ENRICO SACCHETTI

CHAMBER OF PHYSICS

The world's largest underground laboratory has been a success story for Italian science. But 30 years after construction began, its future is uncertain.

BY NICOLA NOSENGO

The drive along Italy's highway A24 from the central Adriatic coast towards Rome begins with a winding climb into the snow-covered Apennine Mountains, followed by a plunge into the 10-kilometre-long tunnel under Gran Sasso, the highest peak in the region. About half way through the tunnel, a detour leads off to the right. It reaches a dead end almost immediately at a heavy iron gate. But press the intercom button and utter the words 'particle physicist' into the microphone, and the gate slides open like something from a James Bond movie.

Not far beyond the gate is a car park. From there one continues on foot, and begins to get some idea of the scale of the infrastructure hidden beneath the mountain. Opening off a long corridor are three huge halls, each about 20 metres wide, 18 metres high and 100 metres long. This vast area is the home of the Gran Sasso National Laboratory, part of the Italian National Institute of Nuclear Physics (INFN).

In fact, the laboratory's 180,000 cubic metres of space is not its most valuable attribute. Lying under 1,400 metres of rock, it offers silence — not an absence of sound, but of cosmic-ray noise, the rain of particles constantly bombarding Earth's surface from space. This lack of cosmic interference has attracted a generation of physicists to these halls, where they can study some of the rarest and most elusive phenomena in the Universe.

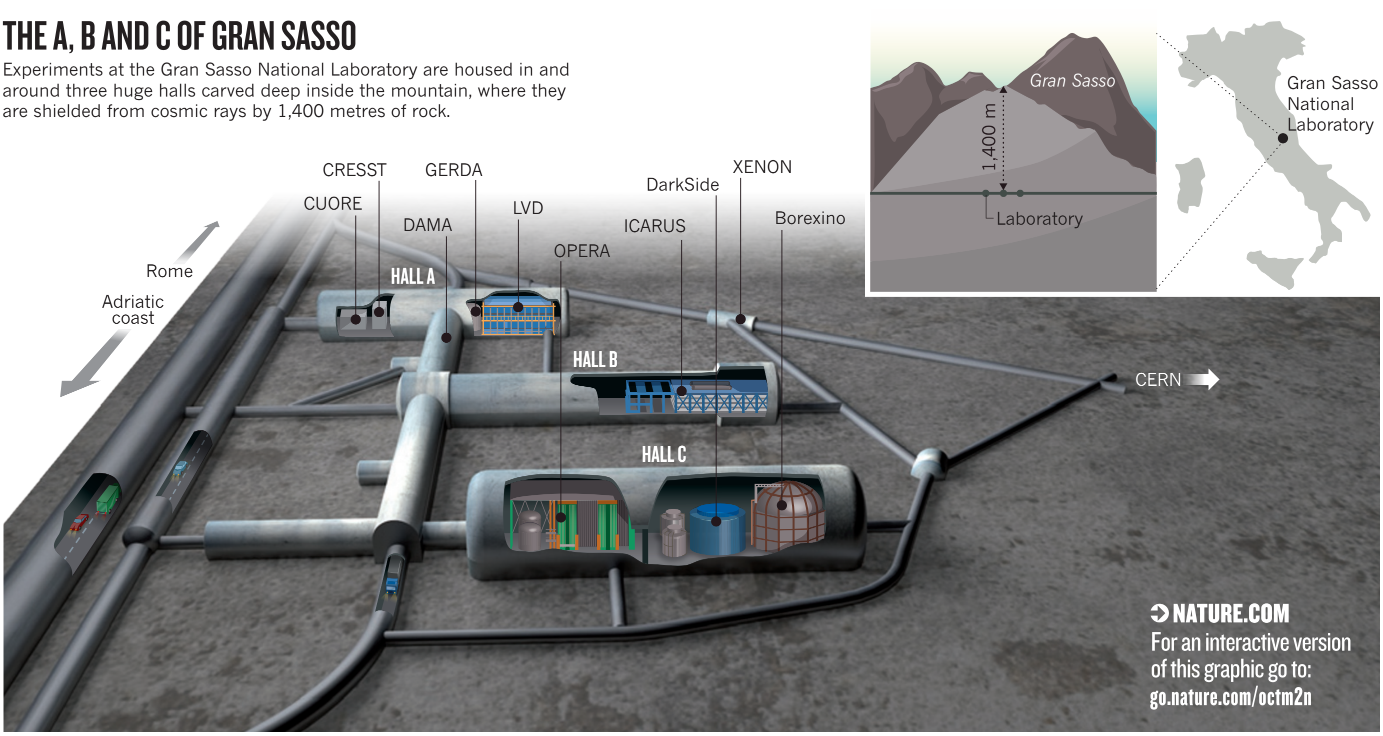
Most people probably first heard of Gran Sasso last September, when its OPERA experiment reported — incorrectly, as it turned out — that neutrinos seemed to travel faster than light. But the laboratory, construction of which began 30 years ago, has long been known to physicists. Gran Sasso "was the first true underground laboratory, the only one purposely built for science", says Stanley Wojcicki, a physicist at Stanford University in Palo Alto, California. It is still by far the largest, serving as a base for 18 experiments and about 950 researchers from 32 countries.

"Gran Sasso's halls have allowed experiments based on different technologies to work side by side, comparing each other's pros and cons, and building multiple generations of the same experiments," says Kevin Lesko, a neutrino physicist at the Lawrence Berkeley National Laboratory in Berkeley, California. The result has been some

Gran Sasso's Large Volume Detector (LVD) searches for neutrino bursts from supernovae.

THE A, B AND C OF GRAN SASSO

Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.



long-standing underground rivalries. But they have helped to make Gran Sasso one of Italy's strongest scientific success stories, responsible for a string of notable results in neutrino and solar physics. "It is our trading currency with the international physics community" says INFN president Fernando Ferroni.

At the age of 30, however, Gran Sasso finds itself in transition. Its scientific priorities are changing, and a long collaboration with CERN, Europe's premier particle-physics laboratory near Geneva in Switzerland, is nearing its end. Budget cuts are making it harder to keep Gran Sasso running. International competition is increasing, thanks to proposals to put in new detectors at other facilities such as SNOLAB near Sudbury in Canada, Japan's Kamioka laboratory and the Soudan laboratory in Minnesota, as well as the proposed Deep Underground Science and Engineering Laboratory at the Homestake gold mine in South Dakota. And although many of its experiments have had important results, Gran Sasso is still waiting for its first big discovery: a groundbreaking finding that would match its size and the ambitions that spawned its creation.

THE MYSTERY OF THE MISSING NEUTRINOS

When Gran Sasso was first conceived in the late 1970s, one of the key motivations was political. Antonino Zichichi, who proposed and oversaw the project as president of the INFN, admits he wanted to give Italy something that would increase its weight in the international physics community and counterbalance CERN's role in European physics.

But there were also two solid scientific drivers. The first was the case of the 'missing' neutrinos. Since the late 1960s, US physicist Raymond Davis had been running an experiment in Homestake to detect neutrinos created in nuclear reactions at the core of the Sun. He found only about one-third of the number predicted by theory. Other physicists had suggested a solution: if neutrinos 'oscillate' as they travel in space, spontaneously transforming from one of their three types to another, they would be so thoroughly mixed by the time they arrived at Earth that only about one-third would still be the type that Davis's detector could pick up. But because neutrinos interact so weakly with other particles, testing that idea would require a detector shielded from cosmic rays by hundreds of metres of rock.

The other problem was proton decay. Various efforts to build 'grand unified theories' of particle interactions suggested that the proton was ever so slightly unstable, and would decay into lighter subatomic particles with a half-life many times longer than the age of the Universe. The only hope of seeing such a rare event was to monitor a huge amount of matter for a long time, while shielding it from any background radiation that might swamp the signal.

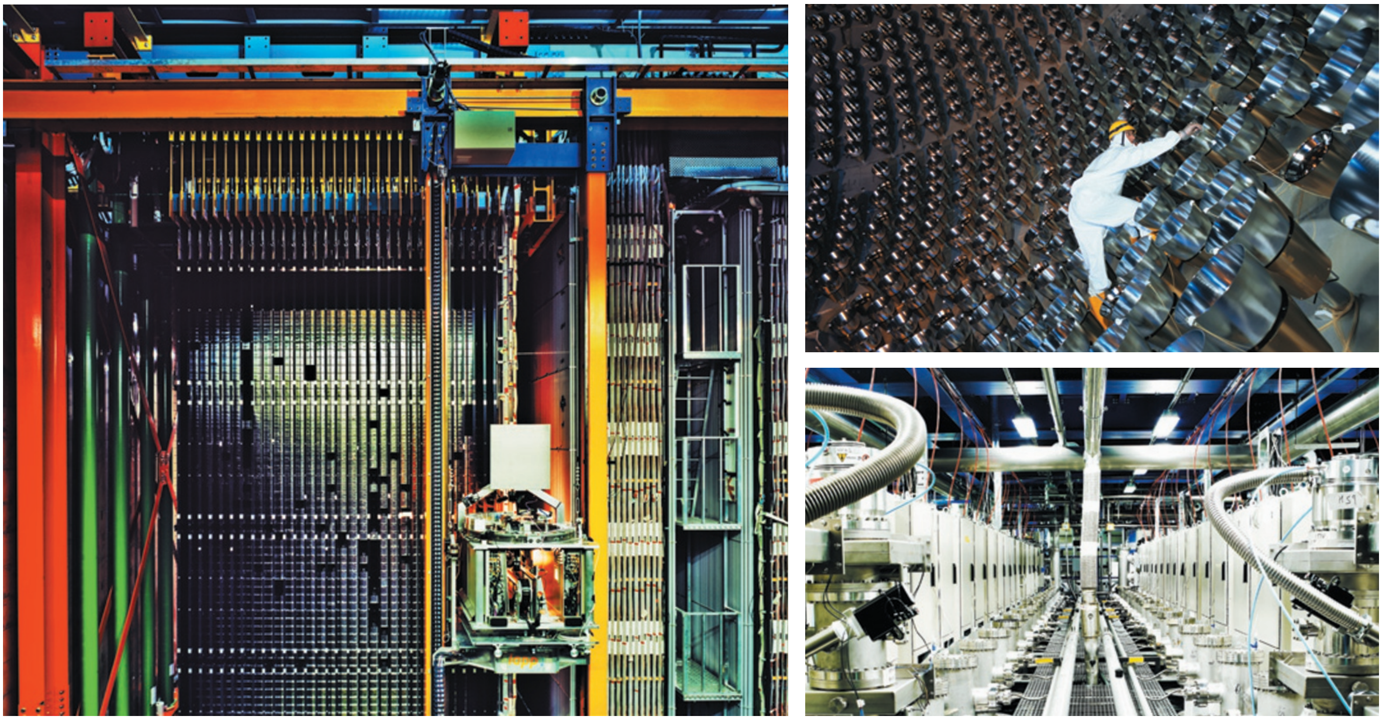
All the project needed was a gigantic cavern in a mountain. Zichichi found it at Gran Sasso, 120 kilometres from Rome, where a highway tunnel under the mountain had been started and then abandoned for economic and political reasons. "The shape of the mountain was ideal", he recalls. "Gran Sasso is flat, so the thickness of the shield remains constant along its length." INFN physicists measured cosmic rays in the gallery, and found that their flux was about one million times lower than at the surface. Radioactivity measurements were also encouraging, one thousand times lower than on the ground. Gran Sasso's dolomite rock is very poor in uranium and thorium, the main sources of natural radioactivity.

A mountain with the ideal physical properties, already containing a tunnel but devoid of traffic — "it seemed too good to be true", says Zichichi. Had they had to build the laboratory from scratch, he says, it would have cost too much. As it was, its estimated price tag came to 77 billion Italian lire, roughly equal to US$160 million today.

Zichichi presented the project to the Italian Parliament in 1979. It was approved in February 1982 — a decision had also been made to complete the abandoned highway — and construction began in September. In 1987, the halls were ready for the installation of the first experiments.

Building a scientific community took longer. "For a long time, Gran Sasso was mostly a training camp for underground physics," says Ferroni — an entirely different endeavour from particle accelerator physics, which was where most of the physicists coming to work in Gran Sasso had learned their craft. Rather than smashing particles against each other and seeing what happens, underground physicists spend their days painstakingly selecting and testing materials for use as shields and detectors, weeding out every conceivable source of background noise, and analysing months and months of data — only to find that, nine times out of ten, a 'signal' is just background noise that somehow got through.

The first-generation of experiments established what could and could not be done with underground detectors. Neutrino physics proved especially fruitful: one of Gran Sasso's most notable early experiments was Gallex, which ran from 1991 to 1997 and provided confirmation that Davis's absent solar neutrinos really were missing[1]. But the effort to measure proton decay was quickly abandoned. "Early theories were



OPERA, ENRICO SACCHETTI; BOREXINO, VOLKER STEGER/SPL; ICARUS, ENRICO SACCHETTI

At Gran Sasso, neutrinos are under intense scrutiny, with the OPERA (left), Borexino (top right) and ICARUS experiments all focused on their detection.

too naive," says Ferroni. "Seeing a proton decay would require one million tonnes of water, or more than 10,000 tonnes of liquid argon. We lack the technology, the laboratory, the money." Also shot down was the quest for magnetic monopoles: theoretical particles with just one magnetic pole, which were the subject of Gran Sasso's first major experiment, a primarily Italian–US collaboration called MACRO. Researchers searched for the particles between 1989 and 2000, but never caught a glimpse of them[2].

OPERA TAKES THE STAGE

By the 2000s, Gran Sasso had entered into a phase marked by new scientific priorities, a fully formed scientific community and the construction of the larger, more ambitious experiments that now fill its halls (see 'The A, B and C of Gran Sasso'). Coming from the car park, one first encounters Hall C and the Borexino experiment, a follow-on from Gallex that studies the full energy range of neutrinos emitted by the Sun. Borexino is a huge dome, 18 metres in diameter, with two concentric spheres nested inside it like Russian dolls. The outer dome is filled with ultrapure water that helps to reduce the radiation reaching the innermost sphere, which detects flashes of light caused by neutrinos hitting a scintillator liquid.

Cristiano Galbiati, a physicist at Princeton University in New Jersey and a member of the Borexino team, says that the experiment's unmatched background-noise reduction is what allowed the team to report last October the first ever detection of low-energy 'pep' neutrinos, which are produced by a rare reaction in the Sun whereby protons and electrons interact to make deuterium[3]. Predicted by theory but never previously observed, pep neutrinos formed one of the last missing pieces in models that explain how the Sun keeps burning. "Low-energy neutrinos from the Sun oscillate in a completely different way from high-energy ones," says Galbiati. "The only way to solve the solar neutrino problem once and for all is to measure neutrinos across the whole spectrum, and this is the only experiment that has knocked background noise down enough."

> "GRAN SASSO IS OUR TRADING CURRENCY WITH THE INTERNATIONAL PHYSICS COMMUNITY."

Right beside Borexino is the now famous OPERA experiment: a detector the height of a three-storey building made of about 150,000 'bricks' of photographic film separated by lead plates. Since 2008, OPERA has been looking for oscillations in a beam of neutrinos fired from CERN, some 730 kilometres away. The beam comprises only muon neutrinos, and the idea is to look for tau neutrinos at the Gran Sasso end, which would prove that they have switched from one type, or 'flavour', to another during their journey. OPERA reported its first tau neutrino in 2010 (ref. 4), and the team expects to confirm one or two more before the end of 2012.

But that achievement was not all that proponents had hoped. The experiment was first proposed in the 1990s, but negotiations with CERN, whose management was wary of distracting staff and funds from its conventional work, dragged on for the better part of a decade. By the time OPERA finally began collecting data, neutrino oscillations had long since been confirmed by similar neutrino-beam experiments in Japan and the United States. The one consolation was that those experiments were only able to record muon neutrinos disappearing from their beams — so far, only OPERA has detected their reappearance as taus.

However, those results were eclipsed by the OPERA team's announcement in September that its neutrinos seemed to be travelling faster than light[5]. The resulting media frenzy exacerbated divisions among team members — some of whom refused to sign the announcement preprint, arguing that the collaboration had no business publicizing what was almost certainly an experimental error. The dissidents' objections were also echoed early and often in neighbouring Hall B, home to OPERA's archrival ICARUS, a pair of rectangular tanks each 20 metres long and filled with 300 tonnes of liquid argon, that competes with OPERA on the detection of tau neutrinos. "OPERA's confidence level on tau neutrinos is not very high," says deputy ICARUS spokesperson Sandro Centro. "We will report our first results this year and we think we can do better." In October, the ICARUS team flatly contradicted OPERA with its own neutrino-velocity measurement, finding that the particles do not travel faster than light[6].

In the end, the dissidents were right: the source of the error, a loose data cable, was disclosed in February. But the incident led to the resignations of both OPERA's spokesperson, Antonio Ereditato, and its physics coordinator, Dario Autiero. Former Gran Sasso director Mario Monacelli, who is now an OPERA scientist and one of those who did not sign the velocity paper, says that the frenzy has not interfered with the experiment's day job. "But it has created tensions that will take some time to go away," he says. "We are now working to prevent the collaboration from breaking into opposing factions."

Another locus of tension can be found in Hall A and its surroundings, much of which are occupied by experiments searching for dark matter. The existence of dark matter is abundantly clear to astronomers, who can see its gravitational effect on galaxies and clusters of galaxies through their telescopes. But its nature is a mystery: the stuff is utterly transparent, and passes through stars and planets as if they weren't there. A prevailing theory holds that it is a haze of weakly interacting massive particles (WIMPs) that formed during the Big Bang, and have permeated the Universe ever since. The trick is to catch and study WIMPs in a laboratory detector — a task that, once again, requires ultra-low background radiation.

Gran Sasso's dark matter (DAMA) experiment, which opened in 1996 and has gone through many upgrades since, looks for flashes of light that occur when dark-matter particles collide with the atoms of a sodium iodide crystal. DAMA works on the assumption that Earth's velocity through the dark matter in our Galaxy varies as it orbits the Sun, producing an annual variation in the flux of dark-matter particles passing through the detector. For 13 years, the team has been reporting just such an oscillation in signal, although one that is consistent with dark-matter particles lower in mass than most theorists expect[7].

"EITHER THEY WILL END UP DESCRIBING SOME PREVIOUSLY UNKNOWN SOURCE OF BACKGROUND NOISE OR THEY WILL GO STRAIGHT TO STOCKHOLM."

The source of the tension lies just a few metres away, in XENON100: a US-led experiment that has been using more than 100 kilograms of liquid xenon as a detector for WIMPs since 2009. With its first publication in 2010, covering its first 11 days of data, the XENON team found no sign of WIMPs in DAMA's mass range[8]. The public finger-pointing goes on to this day. DAMA's Rita Bernabei insists that XENON's results depend on a specific model of dark matter. "There are candidates, scenarios and uncertainties that can account for all the results presented so far," she says, including those from both DAMA and XENON. But XENON scientist Francesco Arneodo is dubious. "You can play with models as much as you want, but it's a pity they did not make any effort to stimulate similar experiments elsewhere, which would close the argument," he says.

Ferroni sees only two possible resolutions for the DAMA controversy. "Either they will end up describing some previously unknown source of background noise," he says, "or they will go straight to Stockholm" to collect a Nobel prize.

THE ROAD AHEAD

Leaving behind the close atmosphere of the underground halls and following the highway tunnel to its western end, it's a short drive to the base of the mountain. Here, in Gran Sasso's above-ground offices, director Lucia Votano is planning its future.

Funding remains a concern, she says. Gran Sasso costs the INFN almost €10 million (US$12.8 million) a year — not including the experiments. The agency's budget has shrunk by one-third during the past decade, and a further 5% cut is anticipated in 2013 owing to Italian austerity measures.

But even without cuts, she says, many things will soon change under the mountain. By the end of 2012, the neutrino beam will vanish when CERN shuts down its accelerators to upgrade its flagship Large Hadron Collider. OPERA and ICARUS will almost certainly be disbanded. "At the moment it's really not clear what the future of neutrino physics in Europe will be," says Centro — although the ICARUS detector will be moved to CERN and used as a testbed to develop much larger detectors.

Gran Sasso, meanwhile, will be left to focus on dark matter, and on a second longstanding mystery just as crucial for understanding phenomena not predicted by the standard model of particle physics: neutrino-less double beta decay. This is a hypothetical form of radioactivity, thought to be extremely rare, that would be possible only if the neutrino is its own antiparticle. In 2001, Hans Klapdor-Kleingrothaus and his colleagues reported detection of the phenomenon using a now-dismantled experiment in Gran Sasso[9]. But no other experiment has been able to replicate the finding so far, and Klapdor-Kleingrothaus's use of statistics has been criticized by some scientists[10]. Although, admits Ferroni, who counts himself a sceptic, "if those results are wrong, they are so in a much less obvious way than the OPERA one".

Votano and Ferroni expect that Gran Sasso's GERDA experiment, which is looking for neutrino-less double beta decay in a detector with exceptionally low background radiation, will decisively confirm or reject the result within a couple of years. In around 2014, it will be joined by CUORE, a tower made from 1 tonne of tellurium dioxide. In the end, both experiments will probably prepare the ground for even larger detectors, which will further increase the probability of spotting the very unlikely event they are after. "It is too early to say which technology works best," says Votano.

As for dark matter, the XENON team is now building a 1-tonne detector — expected to begin collecting data by late 2014 — that will become the world's most sensitive detector for WIMPs. Another experiment in the making, DarkSide, will use 50 kilograms of liquid argon as its detector and will borrow the successful background reduction system of the Borexino experiment. DAMA, meanwhile, will undergo a further upgrade. And the German experiment CRESST is already looking for dark-matter collisions in crystals at temperatures near absolute zero.

Given all that, says XENON spokesperson Elena Aprile, a physicist at Columbia University in New York, "the first detection of a WIMP will come from Gran Sasso". Or, at least, she says, "this is where we will understand if we are completely on the wrong track".

However, they have competition. Similar dark-matter and double-beta-decay experiments are under construction or already running at Homestake, Sudbury and Kamioka. And with the completion of the 2,500-metre-deep Jin-Ping laboratory two years ago, China has joined the dark-matter race. Many of these experiments may take advantage of better natural shielding — something that physicists measure as metres of water equivalent. Gran Sasso's shielding equals 3,300 metres of water, against 4,100 at Homestake and almost 6,000 at Sudbury.

On the other hand, says Votano, Gran Sasso has developed techniques — such as the Russian-doll system pioneered by Borexino — that allow it to simulate a greater depth. It remains the largest and best equipped underground laboratory in the world. And, Aprile says, pointing to the snowy peaks that surround the external laboratories, the location is hard to beat. "If I can make good physics in a place like this, why not?" ■

Nicola Nosengo *is a freelance writer based in Rome.*

1. Anselmann, P. *et al. Phys. Lett. B* **285,** 376–389 (1992).
2. Ambrosio, M. *et al. Eur. Phys. J. C* **25,** 511–522 (2002).
3. Bellini, G. *et al. Phys. Rev. Lett.* **108,** 051302 (2012).
4. Agafonova, N. *et al. Phys. Lett. B* **691,** 138–145 (2010).
5. Adam, T. *et al.* Preprint at http://arxiv.org/abs/1109.4897 (2011)
6. Antonello, M. *et al.* Preprint at http://arxiv.org/abs/1203.3433 (2012).
7. Bernabei, R. *et al. Eur. Phys. J. C* **67,** 39–49 (2010).
8. Aprile, E. *et al. Phys. Rev. Lett.* **105,** 131302 (2010)
9. Klapdor-Kleingrothaus, H. V., Dietz, A., Harney, H. L. & Krivosheina, I. V. *Mod. Phys. Lett. A* **16,** 2409–2420 (2001).
10. Aalseth, C. E. *et al. Mod. Phys. Lett. A* **17,** 1475–1478 (2002).