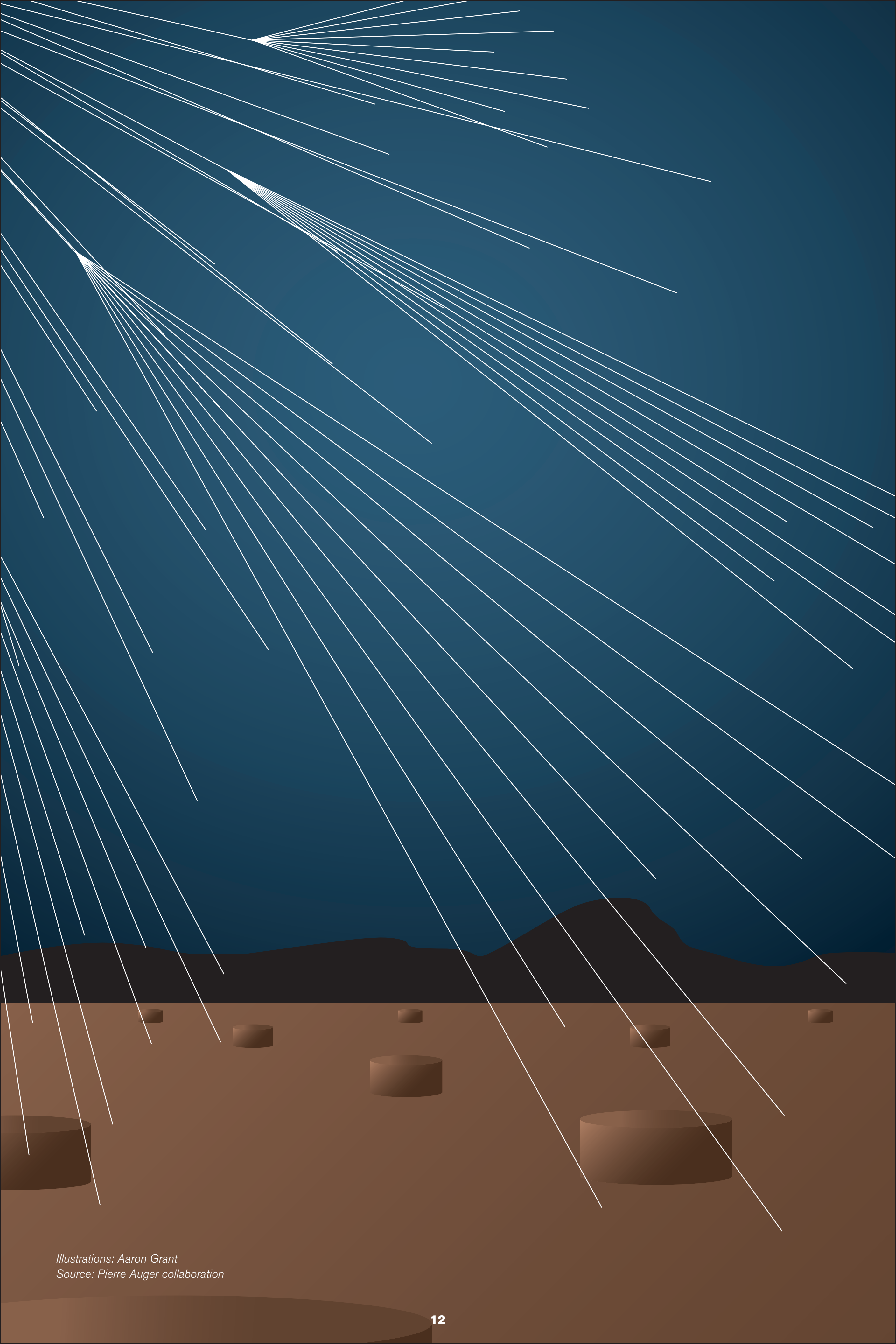
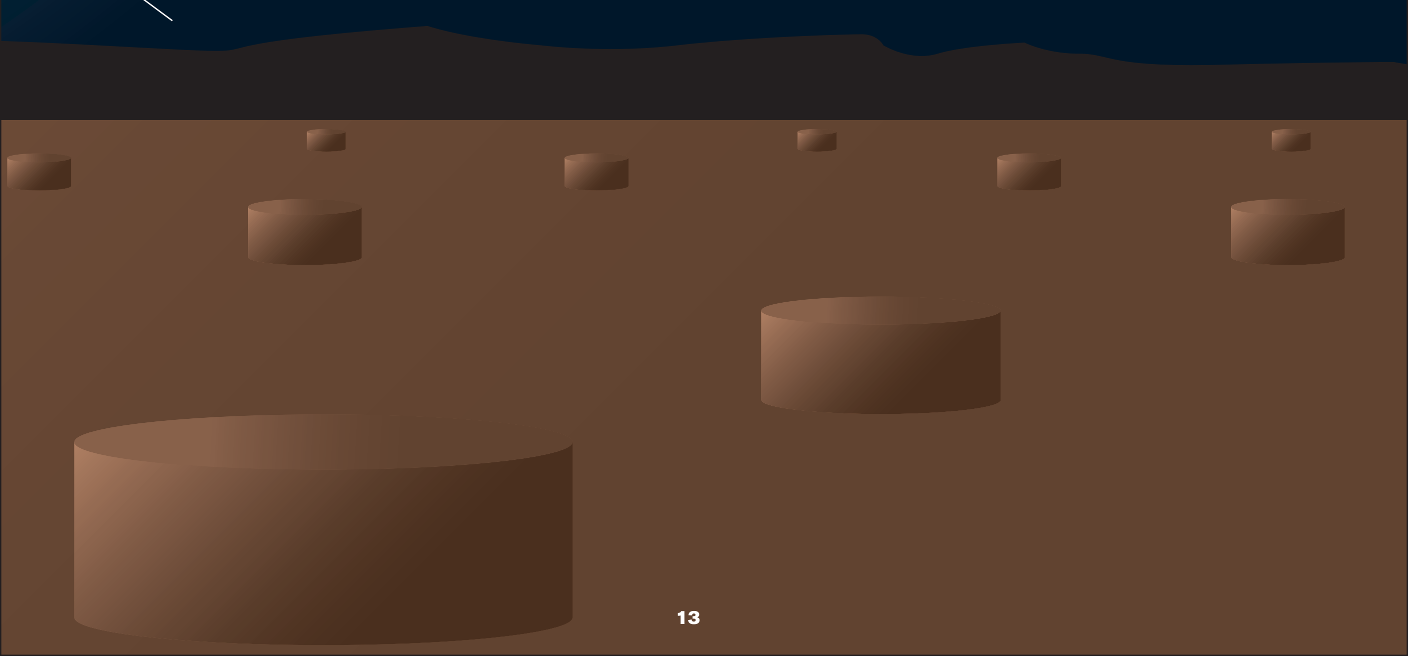


Illustrations: Aaron Grant
Source: Pierre Auger collaboration

Let it Rain

The most energetic particles in the universe have a message for us. The gigantic Pierre Auger Southern Observatory, still under construction in Argentina, is already trying to decipher it. By Davide Castelvecchi

Toward the end of a ten-year experiment in 1991, postdoc Hungye Dai of the University of Utah was puzzling over some really unusual data. The experiment was Fly's Eye, which pioneered a new method of studying ultra-high-energy cosmic rays by monitoring the faint flashes of ultraviolet light produced in the sky when the particles hit the upper atmosphere. Lead scientist Pierre Sokolsky recalls when Dai showed him the anomalous numbers. Sokolsky thought they were a fluke from the detector: "You know, you always expect to see stuff like that, and it's usually just junk," says Sokolsky. "So I told him to go away, and to look at it some more."



Dai and his colleague, Paul Sommers, did just that, spending months re-analyzing the event, expecting it to fade away with other similar data anomalies. But it didn't. It would be more than a year before the team decided to announce their result at a conference.

At $3\text{x}10^{20}$ electron volts (a 3 followed by 20 zeroes), the particle that hit the Utah sky in 1991 was 300 million times more energetic than those made by Fermilab's Tevatron, the world's most powerful particle accelerator. If every proton and neutron in a small virus had as much energy as the one that hit the Utah sky, the virus would pack the punch of a few tons of explosive. To this day, it is still the most energetic particle measured in history, though about a dozen more events above the 10^{20} electron volt mark have been reported by other experiments, notably by the Akeno Giant Air Shower Array (AGASA) experiment in Japan.

Scientists don't know what to make of such data. No ordinary star could generate these energies, and even the most powerful objects in the universe don't look like plausible candidates. "To the extent that we think we understand astrophysical objects, it doesn't seem possible," says Jim Cronin of the University of Chicago.

A new challenge

Cronin, who shared a Nobel Prize with Val Fitch for their 1965 discovery of the asymmetry in the behavior of matter and antimatter, says cosmic rays are the most exciting mystery he's ever tried to solve. Together with Alan Watson of the University of Leeds, Cronin, once a nuclear physicist who had vowed never to get involved in big experiments, began in 1995 to spearhead the Pierre Auger Project, an international effort that now involves 250 scientists from 50 institutions in 15 countries. The project is named for the French cosmic ray pioneer who first characterized the behavior of cosmic rays in the atmosphere.

At its inception, Cronin and Watson envisioned two identical observatories, one in the Northern hemisphere and one in the Southern hemisphere, to cover the entire sky. The Southern Observatory, with its 24 fluorescence telescopes and 1600 detector stations covering an area of 1200 square miles—roughly three times the area of the city of Los Angeles—is now nearing completion in Argentina.

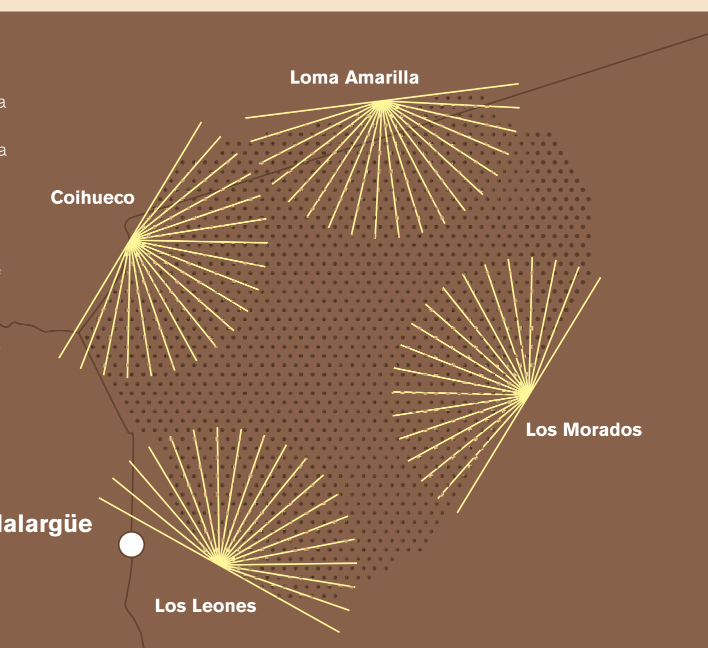
Surface area matters

It takes a wide net to catch the elusive ultra-high-energy cosmic rays. Auger will record enough events, and with enough precision, to draw the first detailed map of the southern ultra-high-energy sky. Seeing "hot spots" could help identify some suspects as the sources of the cosmic rays—perhaps gigantic, dormant black holes in nearby galaxies. Or the map could enable scientists for the first time to "see" dark matter, the invisible stuff that's thought to make up more than 80 percent of any galaxy's mass, including that of our own Milky Way.

As the site for the Southern Observatory, the Auger collaboration chose the Pampa Amarilla, a semiarid plain near the town of Malargüe, about 600 miles west of Buenos Aires. Locals raise cattle and enjoy a dramatic view of the Andes, including the highest peaks in the Americas. "The site is the perfect size, and is flat," which makes Auger's logistics easier, says project manager Paul Mantsch of Fermilab. The region is also fairly free of light pollution, being far from any major urban area.

Built in part with off-the-shelf technology to keep costs down, the 1600 detector stations make a beehive grid, each about a mile

The Southern Site of the Pierre Auger Cosmic Ray Observatory is located in the Pampa Amarilla region of Argentina (left), with detectors spread across Mendoza Province (right). The dots represent the 1,600 detector stations covering 1,200 square miles. The lines indicate the field of vision of each of the four fluorescence telescopes that are located at the edges of the observatory, at Los Leones, Coihueco, Loma Amarilla and Los Morados.



distant from its neighbors. Each station is a four-foot-high, 12-foot-wide plastic tank, filled with 3000 gallons of purified water, which is monitored by three light detectors. The stations are powered by solar cells, and they send back their data using cellphone technology, so no wiring is necessary.

The tanks work day and night, rain or shine. When high-energy cosmic rays—typically protons, but also other particles and heavier atomic nuclei—crash onto the upper atmosphere, the crash produces subatomic debris, which leads to more crashes, and so on. Invisible to the naked eye, a shower of secondary particles quickly spreads and branches its way down like the forks of a lightning bolt. By the time the shower hits the ground microseconds after it began, it consists of billions of electrons, muons, and other charged particles. A major shower could hit as many as 40 of Auger's tanks, covering an area comparable to Manhattan in both size and shape.

Signatures of cosmic rays

At the passage of each charged particle through a tank, the water inside is briefly lit by a bluish streak of light, picked up by the light detectors. The tanks have Global Positioning Systems to precisely synchronize their clocks, and they record the timing of each signal to better than one ten-millionth of a second. Back at a central facility, Auger's software uses the tiny lags between signals coming from different tanks—and some clever trigonometry—to reconstruct the direction of the original particle to one degree, or roughly twice the apparent diameter of the moon.

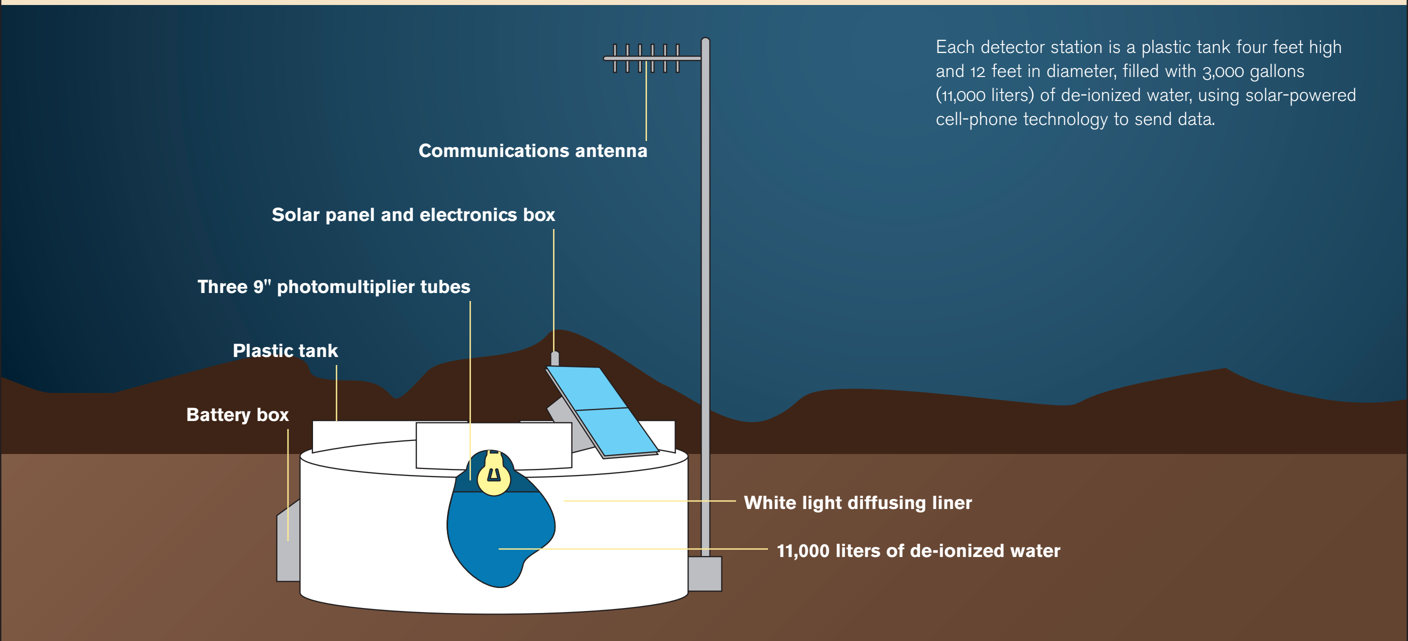
"The detector stations really are the workhorse," says the Argentine collaboration spokesperson Alberto Etchegoyen, of Argentina's National Atomic Energy Commission. The project team expects the tanks to last 20 years, requiring only the replacement, now and then, of a faulty rechargeable battery.

Thanks to the Pampa's dark skies, on clear, moonless nights, scientists can cross-check and calibrate their data using fluorescence telescopes. Set on hills at the edges of the observatory, the instruments are inspired by Fly's Eye and its successors. Cosmic ray showers briefly excite the nitrogen in the air, producing fluorescence in the ultraviolet spectrum. With wide-angle mirrors focusing images on sensitive detectors, the telescopes monitor the sky above the whole observatory, recording events of 10^{18} electron volts and up.

A 10^{20}-plus electron volt particle only lands about once every 40 years on any square mile of the earth's surface. But thanks to its size, Auger should record dozens of such events per year—and also thousands of events of 10^{18} electron volts or more—mapping the cosmic ray sky.

Extreme cartography

At less extreme energies, cosmic ray maps have existed for decades, but they are largely meaningless for identifying the cosmic ray sources. That's because our galaxy has a magnetic field. Most cosmic rays are charged particles, which follow characteristic, corkscrew trajectories in magnetic fields. After circling the galaxy for thousands of years, such particles can fall on earth at pretty much any angle, so their origins cannot be reconstructed. But above 10^{19} electron volts, particles are too energetic to be swayed significantly by galactic magnetic fields and so travel in nearly straight lines, explains Angela Olinto, a theoretical astrophysicist at the University of Chicago and a member of the Auger collaboration. And the higher the energy,



Each detector station is a plastic tank four feet high and 12 feet in diameter, filled with 3,000 gallons (11,000 liters) of de-ionized water, using solar-powered cell-phone technology to send data.

the better. "When you get to 10^{20} electron volts, you should be able to point back directly where they came from," she says.

In 2002, a team claimed that some events from Japan's AGASA experiment—a smaller version of Auger's array of tanks—pointed to four candidate galaxies in a part of the sky near the Big Dipper. But the results were controversial. With only a handful of events at hand, locating sources is a bit like trying to link a rare form of cancer to environmental factors: It's hard to tell if a cluster of a few events is statistically significant, or if it's coincidental.

Auger could reveal the sources for the first time, though it may not solve the question of how sources can produce ultra-high energies in the first place. "If you do a back-of-the-envelope calculation, to see which astrophysical objects we know that can accelerate to these energies, you find zilch," Olinto says. But theorists could at least focus their efforts, she says. "Right now, a lot of people write papers and have fun, but we really don't know what's going on," she says.

Cosmic ray sources

The remnants of supernova explosions, which take place when massive stars collapse under their own gravitational forces, have been considered as possible nurseries of cosmic rays since a seminal 1949 paper by Enrico Fermi. Supernova shockwaves could harbor intense magnetic fields for thousands of years, and particles could bounce around in the magnetic fields like in a pinball—sometimes long enough to gain high energies. But not high enough: Most astrophysicists think it's unlikely that a supernova could produce cosmic rays above 10^{16} electron volts or so. Even less is known about other violent phenomena, such as the recently discovered magnetars, believed to be neutron stars with exceptionally intense magnetic fields.

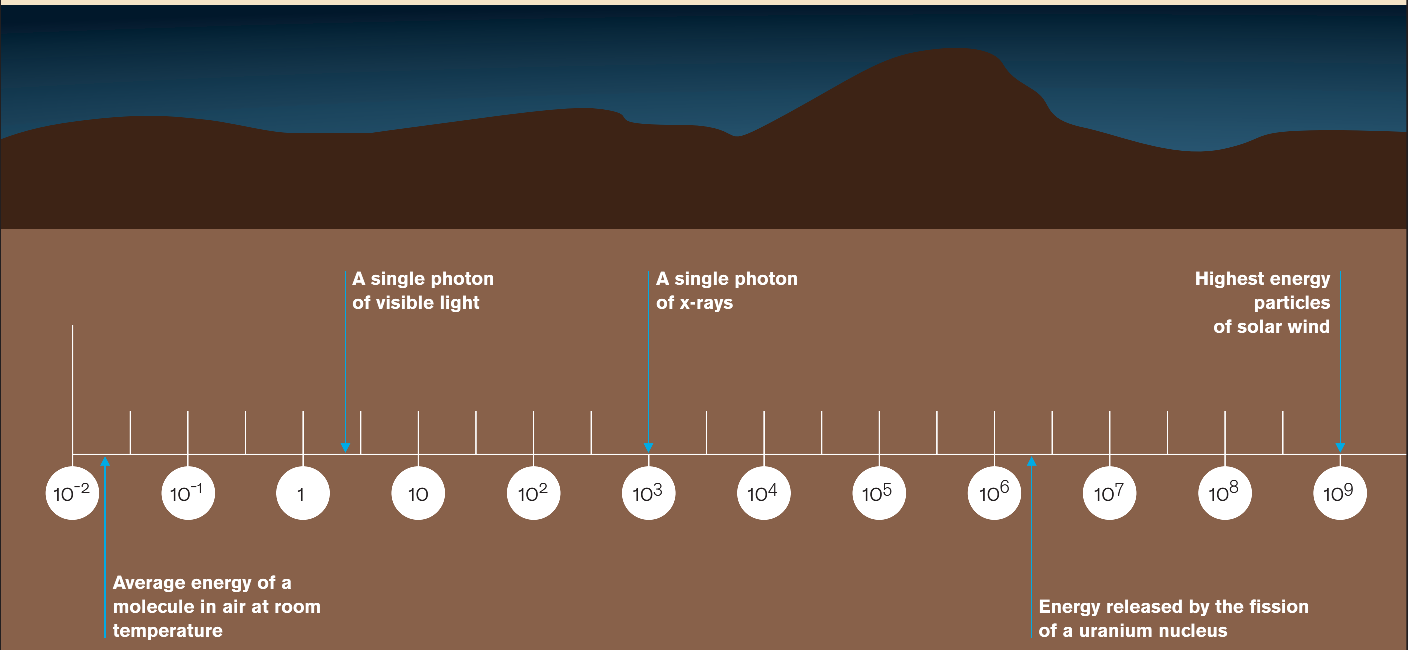
Perhaps the ideal candidates would be quasars, the most energetic objects ever seen in the universe. But quasars are too far away. The early cosmos was populated by these enigmatic monsters, probably supermassive black holes. By looking at billions of light years of distance, telescopes reach billions of years back in time, and still catch the quasars' light. But while their light can travel the universe long after the quasars have petered out, ultra-high-energy cosmic rays cannot travel for too long.

Traversing the universe

In the way of ultra-high-energy cosmic rays is the cosmic microwave background. The CMB is the afterglow of the big bang—a faint noise in the television broadcast frequency range, permeating space, and causing part of the static on your TV screen. To a cosmic ray particle, which flies very close to the speed of light, the CMB radiation looks much more energetic than it does to us, because of the Doppler effect—just as the siren of an ambulance sounds more high-pitched when the ambulance is approaching.

Repeated collisions with CMB photons can slow down anything that's above 5×10^{19} electron volts, an effect called the "GZK cutoff," since it was pointed out by Kenneth Greisen, Georgi Zatsepin, and Vadem Kuzmin in the mid-1960s, soon after the discovery of the CMB. The slow-down can take millions of years. Exactly how long may vary, but scientists believe that virtually no particle can spend more than 150 million years before its energy is pushed down below the cutoff.

Thus, sources of ultra-high-energy cosmic rays must lie within a distance of 150 million



light years. In a visible universe with a radius of about 14 billion light years, that's not a great distance, and it certainly does not take in any live quasars—though there could be some dominant ones. Auger's map should show few, but fairly definite sources: Any culprits must be hiding within the handful of galaxies in the Local Group, our Milky Way's neighborhood.

But what if, instead, the map shows a shapeless spread of dots, the way it happens at lower energies? If the spread looks truly uniform, then something could be severely wrong in our current understanding of fundamental physics, scientists say. Some of the proposed explanations border on the exotic: Perhaps even Einstein's special theory of relativity, which prescribes the rules for the GZK cutoff, could need some mending, according to studies by Sidney Coleman and Sheldon Glashow of Harvard University and others.

A WIMPy way out

A less shocking, but still historic discovery could happen if the signals neither spread evenly, nor concentrate in hot spots, but instead distribute like a halo around the Milky Way. Cosmic rays could then be debris from the decay of dark matter, and Auger would solve two mysteries at once.

Astrophysicists and particle physicists have long sought hints of the identity of dark matter, trying to detect so-called weakly interacting massive particles (WIMPs). WIMPs should be flying all around us, but they seem to manifest themselves only by gravitational attraction, forming an invisible halo that holds galaxies together.

But only extremely massive WIMPs—at least a billion billion times as heavy as a proton, or about the mass of a virus—could produce ultra-high energy cosmic rays, says Edward "Rocky" Kolb, head of Fermilab's new Particle Astrophysics Center.

In 1999, Kolb and his collaborators demonstrated, at least mathematically, that such particles could exist, and dubbed them Wimpzillas. "Usually, dark matter candidates are wimpy WIMPs. Wimpzillas are orders of magnitude more massive than other dark matter candidates," massive enough to explain cosmic rays, Kolb says.

The coming data explosion

Whatever Auger discovers, it will dramatically change cosmic ray science, and perhaps more. Although it's still incomplete, Auger is already the largest observatory in the world, and the first major cosmic ray experiment south of the equator. It has accumulated as much data as any previous ultra-high-energy cosmic ray experiment, and faster than expected. "We're getting far more out of our detector than we ever imagined," says Fermilab's Mantsch. The collaboration also pursues its proposal to build a twin in North America, where most galaxies in the Local Group would be visible.

Auger expects to release its first results in August, at the *International Cosmic Ray Conference* in Pune, India. Meanwhile, the data is being analyzed and checked, and until the official announcement, the collaboration members will not comment on the results. Cronin will limit himself to saying that things are going very well. "But I am not telling you what the answers are," he says.