The most exciting phrase to hear in science, the one that heralds new discoveries, is not “Eureka!” but “That’s funny . . .”

—Isaac Asimov
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NEUTRINO HUNTERS
There he stood, wearing a red parka, Norwegian Prime Minister Jens Stoltenberg, on blindingly white snow against a clear blue sky, 9,000 feet above sea level, with the temperature hovering at minus 20 degrees Fahrenheit. “We are here today to celebrate one of the most outstanding achievements of mankind,” he bellowed out, as the sounds of flags flapping in the wind and snow crushing under a walker’s boots threatened to muffle his voice. His brief remarks over, with a couple of hundred workers, guests, and tourists watching, Stoltenberg unveiled a bust carved in ice, placed atop a waist-high column: “That’s the man!”

The ice sculpture bore the likeness of Stoltenberg’s legendary countryman Roald Amundsen. The low-key ceremony at the bottom of the world marked the centenary of Amundsen and four mates arriving at the South Pole on December 14, 1911, delivering historic glory to the young nation of Norway, which had become independent from Sweden a mere six years earlier. Fueled by relentless determination and aided by dogsleds, Amundsen’s team famously beat the ill-fated expedition led by the British naval officer Robert Falcon Scott by nearly five weeks, scoring what was undoubtedly a remarkable feat of terrestrial exploration.
Today the frozen wasteland where the fierce competition between Amundsen and Scott played out, with the pride of nations and the lives of heroes at stake, is a hotbed of activity for a different breed of explorers with more ethereal goals. Intrepid bands of scientists racing to unravel mysteries of life, our planet, and the universe are the ones laying claim to Antarctica now. In fact, the continent crawls with well over a thousand scientists and support personnel during the summer months. Geologists dig up ice cores and track the movements of glaciers for clues about climate change. Atmospheric scientists fly helium-filled balloons to measure stratospheric ozone, to complement the observations of satellites staring down from space. Paleontologists forage for fossils of creatures that were wiped out by the deadliest of known extinctions 250 million years ago. Biologists scour the dry valleys of Antarctica in search of organisms that thrive in extreme habitats. In early 2012, after many years of drilling, Russian researchers pierced through two miles of ice to reach Lake Vostok, a pristine subglacial reservoir shielded from sunlight and the wind for some 20 million years; they had hopes of encountering hitherto unknown life-forms.

Two years earlier, I got to experience what it was like to live and work on the ice when I went to Antarctica as a member of a meteorite-collecting expedition. We reached McMurdo Station, the American research center on the coast located near Scott’s 1902 landing site, by military transport plane from New Zealand. After a week of preparations, packing, and training, we then flew to a seasonal base camp, where, two by two, we boarded a Twin Otter plane on skis for the final leg of our journey. The small aircraft, operated by Canadian bush pilots, dropped us off on a remote ice field just five degrees from the Pole. That’s where eight of us—two women and six men—camped out in yellow, pyramid-shaped “Scott tents” for the next
five bone-chilling weeks, cut off from the rest of the world except for a satellite telephone and the occasional drop-off of mail and supplies. This being the Antarctic summer, the Sun was always up, tracing a counterclockwise circle in the sky every twenty-four hours. There was no sign of life—human, animal, or plant—to be seen anywhere.

Day after day, if the winds were bearable, we went out on snowmobiles or on foot to search the nearby vast ice field and the moraines next to the hills for rocks that had fallen from space. Wrapped in big red parkas as well as thermal layers, bunny boots, neck warmers, gloves, goggles, balaclavas, and hats, we took care to avoid frostbite and crevasses during our excursions. It was easy to slip and fall on the rock-hard ice and hurt yourself badly. I slid off the Ski-Doo once, but thankfully the thick parka cushioned my fall. Others on the team also had minor mishaps, but we survived the cold, the tedium, and the isolation without any serious problems. In fact, we enjoyed the stark beauty of the landscape—the views from the tops of rocky peaks were especially magnificent—and found ways to entertain ourselves. By the expedition’s end, our team had collected a total of 900 meteorites, which are now available to researchers from around the world for a variety of studies. Our own reward was the remarkable experience itself—and the delightful Adélie and emperor penguins we encountered near McMurdo at the end of the season. My one regret is that I didn’t get to visit the South Pole, despite being so close to it.

The focus of activity at the Pole itself is decidedly extraterrestrial. These scientists seem to have taken to heart Marcel Proust’s adage that “the only true voyage of discovery . . . would not be to travel to new lands, but to possess other eyes.” The most striking part of their apparatus near the Pole is a 10-meter (33-foot) radio dish turned skyward, to map the feeble afterglow
of the big bang. One of my Toronto colleagues, Keith Vanderlinde, spent most of the year 2008 taking care of this telescope; he survived the polar “night” that lasted for six months, temperatures that dipped to minus 100 degrees Fahrenheit, and the overwhelming sense of isolation, not to mention the short showers and the severe boredom. But the most ambitious, and unconventional, of the scientific instruments near the South Pole is buried permanently deep under the ice, and it looks down, not up. Its construction—or burial, to be more accurate—was completed just a year before the Amundsen centennial celebration. All that the visiting dignitaries could see aboveground was a rectangular office trailer on stilts, filled with cables and computers. There was little sign of what lay beneath but for the small flags that scientists had planted helpfully on the ice to mark its mammoth footprint.

IceCube is an observatory like no other. The glacial ice itself, transparent and cleared of air bubbles by extreme pressure at depths greater than a mile, serves the same purpose as the smooth primary mirror of a conventional astronomical telescope. Buried in it are 86 long steel cables standing vertically, with 60 basketball-size globes hanging on each at regular intervals. Every one of the 5,160 globes contains optical sensors and electronics. The sensors, called phototubes, act like lightbulbs in reverse: they collect light and generate electric signals. In the case of IceCube, these sensors scrutinize the subterranean ice for faint blue flashes that occasionally shimmer in the dark stillness. Whenever a sensor detects a flash, it sends a signal to computers on the surface.

The blue flickers mark the passage of elementary particles known as muons, which belong to the same family as electrons but are about two hundred times more massive. By combining
signals from the different nodes of this deeply buried sensor network, physicists can trace a muon’s path in 3-D. But the researchers are not after the muons themselves. They are hunting for neutrinos, by far the most elusive and the weirdest of all known denizens of the subatomic world. These ghostly particles interact every once in a while with protons within ice molecules to release muons, thus betraying their presence as the muons in turn light up the ice. Since a newly created muon travels through ice along the same path as the incoming neutrino did, researchers can tell which direction the neutrino came from by examining the muon’s trail.

Neutrinos are elementary particles, just like electrons that buzz about atomic nuclei or quarks that combine to make protons and neutrons. They are fundamental building blocks of matter, but they don’t remain trapped inside atoms. Also unlike their subatomic cousins, neutrinos carry no electric charge, have a tiny mass, and hardly ever interact with other particles. A typical neutrino can travel through a light-year’s worth of lead without interacting with any atoms. Therein lies the snag: neutrinos are pathologically shy. Their severe reluctance to mingle makes these particles hard to pin down, so neutrino hunting is a tricky business. But every so often, a neutrino does collide with something, such as a proton inside a water molecule, essentially by accident. It is to raise the odds of accidental collisions, and thus to increase our chances of observing neutrinos, that scientists build extremely large detectors like IceCube.

You still can’t see neutrinos directly, but you can get a whiff of their presence from the clues they leave behind. On the rare occasions that neutrinos do interact with matter, they produce charged particles such as muons that physicists can detect with their instruments. But distinguishing neutrino signals from
unrelated “noise” poses a challenge: cosmic rays, fast-moving particles that arrive from deep space, also produce muons, which might be confused with muons produced by neutrino interactions. Neutrino hunters place their equipment deep underground, or under a thick layer of ice, so that cosmic ray muons cannot get through. As Janet Conrad of the Massachusetts Institute of Technology explains, “If you’re trying to listen to a whisper, you don’t want a lot of noise around.”

Neutrinos are hard to catch, but they are also among the “most wanted” of all cosmic messengers for the secrets they hold about the nature of matter, the pyrotechnics of exploding stars, and the structure of the universe itself. Besides, in the words of theorist Boris Kayser of the Fermi National Accelerator Laboratory (Fermilab) near Chicago, which is home to sev-
eral neutrino experiments, “If neutrinos didn’t exist, we wouldn’t be here.” He explains that “the Sun produces energy through nuclear reactions on which life on Earth depends, and those reactions could not occur without neutrinos.” Moreover, the nuclear burning in previous generations of stars, which produced the heavy elements necessary for life, would not have been possible without neutrinos, either. Therefore, he argues that “to make sense of the universe we need to understand neutrinos well.”

Thankfully, neutrinos are as ubiquitous as they are cagey. In fact, neutrinos are the most abundant matter particles in the universe. According to Hitoshi Murayama of the University of Tokyo and the University of California, Berkeley, there are a billion neutrinos for every atom in the universe. He contends that “their sheer number means they have an important role. The contribution of neutrinos to the cosmic energy budget is comparable to that of all the stars.” In fact, about a hundred trillion neutrinos produced in the nuclear furnace at the Sun’s core pass through your body every second of the day and night, yet they do no harm and leave no trace. During your entire lifetime, perhaps one single neutrino would interact with an atom in your body. Neutrinos travel right through the Earth unhindered, like bullets cutting through fog. Besides, the Earth’s bowels generate neutrinos, as radioactive elements decay, and so do collisions of energetic particles from space in the upper levels of the atmosphere. Cataclysmic deaths of massive stars set off tremendous bursts of neutrinos, which escape these sites of mayhem unscathed and bring us news of awesome celestial events millions of light-years away. Moreover, our planet is immersed in a sea of cosmic neutrinos, which sprang forth when the infant universe was barely two seconds old.
The bizarre traits of neutrinos have turned them into pop culture icons of sorts. As far back as 1960, John Updike celebrated them in a delightful poem published in *The New Yorker*. Titled “Cosmic Gall,” it described how neutrinos traverse the Earth as easily as dust bunnies travel down a drafty hall or light passes through a sheet of glass. Klaatu, a Canadian progressive rock band perhaps best remembered for false rumors that they were the Beatles recording under a pseudonym, described the same phantom behavior, of neutrinos passing right through our bodies without alerting us, in the lyrics of a 1976 song. Neutrinos have even starred as hipster characters in the animated television series *Teenage Mutant Ninja Turtles*.

Not surprisingly, references to neutrinos have also popped up on the popular sitcom *The Big Bang Theory*, in which two of the main characters are physicists. The show’s science consultant, David Saltzberg of the University of California, Los Angeles, is himself a physicist who works on neutrino telescopes, among other topics. In one scene, the co-lead Sheldon Cooper is fiddling with equations on a whiteboard in his office when his fellow physicist and roommate Leonard Hofstadter enters along with their engineer friend Howard Wolowitz. Sheldon exclaims, “Oh, there’s my missing neutrino. You were hiding from me as an unbalanced charge, weren’t you, you little subatomic Dickens?” Instead of acknowledging his friend’s greeting, he continues, “Here, look, look, I found my missing neutrino.” Howard responds drily, “Oh, good, we can take it off the milk cartons.”

Neutrinos have made numerous appearances in science fiction, of course, typically as the culprits behind strange or catastrophic events. In Robert J. Sawyer’s novel *Flashforward*, a burst of neutrinos from a dying star is responsible for making everyone lose consciousness briefly and see themselves as they would be some twenty-one years in the future. In Greg Bear’s
*Foundation and Chaos*, a freak neutrino storm wipes out the rules that robots are programmed to follow (à la Isaac Asimov’s original Foundation series), resulting in complete mayhem. More recently, neutrinos were blamed for heating the Earth’s core, triggering ferocious earthquakes and floods, in the Hollywood disaster flick *2012* directed by Roland Emmerich.

Despite neutrinos’ quirky appeal as cultural icons, few people outside the physics community paid much attention to the science of real-life neutrinos until they made headlines recently for possibly breaking the cosmic speed limit set by Albert Einstein back in 1905. A large international collaboration of physicists known as OPERA (acronym for the unwieldy title Oscillation Project with Emulsion-tRacking Apparatus) made the startling announcement in a research paper posted online and at a press conference in late September of 2011. The particles appeared to travel faster than light between CERN, the European Organization for Nuclear Research and its Laboratory for Particle Physics in Geneva, Switzerland, and an underground detector 454 miles away in Gran Sasso, Italy, arriving 60 nanoseconds sooner than expected.

Despite the OPERA spokesman’s cautionary words, and skepticism from the vast majority of neutrino researchers, the news reverberated around the globe. Perhaps the commotion was not surprising given the astounding implications. If true, the finding would violate Einstein’s theory of special relativity, a cornerstone of modern physics. As *Time* magazine put it, “If the Europeans are right, Einstein was not just wrong but almost clueless.” Most physicists and journalists emphasized that the extraordinary claim required further investigation and independent verification. “If true, it is a result that would change the world. But that ‘if’ is enormous,” said The New York Times.

But all that hedging failed to rein in rampant speculations
about superluminal voyages and grandiose visions of new physics. Suddenly jokes about neutrino time travel were everywhere. Some quipped that neutrinos had obeyed the law in Switzerland but broken the speed limit once they crossed over to Italy. On the sitcom *The Big Bang Theory*, Sheldon Cooper tried to foster dinnertime conversation by asking, “Faster-than-light particles at CERN: paradigm-shifting discovery or another Swiss export as full of holes as their cheese?” The Irish folk band Corrigan Brothers, which had performed at President Barack Obama’s 2009 inauguration, posted a song they performed with Pete Creighton on YouTube, questioning whether $E=mc^2$ still held true now that neutrinos appeared to travel faster than light. Toward the end, however, the song lyrics cautioned against rushing to conclusions and suggested that Einstein might still be right about the cosmic speed limit.

As a way of accommodating the new result without breaking the light barrier, some theorists proposed that the Swiss neutrinos might have tunneled through a hidden extra dimension, *Star Trek*-style, on their way to Italy, reducing the distance they needed to travel. Others suggested a different shortcut due to a crumpling of space-time near the Earth. Many critics pointed to possible experimental errors. Andrew Cohen and Sheldon Glashow of Boston University raised a serious theoretical gripe: a beam of superluminal neutrinos would rapidly lose energy by emitting other particles, so the beam should be depleted of high-energy neutrinos by the time it reached Gran Sasso, something that was not observed. Meanwhile, a second, more precise speed test done by the same OPERA collaboration, announced in mid-November, bolstered the surprising result.

Three months later CERN released a brief but crucial update. It read, in part: “The OPERA collaboration has informed
its funding agencies and host laboratories that it has identified two possible effects that could have an influence on its neutrino timing measurement . . . If confirmed, one would increase the size of the measured effect, the other would diminish it.” The first effect, a possible problem with time stamps of GPS units used to synchronize the clocks at the two sites, would actually make the neutrino speed even faster than previously reported. The other effect, a bad cable connection between a GPS unit and a computer, would mean that the neutrinos had in fact traveled slower than light. Most media reports and commentators focused on the latter possibility. The Wall Street Journal described it as “a potentially embarrassing outcome” for the researchers involved. Then, on March 16, 2012, a different team of physicists, whose ICARUS detector is also located at Gran Sasso, reported a new measurement of flight time for neutrinos from CERN: their speed did not exceed that of light. “The evidence is beginning to point towards the OPERA result being an artifact of the measurement,” said CERN’s research director, Sergio Bertolucci.

Even though neutrinos turned out not to be superluminal in the end, they have taught us a great deal already about the shenanigans of the subatomic realm and allowed us to peer deep into the Sun’s scorching heart. Besides, without neutrinos, nuclear power generators and nuclear bombs would not be possible. Neutrinos were the first harbingers of the dramatic demise of a massive, bloated star that exploded 160,000 light-years away in the Large Magellanic Cloud, a satellite galaxy of the Milky Way that appears as a fuzzy patch in the southern sky. Three underground detectors in Japan, Russia, and the United States recorded a total of two dozen neutrinos from the explosion, out of the billions upon billions that swept through the
Earth, in a short burst on February 23, 1987. It was only a few hours later that astronomers scanning the skies from a far-flung mountaintop observatory in Chile saw the supernova in visible light.

Over the years, neutrinos have drawn the attention of some of the most brilliant minds and colorful personalities in the history of physics. The cast of historical characters associated with neutrinos included the sharp-witted Wolfgang Pauli, who invoked these particles in the first place to dodge a crisis in physics; the troubled genius Ettore Majorana, who theorized about neutrinos’ mirror twins before disappearing without a trace at the age of thirty-two; and the committed socialist Bruno Pontecorvo, who realized that neutrinos might morph between different types and caused a Cold War ruckus by defecting to the Soviet Union. Some neutrino hunters built experiments deep underground to peer into the heart of the Sun, while others set up traps next to powerful nuclear reactors to catch neutrinos changing form. During the past two decades, many more scientists have caught the neutrino bug and joined the quest.

That’s because, for neutrino hunters, the best is yet to come. These shadowy particles promise to unlock some of the greatest secrets of the universe. They could tell us about the birth sites of enigmatic cosmic rays that bombard the Earth around the clock. For astronomers, who have had to rely almost exclusively on electromagnetic radiation in the form of visible light, radio waves, and X-rays from distant celestial bodies, neutrinos offer an exciting new window on the most violent phenomena in nature. In fact, neutrinos may have a lot to do with triggering spectacular stellar explosions in the first place. Some scientists have proposed that a sterile variety of neutrinos could account for so-called dark matter, which makes up nearly a quarter of
the universe but remains undetected except through its gravitational tug on galaxies. The imprints left by primordial neutrinos on the faint afterglow of the big bang, which is still measurable with microwave telescopes, could reveal the conditions very soon after the universe was born.

What’s more, we may have neutrinos to thank for the simple fact that the universe is not empty of matter, and thus for our very existence. Just after the big bang, there was lots of energy to give rise to particle and antiparticle pairs. The cosmic density was so high back then that these pairs should have come together and annihilated each other quickly, leaving only a sea of radiation. To avoid the catastrophe, there must have been a tiny preponderance of normal matter over antimatter. Physicists struggle to understand how such an asymmetry came about. One popular explanation is that super-heavy cousins of neutrinos in the early universe decayed in such a way as to make one extra particle of matter for every billion particle-antiparticle pairs. Measuring subtle properties of today’s light neutrinos could tell us whether such a scenario was indeed responsible for tipping the balance ever so slightly in favor of matter. As Boris Kayser points out, “Again, if not for neutrinos, we may not be here.”

Most exciting, if not unsettling, is the prospect of physics beyond the so-called standard model. Formulated in the early 1970s, the standard model incorporates two dozen elementary particles of matter and their antimatter twins, three types of interactions among them, and the symmetries that govern those interactions. It is the best description of the subatomic world that we have, and countless experiments over three decades have verified its predictions with exquisite precision. The fabled Large Hadron Collider at CERN, the most powerful and expensive
atom smasher ever, was constructed at a jaw-dropping price tag of roughly $9 billion in large part to nail down the final missing piece of the theory. The LHC confirmed the existence of the Higgs boson, a particle hypothesized to be responsible for endowing other elementary particles with mass. The standard model, however, presumed that neutrinos have no mass, come in three flavors, and cannot change form. So the discovery that neutrinos do have a very small but nonzero mass, and a chameleonlike tendency to morph among the three types, has exposed a crack in the model’s elegant edifice. If it turns out that there are more than three neutrino flavors, as some data hint, such a revelation could shatter the very foundations of physics. As physicist Kate Scholberg of Duke University puts it, “We’re right on the verge of exploring a new regime in physics. Several unknowns out there are teasing us.” She points out that “neutrinos provide us with a whole new sector of phenomena that we can measure to investigate the nature of the universe.”

The starring role of neutrinos in a great many sagas unfolding across physics, cosmology, and astronomy explains why scientists make considerable efforts to trap these minuscule particles. Over the past two decades, they have built ever more sophisticated neutrino experiments dotting the globe. From a deep nickel mine in Ontario to a freeway tunnel crossing a mountain in central Italy, and from a nuclear waste site in New Mexico to a bay on the South China Sea, neutrino hunters are chasing their quarry.

The most impressive of their traps remains IceCube, the world’s biggest neutrino telescope, built at a cost of over $270 million. Its completion is a long-held dream come true for its visionary director, Francis Halzen. Growing up in Belgium,
Halzen hoped to become a schoolteacher, but at university he got interested in physics, and he never looked back. After working at CERN for a few years, he moved to the University of Wisconsin–Madison, where he has been a professor for four decades. As a theoretical physicist, he worked on some aspects of quantum mechanics before he turned his attention to neutrino hunting in the mid-1980s. Halzen first heard about attempts to detect neutrinos in Antarctica from colleagues at the University of Kansas, while he was visiting there to deliver a lecture. They told him that Russian scientists had been using radio antennas at their Antarctic research station to search for electric sparks resulting from cosmic neutrinos colliding with the ice. Halzen found the experiment intriguing, and together with two colleagues, he set out to calculate how strong such signals would be. They were disappointed to find that radio emissions produced by most neutrino interactions would be far too weak to register. They concluded that the Russian experiment was doomed to fail. Instead, they realized, it would make more sense to look for bursts of blue light in the ice, which would also indicate the arrival of neutrinos. Halzen was convinced that sinking an array of light sensors deep into the Antarctic ice was a great way to catch neutrinos coming from the far reaches of space.

Excited about the prospect of developing a novel neutrino telescope in Antarctica, Halzen e-mailed several other physicists to ask what they thought about his idea. John Learned at the University of Hawaii was among them. Born to an old New England family whose ancestors included a general who fought in the American Revolutionary War, Learned grew up on Staten Island and spent his childhood summers with his grandparents in upstate New York. He enjoyed acting like an outsider in both
places: “In the country I was a city kid and in the city I was a
country kid,” he says. In middle school, he worked on the school
newspaper and ran a weather station on the school roof. He also
remembers volunteering to take a traveling science exhibit around
the school “because it was a great excuse to get out of the class-
room.” Later, at Brooklyn Technical High School, he took many
shop classes, which have served him well as an experimental
physicist. As a graduate student at the University of Washington,
Learned investigated the prospects for measuring cosmic ray
particles underwater. He built a barge, anchored it in the mid-
dle of Lake Chelan, and lowered particle detectors into the
clear, deep water. After completing his doctorate, he took a job
at a research station at Echo Lake in the Rocky Mountains of
Colorado, where he lived in a log cabin with his wife and two
small children. It was during that period that Learned got seri-
ously interested in neutrinos, and he later moved to Hawaii
in the hope of deploying a giant array of underwater neutrino
detectors in deep waters of the Pacific Ocean surrounding the
volcanic islands. Given Learned’s interests and expertise, it was
no surprise that Halzen reached out to him for his opinion
about burying neutrino detectors in Antarctica.

The two physicists discussed the attractions of Halzen’s
scheme. “Learned immediately appreciated the advantages of
an Antarctic neutrino telescope,” according to Halzen. For
starters, polar ice is clear, dark, stable, and sterile, and free of
background light from bioluminescent organisms and emissions
from radioactive decay of sea salt, which could confuse detec-
tion of the neutrino signals. Equally important was the fact that
the National Science Foundation (NSF) was already operating
a research base at the South Pole, and therefore was in a posi-
tion to provide vital logistical support. Encouraged by Learned’s
enthusiasm and input on detector design, Halzen presented their concept at a conference in Poland, and wrote it up in a paper in 1987, but left it at that, perhaps because as a theorist he didn’t have experience building experiments and hesitated to take on such an ambitious task himself.

Halzen recalls a phone call he received from an irate official at the NSF about a year later. The official complained that two young physicists from the University of California, Berkeley, had tried to sneak a string of phototubes into Antarctica to place inside a drill hole, without proper authorization. He asked whether Halzen was responsible for putting “this crazy idea” into their heads. Halzen assured the official that he had never heard of the two Berkeley physicists, who had apparently gotten the notion from attending a conference where Halzen and Learned had discussed their scheme.

Later, Halzen teamed up with the Berkeley group to pursue the idea in earnest. First they tested its feasibility by sinking a 200-meter-long (656-foot) strand with three phototubes into a hole drilled by glaciologists in Greenland. Then they began work on a pilot experiment called AMANDA (for Antarctic Muon and Neutrino Detector Array), with funding and support from the NSF, in the austral summer of 1992. They borrowed a technology that glaciologists had developed to bore holes in the ice: a drill that shot out hot water, as if from a high-pressure showerhead, which melted its way down. The cavity did not refreeze for several days, giving them enough time to deploy the sensors attached to a cable.

As the team lowered the first string of phototubes into the ice on Christmas Eve of 1993, Halzen was at his family’s house in Belgium. Being a theorist, he wasn’t needed at the work site. He had a lot at stake, though, and glanced often at a computer
on his lap during the meal, hoping for e-mail updates from the South Pole. As he wrote later, “To have your career on the line half a world away is hard enough. But to know that you have embroiled so many others in the same improbable adventure, that your funders and colleagues expect results, and that you are totally powerless to affect the outcome, is a form of exquisite torture.” Just as dessert was being served, Halzen was relieved to receive a message confirming that the deployment was a success.

The team’s delight didn’t last long, because they encountered unexpected challenges. One problem was that the phototubes registered lots of blue flashes from muons created by cosmic rays. The researchers had expected the cosmic ray muons to peter out by the time they reached half a mile beneath the ice, making it easy to identify the few muons generated by neutrinos arriving from below, from the other side of the Earth. That wasn’t the case: what they saw was “a nearly meaningless blur,” as Halzen put it. But their biggest problem had to do with air bubbles in the ice, which scattered the blue flashes generated by neutrino events, making them harder to pinpoint. They found lots of bubbles at this depth, and the bubbles were fifty times bigger than they had anticipated. So the project was delayed while the team figured out what improvements to make. The solution, they found, was to dig deeper holes and sink the sensors down to a mile below the surface. At these greater depths, the researchers would have a clearer view of the blue flashes associated with neutrino arrivals, because higher pressures would squeeze out the bubbles in the ice.

The AMANDA experiment, from the first drilling to the final shutdown, lasted for a decade. (Meanwhile, Learned and his collaborators had abandoned their project off the coast of
Hawaii after many years of effort, because of technical problems.) Over that time, Halzen and his colleagues learned a lot about Antarctic ice as well as neutrino detection. Drawing on their experience, the team started construction of IceCube, designed to be a hundred times bigger than its predecessor, in 2005.

IceCube is truly a marvel of extreme engineering. Just as with AMANDA, not only its components, drilling equipment, and personnel, but also food and fuel, had to be transported to Antarctica from various parts of the world. Ski-equipped C-130 Hercules cargo planes, operated by U.S. Air Force crews, hauled them for the last leg of the journey, from McMurdo Station on the Antarctic coast to the South Pole, a distance of 800 air miles. Engineers used a custom-built high-pressure drill, with hot water shooting out of a nozzle at its end, to puncture the ice sheet to a depth of a mile and a half. It took two days of nonstop drilling, and 4,800 gallons of gasoline, to bore one hole, melting 200,000 gallons of ice in the process. Once the shaft was clear, they gently lowered the steel cable with the sensors. Hole by hole, IceCube was “built” over six austral summers, taking advantage of continuous sunlight and relatively balmy working conditions from November to February.

For Halzen, the project’s completion in December 2010 was “a great relief.” “Now that IceCube is built, people forget how incredibly risky and challenging this undertaking was. I’ve made a list of all the points when I thought the project had failed,” he added. There was little room for error, with the biting cold, high altitude (of over 9,000 feet above sea level), and dreadful isolation exacerbating the risks. Once during construction a worker mistakenly grabbed a hose hanging from a drill tower, and was thrown on his back on the rock-hard ice when the hose pulled up. The victim had to be flown to New Zealand
for treatment, and it took a few weeks for him to recover completely.

Yet the gamble that Halzen and his colleagues took in building IceCube has begun to pay off already. In the first couple of years of its operation, the observatory has recorded two unusual neutrino signals, with energies far greater than any seen before. At a conference in Kyoto in the summer of 2012, team member Aya Ishihara of Chiba University in Japan showed these “PeV events,” so dubbed because their energies are in the “peta-electron volt” (or quadrillion electron volt) range, corresponding to about a million times the mass-energy of a proton. The extreme energies surprised many astrophysicists. As Spencer Klein of the Lawrence Berkeley National Laboratory in California points out, “These neutrinos have energies more than
a thousand times higher than any neutrinos that we have pro-
duced in particle accelerators.”

At first, the researchers wondered whether collisions between
highly energetic cosmic rays and oxygen or nitrogen atoms in
the Earth’s atmosphere were responsible for producing these
PeV neutrinos. After further monitoring and analysis, they’re
now convinced that’s probably not the case. As Halzen puts it,
“It is unlikely that they are atmospheric, and that is the exciting
part.” In other words, we may have to look to distant celestial
sources to uncover the violent origins of these neutrinos. In fact,
researchers think the particles may come from powerful jets shot
out by monstrous black holes at the hearts of galaxies, or from
incredible explosions known as gamma ray bursts (GRBs), which
appear to be even more potent than supernovae.
Over the past two decades, astronomers have confirmed that many galaxies, including our own Milky Way, harbor gigantic black holes at their centers, and have observed high-speed jets coming off their poles. They think these jets form because black holes drag matter in from their surroundings and launch some of that material back into space with the help of magnetic fields. The particles in the jets, accelerated to speeds close to that of light, could produce energetic neutrinos, such as those that IceCube has detected. Researchers have speculated that GRBs, which might herald the death of very massive stars, could be another source of high-energy neutrinos. Discovered by chance in the late 1960s by satellites designed to look for gamma rays from secret nuclear tests in space, GRBs have confounded scientists for decades. Recent findings suggest that most GRBs consist of narrow beams of fast-moving particles ejected during the collapse of hefty stars into black holes or neutron stars. In either case, IceCube may have captured messengers coming straight from the scene of the action, so it could help us better understand some of the most ferocious phenomena in the universe.

IceCube is just the most exotic of a new generation of neutrino facilities with unprecedented sensitivity. Some, like IceCube itself and an even bigger network to be deployed on the Mediterranean seafloor, are, as we’ve seen, designed to catch neutrinos coming from outer space or produced when cosmic rays hit the Earth’s atmosphere. Others, such as the cathedral-scale detector under Mount Kamioka in Japan and another, weighing nearly as much as 5,000 automobiles, tucked away in a Minnesota mine, measure neutrino beams generated by giant particle accelerators hundreds of miles away. Experiments of yet another type, located at the village of Chooz in France and at
Daya Bay in China, harness neutrinos produced in commercial nuclear power plants.

Together, these facilities make up the formidable arsenal of today’s neutrino hunters. Their advent signals that neutrino chasing, once an esoteric sideline, is now ready for prime time. In the coming chapters, we will follow that thrilling chase, along with its bewildering twists, just as we enter a brave new era that promises to unravel cardinal mysteries of the universe, from its puniest scale to its grandest, and quite possibly upend our most cherished theories about the nature of things. Along the way, we will meet the men and women who have made it their business to track down this most elusive of particles—from the early theorists who laid the groundwork for teasing out the neutrino’s existence to the modern experimentalists who try to make sense of its quirky character—and we will catch glimpses of their heroic endeavors and fascinating lives.