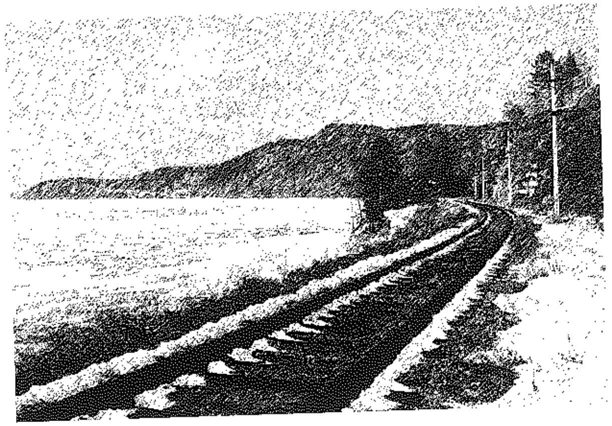


3 · LITTLE NEUTRAL ONES

ABOUT 25 MILLION YEARS AGO, the earth parted in the southeast corner of Siberia. Since then, countless rivers have converged on the gaping continental rift, creating the massive body of water known as Lake Baikal. Surrounded by mountains, this inland sea has forever been isolated from other lakes and oceans, leading to the evolution of unusual flora and fauna, three-quarters of which are not found elsewhere on Earth. Russians regard it as their own Galápagos. The lake contains 20 percent of the world's unfrozen fresh water, and 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, two days into my trip to the region, I found myself on the lake near the town of Listvyanka, which is nestled in a crook in the shoreline. I was in an old van that was 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 along, 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. The driver seemed to be contemplating going around them to look for thick, solid ice that would let us continue to 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 him 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 svidania*. The last thing I wanted to say to him at this point was "Goodbye."

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 speeds 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'd 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 3-foot-high Christmas tree. We still had 35 kilometers 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 late March, and we were on the ice in an old olive-green military jeep. "Sorry, sometime in early April," Budnev corrected himself. *Phew*.

Earlier that morning, Budnev had picked me up at Irkutsk's dilapidated airport. I had flown in from Moscow, and the contrast between the capital's glitzy new international terminal at Domodedovo airport and the one in Irkutsk was stark. The dusty-yellow tarmac bus that ferried us from the plane to the Irkutsk terminal was so overloaded that its rear scraped the ground, and the terminal's concrete structure was falling apart. (The Irkutsk airport was in the news three months later; the very flight I had flown in on crashed after landing, killing 125 people and injuring 78 others.) In the past, when Russia's influence spread beyond Siberia into Alaska and even California, Irkutsk had been a prosperous city. On this cold, gray morning in 2006, the city center looked rundown, its decaying wooden buildings only hinting at that impressive past.

We stopped to collect Heinze from his hotel. A tall man, he had to scrunch to fit into the jeep's front seat. Soon we were speeding away from Irkutsk toward Listvyanka, on a wide road with forests on either side, the speckled white of the winter-bare birches broken occasionally by evergreen pines. We soon overtook a van—the same van that would be a source of angst two days later—taking other researchers to the observatory. In the van's rooftop rack were planks of wood. "See those planks?" said Budnev. "We use it to cross cracks in the ice."

Before I could voice my anxiety, Budnev went on to explain that if the cracks were less than about a foot and a half wide, the planks were not used. The driver could speed up and clear such cracks, he said, embellishing the explanation with sound effects—the *swoosh* of a vehicle taking off and landing with a thud on the other side.

Could the ice handle the weight of the jeep? I wondered aloud. Budnev assured us that the ice could support a tank. In fact, it could support a train. Well, almost. Before the Trans-Siberian Railway was completed, the tracks stopped on the western shore of Lake Baikal, then continued from the eastern shore. The entire train—carriages, engine, cargo, and passengers—was ferried by specially built icebreakers across the lake. Once, in the winter of 1904, during the Russo-Japanese War, the ice had held firm and reinforcements were urgently needed on the other side, so the Russians laid railroad tracks on the frozen lake. An engine was sent to test the ice. It never made it across and still lies somewhere on the bottom. If I had known this at the time, Budnev's words would have seemed less reassuring.

However, it is the ice that makes possible an extraordinary enterprise. 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 "little neutral ones"—elusive subatomic particles called neutrinos. Artificial eyes deep below the surface of the lake look for tiny flashes of blue light, caused by an unlikely collision between a neutrino and a molecule of water. I was told that human eyes could see these flashes, too, if our eyes were the size of giant watermelons. Indeed, each artificial eye is more than a foot in diameter and the Baikal neutrino telescope, the first such instrument in the world, has 228 eyes patiently watching for these messengers from outer space.

The telescope, which is a few kilometers offshore, operates underwater all year round. Cables run from it to a shore station, where the data is collected and analyzed. It's a project on a shoestring budget. Without the luxury of expensive ships and remote-controlled submersibles to allow them to work on the telescope, the 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 onto the ice from a depth of 1.1 kilometers, carry out routine maintenance, and lower it back into the water. And each year they race against time to complete their work, towing their equipment back to the shore 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 go right through matter, traveling unscathed from the time they were created—some of them right after the big bang—and carrying information in a way no other particle can. The universe is optically opaque at extremely high energies, for ultraenergetic photons are absorbed by the matter and radiation that lie between their source and Earth. However, neutrinos, which are produced by the same astrophysical processes that generate high-energy photons, barely interact with anything along the way. They can escape even from within astrophysical objects. 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 solar heart. Neutrinos represent a unique window into an otherwise invisible universe.

While these particles are essential to astrophysics, they have something important to contribute to cosmology as well: They could unveil dense pockets of dark matter in our galaxy. Theory suggests that over time the gravity wells created by Earth and the sun would have sucked in an enormous number of dark-matter particles. There is an even bigger gravity well nearby (relatively speaking), created by the supermassive black hole at the center of the Milky Way. Dark-matter particles should be clustered there, too. Wherever they gather in great concentrations, these particles should collide with one another and annihilate, spewing out, among other things, neutrinos. It's 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. Detecting neutrinos coming from the center of our galaxy would be akin to detecting dark matter, albeit indirectly.

Fortunately for physicists, neutrinos are known particles, unlike those that make up dark matter. But neutrinos come in a range of energies, and those expected to be produced by the collision of dark-matter particles would have about the same energy as those produced nearer home, in the atmosphere. When cosmic rays strike the upper atmosphere, they generate a secondary shower of particles, some of which are neutrinos. These so-called atmospheric neutrinos make up by far the greatest proportion of neutrinos arriving on Earth. They have to be studied in great detail, and their properties and statistical distribution across the sky diligently mapped, because any neutrinos produced by dark matter at the galactic center will appear as a mere blip against this background. Without a clear understanding of the background, the dark-matter signal will be missed.

There is yet another way in which neutrinos might illuminate the search for dark matter. It has to do with the standard model of particle physics. As noted, nothing in the standard model explains dark matter; it's clear that only new physics can do so. Just what this new physics is depends on discoveries that reveal other inadequacies of the standard model. Neutrinos can help here, because they, too, have properties that cannot be explained by the standard model. That neutrinos play such a key role in advancing physics would have surprised physicists of two 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 an atom changes from, say, carbon-14 to nitrogen-14. 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, violating the law of conservation of energy. It was the Austrian-born physicist and Nobel laureate Wolfgang Pauli who finally figured out what was going on.

On December 4, 1930, Pauli penned an intriguing letter to colleagues who had gathered for a conference on radioactivity in Tübingen, Germany. Pauli began the letter "Dear radioactive ladies and gentlemen," and wrote about how he had hit upon a "desperate remedy" to rescue the law of conservation of energy. He theorized that the beta-decay process must emit an as-yet-undiscovered neutral particle. Though Pauli called this hypothetical particle a neutron, he was not talking about the neutron we know today as one of the constituents of atomic nuclei (this particle would be discovered in 1932). Pauli was aware that his idea was highly speculative. "I admit that my remedy may seem only slightly probable, because if neutrons do exist they should certainly have been observed long ago," he wrote.

A couple of years later, the theorist Enrico Fermi jokingly renamed the particle a neutrino, Italian for "little neutral one," and the name stuck. But for decades, the neutrino remained a theoretical construct, a useful particle that helped physicists save their theories from embarrassment. No one had seen one. No one even knew how to find one. Theory suggested that some neutrinos, especially low-energy ones, could go through lead light-years thick, so it was no wonder that experimental physicists were pessimistic about finding these ghostly particles. Unless, of course, something on Earth was producing neutrinos in unimaginably large quantities.

And there was. By the 1950s, America's nuclear weapons program was well under way, and Frederick Reines, a researcher in his early thirties working at the Los Alamos Laboratory in New Mexico, realized that a nuclear bomb would be a significant source of neutrinos (anti-neutrinos, to be precise, but treating them as neutrinos—as we will do throughout the book—does not compromise the explanation). Reines and his colleague Clyde L. Cowan Jr. reasoned that a nuclear power plant would also be such 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. Neutrinos are electrically neutral, which is one of the reasons they pass so cleanly through matter. They could be seen 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. On June 14, 1956, the two scientists announced that their "Project Poltergeist" had tracked down this ghost of a particle. The duo sent a telegram to Pauli, telling him of their results. Pauli happened to be at a meeting in Europe when the telegram arrived. He told everyone at the meeting the news, and later he and his colleagues celebrated by drinking an entire case of champagne.

In 1995, Reines would receive the Nobel Prize for this momentous discovery. (Cowan had died two decades earlier.) Between 1930, when Pauli decided that neutrinos must exist, and the Nobel for Reines, the neutrino had only grown in importance. Physicists were increasingly persuaded that neutrinos were central to the very fabric of the universe. They seemed to be everywhere. Some neutrinos were being produced right here on Earth; others had been created mere seconds after the big bang. And processes that span every instant of time, from the big bang to this moment, have made or are making neutrinos, from the fusion reactions that power the sun to the stupendous cosmic explosions called supernovae that signify the death of massive stars. The biggest source of Earthbound neutrinos is the sun. In any given second, close to a trillion solar neutrinos go right through just the palm of your hand.

By the 1960s, physicists had started building neutrino detectors inside mines as a natural way to shield them from cosmic rays, which wreak havoc just as they do in dark-matter experiments. In 1968, Raymond Davis and his colleagues from Brookhaven National Laboratory completed one 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 chlorine, the atom was transformed into one of radioactive argon. By counting the number of argon atoms that had been produced, the physicists could calculate the number of neutrinos that were coming from the sun (after accounting for the fact that only a tiny fraction were interacting with the chlorine). And they were surprised to find far fewer than expected. This came to be called the mystery of the missing solar neutrinos.

Meanwhile, neutrino detectors got bigger and better. One of them was the Kamiokande detector, situated inside an active zinc mine in the Japanese Alps. Another was the Irvine-Michigan-Brookhaven (IMB) experiment, sited deep within the Morton Salt Mine, near Cleveland, Ohio. Still another was the Baksan Neutrino Observatory deep underground in the Russian Caucasus. On February 23, 1987, all three detectors saw something unexpected: a burst of neutrinos from outside the solar system. These neutrinos had come from the supernova SN1987A, which had exploded in the Large Magellanic Cloud. To this day, these remain the only neutrinos from outer space—besides solar neutrinos—that have been seen on Earth. The experiments also confirmed that the mystery of the missing solar neutrinos was real.

It took two even bigger detectors—the Super-Kamiokande (Super-K), which began operating in 1996 inside the same mine as the Kamiokande detector, and the Sudbury Neutrino Observatory (SNO), built inside a nickel mine in Ontario, Canada—to solve the mystery. According to the standard model of particle physics, neutrinos come in three types: electron, tau, and muon. Between them, Super-K and SNO were sensitive to two of the three types of neutrinos, and their combined data were able to show that solar neutrinos were changing from one type to another as they sped toward Earth, a phenomenon known as neutrino oscillation. Even though the sun was producing the predicted amount of a given type, the neutrinos were morphing on their way to Earth, leading to the deficit in detectors that were designed to observe only one type, the electron neutrino. The Super-K confirmed oscillations in atmospheric neutrinos as well.

The observations of oscillating neutrinos posed a serious problem for the standard model. Neutrinos, according to the model, have no mass, but they can oscillate only if they do have mass. Hitoshi Murayama, a theoretical physicist at the University of California, Berkeley, was at the Super-K team's announcement in Japan in 1998. He wrote later, "It was a moving moment. Uncharacteristically for a physics conference, people gave the speaker a standing ovation. I stood up too. Having survived every experimental challenge since the late 1970s, the Standard Model had finally fallen. The results showed that at the very least the theory is incomplete."

The Japanese had perfected the method of using tens of thousands of tons of water in a tank 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 when one does occasionally hit a nucleus of hydrogen or oxygen, the collision can sometimes 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.

Even as the Super-K and SNO experiments were being built, physicists were training their sights beyond the sun. But this brought new challenges. Most astrophysical neutrinos, including those produced by any dark matter at the galactic center, are higher in energy than solar neutrinos. While such neutrinos are easier to detect (because they produce brighter and longer streaks of light in water), their numbers fall dramatically with increasing energy. The only chance of seeing one is to monitor far greater volumes of water than is possible in underground detectors, which are limited in size by the mines that confine them. Where could one find such an abundance of clear water?

In the 1960s, the Russian physicist Moisey Alexandrovich Markov, a "poet" of astroparticle physics, had suggested using natural bodies of water as neutrino detectors. Instead of building tanks of water inside mines, why not just 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. It was an enticing idea, but there were enormous practical difficulties. For one thing, without rock above to protect it, a detector would be exposed to cosmic rays that could swamp any signals from neutrinos.

When cosmic rays strike the upper atmosphere, they generate neutrinos, but they also generate muons in roughly the same numbers. Cosmic-ray muons and atmospheric neutrinos will both reach the water, but for every neutrino that interacts and creates a muon that lights up the water, a billion cosmic-ray muons will do the same. So if a neutrino detector is placed near the surface of a lake, it will be overwhelmed by the Cherenkov light from cosmic-ray muons striking the water and unable to distinguish any muon generated by a neutrino. More to the point, sunlight (which is not a problem inside mines) will blot out the Cherenkov light. The solution for both problems is to go deep, where the sun's rays cannot reach. Water also blocks many of the cosmic-ray muons, and about a thousand times fewer muons reach the bottom of a deep lake. But even that is too many.

Physicists realized that they could use Earth itself as a shield. While many muons can make it through a kilometer of water, a similar stretch of rock will stop them cold. So a neutrino detector can sit near the lakebed, positioned to look 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 Earth can penetrate the planet. Neutrinos, however, zip right through, and occasionally one will hit a nucleus in the water or in the lakebed 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 Earth.

All that was needed was a suitable body of water. By the mid-1980s, the Russians realized that they had a massive tank (636 kilometers long and 80 kilometers at its widest) of pure water in their own backyard: Lake Baikal.

Lake Baikal is the world's deepest body of fresh water. Inflowing rivers have, over time, deposited nearly 7 kilometers of sediment, but despite this the lake is 1.7 kilometers deep in places. This depth is crucial to the neutrino experiment.

On my first morning in Siberia, we drove across the lake toward the telescope. But before our jeep reached the site, we stopped, gathering with our fellow travelers in the van and another military-green jeep. I knew of the Russians' love for drink, and I was carrying a bottle of fine Scotch whisky to share with my hosts. But I was hardly prepared for the charming ritual I witnessed on the ice—at 10:00 A.M., no less. The white, frozen lake spread for miles around us in every direction except to the northwest, where we were relatively close to shore. 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 twenty years, Wischnewski was the reason I was here. I had met this ruddy-faced man, who was graying at the temples, six months earlier in London, outside 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 it was still morning. The Russians had planned a traditional welcome drink for Heinze, head of the Moscow office of the Helmholtz Association (the German equivalent of the U.S. National Science Foundation). Kolja Budnev bounded out of our jeep with a bottle of vodka. The jeep's expansive hood became a table, and another bottle of vodka appeared, as did a giant jar of pickled cucumbers. Someone sliced a sausage into circular pieces. As a vegetarian, I was relieved to see that there was some bread. Bright yellow, blue, and red plastic cups were set up on the hood and soon everyone had a vodka-filled cup in their hands. Budnev dipped a finger into his and flicked a few drops of vodka onto the ice—an offering to Burkhan, the great spirit of Lake Baikal. Others did the same before drinking their vodka, and I followed tentatively, not wanting to be drunk as well as jet-lagged (I'd just flown across eight time zones).

We got back into our vehicles and headed toward the neutrino telescope, staying near the northwestern coast. An old railway track, completed in 1904, snakes along the mountainous shoreline. For decades it was an integral segment of the Trans-Siberian Railway. But a hydroelectric power plant built near Irkutsk in the 1950s dammed the Angara River, which flows out of Lake Baikal, and large sections of the track were flooded. New tracks were built beyond the mountains, rendering much of this hundred-year-old engineering feat somewhat obsolete, though local trains still use it. The neutrino experiment outpost depends on these trains to bring in equipment and, more important, groceries. During winter, someone occasionally drives 40 kilometers on the ice to the nearest town for provisions, but the train is the real lifeline, and the only one when the lake is not frozen. About twenty-five years ago, when the experiment started up, the researchers converted two former railway buildings for their own use. The building at kilometer 106 (signifying the distance from Irkutsk) became the shore station—the control room housing all the electronics and some of the staff during their two-month stay every winter. The other building, at kilometer 107, became the canteen and home to the experiment's chief spokesman, Grigory Domogatsky. Trains still stop at the rudimentary platforms of wooden planks, but none that can match the majesty of the Trans-Siberian a century ago.

Four kilometers offshore from Building 106 is the neutrino telescope's ice camp. From the shore, the camp looks like a line of indistinct black dots on the white expanse, towering snow-covered mountains on the far shore acting as a dramatic backdrop. As you get closer, the dots morph into cabins, cranes, jeeps, trucks, an electricity generator, and, closer still, people. On the day I visited, almost everyone was clad in a gray-blue jumpsuit, except for one man who was bare-chested, presumably warm from the work. They were all huddled around a square hole in the ice. A winch had just pulled up one string of the neutrino telescope from the depths of the lake. The top of the string, a collection of hollow balls that act as a large buoy, lay in a tangle on the ice. The rest of the string was still below in the dark waters, and attached to the submerged part of the string were the photomultiplier tubes, to be brought up to the surface for repairs and upgrades.

The Lake Baikal neutrino telescope is made of eleven strings of

photomultiplier tubes—each with a large buoy at the top and a counterweight at the bottom—that float nearly 1.1 kilometers below the surface (the water here is 1.4 kilometers deep, enough for a building three times as tall as New York's Empire State to sink without a trace). Smaller buoys attached to the strings float about 10 meters below the surface. All year round, a total of 228 PMTs watch for the Cherenkov cones created by neutrinos, monitoring 40 megatons of water. Each winter, once the ice camp has been set up, the team has to locate the telescope, the upper part of which drifts slightly over the course of the year. A diver plunges into the ice-cold water to locate the small buoy fixed to the center of the telescope. Then the researchers cut holes in the ice above each string (whose positions they know relative to the center) and attach a winch to the small buoys to haul up the strings. 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. They have perfected their technique; only once in two decades of operation did they have a problem retrieving a string. In 1994, a rusty metal cable broke, severing the buoy from its string, causing the string to sink to the bottom.

Budnev retrieved it. Diving that deep was out of the question, but Budnev knew that the string—though its counterweight was on the lakebed—would still be vertical because of the buoyancy of the PMTs. What he did next was ingenious. He fashioned a propeller and tied it to the end of a long rope, dropping the propeller into the water. The angle of the blades was such that as the propeller sank it started rotating, making huge circles. Budnev used this simple tool to sweep the waters below. Soon, the propeller snagged the errant string, and the team pulled it up. Wischnewski narrated the story of Budnev's heroics as we stood on the ice, surrounded by the hardiest physicists I had ever seen. The term "experimental physics" took on new meaning in this biting cold, which at times dropped to –4°F.

My admiration for these men increased when I saw just how tough their living conditions were. Wischnewski had warned me in London that things were difficult. Most of the physicists lived in 10-by-20-foot cabins, two to a cabin. Others slept in bunk beds in 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. Drinking water was collected each morning from a hole in the ice near the shore—Lake Baikal was pure enough to drink from, the very quality that made it so good for neutrino physics. Toilets were mere pits in the ground, with a wooden cabin around them for privacy. The extreme cold helped control the stench, but it still wafted up when warm urine hit the pit.

There was one luxury here: the *banya,* a traditional Russian sauna. Everyone used it to get clean, but more important, to relieve the stress of working in this bleak, albeit beautiful place. "It is much more important than one can imagine," said Wischnewski of the *banya.* "It is the central part of the weekly rhythm of life here." Naked men sit in an outbuilding, chuck water on hot stones to raise steam, and beat each other with leafy twigs and branches of birch. Then they go out into the freezing cold and pour cold water or rub ice on themselves. It's supposed to bring blood rushing to your skin, open pores, expel toxins, cure disease. Heinze, the German geologist with whom I was sharing a room in a log cabin, swore that he had gone to the *banya* with an upset stomach and had come out feeling fine.

A wicked wind kicked up one evening. Locals call it the *Kultuk,* after the village on the southwestern tip of the lake. It was time for everyone to leave the open ice and head back to the shore station. Once in the shore station, a few of us sat in the kitchen, which looked like a kitchen you would find in a college fraternity house. Years of use had stained the coffee mugs. Dented, discolored pots and pans lay scattered on the shelves. Someone heated up water for tea. I gratefully sat down for a cup, and a can of sweet, syrupy condensed milk materialized. "After a while [here], I start craving chocolate and sugar," said one researcher. "Stress, I guess," he added, as if he needed an excuse for the craving. Another 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 walk to the canteen at kilometer 107 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. Now I had to make my way over the lake to the canteen in the dark. I followed Wischnewski. While we were still onshore, I walked along vehicle tracks, where the ice had turned slushy and provided some traction. But 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 while walking on the lake, but that night, fear nearly paralyzed me. Fortunately, a jeep pulled up beside us, 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.

The cabin was a simple affair—one half had two bunk beds, with a long table in the middle. The place bristled with electronics—computers, modems, radios, wires. Belolaptikov shared it with Andrei Panfilov, from the Institute of Nuclear Research in Moscow. We talked for an hour, stopping only for some honey-sweetened tea that Panfilov made. Konstantin Konischev, the bare-chested scientist I'd seen earlier on the lake, now dressed in warm clothes, joined in every now and then, especially when the others struggled with their English.

"My business is the reconstruction of muons and neutrinos," said Belolaptikov, 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 PMTs at different times. The skill lies in collecting all the information reaching the PMTs 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 has to identify the source of neutrinos in the sky, and the Lake Baikal instrument can do so with an angular resolution of about 2.5°, meaning that it can distinguish neutrinos coming from points in the sky separated by a distance of five full moons. The Baikal telescope—like all other neutrino telescopes that use natural bodies of water or ice—has seen only atmospheric neutrinos. Everyone here is waiting for the day when a high-energy neutrino from outer space will make its presence felt in their little corner of the lake.

Belolaptikov recalled his first neutrino—indeed, the Baikal detector's first. "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 by the PMTs along the way. "This is the first one—the real, reconstructed one." Teenagers have pin-ups on their walls; Belolaptikov had this drawing of an event from 1993. And why not? It was the first-ever neutrino seen by humans using a natural body of water as a detector. He and his colleagues had done the reconstruction and put the Lake Baikal detector on the map.

Such scientific scoops must make up for the stress of this job. The expedition, as the Baikal team calls their annual two-month effort, starts with the making of an ice road from Listvyanka to the ice camp. Around mid-February, after the lake's surface has fully frozen, a scouting team sets off from Listvyanka, looking for stretches of ice that seem safe to drive on. Every couple of kilometers, they drill into the ice and remove a core, just to make sure the ice is thick enough. Then they stick a small spruce tree—a recycled Christmas tree—into the hole, and the water freezes around it, leaving the tree stuck firmly in the ice.

Once they make this tree-marked path over the ice, stretching nearly 40 kilometers from the town to their experiment site, the scientists set about locating the submerged telescope. The year I was there, the ice was relatively smooth and the work had been correspondingly easy. But Belolaptikov recounted a particularly harrowing year when the snowfall had been heavy and ice sheets were crashing against each other everywhere, creating massive ridges lined with insurmountably high chunks of ice. One day, Belolaptikov was in the shore station while the others were cutting holes in the ice above the telescope, 4 kilometers from shore. He got a radio call. They were in trouble. "There were big crashes, and very dangerous crashes," Belolaptikov said.

"The ice had shifted in one hour," Konischev, who had been one of the stranded physicists, recalled. Massive cracks, 2 to 3 meters wide, opened up in some places, separating those at the ice camp from the shore station. The team drove along the cracks for nearly 8 kilometers, looking for a way back. "We found one place where we could cross, but we had a bad feeling," said Konischev. "So we called Igor." Belolaptikov scouted the crack from the shore side and found another section that looked safer. "I had to decide something, and I decided that this place was OK," he recalled. "It was really terrible." But Belolaptikov's hunch proved right, the ice held firm, and everyone got safely ashore.

The temperature outside had dropped dramatically. The scientists were almost done with work for the night. Wischnewski had invited everyone to the shore station for a drink—I was to bring my bottle of Chivas Regal. Panfilov joined us, as did Vasily Prosin, a slightly built, extremely fit fifty-nine-year-old physicist from Moscow (he routinely skied the 40 kilometers from Listvyanka to the shore station). Prosin's lanky colleague from Moscow, Leonid Kuzmichev; two Tartars, Vladimir Aynutdinov and Rashid Mirgazov; and a German student named Eike Middell rounded out the group. The whisky was a welcome change from the traditional vodka and Aynutdinov decided that fine whisky should be had on the rocks. He stepped out to get some from the lake, but could not brave the trek down to the shore in the cold. He returned with some sorry-looking lumps snapped off the icicles hanging from the roof of the shore station. During the third round of shots, Prosin and Kuzmichev revealed that they had been fans of Bollywood during their youth, and Prosin and

I broke into a song, *Awaara Hoon* ("I'm a Vagabond"), from a 1960s Hindi film. Wischnewski seemed bemused, clueless as to this cross-cultural exchange.

The whisky finished, Wischnewski brought out a bottle of vodka and poured everyone a shot. As if on cue, each of us dipped a finger into our drinks and flicked a few drops of vodka onto the ground (the gods, it seems, do not care for whisky). The night became fuzzier, despite my gorging on food to keep up with everyone. The conversation flowed, switching easily from Russian to English, and occasionally Italian or German. Wischnewski made the last toast to the Lake Baikal telescope.

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 condensed milk with paper to prevent "little animals," as Wischnewski calls insects, from getting in. And then there was my first visit to the outhouse, at 2:00 A.M. Even as I went to sleep the first night, I was worried about this, with temperatures going down to 5°F outside. But nature called, and it meant getting out of my Russian military-issue sleeping bag and into layers of thermals, T-shirts and jackets, thick socks and shoes. A blast of vicious cold hit me as I stepped out of the relatively warm, heated cabin into the naked winter outside. The tire tracks of jeeps that had turned the ground slushy during the day were frozen solid. I was treading on treads. The two-minute walk was its own mini-expedition. Within days, this too became commonplace and the cold just a state of mind. I was walking out in socks and sandals by the end of my stay.

The mornings were ethereal. From my cabin, I could see clear across the lake, its snow-white stillness broken only by patches of bare ice that appeared dark against the snow. I had to remind myself that I was looking at a lake that has more water than the five Great Lakes of North America put together, a lake with a surface area larger than Belgium's. Eighty percent of Russia's fresh water was

here. Even at great depths, the lake is well oxygenated, making it one of the most hospitable waters for life.

On a visit to the Lake Baikal museum in Listvyanka, I learned why this body of water is so precious for astroparticle physics. It's 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.

Budnev, who lives in Irkutsk, was on his twenty-sixth neutrino expedition. And he spends time at Lake Baikal at other seasons of the year. "It is a very, very kind water," he said. "It is very important for Russia to preserve Baikal." But that's not necessarily happening. A paper and pulp mill had been operating since the 1960s in the town of Baikalsk, polluting its corner of the lake for decades. And a week before my arrival, protests took place in Irkutsk against an oil pipeline that was to be built along the northern shore. Local politicians and scientists joined hands to fight this plan, which they argued was ill-advised in such a seismically active region. An oil spill would devastate the lake. But no one from Moscow appeared to be listening. This balding physicist, with blue eyes, a stocky build, and thick, rough fingers that belonged to someone unafraid of working with his hands, softened as he spoke of the lake. "If you kill Baikal biology, then there is no way to clean the water," he said. Though he was speaking about the lake's ecology, his manner suggested a greater kinship with these pristine waters.

Besides the lake, Budnev is proud of their detector, which has pioneered the technology of underwater neutrino telescopes. Ironically, the team owes this honor partly to the Soviet Union's invasion of Afghanistan. In the 1970s, an international collaboration that included Americans and Russians was working on building DUMAND, the Deep Underwater Muon and Neutrino Detection Project, in the Pacific Ocean off the coast of Hawaii. Then the Soviet military marched into Afghanistan in 1979, and the partnership started to unravel. The U.S. government threatened to pull funding if the Americans kept working with the Russians, so the teams went their separate ways. The Russians turned to Lake Baikal and the Americans, led by John Learned of the University of Hawaii, stuck to the Pacific. Then, in 1993, disaster struck DUMAND. The researchers had managed to place a string of photomultiplier tubes at the bottom of the Pacific, at a depth of 4.8 kilometers. But soon after it was deployed, the string short-circuited, and the physicists could not communicate with their equipment. Harsh winds and waves kept making things difficult, and finally, in 1995, the U.S. Department of Energy pulled the funding altogether. The Russians went on to build the Lake Baikal telescope, and when it was turned on in 1993, it was the only game in town.

That has now changed, as European physicists have started building similar detectors in the Mediterranean. And a new American-European team moved 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. I would find myself, many moons later, at the South Pole, wondering which of these detectors would make history by seeing the first neutrinos from deep space.

Meanwhile, despite the enormous political chaos that followed the fall of the Soviet Union, the Baikal group has persevered. They still believe that the lake is an extraordinary place to look for neutrinos. While the Antarctic ice is clearer than the waters of Lake Baikal, the water has an edge. Light can travel more than ten times farther in the lake before it is scattered than it can in the ice. 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 harder to work out their original direction. This means that more photomultiplier tubes are needed in the Antarctic ice to gather the information needed to infer the direction of neutrino-induced muons. The Lake Baikal water allows for a less dense array of PMTs. A kilometer-cube detector in these waters would likely be cheaper to build and maintain than the one being built at the South Pole.

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. Domogatsky smoked filterless Russian cigarettes nonstop. His English was halting, and he had a habit of drumming his fingers on the table or snapping them as he searched for the right words. Despite a rasping smoker's cough that could stop him mid-conversation, he passionately argued that the biggest neutrino detector should be built 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 PMTs 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," said Domogatsky, with the gentle yet triumphant note of a teacher who has just made a telling point. Of course. Neutrino detectors can see only those neutrinos that come through the Earth. While optical telescopes can study the Milky Way's center from the Southern Hemisphere, only the Baikal detector and the three being built in the Mediterranean—off the coasts of France, Italy, and Greece—will be able to see neutrinos coming from the heart of our galaxy. So physicists need a detector the size of IceCube in the Northern Hemisphere to best observe our galaxy's center—a must for the indirect detection of dark matter.

Domogatsky further argued that Lake Baikal was the best body of water in which to build such a detector, for there are no deep-water currents to contend with, as there are in the Mediterranean. "The currents really don't exist. 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. 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.

Amid this discussion, Domogatsky made tea and laid out a spread of dates, raisins, biscuits, and nuts. He continued smoking, despite his cough. His heavily furrowed face clearly showed the effects of forty years of physics, many of them spent in this hostile place. Now he was looking to pass the baton. The team had just figured out that the telescope they had built so far—eight strings with a total of 192 PMTs within 21 meters of the center and three more strings with a total of 36 PMTs within 100 meters of the center—could form a cell of a much, much larger telescope. Put next to each other, like hexagonal tiles on a floor, such cells could cover a gigaton, 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 projects or at the South Pole.

The fire died. Outdoors, the sun was setting.

"I hope to help start this project," said Domogatsky. "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 and started walking back to the shore station along the railway line from kilometer 107 to 106. The dark silhouette of the canteen's wooden building stood out against an orange-pink twilight sky. A light shone through the dining room doors. Somewhere far behind me, a train sounded a long, low hoot.

There was just one thing left to do. Wischnewski had suggested that my visit would be incomplete without spending a night on the ice. He said I could sleep 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 frozen surface, he said, the water beneath is alive and kicking. Sometimes the entire sheet of ice below the camp can jerk and lurch. When that happens the first time at night, you are so scared that you scamper out of your sleeping bag and head straight for open ice. Wischnewski assured me that nothing serious would happen unless a magnitude-6 earthquake hit the region. I wasn't amused.

Walking along the snow-covered railway track, taking care to step gingerly on the wooden railroad ties, I realized that I was afraid. The thought of the ice creaking, groaning, and shifting beneath me as I slept was too much to contemplate. But by the time I got back to the shore station, arrangements had already been made. Someone at the ice camp had agreed to give up his bed for the night. There was no backing out now.

Night came, and Wischnewski and I raced over the ice toward the camp in someone's brand-new Japanese 4 x 4, a far cry from the Russian military jeeps. Flashlights in hand, we walked across the ice for the last few meters; vehicles weren't allowed beyond a certain marker. The sure-footedness I had developed over the last couple of days had disappeared. The cranes and winches looked ominous in the dark. Wischnewski knocked on the steel door of one of the cabins, and a young graduate student named Alexey Kochanov admitted us. He told me not to worry; small earthquakes happened here all the time, he said. Hardly reassuring.

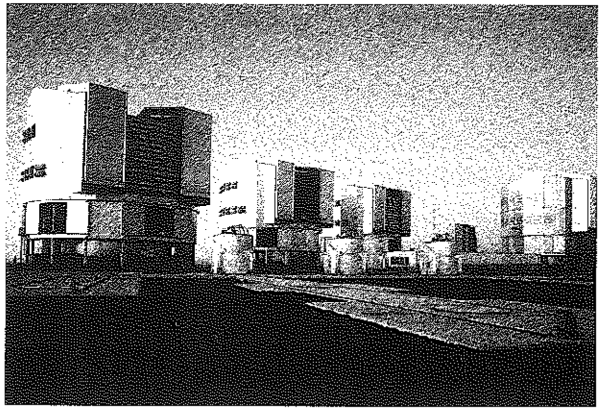
I got into my sleeping bag and again voiced my concern. Kochanov said that he found the sound of ice creaking beneath him relaxing. Obviously he had been here way too long. But then he explained. The creaking means that the ice cover is solid. It is the sound of ice moving in response to the motion of 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. So much give, in fact, that you shouldn't be on the lake.

Suddenly, the ice's protestations were music to my ears. All night it groaned, a sound like nothing I had ever heard, and the sheer variety of groans was tremendous. When they came from far away, they sounded like muffled gunshots or cannon fire or steel doors being slammed shut. The closer sounds were sharper, more like the crack of a whip. Sometimes it lasted a couple of seconds, and sometimes it was right beneath us, a split streaking through the ice below. I finally fell asleep.

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 put on my layers of clothing and my socks and shoes and 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. Everywhere, thinner cracks had refrozen, forming intricate patterns. In the feeble beam of my flashlight, these flowerlike designs appeared in relief against the darkness below. A generator hummed nearby, but it did not ruin the quiet and stillness of this immensely cold place. Moonlight played with the ice, barely hinting at its thickness and the vast expanse of bone-chilling water beneath. 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.

I got back into the cabin and into a bed warmed by electric heaters. 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 on its way, and gone right through the center of the Earth, only to collide with a molecule of water in Lake Baikal and disappear in a flash of light. Will the artificial eyes below see such a flash one day and know that they have seen, for the first time, a ghostly particle from the center of the Milky Way?

If so, it could help unravel the mystery of dark matter and illuminate the makeup of about a quarter of the universe. To understand how cosmologists are tackling the rest of the unknown, I traveled to a place that is the antithesis of Siberia: a parched desert in the Chilean Andes.



4 · THE PARANAL LIGHT QUARTET

THE FIRST THING that struck me as I flew into Antofagasta was that the city had few trees. Everything in the landscape was a shade of brown or gray, from dark, rusty rocks to pale, ashen silt. The dust-laden trees lent some semblance of green, but even they seemed forlorn and entirely out of place in this desolate land. Antofagasta is a port city on Chile's northern coast, on the edge of the Atacama Desert. To the west lies the Pacific Ocean, which today looked sullen beneath a cloudy sky. To the east are the barren hills of the Cordillera de la Costa, which rise abruptly and dramatically. Antofagasta is, like most of Chile, a sliver of land wedged between mighty mountains and an immense ocean.

That's how a middle-aged, stubbled, and very tired-looking Chilean had put it a few hours earlier, in the Santiago airport, animating his halting English by holding his forefinger and thumb an inch apart to indicate just how thin his country is. We were both waiting for the flight to Antofagasta. I told him I was headed to Cerro (Mount) Paranal to see the observatory. He had heard not just of Paranal but