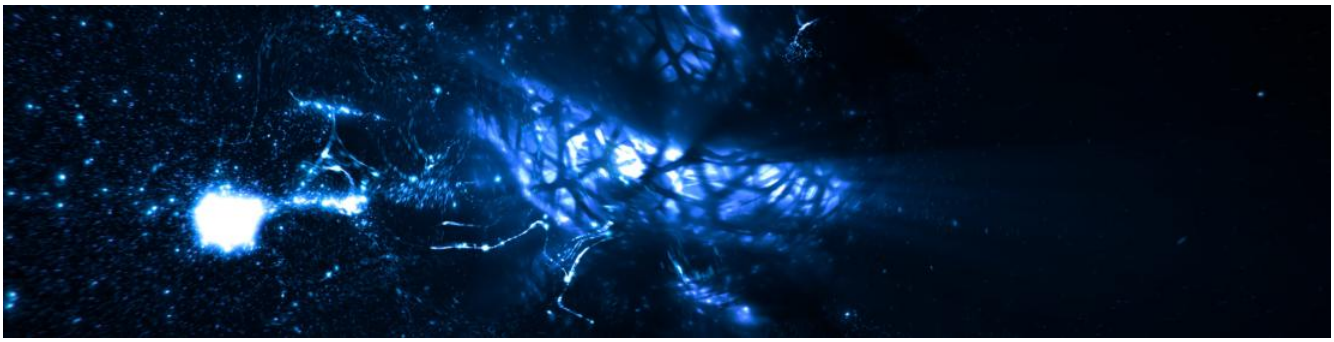
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Europe's deep-sea telescope on a hunt for the origins of the universe

Deep under the Mediterranean, scientists have recorded the highest-energy neutrino ever detected. Now they are working out what this elusive particle could reveal about the universe we live in.

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Below the waves of the Mediterranean, Europe's KM3NeT neutrino telescope is on a cosmic hunt. Towering strings of sensors stretch a kilometre down to the seafloor, arranged in a vast 3D grid.

Its mission? To capture ghostly subatomic particles called neutrinos, messengers that can travel unhindered across the universe – even through planets and stars – carrying clues about events far beyond our solar system.

In the early hours of 13 February 2023, KM3NeT detected something astonishing. An intense flash of pure energy signalled the most energetic neutrino ever observed – 30 times higher than any previous recording. Scientists have been trying to work out where it came from ever since.

Why chase neutrinos?

Neutrinos were first theorised in the 1930s and detected decades later. They are among the most abundant particles in the universe, yet also the most elusive.

Every second, billions of neutrinos pass through our bodies without leaving a trace. They have no electric charge and almost no mass – at least a million times lighter than an electron – and they rarely interact with matter, which makes them extremely hard to detect.

It is this ghostly quality that makes them so fascinating to physicists.

“Neutrinos are the most interesting particles around at the moment,” said Paschal Coyle of the French National Centre for Scientific Research, who coordinates an EU-funded project called KM3NeT-INFRADEV2 that is supporting the development of the KM3NeT infrastructure. “There are lots of mysteries surrounding them. They’re the least understood of the fundamental particles.”

Because neutrinos can cross the universe without being absorbed, they carry pristine information from the most extreme environments known to science: exploding stars, black holes and cosmic collisions.

Studying them could reveal how the universe works – and even why matter exists at all.

“Neutrinos are the closest thing to nothing we can imagine, but they are key to fully understanding the workings of the universe,” said Coyle.

Ghost hunters

Every so often, a neutrino strikes an atomic nucleus, creating a shower of secondary particles. In dense, transparent material like ice or water, this collision releases a faint blue flash of light known as Cherenkov radiation. KM3NeT’s sensors are designed to catch this signal.

This approach is shared by other neutrino observatories, such as IceCube in Antarctica and Super-Kamiokande in Japan. IceCube scans deep polar ice, while KM3NeT peers through the dark waters of the Mediterranean Sea.

KM3NeT is one of Europe’s flagship research infrastructures and one of the world’s most ambitious physics projects. Backed by an international consortium with EU and national funding, it consists of two separate installations.

ARCA (Astroparticle Research with Cosmics in the Abyss), based off the coast of Sicily, is designed to track high-energy neutrinos from deep space. ORCA (Oscillation Research with Cosmics in the Abyss), near Toulon in France, focuses on neutrino behaviour and mass.

Each array is built from vertical lines of basketball-sized glass spheres containing ultra-sensitive optical sensors. These lines rise from the seafloor like underwater skyscrapers, stretching a kilometre into the dark. More than 1 000 modules are already in place, with 6 000 planned by 2027.

“It seemed like a crazy idea to build a detector at the bottom of the sea to catch these very weird particles,” said Aart Heijboer, a senior physicist at the Dutch National Institute for Subatomic Physics, who helped design the telescope. “That caught my imagination.”

All this engineering is for a single purpose: to glimpse those rare flashes when a neutrino finally reveals itself.

A record-breaking signal

The neutrino detected in 2023, named KM3-230213A, registered an energy charge of 220 petaelectronvolts (PeV) – an extraordinarily large figure for a single particle and almost inconceivable in particle physics. “We weren’t really expecting to find such an event,” said Coyle. “We had to redo a whole load of simulations.”

Where did it come from? That remains the big mystery.

Neutrinos are produced by a variety of sources, from the nuclear reactions powering the Sun to exploding stars (supernovae) and other high-energy cosmic events. One theory proposes that the most energetic neutrinos originate from blazars – active galaxies whose supermassive black holes hurl jets of energy directly towards Earth.

Another possibility is that high-energy cosmic rays, streaming across the universe, collide with photons of light to generate neutrinos. If KM3-230213A was produced this way, it would suggest cosmogenic neutrinos are more common than expected.

“Or we were just lucky,” admits Coyle. “It could be that KM3NeT managed to spot a rare, very high-energy neutrino by chance.”

Researchers are refining calculations to trace its exact origin. “In the coming months, we’ll have a much more precise measurement of its direction,” said Heijboer. “If it’s coming from a blazar, that’s very exciting. If it’s cosmogenic, that’s also exciting.”

Probing the nature of matter

While ARCA hunts for the source of the universe’s most powerful particles, ORCA focuses on how neutrinos change identity, or oscillate, between the three different “flavours” – electron, muon and tau – as they travel through space.

These oscillations may reveal the ordering of neutrino masses, a missing piece in the Standard Model of physics, the theory that describes the fundamental particles of matter. Mass ordering refers to the sequence of the three neutrino mass states from lightest to heaviest.

Why does this matter? Because understanding neutrinos might explain why there is something rather than nothing.

After the Big Bang 13.7 billion years ago, matter and antimatter should have destroyed one another, leaving only empty space. Yet matter survived. Neutrinos may hold the key, particularly if they prove to be their own antiparticle – a possibility scientists are eager to test.

“All the experiments that try to measure the difference between a neutrino and an anti-neutrino get confused because they don’t know what the mass ordering is,” explained Coyle. “It’s an important input to figuring out why there’s more matter than antimatter.”

Europe’s deep-sea advantage

By building KM3NeT, Europe has secured a leading role in this global scientific endeavour. “Very importantly, we got funding from the EU to do a design study in 2006,” said Coyle. From there, additional European and national support helped turn the concept into reality.

Already, that investment is paying off, with detections like KM3-230213A and more discoveries expected as the telescope expands.

“We don’t know their mass, we don’t know their mass ordering, we don’t know if they are their own antiparticle,” said Coyle. “So neutrinos are where it’s at at the moment.”

With thousands more sensors still to be deployed, KM3NeT is not only strengthening Europe’s role in fundamental research, but also listening to some of the faintest signals in nature.

Each flash of light deep beneath the Mediterranean might hold a message about the birth of the universe, or even a clue as to why there is something rather than nothing.

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More info

- KM3NET-INFRADEV2 (CORDIS)
- KM3NeT website
- European Research Infrastructures
- EU space policy
- European Strategy Forum on Research Infrastructures
- Observation of an ultra-high-energy cosmic neutrino with KM3NeT, Nature, February 2025