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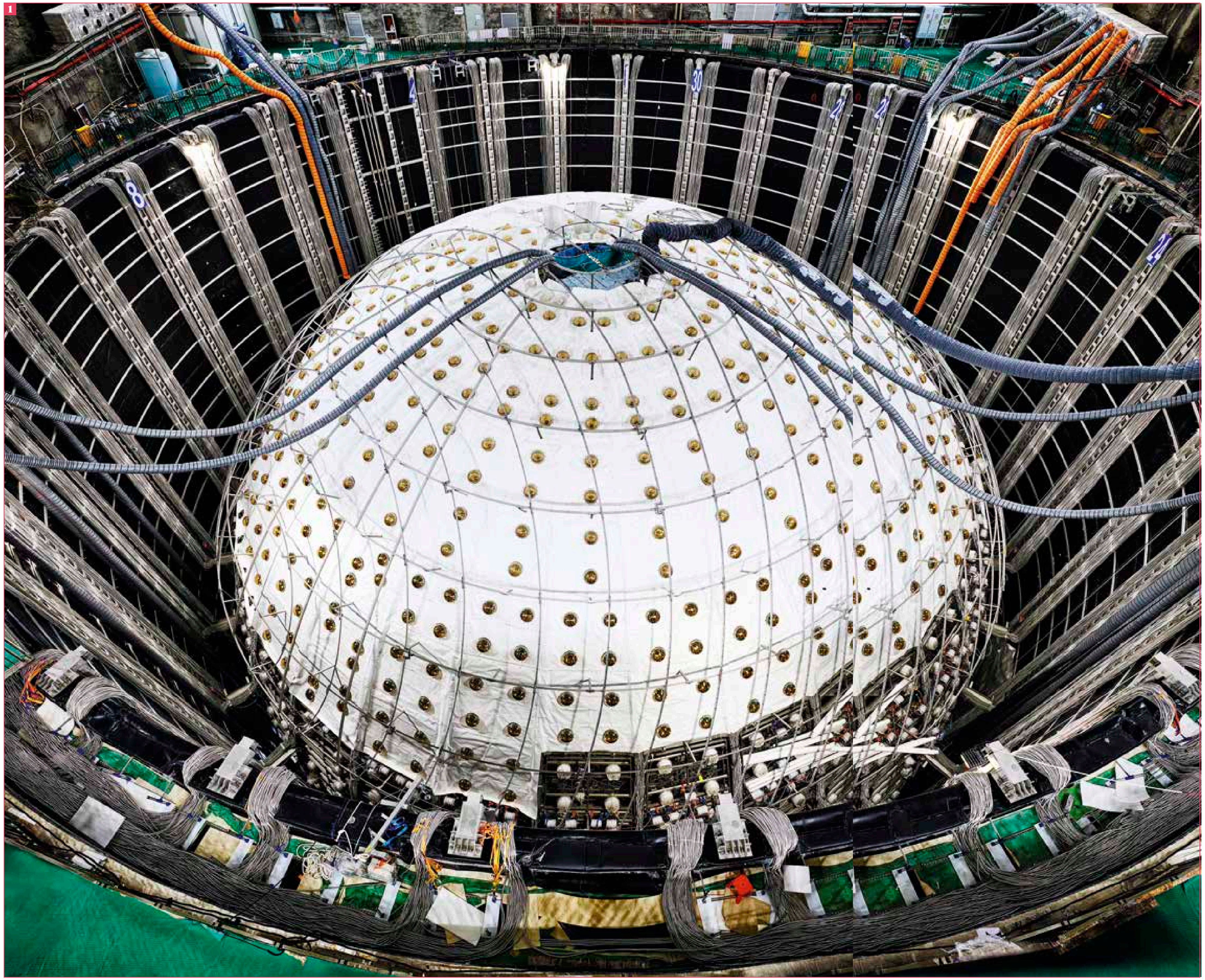

ENRICO SACCHETTI

GHOST DETECTOR

Currently under construction, the Jiangmen Underground Neutrino Observatory (JUNO) is set to unlock the secrets of nature's most elusive subatomic particle: the neutrino. It may ultimately provide the missing pieces of the unified 'Theory of Everything'

by MARCUS CHOWN

In an enormous cavern, 700m (almost 2,300ft) beneath a wooded hill in southern China, an extraordinary scientific instrument is being built. The Jiangmen Underground Neutrino Observatory (JUNO), a 20,000-tonne (almost 19,700-ton) sphere of a detector liquid surrounded by 43,000 super-sensitive light detectors, is set to probe the secrets of nature's most elusive subatomic particle: the neutrino.

"We've had to overcome many difficulties and challenges in building JUNO," says Dr Yifang Wang, the Director of the Chinese experiment, who came up with the concept and design in 2008 after reading a paper by Italian theorist Prof Serguey Petcov.

"JUNO is a formidable feat of engineering," says Prof Jennifer Thomas, a particle physicist at University College, London, who sits on the international advisory panel of the Chinese experiment. "It's scheduled to start operating in 2025 and we're extremely excited."

Neutrinos are the second most common subatomic particles in the Universe after photons of light. They're abundant in the extreme, but practically refuse to interact with any type of physical matter, hence they're commonly referred to as 'ghost particles'. Hold up your thumb. An astonishing 100 billion or so neutrinos are passing through your thumbnail every second. They were created by the nuclear reactions that generate sunlight. And eight and a half minutes ago they were in the heart of the Sun.

Neutrinos only interact with the atoms of matter on exceptionally rare occasions. Your thumbnail is not nearly enough to stop them in their tracks. As American novelist Michael Chabon observed: "Eight solid light-years of lead… is the thickness of that metal in which you would need to →

1. The Jiangmen Underground Neutrino Observatory's (JUNO) neutrino detector. Visible on its exterior are the spherical brown Photomultiplier Tubes, 2,400 of which are installed outside the stainless steel structure. Coiled around the sides of the sphere are the Earth Magnetic Field compensation coils.

2. Liquid scintillator mixing vats in the Surface Liquid Scintillator Building. Scintillator is a cocktail of a linear alkylbenzene combined with a solvent.

3. Researchers on the project testing Photomultiplier Tubes in the Surface Assembly Building.

4. An aerial photograph showing the JUNO construction site, located in Jiangmen in south China's Guangdong Province.

5. Construction workers have to ride a special funicular down the steep slope of a 1,200m (almost 4,000ft) tunnel to reach the 44m-diameter (144ft) experiment chamber to finish building the JUNO detector facility.

→ encase yourself if you wanted to keep from being touched by neutrinos."

Faced with the elusiveness of their quarry, the physicists' strategy is to put a very large number of atomic nuclei in the path of the neutrinos, boosting the chance of stopping at least some of them. Hence the 20,000-tonne 'target' of liquid in the $300 million (approx £229 million) JUNO.

Although JUNO will be able to detect solar neutrinos, its principal source of the particles will be closer to home: vast throngs of them, streaming out of two nearby nuclear plants. "We have more knowledge about the human-made neutrinos than the ones God made," says Thomas. One of the nuclear plants, at Yangjiang, consists of six reactors; the other, at Taishan, has two. The neutrinos – actually, they're antineutrinos, the antimatter counterpart of neutrinos – come from the disintegration (beta decay) of unstable atomic nuclei created in the splitting (fission) of the uranium and plutonium fuel powering the reactors.

INTERNATIONAL COLLABORATION

JUNO, not far from the town of Jiangmen in rural Guangdong province, is a collaboration of about 700 scientists from 76 institutions in 18 countries. It was specifically located 52.5km (32.6 miles) from each nuclear plant. This maximises the chance of the antineutrinos undergoing a personality change during their journey to the underground experiment. For there isn't just one type of neutrino and one type of antineutrino; there are three of each. And, as they travel, they periodically morph one into another.

No one suspected this bizarre, 'oscillating', behaviour until the 1960s when an American physicist called Dr Raymond Davis built a neutrino detector consisting of 100,000 gallons of cleaning fluid 1.5km (almost a mile) down a mine in Lead, South Dakota. He was looking for chlorine atoms in his detector that converted into argon when they interacted with solar neutrinos. Other scientists thought Davis was nuts. To everyone's amazement, however, he detected only a third of the neutrinos predicted to be coming from the sunlight-generating nuclear reactions. Davis's result was explained by physicists later at the Sudbury Neutrino Observatory in Ontario, and one of them, Prof Arthur McDonald, shared the 2015 Nobel Prize in Physics for it.

It turns out there are three 'flavours' of neutrino: the electron-neutrino, associated with the electron; the muon-neutrino, associated with the heavier muon; and the tau-neutrino, associated with the even heavier tau particle. The weirdest thing is that neutrinos have three mass states – m_1, m_2 and m_3 – but →

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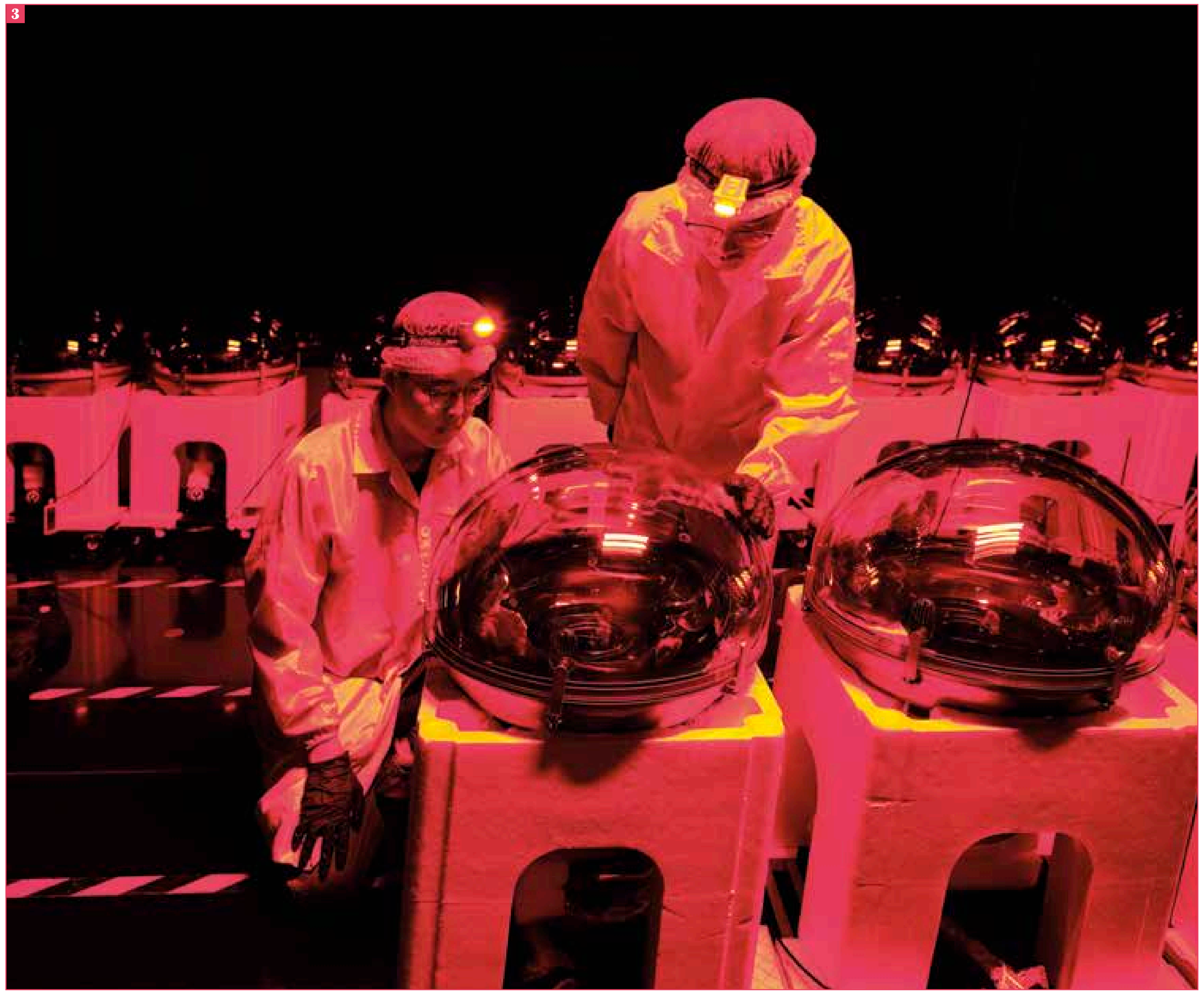

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6. Miles of cables carry signals from the photomultiplier tubes to the facility's computer farm for processing.

7. There are over 17,500 photomultiplier tubes in the detector to pick up the light from a neutrino reaction in the liquid scintillator.

→ they're not the same as 'flavour states'. Instead, each flavour is a different mix, or 'superposition', of the probability waves associated with each mass.

Crucially, the waves within the superposition travel at different speeds. So, as neutrinos move, the mix changes. An electron-neutrino morphs into a muon-neutrino and then a tau-neutrino, before repeating. Davis's shortfall of solar neutrinos therefore occurred because his detector was sensitive only to electron-neutrinos and solar neutrinos are electron-neutrinos for only a third of the time!

LIGHTEST COMMON PARTICLE

Neutrinos have ridiculously tiny masses compared with other subatomic particles – they're about a million times more insubstantial than an electron, the lightest common subatomic particle. No one knows their exact masses or even whether a muon-neutrino is less or more massive than a tau-neutrino. This is where JUNO comes in.

The Chinese experiment is designed to measure the 'mass hierarchy': whether the masses of the neutrinos go up in step with the increasing masses of the electron, muon and tau (a 'normal hierarchy') or whether this isn't the case and there's an 'inverted hierarchy'. Physicists have already determined that m_2 is slightly heavier than m_1 and that there's a greater mass difference between m_3 and the other two mass states. To determine the mass hierarchy, JUNO intends to pin down the missing jigsaw piece: whether m_3 is bigger than m_1 or vice versa.

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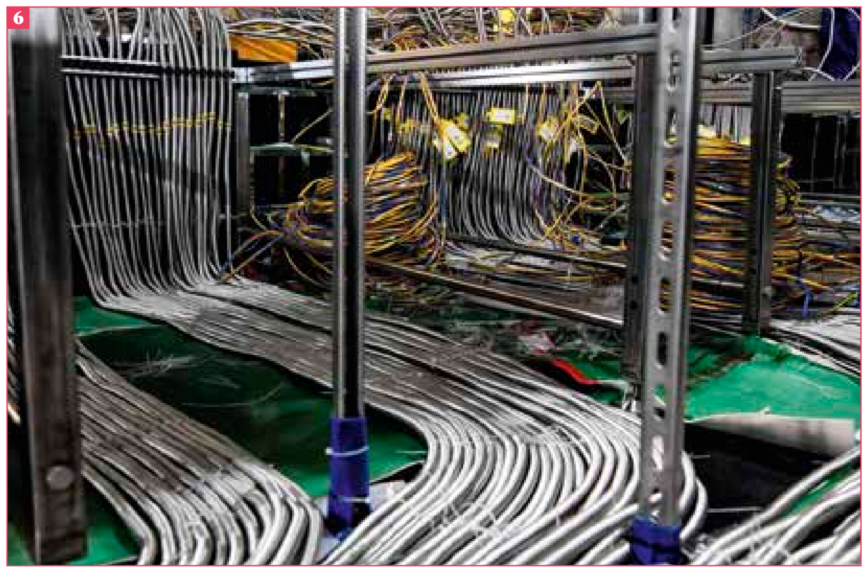
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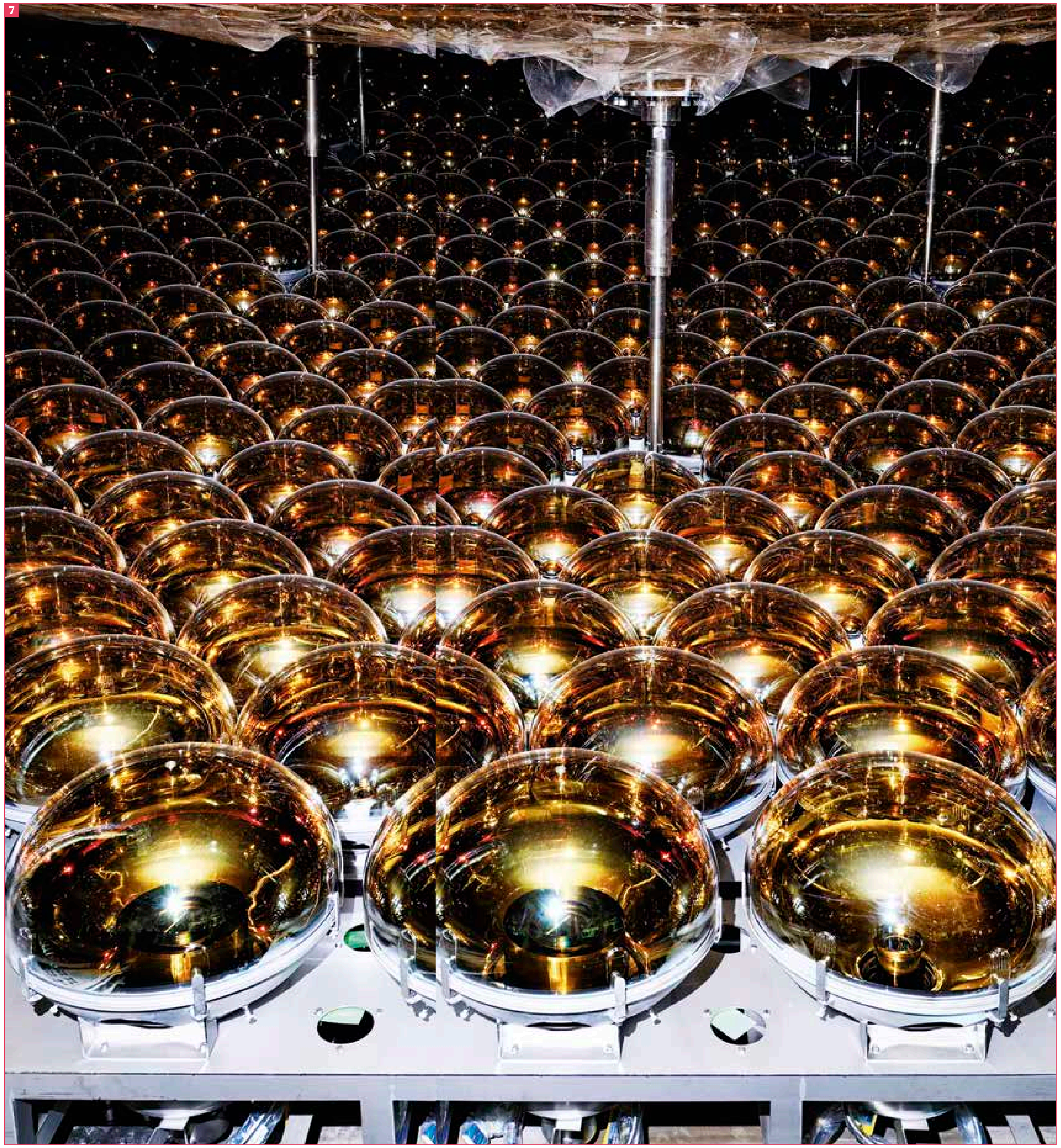
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From the 500 million billion neutrinos per second coming from the two nuclear plants, the JUNO physicists expect to only detect about 40 to 60 anti-neutrinos a day. And the signal they're looking for is so subtle that they estimate they'll need to register 100,000 events to distinguish it from the background signal, which will take about six years.

"JUNO will detect electron-antineutrinos coming from the two nuclear reactors to determine what fraction of the expected number is missing because they have flipped into muon- or tau-neutrinos," says Thomas. The flipping probability is subtly related to whether m_3 is bigger than m_1 and, therefore, whether the mass-hierarchy is normal or inverted.

The signal JUNO detects is the light produced when an antineutrino interacts with a proton in the transparent detector liquid – known as a 'scintillator' – creating a positron and a neutron. The positron quickly meets an electron, its antiparticle, and annihilates into high-energy light known as gamma rays. The neutron blunders around for about 200 microseconds before combining with an atomic nucleus with the emission of gamma rays. These rays cause the scintillator to produce light, which is picked up by the light detectors (photomultiplier tubes) around the sphere of scintillator, and allows the trajectory and energy of the incident antineutrino to be deduced.

The 'double flicker' signal, which has a 200-microsecond gap, allows the JUNO scientists to rule out confusing background events that can also trigger the light detectors, such as those created by muons (highly penetrating particles that arise when high-energy particles from space slam into atoms at the top of the atmosphere). This is why JUNO is buried under 700m (almost 3,000ft) of rock – to shield it from as many muons as possible.

NEW PHYSICS

If finding out whether the neutrino mass hierarchy is normal or inverted seems esoteric, it turns out that anything we can learn about neutrinos has the potential to point to exciting new physics. "Neutrinos were predicted in the 1930s and discovered in the 1950s," says Prof Patrick Huber, a theoretical physicist at the Virginia Polytechnic Institute and State University in the US. "Yet we know less about neutrinos than we know about →

8. A contractor working on the construction of the detector moves one of the supporting bars into place. These will hold the structure steady. JUNO's acrylic sphere is 35.4m (116ft) in diameter and can hold 20,000 tonnes of the liquid scintillator. The acrylic panels are having to deal with high levels of internal stress.

9. Construction of JUNO's sphere continues apace. The team has faced numerous challenges, including limiting the amount of water leaking through the mountain into the experiment chamber. Despite the issues, this ambitious project has stayed close to its original schedule and has hit all of its key technological milestones.

→ the Higgs particle, which was discovered as recently as 2012."

Currently, our best theory of physics is the Standard Model. The highpoint of 350 years of physics, it provides an extraordinarily successful description of how the fundamental building blocks of matter – quarks and leptons – interact via three fundamental forces. But the Standard Model doesn't tell us why the fundamental particles have the masses they have – why, for instance, the top-quark is a million times heavier than the electron – or why the forces have the strengths they have. And, crucially, the Standard Model didn't predict that neutrinos would have a mass.

Neutrinos, in short, are a hairline fracture in the edifice of the Standard Model. The hope is that determining the mass-hierarchy will provide clues to a deeper 'Theory of Everything', of which the Standard Model is an approximation. Processes involving neutrinos are also strongly suspected to have played a role in creating a Universe that's made of matter with pretty much no antimatter, which is one of the biggest mysteries of cosmology.

But determining the mass-hierarchy is important for another reason. Neutrinos, as the second most common subatomic particles in the Universe, would have significantly affected the evolution of the Universe. The greater their masses, the greater their gravity and so the slower the matter of the Universe flew apart in the aftermath of the Big Bang. Neutrinos with greater masses also disrupt galaxy formation, resulting in a Universe where galaxies and galaxy clusters tend to be smaller and less massive than they are in a Universe with less massive neutrinos.

UNDER CONSTRUCTION

Work continues apace on assembling JUNO. Construction workers in hard hats and overalls ride a special funicular down the steep slope of a 1,200m (almost 4,000ft) tunnel to reach the 44m-diameter (144ft) experiment chamber. On 7 March, engineers started pumping scintillator – a cocktail of a linear alkylbenzene and a solvent – into a miniature version of the spherical container. They needed to demonstrate that this can be done without a hitch

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because, once the 20,000 tonnes of liquid starts pouring into the 35.4m-diameter (116ft) acrylic sphere of the full-scale JUNO, there'll be no going back. The scintillator contains extremely low quantities of radioactive material, which can cause a confusing background signal, and pumping it out and back in again could seriously compromise this ultra-purity.

Wang says the JUNO team has faced numerous problems, including achieving a scintillator of sufficient transparency and purity, fabricating the vast number of photomultiplier tubes and limiting water leaking though the mountain into the experiment chamber. "A big surprise has been that the panels of the acrylic sphere are experiencing more internal stress than we expected," says Wang. "We think we've solved the problem for the 30-year lifetime of JUNO, but we're not 100-per-cent sure."

"At several levels JUNO has broken new ground: getting scintillator that's transparent enough, building the very large acrylic inner vessel and creating a factory for a new style of large photomultiplier tubes," says Huber. "The fact that this ambitious project is staying close to its original schedule and has been hitting all key technological milestones is impressive."

In 2025, when it starts operating, JUNO will not only provide answers to some of the fundamental questions about neutrinos, it'll also be able to spot 'geoneutrinos' coming from the radioactive decay of uranium and thorium deep inside Earth. Since such decays keep the interior of the planet molten, 4.55 billion years after its birth, the geo-neutrinos will enable scientists to visualise the churning motion of the mantle deep inside Earth. Over the course of one year, JUNO is expected to bag 400 geoneutrinos – that's more than the total number detected to date.

JUNO will also be able to detect neutrinos from the Sun and from massive stars exploding as supernovae. And, if you think neutrinos have nothing to do with you, it's supernovae that connect the elusive particles directly to your existence. Vast quantities are unleashed when a star at the end of its life implodes to form a super-compact neutron star, and they drive the explosion of its outer layers. If the neutrinos didn't do this, the heavy elements such as carbon, calcium and iron, forged by nuclear reactions over the lives of massive stars, would stay locked inside them forever. In other words, there would be no heavy elements to make a star like the Sun, a rocky planet like Earth, or people such as you and me.

Within the next decade, when JUNO has determined the elusive neutrino mass-hierarchy, Wang intends to upgrade the experiment to look for a process known as neutrino-less double beta decay. This will occur only if the neutrino is its own antiparticle, so that the two neutrinos involved in the two beta decays annihilate each other. "This will tell us something else we don't know about neutrinos and help us zero in on the correct theory that describes these fascinating and elusive particles," says Wang. **SF**

by MARCUS CHOWN (@marcuschown)
Marcus is the author of A Crack in Everything: How black holes came in from the cold and took cosmic centre stage *(Bloomsbury, 2024).*

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