Age of the NEUTRINO

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As researchers at CERN, Europe's particle-physics laboratory near Geneva, dream of super-high-energy colliders to explore the Higgs boson, their counterparts in other parts of the world are pivoting towards a different subatomic entity: the neutrino.

Neutrinos are more abundant than any particle other than photons, yet they interact so weakly with other matter that every second, more than 100 billion stream — mainly unnoticed — through every square centimetre of Earth. Once thought to be massless, they in fact have a minuscule mass and can change type as they travel, a bizarre and entirely unexpected feature that physicists do not fully understand (see 'An unconventional particle'). Indeed, surprisingly little is known about the neutrino. "These are the most ubiquitous matter particles in the Universe that we know of, and probably the most mysterious," says Nigel Lockyer, director of the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois.

Four unprecedented experiments look poised to change this. Two — one in China and one in India — already have the go-ahead, and plans to erect detectors in Japan and the United States are in the works (see 'Where they will be detected'). Buried underground to prevent interference from other particles, all four are designed to detect many more neutrinos, and to probe the switching process in more detail, than any existing experiment.

The results are expected to feed into some of the most fundamental questions in cosmology (see 'Flurry of experiments'). Some of the experiments will make their own neutrinos; all will use any they can capture from the Sun or from supernova explosions. "The age of the neutrino," Lockyer says, "could go on for a very long time."

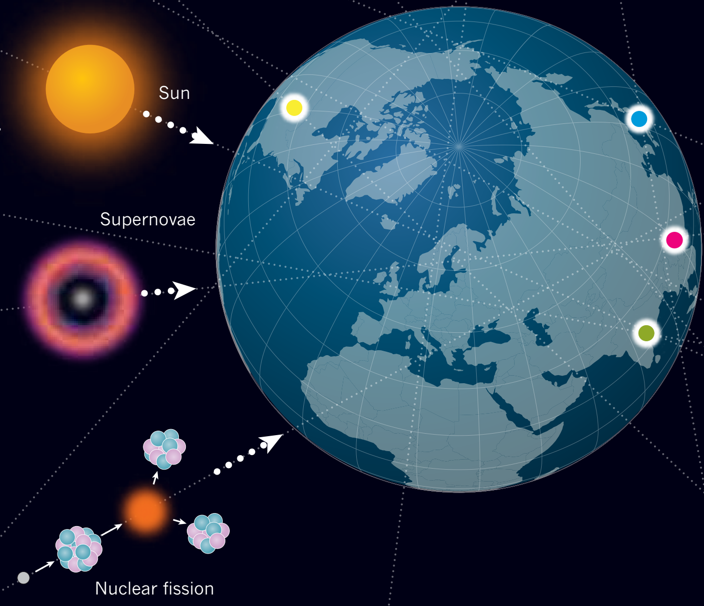
NEUTRINO FACTORIES

Neutrinos are everywhere, generated by a variety of processes.

Fusion of hydrogen nuclei to form helium in the Sun.

Supernovae and collisions between cosmic rays and air particles in Earth's atmosphere.

Particle accelerators smashing protons into a target and fission from the radioactive decay of elements inside nuclear reactors.



WHERE THEY WILL BE DETECTED

Deep Underground Neutrino Experiment (DUNE), United States
Status: Planned
Cost: US$1 billion
Will make highest-energy neutrinos of any experiment.

Hyper-Kamiokande, Japan
Status: Planned
Cost: About $800 million
Will be the world's largest neutrino detector — it is 25 times bigger than its predecessor, Super-Kamiokande.

Jiangmen Underground Neutrino Observatory (JUNO), China
Status: Construction begun
Cost: $330 million
Sits under 700 metres of rock.

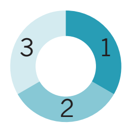
India-based Neutrino Observatory (INO), India
Status: Funding approved
Cost: $233 million
Will be largest experimental basic-science facility in India.

AN UNCONVENTIONAL PARTICLE

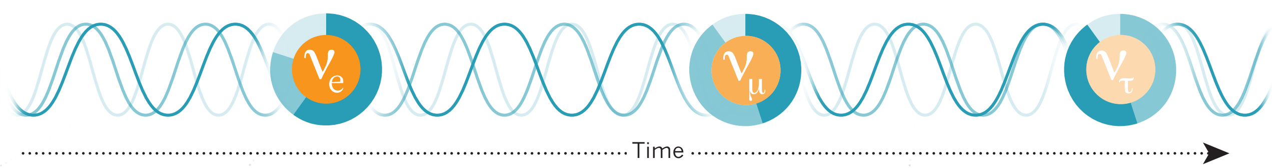
A neutrino (ν), or its antimatter counterpart the antineutrino, is always produced alongside an electron (e) or one of the electron's heavier cousins, the muon (μ) or tau (τ) particle — and the presence of this partner particle gives the neutrino a 'flavour'.

Flavours

Unlike electrons, muons and tau particles, neutrinos do not have definite masses. Instead, every neutrino is a mixture — or quantum superposition — of three 'mass states', and those states mix in different proportions to make different flavours.



Mass states



As a neutrino travels, each state contributes to its mass at a varying rate, causing the neutrino to change flavour over time. The frequency of the changes depends on the differences between the mass states, the neutrino's energy and parameters that govern how the states are allowed to mix.

Flurry of experiments

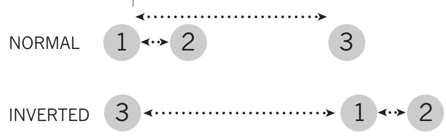
The detectors in China (JUNO) and India (INO) are designed to untangle the relationship between the three mass states, with implications for the origins of the forces of nature. By contrast, DUNE in the United States and Hyper-Kamiokande in Japan aim to spot differences in how neutrinos and antineutrinos oscillate between flavours. That could solve a second cosmological puzzle: why the Universe is made up of matter rather than antimatter. All four detectors will also hunt for a hypothesized 'sterile' neutrino.

BIG QUESTIONS

What is the mass hierarchy?

Although physicists know that neutrinos exist in three different mass states, which state is the lightest and which is the heaviest remains a mystery. Knowing that would help scientists to decide between rival theories about how the four forces of nature unite as a single force at high energies, similar to those experienced in the moments after the Big Bang.

Physicists know the differences between the first and second and the first and third mass states. They also know that that the second mass state is bigger than the first. That leaves just two possibilities for the hierarchy:



Why is there so little antimatter?

A major puzzle is why the Universe is filled with matter, rather than antimatter. Differences in how neutrinos and antineutrinos oscillate between flavours as they travel could provide a clue.

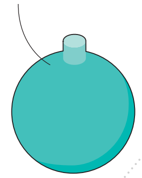
Is there a 'sterile' neutrino?

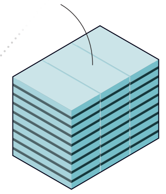
Some theories propose a fourth, sterile, neutrino. If it exists, it would interact with matter even more weakly than the other flavours, and could account for the as-yet-undetected dark matter that is thought to make up 85% of all the matter in the Universe. If neutrinos mysteriously 'disappear' at a detector, that could be a sign that they have switched into sterile neutrinos.

2020

JUNO

Will measure the rate at which antineutrinos of different energies created at the Yangjiang and Taishan nuclear power plants (53 kilometres apart) switch flavour to calculate the differences between mass states.





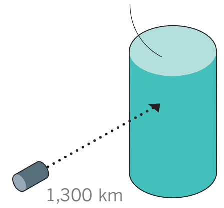
INO

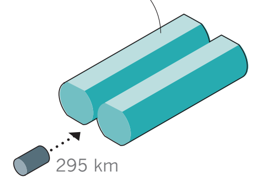
Will detect neutrinos and antineutrinos produced by cosmic rays from the other side of Earth. If the journey boosts neutrino switching, this implies a normal mass hierarchy; if antineutrino switching speeds up, the inverted hierarchy is likely.

2025

DUNE

Will send neutrinos of different energies from Fermilab to the Sanford Underground Research Facility in South Dakota. Physicists will record differences in the way neutrinos and antineutrinos oscillate and how this depends on their energy.





Hyper-Kamiokande

Neutrinos and antineutrinos will travel from the Japan Proton Accelerator Research Complex (J-Parc) in Tokaimura. Particles will be of a single energy, selected to maximize the detection of flavour switching over the distance from J-Parc.