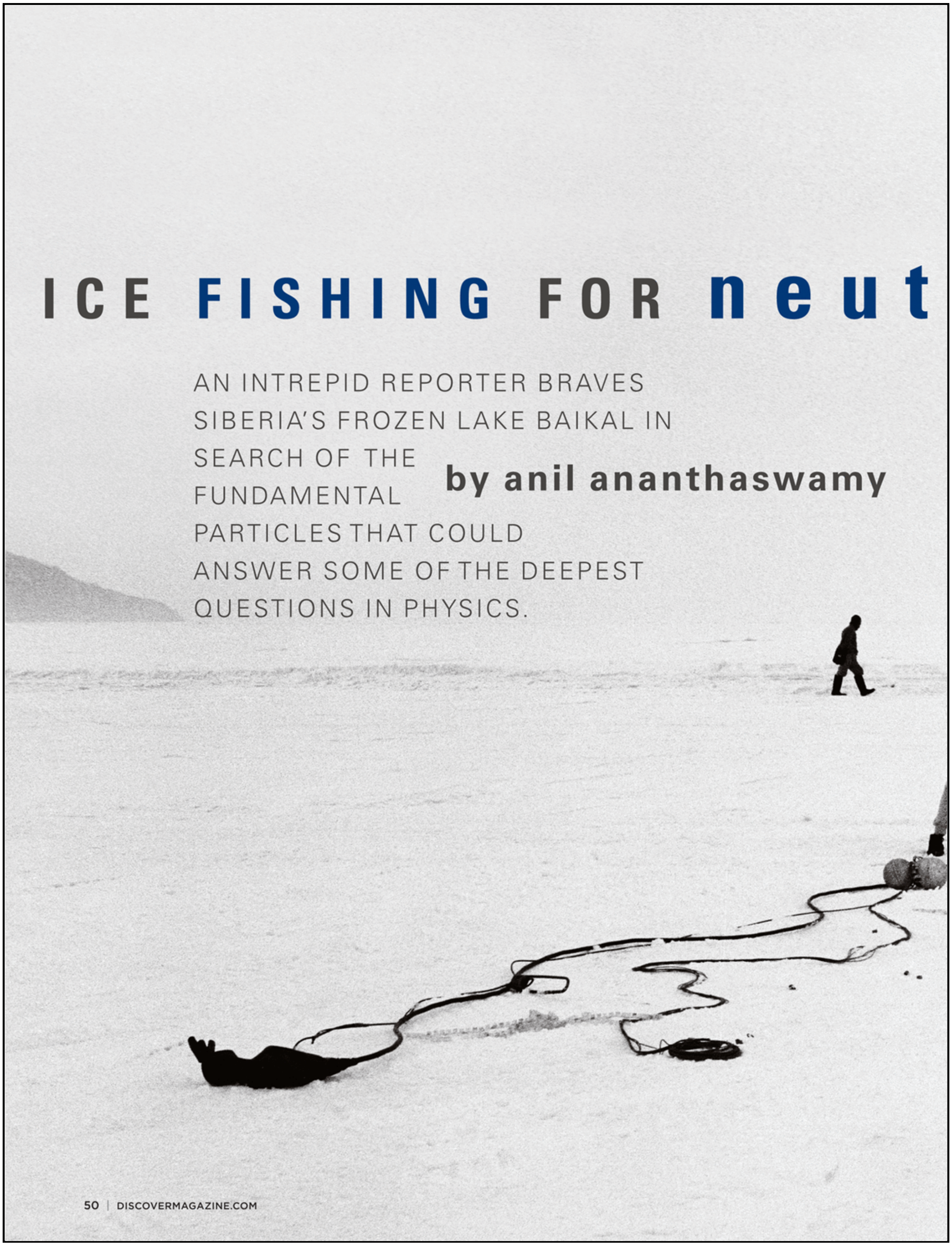
ICE FISHING FOR neut

AN INTREPID REPORTER BRAVES SIBERIA'S FROZEN LAKE BAIKAL IN SEARCH OF THE FUNDAMENTAL PARTICLES THAT COULD ANSWER SOME OF THE DEEPEST QUESTIONS IN PHYSICS.

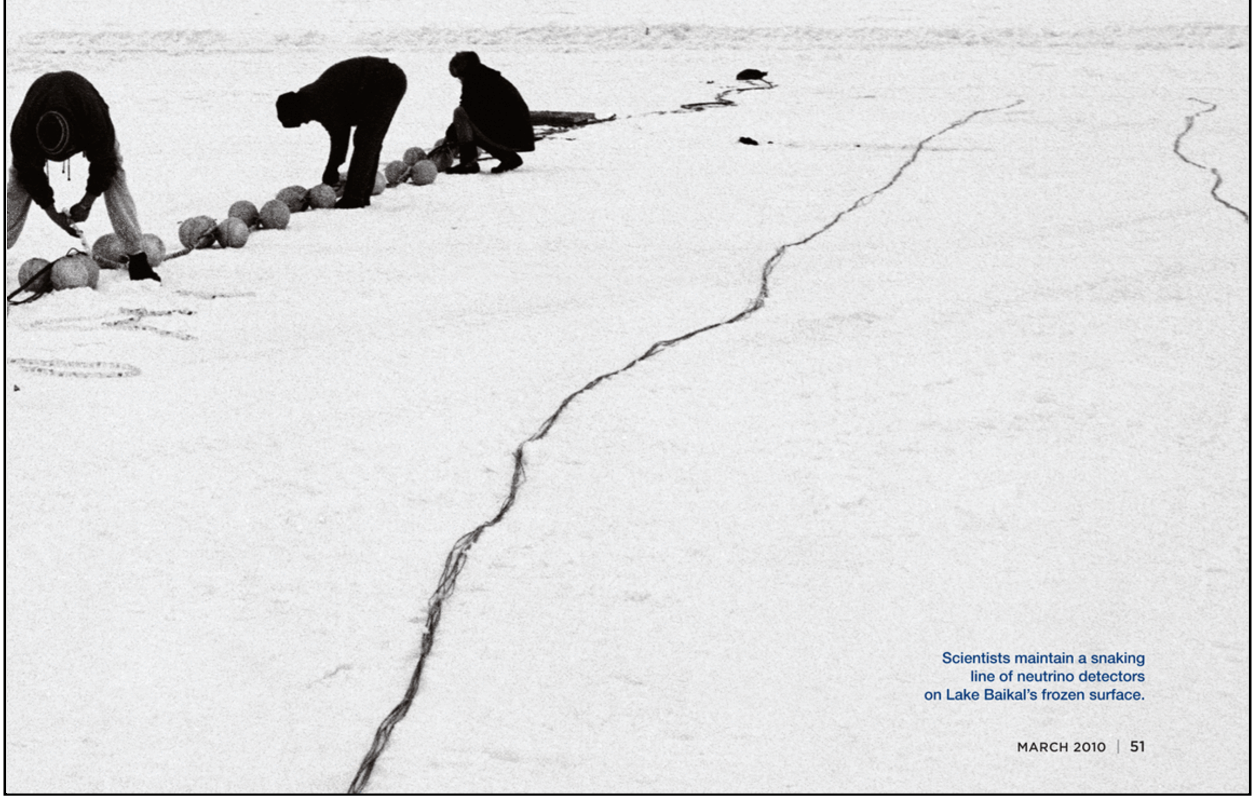
by anil ananthaswamy



rinos

about 25 million years ago, Earth parted in the southeast corner of Siberia. Since then, countless rivers have converged on the gaping continental rift, creating the vast body of water known as Lake Baikal. Surrounded by mountains, this 400-mile-long inland sea has remained isolated from other lakes and oceans, leading to the evolution of unusual flora and fauna, more than three-quarters of which are found nowhere else on the planet. Russians regard it as their own Galápagos. The lake contains 20 percent of the world's unfrozen freshwater—or just a little less during the severe Siberian winter when, despite its enormous size and depth, Baikal freezes over.

On one such winter's day, I found myself on the lake near the town of Listvyanka, which is nestled in a crook of the shoreline. I was in an old van that was



Scientists maintain a snaking line of neutrino detectors on Lake Baikal's frozen surface.

trying to head west, not along a coastal road—for there was none—but over the ice. The path, however, was blocked by a ridge. It looked like a tectonic fault: Two sections of the lake's solid surface had slammed together and splintered, throwing up jagged chunks of ice. The driver, a Russian with a weather-beaten face, peered from underneath his peaked cap, looking for a break in the ridge. When he spied a few feet of smooth ice, he got out and prodded it with a metal rod, only to shake his head as it crumbled: not thick enough to support the van. We kept driving south, farther and farther from shore, in what I was convinced was the wrong direction. The van shuddered and lurched, its tires crunching on patches of fresh snow and occasionally slithering on ice. The ridge continued as far as the eye could see. Suddenly we stopped. In front of us was a dangerous-looking expanse littered with enormous pieces of ice that rose from the lake's frozen surface like giant shards of broken glass.

Above: A frigid, rustic campsite is home to the scientists who maintain the Baikal Neutrino Telescope. Right: One of the telescope's 228 detectors, which pick up flashes of light triggered by passing neutrinos.

ALL PHOTOS: CHRISTIAN THIEL/IMAGES.DE

The driver seemed to be contemplating going around them to look for thick ice that would let us reach our destination, an underwater observatory operating in one of the deepest parts of the lake. But if he did that, we'd get even farther from the shore, and it would take just one punctured tire to strand us. The sun was little more than an hour from setting, and the temperature was falling. I couldn't ask the driver if he had a radio or a phone to call for help, since he did not speak a word of English and the only Russian phrase I knew was *do svidaniya*. The last thing I wanted to say to him at this point was "Good-bye."

Thankfully, he decided to turn around. We drove along until we came upon vehicle tracks that went over some ice covering the ridge. The driver swung the van westward and cleared the ridge, and soon we were racing across the lake at a speed that turned every frozen lump into a speed bump. The van's front rose and fell sickeningly, rattling the tools strewn around on the front seat. I worried that the ice would give way and we would plunge into the frigid waters below. But it remained solid, and the van, despite its appearance, was in fine mechanical fettle, its shock absorbers holding firm. In the distance I spied a dark spot on the otherwise white expanse. As we approached, the spot grew to its full size, revealing itself as a three-foot-high Christmas tree. We still had 20 miles to cover, and the sun would soon disappear below the icy horizon. But now that we had found the Christmas tree, I knew we were fine.

I had first seen the tree two days earlier, with Nikolai (Kolja) Budnev, a physicist from Irkutsk State University, and Bertram Heinze, a German geologist. We were headed to the site of the Lake Baikal neutrino observatory, which lay deep beneath the ice. We had just driven onto the lake from the shore near Listvyanka when Heinze asked, "When does the ice start breaking?"

"Sometime in early March," Budnev answered. My heart skipped a beat. It was already *late* March, and we were on the ice in an old, olive-green military jeep. "Sorry, sometime in early April," Budnev corrected himself. Phew.

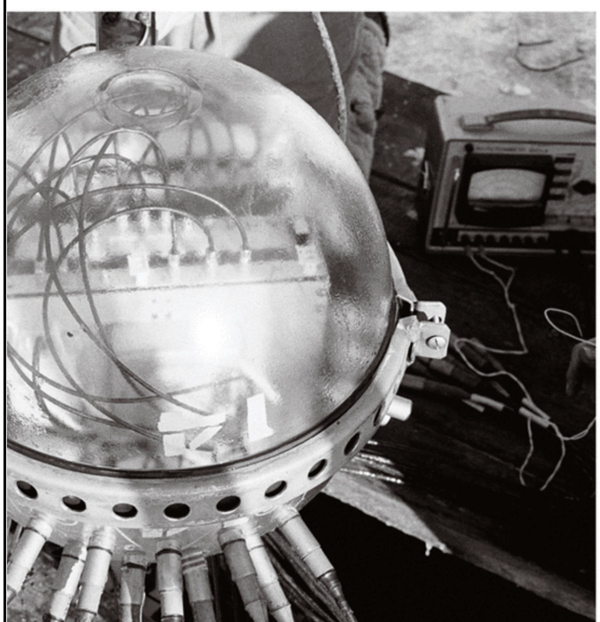
For more than two decades now, Russian and German physicists have camped on the frozen surface of Lake Baikal from February to April, installing and maintaining instruments to search for the elusive subatomic particles called neutrinos. Artificial eyes deep below the

EACH YEAR THEY SET UP **an ice camp, racing against time to** FINISH THEIR WORK BEFORE **the lake's frozen surface** STARTS TO CRACK.

surface of the lake look for dim flashes of blue light caused by a rare collision between a neutrino and a molecule of water. I was told that human eyes would be able to see these flashes too—if our eyes were the size of watermelons. Indeed, each artificial eye is more than a foot in diameter, and the Baikal neutrino telescope, the first instrument of its kind in the world, has 228 eyes patiently watching for these messengers from outer space.

The telescope, which is located a few miles offshore, operates underwater all year round. Cables run from it to a shore station where data are collected and analyzed. It is a project on a shoestring budget. Without the luxury of expensive ships and remote-controlled submersibles, scientists wait for the winter ice to provide a stable platform for their cranes and winches. Each year they set up an ice camp, haul the telescope up from a depth of 0.7 mile, carry out routine maintenance, and lower it back into the water. And each year they race against time to complete their work before the sprigs of spring begin to brush away the Siberian winter and the lake's frozen surface starts to crack.

What is it about the neutrino that makes scientists brave such conditions? Neutrinos—some of them dating back to right after the Big Bang—go through matter, traveling unscathed from the time they are created and carrying information in a way no other particle can. The universe is opaque to ultraenergetic photons, or gamma rays, which are absorbed by the matter and radiation that lie between their source and Earth. But neutrinos, produced by the same astrophysical processes that generate high-energy photons, barely interact with anything along the way. For instance, neutrinos stream out from the center of the sun as soon as they are produced, whereas a photon needs thousands of years to work its way out from the core to the sun's brilliant surface.

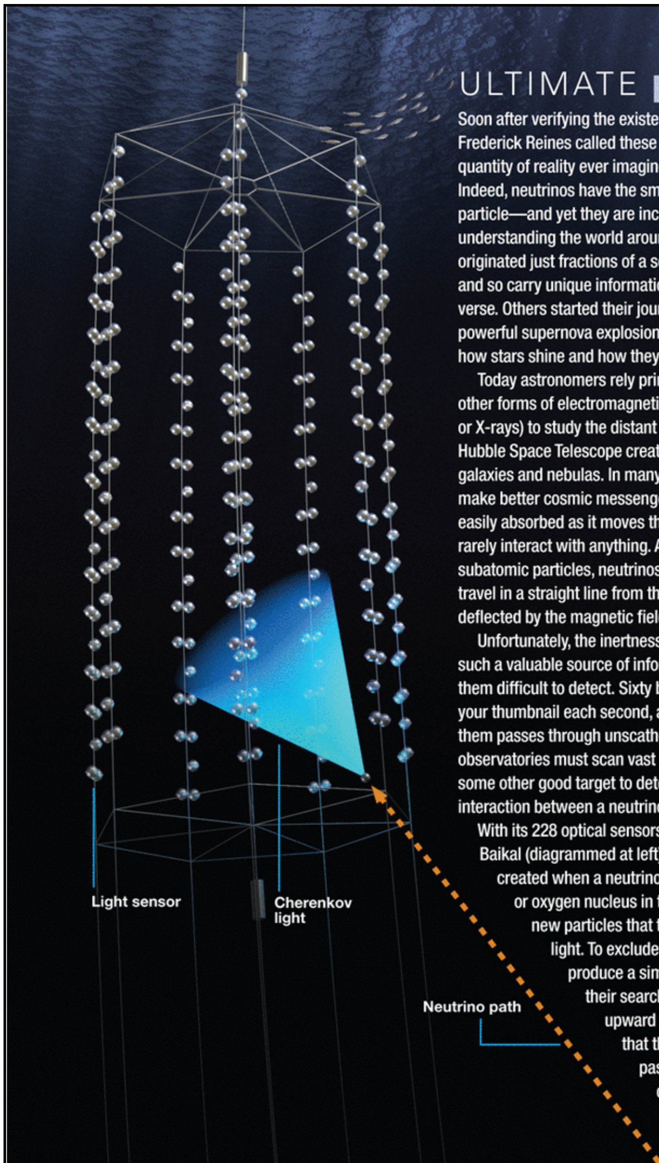


Neutrinos therefore represent a unique window into an otherwise invisible universe, even offering clues about the missing mass called dark matter, whose presence can be inferred only by its gravitational influence on stars and galaxies. Theory suggests that over time the gravity wells created by Earth, the sun, and the Milky Way would have sucked in an enormous number of dark-matter particles. Wherever they gather in great concentrations, these particles should collide with one another, spewing out (among other things) neutrinos. It is as if a giant particle accelerator at our galaxy's center were smashing dark-matter particles together, generating neutrinos and beaming them outward, some toward us.

THAT neutrinos play such a key role in advancing physics would have surprised scientists of a few generations ago. For them the neutrino was a figment of imagination, a theoretical necessity, but one that seemed impossible to detect because of its ethereal nature—a ghost of a particle. The story of the neutrino begins in the late 1920s. Physicists had been puzzling over something called radioactive beta decay, in which one kind of atom changes into another. For instance, carbon-14 has eight neutrons and six protons. During beta decay, one of these neutrons decays into a proton and emits an electron. The new nucleus, now with seven protons and seven neutrons, is transformed into nitrogen-14. But during this process, some energy seemed to go missing. It was the Austrian-born physicist and Nobel laureate Wolfgang Pauli who theorized that beta decay must emit an as yet undiscovered neutral particle. A few years later, the physicist Enrico Fermi jokingly named the particle a neutrino, Italian for "little neutral one," and the name stuck.

For decades the neutrino remained a theoretical construct, a useful particle that helped physicists save their theories from embarrassment. Nobody had seen one. Nobody even knew how to find one—until Frederick Reines, a researcher working at Los Alamos during the 1950s, realized that a nuclear bomb would be a significant source of neutrinos. Reines and his colleague Clyde L. Cowan Jr. thought a nuclear power plant would also be a source. They calculated that a detector near a nuclear reactor would encounter nearly 10^{13} neutrinos per square centimeter per second. There was just one small problem: Since neutrinos are electrically neutral, they could be detected only if they directly hit the nucleus of an atom. Reines and Cowan would have to look for the signature of such a collision. And they found it.

By the 1960s, physicists following up on Reines's work had started building neutrino detectors inside mines, using the ground as a natural shield from cosmic rays, which can swamp the signal from neutrinos. (Neutrinos can pass through the thick walls of the mines, but cosmic rays cannot.) In 1968 Raymond Davis and his colleagues from Brookhaven National Laboratory completed an experiment inside the Homestake Gold Mine in Lead, South Dakota. They used a tank containing 100,000 gallons of tetrachloroethylene, a common dry-cleaning agent. When a neutrino smashed into an atom of



ULTIMATE **particle**

Soon after verifying the existence of neutrinos, physicist Frederick Reines called these particles "the most tiny quantity of reality ever imagined by a human being." Indeed, neutrinos have the smallest mass of any known particle—and yet they are incredibly important for understanding the world around us. Most neutrinos originated just fractions of a second after the Big Bang and so carry unique information about the infant universe. Others started their journey in the sun's core or in powerful supernova explosions, revealing secrets about how stars shine and how they die.

Today astronomers rely primarily on visible light or other forms of electromagnetic radiation (like radio or X-rays) to study the distant universe; that is how the Hubble Space Telescope creates its beautiful images of galaxies and nebulas. In many ways, though, neutrinos make better cosmic messengers. Unlike light, which is easily absorbed as it moves through space, neutrinos rarely interact with anything. And unlike many other subatomic particles, neutrinos have no charge, so they travel in a straight line from their source without being deflected by the magnetic fields around stars.

Unfortunately, the inertness that makes neutrinos such a valuable source of information also makes them difficult to detect. Sixty billion solar neutrinos hit your thumbnail each second, and nearly every one of them passes through unscathed. As a result, neutrino observatories must scan vast quantities of water or some other good target to detect the exceedingly rare interaction between a neutrino and another particle.

With its 228 optical sensors, the observatory at Lake Baikal (diagrammed at left) looks for the debris created when a neutrino collides with a hydrogen or oxygen nucleus in the water: a shower of new particles that triggers a cone of bluish light. To exclude other particles that can produce a similar signal, scientists limit their search to showers cascading upward from below. This ensures that the original particle has passed through the Earth's crust, a feat that only a neutrino can accomplish. ANDREW GRANT

chlorine, the atom was transformed into one of radioactive argon. By counting the number of argon atoms that were produced, the physicists could calculate the flux of neutrinos coming from the sun. Then in the early 1980s, researchers around the world built detectors using thousands of tons of water in underground tanks lined with photomultiplier tubes (PMTs). The PMTs look for light emitted when a neutrino smashes into water. Normally the neutrino will pass right through water without any interaction. But on the rare occasions when one does hit a nucleus of hydrogen or oxygen, the collision can spit out another subatomic particle, a muon. The charged muon interacts with the water electromagnetically, and because it is moving faster than the speed of light in water, it leaves in its wake a cone of blue light. This is called a Cherenkov cone, after the Russian physicist who first described the phenomenon. It is analogous to the sonic boom caused by an aircraft traveling faster than the speed of sound.

It was another Russian researcher, Moisey Alexandrovich Markov, a "poet" of astroparticle physics, who suggested using natural bodies of water as neutrino detectors. Instead of building tanks of water inside mines, why not use lakes or even oceans? Just submerge long strings of photomultiplier tubes into the water and watch for the Cherenkov light left behind by neutrino-generated muons. The idea was enticing, but there were huge practical difficulties. For one thing, without rock above to protect it, a detector would be exposed to cosmic rays that could drown out signals from neutrinos. More to the point, sunlight (not a problem inside mines) would blot out the Cherenkov emission.

The solution was to go deep, where the sun's rays could not reach. The physicists realized that they could use the Earth itself as a shield. While many muons can make it through a mile of water, a similar stretch of rock will stop them cold. So a neutrino detector can sit deep underwater, near the lake bed, looking downward for muons created by neutrinos that come from below. None of the muons created by cosmic rays in the atmosphere on the other side of the Earth can penetrate the planet. Neutrinos, however, zip right through, and occasionally one will hit a nucleus in the water or in the lake bed itself. Such a collision generates a muon, which then shoots up toward the surface. Catch an upward-moving muon and you have essentially detected a neutrino that came from the other side of the Earth. All that was needed was a suitable body of water. By the mid-1980s, the Russians realized that they had a massive tank of pure water in their own backyard: Lake Baikal.

On my first morning in Siberia, we drove across the lake toward the telescope. The frozen white lake spread for miles around us in every direction except to the northwest, where we were relatively close to shore. When we stopped to rest, men milled around the vehicles. The subzero temperature seemed to affect everyone differently. Some stood bareheaded; others had woolen caps rolled down to the tips of their ears. And then there was Ralf Wischnewski, in his enormous Russian fur cap that looked like a fluffed-up rabbit. A German neutrino physicist who had been working with the Russians at Lake Baikal for 20 years, Wischnewski was the reason I was here. I had met this ruddy-faced man six months earlier in London, outside

ILLUSTRATION BY JOHN MACNEILL

the Tate Modern museum on the south bank of the Thames. We walked over to a Greek pub and discussed the Baikal expedition over chilled lager. It was he who had alerted me to the tradition of bringing spirits to share with the Russians during the winter evenings.

And here we were, except that it was still morning. The Russians had planned a welcome drink for Heinze. Kolja Budnev bounded out of our jeep with a bottle of vodka. Someone sliced a sausage into circular pieces. Bright yellow, blue, and red plastic cups were set up on the jeep's expansive hood, and soon everyone had a vodka-filled cup in hand. Budnev dipped a finger into his and flicked a few drops onto the ice—an offering to the great spirit of Lake Baikal.

> BUDNEV FLICKED A FEW **drops of vodka onto the ice**—AN OFFERING TO THE GREAT SPIRIT OF LAKE BAIKAL.

Soon we got back into our vehicles and headed toward the neutrino telescope, a contraption made of 11 strings of photomultiplier tubes, each with a large buoy at the top and a counterweight at the bottom. Smaller buoys attached to the strings float about 30 feet below the surface. All year round, a total of 228 PMTs watch for the Cherenkov cones. Each winter the team has to locate the telescope, the upper part of which drifts slightly over the course of the year. The team has two months to carry out any routine maintenance, put the strings back in the water, and get out before the ice cracks.

The term "experimental physics" took on new meaning in this biting cold, which at times dropped to –4 degrees Fahrenheit. Most of the physicists lived in 10-by-20-foot cabins, two to a cabin. Others slept in bunk beds at the shore station, amid workbenches cluttered with computers, electronics, wires, and cables. They worked long hours, from early in the morning to sometimes well past midnight. There was no running water, which meant no showers for two months. Toilets were wooden cabins with pits in the ground. The extreme cold helped control the stench, but it still wafted up when warm urine hit the pit. There was one luxury: the *banya,* a traditional Russian sauna. Naked men sat in an outbuilding, chucked water on hot stones to raise steam, and beat one another with leafy twigs and branches of birch.

A wicked wind kicked up one evening. It was time for everyone to leave the open ice and head back to the shore station. Once there, I gratefully sat down for a cup of tea, and a can of sweet, syrupy condensed milk materialized. One scientist looked at the can wistfully. Condensed milk had been his dream as a child growing up in the Siberian city of Tomsk. "They had this in Moscow," he said, "but not in Tomsk."

Later that evening, I had to head back out and traverse part of the icy lake to reach the canteen for dinner. It wasn't going to be easy. I had turned up on a frozen lake in the depths of a Siberian winter in "European summer shoes," as Wischnewski put it, disbelief in his voice. On the lake I found walking nearly impossible, my smooth-soled shoes slipping the entire way. After a few days, I learned to find fresh snow for my shoes to grip, but that night, fear nearly paralyzed me. Fortunately, a jeep pulled up beside me, and Wischnewski, having noticed my plight, asked the driver—Igor Belolaptikov, a tall, mustached physicist from the Joint Institute of Nuclear Research in Dubna, near Moscow—to take me to the canteen. I sat with Belolaptikov at dinner and happily accepted a ride back to his small cabin for a chat about neutrinos.

"My business is the reconstruction of muons and neutrinos," Belolaptikov said, laughing with a childlike joy as he made this disclosure. That reconstruction is tricky business. Hundreds of photomultiplier tubes watch for the flashes of Cherenkov light at the bottom of Lake Baikal. As a neutrino-induced muon races through the water, the light from its Cherenkov cone reaches different tubes at slightly different times. The skill lies in collecting all the information and sifting through it to reconstruct the path of the upward-moving muon. This can then be used to calculate the path of the original neutrino. It is this ability to figure out where a neutrino comes from that differentiates a neutrino telescope from a mere neutrino detector. A telescope must identify the source of neutrinos in the sky, and the Lake Baikal instrument can do so with an angular resolution of about 2.5 degrees, meaning that it can distinguish neutrinos coming from points in the sky separated by a distance of five full moons. So far the Baikal telescope has seen only atmospheric neutrinos, secondary particles created by cosmic rays crashing into atoms in the air. Everyone here is waiting for the day when a high-energy neutrino from outer space makes its presence felt in their little corner of the lake.

Scientists retrieve light detectors for maintenance above the Siberian ice before returning them to the depths of Lake Baikal.

Belolaptikov recalled his first neutrino—indeed, the Baikal detector's first—from 1993. "It was great," he said. "Here, you can see." He leaned over his bunk bed and removed a piece of paper pinned to the wall above. It was a printout of the path of an upward muon, reconstructed from the detection of its Cherenkov cone: the first-ever neutrino seen by humans using a natural body of water as a detector. Belolaptikov and colleagues had done the reconstruction and put the Lake Baikal detector on the map.

The next two days slid by, but even in this short time a rhythm was established. A trip down to the lake in the mornings to get a bucketful of drinking water from a hole in the ice. Then back to the cabin for coffee with condensed milk and honey, making sure to plug the hole in the can of milk with paper to prevent "little animals" (as Wischnewski calls insects) from getting in. From my cabin I could see clear across the lake, and I had to remind myself that it had more water than America's five Great Lakes put together and a surface area larger than Belgium. Eighty percent of Russia's freshwater was here. Even at great depths, the lake is well oxygenated, making it one of the most hospitable waters for life. Because of the voracious crustaceans that live at all depths, nothing dead or dying lasts more than a few days in this lake. If fishermen leave their catch in the nets too long, the crustaceans invade the fish through their mouths and gills, eating them from the inside out. These critters keep the lake free of dead matter, leaving it unimaginably clear, especially deep down. Murky waters would make watching for muons nearly impossible. "It is a very, very kind water," Budnev said.

when the Russians turned on the Lake Baikal telescope in 1993, it was the only game in town. That has since changed. European physicists have started building similar detectors in the Mediterranean. And an American-European team went to the South Pole in the mid-1990s to construct the Antarctic Muon and Neutrino Detector Array (AMANDA) while laying the groundwork for IceCube,

the largest-ever neutrino detector. Several German physicists who had worked at Lake Baikal joined the South Pole team. For a few years Wischnewski, too, split his time between Antarctica and Baikal before committing fully to Baikal. The South Pole detectors are looking for Cherenkov light emitted when muons hit the ice, and IceCube will be watching a cubic kilometer of ice for these ephemeral flashes.

The innovations at Baikal—including Belolaptikov's work on reconstructing muons—inspired the early efforts in Antarctica. Although Antarctic ice is clearer than the waters of Lake Baikal, for now the water has a unique advantage. Light can travel more than 10 times as far in the lake as it can in the ice before it is scattered. Catch the photons before they scatter and you can tell exactly where they are coming from. Catch them after they have been scattered a few times and it gets hard to work out their original direction. This means that more PMTs are needed in the Antarctic ice to achieve the same end.

Grigory Domogatsky, spokesman for the Baikal project, made this point emphatically one evening while we were sitting at a table in his cabin next to a roaring fire. Despite a rasping smoker's cough that could stop him in midsentence, he passionately argued that the world's biggest neutrino detector should be built right here in Lake Baikal. The Americans and their European partners were spending $270 million on IceCube, and Domogatsky thought that a tenth of that would be enough to build a comparable detector in Siberia. Besides the advantage of needing far fewer photomultiplier tubes to detect high-energy neutrinos, Domogatsky pointed out that only a detector in the Northern Hemisphere could see neutrinos from the center of our galaxy.

"But you can see the center of the Milky Way from the South Pole," I said, somewhat puzzled.

"Yes, but not neutrinos," Domogatsky replied, with the gentle yet triumphant note of a teacher who has just made a telling point. Of course: Neutrino detectors that use natural bodies of water or ice can see only those neutrinos that come through the Earth, so they have to look upside down—and from that vantage, the center of the Milky Way never comes into view at the South Pole. Domogatsky further argued that Lake Baikal was the best body of water in which to build such a detector, for there are no deepwater currents, as there are in the Mediterranean. "Lake Baikal is like an aquarium," he said. Besides, scientists in the Mediterranean need ships to lower their strings into the sea and remote-controlled submersibles to wire them up, making the operation expensive. Here, winter ice makes retrieving and working on the detectors comparatively simple. But, Domogatsky sighed, convincing people to work in Siberia during the winter, when the alternative was the sun-soaked Mediterranean, was going to be hard.

Domogatsky's heavily furrowed face showed the effects of 40 years of physics, many of them spent in this hostile place. Now he was looking to pass the baton. His team had just figured out that the telescope they had built so far could form a cell of a much, much larger telescope. Put next to each other, such cells could cover a cubic kilometer of water. All he needed was about $25 million, an order of magnitude less than the money being spent on the Mediterranean neutrino projects or at the South Pole.

The fire died. Outdoors the sun was setting. "I hope to help start this project," Domogatsky said. "But the work should be performed by younger physicists." We stepped outside. I took a picture of this grand old man of contemporary Russian physics against the backdrop of his beloved lake, then started walking back to the shore station. There was just one thing left to do. Wischnewski had suggested that my visit would be incomplete without my spending a night in one of the cabins at the ice camp. I had agreed. But then he casually mentioned that the ice heaves. Despite the lake's thickly frozen surface, the water beneath is alive and kicking. Sometimes the entire sheet of ice below the camp can jerk and lurch. That night we drove to the ice camp and a graduate student named Alexey Kochanov ushered me into his cabin. He told me not to worry; he found the sound of ice creaking beneath him relaxing. Obviously he had been here way too long—but then he explained. The creaking means that the ice cover is solid. It is the sound of ice moving in response to the motion of the water beneath. It is only when you don't hear the creaking that you should worry. That's when the cracks are so big that there is plenty of give in the ice and you should not be on the lake.

Suddenly the ice's protestations were music to my ears. All night it groaned. When sounds came from far away, they were like muffled gunshots; when they were close, more like the crack of a whip. At five in the morning, the ice heaved. It was the only significant movement I had felt all night. I couldn't go back to sleep, so I went outside. It was still dark. The ice did not open to swallow me. Thin cracks crisscrossed the surface. You could tell that the new fissures had formed in the night because they had not yet been covered by snow. Scorpio's tail was visible next to the moon, and overhead was Ursa Minor. On the far shore, embers of a forest fire glowed on the slopes of the Khamar-Daban range.

Somewhere deep below, a cone of bluish light raced upward through the cold water. A neutrino had traveled from some distant part of the universe, escaped collision with every bit of matter across trillions of miles, and gone through the center of the Earth, only to collide with a molecule of water in Lake Baikal and disappear in a flash of light. D

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NEUTRINO SPOTTING

Lake Baikal is not the only place where physicists are using elaborate detectors to study the most evasive particles in the universe. Here are other sites around the globe where the work goes on:

ICECUBE, ANTARCTICA The latest and greatest neutrino observatory can be found in one of the most inhospitable locales on Earth. Scientists have buried beads of optical sensors under almost a mile of ice, where it is dark and clear enough to detect the blue light of a neutrino-induced particle shower even from hundreds of feet away.

SUPER-KAMIOKANDE, JAPAN Within a mine more than half a mile underground, 13,000 detectors probe 50,000 tons of purified water for the blue-flash signature of neutrinos. In 1998 scientists at Super-Kamiokande found the first evidence that neutrinos have mass.

SUDBURY NEUTRINO OBSERVATORY (SNO), CANADA An engineering marvel, SNO is a transparent spherical chamber filled with liquid, ringed with sensitive light detectors and submerged in a water-filled mine. To improve sensitivity, researchers removed the heavy water that initially filled the chamber so that a petroleum-like liquid could be injected instead.

MAIN INJECTOR NEUTRINO OSCILLATION SEARCH (MINOS), U.S. This underground observatory in Minnesota detects neutrinos beamed from Fermilab, 450 miles away near Chicago. Scientists at MINOS hope to learn more about the three neutrino "flavors": electron, muon, and tau.

OSCILLATION PROJECT WITH EMULSION-TRACKING APPARATUS (OPERA), ITALY Here, a man-made beam of neutrinos (created near Geneva) hits 150,000 lead bricks separated by photosensitive plastic. A. G.