in binary star systems. On average, Fermi's LAT detects 10 photons per day from a pulsar. This means that detecting patterns with fine resolution requires years of data and enormous computing power. Einstein@Home accelerates the search dramatically by putting citizens' computers on the trail. The project eventually aims to detect gravitational waves from pulsars, a feat that had never been done prior to groundbreaking results from the North American Nanohertz Observatory for Gravitational Waves Physics Frontiers Center in June 2023.



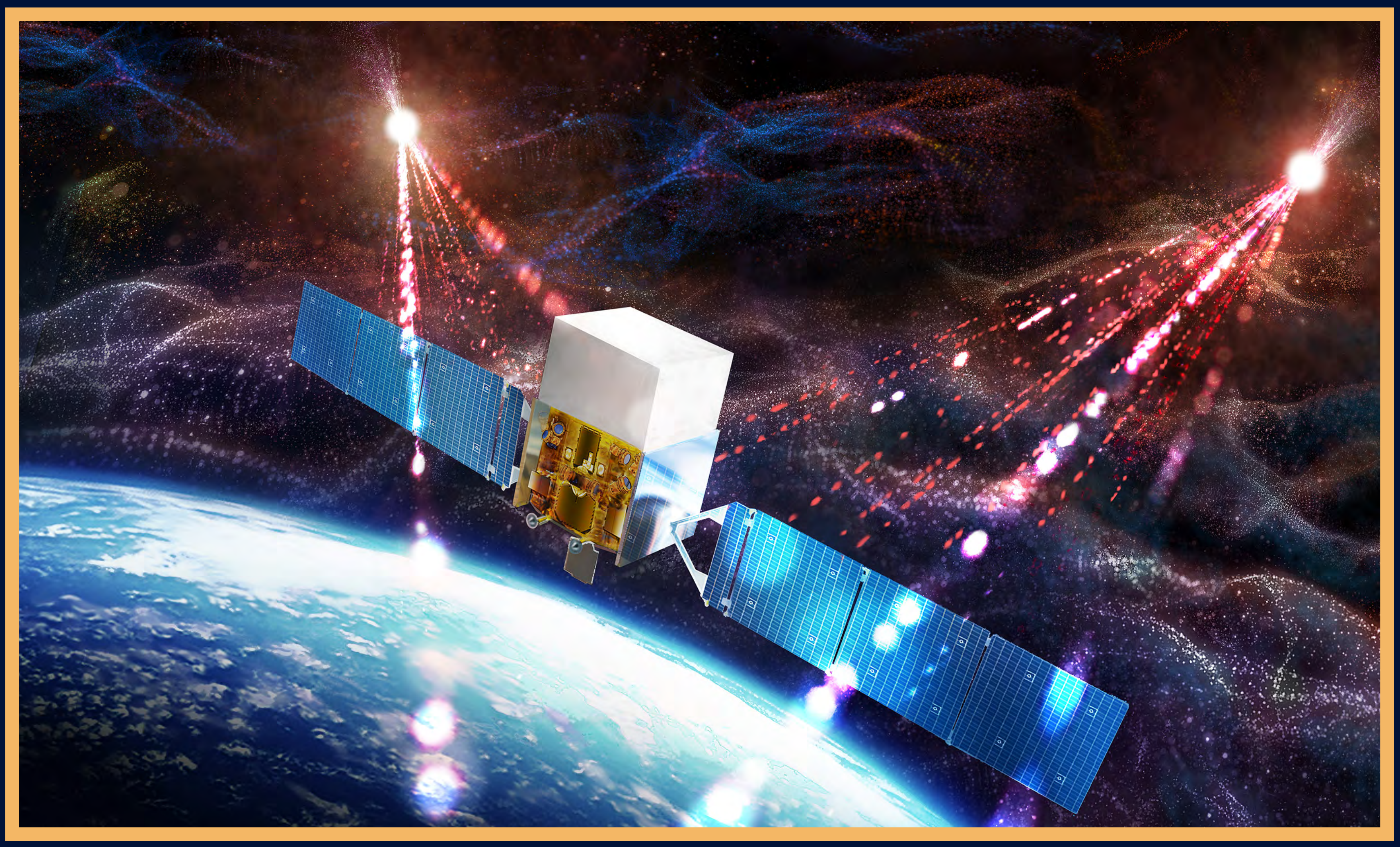
The entire sky as seen by Fermi and the 13 pulsars discovered by Einstein@Home that were published in January 2017. The field below each inset shows the pulsar's name and rotation frequency. The flags in the insets show the nationalities of the volunteers whose computers found the pulsars.

Credit: Knispel/Clark/Max Planck Institute for Gravitational Physics/NASA/DOE/Fermi LAT Collaboration

Pulsar Timing Array

Since Fermi's launch, the number of discovered gamma-ray pulsars has multiplied dramatically. Today, scientists know of more than 300 gamma-ray pulsars, enabling them to better study their properties and oddities. One of the most interesting uses for pulsars is as a pulsar timing array: a set of pulsars whose steady pulse intervals tell us about the space between us and them. Each time the pulsar's lighthouse-like beam swings by Earth, Fermi and other telescopes detect a pulse, building up a record of the pattern. Sometimes, the pulsar beam swings by earlier or later than expected from the pattern, which signals to scientists that something has perturbed the space-time between us and it. This is a technique used primarily to search for gravitational waves, ripples in space-time that travel at the speed of light. Since gravitational waves squeeze and stretch everything in their path, they cause the pulsar's beam of radiation to arrive at Fermi at a different time than expected if no gravitational waves were present. Scientists typically choose millisecond pulsars for pulsar timing arrays because of their clockwork-like consistency. The disruption from gravitational waves is as short as billionths of a second!

A 2022 study used 12.5 years of LAT data from 35 of the most stable millisecond pulsars known to search for the gravitational wave background (GWB). The GWB is a "background hum" of gravitational waves pervading the universe from many different unidentified sources, akin to the murmur of indistinct voices in a crowd. Astrophysicists believe the GWB comes from supermassive black holes that are drawing closer together at the centers of merging galaxies. Though they had been theorized about more than 100 years ago, the first gravitational waves weren't detected until 2015, when the National Science Foundation's LIGO (Laser Interferometer Gravitational-Wave Observatory) detected merging black holes around the size of our Sun. Prior to Fermi, scientists relied primarily on radio telescopes to hunt for the GWB. Fermi provides a complementary way to search for the GWB because gamma rays are not affected by the interstellar medium, which can obscure signals to a radio telescope. The study found that while Fermi's pulsar timing array is not yet sensitive enough to detect the GWB signals seen by radio telescopes, it will continue to improve over time with more pulsar detections and more years of data. The LAT team is hoping to detect the GWB within the next five years.



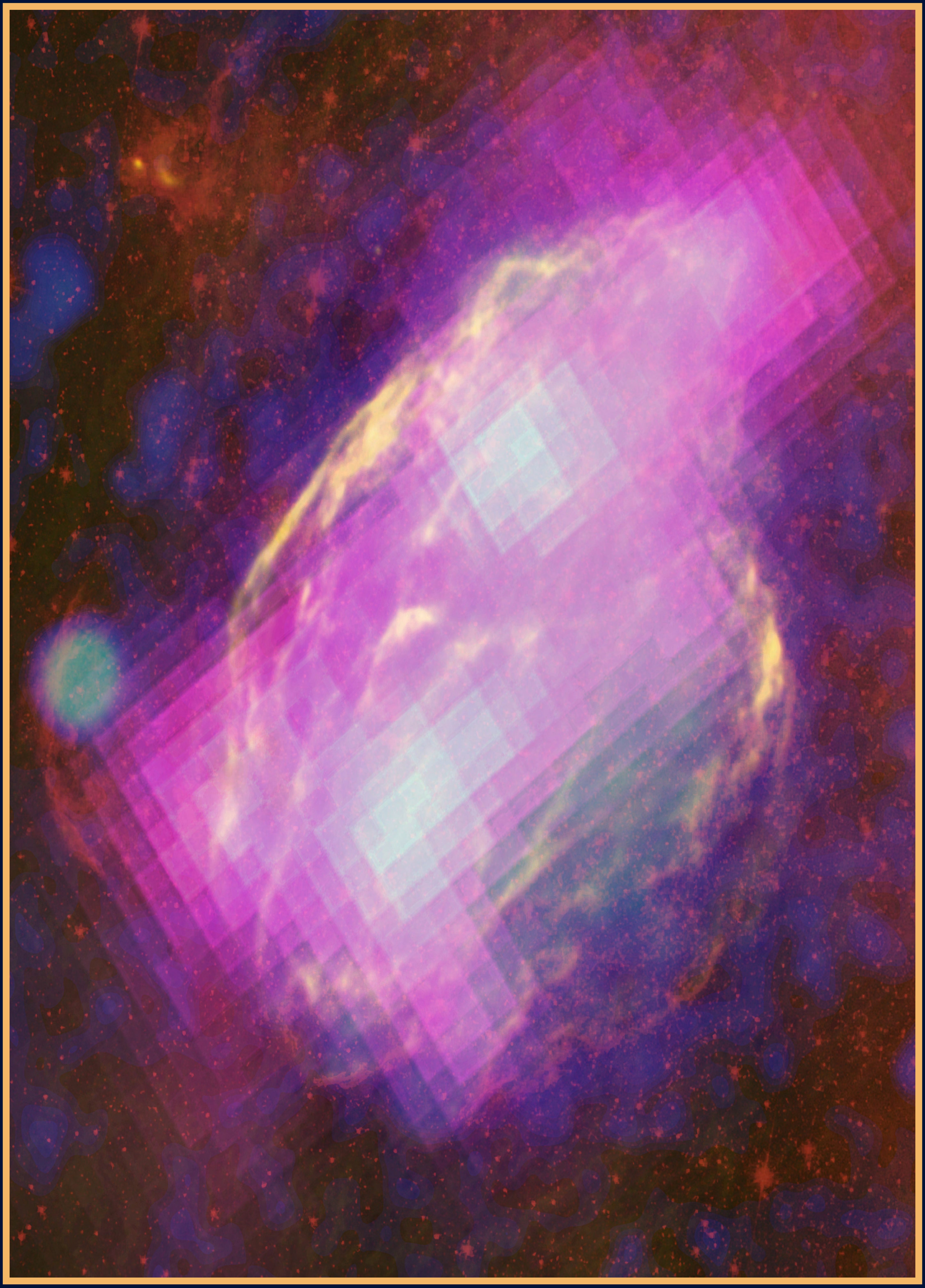
Fermi, illustrated here, collects gamma rays from rapidly rotating stellar remnants called pulsars. As the high-energy light travels across the Milky Way, it encounters a sea of gravitational waves which slightly affect the arrival time of gamma rays, something Fermi should be able to detect.

Credit: Daniëlle Futselaar/MPIfR

Supernova Remnants

Some of the fastest-moving matter in the universe comes from some of its largest explosions: supernovae. When a star explodes, it transforms over thousands of years into a supernova remnant, a rapidly expanding cloud of gas contained by a shock wave with a strong magnetic field. Charged particles trapped within the magnetic field repeatedly cross the shock wave, a process called Fermi acceleration after its discoverer, Enrico Fermi. Crossing the shock wave boosts the speed of the particles, and after many passes, they gain enough speed to break free from the magnetic field and escape into the galaxy as a cosmic ray. Cosmic rays are electrically charged subatomic particles that travel near the speed of light. Ninety percent of cosmic rays are made of particles called protons, but they can also include electrons or atomic nuclei. As these accelerated particles travel, other magnetic fields deflect them, which makes it impossible for scientists to trace their origins directly. Cosmic rays constantly bombard Earth, producing a shower of even smaller particles upon impact with our atmosphere.

Fermi's LAT tracks cosmic rays using the gamma rays emitted from their interactions with nearby matter. Sourcing these gamma rays therefore serves as a proxy for tracking the origins of cosmic rays. Supernova remnants had long been candidates for the origin of cosmic rays because they emit gamma rays with energies of more than a billion electron volts (for comparison, visible light's energy range is 2-3 electron volts). In 2013, Fermi confirmed this theory using two particular supernova remnants: IC 443 and W44. These remnants are expanding into cold, dense clouds of interstellar gas, causing the clouds to emit gamma rays when high-speed particles escaping the remnants strike them. Analyzing years of data enabled Fermi scientists to determine that the escaping particles are accelerated protons. Confirming that cosmic rays come from supernova remnants was an important step forward in understanding these speedy and energetic particles.



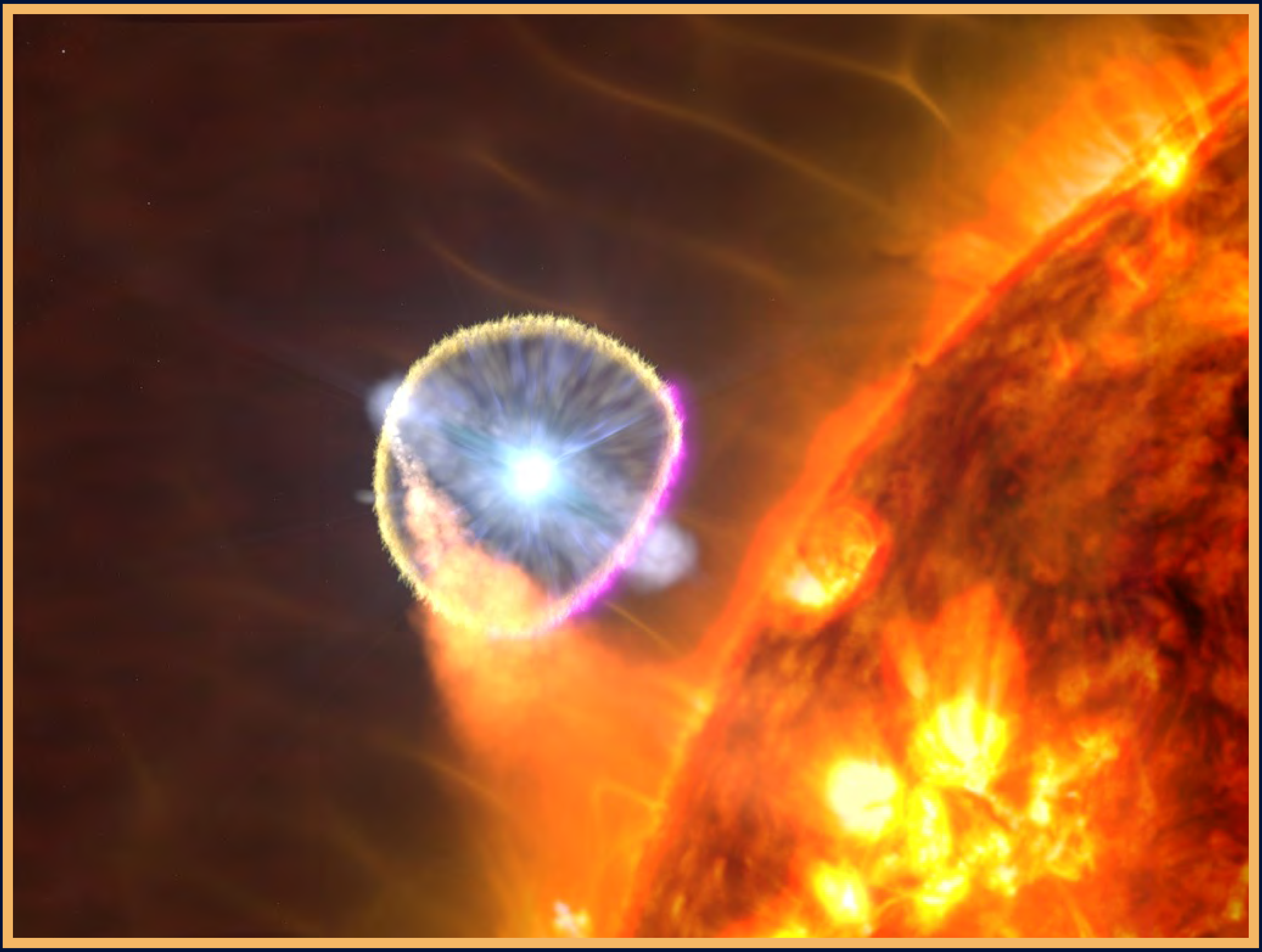
These composite images show supernova remnants IC 443 (left) and W44 (above). The remnants are expanding into cold, dense clouds of interstellar gas, where protons accelerated in the remnants emit gamma rays. In the left image, Fermi gigaelectron volt (GeV) gamma-ray emission is magenta, optical wavelengths are yellow, and infrared wavelengths are blue, cyan, green, and red. In the above image, Fermi GeV gamma-ray emission is magenta, X-rays are blue, infrared light is red, and radio waves are yellow.

Credits: Left, NASA/DOE/Fermi LAT Collaboration, Tom Bash and John Fox/Adam Block/NOAO/AURA/NSF/JPL-Caltech/UCLA; Right, NASA/DOE/Fermi LAT Collaboration, CXC/SAO/JPL-Caltech/Steward/O. Krause et al., and NRAO/AUI

Novae

Explosions in space are unlike anything seen on Earth. A classical nova releases as much energy as two trillion trillion tons of TNT. (That's a two followed by 24 zeros.) This is between 10,000 and 100,000 times more energy than our Sun produces in a whole year. Classical novae result from thermonuclear explosions on the surfaces of white dwarfs, the dense, hot cores of Sun-like stars that have exhausted their nuclear fuel. Novae happen when a white dwarf that is part of a binary star system slowly accretes matter from a companion star. When enough hydrogen builds up on the surface, an explosion occurs that ejects the accreted gas. The white dwarf brightens dramatically but remains intact. The ejected material expands into space, creating shock waves that accelerate particles to near the speed of light, causing them to emit gamma rays.

Fermi's LAT discovered that classical novae almost always produce gamma rays, a finding that was wholly unexpected. Fermi's first gamma-ray detection from a nova occurred in 2010. The source, named V407 Cygni, is a rare star system where the white dwarf's companion was a red giant, a type of star more than 100 times the size of our Sun. The rarity of the star system initially led scientists to think the gamma-ray detection was a fluke, or at least limited to these types of star systems. Then, in 2012 and 2013, Fermi's LAT detected three classical novae, leading scientists to hypothesize the gamma-ray detections were a pattern rather than a coincidence. Since its launch, Fermi has detected about 20 novae in gamma rays, but scientists hypothesize that most novae go undetected due to interstellar dust obscuring their lower-energy light. Studying novae in high-energy light may help scientists to discover ever increasing numbers of these stellar explosions.



This is an artist's rendering of the white dwarf star in V407 Cygni that went nova in 2010. Scientists think the outburst primarily emitted gamma rays (magenta) as the blast wave plowed through the gas-rich environment near the system's red giant star.

Credit: NASA's Goddard Space Flight Center/S. Wiessinger

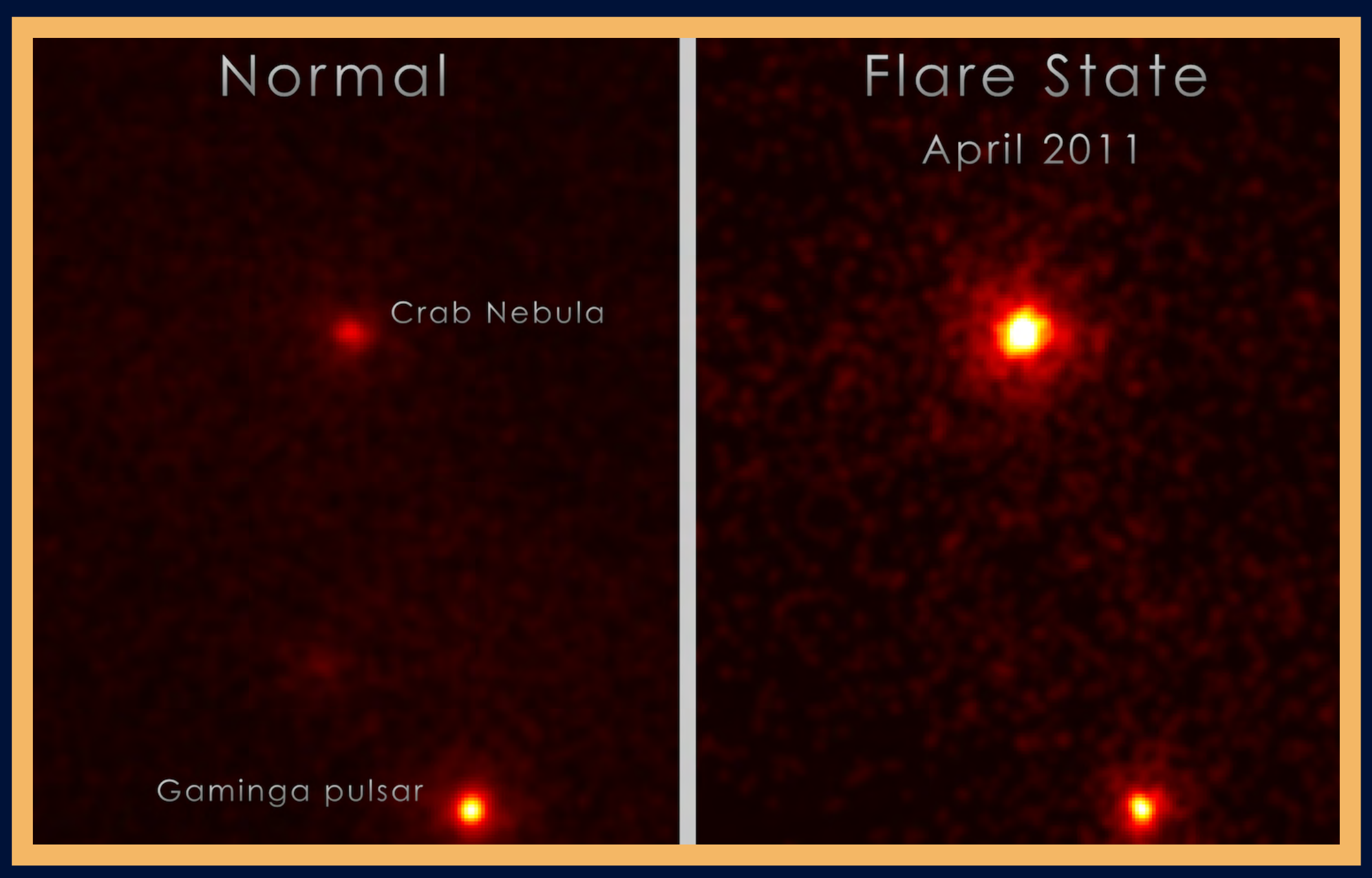
Crab Nebula

If you've ever seen a crab scuttling along at the beach, you'll remember its curved legs and sharp pincers. An Irish astronomer saw a crab's likeness in the sky in 1844. Now the Crab Nebula is known as one of our galaxy's most energetic objects. It is the wreckage of an exploded star that people on Earth observed as a supernova in 1054. Located 6,500 light-years away, its tentacle-like structure is made of expanding gas, and at its center lies a pulsar, the leftover core from the original star, that spins over 30 times per second. Fermi's LAT records consistent gamma-ray pulses from the pulsar's lighthouse-like beam of radiation, but it also picks up a background signal of high-energy radiation from the Crab. Scientists believe that as the magnetic field around the Crab's pulsar changes, it accelerates particles like electrons to velocities near the speed of light. When the accelerated particles interact with the magnetic field, they emit gamma rays.

Sometimes, the Crab Nebula flares up. In 2011, scientists detected an outburst five times more powerful than any previous flare and 30 times more powerful than the normal background with Fermi's LAT. The flare lasted six days and produced gamma rays with energies over 100 million electron volts (visible light is between 2 and 3 electron volts). Given the flare's strength, scientists think that the gamma rays came from a region comparable in size to our solar system and about one-third of a light-year from the central pulsar.

Fermi isn't the only telescope interested in the Crab; NASA's Chandra X-ray Observatory also routinely monitors the supernova remnant. When the LAT observed the 2011 flare, the Fermi team alerted the Chandra team. Interestingly, though Chandra caught lots of activity, the team saw no brightness in X-rays associated with the giant flare. In the years since, Fermi has detected numerous lower-intensity flares, too.

Over time, the Crab's brightness has been thought to be extremely steady, allowing scientists to use it to calibrate instruments and define the brightness of other gamma-ray sources. There is even a unit of measurement called the millicrab: something that is 1 millicrab in brightness is 1/1000th as bright as the Crab. However, two years of data from Fermi's GBM revealed in 2010 that the Crab had gotten fainter by 7% since Fermi launched in 2008. This discovery shocked the astronomy community and caused people to rethink the way they rely on the Crab. In the years since, Fermi's GBM has shown that the Crab's brightness has continued to vary, brightening and dimming over time.



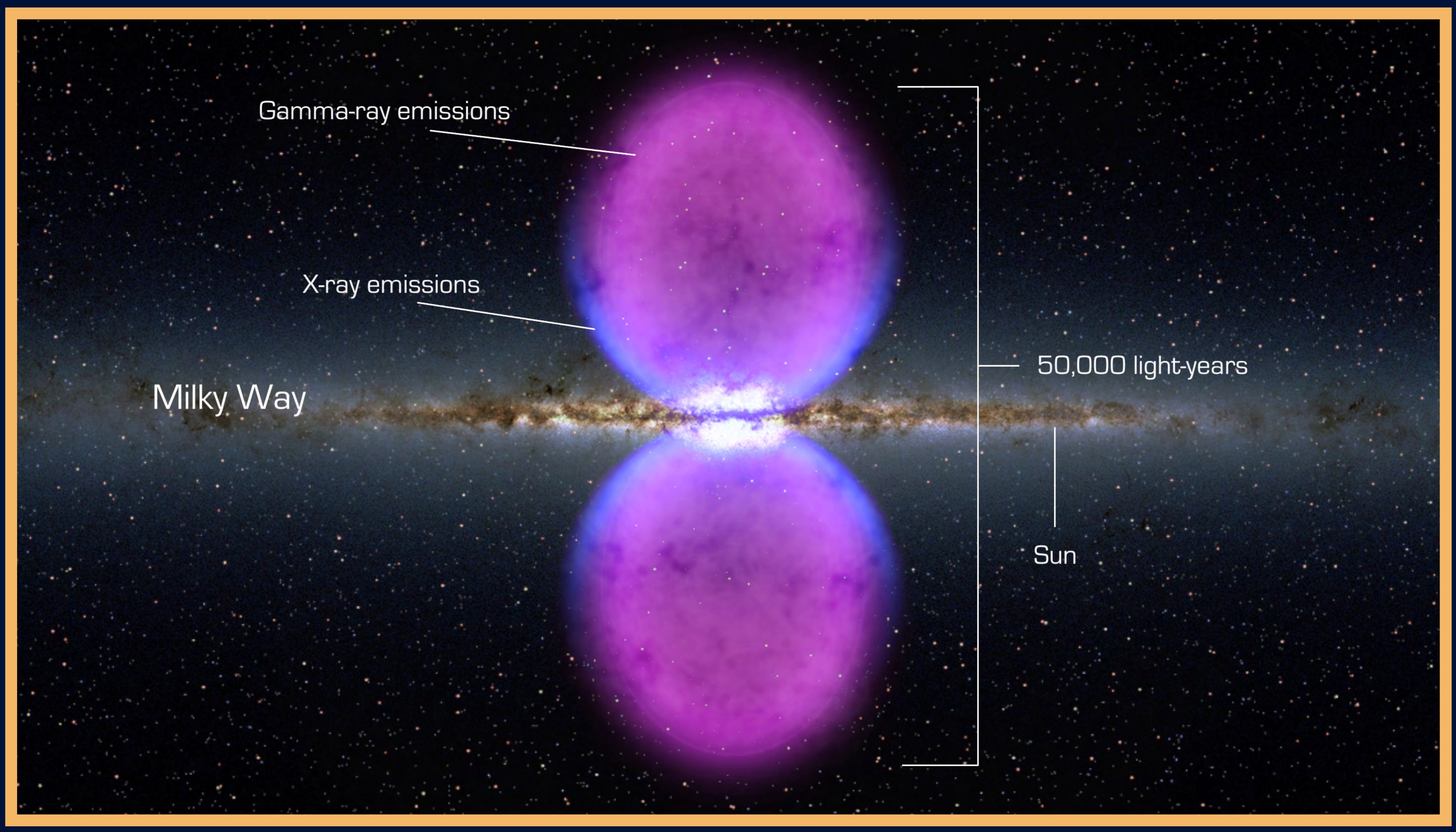
Fermi's LAT discovered a gamma-ray "superflare" from the Crab Nebula on April 12, 2011. These images show the number of gamma rays with energies greater than 100 million electron volts from a region of the sky centered on the Crab Nebula. At left is the area 20 days before the flare; at right is April 14.

Credit: NASA/DOE/Fermi LAT/R. Buehler

Fermi Bubbles

One of the most exciting parts of science is finding things you never knew to look for. The Fermi Bubbles, discovered by a team of scientists at the Center for Astrophysics | Harvard & Smithsonian (CFA) in 2010, are exactly that type of finding. The Fermi Bubbles are two lobe-shaped structures above and below the center of our galaxy that emit higher-energy gamma rays than the rest of the galaxy. The lobes are each about 25,000 light-years tall. Within them, extremely energetic electrons interact with ultraviolet or lower-energy light and interstellar gas to produce gamma rays. Scientists believe the bubbles may be related to the vast amounts of energy that the supermassive black hole in the center of our Milky Way emits. In the past, the black hole may have produced high-energy jets — a phenomenon seen in other galaxies — that left behind the lobes. The bubbles could also have formed thanks to a massive burst of star formation. Other telescopes have found similar structures in different wavelengths of light; the German-Russian eRosita (extended ROentgen Survey with an Imaging Telescope Array) instrument found even larger bubbles in X-rays, and NASA's WMAP (Wilkinson Microwave Anisotropy Probe) found a microwave haze above and below the galactic plane.

The Fermi Bubbles are a discovery made possible only by Fermi's extensive data archive. Since Fermi's data is open and available to the public immediately upon processing, scientists around the world are able to download it and conduct science. The CFA team, which expanded on previous work by other scientists, was actually searching for dark matter when they discovered the Fermi Bubbles. Previous astronomers never found them due to diffuse gamma-ray emission, a sort of fog of gamma rays across the sky that had obscured the bubbles. Diffuse gamma rays occur when superfast particles interact with light and interstellar gas in the Milky Way. When the CFA team subtracted the gamma-ray fog from the Fermi all-sky data, the bubbles suddenly emerged. Since the discovery of the Fermi Bubbles, scientists have been hard at work researching their true origins. In recent years, scientists using the National Science Foundation's IceCube Neutrino Observatory in Antarctica discovered 10 neutrinos — highly energetic particles from the interaction of cosmic rays — that may have been sourced from the bubbles.



In this illustration, the Fermi bubbles are shown extending 50,000 light-years end to end — roughly half of the Milky Way's diameter. If the structure were rotated into our galaxy's plane, it would extend beyond our solar system. In this image, gamma rays are magenta and X-rays are blue.

Credit: NASA's Goddard Space Flight Center

Fun Fact:
Fermi in the Kitchen

Doing science with Fermi can really work up an appetite! The Fermi team loves to get creative in the kitchen by baking and sharing treats inspired by the observatory. From focaccia featuring the telescope to tiered cakes depicting the stages of binary neutron star mergers, Fermi team members frequently look to the cosmos for culinary inspiration.

How to bake a Fermi sugar cookie:

Batter Ingredients

1 cup (226 g) unsalted butter (room temperature)
1 cup (200 g) granulated sugar
1 teaspoon vanilla extract
1 large egg
2 ¾ cup (345 g) all-purpose flour
2 tablespoons cornstarch
¼ teaspoon baking powder
½ teaspoon salt

Icing Ingredients:

3 tablespoons (30 g) meringue powder
3 cups (339 g) powdered sugar
6 tablespoons water (90 g)
Gel food coloring (black, blue, red, yellow)

Baking Instructions:

1- Preheat the oven to 350°F (175°C) and line two cookie sheets with parchment paper.
2- Beat the butter and sugar in a stand mixer with a paddle attachment or a hand mixer until lighter in color and fluffy. This may take several minutes.
3- Add the egg and vanilla, and continue to mix until combined, scraping the sides of the bowl as needed.
4- In a separate bowl, combine flour, cornstarch, baking powder, and salt. Whisk to thoroughly combine.
5- With the mixer on low speed, slowly add the dry ingredients to the butter mixture, and mix just until the dry mixture is incorporated.
6- Form the dough into a disk, cut it in half, and place one half on a fresh piece of parchment paper. Place another piece of parchment paper on top. If the dough is really sticky, add a little bit of flour between the dough and the parchment paper.
7- Use a rolling pin to roll out the dough between the two pieces of parchment paper to ¼" (6.5 mm) thickness.
8- Remove the top sheet of parchment paper and use an oval cookie cutter to cut out sky map all-sky projection shapes. If needed, dip the cookie cutter in flour.

9- Remove the excess dough and peel the cookies off the parchment paper. Repeat with the second half of the dough.
10- Place the cookies on the prepared pans, and reroll and cut the excess dough until it is used up.
11- (Optional) Chill the unbaked cookies on trays in the refrigerator until your oven is preheated to reduce spread while baking.
12- Bake the cookies for 10 minutes until set and very lightly golden.
13- Let the cookies cool completely on trays before decorating.

Decorating Instructions:

1- Combine the powdered sugar, meringue powder, and water in a mixing bowl.
2- Beat on medium speed with a stand mixer or hand mixer until the royal icing is slightly fluffy, scraping the bowl as necessary. The icing should be a thick flood consistency.
3- Split the royal icing into four small bowls with 75% split between two bowls, and the remaining 25% split between two bowls. Add a few drops of food coloring to color the larger bowls black and blue and the smaller bowls red and yellow. Keep adding color until they are vibrant, but note that icing will continue to darken as it absorbs color.
4- Scrape each bowl of royal icing into separate piping bags or sandwich bags, fitting them with small round piping tips or cutting tiny holes in the corners.
5- Working on one or two cookies at a time, pipe an oval outline in black icing (the universe).
6- Pipe a horizontal yellow line for the galactic plane that gets thicker toward the middle of the cookie (the galactic center).
7- Outline the yellow line with red icing for the galactic disk. Pipe lobes above and below the galactic center for the Fermi Bubbles.
8- Outline the red icing with blue icing and fill in remaining outer gaps with black icing.
9- Use a toothpick or cookie scribe tool to swirl the yellow and red icings, filling in any holes. Swirl the blue and black icings until icing has filled all of the gaps.
10- Carefully add tiny dots of red above and below the galactic plane to represent extragalactic blazars.
11- Wipe off the toothpick or scribe tool between cookies, and continue to decorate until you have Fermi gamma-ray sky maps on all of your cookies.
12- Let the cookies dry at room temperature until the icing has hardened, which could take 6-8 hours depending on the humidity. Do not cover the cookies until they are fully dry.
13- Once dry, store the cookies in an airtight container at room temperature and enjoy.

We’d love to see your finished Fermi cookies! Tag @NASAUniverse on social media or share your photos in the comments on Fermi’s posts.

Fermi sugar cookies depicting the gamma-ray all-sky map.

Credit: Photo courtesy of Jeanette Kazmierczak, recipe courtesy of Judy Racusin

Magnetars

Ever wonder what the most powerful magnet in the universe is? It's actually a type of neutron star called a magnetar. These stars are characterized by their extremely powerful magnetic fields, which are about 10 trillion times stronger than an average commercial magnet and a trillion times stronger than our Sun. Such an intense magnetic field heats the star's surface to around 18 million degrees Fahrenheit. Magnetars release huge amounts of electromagnetic radiation, including gamma rays. They are known to have bursts of radiation without warning, followed by a quiet period which makes them exceedingly hard to track down. Some magnetars are also pulsars, the crushed cores of massive stars that emit radiation which sweeps around the sky like lighthouse beams. Magnetars weren't understood to be a separate class of neutron star until recently, but scientists have since detected 31 out of thousands of known neutron stars in our galaxy. The reason behind magnetars' intense magnetic fields — and why these stars only have strong magnetic fields for about 10,000 years — is yet to be discovered.

In April 2020, Fermi and other observatories detected a flash of gamma rays from a magnetar in the Sculptor galaxy, over 11 million light-years from Earth. Classified as a rare giant magnetar flare, the burst released as much energy in 140 milliseconds — just the blink of an eye — as our Sun does in 100,000 years. Scientists suspect the cause was a starquake, where the magnetar's crust fractured. This quake, which was 1,000 trillion trillion times more powerful than the largest known terrestrial earthquake, released an intense barrage of gamma rays. Soon after, matter ejected by the starquake interacted with piled-up gas and produced shock waves that accelerated electrons, producing higher-energy gamma-ray emission. Scientists using Fermi's GBM have shown that a tiny fraction of events previously thought to be short gamma-ray bursts in the distant universe are in fact giant magnetar flares from nearby galaxies.

In addition to giant magnetar flares, there are also storms of hundreds of smaller magnetar flares. One such storm occurred in our galaxy from October 2008 to April 2009, when a single magnetar produced hundreds of bursts, each lasting as little as 20 minutes. The most intense explosions emitted more total energy than the Sun does in 20 years. Fermi's GBM is particularly well-suited to catch these rapid bursts. These starquakes give us new insight into the structure of neutron stars more generally.

This artist's rendering shows a rupture in the crust of a highly magnetized neutron star that can trigger high-energy eruptions. Fermi observations of these blasts include information on how the star's surface twists and vibrates, providing new insights into what lies beneath.

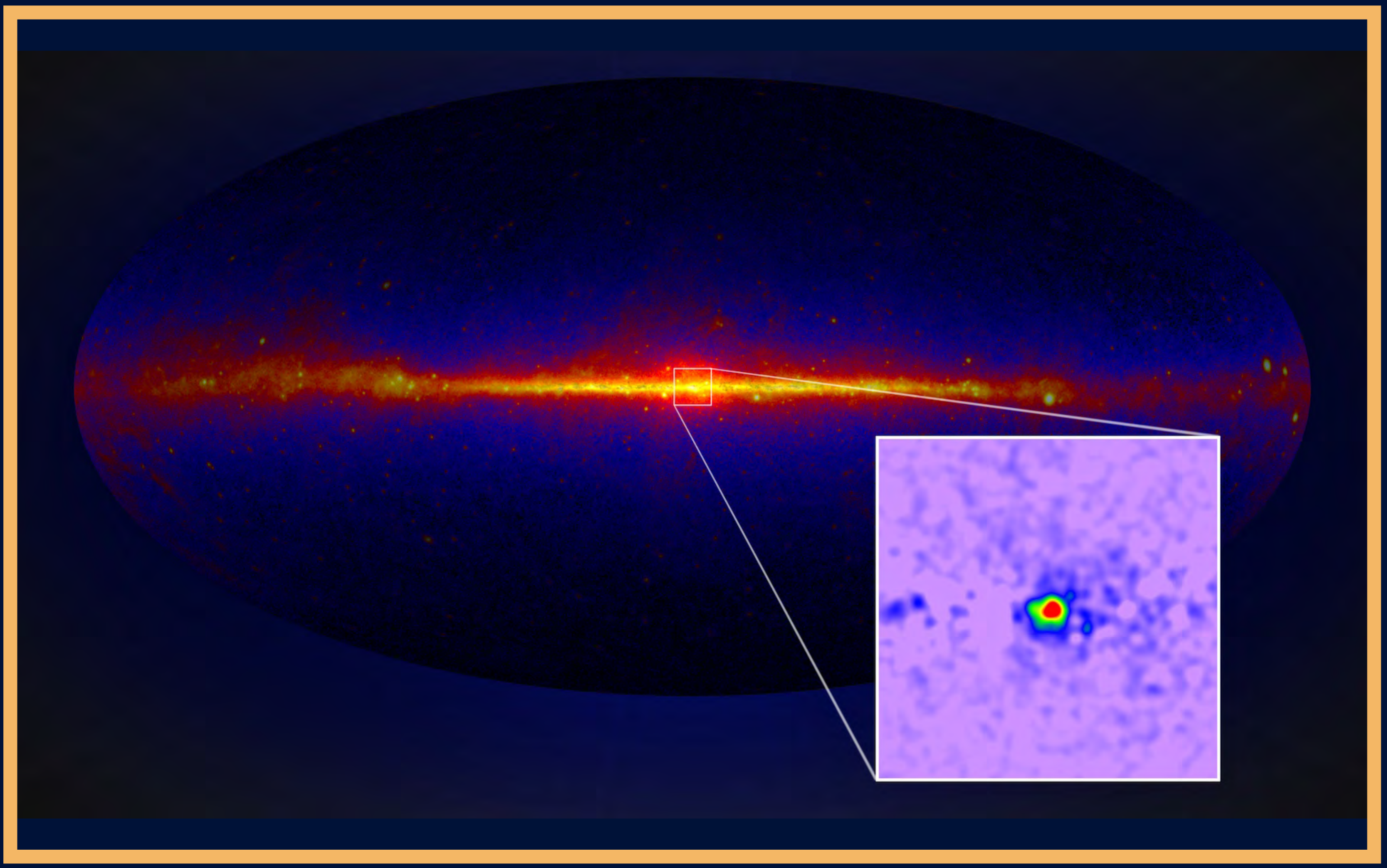
Credit: NASA's Goddard Space Flight Center/S. Wiessinger

Galactic Center

Though mysteries abound throughout the cosmos, some of the biggest puzzles are right in our backyard. One of the most baffling is called the galactic center excess. Conventional models of our Milky Way galaxy combine known gamma-ray sources like pulsars with diffuse gamma-ray emission, the gamma rays produced when high-energy cosmic rays interact with interstellar matter and low-energy light. However, when Fermi's LAT observed the center of our galaxy, it discovered far more gamma rays at high energies than expected from models.

Scientists still don't fully understand why the galactic center is so bright in gamma rays. Models may be underestimating the amount of cosmic rays or interstellar gas, two ingredients in producing diffuse gamma rays, or may be missing gamma-ray contributions from the Fermi Bubbles. Or, as some astrophysicists theorize, the galactic center excess may indicate the presence of dark matter. Scientists believe that the center of our galaxy hosts a high concentration of dark matter due to the strength of the gravitational attraction that holds together the Milky Way's stars and gas. Since scientists reason that dark matter particles annihilate each other to produce gamma rays, observing high quantities of gamma rays from the galactic center would be potential evidence for dark matter. Interestingly, though, other regions of the galactic plane show similar excess amounts of gamma rays, even though dark matter is not expected to exist there. To further study the presence of dark matter, scientists working with the Event Horizon Telescope, a global network of synchronized radio observatories, are studying images of the shadow of the black hole at the galactic center. Properties of the black hole's shadow should in turn reveal information about the dark matter present around it.

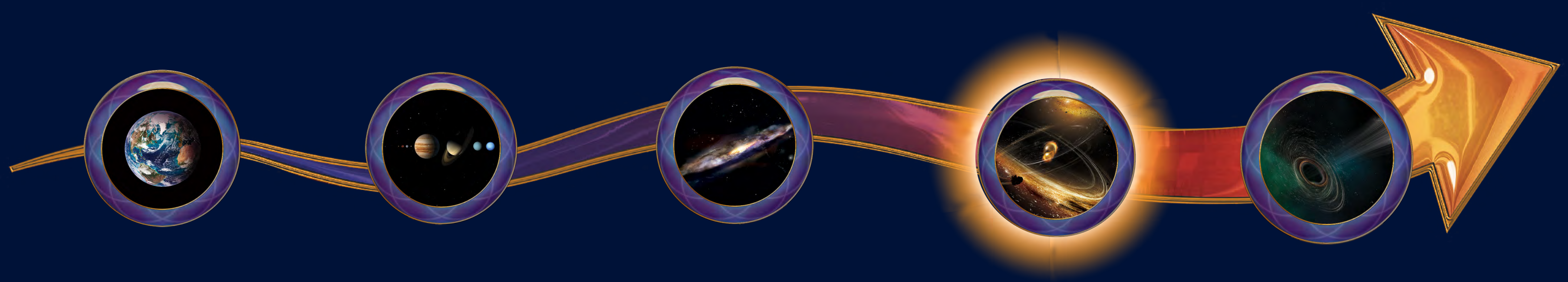
A significant counter-hypothesis is that instead of — or in addition to — dark matter, there is an undiscovered population of gamma-ray-emitting objects near the galactic center. The most likely candidates are millisecond pulsars, which spin even faster than regular pulsars and emit pulses of gamma rays at extremely regular intervals. Deciphering the galactic center excess is one of Fermi's most significant research projects and will continue to be a source of debate and discovery in the telescope's coming years.



A view of the entire gamma-ray sky from Fermi's LAT, shaded to emphasize the central galaxy. The inset to the right is a map of the galactic center with known gamma-ray sources removed, which reveals the gamma-ray excess found there (in red, green, and blue, where red indicates the greatest number of gamma rays).

Credit: NASA/DOE/Fermi LAT Collaboration and T. Linden (Univ. of Chicago)

Nearby Galaxies

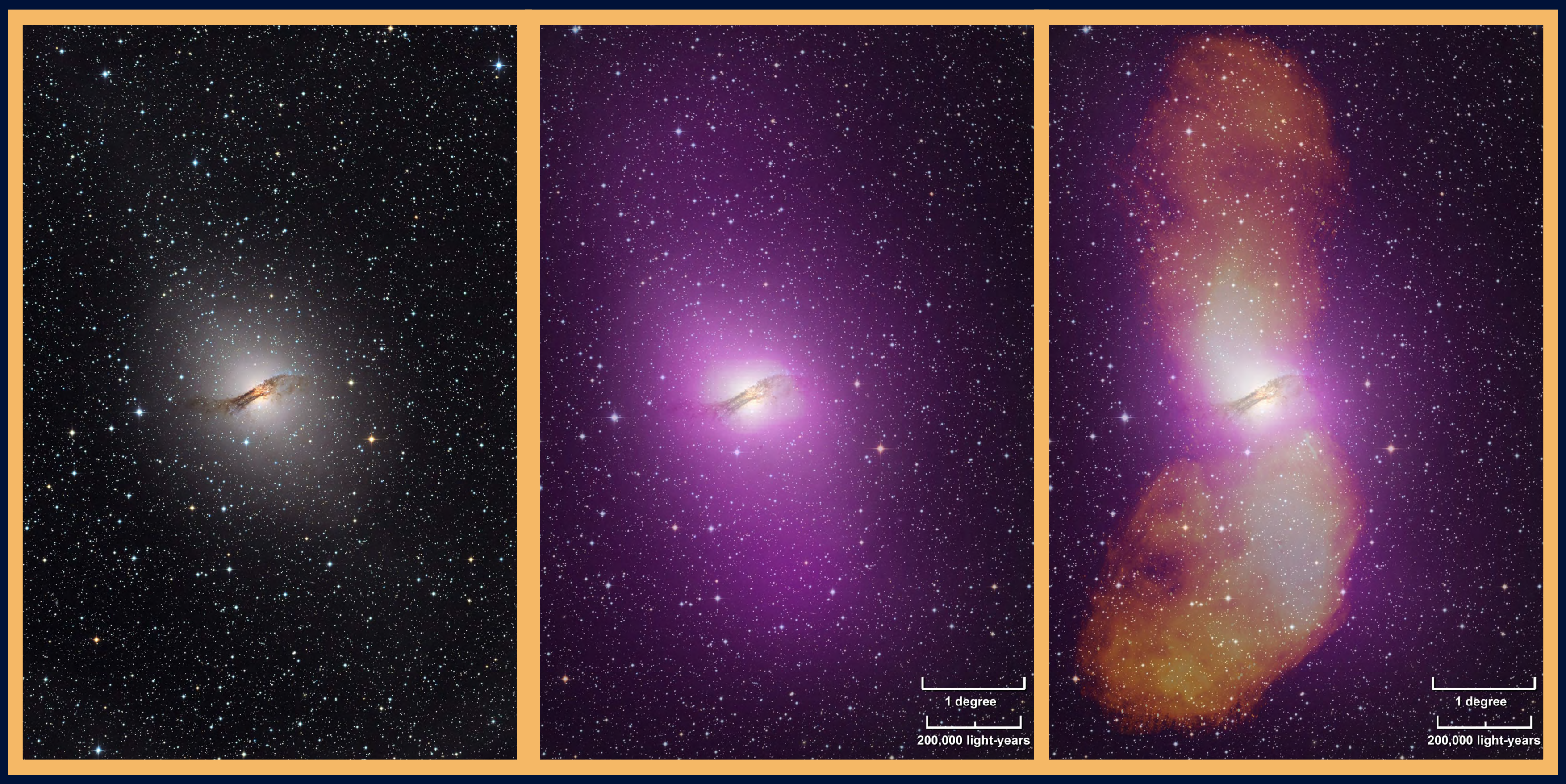


Credit: NASA/Sonoma State University, Aurore Simonnet

Radio Galaxies

Active galaxies — those that have a small core of emission in their centers from matter falling toward a supermassive black hole — come in many forms. One form, first discovered in the 1950s, is called a radio galaxy: a type with strong jets of radiation that travel far into space. As expected from its name, a radio galaxy emits most of its light in the radio part of the electromagnetic spectrum. Some of this radio emission can extend millions of light-years away from the center of the galaxy, making radio galaxies an important target for observatories.

One of the most famous radio galaxies is Centaurus A. Nicknamed Cen A and officially cataloged as NGC 5128, this galaxy is about 12 million light-years away and has two jets of gas, each nearly 1 million light-years long. Over millions of years, these jets caused two giant radio lobes filled with energetic particles and magnetic fields to form around the galaxy. In 2010, Fermi's LAT detected gamma-ray emission from Cen A's lobes nearly 10 times greater than their radio emission. Scientists reason that as a photon collides with a superfast particle in the radio lobes, the photon receives a boost of energy that turns it into a gamma ray — a process called inverse Compton scattering. We are able to see this region in such spectacular resolution because Cen A is relatively close to Earth, in cosmic terms. This means it stretches across a huge area of the sky. Scientists are still investigating how much radio galaxies contribute to diffuse background gamma radiation, which are the gamma rays from unidentified sources seen all across our universe.



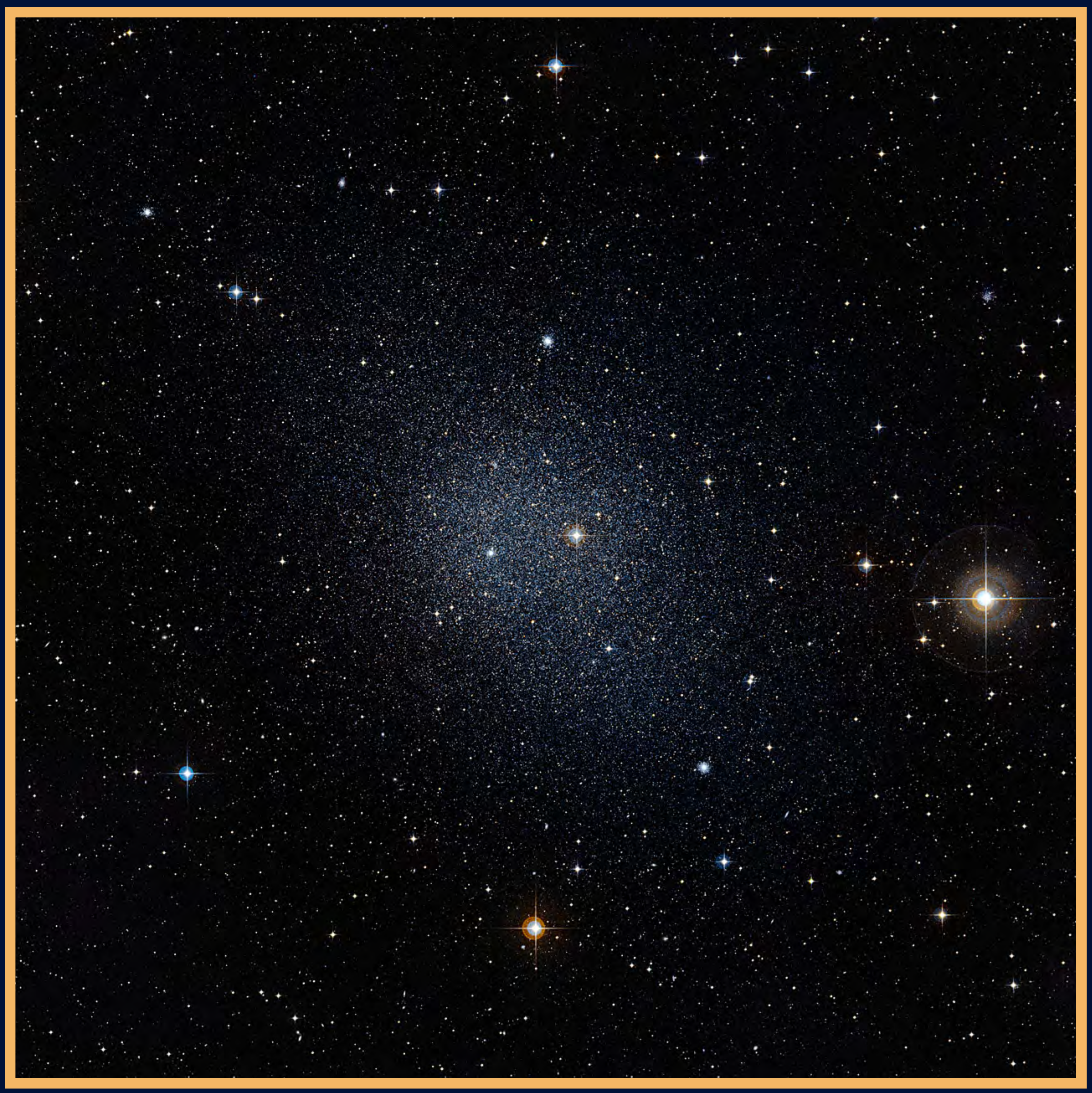
The giant elliptical galaxy NGC 5128 hosts the radio and gamma-ray source known as Centaurus A. In the left image, the galaxy is shown in only optical light. In the middle image, the galaxy is shown with its gamma-ray output in magenta. In the right image, the galaxy is shown in radio (orange), optical, and gamma-ray (magenta) light to illustrate the full extent of Cen A's vast emitting lobes. Radio data reveals that the structures span more than 1.4 million light-years, and Fermi's LAT data show that the gamma-ray output of the lobes exceeds the radio output by more than 10 times.

Credits: Left, Capella Observatory; middle, NASA/DOE/Fermi LAT Collaboration, Capella Observatory; right, NASA/DOE/Fermi LAT Collaboration, Capella Observatory, and Ilana Feain, Tim Cornwell, and Ron Ekers (CSIRO/ATNF), R. Morganti (ASTRON), and N. Junkes (MPIfR)

Dwarf Spheroidal Galaxies

Among all the cosmic mysteries that Fermi studies, dark matter is the most puzzling. It comprises around 85% of the universe's matter but has yet to be observed directly. Astronomers are constantly searching for areas where they might find dark matter and have found many promising candidates. One such candidate is a type of galaxy known as a dwarf spheroidal. These galaxies are small, roughly spherical, low-luminosity objects that contain old stars and little interstellar gas and dust. Their faintness shows they contain few light-emitting objects, like stars. The motions of the stars within these galaxies, however, indicate that they have much greater masses than can be accounted for by the material astronomers can see with optical and infrared measurements. This suggests dwarf spheroidals contain significant amounts of non-visible matter, which could be dark matter.

Fermi's LAT has been an important instrument for studying dwarf spheroidal galaxies. At least six of these galaxies are closer than 330,000 light-years — veritable galactic neighbors at cosmic scales — to the Milky Way's center, which makes them excellent candidates for observation. While dark matter itself does not emit gamma rays or any other form of electromagnetic radiation, some proposed models suggest that as its particles collide, they annihilate and produce gamma rays. Gamma rays can therefore serve as a proxy for locating dark matter sources. Importantly, the closeby dwarf spheroidal galaxies are expected to be mostly free from other bright sources of gamma rays, such as pulsars, that might confuse or overwhelm any dark matter signals. Studies are ongoing, but as of yet the LAT has not picked up any significant signal of gamma rays from dwarf spheroidal galaxies. This result does not mean scientists didn't learn anything, though; the observations ruled out many of the most popular dark matter models up to that point.



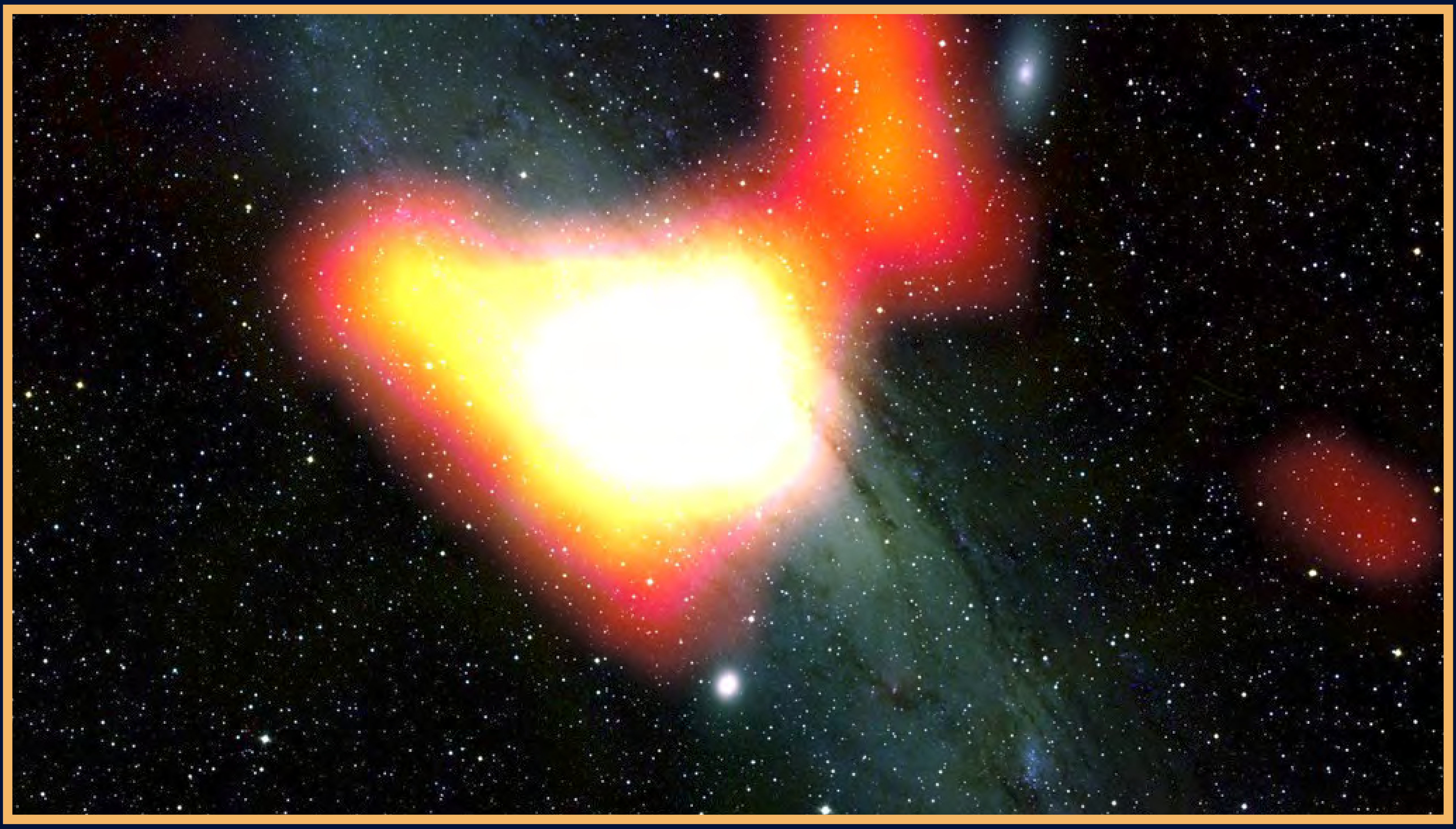
This dwarf spheroidal galaxy in the constellation Fornax is a satellite of our Milky Way and is used in Fermi's dark matter search. The motions of the galaxy's stars indicate that it is embedded in a massive halo of matter that cannot be seen.

Credit: ESO/Digital Sky Survey 2

Andromeda Galaxy (M31)

In the perplexing world of dark matter, it's okay to spy on your neighbor! Scientists are investigating hints of dark matter in the Milky Way's closest neighboring galaxy of similar size, Andromeda. Also called M31, this galaxy is the nearest large spiral galaxy to us, which can provide clues about our own galaxy. Since we can't observe dark matter directly, these clues come in the form of gamma rays, which scientists think dark matter particles produce as they annihilate each other. Fermi's LAT discovered a gamma-ray signal at the center of Andromeda that is uniquely concentrated. It's similar to one Fermi detected at the center of the Milky Way, which means it could reveal more about high-energy phenomena even closer to home. So far, the observations cannot eliminate alternative possibilities, such as a high concentration of pulsars in the heart of Andromeda.

Finding similar gamma-ray signals in Andromeda and the Milky Way allows scientists to better study and compare two similar galaxies. Due to our position within the Milky Way, emission from the galactic disk obscures some of our view; studying Andromeda can therefore serve as a proxy for viewing our own galaxy from an outside vantage point. Scientists will keep studying observations made with Fermi's LAT to examine the gamma-ray emission from Andromeda's galactic center and maybe learn more about elusive dark matter.



This image of the Andromeda galaxy, M31, shows a yellow-white gamma-ray excess found by Fermi at its center. Scientists think a variety of processes could produce the excess, including a population of pulsars or the presence of dark matter.

Credit: NASA/DOE/Fermi LAT Collaboration and Bill Schoening, Vanessa Harvey/REU program/ NOAO/AURA/NSF

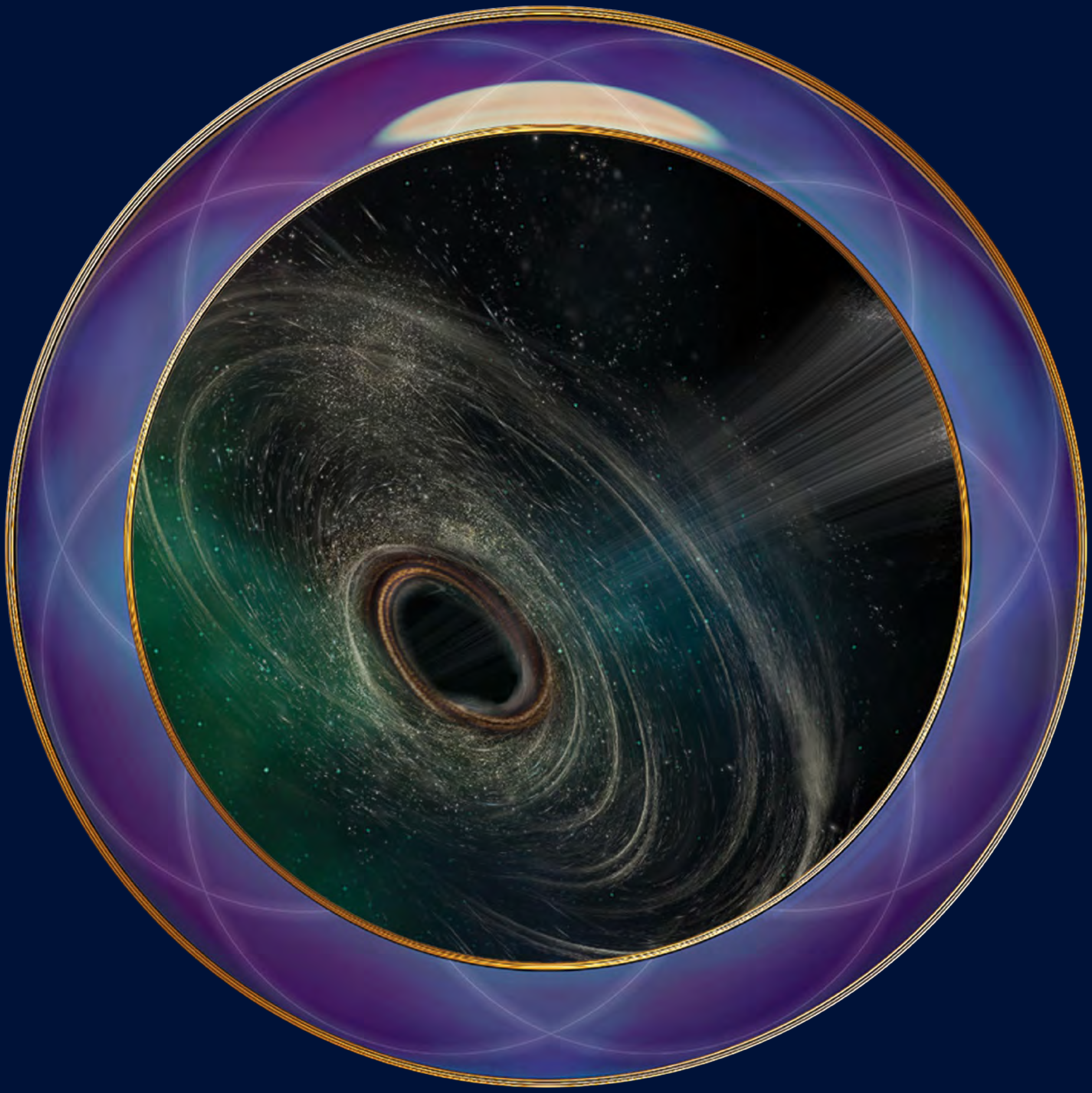
Fun Fact:
School's In for Summer

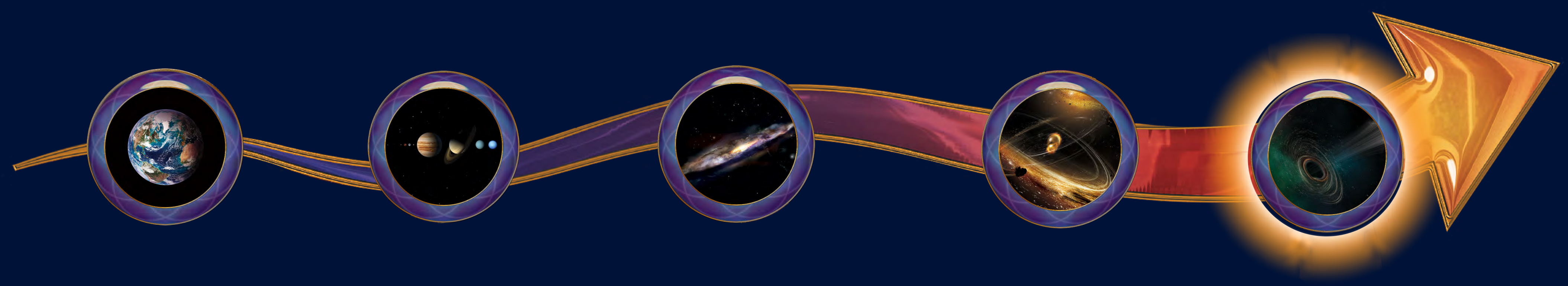
Part of Fermi's mission is to make gamma-ray science accessible for all. Starting in 2011, an integral part of this mission has been the Fermi Summer School. Each year, the Fermi team invites early career scientists to the University of Delaware Conference Center in Lewes, Delaware, for training in high-energy astrophysics. Days of lectures, hands-on workshops, and research culminate in student-led projects. The students, who range from graduate students to post-doctoral researchers, work directly with experts in gamma-ray instrumentation, analysis, theory, and modeling. Applications for the summer school are due each winter, and interested early career scientists are encouraged to apply.

Students at the Fermi Summer School prepare a simple Cherenkov telescope for a backyard demonstration. The telescope works by capturing faint blue flashes of light from cosmic rays that enter Earth's atmosphere. Much larger and more sophisticated Cherenkov telescopes record flashes by very energetic gamma rays.

Credit: Courtesy of Elizabeth Hays

The Distant Universe





Credit: NASA/Sonoma State University, Aurore Simonnet

Blazars

Supermassive black holes power thousands of the universe's most luminous galaxies. Many of these galaxies contain an active galactic nucleus (AGN), a dense core that is more than 100 times brighter than the combined light of the galaxy's stars. Approximately a tenth of these galaxies are a subtype called blazars.

A telltale signal of an AGN are jets of radiation and charged particles that shoot outward from the galaxy at close to the speed of light. These jets originate from what is known as an accretion disk: a flattened, rotating cloud of hot gas and dust surrounding a massive object (in this case, a supermassive black hole). As matter falls toward the black hole, it joins the accretion disk, where it compresses and heats. Forces including friction redirect the matter nearest the black hole into a pair of particle jets that blast outward in opposite directions at nearly the speed of light. In some AGN, scientists can track the jets for thousands of light-years. Blazars contain AGN where the jets point toward Earth. Many blazars contain black holes billions of times more massive than our Sun.

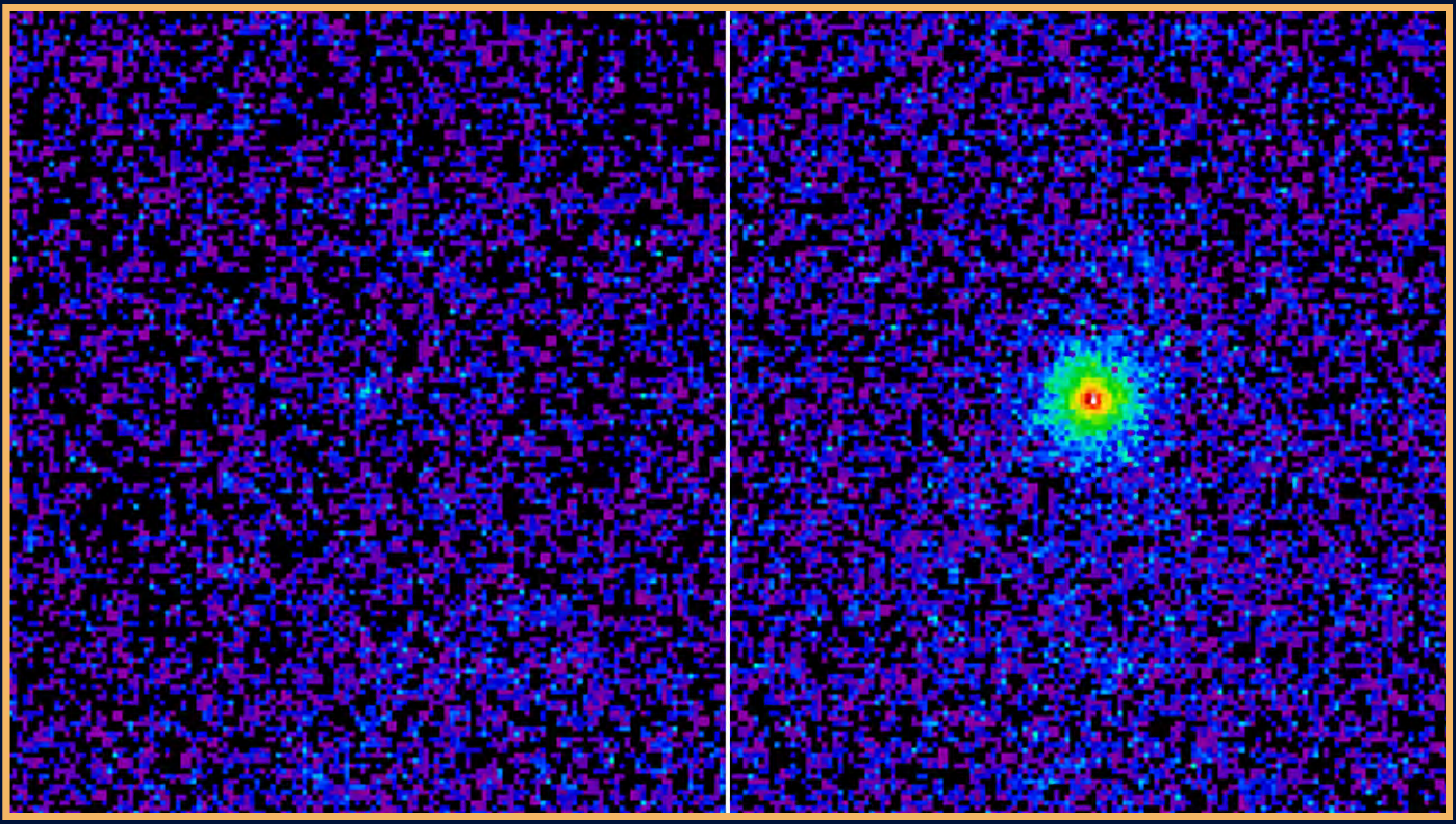
Blazars radiate energy across the electromagnetic spectrum. They constitute as much as half of the gamma-ray sources that Fermi's LAT detects. Radiation from blazars has a unique "fingerprint" that scientists use to identify their emission in infrared and gamma-ray light. This process is one way scientists cross-reference data from multiple NASA telescopes that study different parts of the electromagnetic spectrum. Occasionally, blazar jets flare up, greatly brightening for days to years. Since these flares occur randomly, blazars require consistent monitoring, which Fermi provides. Many of the gamma-ray sources which Fermi has yet to classify are likely related to blazars.

Black-hole-powered galaxies called blazars, illustrated here, are the most common sources Fermi detects. As matter falls toward the supermassive black hole at the galaxy's center, some of it is accelerated outward at nearly the speed of light along jets pointed in opposite directions. To be classified as a blazar, one of the jets must be aimed toward Earth.

Credit: M. Weiss/CfA

Diving Deeper: Flare 3C 279

Certain events have found their way to great fame among the astronomical community. One example is the record-setting flare from blazar 3C 279. This galaxy is powered by a supermassive black hole that experienced a disturbance around 5 billion years ago. The disturbance emitted high-energy light, which Fermi's LAT and other observatories detected in June of 2015, when it finally reached our planet. The black hole at the center of 3C 279 weighs up to a billion times more than our Sun and compares in size to our entire solar system. During the flare, the jets from the black hole emitted very high-energy gamma rays, on the order of 100 million to 100 billion electron volts. The entire flare lasted around three days, with observatories like NASA's Neil Gehrels Swift Observatory, the Italian Space Agency's AGILE gamma-ray satellite (called "Astrorivelatore Gamma a Immagini Leggero" in Italian), European Space Agency's INTEGRAL (International Gamma-ray Astrophysics Laboratory) spacecraft, and ground-based optical and radio telescopes getting in on the action with Fermi.



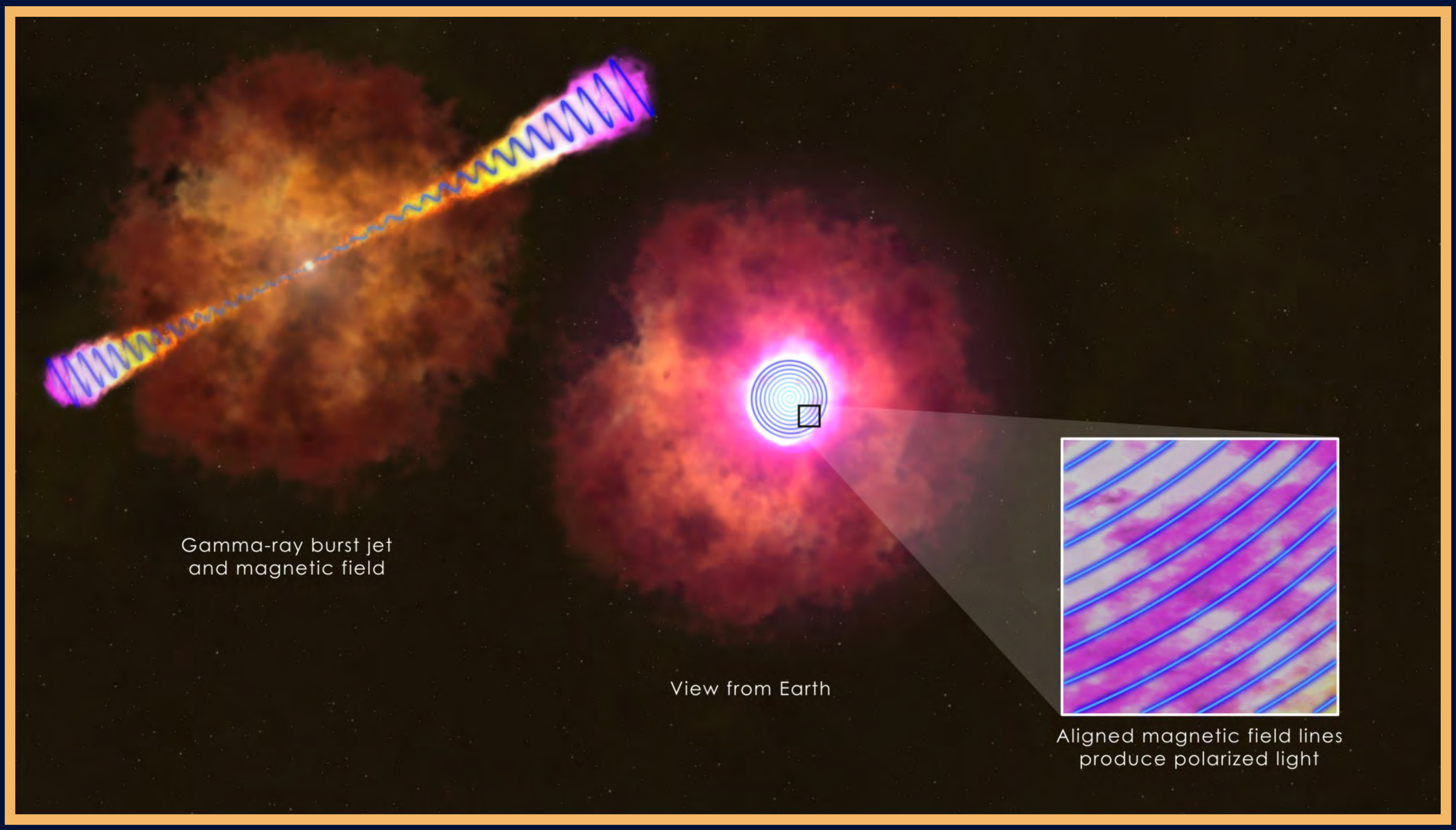
Between June 14 and 17, 2015, Fermi observed a shower of gamma rays streaming from blazar 3C 279. At the time, the flare was the most dramatic the satellite had ever seen. This image shows how the gamma-ray sky looked before the blazar's flare (left) and during (right).

Credit: NASA/DOE/Fermi LAT Collaboration

Diving Deeper: Understanding Jets

Despite all Fermi has taught scientists about blazars in gamma rays, unpacking these cosmic curiosities requires studying many different qualities of light. Astronomers can measure what is known as the polarization of light to understand more about the structure of blazar jets. Light from our Sun or from a candle is called unpolarized light, because the electromagnetic waves vibrate in a variety of directions as they travel through space. Polarized light, on the other hand, vibrates on only one plane — for example, up and down or left and right. You have interacted with polarized light more than you think; polarization is used in some sunglasses to block glare — in reality, some directions of electromagnetic waves — from sunlight.

Blazar jets all emit light that is somewhat polarized. Scientists can measure the degree of a jet's polarization to tell more about the jet's structure. For example, if the jet shows a high amount of polarization, the jet's magnetic field is more orderly. If there is a low degree of polarization, the jet must have a lot of turbulence that scrambles the magnetic field. If the polarization changes over time, this can signal that the jet's magnetic field has a spiral shape. In general, blazars that emit a lot of gamma rays have more polarized light — and therefore more orderly magnetic fields — than blazars that emit fewer gamma rays. Sometimes, a blazar's changing polarization can even correlate with a gamma-ray flare.



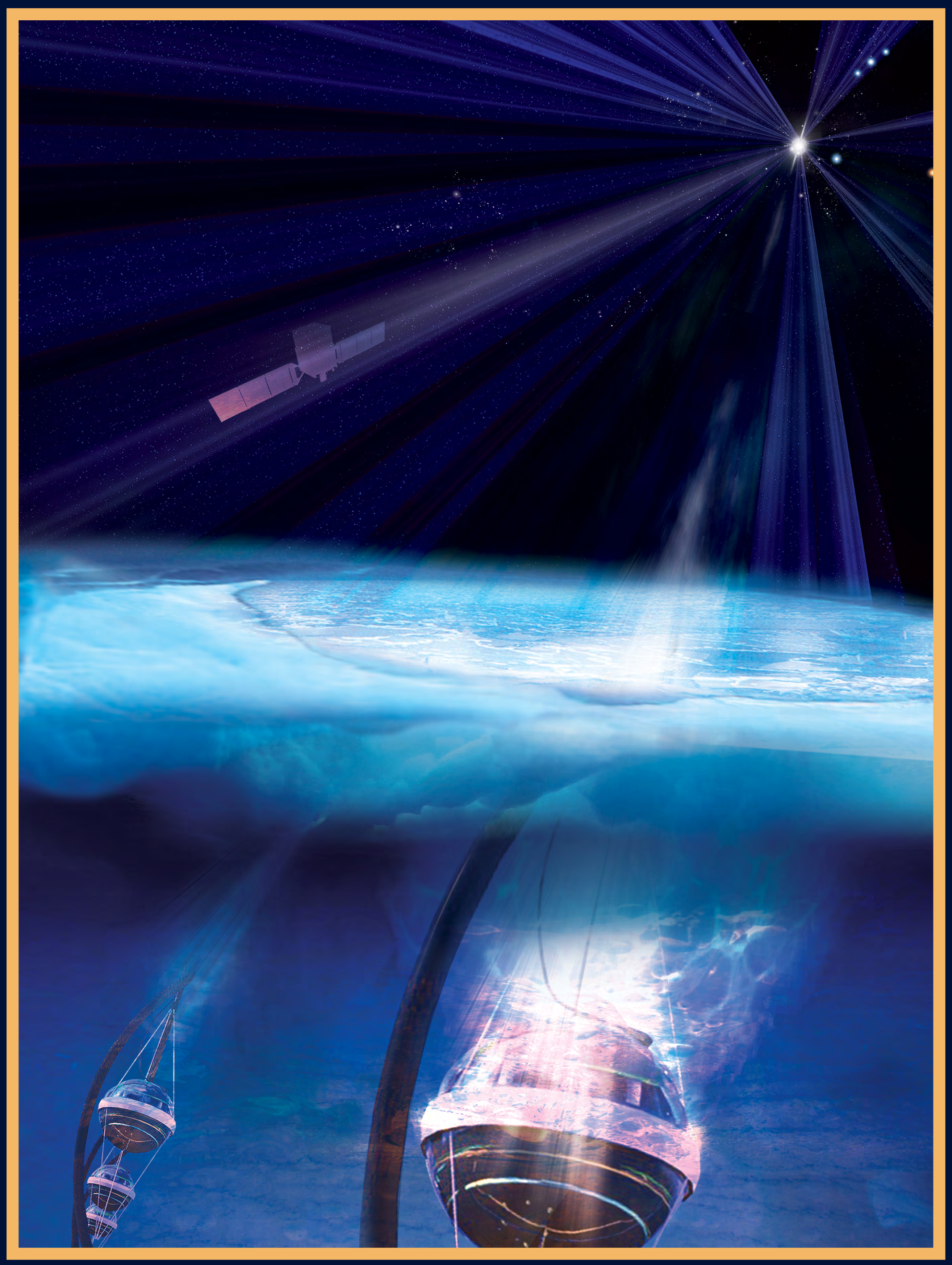
Scientists can use measurements of a fast-moving jet's polarized light to determine characteristics about the jet's structure. In this illustration, scientists used the same technique to reveal qualities about jets from a gamma-ray burst. Polarized light indicated that the magnetic field (right) was orderly, which signaled to scientists that there was a hidden black hole emitting a lot of gamma rays.

Credit: NASA's Goddard Space Flight Center/S. Wiessinger

Diving Deeper: Neutrinos

If you thought gamma rays were hard to detect, they have nothing on neutrinos. These tiny subatomic particles have no charge and almost zero mass. They interact so little with other matter that scientists have nicknamed them "ghost particles." Incredibly, though, they are the most common particle in the universe — so a proportion of them must interact with matter and be detectable. The world's leading neutrino detector is the IceCube Neutrino Observatory in Antarctica. When a high-energy neutrino interacts with the ice in IceCube, it generates a slew of particles that create a flash of light called Cherenkov radiation. IceCube detects this radiation and records the direction of the neutrino, which travels in a straight line. A similar process is used in ground-based observatories that detect gamma rays.

While scientists have gotten better at identifying neutrinos, they still struggle to determine their sources. One of the more promising possibilities is blazars, the active galactic nuclei that shoot out jets of charged particles toward Earth. Blazar TXS 0506+056 was the first to provide evidence that blazars may emit neutrinos, since its gamma-ray emission was confirmed and neutrinos were found coming from its direction. An IceCube study later used 137 blazars detected by Fermi's LAT to search for signs of neutrinos, but unfortunately did not find any definitive neutrino signals. However, IceCube has since detected evidence of neutrinos from the galaxy. Collaborations between IceCube and Fermi are an example of multimessenger astronomy because they combine observations from multiple signals: neutrinos and gamma-ray light. They are some of the most important studies for Fermi's future, and both the GBM and LAT continue to monitor the sky for evidence of neutrino sources.



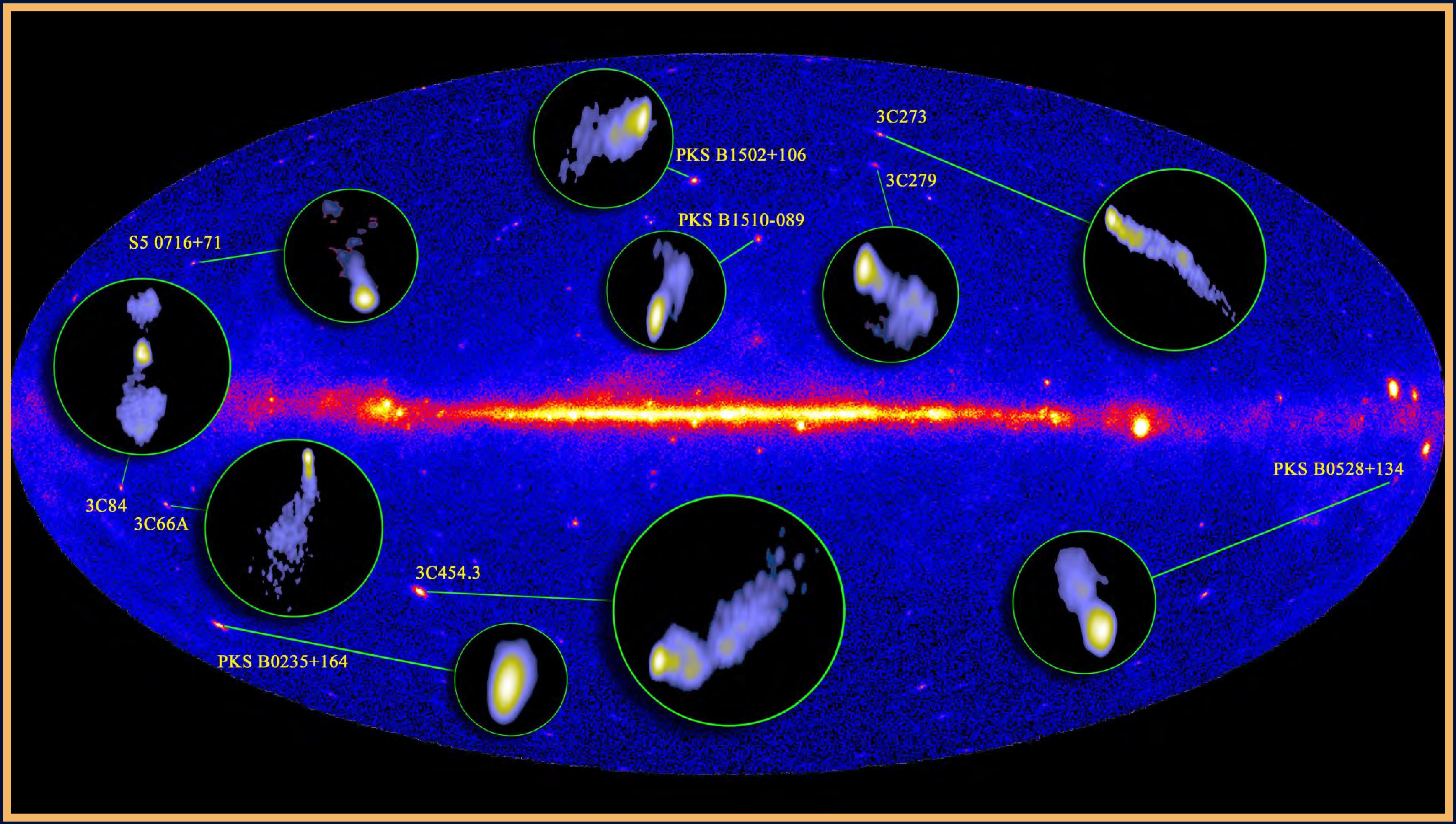
In this illustration, the IceCube Neutrino Observatory at the South Pole is represented by strings of sensors under the ice. On September 22, 2017, IceCube detected a high-energy neutrino that appeared to come from deep space. Fermi (top left) pinpointed the source as a supermassive black hole in a galaxy located about 4 billion light-years away. It was the first ever identified source of a high-energy neutrino from outside our galaxy.

Credit: NASA/Fermi and Aurore Simonnet, Sonoma State University

Diving Deeper: Radio Collaboration

Studying blazars is not without challenges. Due to the relatively small amount of gamma rays Fermi's LAT detects, its resolution — think of it as the sharpness of Fermi's LAT images — is fairly fuzzy. This means that when Fermi detects gamma rays from faraway sources, the telescope is more sure of the general direction from which they came rather than the particular source. This constraint is due to the LAT's pair production process, which is different from a telescope like Hubble or Webb that focuses light.

Radio telescopes can take Fermi's data and identify which blazar created the gamma-ray-producing jets Fermi observed, often from hundreds in a specific area of the sky. This process works because blazars also emit strong radio radiation, making them unique objects that emit radiation from the lowest to the highest energies.



In this image, the radio jets of several active galaxies mapped by the Very Long Baseline Array (VLBA) are inset into Fermi's gamma-ray sky map. Some of the most active galaxies emit strongly in both radio and gamma rays.

Credit: NASA/DOE/Fermi LAT Collaboration and NRAO/AUI/MOJAVE Team/M. Kadler

Fun Fact:
Too Close for Comfort

Even though the space deemed low-Earth orbit is vast, it's far from empty. On March 29, 2012, NASA's Conjunction Assessment Risk Analysis (CARA) team at NASA's Goddard Space Flight Center alerted the Fermi team to an important orbital traffic issue: Cosmos 1805, a defunct Cold War spy satellite, was on an orbit set to cross Fermi's in six days' time. The two spacecraft would miss each other by a mere 700 feet (~200 meters) — far too close for comfort. Cosmos 1805 weighed 3,100 pounds (1,400 kilograms) and had a relative speed to Fermi of 27,000 miles per hour (17,000 kilometers per hour), posing certain destruction to both spacecraft if a collision occurred. The uncertainties present in predicting spacecraft orbits one week out meant that the Fermi team couldn't be too careful. In fact, as the days before the flyby passed, orbital traffic controllers indicated that the two spacecraft would occupy the same point in space within only 30 milliseconds of each other.

Luckily, Fermi had a tool that enabled it to dodge trouble: its thrusters, designed to bring the spacecraft out of orbit when its mission ended. This wasn't a fail-safe approach. The thrusters had never been tested before out of concern that the highly flammable fluids might cause a leak or an explosion. But as Cosmos 1805 and Fermi barrelled toward each other, the Fermi team had little choice. Many people collaborated to select the time and the amount of push needed, and to check that the new orbit wouldn't put Fermi at risk of colliding with another object. Shortly after noon EDT on April 3, Fermi stopped its all-sky survey and fired its thrusters for only one second. The plan was a success. Scientists reported that it felt like a weight had been lifted. By 1:00 p.m., Fermi was doing normal science operations once again, and the next day, Cosmos 1805 soared by with a roomy six miles of space. Talk about a close call!

Though Fermi has not needed another maneuver in its lifetime, CARA and the flight operations team continue to monitor potential traffic jams and plan accordingly.

On March 29, 2012, the Fermi science team learned that a defunct Cold War spy satellite was expected to occupy the same point in space as Fermi within 30 milliseconds. Thanks to a maneuver by the Fermi science team, a collision was avoided.

Credit: NASA'S Goddard Space Flight Center

Gamma-ray Bursts

One high-energy phenomenon is so compelling that it warranted a dedicated instrument onboard Fermi: gamma-ray bursts (GRBs). GRBs are short-lived bursts of gamma rays that last from milliseconds to several minutes, followed by a light show across the electromagnetic spectrum that can last hours to years. Their energy is hundreds of times larger than that of normal supernovae, and they are around a million times brighter than the Sun. Aside from the big bang, they are the most powerful explosions in the universe. Scientists first discovered GRBs in the late 1960s when U.S. military satellites searched for evidence of covert nuclear tests, whose explosions also produce gamma rays. GRBs occur both close by and at the farthest reaches of the observable universe, when the universe was billions of years younger than it is today. Scientists use the GBM and LAT to localize GRBs, thereby attributing them to general areas in space. We detect GRBs when their radiation, concentrated into a narrow jet traveling at the speed of light, points at Earth.

Gamma-ray bursts begin with the birth of a new black hole, which launches these high-speed jets of material. Astronomers divide the initial burst of gamma-rays into two main categories that are roughly split by duration: short and long. Short-duration bursts last less than two seconds. They typically occur when two neutron stars — the collapsed cores of massive stars — merge violently to form a new black hole, or when a neutron star merges with a black hole to form a larger black hole. Direct evidence of this second kind has yet to be observed. Long-duration bursts last longer than two seconds. They typically occur when massive stars explode in supernovae, though not every supernova produces a GRB.

After the initial burst, the high-energy jets expand outward, interacting with the surrounding environment to produce what's known as an afterglow. Studying the afterglow tells us about the evolution of the star system that exploded and the environment it called home. Afterglows emit radiation from radio to very high-energy gamma-rays, enabling many other telescopes like Swift and Hubble to work with Fermi to learn more about GRBs. Today, Fermi is at the front of the GRB field, detecting about one per day. The number of detected gamma-ray bursts indicates that our early universe was turbulent and full of fascinating energetic phenomena.

A cartoon of a gamma-ray burst and its powerful jets.

Credit: NASA's Goddard Space Flight Center.

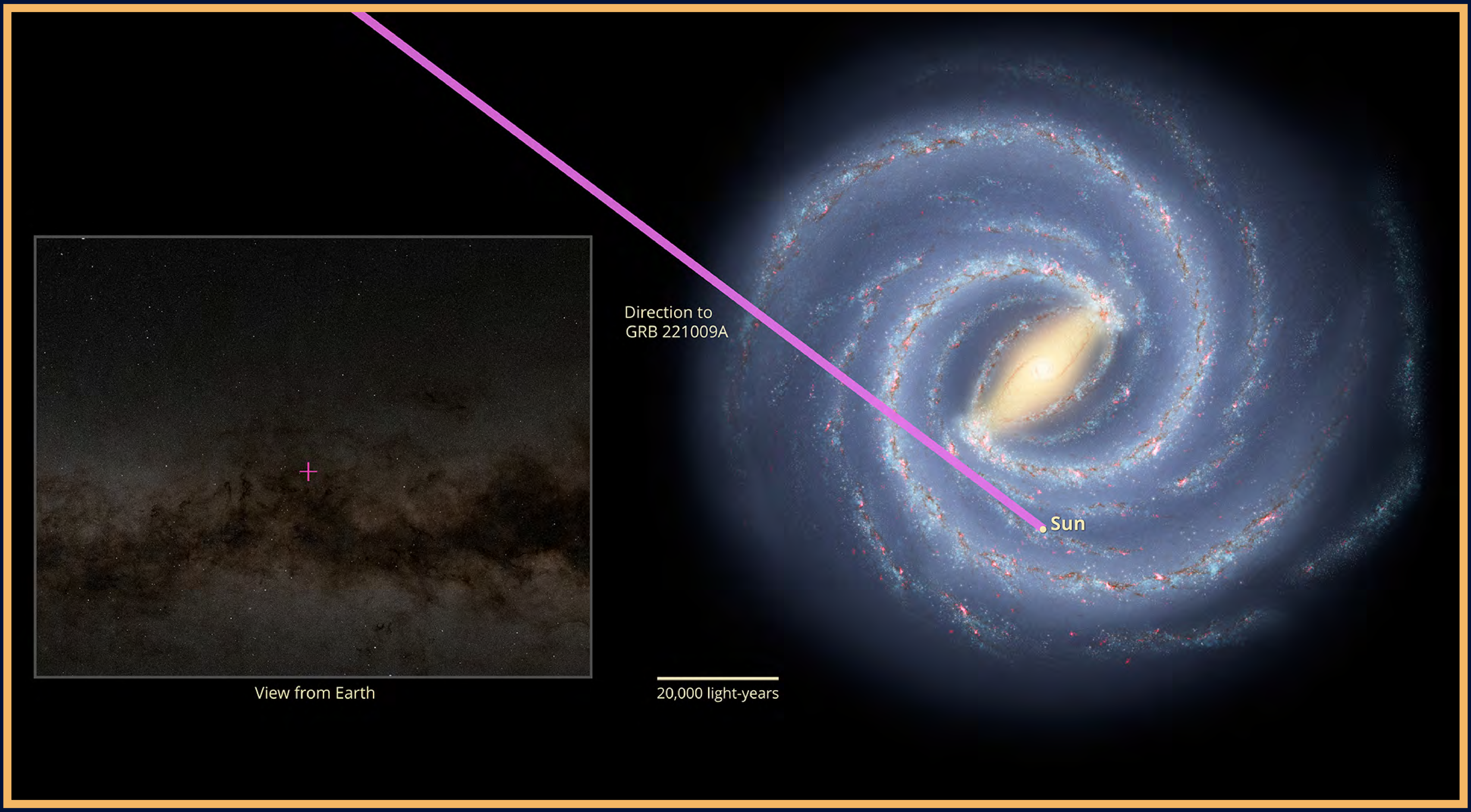
An illustration showing two neutron stars beginning to merge, blasting a jet of high-speed particles and producing a cloud of debris. This kind of intense merger produces a short gamma-ray burst.

Credit: A. Simonnet (Sonoma State Univ.) and NASA's Goddard Space Flight Center

Diving Deeper: The BOAT

Gamma-ray bursts are always finding ways to impress scientists. In 2022, Fermi and other observatories recorded a gamma-ray burst so massive it earned a distinctive title: the BOAT, or brightest of all time. Officially named GRB 221009A, the BOAT was likely the brightest high-energy burst in the history of human civilization, since bursts of this magnitude occur only once every 10,000 years. The BOAT was so bright that it overloaded most gamma-ray instruments, but Fermi's GBM reconstructed its data to determine the event was 70 times brighter than any other burst ever seen. The light from the BOAT traveled for around 1.9 billion years to reach Earth and was categorized as a long-duration GRB which lasted 289 seconds — longer than most other bursts Fermi has seen.

Long-duration bursts are typically followed by supernovae, since the GRB signals the collapse of a massive star to form a black hole. NASA's Webb and Hubble have been enlisted to study the area around the burst to search for the supernova, and may have found a signal in August 2023. Such a close and powerful GRB enables scientists to learn about the birth of a GRB jet, the kinds of radiation it emits over time, and even how black holes might recycle energy back to the universe rather than consume it.



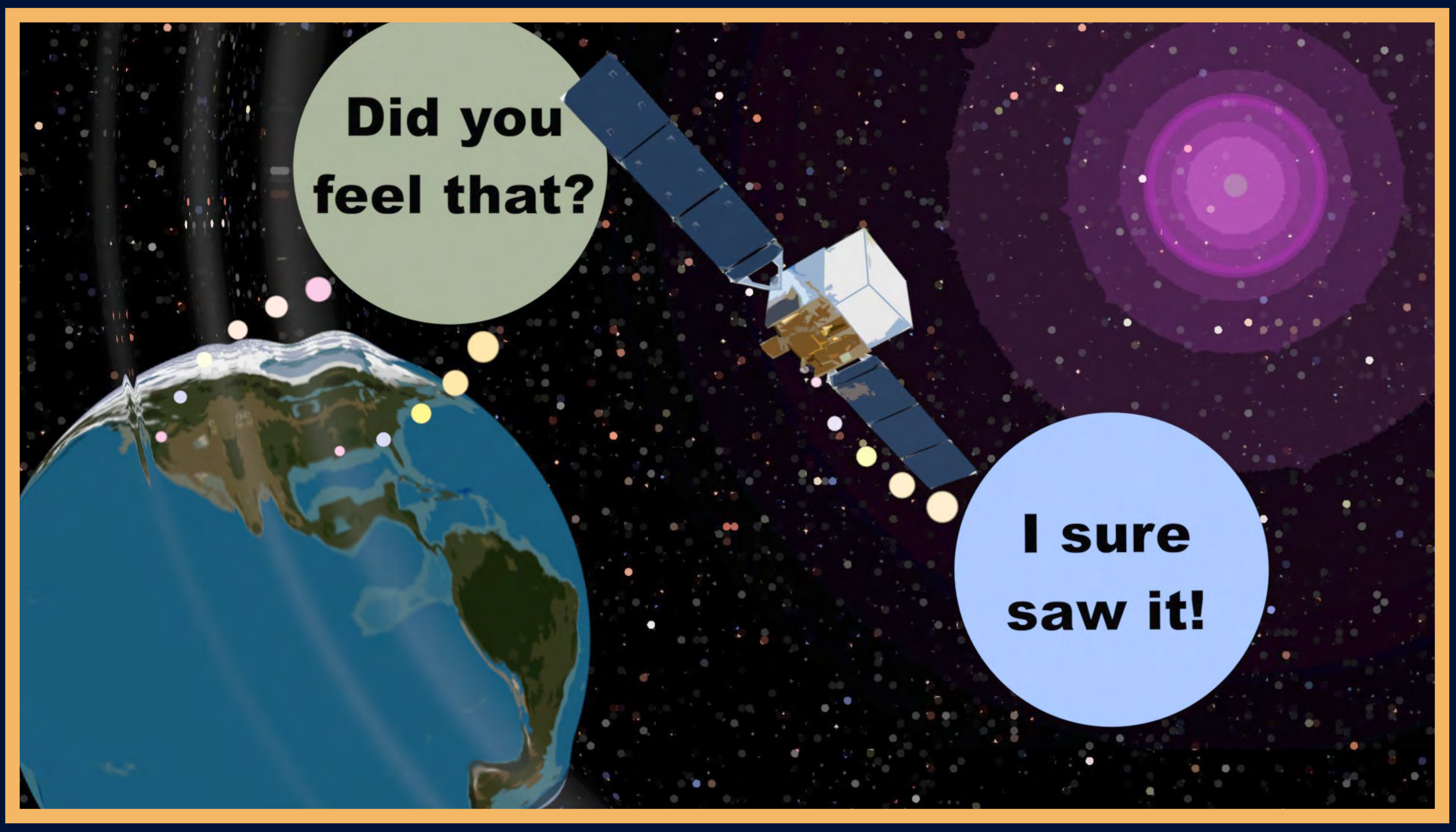
This illustration shows the BOAT GRB's location as seen from Earth (left) and our line of sight to it through our Milky Way galaxy (right). The BOAT is thought to have been the brightest gamma-ray burst since human civilization began.

Credit: NASA's Goddard Space Flight Center

Diving Deeper: Gravitational Wave Counterparts

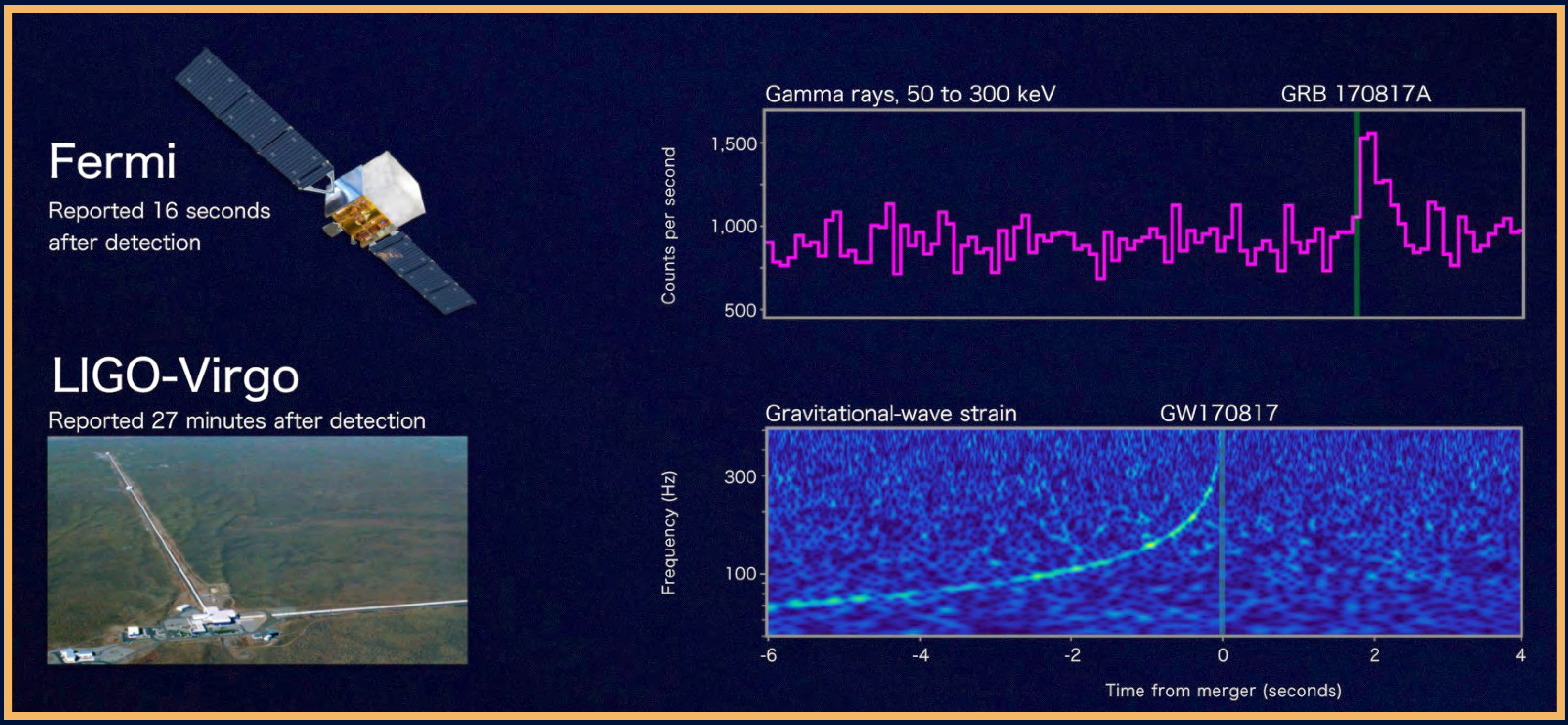
Cosmic events often signal their occurrences to us in more ways than one — we just have to figure out how to interpret them. Gamma-ray bursts are one clear signal of powerful events in our universe's past. Gravitational waves, ripples in space-time predicted by Einstein, can be another. On August 17, 2017, the gravitational-wave observatories LIGO (The National Science Foundation's Laser Interferometer Gravitational-Wave Observatory) and Virgo (funded by Italy's Istituto Nazionale di Fisica Nucleare and France's Centre National de la Recherche Scientifique) detected gravitational waves seconds before Fermi's GBM detected an almost two-second GRB. The timing of the two signals indicated that they originated from the same event: the merging of two neutron stars. While it may seem logical for two energetic phenomena to result from the same high-energy event, this was actually the first time scientists ever detected light and gravitational waves from the same source. In effect, astronomers linked what we can "see" (light) and what we can "hear" (gravitational waves).

Detecting this monumental event gave scientists the first-ever measurement of the speed of gravity, which turns out to travel at essentially the speed of light. Additionally, over 70 telescopes observed a kilonova (a bright blast of electromagnetic radiation from merging neutron stars) and its afterglow that resulted from the same event that caused the GRB. Such a huge, coordinated observation effort had never been seen before and led to many physics and astronomy discoveries. To continue finding evidence of gravitational waves, astrophysicists can comb the data around the time of short GRBs, since the merging of neutron stars consistently produces both signals. By putting the two signals together into one powerful tool, we can probe what happened before and after the neutron stars merged.



A cartoon from 2017 showing Fermi observing a gamma-ray burst from the same merging neutron stars that caused gravitational waves to reach Earth. "Seeing" light and "hearing" gravitational waves from the same event enhances our ability to understand extreme cosmic phenomena.

Credit: NASA's Goddard Space Flight Center



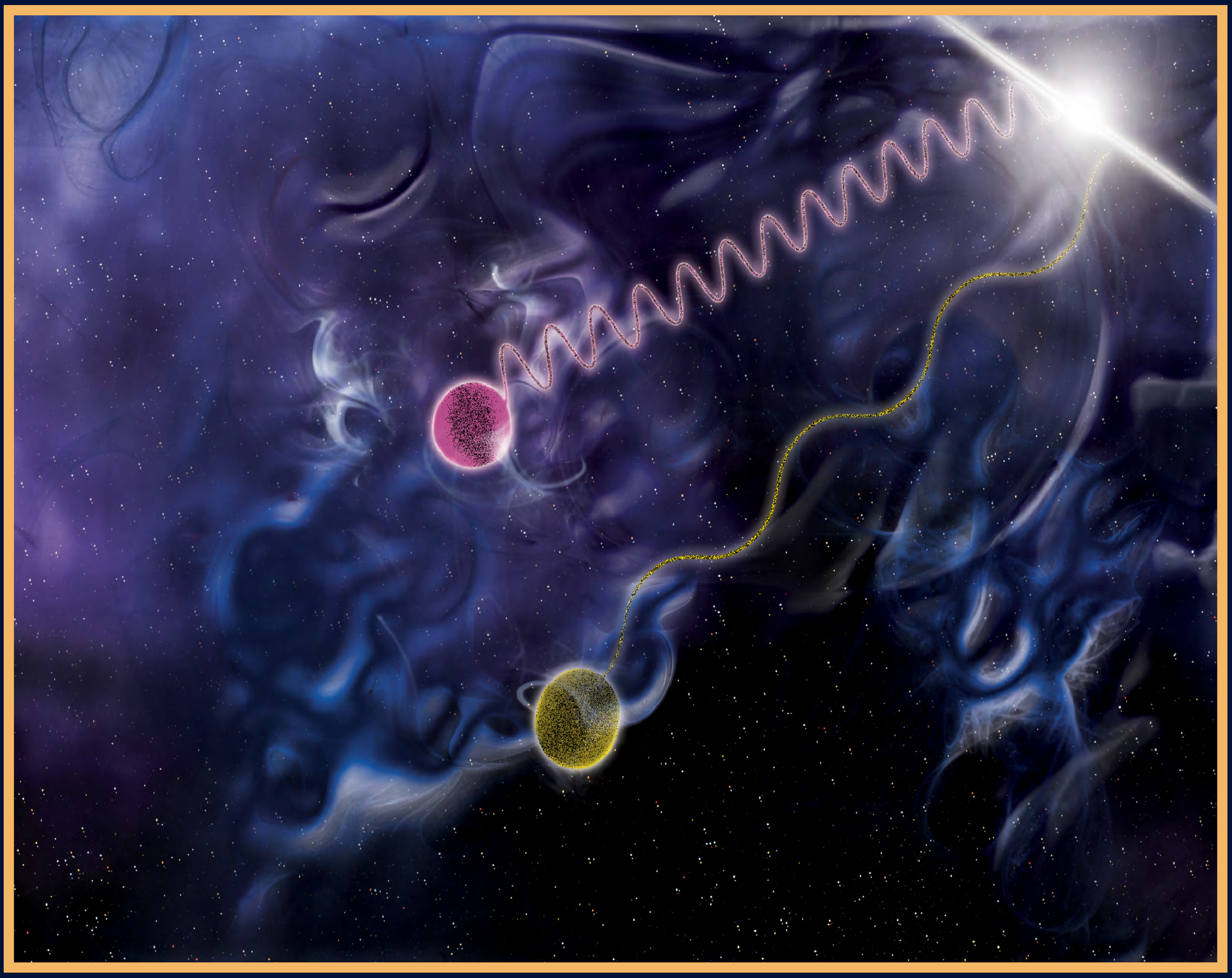
The first sign of the 2017 neutron star merger was a detection of a signal in gravitational waves (bottom). Fermi's GBM detected a brief burst of gamma rays (top) 1.7 seconds later. This was the first-ever detection of gravitational waves and light from the same event.

Credit: NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

Diving Deeper: Lorentz Invariance Violation

As our understanding of the world progresses, scientists often come back to the very principles that we use as our framework. Probing the theories at the foundation of physics helps us to confirm or rethink how our universe might be organized. One such principle is called Lorentz invariance. It expresses the idea that the laws of physics are the same no matter the observer and is a central tenet of Einstein's theory of special relativity. For example, the speed of light would be the same for you, standing on the ground, and your friend, sitting on a train moving hundreds of miles per hour. The past century of experiments has confirmed Lorentz invariance. However, that doesn't stop scientists from theorizing. Theoretical physicists propose that due to the different energies of light, there might be tiny differences in light's speed. Experiments to test this idea need to be at the smallest of scales, with extremely sensitive measurements.

One candidate for probing Lorentz invariance is gamma-ray bursts. Since GRBs release some of the highest-energy light over some of the longest distances, scientists are using Fermi to delve into this area of theoretical physics. Scientists hypothesize that if Lorentz invariance can be violated, we would observe a difference in the amount of time two photons of light with different energies take to travel to us from the same distant cosmic source. One team used four GRBs to conduct their analysis, focusing on the time in the GRBs when there is the most variability in the light pulse's timing. While the study did not find a violation of Lorentz invariance, it did constrain what the energy difference between the photons could be. More recent studies used the same methods with similar results. Lorentz invariance violation is an exciting example of how Fermi's work can apply observing the cosmos' energetic events to rethinking the very principles of physics that govern them.



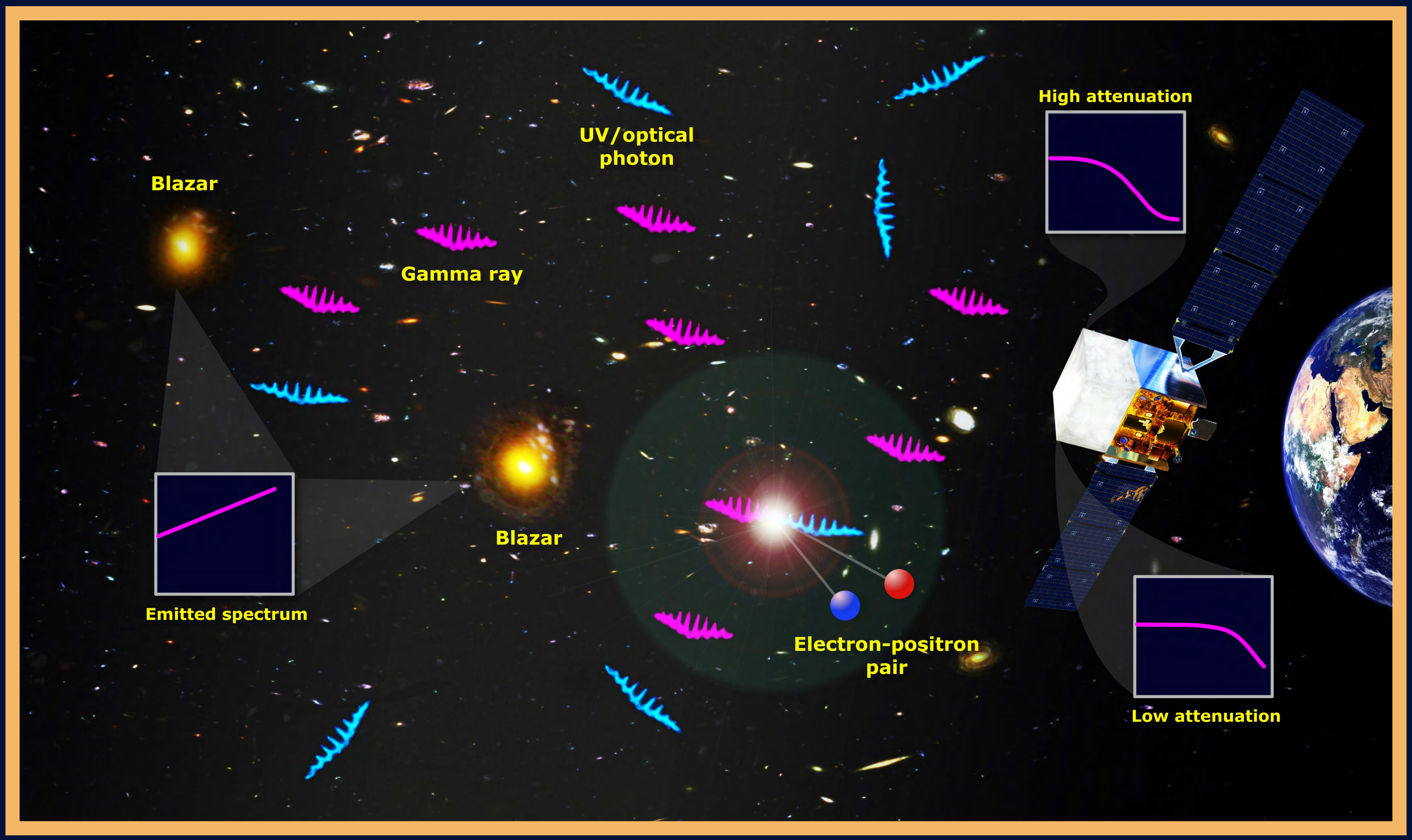
Some theorists predicted travel delays for higher-energy photons that interact more strongly with space-time, as suggested in this illustration, where one gamma-ray photon (purple) carries a million times the energy of the other. Yet Fermi data from a gamma-ray burst failed to show this effect, upholding the theory of Lorentz invariance, a central idea in theories of gravity.

Credit: NASA/Sonoma State University/Aurore Simonnet

Extragalactic Background Light

We often imagine the area between stars and galaxies as a vast black space, devoid of light. But this isn't quite true. The universe has a very faint glimmer from all of the stars, galaxies, and active galactic nuclei that have ever existed, whose emitted light continues to travel through the cosmos. Combining the total light from all of these objects is called extragalactic background light (EBL). EBL covers light from the infrared to the ultraviolet and can be tricky to measure due to the nearby bright sources of light in our Milky Way obscuring the background signal. Despite challenges, scientists have pushed to study EBL to help us learn about the formation and evolution of our fascinating universe.

Astronomers developed a clever way to measure EBL: using gamma rays. In principle, gamma rays emitted by distant sources like blazars and gamma-ray bursts interact with EBL photons to create electron-positron pairs. This process effectively absorbs the gamma rays — just like in the Fermi LAT — and leaves a distinct imprint in the gamma-ray spectrum of cosmic sources. You can think of this process of dampening the gamma-ray signal much like fog dimming the light of a distant lighthouse. Scientists can measure the imprint and work backward to measure EBL itself. Using Fermi's LAT, scientists found that the amount of gamma rays absorbed by EBL differs based on the age of the universe when the gamma rays were emitted. They attribute this finding to the increase in star formation over our universe's history. Many other observatories are also hard at work measuring EBL, with important contributions from observatories that study the most energetic gamma rays in the teraelectron volt range. Fermi has yet again helped scientists to constrain one of the underlying characteristics of our universe, effectively shining light on the light that shines on us.

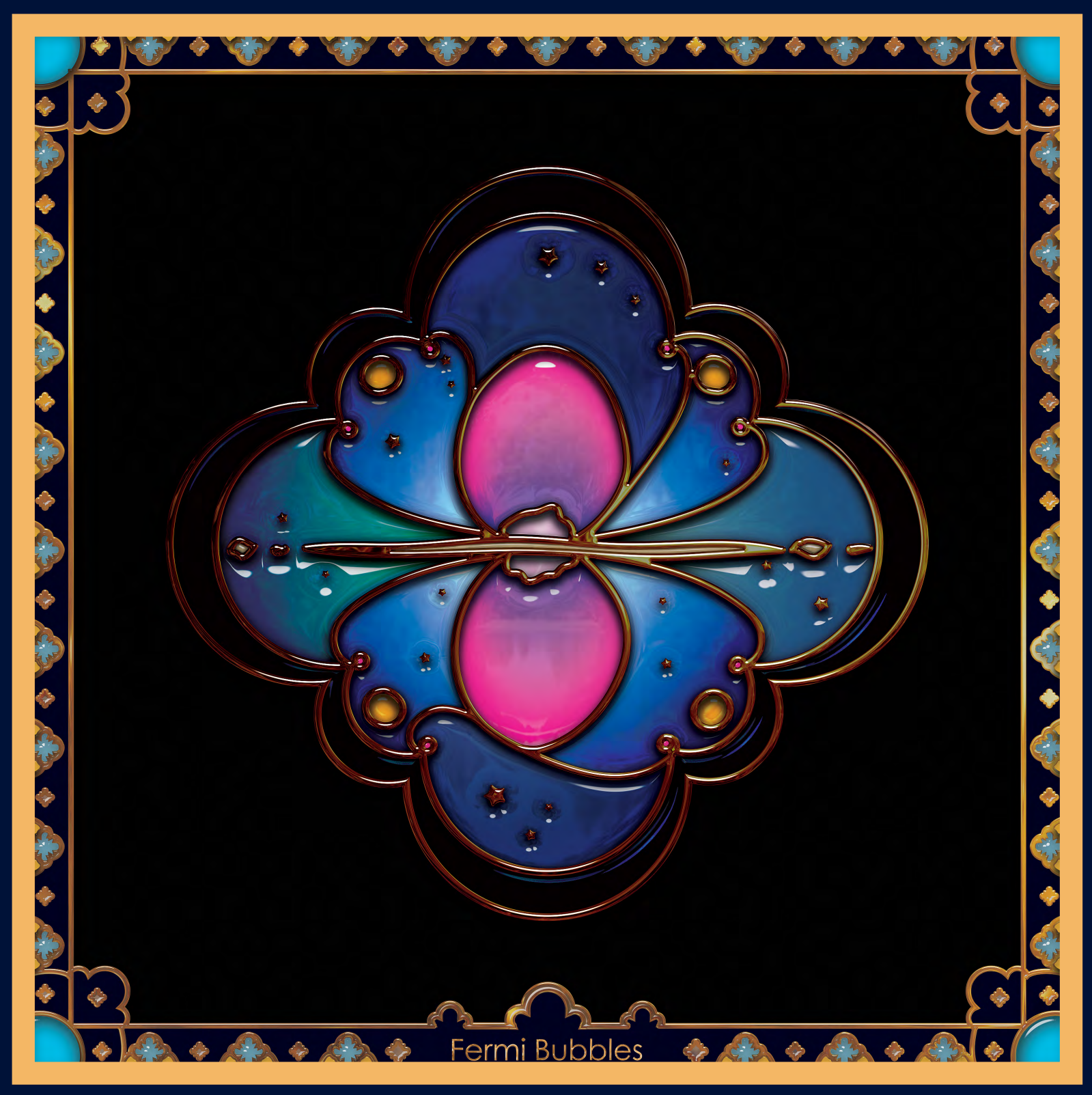


Gamma rays interact with EBL, which gives astronomers a way to probe the stellar content of the cosmos. When a gamma ray (magenta) strikes ultraviolet or visible light (blue), the photons are transformed into an electron and its antimatter counterpart, a positron. This process, shown in the middle of the graphic, removes gamma rays from the spectra of bright sources like blazars. Farther sources have more removed gamma rays (more attenuation) than closer ones.

Credit: NASA's Goddard Space Flight Center

Looking to Fermi’s Future

Active Galaxies



Fermi Bubbles

Fermi Skymap

Merging Neutron Stars

Fermi Satellite

Supernova Remnants

These artistic designs of different important Fermi concepts show the beauty of the spacecraft and gamma-ray science.

Credit: NASA/Fermi Gamma-ray Space Telescope/Sonoma State University/Aurore Simonnet

Welcome back from your journey through Fermi's high-energy universe! You've learned about cosmic curiosities from near to far and how Fermi helps scientists study them.

Fermi has made many incredible discoveries over its first 15 years, but its work is far from over. The telescope remains healthy and will continue to serve as a cornerstone of gamma-ray exploration for years to come. As scientists delve deeper into the gamma-ray universe, their work with Fermi will focus on a few main areas. These include searching for high-energy phenomena that exist but Fermi hasn't yet detected, collaborating with new ground-based observatories, making ongoing progress toward astrophysics' big questions, and probing the "unknown unknowns" of gamma-ray science.

Observing the Extraordinary

Fermi has yet to detect some of the highest-energy phenomena scientists know of. This is the case for a number of reasons, including gas and dust obscuring Fermi's view of the events, the faintness of the events, or just statistical improbability. Astronomers hope that Fermi's keen eye will detect such events in the near future, lending us greater detail about the gamma rays these events produce.

Observing a galactic supernova is at the top of the list of must-sees. The last supernova in our Milky Way galaxy was detected in 1604 by German astronomer Johannes Kepler. The next closest supernova, 1987A, occurred in 1987 in the Large Magellanic Cloud, a companion galaxy of the Milky Way. Astronomers estimate that one to three stars in our galaxy should statistically explode as a supernova every century, making us "overdue." Scientists are on the lookout for a supernova not only in light, but also in neutrinos and gravitational waves. Today, the astrophysical community would know a supernova was occurring before any telescope saw it. A network of neutrino detectors called the Supernova Early Warning System (which includes frequent Fermi partner, the NSF's IceCube Neutrino Observatory) would record hundreds or thousands of neutrinos. Gamma-ray detections would surely follow, enabling scientists to collect detailed information about supernovae like never before.

Another phenomenon the Fermi team hopes to observe is a galactic magnetar flare. Scientists have not had to wait nearly as long for such an event — the last one occurred in 2004 — but neither Fermi nor its predecessor, Compton, were in orbit at the time. Magnetar flares are so intense that their light has temporarily overloaded scientific instruments in the past, so astronomers hope to record future flares with more precision. As with nearby supernova 1987A, a nearby magnetar flare in the Sculptor galaxy in 2020 provided insight as to what a magnetar flare in our galaxy could look like. The next time around, scientists will also rely on LIGO (The NSF's Laser Interferometer Gravitational-Wave Observatory), Virgo (funded by Italy's National Institute of Nuclear Physics, INFN, the French National Center for Scientific Research, CNRS, and the Netherlands' Nikhef), and KAGRA (the Kamioka Gravitational Wave Detector funded by Japan's Ministry of Education, Culture, Sports, Science, and Technology), three gravitational wave detectors, to measure the event. The three detectors comprise the International Gravitational Wave Network (IGWN). Studying magnetar flares in light and gravitational waves will help us better understand their high-energy inner workings.

Fermi will continue observing the sky as long as it is in operation, reassuring scientists that if a rare cosmic spectacle occurs, Fermi will be there to capture it.

In this illustration, a black hole drives powerful jets of particles traveling near the speed of light. The jets pierce through the star, emitting light across the electromagnetic spectrum as they stream into space.

Credit: NASA/Swift/Cruz deWilde

Pioneering Multimessenger Astronomy

When it comes to astrophysics, the more observatories the merrier. Collaboration is at the heart of science, and observatories frequently work together to uncover more information about our universe. However, prior to the late 20th century, gamma-ray science was an understated part of collaboration in astrophysics. The detectors used to study gamma rays were not yet advanced, and optical and infrared telescopes took center stage. As science has advanced, though, space agencies and science institutions around the world have built numerous other observatories to study all wavelengths of light and cosmic signals like neutrinos and gravitational waves. In this new era of astronomy, Fermi is an invaluable member. Gamma rays provide a unique look into the highest-energy phenomena of our universe, complementing the work of telescopes exploring lower-energy light as well as particle observatories. Studying events using multiple cosmic signals is called multimessenger astronomy and is central to Fermi's future at the forefront of astronomy. Combining Fermi's extensive gamma-ray record with new observations by a multitude of telescopes gives new meaning to Fermi's data and demonstrates its ongoing importance in the astronomical community.

One of the most exciting Fermi collaborations is with the IceCube Neutrino Observatory. Spanning about one-fourth of a cubic mile (or a cubic kilometer) and buried in the Antarctic ice, IceCube detects light emitted by particles that neutrinos produce when they interact with ice. It is the largest neutrino detector ever built and has already detected the highest-energy neutrinos ever observed. Scientists theorize that neutrinos and gamma-rays can come from the same cosmic sources, like active galactic nuclei and gamma-ray bursts. Combining measurements from Fermi and IceCube provides fascinating insight into the highest-energy phenomena known. For example, IceCube discovered a neutrino that Fermi's LAT and other observatories confirmed came from a blazar jet. This finding shocked the astrophysics community by proving that the process where a black hole creates blazar jets must be powerful enough to boost protons — which decay into neutrinos — to near the speed of light. Prior to this neutrino observation, scientists believed that the jet creation process was only powerful enough to accelerate electrons, which are 1,000 times smaller than protons. Such a finding showed astrophysicists that there must be a missing component in how we understand the energy around black holes. Future IceCube-Fermi collaborations are sure to excite particle physicists and astronomers alike.

Another key collaboration is between Fermi and gravitational wave detectors like the LIGO, Virgo, and KAGRA. Gravitational waves, the ripples in space-time about which Einstein theorized, weren't detected until 2015. Since that tremendous accomplishment, the field has advanced rapidly. Studying gravitational waves is important because they provide complementary information to light and are not as distorted by matter and gravity, meaning that they reveal different information about source objects. Scientists believe that using gamma rays can help detect more gravitational waves, both of which come from powerful cosmic events like supernovae and merging neutron stars. Fermi will continue to watch the sky for gamma-ray bursts that may be counterparts to gravitational wave events, and alert other telescopes to its findings.

A second collaborative technique is pulsar timing arrays: a way to study the tiny variations in the timing of millisecond pulsars' pulses to determine that gravitational waves interacted with their light. Here, the goal is to measure gravitational waves from merging supermassive black holes, not merging neutron stars. The single most important way to advance this work is for Fermi to detect more pulsars, strengthening the patterned data so that disruptions by gravitational waves are more apparent. Radio telescopes use these pulsars to form their own pulsar timing array, while Fermi itself can be used as a gamma-ray pulsar timing array. Fermi has already detected 150 millisecond pulsars, and its LAT continues scanning for more.

Not only does Fermi collaborate in multimessenger astronomy, but it also works with other gamma-ray observatories by telling them where to look. The multinational Cherenkov Telescope Array (CTA), soon to be the first ground-based gamma-ray observatory in the world with publicly available data, will focus on higher-energy gamma-ray light (100 gigaelectron volts (GeV) to 10 teraelectron volts (TeV)). CTA will push gamma-ray science further into the spotlight, engaging the worldwide scientific community in studying the highest-energy light known. While gamma rays cannot reach Earth's surface due to the protection of our atmosphere, gamma rays that interact with the atmosphere produce a slew of particles that release a visible glow called Cherenkov light, which CTA will detect. Unfortunately, this process is so rare that scientists predict only one bright gamma-ray photon per square meter can be detected each year. CTA will therefore have more than 60 telescopes that look at the gamma-ray sky, with expectations to detect more than 1,000 new gamma-ray-emitting objects. When CTA is completed in 2025, it will be able to probe the gamma-ray sources Fermi detects at even higher energies, enabling scientists to better study the most energetic areas of the cosmos like the regions around neutron stars and black holes.

A cartoon of two neutron stars as they spiral around each other before a collision that produces a gamma-ray burst.

Credit: NASA's Goddard Space Flight Center.

Fermi (top left), NASA's Neil Gehrels Swift Observatory (top right), and the MAGIC CTA observatory in the Canary Islands observe GRB 190114C in this illustration.

Credit: NASA/Fermi and Sonoma State University, Aurore Simonnet

Asking the Big Questions

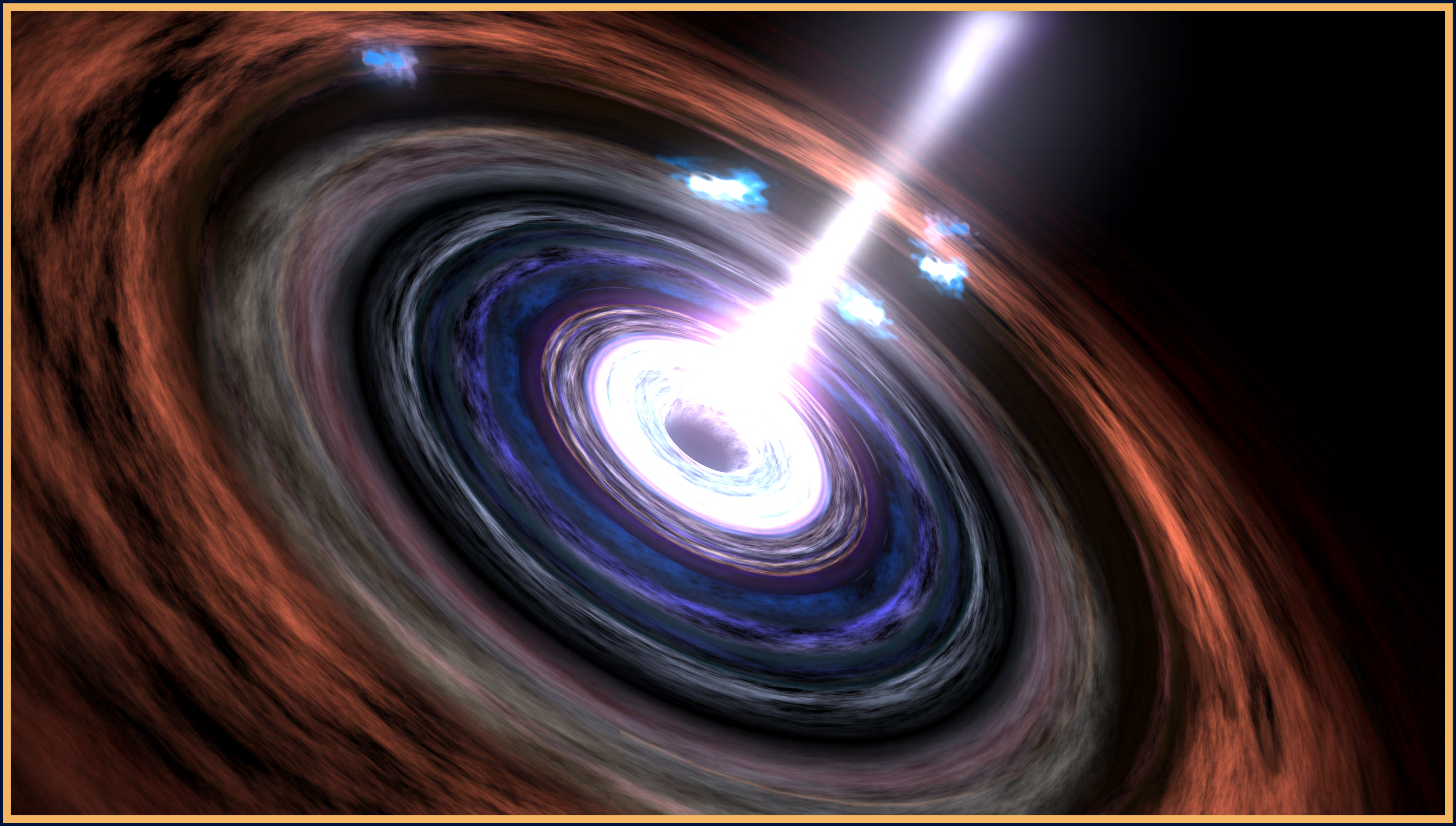
Just as philosophers question the meaning of life, theoretical physicists question the nature of the universe. What happened just after the big bang? Why is the universe's expansion speeding up? What is the nature of dark matter? Enormous as these questions are, scientists explore them by merging theory with ever more precise observations. Scientists use experiments and telescopes like Fermi to design and test hypotheses that reveal details about our universe's history and properties. Fermi, in effect, gives scientists the tools they need to ask the right questions.

Scientists have always been intrigued by the objects that lend themselves exceedingly well to sci-fi: black holes. Fermi has studied the gamma rays from stellar-scale to supermassive black hole jets, but we still don't know much about the nature of the black holes or their environments. For one, how does a black hole accelerate particles to nearly the speed of light to form jets? What are those jets made of? IceCube discovered that neutrinos can also be in the jets, but we don't know if this is true in all cases. Fermi will continue to observe gamma-ray bursts and blazars to hopefully answer some of these fascinating questions.

Astronomers also hope to push the limits of space-based astronomy by asking questions like: How early in the universe can we see gamma rays from black holes? In 2023, NASA's Webb discovered the oldest black hole yet, existing only 570 million years after the big bang. The Fermi team hopes to observe gamma rays from black holes — a dead giveaway that the black hole is accreting energy and spewing it out as jets — to see what kind of emission shaped our early universe. Additionally, scientists are searching the universe to ask: Can we detect pairs of supermassive black holes using gamma rays? The leading technique is actually designed to identify long gravitational waves, which theorists believe result from orbiting pairs of supermassive black holes. Detecting tiny changes in the timing of light emanating from an array of gamma-ray pulsars would tell us details about their source black hole system — for example, its mass — which are otherwise too hard to discern due to distance. Astronomers are so confident in this technique that the question is more "when" than "if" this detection will happen. Fermi's unique gamma-ray skillset will ultimately help theorists probe the large lingering questions about how black holes form and grow.

Perhaps chief among all of space's mysteries is the nature of dark matter. We know dark matter comprises about 85% of the universe's total matter and 25% of its total energy, but most of its other characteristics elude us. Some of the open questions include: What is dark matter made of? Is dark matter present in all galaxies? Can normal matter decay into dark matter? Will we ever detect dark matter directly? Fermi astronomers aim to keep searching for gamma rays that result from the annihilation of dark matter particles, and therefore constrain more about the mysterious substance that pervades our cosmos. Often, findings in this area take the shape of ruling out where dark matter cannot exist. Some of the places where scientists were sure they would find dark matter (like galaxy clusters) actually came up empty. Constraining what dark matter is not has proven a valuable approach in the search for this strange material.

Another one of astronomy's big questions Fermi had a hand in opening: What causes the excess of gamma rays at the galactic center? Seen both in the Milky Way and nearby Andromeda galaxies, there is a mysterious concentration of extra gamma rays coming from the center. Scientists have yet to determine if this excess high-energy light is due to a hidden population of pulsars or elusive dark matter. Determining the answer would not only help constrain our knowledge of dark matter but also teach us more about our home and our nearest neighbor in the universe.



In the heart of an active galaxy, matter falling toward a supermassive black hole creates jets of particles traveling near the speed of light, illustrated here. Scientists are hoping Fermi can help reveal what these jets are composed of.

Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

Exploring the Unknown Unknowns

The astronomy community is doubtlessly excited about the future of Fermi research. There are many open questions that scientists are itching to explore. Though potentially more exciting are the questions we have yet to ask. The universe is incomprehensibly large and holds an astounding number of cosmic objects. As Fermi keeps probing the universe from far to near, from the beginning to the present, the chances of uncovering something rare or unexpected increase. In fact, the Fermi community has found more surprises as the mission has continued, including the Fermi Bubbles, gamma-ray-only pulsars, and gamma rays from novae. These "unknown unknowns" are what drive scientific exploration. What does humanity have yet to discover that will challenge our understanding of physics and redirect astronomical efforts? What cosmic curiosities will be the missing piece to our most puzzling theories, and which ones will open up entirely new hypotheses? What objects will remind us of our home galaxy, and which ones will look unlike anything ever seen? The unknown unknowns are what keep science exciting and make Fermi's mission ongoing. The universe is vast and full of wonder; with Fermi constantly surveying the sky, we can only dream about what we will discover next.

An artist's rendering of NASA's Fermi Gamma-ray Space Telescope in orbit above Earth.

Credit: NASA's Goddard Space Flight Center/Chris Smith (USRA/GESTAR)

Glossary

ACCRETION DISK
A relatively flat cloud of gas or dust surrounding any massive object growing in size by attracting matter, such as a newborn star or black hole.

ACTIVE GALACTIC NUCLEUS/NUCLEI (AGN)
A class of galaxies whose central regions appear much brighter than ordinary galaxies and are also strong sources of X-ray, gamma-ray, and other radiation. Astronomers think supermassive black holes at the centers of AGN produce this additional energy as they accrete matter. Radio galaxies, quasars, and blazars are all types of AGN.

AFTERGLOW
Electromagnetic radiation that often follows the initial burst of gamma rays in a gamma-ray burst. It occurs due to the interaction of the jet with the surrounding environment. Afterglows can persist for days to weeks, gradually dissipating with time. In extreme cases, they can endure for years.

ALL-SKY MAP
A single map showing data across the entire sky, similar to a single map showing Earth's entire surface. The Fermi all-sky map is usually depicted as a blue oval with a yellow and orange band representing brighter gamma-ray emission along our galaxy's central plane. Brighter gamma-ray sources, like pulsars and active galaxies, are depicted as distinct white, orange, and yellow dots.

ANGULAR MOMENTUM
A property of a mass or system of masses turning about some fixed point, for example, a planet in orbit around a star. It is defined as the body's mass multiplied by its velocity and its distance from the center of motion. In a closed system, it is a conserved quantity in physics, which means it remains constant.

ANNIHILATION
The mutual conversion of a particle and its antiparticle into electromagnetic radiation, converting their mass (m) into energy (E) according to Einstein's famous formula, E = mc2, where c is the speed of light. An electron and a positron annihilate to produce two gamma-ray photons, each with an energy of 511 keV.

ANTICOINCIDENCE DETECTOR (ACD)
A system that detects unwanted charged particles so they are not confused with target particles or gamma rays. On the Fermi Gamma-ray Space Telescope, the LAT ACD triggers when it detects a charged particle entering the telescope so the particle is not mistaken for a gamma ray.

ANTIMATTER
Counterparts of the subatomic particles making up normal matter that have opposite properties, typically electrical charge. When a particle and its antiparticle collide, they annihilate. The positron is the antiparticle of the electron.

ARCMINUTE
An angular measurement equal to 1/60th of a degree. It is approximately the smallest angle discernible to the unaided human eye. As viewed from Earth, both the Sun and the Moon appear about 30 arcminutes across.

ASTRONOMY
The scientific study of matter in outer space, especially the positions, dimensions, distribution, motion, composition, energy, and evolution of celestial bodies and phenomena.

ASTROPHYSICS
The branch of astronomy concerned with the physical nature of stars, galaxies, interstellar clouds, and other objects, including their luminosities, temperatures, densities, and chemical composition.

ATMOSPHERE
The envelope of gas that surrounds a planet or star.

BIG BANG
A widely accepted model of the universe that explains its observed properties by postulating that it originated as a tiny, superdense, rapidly expanding fireball about 13.8 billion years ago. The universe expanded, cooled, and condensed into subatomic particles that later accumulated into the matter that formed stars and galaxies. The model naturally explains the cosmic microwave background, the expansion of space, and the ratio of hydrogen, helium, and other light elements observed throughout the universe.

BINARY STARS
Two stars that are gravitationally bound together and orbit their common center of mass.

BLACK HOLE
An object whose gravity is so strong that not even light can escape from it. Black holes are completely characterized by only three parameters: mass, rotation, and electrical charge. Supermassive black holes weighing hundreds of thousands to billions of solar masses are observed at the centers of most large galaxies and power AGNs.

BLAZAR
A type of active galactic nucleus often appearing as a bright, highly variable point-like source. Blazars vary dramatically in all observable parts of the electromagnetic spectrum, so studying them requires simultaneous multiwavelength observations. An accreting supermassive black hole at the center of a blazar expels jets of matter in opposite directions that travel at nearly the speed of light. Blazars appear so bright and variable because we are looking almost directly down the barrel of one jet.

CALORIMETER
An instrument that measures the energy of a particle or photon through the amount of heat or light the particle or photon deposits in a material.

CHERENKOV RADIATION
High-energy gamma rays and cosmic rays observed through the faint flashes of blue light they produce when interacting with Earth's atmosphere. High-energy radiation entering the atmosphere eventually collides with molecules in the air. Each impact shatters the molecule's atoms into their constituent particles — protons, neutrons, electrons — and produces others, such as muons and pions. These particles then strike other atoms, producing more fast-moving debris that breaks apart more atoms, and so on. This cascade of particles moves faster through air than light is able to, which results in a broad blue flash called Cherenkov light, named for the Russian physicist Pavel Cherenkov (1904–1990).

CITIZEN SCIENCE
A form of open collaboration in which individuals or organizations participate voluntarily in the scientific process.

COMPTON GAMMA RAY OBSERVATORY
NASA's first gamma-ray observatory and Fermi's predecessor. Compton launched in April 1991, and the mission ended in June 2000. Compton created the first all-sky gamma-ray map.

COMPTON SCATTERING
A transfer of energy between a photon and a particle, such as an electron, that lowers the photon's energy and increases the particle's velocity. Inverse Compton scattering occurs when a charged particle transfers some of its energy to a photon, boosting it to higher energy, and plays an important role in astrophysics. When light from microwave to ultraviolet wavelengths collides with a high-energy particle, the interaction can boost the photon to gamma-ray energies.

COSMIC DUST
Irregularly shaped grains of carbon and/or silicates measuring a fraction of a micron across which are found between the stars.

COSMIC RAYS
Atomic nuclei — about 90% of them protons — and elementary particles, such as electrons, that travel through interstellar space at speeds approaching that of light.

DARK MATTER
Hypothetical matter of unknown composition that does not emit or reflect enough electromagnetic radiation to be observed directly, but whose presence can be inferred from gravitational effects on visible matter. It is now thought to comprise 26.8% of the total mass-energy in the universe. Candidate particles include WIMPs, axions, and even primordial black holes.

DENSITY
The ratio between the mass of an object and its volume. In the metric system, density is measured in grams per cubic centimeter (or kilograms per liter).

DISK
A flattened, circular region of gas, dust, and/or stars. It may refer to material surrounding a newly formed star, material accreting onto a black hole or neutron star, or the large region of a spiral galaxy containing the spiral arms.

DWARF SPHEROIDAL GALAXIES
Small satellite galaxies that are neighbors to the Milky Way that scientists theorize possess large amounts of dark matter. They contain few stars and little interstellar gas and dust.

EJECTA
Matter that is hurled outward from an explosive event, such as a volcanic eruption, meteorite impact, or supernova.

ELECTROMAGNETIC RADIATION (WAVES)
Light in all of its forms, including radio, microwave, infrared, visible or optical light, ultraviolet, X-rays, and gamma rays. Electromagnetic radiation moves at the speed of light and as a traveling periodic fluctuation of an electric and magnetic field. These fields oscillate at right angles to each other and to the wave’s travel direction.

ELECTROMAGNETIC SPECTRUM
The full range of frequencies, from radio waves to gamma rays, that characterizes electromagnetic radiation (light).

ELECTRON
A negatively charged particle commonly found in the outer layers of atoms. The electron has only 0.0005 the mass of the proton.

ELECTRON VOLT (EV)
The change of potential energy experienced by an electron moving from a place where the potential has a value of V to a place where it has a value of V+1 volt. This is a convenient energy unit when dealing with the motions of electrons and ions in electric fields; the unit is also used to describe the energy of X-rays and gamma rays. A keV (or kiloelectron volt) is equal to 1,000 electron volts. An MeV (or megaelectron volt) is equal to one million electron volts. A GeV (or gigaelectron volt) is equal to one billion (109) electron volts. A TeV (or teraelectron volt) is equal to a million million (1012) electron volts.

ELEMENT
A substance made from atoms that have the same number of protons in their nuclei (their atomic number). Elements cannot be chemically interconverted or broken down into simpler substances and are primary constituents of matter; there are 118 elements known. Hydrogen and helium are the simplest and most abundant elements in the universe, making up about 74% and 24% of all the matter, respectively. Heavier elements — often collectively called “metals” in astronomy — comprise about 2% of the Milky Way’s disk but can greatly influence astronomical phenomena.

EMISSION
The production of electromagnetic radiation by an atom or other object.

ENRICO FERMI
A pioneer in high-energy physics and the Fermi spacecraft’s namesake.

EXTRAGALACTIC
Beyond our own galaxy, the Milky Way.

EXTRAGALACTIC BACKGROUND LIGHT
The total light from all of the stars (and to a lesser extent, galactic nuclei) that have ever existed in the observable universe. It extends from the infrared through the optical and into the ultraviolet.

FERMI ACCELERATION
A process by which charged particles gain energy through repeatedly passing through magnetic fields, typically those associated with the shock waves produced by solar flares or supernova explosions. This process produces high-energy cosmic rays, which travel close to the speed of light.

FERMI BUBBLES
Giant gamma-ray emitting lobes that extend above and below the center of the Milky Way and span 50,000 light-years tip to tip. The bubbles may be related to activity from the supermassive black hole at the center of the galaxy or a past burst of star formation.

FERMI GAMMA-RAY SPACE TELESCOPE
NASA’s premier space-based gamma-ray observatory. Fermi launched in 2008 and has discovered over 6,000 gamma-ray sources.

FERMI SCIENCE SUPPORT CENTER (FSSC)
A branch of the Fermi mission based at NASA’s Goddard Space Flight Center that maintains and distributes the telescope’s data, provides data analysis tools for the scientific community, plans and schedules the science activities on the telescope, and manages the Guest Investigator Program, which provides funding to U.S.-based scientists for projects with Fermi.

FLARE
A sudden, brief, and intense increase in an astronomical object’s brightness.

FLUX
A measure of the amount of energy given off by an astronomical object over a fixed amount of time and area. Flux measurements make it easy for astronomers to compare the relative energy output of objects with very different sizes or ages.

FREQUENCY
A property of a wave that describes how many wave patterns or cycles pass by in a period of time. Frequency is often measured in hertz (Hz), where a wave with a frequency of 1 Hz will go through one cycle each second.

GALACTIC CENTER
The center of our Milky Way galaxy. It contains a supermassive black hole, extremely hot clouds of gas, and orbiting stars, including neutron stars and white dwarfs.

GALACTIC DIFFUSE EMISSION
Widespread gamma-ray emission along the plane of our Milky Way galaxy. It arises mostly from cosmic rays interacting with interstellar gas, dust, and starlight.

GALACTIC PLANE
An invisible plane that divides our galaxy into northern and southern halves (similar to the Earth's equator). Most of the stars and gas in the Milky Way lie along this plane.

GALAXY
A component of our universe made up of gas, dust, and numerous (usually more than a million) stars held together by gravity.

GALAXY CLUSTER
A system of galaxies containing anywhere between a few and a few thousand member galaxies that are gravitationally bound together.

GAMMA RAY
The highest-energy, shortest-wavelength electromagnetic radiation. Usually, thought of as any light having energies greater than about 500 keV.

GAMMA-RAY BURST (GRB)
A burst of gamma rays from space lasting from a fraction of a second to many minutes. In general, GRBs longer than two seconds are associated with supernovae and are thought to occur when a collapsing massive star forms a black hole, driving high-energy jets that drill through the star and emit gamma rays when they emerge. Shorter bursts are associated with the end stage of binary systems containing either a pair of neutron stars or a neutron star and a black hole, which produce similar jets of matter when they merge.

GAMMA-RAY BURST MONITOR (GBM)
The Fermi Gamma-ray Space Telescope's secondary instrument. It views two-thirds of the entire sky at all times and has an energy range of 8 keV to 40 MeV. It detects around 240 gamma-ray bursts each year, as well as solar flares, terrestrial gamma-ray flashes, and other gamma-ray events.

GAMMA-RAY LARGE AREA SPACE TELESCOPE (GLAST)
Fermi's name before it launched.

GAS
One of four states of matter, in which atoms, molecules, or ions move freely and are not bound to each other. In astronomy, it usually refers to hydrogen or helium.

GENERAL RELATIVITY
The geometric theory of gravitation developed by Albert Einstein (1879–1955), which incorporated and extended his theory of special relativity to include accelerated frames of reference and introduced the principle that gravitational and inertial forces are equivalent. The theory has consequences for the bending of light by massive objects, the nature of black holes, and the fabric of space and time.

GRAVITATIONAL WAVES
Ripples in space-time caused by the acceleration of massive objects. The first directly detected sources include binary systems where orbiting black holes or neutron stars merged together. Gravitational waves are also thought to emanate from the motion of matter during the big bang.

GRAVITY
A mutual physical force attracting two bodies.

HIGH-ENERGY ASTRONOMY
The study of astronomical objects that release radiation at the upper end of the electromagnetic spectrum, including X-rays and gamma rays, as well as energetic particles like neutrinos and cosmic rays.

HYDROGEN
The lightest and most abundant element. A hydrogen atom consists of one proton and one electron. Hydrogen makes up about 75% of the Sun's mass, but only a tiny fraction of Earth's.

INFRARED
Electromagnetic radiation at wavelengths longer than the red end of visible light and shorter than microwaves (roughly between one and 100 microns). Almost no infrared light can reach Earth's surface from space, although some portions can be observed by high-altitude aircraft or telescopes atop high mountains.

INTERSTELLAR MEDIUM
Gas, dust, and other material that exists in the space between stars.

JETS
Oppositely directed beams of particles moving near the speed of light, usually emitted by supermassive black holes in active galaxies, pulsars, or gamma-ray bursts.

LARGE AREA TELESCOPE (LAT)
The Fermi Gamma-ray Space Telescope's primary instrument. It is a pair-production telescope that views one-fifth of the entire sky at all times. The LAT is around 30 times more sensitive than any previous space-based gamma-ray instrument and has an energy range of 20 MeV to 300 GeV.

LIGHT
Electromagnetic radiation of all types, from radio waves to gamma rays. Visible or optical light refer to the wavelengths detectable by the human eye.

LIGHT-YEAR
A unit of length that equals the distance light travels in a year. At the rate of 671 million miles per hour (300,000 kilometers per second), one light-year is equivalent to 5,880,000,000,000 miles (9,461,000,000,000 kilometers).

LIMB
The outer edge of the apparent disk of a celestial body.

LORENTZ INVARIANCE
The proposition that the laws of physics are the same for different observers. It is the pillar of Einstein's theory of special relativity.

LUMINOSITY
The rate at which a star or other object emits electromagnetic radiation.

MAGNETAR
A type of neutron star possessing an unusually intense magnetic field, between 100 and 1,000 times stronger than that of a typical pulsar. Astronomers have identified some 30 magnetars.

MAGNETIC FIELD
A description of the strength of the force exerted by a magnetic object.

MASS
A measure of the total amount of material in a body, defined either by the body's inertial properties or by its gravitational influence on other bodies.

MATTER
Any substance that occupies space and possesses mass.

MICROWAVE
Electromagnetic radiation with wavelengths between about 0.04 and 11.8 inches (one millimeter and 30 centimeters). Microwaves can be used to study the universe, communicate with satellites in Earth orbit, and cook popcorn.

MILLISECOND PULSAR
A pulsar with a rotational period between one and 10 milliseconds. The fastest discovered pulsar spins 716 times per second.

MISSION OPERATIONS CENTER (MOC)
The home of Fermi operations where engineers monitor the spacecraft's health and safety data, send commands to the spacecraft, and transfer its science data to the LAT and GBM teams for processing. The MOC is hosted at NASA's Goddard Space Flight Center and staffed by the Fermi Flight Operations Team.

MULTIMESSENGER ASTRONOMY
A branch of astronomy that combines information from different signals, including light, gravitational waves, neutrinos, and other cosmic particles.

NASA
The National Aeronautics and Space Administration, founded in 1958 as the successor to the National Advisory Committee for Aeronautics.

NEBULA (PL. NEBULAE)
A cloud of interstellar dust and gas.

NEUTRINO
A fundamental particle produced in nuclear reactions, such as those occurring in stars. They are hard to detect because the vast majority of them pass completely through Earth without interacting with other matter.

NEUTRON
A particle with approximately the mass of a proton but zero charge, commonly found in the nuclei of atoms.

NEUTRON STAR
The remnant compact core of a massive star that exploded as a supernova. Neutron stars host more than the Sun's mass in a ball about 12.5 miles (20 kilometers) across and can be observed as pulsars and magnetars.

NOVA (PL. NOVAE)
A star that experiences a sudden outburst of radiant energy, temporarily increasing its luminosity by up to 100,000 times before fading back to its original luminosity.

NUCLEUS (PL. NUCLEI)
In physics, the positively charged core of an atom, composed of protons and (usually) neutrons, that makes up nearly all of its mass and around which electrons orbit. The term is also used in astronomy for the solid body of a comet and for the central emitting region of active galaxies.

ORBIT
The elliptical course of a celestial object or spacecraft about a star, planet, or moon. Also, a complete circuit round an orbited body.

PAIR PRODUCTION
The physical process whereby a gamma-ray photon, usually through an interaction with the electromagnetic field of an atom's nucleus, produces an electron and an anti-electron (positron). The original photon no longer exists, its energy having gone into producing the two resulting particles. The inverse process, pair annihilation, creates two gamma-ray photons from the mutual destruction of an electron/positron pair.

PHOTON
A particle representing the smallest amount (a quantum) of electromagnetic radiation. Photons have zero rest mass, no electrical charge, always travel in a vacuum at the speed of light, and carry energy equal to their radiation frequency multiplied by Planck's constant.

POLARIZATION
A property of light in which the vibrations of waves in a light beam are at least partially aligned. Light may be polarized by reflection or by passing it through filters that transmit vibration in one plane but not in others. Polarization measurements allow astronomers to learn much more about an object, including their 3D shapes and the strength of their magnetic fields.

POSITRON
The antimatter counterpart of the electron, with the same mass and spin but carrying a positive charge.

PROTON
A particle with a positive charge found in the nuclei of all atoms. The nuclei of each chemical element hold a characteristic number of protons, which is known as the atomic number.

PULSAR
A rotating neutron star that generates regular pulses of radiation. Pulsars were discovered by observations at radio wavelengths but have since been observed at optical, X-ray, and gamma-ray energies.

PULSAR TIMING ARRAY
A method for detecting gravitational waves by monitoring a large number of well-understood millisecond pulsars. The passing waves produce correlated changes in the pulse arrival times to an observatory.

RADIO
Electromagnetic radiation with the lowest frequencies and the longest wavelengths, produced by charged particles moving back and forth.

RADIO GALAXY
A type of galaxy that has giant lobes of radio emission extending well beyond its visible structure. These lobes, which occasionally emit gamma rays, are powered by jets from the active galactic nucleus at its center.

RED GIANT
A low- or intermediate-mass star (born with a mass between about 0.5 and five Suns) in an advanced phase of stellar evolution, exhibiting high luminosity and low surface temperature. Due to internal changes related to the depletion of hydrogen fuel in their cores, the outer envelopes of red giants expand greatly, making them hundreds of times larger than the Sun.

RESOLUTION (SPATIAL)
In astronomy, the ability of a telescope to differentiate between two objects in the sky that are separated by a small angular distance. The closer two objects can be while still allowing the telescope to see them as two distinct objects, the higher the resolution of the telescope.

RESOLUTION (SPECTRAL OR FREQUENCY)
Similar to spatial resolution, spectral resolution is the ability of the telescope to differentiate two light signals that differ in frequency by a small amount. The closer the two signals are in frequency while still allowing the telescope to separate them as two distinct components, the higher the spectral resolution of the telescope.

ROTATION
The spinning motion of a celestial body around its own axis.

SATELLITE
A body, either natural or artificial, that revolves around a larger body. The Moon is a natural satellite of Earth, while the International Space Station is an artificial one.

SENSITIVITY
A measure of how bright objects need to be in order for a telescope to detect them. A highly sensitive telescope can detect dim objects, while a telescope with low sensitivity can detect only bright ones.

SHOCK WAVE
A strong compression wave where there is a sudden change in gas velocity, density, pressure, and temperature.

SOLAR FLARES
Violent eruptions on the Sun’s surface.

SOLAR MASS

The mass of the Sun, a convenient unit for describing the masses of other stars, star clusters, galaxies, and other objects. One solar mass equals 4.384 × 1030 pounds (1.988 × 1030 kilograms), or about 333,000 Earth masses.

SOLAR SYSTEM

A gravitationally bound collection of one star (the Sun), eight planets (including Earth, the only planet known to support life), five dwarf planets, and at least 290 moons. It is located about midway out from the center of our Milky Way galaxy.

SPACE WEATHER

Variable conditions on the Sun, in the solar wind, and near Earth (within its upper atmosphere and magnetosphere) that can degrade the performance and reliability of technology and endanger human health. Strong events are sometimes called solar storms. Solar activity is the main source of space weather. This includes coronal mass ejections — immense fast-moving clouds of plasma launched into space — and brief, sudden eruptions of X-rays from solar flares. Severe space weather events pose a risk to astronauts and can damage satellites, disrupt communications, and, by inducing additional currents in electrical transmission wires, disrupt power systems on the ground.

SPECIAL RELATIVITY

The physical theory of space and time developed by Albert Einstein (1879–1955), based on postulates that all laws of physics are equally valid in all frames of reference moving at a uniform velocity and that the speed of light from a uniformly moving source is always the same, regardless of how fast or slow the source or its observer are moving. The theory's consequences include the relativistic mass increase of rapidly moving objects, time dilation, and the principle of mass-energy equivalence.

SPEED OF LIGHT

The speed at which electromagnetic radiation propagates in a vacuum, defined as 186,282 miles per second (299,792,458 meters per second). Put another way, light takes a nanosecond to travel 11.8 inches (29.98 centimeters). Light travels at slightly slower speeds when it moves through materials like glass or air.

SPIDER BINARY

A millisecond pulsar and a lower-mass star that orbit each other as the pulsar's emissions erode its companion.

STAR

A large ball of gas that creates and emits its own radiation.

SUNSPOTS

Cooler (and thus darker) regions on the Sun where loops of magnetic field rise up from the solar surface.

SUPERNOVA (PL. SUPERNOVAE)

1. The explosion of a massive star, resulting in a sharp increase in brightness followed by a gradual fading. At peak light output, this type of supernova (called type II) can outshine a galaxy. The star's outer layers blast outward in a radioactive cloud. Visible long after the initial explosion fades from view, this cloud forms a supernova remnant.
2. The explosion of a white dwarf that has either merged with another white dwarf or has accumulated enough material from a companion star to reach the Chandrasekhar limit — the theoretical maximum mass of a white dwarf, equal to about 1.4 solar masses. This type of supernova (called type Ia) has roughly the same intrinsic brightness and plays an important role in determining distances.

TERRESTRIAL GAMMA-RAY FLASHES

Gamma-ray events lasting less than a millisecond that are produced by lightning in storms on Earth.

TRACKER

A subsystem of Fermi's Large Area Telescope consisting of 16 towers of silicon detectors interleaved with tungsten foils that determine the direction a gamma-ray came from.

TRACKING AND DATA RELAY SATELLITES (TDRSS)

NASA's network of specialized communications satellites in geosynchronous orbit that provide communications services to many NASA spacecraft, including Fermi.

TRANSIENTS

Astronomical objects that exhibit a large difference in brightness over a relatively short time, seen as a low, or off, state and a high, or on, state. The brighter state often, but not always, occurs only once. Examples include gamma-ray bursts, novae, supernovae, and blazar and solar flares.

TRANSITIONAL PULSAR

Millisecond pulsars in a binary system that switch rapidly between emitting one kind of emission to another, for example, from X-rays to radio and back.

ULTRAVIOLET (UV)

Electromagnetic radiation at wavelengths shorter than the violet end of visible light, ranging from 100 to 380 nanometers. Earth's atmosphere blocks most UV light from reaching the surface.

UNIVERSE

Everything that exists, including Earth and other planets, stars, galaxies, and all that they contain; the entire cosmos.

VERY HIGH-ENERGY (VHE) GAMMA RAYS

Gamma-rays above 100 GeV. VHE emissions result from extreme phenomena such as gamma-ray bursts, blazar jets, and particle acceleration in supernova remnants.

VISIBLE (OPTICAL) LIGHT
Electromagnetic radiation at wavelengths the human eye can see, ranging from red (about 750 nanometers) to violet (380 nanometers).

WAVELENGTH
The distance between adjacent peaks in a series of periodic waves.

WHITE DWARF
A star that has exhausted most or all of its nuclear fuel and has collapsed to a size comparable to Earth's. Typically, a white dwarf packs a mass roughly equal to the Sun's into a ball just 1% the Sun's size.

X-RAY
Electromagnetic radiation of very short wavelength and high energy. X-rays have shorter wave lengths than ultraviolet light but longer wavelengths than gamma rays.

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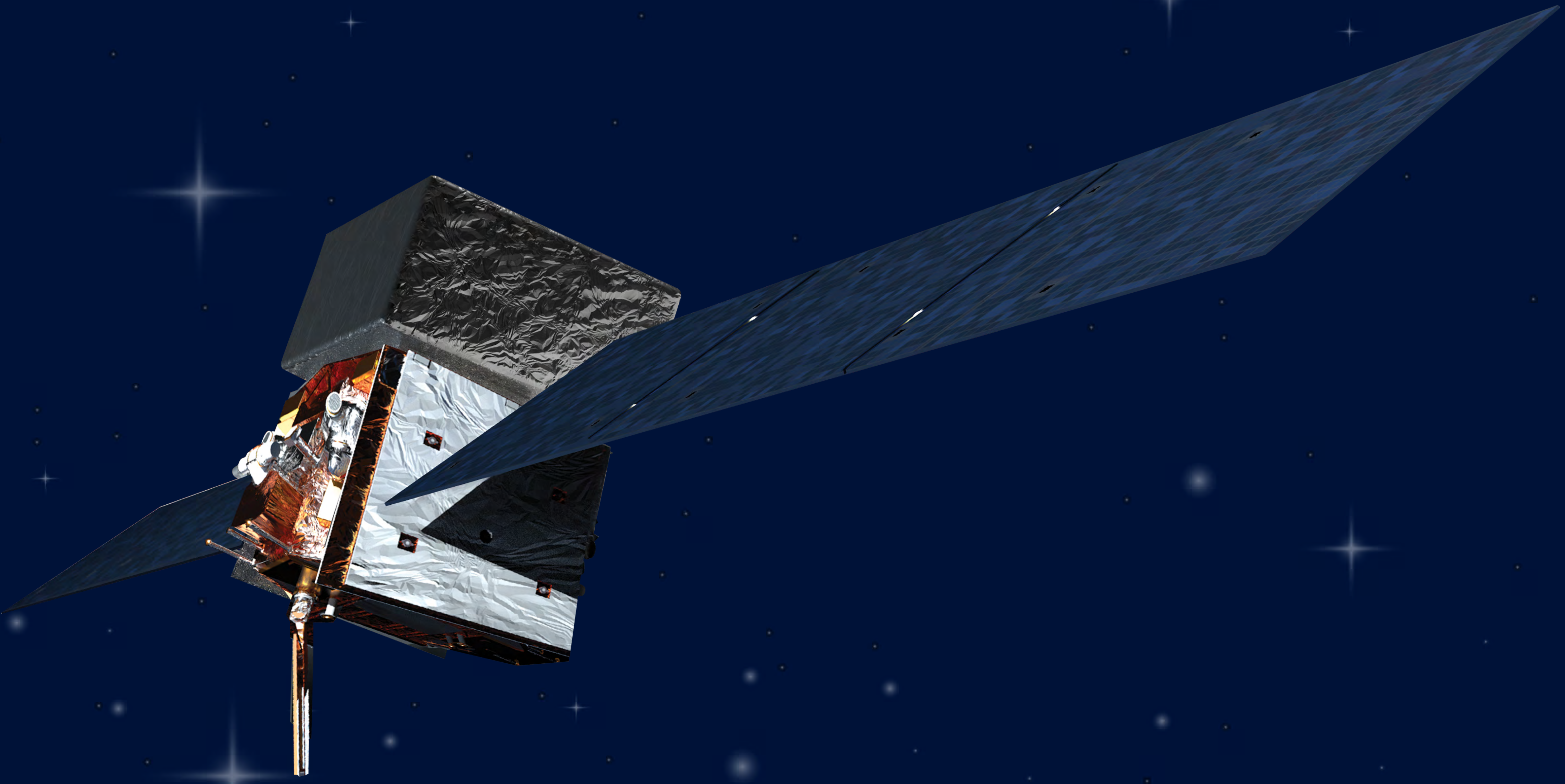

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