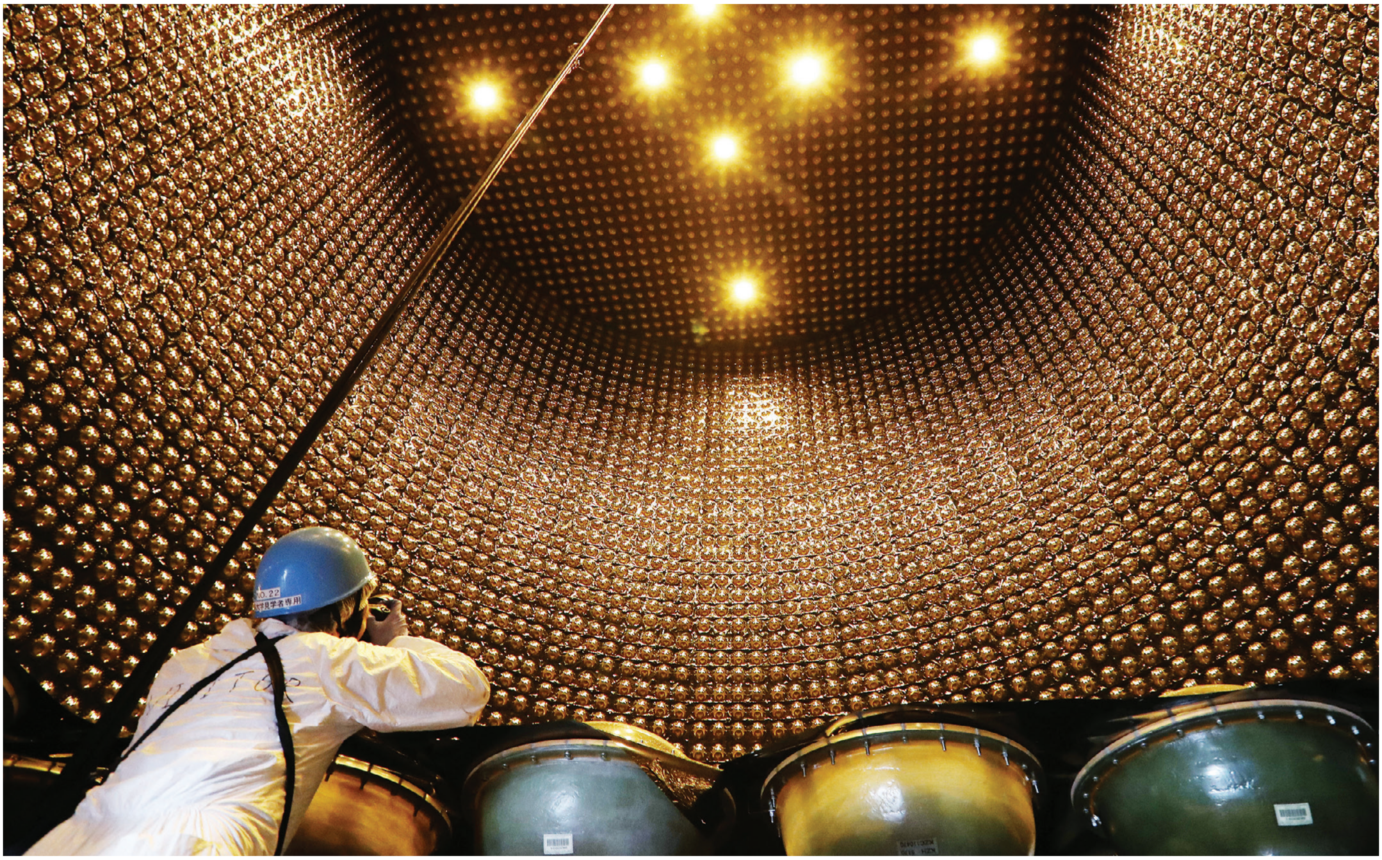

Observations by the Super-Kamiokande neutrino detector have forced theorists to amend the standard model of particle physics.

ASAHI SHIMBUN/GETTY

PHYSICS

Gigantic Japanese detector seeks supernova neutrinos

Tracing the history of exploding stars is a goal of the revamped Super-Kamiokande.

BY DAVIDE CASTELVECCHI

Eleven thousand giant orange eyes confront the lucky few who have entered the Super-Kamiokande underground neutrino observatory in Japan — by far the largest neutrino detector of its kind in the world. A chance to see these light sensors is rare because they are usually submerged in 50,000 tonnes of purified water. But a major revamp of Super-K that was completed in January offered a rare chance to peer inside this grand cathedral of science.

For the first time in more than a decade, between June and January, the water was drained from the detector as part of a ¥1.1-billion (US$10-million) refurbishment. Among other things, the upgrade will allow Super-K to hunt for neutrinos emitted by remote supernovae, explosions that occur when an ageing star collapses under its own weight. These data will help astronomers to better understand the history of supernovae in the Universe — but the neutrinos that the explosions emit have been difficult to detect.

“Every 2–3 seconds, a supernova goes off somewhere in the Universe, and it produces 10^{58} neutrinos,” says Masayuki Nakahata, who heads the Super-K, an international collaboration led by Japan and the United States. With the upgrade, the detector should be able to count a few of these ‘relic’ neutrinos every month, says Nakahata, who is a physicist at the University of Tokyo.

Super-K sits 1,000 metres under a mountain near Hida in central Japan. Inside, water molecules catch neutrinos that stream through the ground from the Sun and the atmosphere, or that are beamed in from a particle accelerator hundreds of kilometres away. Later this year, the observatory will add the rare-earth metal gadolinium to the water. This will make the detector much better at distinguishing between different types, or ‘flavours’, of neutrino, as well as their antiparticles, antineutrinos.

In 1987, the Kamiokande detector, Super-K’s smaller predecessor, detected the first neutrinos from a supernova. The dozen neutrinos came from Supernova 1987A, which occurred in the Large Magellanic Cloud, a small galaxy that orbits the Milky Way. Head experimenter Masatoshi Koshiba shared the 2002 Nobel physics prize partly for that discovery. But no neutrinos have been linked to a supernova since then.

Most solar neutrinos reveal themselves by knocking an electron off a water molecule at high speed, thereby producing a faint flash of light (which is what Super-K’s ‘eyes’ see). But other neutrinos — and, in particular, the antineutrinos that constitute the bulk of supernova emissions — interact with a proton in an atomic nucleus instead of with an electron.

This collision releases a neutron and a positron, the antimatter version of the electron. The positron's signal is difficult for the detector to distinguish from that of an electron from a solar neutrino. But the neutron produces its own signature — a γ-ray — when captured by another nucleus.

Gadolinium nuclei are much more effective than are water's hydrogen or oxygen nuclei at capturing such stray neutrons, and the γ-rays they produce are easier for Super-K to detect, as another flash of light. Thus, when an antineutrino hits, Super-K will see not one flash but two, a few microseconds apart.

John Beacom, a theoretical astrophysicist at Ohio State University in Columbus, and Mark Vagins, a Super-K experimentalist now at the Kavli Institute for the Physics and Mathematics of the Universe in Kashiwa, Japan, came up with the idea of adding gadolinium to Super-K in the early 2000s (J. F. Beacom and M. R. Vagins *Phys. Rev. Lett.* **93**, 171101; 2004). Gadolinium had been used in smaller neutrino experiments, but never in a water detector.

"When we first started, everybody we talked to gave us a list of ten reasons why it would be impossible," says Beacom. The biggest challenge, Vagins says, was whether the detector's water could be continuously filtered to remove impurities without removing the gadolinium at the same time. He led a decade-long effort to demonstrate that the idea could work, which involved building a $6-million neutrino detector, humorously called Evaluating Gadolinium's Action on Detector Systems (EGADS).

By 2015, Beacom and Vagins had persuaded the collaboration to include gadolinium in the next upgrade. That part of the revamp is unofficially known as Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super! (GADZOOKS!).

> **"Everybody we talked to gave us a list of ten reasons why it would be impossible."**

Super-K has already been hugely successful. In 1998, two years after operations began, the detector provided the first solid evidence that neutrinos and antineutrinos can 'oscillate', or cycle, between three flavours. The discovery forced theorists to amend the standard model of particle physics — the explanation of the Universe's particles and forces — and raised a slew of new questions. (Takaaki Kajita, who is Nakahata's colleague and the former leader of Super-K, shared the 2015 Nobel physics prize for his discovery of neutrino oscillation.)

"Super-K has been as influential on particle physics, if not more influential, than LHC, the collider at CERN that discovered the Higgs boson," says Janet Conrad, a neutrino physicist at the Massachusetts Institute of Technology in Cambridge.

"I am thrilled that Super-K is starting up with gadolinium doping now. I think the physics is very exciting," says Conrad.

As Super-K starts afresh, Japanese physicists are pushing for an even bigger sibling called Hyper-Kamiokande. The University of Tokyo has thrown its weight behind the ¥55-billion project, and researchers are now waiting to hear whether the national government will fund it. A decision is expected in August. "We aim to start Hyper-K construction in two years, and then start operation in 2027 or so," says project leader Masato Shiozawa, a physicist at the university and a long-time member of the Super-K collaboration.

Hyper-K's tank would hold 260,000 tonnes of water. Its sheer size would make it much more effective than Super-K at detecting supernovae, but it should also help it to investigate why the Universe seems to be made mainly of matter, with little antimatter around. A crucial step towards understanding this difference will be to measure an asymmetry between neutrinos and antineutrinos, specifically, a difference in the speed at which antineutrinos cycle through their three flavours, compared with neutrinos. Super-K has already seen strong hints of such a difference, but Hyper-K would be able to make more-precise measurements. ■